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EDITORIAL

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PREFACE

The present issue of *History of Science and Technology* brings together a diverse collection of studies devoted to the historical development of scientific knowledge, technological systems, research institutions, and socio-technical transformations across different regions of the world. The contributions included in this volume cover a broad chronological range, extending from pre-modern documentary cultures and early administrative systems to contemporary discussions concerning energy technologies, industrial innovation, and technological heritage. Together, they demonstrate the vitality of the history of science and technology as an interdisciplinary field and highlight the value of approaches that connect technical developments with political, social, economic, and cultural contexts.

A common feature shared by many of the studies presented in this issue is their attention to the institutions, communities, and environments within which scientific knowledge is produced and technological practices evolve. Rather than treating science and technology as autonomous domains, the authors examine the interaction between innovation and governance, expertise and power, material culture and social change. The issue therefore contributes to broader historiographical discussions concerning the circulation of knowledge, the construction of technological systems, and the role of science and technology in shaping historical processes.

The issue opens with Gennadiy V. Bulavko's article *"Sunlight harvested: A historical evolution of materials for photovoltaics, solar fuels, photocatalysis, and emerging light-charged devices"*. The author examines the historical evolution of materials used for the conversion, storage, and utilization of solar energy. By integrating the histories of photovoltaics, photocatalysis, solar fuels, and photo-assisted energy storage within a single analytical framework, the study identifies common technological trajectories and material-design principles that have shaped modern sustainable-energy research. Particularly valuable is the article's long-term perspective, which reveals how recurring questions of efficiency, durability, resource availability, and environmental sustainability have influenced successive generations of energy technologies. In doing so, the contribution demonstrates that many challenges currently associated with the green-energy transition have deep historical roots extending well beyond contemporary climate debates.

Questions of administration, information management, and state governance are addressed in the contribution by Sherzodjon Choriyev and his co-authors devoted to the archival system of the Bukhara Khanate. Their study demonstrates how documentary practices, chancery procedures, and recordkeeping systems functioned as essential instruments of political authority and administrative control in Central Asia. By reconstructing the organization of archival documentation and its practical functions, the authors contribute to a deeper understanding of information management in pre-modern states and expand the documentary history of the region.

The role of individuals whose scientific contributions remained largely invisible for decades is explored in Yolanda Muñoz Rey's article on women employed as calculators at *the Royal Observatory of the Navy in San Fernando*. The study contributes to the growing historiography of gender and science by restoring the place of women within the institutional history of astronomy and scientific labour.

The circulation of agricultural knowledge and the formation of professional scientific communities constitute the focus of Svitlana Nyzhnyk's contribution. Through the history of scientific meetings and congresses, the article reveals how mechanisms of communication and exchange shaped the development of agricultural science and facilitated the dissemination of expertise across institutional and regional boundaries. The study highlights the importance of scientific networks in transforming local knowledge into broader professional practices.

A different perspective on science and technology is offered next article in examination of the Chernobyl disaster. Rather than treating the accident solely as a technological failure, the author situate it within broader discussions of safety culture, organizational decision-making, and the governance of complex technological systems. The article demonstrates that the consequences of Chernobyl extended far beyond the immediate events of April 1986 and profoundly influenced international approaches to nuclear safety, risk management, and regulatory oversight. By linking the disaster to wider questions of institutional responsibility and technological governance, the author emphasize its enduring significance for both the history of nuclear energy and contemporary debates concerning high-risk technologies.

The complex relationship between scientific knowledge and political repression is explored in the article by Marat Ybyraikhan and his co-authors devoted to *the Scientific Agricultural Experimental Station of Karlag*. Drawing upon archival sources, the authors reconstruct the activities of imprisoned scientists and reveal how research continued to be conducted within one of the most restrictive environments of the Soviet era. Their findings contribute to a growing body of scholarship on repressed science and demonstrate the paradoxical coexistence of scientific productivity and political coercion within the Soviet camp system. The article also provides valuable biographical and institutional insights into the lives and work of researchers whose contributions remained largely absent from mainstream historical narratives.

The history of encyclopedic knowledge receives attention in the contribution by Mykola Zhelezniak and Oleksandr Ishchenko, who analyze the development of *the Istituto della Enciclopedia Italiana (Treccani)*. Their research demonstrates how encyclopedias function not only as repositories of knowledge but also as instruments that shape national and international representations of history, culture, and identity. Particularly noteworthy is the discussion of Ukraine-related entries within the *Treccani corpus*, which provides a useful perspective on the ways in which Ukrainian history and culture have been represented within European intellectual traditions. More broadly, the article illustrates how encyclopedic projects adapt to changing technological environments while preserving their role as authoritative sources of knowledge.

Agrarian modernization, state policy, and food security emerge as central themes in Pantelis Zoiopoulos's study of interwar Greece. By examining debates surrounding agricultural development and national self-sufficiency, the article highlights the important role played by scientific expertise in economic planning and rural transformation. The study further illustrates how agricultural policy became intertwined with broader questions of modernization, national development, and social stability.

Material culture and technological heritage are represented by the article of Zoya Chegusova, Mykhailo Bokotei and, Volodymyr Khyzhynskyi devoted to *Ukrainian huta glass*. Combining the history of technology with art-historical approaches, the authors reconstruct the development of glassmaking traditions and emphasize their significance within the broader history of Ukrainian craftsmanship and industrial culture. The study demonstrates that huta glass should be understood not only as an artistic phenomenon but also as a technological achievement shaped by local resources, production techniques, and professional knowledge. By integrating material, technological, and cultural perspectives, the article contributes to ongoing discussions concerning the preservation and interpretation of industrial and artistic heritage.

The interaction between technology and everyday life is examined in Rostyslav Konta's study of Mayak tape recorders in late Soviet Ukraine. Through the analysis of production practices, technological constraints, and patterns of consumption, the article demonstrates how sound-recording technologies became integrated into the social and cultural experience of late socialism. In doing so, it offers valuable insights into the relationship between industrial production and everyday technological practices.

Urban modernization and technological change form the central theme of Mohamad Khairul Anuar Mohd Rosli's contribution on the history of lighting in Kuala Lumpur. The transition from traditional forms of illumination to electrified urban environments is presented as a process that transformed not only infrastructure but also daily routines and perceptions of urban space. The article thus connects the history of technology with broader questions of urban development and modernization.

The history of medicine is represented by the article of Vivi Sandra Sari and her co-authors, who examine the development of ophthalmological services in Indonesia. Their study highlights the institutional, professional, and social dimensions of healthcare modernization and demonstrates how medical knowledge became embedded within broader processes of societal transformation. The contribution also illustrates the importance of regional perspectives in understanding the global history of medicine.

The issue concludes with Andrii Tarasenko's contribution on compartmentalization and system ranking in armored vehicle design. By comparing engineering approaches developed in different countries, the author demonstrates how technological solutions emerged in response to common military challenges and how their legacy continues to influence contemporary armored-vehicle development. The article provides an important reminder that many current engineering concepts originate in earlier periods of technological experimentation and strategic competition.

Taken together, the articles published in this issue confirm that the history of science and technology remains one of the most dynamic and intellectually diverse areas of historical scholarship. The studies presented here examine not only inventions, discoveries, and technological artefacts, but also the institutions, communities, and social processes that enabled their emergence and dissemination. They demonstrate that scientific knowledge is always produced within specific historical circumstances and that technological systems are shaped as much by human choices and social conditions as by technical considerations alone.

The volume also illustrates the increasingly international character of research in the history of science and technology. Contributions from scholars representing different academic traditions and geographical regions provide opportunities for comparative perspectives and methodological exchange. Although the subjects examined range from pre-modern archival systems to contemporary energy technologies, many of the articles share a common concern with the ways in which knowledge is organized, transmitted, preserved, and applied in changing historical environments.

The Editorial Board hopes that the studies assembled in this issue will stimulate further scholarly discussion, encourage international cooperation, and inspire new research into the historical dimensions of science, technology, and innovation. By bringing together contributions that cross disciplinary, chronological, and geographical boundaries, this volume seeks to promote a deeper understanding of the complex processes through which scientific knowledge and technological systems have shaped human societies in the past and continue to influence them in the present.

The Editorial Board expresses its sincere gratitude to the authors, reviewers, and members of the editorial team whose efforts made the publication of this issue possible.

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Sunlight harvested: A historical evolution of materials for photovoltaics, solar fuels, photocatalysis, and emerging light-charged devices

Abstract. *This review treats sunlight as a central driving resource for sustainable technologies and analyzes how materials have been developed to capture, convert, and store solar energy in distinct yet related functional pathways. A historically grounded and cross-disciplinary framework is applied to four main classes of sunlight-driven processes: conversion of solar radiation to electricity, storage of solar energy in chemical bonds, photocatalytic degradation of pollutants, and direct light-assisted energy storage. The evolution of photovoltaic systems is examined from crystalline and multicrystalline silicon to thin-film absorbers, dye-sensitized and organic solar cells, and contemporary metal halide perovskites and tandem configurations, with emphasis on the interplay between efficiency, stability, and material availability. Photoelectrochemical and catalytic routes to solar fuel production are analyzed with specific attention to the development of metal oxides, molecular complexes, nanostructured catalysts, and selective* CO_2 *reduction systems as platforms for storing sunlight in chemical bonds. Photocatalytic environmental remediation is considered in the context of semiconductor design, interfacial charge-transfer processes, and the integration of light-harvesting materials into water and air treatment schemes. Recent advances in light-charged and photo-assisted energy storage, including photo-batteries, photo-supercapacitors, redox-based solar energy storage concepts, and photo-responsive concentration cells, are evaluated as emerging approaches that seek to couple photon absorption, charge separation, and storage within unified device architectures. Across these domains, the study identifies recurrent materials design principles, including band gap and band alignment optimization, catalyst coordination environment, interfacial and kinetic control, operational durability, reliance on abundant and low-toxicity elements, and life-cycle compatibility with large-scale deployment. By comparing these trajectories within a single analytical framework,* *the work delineates common patterns of technological success and failure and defines realistic directions for the rational development of adaptive molecular, hybrid, and semiconductor materials for next-generation sunlight-driven energy and environmental technologies.*

Keywords: *materials history; photo-assisted energy storage; light-harvesting materials; CO_2 reduction; sustainable materials design*

1. Introduction.

Physically, solar radiation represents the dominant primary clean energy flux at the Earth's surface (Chu & Majumdar, 2012; Lewis & Nocera, 2006).

Technologically, it underpins a broad range of concepts that seek to generate electricity, store energy in chemical bonds, drive redox transformations, and remove pollutants without additional carbon-intensive inputs (Ardo et al., 2018; Fujishima & Honda, 1972; Hoffmann, Martin, Choi, & Bahnemann, 1995).

Treating sunlight explicitly as this common locomotive allows different materials-based approaches to be viewed within a single framework rather than as isolated thematic fields (Lewis, 2007).

From a historical perspective, four principal sunlight-driven transformation pathways have crystallized into distinct research and technology domains. The first is the direct conversion of solar radiation into electricity in photovoltaic systems (Fig 1. a) (Su, Zhang, Lai, Feng, & Shi, 2010), which traces back to the first observation of the photovoltaic effect by Edmond Becquerel in 1839 (Bulavko, 2024). The photovoltaic effect refers to the generation of an electromotive force and electric current in a material upon exposure to light, as originally observed by Edmond Becquerel in an electrochemical cell. It is distinct from the photoelectric effect, demonstrated by Heinrich Hertz in 1887, which involves the emission of electrons from a surface irradiated by light of sufficient energy. Both phenomena are rooted in the quantum nature of light-matter interaction, yet the photovoltaic effect specifically entails charge separation and current generation within a device, which became the physical basis for solar cell technology. The first practical silicon p–n junction devices at Bell Labs in 1954 (Chapin, Fuller, & Pearson, 1954) then translated this principle into a working power source.

The field subsequently expanded through thin-film absorbers and into organic and molecular approaches. The first efficient planar heterojunction organic solar cell was reported by Tang in 1986, using a CuPc-perylene bilayer architecture (Tang, 1986). The bulk-heterojunction concept was enabled by the discovery of ultrafast photoinduced electron transfer from conjugated polymers to fullerenes in 1992 (Sariciftci, Smilowitz, Heeger, & Wudl, 1992) and implemented in high-efficiency polymer-fullerene devices in 1995 (Yu, Gao, Hummelen, Wudl, & Heeger, 1995).

A parallel molecular pathway arose with dye-sensitized solar cells introduced by O'Regan and Grätzel in 1991 (O'Regan & Grätzel, 1991).

In the past decade, metal-halide perovskites emerged from sensitized cells to solid-state and meso-superstructured architectures, beginning with the 2009 JACS report of perovskite sensitizers (Kojima, Teshima, Shirai, & Miyasaka, 2009) and followed by solid-state devices in 2012 that rapidly achieved near-10% efficiency (Kim et al., 2012; Lee, Teuscher, Miyasaka, Murakami, & Snaith, 2012), ultimately leading to today's perovskite and perovskite-silicon tandem configurations.

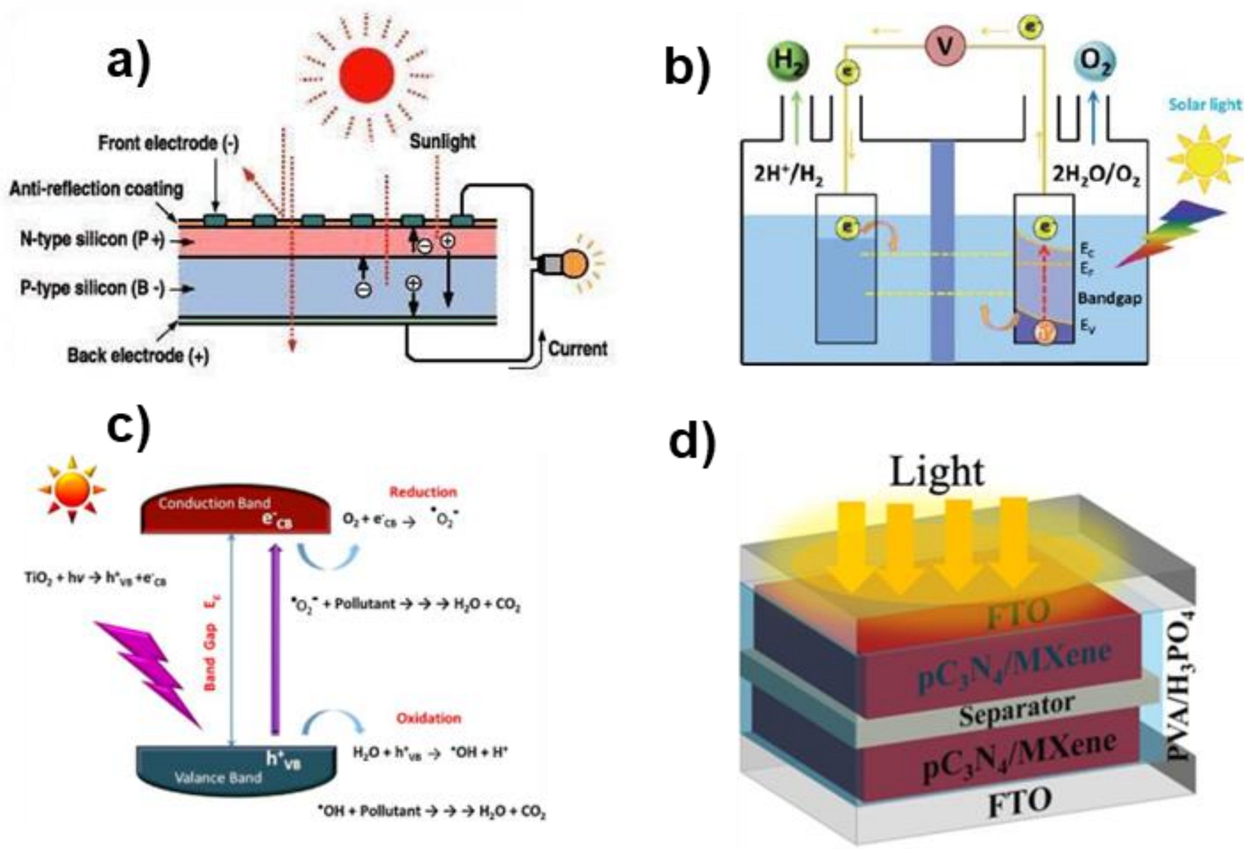

Figure 1. Principal sunlight-driven transformation pathways: (a) photovoltaics (Su, Zhang, Lai, Feng, & Shi, 2010); (b) solar fuels (Bhatt & Lee, 2015); (c) photocatalytic remediation (Wei, Wu, Meng, Zhang, & Cao, 2023); (d) light-charged storage (Kumar, Mondal, Panwar, Shekhawat, & Misra, 2024).

The second pathway concerns the storage of sunlight in chemical bonds through photoelectrochemical and photocatalytic processes for water splitting and carbon dioxide reduction (Fig.1. b) (Bhatt & Lee, 2015). The modern field originates with the demonstration of water splitting on TiO_2 photoanodes by Fujishima and Honda in 1972, which established semiconductor photoelectrochemistry as a route to solar fuels (Fujishima & Honda, 1972). Subsequent progress included integrated devices that couple light absorption with electrolysis, notably the monolithic photovoltaic photoelectrochemical cell for hydrogen production reported by Khaselev and Turner in 1998 (Khaselev & Turner, 1998). Photocatalytic and photoelectrocatalytic reduction of CO_2 emerged soon after the water-splitting breakthrough, with Halmann's 1978 demonstration of photoassisted CO_2 reduction on p-type GaP photocathodes (Halmann, 1978) and the 1979 report by Inoue, Fujishima, Konishi, and Honda showing CO_2

conversion to fuels in aqueous semiconductor suspensions (Inoue, Fujishima, Konishi, & Honda, 1979).

The motivation for these pathways is the production of green hydrogen and solar-derived carbon products that support deep decarbonization targets articulated in international frameworks such as the Paris Agreement and in strategic assessments of hydrogen's role by the International Energy Agency.

Materials development has progressed from mainly UV-active oxides to visible-light-responsive photocatalysts and increasingly selective molecular and heterogeneous catalysts for CO_2 reduction, as summarized in critical reviews of photocatalytic water splitting and solar CO_2 conversion (Chang, Wang, & Gong, 2016; Kudo & Miseki, 2009).

The third pathway concerns the use of semiconductor photocatalysts for the oxidation and mineralization of pollutants in water and air, as well as for self-cleaning surfaces (Fig 1. c) (Wei, Wu, Meng, Zhang, & Cao, 2023). Early proof-of-concept studies demonstrated heterogeneous photocatalytic oxidation of toxic anions such as cyanide and sulfite on illuminated semiconductor powders, establishing titanium dioxide as a benchmark material (Frank & Bard, 1977).

Foundational reviews then consolidated mechanisms and application prospects for TiO_2 photocatalysis across environmental media (Fujishima, Rao, & Tryk, 2000).

The concept of transparent self-cleaning TiO_2 coatings on glass was introduced in the mid-1990s, providing a route to photodegrade organic films directly on surfaces (Paz, Luo, Rabenberg, & Heller, 1995), followed by studies detailing substrate effects and mitigation strategies (Paz & Heller, 1997). Commercialization arrived with photocatalytic self-cleaning architectural glazing, exemplified by Pilkington Activ in 2001, which coupled UV-driven photocatalysis with photoinduced hydrophilicity to enable rain-assisted cleaning.

To expand activity into the visible range, nitrogen-doped TiO_2 and related band-gap engineering approaches were reported in the early 2000s (Asahi, Morikawa, Ohwaki, Aoki, & Taga, 2001). Subsequent material families, including graphitic carbon nitride, broadened the palette of visible-light photocatalysts and entered environmental degradation studies alongside solar-fuel chemistry (Xinchen Wang et al., 2009).

Standardized assessment protocols for gas-phase depollution, particularly NO and NO_2 abatement on photocatalytic construction materials, were established through ISO 22197 methods and are now widely used in laboratory and field evaluations.

Current research targets include dyes and pharmaceuticals in water, volatile organic compounds and nitrogen oxides in air, and durable self-cleaning or depolluting building surfaces. Reported field deployments show both promise and variability in real-world NO_x reduction, underscoring the need for rigorous kinetics, long-term durability studies, and realistic illumination and flow conditions during performance testing (Dahl, Jensen, Bigi, & Ghermandi, 2023; Russell, Frederickson, Hertel, Ellermann, & Jensen, 2021; Sanchez, Santiago, Martilli, Palacios, Núñez, Pujadas, & Fernández-Pampillón, 2021).

The fourth pathway concerns direct or assisted storage of energy in light-charged devices, where light harvesting, charge separation, and storage are coupled within unified architectures (Fig. 1. d.) (Kumar, Mondal, Panwar, Shekhawat, & Misra, 2024). Foundational proposals that linked illumination to storage appeared in the 1970s (Hodes, Manassen, & Cahen, 1976). Early device embodiments were dye-sensitized photocapacitors, first shown as a two-electrode self-charging capacitor in 2004 and improved with a three-electrode configuration in 2005 (Chen, Yulius, Woodall, & Broadbridge, 2004; Murakami, Kawashima, & Miyasaka, 2005). Integration with battery chemistries followed, including direct solar charging of Li-ion cells and related photo-assisted batteries in the mid-2010s, and fully photo-rechargeable Li-ion operation under ambient light in 2021. Parallel progress in solar flow batteries demonstrated monolithic architectures with double-digit solar-to-output electricity efficiency (Fu, Li, Yang, Lin, Veyssal, He, & Jin, 2021). As an emerging molecular route, a spiropyran based photoelectrochemical concentration cell shows visible-light self-recharging via reversible Zn-spiropyran complexation, illustrating adaptive photochromic chemistry as a viable light-charged storage motif (Hrebonkin & Bulavko, 2025).

Existing literature provides extensive and authoritative reviews within each of these domains. Comprehensive assessments of photovoltaic materials, covering crystalline and thin-film technologies as well as efficiency benchmarks, are given in (Polman, Knight, Garnett, Ehrler, & Sinke, 2016), while the operational principles and performance limits of molecular-sensitizer-based architectures are detailed in reviews of dye-sensitized solar cells (Hagfeldt, Boschloo, Sun, Kloo, & Pettersson, 2010) and organic solar cells (Bulavko, 2024). The mechanistic and materials foundations of semiconductor-mediated water splitting and hydrogen evolution are treated in (Hisatomi, Kubota, & Domen, 2014; Kudo & Miseki, 2009; Walter, Warren, McKone, Boettcher, Mi, Santori, & Lewis, 2010), and the catalytic and computational aspects of CO_2 photoconversion are addressed in (Kovačič, Likozar, & Huš, 2020; Qiao, Liu, Hong, & Zhang, 2014). For environmental applications, foundational and updated accounts of TiO_2-based remediation and surface photochemistry appear in (Hoffmann, Martin, Choi, & Bahnemann, 1995; Nakata & Fujishima, 2012), and the principles and device concepts for integrated photo-rechargeable systems are consolidated in (Pujari, Kim, Abbasi, Lee, Greenham, & De Volder, 2024; Schmidt, Hager, & Schubert, 2016; Yu, McCulloch, Huang, Trang, Lu, Amine, & Wu, 2016). However, these analyses are most often confined to a single technology class or to a narrow subset of materials and performance metrics. They rarely address how different sunlight-driven approaches compete and complement one another, how they rely on overlapping design principles for absorbers, catalysts, and interfaces, or how they collectively translate the same primary solar resource into distinct but interconnected functional outputs. There is also limited systematic discussion of how considerations such as elemental abundance, device stability, end-of-life management, and life-cycle sustainability have historically influenced materials choices across these fields in a comparable manner.

The present study addresses this gap by examining in an integrated way the four transformation pathways in which sunlight acts as the initiating resource: photovoltaic electricity generation, solar fuel production via photoelectrochemical and photocatalytic routes, photocatalytic environmental remediation, and light assisted energy storage. For each pathway, the historical evolution of key materials systems is outlined from foundational demonstrations to state-of-the-art solutions, with emphasis on the scientific and technological conditions under which specific semiconductors, molecular absorbers, catalysts, polymeric and hybrid structures, and interfacial architectures became relevant. Particular attention is given to cross cutting criteria that recur across different technologies, including band gap and band edge alignment with the solar spectrum and target reactions, control of bulk and interfacial charge transport, catalyst coordination environment and active site design, resistance to photochemical and electrochemical degradation under realistic operation, reliance on abundant and non-critical elements, compatibility with scalable manufacturing, and overall life cycle sustainability. Because photovoltaics represent the longest-established and most extensively documented of the four pathways, and because many design principles first articulated for solar cells were subsequently adapted in solar fuels, photocatalysis, and light-charged storage, the photovoltaic section is treated in greater depth and serves as a reference framework for the analysis of the remaining three domains.

Methodologically, this comprehensive review is based on a critical and selective analysis of peer reviewed literature, including seminal experimental reports, landmark conceptual papers, and recent high impact reviews in photovoltaics, electrochemistry, catalysis, polymer and materials science. The discussion incorporates established reference works on dye sensitized and organic photovoltaic systems, photoelectrochemical and photocatalytic solar fuels, and sunlight driven environmental remediation, as well as key contributions on emerging light charged storage concepts. The evaluation is informed by the author’s own research on organic and hybrid photovoltaic devices and on light responsive electrochemical systems, including previous work on the historical development and prospects of organic photovoltaics in a cross disciplinary context (Bulavko, 2024). The approach combines historical reconstruction of key milestones, thematic grouping of related technologies, and comparative assessment of shared materials selection principles and sustainability constraints across the four pathways.

In terms of historiographical orientation, the present study goes beyond a purely chronological listing of milestones. It seeks to identify, at each stage, how the availability of new characterization methods, the shifting priorities of funding agencies and energy policy frameworks, and the interaction between distinct research communities influenced the direction and pace of materials development. Particular attention is paid to episodes in which a technology that appeared promising on efficiency grounds failed to progress because of material scarcity, instability, or incompatibility with manufacturing realities, and conversely, to cases where a seemingly modest material platform achieved dominance through a combination of processability, durability, and cost reduction. This approach allows the historical narrative to serve not only as a record of discoveries but also as an analytical tool for understanding why certain materials design strategies succeeded while others remained confined to the laboratory.

The aim of this comprehensive review is to provide an integrated historical and materials focused assessment of how sunlight has been harnessed as a driving force for green energy and environmental applications, to identify unifying principles that link photovoltaics, solar fuels, photocatalysis, and light assisted energy storage, and to delineate realistic directions for the rational development of adaptive molecular, hybrid, and semiconductor materials for next generation sunlight driven technologies.

2. Sunlight to Electricity: The Photovoltaic Backbone.

Among the four sunlight-driven pathways considered in this review, photovoltaics represent the most technologically mature and widely deployed route from photons to usable energy. The historical evolution of PV materials reflects a recurring tension between efficiency limits, elemental abundance, long-term stability, manufacturability at the terawatt scale, and device architectures that minimize optical and electrical losses. While the portfolio of absorbers and junction concepts has expanded from crystalline silicon to III-V compounds, thin films, dye-sensitized and organic systems, metal-halide perovskites, and multi-junction configurations, only a subset has crossed the threshold from laboratory demonstrator to industrial backbone.

2.1. From the First Silicon Cells to the Silicon Dominance Regime.

The foundational milestones of PV include Edmond Becquerel's observation of the photovoltaic effect in 1839, early selenium and Cu_2O cells in the late nineteenth and early twentieth century, and the breakthrough crystalline silicon p-n junction cell at Bell Labs in 1954 with an efficiency of about 6 % under sunlight (Chapin, Fuller, & Pearson, 1954). These devices established the archetype of a shallow junction in a high purity semiconductor with a built-in electric field for selective carrier extraction.

Over subsequent decades, improvements in crystal growth, dopant and defect control, surface passivation, antireflection coatings, and contact design transformed crystalline silicon from a space technology into the main terrestrial PV platform. Commercial cell efficiencies, which were near 10 to 15 % in the 1970s and 1980s, now routinely reach about 22 to 24 % for industrial PERC, TOPCon, and heterojunction architectures, while best laboratory silicon heterojunction cells approach 27 %, as documented in consolidated efficiency tables. Crystalline silicon offers a near optimal band gap close to 1.1 eV for single junction operation, relies on an abundant and relatively benign element with established production and recycling routes, and demonstrates operational lifetimes of at least 25 to 30 years with modest degradation. At the same time, its indirect band gap requires relatively thick wafers and high temperature processing, and current architectures approach practical limits for single junction performance. This situation has stimulated intensive efforts toward thin film, multi junction, and tandem concepts that can exceed the Shockley-Queisser limit or reduce cost and energy payback time.

2.2. III-V Compounds and the Multi Junction Paradigm.

III-V semiconductors such as GaAs, InP, and their alloys enabled high efficiency single junction and multi junction cells with precisely tunable band gaps and excellent radiative properties. Under one sun, GaAs research cells have surpassed 28 to 29 % efficiency (Green et al., 2025). In concentrator and multi junction configurations, for example GaInP/GaAs/Ge and related stacks with bandgap grading across the solar spectrum, independently certified efficiencies have exceeded 40 % and advanced designs approach the high 40 % range in optimized concentrator systems (King et al., 2007).

These results define the practical upper envelope of photovoltaic performance under realistic conditions and highlight the benefits of spectrally cascading absorbers in multi junction architectures. Historically, however, III-V devices have remained confined to space power and niche concentrator applications. Limitations arise from complex epitaxial growth, high manufacturing cost, and reliance on critical elements such as indium, gallium, and germanium. The III-V trajectory illustrates a general principle that efficiency alone is insufficient if material supply, cost, and large-scale manufacturability are not compatible with terawatt deployment.

2.3. Thin Film Silicon, CdTe, and CIGS: Materials Utilization and Manufacturing.

The drive to reduce material consumption and enable large area, low-cost production led to thin film PV technologies based on amorphous and microcrystalline silicon, cadmium telluride, and copper indium gallium diselenide (CIGS) (Sivasankar, Amorim, & da Cunha, 2025).

Amorphous and microcrystalline silicon (a-Si:H, microcrystalline stacks) use well established, relatively safe chemistries and support flexible or building integrated modules, but suffer from light induced degradation and limited stabilized efficiencies, typically below about 10 to 12 % for commercial modules (Avrutin, Izyumskaya, & Morkoç, 2014).

Cadmium telluride (CdTe) combines a nearly ideal direct band gap of about 1.45 eV with strong absorption, enabling thin absorbing layers and high throughput manufacturing. Best research CdTe cells exceed 22 % efficiency, and commercial modules reach high teens to around 20 %.

Key concerns include cadmium toxicity and the limited availability of tellurium, which require strict process control and closed loop recycling, although life cycle analyses often show favorable energy payback times and competitive carbon footprints.

CIGS offers a tunable band gap in the approximate range from 1.0 to 1.7 eV and very high absorption coefficients. Record CIGS cells surpass 23 % efficiency, with commercial modules somewhat lower (Feurer et al., 2017). However, complex stoichiometry, sensitivity to alkali doping, process uniformity, and dependence on indium and gallium have constrained large scale expansion. Together, CdTe and CIGS demonstrate that thin absorbers with high optical cross sections can reduce material intensity and enable alternative manufacturing routes, but their long-term competitiveness depends on addressing toxicity, resource constraints, and process reproducibility.

2.4. Dye Sensitized and Organic Solar Cells: Molecular Routes and Their Limits.

The introduction of dye sensitized solar cells by O'Regan and Grätzel in 1991 (O'Regan & Grätzel, 1991) established a molecular inorganic hybrid architecture, in which a sensitizer dye absorbs light on a mesoporous TiO_2 scaffold and a redox electrolyte or hole conductor completes the circuit. DSSCs enabled tunable color, semi transparency, and relatively simple low temperature fabrication. Over years of development, co sensitization, cobalt based redox couples, and solid-state hole transport materials pushed record efficiencies to around 13 to 14 % under standard test conditions. Nonetheless, issues with liquid electrolyte volatility, sealing, long term stability, and limited open circuit voltage have restricted DSSCs to niche segments such as building integrated and indoor photovoltaics rather than mainstream power generation.

2.5. Organic Solar Cells.

Organic solar cells based on conjugated polymers and small molecules, progressed from Tang's planar heterojunction CuPc perylene cell in 1986 (Tang, 1986) to bulk heterojunction architectures following the demonstration of ultrafast charge transfer in polymer fullerene blends in 1992 (Sariciftci, Smilowitz, Heeger, & Wudl, 1992). The introduction of non-fullerene acceptors yielded a rapid rise in efficiencies, with certified single junction organic cells approaching about 18 to 19 % (Xuelin Wang et al., 2021). Organic systems offer solution processability, low weight, flexibility, and broad spectral tunability. However, intrinsic and extrinsic degradation under oxygen, moisture, and light, morphology instability, and challenges in large area uniform processing still limit their deployment in long lifetime outdoor installations. As a result, organic PV remains focused on flexible, indoor, portable, and semi-transparent applications. Historically, DSSCs and organic solar cells expanded the conceptual design space for light harvesting and interfacial charge transfer, but did not displace crystalline silicon as the photovoltaic backbone.

2.6. Metal Halide Perovskites, Tandems, and Emerging Multi Junction Architectures.

Metal halide perovskites originated in 2009 as efficient sensitizers in liquid electrolyte cells and quickly transitioned to solid state mesoscopic and planar devices that exceeded 10 % efficiency by 2012 (Lee, Teuscher, Miyasaka, Murakami, & Snaith, 2012). Within little more than a decade, certified single junction perovskite cells have surpassed 26 %, and perovskite silicon tandem cells have exceeded 33 % in two terminal architectures, as documented in standard efficiency charts (Polman, Knight, Garnett, Ehrler, & Sinke, 2016).

Perovskites combine strong absorption, long diffusion lengths, defect tolerant electronic structure, and compositional band gap tunability in a form compatible with solution processing, low temperature deposition, and direct integration on established silicon technologies (Saparov & Mitzi, 2016).

This combination has made perovskite-based tandems the leading candidate for next generation multi junction architectures beyond pure III-V stacks. All perovskite tandems, perovskite on silicon tandems, and other hybrid multi junctions seek to exploit spectral splitting to surpass the single junction Shockley-Queisser limit while leveraging less resource intensive materials and simpler processing. At the same time, the soft ionic lattice of perovskites leads to sensitivity to moisture, oxygen, heat, and electric fields, with ion migration, phase segregation, and interface degradation still limiting operational stability.

The use of soluble lead in most high efficiency compositions raises environmental and regulatory questions, especially for large area deployment, although lead content per watt is low and closed loop strategies are under development.

Thus, perovskites and perovskite-based tandems currently occupy an intermediate status: technologically disruptive in terms of efficiency and architectural flexibility, but not yet fully bankable at the scale and lifetime demonstrated by crystalline silicon. Their future role will depend on sustained advances in stability, encapsulation, scalable manufacturing, and end of life management.

2.7. Efficiency Trajectories, Commercial Reality, and Materials Constraints.

The evolution of record efficiencies across different PV technologies provides a compact historical fingerprint. Crystalline silicon progressed from single digit efficiencies in the 1950s to about 27 % in the best modern cells. CdTe and CIGS advanced from below 10 % to beyond 20 % in optimized devices. III-V multi junction concentrator cells moved from around 20 % to well above 40 %. Metal halide perovskites increased from initial values near 3 to 4 % in 2009 to beyond 26 %. Dye sensitized and organic solar cells, starting from sub one percent prototypes, reached approximately 12 to 14 % and up to about 18 to 19 %, respectively, in advanced architectures. Multi junction and tandem configurations that combine complementary absorbers now define the absolute efficiency frontier in both III-V and perovskite silicon families (Fig. 2. a). In parallel with these efficiency gains, global module prices collapsed by roughly one order of magnitude over the last two decades, from around 6–7 $/W in the early 2000s to about 0.26 $/W by 2024, a decline on the order of 90–95 %, which underpins the rapid commercialization of PV at terawatt scale (Fig. 2. b).

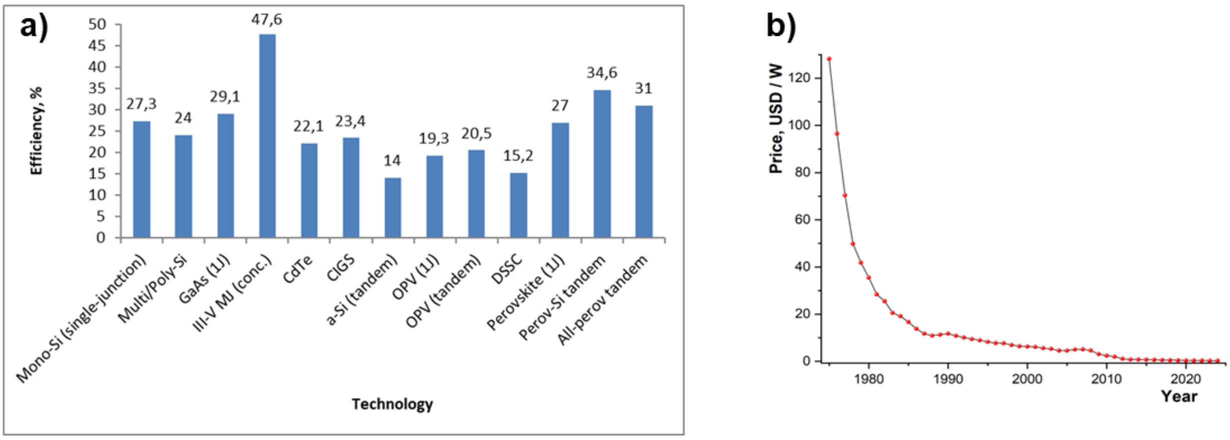

Figure 2. Record efficiencies of key photovoltaic technologies (a); Inflation-adjusted PV module prices, 1975–2025 (b) (Author's source).

At the same time, record efficiencies must be clearly distinguished from technologies that form the practical backbone of global PV deployment. Crystalline silicon modules provide the overwhelming majority of installed capacity. CdTe contributes significantly in utility scale thin film installations. CIGS, amorphous silicon, organic and dye sensitized technologies remain specialized. III-V and complex multi junction stacks are essential in space power and high concentration systems, but their material and cost profiles are incompatible with mass terrestrial deployment. Perovskite and perovskite silicon tandem modules are emerging at pilot scale and could become a major component if stability and reliability targets are met.

Historically successful PV technologies share not only high conversion efficiencies, but also the use of elements with secure and scalable supply, compatibility with large area industrial processing, proven durability over decades in outdoor conditions, and favorable levelized cost of electricity under realistic spectra and climates.

Systems that depend on scarce or toxic elements, fragile liquid components, intricate multi element stoichiometry, or unresolved degradation mechanisms tend to remain confined to niches despite impressive laboratory records.

In this sense, the history of sunlight to electricity conversion provides a reference template for the rest of this review. It demonstrates that absorber electronic structure, junction and interface design, and spectral management must be evaluated together with resource availability, stability, manufacturing routes, and end of life strategies. These same constraints will recur in the analysis of solar fuels, photocatalytic remediation, and light charged storage technologies in the following sections.

3. Sunlight to Chemical Bonds: Solar Fuels, PEC, and CO_2 Reduction.

Converting sunlight into storable chemical energy proceeds through three tightly linked routes: photoelectrochemical water splitting in liquid junctions, particulate photocatalysis in suspensions or sheets, and photovoltaic-powered electrolysis that couples solid-state PV with commercial electrolyzers. Performance is measured as solar-to-hydrogen or, more generally, solar-to-chemical efficiency, defined by the

Gibbs free energy stored per incident solar power under AM 1.5 G illumination with a specified device geometry and product accounting. Meaningful comparison also requires long-term stability under operating current, corrosion resistance at the semiconductor-electrolyte interface, and reliance on scalable, low-toxicity materials (Walter, Warren, McKone, Boettcher, Mi, Santori, & Lewis, 2010).

3.1. Photoelectrochemical Water Splitting.

Modern PEC begins with the 1972 report of bias-assisted water splitting on TiO_2, which established the semiconductor-electrolyte junction as a workable solar-fuel architecture (Fujishima & Honda, 1972).

An integrated path to the required photovoltage arrived in 1998 with a $GaInP_2$/GaAs tandem that split water at 12.4 % solar-to-hydrogen in a monolithic photovoltaic-photoelectrochemical device, setting the benchmark for unbiased operation and certified reporting (Khaselev & Turner, 1998). Subsequent progress centered on protection layers and catalysts that pass carriers while blocking corrosion. Conformal amorphous TiO_2 grown by atomic layer deposition became a widely adopted strategy, stabilizing Si, GaAs, and GaP photoanodes during oxygen evolution without sacrificing electronic contact (Hu, Shaner, Beardslee, Lichterman, Brunschwig, & Lewis, 2014). With careful interface and catalyst engineering, perovskite absorbers have now been integrated into fully submersed PEC cells that reach 20.8 % solar-to-hydrogen, demonstrating that high photovoltage and defect tolerance can coexist in aqueous operation (Fehr et al., 2023).

3.2. Particulate Photocatalysis.

A complementary route disperses light absorbers as powders or immobilized sheets and collects product gases directly from the reactor. Recent demonstrations report 9.2 % solar-to-hydrogen using InGaN-based catalysts under concentrated sunlight and pure water, while outdoor panels have validated scale-up concepts and highlighted the central challenges of bubble management, mass transport, and long-term catalyst integrity (Zhou et al., 2023). These results show that high optical cross-sections and cocatalyst engineering can deliver competitive efficiency, while practical deployment hinges on stable reactor designs and efficient gas separation.

3.3. PV–Electrolysis Coupling.

Using mature photovoltaics to drive state-of-the-art electrolyzers currently sets the commercial baseline and the near-term efficiency ceiling. Laboratory one-sun systems that electrically match multijunction PV to low-overpotential electrodes have exceeded 30 % solar-to-hydrogen, with a straightforward durability pathway that leverages existing PV and electrolyzer supply chains (Jia et al., 2016).

3.4. CO_2 Reduction: From Proofs to Selective and Integrated Systems.

Photoassisted CO_2 conversion was demonstrated soon after PEC water splitting. In 1978, p-GaP photocathodes reduced aqueous CO_2 to C_1 products under illumination in liquid-junction cells, followed in 1979 by illuminated semiconductor suspensions that produced formate, formaldehyde, methanol, and methane, thereby establishing both photoelectrochemical and particulate routes (Halmann, 1978; Inoue, Fujishima, Konishi, & Honda, 1979). Homogeneous molecular catalysis delivered early selectivity milestones, notably with Re(bpy)$(CO)_3$X complexes that reduce CO_2 to CO under visible light and inspired extensive mechanistic and ligand-design work, including Mn analogues based on earth-abundant metals (Johnson, George, Hartl, & Turner, 1996). On heterogeneous electrodes, copper remains unique in forming multi-carbon products, while gas-diffusion architectures and electrolyte design have lifted currents and selectivity; comprehensive reviews codify activity-selectivity trends and the remaining scale-up barriers (Nitopi et al., 2019). Fully solar-integrated devices have progressed from perovskite-powered CO_2-to-CO leaves at more than 6.5 % solar-to-CO to flow electrolyzers coupled to triple-junction PV that approach about 20 % solar-to-CO at high Faradaic efficiency, illustrating that selective CO production is technically within reach, while multi-carbon liquids still require advances in catalyst stability and carbon-capture integration (Gao et al., 2022; Schreier et al., 2015).

3.5. Nitrogen Fixation Under Sunlight.

Solar ammonia is an appealing target because ammonia is both a fertilizer and a potential energy carrier, yet direct nitrogen reduction remains technically and metrologically challenging. Recent reviews compare photocatalytic, photoelectrochemical, PV-electrocatalytic, and photothermal approaches, emphasize the extreme inertness of N_2, and call for careful benchmarking of solar-to-ammonia figures of merit and productivity per illuminated area (Collado, Pizarro, Barawi, García-Tecedor, Liras, & de la Peña O'Shea, 2024). The field has been shaped by rigorous protocols that use $^{15}N_2$ labeling and contamination control to avoid false positives from ambient ammonia or nitrogen-containing impurities. These studies show that many early reports overestimated activity and that validated rates at ambient conditions are still very low, although lithium-mediated and tandem-catalyst concepts provide credible mechanistic pathways for progress (Andersen et al., 2019; Choi et al., 2020). In parallel, nitrate and nitrite reduction offer near-term solar routes to ammonia that are relevant for wastewater valorization, while true N_2-to-NH_3 photofixation will require stable catalysts with demonstrable turnover, standardized ^{15}N accounting, and device architectures that combine selective cathodes with robust photoanodes.

3.6. Status and Outlook.

Among solar-fuel strategies, PV-electrolysis is already commercial and benefits directly from PV and electrolyzer learning curves, while particulate photocatalysis and integrated PEC are pre-commercial despite rapid efficiency gains and credible outdoor scale-ups (Jia et al., 2016). For CO_2 reduction, selective CO and formate production has reached device-level solar-to-chemical figures above ten percent in some architectures, whereas durable solar routes to multi-carbon liquids remain research-stage and hinge on suppressing degradation at reactive interfaces and on efficient carbon capture coupling (Gao et al., 2022; Nitopi et al., 2019). For nitrogen, the consensus from best-practice studies is that validated solar ammonia rates are presently far from practical targets, which makes nitrate and nitrite upgrading attractive interim objectives while mechanistically guided catalyst design and standardized ^{15}N protocols continue to advance the true N_2 pathway (Andersen et al., 2019; Choi et al., 2020). Across all routes, the shared materials playbook is clear: align band edges with target redox reactions, control defects and buried interfaces to suppress recombination and corrosion, engineer catalytic microenvironments for selectivity, and favor abundant elements and scalable processing from the outset (Walter, Warren, McKone, Boettcher, Mi, Santori, & Lewis, 2010).

4. Sunlight to Environmental Remediation: Photocatalysis for a Cleaner Planet.

Environmental photocatalysis uses illuminated semiconductors to oxidize or transform pollutants in water and air and to maintain self-cleaning or antimicrobial surfaces. Performance is commonly reported as apparent quantum yield, pseudo first order rate constants normalized to surface area or catalyst mass, and for air depollution as areal removal rates of NO and NO_2 under standard gas flows and illumination. Robust benchmarking requires explicit photon accounting, control of mass transfer, and durability testing under realistic humidity, temperature, and fouling conditions, together with careful identification of intermediates and mineralization products (Hoffmann, Martin, Choi, & Bahnemann, 1995; Nakata & Fujishima, 2012).

4.1. Foundational Demonstrations and the TiO_2 Benchmark.

Early heterogeneous studies showed that illuminated semiconductor powders can oxidize toxic anions and organics, which positioned TiO_2 as the reference material for environmental remediation and mechanistic work on radical-driven pathways and interfacial charge transfer (Frank & Bard, 1977; Hoffmann, Martin, Choi, & Bahnemann, 1995). The concept of transparent self-cleaning TiO_2 coatings on glass was then introduced, establishing a route to photodegrade organic films directly on surfaces and to couple photocatalysis with photoinduced hydrophilicity that enables rain assisted cleaning in real environments (Paz, Luo, Rabenberg, & Heller, 1995; Paz & Heller, 1997).

4.2. Extending Activity Into the Visible.

Classic TiO_2 responds mainly to UV-light. Band gap engineering and dopants were adopted to harvest a larger fraction of sunlight. A landmark was the report of visible light activity in nitrogen doped TiO_2, which stimulated extensive work on anion and cation modified oxides and on defect mediated absorption tails (Asahi, Morikawa, Ohwaki, Aoki, & Taga, 2001). In parallel, metal free graphitic carbon nitride emerged as a visible light photocatalyst and broadened the palette of materials used in environmental and solar fuel transformations, often in heterojunctions with oxides to improve charge separation and spectral coverage (Nakata & Fujishima, 2012; Xinchen Wang et al., 2009).

4.3. Water Treatment: Organics, Dyes, and Pharmaceuticals.

In water, semiconductor photocatalysts target dyes, endocrine disruptors, antibiotics, and other micropollutants. Reviews have consolidated kinetics, reactor geometries, and pathways, including the roles of hydroxyl radicals, valence band holes, and adsorbed oxygen species, and have emphasized that real matrices with natural organic matter and carbonate buffers can suppress apparent rates relative to idealized lab solutions (Chong, Jin, Chow, & Saint, 2010). Immobilized films and photocatalytic membranes reduce post treatment separation steps but introduce additional mass transfer limitations that must be accounted for in reporting.

4.4. Air Depollution and Building Materials.

Gas phase depollution focuses on NO and NO_2 abatement, volatile organic compounds, and bioaerosol inactivation. Laboratory assessments for NO_x commonly adopt the ISO 22197 methodology, and large bodies of work have translated oxide photocatalysts into cements, renders, and coatings for building and urban infrastructure. Field deployments and meta-analyses report both promising reductions and significant variability depending on irradiance, humidity, pollutant load, and substrate weathering, which underscores the need for realistic illumination and flow conditions, as well as for long term durability studies and maintenance protocols (Dahl, Jensen, Bigi, & Ghermandi, 2023; Russell, Frederickson, Hertel, Ellermann, & Jensen, 2021; Sanchez, Santiago, Martilli, Palacios, Núñez, Pujadas, & Fernández-Pampillón, 2021).

4.5. Architectures and Interfacial Design.

Modern environmental photocatalysts rarely rely on a single oxide in isolation. Heterojunctions with type II, direct Z-scheme, or S-scheme band alignments and plasmonic or carbonaceous co components are designed to improve charge separation and reaction selectivity, while cocatalysts such as Pt, Pd, or transition metal oxides accelerate specific interfacial steps. The most durable coatings balance optical absorption with porosity and wettability, incorporate binders and UV stabilizers compatible with outdoor exposure, and maintain activity after soiling and cleaning cycles. These strategies follow the same playbook as solar fuel photocatalysis, adapted to low reactant concentrations and to mass transfer regimes dominant in thin films and porous surfaces (Hoffmann, Martin, Choi, & Bahnemann, 1995).

Environmental photocatalysis is technologically mature for niche but impactful uses, including self-cleaning glazing, anti-fogging and antimicrobial surfaces, and specialty cements for localized NO_x abatement. At city scale, measured impacts vary widely and depend on climate, geometry, and maintenance, so rigorous outdoor trials with standardized reporting remain essential before broad municipal deployment claims can be generalized (Sanchez, Santiago, Martilli, Palacios, Núñez, Pujadas, &

Fernández-Pampillón, 2021). Continued progress will come from realistic reactor engineering, better photon management in scattering media, catalysts that maintain activity under complex environmental exposures, and life cycle assessments that include end of life handling of photocatalytic surfaces. As with other sunlight driven technologies, success depends on aligning band structures and interfaces with the target chemistry, sustaining activity under real operating stressors, and choosing abundant, low toxicity elements that can be manufactured and maintained at scale (Hoffmann, Martin, Choi, & Bahnemann, 1995).

5. Emerging Light-Charged Devices: From Photo-Batteries to Molecular Photochemical Cells.

Devices that harvest light and store the harvested energy inside the same architecture now span several families. Photocapacitors couple a photovoltaic or sensitized junction to an electric-double-layer or pseudocapacitive reservoir inside one stack. Photo-batteries integrate light absorbers with intercalation hosts so that illumination directly charges a redox pair. Solar flow batteries merge light harvesting with dissolved redox couples that can be circulated and stored. A newer molecular branch uses light to shift chemical equilibria and thereby build ionic gradients that are then converted to electrical work. Across all of these, the central figures of merit are solar-to-stored or solar-to-output efficiency, charge and energy per unit area, retention in the dark, cycling durability, and scalability of the materials set.

5.1. Historical Stepping Stones and Archetypes.

Early dye-sensitized photocapacitors proved that a single, compact stack can both generate and store charge. A two-electrode dye-sensitized "photocapacitor" was introduced in 2004, followed by a three-electrode configuration in 2005 that raised the charge-state voltage and areal energy density by engineering separate photo- and storage electrodes within one device (Miyasaka & Murakami, 2004; Murakami, Kawashima, & Miyasaka, 2005). A comprehensive modern synthesis of the photocapacitor field is provided by a 2023 Chemical Reviews article that maps device layouts, materials choices, and loss channels (Flores-Diaz, De Rossi, Das, Deepa, Brunetti, & Freitag, 2023).

5.2. Photo-Batteries and Photo-Assisted Batteries.

Photo-batteries aim to directly raise the electrochemical potential of an insertion compound under illumination, so that charging proceeds without an external photovoltaic panel. Two-electrode demonstrations include light-assisted delithiation of $LiFePO_4$ hybrid photocathodes, which established clear photo-driven shifts in state of charge and offered a mechanistic template for band-edge alignment to battery redox couples (Paolella et al., 2017). More recently, architectures that exploit semiconductor-insertion heterojunctions have delivered fully photo-rechargeable Li-ion operation under ambient light with vanadium oxide based cathodes and related designs, while also clarifying how to separate true photocharging from thermal artifacts (Liu et al., 2024; Pujari, Kim, Abbasi, Lee, Greenham, & De Volder, 2024; Salunke, Chamola, Mathieson, Boruah, de Volder, & Ahmad, 2022). These studies converge on practical conditions for light-rechargeability: the quasi-Fermi level under illumination must exceed the intercalation or plating potential at the negative electrode, interfaces must pass charge faster than recombination, and the device must be optically and ionically balanced to avoid parasitic losses.

5.3. Solar Flow Batteries.

Solar flow batteries integrate a photoelectrode or photovoltaic junction with a redox-flow cell so that light input is converted and parked in liquid redox couples. Monolithic laboratory devices have reached double-digit solar-to-output electricity efficiency, including a III-V based integrated cell at 14.1 % and a single-junction GaAs photoelectrode based system at 15.4 %, while subsequent work has mapped design rules for photoelectrodes, redox pairs, and light management in integrated stacks (Bae, Kanellos, Faasse, Dražević, Venugopal, & Smith, 2020; Cao, Skyllas-Kazacos, & Wang, 2018; Fu, Li, Yang, Lin, Veyssal, He, & Jin, 2021; Li, Fu, Zhao, He, & Jin, 2018; Lu, Leung, Su, Yang, & Xu, 2021). The attraction of the flow format is the decoupling of power and energy through external electrolyte tanks, together with the use of mild redox kinetics that relax stability demands on the illuminated components (Fu, Li, Yang, Lin, Veyssal, He, & Jin, 2021).

5.4. A Spiropyran-Based Light-Rechargeable Concentration Cell.

A recent molecular blueprint replaces the semiconductor junction with a photoswitchable coordination complex whose light-driven chemistry generates the charging force. The device uses identical zinc electrodes separated by a membrane and filled with a solution of a Zn-spiropyran complex in acetonitrile. When one half-cell is illuminated with visible light, the complex partially decoordinates and releases free Zn^{2+}, which creates a concentration gradient between the bright and dark sides. The gradient sets a Nernst-type electromotive force that is read out between the two zinc electrodes. In the dark, the complex reforms and the system resets, enabling repeated, autonomous light-induced recharge cycles with reproducible tens of millivolts per cell and microampere-level currents, including operation with a smartphone LED (Hrebonkin & Bulavko, 2025). The choice of zinc addresses availability and toxicity, while the aprotic solvent supports reversible complexation and free-ion populations. The key novelty is the direct conversion of photon-controlled coordination equilibria into ionic chemical potential, with no semiconductor junction and no external bias, which establishes a distinct class of “molecular photochemical cells” governed by equilibrium thermodynamics rather than photovoltage at a solid-liquid interface (Figure 3) (Hrebonkin & Bulavko, 2025).

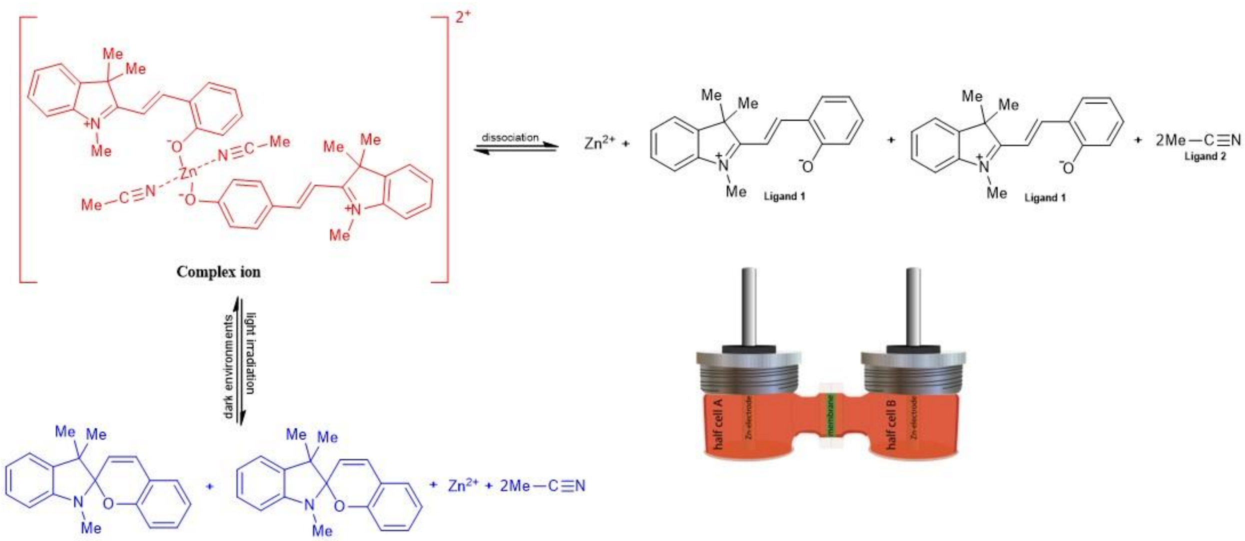

Figure 3. Spiropyran-based photoelectrochemical cell with light-induced charging: schematic of the Zn-spiropyran complex and a symmetric Zn–Zn H-cell (Hrebonkin & Bulavko, 2025).

The spiropyran cell decouples light harvesting from solid-state junctions and shifts the optimization space to photochemical equilibrium contrast, diffusion control, and membrane selectivity. Photovoltage scales with the logarithm of the Zn^{2+} activity ratio, so higher contrast requires complexes that exhibit large, reversible light-induced shifts in stability constants, faster forward photokinetics relative to back reactions, and separators that suppress back-diffusion without excessive ohmic loss. Concentrating the photoactive volume near the separator, patterning bright and dark regions at short distances, raising complex concentration within solubility limits, and tethering spiropyrans to polymer backbones to reduce crossover are clear materials levers. The same principle is extendable to alternative ligands, counter-anions, and even aqueous media if reversible coordination can be retained in water.

Relative to photocapacitors, storage here resides in a solution-phase chemical potential gradient rather than in electron-ion layers at internal interfaces. Unlike photo-batteries, no intercalation hosts are required, so mechanical strain and the formation of new solid interfaces are avoided. In contrast to solar flow batteries that rely on photovoltage-generating photoelectrodes and often precious-metal catalysts, this device uses a photoswitchable complex that can, in principle, be formulated from abundant elements. The present trade-offs are modest per-cell voltage and diffusion-limited current, both of which can be mitigated by cell geometry, ion-selective membranes, and series stacking.

5.5. Materials Playbook and Metrics.

For all light-charged platforms, the core constraints rhyme. Band-edge alignment to battery redox couples determines whether light can do useful charging work in photo-batteries, and this has been formalized in recent analyses that provide practical diagnostics for true photocharging versus photothermal effects (Pujari, Kim, Abbasi, Lee, Greenham, & De Volder, 2024). In photocapacitors, optical coupling between the light absorber and the storage element, interfacial series resistance, and electrolyte stability set the ceiling for areal energy and round-trip efficiency (Flores-Diaz, De Rossi, Das, Deepa, Brunetti, & Freitag, 2023). In solar flow batteries, the pairing of photoelectrode output with redox couple potentials, light management at the semiconductor-electrolyte interface, and crossover suppression dictate the achievable solar-to-output electricity efficiency and the service lifetime (Bae, Kanellos, Faasse, Dražević, Venugopal, & Smith, 2020; Li, Fu, Zhao, He, & Jin, 2018).

5.6. Use cases and Near-Term Prospects.

Photocapacitors and compact photo-batteries are natural candidates for self-powered sensors, badges, and micro-actuators where transparency, low weight, and minimal part count are prized over absolute areal power. Solar flow batteries bridge toward distributed and grid-adjacent storage by separating light harvesting from storage volume and enabling safe, long-life electrolytes. Molecular photochemical cells, inaugurated by the spiropyran concentration-cell concept, target low-voltage light-rechargeable sources that can be addressed optically and fabricated from commodity components, with a clear route to series stacking and arrayed operation for higher voltages (Hrebonkin & Bulavko, 2025).

5.7. Outlook.

The field is diversifying beyond semiconductor-centric stacks. Photocapacitors and photo-batteries will continue to push energy densities through better heterojunction design and transport management, guided by emerging quantitative criteria for light-rechargeability and by strategies that suppress photodegradation at buried interfaces (Flores-Diaz, De Rossi, Das, Deepa, Brunetti, & Freitag, 2023; Pujari, Kim, Abbasi, Lee, Greenham, & De Volder, 2024). Solar flow batteries will likely define the high-efficiency end of integrated conversion-plus-storage for liquid redox systems, with demonstrated double-digit solar-to-output efficiencies and credible stability pathways (Fu, Li, Yang, Lin, Veyssal, He, & Jin, 2021; Li, Fu, Zhao, He, & Jin, 2018). The spiropyran platform offers a complementary molecular route: illumination writes a chemical-potential gradient that is read electrically and erased in the dark. This opens a wide search space for robust, photoresponsive complexes and improved separators. Immediate priorities are to increase per cell voltage, quantify the full cycle efficiency from solar input to stored energy and then to delivered electricity, demonstrate stability over many cycles, and shift operation to benign solvents, including water. On the strength of the first reproducible visible light self-recharging cell and a clear set of controllable parameters, this concept credibly expands the design space for light charged electrochemical systems (Hrebonkin & Bulavko, 2025).

6. Discussion.

The four sunlight-driven pathways examined above developed largely within separate research communities, yet their historical trajectories reveal a set of shared patterns that merit explicit comparison. In each domain, the initial proof of concept relied on a wide-band-gap oxide or a high-purity crystalline semiconductor, and subsequent progress depended on expanding the spectral response, improving interfacial charge transfer, and reducing reliance on scarce or toxic constituents. The order in which these challenges were addressed, and the degree to which they have been resolved, differs substantially across the four fields, and these differences explain much of the variation in technological maturity observed today.

Photovoltaics have advanced furthest along the path from laboratory discovery to industrial scale. The decisive factors were not peak efficiency alone but the convergence of adequate performance with processability, durability, and cost reduction over decades of incremental engineering. Crystalline silicon exemplifies this pattern most clearly. By contrast, solar fuels and photoelectrochemical systems, despite reaching impressive solar-to-chemical efficiencies in controlled settings, have not yet resolved the corrosion, sealing, and catalyst stability issues that limit continuous outdoor operation. The gap between photovoltaic and solar-fuel maturity is therefore less a matter of fundamental physics than of materials durability and systems engineering under realistic conditions.

Environmental photocatalysis occupies an intermediate position. Self-cleaning coatings and depolluting cements have reached commercial deployment, but their performance in the field varies widely depending on irradiance, humidity, and surface fouling. The recurring lesson is that laboratory photocatalytic rates measured under idealized illumination and gas flow often overestimate real-world outcomes, a problem that closely parallels the overestimation of solar-fuel yields in early reports that lacked rigorous product quantification.

Light-charged storage devices remain the least mature of the four classes, yet they illustrate an important convergence: the same band-edge alignment, interfacial passivation, and charge-transport criteria that govern photovoltaic and photoelectrochemical performance also determine whether a photo-battery or a solar flow battery can deliver useful charging work. The recent emergence of molecular photochemical cells, which replace semiconductor junctions with photoswitchable coordination equilibria, suggests that the design space for coupling light absorption to energy storage is broader than early device concepts implied.

Across all four domains, a consistent hierarchy of constraints governs whether a given materials platform progresses beyond the prototype stage. Efficiency is necessary but not sufficient; long-term operational stability under realistic environmental stresses acts as the primary filter. Beyond stability, the availability and toxicity of constituent elements, compatibility with scalable manufacturing, and prospects for end-of-life recovery determine whether a technology can be deployed at the scale required for meaningful impact on the energy system. Technologies that address these constraints from the outset tend to advance faster and more reliably than those that defer them to later development stages.

The comparison also highlights a productive feedback loop among the four pathways. Protection layers developed for photoelectrochemical anodes have informed encapsulation strategies for perovskite solar cells. Heterojunction concepts optimized for photocatalytic charge separation have been adapted for photo-battery cathodes. Photon management techniques refined in tandem photovoltaics are now applied to particulate photocatalyst sheets. Recognizing these cross-pathway transfers as a deliberate design strategy, rather than as incidental borrowing, can accelerate materials development in each field by drawing systematically on solutions already validated in adjacent domains.

7. Conclusions.

Across all sunlight-driven technologies a consistent tradeoff governs progress. Simple and scalable chemistries tend to defeat exotic but fragile ones. Crystalline silicon, robust oxides, and durable polymer or glass matrices moved from lab curiosity to industry because they tolerate imperfect processing and outdoor stress and because they fit established manufacturing lines. Systems that depend on rare elements, tight stoichiometry windows, or many tightly coupled layers often stall at the prototype stage. Record efficiency matters only when it travels together with bankability, predictable yield, and a supply chain that can grow to the terawatt scale.

The history of photovoltaics illustrates this rule. Silicon did not become dominant by peak numbers alone. It combined respectable efficiency with multi-decade stability and a learning curve that collapsed cost. Thin-film CdTe and CIGS earned durable niches by balancing absorber quality with throughput and recycling plans. By comparison, DSSC and most organic PV architectures delivered elegant physics and attractive form factors yet struggled outdoors over long lifetimes. Perovskites are the present test case. They already rival the best single-junction silicon cells and they unlock practical tandems, yet long-term stability, ion migration, and encapsulation still set the pace for deployment. The same pattern repeats in solar fuels and environmental photocatalysis, where stable interfaces, corrosion control, and benign electrolytes are decisive. High solar-to-chemical figures are not enough without operation over many hundreds or thousands of hours under realistic illumination, temperature, and mass-transfer conditions.

Materials choices are also filtered by toxicity, critical-element exposure, and prospects for circularity. Silicon scores well on abundance and end-of-life recovery. CdTe and CIGS show that elements with toxicity or supply constraints can still be viable when processes are tightly contained and recycling is proven. For PEC and flow systems, precious metals are acceptable only in trace amounts and only when protected against loss. Emerging light-charged devices should begin with benign solvents and abundant ions, then add performance. Designing for disassembly, solvent recovery, and closed-loop electrolyte management should be a baseline requirement rather than a late addition.

The four technology tracks connect into one sunlight infrastructure. Photovoltaics are the backbone that already powers commercial electrolyzers for hydrogen and can drive electrochemical CO_2 conversion where catalysts are selective and durable. PEC and particulate photocatalysis offer compact, direct solar-to-fuel routes where wiring and power electronics are impractical and they serve as testbeds for protection layers and catalysts that can later migrate into PV-coupled plants. Environmental photocatalysis sits at the hygiene and maintenance layer of the same system. Self-cleaning and depolluting surfaces preserve optical throughput, extend service intervals, and reduce chemical use in buildings and water systems. All tracks share the same engineering vocabulary: band-edge alignment, defect and interface passivation, photon management in scattering media, and credible life-cycle accounting.

Where progress proved durable, the winning strategies favored defect tolerance, simple stacks, and forgiving processes. Textured silicon with high-quality passivation, single-phase oxides with robust cocatalysts, and flow batteries with mild electrolytes all fit this pattern. Where progress stalled, warning signs were visible early. Liquid electrolytes in large outdoor devices without guaranteed sealing, unstable redox shuttles, photofixation claims without isotope validation, and stacks that multiply optical interfaces and buried boundaries tend to fail in scale-up. In CO_2 and nitrogen conversion, rigorous metrology became the gatekeeper. Gas-diffusion architectures, isotopic labeling, and quantitative product analysis filtered optimistic reports and clarified which routes are ready for coupling to sunlight at useful rates.

Near-term opportunities are pragmatic and specific. Perovskite-silicon tandems are the most immediate step beyond the single-junction limit, provided ion migration and interfacial degradation are suppressed with stable transport layers and strong encapsulation. Integrated PEC platforms can matter where direct solar fuels make sense, especially if protection layers and earth-abundant catalysts deliver thousands of hours in buffered electrolytes. Solar flow batteries already show double-digit solar-to-electricity output with credible lifetimes and offer a modular way to combine light capture with storage volume. In environmental photocatalysis, durable heterojunction coatings, standardized outdoor testing, and designs that keep activity through soiling and cleaning cycles will separate deployable products from laboratory curiosities.

Within light-charged storage, a complementary molecular branch has appeared. The spiropyran-based concentration cell demonstrates that illumination can write a chemical-potential gradient in solution that is read electrically and erased in the dark. This route stores solar input without solid intercalation hosts or heavy photoelectrodes and uses abundant elements. First devices deliver modest voltage and diffusion-limited current, yet they offer clear levers for improvement: stronger light-driven equilibrium shifts, shorter diffusion paths, ion-selective membranes, and series stacking. The broader idea is to exploit reversible light-controlled coordination or acid-base equilibria to create simple, transparent charge reservoirs. Such cells are unlikely to compete with PV for bulk power, but they can fill low-voltage niches, seed new hybrid chemistries, and add design freedom to photocharged electrochemistry.

These considerations motivate a set of system level recommendations for the decade ahead. Focus on interfaces first, because buried contacts and transport layers set both stability and efficiency whether the target is a tandem PV, a PEC-stack, a photocatalytic wall, or a light-charged cell. Use standardized, device-relevant metrics: AM 1.5 G power accounting for PV and PEC, photon-to-product balances for photocatalysis, round-trip efficiency and self-discharge for storage. Favor abundant elements and simple processes from the first prototypes so that scale-up paths are obvious. Build in recycling and recovery steps at design time, not after pilot runs. Couple materials discovery with realistic reactors and field trials so that durability and maintenance are measured rather than assumed.

Taken together, sunlight to electricity, to fuels, to clean air and water, and to stored charge are branches of the same design problem. The task is to place electronic levels and catalytic sites so that photons create carriers, carriers do useful chemistry, and the structure survives long enough to matter at scale. The record of the past half century is consistent. Technologies that align performance with stability, abundance, and manufacturability reshape the energy system; those that rely on fragile stacks, scarce elements, or optimistic metrology fade. The near-term landscape is therefore pragmatic. Silicon remains the base. Perovskite tandems, protected PEC cells, and solar flow batteries carry the next wave if durability and circularity are proven. Environmental photocatalysis improves the built environment where exposure and maintenance are matched to reality. Molecular light-charged cells open a fresh space for simple, optically addressed storage and sensing. Together these paths outline a realistic, connected, and scalable sunlight infrastructure.

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The author declare no conflict of interest.

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Сонячне світло на службі енергетики: Історична еволюція матеріалів для фотовольтаїки, сонячних палив, фотокаталізу та новітніх світлозаряджуваних пристроїв

Анотація. *У цьому огляді сонячне випромінювання розглядається як ключовий рушійний ресурс сталих технологій і аналізується, як розвивалися матеріали для захоплення, перетворення та зберігання сонячної енергії за окремими, але взаємопов'язаними функціональними шляхами. Історично обґрунтований і міждисциплінарний підхід застосовано до чотирьох основних* *класів процесів, керованих сонячним світлом: перетворення сонячного випромінювання на електроенергію, акумулювання сонячної енергії в хімічних зв’язках, фотокаталітична деградація забруднювачів та пряме світлоасистоване зберігання енергії. Еволюцію фотовольтаїчних систем розглянуто від кристалічного та полікристалічного кремнію до тонкоплівкових абсорберів, сенсибілізованих барвниками і органічних сонячних елементів, а також сучасних галогенідних перовськітів і тандемних конфігурацій, з акцентом на взаємозв’язок між ефективністю, стабільністю та доступністю матеріалів. Фотоелектрохімічні та каталітичні шляхи одержання сонячних палив проаналізовано з особливою увагою до розвитку оксидів металів, молекулярних комплексів, наноструктурованих каталізаторів і систем вибіркового відновлення CO_2 як платформ для зберігання сонячного світла в хімічних зв’язках. Фотокаталітичне усунення забруднень розглянуто в контексті проєктування напівпровідників, міжфазних процесів перенесення заряду та інтеграції світлозбиральних матеріалів у схеми очищення води й повітря. Останні досягнення у світлозаряджуваному та фотоасистованому зберіганні енергії, включно з фотобатареями, фотосуперконденсаторами, редокс-концепціями зберігання сонячної енергії та фоточутливими концентраційними комірками, оцінюються як нові підходи, спрямовані на поєднання поглинання фотонів, розділення заряду та його зберігання в єдиній архітектурі пристрою. У всіх цих доменах дослідження виокремлює повторювані принципи дизайну матеріалів, включно з оптимізацією ширини забороненої зони та вирівнювання зон, координаційного оточення каталізаторів, міжфазного й кінетичного контролю, експлуатаційної довговічності, опорою на поширені та малотоксичні елементи, а також сумісністю життєвого циклу з розгортанням у великому масштабі. Порівнюючи ці траєкторії в межах єдиної аналітичної рамки, робота окреслює спільні закономірності технологічних успіхів і невдач та визначає реалістичні напрями раціональної розробки адаптивних молекулярних, гібридних і напівпровідникових матеріалів для енергетичних та екологічних технологій наступного покоління, що працюють на основі сонячного випромінювання.*

***Ключові слова**: історія матеріалів; фотоасистоване накопичення енергії; світлозбиральні матеріали; відновлення CO_2; сталий дизайн матеріалів*

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The history of the court archive of the Bukhara Khanate (later Emirate) in Central Asia

Abstract. *This research analyzes the formation and operation of the palace archive systems within the Bukhara Khanate (later the Emirate) within the broader* *context of Central Asian state administration traditions. The study applies a comprehensive approach to examine administrative structures, focusing specifically on the role of the divans (chanceries) in organizing the archival system. The findings demonstrate that the divans functioned not only as executive bodies but also as central nodes coordinating the processes of document collection, systematization, and preservation. Within the palace infrastructure, the institutions of the library (kutubkhona) and the treasury (khazinakhana) performed secondary yet vital archival functions, serving as centralized repositories for documents of political, economic, and diplomatic significance. Document turnover was managed through a system of registers (daftars), which simultaneously served as data-recording tools and a scientific-reference apparatus. Notably, the alphabetical arrangement of geographical names within these registers facilitated rapid information retrieval and ensured greater administrative efficiency. Source analysis indicates that these registers were more than mere accounting tools; they functioned as essential institutional mechanisms for ensuring the stability of state power, maintaining systematic control over the administrative apparatus, and providing a documentary basis for decision-making processes. Furthermore, the systematic archiving of separate registers for each type of revenue and expenditure, coupled with the rigorous oversight of responsible officials, reflects a high degree of financial discipline and accountability. Despite the Bukhara Emirate becoming a protectorate of the Russian Empire after 1868, local traditions of record-keeping and archiving successfully persisted. The research concludes that the archival system in Bukhara's state administration functioned not merely as a passive means of information storage, but as a critical, active institution for economic and administrative control. While the Bukhara Khanate (and subsequent Emirate) shared distinct similarities with other Muslim states regarding governance, record-keeping, and archival systems, the transition of power between ruling dynasties introduced specific modifications, even as the traditional preservation of permanent archival records remained a constant, defining feature of the state.*

Keywords: *Central Asia; Bukhara Khanate; Emirate; chancery (divankhana); register (daftar); court archive; museums of Bukhara*

Introduction.

Archives developed within world civilization during ancient times, and their evolutionary stages are categorized into various historical periods. The emergence of archives in antiquity is considered to be directly linked to the history of statehood. In turn, the scientific evaluation of the regional characteristics of archives is conducted based on their general historical function. This function is determined by the integration of archives into a specific cultural environment, the level of civilizational progress, the state structure, the political system, the materials used for writing, and the state of preservation of the documents. (Wirth, 1980, p. 577).

The most ancient archives operated in the territories of Egypt and Mesopotamia, which are considered the earliest cradles of civilization, and some of these have survived to the present day (Yeo, 2021, p. 222). These include, in particular, the temple and palace archives in the city of Lagash, the temple treasury in the city of Nippur, the archive of the Babylonian king Hammurabi, the archives of the city of Hattusa in the Hittite Kingdom where more than 20,000 inscribed tablets were preserved as well as the archives of the ancient city of Ugarit (Lebedeva & Mukhamadeyeva, 2022, pp. 151–154). Although the ancient archival materials preserved today are quite comprehensive and reflect the history of the ancient world, modern archival researchers have very little information regarding the purpose, operation, and management of these archives (Brosius, 2003, p. 1).

In the Early Middle Ages, other types of documents were neglected because only significant documents specifically those related to the legal activities of the ruling class in palaces and religious institutions were preserved separately. Furthermore, as a result of wars, many archives were, in some cases, destroyed by invaders. It should be noted that in recent years, although archival history research has been a part of medieval history based on historical documents and inventories kept in state archives and libraries, it has focused on studying and reconstructing the history of the formation and organization of lost institutional archives (Allen & Paul, 2024; Milani & Antonelli, 2024; Gottschalk, 2023). Additionally, particular attention is being paid to creating digital archives of medieval documents, developing online platforms, and presenting them to the general public online (Kowalewski, 2025; Sousa, Botelho, & Sebastian, 2025).

Palace archives also existed in the territories of Central Asia during ancient times; the archives of the Kharazmshahs (Afrighid dynasty, 305–955) and the archives of Dewashtich, dating back to the 2nd–8th centuries AD, serve as examples (Choriyev, Shaydullaeva, & Raxmonkulova, 2023, pp. 47–48). With the inclusion of the Central Asian region into the Umayyad Caliphate (41–132 AH / 661–750 CE) at the beginning of the 8th century, the system of state administration and archival activities became closely intertwined with the Arabic language. Upon the establishment of Arab rule in Central Asia, Arabic became the primary language for state governance and legal documentation. It maintained its status as the language of official documentation even after the emergence of local sovereign states in Khorasan and Transoxiana (Mawarannahr) during the first quarter of the 9th century.

It should be noted that as a result of the active assimilation policies of the Arabs and Persians, by the mid-10th century, the Persian language (Farsi/Dari) had displaced the Sogdian language in Sogdia and the Bactrian language in Tokharistan. Consequently, it began to compete openly with Arabic not only in poetry but also in the fields of public administration and science (Khusnutdinov & Babajanov, 2024, pp. 77, 81). It can be argued that Arabic maintained its status as an administrative language during the reigns of the Tahirid (806–877) and Samanid (875–999) dynasties. However, during the 10th century, the Persian language consistently rose as one of the major literary languages, both within the Islamic world and on a global scale. Furthermore, in the territories of Central Asia during the subsequent reigns of the Ghaznavids (962–1186), Seljuks (1040–1160), Karakhanids (990–1212), Kharazmshahs (1097–1231), as well as Amir Timur and the Timurids (1370–), Persian and Turkic languages both using the Arabic script were extensively employed in the state administrative system, official correspondence, and literature in place of the Arabic language (Buriev & Toshev, 1999, pp. 6–20). Following the Timurid period, the administrative system based on the Arabic script a practice spanning back to the era of the Arab Caliphate was continued within the Bukhara Khanate (founded by the Shaybanids in 1501 and later known as the Emirate of Bukhara, 1785–1920), the Kokand Khanate (1709–1876), and the Khiva Khanate.

In global archival science, historians generally emphasize the significance of the decree adopted on 7 Messidor, Year II of the Republic (June 25, 1794), following the Great French Revolution. This decree established two principles that remain in effect today: the centralization of the state archive system and the right of citizens to free access to archives (Pimenova, 2018, p. 269). However, these archival reforms did not reach the Central Asian khanates. Consequently, they lagged behind in areas such as the preservation of historical documents, the creation of a scientific-reference apparatus (finding aids), and the construction of dedicated archival buildings. Following the Russian Empire's military invasions of Kokand, which began in 1853, the khanate was abolished in 1876 after the annexation of the Fergana Valley territory (Morrison, 2019, p. 921). The Emirate of Bukhara (Burton, 2020) and the Khanate of Khiva (Wood, 2019) were abolished in 1920.

During the Russian Empire's military campaigns against the Khiva Khanate, Alexander Kun and his Tajik assistant, Mirza Abdurahman, collected rare manuscripts and archival documents written on parchment from the Khan's palace, which were then sent to the Imperial Library (Morrison, 2020, p. 361). Similarly, during the military campaigns in the Kokand Khanate, A. Kun located the Khan's palace and libraries (Morrison, 2020, p. 392), collecting numerous archival documents and manuscripts that were subsequently taken to the M. E. Saltykov-Shchedrin Library in Saint Petersburg (Sagdiyev, 1960, p. 59). Only the court archive documents of the Bukhara Emirate were discovered in the Ark of Bukhara during the 1930s. In 1938, a portion of these documents was transferred to the Central Historical Archive in Tashkent (now the National Archive of Uzbekistan), while the remainder was kept at the Bukhara Museum of Local Lore and History (Isakova, 2023). It should be noted that the invasion of the Russian Empire resulted in the destruction and loss of much cultural heritage, including archival documents.

In 1936, P. P. Ivanov discovered archival documents at the M. E. Saltykov-Shchedrin Library that had been removed from the Khiva Khanate in 1873 and introduced them to the scientific community. In 1961, more than 3,000 additional archival documents related to the Khiva Khanate were identified, and in 1962, they were returned to the Central State Archive of the Uzbekistan SSR (now the National Archive of Uzbekistan) (Bregel, 1967, p. 10).

Following the conquest of the Kokand Khanate in 1876, the fate of the Khan's archival documents remained unknown to science for a long period. In 1939, during P. P. Ivanov's study of the Khiva Khanate archives at the M. E. Saltykov-Shchedrin Library, M. Yu. Yuldoshev reported in 1951 that archival documents written in the

Fergana Tajik dialect were, in fact, the archival records of the Kokand Khanate. These documents were in very poor condition and underwent restoration for two years (Troitskaia, 1969, pp. 3–4).

As a result of reforms in the archival sector of the Republic of Uzbekistan, particular attention is being paid to studying the historical significance of archival documents, their preservation, and their transmission to future generations. Notably, during the meeting of the International Advisory Committee of the UNESCO "Memory of the World" program held in Paris on October 24–27, 2017, the collection of "Archival Documents of the Khiva Khanate" was included among 78 documentary heritage items from around the world and presented with a special certificate as cultural heritage of global significance (UNESCO). Furthermore, at the 216th session of the UNESCO Executive Board held in Paris from May 10–24, 2023, the archival fund numbered I-126, titled "Chancery of the Kushbegi of the Emir of Bukhara", which is held in the National Archive, was also added to the Memory of the World Register (Isakova, 2023).

It is pertinent to emphasize that as a result of the Russian Empire's military invasions, a vast amount of cultural heritage belonging not only to Uzbekistan but to all peoples of Central Asia was removed. Although many scientific studies were conducted on the historical source value of these documents since the Khiva and Kokand archives were returned to Uzbekistan in 1962, comprehensive research regarding the history and operation of archival work during the period of the Central Asian Khanates has not yet been carried out.

Based on the historical data and considerations mentioned above, the primary objective of this research is to elucidate the activities of archives in the Central Asian Khanates, highlight the specific features of their archival systems, and demonstrate the source-study significance of the surviving historical documents.

According to the historian V. Bartold, the system of administration, documentation, and the order of document preservation in the Central Asian khanates continued to improve throughout the 18th and 19th centuries. Later, while discussing the conquest of Central Asia by Russia, the author expressed regret that "no measures were taken to preserve the libraries and archives of the khanates during this process" (Ivanov, 1939, p. 11). It should also be noted that following the Soviet government's policy of transitioning to the Latin alphabet in 1928, the use of the Arabic script in the documentation system of Central Asia was completely halted.

During the Soviet period, although numerous studies were conducted to highlight the source-study significance of the archival documents of the Central Asian khanates, these research efforts were carried out within a purely historical context rather than an archival science context; consequently, only a limited number of studies focused on the archival management system. Research specifically dedicated to the activities, types, and functional duties of the archives remained largely unaddressed.

Research Methods.

This study is grounded in a comprehensive methodological framework aimed at ensuring the reliability and scholarly validity of the findings. The selection of methods is driven by the need for a systematic and multifaceted analysis of the history of palace archives in the Bukhara Khanate (Emirate). In addition to conventional historical methods, supplementary analytical approaches were employed in accordance with the specific nature of the source base.

Defining the palace archives of the Bukhara Khanate (Emirate) as the core research object determines the focus on court documentation, administrative practices, and archival complexes formed within central governing institutions. The formation and development of palace archives have been examined using the chronological method.

Given the intrinsic link between archival structures and state administration, the study adopts an institutional-historical approach to analyze the role of the court administration, the divan system, and central governing bodies in the creation, preservation, and use of archival documents. Particular attention has been paid to the functioning of the court chancery (divankhana), record-keeping procedures, and document circulation.

To assess the long-term development of archival traditions in Central Asia, an evolutionary approach has been employed, allowing for the identification of patterns of continuity and transformation in documentary culture, including the influence of Arabic script and administrative practices.

Considering the subject-specific nature of the study, methods from archival science and source criticism have been applied. Theoretical and methodological approaches developed in global archival scholarship have provided the conceptual basis for interpreting palace archives as a distinct type of archival institution.

The source base has been compiled through the integration of primary and secondary materials. The works *"Majma' al-arkām"* and *"Tarixi Turkiston"* have been as complementary sources: the former enables the reconstruction of court administrative practices and record-keeping mechanisms, while the latter provides insight into the broader political and social context. Secondary literature, including studies by G. Y. Astanova and M. A. Abduraimov, supports the institutional analysis of administrative structures. International scholarship, particularly Alexander Morrison, contributes to a broader analytical context, while approaches by R. Allen and B. Pohl inform the comparative dimension of the study. Comparative analysis of archival systems in Muslim states has been further developed through the works of M. Mehdi Ilhan and U. Sultonov, enabling the identification of both common and distinctive features of palace archives in the Bukhara Emirate.

The study also partially addresses the scientific reference apparatus of archives, including issues of source provenance, preservation, and reliability.

At the same time, it should be noted that a detailed analysis of document requisites, formular structure, as well as diplomatic and paleographic characteristics is beyond the scope of this article and is identified as a direction for future specialized research.

At the final stage, a systems approach has been employed to synthesize the findings, allowing for the formulation of substantiated conclusions regarding the structure of palace archives and their role within the system of state administration.

Results and Discussion.

Archives contribute to a nation's ability to revisit and understand its past; through them, historical memory is shaped (Meirian Jump, 2012, p. 150), and they play a crucial role in the restoration of historical memory. The activities of archives are directly connected to the history of the state administration system, the administrative language, and the writing alphabet.

The activities of the *divans* (chanceries) hold significant importance in the formation of the court archives of the Central Asian khanates. The term *divan* was borrowed into Arabic from the Old Persian words "dfyw'n" and "dyw'n". According to linguists, this word originated from the Old Persian word "dipīr", meaning "writing" or "document". The word "dipīr", in turn, entered Old Persian through the Elamites from the Akkadian word "tuppu" and the Sumerian word "dub" (meaning a clay tablet used for cuneiform writing). By the time the Arabs adopted this word, it was used in Middle Persian in the form of "dīwān".

During the Ilkhanid period, the structure of the chancery (*divankhana*) became more complex, and the *ulug bitikchi* (chief scribe), who managed financial and correspondence affairs, operated alongside his subordinate officials. During the Aq Qoyunlu and Safavid periods, reforms were carried out in the *divan* system, and the types of documents expanded. Specifically, the *divan-i parvonachi* prepared legislative documents, while the *dar al-insha* functioned as the center for official correspondence. As a result, a specialized class of scribes emerged who maintained financial registers, land and tax records, and various official correspondence (Sultonov, 2019, p. 28). Based on this information, it can be argued that the *divan* system formed during the era of Islamic states, particularly the Umayyads and Abbasids was not merely a centralized institution of state governance. The systematic establishment of archival work and document preservation, where documents were prepared and regulated by special scribes within the *divans*, allows court chanceries to be evaluated as archival repositories. In particular, state decrees, financial reports, and official correspondence were systematically compiled and preserved in structures such as the *divan al-insha* (chancery of correspondence) and the *divan-i istifo-i mamolik* (chancery of state finances).

During the Abbasid period, this system was further perfected, and the practices of registering, classifying, and preserving documents developed significantly. Specialized scribes and munshis (secretaries) within the *divans* not only drafted documents but also executed the processes of their accounting and preservation. In this regard, the *divan* system played a crucial role in the formation of archives. Specifically, in the Central Asian khanates namely Khiva, Bukhara, and Kokand the chancery system also functioned as court archives. State decrees, diplomatic correspondence, and financial documents were stored in the court chanceries of the Central Asian khanates. In the Bukhara, Kokand, and Khiva khanates, the chancery served as the center for document preservation and administration, where decrees (*farmans*), edicts (*yarlighs*), and records concerning tax and land relations were compiled. At the same time, archival repositories did not operate as independent institutions, but as integral parts of the chancery. This fact indicates that archival work had not yet been fully institutionalized.

The formation of the Bukhara Khanate in Central Asian history is associated with the decline of the Timurid state in the late 15th and early 16th centuries; amidst intensifying struggles among local rulers, Muhammad Shaybani Khan seized power in 1501. Later, during the reign of Abdullah Khan II, Bukhara became the political center of the state.

In the early 17th century, the Ashtarkhanid dynasty came to power. During the reign of Abulfayz Khan, one of their last representatives, internal conflicts, tribal struggles, and the weakening of central authority led to the state's decline. External factors, particularly the policies of Nadir Shah, played an important role in this process. With his support, Muhammad Rahim-biy succeeded in taking power. Consequently, at the end of the 18th century specifically in 1785, during the reign of Shahmurad the Manghit dynasty officially came to power, bringing an end to Ashtarkhanid rule (Shodiyev, 2010, pp. 8–10). A rather complex administrative apparatus operated within the Emirate of Bukhara. Despite the fact that three dynasties the Shaybanids, Ashtarkhanids, and Manghits ruled the Emirate of Bukhara from the 16th to the early 20th centuries, the administrative system was fundamentally based on the procedures established during the state of Amir Timur and the Timurids, though it underwent certain modifications in accordance with practical conditions and specific Uzbek traditions.

The history of archival work is closely connected with the history of statehood; therefore, examining the administrative system of the Central Asian khanates is essential to elucidating the history of their archival practices. The state administrative systems of not only Bukhara but also the Khiva and Kokand khanates were structured upon the political and legal foundations of Islamic statehood, where the supreme ruler was the khan, who wielded unrestricted power (Pochekayev, 2017, p. 108). Archival work in the Central Asian khanates was inextricably linked to the state administration system, with documents serving as the primary tool for executing administrative and legal processes. Consequently, archives emerged as institutions that consolidated the absolute character of power and documented its decisions.

During the Shaybanid period, having taken power after the Timurids, the state apparatus in the Bukhara Khanate consisted of the *dargoh* (court) and the devons (chanceries), which were subordinate to the khan (emir). Under Shaybanid rule, the chancery system was reformed, and many of its functions were reassigned to specific officials within the court. Furthermore, the Shaybanid era fundamentally altered the political and administrative dynamics of the region; the state administrative system became a hybrid based on Islamic Sharia, ancient Turkic customs and traditions, and the Genghisid administrative system. Among the supreme administrative institutions of the Shaybanid state, the *Divan-i Humoyun*, *Divan-i Mol* (finance), *Divan-i Musharraf*, *Divan-i Oliy*, *Divan-i Tavoshti*, and *Divan-i Sarkori* held significant importance (Abdulqodir Majid, 2024, pp. 196–197, 236). Based on the analysis of these studies, it can be argued that the administrative system of the Bukhara Emirate was inherited from the Timurid period; during the Shaybanid era, the activities of the chanceries were refined and restructured, with a portion of their duties transferred to individual officials. It must be emphasized that this system was of a hybrid nature, combining Islamic Sharia, Turkic traditions, and Genghisid governance. In particular, the duty of delivering the supreme ruler's decrees, edicts, and other official documents to the responsible persons or executors was assigned to the parvonachi. The tasks of receiving applications and complaints, as well as formalizing the responses, fell under the duties of the *dodxoh*.

The chanceries during the Shaybanid period possessed a unique executive system. The *Divan-i Humoyun* made decisions regarding military campaigns and the appointment of deputies to conquered territories. The *Divan-i Mol* organized state finances and tax activities, while the *Divan-i Musharraf* was an institution that oversaw state affairs and monitored certain dynasty members and key officials. Additionally, the *Divan-i Oliy* managed the activities of all state institutions and court offices; the *Divani Tavoshti* managed the soldiers; and the *Divan-i Sarkor-i Xossa* collected orders regarding state revenue-generating trade locations, mills, and state properties, gathering the necessary expenditures demanded by the khan. Besides the aforementioned chanceries, important decisions were also made through councils such as the *Kinjish, Marosimi Mashvarat, Bobi Mashvarat*, and *Majlisi Oliy* (Abdulqodir Majid, 2024, pp. 236–239). Based on this data, it is evident that the activities of the court archives in the Central Asian khanates were intrinsically linked to the system of statehood, directly influencing the creation, circulation, and preservation of archival documents. Institutions operating within the centralized administrative system of the Shaybanid era, such as the *Divan-i Humoyun*, *Divan-i Mol*, *Divan-i Musharraf*, and *Divan-i Oliy*, not only performed administrative functions but also served as the foundation for the processes of document circulation and archiving. For instance, the maintenance of tax and financial reports by the *Divan-i Mol*, the formulation of control documents through the *Divan-i Musharraf*, and the recording of military orders and decrees in the *Divan-i Humoyun* laid the groundwork for the formation of archival records.

The administrative structure formed within the framework of the court's documentation system constituted the institutional basis of the archive system. The operations of the court and its subordinate chanceries indicate that the creation, formalization, and preservation of documents were subject to specific rules and procedures. Concurrently, the functional grouping of documents within the chanceries (financial, military, administrative) ensured their systematic storage and the ability to reference them later. From an archival science perspective, the processes of recording, accounting for, and storing the documents of the court documentation system not only met daily administrative needs but also laid the foundation for the state archive system. Furthermore, the systematic recording of data regarding state property and economic resources in institutions like the *Divan-i Sarkori Xossa* ensured the emergence of economic archival documents as a distinct category. Decisions adopted in advisory bodies such as the *Majlisi Oliy* and *Bobi Mashvarat* led to the formation of political archival documents.

According to research analyses, there are similarities between the chancery systems of the Bukhara Khanate and the Ottoman State. Based on studies concerning the history of Ottoman archival work, the early Ottoman administration primarily consisted of chanceries such as the Imperial Council (*Divan-i Hümayun*), the Treasury (*Hazine-i Amire*), and the Imperial Registry (*Defterhane-i Hakani*). The territorial and administrative expansion of the Ottoman Empire led to the increasing complexity of these institutions structures. Particularly after Topkapi Palace became the central institute of state administration (until the end of the 18th century), the activities of these offices became even more institutionalized. During and after this period, imperial administration was conducted through the Imperial Chancery (*Divan-i Hümayun*), with the Grand Vizier regularly informing the Sultan regarding the decisions made in this council. Official records of the council meetings were maintained in a special secretariat known as the *Divan-i Qalam* (*Divan-i Kalem*). This office was managed by the Secretary of the State Council, the *Beylikçi*, who in turn was subordinate to the *Reisül-küttab* (chief scribe). This indicates a clearly defined hierarchical relationship and functional division within the chancery's administrative apparatus. This governance system continued until the establishment of the *Bab-i Asafi* (Palace of the Grand Vizier) in 1839 (Ilhan, 2008, pp. 23–24). Although the Shaybanid and Ottoman state administrative systems both relied on general Islamic-bureaucratic traditions, they differed in their level of institutional development and scale of centralization. In both states, the chancery system occupied a central position, and the processes of document circulation and archiving were conducted through these offices. In the Shaybanid state, while the chanceries were functionally specialized, their operations were shaped more by tradition (Sharia, Turkic customs, and Genghisid governance), and archival practices primarily served practical administrative needs. Conversely, in the Ottoman State, the chancery system was highly institutionalized and possessed a strict hierarchical structure. Specifically, the systematic recording, classification, and preservation of documents were established through the *Divan-i Hümayun*, *Dafterkhane*, and the central secretariat. This demonstrates that archival work had become an independent and developed sector.

During the Shaybanid era, the *Divanbegi* was responsible for managing the activities of the chanceries, performing secretarial duties alongside administrative and economic affairs. Scribes or munshis were responsible for writing the documents within the chanceries. The scribes were called munshi, while the office they executed was termed *boshkotiblik* (chief secretariat) or *kotibiyat* (secretariat). The head of the scribes was titled *mirzaboshi*. In addition to acting as personal secretaries to the khans, the scribes were also responsible for writing orders for lower-tier officials in the administrative structure. *Munshis* who were masters of textual composition were carefully selected (Abdulqodir Majid, 2024, p. 248). In turn, according to the analysis of surviving historical documents and research, the Persian language was widely used in Shaybanid state documentation, and the majority of historians and masters of the scribal arts had been active since the Timurid and Safavid periods (Comstock-Skipp, 2023, p. 5). In our view, within the operations of the Shaybanid court chanceries, the scribes and *munshis* were responsible not only for preparing documents and managing correspondence but also for preserving current archival records. Chancery staff essentially performed the duties of both clerks and archivists simultaneously. The very fact that the aforementioned documents have reached us proves they were preserved in uniquely important chancery archives.

In recent years, research conducted on the Ashtarkhanid period has provided clarity regarding important information on documentation and archival activities within the state chancery system. During the Ashtarkhanid dynasty, the chancery continued to handle financial matters and was managed by the *Divanbegi Kalon* (Chief Divanbegi). The primary duty of the *Divanbegi Kalon* was to oversee the activities of the *Oliy Daftarxona* (Supreme Registry), which recorded financial documents of income and expenditure. The *Oliy Daftarxona* housed registers such as the *in'om daftari* (register of gifts), *tanobona daftari* (register of land/crop taxes), *kirim daftari* (register of income), *chiqim daftari* (register of expenses), and the *oliy barotlar daftari* (register of supreme drafts/orders) (Sangirov, 2024, p. 12). There were also specialized officials within the chancery who maintained the aforementioned registers. For example, the *mushrif* official in the chancery recorded the gifts, endowments, charity, and favors granted by the khan into the special in'om daftari and oversaw their execution. The *daftardor* present in the chancery was responsible for the register recording the holders of *tanxo* and *suyurgol* (fiefs and land grants). The official of the *tanobona daftari* chancery calculated the income taxes and expenditure costs derived from spring and autumn crops, recording them in the *tanobona daftari*. The chancery of *tavjih* and *avorij* was responsible for the accuracy of the *xavorij* (calculation of taxes, *kharaj, zakat, and customs* funds) register and the *tavjih* (expenditure) register. The office of *poygirnavis* also operated within the chancery. Notably, when Mirza Badi Divan mentions this role, he provides no information about its duties. Full details regarding this position can be derived from the mandate (*manshur*) appointing Mullo Orif to the post. In it, the position is recorded in full as *poygirnavis-i baravoti daftar-i oliy* (the *poygirnavis* of the supreme register of drafts). The primary duty of this official was to oversee the *oliy barotlar daftarlari* (registers of supreme drafts).

According to Semenov, during the reign of this dynasty, the court chancery documentation system was conducted by personnel such as the *Divan-i Kalon*, *Divan-i Mushrif*, *Daftardor*, and *Divan-i Tanobona*. They were referred to as the *ahli qalam* (state secretary), a term we believe can be equated with "record-keepers" or "clerks". The *Divan-i Kalon* maintained the supreme registers known as the *daftar-i tanxo* and *daftari bilgu* (according to Semenov's interpretation). These registers tracked cash entering the court treasury, land right documents granted to officials, natural tax revenues, and land lease documents. The *Divan-i Mushrif*, on the other hand, maintained records for the court household. The *Daftardor* reviewed and edited the texts of the documents, and with his authorization, the document was authenticated with a seal. The *Divan-i Tanobona* held the authority to collect the xiroj (land tax) from the *tanobona* lands and to expend the derived revenues according to the supreme khan's decree (Semenov, 1948, pp. 141–142).

Based on these historical details, it can be concluded that each of these chancery representatives maintained documents concerning the influx of specific financial funds, and they preserved these documents regarding tax collection, land ownership rights, and other matters in separate chancery archives. It must be emphasized that these chancery personnel simultaneously fulfilled the roles of both record-keeper and archivist.

Semenov’s research notes that there was also a position of librarian (*kutubxonachi*) at the court. The librarian received works submitted by religious and secular scholars, writers, and poets, and issued them after they were approved by the ruler. Additionally, his duties included the restoration and repair of books in the palace library (Semenov, 1948, p. 143).

It can be argued that, along with repairing books, the librarian at the request of the chancery scribes - performed the task of binding documents from the palace chancery, specifically the registers (*daftars*), in the form of “archival file”. This process, in turn, played an important role in organizing the documentation system within the chanceries and preserving the registers in an archived state.

According to A. Semenov, there were also chanceries managed by the baxshi and the court stables (*otxona*), which accepted goods and money into the treasury (warehouse) and maintained their records in separate register documents. Furthermore, there was a chancery managing the affairs of the treasury (warehouse) whose duty was to receive various items into the state treasury and register them. Subordinate to these activities were the junior mushrif, the secretary of edicts (yorliqlar kotibi), the chancery of the maxrams (confidants), and the chancery of the yasavuls.

Sadr-i Ziyo (Muhammad Sharifjon ibn Qazi Abd ush-Shakur), the *Qazi Kalon* (Supreme Judge) of Bukhara, discusses the positions, titles, and duties of their holders in his memoirs, categorizing the state secretary (*ahli qalam*) into several groups. Specifically, he describes 16 types of state secretary, providing detailed information on the duties of state chancery scribes, personal secretaries of officials, secretaries for palace household affairs and their assistants, as well as high-ranking officials who performed duties directly for the supreme ruler, such as the *divanbegi kalon*, *parvonachi*, and *dodxoh* (Mirzo Olim Mahdum xoji, 2008, pp. 165–166).

Historically, after the Manghit dynasty (1756–1920) came to power in the Bukhara Khanate, the state became known as an Emirate. An analysis of research shows that the operation of archives was improved during the Manghit period. A crucial factor in the formation of the archive was the significant strengthening of the Kushbegi’s power at the end of the 18th century. The Bukhara Emirs granted the Kushbegi nearly unlimited authority in all spheres of the khanate's economic and political life. Consequently, a major portion of the documentation process began to be executed through the chanceries of the Kushbegi (Abduraimov, 1974, p. 60). As a result, numerous important documents of political, administrative, socio-economic, and cultural significance were accumulated in these secretariats. The increased centralization under the Manghit dynasty directly influenced archival work; specifically, as the Kushbegi's powers grew, document circulation was consolidated within his chancery. This led to a more systematic approach to record-keeping and the consistent preservation of documents.

In the court of the Emirate of Bukhara, the accumulation of documents occurred through two primary sources:

1. Documents received from the Chancery of the Bukhara Emirs;
2. Documents produced during the Kushbegi's own administrative processes.

The first group of documents was amassed in the Kushbegi archive as a result of correspondence between the Emirs of Bukhara and their "prime ministers" (*qull-i kushbegi*). These included various decrees (*farman*), edicts (*yarligh*), insignia (nishons), congratulatory letters address (*mubaraknama*), and other official documents that were subsequently stored in the secretariat. In this manner, approximately 5,000 such documents from the Emirate were collected in the Kushbegi archive.

The second part of the archive consisted of documents prepared directly within the Kushbegi's chancery. The chancery (*divakhana*) included the *mirza-khana-i kalon* (chief scribal office), the *mirza-khana* (secretariat), and the office of the *Divanbegi*. The *mirza-khana-i kalon* was, in turn, divided into a main secretariat consisting of 10 scribes (mirza) and a second chancery of 8–10 scribes. The first section dealt with accounting for gold, *khiraj* (land tax), and other income and expenditures, while the second managed regional relations, the issuance of passports, and other matters. The *mirza-khana* also employed 8–10 scribes who handled correspondence with the Russian political agency and all matters related to Russo-Bukhara relations (Astanova, 1985, p. 55). The formation of documents through these two sources (the Emir's chancery and the Kushbegi's chancery) implies that documents were organized systematically. This process enabled the systematic archiving of records. The functional specialization of units like the *mirza-khana-i kalon* and *mirza-khana* (financial accounting, diplomatic correspondence, administrative affairs) gave rise to a thematic and sectoral classification of documents. This, in turn, ensured the systematic grouping of materials stored in the archive and enabled their effective use.

Following the conquest of Bukhara by Bolshevik forces in 1920, the Emir's palace was looted. To preserve surviving archival documents, a group consisting of staff from the Tashkent Central Bureau of Archival Affairs was mobilized in September 1920. This team collected the archival records of the Bukhara Kushbegi and decided to transfer them to a library for safekeeping. For a long period thereafter, no further information regarding the archive of the Bukhara Emirate surfaced.

Subsequently, Haydarov, the director of the Bukhara Regional Archive Bureau, transferred all these documents along with two registers to the Bukhara State Museum. A second portion of the archive was organized by a group of Orientalists led by

D. I. Nechkin, the head of the Central Archival Affairs Administration, and sent to the Bukhara People’s Soviet Republic (BPSR) in early September 1920. The commission was tasked with taking immediate measures to preserve archival documents, written sources, and examples of ancient art. In cases of looting or loss, they were instructed to cooperate with the Bukhara Revolutionary Committee to prevent further damage and transfer the most valuable documents to the Commissariat of People’s Education (Nafiddinova & Kalandarova, 2020, pp. 26–29).

In December 1931, a disorganized mass of documents written in the Arabic script (Persian language) was discovered in the basement of the Bukhara Emir’s palace (the Ark). These documents were initially brought to the Bukhara Museum, where they were systematized for the first time. Between 1937 and 1938, a collection of 7,764 documents was transferred to the Central State Archive of the October Revolution of the Uzbek SSR (now the National Archive of Uzbekistan), where they underwent further scholarly processing.

Research indicates that the Kushbegi’s chancery (*divankhana*) was located within the *Ark* and consisted of 20–25 scribes (*mirzas*) led by a chief. This head official - the *Mirza-i Kalon* – essentially functioned as both the chief accountant and the director of the entire chancery. Specialized roles were often absent; consequently, routine, small-scale accounting tasks - maintained on long rolls of paper known as scrolls (*daftar* or *lula*) could be assigned to almost any scribe (Andreyev & Chexovich, 1972, p. 55). When Soviet troops occupied Bukhara, several chests containing documents were found in the basement of the Ark. Some documents were on shelves, while others lay on the floor. Based on translations of archival records provided by G. Astanova, the archive was initially unsystematized. However, in the early 20th century, during the tenure of Nasrulla Kushbegi, documents began to be stored in specialized chests known as *yaxdana*, placed on shelves in the basement of the *Ark* (Astanova, 1985, p. 56). The presence of shelves in the room where the documents were found suggests that this space was intentionally designed as a specialized storage facility. This implies that, in addition to the current (active) archives within the chanceries, permanent archival repositories were established in the palace basements, with records preserved in dedicated chests and cabinets.

According to reports, these documents were state records left behind by the Emir’s officials. Supervisory authorities placed these documents into boxes without any order or inventory and sent them to the Council of People's Commissars. Subsequently, until the formation of the Uzbekistan SSR, they were stored in the basement of the Commissariat of International Relations.

In 1924, a portion of the documents was transferred to the Bukhara State Library under the supervision of Musa Saidjanov, formalized by an official transfer act. This act recorded Oriental documents consisting of 69 scrolls, 52 registers (*daftars*), and 50 books. The portion of the Kushbegi archive preserved in the State Library was organized by M. R. Hakimov. In 1932, the archive was handed over to the Bukhara Regional Archival Bureau.

Ultimately, these archival documents were transferred to the Central State Historical Archive (now the National Archive of Uzbekistan). According to Musa Saidjonov, a minister of the Bukhara People's Soviet Republic, two primary types of archives existed in the Bukhara Emirate:

1. The archival documents of the Emir's Chancery;
2. The archive of the Kushbegi of the Bukhara Emirate.

In our view, the structural reality was slightly more complex. Within the Emir's palace, there likely existed three distinct repositories: a specialized library-archive belonging personally to the Emir, the chancery archive, and the Kushbegi archive.

Regarding the existence of the Emir's personal library-archive, the Orientalist V. A. Vyatkin provided a compelling account in a letter written to V. V. Bartold at the end of the 19th century: "Based on the gathered information, it can be said that the Emir has his own library. Dressed in local attire, I went to the *Ark* with a *sart* from Samarkand. In response to my cautious questions, the palace officials confirmed that there was indeed a library in the *Ark*. However, like other rooms, the library could only be accessed with the Emir's personal permission. Later, according to a Tatar master craftsman who repaired the palace, he saw three rooms full of books, scrolls, and papers. I later heard that the Emir did not want to show the library because the state archive was located there at the same time. The Emir feared that the information stored there would not please the Russians or that secret information would be revealed. For this reason, he preferred to keep the documents hidden rather than show them" (Lunin, 1965, p. 178).

Based on Vyatkin's account of the Tatar craftsman observing three rooms filled with books, scrolls, and papers and the simultaneous presence of an archive there it can be posited that the Emir's library-archive also stored sensitive diplomatic documents, records protecting the Emir's sovereign rights, and deeds related to his personal land ownership. The library was located in one of the Emir's private rooms, and the books were typically kept in chests. According to sources, the last two Emirs paid little attention to books; there was not even a dedicated librarian during their reigns. On rare occasions, if a particular book was needed, it would be searched for or brought upon the Emir's request (Andreyev & Chexovich, 1972, p. 53). As Vyatkin highlighted, the co-location of the library and the archive in the Emirate reflects a characteristic feature of institutional systems in Eastern Muslim states. However, the decline in attention given to the library during the reigns of the final Emirs can be evaluated as a sign of cultural and administrative stagnation. The absence of a specialized librarian position meant that books were kept in a disorderly manner and were practically unused. While the library-archive held significant importance initially, its relevance diminished in its final stages, leaving the collection neglected.

Unlike modern, static repositories, the chancery archival documents were highly mobile and were continuously kept by the Emirs at their respective active residences. For instance, Emir Muzaffar stored them at his Shirbudin residence in the city of Bukhara, while his son, Emir Abdulahad, relocated the archival documents to his residence in Karmana (in present-day Navoi region in Uzbekistan). During the reign of

Emir Alim Khan, the documents were returned to Bukhara. The official responsible for overseeing the Emir's chancery and its accompanying archive was the *parvanachi*.

In December 1931, a systematic classification of the discovered documents was undertaken by Ashurov and V. A. Shishkin, resulting in the identification of seventeen distinct thematic categories. These included: 1) messages sent to the Emir by high-ranking officials and *beks*; 2) reports and information received from various provinces and districts; 3) the administrative archival documents of the Kushbegi; 4) records and data compiled by the *Munshi* (State Secretary); 5) autograph notes written in the Emir's own hand; 6) various personal documents of the Emir, encompassing both specialized and private records; 7) reports concerning a wide array of political matters; 8) confidential intelligence received directly by the Emir; 9) formal correspondence with the Russian Political Agency; 10) letters dispatched by regional *beks* to the Kushbegi; 11) the Kushbegi's own correspondence with Russian officials; 12) comprehensive financial documents; 13) rosters and registers of military officials and the clergy; 14) legal documents regarding private property (*vasiqa*); 15) records concerning land and water resource distribution; 16) railway and postal-telegraph administrative documents; and 17) miscellaneous materials such as newspapers, journals, certificates, and passports (Jumayev, 2025, pp. 1729–1739; Nafiddinova & Kalandarova, 2020, pp. 26–29). It should be noted that this categorization was not exhaustive; many of these groups, particularly those combining disparate elements like military rosters with clerical lists or infrastructure records with personal identification, could be further subdivided for more granular thematic analysis.

According to the latest catalog of the Kushbegi fund at the National Archive of Uzbekistan, the collection is housed in 2,656 folders, totaling over 100,000 individual documents. These records primarily date from the late 19th to the early 20th century. They contain invaluable data on internal and external policy, regional administration, the tax system, judicial proceedings, and even social history, such as the organization of public holidays and peasant unrest.

The surviving documentation confirms the existence and active operation of specialized palace archives in the Central Asian khanates. These repositories centralized administrative, financial, military, and diplomatic records. While earlier research often emphasized the "disorderly" state of these records, such a view may be overly critical. The chaotic state in which they were found was largely a result of the rapid evacuation and looting during military invasions. In reality, the functional classification of documents separating financial, military, and diplomatic spheres demonstrates a level of systematic archiving that served the practical needs of the state.

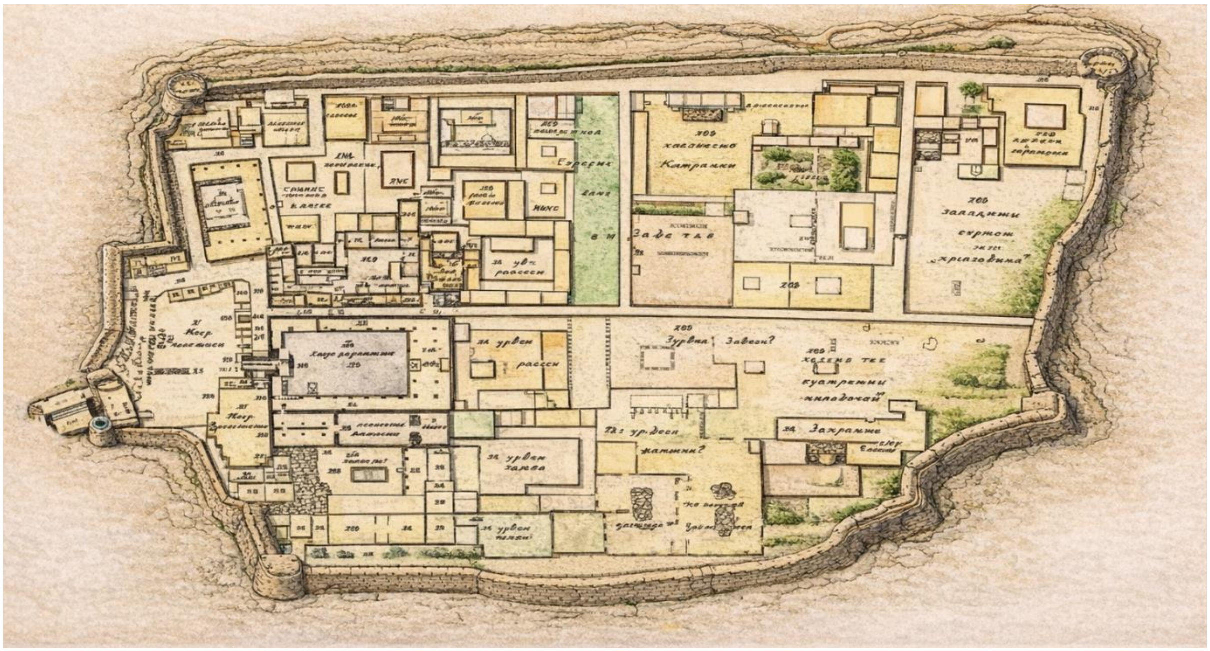

Figure 1. Schematic plan of Bukhara Arch (The image is rendered in color using artificial intelligence). (Andreyev & Chexovich, 1972, p. 144)

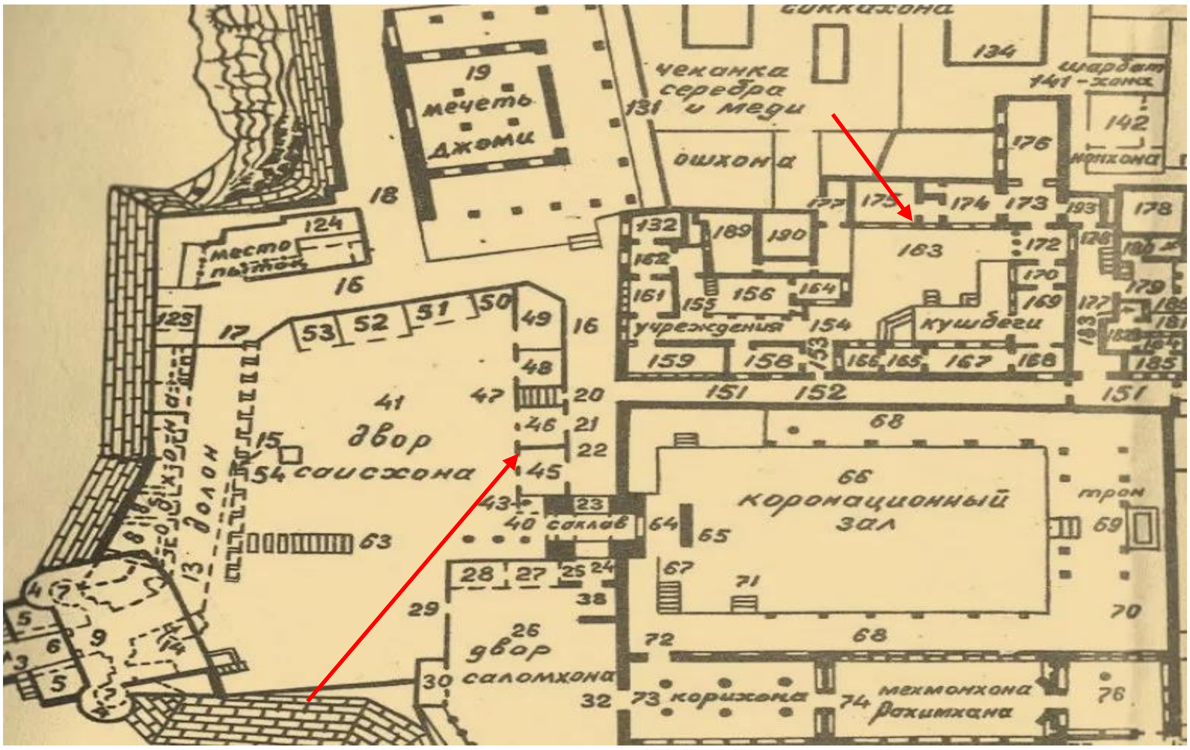

Figure 2. According to Andreev, rooms 174–175 are *Mirza-khana-i kalon* chancellery; 176-*Divanbegi* chancery; Rooms 45–46 are the office of the Russian Political Agency. (The image is rendered in color using artificial intelligence) (Andreyev & Chexovich, 1972, p. 144)

It is noteworthy that in the Middle Ages, specific methods of confidentiality were employed in the creation of court documents. It is well known that in the court chanceries of Eastern states, to prevent the disclosure of information regarding the sources and expenditures of the state treasury and to eliminate the possibility of forgery in the income and expenditure registers a system of specialized symbols known as *Siyoqat* was introduced instead of ordinary numerals. L. Fekete, who studied the use of *Siyoqat* among the Ottoman Turks, noted that its origins date back to the period of the Umayyad Caliphate.

The *Siyoqat* symbols were formed through the abbreviation and modification of Arabic numerals. In addition to numbers, these symbols were used to express weights, measurements of length, currency units, and other indicators. Because these symbols were initially used in state secretariats, they were referred to as *arqomi divaniy* (chancery numerals). Later, *Siyoqat* spread widely, being used not only in chanceries but also in trade and other financial documents, becoming popular across the Near and Middle East. Similarly, in Central Asia, this system was called *siyoq*, and its symbols were known as *ruqum* (an alternative plural form of the Arabic word *raqam* (number)), distinguishing them from *arqom*, which referred to ordinary numerals.

In illustrating the registers (*daftars*) maintained in the chanceries of the Bukhara Khanate and their executive functions, the work "Majma' al-arqam" by Mirza Badi Divan serves as a vital historical source; it is considered an official manual for 18th-century Bukhara chancery record-keeping. According to this historical source, the two oldest and most fundamental types of documents in the chanceries of Eastern states were the *daftar-i abaridja* and the *tavdjikha*. Estimated data suggests that registers of the *abaridja* type existed as early as the chanceries of the Sassanid period. The *abaridja* register recorded the total sum of permanent and fixed taxes collected from state lands, allowing for the precise determination of the state's primary assets at any given time. Secondary assets were maintained in the *tavdjikha* register.

Over time, various supplementary documents concerning different items of income and expenditure branched out from these primary registers. For example, the *daftar-i zabita* – which recorded lease payments, tolls, and revenues from the trade of specific goods emerged from the *abaridja*. From the *tavdjikha*, the *daftar-i tafsil* emerged, which recorded funds entrusted to state officials for the purchase of treasury goods.

The *Majma' al-arqam* mentions the following types of documents and registers that existed in the 18th-century Bukhara chancery: *avaridja, tavdjikha, tafsil, mukhosama, muazzaf, ziraat-khana, tanobkhana, divan-i sarkor, daftar-i tavdjikha barot, sanad*, and others (Mirza Ba'di Divan, 1981. pp. 14–15). Based on this information, it can be argued that several record-keeping systems within the chancery systems of Eastern states were modeled after systems used in the history of Iranian statehood.

The paper provides significant details regarding the functional roles of these registers. For instance, the *Abaridja* register served as a registry of tax objects and their corresponding cash and natural (in-kind) revenues. It listed the names of villages belonging to each district in alphabetical order. Under the name of each village, the amount of money or the volume of grain and other products to be collected was indicated. Additionally, the name of the recipient of this revenue, their tribal affiliation, and their official position were recorded (Mirza Ba'di Divan, 1981. pp. 14–15). It should be emphasized that the alphabetical listing of geographical regions in the *Abaridja* register demonstrates that the alphabetical cataloging system widely used today in the finding aids of libraries and archives was extensively utilized in the chancery documentation systems of that time.

The first page of the Tavdjikha register contained the name of the salary recipient; below this, the name of the village from which the salary was derived and the amount were indicated. All types of rewards and grants *tankho*, *suyurghal*, as well as grain, gifts, clothing, and more were registered in the *tavdjikha* register.

Separate registers and responsible officials existed for each type of revenue and expenditure. *Kharaj* (land tax) receipts in the form of grain or cash were recorded in the *abaridja* registers. There were two distinct types of books for the *kharaj*, including registers for *mu'azzaf* (a fixed tax determined by the size of the land area).

There was also the *muqasama* tax, which consisted of a specific share of the harvest and was collected twice a year, in spring and autumn. The financial chancery, managed by the *mu'azzaf*, handled *kharaj* affairs and issued a check called a *bilgu* in the name of those receiving salaries from the *kharaj* revenues. Individuals supported by the *kharaj* received a *bilgu* according to the *muqasama* share, and these documents were formalized by the *daftardor*. The financial chancery, the *daftardor*, and the *bilgus* were authenticated with the seals of the Grand Chancery, the *divanbegi*, and the head of state. For every *bilgu* written (the document handed to the owner), the secretariat prepared a *sanad* (a copy of the issued document) and archived it for its own records. Regarding the *tahvil* report in *Majma' al-arqam*, it recorded the amount of precious metals submitted to the mint and the names of the individuals responsible for minting coins. The *daftardor* was responsible for accounting for *tankho* lands. The *Divan-i Sarraf* maintained the register of grain and cash revenues entering the state treasury. The *Katta Mushrif* (Senior Overseer) kept accounts of the salaries paid to the army, for weaponry, and to military officials and the *ulama* (religious scholars) (Mirza Ba'di Divan, 1981. pp. 14–15). The archive of the Bukhara chancery was based on a centralized accounting-registry system, where the *abaridja* recorded primary revenues and the *tavdjikha* recorded expenditures and distributions. These two archives ensured the systematic accounting and control of information. The subsequent emergence of specialized registers and the chancery archive formed the core of the state's financial management.

More than 40 types of documents were maintained within the palace chanceries. The table below outlines the primary categories.

Table 1. Names and functions of documents within the Bukhara court chanceries (Kazakov, 1987, pp. 17–29).

№	Document type	Functional Description
1	Hujjat (Act)	A written source officially recording specific social, legal, or economic relations.
2	Farmon (Decree)	An order or directive issued by the Supreme Ruler.
3	Nishan (Mandate)	A formal instruction or document with executive force issued by the Ruler.
4	So'z (Oral Command)	An oral order or instruction from the Ruler that was formally recorded.
5	Yorlig' (Edict)	A command issued by the Ruler or a high state representative.
6	Hukm (Ordinance)	A binding legal order, decree, or judicial decision issued by the Ruler.
7	Amr (Order)	An official document conveying a specific administrative command.
8	Xatt-i Ibro (Waiver)	A document confirming the relinquishment of a claim or the cancellation of a legal demand.
9	Inoyatnama	An official letter of favor regarding rewards, the granting of privileges, or royal grace.
10	Marhamatnama	A document regarding the bestowal of gifts or charitable grants.
11	Darbast (Immunity)	A charter granting complete land privileges (tax exemption and administrative independence).
12	Vasiqa-i Bay-i Bot	A legal deed formalizing the absolute sale (purchase-sale) of property.
13	Xatt-i Ijara	A document confirming the temporary use (lease) of property.
14	Waqfiya (Endowment)	A deed designating property for religious or charitable purposes (*waqf*).
15	Vasiyatnama	A formal testament or will regarding the distribution of inheritance.
16	Vasiqa-i Muqassa	A legal document recording a sale process exclusively on behalf of the seller.
17	Mu'of (Exemption)	A grant of tax immunity or the partial/full exemption of lands and water from taxes.
18	Vasiqa-i Baxshish	A deed of gift for the gratuitous transfer of property to a private individual.
19	Vasiqa-i Bay-i Joiz	A mortgage or pledge document regarding property used as collateral.
20	Xatt-i Nikoh	A marriage contract or certificate (*ahd-noma*).

Conclusions.

To sum up, it can be said that the functioning of the palace archives in the Bukhara State was directly linked with the activities of the chanceries (*divans*). Depending on the state's administrative structure, the responsibility for record-keeping and document preservation was assigned to specific high-ranking officials or specialized ministries (*divans*) under the ruler's authority. Consequently, state records were accumulated either within various state institutions or held by individual officials. However, in the Central Asian khanates specifically the Bukhara Khanate and the subsequent Emirate – the roles of these chanceries changed as power shifted between different dynastic representatives. The activity of the court chanceries developed as an integral functional component of state administration; each department was responsible for the creation, preservation, and a certain degree of systematization of documents within its specific jurisdiction.

The “treasuries” (*khazinakhana*) and libraries of the rulers also served as centralized archives for political and economic documents of national importance. Documents were preserved in chests (*sandiq*) or on shelves, with information retrieval facilitated through registration journals. While the chanceries utilized alphabetical cataloging systems for maintaining their registers (*daftars*), the storage facilities lacked a fully centralized system for accounting, description, and the formation of a unified scientific-reference apparatus.

Finally, it is worth noting that although the Bukhara Emirate had become a political dependency of the Russian Empire and was geographically adjacent to the Turkestan General-Governorate, the Russian imperial administrative and archival systems did not exert a significant influence on Bukhara’s internal record-keeping. The Emirate maintained its traditional, indigenous system of documentation and archiving until its collapse in 1920.

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The authors declare no conflict of interest.

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Історія придворного архіву Бухарського ханства (згодом Емірату) в Центральній Азії

Анотація. *Це дослідження аналізує формування та функціонування палацових архівних систем у Бухарському ханстві (згодом Еміраті) в ширшому контексті традицій державного управління Центральної Азії. У роботі застосовано комплексний підхід для вивчення адміністративних структур із особливим акцентом на ролі диванів (канцелярій) в організації архівної системи. Результати показують, що дивани виконували не лише виконавчі функції, але й були центральними вузлами, які координували процеси збору, систематизації та збереження документів. У межах палацової інфраструктури інституції бібліотеки (кутубхона) та скарбниці (хазінахона) виконували допоміжні, але важливі архівні функції, виступаючи централізованими сховищами документів політичного, економічного та дипломатичного значення. Документообіг здійснювався через систему реєстрів (дафтари), які одночасно слугували інструментами обліку та науково-довідковим апаратом. Зокрема, алфавітне розташування географічних назв у цих реєстрах забезпечувало швидкий пошук інформації та підвищувало ефективність управління. Аналіз джерел свідчить, що ці реєстри були не лише обліковими документами, а й ключовими інституційними механізмами, які забезпечували стабільність державної влади, системний контроль над адміністративним апаратом та інформаційну основу для ухвалення рішень. Крім того, системне ведення окремих реєстрів для кожного виду доходів і витрат, а також суворий контроль відповідальних осіб свідчать про високий рівень фінансової дисципліни та підзвітності. Попри те, що Бухарський емірат після 1868 року став протекторатом Російської імперії,* *місцеві традиції ведення документації та архівування збереглися. Дослідження робить висновок, що архівна система в державному управлінні Бухари функціонувала не лише як пасивний засіб збереження інформації, а як активний інструмент економічного та адміністративного контролю. Хоча Бухарське ханство (а згодом Емірат) мало спільні риси з іншими мусульманськими державами щодо управління, діловодства та архівних практик, зміна правлячих династій призводила до певних модифікацій системи, тоді як традиція збереження постійних архівних документів залишалася стабільною й визначальною характеристикою держави.*

Ключові слова: *Центральна Азія; Бухарське ханство; Емірат; канцелярія (диванхона); реєстр (дафтар); придворний архів; музеї Бухари*

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Women as calculators in a military Observatory in Spain

Abstract. *The Royal Astronomical Observatory of the Navy in San Fernando is one of Spain's oldest and most important scientific institutions, and led by director Cecilio Pujazón, actively participated in the international astronomy cooperation project The Sky Map, launched in Paris in 1887 in the Conference of Astronomists and proposed by Mouchez. As a military institution, women's access to its work was historically difficult, compounding the already difficult access of women to the world of science. However, like other observatories, the Observatory of San Fernando hired women to perform measurements and calculations for astrophotographic plates, a painstaking task requiring many hours of work. This strategy was implemented because hiring women was more economical and submissive. This study, with a methodology of bibliography and documental research which includes consultation of the Observatory of San Fernando's historical archives (especially the Master Books), seeks to discover, make visible, and empower the presence of these women from a gender perspective. Information was found on 30 women hired between 1919 and 1967 and this period coincided with a very difficult political and social time for women in Spain. They were hired in lower positions and were fired when they got married. Although their work was rendered invisible and their roles subordinate, their presence in a male-dominated military institution paved the way for future hiring. The analysis concludes that, both in this observatory and in others, the discriminatory circumstances of their work highlight the persistent gender inequality in science. This study joins others already underway at observatories around the world (Harvard, Melbourne, Paris, the Vatican) where women were also hired under similar circumstances. All these studies aim to bring these women out of anonymity and conduct gender studies within the scientific community. At the international level, it has been agreed to rename them as Women Astronomical Computers, and in future research, the aim is to create a common bank of digitized documentation of their work.*

Keywords: *Royal Astronomical Observatory of the Navy of San Fernando; Women Astronomical Computers; History of Science; gender studies*

Introduction.

With over 250 years of uninterrupted scientific activity, the Royal Astronomical Observatory of the Navy of San Fernando, Spain (Hereinafter, ROA), the oldest in the country, is one of its most important scientific institutions (Lafuente & Selles, 1988). Being a military institution from its origins, this further hampered the already difficult access of women to participate in its projects and work. In 1887 the international astronomical cooperation project The Sky Map was launched in Paris and the ROA participated in this project (Fundación Descubre, 2025). It was one of the most active observatories in the project, one of the few that completed its assigned work, and almost the only one that today preserves all the instruments used and the plates generated during the project. Its commission ended in 1923, at the same time as Greenwich and Oxford, but the Gautier astrograph continued to be used for other projects until 2008. At the ROA, as at other observatories around the world, women were also hired to perform measurements and calculations for astrophotographic plates, as they were more economical and thorough.

The first question I must address, is explain where we are, because the ROA is a sometimes-unknown observatory and to understand its importance also. The ROA is in a very strategic location, especially in the 18th century, which was the point of contact between Europe and Africa and the passage from the Mediterranean Sea to the Atlantic Ocean, with all that this entailed for Spain's control of commercial routes, especially its monopoly with America and, therefore, its military and political position (Orozco, 1988). Cádiz is a city open to the ocean, very close to Gibraltar and it sits on an island overlooking the Bay of Cádiz, surrounded by other small cities such as Rota, Puerto de Santa María, Puerto Real, and San Fernando, where the ROA will be relocated after being initially founded in the city of Cádiz.

In 1753, the Royal Observatory of Cádiz, the southernmost in Europe and the oldest in Spain in this time, was created as an annex to the Academy of Marine Guards in the Castle of the Villa de Cádiz, by order of the Marquis of Ensenada (1702–1781) and King Charles III (1716–1788), at the request of the naval officer and scientist Jorge Juan Santacilia (1713–1773). But, after, in 1798, the Observatory was moved to the city of San Fernando, to a new building, which has survived to this day, designed by the Marquis of Ureña (1741–1806) based on the plan of the Oxford Observatory (La Fuente & Sellés, 1988).

In the 18th and 19th centuries, the observatory had an important history and played an important role in the country's economy and politics. For example: it had very important naval officers, scientists, and directors such as Jorge Juan Santacilia (1713–1773), Luis Godin (1704–1760), Vicente Tofiño (1732–1795), Saturnino Montojo (1796–1856), José Sánchez Cerquero (1784–1850), Cecilio Pujazón (1833–1891), Tomás Azcárate (1849–1921), León Herrero (1862–1947), and Wenceslao Benítez (1879–1954), and it participated in the great expeditions of the last third of the 18th century, such as the measurement of the Transit of Venus in 1769 and the Malaspina Expedition in 1789, etc. The 0-meridian passed through this Observatory for more than 100 years until 1884, when it was finally established in Greenwich. As

Routine Activities it was calculation of the Ephemerides, publication of the Nautical Almanac, Advanced Studies Course, depot for Chronometers and Naval Instruments, meteorological, seismic, and magnetic observations, and scientific determination of time (González, 1992).

During the 20th century, despite the country's political crisis, the ROA did not stop its scientific activity, despite after the Spanish Civil War, many of its scientists went into exile. During the dictatorship of Franco, there was a setback, but the ROA continued to function and even collaborated with NASA in the space race (González, 1992). Since the democratic era in Spain, from 1975, the ROA has participated in sounding rocket programs, artificial satellites, and expeditions to Antarctica. At the end of the 20th century, it began to recognize its historical heritage and initiated programs for its conservation.

Nowadays, the ROA has an important scientific activity adapted to the changing times and it is one of the most important scientific institutions in the country. Today the ROA has the next organization and sections: Ephemerides Section, Positional Astronomy Section, Time Section, Geophysics Section, Senior Assistant, School of Advanced Studies (for military people), Management, and Library, which is responsible for the management of historical heritage (Ministerio de Defensa & Real Observatorio de la Armada de San Fernando, 2020). Each of these sections has several units.

The ROA, located on a hill of bedrock in the highest part of the city (which is also an island), is surrounded by the city today. Therefore, due to light pollution, it has had to relocate its nighttime sky observation activities to the Observatory located in the Canary Islands, and the ROA has focused on other astronomical activities and projects. The ROA has a new clock building for the calculation of official time, and a laser system used to monitor the satellites and the space debris.

The ROA today has the following routine scientific activities: calculation of Ephemerides, collaboration on projects with the International Astronomical Union and other similar institutions, determination, maintenance, and dissemination of physical and astronomical time scales, in accordance with international requirements, collaboration with the International Geodetic and Geophysical Union and other similar institutions, research works assigned by the Naval Staff, including the training and development of its own scientific and military staff, acquisition, maintenance, inspection, classification, repair, and study of the Navy's chronometric equipment, participation and leadership in international research projects such as space debris tracking, and recovery, conservation, management, and dissemination of its historical heritage.

About the historical heritage, the most important thing is that the ROA has preserved almost all its heritage, and it is *in situ*, contextualized (Muñoz, 2001). The ROA has a Library, with thirty thousand volumes (González, 1997; González, Gutiérrez & Merino, 1993), a Cartographic Collection, with three thousand five hundred maps (González, 2002), an Historical Archive, with six hundred and three boxes, so one thousand one hundred eighty-seven volumes (González, García &

Merino, 1988), and a Collection of Historical Instruments, with one thousand two hundred and forty-five instruments (González, López & Espada, 2020). All of them are inventoried and catalogued, and there is free access to researchers to them.

Despite being a military institution, that is a problem to open itself, in recent years the ROA has begun to open to the public and carry out various scientific divulgation activities, for example: the celebration of Seminar on Astronomical Navigation for 20 years; the organization of exhibitions and concerts, so we can see in the closed park an installation that commemorates the crossing of the 0-meridian; also, in collaboration with the city council and the tourist office, they organize guided tours with different topics throughout the year.

Research Methods.

The objective of our study is to recover information about the women who worked at the Observatory and to empower their presence by conducting a gender analysis, since we believe that their contribution has been silenced not only socially but also in documentation.

So, we conducted a study of bibliographic sources and contacted other researchers working on this topic to understand the reality of this case in other observatories (for example, Harvard, Paris, Vaticano, and Melbourne). We also studied the historical circumstances of the ROA regarding the subject of study and the conclusions presented in relevant gender studies. Finally, we consulted the ROA's Historical Archive (1887–1985) to identify and retrieve existing data on women employed there. We have consulted boxes 144, 1780, 1781 and 1658 of the Archive, as well as the Master Book. After presenting the contrasting results of all this, we conducted an analysis of the topic from a gender perspective.

With this study, we hope to discover, make visible, empower, and contribute important conclusions from a gender perspective and analysis about the presence of women in the history of ROA as Women Astronomical Computers. Following this investigation, and in line with other research being conducted by other observatories, we have located information on 30 women hired between 1919 and 1967 at the ROA. The results, that we are going to expose next section, have been highly significant, as this period also coincides with a very difficult political and social times for women in Spain, so their impact, although weak, is particularly noteworthy. Today, women are present in the ROA in technical and highly qualified scientific positions, although they remain a very small minority. These include, for example, the author (Muñoz, 2001), who designed the museum program for the ROA, and Gabriella di Florio (2021), who carried out the restoration of the plaques of the Sky Map. We have also studied the books published by them.

Results and Discussion.

The ROA in the Sky Map Project.

Since approximately 1874, photography has opened a new era in observational astronomy, both in determining positions (astrometry) and in the physical study of celestial bodies (astrophysics). Its advantages include maintaining a faithful and lasting image in the photographic image, the greater sensitivity of the camera compared to the human eye, and the ability to perform precision measurements. Thanks to all this, astronomical photography could be used in the study of solar physics, in the discovery of new celestial bodies, and in the determination of stellar parallaxes (di Florio, 2021).

The ROA participated in the Sky Map Project since 1887 proposed in Paris by Mouchez (1821–1892). The Paris Academy of Sciences sponsored the meeting and extended invitations to various scientific societies and the directors of the most important observatories of the time, who attended the first meeting in Paris in 1887, constituting the International Astrophotographic Congress or Paris Conference of Astronomists. The entire work plan was organized and implemented in subsequent meetings. Its objective was to observe ten million stars up to magnitude 14 and catalog the coordinates of objects brighter than magnitude 11. The project was defined down to the last detail with a common proposal for all observatories, including the type of telescope, lens aperture, focal length, the size, and information to be contained in the photographic plates, and the observation and data reduction strategy – all the ingredients of a modern-day observing consortium. Many countries, including Spain, had to make significant investments to begin taking the first plates in 1892. Today, in the field of Astrometry, the Gaia Project has taken up the mantle, sending information to ESA stations at a rate of 40 Gbytes per day since its launch in 2013. Our observatory completed the project. And today it preserves all the instruments, plates, and photographs. About the ROA's participation in the Sky Map, we can summarize it as follows (González, 1989; González, 2024): the director of the ROA in that time, Cecilio Pujazón, attended the International Astrophotographic Congress in Paris in 1887, so it was one of the observatories to participate in the Sky Map from the beginning. In 1888, the ROA commissioned Gautier to design the Equatorial Photographic Telescope, the dome, and a plate-measuring machine. A dome, photographic laboratories, and calculation offices were built. In 1889, Cecilio Pujazón attended the International Permanent Committee Meeting in Paris, where the work plan for the 18 observatories was established. After a year of testing, the final work began in 1891, but Cecilio Pujazón dies. However, the next director of the ROA and the astronomers continue the project. San Fernando was assigned the declination zone between -3° and -9°, and they must produce 1,260 plates. In 1894, the ROA completed the 1,260 plates for the Catalog. In 1919, the first women were hired at the ROA to perform the calculations. In 1923, the ROA completed the Map at the same time as Oxford and Greenwich. New calculations and adjustments continued to be made with the plates until 1975. The Gautier astrograph was used for other projects until 2008, measuring satellite positions. In 2001–2020, three women (Yolanda Muñoz Rey, Belen Vicente, and Gabriella di Florio) recover the memory of the Sky Map: museology, restoration, new calculations.

The ROA currently houses many materials related to astrophotography in its heritage collections: astrophotographic instruments and accessories, glass plates, and plate holders, etching matrices, and printed material from the Sky Map: the Gautier astrograph, built in Paris in 1889, two plate measuring machines produced in the same workshop in 1892 and 1906 respectively, as well as numerous accessories. The Archive houses both the collection of glass plates corresponding to the observations in the Astrophotographic Catalogue and the Sky Map, as well as another 287 boxes (with an average of 12 plates each) from other observation programs carried out with the Gautier astrograph until the early 1980s. The ROA also houses a complete collection of the 720 printed sheets corresponding to the observation area assigned to it in the project, in addition to several thousand sheets corresponding to the areas assigned to other observatories. In addition to all this scientific and cultural heritage, we must add the 403 copper plates prepared in Paris to be used as engraving matrices for the Chart sheets. These plates were rescued relatively recently, at the end of 2015, from a warehouse where they had remained forgotten for several decades.

Women Astronomers in the World and in Spain.

We know that in historical times, the presence of women in science has been anecdotical due to the prevailing social organization and way of thinking based on patriarchy, in which women were relegated to the domestic sphere and legally subject to men. We must wait until the 19th century, during the Industrial Revolution and the fall of the Ancient Régime in European countries, for a truly feminist activist movement emerging, fighting for equality and breaking old patterns. Among these was the need to allow and normalize the presence of women in scientific fields, universities, and research.

In the case of astronomy, from ancient times, we have records of En'Heduana (2353 BC) in Babylon, Aglaonike (2nd century) in Greece, and Hypatia (4th century) in Alexandria. In Europe during the Middle Ages and the early modern period, there were also occasional and anecdotical women who were interested in astronomy and made observations, studies, and writings, most of them daughters of male astronomers. In all cases, their presence was relegated to auxiliary duties, and their significant contributions, when they existed, were silenced, hidden, or appropriated by their male entourages (fathers, brothers, or husbands). Their dedication to these activities was always difficult, socially challenged, and hampered, even impeded, by their domestic and family obligations.

In the case of Spain, we only find historical references to a Spanish woman, Fátima De Madrid (10th century), from the time of the Caliphate of Córdoba. Fátima was the daughter of the Andalusian astronomer, mathematician, and philosopher Abul Qasim Maslama ibn Ahmad al-Mayrity, with whom she learned and collaborated. Notable among her works is *The Corrections of Fátima*, in which she presented an updated review of the astronomical knowledge existing at the time.

Already in the 19th century, in the new society and with the support of feminist movements, the female presence in the field of astronomy increased (Ling et al., 2015). In Europe and the United States, some women managed to complete university studies in astronomy and even obtain doctorates, contributing important discoveries with their research. Henrietta S. Leavitt (1868–1921), Williamina Fleming (1857–1911), and Cecilia Payne-Gaposhkin (1900–1979) are some of the pioneers.

In the case at hand, the Sky Map, many of the participating observatories implemented the strategy invented by Pickering (1846–1919) at Harvard from 1877 (Smith, 2021): hiring women to do the tedious work of measuring and calculating photographic plates, since this required many hours of work and hiring women was cheaper and submissive than hiring men, especially if they were hired not as astronomers but as assistants with different titles. Later, other observatories such as Paris, Melbourne and the Vatican did the same.

They identified thousands of stars in glass photographic negatives by comparing them with published catalogs, measured stellar magnitudes, classified spectra, and detected new objects of interest such as nebulae, variables, and rare star types. They spent their days performing mathematical calculations for the male astronomers who worked the telescopes at night. The female calculators took the astronomers observation notebooks and reduced the data recorded in them, averaging numbers and correcting for refraction, parallax, and the inherent error of different instruments to record an object's absolute position in the sky. Previously, these calculation tasks have been performed by children from vocational schools or orphanages or by young men aspiring to be astronomers (these were promised a rising career, but no women). The tedious, long-hour calculations took their toll on the women working at the Harvard Observatory, both mentally and physically, resulting in everything from stress to illness and muscle problems. The salary was low; they earned 30% less than men in the same position and it was barely enough for them to survive. In many cases, the women hired were relatives of the men working at the observatory. They were often not even recorded in the institutions' administrative documentation and often worked on a voluntary basis. But in some ways, Pickering acted as a supporter of female astronomy education, helping female astronomy professors establish observatories, training female students in the use of physics laboratories, and writing about the potential for women to make influential discoveries in astronomy. At other observatories studied, the circumstances were similar. At the Melbourne Observatory (Stevenson, 2023), separate workrooms and toilets were built for them, they were given an entrance exam, and their work was closely monitored and supervised.

In Spain, one, of the pioneers women in Astronomy, was Antonia Ferrín Moreiras (1914–2009) (Núñez, 2020; Ling, 2014) who, in the first half of the 20th century, obtained several degrees and was the first Spanish woman to earn a doctorate in Mathematics (in Astronomy). Another legendary figure in Spanish astronomy was Asunción Catalá i Poch (1925–2009), the first professional astronomer to obtain a teaching position at a Spanish university (Masegosa, 2009).

Nowadays, although the trend is upward, there are still few women in scientific university programs, pursuing doctorates, and holding positions in scientific institutions as researchers and in management positions. The representation of Spanish women (compared to Spanish men) in the IAU (International Astronomical Union) is 23% (2010). The "glass ceiling," work-life balance issues, and the attitudinal, administrative, and educational micro-sexisms that still exist in the system continue to hinder progress toward equality (Pérez & Kiczkowsky, 2010).

Today, the Spanish government and the CSIC (Higher Council for Scientific Research in Spain) have promoted studies on current and historical Spanish astronomers. Among the activities carried out to commemorate the 2009 International Year of Astronomy, the pillar project "She is an Astronomer" was carried out, with the main objective of illustrating to what extent women astronomers throughout history have participated in the great discoveries that have led us to our current knowledge of the Universe (UNED, CSIC & Sociedad Española de Astronomía, 2009). This project showcased the contributions of 139 Spanish astronomers from the last 100 years. Also, "AstrónomAs" in 2021 (Ling, 2022; CSIC, 2021) is a virtual exhibition focusing on women dedicated to the study of astronomy and astrophysics. Hosted on the website www.astronomas.org, it includes information on more than three hundred astronomers who work or have worked in one or more of the fourteen themes that comprise the exhibition. It reflects a wide variety of ethnicities, geographical areas, professional categories, and functional diversity. It has been founded by *Fundación Española para la Ciencia y la Tecnología* from *Ministerio de Ciencia e Innovación and Sociedad Española de Astronomía (SEA)*. It is complemented by various educational and informative materials. Its nature is based on the success of the previous museum exhibition, "With an A for Astronomers," in 2009, which toured numerous venues for twelve years. Also, we can see the "11defebrero" project (Valdés-Solis, 2009; Castro, 2022), which aims to highlight the work of women scientists. Also, "Henrietta Levitt's Secret Diary" is an outreach project of the Institute of Astrophysics of Andalusia and the CSIC, which, in video-blog format, discusses astronomy and Harvard calculators (CSIC, 2023).

2025 marks the "Centennial of Stellar Atmospheres, Cecilia Payne-Gaposchkin's Groundbreaking PhD Dissertation" (Harvard University, 2024), the first astronomy PhD awarded by Harvard, and a foundational text in astrophysics. For her research, Payne-Gaposchkin drew on more than forty years of glass plate astronomical data from the Harvard College Observatory. Her work built upon and was enabled by a pioneering group of women astronomers who created, studied, and preserved this glass plate collection, initially funded by Anna Palmer Draper. The "PHaEDRA" project (Harvard University, 2025) seeks to recover the names of all the women who worked at Harvard by tracing the notes they left on envelopes and documents of their calculations. Whether these individuals spent time at the Harvard Observatory as volunteers, computers, astronomers, researchers, or students, the glass plate collection was recognized as a space for women, a refuge filled with numbers and stars.

These types of actions always aim to empower what has already been achieved and what is in progress, to make it visible to value it, and to foster new vocations.

Women at ROA.

There is just research on women hired to perform calculations for the Sky Map project at other observatories around the world, such as Harvard, Greenwich, Paris, Melbourne, and the Vatican.

We know that in the beginning at San Fernando, this work was carried out by the observatory's astronomers. There is no record of women being hired for this until 1919. After the Gautier Astrographer took each photograph (three photos per exposure), they went through a laborious process of measurement, matching, and transfer from glass plates to bronze plates and paper. All of this had to be done with a Gautier measuring and calculating machine, which required many hours and was a very mechanical and not very complicated process.

It is very important to understand that feminism in Spain lagged due to the country's tortuous political evolution in the 19th century. Then also, in the 20th century, we must add the Civil War and Franco's dictatorship, which marked a reversal of the little that had been achieved.

Furthermore, the ROA is a military institution, and its scientists are military staff, which makes it even more difficult for women to work there. Women's access to the Spanish army has been anecdotical in historical times, impossible during Franco's dictatorship, and only really began with the arrival of democracy, especially after 1990.

In the ROA's Historical Archive, there is a box dedicated to the Sky Map, and it hasn´t documentation referring to these women (Historical Archive of the Royal Observatory of the Navy, 1887–1985, Box 144). Pujazón (1890a; 1890b) published two articles on the work of the Sky Map. One of them, in the journal *Naturaleza*, provides no information on the presence of women computers at observatories, although they already existed by that time. But at last, in the article in the *Revista General de Marina*, he points out that:

"…a certain number of observers (men) cooperating in the photographic work, although willing to carry out the two series of plates necessary for the chart and for a catalog, are refraining from promising their participation in the latter, believing that, as some claim, it is a work of many years, and will entail considerable expenses" (p. 204).

And in a letter written in 1789 Pujazón mentions that women have been hired in other observatories (box 144, Historical Archive of the ROA, section 4.1.2. Astrophotography).

In addition, García published a small, very detailed and precise manual on how to perform the calculations for the work on the Sky Map, first in manuscript (1921a) and later printed (1921b), in which he lists the astronomers and assistants who participated in these calculations, but does not mention any women. He does point out that "...the lack of personnel [in 1892] and the difficulty of finding non-professionals with the aptitude for measurement, caused a great delay in being able to employ it" (1921b, p. 48).

In all the documentation preserved in the ROA Historical Archive, only in box 1781 (section 4.1.2. Astrophotography) a woman named Pilar is mentioned, in a document consisting of loose pages that appear to be a draft, handwritten routine diary. This document is neither dated nor signed but based on its characteristics and the context of the other accompanying documents, which are dated 1973, we can place it around this time. It seems to have been written by the chief astronomer and narrates, in a personal style, the measurement and calculation operations performed on astrophotographic plates. He recounts that they carried out this work from 9:00 a.m. to 6:00 p.m., with an hour and a half break. He mentions that *Pilar* takes measurements while two other male workers record them. Or that *Pilar* stays behind taking measurements while he goes to a meeting or talks with someone. He also mentions that she and he take the same measurements, secondhand. He mentions her frequently; it is a collaborative effort. It recounts the problems they encounter and the mistakes they make. Comparing this with the data table (see Appendix) obtained from the research in the Master Book, we deduce that it must have been María del Pilar Rodríguez Sáenz de Urraca, because we see that in 1977, she was still working, having received a promotion that year, while the only other woman named *Pilar* was dismissed in 1959 for getting married. I transcribe the mentions about *Pilar* in mentioned document:

"Then I took over and measured Nesta, which Pilar then did. The system was the same as for the stars, but... The result was...". "I start by measuring Mars using both methods. Then Pilar measures the entire plate, with Azcona and De Pablo taking notes... At a quarter to one, when I return to the machine, Pilar has just finished, and I measure the 15 stars...". "...while Pilar was measuring and a technical engineer was taking notes, I had interviews...". "...we went to visit the observatory of...while Pilar stayed behind taking measurements, and on this occasion, De Pablo measured plate 41, which is second-hand." "When it's Pilar's turn, she does the same operation as me on star number 6." (Historical Archive ROA, box 1781, 1973).

Apart from this, the only data about women in ROA we find is in the ROA's Master Books, which contain a complete list of all the people employed by the ROA from the mid-19th century to the present. These books detail the bureaucratic or administrative processes of their working lives: promotions, dismissals, recognitions, contracts, leaves, etc. As there are so few of them, we have analyzed not only the women astronomical computers, but also all the women registered in these books.

The results of this research were as follows (You can see a table with all the data in the Appendix). A total of 30 women were hired between 1919 and 1967. There are two periods when several hiring coincides: in 1919–1920 and 1943–1956. The hiring age is around 20 years old, but some of the hired workers were 14 years old. Many of them were sisters or cousins among them. Although women were hired as *private maids* or *cleaners*, the case at hand (astronomical computer) is that of women hired under the following titles: *typist, 2nd-class operator, astrophotographic plate measuring assistant, administrative assistant, calculation assistant*, and *3rd-class official*. Those hired for this purpose had no astronomy training or even basic education. Many of them earned their high school certificates while they were working at the ROA. Neither of them ever completed university studies. Their work was only on calculators, so they did not conduct astronomy research. Improvements in their contracts and promotions resulted from having been employed for many years, and several of them reached the rank of *1st-class Analyst*. Particularly relevant is the reason for dismissal: two due to death, two due to individual choice, one due to incapacity for work by illness, five due to retirement, but seven due to marriage, as the laws during Franco's dictatorship prohibited women from working if they were married.

Apart from the Astronomical Computer: in 1961, María de la Concepción Herrero Valdés, a highly specialized and trained woman was hired for the first time to manage the Library and the Historical Archive; in 2001, Yolanda Muñoz Rey designed the museological program for the ROA's collection of historical scientific instruments with a research grant from Alvargonzález Fundation; from 2004 till 2016, Astronomer Belén Vicente, an expert in stellar astrometry and specialized in the characterization and kinematics of star clusters, analyzed the Sky Map data collected by the ROA more than 100 years ago; and in 2021, Italian restorer Gabriella di Florio restored the Sky Map plates with a contract after having conducted research on the subject for his Master's Thesis. In addition to conducting a historical study of photography in the ROA and its historical photographic collection, it is designing a preventive conservation project in four phases.

Gender Analysis and Conclusions.

In recent decades, gender studies have increased, confirming that despite everything, there is still inequality in the numerical presence of women in the field of science (training, research, and work). From a qualitative perspective, women are invisibilized, and there is even a presence of micro-sexisms and situations of undervaluation and access to opportunities. There are discrimination and harassment. Within the academic sphere itself, there are pernicious lines of thought such as relying on future improvement through natural evolution rather than conscious and active action, as well as avoiding conflict, failing to recognize micro-sexisms, and thinking that inequality is something of the past, or of previous generations and already overcome. When a woman scientist is mentioned in the press (this already happened in the 19th century, but it still happens today), the headline focuses on the fact that “she's a woman” and not on the scientific achievement itself as a person.

Currently, some gender studies have been conducted regarding the hiring of female calculators at astronomical observatories. The Harvard case is particularly striking, as it has also been cited in the literature under the unfortunate title “Pickering's Harem,” a term that alludes to sexual ownership, objectification, and domination over women. It is also noteworthy how the authors of these contracts falsely argued that “women have greater qualities for detailed and meticulous work,” rather than the real argument that they were cheaper and more submissive (the latter due to education, social imperative, and economic necessity). They were not hired as astronomers but with auxiliary titles, and their work was silenced: their names did not appear in documents, reports, results, or publicity. The ROA Historical Archive contains a large amount of documentation about the Sky Map, and in all of it there is no mention of the women hired.

This study has achieved to make visible, empower, and analyze the historical presence of Women Astronomical Computer during the history of ROA from a gender perspective. In this regard, we would like to highlight the following points. We must understand that these types of mechanical and office jobs were a safe place for many women in Spain during this time of repression (Angulo, Guijarro & Garrido, 2025), when women were not allowed access to work (Franco's dictatorship). They were in auxiliary, submissive positions where they were controlled, but it allowed them to earn a salary, as women who had no other normal means of subsistence at this time and in this context of repression, namely, marriage or support from others family members. These jobs were few, and it is noteworthy that most were fired upon marriage. Their career prospects were limited and invisible in the documentation and in public knowledge. However, they contributed the fact of their presence there and the fact that a 100% male military institution accepted the presence of women, which opened the door to future hiring once democracy arrived. We have managed to locate and identify the names of 30 previously invisible women, thereby empowering them. Based on the data obtained, we have been able to confirm gender discrimination and their employment circumstances, which are identical to those found in other observatories conducting similar studies. The methodology used has made this possible.

This study is still in its initial phase, and I would like to continue taking the following steps: identify the calculation documents generated by them and other internal documents to determine if they are named, so do their names appear in the notes and documents of the calculations they performed? Is there a bias toward making them invisible compared to the same type of documentation generated by men? find data on the salaries they received in case they were lower than those of their male colleagues, and were there men hired for the same job? why them? Did they have family or similar relationships with other ROA workers? In this sense, one of the last hired, Agustina Panellés Lazaga, we know that her brother was a Navy Captain and we have seen some surname coincidences in astronomers or other military positions in years prior to the presence of some hired women; locate photographs of them working at the ROA, which has not been possible until now; conduct newspaper research to locate press releases about them (if any) and identify gender biases; we don't know anything about the work environment they experienced, or whether they suffered discrimination in their work context; identify the criteria that existed to determine which workers lived within the ROA premises and which ones outside, and whether they were affected by any gender discrimination in this matter.

Some of the gender-based outreach efforts we should be doing in the future with this case include: rename them fairly from a gender perspective and in accordance with other international studies on the same case; integrate their work into the historical narrative of Spanish women astronomers include their story in guided tours; promote gender studies at the ROA; and establish a network with other national and international projects on this topic, launch a project like PHaEDRA in the ROA.

Although the case of the Women Astronomical Computers was an entry-level solution for women in astronomy, the discriminatory circumstances in which they worked are evidence of the gender inequality that existed at that time in the world of science, which even today, despite the progress made, continues to sustain unequal tendencies that require further work.

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The author declare no conflict of interest.

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Appendix

Table 1. List of the 30 women hired by the ROA between 1919 and 1967. Source: Historical Archive of the Royal Naval Observatory of San Fernando. (1899–1995). Master Books. (nº 1–7). San Fernando, Spain. (Authors' source).

Name	Date of birth	It comes from another unit	Hiring date	Workstation	Promotion 1	Promotion 2	Promotion 3	Promotion 4	Contract end date	Reason for termination of contract
Moreno Jiménez, Angustias	1914	Naval Military Academy from 1939	06/21/1943	Typist	04/18/1945 3rd grade Administrative Assistant (typist)	11/16/1948 2nd grade administrative assistant (typist)				
Espín Peña, Manuela	1894		06/16/1919	Temporary Typographic Operator	1932 Corps of Technical Services Assistants of Arsenals	10/06/1944 1st Section of the Navy Arsenal. 2nd Class Operator	03/06/1945 First-class operator (typesetter)		1958	Retirement
Cruz Belizón, Concepción	1889		1919	Temporary Typographic Operator	1933 2nd Section Technical Services of the Navy	10/06/1944. 1st Section of the Workshop. 2nd Class Operator	03/06/1945 First-class operator		1954	Death
Espín Peña, Isabel	1900		1919	Temporary Typographic Operator	08/07/1933 2nd Section of the Navy's	10/06/1944. 1st Section of the	06/03/1945 First-class operator		1960	Retirement due to physical

Name	Date of birth	It comes from another unit	Hiring date	Workstation	Promotion 1	Promotion 2	Promotion 3	Promotion 4	Contract end date	Reason for termination of contract
					Technical Services	Workshop. 2nd Class Operator				disability (loss of vision)
Romero Márquez, Regla María	1893		1919	Temporary Typographic Operator	1933. 2nd Technical Services Section of the Navy	03/06/1945. First-class operator (typesetter)			1958	Retirement
Carmona Peña, Manuela	1906		09/07/1920	Temporary Typographic Operator	1933. 2nd Technical Services Section of the Navy					
Gómez Lagóstena, Carmen		San Carlos Naval Hospital	07/20/1943	Operator 2nd Section C.A.S.T.A. as a package seller	1944. Naval Workshop. 3rd Section. Second Class Worker	1948. First-class worker			1953	Retirement
Rivero Romero, María de la Oliva	1931		08/25/1951	Measurement of astrophotographic plates					06/30/1957	Marriage
Rivero Romero, María Teresa	1934		1959	Administrative Assistant					1960	Marriage
Rodríguez Sáenz de Urraca, María del Pilar	1930		08/25/1951	Measurement of astrophotographic plates	1957 Administrative Assistant	1961 Second Class Administrative Officer	1971. 2nd Class Analyst	1977. Analyst 1st		
Rodríguez Sáenz de Urraca, María del Carmen	1924		05/30/1956	She is hired as an administrative assistant to provide services as a calculation assistant	1961. Second Class Administrative Officer	1971. 2nd Class Analyst	1977. Analyst 1st			
Ristori Fernández, Amalia	1907		08/30/1951	Measurement of astrophotographic plates	1957. Administrative Assistant	1961. Second Class Administrative Officer	1971. 2nd Class Analyst		1974	Voluntary resignation
Valverde Peralta, María del Carmen	1933		08/25/1951	Measurement of astrophotographic plates	1957. Administrative Assistant	1961. Second Class Administrative Officer			1961	Marriage
Valverde Quintana, María del Pilar	1937		05/30/1952	Private maid. Profession: typographer.	1959. Administrative Assistant				1959	Marriage
Jiménez Castañeda, Josefa	1935		08/06/1954	Private maid					1958	
Quintana Pizarro, Carmen	1936		08/06/1954	Private maid					1961	Marriage
Sánchez Hidalgo, Mercedes	1925		08/06/1954	Private maid	1963. Third Officer					
Serrano Cano, Carmen	1939		08/06/1954	Private maid	1963. Third Officer					
Serrano Cano, Úrsula	1943		1958	Private maid					1963	
Aceytuno García, María del Rosario	1929		1960	Measurement and calculation of astrophotographic plates. Second-level administrative officer					1964	Marriage
Espino Pineda, María del Carmen	1905		12/10/1955	Administrative Assistant of 2nd Workshop					1970	Retirement
Herrero Valdés, María de la Concepción			03/27/1961	Official of the 8th category of the Faculty Corps of Archives, Libraries and Archaeologists						
Navarro González, María del Carmen	1931		05/22/1956	Calculation Assistant	1961. Second Class Administrative Officer	1971 Second-level Analyst	1977 Analyst 1st		1995	Early retirement
Lazaga González, Consuelo	1938		1962	Second Class Administrative Officer					1967	Marriage
Panelles Lazaga, Agustina	1939		1964	Second administrative officer, for measuring astrophotographic plates and calculation	1971. 2nd Class Analyst				1975	Death
Ramírez Rubio, Natividad			1967	Cleaner					1977	Voluntary resignation

Name	Date of birth	It comes from another unit	Hiring date	Workstation	Promotion 1	Promotion 2	Promotion 3	Promotion 4	Contract end date	Reason for termination of contract
Romero Sánchez, Marina	1923		1967	Cleaner					1979	Work incapacity
Sánchez López, Josefa			1967	Cleaner					1980	
Sánchez Hidalgo, Mercedes			1967	Third-class typesetter at the printing press						
Serrano Gamo, Carmen			1967	Third-class typesetter at the printing press						

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Жінки-обчислювачки у військовій астрономічній обсерваторії Іспанії

Анотація. *Королівська астрономічна обсерваторія Військово-морських сил у Сан-Фернандо є однією з найстаріших і найважливіших наукових установ Іспанії. Під керівництвом директора Сесіліо Пухасона вона брала активну участь у міжнародному астрономічному проєкті «Карта неба» (Carte du Ciel), започаткованому в Парижі у 1887 р. на Конференції астрономів за ініціативою Муше. Як військова установа, обсерваторія тривалий час залишалася практично недоступною для жінок, що додатково ускладнювало й без того обмежений доступ жінок до наукової діяльності. Проте, подібно до інших астрономічних обсерваторій, обсерваторія Сан-Фернандо залучала жінок для виконання вимірювань і розрахунків, пов'язаних з обробкою астрофотографічних пластин, – надзвичайно кропіткої роботи, що потребувала багатьох годин праці. Така практика пояснювалася тим, що праця жінок була дешевшою, а самі вони вважалися більш слухняними виконавицями. У цьому дослідженні, заснованому на методах бібліографічного та документального аналізу із залученням матеріалів історичного архіву обсерваторії Сан-Фернандо (передусім реєстраційних книг персоналу), зроблено спробу виявити, висвітлити та переосмислити присутність цих жінок крізь призму гендерного підходу. Було встановлено відомості про 30 жінок, які працювали в обсерваторії у 1919–1967 рр. Цей період збігся з одним із найскладніших політичних і соціальних етапів в історії Іспанії для жіноцтва. Жінок приймали на роботу лише на нижчі посади, а після одруження вони підлягали звільненню. Незважаючи на те, що їхня праця залишалася майже непомітною, а службові функції були підпорядкованими, сама їхня присутність у військовій установі, де традиційно домінували чоловіки, відкривала можливості для подальшого залучення жінок до роботи в подібних закладах. Проведений аналіз показує, що як у цій, так і в інших обсерваторіях, дискримінаційні умови праці жінок відображали стійку гендерну нерівність у науковому середовищі. Це дослідження долучається до низки аналогічних проєктів, які вже здійснюються в обсерваторіях світу (Гарвардській, Мельбурнській, Паризькій, Ватиканській), де жінки також працювали за подібних обставин. Усі ці дослідження мають на меті повернути цих жінок із* *забуття та розвивати гендерні студії в історії науки. На міжнародному рівні досягнуто домовленості використовувати щодо них назву «жінки астрономічні обчислювачки» (Women Astronomical Computers), а перспективою подальших досліджень є створення спільного банку оцифрованих документів, що висвітлюють їхню професійну діяльність.*

Ключові слова: *Королівська астрономічна обсерваторія Військово-морських сил у Сан-Фернандо; жінки астрономічні обчислювачки; історія науки; гендерні дослідження*

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The academic platform for the history of agricultural education, science, and technology (2002–2025): From the concept of its creation to the academic tradition of personalized forums

Abstract. *This article presents a historical and scientific analysis of the formation and development of the research platform «History of Education, Science, and Technology in Ukraine» during the period 2002–2025. Its development reflects the process of institutionalizing historical and scientific research and the evolution of contemporary forms of academic communication in Ukraine. The aim of the study is to reconstruct and summarize the evolution of this scientific platform–from the concept of its creation at the beginning of the 21st century to the establishment of a stable academic tradition of holding thematic and personalized scientific forums. The methodological foundation is an interdisciplinary approach that combines historical-scientific analysis with content analysis of sources and conference materials. Systemic and structural-functional approaches made it possible to view the platform as a holistic scientific and communicative environment. It has been shown that the launch of the scientific platform, founded by the National Scientific Agricultural Library of the National Academy of Agrarian Sciences and established by V. Vergunov, has become a key factor in the creation of a regular academic forum for discussing issues in the history of education, science, and technology. The main stages of its development, the transformation of its organizational forms of activity, and the expansion of the range of research topics are traced. Particular attention is paid to the establishment and development of the tradition of personalized scientific forums dedicated to prominent figures in Ukrainian science, education, and technology. It is argued that this model of organizing scientific events contributes to the deepening of historical-scientific research through the prism of scientific biographies, intellectual networks, and scientific schools. In this context, examples of forums dedicated to outstanding scientists, in particular O. Sozinov, are examined, demonstrating the growing significance of the personalistic approach in contemporary historical-scientific studies. The article examines the platform's operation amid the pandemic and military* *challenges, which necessitated a transformation of the forum's format to align with new social realities while simultaneously demonstrating its viability, adaptability, and crucial role in maintaining the continuity of scientific communication. It has been established that over the course of more than two decades, the platform has taken on the characteristics of a stable institutional form of scientific communication, combining conference practices, scientific publishing activities, and interdisciplinary research initiatives.*

Keywords: *scientific platforms; history of science; history of education; scientific communications; O. Sozinov; scientific conferences*

Introduction.

In contemporary humanities and science studies discourse, research focusing on the formation and functioning of scientific platforms–as hubs for communication, consolidation of the scientific community, and presentation of the results of historical and scientific studies–has become particularly relevant. In the context of the development of the history of science and technology in Ukraine at the beginning of the 21st century, specialized scientific communities have gained significant importance; they facilitate the integration of researchers around specific thematic areas, establish traditions for holding scientific forums, and promote the development of bibliographic, biographical, and source studies.

Scientific platforms and research centers in Ukraine emerged during various historical periods and differed in terms of their organizational development, duration of operation, structure, thematic priorities, and areas of scientific activity. Some of them have remained active in the present day, notably the State Institution «G. M. Dobrov of the National Academy of Sciences of Ukraine», the National Technical University «Kharkiv Polytechnic Institute», the National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute», the O. P. Borodin Center for Research on the History of Science and Technology, and other centers whose activities are aimed at developing historical and scientific research in Ukraine.

A special place among them is held by the Scientific Platform for the History of Agricultural Education, Science, and Technology, established on the basis of the National Scientific Agricultural Library of the National Academy of Agrarian Sciences and the Institute of the History of Agrarian Science, Education, and Technology. Over more than two decades, it has undergone a complex transformation–from the idea of discussing specific thematic issues to a consolidated scientific community of regular, personalized forums, which have become an important component of Ukrainian academic life and historical-scientific communication.

The subject of this study is the process of formation, development, and institutionalization of the Scientific Platform for the History of Agricultural Education, Science, and Technology in 2002–2025, as well as the formation, based on it, of a tradition of personalized scientific forums dedicated to prominent figures in agricultural science, education, and technology. The focus is on the conceptual foundations of the platform's creation, the directions of its activities, the organizational forms of scientific communication, and its role in the development of historical and epistemological research and the preservation of scientific memory.

The concept of a «scientific platform» encompasses such semantic aspects as communication, discussion, the clash of scientific views, and the exchange of ideas. Within the scope of this study, the «scientific platform» is proposed to be viewed as a form of scientific interaction that is of great importance for the development of contemporary concepts, the institutionalization of new knowledge, the testing of innovative approaches, and the legitimization of the latest hypotheses. At the same time, it serves as a factor in the progress of science in general, contributing to the development of scientific activity, the deepening of inter-institutional cooperation, and the consolidation of scientific institutions, organizations, and professional communities.

The relevance of this topic stems from the need to reflect on the development of sector-specific historical and scientific research amid the transformation of the Ukrainian academic landscape, the strengthening of interdisciplinary connections, and the growing importance of a personalized approach in the history of science. The scientific platform for the history of agricultural education, science, and technology has become an important hub for bringing together researchers of the agrarian history of science, fostering a specialized scientific community, and promoting the legacy of Ukrainian scholars. Its distinctive feature is the systematic combination of historical-scientific, bibliographic, biographical, and commemorative practices, which has contributed to the establishment of a tradition of personalized scientific forums and the development of Ukrainian agrarian science studies.

The subject matter of this study has long been a focus of attention for Ukrainian scholars and is situated at the interdisciplinary intersection of the history of science, the history of education, the history of technology, the sociology of science, and scientific communication. A significant contribution to the formation of modern approaches to the study of the history of agricultural science, education, and technology in Ukraine was made by V. Vergunov, who initiated systematic research into the history of agricultural research, the development of agricultural education, and scientific institutions. His works reveal the evolution of organizational forms of agricultural science, highlight the activities of scientific institutions and personalities, and lay the foundations for a scientific school of historical and scientific research in the field of agricultural knowledge. The scholar's fundamental works on the history of agricultural science (Verhunov, 2012; Verhunov, 2018) have become an important source and methodological basis for further research in the field of the history of sectoral science and scientific communications.

A separate group consists of works by scholars at the G. M. Dobrov Institute for Research on Scientific and Technical Potential and the History of Science of the National Academy of Sciences of Ukraine, dedicated to the theoretical and methodological foundations of the history of science and technology, issues of scientific communication, the institutionalization of historical-scientific research, and the development of scientific communities. In particular, A. Lytvynko analyzes organizational forms of popularizing historical-scientific knowledge and international cooperation in this field, summarized the experience of holding youth conferences on the history of science and technology, and described the activities of international scientific associations in the field of the history of science and technology (Lytvynko, 2018; Lytvynko & Ponomarenko, 2012). In collaboration with O. Lugovskyi, the author examines the process of institutionalizing the history of science and technology within the National Academy of Sciences of Ukraine, analyzing the creation of specialized structures, the formation of scientific schools, and the contribution of scholars to the development of historical-scientific knowledge (Lytvynko & Lugovskyi, 2018).

D. Bukhor examines the development of Ukrainian mechanics in the context of scientific publications by 19th-century scholars from Kharkiv (Buhor, 2025), which made it possible to trace the formation of scientific traditions in technical fields. The historical aspects of the development of engineering thought and construction technologies are highlighted in the work of O. Strelko (Strelko, 2023), dedicated to the history of the construction of metal bridges in the 20th century using welding technology.

A separate group of studies consists of works aimed at analyzing scientific communications and the formation of the scientific environment. In particular, N. Pasichnyk, R. Rizhnyak, and N. Deforge studied the coverage of the activities of congresses of natural scientists and mathematicians (Pasichnyk, Rizhniak, & Deforzh, 2023), which made it possible to trace the role of scientific forums in the development of scientific exchange and the dissemination of knowledge.

V. Sokolov analyzes the contribution of the National Scientific and Research Institute of Agricultural Engineering of the National Academy of Agrarian Sciences to the study of the history of agricultural science and technology, highlighting the institute’s bibliographic and research activities in the 2000s (Sokolov, 2012).

The methodological foundations of the history of science and technology are examined in the works of L. Griffen, N. Ryzheva, D. Nefyodov, and L. Khryashchevskaya, who analyze the object and subject of this field of knowledge, its place in the system of sciences, and the specifics of historical and scientific knowledge (Griffen, Ryzheva, Nefodov, & Hryashchevskaya, 2022). The methodological aspects of the development of historical science and the formation of its conceptual apparatus are highlighted in the study by Yu. Isak and O. Slipetsky (Isa & Slipets'kyy, 2023), which analyzes contemporary approaches to understanding the categorical apparatus of historiography and emphasizes the need to rethink the theoretical foundations of historical science in the context of rapid scientific and technological development.

A distinct branch of historiography focuses on the study of scientific forums and conferences as important forms of academic communication and the formation of scholarly traditions. In this context, the proceedings of the conference series «History of Education, Science, and Technology in Ukraine» (Verhunov, 2002, 2025) are of significant importance, as they have served as a platform for the development of historical-scientific dialogue, highlighting the contributions of Ukrainian scholars and the evolution of thematic and methodological approaches in the study of the history of science.

The works of V. Onopriienko are important for understanding the development of scientific communication and the methodology of historical-scientific research; they examine the stages of development of Ukrainian science, its institutional formation, and the role of scientific communication in the processes of knowledge production and dissemination (Onopriyenko, 2004).

A separate area of research focuses on contemporary digital transformations in the academic community. In their works, O. Mekh and S. Bublik highlight the challenges of scientific and scientific-pedagogical activities in the context of global digitalization, particularly the phenomenon of the "digital divide" and the transformation of communication practices in science (Mekh & Bublyk, 2023).

At the same time, an analysis of scholarly works shows that most research focuses on the activities of individual scholars, academic schools, and specific fields. In contrast, the evolution of scientific platforms and forums as institutional mechanisms for the formation of historical-scientific knowledge and the development of personalized forms of scientific communication has not been sufficiently explored.

Thus, despite a significant body of publications on the history of science and scientific communication, a comprehensive study of the development of scientific platforms in the fields of education, science, and technology in Ukraine remains underdeveloped. Further study is needed on the processes by which individual scientific initiatives transform into established institutional traditions capable of consolidating research communities and forming scientific schools.

The purpose of this article is to reconstruct and analyze the evolution of the academic platform «History of Education, Science, and Technology in Ukraine» from 2002 to 2025, with an emphasis on identifying the key stages of its formation and development, its organizational and structural models of operation, as well as the specifics of personalized forums as a form of academic communication and representation of historical and scientific knowledge.

Research Methods.

The methodological foundation of this study consists of a set of general scientific and specialized historical methods, which ensured a comprehensive analysis of the process of forming and developing the scientific framework for the history of agricultural education, science, and technology from 2002 to 2025, as well as the objectivity and scientific reliability of the study. First of all, the historical-scientific method was used, which made it possible to trace the prerequisites for the creation of the scientific platform, the stages of its formation, institutionalization, and further transformation into a scientific tradition of holding personalized forums. Thanks to this method, the historical dynamics of the development of the research environment have been reconstructed, the main directions of its thematic expansion and its role in the formation of contemporary historical and scientific discourse have been determined.

The historical-chronological method made it possible to consistently reconstruct the key stages of the platform's evolution over a specific period (2002–2025), trace changes in its organizational forms and the topics of scientific events. Content analysis made it possible to identify the main thematic areas of research presented within the platform, determine the dominant scientific problems, and trace the change in research focus during the period under study. In order to compare the different stages of the platform's functioning, a comparative-historical method was used, which made it possible to analyze the peculiarities of its development at different stages: from the concept of creation and formation of organizational foundations to the establishment of a stable scientific tradition of holding thematic and personalized forums.

In addition, systemic and structural-functional approaches were used, which made it possible to consider the scientific platform as a complex institutional and communicative environment that unites researchers of the history of science, education, and technology, promotes interdisciplinary dialogue, and disseminates the results of historical and scientific research.

Results and Discussion.

The Background to the Creation of the Scientific Platform (Early 2000s).

Ukrainian science during the period of independence, as in previous decades, consistently affirmed its commitment to development despite systemic challenges – chronic underfunding, institutional transformations, generational shifts among researchers, and, later, military threats. At the same time, it was precisely the era of state independence that opened up new opportunities for shaping its own scientific priorities, rethinking its historiographical heritage, and integrating into the global academic space.

The preservation and development of national intellectual identity, the maintenance of the continuity of scientific traditions, and the personalization of research narratives became not only an academic task but also a factor in the consolidation of the professional community. In this context, the development and evolution of the academic platform for the history of agricultural education, science, and technology serve as an example of the institutionalization of such a strategy–from a conceptual initiative to an established tradition of specialized academic forums.

The Central Scientific Agricultural Library of the Ukrainian Academy of Agrarian Sciences (now the National Scientific Agricultural Library of the National Academy of Agrarian Sciences) served as the organizational foundation for the launch of the scientific platform, initiating the development of a new format for scientific communication in the field of the history of agricultural science and technology. It was within this institutional framework that the concept of an interdisciplinary platform was developed, designed to bring together researchers in the history of education, science, and technology on the basis of open professional dialogue, a historical-biographical approach, and a solid foundation in source studies.

It is important to emphasize that from the very beginning, the platform was conceived as a consolidation project: in addition to the NNSGB of the NAAS, other research institutions within the NAAS system, the National Academy of Agrarian Sciences of Ukraine, the National Academy of Higher Education of Ukraine, as well as higher education institutions and sectoral research centers, joined the initiative. This model of cooperation reflected the initial concept of creating the platform as an open, integrative space that brings together academic science, the university environment, and sectoral research structures.

The founder and principal initiator of the academic platform «History of Education, Science, and Technology in Ukraine» was Viktor Vergunov – a renowned Ukrainian agricultural scientist, an expert in agricultural land reclamation, a historian of natural sciences, an organizer of specialized library services, a Doctor of Agricultural and Historical Sciences, a professor, and an academician of the National Academy of Agrarian Sciences (Verhunov, Tatarchuk, Nyzhnyk, & Lyamets', 2022, p. 88). His scientific vision was to create a permanent intellectual platform that would ensure the systematic study of the personalized history of science, the revitalization of the scientific legacy of prominent figures, and the establishment of a tradition of thematic forums dedicated to anniversaries and commemorative dates.

One of the defining features of the platform's activities was the combination of experienced scientists and young researchers – graduate students, doctoral candidates, and postdoctoral fellows. Personalized forums dedicated to prominent figures in science and education have contributed not only to the deepening of historical and biographical studies but also to the formation of a tradition of reflecting on the scientific legacy as a factor in the contemporary development of the field. Within the platform, a circle of researchers with shared research questions, methodologies, and thematic priorities has gradually emerged, suggesting the formation of a scientific school in the history of education, science, and technology in Ukraine. At the same time, support for young scholars has ensured the continuity of intellectual tradition and the succession of research approaches.

Thus, from the outset, the concept behind the platform's creation envisaged not only the organization of individual academic events but also the establishment of a lasting academic tradition – personalized historical-academic forums that combined research, communication, and educational functions. It was precisely this strategic idea that later shaped the platform's evolution from an initiative project into a recognizable academic phenomenon within the Ukrainian humanities and agricultural research community.

The establishment and development of a research platform on the history of agricultural education, science, and technology from 2002 to 2025 have demonstrated the gradual transformation of a separate initiative to hold thematic scientific events into a sustainable system of scientific communication that integrates historical-scientific research, library and information support, and personalized forms of representing scientific heritage. In this context, a trend can be observed toward rethinking the role of the history of agricultural science not only as a field of retrospective analysis but also as an important tool for shaping scientific memory, professional identity, and inter-institutional interaction within the scientific community.

Institutionalization and Development of Research Focus.

On May 30, 2002, the First Conference of Young Scholars and Specialists, «The History of Education, Science, and Technology in Ukraine», was held, marking the starting point for the institutionalization of the platform. Its goal was to highlight and professionally discuss current issues in the history of Ukraine's scientific, educational, and technical development, as well as to foster an environment for professional discourse and support for young researchers. Based on the results of the conference, a collection of participants' presentations and papers was prepared and published (Verhunov, 2002), demonstrating the organizers' commitment to systematizing and popularizing the findings.

The event organizers have set the following strategic objectives: to promote the consolidation of scholarly efforts in researching current issues in the history of education, science, and technology, regardless of political affiliations and regional boundaries; to ensure a comprehensive and unbiased account of the evolution of scientific and educational thought in Ukraine; to stimulate the younger generation's interest in historical and scientific studies and encourage them to undertake new research initiatives.

The editorial board of the First Conference consisted of 17 members and was distinguished by its interdisciplinary composition. It included two Doctors of Historical Sciences, professors (V. Mykhailiuk, V. Savchuk), Doctor of Biological Sciences, Professor O. Pylypchuk, and Candidates of Agricultural, Economic, and Technical Sciences, including T. Grygorov, N. Basun, N. Grytsenko, V. Gudzevaty, L. Zaitseva, L. Zinchenko, Z. Kirpal, O. Mudruk, and others. This composition of the editorial board demonstrated a commitment to integrating natural science, technical, and humanities components in the interpretation of the history of science.

Thus, the first conference served not only as an academic event but also as an institutional step toward establishing a sustainable communication platform. It defined the concept of the forum as a space for personalized historical and scientific research, which eventually evolved into an academic tradition, ensuring the platform's continuous development in the years to come.

Between 2002 and 2025, the focus of the research platform underwent a gradual evolution – from defining the general theoretical foundations of the history of science to the formation of a broad interdisciplinary scope with a distinct sectoral and personalized dimension.

In the initial phase (2002), conference discussions centered on general questions of the history of science, its understanding as a component of cultural history, and research into the history of science, education, and technology in Ukraine. Thus, the conceptual foundation of the platform was laid – the integration of historical-scientific studies into a broader sociocultural context and the affirmation of the Ukrainian dimension of scientific development.

Gradually, the scope of research expanded to include the history of agricultural science, education, and technology, as well as issues related to the history of natural sciences in Ukraine and the history of research and testing. Alongside general questions regarding the formation and development of domestic science, a new direction was initiated: information and library support for the scientific and educational sectoral process. This marked a transition from general historical generalizations to a focus on specific sectoral and institutional aspects of scientific development.

In 2008 and 2010, a stabilization and, at the same time, a deepening of certain areas was observed: the history of agricultural science, issues in natural science, general questions regarding the development of science, education, and technology, as well as information and library support for scientific and educational activities. This thematic consistency indicated the formation of the core of a scientific platform and the consolidation of the professional community around priority research vectors.

A significant expansion of the scientific platform took place in 2012, when applied and environmental aspects were integrated alongside traditional historical and scientific fields: improving the efficiency of land use in drained soils of the humid zone, issues related to the operation of the drainage network, the environmentally sound use of wetlands, and current issues in the scientific support of agriculture in Ukraine. Thus, the conference took on a distinctly interdisciplinary character, combining historical and scientific analysis with contemporary challenges in agricultural land use and sustainable development. At the same time, the separate emphasis on the history of agricultural sciences reflected a trend toward internal specialization in research.

Since 2020, the forum's themes have reflected a qualitatively new level of conceptualization. The history of agricultural science, education, and technology is examined within the broader context of Ukrainian history; natural sciences are interpreted through the lens of the evolution of scientific thought. Thus, there has been a transition from separate thematic blocks to a holistic vision of science as a component of the national historical narrative and a strategic resource for the country's development.

It should be noted that, starting with the second forum, the conferences of the scientific platform were organized to coincide with the anniversaries of leading scientific institutions or prominent figures whose work played a significant role in the formation and development of agricultural science in Ukraine. This approach facilitated the integration of contemporary historical and scientific research with the celebration of the institutional and personal legacy of Ukrainian scientific thought, while also broadening the scope of research toward understanding the role of scientific schools, institutions, and individual scholars in shaping the scientific potential of the agricultural sector.

Thus, individual conferences were dedicated to significant anniversary events: the 125th anniversary of the founding of the M. Vavilov Poltava Institute of Agro-Industrial Production of the NAAS; the 100th anniversary of the establishment of the V. Yuryev Institute of Plant Growing of the NAAS; the 80th anniversary of the founding of the National Academy of Agrarian Sciences of Ukraine; and the 10th anniversary of the Center for the History of Agrarian Science at the State Scientific Agricultural Library of the NAAS, among others. Special attention was also paid to the anniversaries of prominent figures in agricultural science – P. Budrin (the first director of the Kharkiv Breeding Station and author of one of the first domestic textbooks on plant breeding); P. Slyozkin (the founder of seed inspection in Ukraine); A. Ternichenko (author of the first textbook in the state language, «Course in Agriculture»); M. Vavilov (an outstanding geneticist); V. Vernadsky (a natural scientist and the first president of the National Academy of Sciences of Ukraine) and others.

This practice has established a long-standing tradition of personalized and thematically focused academic conferences aimed at examining the history of science through the lens of its leading institutions, academic schools, and prominent figures. In this context, the 15th All-Ukrainian Scientific Conference (2020), dedicated to the anniversaries of M. Wolf, K. Osmak, and Academician O. Sozinov, served as a striking example of the expansion of the conference platform's thematic and methodological horizons. The focus on these figures made it possible to combine various dimensions of historical and scientific research – from socio-political and educational activities to the development of natural and agricultural sciences. A special place in this context was occupied by the examination of the scientific legacy of O. Sozinov – an outstanding geneticist, plant breeder, biotechnologist, and science administrator, and the first president of the National Academy of Agrarian Sciences of Ukraine in independent Ukraine (1990–1996) (Nyzhnyk, 2025). His work reflected the latest trends in genetics and plant breeding during the second half of the 20th century and the early 21st century, which led to the inclusion of these topics within the conference program. The focus on Academician O. Sozinov during the 2020 anniversary conference not only helped popularize his scientific legacy but also brought to the forefront research on the history of genetics, plant breeding, biotechnology, and interdisciplinary approaches to the study of the agricultural sector. At the same time, this demonstrated the gradual expansion of the scientific scope of the conference platform «History of Education, Science, and Technology in Ukraine», which is increasingly integrating historical-scientific studies with an analysis of the intellectual legacy of leading scientists and their influence on the formation of modern scientific paradigms.

Thus, holding anniversary and personalized conferences within the scientific platform has become not only a form of scientific communication but also an important mechanism for the development of historical-scientific issues, the popularization of the scientific legacy of outstanding figures, and the formation of a tradition of understanding the evolution of agricultural science through the activities of its leading institutions and individuals.

In the context of the institutionalization of the research platform the activities of the editorial board take on significant importance as the organizational and conceptual core of the publication. It is precisely through personnel dynamics, the distribution of functional responsibilities, and the continuity of management approaches that the transformation of the platform's format in response to societal challenges and changes in the scientific environment can be traced.

A key component of the scientific platform's operations was its publishing activity, which not only documented the outcomes of scientific discourse but also helped create a comprehensive information space on the history of agricultural education, science, and technology.

The platform's main publishing activities include: a) collections of materials and proceedings from scientific conferences; b) the professional electronic scientific journal «History of Science and Biographical Studies», which has become a specialized platform for the publication of historical-scientific and biographical studies; c) historical-biographical series of publications, initiated by the National Scientific Agricultural Library of the National Academy of Agrarian Sciences, dedicated to prominent figures in agricultural science, education, and natural sciences.

Among the main areas of publishing activity, the following were of particular importance: the preparation of biobibliographic indexes and scholarly biographies; coverage of the development of academic schools and institutions; research into the evolution of agricultural science and education; the introduction of archival documents and little-known sources into scholarly circulation; and the creation of a national historical and scholarly information resource.

The materials from each conference were published in corresponding collections of scientific papers and abstracts, which, between 2002 and 2025, formed a separate thematic body of publications related to the platform's activities.

The first collection was published in 2002 and contained abstracts of reports and presentations by 58 of the 61 registered participants. From the very beginning, the publication served not only a representative but also a consolidating function, bringing together researchers in the history of science, agricultural education, library science, biographical studies, and related fields. In subsequent years, as the scope of the scientific forum expanded, the number of participants, the geographical range of represented institutions, and, accordingly, the volume of published materials grew. This attested to the conference's gradual establishment as a permanent platform for scientific communication and an important hub for professional exchange.

Of particular significance is the fact that, since the platform's inception, prominent Ukrainian historians of science, representatives of the National Academy of Sciences of Ukraine and the National Academy of Agrarian Sciences of Ukraine, as well as scholars from institutions of higher education, sector-specific research institutions, libraries, archives, and museums have joined its activities. This contributed to the formation of an interdisciplinary scientific community that brought together historical, agricultural, educational, biographical, and source studies.

With the development of information and digital technologies, the platform's publishing activities underwent transformations: conference proceedings began to be published in both print and electronic formats.

Between 2002 and 2025, the journal's editorial board underwent structural and personnel changes, reflecting both an expansion of its scholarly scope and an adaptation to new standards of academic communication. At the same time, its chair – NAAS Academician V. Vergunov – remained unchanged, ensuring the strategic continuity of the publication's development, the preservation of its conceptual foundations, and the formation of a stable scientific tradition. His long-term leadership contributed to establishing the platform as an authoritative professional forum on the history of agricultural science, education, and technology, as well as strengthening its institutional status within the system of sectoral scientific communications.

The following individuals have served as deputy editors-in-chief over the years: V. Derlemenko (2002); V. Kotsur and O. Pylypchuk (2006); V. Petrenkova (2008); S. Kovalenko (2011); and O. Tarabrin (2013).

The functional continuity of the editorial process was ensured by executive secretaries, who coordinated the preparation of materials, communication with authors and reviewers, and later – the implementation of electronic document management and digital distribution formats. Over the years, these duties were performed by: T. Grygora (2002); O. Anikina (2006, 2013, 2015); V. Ozerelyeva (2008); H. Pipan (2011–2014); A. Bilotserkivska (2015–2019); N. Annenkova (2020–2022); S. Nyzhnyk (2023–2025).

Thus, unlike traditional conference formats, the platform under study emerged as an integrative environment that combined historiographical and source-based approaches. Personalized forums dedicated to prominent agricultural scholars played a significant role in its activities, facilitating an understanding of individual researchers' contributions, the evolution of academic schools, and research traditions. At the same time, the evolution of the editorial board's membership reflected the process of institutional strengthening of the platform, ensuring the continuity of the scholarly tradition and its adaptation to contemporary challenges, particularly digitalization and wartime conditions.

Transforming the Forum Format in the Face of Societal Challenges.

In the context of the institutionalization of the academic platform for the history of agricultural education, science, and technology, an important stage in its development was its adaptation to the societal challenges of the early 21st century, which have significantly transformed the forms of academic communication. The COVID-19 pandemic and the imposition of quarantine restrictions significantly complicated the holding of traditional scientific events, requiring a rapid rethinking of the conference format. Under these circumstances, the organizers were forced to cancel the in-person portion of the forum; however, the scientific process was not interrupted: the conference materials were collected, compiled, and published as a scientific volume. This approach demonstrated the platform's institutional flexibility, its ability to adapt to crisis conditions while ensuring the continuity of scientific dialogue and the preservation of established traditions.

The 2021 forum marked a significant milestone in the platform's modernization, as it was held entirely online for the first time. The use of online scientific communication tools made it possible not only to maintain the regularity of the event but also to expand the circle of participants, ensuring broader representation of scientific institutions and regions. Thus, the transition to a remote format demonstrated the organizers' ability to respond quickly to new social conditions and implement modern forms of academic interaction.

The year 2022 was particularly telling in this context. The conference was held online amid a full-scale war against Ukraine and took place under the symbolic slogan "Live Despite the War! Make plans and know, believe that they will come true!" Under these circumstances, the scientific forum took on not only academic but also significant ideological significance, becoming a platform for consolidating the scientific community, fostering professional solidarity, and preserving the country's intellectual potential.

It should be noted that despite the challenging socio-political context and extraordinary circumstances facing the Ukrainian academic community–particularly during the period of full-scale war – the conference activities of the academic platform remained active and retained their capacity to foster unity. Indeed, within two months of the start of the full-scale invasion, over 140 researchers representing 48 scientific and educational institutions from 18 regions of Ukraine participated in the conference. Such a broad geographic range of participants demonstrated the platform's nationwide scope, its ability to unite the scientific community even under crisis conditions, as well as the resilience of the established network of scientific communication and cooperation between research and educational institutions. Furthermore, the participants' engagement underscored the importance of maintaining intellectual dialogue and upholding scholarly traditions during times of societal upheaval.

As early as 2023–2025, the forum will gradually resume its normal operations and transition to a hybrid format, combining in-person and remote participation. At the same time, modern digital tools for scientific communication – such as online platforms, video conferences, and electronic resources for presenting and discussing research findings – are being actively utilized. This contributes to expanding the geographic reach of participants, maintaining the continuity of scholarly dialogue, and further developing the platform as a hub for professional communication among researchers in the history of education, science, and technology.

It should be emphasized that in the fifth year of full-scale war in Ukraine, this scholarly platform continues to function as an open international space for communication. Its work involves not only Ukrainian scholars but also researchers from other countries, which contributes to the expansion of academic dialogue and the integration of Ukrainian historical and scientific studies into the broader European and global scientific context.

Another key feature of the forum is the participation of representatives from the diplomatic corps. Over the years, representatives from the embassies of Germany, Poland, France, and Israel in Ukraine have taken part in its events. Their presence demonstrates the international community's interest in developing scientific and educational contacts and underscores the significance of this platform as a venue for intercultural and inter-institutional dialogue.

It should be noted that the geographic scope of the scientific platform's participants expands every year. Researchers from Poland, Moldova, Bulgaria, Lithuania, and other countries are actively joining its work. The international component of the forum's activities demonstrates its integration into the broader European scientific space and contributes to the establishment of the Ukrainian historical-scientific school within the context of contemporary global research trends.

Expanding the geographical scope of participants strengthens the comparative dimension of research, enables a deeper understanding of the history of science and technology in Ukraine within the context of transnational processes, and fosters a more extensive exchange of archival materials, source bases, and methodological approaches. This, in turn, contributes to raising the level of scholarly discourse and the formation of a shared research space.

Thus, the scientific platform has become a key factor in the formation of a sustainable historical-scientific community based on the principles of openness, scientific continuity, the personalization of historical knowledge, and international cooperation. Its evolution attests to the transition from an initiative-driven project to an established scholarly tradition that ensures the continuity of the development of the history of education, science, and technology as a distinct field of humanities research.

Thus, the platform's operation amid the pandemic and military challenges has demonstrated its viability, adaptability, and vital role in maintaining the continuity of scientific communication. Its experience demonstrates that the modern scientific community must learn not only to maintain the continuity of intellectual dialogue in times of crisis, but also to actively respond and evolve in the face of global emergencies.

The Scientific Platform for the History of Agricultural Education, Science, and Technology (2002–2025) became a key factor in the development of historical and scientific research in Ukraine, fostering the consolidation of scholars, the creation of an interdisciplinary environment, the development of research schools, and the training of young researchers. The platform facilitated the validation of research findings, the transfer of research expertise, and the integration of young scholars into the academic community. Its activities promoted international scientific collaboration, the development of digital forms of communication, and the integration of electronic resources into the scientific landscape. The platform's evolution demonstrated a transition from a pioneering project to an established tradition of personalized scientific forums, and its continued operation amid the pandemic and military challenges confirmed its adaptability and importance for maintaining the continuity of scientific dialogue.

Conclusions.

The evolution of the academic platform for the history of agricultural education, science, and technology between 2002 and 2025 demonstrates the gradual transformation of an innovative academic project into an established intellectual tradition of historical and scientific research. During this time, a stable scientific community has formed, bringing together researchers from different generations and academic schools interested in studying the history of Ukrainian science, education, and technology, as well as in rethinking the role of scientific figures in the development of scientific knowledge. The platform gradually transformed into an open communication space that combined academic research, conference discussions, publishing activities, and inter-institutional cooperation.

A key feature of the platform's development has been the establishment of a tradition of personalized academic forums centered on prominent scholars and their contributions to the development of specific fields of knowledge. This approach has facilitated the integration of historical and biographical analysis with the study of the evolution of scientific ideas, scientific schools, and the institutional environment, which aligns with contemporary trends in the history of science, where increasing attention is being paid to the role of individuals and scientific networks in the development of knowledge.

Thus, between 2002 and 2025, the platform for the history of agricultural education, science, and technology in Ukraine evolved from a conceptual idea into an established scholarly tradition, ensuring the continuity of research, the development of a personalized approach to the history of science, and the strengthening of the academic community of researchers in the history of Ukrainian science and education. Its further development is linked to the expansion of international cooperation, the digitization of scientific resources, and the deepening of interdisciplinary research, which will contribute to the promotion of Ukraine's scientific heritage in the global intellectual space.

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Наукова платформа історії сільськогосподарської освіти, науки і техніки (2002–2025): від концепції створення до наукової традиції персоналізованих форумів

Анотація. *У статті здійснено історико-науковий аналіз становлення та розвитку наукової платформи «Історія освіти, науки і техніки в Україні» упродовж 2002–2025 рр. Її формування відображає процес інституціоналізації історико-наукових досліджень та розвиток сучасних форм академічної комунікації в Україні. Мета дослідження полягає у реконструкції та узагальненні еволюції зазначеної наукової платформи – від концепції її створення на початку XXI ст. до утвердження сталої академічної традиції проведення тематичних і персоналізованих наукових форумів. Методологічну основу становить міждисциплінарний підхід, що поєднує історико-науковий аналіз, контент-аналіз джерел і матеріалів конференцій. Системний і структурно-функціональний підходи дали змогу розглядати платформу як цілісне науково-комунікаційне середовище. Показано, що започаткування наукової платформи, засновником якої є Національна наукова сільськогосподарська бібліотека Національної академії аграрних наук України, а фундатором – В. Вергунов, стало важливим чинником формування регулярного академічного простору для обговорення проблем історії освіти, науки і техніки. Простежено основні етапи її розвитку, трансформацію організаційних форм діяльності та розширення кола дослідницьких проблем. Особливу увагу приділено становленню й розвитку традиції персоналізованих наукових форумів, присвячених визначним діячам української науки, освіти й техніки. Обґрунтовано, що така модель організації наукових заходів сприяє поглибленню історико-наукових досліджень крізь призму наукових біографій, інтелектуальних мереж і наукових шкіл. У цьому контексті розглянуто приклади форумів, присвячених видатним ученим, зокрема О. Созінову, що засвідчує зростання значення персоналістичного підходу в сучасних історико-наукових студіях. Висвітлено функціонування платформи в умовах пандемії та воєнних викликів, що зумовило трансформацію формату форуму відповідно до нових суспільних реалій і водночас засвідчило його життєздатність, адаптивність та важливу роль у підтриманні безперервності наукової комунікації. Встановлено, що упродовж понад двох десятиліть платформа набула ознак сталої інституційної форми наукової комунікації, поєднавши конференційну практику, науково-видавничу діяльність і міждисциплінарні дослідницькі ініціативи.*

Ключові слова: *наукові платформи; історія науки; історія освіти; наукові комунікації; О. Созінов; наукові конференції*

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Chernobyl and the transformation of nuclear safety culture: Technological governance, risk, and expertise after 1986

Abstract. *The Chernobyl disaster of 26 April 1986 remains one of the most significant technological accidents of the twentieth century and a defining event in the history of science and technology. While early interpretations of the accident focused primarily on reactor design deficiencies and operator actions, subsequent investigations demonstrated that its origins were rooted in a broader interaction of technological, organizational, and institutional factors. This article examines the Chernobyl disaster as a turning point in the evolution of nuclear safety culture and technological governance. Particular attention is devoted to the role of Soviet modernization policies, the development of the RBMK reactor programme, organizational culture within the Soviet nuclear industry, and the management of technical knowledge before and after the accident. The study employs methods of historical analysis, historiographical review, comparative analysis, and socio-technical systems analysis. It is based on international scientific literature, reports of the International Atomic Energy Agency, publications of the Chernobyl Forum, and recent studies in the history of technology, risk governance, and nuclear safety. The article analyses the technical and institutional origins of the disaster, the subsequent reassessment of nuclear risk, the crisis of technological expertise revealed by the accident, and the emergence of the concept of safety culture as a new framework for understanding technological reliability. The findings demonstrate that Chernobyl cannot be adequately explained as the consequence of either technical failures or human errors alone. The disaster represented a systemic failure arising from interactions among reactor design characteristics, organizational practices, institutional constraints, and deficiencies in the circulation of safety-related information. The study shows that the accident fundamentally transformed international approaches to technological risk, encouraged the development of safety culture as a key principle of nuclear governance, and stimulated new forms of international cooperation in the fields of nuclear safety, emergency preparedness, and* *regulatory oversight. The modernization of RBMK reactors after 1986 further illustrates how technological systems evolve through processes of institutional learning and adaptation. The article argues that the historical significance of Chernobyl extends far beyond the nuclear sector. The lessons derived from the disaster contributed to broader changes in the governance of complex technologies and remain relevant to contemporary discussions concerning sustainable technological development, risk management, and institutional resilience. Particular relevance is identified in relation to the United Nations Sustainable Development Goals associated with public health, sustainable energy, resilient infrastructure, and effective institutions. From the perspective of the history of science and technology, Chernobyl represents a crucial case study demonstrating how major technological accidents can reshape scientific knowledge, organizational practices, and international approaches to technological governance.*

Keywords: *Chernobyl disaster; nuclear safety culture; technological governance; Soviet nuclear industry; technological risk; sustainable development*

Introduction.

The accident at Unit 4 of the Chernobyl Nuclear Power Plant on 26 April 1986 occupies a unique place in the history of science and technology. Beyond being the most severe accident in the history of civilian nuclear power, it became a turning point in the development of nuclear safety, risk assessment, technological governance, and international cooperation in the nuclear field. During the decades following the accident, Chernobyl evolved from a Soviet industrial disaster into a global reference point for discussions concerning the reliability of complex technological systems, the role of expert knowledge, and the relationship between technological progress and societal responsibility.

Early interpretations of the accident primarily focused on technical failures and operator actions. The reports presented at the International Atomic Energy Agency (IAEA) review meeting in Vienna in 1986 emphasized violations of operating procedures and deficiencies in reactor operation (IAEA, 1986a, 1986b; Wakabayashi, Mochizuki, Midorikawa, Hayamizu, & Kitahara, 1987; WCED, 1987). Subsequent investigations, however, demonstrated that the causes of the disaster were considerably more complex. The reassessment published by the International Nuclear Safety Advisory Group (INSAG-7) concluded that the accident resulted from the interaction of reactor design characteristics, operational decisions, organizational shortcomings, and weaknesses in safety management rather than from operator actions alone (IAEA, 1992).

The publication of INSAG-4 and INSAG-7 marked an important shift in international thinking about technological risk. These reports introduced and subsequently developed the concept of safety culture, which became one of the most influential ideas in modern nuclear governance. According to INSAG, safety could no longer be understood exclusively as a technical property of a reactor or engineering system. It also depended on organizational practices, institutional learning, communication of operational experience, and the values shared by designers, regulators, managers, and operators (IAEA, 1991; IAEA, 1992).

The historical significance of Chernobyl extends beyond the immediate circumstances of the accident. Research conducted during the last two decades has increasingly examined the disaster within the broader context of Soviet scientific and technological development. Studies by Schmid (2006, 2011, 2015, 2016, 2018, 2019) demonstrated that the Soviet nuclear industry was shaped not only by engineering considerations but also by institutional structures, professional identities, planning mechanisms, and specific approaches to expertise and decision-making. From this perspective, the Chernobyl accident may be interpreted as a manifestation of deeper systemic problems affecting the circulation of technical knowledge, the management of uncertainty, and the implementation of safety principles within large technological organizations.

At the same time, historians of technology have emphasized that Chernobyl significantly influenced international approaches to technological governance. The accident stimulated the modernization of RBMK reactors (Reaktor Bolshoy Moshchnosti Kanalnyy, or High-Power Channel-Type Reactor), accelerated the development of international nuclear safety standards, strengthened transnational cooperation in the field of emergency preparedness, and contributed to new approaches for managing technological risks (Arnhold, 2020; D'Auria et al., 2008a; Schmid, 2016). These developments remain relevant in contemporary debates concerning sustainable technological development, particularly in sectors characterized by high complexity, significant societal impact, and long-term environmental consequences.

The continuing relevance of Chernobyl is reflected in the growing body of interdisciplinary scholarship addressing its technical, environmental, medical, social, and cultural consequences. Studies published by the Chernobyl Forum and subsequent international assessments have demonstrated that the long-term legacy of the accident includes not only radiological effects but also substantial social, economic, and psychological consequences for affected communities (Havenaar et al., 1997; Marples, 1988; Perrow, 1999). More recent research has further highlighted the importance of institutional trust, risk communication, and public perceptions of technological hazards in shaping societal responses to nuclear accidents (Bromet, 2014; Oe, Takebayashi, Sato, & Maeda, 2021; Schmid, 2019).

At the same time, the historiography of Chernobyl has undergone significant transformation. Earlier studies focused primarily on technical explanations of the accident and assessments of its radiological consequences. More recent scholarship within the history of science and technology has increasingly examined the disaster as a socio-technical phenomenon shaped by interactions among technological design, institutional structures, expert cultures, and systems of governance. Historians have demonstrated that the significance of Chernobyl extends beyond the events of April 1986 and includes its influence on scientific expertise, technological regulation, public trust, and international approaches to risk management (Arnhold, 2020; Guth, Gestwa, Penter, & Richers, 2019; Schmid, 2015). This historiographical shift provides an important framework for understanding the accident not only as a failure of a technological system but also as a turning point in the historical evolution of technological governance.

Within the framework of the United Nations Sustainable Development Goals (SDGs), the historical experience of Chernobyl remains particularly relevant to discussions associated with sustainable energy systems (SDG 7), resilient infrastructure and innovation (SDG 9), public health and well-being (SDG 3), and effective institutions (SDG 16). The accident demonstrated that technological sustainability cannot be reduced to technical efficiency alone. It also requires transparent governance, effective safety management, continuous organizational learning, and the responsible integration of scientific knowledge into decision-making processes.

The relevance of these issues has increased in the twenty-first century as societies continue to rely upon increasingly complex technological systems characterized by high levels of interdependence and uncertainty. Contemporary discussions concerning artificial intelligence, critical infrastructure, climate-related technologies, advanced energy systems, and digital infrastructures frequently address questions similar to those raised by the Chernobyl experience: how risks should be assessed, how expertise should be organized, how safety-related information should be communicated, and how institutions can promote organizational learning in environments characterized by technological complexity. Consequently, the historical lessons of Chernobyl remain relevant far beyond the nuclear sector itself.

Although the technical causes of the accident, its environmental consequences, and its political implications have been extensively investigated, comparatively less attention has been devoted to analysing Chernobyl as a historical turning point in the evolution of safety culture and technological governance. Existing studies often examine these themes separately, whereas the long-term transformation of international approaches to technological risk emerged through the interaction of reactor design, organizational culture, institutional secrecy, expert authority, and post-accident learning processes. This article seeks to integrate these dimensions within a single historical framework.

The article is structured in five interconnected sections. The first section examines the role of nuclear energy within Soviet modernization policies and analyses the institutional characteristics of the Soviet nuclear programme. The second section investigates the technical and organizational origins of the Chernobyl accident. The third section explores the crisis of technological expertise and the reassessment of nuclear risk after 1986. The fourth section analyses the emergence of the concept of safety culture and the transformation of international nuclear governance. Finally, the fifth section considers the long-term consequences and historical legacy of the disaster in the broader context of sustainable technological development and contemporary approaches to risk governance.

The purpose of this study is to examine the Chernobyl disaster as a turning point in the evolution of nuclear safety culture and technological governance. Particular attention is devoted to the relationship between reactor design, organizational culture, institutional secrecy, and the circulation of technical knowledge within the Soviet nuclear industry. By analysing the origins, consequences, and long-term legacy of the accident, the article seeks to demonstrate how Chernobyl contributed to the transformation of international approaches to nuclear safety and to the development of principles that continue to influence contemporary discussions of sustainable technological development.

Research Methods.

This study is situated within the fields of the history of science and technology, nuclear history, and science and technology studies. It examines the Chernobyl disaster not only as a technological accident but also as a historical event that transformed understandings of nuclear safety, technological governance, and the relationship between scientific expertise and society. The research adopts an interdisciplinary historical approach that combines the analysis of technological systems with the investigation of institutional, organizational, and socio-political factors that shaped the origins and consequences of the accident.

The study is based primarily on the analysis of published documentary sources, international regulatory documents, historical scholarship, and scientific literature. Particular attention is devoted to the reports of the IAEA, especially INSAG-4 (*Safety Culture*) and INSAG-7 (*The Chernobyl Accident: Updating of INSAG-1*), which played a decisive role in the international reassessment of the accident and the subsequent development of the concept of safety culture (IAEA, 1991; IAEA, 1992). These documents are treated not only as sources of technical information but also as historical evidence reflecting changing international understandings of technological risk and organizational responsibility.

The historiographical foundation of the study includes works devoted to the history of the Soviet nuclear programme, the institutional culture of the Soviet nuclear industry, the history of technological accidents, and the development of international nuclear governance. Particular attention is given to studies by Schmid (2006, 2011, 2015; 2016, 2018, 2019), which analyse Soviet nuclear expertise, organizational culture, and post-Chernobyl transformations in nuclear safety policy. These works are complemented by broader historical and interdisciplinary scholarship addressing the political, social, and technological dimensions of the Chernobyl disaster.

Several historical methods were employed. The historical-genetic method was used to reconstruct the evolution of the Soviet nuclear programme and the development of RBMK reactor technology prior to 1986. The historical-comparative method facilitated the analysis of changes in international approaches to nuclear safety before and after the accident. The problem-chronological method was applied to examine the sequence of events leading to the disaster and the subsequent evolution of safety concepts, regulatory frameworks, and international cooperation. Elements of systems analysis were also employed to investigate the interactions between technological design, organizational practices, institutional structures, and decision-making processes.

The study further draws upon approaches developed within science and technology studies, which view technological systems as socio-technical constructs shaped by interactions among technical artefacts, expert communities, institutions, and political environments. This perspective allows the Chernobyl accident to be analysed not simply as the failure of a reactor or the consequence of individual actions, but as the product of a complex system involving technological design, organizational culture, information management, and institutional governance.

The source base also includes studies of the long-term health, environmental, and psychological consequences of the accident, reports of the Chernobyl Forum, and research concerning post-accident modernization of RBMK reactors. These materials were used to assess how scientific understanding of the disaster evolved over time and how the lessons of Chernobyl influenced subsequent developments in nuclear safety, risk assessment, and technological governance.

The methodological framework adopted in this article makes it possible to examine Chernobyl simultaneously as a technological disaster, a historical turning point in the development of nuclear safety culture, and a case study in the evolution of modern approaches to the governance of complex technological systems. Such an approach allows the accident to be considered not only within the context of Soviet nuclear history but also within broader discussions concerning sustainable technological development and the historical foundations of contemporary risk governance.

Results and Discussions.

1. Soviet Nuclear Modernity before Chernobyl.

1.1. Nuclear Energy in Soviet Modernization Policy.

The development of nuclear energy occupied a central position in Soviet visions of scientific and technological progress after the Second World War. Although the Soviet atomic programme initially emerged within the context of military competition and nuclear weapons development, by the mid-1950s nuclear technologies increasingly became associated with broader goals of economic modernization and industrial development. The commissioning of the world's first grid-connected nuclear power plant at Obninsk in 1954 was presented not only as a scientific achievement but also as evidence that atomic energy could serve peaceful economic purposes and contribute to the construction of a technologically advanced socialist society (Josephson, 2000; Schmid, 2018).

Unlike many Western nuclear programmes, which were frequently justified through projected energy demand and economic efficiency, Soviet nuclear development was closely integrated into state-led modernization strategies. Nuclear power plants were expected to perform multiple functions simultaneously: generating electricity, supporting industrial expansion, strengthening technological self-sufficiency, and demonstrating the scientific capabilities of the Soviet state. As

Josephson (2000) has argued, large technological systems occupied a privileged place within Soviet development thinking because they symbolized the capacity of science and engineering to transform both nature and society.

The expansion of civilian nuclear energy during the 1960s and 1970s occurred within a highly centralized planning framework. Research institutes, design bureaus, industrial ministries, and political authorities were linked through administrative mechanisms that coordinated technological development on a national scale. This system enabled the rapid construction of large industrial projects and facilitated the growth of nuclear generating capacity across the Soviet Union. At the same time, centralized decision-making often concentrated authority within a relatively small number of institutions, reducing opportunities for independent review and external assessment of technological choices (Perrow, 1999; Schmid, 2015).

Nuclear energy also acquired considerable symbolic significance within Soviet political culture. Official publications, exhibitions, educational programmes, and popular science literature portrayed the "peaceful atom" as one of the defining achievements of modern science. As Schmid (2006) has demonstrated, Soviet exhibitions devoted to atomic energy presented nuclear technologies as visible manifestations of progress, rational planning, and scientific modernity. The atom became a powerful symbol of the Scientific-Technological Revolution that Soviet leaders expected would transform industry, agriculture, transportation, and everyday life.

This technological optimism was not limited to electricity generation. Nuclear technologies were incorporated into ambitious projects involving desalination, regional development, scientific research, and large-scale industrial infrastructure. Guth's study (2022) of the city of Shevchenko (now Aktau) illustrates how nuclear energy became embedded within broader programmes aimed at transforming geographically remote regions through technological innovation. Such projects reflected widespread confidence that advanced technologies could overcome environmental and economic constraints while accelerating modernization.

The rapid growth of the Soviet nuclear sector was accompanied by increasing institutional complexity. By the late 1970s and early 1980s, reactor designers, research institutes, operating organizations, industrial ministries, and political authorities formed an extensive network responsible for the development and management of nuclear technologies. While this structure facilitated technological expansion, it also created challenges related to communication, coordination, and the circulation of safety-related knowledge. Historians of Soviet technology have noted that information concerning operational experience and emerging technical concerns was not always disseminated effectively across organizational boundaries, limiting opportunities for institutional learning and critical reassessment (Balonov & Bouville, 2020, Guth, Gestwa, Penter, & Richers, 2019, Josephson, 2000).

These characteristics reflected broader features of Soviet modernization. Large technological systems were frequently regarded as instruments through which scientific knowledge could be transformed into economic growth and social progress.

As a result, technological achievement often occupied a prominent position in official narratives of development. At the same time, confidence in scientific and engineering expertise sometimes contributed to assumptions that technical challenges could be resolved primarily through technological solutions, while organizational and institutional dimensions received comparatively less attention (Kuchinskaya, 2014, Perrow, 1999, Schmid, 2018).

The significance of these developments became particularly evident after the Chernobyl accident. Subsequent investigations demonstrated that the disaster could not be explained solely through technical deficiencies or operator actions. It also reflected characteristics of the institutional environment within which Soviet nuclear technologies were developed, managed, and regulated. The rapid expansion of nuclear power, the concentration of expertise within specialized organizations, limitations in the circulation of safety-related information, and strong confidence in technological progress all formed part of the broader historical context that shaped the origins of the accident (IAEA, 1992; Kuchinskaya, 2014, Schmid, 2015).

Soviet nuclear energy should therefore be understood not merely as a source of electricity but as a key component of a wider modernization project. The Chernobyl disaster exposed some of the contradictions inherent in this project, demonstrating both the transformative potential of large technological systems and the risks associated with their governance. Understanding these historical conditions is essential for explaining why Chernobyl became a turning point not only in the history of nuclear energy but also in the evolution of technological risk management, safety culture, and international approaches to technological governance.

1.2. The RBMK Reactor and the Soviet Nuclear Program.

The rapid expansion of Soviet nuclear power during the 1970s and early 1980s was closely associated with the development of the RBMK reactor series. The acronym RBMK referred to a graphite-moderated, light-water-cooled reactor designed for large-scale electricity generation. By the mid-1980s, RBMK reactors constituted one of the principal components of the Soviet nuclear energy programme and operated at major nuclear power plants including Chernobyl, Leningrad, Kursk, Ignalina, and Smolensk (Guth, Gestwa, Penter, & Richers, 2019, IAEA, 1992; Schmid, 2015).

The origins of the RBMK concept can be traced to earlier Soviet reactor technologies developed for both military and civilian applications. Unlike pressurized water reactors that became dominant in many Western nuclear programmes, the RBMK employed a channel-type design in which individual fuel channels passed through a large graphite moderator. This configuration allowed refuelling during operation and enabled the construction of reactors with exceptionally high electrical output. Equally important, the design could be implemented using the capabilities of Soviet heavy industry without requiring the large reactor pressure vessels necessary for many Western reactor systems.

The decision to expand the RBMK programme reflected broader priorities of Soviet modernization policy. During the 1960s and 1970s, state planners viewed nuclear energy as an essential component of long-term economic development and energy security. Reactor technologies capable of rapid deployment and large-scale electricity generation were therefore particularly attractive. As Schmid (2018) has demonstrated, the RBMK was regarded not merely as an engineering solution but as an instrument of industrial modernization that could support regional development and reduce dependence on fossil fuels in strategically important areas of the Soviet Union. The technological characteristics of the RBMK were closely linked to these institutional and economic priorities. The reactor's large capacity, online refuelling capability, and relatively flexible construction requirements made it well suited to the objectives of centralized economic planning. However, historians of technology have emphasized that technological choices are never determined solely by engineering considerations. They are also shaped by political priorities, industrial capabilities, organizational structures, and prevailing assumptions regarding acceptable risk. The RBMK emerged from this broader context and therefore reflected both technical ambitions and institutional constraints of the Soviet nuclear programme.

At the same time, the RBMK possessed several characteristics that distinguished it from most commercial reactor designs operating elsewhere in the world. The combination of graphite moderation and water cooling produced specific neutronic properties, including a positive void coefficient under certain operating conditions. In addition, the large dimensions of the reactor core created challenges associated with monitoring and controlling reactor behaviour during transient conditions. Prior to 1986, these characteristics were generally regarded by reactor designers as manageable within the established operational framework of Soviet nuclear power plants (IAEA, 1992; Josephson, 2000; Wakabayashi, Mochizuki, Midorikawa, Hayamizu, & Kitahara, 1987).

Research conducted after the Chernobyl accident demonstrated that some of these design characteristics acquired critical significance under specific operating conditions. Investigations published during the late 1980s and early 1990s identified the interaction between reactor physics, control rod design, and operational circumstances as a key element in the development of the power excursion that destroyed Unit 4. Early analyses by Japanese nuclear specialists confirmed that the sequence of events observed during the accident was consistent with known characteristics of RBMK behaviour under unstable operating conditions (Chan & Dastur, 1989; IAEA,1986a, 1986b, 1991; Wakabayashi, Mochizuki, Midorikawa, Hayamizu, & Kitahara, 1987).

Subsequent investigations provided a more detailed understanding of these processes. The INSAG-7 report concluded that deficiencies in the design of the control and protection system contributed significantly to the accident (IAEA, 1992). Particular attention was directed toward the graphite displacers attached to the control rods, which under specific conditions could initially introduce positive reactivity during emergency shutdown. Further analyses demonstrated that this design feature played an important role in explaining the rapid power increase observed during the final seconds before the explosion (Chan & Dastur, 1989; D'Auria, et al., 2008a, 2008b, 2008c).

However, reducing the origins of the disaster solely to reactor design would oversimplify the historical reality. Historians and scholars of technology have increasingly emphasized that technological systems must be understood within the institutional environments in which they are developed and operated (Kuchinskaya, 2014; Perrow, 1999; Schmid, 2011, 2015). The RBMK was not simply a reactor design; it was also a product of Soviet planning institutions, scientific organizations, industrial ministries, design bureaus, and operating practices. Decisions regarding its development reflected contemporary understandings of safety, economic efficiency, technological feasibility, and national development priorities.

The accident at Chernobyl fundamentally transformed international perceptions of the RBMK. During the years following 1986, extensive modernization programmes were implemented at operating RBMK plants. Reactor control characteristics were modified, safety systems were upgraded, operating procedures were revised, and regulatory oversight was strengthened. These measures reflected a broader shift from confidence in technological capability alone toward a more comprehensive understanding of nuclear safety that incorporated organizational learning, regulatory review, and continuous reassessment of operational experience (D'Auria, et al., 2008a, 2008b, 2008c; IAEA, 1991, 1992).

The historical importance of the RBMK extends beyond its role in the Chernobyl accident. The reactor illustrates how technological artefacts embody the political, economic, and institutional assumptions of the societies that produce them. The history of the RBMK therefore provides valuable insight into the relationship between technological innovation, state modernization strategies, organizational culture, and the governance of technological risk in the late Soviet period.

1.3. Organizational Culture and Professional Identities in the Soviet Nuclear Industry.

The Soviet nuclear industry was not merely a collection of reactors, research institutes, and power plants. It constituted a complex socio-technical system in which technological development depended on interactions among scientists, engineers, plant operators, industrial ministries, regulatory authorities, and political institutions. Understanding the organizational culture of this system is essential for explaining both the achievements of Soviet nuclear technology and the difficulties that became apparent after the Chernobyl accident.

From its inception, the Soviet nuclear programme operated under conditions of exceptional political significance and institutional secrecy. The strategic importance of nuclear technologies encouraged the formation of highly specialized professional communities whose members possessed unique technical expertise and frequently worked within relatively closed organizational environments. As a result, professional identity within the nuclear sector became closely associated with scientific competence, technological achievement, and service to the state. Nuclear specialists often regarded themselves as participants in a national project that combined scientific progress, economic modernization, and geopolitical competition (Guth, Gestwa, Penter, & Richers, 2019; Josephson, 2000; Schmid, 2015).

This professional culture contributed significantly to the successes of the Soviet nuclear programme. Scientists and engineers generally viewed nuclear technology as a symbol of progress and modernity and were strongly committed to technological innovation and engineering problem-solving. Such attitudes facilitated the rapid development of nuclear infrastructure and supported ambitious reactor construction programmes. However, historians have also noted that strong confidence in technological capability could influence the ways in which risks, operational anomalies, and safety concerns were interpreted within professional communities (Perrow, 1999; Schmid, 2015, 2018).

An important characteristic of the Soviet nuclear system was the coexistence of multiple institutional actors with distinct responsibilities and priorities. Research institutes focused on reactor design and scientific innovation, operating organizations concentrated on electricity production, while ministries and political authorities pursued broader economic and strategic objectives. Although these institutions were formally integrated within a centralized administrative structure, communication between them was not always effective. Information concerning operational incidents, equipment deficiencies, or safety-related concerns could remain confined within particular organizations rather than being systematically disseminated throughout the entire nuclear sector.

The management of technical knowledge represented a particularly significant challenge. As the nuclear programme expanded during the 1970s and 1980s, increasing organizational complexity required effective mechanisms for collecting operational experience and transforming it into improvements in reactor design, operating procedures, and personnel training. Investigations conducted after the Chernobyl accident demonstrated that such mechanisms were not always sufficiently developed. Lessons derived from operational events were not consistently incorporated into industry-wide decision-making processes, limiting opportunities for institutional learning before 1986 (IAEA, 1992; Josephson, 2000; Schmid, 2015).

The role of secrecy further complicated these processes. Secrecy fulfilled important functions within a state whose nuclear technologies possessed both civilian and military significance. However, historians have argued that the classification of technical information sometimes created barriers to the broader exchange of operational experience and safety-related knowledge. In certain cases, information concerning design vulnerabilities or operational anomalies remained restricted to relatively narrow professional circles. As a consequence, knowledge that might have contributed to improved safety did not always reach all organizations responsible for reactor operation, personnel training, and regulatory oversight.

Studies of Soviet expertise have also emphasized the relationship between authority and technological decision-making. Scientific expertise occupied a highly respected position within Soviet society, and technical specialists often exercised considerable influence over technological policy. Nevertheless, expert authority operated within a hierarchical institutional environment shaped by administrative planning and political priorities. Under such conditions, evaluations of technological risk could be influenced not only by scientific evidence but also by organizational expectations, production goals, and broader development strategies. As Schmid (2015) has demonstrated, expertise within the late Soviet system was closely connected to questions of institutional legitimacy and political authority.

These characteristics should not be interpreted as unique to the Soviet Union. Research on technological accidents in different national contexts has shown that tensions between production objectives, expert judgment, organizational learning, and risk management are common features of many large technological systems. Perrow (1999), for example, argued that accidents in complex and tightly coupled systems often emerge from interactions among multiple organizational and technological factors rather than from isolated failures. Similarly, Vaughan's (1996) study of the Challenger disaster demonstrated how organizational cultures can normalize risk and contribute to catastrophic outcomes despite the presence of highly qualified technical personnel.

Viewed from this broader perspective, the Chernobyl accident appears not simply as the failure of a reactor or the result of mistakes made by individual operators. It also reflected systemic challenges associated with the governance of complex technological systems. The accident exposed limitations in the circulation of technical knowledge, the communication of operational experience, and the institutional mechanisms through which safety concerns were identified, evaluated, and addressed. These issues subsequently became central to international discussions of safety culture, organizational learning, and technological governance (IAEA, 1991, 1992).

Historically, organizational culture played a crucial role in shaping technological outcomes. The Chernobyl disaster demonstrated that technological reliability depends not only on engineering design but also on the institutional environments within which technologies are developed, regulated, and operated. Understanding the organizational culture of the Soviet nuclear sector is therefore essential for explaining why the accident became a watershed event in the history of nuclear energy and why its consequences extended far beyond the boundaries of a single reactor or power plant.

2. The Chernobyl Accident: Technical and Institutional Origins.

2.1. The April 1986 Safety Test.

On 26 April 1986, Unit 4 of the Chernobyl Nuclear Power Plant was destroyed during a turbine-generator rundown test conducted as part of a scheduled reactor shutdown for maintenance. The objective of the experiment was to determine whether the residual rotational energy of the turbine could provide sufficient electrical power to essential safety systems during the interval between the loss of external power and the activation of emergency diesel generators. Similar tests had previously been performed at other Soviet nuclear facilities, and the experiment itself was not considered unusual within the operational practices of the Soviet nuclear industry

(IAEA, 1992; Schmid, 2015; Wakabayashi, Mochizuki, Midorikawa, Hayamizu, & Kitahara, 1987).

The events preceding the accident have been reconstructed in considerable detail through investigations conducted by Soviet authorities, IAEA, and subsequent independent researchers. During preparation for the test, a combination of operational delays, changes in reactor conditions, and decisions made by plant personnel resulted in a reactor state that differed significantly from the parameters originally envisaged in the test programme. Reactor power decreased to an unexpectedly low level, xenon poisoning developed within the core, and operators undertook a series of actions intended to restore power and maintain reactor operation. As a consequence, the reactor entered a regime characterized by reduced operational reactivity margin and increased sensitivity to disturbances (IAEA, 1992; Schmid, 2015; Wakabayashi, Mochizuki, Midorikawa, Hayamizu, & Kitahara, 1987).

The historical significance of the safety test lies not only in the events themselves but also in the ways they were subsequently interpreted. The first official Soviet explanation, presented at the IAEA review meeting in Vienna in August 1986, emphasized violations of operating procedures and identified operator actions as the principal cause of the accident. This interpretation strongly influenced international understanding of the disaster during the late 1980s and contributed to a widespread perception that Chernobyl resulted primarily from human error committed during the execution of the experiment (IAEA, 1986a, 1986b).

Subsequent investigations fundamentally altered this interpretation. During the late 1980s and early 1990s, growing evidence demonstrated that the accident could not be adequately explained through operator actions alone. Detailed analyses revealed that reactor design characteristics, deficiencies in safety analysis, limitations in operating documentation, and weaknesses in organizational communication had also played important roles in the development of the accident sequence (Balonov, 2007; Chan & Dastur, 1989; Kuchinskaya, 2014).

The publication of INSAG-7 in 1992 marked a major turning point in the interpretation of the disaster (IAEA, 1992). The report concluded that the accident resulted from a complex interaction between technological characteristics, organizational deficiencies, and human actions. It acknowledged that operators violated procedures but simultaneously recognized that plant personnel lacked complete information concerning important reactor characteristics and that several design deficiencies had not been adequately communicated to operating organizations. Consequently, responsibility for the accident could no longer be attributed solely to the actions of individuals working in the control room during the night of 25–26 April 1986.

This reinterpretation reflected broader changes in international thinking about technological accidents. During the late twentieth century, researchers increasingly challenged explanations that focused exclusively on human error. Studies of complex technological systems demonstrated that accidents often emerge through interactions among technical components, organizational structures, institutional cultures, and decision-making processes. In this context, the Chernobyl accident became one of the most influential examples supporting a systemic interpretation of technological failure (Jasanoff, 2003; Perrow, 1999; Vaughan, 1996; Yurchenko, Strelko, Vasilova, Rudiuk, Goretskyi, 2023).

Historians of technology have similarly emphasized that the April 1986 test should not be viewed as an isolated operational event (Marples, 1988; Perrow, 1999). Schmid (2015) argues that the actions of plant personnel occurred within a broader institutional environment shaped by assumptions regarding reactor safety, technological reliability, and organizational authority. The decisions made during the test were therefore influenced not only by immediate operational circumstances but also by the professional cultures, institutional structures, and knowledge-management practices that characterized the Soviet nuclear industry.

The reassessment of the safety test also transformed understandings of responsibility. Rather than searching for a single cause or a single group of individuals responsible for the disaster, researchers increasingly examined how design assumptions, operational procedures, organizational practices, and institutional arrangements interacted to create conditions under which catastrophic failure became possible. This shift from individual blame toward systemic analysis would later become one of the intellectual foundations of the concept of safety culture developed by the International Nuclear Safety Advisory Group (IAEA, 1991, 1992).

Historically, the significance of the April 1986 safety test extends far beyond the technical sequence of events that culminated in the destruction of Unit 4. The accident became a catalyst for the reassessment of long-established assumptions concerning technological reliability, expert authority, and risk management. It encouraged scholars, engineers, and policymakers to recognize that the safe operation of complex technologies depends not only on technical design but also on the organizational and institutional environments within which technological systems are developed, regulated, and operated.

The events of 26 April 1986 thus occupy a pivotal place in the history of technological risk. The safety test that began as a routine engineering experiment ultimately became one of the most influential case studies in modern discussions of accident causation, organizational learning, and technological governance. Its reinterpretation over subsequent decades illustrates how scientific understanding of technological disasters evolves through the continuous reassessment of evidence, institutional practices, and historical experience.

2.2. Design Characteristics of the RBMK-1000 Reactor.

The reassessment of the Chernobyl accident conducted after 1986 demonstrated that several design characteristics of the RBMK-1000 reactor played a significant role in the development of the disaster. While early explanations emphasized operator actions and procedural violations, subsequent investigations revealed that important features of the reactor itself contributed to the rapid escalation of the accident. These findings fundamentally altered international understandings of nuclear safety and reinforced the growing recognition that technological design and organizational practices must be analysed as interconnected elements of complex socio-technical systems.

The RBMK-1000 differed substantially from most commercial nuclear reactors operating in Western countries during the 1970s and 1980s. It employed graphite as a neutron moderator and ordinary light water as a coolant. This combination offered several advantages, including high power output, online refuelling capability, and flexibility in fuel utilization. Such characteristics made the reactor particularly attractive within the Soviet energy programme, where rapid expansion of generating capacity and compatibility with domestic industrial capabilities were considered strategic priorities.

The technological configuration of the RBMK reflected broader institutional and economic considerations. Unlike many Western reactor designs, the RBMK could be constructed without large reactor pressure vessels, reducing dependence on certain manufacturing capabilities and facilitating large-scale deployment within the Soviet Union. Historians of technology have noted that reactor design choices are rarely determined solely by engineering criteria; they are also influenced by industrial infrastructure, political priorities, economic constraints, and prevailing conceptions of acceptable risk. The RBMK emerged from this broader context and therefore embodied both technical ambitions and institutional assumptions of the Soviet nuclear programme (Jasanoff, 2003; Josephson, 2000; Schmid, 2018).

Among the reactor characteristics that attracted particular attention after the accident was the positive void coefficient of reactivity. Under normal operating conditions, water circulating through the reactor core functioned not only as a coolant but also as a neutron absorber. When steam bubbles formed within coolant channels, neutron absorption decreased and reactor power could increase. In the RBMK, this effect became especially pronounced under certain operating conditions. Investigations conducted after the accident demonstrated that this characteristic could contribute to rapid increases in reactivity if reactor parameters moved beyond intended operating regimes (IAEA, 1992).

The large physical dimensions of the reactor core represented another important design feature. Unlike compact reactor configurations used in many pressurized water reactors, the RBMK contained thousands of fuel channels distributed throughout a massive graphite moderator. This arrangement created complex spatial distributions of neutron flux and reactivity. Subsequent analyses showed that these characteristics could influence reactor behaviour during transient conditions and contribute to the emergence of unstable operating states under specific circumstances (D'Auria, et al., 2008a, 2008b, 2008c; Schmid, 2015; Wakabayashi, Mochizuki, Midorikawa, Hayamizu, & Kitahara, 1987).

Particular attention was devoted to the design of the reactor's control and protection system. Following the accident, investigators determined that the control rods incorporated graphite displacers attached to their lower sections. During the initial stage of insertion, these graphite sections displaced neutron-absorbing water from portions of the core. Under certain conditions, this process could temporarily increase reactivity before the absorber sections of the rods entered the reactor and began reducing power. Although this phenomenon was known within specialized technical circles, its significance under extreme operating conditions was not fully appreciated before the accident (IAEA, 1992).

Subsequent studies examined this issue in greater detail. Chan and Dastur (1989) demonstrated that positive scram reactivity could be introduced during emergency shutdown if specific neutron flux distributions existed within the reactor core. Later analyses by D'Auria et al. (2008a, 2008b, 2008c) further clarified the physical mechanisms responsible for this effect and confirmed its importance in explaining the rapid power excursion observed during the final seconds before the explosion. These investigations contributed significantly to the reinterpretation of the accident and influenced subsequent modernization programmes implemented at operating RBMK facilities.

The reassessment of reactor design also highlighted shortcomings in the communication of technical knowledge. The INSAG-7 report concluded that reactor operators did not possess complete information regarding all characteristics of the control and protection system. Certain design features and their potential consequences under abnormal operating conditions were insufficiently reflected in operating documentation and training materials. Consequently, plant personnel could not fully evaluate the risks associated with reactor operation under the conditions that developed during the safety test.

From a historical perspective, these findings challenged simplified explanations of technological accidents. The Chernobyl disaster did not occur solely because of a defective reactor design, nor solely because of operator actions. Rather, it emerged from interactions among technological characteristics, operational decisions, institutional practices, and the circulation of technical knowledge. The RBMK reactor functioned within a broader organizational environment that influenced how design assumptions were interpreted, communicated, and implemented in practice (Balonov, 2007; Knoglinger, Wölfl, & Kaliatka, 2015; Sato & Lyamzina, 2018).

The significance of the RBMK therefore extends beyond the technical causes of the accident itself. The post-Chernobyl reassessment of its design characteristics contributed directly to the development of new approaches to nuclear safety analysis, reactor regulation, and risk assessment. It also reinforced the growing recognition that safety cannot be treated exclusively as a property of technology but must be understood as a product of interactions between technological systems and the organizations responsible for their design, operation, and oversight.

Following the accident, extensive modifications were introduced at operating RBMK plants. These included reductions in the positive void coefficient, redesign of control rods, enhancement of emergency protection systems, revision of operating procedures, and strengthening of regulatory oversight. Such measures significantly improved reactor safety and illustrate how major technological accidents can stimulate institutional learning, technological adaptation, and the production of new forms of engineering knowledge. In this sense, the history of the RBMK after 1986 is not only a history of failure but also a history of reassessment, modernization, and the emergence of new safety paradigms within the international nuclear community (Schmid, 2015, 2018, 2019; Uspuras & Kaliatka, 2012).

The RBMK-1000 provides an important historical example of how technological artefacts embody scientific assumptions, institutional priorities, and political choices. Its history demonstrates that technological design cannot be separated from the social and organizational environments within which technologies are created and operated. The reinterpretation of RBMK technology after Chernobyl therefore played a crucial role in transforming international understandings of risk, responsibility, and technological governance.

2.3. Human Factors, Organizational Decision-Making, and Institutional Constraints.

The reassessment of the Chernobyl accident during the late 1980s and early 1990s fundamentally changed the interpretation of technological disasters. While the first official explanations emphasized violations of operating procedures and errors committed by plant personnel, subsequent analyses demonstrated that such interpretations provided only a partial understanding of the accident. Attention gradually shifted from individual responsibility toward broader questions concerning organizational behaviour, institutional decision-making, and the governance of technological risk (Guth, Gestwa, Penter, & Richers, 2019; Jasanoff, 2003; Kuchinskaya, 2014).

Human actions undoubtedly played an important role in the events preceding the destruction of Unit 4. During the preparation and execution of the turbine-generator rundown test, operators departed from several established procedures, and the reactor entered a condition that was not envisaged in the original test programme. However, later investigations demonstrated that these actions occurred within an institutional environment shaped by specific assumptions regarding reactor safety, operational flexibility, and the relationship between operators and technological systems. Consequently, the behaviour of plant personnel cannot be understood independently of the organizational context in which decisions were made (IAEA, 1992; Schmid, 2015).

One of the central conclusions of the INSAG-7 reassessment was that deficiencies in reactor design and safety management significantly influenced operator decision-making. The report noted that plant personnel did not possess complete information regarding several important characteristics of the RBMK reactor, including the potential consequences of emergency shutdown under specific operating conditions. As a result, actions that appeared reasonable from the perspective of operators could produce consequences that were neither anticipated nor fully understood by those responsible for reactor operation. This finding challenged earlier attempts to explain the accident primarily through individual mistakes and highlighted the importance of communication between designers, regulators, and operating organizations (IAEA, 1992).

The accident also exposed weaknesses in the institutional mechanisms through which operational experience was collected, interpreted, and disseminated. By the mid-1980s, the Soviet nuclear industry had accumulated considerable experience in the operation of RBMK reactors. Several incidents and operational anomalies had occurred at different facilities, including events involving reactor instability and unexpected reactivity effects. Nevertheless, information derived from these experiences was not always translated into systematic modifications of reactor design, operating procedures, or personnel training. The existence of technical knowledge within individual organizations did not necessarily guarantee its effective circulation throughout the broader nuclear sector.

Studies of Soviet technological expertise suggest that this problem was partly related to the structure of decision-making within the nuclear industry (Balonov, 2007; D'Auria et al., 2008b; Kuchinskaya, 2014). Responsibility for reactor design, plant operation, scientific research, and regulatory oversight was distributed among numerous organizations whose priorities were not always identical. Under such conditions, information could become fragmented across institutional boundaries. Knowledge available within one part of the system might not be fully integrated into decision-making processes elsewhere. Schmid (2015) argues that these characteristics reflected broader features of Soviet expert culture, where highly specialized professional communities often operated within relatively autonomous organizational environments.

Institutional secrecy further complicated the circulation of technical information. Although secrecy was a common feature of nuclear programmes throughout the world, its role within the Soviet system extended beyond the protection of strategically sensitive information. The classification of technical data sometimes limited opportunities for independent review and constrained broader discussions of operational problems. In such an environment, the identification and communication of potential safety concerns could become more difficult, particularly when those concerns challenged established assumptions regarding reactor performance or organizational effectiveness (IAEA, 1992).

The Chernobyl accident therefore revealed limitations not only in reactor technology but also in the governance of complex technological systems. The disaster demonstrated that technological safety depends upon effective communication between institutions, transparent evaluation of operational experience, and continuous reassessment of existing practices. These conclusions paralleled broader developments in research on technological accidents, which increasingly emphasized the role of organizational factors in shaping catastrophic outcomes (Perrow, 1999; Vaughan, 1996).

Perrow's theory of "normal accidents" provides a particularly useful framework for interpreting the Chernobyl disaster. According to Perrow (1999), accidents in highly complex and tightly coupled systems often emerge from unexpected interactions among multiple components rather than from isolated technical failures or individual mistakes. From this perspective, the accident at Unit 4 can be understood as the product of interactions among reactor design characteristics, operational decisions, organizational structures, and institutional constraints. Similarly, Vaughan's (1996) analysis of the Challenger disaster demonstrated how organizational cultures may gradually normalize risk and contribute to catastrophic outcomes despite the presence of technically competent personnel.

From a historical perspective, the significance of human factors in the Chernobyl accident lies not in the identification of individual errors but in the recognition that human actions are shaped by organizational structures, technological assumptions, institutional cultures, and systems of authority. The disaster illustrated the limitations of explanations that separate technical and social causes of technological failure. Instead, it revealed the extent to which engineering design, operational practice, regulatory oversight, and institutional decision-making are interconnected elements of a single socio-technical system.

This reinterpretation of the accident contributed directly to the emergence of the modern concept of safety culture. International experts increasingly concluded that technological reliability could not be ensured solely through engineering improvements or procedural controls. It also required organizational environments capable of encouraging critical evaluation, learning from operational experience, and maintaining effective communication among all participants in the technological process. These conclusions would become one of the most enduring legacies of the Chernobyl disaster and would profoundly influence the future development of nuclear safety governance worldwide. The reassessment of human factors after Chernobyl represents an important intellectual shift in the understanding of technological accidents. The disaster encouraged a move away from explanations centred on individual blame toward systemic analyses of technological risk, organizational behaviour, and institutional responsibility. This shift would subsequently shape international approaches to safety culture, organizational learning, and the governance of complex technologies far beyond the nuclear sector.

3. Chernobyl and the Crisis of Soviet Technological Expertise.

3.1. Information Management and Institutional Secrecy.

The Chernobyl accident exposed not only deficiencies in reactor design and operational practices but also deeper problems related to the management of technical information within the Soviet nuclear sector. In the years following the disaster, researchers increasingly recognized that the reliability of complex technological systems depends not only on engineering solutions but also on the ways in which knowledge is generated, communicated, and incorporated into decision-making processes. From this perspective, the accident revealed important limitations in the institutional mechanisms responsible for the circulation of expertise and the evaluation of technological risk.

The Soviet nuclear industry developed within a political and administrative environment in which secrecy played a central role. Many aspects of reactor design, operational performance, and safety analysis were treated as restricted information because of the strategic significance of nuclear technologies. Although secrecy was common in nuclear programmes worldwide, several historians have noted that within the Soviet system it became closely integrated into administrative decision-making and institutional communication. As a consequence, the exchange of information among research institutes, design organizations, regulatory authorities, and operating facilities was often constrained by organizational boundaries and classification practices.

The management of operational experience represented a particularly important challenge. By the mid-1980s, several RBMK reactors had accumulated years of operating history, generating valuable information concerning reactor behaviour, equipment performance, and safety-related events. Subsequent investigations revealed that some operational incidents had already exposed characteristics of RBMK reactors that later became relevant during the Chernobyl accident. However, lessons derived from these events were not always translated into industry-wide modifications of reactor design, operational procedures, or personnel training (IAEA, 1992; Schmid, 2015).

This problem reflected broader features of Soviet expert culture. According to Schmid (2015), the Soviet nuclear industry was characterized by highly specialized professional communities possessing substantial technical expertise but often operating within relatively autonomous institutional structures. Design institutes, research organizations, plant operators, and administrative authorities maintained distinct responsibilities and channels of communication. Under such conditions, knowledge could remain compartmentalized within individual organizations rather than becoming part of a comprehensive system of organizational learning. Similar observations have been made by Josephson (2000), who emphasized the fragmented character of technological governance in several sectors of the late Soviet economy.

The role of secrecy further complicated these processes. While the protection of sensitive information was justified by military and strategic considerations, the classification of technical data could also limit opportunities for independent review and critical evaluation. Investigations conducted after the accident demonstrated that information concerning certain reactor characteristics and operational anomalies was not always communicated effectively across institutional boundaries. Consequently, knowledge that might have contributed to improved safety was not consistently available to all organizations responsible for reactor operation and regulation (Schmid, 2015).

The accident also revealed tensions between technological optimism and the recognition of risk. Throughout much of the post-war period, nuclear energy occupied a privileged position within Soviet narratives of scientific and technological progress. Official discourse frequently presented atomic energy as evidence of the capacity of science and engineering to overcome economic and environmental limitations. As historians of Soviet technology have argued, such narratives contributed to confidence in technological systems and sometimes reduced incentives for questioning established assumptions regarding safety and reliability (Guth, 2022; Schmid, 2015, 2016, 2018).

Schmid's analysis of late Soviet politics of expertise suggests that Chernobyl transformed risk from a primarily technical category into a broader social and political issue. Questions concerning reactor safety, environmental contamination, and institutional accountability increasingly moved beyond specialized professional communities and entered public and political debate. As a result, the authority of scientific and technical institutions became subject to new forms of scrutiny, while demands for transparency and accountability acquired greater significance in discussions of technological governance (Guth, Gestwa, Penter, & Richers, 2019; Schmid, 2015).

The significance of these developments extended beyond the immediate circumstances of the accident. The crisis generated by Chernobyl demonstrated that technological systems cannot be governed effectively through technical expertise alone. Reliable operation requires institutional environments capable of identifying potential problems, encouraging the exchange of information, and integrating diverse forms of knowledge into decision-making processes. Similar conclusions have been reached within the broader literature on technological accidents and organizational failure, which emphasizes the importance of communication, institutional learning, and transparency in managing complex socio-technical systems (Perrow, 1999; Vaughan, 1996; Yurchenko, Strelko, Rudiuk, Horban, Bernatskyi, 2023).

Viewed historically, the experience of Chernobyl contributed to a redefinition of the relationship between expertise, institutions, and technological governance. The accident highlighted the limitations of highly centralized systems that relied heavily on internal communication while providing limited opportunities for external review. It also demonstrated that effective risk management depends upon the ability of organizations to learn from operational experience and communicate emerging concerns before they develop into major failures (IAEA, 1991, 1992).

The reassessment of these issues after 1986 played a crucial role in the emergence of new approaches to nuclear safety and organizational learning. It also laid the foundation for international discussions concerning safety culture, transparency, and institutional responsibility that continue to influence the governance of complex technological systems today.

3.2. The Reassessment of Nuclear Risk.

The Chernobyl accident marked a turning point in the historical understanding of technological risk. Prior to 1986, discussions of nuclear safety were largely dominated by technical considerations, including reactor reliability, engineering redundancy, probabilistic risk assessment, and compliance with operational procedures. Although concerns regarding severe accidents existed within specialist communities, the prevailing assumption in many countries was that improvements in reactor design and regulatory controls would progressively reduce the likelihood of catastrophic failures.

The destruction of Unit 4 challenged these assumptions. The scale of radioactive releases, the transboundary nature of contamination, and the extensive social consequences of the accident demonstrated that nuclear risk could not be understood solely through technical calculations. Chernobyl revealed that technological failures could affect public health, environmental management, economic development, political legitimacy, and public confidence in scientific institutions simultaneously. Consequently, risk increasingly came to be viewed as a multidimensional phenomenon extending beyond the boundaries of engineering analysis (Arnhold, 2020; Balonov, 2007; Josephson, 2000).

One of the most significant outcomes of the accident was the growing recognition that uncertainty itself constituted an important dimension of technological governance. During the months and years following the disaster, experts encountered substantial difficulties in estimating the long-term consequences of radioactive contamination, evaluating health risks, and communicating scientific findings to affected populations. These challenges exposed limitations in existing approaches to risk assessment and highlighted the need for greater attention to uncertainty, institutional learning, and public communication.

The transformation of risk discourse was particularly evident within the Soviet Union. Schmid (2015) has demonstrated that Chernobyl altered the political role of expertise by moving discussions of technological risk from relatively closed expert communities into the public sphere. Questions concerning reactor safety, environmental contamination, and institutional accountability increasingly became subjects of public debate and political contestation. As a result, risk ceased to be treated exclusively as a technical issue and became intertwined with broader concerns regarding governance, transparency, and public responsibility.

The international nuclear community underwent a similar process of reassessment. Investigations conducted by the International Atomic Energy Agency concluded that conventional distinctions between technical failures and organizational failures were often artificial. The INSAG-7 report emphasized that reactor safety depended not only on engineering design but also on management practices, communication systems, regulatory effectiveness, and organizational culture (IAEA, 1992). This interpretation represented an important departure from earlier approaches that focused primarily on technological reliability.

The broader significance of these conclusions was reinforced by contemporary scholarship on technological accidents. Perrow (1999) argued that accidents in highly complex and tightly coupled systems frequently emerge from interactions among multiple components rather than from isolated failures. Similarly, Vaughan (1996), in her analysis of the Challenger disaster, demonstrated how organizational processes and institutional cultures can contribute to catastrophic outcomes even in technologically advanced environments. Although these studies examined different technological domains, their findings helped establish a broader theoretical framework within which Chernobyl could be interpreted as a systemic failure of a socio-technical system rather than as a purely technical malfunction.

The reinterpretation of nuclear risk also influenced international preparedness strategies. As Schmid (2016) has noted, the experience of Chernobyl encouraged a shift from assumptions that severe accidents could be prevented entirely toward approaches emphasizing preparedness, resilience, and emergency response capabilities. While accident prevention remained a central objective, policymakers increasingly acknowledged that complex technological systems could never be rendered completely free of uncertainty. Consequently, greater attention was devoted to accident management, emergency planning, and post-accident recovery.

Recent historical research has further demonstrated that the legacy of Chernobyl extends beyond the nuclear sector. Arnhold (2020) argues that the accident contributed to the normalization of discussions concerning technological hazards and influenced broader approaches to risk governance in contemporary societies. Rather than treating technological accidents as exceptional anomalies, experts and policymakers increasingly began to view them as events that must be incorporated into long-term planning, institutional design, and regulatory practice.

The consequences of this intellectual transformation can be observed in the emergence of new approaches to technological governance during the late twentieth and early twenty-first centuries. Increasing emphasis was placed on transparency, organizational learning, independent oversight, and international cooperation. Risk management gradually evolved from a predominantly technical activity into a multidisciplinary field that incorporated engineering, environmental science, public health, sociology, and public policy.

From a historical perspective, the reassessment of nuclear risk after Chernobyl represents one of the most important intellectual consequences of the disaster. The accident transformed understandings of safety, uncertainty, and responsibility, influencing not only nuclear energy but also wider debates concerning the governance of complex technologies. In doing so, it helped establish the foundations for a more comprehensive approach to technological risk that integrated engineering expertise, organizational learning, regulatory oversight, and societal participation.

The evolution of these ideas created the conditions for the emergence of one of the most influential concepts in contemporary technological governance—the concept of safety culture. It was through attempts to understand why existing technical and regulatory measures had failed at Chernobyl that international experts began to formulate a new framework linking technological reliability to organizational values, institutional practices, and human behavior.

3.3. Public Trust and Expert Authority after 1986.

The Chernobyl disaster significantly transformed the relationship between scientific expertise, public institutions, and society. While the technical consequences of the accident have been extensively studied, its impact on public trust and perceptions of expert authority was equally profound. The disaster exposed weaknesses not only in reactor technology and organizational practices but also in the mechanisms through which scientific knowledge was communicated, interpreted, and legitimized within society.

Before 1986, nuclear energy occupied a prominent position within Soviet narratives of scientific and technological progress. Nuclear scientists and engineers were widely regarded as representatives of one of the most advanced sectors of the Soviet economy, and their expertise carried considerable institutional authority. Public discussions of nuclear safety remained limited, while assessments of technological risks were largely confined to specialized professional communities. Under these conditions, confidence in scientific expertise was closely linked to confidence in state institutions and their capacity to manage complex technological systems (Jasanoff, 2003; Josephson, 2000; Schmid, 2015).

The accident fundamentally altered this relationship. Delays in public disclosure, uncertainty regarding the scale of contamination, and contradictory information that emerged during the first weeks after the explosion contributed to growing public skepticism toward official sources. In many affected regions, citizens experienced considerable difficulties obtaining reliable information about radiation exposure, health risks, and environmental contamination. As a consequence, confidence in governmental institutions and expert organizations declined, while informal networks and alternative channels of communication became increasingly important (Kuchinskaya, 2014, Marples, 1988; Schmid, 2018).

The consequences of these developments were not limited to the Soviet Union. Internationally, the accident generated widespread debate concerning the reliability of expert assessments, the transparency of technological governance, and the accountability of institutions responsible for managing technological risks. The transboundary character of radioactive contamination demonstrated that nuclear accidents could no longer be treated as purely domestic affairs. Governments, regulatory authorities, scientific institutions, and international organizations faced growing pressure to provide accurate information and justify their decisions before both national and international audiences (Arnhold, 2020; IAEA, 1992; Schmid, 2016).

Historians and scholars working within science and technology studies have argued that Chernobyl contributed to a broader transformation in the social role of expertise. Rather than being regarded as an unquestionable source of authority, scientific expertise increasingly became subject to public scrutiny and debate. The accident highlighted the distinction between possessing technical knowledge and maintaining public trust. Expert institutions could no longer assume that scientific competence alone would guarantee societal legitimacy; transparency, accountability, and effective communication became equally important components of technological governance.

This transformation is particularly evident in studies of risk communication. Research conducted after Chernobyl demonstrated that public responses to technological hazards are influenced not only by measurable levels of danger but also by perceptions of institutional credibility, fairness, and trustworthiness (Kuchinskaya, 2014; Oe, Takebayashi, Sato, & Maeda, 2021; Schmid, 2019). In many cases, uncertainty and conflicting information may generate long-lasting social consequences even when objective levels of risk decline over time. The experience of Chernobyl therefore illustrated that managing technological risk requires attention to social and institutional dimensions alongside technical considerations.

The long-term social consequences of the accident further reinforced these conclusions. International assessments increasingly recognized that psychological stress, fear of radiation, social stigmatization, forced relocation, and the erosion of confidence in public institutions constituted significant components of the disaster's legacy. According to the findings of the Chernobyl Forum, many affected communities experienced persistent social and psychological challenges that often proved more durable than immediate radiological effects (Balonov, 2007). Comparative analyses of Three Mile Island, Chernobyl, and Fukushima have similarly demonstrated that perceptions of institutional trust play a central role in determining long-term community resilience following technological disasters (Oe, Takebayashi, Sato, & Maeda, 2021).

The crisis of expert authority that emerged after Chernobyl also encouraged important institutional reforms within the international nuclear community. Greater emphasis was placed on transparency, independent regulation, public communication, peer review, and international information exchange. The conventions adopted after 1986, together with the growing role of the International Atomic Energy Agency in coordinating safety assessments and emergency preparedness activities, reflected a broader recognition that technological governance depends upon institutional legitimacy as much as upon technical competence (IAEA, 1992; Sato & Lyamzina, 2018; Schmid, 2016).

From a historical perspective, the significance of Chernobyl lies partly in its contribution to changing understandings of expertise itself. The accident demonstrated that expert authority is not solely a product of specialized knowledge. It is also shaped by institutional practices, communication strategies, and societal perceptions of legitimacy. This lesson became increasingly influential during the late twentieth century as governments and international organizations confronted new technological risks characterized by uncertainty, complexity, and extensive societal consequences.

The experience of Chernobyl therefore helped redefine the relationship between science, technology, and society. It demonstrated that effective governance of complex technological systems requires not only scientific expertise and engineering competence but also public trust, transparency, and mechanisms capable of integrating diverse forms of knowledge into decision-making processes. These conclusions became an important foundation for the emergence of the concept of safety culture and continue to influence contemporary discussions concerning technological governance and sustainable development.

4. From Nuclear Safety to Safety Culture.

4.1. INSAG and the Emergence of the Safety Culture Concept.

Among the many consequences of the Chernobyl disaster, one of the most influential was the emergence of a new understanding of technological safety. Prior to 1986, safety within the nuclear industry was generally viewed primarily as a matter of engineering reliability, regulatory compliance, and adherence to established operational procedures. Although organizational factors were not entirely ignored, they rarely occupied a central place in discussions of accident prevention. The Chernobyl accident demonstrated the limitations of this perspective and encouraged a broader reassessment of the relationship between technology, organizations, and risk (IAEA, 1992; Perrow, 1999).

In the years immediately following the disaster, international experts sought to identify the deeper causes of the accident and determine why existing safety mechanisms had failed. These efforts were coordinated largely through the International Atomic Energy Agency and the International Nuclear Safety Advisory Group. Early investigations gradually shifted attention away from explanations focused exclusively on operator error or technical deficiencies and toward a broader examination of organizational practices, institutional behaviour, communication systems, and management structures (IAEA, 1992; Schmid, 2015).

A decisive step in this process occurred with the publication of the INSAG report *Safety Culture* in 1991. For the first time, an international organization introduced a comprehensive conceptual framework linking technological safety to organizational values and human behaviour. The report defined safety culture as the set of characteristics and attitudes within organizations and among individuals that establish safety as an overriding priority. According to INSAG, technological reliability depends not only on engineering design but also on leadership practices, communication systems, professional responsibility, training, and institutional commitment to safety (IAEA, 1991).

The concept represented a significant departure from earlier approaches to accident prevention. Traditional safety models tended to focus on hardware, technical procedures, and compliance with regulations. Safety culture expanded this perspective by recognizing that organizational environments shape how technologies are designed, operated, maintained, and regulated. Consequently, accidents could originate not only from equipment failures but also from deficiencies in communication, management, supervision, and institutional learning. In this respect, the concept reflected broader developments in studies of organizational reliability and technological risk that emerged during the late twentieth century (Perrow, 1999; Vaughan, 1996).

The reassessment presented in INSAG-7 further reinforced these conclusions. Rather than identifying a single cause of the Chernobyl accident, the report described a complex interaction of technical, organizational, and human factors. Deficiencies in reactor design, weaknesses in operating procedures, insufficient communication between designers and operators, and limitations in regulatory oversight all contributed to the conditions that allowed the accident to occur (IAEA, 1992). This interpretation became highly influential because it offered a framework capable of explaining technological failures without reducing them either to engineering defects or to individual mistakes alone.

The emergence of safety culture reflected broader changes in the understanding of technological systems during the late twentieth century. Researchers increasingly recognized that highly complex technologies operate within organizational environments that influence decision-making, risk perception, and responses to unexpected events. From this perspective, safety came to be understood as an emergent property of socio-technical systems rather than as a characteristic of technological components alone.

Historical studies have emphasized that the concept of safety culture emerged at a moment when confidence in purely technical approaches to risk management was being reassessed. As Schmid (2015) has shown, the Chernobyl disaster exposed weaknesses not only in reactor design but also in the organizational structures responsible for managing technical knowledge and operational experience. Likewise, Arnhold (2020) argues that the accident contributed to broader transformations in international approaches to technological governance by encouraging greater attention to institutional responsibility, transparency, and the management of uncertainty.

The influence of the safety culture concept rapidly extended beyond the nuclear industry. During the 1990s and 2000s, similar approaches were adopted in aviation, transportation, healthcare, chemical manufacturing, and other sectors characterized by high levels of technological complexity. In each case, attention shifted toward organizational learning, communication practices, leadership, and institutional accountability as essential elements of risk management. Consequently, the legacy of Chernobyl contributed to a wider transformation in international thinking about technological governance and safety management (IAEA, 1991; Schmid, 2016).

The significance of this transformation extends beyond the practical regulation of nuclear energy. From the perspective of the history of science and technology, the development of safety culture represents an important intellectual shift in the understanding of risk and responsibility in modern technological societies. It challenged deterministic views of technological safety and encouraged the recognition that reliability emerges from interactions among technical systems, institutions, and human actors. In doing so, it provided a conceptual foundation that continues to influence contemporary approaches to technological governance, risk management, and sustainable development.

The emergence of safety culture therefore constitutes one of the most important intellectual legacies of the Chernobyl disaster. It transformed understandings of safety, responsibility, and organizational behaviour while establishing a framework that remains central to the governance of complex technologies nearly four decades after the accident.

4.2. International Responses to Chernobyl.

The international response to the Chernobyl accident represented one of the most significant transformations in the history of nuclear governance. Prior to 1986, cooperation among national nuclear programmes existed primarily in the areas of scientific research, reactor development, and the exchange of technical expertise. Although international organizations such as the International Atomic Energy Agency played important coordinating roles, responsibility for nuclear safety remained largely a national matter. The transboundary consequences of the Chernobyl accident exposed the limitations of this approach and created strong incentives for the development of new mechanisms of international cooperation (Jasanoff, 2003; IAEA, 1992; Schmid, 2016).

One of the most immediate lessons of the disaster was the necessity of rapid information exchange during nuclear emergencies. Radioactive contamination spread across national borders within days of the accident, affecting numerous European countries before detailed information regarding the event became publicly available. The detection of elevated radiation levels in Sweden and other European states highlighted deficiencies in existing communication arrangements and demonstrated that nuclear accidents could have consequences extending far beyond the territory of the country in which they occurred (Arnhold, 2020; Balonov, 2007; Schmid, 2015).

In response, the international community adopted several important legal instruments. Among the most significant were the Convention on Early Notification of a Nuclear Accident and the Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency, both adopted under the auspices of the IAEA in 1986. These agreements established formal procedures for information exchange, emergency communication, and international assistance. Their adoption reflected growing recognition that nuclear safety could no longer be addressed solely within national frameworks and required institutionalized forms of international cooperation (IAEA, 1986a, 1986b).

The accident also stimulated substantial changes in the role of the IAEA itself. During the years following Chernobyl, the Agency expanded its activities related to operational safety, emergency preparedness, peer review, and the development of international safety standards. New programmes encouraged the systematic exchange of operational experience, the identification of safety deficiencies, and the dissemination of lessons learned from accidents and near-miss events. These initiatives reflected a broader shift from reactive responses toward continuous organizational learning and preventive risk management (IAEA, 1991, 1992).

An important aspect of this transformation was the growing emphasis on peer review and external evaluation. Prior to the accident, safety assessments were conducted primarily within national regulatory and operating organizations. After Chernobyl, international review missions became increasingly common, allowing experts from different countries to evaluate safety practices, identify weaknesses, and share operational experience. Historians of nuclear governance have noted that these mechanisms contributed to greater transparency and reduced the likelihood that critical safety information would remain confined within individual organizations or national systems (Arnhold, 2020; Sato & Lyamzina, 2018; Schmid, 2016).

The concept of safety culture played a central role in these developments. As the international nuclear community sought to understand the causes of the accident, it became increasingly apparent that technical standards alone could not guarantee safe operation. Attention therefore shifted toward organizational behaviour, leadership, communication practices, management systems, and institutional responsibility. Training programmes, regulatory frameworks, and operational procedures were progressively revised to incorporate these principles, resulting in a more comprehensive understanding of safety that integrated technological and organizational dimensions (IAEA, 1991, 1992).

The influence of Chernobyl extended beyond formal regulatory structures. The accident encouraged the development of international networks dedicated to emergency preparedness, radiation monitoring, environmental assessment, and public communication (see Table 1). Scientific cooperation intensified as researchers from different countries worked together to investigate the health, environmental, and social consequences of the disaster. The work of the Chernobyl Forum and subsequent international research programmes demonstrated the growing importance of multidisciplinary and multinational approaches to the study of technological disasters (Balonov, 2007; Balonov & Bouville, 2020).

Table 1. Evolution of International Approaches to Nuclear Safety after Chernobyl.

Period	Dominant safety paradigm	Key characteristics
Before 1986	Technical reliability	Focus on reactor design, engineering systems, procedural compliance
1986–1991	Systemic reassessment	Recognition of organizational and institutional factors
After INSAG-4 (1991)	Safety culture	Integration of organizational behaviour, management, communication, and training
1990s–2000s	International governance	Peer reviews, conventions, international cooperation, transparency
21st century	Risk governance and resilience	Preparedness, organizational learning, public trust, sustainability

Historical analyses suggest that the international response to Chernobyl represented a broader transformation in technological governance. Rather than treating accidents as isolated national events, policymakers increasingly recognized that complex technologies operate within global systems characterized by interconnected risks and shared responsibilities. Effective governance therefore required not only technical expertise but also international cooperation, institutional transparency, and mechanisms for collective learning. In this respect, Chernobyl contributed to the emergence of new models of transnational governance that extended beyond the nuclear sector itself (Arnhold, 2020; Jasanoff, 2003).

The significance of these changes became particularly evident following later nuclear emergencies, most notably the Fukushima Daiichi accident in 2011. Many of the institutional mechanisms, emergency response procedures, and safety principles applied during the Fukushima response had their origins in reforms introduced after Chernobyl. Schmid (2016) argues that the experience of 1986 fundamentally reshaped international preparedness strategies and influenced the ways in which governments and organizations approached the management of technological uncertainty in the decades that followed.

From the perspective of the history of science and technology, the international response to Chernobyl demonstrates how major technological disasters can stimulate institutional innovation. The accident prompted the creation of new forms of cooperation, encouraged the diffusion of knowledge across national boundaries, and strengthened the role of international organizations in technological governance. It also contributed to the emergence of new understandings of accountability, transparency, and shared responsibility in the management of technological risks. In this sense, Chernobyl influenced not only the future development of nuclear safety but also broader approaches to global technological governance that remain relevant in the twenty-first century.

4.3. Post-Chernobyl Modernization of RBMK Reactors.

The destruction of Unit 4 at the Chernobyl Nuclear Power Plant did not bring an immediate end to the RBMK reactor programme. At the time of the accident, RBMK units constituted an important component of electricity generation within the Soviet Union, and several reactors remained in operation at Chernobyl, Leningrad, Kursk, Ignalina, and Smolensk nuclear power plants. Consequently, one of the principal challenges facing the nuclear industry after 1986 was determining whether these reactors could continue operating safely and what modifications would be required to reduce accident risks (D'Auria, Soloviev, Mazzini, & Sollima, 2008c; IAEA, 1992; Uspuras & Kaliatka, 2012).

Post-accident investigations identified several reactor characteristics that required immediate attention. Particular concern was directed toward the positive void coefficient, the design of the control and protection system, operational reactivity margins, and emergency shutdown performance. Analyses conducted during the late 1980s and early 1990s demonstrated that significant engineering modifications would be necessary if RBMK reactors were to satisfy evolving international safety expectations (Chan & Dastur, 1989; IAEA, 1992; Schmid, 2015).

One of the first priorities involved improving the neutron-physical characteristics of the reactor core. Modifications included increasing fuel enrichment, introducing additional fixed absorbers, and implementing changes in fuel management strategies. These measures substantially reduced the positive void coefficient and improved reactor stability during low-power operating conditions. At the same time, new operational restrictions were introduced to prevent reactor states similar to those that had developed during the final stages of the Chernobyl safety test (D'Auria, et al., 2008a, 2008b, 2008c; IAEA, 1992; Uspuras & Kaliatka, 2012).

The control and protection system was also extensively redesigned. Modifications included changes to the geometry of control rods, improvements in insertion characteristics, and revisions to emergency shutdown procedures. These measures were intended to eliminate the possibility that activation of emergency protection systems could produce an initial increase in reactivity under specific operating conditions. Subsequent technical assessments concluded that the implemented modifications effectively addressed one of the principal design vulnerabilities identified after the accident (Uspuras & Kaliatka, 2012).

During the 1990s and early 2000s, reactor modernization increasingly evolved from a series of engineering corrections into a comprehensive safety improvement programme. Researchers and regulators gradually adopted a broader systems perspective that incorporated reactor design, operational procedures, personnel training, emergency preparedness, and regulatory oversight. This transition reflected the growing influence of the safety culture concept and the recognition that technological safety depends on interactions among technical, organizational, and institutional factors (Schmid, 2015).

International cooperation played a significant role in this process. Safety assessments and modernization initiatives involved specialists from Russia, Lithuania, Ukraine, and several Western countries. Collaborative research programmes focused on reactor physics, thermal-hydraulic processes, accident management strategies, severe accident analysis, and probabilistic safety assessment. These efforts contributed not only to technical improvements but also to the development of shared approaches to nuclear safety evaluation and risk management (D'Auria et al., 2008a, 2008b, 2008c; Fesenko et al., 2006; Havenaar et al., 1997).).

From a historical perspective, the modernization of RBMK reactors illustrates an important transformation in engineering practice following major technological accidents. Rather than treating the accident as an isolated failure, researchers increasingly approached RBMK technology as a system requiring continuous reassessment and adaptation. The extensive analytical work undertaken after 1986 generated new knowledge concerning reactor behaviour, accident progression, and safety management. In this sense, the modernization programme functioned not merely as a technical response but also as a process of institutional and scientific learning.

The reassessment of RBMK safety also contributed to broader methodological developments within nuclear engineering. Studies performed after Chernobyl encouraged wider adoption of probabilistic safety assessment, risk-informed regulation, severe accident management strategies, and integrated approaches to reactor evaluation. According to D'Auria and colleagues (2008a), the RBMK modernization programme became an important case study in the evolution of modern nuclear safety methodologies, demonstrating how operational experience can be incorporated into both engineering design and regulatory practice.

Subsequent analyses have demonstrated that the post-Chernobyl RBMK differed substantially from the reactor configuration that existed in April 1986. Investigations by Uspuras and Kaliatka (2012) documented major improvements in reactor safety characteristics, while studies by Knoglinger, Wölfl, and Kaliatka (2015) illustrated continuing efforts to improve understanding of RBMK thermal-hydraulic and graphite-core behaviour. Although these modifications did not eliminate all challenges associated with RBMK technology, they significantly reduced the likelihood of accident scenarios comparable to those of 1986 and strengthened the overall safety framework governing reactor operation.

The modernization programme also altered international perceptions of reactor development. Historians of technology have observed that major accidents are often interpreted as endpoints that reveal the limitations of particular technological trajectories. The RBMK experience suggests a more complex picture. Rather than leading immediately to the abandonment of the technology, the accident initiated a prolonged process of redesign, reassessment, and adaptation. This process illustrates how technological systems evolve through interactions between operational experience, scientific knowledge, regulatory intervention, and institutional learning.

The post-Chernobyl history of RBMK reactors therefore represents more than a technical response to a specific accident. It reflects a broader transformation in nuclear safety philosophy, from an emphasis on engineering performance alone toward an integrated approach combining technological design, organizational learning, regulatory oversight, and international cooperation. From the perspective of the history of science and technology, the modernization of RBMK reactors provides a valuable example of how technological systems respond to failure and how knowledge generated by accidents can contribute to long-term improvements in safety and governance.

5. Long-Term Consequences and Historical Legacy.

5.1. Health, Environmental, and Psychological Consequences.

The long-term consequences of the Chernobyl disaster have been the subject of extensive scientific investigation for nearly four decades. While early discussions frequently focused on worst-case scenarios and highly uncertain projections, subsequent research has provided a more nuanced understanding of the accident's health, environmental, and social impacts. This evolving body of knowledge represents an important chapter in the history of science, illustrating how scientific assessments of technological disasters change as new evidence becomes available and how international research communities address uncertainty in the study of long-term environmental hazards (Balonov, 2007; Bromet, 2014; Lindee, 2016).

One of the most immediate consequences of the accident was the exposure of plant personnel, emergency responders, and nearby populations to ionizing radiation. According to the assessments conducted by the Chernobyl Forum and UNSCEAR, 134 emergency workers and plant staff were diagnosed with acute radiation syndrome, and 28 of them died within the first months following the accident as a direct consequence of radiation exposure (Balonov, 2007; UNSCEAR, 2011). These findings remain among the most firmly established health effects attributable to the disaster and constitute a rare example of a large-scale radiological accident for which immediate medical consequences have been documented in considerable detail.

The long-term health consequences proved considerably more difficult to evaluate. The most clearly demonstrated effect has been the substantial increase in thyroid cancer among individuals exposed during childhood and adolescence, primarily associated with the ingestion of radioactive iodine-131 released during the accident. Large epidemiological investigations conducted in Belarus, Ukraine, and the Russian Federation identified thousands of excess thyroid cancer cases among populations exposed at young ages (Cardis et al., 2006; Tronko et al., 2006). Although the survival rate for these patients has generally been high, the increase in incidence represents one of the most important scientifically established long-term consequences of the disaster.

By contrast, assessments of other forms of cancer and non-cancer diseases have generated more complex scientific debates. UNSCEAR and the World Health Organization have generally concluded that evidence for substantial increases in most cancer types among the general population remains limited, particularly at lower exposure levels. At the same time, some researchers have argued that the full range of health consequences may be difficult to quantify because of methodological challenges, uncertainties in dose reconstruction, migration processes, and the influence of socioeconomic factors on population health (Balonov & Bouville, 2020). These discussions illustrate broader difficulties associated with studying long-term effects of low-dose radiation exposure and demonstrate how scientific knowledge evolves through continuing reassessment of evidence.

Environmental contamination extended far beyond the territory immediately surrounding the Chernobyl Nuclear Power Plant. Radioactive materials were dispersed across large areas of Europe, with deposition patterns strongly influenced by meteorological conditions during and after the accident. Significant contamination occurred in Belarus, Ukraine, and parts of the Russian Federation, while measurable fallout was recorded in numerous European countries (UNSCEAR, 2011; Balonov & Bouville, 2020). The transboundary nature of contamination transformed Chernobyl from a national emergency into an international environmental issue and stimulated unprecedented scientific cooperation in radioecology, environmental monitoring, and radiation protection.

The environmental consequences of the disaster also contributed to the development of new approaches to long-term risk management. Researchers and policymakers were required to address challenges involving contaminated agricultural land, forestry management, food safety, and environmental remediation. Studies conducted during the decades following the accident demonstrated that countermeasures such as restrictions on agricultural production, food monitoring programmes, soil treatment, and land-use management could substantially reduce radiation exposure among affected populations. The experience gained through these programmes significantly influenced international recommendations concerning post-accident recovery and environmental protection (Balonov, 2007; Fesenko et al., 2006).

Perhaps the most unexpected lesson of Chernobyl emerged from investigations of its psychological and social consequences. During the 1990s and early 2000s, international assessments increasingly recognized that many of the most persistent effects of the disaster were not directly related to radiation exposure itself. Fear of radiation, uncertainty regarding future health risks, forced relocation, social stigmatization, and economic disruption affected millions of people living in contaminated regions (Balonov, 2007). In many cases, these factors had a greater influence on everyday life than measurable radiological hazards.

Research on mental health outcomes has consistently demonstrated elevated levels of anxiety, depression, stress-related disorders, and risk perception among affected populations. Havenaar et al. (1997) identified long-lasting psychological effects among residents of contaminated regions, while Bromet (2014) argued that the psychological legacy of Chernobyl constitutes one of the most significant public health consequences of the disaster. These findings contributed to a broader recognition that technological accidents must be analysed not only through physical health indicators but also through their social and psychological dimensions.

Recent comparative studies examining Three Mile Island, Chernobyl, and Fukushima have reinforced these conclusions. Oe et al. (2021) argue that psychological consequences frequently persist longer than immediate physical health effects and may become central determinants of long-term community resilience. The Chernobyl experience demonstrated that public responses to technological accidents are shaped not only by measurable hazards but also by perceptions of risk, institutional trust, media narratives, and the effectiveness of communication strategies.

The scientific investigation of Chernobyl's consequences has itself become an important subject of historical analysis. As Lindee (2016) observes, research on radiation effects after major nuclear events contributed to the formation of international scientific networks and influenced broader understandings of risk, uncertainty, evidence, and expertise in environmental health sciences. The accident stimulated extensive international collaboration among epidemiologists, medical researchers, environmental scientists, and radiation protection specialists, thereby transforming not only knowledge about Chernobyl but also the institutional organization of scientific research itself.

From a historical perspective, the evolution of knowledge concerning Chernobyl's consequences illustrates the complex relationship between science, uncertainty, and public policy. Initial assessments were often shaped by limited data and substantial uncertainty, whereas subsequent decades brought more sophisticated epidemiological methods, environmental monitoring systems, and risk assessment techniques. The resulting body of research has not eliminated all controversies, but it has significantly improved understanding of the health, environmental, and psychological dimensions of nuclear accidents.

The long-term consequences of Chernobyl therefore represent more than a catalogue of damages caused by a technological disaster. They also demonstrate how scientific knowledge develops through sustained investigation, international cooperation, methodological refinement, and the continuous reassessment of evidence. These processes played a crucial role in shaping contemporary approaches to radiation protection, environmental management, public health, disaster recovery, and technological risk governance.

5.2. Scientific Lessons of Chernobyl.

The significance of the Chernobyl disaster extends far beyond its immediate technical, environmental, and social consequences. During the decades following the accident, Chernobyl became one of the most influential case studies in the history of science and technology, contributing to fundamental changes in how experts understand technological risk, organizational failure, and the governance of complex socio-technical systems. Many concepts that are now considered essential elements of modern safety management were either strengthened or substantially redefined through attempts to explain the causes and consequences of the accident.

One of the most important scientific lessons concerned the limitations of purely technical approaches to safety. Before 1986, nuclear safety was often understood primarily in terms of reactor design, engineering reliability, and compliance with technical regulations. The Chernobyl accident demonstrated that even sophisticated technological systems could experience catastrophic failure when organizational and institutional factors were not adequately considered. Subsequent investigations concluded that safety should be understood as a property of the entire socio-technical system rather than as a characteristic of technological components alone (IAEA, 1992; Perrow, 1999).

This realization contributed directly to the emergence of the concept of safety culture. As outlined in the INSAG reports, safety depends not only on hardware and procedures but also on organizational values, leadership, communication practices, professional responsibility, and institutional commitment to continuous learning (IAEA, 1991). The influence of this concept rapidly extended beyond the nuclear industry and became increasingly important in aviation, chemical engineering, transportation systems, healthcare, and other high-risk sectors. In this respect, the legacy of Chernobyl reached well beyond nuclear energy and contributed to broader transformations in international approaches to risk management and organizational governance (Le Coze, 2018).

A second important lesson involved the relationship between expertise and uncertainty. The accident revealed that scientific knowledge is often incomplete when dealing with complex technological systems and unprecedented events. During the years following the disaster, researchers encountered significant difficulties in assessing long-term health effects, environmental contamination, and social consequences. These challenges encouraged greater recognition of uncertainty as an inherent feature of technological governance rather than as a temporary absence of information (Lindee, 2016; Pylypchuk, O. Ya., Strelko, & Pylypchuk, O. O., 2021; Schmid, 2015). Consequently, risk assessment increasingly incorporated probabilistic approaches, scenario analysis, adaptive management, and precautionary decision-making strategies.

The Chernobyl disaster also transformed understandings of organizational learning. Investigations demonstrated that information concerning reactor behaviour and operational anomalies had existed before 1986 but had not always been effectively communicated throughout the nuclear sector. This finding highlighted the importance of knowledge management, institutional memory, and the systematic exchange of operational experience. Modern approaches to safety management increasingly emphasize learning from incidents, near misses, and operational feedback, reflecting lessons that emerged directly from the reassessment of Chernobyl (Arnhold, 2020; Balonov & Bouville, 2020; Schmid, 2015).

Another significant contribution involved the development of international scientific cooperation. The transboundary consequences of radioactive contamination required collaboration among researchers, regulatory authorities, and international organizations across multiple countries. New monitoring networks, epidemiological studies, environmental research programmes, and emergency preparedness initiatives emerged as a result of these efforts. The work of the Chernobyl Forum represented one of the most extensive international scientific assessments ever conducted in relation to a technological disaster and demonstrated the importance of multidisciplinary approaches to understanding complex technological events (Balonov, 2007).

The accident also reshaped scientific thinking regarding preparedness and resilience. Prior to Chernobyl, many safety strategies focused primarily on accident prevention. Although prevention remains essential, the experience of 1986 demonstrated that severe accidents cannot always be completely excluded. Consequently, increasing attention was devoted to emergency preparedness, accident management, recovery planning, institutional resilience, and long-term adaptation. Schmid (2016) has argued that these developments fundamentally influenced the evolution of international nuclear safety policy and later shaped responses to subsequent nuclear emergencies, including the Fukushima Daiichi accident.

Historical scholarship has further emphasized that Chernobyl challenged conventional distinctions between technical and social explanations of technological failure. The accident demonstrated that engineering systems, organizations, political institutions, and social environments operate as interconnected components of broader socio-technical networks. This perspective has become increasingly influential within science and technology studies, the history of technology, and risk research. Scholars now routinely analyse technological accidents as products of interactions between material systems and institutional structures rather than as isolated technical malfunctions (Arnhold, 2020; Guth, Gestwa, Penter, & Richers, 2019; Jasanoff, 2003).

The reinterpretation of Chernobyl also contributed to a broader reassessment of expert authority in technologically advanced societies. The accident revealed that technical expertise alone cannot guarantee safe technological operation if institutions lack mechanisms for transparency, communication, and accountability. As a result, scientific expertise increasingly came to be viewed as part of a wider governance framework involving regulators, operators, policymakers, local communities, and international organizations (Jasanoff, 2003; Kuchinskaya, 2014; Le Coze, 2018). This shift remains one of the most important intellectual consequences of the disaster.

The lessons of Chernobyl remain highly relevant because many contemporary technologies exhibit characteristics similar to those of the nuclear systems examined after 1986. Advanced energy infrastructures, digital networks, artificial intelligence systems, biotechnology, and other complex technologies involve high levels of uncertainty, extensive organizational interdependence, and potentially significant societal consequences. The analytical frameworks developed in response to Chernobyl therefore continue to inform contemporary debates concerning technological governance, responsible innovation, and the management of systemic risks.

From a historical perspective, perhaps the most enduring lesson of Chernobyl is the recognition that technological progress and technological risk are inseparable. The disaster demonstrated that innovation requires not only scientific and engineering expertise but also institutions capable of learning, adapting, communicating uncertainty, and maintaining public trust. These insights continue to shape international discussions concerning the governance of complex technologies and remain highly relevant to contemporary efforts aimed at achieving sustainable technological development.

5.3. Chernobyl and Sustainable Technological Development.

The relevance of the Chernobyl disaster extends beyond the history of nuclear energy and continues to influence contemporary discussions concerning sustainable technological development. Although the concept of sustainable development gained international prominence shortly after the accident, particularly following the publication of the *Brundtland Report. Our Common Future* in 1987, many of the challenges exposed by Chernobyl remain central to present-day debates regarding the governance of complex technologies (WCED, 1987). The disaster demonstrated that technological progress cannot be evaluated solely in terms of economic efficiency, production capacity, or scientific achievement. Long-term sustainability also depends on safety, institutional accountability, transparency, and the capacity of organizations to learn from experience.

One of the most important lessons of Chernobyl concerns the relationship between innovation and risk. The rapid expansion of nuclear energy in the Soviet Union reflected a broader commitment to technological modernization and industrial development. However, the accident revealed that technological advancement may generate new forms of vulnerability when institutional and organizational capacities fail to evolve at the same pace as technical systems. Historical analyses of the Soviet nuclear programme have shown that technological innovation alone cannot guarantee sustainable development if mechanisms for risk assessment, organizational learning, and regulatory oversight remain insufficiently developed (Josephson, 2000; Schmid, 2015, 2018).

The experience of Chernobyl also highlighted the importance of integrating scientific knowledge into decision-making processes. Investigations conducted after the accident demonstrated that safety-related information was not always effectively communicated between reactor designers, operators, regulators, and policymakers. These findings contributed to growing recognition that sustainable technological systems depend upon institutions capable of facilitating the circulation of knowledge, encouraging critical evaluation, and incorporating operational experience into future development strategies (IAEA, 1992; Schmid, 2015). In contemporary terms, these principles are closely associated with evidence-based governance and adaptive management.

Another important aspect concerns institutional resilience. The accident revealed that the ability of organizations to respond to unexpected events is often as important as their capacity to prevent them. Modern approaches to sustainable development increasingly emphasize resilience as a fundamental characteristic of technological systems operating under conditions of uncertainty. Following Chernobyl, international nuclear governance gradually shifted from a narrow focus on accident prevention toward broader strategies incorporating preparedness, emergency response, recovery planning, and institutional adaptability (Kuchinskaya, 2014; Sato & Lyamzina, 2018; Schmid, 2016).

The development of safety culture provides a particularly important example of this transformation. By linking technological reliability to organizational behaviour, leadership practices, communication processes, and institutional values, the concept expanded traditional understandings of safety beyond technical design alone. This broader perspective subsequently influenced numerous sectors, including aviation, transportation, healthcare, chemical manufacturing, and critical infrastructure management. As Le Coze (2018) has argued, major technological accidents have played a central role in shaping contemporary approaches to organizational safety and risk governance.

The accident further demonstrated the importance of public trust in the successful operation of complex technological systems. Scientific expertise remains essential for the development and regulation of advanced technologies, but public acceptance increasingly depends on transparency, accountability, and effective communication. The erosion of trust that followed the accident illustrated how deficiencies in information management can amplify the social consequences of technological failures. Contemporary approaches to sustainable development therefore place greater emphasis on stakeholder engagement, public participation, and institutional legitimacy in decision-making processes.

Historical analyses have also emphasized that Chernobyl transformed international approaches to cooperation in science and technology. The transboundary consequences of radioactive contamination encouraged the development of new mechanisms for information exchange, emergency preparedness, environmental monitoring, and scientific collaboration. These developments demonstrated that technological risks often transcend national boundaries and require coordinated international responses. In this respect, the legacy of Chernobyl anticipated many contemporary discussions concerning global governance and shared responsibility in the management of technological hazards.

The significance of these developments can also be viewed through the lens of sustainable development theory. Scholars have increasingly argued that sustainability depends not only on environmental protection but also on the capacity of institutions to manage uncertainty, maintain public confidence, and adapt to changing technological conditions. The post-Chernobyl evolution of nuclear safety demonstrates that long-term sustainability requires continuous reassessment of technological systems and the integration of social, organizational, and technical dimensions of risk.

From the perspective of the history of science and technology, the significance of Chernobyl lies not only in the failures that culminated in the accident but also in the institutional and intellectual transformations that followed. The disaster stimulated new approaches to risk assessment, organizational learning, regulatory oversight, and international cooperation. These developments contributed to the emergence of principles that now occupy a central place in discussions of sustainable technological development.

The continuing relevance of Chernobyl demonstrates that sustainability cannot be reduced to environmental protection or economic performance alone. It also encompasses the quality of institutions, the effectiveness of governance systems, the management of uncertainty, and the responsible application of scientific knowledge. As contemporary societies confront challenges associated with climate change, energy transitions, artificial intelligence, and other emerging technologies, the lessons derived from Chernobyl remain highly relevant. The disaster serves as a reminder that sustainable technological development requires not only innovation but also the institutional capacity to anticipate risks, learn from failures, and maintain public trust.

5.4. Relevance to the United Nations Sustainable Development Goals.

Although the United Nations Sustainable Development Goals were adopted almost three decades after the Chernobyl disaster, many of the principles underlying the SDG framework reflect lessons that emerged from the reassessment of technological risks following the accident. The historical significance of Chernobyl therefore extends beyond the nuclear sector and remains relevant to contemporary discussions concerning sustainable development, responsible innovation, and institutional governance. The disaster demonstrated that technological systems are inseparable from the social, political, and organizational environments within which they operate, a principle that lies at the heart of the 2030 Agenda for Sustainable Development (United Nations, 2015).

One of the most direct connections can be observed in relation to SDG 3, *Good Health and Well-Being*. The accident demonstrated the long-term health consequences that may result from failures in the management of hazardous technologies. Beyond the immediate effects of radiation exposure, international assessments highlighted the importance of psychological well-being, risk communication, social resilience, and public confidence in health institutions. Research conducted after Chernobyl contributed significantly to the development of modern approaches to radiation protection, emergency medicine, epidemiological monitoring, and public health preparedness (Balonov, 2007; Oe, Takebayashi, Sato, & Maeda, 2021). These lessons continue to inform international responses to technological and environmental emergencies.

The experience of Chernobyl is also highly relevant to SDG 7, *Affordable and Clean Energy*. Nuclear energy remains an important component of many national strategies aimed at reducing greenhouse gas emissions and achieving low-carbon energy transitions. At the same time, the accident demonstrated that the sustainability of energy systems cannot be assessed solely through their capacity to generate electricity. Long-term sustainability also requires effective safety management, robust regulatory frameworks, transparent decision-making, and public trust. The post-Chernobyl evolution of international nuclear safety standards illustrates how technological innovation must be accompanied by continuous institutional learning and risk governance (Balonov & Bouville, 2020; Lindee, 2016; Schmid, 2015, 2019).

Important connections also exist with SDG 9, *Industry, Innovation and Infrastructure*. One of the central lessons of Chernobyl is that technological innovation must be accompanied by mechanisms capable of identifying, assessing, and managing emerging risks. The accident highlighted the importance of integrating engineering design, organizational learning, regulatory oversight, and operational experience throughout the lifecycle of complex technological systems. Many contemporary approaches to industrial safety, resilience engineering, and risk-informed regulation reflect principles that gained prominence through the international reassessment of nuclear safety after 1986 (IAEA, 1991; Le Coze, 2018; Sato & Lyamzina, 2018).

Perhaps the strongest relationship can be identified with SDG 16, *Peace, Justice and Strong Institutions*. Investigations conducted after the accident repeatedly emphasized the importance of transparency, accountability, information sharing, and institutional effectiveness. The difficulties encountered in communicating information during and after the disaster demonstrated that technological safety depends not only on scientific expertise but also on the quality of governance structures responsible for managing risk and responding to emergencies. The subsequent development of international notification systems, peer-review mechanisms, and safety oversight procedures reflected a growing recognition that strong institutions are essential components of technological sustainability (Arnhold, 2020; IAEA, 1992; Kuchinskaya, 2014).

The relevance of Chernobyl to the SDGs is not limited to the nuclear sector. The analytical frameworks that emerged from the study of the accident have influenced broader discussions concerning climate technologies, critical infrastructure, biotechnology, artificial intelligence, and other fields characterized by high levels of complexity and uncertainty. In each of these domains, sustainable development depends upon the ability of institutions to balance innovation with responsibility, scientific advancement with risk management, and technological progress with societal trust (Jasanoff, 2003; Kuchinskaya, 2014; Lindee, 2016).

From the perspective of the history of science and technology, the connection between Chernobyl and the SDGs illustrates the enduring value of historical experience in addressing contemporary challenges. The disaster demonstrated that technological systems are embedded within broader social, political, and institutional environments. Consequently, sustainable development requires not only technological innovation but also effective governance, organizational learning, international cooperation, and the responsible application of scientific knowledge. These principles, which emerged with particular clarity from the reassessment of Chernobyl, remain fundamental to contemporary efforts aimed at building more resilient and sustainable technological societies.

The historical legacy of Chernobyl therefore supports a broader interpretation of sustainable development in which technological progress is inseparable from institutional responsibility. The accident revealed that failures of communication, governance, and organizational learning can undermine even the most advanced technological systems. Conversely, the reforms implemented after 1986 demonstrated that transparency, international cooperation, and continuous learning can strengthen technological resilience and improve long-term sustainability. In this sense, Chernobyl remains not only a historical case study but also a continuing source of lessons for policymakers, regulators, engineers, and scholars seeking to address the technological challenges of the twenty-first century.

Conclusions.

The Chernobyl disaster occupies a distinctive place in the history of science and technology because its significance extends far beyond the immediate circumstances of the accident that occurred on 26 April 1986. This study has demonstrated that the catastrophe cannot be adequately explained through technical deficiencies or operator actions alone. Rather, it emerged from the interaction of reactor design characteristics, organizational culture, institutional structures, and mechanisms governing the production and circulation of technical knowledge within the Soviet nuclear industry. The accident therefore represented a systemic failure within a complex socio-technical system rather than an isolated technological malfunction.

The analysis has shown that the origins of the disaster were closely connected to broader processes of Soviet scientific and technological modernization. Nuclear energy occupied a central position within Soviet development strategies and was regarded as a symbol of scientific progress and industrial achievement. However, the institutional arrangements that supported the rapid expansion of nuclear power also created challenges related to communication, organizational learning, and the management of technological risk. The history of the RBMK reactor demonstrates how technological artefacts are shaped not only by engineering considerations but also by political priorities, industrial capabilities, institutional cultures, and assumptions regarding acceptable risk.

A second important conclusion concerns the crisis of technological expertise revealed by the accident. Chernobyl exposed limitations in the circulation of safety-related information, the integration of operational experience into decision-making processes, and the communication of technical knowledge between designers, operators, and regulators. In this respect, the disaster highlighted the importance of institutional transparency, knowledge management, and organizational learning in the governance of complex technological systems. The accident therefore became a catalyst for the reassessment of established relationships between expertise, authority, and technological decision-making.

The study has further demonstrated that one of the most significant intellectual consequences of Chernobyl was the transformation of international understandings of technological risk. Prior to 1986, safety was frequently treated primarily as an engineering problem. Following the accident, risk increasingly came to be understood as a multidimensional phenomenon encompassing technical, organizational, social, and institutional factors. This shift encouraged the adoption of systemic approaches to accident analysis and contributed to the growing recognition that technological failures emerge through interactions among multiple components of socio-technical systems.

Within this context, the emergence of the concept of safety culture represents one of the most enduring legacies of the disaster. Developed through the work of the International Nuclear Safety Advisory Group, the concept fundamentally altered international approaches to nuclear safety by linking technological reliability to organizational behaviour, communication practices, leadership, professional responsibility, and institutional values. The influence of safety culture subsequently extended far beyond the nuclear sector and became an important element of safety management in aviation, transportation, healthcare, chemical manufacturing, and other high-risk industries.

The post-Chernobyl transformation of international nuclear governance constituted another important outcome of the accident. As demonstrated in this study, international approaches to nuclear safety evolved from a primary focus on technical reliability toward broader frameworks incorporating safety culture, organizational learning, international cooperation, resilience, and risk governance. New mechanisms for information exchange, emergency preparedness, peer review, and international collaboration emerged in response to the deficiencies revealed in 1986. At the same time, extensive modernization programmes implemented at operating RBMK facilities demonstrated how technological systems can evolve through processes of reassessment, adaptation, and institutional learning.

The long-term legacy of Chernobyl also extends to contemporary discussions concerning sustainable technological development. The disaster demonstrated that technological sustainability cannot be reduced to efficiency, productivity, or innovation alone. Sustainable technological systems require effective institutions, transparent governance, robust safety cultures, and the capacity to learn from operational experience and unexpected failures. The experience of Chernobyl therefore remains highly relevant to present-day discussions concerning resilience, risk governance, and the responsible management of complex technologies.

The findings of this study are particularly significant in relation to the United Nations Sustainable Development Goals. The historical experience of Chernobyl illustrates the importance of protecting public health and well-being (SDG 3), ensuring the safe and responsible development of energy systems (SDG 7), promoting resilient infrastructure and innovation (SDG 9), and strengthening effective, accountable institutions capable of managing technological risks (SDG 16). The disaster demonstrated that long-term technological progress depends not only on scientific and engineering achievements but also on the quality of institutions responsible for governing technological change.

From the perspective of the history of science and technology, Chernobyl should be understood not merely as a nuclear accident but as a critical moment in the historical evolution of technological governance. The disaster revealed the limitations of approaches that treated safety primarily as a technical problem and contributed to the emergence of new understandings of risk, expertise, organizational learning, and institutional responsibility. In this sense, the significance of Chernobyl lies not only in the failures that produced the accident but also in the intellectual, organizational, and regulatory transformations that followed. Nearly four decades later, the disaster remains one of the most influential historical case studies for understanding how modern societies govern complex technologies under conditions of uncertainty. Its legacy continues to inform contemporary debates on safety culture, technological risk, and sustainable development in the twenty-first century.

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Чорнобиль і трансформація культури ядерної безпеки: управління технологіями, ризик та експертиза після 1986 року

Анотація. *Чорнобильська катастрофа 26 квітня 1986 р. залишається однією з наймасштабніших техногенних аварій XX ст. та однією з ключових подій в історії науки і техніки. Якщо ранні інтерпретації аварії переважно зосереджувалися на конструктивних недоліках реактора та помилках оперативного персоналу, то подальші дослідження засвідчили, що її причини були значно складнішими та охоплювали взаємодію технічних, організаційних і інституційних чинників. Метою статті є дослідження Чорнобильської катастрофи як поворотного моменту в еволюції культури безпеки та технологічного врядування у сфері використання складних технологій. Особливу увагу приділено місцю ядерної енергетики в радянській модернізаційній політиці, розвитку програми реакторів РБМК, особливостям організаційної культури радянської ядерної галузі, а також управлінню технічними знаннями до та після аварії. Методологічну основу дослідження становлять методи історичного аналізу, історіографічного огляду, порівняльного аналізу та аналізу соціотехнічних систем. Джерельну базу формують документи Міжнародного агентства з атомної енергії, матеріали Чорнобильського форуму, а також сучасні дослідження з історії науки і техніки, ядерної безпеки, ризикології та технологічного врядування. У статті проаналізовано технічні та інституційні передумови аварії, кризу технологічної експертизи, переосмислення поняття ядерного ризику після 1986 р., а також формування концепції культури безпеки як нового підходу до забезпечення надійності складних технологічних систем. Встановлено, що Чорнобильська катастрофа не може бути адекватно пояснена виключно технічними несправностями або людськими помилками. Аварія стала проявом системної несправності, що виникла внаслідок взаємодії конструктивних особливостей реактора, організаційних практик, інституційних обмежень і недоліків у циркуляції інформації, пов'язаної з безпекою. Показано, що катастрофа суттєво вплинула на міжнародні підходи* *до оцінювання технологічних ризиків, сприяла становленню концепції культури безпеки як одного з ключових принципів ядерного врядування та стимулювала розвиток нових механізмів міжнародного співробітництва у сфері ядерної безпеки, аварійної готовності та регуляторного нагляду. Обґрунтовано, що історичне значення Чорнобиля виходить далеко за межі ядерної енергетики. Уроки катастрофи вплинули на формування сучасних підходів до управління складними технологіями, ризик-менеджменту та інституційної стійкості. Особливу актуальність вони зберігають у контексті досягнення Цілей сталого розвитку ООН, насамперед у сферах охорони здоров'я, сталої енергетики, інноваційної інфраструктури та ефективного врядування. З позицій історії науки і техніки Чорнобильська катастрофа постає важливим прикладом того, як великі технологічні аварії здатні трансформувати наукові знання, організаційні практики та міжнародні підходи до управління технологічними ризиками.*

Ключові слова: *Чорнобильська катастрофа; культура ядерної безпеки; технологічне врядування; радянська ядерна промисловість; технологічний ризик; сталий розвиток*

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Repressed science in the service of agrarian development: The contribution of Karlag's incarcerated scientists to Soviet agricultural science, 1930s–1950s

Abstract. *This article examines the Karaganda Agricultural Experimental Station (SKhOS) of the Karaganda Corrective Labour Camp (Karlag) as a scientific institution operating within the Soviet GULAG system in Central Kazakhstan from the 1930s to the 1950s. Despite its origins in a system of forced labour, the station made a significant contribution to Soviet agricultural science. The study is based on primary archival materials from the State Archive of Karaganda Region for Scientific and Technical Documentation (GAKO NTD, fond 26), verified through comparison with published collections of GULAG documents and memoir sources. The research employs the methods of institutional history, prosopographical analysis, and content analysis of archival scientific texts. The article reconstructs the organisational structure of SKhOS, a station comprising six scientific departments and a staff of ninety-eight employees, approximately 64 per cent of whom were prisoners. It offers a detailed analysis of the scientific contributions of seven identified prisoner-scientists:*

V. S. Pustovoit, who developed high–yielding varieties of rye and millet that tripled field productivity; S. A. Arkhangelskii, whose vegetable–breeding programme produced zoned varieties, including a tomato variety registered in thirteen oblasts of the Kazakh SSR; A. A. Kornilov, whose experiments on photoperiodism in spring wheat hybrids and on the continuous illumination of millet challenged established assumptions in Soviet plant physiology; P. A. Verteletskii, who developed the drought–resistant spring wheat variety Karagandinskaia*, recognised as a regional standard and sown by 1949 on an area exceeding 7,000 hectares; A. V. Lanina, whose work in livestock breeding contributed to the creation of the Kazakh White-Headed beef cattle breed, awarded the Stalin Prize in 1940; Ia. E. Vasiltsev, who organised a systematic campaign against glanders in the camp's horse population; and B. K. Fortunatov, whose programme for breeding fine–fleeced fat–tailed sheep was interrupted by his death from brucellosis in 1940. Over two decades, SKhOS registered ninety-two new varieties of agricultural crops, sixteen of which were approved by the State Commission for Variety Testing for cultivation in several regions of the USSR. The station also supplied district seed–production farms with more than 37,837 centners of elite-category grain seed. The article argues that SKhOS represented a distinctive regime of knowledge production – coerced expert science – in which repressive institutional control, practical agrarian demand, and the professional culture of prisoner-scientists generated a contradictory yet measurable scientific outcome. The gradual absorption of the station into the mainstream of Soviet and Kazakhstani agronomy following the liquidation of Karlag in the mid-1950s is interpreted as an unrecognised transfer of scientific heritage created under conditions of state coercion. A promising direction for further research is the specialised study of the surviving issues of* Transactions of the Karaganda Agricultural Experimental Station *and of the holdings of the museum in Dolinka.*

Keywords: *GULAG science; coerced knowledge production; expert knowledge under coercion; camp economy; Central Kazakhstan; Stalin-era biology*

Introduction.

The history of Soviet science during the Stalinist era encompasses one of its most paradoxical phenomena: the emergence of 'repressed science'– scientific activity carried out by specialists imprisoned within the Gulag camp system. The Karaganda Corrective Labour Camp (Karlag), established in Central Kazakhstan in 1931, became one of the largest centres for the concentration of scientific and technical personnel within this camp–based empire. The camp's agrarian complex – the state farm Gigant– required qualified specialists not only as a labour force but also as researchers. In response to this need, the Karlag administration established a network of research laboratories, which in 1938 were consolidated into the Karaganda Agricultural Experimental Station (Selskokhoziaistvennaia Opytnaia Stantsiia, hereafter SKhOS).

The scientific legacy of Karlag remains insufficiently studied. Existing historiography addresses the general history of political repression in Kazakhstan (Shaimukhanov & Shaimukhanova, 1997; Dilmanov, 2001; Kuznetsova, 2013), documents individual biographies of repressed intellectuals (Mogil'nitskii, 2001), and provides historiographical overviews of the broader subject (Abdrakhmanova, 2020). However, the detailed institutional and scientific content of the SKHOS–its organisational structure, the specific research conducted by particular scholars, the archival texts of their work, and their concrete results–has not been subjected to systematic scholarly analysis based on primary archival sources.

The article asks not only what scientific results were achieved at SKhOS, but also how precise agricultural knowledge could be produced within an institution founded on coercion, security-regime control, and restricted scholarly communication. Its contribution lies in examining SKhOS as a scientific institution operating under the conditions of the camp system – a distinctive regime of knowledge production in which repressive power, the practical demand for expert competence, and the professional culture of prisoner–scientists formed a contradictory yet productive institutional configuration.

This article aims to address this gap in the literature. It is based primarily on materials from the State Archive of the Karaganda Region for Scientific and Technical Documentation (GAKO NTD), Fond 26-the collection of the Karaganda Research Institute of Plant Cultivation and Breeding, which originated from Karlag's Scientific Cabinet–as well as on published documentary collections on the Gulag (Kokurin & Petrov, 2000), a reference work on the system of corrective labour camps (Smirnov, 1998), and scholarly studies on repressed science in the USSR (Iaroshevskii, 1991; Markova, Volkov, Rodnyi, & Iasnyi, 1998). Memoir sources – including the recollections of former prisoner A. Berg, published in the Karaganda press (1989), and family memoirs by the daughter of I. K. Fortunatov (Pankov, 2019) – complement the archival evidence.

The article pursues three principal objectives: first, to outline the institutional history and organisational structure of the SKHOS; second, to reconstruct the scientific biographies and research contributions of key prisoner–scientists; and third, to assess the broader significance of Karlag's scientific activity within the context of both Soviet agrarian history and the history of repressed science.

Literature Review.

The subject of repressed science in the USSR began to attract sustained scholarly attention only in the late 1980s, when the policy of glasnost under Mikhail Gorbachev enabled researchers to engage with previously prohibited topics. A landmark collective volume, *Repressed Science* (Iaroshevskii, 1991), brought together contributions from leading Soviet historians, philosophers, and scientists who examined the mechanisms through which the Stalinist administrative–command system distorted and suppressed scientific development. Academician M. G. Iaroshevskii (1991) analysed the fate of Soviet science as a whole, while V. S. Kirpichnikov's chapter on Nikolai Vavilov and genetics highlighted the particularly destructive impact on the biological sciences. The editors concluded that ideologically orchestrated 'discussions' constituted the principal mechanism of repression, their true purpose being the complete subordination of all Soviet scholars to Party control.

With regard to Kazakhstan, the first serious attempts to interpret repression and the camp system emerged in journalistic publications of the late 1980s – articles by V. Dik (1990) and E. Kuznetsova (2013) in the regional press. Although not academic in nature, these works stimulated broad public and scholarly interest in the subject. The first monograph to examine Karlag systematically was D. A. Shaimukhanov and S. D. Shaimukhanova's Karlag (1997), based on materials from the archive of the Karaganda Regional Directorate of Internal Affairs and addressing, inter alia, the conditions of detention and the scientific activity of prisoner-scholars. S. Dilmanov's study (2001) analysed the economic utilisation of prisoner labour within the camp system of Kazakhstan, providing statistical data on both agricultural and industrial output. E. B. Kuznetsova (2013) produced the most comprehensive general history of Karlag to date, situating it within the broader context of Soviet penal history.

More specifically on the question of science in Karlag, K. K. Abdrakhmanova (2013, 2020) made two significant contributions: first, a study of the research activities of prisoner–scientists at the SKHOS during the 1930s-1950s based on archival materials and memoirs; and second, a historiographical review of the literature on Karlag's scientific and creative intelligentsia. In her 2020 work, Abdrakhmanova demonstrated that the history of the SKHOS had not been the subject of comprehensive archival investigation and characterised the field as both underdeveloped and innovative.

Russian historiography on science in the Gulag includes studies by E. V. Markova, V. A. Volkov, A. N. Rodnyi, and V. K. Iasnyi (1998, 1999), which examine prisoner–scientists in the Vorkuta and Pechora camps, thereby providing a comparative framework for understanding the Karlag case. Western historiography, represented by the works of Zbigniew Bzhezinskii (1990), Hannah Arendt (1996), and Aleksandr Solzhenitsyn – whose The Gulag Archipelago (1989) offered the first major literary-documentary portrayal of the camp world–has tended to focus primarily on the political and systemic dimensions of Stalinism, paying comparatively less attention to its scientific aspects.

In situating the case of SKhOS within international historiography, particular importance attaches to studies on the history of Soviet science and its dependence on political and institutional context. The works of N. Krementsov (1997), E. Pollock (2006), and A. Kojevnikov (2004) have shown that Soviet science in the Stalinist and post–Stalinist periods cannot be understood solely through the binary opposition of 'science versus ideology'. It is more productive to approach it as a system in which scientific disciplines, professional communities, state funding, party control, and institutional patronage were closely interconnected. In this respect, the history of SKhOS in Karlag represents an especially concentrated example of such dependence: here, the state patron of science simultaneously functioned as a repressive authority, an economic client, and a supervisory body.

The historiography of Lysenkoism and Soviet biology is of particular relevance. The studies of D. Joravsky (1970), N. Krementsov (1997), and N. Roll–Hansen (2005) make it possible to examine biological and agronomic works of the 1930s and 1940s not merely as scientific texts, but also as components of an ideologically charged field in which concepts such as 'Michurinist biology', 'directed upbringing', and criticism of classical genetics carried not only methodological but also political significance. For the analysis of SKhOS, this is especially important with regard to A. A. Kornilov's work on photoperiodism.

No less important are studies of scientific labour within the GULAG system. A. Siddiqi's work (2017) on specialists in Stalinist 'sharashki' and G. Alexopoulos's research (2017) on medical research laboratories in the GULAG show that the coerced use of expert knowledge was a stable practice of the Soviet repressive system. Most such studies, however, have focused on engineering and medicine. The case of Karlag is fundamentally different in that it demonstrates an agrarian form of camp science.

Studies of the GULAG economy – above all the works of P. Gregory and V. Lazarev (2003), and S. Barnes (2011) – allow Karlag to be viewed not only as a space of punishment, but also as an element of the Stalinist mobilisation economy. Particular attention should be given to S. Barnes's monograph 'Death and Redemption: The Gulag and the Shaping of Soviet Society' (2011), based on materials from Kazakhstani and Russian archives, which proposed a conception of the GULAG as a 'total institution' aimed at transforming the individual through forced labour. Barnes considered Karlag as a point of intersection between punishment and 'reforging', a framework that may be correlated with the mechanism for mobilising expert knowledge at SKhOS: repressive power destroyed the biographies of scientists, yet at the same time preserved and exploited their professional competence.

The present article develops the existing historiography by systematically combining the content of specific archival scientific works produced at SKhOS with the biographical profiles of their authors. Its key historiographical contribution lies in demonstrating that Karlag scientists preserved theoretical scientific standards even under conditions of isolation, thereby complicating the thesis that GULAG science was purely applied in character.

Methodology and Source Analysis.

The methodological framework of this study is shaped by the need to examine SKhOS simultaneously as a scientific institution, a subdivision of the camp economy, and part of the broader system of Soviet agrarian modernisation. The article combines approaches drawn from institutional history, the history of science, the social history of forced labour, and the source–critical analysis of departmental documentation.

The main body of sources consists of materials from fond 26 of GAKO NTD. Documents were selected according to their relevance to three interconnected levels of SKhOS history: the organisational structure of the station, the content of its scientific research, and the biographies of its specialists. The analysis includes annual plans, reports, memoranda, official correspondence, manuscripts of scientific articles, materials from the station's 'Transactions', statistical data on personnel composition, and documents relating to variety testing and seed production.

Archival data were verified through cross–comparison: information contained in official reports was correlated with memoir evidence, including the recollections of A. Berg and the family memoirs of I. K. Fortunatov's daughter. NKVD–MVD documentation is interpreted with due regard to its specific institutional character: official production reports generally tended to understate human costs and exaggerate achievements, whereas internal correspondence often recorded structural contradictions with greater frankness. Where archival documents do not allow the legal status of a researcher to be established with certainty – as in the case of P. A. Verteletskii – this circumstance is explicitly noted in the text.

The methods employed include the comparative–historical method, used to compare Karlag with the Vorkuta and Pechora camps as well as with 'sharashki'; the chronological method, used to reconstruct the institutional history of SKhOS; prosopographical analysis, used to compile collective biographical profiles of prisoner–scientists; and content analysis of archival scientific texts, which makes it possible to assess their theoretical level and methodological rigour. The limitations of the study are connected with the character of the surviving sources: the documents of fond 26 make it possible to reconstruct the institutional activity of the station, but do not always allow the complete biographies of its personnel, their legal status, or the mechanisms of internal control to be established.

Main Research Results.

1. Karlag: Institutional Structure and Scale.

The Karaganda Corrective Labour Camp (Karlag) was officially established on 17 September 1931 on the basis of the state farm Gigant, which had been created in 1930 by the Kazakhstan ITL of the OGPU (Smirnov, 1998). The administrative centre of the camp was located in the settlement of Dolinka, approximately 45 kilometres south of Karaganda. The camp occupied a territory of 1,767,024 hectares – extending approximately 300 kilometres from north to south and 150–200 kilometres from east to west – situated at the juncture of the dry steppe and semi-desert zones (Kokurin & Petrov, 2000, p. 763).

The camp's principal function was agricultural production: the creation of a major food–supply base for the rapidly developing coal and metallurgical complex of Central Kazakhstan – the Karaganda coal basin and the Dzhezkazgan and Balkhash copper–smelting combines. In GULAG documents, Karlag was explicitly characterised as a specialised sheep–breeding camp, which distinguished it from other large agricultural camps, such as Siblag, which specialised in pig breeding. By 1940, the camp held 148,425 sheep, including 93,000 ewes; 21,296 head of cattle, including 6,413 cows; as well as substantial numbers of horses, camels, and pigs. The camp's sown area amounted to approximately 69,000 hectares of grain, oilseed, vegetable, and fodder crops (Kokurin & Petrov, 2000, pp. 763–764).

The number of prisoners in Karlag increased substantially over the course of its existence: from 10,400 individuals in December 1932 to a peak of 65,673 by January 1949, after which it began to decline, reaching 16,957 by January 1959 (Smirnov, 1998). In 1940, the total prisoner population stood at 34,536, of whom 19,181 had been convicted of 'counter–revolutionary crimes'– a category encompassing the overwhelming majority of the camp's intelligentsia and specialists (Razgon, 1994, p. 17). Among these so-called 'counter-revolutionaries' were hundreds of agronomists, zoologists, geneticists, veterinary specialists, and soil scientists whose expertise proved indispensable to the camp's agrarian mission.

The climatic conditions of the region posed formidable challenges to both scientific and agricultural work. The area was characterised by a sharply continental climate, with average annual precipitation of around 200 millimetres, winters with minimal snowfall and temperatures dropping to −47 to −48°C, short and hot summers, and poor light chestnut soils frequently affected by solonetz formations (saline soils). As stated in an internal report of the SKHOS submitted to the Council of Ministers of the Kazakh SSR in 1950, these conditions 'seemed to constitute an insurmountable obstacle to the development of agriculture in this territory, where for centuries only one branch of agriculture–nomadic pastoralism–had existed' (GAKO NTD, F. 26, Op. 3–1, D. 353a, L. 138).

2. Scientific Cabinet and SKhOS: Organisational Structure.

2.1 From the Scientific Cabinet (a research unit within the camp administration) to the SKHOS.

Scientific work within the Karlag system began almost simultaneously with the establishment of the camp itself. In May 1931, the OGPU organised a Scientific Cabinet within the Karaganda camp, located on the lands of the Karaganda state farm in the central settlement of Dolinka, covering a total area of 3,000 hectares where experimental fields were established (GAKO NTD, F. 26, Op. 3–1, D. 287, L. 95). In its initial years, the Scientific Cabinet comprised several specialised experimental units–dryland (rain–fed), irrigated, and liman (floodwater-retention) experimental fields, as well as an agrochemical laboratory–each addressing specific challenges of agriculture under the semi–desert conditions of Central Kazakhstan.

By a resolution of the Council of People's Commissars of the USSR dated 29 April 1938, all existing research and experimental units of the Karaganda state farm were consolidated into a single integrated institution: the Karaganda Agricultural Experimental Station (Selskokhoziaistvennaia Opytnaia Stantsiia, SKhOS). At the same time, under a special agreement between the Karlag administration and the Main Variety Administration of the People's Commissariat of Agriculture of the USSR, the SKHOS assumed the functions of the Karaganda Regional State Breeding Station. In this capacity, it became responsible not only for meeting the internal needs of the camp's agrarian complex but also for conducting state varietal testing and producing elite seed stock for the entire Karaganda and Akmolinsk regions – that is, for territories later incorporated into the Virgin Lands of Kazakhstan (GAKO NTD, F. 26, Op. 3–1, D. 353a, L. 255).

2.2 Departmental Structure.

The SKHOS was organised into a number of scientific departments, the composition of which evolved over time. By the mid-1940s, according to an internal memorandum addressed to the head of Karlag's Political Department (GAKO NTD, F. 26, Op. 3–1, D. 353a, L. 255–257), the station comprised six major departments:

Department of Plant Breeding and Seed Production of Cereals, Oil Crops, and Fodder Grasses – responsible for developing new varieties of wheat, rye, millet, barley, oats, sunflower, and perennial grasses adapted to local conditions.

Department of Agrotechnics and Agrochemistry – responsible for the study of crop rotation systems, methods of soil cultivation, the application of fertilisers, and the implementation of grass–field (ley farming) systems of agriculture.

Department of Vegetable Cultivation – responsible for the breeding, seed production, and agronomic practices of potatoes, tomatoes, cucumbers, cabbage, melons, watermelons, and other vegetable and cucurbit crops.

Department of Horticulture – established in 1945, responsible for the introduction and testing of fruit and berry crops and, from that time, for the development of new locally adapted varieties suited to the harsh climatic conditions of Central Kazakhstan.

Department of Plant Physiology and Microbiology – responsible for theoretical research in plant physiology, photoperiodism, drought resistance, frost resistance, and applied microbiology.

Department of Plant Protection – responsible for identifying pests and plant diseases and for developing methods of their control.

Supporting units included a Scientific Library, a Scientific Archive, a photographic laboratory, and a meteorological station. The total number of scientific personnel at the station ranged from 70 to 98 individuals, depending on the period (GAKO NTD, F. 26, Op. 3–1, D. 353a, L. 255, 68–69).

2.3 Personnel Composition: Prisoners and Civilian Staff.

One of the most distinctive and ethically complex features of the SKhOS was its dual personnel structure: the station's research staff included both civilian employees and prisoners. An official report submitted to the Council of Ministers of the Kazakh SSR in 1949–at the time when the camp population reached its peak (GAKO NTD, F. 26, Op. 3–1, D. 353a, L. 68–69)–provides the following breakdown of the station's scientific and production personnel, which totalled 98 individuals (Table 1).

This table reveals a fundamentally important structural reality: prisoners constituted approximately 64% of the total scientific and production personnel. At the level of senior research fellows – that is, among those directly responsible for designing and conducting experiments – prisoners and civilian staff were represented in almost equal proportions (11 prisoners compared to 12 civilians). Among junior research staff and technical laboratory personnel, however, prisoners overwhelmingly predominated

(9 of 16 junior researchers; 41 of 45 agronomists and laboratory assistants). Administrative and managerial positions – director, deputy director, and heads of departments – were occupied exclusively by civilian personnel, the majority of whom were career officers of the NKVD–MVD or specialists entrusted by them.

Table 1. Personnel Composition of the SKhOS by Category (1949).

Position	Civilian Staff	Prisoners	Total
Director	1	–	1
Deputy Director for Research	1	–	1
Scientific Secretary	1	–	1
Heads of Departments	6	–	6
Senior Research Fellows	12	11	23
Junior Research Fellows	7	9	16
Agronomists and Laboratory Assistants	4	41	45
Head of Library	1	–	1
Artists and Photographers	2	2	4
Total:	35	63	98

Source: State Archive of the Karaganda Region for Scientific and Technical Documentation (GAKO NTD), Fond 26, Opis' 3–1, Delo 353a, fols. 68–69.

On a broader scale, archival materials indicate that prior to the Second World War Karlag held 159 highly qualified agronomists, 70 livestock specialists in cattle breeding, 32 veterinary surgeons, 56 veterinary assistants, and 15 sheep-breeding specialists. These figures increased significantly after the war: by 1950, more than 200 agronomists were employed in the camp's agricultural enterprises (Abdrakhmanova, 2013, p. 63; Shaimukhanov & Shaimukhanova, 1997, p. 136).

2.4 Agricultural Zones Served by the SKhOS.

The scientific output of the SKhOS was directed not only towards meeting the internal production needs of Karlag but increasingly towards servicing the collective and state farm sector of the Karaganda and neighbouring regions. A list of kolkhozy, sovkhozy, and subsidiary farms included in suburban zones and specialising in the cultivation of potatoes, vegetables, fruit, berries, and dairy production–attached to Resolution No. 807 of the Council of Ministers and the Central Committee of the Communist Party (Bolsheviks) of Kazakhstan, dated 19 August 1950 – clearly illustrates the geographical scope of the SKhOS's practical influence (Table 2).

3. Scientists, Their Works, and Scientific Contributions.

3.1 Vasilii Stepanovich Pustovoit: Plant Breeding under Conditions of Imprisonment.

Vasilii Stepanovich Pustovoit (1886–1972) was among the first and most prominent scientists to work in Karlag. Prior to his arrest in August 1930 in Krasnodar, he had established the experimental breeding station Kruglik near Ekaterinodar, headed a department at the Kuban Agricultural Institute, and enjoyed a reputation as one of Russia's leading specialists in plant breeding. Convicted by the OGPU Collegium under Articles 58–7, 58–10, and 58–11 as an 'enemy of the people' and sentenced to ten years in a corrective labour camp with confiscation of property, he was sent to Karlag, where he was assigned to the research laboratory of the state farm Gigant (Abdrakhmanova, 2013, p. 62; Mogil'nitskii, 2001, p. 88).

Table 2. Agricultural Zones Served by the SKHOS (as of 1950).

Zone	Districts	Included Farms
Karaganda and Temirtau Zone	Telman District	All 25 kolkhozy
	Osakarov District	7 kolkhozy: Internatsional'nyi, Zaishimskii, Pionerskii, Osakarovka, Toksumak, Peredovik, Iuzhnyi
	Voroshilov District	2 kolkhozy: Vozrozhdenie and imeni Kirova; State farms No. 1, 3, 4, and Dubovka under the Ministry of State Farms of the Kazakh SSR
Zhezkazgan Zone	Zhezkazgan District	8 kolkhozy: Balazhezdy, Ornek, imeni Kirova, imeni Voroshilova, Pioner, Baikonur, Talap, Kyzyl Asker; subsidiary farms of the copper smelting combine
Balkhash Zone	–	Subsidiary farms of the copper smelting plant and Pribalkhashstroi
Ekibastuz Zone	–	Subsidiary farm of Irtyshuglestroi

Source: State Archive of the Karaganda Region for Scientific and Technical Documentation (GAKO NTD), Fond 26, Opis' 3–1, Delo 353a, fol. 127.

Pustovoit's contribution to the SKHOS during his imprisonment – initially until his early release in May 1934, and subsequently as a civilian director of the Central Experimental Field of the Karaganda camp until March 1935 – was of foundational significance. He developed a high–yielding variety of rye and two varieties of millet–the so-called 'Dolinka' varieties–which increased field productivity threefold. His detailed study of local soils enabled him to propose replacing deep ploughing, which inverted the 14-15 cm fertile chernozem layer beneath infertile saline subsoil, with disc cultivation, a method that proved far more effective under the specific soil conditions of the Karaganda steppe.

Pustovoit's name appears among the authors of the winter rye variety Dolinskaia in the official nomenclature of the State Commission for Variety Testing, as recorded in the SKHOS report of 1951: 'Winter rye Dolinskaia – authors V. S. Pustovoit, V. I. Sazanov, and L. I. Eremin' (GAKO NTD, F. 26, Op. 3–1, D. 353a, L. 167). This variety was subsequently zoned (approved for cultivation) in five regions of the Kazakh SSR and in Primorskii Krai of the Russian SFSR.

Following his release and departure from Kazakhstan in 1936, Pustovoit continued his scientific career in sunflower breeding and achieved outstanding distinction: he was twice awarded the title Hero of Socialist Labour, became first a Corresponding Member and later a Full Member of the All–Union Academy of Agricultural Sciences (VASKhNIL; 1956) and the Academy of Sciences of the USSR (1964), and was the recipient of both the Lenin Prize and the Stalin Prize.

3.2 Sergei Aleksandrovich Arkhangel'skii: A Prisoner – Vegetable Specialist.

Sergei Aleksandrovich Arkhangel'skii (1900–1962), an agronomist and plant–breeder, headed the Department of Vegetable Cultivation at the Karaganda Agricultural Experimental Station of the NKVD state farm from 1941 onwards. His scientific work during his time in Karlag was exceptionally productive, encompassing both theoretical and applied dimensions.

As early as 1932, Arkhangel'skii conducted the first systematic trials of vegetable and field crop varieties under irrigation conditions in the Karaganda region, aiming to identify varieties suitable for a zone that, for many crops–particularly vegetables–represented an entirely new cultivation area. His report, 'Varietal Testing of Vegetable (and Field) Crops under Irrigation' (1932), established baseline agronomic data for potatoes, white cabbage, cauliflower, tomatoes, watermelons, cucumbers, and carrots under irrigated conditions in the Karaganda steppe.

Arkhangelskii's archival article of December 1940 represents a rare example of institutional self–assessment within Soviet scientific record-keeping. Combining a report on achievements with an energetic critique of structural shortcomings, it exposes the central contradiction of SKhOS as a scientific enterprise embedded within the administrative system of the camp. The assertion that the station ranked first among sixty–three breeding research institutions of the People's Commissariat of Agriculture in terms of the number of varieties transferred to the state variety–testing network – twenty–seven between 1937 and 1940 – indicates that the scientific results of SKhOS were not peripheral to the Soviet agrarian system. Rather, they were recognised at the regional level and, in some cases, at the all–Union level, despite the camp context in which they were produced (GAKO NTD, F. 26, Op. 3–1, D. 277, L. 6–7).

At the same time, the self–critical section of the article – recording the failure to fulfil the snow–retention plan, which had reached only 15 per cent by December, the shortage of building materials for greenhouses, and delays in systematic agronomic planning – points to a structural contradiction. The Karlag administration treated SKhOS as an ordinary division of the state farm, while failing to take adequate account of the specific nature of experimental scientific work and of the resources it required (GAKO NTD, F. 26, Op. 3–1, D. 277, L. 9).

Arkhangelskii's breeding achievements in potato cultivation – three varieties exceeding the standard yield by 50-55 per cent and occupying more than 1,000 hectares by 1949 – together with the zoning of the tomato variety 'Erliana Dolinskaia 142' in thirteen oblasts of the Kazakh SSR, confirm that practically verifiable agricultural research conducted by prisoner–scientists could produce genuinely measurable results even under conditions of chronic resource scarcity (GAKO NTD, F. 26, Op. 3–1, D. 353a, L. 24, 167–168).

Thus, the material concerning Arkhangelskii reveals the central paradox of SKhOS: an institution deprived of administrative and legal autonomy nevertheless preserved a space for professional scientific measurement, precisely because varietal yield and resistance to frost could not be adjusted by ideological decree.

Other works attributed to Arkhangel'skii in archival records include the articles 'Science Conquers the Steppe' (1940), 'Conquering Nature' (1940), 'Agriculture in the Desert' (1940), and 'The Experimental Station of the Karaganda NKVD State Farm' (1941), all of which were published in the regional press and specialised agricultural journals.

After completing his sentence, Arkhangel'skii continued his work in scientific institutions of the Kazakh SSR, publishing research on potato and vegetable cultivation until his death in 1962.

3.3 Aleksandr Aleksandrovich Kornilov: Plant Physiology and Genetics at the Forefront of Soviet Science.

Aleksandr Aleksandrovich Kornilov served as deputy director of SKhOS for scientific affairs. His archival writings represent the most theoretically ambitious works produced at the station.

Kornilov's work must be considered in the context of Soviet biology in the 1940s, when the boundaries between plant physiology, plant breeding, genetics, and the ideologically sanctioned 'Michurinist biology' were especially fraught. By the mid–1940s, classical genetics was already under intense political pressure, and after the August 1948 session of VASKhNIL – the All-Union Academy of Agricultural Sciences named after V. I. Lenin – Lysenkoism acquired institutionally entrenched dominance. In this context, Kornilov's terminology – 'the control of development', 'directed upbringing', and the decisive role of external conditions – reflected not only the language of experimental agrobiology, but also the compulsory discursive regime of Soviet science. Yet his experiments on photoperiodism should not be reduced to ideological rhetoric. They demonstrate substantive experimental work with plant developmental phases, light regimes, and hybrid material. It is precisely this combination of ideologically permissible language and scientifically significant experimental practice that makes Kornilov's work especially important for the history of Karlag science.

Kornilov was the author of two archival scientific articles preserved in fond 26. Both were published in the Transactions of the Karaganda Agricultural Experimental Station – in issue 2 (1946) and issue 3 (1946) – which, despite being camp publications of limited circulation, were distinguished by a genuinely high scholarly standard.

Kornilov's two archival texts together constitute a single research programme directed against established dogmas in plant physiology. In the first article, he argues that photoperiodic treatment of wheat hybrids at the critical moment of the light stage – a 10-11–hour day from the emergence of the second leaf to the formation of the fifth – made it possible to regulate the productivity of the ear, almost doubling grain set. In doing so, he translated the Michurinist principle of the plasticity of heredity into a concrete agrotechnical instrument (GAKO NTD, F. 26, Op. 3–1, D. 392, L. 3–7). In the second article, Kornilov criticises Razumov's thesis concerning the necessity of darkness for short–day plants, demonstrating that millet under continuous illumination nevertheless proceeds to panicle emergence – later and with a different morphology, but nevertheless does so (GAKO NTD, F. 26, Op. 3–1, D. 393, L. 10). He explains this process through Kholodnyi's hormonal hypothesis (1939), according to which generative development is determined not by the light/dark rhythm, but by the accumulation of a complex of phytohormones. Taken together, the two texts demonstrate a single methodological position: Kornilov consistently replaces binary physiological schemes – long day/short day, light/darkness – with dynamic models in which controlled environmental conditions and the hormonal balance of the plant are more important than rigid categorical distinctions.

The scientific significance of this work extends beyond its immediate agronomic context. Kornilov's challenge to Razumov's formulation – published under conditions of almost complete scholarly isolation, without access to international journals, and using laboratory equipment assembled from camp resources – indicates that the intellectual standards of Karlag scientists were not merely pragmatic or applied, but genuinely theoretical.

From the perspective of the Lysenkoist context, it is significant that Kornilov publicly challenged an accepted Soviet formulation at a time when any disagreement with official authorities was becoming increasingly dangerous. This raises the question of whether Karlag's physical and administrative remoteness from Moscow's scientific centres may have provided a certain space for intellectual independence, one that was unattainable for 'free' scientists operating under the pressure of ideological conformity.

3.4 P. A. Verteletskii: Breeding Wheat for the Steppe.

Pavel Aleksandrovich Verteletskii is identified in the archival documents of Fond 26 as the author of one of the most successful breeding achievements of the SKhOS – the spring wheat variety Karagandinskaia. This variety was developed through a method of complex (stepwise) hybridisation involving three components–Milturum 321 × Pseudo–Gostianum S.305 × Lutescens 78–combined with accelerated breeding techniques. The result was a variety characterised by an awnless, pubescent ear and red grain, combining drought resistance with high yield (exceeding the zoned standard variety Caesium 111 by more than 2 centners per hectare), as well as resistance to shattering and to diseases such as smut and rust (GAKO NTD, F. 26, Op. 3–1, D. 353a, L. 21–22).

By 1949, Verteletskii's Karagandinskaia wheat was sown on more than 7,000 hectares in the collective and state farms of the Karaganda region and had been zoned by the State Commission as a standard variety for the region (GAKO NTD, F. 26, Op. 3–1, D. 353a, L. 167). In a broader report submitted by the SKHOS to the Council of Ministers of the Kazakh SSR (1949), the variety is listed among the station's key achievements. The report also describes the continuation of breeding work involving branched wheat forms, including the production of 17,200 hybrid grains and the accelerated propagation of the most promising lines in greenhouses during the winter of 1950–1951 (GAKO NTD, F. 26, Op. 3–1, D. 353a, L. 22–23).

Archival sources do not provide complete biographical information regarding Verteletskii's legal status during his work at the SKHOS. Nevertheless, his identification in the documents as a researcher at the experimental station of the Karaganda NKVD state farm–at a time when the overwhelming majority of senior researchers were either prisoners or former prisoners employed under conditions of restricted freedom–places him within the broader community of repressed specialists who shaped the scientific agenda of the SKhOS.

3.5 Anna Vladimirovna Lanina: Livestock Breeding and the Stalin Prize.

Anna Vladimirovna Lanina (born 1905), a livestock specialist and breeder and a former staff member of the All-Union Institute of Animal Husbandry in Moscow, arrived in Karlag in 1939. She initially worked as Chief Zootechnician of the Livestock Department and, from 1940, headed the Research Station for Animal Husbandry, where she conducted breeding work with cattle.

The breeding programme in which Lanina played a leading role culminated in the creation of the Kazakh White–Headed breed of cattle–a meat and dual–purpose (meat–and–dairy) breed characterised by an average live weight of 540 kg for cows (with the best specimens reaching up to 800 kg) and up to 1,100 kg for bulls. Dairy–oriented cows produced up to 3,000 kg of milk per lactation. The breed was specifically adapted to year–round pasture conditions in semi-arid environments, combining high meat productivity with the ability to withstand the harsh climatic conditions of Central Kazakhstan.

This achievement was the result of several years of research conducted within Karlag. The origins of this work can be traced to the Proceedings of the Karlag Scientific Cabinet (1933), where studies on the utilisation of Kazakh livestock and the pastures of Central Kazakhstan emphasised the importance of incorporating local breeds into breeding programmes. Researchers focused on crossbreeding native cattle with Kalmyk and Hereford breeds. Investigations initiated by V. S. Garkavi were brought to fruition through the successful experiments of A. V. Lanina, resulting in the development of the Kazakh White–Headed breed, noted for its high productivity and adaptability to the sharply continental and severe climatic conditions of the region (GAKO NTD, F. 26, Op. 3–1, D. 90, L. 9).

In 1940, Lanina was awarded the title of Laureate of the State (Stalin) Prize for her achievements in animal husbandry and the development of this new cattle breed. This recognition is noteworthy in two respects: it demonstrates that her scientific contribution was acknowledged at the highest level of the Soviet state; at the same time, archival evidence indicates that the award did not result in any mitigation of her sentence or early release (GAKO NTD, F. 26, Op. 3–1, D. 287, L. 22). The disjunction between scientific recognition and legal–political status was absolute: a recipient of the Stalin Prize remained a prisoner without rights. Only in 1951 did the award finally serve as grounds for the removal of her criminal conviction.

Following her release, Lanina taught at the Alma-Ata Zooveterinary Institute and subsequently worked within the All-Union Academy of Agricultural Sciences (VASKhNIL) until 1988.

3.6 Iakov Efimovich Vasil'tsev: Veterinary Science under Camp Conditions.

Professor Iakov Efimovich Vasil'tsev of the Kursk Veterinary Institute served his sentence in Karlag as a leading specialist in the control of glanders–a highly contagious bacterial disease that posed a serious threat to the camp's many thousands of horses. Vasil'tsev led expeditions across the camp's extensive territory to identify infected animals, developed protocols for the isolation of diseased horses, and organised systematic diagnostic and anti–epizootic measures on a scale previously unprecedented in the region (GAKO NTD, F. 26, Op. 3–1, D. 287, L. 75).

Following his release from Karlag, he was appointed Chief Veterinary Surgeon of the Karaganda State Farm Trust–a telling indication that the authorities regarded his expertise as too valuable to permit his return to central scientific institutions.

3.7 Boris Konstantinovich Fortunatov: Sheep Breeding and Personal Tragedy.

Boris Konstantinovich Fortunatov (1886–1940)–not to be confused with his brother Igor Konstantinovich Fortunatov–followed a remarkable life trajectory, moving from revolutionary politics to zoological science. A member of the Socialist Revolutionary Party, he commanded a cavalry detachment during the Civil War before joining the Red Army. In the 1920s, he worked as a manager of nature reserves in Ukraine and Crimea and served as Deputy Director of the Askania–Nova Reserve, where he was engaged in the restoration of the European bison through absorptive crossbreeding. Arrested in 1933 as a 'former SR' and sent to Karlag, he was appointed head of the Research Station for Animal Husbandry, where he led efforts to develop semi–fine wool fat–tailed sheep producing combing wool (Abdrakhmanova, 2013, p. 63).

The breeding of fine-fleeced fat-tailed sheep in Karlag represented a scientifically complex undertaking. Archival materials from Fond 26–including the 1939 work plan for the development of fine–wool fat–tailed sheep (GAKO NTD, F. 26, Op. 3–1, D. 227, L. 1–4) – describe in detail three methods employed within the camp's breeding programme: the use of partially developed stock that had formed spontaneously within the state farm flocks; interbreeding first–generation crossbreeds, which yielded approximately two rams per 1,000 animals with small fat tails and first-class hybrid wool; and backcrossing first–generation hybrids with purebred fat-tailed sires–a method that was in fact adopted in Karlag due to the absence of a sufficiently large hybrid population required for the second approach. The programme produced its first individual animals combining fine fleece with properly developed fat tails as early as 1938; specific specimens (rams Nos. 424, 581, and 639, and ewes Nos. 75 and 137) are documented in archival photographs and planning materials (GAKO NTD, F. 26, Op. 3–1, D. 227, L. 4).

Fortunatov's work was tragically cut short. In 1940, he contracted brucellosis–a bacterial infection endemic among the camp's livestock–and died in the Dolinka camp hospital. His death exemplifies one of the most acute structural risks faced by prisoner–scientists in Karlag: the lack of adequate medical protection and direct exposure to zoonotic diseases during field research. Following his death, the programme for the development of fine-wool fat-tailed sheep in Karlag was discontinued (Abdrakhmanova, 2013, p. 63).

4. Scientific Achievements: Results and Scale.

The cumulative scientific output of the SKhOS between 1931 and 1951 would be noteworthy for any research institution; when considered in light of the conditions under which it was produced, it becomes truly exceptional. According to an extensive report submitted to the head of the Political Department of Karlag (MVD) (GAKO NTD, F. 26, Op. 3–1, D. 353a, L. 255–260), as well as a subsequent retrospective report by Director P. S. Drozdovskii (GAKO NTD, F. 26, Op. 3–1, D. 353a, L. 166–170), the station's achievements may be summarised as follows.

In the field of plant breeding. Over twenty years of activity (1931–1951), the SKHOS developed a total of 92 new varieties of field, vegetable, fruit, and fodder crops. Of these, 16 varieties of cereals, grasses, and vegetables were zoned by the State Commission for Variety Testing of the Ministry of Agriculture of the USSR for cultivation in multiple regions of the Soviet Union. The 'Dolinskie' millet varieties (Dolinskoe 086, 012, 155, 3151, among others) had, by the late 1940s, been zoned in 20 oblasts, kraia, and autonomous republics of the USSR, including nine oblasts of the RSFSR, six oblasts of the Kazakh SSR, Altai Krai, and three autonomous republics. The winter rye variety Dolinskaia was zoned in Primorskii Krai and five regions of Kazakhstan; the winter wheat variety Alabasskaia in Altai Krai, Omsk and Novosibirsk oblasts, and six regions of Kazakhstan; and the spring wheat variety Karagandinskaia in the Karaganda region.

In the field of elite seed production. Between 1938 and 1950, the SKhOS consistently fulfilled and exceeded state contracts for the supply of elite seeds to district seed farms in the Karaganda and Akmolinsk regions, delivering a total of more than 37,837 centners of elite seed of cereals and oil crops over this twelve-year period, with an average fulfilment rate of 110%. In 1944 alone, the station supplied the state with 3,614 centners of high-quality elite seed (GAKO NTD, F. 26, Op. 3–1, D. 353a, L. 169, 256).

In the field of horticulture. The SKhOS established the first orchards in Central Kazakhstan. By 1950, the station's nursery had provided planting material for nearly all orchards in the Karaganda region, covering a total area of 1,500 hectares. In that year alone, the station supplied collective and state farms with 100,000 saplings of pome and stone fruit species (GAKO NTD, F. 26, Op. 3–1, D. 353a, L. 170). The station's experimental orchard, described in a scientific report by Director N. M. Rusanov (1952) (GAKO NTD, F. 26, Op. 3–1, D. 466, L. 59–65), expanded to 132 hectares and tested 522 varieties of fruit and berry crops drawn from across the Soviet Union.

In the field of agronomy. The station developed and published comprehensive agronomic manuals adapted to local conditions – Agrotechnics of Field Crops (1941), Agrotechnics of Vegetable Crops (two editions, 1941 and 1943), and Agrotechnics of Fruit and Berry Crops (1943; second edition 1948)–which, according to the station's own assessment, became 'the principal and, indeed, the only manuals available to agricultural workers not only in the Karaganda region but also in other regions of Kazakhstan' (GAKO NTD, F. 26, Op. 3–1, D. 353a, L. 258).

In the field of scientific publications. Researchers at the SKhOS published approximately 200 scientific and popular–scientific articles in specialised journals (Doklady Akademii Nauk SSSR, Vestnik Akademii Nauk Kazakhskoi SSR, Agrobiologiia, Selektsiia i semenovodstvo, Sovetskaia agronomiia, Pochvovedenie, Mikrobiologiia) and in the regional press, and delivered more than 80 papers and presentations at all–Union and republican congresses, conferences, and meetings devoted to agricultural issues. Three volumes of the station's own Proceedings were published. At the All–Union Agricultural Exhibition of 1939, the SKhOS was awarded a First–Degree Diploma and a prize of 10,000 roubles, as well as a passenger automobile (GAKO NTD, F. 26, Op. 3–1, D. 353a, L. 144–145, 170).

5. Constraints and Limiting Factors.

The scientific achievements of the SKhOS were attained under conditions of profound structural constraint. On the basis of archival materials, four principal categories of limiting factors may be identified.

Regime–imposed restrictions. The most fundamental constraint was the legal status of the majority of the station's scientific personnel as prisoners. Their research was conducted under the supervision of the NKVD–MVD, and the dissemination of results was strictly controlled. An internal report by Arkhangel'skii notes that the second and third issues of the Proceedings were 'prohibited from distribution' by the Agricultural Department of the Gulag–a decision that the station repeatedly petitioned to have reconsidered in light of the resolutions of the February Plenum of the Central Committee, which called for the rapid implementation of agricultural scientific achievements in production (GAKO NTD, F. 26, Op. 3–1, D. 353a, L. 260). Prisoner–scientists lacked independent access to correspondence, were unable to participate freely in scientific conferences, and depended on the discretion of camp authorities for any external professional contact.

Resource scarcity. The station suffered chronically from a shortage of equipment. By the mid-1940s, it lacked basic agricultural machinery necessary for precise experimental work, including precision seed drills, cultivators, and irrigation systems. Laboratories received no new equipment or reagents throughout the war years, which precluded many essential analyses and delayed breeding work aimed at improving grain quality. The station possessed only four tractors (two STZ–NATI tracked tractors and two wheeled STZ tractors acquired in 1938) and two Kommunar combine harvesters–aging equipment with inadequate maintenance. Its single motor vehicle had been assembled from spare parts of decommissioned camp machinery (GAKO NTD, F. 26, Op. 3–1, D. 353a, L. 68–69, 259–260).

Financial subordination. The research activities of the SKhOS were financed not by the Ministry of Agriculture but by the Karaganda state farm–effectively the Karlag administration–despite the fact that the station's outputs served not only the camp but also the collective and state farm sector across several regions. This arrangement produced chronic budgetary imbalance. From 1947 onwards, the Ministry of Agriculture ceased allocating capital investment funds to the SKHOS, while the station's operational costs for elite seed production increasingly exceeded the procurement prices set by Zagotsortzerno. By 1950, the station required a state subsidy of 773,500 roubles to cover the gap between production costs and procurement prices–almost double the 419,000 roubles received in 1945. This imbalance is documented in official correspondence between the camp commandant, Colonel Maevskii, and the head of the Variety Administration of the Ministry of Agriculture of the USSR (GAKO NTD, F. 26, Op. 3–1, D. 353a, L. 107–109).

Natural and climatic factors. The harsh conditions of the Central Kazakh semi–desert imposed constraints that no institutional effort could overcome in the short term. The brevity of the frost–free period (with late spring frosts possible until 12 June and early autumn frosts from late August), low annual precipitation (198 mm), deep soil freezing (up to two metres), and the intensity of summer dust storms and winter blizzards meant that entire experimental crops could be destroyed. Years such as 1949–described in station reports as a 'dry and unfavourable summer'– tested the limits even of the most carefully developed agronomic systems. Nevertheless, the SKHOS achieved yields of 13.8 centners per hectare of cereals against a planned 11.5, 349 centners of vegetables against a planned 283, and 221 centners of potatoes against a planned 130 (GAKO NTD, F. 26, Op. 3–1, D. 353a, L. 37–38).

The human factor. In addition to the legal constraints of camp life, prisoner–scientists endured severe physical conditions: overcrowded barracks with only 1–1.8 square metres per person, inadequate nutrition, endemic diseases (including dysentery, pellagra, typhus, and tuberculosis), and exhausting labour norms applied to them on an equal basis with other prisoners (Abdrakhmanova, 2013, p. 61). The death of B. K. Fortunatov from brucellosis in 1940 is well documented; other instances of mortality and deteriorating health among scientific personnel, although not systematically recorded in the examined archival sources, can be readily inferred from the general conditions of confinement.

6. The SKHOS in Historical Context: From Camp Institution to Regional Science.

The trajectory of the SKHOS illustrates a dynamic that is paradoxical in nature yet historically consistent: an institution created to serve the repressive needs of a forced labour camp evolved, over two decades, into one of the most productive centres of agricultural research in Kazakhstan. By the early 1950s, the station was explicitly commended in a resolution of the Council of Ministers of the Kazakh SSR dated 3 January 1950 for its 'substantial achievements in the scientific investigation of issues related to the agricultural development of the dry steppes and semi–desert regions of Central Kazakhstan' (GAKO NTD, F. 26, Op. 3–1, D. 353a, L. 90).

The institutional trajectory of SKhOS exposes a profound contradiction within Soviet agrarian policy: an institution entrusted with tasks of national significance – the implementation of the Dokuchaev–Williams agronomic system, protective afforestation, and the supply of planting stock to entire oblasts – at the same time remained a structural subdivision of the Ministry of Internal Affairs (MVD), was administered by officers, and depended on the labour of prisoners. The liquidation of Karlag in the mid–1950s and the transformation of the station into the Karaganda Research Institute of Crop Production and Breeding resolved this contradiction not through acknowledgement, but through absorption: the scientific legacy produced under conditions of coercion was quietly incorporated into the mainstream of Soviet and Kazakhstani agronomy, without any inventory of its camp origins.

The record-keeping correspondence of SKhOS for 1949–1952 shows that, despite its subordination to the camp system, the station was organically integrated into the all-Union network of scientific and seed-production exchange. Its results were in steady demand among institutions of various levels throughout the USSR. The Ukrainian Research Institute of Crop Production, Breeding and Genetics requested that the station send spring wheat samples of 100-200 grams to replenish its collection material (GAKO NTD, F. 26, Op. 3–1, D. 423b, Book 3, L. 3), while the Moscow State Seed Station requested seed material for supply purposes and distribution to collective farms (GAKO NTD, F. 26, Op. 3–1, D. 423b, Book 3, L. 1). The very fact of systematic correspondence – thirty–eight folios of requests and replies over three years – indicates that interest in the breeding achievements of SKhOS was not episodic, but regular, and extended across institutions from Ukraine to Kazakhstan. Thus, the scientific authority of the station developed independently of its legal status as a subdivision of Karlag, which predetermined the relatively smooth incorporation of its legacy into the mainstream of Soviet agronomy after the liquidation of the camp in the mid–1950s.

The Karlag system was officially abolished in 1959-1960. In the 1960s-1980s, the former camp divisions and the Agricultural Experimental Station (SKhOS) were transferred to the jurisdiction of civilian ministries of the USSR and developed as ordinary large specialised state farms and research institutes of the Kazakh SSR. Former Karlag camp sites and divisions became independent state farms – for example, 'Gigant' and the state farm named after the 50th Anniversary of the USSR – which supplied food to the Karaganda coal basin. SKhOS continued its work as a major scientific institution. Its agronomists and breeders introduced advanced technologies of irrigation, agroforestry reclamation, and acclimatisation under the sharply continental climatic conditions of Central Kazakhstan.

At present, Karaganda SKhOS LLP bears the name of A. F. Khristenko – an agronomist and scientist, an innovator in agricultural production, and one of the youngest state-farm directors in the USSR. Its principal activities are the cultivation of grain and leguminous crops, including seed production, as well as the conduct of scientific research and experimental development in the field of biotechnology.

Conclusions.

The present study has shown that the Karaganda Agricultural Experimental Station of Karlag functioned in the 1930s-1950s as a genuine scientific institution of regional significance, with certain results gaining interregional and all-Union recognition, despite its origins within one of the largest Soviet forced-labour camps.

The scientific contribution of SKhOS rested on the intellectual labour of prisoner-scientists – V. S. Pustovoit, S. A. Arkhangelskii, A. A. Kornilov, P. A. Verteletskii, A. V. Lanina, Ia. E. Vasiltsev, and B. K. Fortunatov. The archival texts of their works demonstrate a level of theoretical rigour that refutes any characterisation of Karlag science as purely pragmatic.

The achievements of SKhOS were secured despite structural obstacles: the camp regime, shortages of resources, financial dependence on the MVD, and severe natural conditions. The death of B. K. Fortunatov from brucellosis, the prohibition on distributing the station's 'Transactions', and many years of underfunding all give concrete meaning to the concept of 'repressed science' in the Kazakhstani context.

From the perspective of the historiography of Soviet science, the findings of this study require adjustments to both dominant interpretative models. The concept of the 'deformation' of Soviet science under ideological pressure is valid with regard to official scientific centres; however, the materials of SKhOS demonstrate that camp science developed according to a different logic. Karlag's remoteness from Moscow's ideological centres evidently created a certain space for scientific independence, as indicated by Kornilov's willingness to challenge Razumov's thesis precisely at the height of the Lysenkoist offensive.

This space may be defined as limited, or conditional, autonomy. It was not freedom in the academic sense: prisoner-scientists did not control their own mobility, correspondence, or publications. Nevertheless, within a particular experiment or breeding programme, they were able to preserve elements of professional rationality. The emergence of such autonomy can be explained by the practical verifiability of agrarian science – a variety either produced a yield or it did not – by the dependence of the camp economy on expertise, and by the professional identity of the scientists themselves. Departmental supervision controlled the scientist as a prisoner, but it could not always control the scientific procedure itself at the level of agronomic or physiological competence.

Thus, the article's principal historiographical contribution is as follows: it demonstrates not merely the presence of scientists in Karlag, nor simply a list of their achievements, but the institutional mechanism through which repressed expert knowledge was transformed into a resource for Soviet agrarian modernisation. SKhOS was an institution in which forced labour and scientific achievement coexisted not by accident, but as part of a state design that required the very expertise it had itself placed under detention. A promising direction for further research is the specialised study of the surviving issues of 'Transactions of the Karaganda Agricultural Experimental Station' and the search for copies of these publications in the holdings of the museum in Dolinka.

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Conflicts of Interest.

The authors declare no conflict of interest.

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Державний архів Карагандинської області з науково-технічної документації, Казахстан

Наука в умовах репресій та аграрний розвиток: внесок учених-в'язнів Карлагу в розвиток радянської аграрної науки (1930–1950-ті роки)

Анотація. *У статті досліджується Карагандинська сільськогосподарська дослідна станція (СГДС) Карагандинського виправно-трудового табору (Карлагу) як наукова установа, що функціонувала в системі радянського ГУЛАГу в Центральному Казахстані у 1930–1950-х роках. Незважаючи на своє походження в умовах системи примусової праці, станція зробила вагомий внесок у розвиток радянської аграрної науки. Дослідження ґрунтується на первинних архівних матеріалах Державного архіву Карагандинської області з науково-технічної документації (ГАКО НТД, фонд 26), перевірених шляхом зіставлення з опублікованими збірниками документів ГУЛАГу та мемуарними джерелами. У роботі застосовано методи інституційної історії, просопографічного аналізу та контент-аналізу архівних наукових текстів. У статті реконструйовано організаційну структуру СГДС, яка включала шість наукових відділів і штат із дев'яноста восьми працівників, з яких близько 64 % становили ув'язнені. Подано детальний аналіз наукового внеску семи ідентифікованих учених-в'язнів: В. С. Пустовойта, який створив високоврожайні сорти жита та проса, що дозволили утричі підвищити польову врожайність; С. А. Архангельського, чия програма селекції овочевих культур забезпечила виведення районованих сортів, зокрема сорту томатів, зареєстрованого у тринадцяти областях Казахської РСР; А. А. Корнілова, чиї експерименти з фотоперіодизмом гібридів ярої пшениці та безперервним освітленням проса поставили під сумнів усталені уявлення радянської фізіології рослин; П. А. Вертелецького, який створив посухостійкий сорт ярої пшениці «Карагандинська», визнаний регіональним стандартом і висіяний до 1949 року на площі понад 7000 гектарів; А. В. Ланіної, чия робота у сфері тваринництва сприяла створенню казахської білоголової породи великої рогатої худоби, відзначеної Сталінською премією у 1940 році; Я. Є. Васильцева, який організував систематичну кампанію боротьби із сапом серед табунного поголів'я коней табору; а також Б. К. Фортунатова, чия програма селекції тонкорунних курдючних овець була перервана його смертю від бруцельозу у 1940 році. Упродовж двох десятиліть СГДС зареєструвала дев'яносто два нові сорти сільськогосподарських культур, шістнадцять із яких були схвалені Державною комісією з сортовипробування для вирощування в кількох регіонах СРСР. Станція також забезпечила районні насінницькі господарства понад 37837 центнерами елітного зернового насіння. У статті стверджується, що СГДС являла собою специфічний режим виробництва знань – примусову експертну науку, у межах якої репресивний інституційний контроль, практичні потреби аграрного сектору та професійна культура* *вчених-в’язнів формували суперечливий, але вимірюваний науковий результат. Поступове включення станції до загального русла радянської та казахстанської агрономії після ліквідації Карлагу в середині 1950-х років інтерпретується як маловідомий процес передачі наукової спадщини, створеної в умовах державного примусу. Перспективним напрямом подальших досліджень є спеціалізоване вивчення збережених випусків «Праць Карагандинської сільськогосподарської дослідної станції» та фондів музею в селищі Долинка.*

Ключові слова: *наука ГУЛАГу; примусове виробництво знань; експертне знання в умовах примусу; табірна економіка; Центральний Казахстан; біологія сталінської доби*

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History of the formation of the Italian national encyclopaedic tradition: The Treccani Project (1925–2025). A preliminary enquiry

Abstract. *The study examines the emergence and development of Italy's national encyclopaedic tradition as shaped by the activities of the Istituto della Enciclopedia Italiana fondata da Giovanni Treccani. Its centenary in 2025 provides an important context for reassessing its cultural mission. The research uses descriptive and analytical methods to systematise, interpret, and compare primary and secondary sources related to Italian encyclopaedism. It identifies the core features that established the Treccani project as a state-building intellectual initiative. These include the early integration of academic expertise, geographically and disciplinarily diverse authorship, and a sustained commitment to presenting verified knowledge within a unified humanistic paradigm. The analysis shows how the Institute evolved from an ambitious interwar publishing initiative into a major scholarly institution with long-term influence on the humanities and social sciences in Italy. Particular attention is devoted to the digital transformation undertaken in the twenty-first century. This transformation significantly expanded the accessibility, thematic breadth, and public relevance of the Institute's encyclopaedic resources. Ukrainian-related materials within the Institute's print and digital collections are also explored, with no evidence found of direct participation by Ukrainian scholars in the creation of the original encyclopaedic corpus. This absence indicates the need for further research into how Ukrainian topics have been mediated through Italian intellectual traditions and represented within European reference culture. The findings highlight Treccani's role as a durable model of national knowledge consolidation and demonstrate the broader* *significance of encyclopaedic institutions for cultural diplomacy and transnational intellectual history. Future research should examine how Ukrainian-related entries in Treccani are constructed at the level of authorship, sources, and narrative framing, as well as how these representations differ from those found in Ukrainian encyclopaedic traditions.*

Keywords: *history of reference and information science; intellectual traditions; European encyclopaedism; Italian encyclopaedic culture; national knowledge institutions; digital humanities*

Introduction.

Over recent decades, encyclopaedism has increasingly been examined within the broader frameworks of the history of knowledge, knowledge infrastructures, and cultural policy. In Western humanities scholarship, a distinct research tradition has emerged that investigates the evolution of European encyclopaedias from the early modern period to the digital age. Foundational contributions in this field include the works of S. Jackson (1977), R. Yeo (2007), J. König and G. Woolf (2013), and D. Loveland (2019).

More recent studies conceptualise encyclopaedias as elements of a wider "knowledge infrastructure" that organises, structures, and communicates scientific information to society. Far from losing relevance in the digital age, encyclopaedias have acquired a renewed function as tools of reliable orientation in conditions of informational overload (Jermen, 2023). Parallel to this, online encyclopaedias have become the focus of research in education studies, particularly in Anglophone and Ukrainian contexts, which highlight their potential as didactic resources and components of contemporary learning environments (Syaflin, Ayurachmawati, & Sunedi, 2023). Another significant body of work addresses the challenges posed by digital transformation, including the impact of generative artificial intelligence on academic standards, authorship, and expertise in current encyclopaedic practice (Zhelezniak & Ishchenko, 2025).

Within digital humanities, encyclopaedic resources are analysed as components of digital infrastructures for humanities research. They combine traditional principles of knowledge organisation with new modes of representation and interaction (Pawlicka-Deger & Thomson, 2023). Scholars also draw attention to the digitisation of printed encyclopaedias and the development of modern digital reference systems as important mechanisms for preserving and disseminating cultural and historical heritage (Dubrovina, Lobuzina, Onyschenko, & Boriak, 2020).

In recent years, Ukrainian scholarship has shown growing interest in encyclopaedism as a form of institutionalising knowledge in the humanities (Borchuk, 2017). The *Encyclopaedia of Modern Ukraine* and Ukrainian digital encyclopaedic projects have received considerable attention, especially in relation to wartime communication, educational reform, digital-humanities initiatives, and the application of AI technologies (see, for example, Zhelezniak & Ishchenko, 2023; Ishchenko & Stepanenko, 2024). These studies identify encyclopaedias as instruments of cultural diplomacy, vehicles for shaping the international image of Ukraine, and means of consolidating national identity.

At the same time, the role of national encyclopaedic institutions in other European countries has been comparatively little studied in Ukrainian research. The Italian encyclopaedic tradition, in particular, remains insufficiently explored, despite the existence of works within the Italian scholarly community that examine the activities of the country's principal encyclopaedic centre, the Istituto della Enciclopedia Italiana fondata da Giovanni Treccani (e.g., Benedetti, 2005; Cavaterra, 2014; Gregory, 2011; Gregory & Bray, 2015).

Given the current state of research, this article aims to outline the formation and development of Italian encyclopaedism through the activities of the Istituto della Enciclopedia Italiana fondata da Giovanni Treccani (hereafter IEI). It also offers a preliminary delineation of how Ukrainian-related themes are represented in IEI's publications within the wider European encyclopaedic discourse.

The relevance of this study is determined by two factors. First, the year 2025 marks the centenary of the Treccani Institute (Savchenko, 2025). Second, the ongoing Russian-Ukrainian war has significantly reshaped international scholarly interaction and heightened interest in Ukraine within the European academic community, lending additional importance to the question of how Ukraine is represented in major cultural and educational institutions. Italy is among the states that have consistently supported Ukraine in both political and humanitarian domains (Lakishyk, 2023, p. 88), opening new prospects for intercultural dialogue. In this context, an examination of Treccani's materials makes it possible to observe how representations of Ukraine take shape within the European intellectual sphere and suggests directions for further research on how Ukrainian topics are interpreted within the Italian scholarly tradition.

Methodology.

The study employs historical-source analysis and qualitative content analysis applied to the digital resources of the IEI. Since the printed volumes of the *Enciclopedia Italiana* (1929–1937; hereafter *EI*) and their appendices are not available in Ukrainian academic libraries, all research was conducted exclusively on the basis of the online platform treccani.it (accessed 2024–2025). The digital corpus integrates both digitised historical materials and a large number of newly created entries, although in many cases the platform does not indicate whether a particular article originates from the original edition or represents a later addition. Therefore, the analysis of the online corpus cannot be treated as an indirect reconstruction of the printed encyclopaedia; it reflects only the structure and content of Treccani's current digital knowledge system.

A systematic keyword search was performed using Italian, Latin, Ukrainian and historical toponyms and ethnonyms (Ucraina, Ruthenia, Cossacchi, Crimea, Galizia, Kyiv, etc.). All retrieved articles were manually screened to assess their relevance. In total, more than two hundred biographical and thematic entries related to Ukraine were identified. Particular attention was paid to the authorship information available in the digital version in order to determine whether any Ukrainian contributors participated in the preparation of *Treccani* volumes. The analysis is qualitative and descriptive, aimed at identifying the main modes of representation of Ukrainian topics in the current *Treccani* ecosystem.

The main limitations of the article arise from the structure of the online corpus. Most articles do not include chronological metadata, and the corpus integrates both historical and contemporary content. In addition, limited access to pre-1945 archival documentation of the Institute restricts the possibility of distinguishing between original and later editorial layers. These constraints should be taken into account when interpreting the findings related to authorship and historical representation.

Results and Discussion.

Throughout the twentieth century, the leading European nations implemented large-scale cultural and scholarly initiatives aimed at creating national encyclopaedias. These projects were intended not only to systematise reliable knowledge about different peoples, their histories, traditions, and cultural heritage but also to serve as symbols of a nation's intellectual maturity. In France, this role was performed by the *Grand Larousse du XXe siècle*; in Germany by the *Brockhaus Enzyklopädie*; and in the United Kingdom by the *Encyclopaedia Britannica*. In Italy a comparable mission was fulfilled by the *Enciclopedia Italiana di Scienze, Lettere ed Arti*, known today simply as *Treccani*. This undertaking laid the foundations of modern Italian encyclopaedism and now occupies a prominent position among Europe's leading academic online encyclopaedias. The centenary year of 2025 prompts renewed reflection on the origins and evolution of Italy's national encyclopaedic tradition, naturally directing scholarly attention to the publications of the IEI. Despite its relevance, the history of Italian encyclopaedism remains insufficiently explored, including within Ukrainian humanities research.

In 1925, the IEI was originally founded in Rome as the *Istituto Giovanni Treccani per la pubblicazione della Enciclopedia Italiana e del Dizionario Biografico degli Italiani* (Giovanni Treccani Institute for the Publication of the Italian Encyclopaedia and the Biographical Dictionary of Italians). Its original, deliberately extensive name, later shortened to the IEI, immediately proclaimed its dual programme: the preparation of a comprehensive general encyclopaedia and the creation of a national biographical dictionary that would articulate the country's intellectual and cultural pantheon (Treccani degli Alfieri, 1939). These two aims defined the development of Italian encyclopaedism throughout the twentieth century.

The principal architects of this undertaking were Giovanni Treccani degli Alfieri (1877–1961) and Giovanni Gentile (1875–1944). Treccani was an industrialist and patron who provided financial support for the Institute's establishment. Gentile, a philosopher, served as Minister of Public Education in Benito Mussolini's first government. Treccani argued that a nation that had given the world Dante, Galileo, Michelangelo, and Verdi should have its own national encyclopaedia capable of presenting Italian culture on a par with that of Europe's leading nations. Gentile, for his part, endowed the project with a distinct philosophical and cultural mission: he envisioned the encyclopaedia not as a mere reference tool, but as an instrument of national spiritual self-awareness, weaving knowledge, history, science, and the arts into an integrated humanistic whole. In his view, the *EI* was to serve as an intellectual mirror of national unity, a "portrait of the Italian mind", in which each entry revealed a facet of the collective cultural heritage (Gentile, 1929).

From the outset, the IEI was not intended as a commercial publishing enterprise, as it has partly become in more recent decades. Rather, the creation of a national encyclopaedia (and of a dedicated institution to oversee its preparation) formed part of a broader early-twentieth-century cultural movement aimed at institutionalising the humanities and forging new symbols of cohesion for a nation that had achieved political unification only in the previous century. The project's guiding purpose was the strengthening of national identity and the dissemination of scholarly knowledge throughout Italian society.

Preparatory work began immediately after the Institute's establishment. By 1926 an editorial board had been formed, bringing together leading authorities across a wide range of disciplines. Within the Institute, discipline-specific editorial committees operated under the guidance of eminent scholars who supervised the selection of headwords, peer review, and the standardisation of terminology. This structure ensured both scholarly rigor and a genuinely collegial working environment. Compiling the lemmario (the master list of entries) required several years, but the editorial team proceeded in parallel by commissioning and preparing articles. The first volume published in 1929, and subsequent volumes followed at a remarkable pace of approximately one every three months, which was unmatched by similar projects of the period. As a result, the thirty-five-volume set was completed in less than a decade (1929–1937). Between 1934 and 1938, supplementary updates and appendices were published; these were eventually consolidated into a thirty-sixth volume (Appendice I), issued in 1938. The achievement received international recognition, and the *EI* was soon ranked alongside the most distinguished European and global encyclopaedias.

Giovanni Gentile, appointed scientific director, served as the project's intellectual architect and articulated its overarching conceptual groundwork. For Gentile, a national encyclopaedia was far more than a compendium of verified facts. It functioned as a form of spiritual self-organisation for an entire people, in which each discipline, figure, and concept contributed to a unified humanistic worldview. Within his idealist philosophy of culture, knowledge could never be abstract or detached. It was always historically and nationally grounded. In this context, the encyclopaedic form offered the nation a means of recognising itself as a cultural subject. This vision transformed the *EI* from a purely scholarly undertaking into a broader cultural (and inevitably political) phenomenon that joined the universal aspirations of knowledge with an explicitly national mission.

At the same time, the project's conceptual foundations proved strikingly compatible with the ideological climate of the Fascist era. Consequently, during the 1930s Mussolini's government gradually brought the encyclopaedic initiative under state control, securing its funding and ultimately nationalising the Institute. In practice, this meant that the regime appropriated the encyclopaedia as an instrument of its own cultural policy. The leadership of the Encyclopaedia appears to have accepted this arrangement without significant resistance. As recent scholarship notes, Giovanni Treccani's position during the Fascist period combined formal loyalty to the regime with a determined effort to preserve the project's intellectual autonomy. He himself described this stance as one of apoliticism and principled indifference (Castellani, 2020).

In the early 1920s, Italian Fascism was viewed by parts of society as a movement of national renewal. Only later did it become a repressive dictatorship, especially after the alliance with Nazi Germany. Italian historians describe Fascism in its initial phase as an expression of political modernism, an attempt to reconcile nationalism with new forms of governance (Gentile, 2003, p. 2). Even at that stage, however, the regime was marked by political violence. Mussolini's rise to power included the murder of an opposition deputy and the passage of a series of repressive laws. Historians agree that the *EI* would not have been realised without Mussolini's explicit early approval (Turi, 2002). Many Italian intellectuals understood this dependence and therefore viewed the project with scepticism. They questioned whether it could genuinely be regarded as an impartial scholarly and cultural undertaking rather than an ideologically compromised one. For political reasons, a number of prominent intellectual figures and committed anti-fascists declined invitations to contribute to the project, seeking to maintain their independence from the regime's cultural initiatives. The publication of volume 14 in 1932 featured the entry "Fascismo". While the entire entry was signed by Mussolini, it was a collaborative effort: the first part, "Dottrina del Fascismo", was written by Giovanni Gentile (though it remained unsigned), while Mussolini himself authored the "Movimento fascista" section. The text resembled a political manifesto rather than an objective encyclopaedic article, and it significantly deepened mistrust of the project within educated circles.

Despite clear signs of political opportunism, the *EI* remains a work of exceptional scope and scholarly quality. A substantial number of its contributors, even under ideological pressure, upheld academic integrity and ensured a high level of factual accuracy and conceptual depth. This is precisely why the encyclopaedia did not disappear with the fall of the regime that had brought it into being. Instead, it became part of Italy's enduring cultural heritage. Italian scholars continue to debate the degree to which the encyclopaedia actively disseminated Fascist ideology. This question is particularly salient in studies of its economic entries (Di Matteo, 2024).

Specialists in the history of encyclopaedism adopt a more unequivocal position. Jeff Loveland argues that the *EI* was subject to two distinct forms of censorship. First, articles dealing with political subjects were written in conformity with Fascist ideology and aligned with official government positions. As early as 1933, the editor Giovanni Gentile personally assured Mussolini that nothing antifascist would appear in the encyclopaedia. Second, the Catholic Church exercised a parallel influence. The managing editor was required to take ecclesiastical sensitivities into account, since Treccani, the principal patron, was a devout Catholic and commercial success depended on avoiding Vatican condemnation, an institution that even Mussolini had to consider. When the Pope objected to certain formulations in the entry on "Fascism" as incompatible with Catholic doctrine, and when he heard rumors that Gentile rather than Mussolini was its true author, printing was temporarily suspended in order to resolve the potential inconsistencies (Loveland, 2019). This assessment is supported by recent Italian scholarship. Fonzo (2021) demonstrates that the degree of ideological influence on the EI's entries varied considerably across disciplines and increased over time, reaching its peak in the 1938 Appendice I (Fonzo, 2021). At the same time, scholars acknowledge that traces of ideological bias can be found in any classic encyclopaedia (Dziuba, 2021).

One of the most widely praised features of the *EI* is the breadth and diversity of its contributors. At a time when few comparable projects could claim such scope, the undertaking mobilised thousands of specialists from Italy and abroad who represented virtually every field of knowledge. The team drew on scholars affiliated with numerous universities and research centres, as well as on a wide range of methodological traditions and intellectual currents. Within a single volume, one could encounter articles written from positivist, phenomenological, or historicist philosophical perspectives. This variety reflected the richness of Italian intellectual life in the interwar period.

The participation of so many authoritative scholars played a decisive role in establishing the encyclopaedia's reputation as one of Europe's most prestigious reference works. Its balanced treatment of the humanities, the natural sciences, and technology further distinguished it from earlier encyclopaedic enterprises, which often favored the humanities at the expense of other domains.

Among the leading Italian scholars and thinkers enlisted were:

- Federigo Enriques, mathematician and philosopher of science, who established the criteria for scientific precision and logical coherence;
- Federico Raffaele, biologist and zoologist renowned for his microbiological research;
- Roberto Almagià, the eminent geographer and cartographer responsible for maps and spatial descriptions, including those concerning the historical geography of the ancient world; his contributions contain references to the Black Sea, Crimea, and the Carpathians;
- Nicola Parravano, chemist and founder of the Italian school of physical chemistry;
- Enrico Fermi, theoretical physicist and 1938 Nobel laureate, who advised the editorial board on the latest advances in physics;
- Guglielmo Marconi, pioneer of radio communication, senator, and president of the Royal Academy of Italy, who served as president of the IEI (1933–1937) concurrently with his presidency of the Reale Accademia d'Italia. He was not merely an honorary figure but a key contributor, specifically authoring sections on "Radiocomunicazioni";

- Giulio Bertoni and Bruno Migliorini, leading linguists who shaped the encyclopaedia's terminological system and the sections devoted to the history and structure of the Italian language;
- Ugo Ojetti and Pietro Toesca, distinguished art historians responsible for the articles on art history, architecture, and aesthetics.

For entries on foreign countries, the editors enlisted several of Europe's most distinguished geographers. Emmanuel de Martonne of the Sorbonne wrote the sections on France and Romania. Herbert John Fleure contributed the entries on Great Britain and its colonies. Augustin Bernard prepared the material on the French colonial empire. Hans Wilhelmsson Ahlmann authored the sections on Scandinavia, and Griffith Taylor wrote the entry on Australia. The extensive article on Argentina was prepared by an entire team of Argentine scholars, which resulted in one of the longest entries in the encyclopaedia, exceeding 150 pages (Almagià, 1930).

In total, 3,272 individuals are recorded as contributors. The final work contained approximately 60,000 articles and 40,000 illustrations. Payment for a short entry generally ranged from 150 to 200 lire, a sum that provided welcome supplementary income for many academics (Gamba, 2022).

The Second World War brought the IEI into a period of profound crisis, during which operations were suspended and most staff were dismissed. After the war, the Institute was revived and extensively reorganised. As a symbolic gesture of renewal, the new republican government appointed Gaetano De Sanctis (1870–1957), a distinguished classicist and committed anti-fascist, as its president. Under his leadership, the editorial team concentrated on producing a series of updated appendices to the original *Enciclopedia Italiana* (Gerbi, 2003). At the same time, work accelerated on the long-planned national biographical dictionary, the *Dizionario Biografico degli Italiani*. Its first volume appeared in 1960, and the dictionary now comprises more than one hundred of the projected one hundred and ten volumes. A digital version is also available.

As Volodymyr Popyk has noted, biographical encyclopaedism enjoys a long and respected tradition in Italy. As early as the 1830s, under the direction of Emilio De Tipaldo, several volumes of *Biografie di illustri italiani* were published and later served as a model for similar projects. In Turin, Pompeo Tola (1800–1874) produced a three-volume *Dizionario biografico degli uomini illustri sardi* (1837–1838), devoted to notable figures of the Kingdom of Sardinia. At that time, the kingdom comprised Piedmont, Savoy, and Sardinia, and it soon became a stronghold of the movement for Italian unification (Popyk, 2011).

By the 1950s it had become evident that post-war Italy required an entirely new encyclopaedic project, one capable of meeting the intellectual and cultural needs of a transformed society. The IEI sought not only to rebuild public trust after its earlier association with the Fascist regime but also to introduce a renewed model of knowledge dissemination. The aim was to create a resource that was contemporary in content, accessible in form, and responsive to the expectations of a more democratic society.

This resulted in the emergence of the *Dizionario Enciclopedico Italiano*, an encyclopaedic dictionary that combined scholarly rigor with an intentional expansion of accessibility. Its chief editor, Umberto Bosco, sought to bring the encyclopaedia closer to the living language of everyday Italians and to transform it from a strictly academic resource into a practical reference tool for daily use. This goal was achieved primarily by greatly enlarging the list of headwords and substantially shortening the average length of entries. A distinctive feature of the project was the integration of the contemporary Italian lexical corpus into the encyclopaedic structure. In practice, dictionary entries were systematically reworked into concise encyclopaedic notes. It is worth recalling that the idea of producing a compact Italian encyclopaedia had already been considered by Giovanni Gentile during the planning of the original edition.

Between 1955 and 1961, the *Dizionario Enciclopedico Italiano* was published in twelve volumes. This encyclopaedic dictionary both continued the tradition established by the *EI* and introduced a new, more concise and accessible format that would shape many subsequent Italian reference works.

A related, though far more ambitious, undertaking was the *Lessico Universale Italiano*. While its predecessor remained primarily focused on Italian culture and the national context, this universal encyclopaedic dictionary aimed to encompass a much broader range of knowledge. It included material across the sciences and the humanities as well as extensive coverage of international topics and figures, extending far beyond Italy's borders. Its twenty-four volumes appeared between 1968 and 1981.

La Piccola Treccani, a compact twelve-volume encyclopaedic dictionary published by the Institute between 1995 and 1997, continued the trajectory established by the *Dizionario Enciclopedico Italiano* and the *Lessico Universale Italiano*.

Throughout the second half of the twentieth century, the Institute also produced a substantial range of thematic and biographical encyclopaedias, issued both as single-volume works and as multi-volume collections.

In the twenty-first century, the IEI has developed from a traditional publishing house into a modern cultural and scholarly centre that integrates the production of encyclopaedic and lexicographic works with research, educational outreach, and digital initiatives. A key component of this transformation has been the development and ongoing expansion of the portal treccani.it, which since early 2011 has served as Italy's primary access point for encyclopaedic, linguistic, and reference materials. The site unites thousands of articles from the classic *EI*, the biographical dictionary, various encyclopaedic dictionaries, specialised encyclopaedias, and multiple lexicographic databases. It has come to be widely recognised simply as the *Treccani* online encyclopaedia. As early as 2018, the digital *Treccani* offered at least half a million freely accessible articles (Bentzen, 2018).

In contrast to open collaborative platforms, the *Treccani* portal follows the principle of expert authorship, meaning that articles are commissioned, written, and edited exclusively by recognised specialists. This policy enables the encyclopaedia to serve as an intellectual filter and a reliable source of verified information, a role that has become increasingly important in the twenty-first century.

Although the IEI is no longer a state entity, the tradition of governmental patronage continues. Its president is formally appointed by the President of the Italian Republic (Bentzen, 2018). This arrangement underscores the institution's national significance and positions encyclopaedic work as a strategic component of Italy's cultural policy. The post has traditionally been held by distinguished figures from the fields of scholarship, culture, and education. Under the current president, the literary scholar Carlo Ossola, IEI continues to pursue its mission of serving as a "guarantor of verified knowledge" in an era marked by pervasive disinformation.

Within the extensive body of encyclopaedic articles, Ukrainian subjects hold a notable position. They are represented by numerous entries on history, culture, science, and prominent individuals and more than two hundred individuals connected to Ukraine were identified. In the contemporary sections of the portal devoted to international affairs, one finds entries on Ukraine's independence, the Revolution of Dignity, the war that began in 2022, and relations between Ukraine and the European Union. At the same time, we have not found any evidence of Ukrainian participation in the preparation of the original *EI*, either among the contributors or within the editorial staff. As a result, Ukrainian topics appear mainly as subjects interpreted from an external perspective rather than as material shaped directly by Ukrainian scholars. This situation calls for a systematic analysis of Ukrainian themes viewed through the Italian intellectual tradition and the resulting interpretive emphases within European encyclopaedic discourse.

Studies of this kind do more than deepen our understanding of the Ukrainian presence in global culture. They also help illuminate the history of Ukraine within the broadest possible historical and civilisational context. From the earliest periods of their recorded past, the Ukrainian lands formed a contact zone shaped by encounters, rivalries, and mutual influences among diverse civilisational communities. The complex and multifaceted history of the Ukrainian people is an inseparable component of the wider European and global historical process. Without situating this history within the wider course of world civilisation, any attempt to reconstruct a full and objective national narrative, or to clarify the place and role of Ukraine and the Ukrainian people within universal history, remains incomplete (Vidnianskyi, 2017, p. 10).

Conclusions.

The century-long evolution of the Istituto della Enciclopedia Italiana illustrates how a national encyclopaedic initiative of the interwar era developed into a multifaceted cultural and scholarly institution. It now integrates publishing, research, and digital forms of knowledge dissemination. The historical analysis shows that the Institute has maintained high academic standards while adapting to profound intellectual and technological changes. The findings demonstrate that the contemporary online platform preserves the continuity of Italian encyclopaedic culture and successfully translates traditional reference formats into a digital environment. The study identifies more than two hundred Ukraine-related entries. The absence of identifiable Ukrainian contributors in the available corpus points to the need for further research on how such materials may reflect Italian interpretative traditions. Although this article does not aim to reconstruct these interpretative patterns in detail, it highlights the relevance of *Treccani*'s corpus for understanding the dynamics of Ukrainian representation in European encyclopaedic discourse. This suggests the need for targeted comparative analysis of specific entries in order to identify interpretative patterns and the ways in which Ukraine is represented within the Italian encyclopaedic tradition.

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Історія формування італійської національної енциклопедичної традиції: Проєкт Treccani (1925–2025). Попереднє дослідження

Анотація. *У дослідженні проаналізовано виникнення та розвиток національної енциклопедичної традиції Італії, сформованої діяльністю Istituto della Enciclopedia Italiana fondata da Giovanni Treccani, сторіччя якого, що відзначається у 2025 році, створює важливий контекст для переосмислення його культурної місії. У роботі застосовано описовий та аналітичний методи з метою систематизації, інтерпретації та порівняння первинних і вторинних джерел, пов'язаних з історією італійської енциклопедистики. Визначено ключові риси, що утвердили Treccani як інтелектуальний проєкт державотворчого значення, зокрема раннє залучення академічної експертизи, територіально та дисциплінарно різноманітний авторський корпус і послідовне прагнення подавати верифіковані знання у межах єдиної гуманістичної концепції. Проаналізовано, як Інститут еволюціонував від амбітної міжвоєнної видавничої ініціативи до провідної наукової установи, що справила тривалий* *вплив на розвиток гуманітарних і соціальних наук в Італії. Особливу увагу приділено цифровій трансформації XXI століття, яка істотно розширила доступність, тематичний спектр і суспільну значущість енциклопедичних ресурсів Treccani. Досліджено також матеріали, пов'язані з українською тематикою, у друкованих та цифрових колекціях Інституту і встановлено, що українські науковці не брали безпосередньої участі у формуванні первісного енциклопедичного корпусу. Ця обставина засвідчує необхідність подальшого аналізу того, як українські сюжети інтерпретуються крізь призму італійської інтелектуальної традиції та репрезентуються у європейській довідковій культурі. Отримані результати підкреслюють роль Treccani як стійкої моделі національної консолідації знань і демонструють ширшу вагу енциклопедичних інституцій для культурної дипломатії та транскордонної інтелектуальної історії. Перспективи подальших досліджень можуть передбачати порівняльний аналіз національних енциклопедичних традицій та їх сучасних трансформацій.*

Ключові слова: *історія довідково-інформаційної діяльності; інтелектуальні традиції; європейська енциклопедистика; італійська енциклопедистика; енциклопедичні інституції; цифрова гуманітаристика*

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Evolution of Greek agriculture with emphasis on Interwar period: A historical approach

Abstract. *This article reviews the main events composing the developments of Greek agriculture during the Interwar period, paying tribute principally to agriculturists, the main actors to whom the State assigned the task and who bore the burden of materializing State's policy. However, a brief account is given at first to Greek agricultural evolution in the 19th century after the War of Independence of Greece from the Ottoman Empire in 1821, in order to pose the questions and give the physiognomy of the environment wherein various events took place. Such events included the struggle of landless peasants for settlement – a promise given by the State to the veterans of the War of Independence – as well as the Parliamentary Law for the expropriation of big estates (tsifliks) and the efforts for the agricultural settlement of native peasants. As regards the Interwar period there were two colossal tasks to be accomplished. Firstly, the final agricultural settlement of landless peasants, together with that of 1.3 million of Greek refugees arriving at mainland after the Greek catastrophic defeat by the Turks in Minor Asia in 1922. Secondly, the successful tackling of the greatest problem of the Greek agricultural history, namely wheat self-sufficiency and the rise of wheat production as well as the protection of wheat producers, who otherwise would be a prey to usurers' mercy. In addition, further milestones were laid in Greek agriculture during the Interwar period such as the establishment of the Ministry of Agriculture, the foundation of Agricultural Bank, the Agricultural University in Athens, the adoption of the Co-operatives Law, the great efforts for land reclamation and the introduction in the cultivation of modern agricultural machinery. Furthermore, brief account is also given to developments of Greek agriculture from 1940 onwards, including the confrontation of local people's famine during German Occupation through food provisioning, the Resistance, as well as the Civil War, the Truman Doctrine, the Marshal Plan, Food and Agriculture Organization mission to Greece and the country's Reconstruction, arriving at Greece's entry as a full member to the European Economic Community on 1st January 1981.*

Keywords*: Greece; refugees' agricultural settlement; wheat self-sufficiency; land reclamation*

Introduction.

The Interwar period from an agricultural point of view has been characterized as an "agricultural miracle". In general, Greece has a long and eventful history (Clogg, 2002). Being a mountainous country with Mediterranean climate, could not nourish large population, so that, since ancient times, big cities like Athens, imported considerable part of wheat required from abroad. This lack of wheat turned Greeks to the sea, reached naval supremacy, made colonies round the Mediterranean basin and the Black Sea, thus giving the Hellenic civilization to the humanity. Later on, in Byzantium, the torch was taken by Thessaloniki and Constantinople which were distinguished in the roads of international trade. Eventually, Hellenic people won top naval position globally for almost 3000 years up till now. This top naval position is still ongoing despite that Greece is a relatively small country.

Even if it seems oxymoron, starting-point for a brave uplift for Greece in the agricultural sector was the most tragic year of its modern history i.e. 1922, after the catastrophe they suffered in Minor Asia. It was in this tragic scene when, as an expression of contradiction which characterizes the Hellenic race, the great agricultural epic of the Interwar period was born. Following the Parliamentary Law for the creation of Central Agricultural Co-operatives Administration and the establishment of the Ministry of Agriculture during WWI, at that period the native landless peasants' but also the refugees' settlement was completed. In addition, Agricultural Bank was established and land reclamation works started, but especially the dragged-on question for wheat self-sufficiency was tackled and the foundations were put for solving this major problem.

The purpose of the present article is to lighten the relevant historiography so that make known to a broader readership the achievements of Greek agriculturists this era, so that this period to be called as an "agricultural miracle".

Methodology.

The present study tries to put past events composing of works which took place in the agricultural sector during the Interwar period in chronological order. It necessitated the use of archive material taken from various sites throughout Greece, mainly the library of Agricultural University of Athens. Additionally, the author, by reviewing this issue, made use of further sources including dissertations, books, symposia proceedings or scientific journals. Finally, the author used also a narrative approach by interviewing in the past various people who lived and worked for Greek agriculture in the Interwar era. In this respect I talked to Prof. Andreas I. Karamanos, son of Ioannis Stav. Karamanos, Director General in the epic of agricultural settlement of Greek refugees after the Catastrophe in Minor Asia, but I talked also, just before he died, to Prof. Ioannis Papadakis, the one who solved the greatest problem of Greek history, that of achieving wheat self-sufficiency.

Results and Discussion.

Reference to Greek agriculture since the War of Independence from Ottoman Empire up to the end of WWI (World War One).

From year 1821 to 1918.

The arrival of Ioannis Kapodistrias at Greece in January 1828 is usually considered as starting point for the date of the Modern Greek History, although Greece's Independence was declared in 1830 and the borders of its territory were eventually fixed in 1832 (Dakin, 1952). With the beginning of 1827, the situation in Greece had come to a terrible situation and the Greeks finding themselves in front of a dead end, due to the existing civil wars in the country, they decided, above all, to call as a leader a Greek from abroad, since nobody was proposed by the natives. Thus, on 14 April 1827, the Hellenic General Assembly in Trizina elected Ioannis Kapodistrias, minister of Foreign Eastern Affairs of the Char Alexander I at the time. Kapodistrias before arriving at Greece visited various places in Europe to meet members of Philhellenism movement and among them the Swiss banker John-Gabriel Eynard, who became invaluable supporter of his country (Trelawny, 1858).

Arriving at Greece, Kapodistrias found the country in a situation of anarchy. He quickly improved the situation of the country, causing, however, strong and ruthless opposition. So he rushed to the organization of the State according to the Western way of life. His tireless and versatile diligence caused the admiration of the others. Unfortunately, due to the sudden leap in transplanting institutions from abroad, namely the West, with simultaneous ignorance on the internal traditions of the community he failed in his attempt for agricultural reforms and caused criticism to his policy.

Despite the mentality of locals to adopt Western ideas, as far as the agricultural reform is concerned, Kapodistrias put emphasis on strengthening of agriculture, the basic pylon of Greek economy. Poverty, anarchy and lack of means of production, as well as of high yielding animals, were characteristic of that era in Greece. He believed in possibilities of development for plant and animal production, which constitute the main means for the country to rely on its own resources. For the better coordination of his agricultural policy, he established in Tyrintha of Peloponnese a State-owned farm with a model of Agricultural School. However, the measures he undertook could not have substantial results, since the landless peasants had not acquired their own land. Finally, his opponents managed to assassinate him on 27 September 1831 at the town of Nauplia (Woodhouse, 1973).

Before he died, Kapodistrias had called a distinguished Greek agriculturist from France. His name was Gregorios Palaiologos and he appointed him as director of the Agricultural School at Tyrintha 1830. This man offered great services to the affair of Greek agriculture. However, after Kapodistrias' assassination, Palaiologos became a victim of political parties' passions and of the phenomenon of position-seekers, which had emerged from the very first years after the War of Independence. Thus, Palaiologos soon after, driven to despair, left his position and the country. But also, all his successors had the same destiny, so that the Agricultural School at Tyrintha came to a definite close in 1872.

Another agricultural issue one would consider during this period was the raisin or currant crises which was accompanied by the country's bankruptcy and defeat by the Turks in 1897. The average size of Greek holdings was small and to that size suited the cultivation of raisins. In this respect, the vineyards of North and Western Peloponnese were thriving and their product was exported to the market of Great Britain.As a matter of fact, after the appearance of extremely harmful insect Phylloxera (*Phylloxera vastatrix or vitifolia*) in 1878 in French vineyards, the demand of Greek raisins for export increased considerably. But when the French vineyards recovered after control of Phylloxera, the demand for Greek raisins dropped dramatically and the relevant producers were bankrupted, while unemployment prevailed. Then, Greece could not borrow money from abroad and eventually was bankrupted in 1897. The same period a small group of young officers wanted to expand Greece's borders at the time. This alarmed the Turks and Greece as not prepared enough for a war was eventually defeated.

During that period, some achievements took place in the agricultural sector, such as the Parliamentary voting of the Law No 602 for the establishment of central and peripheral unions of Agricultural Cooperatives in 1914 and the establishment of Ministry of Agriculture in 1917, where dominant role had played the distinguished agriculturist Spyridon Chasiotis. The establishment of Agricultural bank took place in 1929 with main actor the agriculturist Socrates Iasemides. Great scientists emerged that era like Panagiotis Gennadios in plant production and Raylond Dimitriades in animal production. The latter, more than one hundred years ago, expressed ideas on animal physiology and metabolism which take precedence over some of the innovative ones of today (Zoiopoulos & Drosinos, 2010). It should be stated also that during this period two schools —no university level though— one was the Averofian Agricultural School in Larissa and the other the American Farm School started operating in Thessaloniki (Marder, 1979).

However, the questions still pending during the period up to the end of WWI were, on the one hand the struggle of landless peasants for settlement, a promise given by the state to veterans of the War of Independence from Ottoman Empire —and on the other, the Parliamentary Law for the expropriation of big private estates (tsifliks) (Evelpides, 1933a). Governments at the time tried to care about peasants since the agricultural political parties had a big number of supporters (Hobsbawm, 1973), so that one could call 20th century as the century of peasant wars (Dakin, 1972; Wolf, 1999). This Law eventually was issued but was ineffective until 1922 when the Greek catastrophe in Minor Asia took place (Alivizatos, 1932; Kane & Mann, 1993).

The Interwar period (1919–1939).

1920 was a milestone year for agriculture in Greece since the first University level institution was established in Athens, the so-called Superior Agricultural School of Athens. This was the result of the efforts mainly of the eminent agriculturist Spyridon Chasiotis, who, as it was mentioned above, he was also the man by whom the establishment of the Ministry of Agriculture was achieved in 1917. Chasiotis was appointed professor and first director of the Superior School.

However, in year 1920, something unexpected happened in the political life of Greece. In brief, the greatest Greek politician of the 20th century, the Cretan Liberal Eleftherios Venizelos, was forced to declare elections in 1920 although he could delay it for a while. Venizelos, contrary to the king of Greece Konstantinos I, foresaw the eventual victory of the Anglo-French alliance, the so-called Entente, against the Germans in WWI and supported Entente, while the king who had married Kaizer's sister Sophia, he wanted Greece to remain neutral. Then a schism was created between the government and the palace. Eventually, King Konstantinos was overthrown by Entente and succeeded by his son Alexander. After the victorious outcome of the war for Entente, the latter granted to Greece, through Venizelos, the city of Smyrna and the surrounding area in Minor Asia.

However, Venizelos' opposition forced him to hold elections on the ground that Greek soldiers who fought continuously for eight years since 1912 in Balcan Wars and later in WWI, should be tired, thus they had to stop war and come back to their homes. Greek people liked this idea and voted against Venizelos who lost the election, but after the victorious election the Conservatives went back on their word and instead of stopping the War they ordered the army to go far in the interior of Turkey, without being able to assist with arms and food supplies the extremely long frontier. Then a gifted leader emerged for Turkey, namely Kemal Ataturk and Turks won the War so that 1.3 million Greek refugees were forced to leave their home places. These people were helped by Greek ships to cross the Aegean Sea and escape to the Greek mainland.

When one refers to Greece of 1922, he/she talks about a country which was coming out of catastrophe in Minor Asia. This poor country of 5.5 million people, with dominant problem that of lack of wheat, had to nourish 1.3 million of ragged refugees who had to share the little cultivated land with the natives, who were producing mainly for self-maintenance. In addition, the landless ones as tenant farmers (crofters) were still waiting for settlement in the framework of agrarian reforms, which took place in 1917, when Law No 1072 had been voted in the Parliament. This Law which constituted the most daring piece of legislation produced in Modern Greece, it had not been applied until the catastrophe in Minor Asia. One could not imagine worse combination of adverse conditions for Greece other than those of 1922 (Eddy, 1931; Mazower, 1987, 1991; Seferiadis, 1999).

There were two kinds of settlements for refugees. The urban one round the two big cities of Greece namely Athens in the south (Kritikos, 2000) and Thessaloniki in the north, as well as the agricultural one mainly in the north districts i.e. Macedonia and Thrace. Venizelos favoured the exchange of populations between Greece and Turky, since, in this sense, State lands would be set free, mainly in Macedonia and Thrace, where they could host the eradicated Greek refugees from Minor Asia. Thoughts on the exchange of populations have been published by Pentzopoulos (1962), Kritikos (2001), Petropoulos (1976) and Ladas (1931). The agricultural settlement of refugees which is an issue of political and sociological nature, was assigned by the

State to agriculturists, although the latter had not heard anything about colonization in their studies.

For the agricultural settlement of refugees at Macedonia and Thrace, as leader was appointed by the State the eminent agriculturist Ioannis Stav. Karamanos (Morgenthau, 1929). It should be stated at this point that the struggle of peasants for reforms in Greece, which started early in the 20th century, continued also during the Interwar period. For the issue of refugees' settlement Howland (1926) and Evelpides (1926) have reported in extent. The agricultural colonization of refugees appears to be more difficult than the urban one, since, in addition, land should have been secured for them. Furthermore, it should be stressed that the settlement of refugees in Greece, together with that of the landless native peasants was effected without any bloodshed, whereas the agricultural reform in Spain during the Interwar period, lead to a bloody Civil War conflict, between the Democrats then in power and the forces of Dictator Franco who eventually prevailed (Malefakis, 1970).

The CSR (Commission for the Settlement of Refugees) was set up by the Society of Nations (the nowadays Organization of the United Nations). First President of the CSR was Henry Morgenthau. This man was succeeded by Charles Howland in 1924 and Charles Eddy in 1926. Henry Morgenthau described the Greek Director General of CSR Ioannis Karamanos as «He was a flashing figure like that of the Homer's hero Achilles, born leader» (Morgenthau, 1929). For the issue of refugees settlement in Greece wrote, among others, Kontogeorgi (1976).

Let us now proceed to the next big question for Greek Agriculture in the Interwar period, namely the efforts for achieving wheat self-sufficiency for the country. Greece compared to the major wheat granaries of the world i.e. Ukraine in Europe and Canada in the Americas, was characterized by the lack of wheat production. Greece being a mountainous country, with Mediterranean climate and few rainfalls, could not nourish large population. Lack of wheat refers to bread production for humans. For animal sector other cereals were grown like barley, oats, rye, whereas sheep and goats were kept in a nomadic way utilizing mountainous grass lands. The lack of wheat was the most crucial question to be answered in Greek agricultural history. Even if it seems oxymoron, starting point for a brave uplift for Greece in this sector, namely wheat self-sufficiency, was the most tragic year in its Modern history i.e. 1922 and this issue was developed just above in the present paper. It was in this tragic scene where, as an expression of a contradiction which characterizes the Hellenic race, the great agricultural epic of the Interwar period was born. Here another paradox happened. The man who took the solution of the most difficult problem of Greece, i.e. wheat self-sufficiency upon his shoulders, was a 20 year old agriculturist, just having graduated from Belgium. His name Ioannis Papadakis.

The author of the present study has published an extensive article in this journal the last couple of years about the Greek scientist Ioannis Papadakis (1903–1997) as being one of the greatest national and ecumenical agriculturists of the 20th century (Zoiopoulos, 2024). In brief, Papadakis studied agriculture in Gembloux near Liege, Belgium and did post-graduate studies in plant propagation in Paris. Returned to

Greece in 1923 as a lecturer of agronomy in the newly established Agricultural University of Athens. There, Professor Spyridon Chasiotis directed him to deal with tackling the problem of wheat self-sufficiency. They appointed him at a new institution in the granary of Greece namely Larissa, and after that Ioannis Karamanos, Director General of CSR, called him to Thessaloniki in the North of Greece, where he built an Institution for Plant Improvement, so that Papadakis worked in the framework of CSR.

Blaxter (1976) spoke about "the art and science of agriculture". Ioannis Papadakis was a versatile genius. He was highly qualified in Mathematics, Statistics as Biometry in particular, Soil Science (Papadakis, 1941a; 1941b), while he wrote the eleven large size pages entry «Soils» in Encyclopedia Britannica (Papadakis, 1998). In addition, Ioannis Papadakis dealt with ecological issues (Papadakis, 1964), but also with social, political and economic subjects. Furthermore, Papadakis devoted himself to the supply of Greece with fertilizers, something which was enhanced with the visit of FAO (Food and Agriculture Organization) mission to Greece (Anonymous, 1947). Papadakis with his efforts on agronomy research managed to increase Greece's yearly wheat production by three times in fifteen years from 1923 to 1938, but wheat self-sufficiency for the country was achieved only by 1957 after the propagation for the use of chemical fertilizers. The rational use of fertilizers is important for a country (Arapostathis, 2017).

Although there was some criticism for the application of single wheat cultivation in Greece,i.e. Ploumidis (2024), who argued whether emphasis should be given to single wheat cultivation by neglecting other crops like forages, nevertheless the need for reaching wheat sustainability in a country is well documented (Korpetis et al, 2023; Tsompanoglou, 2024; Xynias et al, 2020). Jonathan Swift in his book «Gulliver's Travels» quotes: «Whoever could make two ears of corn or two blades of grass to grow upon a spot of ground where only one grew before would deserve better of mankind…». At this point, it should be noted that Papadakis had published a book in French titled «Ecologie Agricole» (Papadakis, 1938), and when Argentina called him to organize the ecological map of the country in 1947 he emigrated to that country permanently, since some rivals researchers in Greece accused him unfairly of being a Leftist.

During the Interwar period, further important agricultural feats where achieved in Greece. Firstly, land reclamation works were started, whereby poor lands where converted to irrigated ones and secondly extensive works were effected on land draining to improve land fertility. The same period, a second Agricultural University was established in 1927 in the north as department of the Aristotle University of Thessaloniki, and a number of research institutions were built and started operating throughout the country. One should not forget to refer to the Balcan conferences which took place during the Interwar period around the year 1930, to improve friendship and commercial cooperation between Balkan countries, during this difficult period (Evelpides, 1930; Papanastasiou, 1932).

In the political scene, Greece stopped operating as a kingdom and from 1924 the State's regime was turned to be a Republic. But this did not last for long (Mavrogordatos, 1983), since from 1935, after a referendum, King George II was called back to reign. During the period of the Republic, and following the economic Crash of 1929 in the States which influenced the international economic situation and the trade of agricultural commodities, Greece pursued the policy of autarky. However, this lead to autarchy rather imposed by dictator General Ioannis Metaxas in August 1936, which lasted until the invasion of Germans to Greece in April 1941 (Cliadakis, 1979; Mazower, 1987, 1991; Sarandis, 1979; Veremis, 1976; Waterlow, 1947).

During the Metaxas' junta in 1937 an event took place which affected adversely higher agricultural education in Greece. Actually, Babis Alivizatos submitted his candidature for a professorship in the Superior School of Agriculture in Athens. He was a man of high scientific caliber, warm-hearted supporter of the agricultural reforms in Greece in favour for the settlement of the landless peasants (Alivizatos, 1932). Unfortunately, Alivizatos earlier had expressed the view that the central School of Agriculture should be moved outside of the capital, to the countryside and he paid dearly for that, since the electorate punished him and voted against his election at the university chair. However, Alivizatos was a fellow-townsman of dictator Metaxas, i.e. from the island of Cephalonia in the Ionian Sea. Then, the dictator ordered the closure of the School of Agriculture in Athens and the latter was transferred to Thessaloniki. The School returned to Athens in 1943 during German Occupation, when a member of the quisling Government of the collaborators G. Pamboukas was elected professor at the School and this man cared so that the closed institution returns to Athens.

The Bitter Decade 1940–1950.

One could divide that period in five parts: 1) the epic of the defending war of Greece in Albania 2) the German Occupation of Greece 3) the Resistance of the natives 4) the Liberation of the country from the Germans and 5) the bloody Civil War. Woodhouse (1981) refers to that period but only from a political point of view. Little has been written about agricultural events. After Greece's army had beaten Mussolini's troops as part of the Axis in the soil of Albania from 28th October 1940 and for six months, eventually Greek Army was defeated by German invaders and Greece was occupied from 21st April 1941 for almost four years. The main problem for Greece during Occupation from Germans was to tackle the harsh famine by providing food to the people.

For German Occupation of Greece and Resistance, as well as the Civil War, Woodhouse (1947, 1976, 1981) has written in extent. It should be underlined that the first winter of the German Occupation was extremely cold and the situation was made much worse due to the lack of food, since the first 15000 tones of food from the Red Cross came from abroad via Turkey in the mid of 1942. At that year, deaths from starvation and famine, mainly for children in urban parts of the country, were the highest, through the period of Occupation, while «black market», inflation and violence prevailed (Kazamias, 1992). During German Occupation, in the framework of Greek Resistance, the organization NLF (National Liberation Front) started operating by both rights (Conservatives) and leftists (Communists). However, these people at the end of the Occupation period appeared to be divided. At the beginning of the Liberation period elections were held in Greece, but the leftists did not participate and chose a guerilla Civil War instead, with bloodshed for both sides (Iatrides & Wringley, 1995; Mathews, 1972; Tsoucalas, 1969; Vlavianos, 1989; Woodhouse, 1947). In 1947 Truman Doctrine, and in a few weeks, the Marshall plan were announced. These were aiming at the financial support, among other Western countries of Greece, with a view to limiting the expanding of Communism from neighbouring countries (Alexander, 1982; Delivanis, 1967; Mazower, 2000; McNeill, 1978; Shaw, 1969; Warren, 1978; Xydis, 1967).

After the German Occupation an unexpected phenomenon took place in Greece. As a matter of fact, during the Greek civil war which followed the German Occupation, various position-seekers belonging to the right-wing who prevailed at the time, accused some rival scientists of being leftists, but this was unfair. It was mentioned earlier that one who suffered from this, was Ioannis Papadakis, who emigrated to Argentina for long. Another was Demetrius Kavadas who was the founder of science of Phytopathology in Greece and taught also Botany. After the WWII he was fired from the Aristotle University of Thessaloniki forever. Following that, Kavadas wrote the colossal nine volume Botanical Dictionary. But the most distinct case was that of Professor Nikolaos Roussopoulos. The latter was fired from the Agricultural University chair at Athens in 1945 for five years. He was teaching the fundamental subject of agricultural chemistry. After coming back, he was elected twice as rector of the University and eventually Member of Athens Academy. N. Roussopoulos during the Greek Civil War wrote the book «Introduction to the Laws of Plant Yields», whereby, forgetting the so far generalized descriptive nature of agricultural education, he moved towards a quantitative approach, by introducing mathematics in the education of agricultural subjects.

From 1950 up Till Now.

There are plenty of activities which constitute what one would call agriculture, as regards plant but also animal production. In Greece, the main cultivated crop is olive tree. Together with two other countries round the Mediterranean basin i.e. Spain and Italy, these are the biggest olive oil producing countries in the world. Cotton also is an important crop in Greece (Christides & Harrison, 1951). Actually, Greece was the only cotton producing Member State when entered into the EEC (European Economic Community) in 1981. As far as animal production is concerned the most important branch, practiced in Greece, is sheep and goats production, kept in a rather extensive way (Volanis et al, 2007). Following quite a long period of democracy in Greece, a new junta by the so-called army Colonels was imposed in 1967, which after seven years of governing, led to another catastrophe of the Hellenism in Cyprus in 1974. The only case an agricultural activity was improved during dictatorship was pig production. Pig production in Greece (Zoiopoulos, 1986) is connected to a special dish, namely «souvlaki», whose consumption is associated with the development of tourism. Greece at the time was much far from being self sufficient in pork. The government then financed and subsidized generously this sector and eventually Greece reached self-sufficiency in pork. It should be mentioned that, from end of '50s, a new dynamic sector, that of aquaculture (fish farming), started being developed in Greece.

After the fall of junta in 1974, Greece living under a democratic regime and based on the vision and efforts of the elected Prime Minister Constantine Karamanlis on 1st January 1981 joined the EEC as its 10th Member State. Then Greece started participating in various Community research projects, particularly in the more critical area, that of animal production (Henry, Vogt, & Zoiopoulos, 1988). The various agricultural matters within the EEC (now EU (European Union) have been always governed by the Community Legislation and, in this respect, Greece did not constitute an exception (Katogianni et al., 2008).

During its stay in the EU, Greece had to face and control certain food crises, like the one on dioxins (Natskoulis & Zoiopoulos, 2014). It should be mentioned that the impact of such crises, like the one with dioxins, which resulted to the drop of Jean-Luke Dean's government in Brussels, is terrible. In tackling food crises, Member States had to apply new techniques in the area of food control such as HACCP (Hazard Analysis and Critical Control Points) (Milios et al, 2013). Furthermore, another delicate subject concerning the safety of the consumer was that of GMO's (Genetically Modified Organisms), particularly in the area of animal feeds, where maize, the top cereal, and soya bean, the top plant protein in the world, are involved (Zoiopoulos, 1998; Zoiopoulos & Natskoulis, 2013). Eventually, new forms of a cleaner agriculture, namely organic, free from the use of chemicals, were proposed and legislated upon by the Community (Zoiopoulos and Hadjigeorgiou, 2013; Zoiopoulos & Natskoulis, 2025).

Conclusions.

Plethora of events took place in the sector of Agriculture in Greece, since the War of Independence from the Ottoman Empire in 1821 till now. However, one should distinguish two outstanding feats, which were achieved during the Interwar period. First, the agricultural settlement of landless peasants, together with that of hundred thousand of Greek refugees coming to mainland after the catastrophic war of Greece in Minor Asia, and second the successful tackling of the greatest problem of the Hellenic race, that of wheat self-sufficiency. The present article concludes with some beneficial effects derived from the rational practicing of agriculture, after Greece's entering into the EEC in 1981.

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Еволюція сільського господарства Греції у міжвоєнний період: історичний підхід

Анотація. *У статті розглядаються основні події, що визначали розвиток сільського господарства Греції в міжвоєнний період, із особливою увагою до аграріїв – головних виконавців, яким держава доручила реалізацію своєї політики і які несли основний тягар її втілення. Водночас на початку подано короткий огляд розвитку грецького сільського господарства у XIX столітті після війни за незалежність Греції від Османської імперії 1821 року з метою окреслення проблематики та характеристики середовища, в якому відбувалися подальші події. Серед них – боротьба безземельних селян за отримання землі (обіцянка, надана державою ветеранам війни за незалежність), прийняття парламентського закону про експропріацію великих маєтків, а також зусилля щодо аграрного розселення місцевих селян. Щодо міжвоєнного періоду, перед державою постали два масштабні завдання. По-перше, завершення аграрного розселення безземельних селян, а також розселення 1,3 млн грецьких біженців,* *які прибули на материкову частину країни після катастрофічної поразки Греції у війні з Туреччиною в Малій Азії у 1922 році. По-друге, успішне вирішення найбільшої проблеми в історії грецького сільського господарства – досягнення самозабезпечення пшеницею, зростання її виробництва та захист виробників пшениці, які інакше могли б стати жертвами лихварів. Крім того, у міжвоєнний період були закладені важливі основи розвитку грецького сільського господарства, зокрема створення Міністерства сільського господарства, заснування Сільськогосподарського банку, відкриття Сільськогосподарського університету в Афінах, прийняття закону про кооперативи, масштабні роботи з меліорації земель і впровадження сучасної сільськогосподарської техніки. Також подано короткий огляд розвитку грецького сільського господарства після 1940 року, включаючи боротьбу з голодом серед місцевого населення під час німецької окупації шляхом забезпечення продовольством, рух Опору, громадянську війну, Доктрину Трумена, План Маршалла, місію Продовольчої та Сільськогосподарської Організації ООН у Греції та відбудову країни, аж до вступу Греції як повноправного члена до Європейського Економічного Співтовариства 1 січня 1981 року.*

Ключові слова: *Греція; аграрне розселення біженців; самозабезпечення пшеницею; меліорація земель*

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Blown glass in Ukraine: Historical and technological features in comparison with Murano and Bohemian glass traditions

Abstract. *The purpose of this study is to identify the historical and technological characteristics of Ukrainian blown glass through a comparative analysis of Ukrainian, Murano, and Bohemian glassmaking traditions. The article examines the development of glass production in Ukrainian lands from the sixteenth century to the twentieth century and evaluates its place within the broader context of European glassmaking. The research is based on methods of historical analysis, comparative technological analysis, and material culture studies. The source base includes historical, archaeological, archaeometric, and art-historical publications devoted to glassmaking technologies, forest glassworks, artistic glass production, and the preservation of traditional manufacturing knowledge. Particular attention is paid to the technological aspects of glass production, including raw materials, glass compositions, furnace technologies, manufacturing practices, and mechanisms of technological knowledge* *transmission. The study demonstrates that Ukrainian blown glass developed under conditions significantly different from those that shaped the Murano and Bohemian traditions. Unlike the highly regulated and centralized production system of Murano, Ukrainian glassmaking evolved through a decentralized network of forest glassworks dependent on local resources and empirical knowledge. In contrast to the increasingly standardized and export-oriented Bohemian model, Ukrainian hutas remained closely connected to regional markets and adapted production technologies to local environmental and economic conditions. The research shows that the technological characteristics of Ukrainian blown glass, including chemical variability, visible inclusions, colour variations, and irregular forms, were direct consequences of the production environment and should be interpreted as material evidence of historical manufacturing processes rather than solely as indicators of technological limitations. The article further analyses the transformation of huta traditions during the twentieth century. It is demonstrated that many technological practices associated with historical forest glassworks survived within artistic glass production, educational institutions, and professional communities. As a result, huta technologies gradually evolved from a regional manufacturing system into a form of technological and cultural heritage. The study concludes that Ukrainian blown glass should be regarded as a distinct historical and technological trajectory within European glassmaking rather than as a peripheral variant of the Murano or Bohemian traditions. The comparative analysis highlights the diversity of technological solutions that coexisted in European glass production and contributes to a broader understanding of the relationship between technology, craft knowledge, natural resources, and cultural development in the history of material technologies.*

Keywords: *Ukrainian huta glass; decorative arts; glassmaking technology; glass art; glassware design; museum glass collections*

Introduction.

Glassmaking belongs to the oldest technological activities in human history and has accompanied the development of societies for more than two millennia. Throughout this period, glass served not only as a material for utilitarian and decorative objects but also as a medium through which technological knowledge, manufacturing skills, and craft traditions were accumulated and transmitted. Although the basic principles of glass production remained relatively stable over long periods, the technological systems that emerged in different regions of Europe varied considerably according to available raw materials, fuel resources, production organization, and market conditions. As a result, historical glass objects provide important evidence for studying the interaction between technology, economy, and culture.

Among the best-known European centres of glass production were Murano near Venice and the glassmaking regions of Bohemia. Both achieved international recognition and exerted a lasting influence on the development of European glassmaking. Murano became famous for the production of highly transparent *cristallo* and for a manufacturing system based on institutional control, technological specialization, and the protection of production knowledge. Research has demonstrated that the success of the Venetian industry depended not only on technological innovation but also on the ability of the Venetian Republic to regulate the movement of skilled craftsmen and maintain control over specialized manufacturing expertise (De Raedt, Janssens, Veeckman, Vincze, Vekemans, & Jeffries, 2001; Trivellato, 2006; Veronesi, 2024). Bohemian glassmaking followed a different path. Relying on forest resources and potash-based glass compositions, Bohemian producers gradually developed a technologically distinctive tradition that culminated in the emergence of crystal glass during the seventeenth and eighteenth centuries (Ogilvie, 2014; Pánová, Jílková, Rohanová, Lahodný, Galusková, & Míka, 2021). Recent archaeometric studies have confirmed the importance of potassium-rich glass systems in the formation of Bohemian glass technology and have highlighted significant differences between Bohemian and Venetian production traditions (Cílová & Woitsch, 2012; Pánová, Rohanová, & Randáková, 2020).

The history of glassmaking in Ukrainian lands evolved under different environmental and economic conditions. From the sixteenth century onward, numerous forest glassworks operated in Volhynia, Polissia, Galicia, and Podillia (Hoshko, 1991; Rozhankivskyi, 1959). These enterprises, commonly known as *hutas*, formed part of a broader Central and Eastern European tradition of forest glass production. Their operation depended on local deposits of silica sand, large quantities of wood fuel, and potash obtained from plant ash. Unlike the concentrated and highly regulated production systems of Murano, Ukrainian glassmaking developed through a dispersed network of relatively small workshops closely connected with woodland resources, estate economies, and regional markets.

The technological consequences of this production model were significant. Variability in raw materials, furnace conditions, and manufacturing practices frequently produced glass with visible bubbles, inclusions, colour variations, and asymmetrical forms. While such characteristics are often evaluated negatively from the perspective of modern industrial standards, they constitute valuable evidence for historians of technology because they preserve information about production environments, material constraints, and manufacturing practices. Historical glass therefore represents more than a finished artefact; it serves as a material record of technological processes and technological knowledge.

In recent decades, scholars have substantially expanded knowledge of historical glassmaking in Europe through the combined use of historical, archaeological, and archaeometric methods. Studies of Murano and Bohemian glass have generated extensive literature devoted to production technologies, raw materials, trade networks, and technological innovation. Research on Ukrainian glassmaking has likewise advanced considerably, particularly regarding the geography of glassmaking centres, the economic role of forest glassworks, and the artistic characteristics of historical glass artefacts. Nevertheless, Ukrainian blown glass continues to be examined primarily within archaeological, ethnographic, or art-historical frameworks. Comparative studies that analyse Ukrainian glassmaking alongside the major European glass traditions from the perspective of the history of technology remain relatively limited.

This situation raises several important questions. To what extent did Ukrainian blown glass share technological characteristics with the better-known glassmaking traditions of Murano and Bohemia? How did differences in natural resources, production organization, and systems of knowledge transmission influence the development of these traditions? Can Ukrainian huta production be understood merely as a regional manifestation of broader European processes, or did it represent a distinct technological trajectory within the history of glassmaking?

The aim of this article is to analyse the historical and technological development of Ukrainian blown glass in comparison with the Murano and Bohemian glassmaking traditions and to determine the factors that shaped its distinctive trajectory within European glass production.

To achieve this aim, the study examines the origins and development of blown glass production in Ukrainian lands, analyses the technological characteristics of raw materials, furnaces, and manufacturing practices, investigates the organizational and technological features of the Murano and Bohemian glassmaking centres, and compares these traditions with Ukrainian glassmaking from the perspective of production systems, technological knowledge, and material technologies. Particular attention is also paid to the transformation of huta traditions during the twentieth century, when many elements of historical glassmaking survived within artistic production, educational institutions, and heritage practices.

Unlike most previous studies, which have examined Ukrainian glassmaking primarily through archaeological, ethnographic, or art-historical approaches, this article considers blown glass as a technological system. The novelty of the study lies in the comparative analysis of Ukrainian, Murano, and Bohemian glassmaking traditions through the lenses of production organization, resource use, technological knowledge, and manufacturing practices. Such an approach makes it possible to identify not only differences in the finished products but also the historical factors that shaped distinct models of glass production in different parts of Europe.

Methodology.

This study is situated within the field of the history of technology and combines approaches drawn from historical research, comparative technological analysis, and material culture studies. The objective is not to reconstruct the artistic evolution of glass objects but to examine the technological systems that shaped the development of glassmaking traditions in Ukraine, Murano, and Bohemia.

The research is based on the principle that glass artefacts can be examined as historical evidence of technological processes. In addition to written sources, information concerning raw materials, production methods, furnace technologies, and manufacturing practices may be derived from the physical characteristics of surviving objects and from archaeometric investigations of historical glass. Consequently, the study integrates evidence from historical documents, archaeological research, materials analysis, and scholarship on glass technology.

The source base includes several categories of materials. The first consists of historical studies devoted to the development of glassmaking in Ukraine, Venice, and Bohemia. The second includes archaeological and archaeometric publications that provide information regarding glass compositions, raw materials, and production technologies. Particular attention is paid to studies employing chemical analyses of historical glass because such investigations make it possible to identify technological differences between soda-lime and potash-based glass traditions. The third category includes publications devoted to artistic glass production and the preservation of huta traditions during the twentieth century. These materials provide evidence concerning the continuity and transformation of technological knowledge after the decline of traditional forest glassworks.

The methodological foundation of the study is comparative historical analysis. This approach allows the examination of similarities and differences between three major European glassmaking traditions while taking into account the specific environmental, economic, and institutional conditions in which they developed. The comparison is conducted according to several technological parameters, including the organization of production, sources of raw materials, composition of glass batches, furnace technologies, methods of knowledge transmission, and product specialization.

The study also employs elements of the systems approach frequently used in the history of technology. Rather than treating individual glass objects as isolated artefacts, glassmaking is considered a technological system composed of interconnected components. These components include natural resources, production facilities, skilled labour, technological knowledge, market structures, and institutional frameworks. Such an approach makes it possible to explain why similar technological objectives were achieved through different production models in Murano, Bohemia, and Ukrainian hutas.

Another important methodological principle is contextualization. Technological processes are analysed within their historical environment rather than evaluated according to modern industrial standards. This principle is particularly important when interpreting characteristics such as bubbles, inclusions, colour variations, and asymmetries in historical glass. Features that may be regarded as imperfections from the perspective of contemporary manufacturing are treated here as evidence of specific production conditions and technological choices.

The study further applies concepts derived from heritage studies and the history of material culture. This perspective is especially relevant for the analysis of twentieth-century developments, when traditional blown glass technologies ceased to function primarily as an economic production system and increasingly became part of cultural and technological heritage. The research therefore examines not only the manufacture of glass objects but also the preservation, transmission, and reinterpretation of technological knowledge.

By combining comparative historical analysis, the systems approach, and the study of material culture, the article seeks to reconstruct the technological logic underlying different European glassmaking traditions and to identify the distinctive features of Ukrainian blown glass within this broader historical context.

Historiography and Sources.

The history of glassmaking has attracted scholarly attention for more than a century and has generated a substantial body of literature spanning archaeology, economic history, art history, archaeometry, and the history of technology. However, research traditions have developed unevenly across Europe. While Murano and Bohemia have become central subjects of international scholarship, Ukrainian blown glass has more often been studied within regional archaeological and artistic contexts.

Research on Murano glass initially developed within the framework of art history and museum studies, focusing on stylistic development, workshop production, and the attribution of individual artefacts. Since the late twentieth century, scholars have increasingly approached Murano as a technological and economic system. Particular attention has been devoted to the organization of production, the circulation of skilled labour, the protection of manufacturing knowledge, and the relationship between technological innovation and state regulation. Francesca Trivellato demonstrated that the development of Venetian glassmaking cannot be understood solely through artistic achievements but must also be analysed through guild institutions, commercial networks, and systems of technological control (Trivellato, 2006). Her work substantially broadened the historiographical understanding of Murano beyond traditional art-historical narratives.

Recent archaeometric investigations have further expanded knowledge of Venetian glass technologies (Burkart, 2021; Verità, Lehuédé, Zecchin, & Bandiera, 2024; Veronesi, 2024). Analytical studies of medieval and Renaissance glass from Murano have revealed the importance of Levantine soda ash and highly purified silica sources in achieving the transparency characteristic of Venetian *cristallo*. These studies have also demonstrated the technological continuity of soda-lime glass production in Venice between the twelfth and fifteenth centuries (De Raedt, Janssens, Veeckman, Vincze, Vekemans, & Jeffries, 2001).

The historiography of Bohemian glass has evolved along somewhat different lines. Earlier studies focused primarily on the emergence of crystal glass and the economic success of Bohemian manufacturers in European markets. During the last two decades, however, archaeometric and experimental research has transformed understanding of historical glass technologies in Central Europe. Particularly important have been investigations into the role of potash as a fundamental component of forest glass production (Ogilvie, 2014; Pánová, Jílková, Rohanová, Lahodný, Galusková, & Míka, 2021; Schmetzer, Gilg, & Ranz, 2023). Cílová and Woitsch demonstrated that potash derived from wood ash constituted a key raw material in Bohemian glassmaking between the fourteenth and seventeenth centuries and significantly influenced the chemical composition and technological properties of the finished glass (Cílová & Woitsch, 2012).

Further advances were achieved through the work of Pánová and colleagues, who reconstructed historical Bohemian and Moravian glass recipes using archaeometric modelling (Pánová, Rohanová, & Randáková, 2020). Their results clarified the relationships between quartz sources, beech ash, potash, and other components used in historical glass batches and provided new insights into the technological evolution of Central European forest glass production.

The historiography of glassmaking in Ukrainian lands developed under different circumstances. Archaeological investigations have long constituted the principal source of knowledge concerning early glass production. Excavations in Kyiv, Chernihiv, Halych, Volodymyr, and other historical centres revealed evidence of glass manufacture and consumption from the period of Kyivan Rus onward (Kalynychenko, 1947; Kis, 1968 Petriakova, 1975). Archaeological studies have also contributed significantly to understanding the distribution of glass artefacts, trade connections, and technological influences affecting Ukrainian territories.

Another important direction of research concerns early modern forest glassworks. During the last decade, substantial progress has been made in reconstructing the geography of glassmaking centres, ownership structures, and economic conditions of production within the territories of the former Polish-Lithuanian Commonwealth. Studies devoted to Volhynia, Galicia, and Polissia have demonstrated the close relationship between glassmaking, woodland exploitation, potash production, and estate economies (Kurdyna, 2015, 2019; Bokotei, 2024). These investigations have significantly improved our understanding of the environmental and economic foundations of Ukrainian blown glass production.

A separate body of literature has examined Ukrainian glass through the perspectives of decorative arts, museum collections, and artistic production. Such studies have documented regional stylistic traditions, artistic techniques, and the development of modern glass art in Ukraine. They have also preserved valuable information concerning the continuity of huta traditions during the twentieth century through artistic workshops, educational institutions, and professional communities.

Despite the substantial volume of existing scholarship, several important gaps remain. Most studies have examined Ukrainian glassmaking either as an archaeological phenomenon, a branch of decorative arts, or a component of regional economic history. Comparatively little attention has been devoted to Ukrainian blown glass as an integrated technological system encompassing raw materials, furnace technologies, workshop organization, manufacturing practices, and mechanisms of technological knowledge transmission. Moreover, direct comparative analyses involving Ukrainian, Murano, and Bohemian traditions remain relatively rare.

The source base of the present study reflects its interdisciplinary character. It includes historical scholarship on European and Ukrainian glassmaking, archaeometric investigations of historical glass compositions, studies of production technologies, research on forest industries and potash manufacture, as well as publications devoted to artistic glass and technological heritage. By combining these categories of sources, the article seeks to examine glassmaking not merely as a form of artistic production but as a technological system shaped by environmental resources, manufacturing knowledge, economic structures, and cultural traditions.

Origins and Development of Blown Glass Production in Ukraine.

The history of glass production in Ukrainian lands extends considerably further back than the emergence of the forest glassworks traditionally known as hutas. Archaeological excavations conducted in Kyiv, Chernihiv, Halych, Volodymyr, and other centres of Kyivan Rus have revealed evidence of local glassworking dating from the tenth to the thirteenth centuries (Kalynychenko, 1947; Petriakova, 1975; Rozhankivskyi, 1959). Glass bracelets, beads, vessel fragments, window glass, crucibles, and production waste indicate that glass processing was already known within urban craft environments. However, these early workshops were relatively small and primarily served local needs. The formation of a widespread network of specialized glassmaking enterprises occurred much later, during the sixteenth and seventeenth centuries.

The rise of huta glass production was closely connected with economic developments within the Polish-Lithuanian Commonwealth. During the sixteenth century, growing urbanization, increasing demand for containers, window glass, tableware, and pharmaceutical vessels stimulated the expansion of glassmaking throughout Central and Eastern Europe. In regions rich in forest resources, glass production became part of a broader economic complex that included charcoal burning, potash manufacture, ironworking, and timber processing. Unlike Mediterranean glassmakers, who relied on imported soda ash, producers in Eastern Europe developed technologies based on potash obtained from wood ash. This difference had far-reaching consequences for the organization of production and the location of glassworks.

The term *huta* itself reflected the technological character of these enterprises. Derived from the German *Hütte*, meaning a furnace workshop or smelting establishment, the word became widespread throughout Central Europe together with mining and metallurgical terminology. By the early modern period, it was commonly used to designate forest glassworks operating in woodland areas remote from major towns. Similar terminology appeared in contemporary Polish, Czech, Slovak, and Ruthenian sources, illustrating the existence of a shared technological vocabulary across the region.

The location of hutas was determined primarily by access to raw materials. A functioning glassworks required large quantities of fuel, silica sand, clay for furnace construction, water, and labour. Forests supplied both firewood and ash for potash production (Petriakova, 1975; Martyniuk, 2004). Historical estimates suggest that several hundred cubic metres of timber could be consumed annually by a medium-sized glassworks. As nearby woodland resources became depleted, many hutas were abandoned and rebuilt elsewhere. Consequently, unlike Murano, where production remained concentrated in a fixed location for centuries, forest glassworks in Ukraine often had a relatively short lifespan.

Research conducted by Yuliia Kurdyna has substantially expanded knowledge about the geography of glassmaking centres in the lands of the former Polish-Lithuanian Commonwealth (Kurdyna, 2014, 2015, 2018, 2019). Archival documentation indicates that by the late sixteenth and seventeenth centuries dozens of glassworks operated in Volhynia, Podillia, and Polissia. Particularly high concentrations have been identified in the territories of present-day Volyn, Rivne, Zhytomyr, and Lviv regions (Kis, 1968; Kurdyna, 2015, 2018).

Several production centres acquired regional significance. Historical records mention glassworks operating near Korets, Olevsk, Liubeshiv, Chortoryisk, Rokytne, Romaniv, and other settlements located within heavily forested areas. Many belonged to influential magnate families such as the Ostrozky, Zaslavsky, Wiśniowiecki, Radziwiłł, and Czartoryski families. Their estates provided access to timber, transportation routes, and labour resources necessary for maintaining production. Monastic institutions also participated in glassmaking activities, particularly in Volhynia and Galicia, where monasteries controlled extensive forest lands.

Archival inventories demonstrate that glassmaking formed part of broader estate economies rather than functioning as an independent industrial sector (Kalynychenko, 1947; Martyniuk, 2004). Landowners viewed glassworks as a means of converting forest resources into marketable products. Potash itself represented an important commercial commodity and was exported to Western Europe for use in glassmaking, soap production, and textile processing. In many cases, the economic viability of a huta depended as much on potash production as on glass manufacture.

The movement of craftsmen played a crucial role in the spread of technological knowledge. Documentary evidence indicates that glassmakers frequently migrated between Bohemia, Silesia, Poland, Lithuania, and Ukrainian territories. As a result, Ukrainian glass production developed within a broader Central European technological environment. Furnace designs, glass recipes, and manufacturing practices circulated across political boundaries together with skilled workers. This process explains why certain technological features observed in Ukrainian archaeological glass closely resemble those found in contemporary Polish and Bohemian assemblages.

At the same time, local conditions produced distinctive adaptations. The quality of silica sand varied considerably from region to region, as did the composition of potash derived from different plant species. These variations affected the colour, transparency, and chemical stability of glass. Archaeological studies of early modern glass from Ukrainian territories frequently report green, olive, yellowish, and brownish hues resulting from iron impurities naturally present in local raw materials. Complete transparency, characteristic of Venetian cristallo, remained difficult to achieve under such conditions.

The product range manufactured by Ukrainian hutas was broader than is sometimes assumed. Excavated materials and museum collections include window panes, bottles, flasks, goblets, stemmed drinking vessels, bowls, pharmaceutical containers, ink bottles, and decorative objects. Window glass became increasingly important during the seventeenth and eighteenth centuries as glazed windows spread among urban residences, administrative buildings, and religious institutions (Petriakova, 1975). The expansion of demand for window glass created stable markets that supported the continued operation of regional glassworks.

By the eighteenth century, some Ukrainian glassworks had begun to exhibit signs of increasing specialization (Rozhankivskyi, 1959). Production volumes expanded, trade networks widened, and contacts with neighbouring regions intensified. Nevertheless, the industry remained fundamentally dependent upon forest resources. This dependence distinguished Ukrainian hutas from the emerging industrial glassworks of Western Europe, where technological modernization increasingly relied upon mineral fuels and centralized production facilities.

The nineteenth century brought profound changes. Industrialization transformed the economics of glassmaking throughout Europe. Coal-fired furnaces allowed higher and more stable temperatures, while improvements in transportation reduced dependence on local resource bases. Large industrial enterprises gradually displaced smaller forest glassworks. Many traditional hutas ceased operation during the first half of the nineteenth century, while others survived only by adapting to changing market conditions.

Despite their decline, hutas left a lasting technological legacy. Techniques of free-form shaping, direct furnace work, and close cooperation between craftsmen remained embedded within local traditions. During the twentieth century, these practices were partially preserved at artistic glass enterprises, particularly in western Ukraine. Researchers has demonstrated that many technological approaches characteristic of modern Ukrainian studio glass originated in much older huta traditions and survived through the continuity of practical knowledge transmitted among generations of glassmakers (Kalynychenko, 1947; Kurdyna, 2014; Bokotei, 2021).

The historical development of Ukrainian blown glass therefore cannot be reduced to a simple regional variant of either Venetian or Bohemian production. It emerged within a distinct environmental and economic context shaped by forest resources, estate ownership, mobile labour, and localized systems of technological knowledge. These conditions determined not only the organization of production but also the technological characteristics of the glass itself, which will be examined in the following section.

Technology of Ukrainian Blown Glass: Raw Materials, Furnaces, and Manufacturing Practices.

The technological characteristics of Ukrainian blown glass were determined primarily by the raw materials available to individual glassworks and by the capabilities of their furnaces (Petriakova, 1975). Unlike modern industrial production, where raw materials are standardized and technological parameters are carefully controlled, early modern glassmakers worked with resources that varied from one locality to another. The composition of sand deposits, the quality of potash, the availability of fuel, and the operating conditions of the furnace directly influenced the appearance and properties of the finished glass.

Silica was the principal component of the glass batch. Most hutas obtained sand from local deposits situated near the production site. The quality of these deposits differed considerably. Historical glass from Ukrainian territories often contains elevated concentrations of iron compounds and mineral inclusions, indicating that raw materials underwent only limited purification before use. As a result, many surviving vessels display green, olive, yellowish, or brownish tones rather than complete transparency. Such colours were not necessarily introduced intentionally but frequently reflected the natural composition of local sands.

The second major component of the glass batch was potash. Throughout much of Central and Eastern Europe, potash replaced the soda ash widely used in Mediterranean glassmaking. It was produced from wood ash obtained during the controlled burning of hardwood species. The manufacture of potash represented a technologically demanding process in its own right. Ash was collected, washed with water, filtered, and evaporated to obtain potassium-rich compounds suitable for glass production. The chemical composition of potash varied according to the species of wood used for ash production and the methods employed during purification. Consequently, even neighbouring glassworks could produce glass with noticeably different chemical characteristics.

The importance of potash for Central European glassmaking has been confirmed by archaeometric research (Pánová, Jílková, Rohanová, Lahodný, Galusková, & Míka, 2021; Rasmussen, 2019). Cílová and Woitsch demonstrated that potassium compounds formed the basis of glass recipes used in Bohemia between the fourteenth and seventeenth centuries and significantly influenced the properties of the finished material. Similar technological principles operated in Ukrainian forest glassworks, which relied on the same raw material base and faced comparable production constraints (Cílová & Woitsch, 2012).

The third major component of the glass batch consisted of stabilizing additives, primarily lime-bearing materials. These were introduced either deliberately through limestone and chalk or indirectly through impurities present in ash and sand. Unlike Venetian workshops, where raw materials were selected and processed according to relatively strict standards, Ukrainian glassmakers adjusted recipes pragmatically according to local conditions and accumulated experience. Production knowledge was transmitted orally and through apprenticeship rather than through written technological manuals.

The preparation of raw materials constituted an important stage of production. Sand was washed and screened before melting. Potash required repeated purification whenever higher-quality glass was desired. Raw materials were mixed manually, and their proportions were adjusted according to the behaviour of previous melts. In practice, glassmakers relied less on precise measurement than on empirical knowledge acquired through long-term observation of furnace performance and glass quality.

The furnace represented the technological core of every glass hotshop. Archaeological investigations of early modern glassworks in Poland, Ukraine, Slovakia, and the Czech Republic reveal a number of common structural features. Most furnaces were built from refractory clay and consisted of a central melting chamber surrounded by firing spaces and auxiliary working areas. Ceramic crucibles containing the glass batch were positioned within the hottest zone of the furnace, where they remained exposed to continuous heating for extended periods.

Maintaining stable temperatures was one of the principal challenges of pre-industrial glass production (Petriakova, 1975). Forest glassworks depended entirely on wood fuel, which produced less predictable thermal conditions than the coal- or gas-fired systems introduced during later industrialization. Modern researchers generally estimate operating temperatures of approximately 1200–1400°C for most forest glassworks. Although sufficient for glass melting, these temperatures did not always ensure complete homogenization of the glass mass. Variations in fuel quality, air supply, furnace design, and worker skill could produce significant differences between individual melting cycles.

Many characteristics commonly observed in Ukrainian blown glass originated directly from these technological conditions. Small bubbles trapped within the glass often indicate incomplete refining of the melt. Mineral inclusions reflect impurities present in raw materials. Variations in colour may result from fluctuations in furnace atmosphere or differences in chemical composition. From the perspective of modern industrial manufacturing such features would be regarded as defects. For historians of technology, however, they provide valuable evidence concerning production methods and technological limitations.

Glass shaping was performed almost entirely by hand. The principal instrument was the blowpipe, which allowed the glassblower to gather molten glass from the crucible and gradually form the desired object. Additional tools included shears, pincers, paddles, wooden blocks, and simple moulds. Most vessels were produced through free-blowing techniques. This method allowed considerable flexibility but inevitably resulted in variations between individual objects. Even products belonging to the same type often differ in dimensions, wall thickness, and proportions.

Archaeological assemblages from Ukrainian territories indicate that glassworks manufactured a broad range of products. Bottles, flasks, drinking vessels, bowls, pharmaceutical containers, window panes, and storage vessels constitute the most frequently encountered categories. Production priorities were largely determined by local demand. Unlike Murano, which specialized in luxury goods intended for elite consumers and international markets, Ukrainian hutas primarily supplied regional markets with practical glassware (see Figure 1).

Window glass represented a particularly important product category during the seventeenth and eighteenth centuries. The spread of glazed windows in churches, monasteries, administrative buildings, and noble residences created stable demand for flat glass. Historical sources indicate that both crown-glass and cylinder-glass methods were employed in various parts of Central Europe. These techniques required substantial skill because the glass had to be expanded, spun, or flattened while retaining sufficient transparency for architectural use.

Chemical analyses conducted on historical forest glass from Central Europe demonstrate significant differences from Venetian soda-lime glass (Spagnolo, Gonella, Viglia, & Ulgiati, 2018). Murano manufacturers relied upon highly purified quartz pebbles and imported soda ash, allowing them to achieve exceptional transparency and optical quality. Ukrainian hutas worked under different technological conditions. Their products generally contained higher concentrations of potassium compounds and exhibited greater variability in composition. This variability should not be interpreted simply as evidence of lower quality. Rather, it reflected a technological system adapted to local resources and regional economic realities.

By the eighteenth century, technological differences between Ukrainian and Bohemian glassmaking became increasingly pronounced. While both traditions originated within the broader framework of forest glass production, Bohemian manufacturers progressively standardized glass compositions and improved refining techniques. These developments eventually enabled the production of high-quality crystal glass suitable for extensive cutting and engraving. Ukrainian hutas remained oriented primarily toward regional markets and therefore retained many characteristics of traditional forest glassmaking.

a b

c d

Figure 1. Representative examples of Ukrainian glass products from museum collections: a – Shtof – 1796. Colored glass blowing painting with enamels; b – Pitcher – 18th century. Colored glass enamel blowing sculpting painting; c – Jar – 18th–19th century. Colored glass blowing sculpting; d – Pitcher – 19th century. Colored colorless glass blowing sculpting corrugation (National Museum of Decorative Arts of Ukraine, n. d.).

The technological practices developed within Ukrainian hutas did not disappear with the decline of the forest glassworks during the nineteenth century. Knowledge associated with furnace work, free-form shaping, and direct interaction with molten glass survived within artistic production and later became an important component of twentieth-century Ukrainian studio glass. In this sense, blown glass represents not merely an early stage in the history of glassmaking but a technological tradition whose influence extended far beyond the period of its original existence.

Murano and Bohemia: Two Alternative Models of European Glassmaking. Although Ukrainian blown glass developed within the broader context of European glassmaking, the technological and organizational conditions under which it evolved differed substantially from those found in the two most influential glass-producing regions of early modern Europe: Murano and Bohemia. Both centres achieved international recognition and exerted a significant influence on the development of glass technology. At the same time, they represented two distinct approaches to organizing production, managing technological knowledge, and controlling product quality.

The rise of Murano as a glassmaking centre is traditionally associated with the decision of the Venetian government in 1291 to relocate glass furnaces from Venice to the island of Murano. Although concerns about fire hazards played an important role in this decision, the concentration of production also facilitated governmental supervision over an industry that had become economically significant. Over the following centuries, Murano developed into one of Europe's most important centres of luxury glass production (De Raedt, Janssens, Veeckman, Vincze, Vekemans, & Jeffries, 2001; Verità, 2021; Veronesi, 2024).

A defining feature of the Murano system was the institutional control of technological knowledge. Glassmaking techniques were regarded as valuable economic assets, and the Venetian authorities implemented measures designed to prevent the emigration of skilled craftsmen. Masters who left Venetian territory without authorization could face severe legal penalties, while members of their families sometimes remained subject to governmental pressure. As Francesca Trivellato has demonstrated, the protection of technological expertise formed an integral part of the broader commercial strategy of the Venetian Republic (Trivellato, 2006).

The technological success of Murano was closely connected with the production of *cristallo*, a highly transparent glass developed during the fifteenth century. Venetian manufacturers achieved exceptional optical clarity through the use of carefully selected quartz pebbles and purified soda ash imported from the eastern Mediterranean. The resulting glass contained relatively low concentrations of colouring impurities and became renowned throughout Europe for its transparency and brilliance. Unlike the potash-rich glasses produced in much of Central and Eastern Europe, Venetian soda-lime glass possessed properties particularly suitable for thin-walled vessels and complex decorative work.

Murano workshops also became centres of technological experimentation. Venetian craftsmen developed techniques such as *vetro a filigrana*, *latticinio*, enamel decoration, gilding, and multi-layered glass construction. Many of these methods required advanced control of glass viscosity, temperature, and colour compatibility. Consequently, Murano's reputation rested not only on raw material quality but also on a sophisticated understanding of glass behaviour during forming and decoration (Spagnolo, Gonella, Viglia, & Ulgiati, 2018; Verità, 2021).

The organization of labour in Murano differed markedly from that of Ukrainian forest glassworks. Production was concentrated in permanent workshops employing highly specialized craftsmen. Tasks associated with batch preparation, furnace operation, blowing, decoration, and finishing were often distributed among different specialists. This specialization contributed to greater consistency in product quality and facilitated the preservation of technological standards across generations.

A different model emerged in Bohemia (Schmetzer, Gilg, & Ranz, 2023). Unlike Murano, Bohemian glassmaking developed within heavily forested regions where wood fuel and potash were readily available. During the sixteenth and seventeenth centuries, numerous glassworks operated throughout Bohemia and neighbouring territories. Their technological foundations resembled those of other Central European forest glass industries, including those found in Ukrainian lands. However, by the late seventeenth century Bohemian manufacturers began to transform this traditional production system into a more specialized and commercially oriented industry.

One of the key factors behind this transformation was the refinement of potash-based glass compositions. Research conducted by Cílová and Woitsch has shown that Bohemian producers successfully exploited the chemical properties of potassium-rich glass, which possessed greater hardness than Venetian soda glass and was therefore particularly suitable for cutting and engraving (Cílová & Woitsch, 2012). These characteristics eventually contributed to the emergence of Bohemian crystal, one of the most successful glass products in European history.

The eighteenth century witnessed the consolidation of Bohemia's position within international markets. Improvements in refining methods, furnace technology, and quality control enabled manufacturers to produce increasingly homogeneous glass masses. At the same time, growing export networks connected Bohemian workshops with consumers throughout Europe. Unlike Murano, whose reputation was built largely upon luxury hand-crafted objects, Bohemian producers increasingly combined artisanal skill with larger-scale commercial production.

Technological innovation in Bohemia was also accompanied by a gradual rationalization of manufacturing processes. Although production remained dependent upon skilled craftsmen, greater attention was paid to recipe standardization, furnace efficiency, and the reproducibility of results. Recent archaeometric studies have demonstrated that Bohemian glass compositions became progressively more consistent over time, reflecting increasing control over raw materials and production procedures (Pánová, Rohanová, & Randáková, 2020).

Viewed from a technological perspective, Murano and Bohemia represented two different solutions to the challenges of glass production. Murano relied on institutional control, technological secrecy, imported raw materials, and luxury markets. Bohemia built its success upon forest resources, potash-based glass chemistry, and progressive production rationalization. Both systems differed substantially from the decentralized structure of Ukrainian blown glass production, which remained more closely tied to local resources and regional markets.

These differences did not imply technological isolation. Craftsmen, techniques, and knowledge circulated throughout Europe, creating numerous points of contact between glassmaking regions. Nevertheless, the historical development of Murano and Bohemia demonstrates how similar technological goals could be achieved through fundamentally different organizational and material frameworks. Understanding these alternative models provides an essential basis for evaluating the distinctive features of Ukrainian blown glass within the broader history of European glassmaking.

Comparative Analysis of Ukrainian, Murano, and Bohemian Glass Traditions.

The comparison of Ukrainian huta glass with the Murano and Bohemian traditions demonstrates that these centres differed not only in the appearance of their products but also in the technological principles that governed production. Differences in raw materials, fuel resources, production organization, labour structure, and access to markets resulted in the emergence of three distinct models of glassmaking. While all three traditions shared common technological foundations based on the melting and forming of silica-based glass, they evolved under different environmental and economic conditions and therefore followed different developmental trajectories. Table 1 summarizes the principal characteristics of the Ukrainian, Murano, and Bohemian glassmaking traditions.

The comparison reveals that the most fundamental distinction concerned the relationship between production and resources. Ukrainian glassmaking remained closely tied to the immediate natural environment. The location of glassworks, the composition of the glass batch, and even the lifespan of individual enterprises depended upon the availability of timber, potash, and suitable sand deposits. This dependence created a flexible but highly variable production system. Glassmakers adapted continuously to changing local conditions, and technological knowledge developed primarily through practical experience.

Table 1. Comparative characteristics of Ukrainian, Murano, and Bohemian glassmaking traditions

Parameter	Ukrainian Huta Glass	Murano Glass	Bohemian Glass
Main period of development	16th–19th centuries	14th–18th centuries	16th–19th centuries
Production environment	Forest glassworks	Urban island workshops	Forest and semi-industrial workshops
Production organization	Decentralized	Highly centralized	Increasingly centralized
Ownership structure	Magnates, monasteries, estates	Guild-controlled workshops	Noble estates and private enterprises
Main fuel	Wood	Wood and imported fuel resources	Wood, later coal
Primary flux	Potash from wood ash	Soda ash	Potash
Main glass type	Potash glass	Soda-lime glass (*cristallo*)	Potassium-calcium crystal glass
Raw material strategy	Local resources	Carefully selected and partly imported materials	Regional resources with increasing standardization
Knowledge transmission	Apprenticeship and oral tradition	Guild-based secrecy	Craft tradition and technological standardization
Degree of recipe standardization	Low	High	Medium to high
Furnace permanence	Often temporary or relocatable	Permanent	Permanent
Product orientation	Regional markets	Luxury and export markets	Export-oriented commercial production
Typical products	Bottles, flasks, tableware, window glass	Luxury vessels, mirrors, decorative objects	Crystal tableware, engraved glass, decorative products
Dominant forming technique	Free blowing	Free blowing and advanced decorative techniques	Blowing followed by cutting and engraving
Optical quality	Variable	Very high	High
Typical inclusions and bubbles	Frequent	Rare	Limited
Suitability for cutting and engraving	Moderate	Limited	Excellent
Main technological advantage	Adaptability to local conditions	Transparency and decorative complexity	Hardness and reproducibility
Main production constraint	Resource variability	Dependence on imported materials	High production costs and competition

Murano followed a different path. The Venetian industry sought to minimize variability by controlling both materials and production processes. The use of carefully selected quartz pebbles and purified soda ash allowed manufacturers to achieve a level of transparency rarely matched elsewhere in Europe. At the same time, institutional mechanisms protected technological knowledge and promoted continuity within the production system. The result was not simply better glass but a manufacturing environment designed to maximize consistency and maintain commercial prestige.

Bohemia occupied an intermediate position between these two models. Like Ukrainian hutas, Bohemian glassworks originated within forested regions and relied heavily on potash-based technologies. However, beginning in the seventeenth century, Bohemian manufacturers increasingly pursued standardization. Improvements in furnace technology, refining methods, and quality control gradually reduced production variability. This process culminated in the emergence of crystal glass specifically designed for cutting and engraving, which became one of Bohemia's most successful export products.

The table also demonstrates that technological development did not follow a single hierarchical path. Traditional narratives often imply that glassmaking evolved from simple forest production toward increasingly sophisticated industrial forms. The evidence suggests a more complex picture. Murano achieved technological success through institutional control and access to international trade networks. Bohemia relied on process optimization and commercial specialization. Ukrainian hutas developed a decentralized system capable of operating effectively under conditions of limited capital investment and fluctuating resource availability.

Particularly revealing is the issue of product quality. If quality is defined exclusively through transparency, homogeneity, and chemical purity, Murano and Bohemian products appear superior. However, such criteria reflect the priorities of luxury and export production. Ukrainian blown glass fulfilled different economic and technological functions. Its primary objective was not the manufacture of elite objects but the supply of regional markets with practical and affordable glassware. Consequently, features such as bubbles, inclusions, colour variations, and asymmetries should be interpreted within the context of the production system that generated them.

From the perspective of the history of technology, these so-called defects are often more informative than perfectly standardized products. They preserve evidence of furnace performance, raw material quality, and manufacturing practices. In this sense, Ukrainian blown glass provides valuable information about the technological adaptation of craftsmen to local environmental conditions. Rather than concealing production processes behind uniformity, it reveals them directly in the material structure of the object.

Another important observation concerns the circulation of technological knowledge. Although Murano attempted to restrict the movement of craftsmen and protect production secrets, and Bohemian manufacturers increasingly relied on standardized procedures, all three traditions participated in broader European networks of technological exchange. Craftsmen migrated between regions, furnace designs spread across political boundaries, and knowledge concerning glass composition circulated through both formal and informal channels. Ukrainian glassmaking therefore developed neither in isolation nor in direct dependence upon a single foreign model. Instead, it selectively incorporated external influences while preserving its own technological identity.

The comparison presented here suggests that Ukrainian blown glass should be understood as a distinct technological tradition rather than as a peripheral variant of Venetian or Bohemian production. Its historical significance lies in the successful adaptation of glassmaking technologies to the environmental, economic, and social realities of Eastern Europe. Examined alongside Murano and Bohemia, Ukrainian glassmaking reveals the diversity of technological solutions that coexisted within European glass production from the early modern period to the nineteenth century.

From Craft to Heritage: The Transformation of Blown Glass Traditions in Twentieth-Century Ukraine.

The decline of traditional forest glassworks during the nineteenth century did not result in the disappearance of Ukrainian huta traditions (Rozhankivskyi, 1959; Kurdyna, 2019). Although industrialization fundamentally altered the economic foundations of glass production, many technological practices developed within the historical hutas survived in new institutional settings. During the twentieth century these practices underwent a gradual transformation from components of a regional manufacturing system into elements of artistic production, professional education, and cultural heritage.

The process began under conditions of increasing industrialization. Throughout Europe, mechanized production gradually displaced many traditional forms of glassmaking. Large factories specializing in bottles, sheet glass, and technical products became economically dominant. Ukraine experienced similar developments. Nevertheless, the manufacture of artistic and decorative glass remained dependent on manual labour. The shaping of complex forms, control of molten glass, and execution of decorative details continued to require highly skilled glassblowers. As a result, technological practices originating in pre-industrial production survived within sectors that resisted full mechanization.

Following the Second World War, artistic glass production became integrated into the institutional framework of Soviet decorative and applied arts. State-supported enterprises provided access to furnaces, raw materials, and professional workshops. Although these enterprises operated within an industrial economy, artistic production remained largely dependent upon techniques associated with direct furnace work.

A particularly important role was played by the Kyiv Plant of Artistic Glass. During the following decades, the enterprise became one of the largest centres of artistic glass production in the Soviet Union. The factory produced decorative vessels, exhibition pieces, commemorative objects, architectural glass, and experimental works created specifically for national and international exhibitions. Despite the industrial scale of the enterprise, many operations continued to rely on free blowing, hot shaping, and direct interaction between artists and master glassblowers. In technological terms, these methods preserved important elements of earlier blown glass practice.

Western Ukraine developed a somewhat different model (Kis, 1968; Kurdyna, 2014). In Lviv, artistic glass production became closely associated with educational institutions and experimental workshops. The Lviv Experimental Ceramic and Sculpture Factory provided opportunities for artistic work with molten glass outside the framework of mass production. Here, the furnace functioned not only as industrial equipment but also as a creative environment in which technological experimentation remained possible. This approach preserved many features characteristic of historical huta production, including the importance of manual forming and the continuous interaction between craftsman and material.

The institutionalization of blown glass traditions was reinforced through professional education. The Lviv National Academy of Arts became one of the principal centres for training glass and ceramics artists in Ukraine (Bokotei, 2024; Khyzhynskyi, Lampeka, & Strilets, 2024; Khyzhynskyi, Osadcha, & Nagirniak, 2025). Unlike traditional apprenticeship systems, educational programmes combined artistic instruction with technological training. Students studied glass composition, furnace technologies, hot-glass forming techniques, and the properties of molten glass. Consequently, technological knowledge that had once circulated primarily within workshops entered formal educational structures and acquired a more systematic character.

An important stage in the preservation of blown glass traditions occurred during the late 1980s with the organization of International Blown Glass Symposiums in Lviv (Chegusova, 2020, 2024). The first symposium, held in 1989, brought together artists, technologists, and glassblowers from different countries and created a platform for the exchange of practical knowledge. Unlike conventional exhibitions, symposiums emphasized the production process itself. Participants worked directly at the furnace, exchanged technical solutions, and demonstrated methods of shaping and decorating hot glass. In this respect, the symposium format reproduced certain aspects of historical craft communities in which technological knowledge circulated through observation and practical participation.

These developments coincided with the growing influence of the international Studio Glass Movement. Emerging in the United States during the 1960s, the movement challenged the separation between artist and production process that had become typical of industrial manufacturing. Small furnaces, independent workshops, and direct engagement with molten glass enabled artists to regain control over technological aspects of production. Similar tendencies appeared in Ukraine, where artistic glass increasingly emphasized experimentation, individuality, and the creative possibilities of furnace-based work.

By the end of the twentieth century, attitudes toward traditional glassmaking had changed significantly. Features that industrial manufacturers had often regarded as evidence of imperfect production began to acquire new cultural value. Variations in form, traces of manual shaping, bubbles, and subtle colour differences came to be interpreted as indicators of authenticity and direct human involvement in the manufacturing process. This reassessment reflected broader changes in heritage studies and the history of technology, where increasing attention was devoted not only to finished artefacts but also to the skills and knowledge required for their production.

Within this context, huta glass became recognized as a form of technological heritage. The concept encompassed more than museum collections or surviving glass objects. It included furnace technologies, practical knowledge of glass behaviour, methods of shaping molten material, workshop traditions, and systems of skill transmission. Preserving such heritage required not only conservation of artefacts but also the continuation of technological practices themselves.

The twentieth century therefore transformed blown glass traditions from an economic activity into a cultural and educational resource. While the historical forest glassworks disappeared, many of the technological principles that had sustained them remained active within artistic workshops, educational institutions, and professional communities. This continuity ensured that huta glass survived not merely as a historical phenomenon but as a living component of Ukraine's technological and cultural heritage.

Conclusions.

The comparative analysis of Ukrainian huta glass, Murano glass, and Bohemian glassmaking demonstrates that these traditions developed within different technological, economic, and institutional frameworks despite sharing common principles of glass production. The differences between them were determined not only by variations in raw materials or manufacturing techniques but also by broader systems of knowledge transmission, production organization, and resource management.

The study has shown that Ukrainian blown glass emerged as a product of a decentralized forest-based manufacturing system that relied on local deposits of silica sand, potash derived from wood ash, and wood fuel. In contrast to the centralized and highly regulated production system of Murano, where technological knowledge was protected through guild institutions and state control, Ukrainian glassmaking developed primarily through dispersed workshops operating within estate economies. Unlike Bohemia, where glass production gradually evolved toward greater standardization and export-oriented specialization, Ukrainian hutas largely remained oriented toward regional markets and retained flexible production practices adapted to local conditions.

The technological characteristics of Ukrainian glass making reflected these conditions. Variability in raw materials, furnace performance, and manufacturing processes resulted in products that often contained bubbles, inclusions, colour variations, and minor asymmetries. Rather than being interpreted solely as indicators of technological limitations, these features should be understood as material evidence of a specific production environment and a distinct technological culture. They provide valuable information about the interaction between craftsmen, natural resources, and production technologies in early modern Eastern Europe.

The comparison with Murano and Bohemia demonstrates that the history of European glassmaking cannot be reduced to a single trajectory of technological progress. Venetian glassmaking achieved international prominence through institutional control, technological secrecy, and access to long-distance trade networks. Bohemian manufacturers built their success on the refinement of potash-based glass compositions, increasing standardization, and integration into international markets. Ukrainian huta glass followed a different path, characterized by adaptability, resource flexibility, and the preservation of locally transmitted technological knowledge.

The study also demonstrates that the significance of Ukrainian glass making extends beyond the period of the forest glassworks themselves. During the twentieth century, many technological practices associated with historical huta production were preserved within artistic glass enterprises, educational institutions, and international professional networks. As a result, blown glass traditions underwent a transition from an economic production system to a form of technological and cultural heritage. This transformation ensured the survival of practical knowledge and manufacturing skills long after the disappearance of the historical glassworks that had originally generated them.

The findings support the conclusion that Ukrainian blown glass should not be regarded as a peripheral or simplified variant of either Venetian or Bohemian glassmaking. It represented a distinct historical and technological trajectory shaped by the environmental conditions, resource base, and social organization of Eastern Europe. Examined within a broader European context, Ukrainian blown glass reveals the diversity of technological solutions that coexisted within pre-industrial glassmaking and contributes to a more nuanced understanding of the relationship between technology, craft production, and cultural development in the history of material technologies.

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Гутне скло в Україні: історико-технологічні особливості у порівнянні з муранською та богемською склярськими традиціями

Анотація. *Метою дослідження є виявлення історико-технологічних особливостей українського гутного скла шляхом порівняльного аналізу української, муранської та богемської традицій скловиробництва. У статті розглянуто розвиток скляного виробництва на українських землях упродовж XVI–XX ст. та визначено його місце в ширшому контексті європейської історії скла. Методологічну основу дослідження становлять методи історичного аналізу, порівняльного історико-технологічного аналізу та студій матеріальної культури. Джерельна база охоплює історичні, археологічні, археометричні та мистецтвознавчі праці, присвячені технологіям скловиробництва, діяльності лісових гут, художньому склу та збереженню традиційних виробничих знань. Особливу увагу приділено технологічним аспектам виготовлення скла, зокрема використанню сировини, складу скломаси, конструкціям скловарних печей, виробничим практикам і механізмам передачі технологічних знань. Встановлено, що українське гутне скло розвивалося в умовах, які суттєво відрізнялися від тих, що визначали формування муранської та богемської склярських традицій. На відміну від високоорганізованої та централізованої системи виробництва Мурано, українське склоробство формувалося на основі децентралізованої мережі лісових гут, діяльність яких залежала від місцевої сировинної бази та емпіричної передачі виробничого досвіду. На відміну від богемської моделі, що поступово набула рис стандартизованого та експортно орієнтованого виробництва, українські гути були переважно зорієнтовані на регіональні ринки та адаптували технології до локальних природних і господарських умов. Показано, що такі особливості українського гутного скла, як хімічна неоднорідність, наявність включень, варіативність кольору та певна нерегулярність форм, були безпосереднім наслідком виробничого середовища й повинні розглядатися як матеріальні свідчення історичних технологічних процесів, а не виключно як ознаки технологічної недосконалості. Окремо* *проаналізовано трансформацію гутних традицій у XX ст. Встановлено, що значна частина технологічних практик, пов'язаних з історичними лісовими гутами, збереглися у сфері художнього скла, системі професійної освіти та діяльності творчих спільнот. Унаслідок цього гутні технології поступово трансформувалися з регіональної виробничої системи у важливий елемент технологічної та культурної спадщини. Зроблено висновок, що українське гутне скло слід розглядати як самостійну історико-технологічну траєкторію розвитку європейського скловиробництва, а не як периферійний варіант муранської чи богемської традицій. Проведений порівняльний аналіз демонструє різноманіття технологічних рішень, що співіснували в європейському склоробстві, та сприяє глибшому розумінню взаємозв'язку між технологіями, ремісничими знаннями, природними ресурсами й культурним розвитком у історії матеріальних технологій.*

Ключові слова: *гутне скло України; декоративне мистецтво; технологія скловиробництва; художнє скло; дизайн скловиробів; музейні колекції скла*

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Mayak tape recorders in late socialist Ukraine: Industrial planning, technological constraint, and everyday sound practices

Abstract. *The article reconstructs the lifecycle of Mayak tape recorders in Soviet Ukraine as a socio-technical infrastructure shaped by centralized industrial planning, defense sector priorities, and everyday practices of domestic sound recording in the 1970s and 1980s. The study draws on a broad body of internal ministerial and factory documentation. It uses conjunctural market reviews, calculations of effective consumer demand, economic reports of the household magnetic recording industry, and internal quality analyses. A separate group of sources consists of survey materials and oral testimonies of users of Soviet household electronics, which make it possible to reconstruct everyday experiences of tape recorder use. The research applies infrastructural analysis, source criticism, and historical reconstruction of statistical data. This approach makes it possible to trace the relationship between industrial organization and everyday sound practices. Documentary evidence indicates that technological quality functioned as an economic category. It was measured through defect losses, warranty repair costs, and post-production expenses, linking technological limitations with financial and institutional outcomes. The findings demonstrate that structural shortage, uneven assortment, and dependence on repair infrastructures shaped domestic listening practices. They also facilitated informal sound circulation, including home copying and magnitizdat. The study concludes that Mayak tape recorders functioned simultaneously as planned commodities and as media infrastructures of private sonic life. They defined the material conditions for the formation of the personal acoustic environment in late socialist Ukraine. The analysis also demonstrates the reciprocal relationship between technological systems and user practices, showing how everyday uses of recording technology contributed to redefining notions of quality, functionality, and accessibility within the late socialist industrial framework.*

Keywords: *magnetic recording; Mayak tape recorders; planned economy; shortage; domestic sound recording; personal acoustic environment*

Introduction.

During the 1970s–1980s magnetic tape recording became one of the most influential domestic technologies in the Soviet Union. The tape recorder enabled households not only to listen but also to record, reproduce, and circulate sound independently of official broadcasting institutions. This technological shift transformed the structure of auditory experience, allowing individuals and families to organize their own acoustic environments within domestic space. In Soviet Ukraine, the spread of tape recorders occurred within the institutional framework of late socialist industrial planning. Unlike market economies, where the development of consumer audio equipment was shaped by competition and consumer demand, Soviet recording technologies evolved within a centralized system governed by administrative planning, inter-ministerial coordination, and resource allocation. Civilian electronics production was closely connected with the defense-industrial complex, influencing technological priorities, component availability, and production strategies

The Mayak tape recorder, produced in Kyiv within the Ministry of Communications Equipment Industry, provides a revealing example of this system. Despite its wide distribution, its technological trajectory and reliability were shaped by shortages of electronic components, slow renewal of models, and structural imbalances between planned production and actual demand (see Figure 1).

Figure 1. Quality control inspector of the Kyiv Scientific-Production Association "Mayak," N. Shatokhina, demonstrating the cassette tape recorder unit "Mayak-231-Stereo" (Kyiv, June 20–21, 1983), illustrating final inspection and presentation of consumer audio equipment in late socialist industry (Central State Audiovisual and Electronic Archive, n.d.).

Internal industrial documentation repeatedly emphasized that decisions concerning consumer electronics were embedded in broader industrial priorities, including defense-related production and resource limitations (Kon'iunkturnyi obzor…, 1975, pp. 5, 43).

This article examines Mayak tape recorders as a socio-technical infrastructure that connected industrial organization with everyday sonic experience. It explores the ways centralized planning and defense industrial priorities shaped the development of domestic recording technology, and how technological limitations were translated into economic and institutional definitions of quality. At the same time, these limitations should not be understood as purely objective technical constraints. Following Science and Technology Studies approaches, technological properties may be interpreted as relational and context-dependent, shaped by intended use, cultural expectations, and institutional frameworks. The study also investigates how structural shortages and distribution mechanisms influenced patterns of access to tape recorders, and how everyday recording practices contributed to the emergence of personal acoustic environments and forms of informal sound circulation.

State of Research.

Research on socialist consumer technology emphasizes the systemic role of structural shortage and centralized planning in shaping production and distribution mechanisms (Chernyshova, 2013, pp. 6–10, 38–45). Broader histories of technology likewise stress that technological change does not necessarily follow innovation-driven market trajectories but may instead develop under institutional and resource constraints (Edgerton, 2006, pp. 3–8, 77–82). Within the field of sound studies, recording technologies are conceptualized as infrastructures that shape listening practices and acoustic environments (Sterne, 2003, pp. 15–22, 223–230; Bijsterveld & Pinch, 2011, pp. 1–12, 55–63). The material characteristics of recording media (including mechanical stability, noise, durability, and accessibility) are understood to influence not only perceived sound quality but also patterns of sound circulation and everyday auditory experience (Birtwistle, 2021, pp. 140–155). Recent studies further highlight the analytical value of technological noise and material degradation as indicators of underlying social and industrial conditions (Kendall, 2023). Comparative research on cassette cultures demonstrates that recording media frequently enabled alternative forms of sound circulation in contexts of media control (Manuel, 1993, pp. 2–8, 21–32; Simon, 2022, pp. 35–52, 167–182).

In addition to these Western approaches, this study engages with Soviet and post-Soviet scholarship on technology, consumption, and everyday life. Soviet-era technical and economic literature conceptualized recording technology primarily within the framework of industrial planning, emphasizing production efficiency, standardization, and the fulfillment of quantitative targets. Within this epistemic paradigm, technological quality was defined through measurable indicators (such as defect rates, durability, and production costs) and embedded in administrative reporting systems, rather than interpreted through user experience or cultural practice.

Post-Soviet scholarship, by contrast, has shifted analytical attention toward everyday life, informal economies, and user adaptation under conditions of structural shortage. Studies of late Soviet consumption and material culture demonstrate that access to technology was mediated not only through formal distribution systems but also through repair networks, personal connections, and practices of modification and reuse (Yurchak, 2006; Ledeneva, 1998; Zhuk, 2010). These perspectives are reinforced by research on Soviet do-it-yourself culture, which highlights the role of technical competence and user intervention in stabilizing everyday technologies and compensating for systemic industrial limitations (Golubev & Smolyak, 2013).

Taken together, these historiographic traditions reveal a significant analytical gap. Western scholarship has tended to conceptualize recording technologies primarily as cultural and infrastructural systems shaping auditory experience, while Soviet-era literature approached them as objects of industrial planning and economic calculation. Post-Soviet studies, in turn, have emphasized everyday practices and informal mechanisms of technological use, often without systematic integration of industrial documentation. This article positions itself at the intersection of these approaches. By combining the analytical reconstruction of Soviet industrial sources with insights from post-Soviet studies of everyday practices, it integrates institutional and user-centered perspectives on technology. In doing so, it bridges the gap between administrative definitions of technological performance and the socially embedded realities of technological use, offering a more comprehensive understanding of recording technology as a socio-technical system in late socialist Ukraine.

Methodology.

The study employs a multi-layered methodological framework. First, source criticism is applied to internal industrial documents, recognizing their administrative and institutional character. Second, statistical reconstruction is used to analyze production, demand, and quality indicators contained in economic reports and conjunctural reviews. Third, institutional analysis examines planning mechanisms and distribution structures shaping technological development. Fourth, an infrastructural approach interprets tape recorders as socio-technical systems linking production, distribution, maintenance, and use. The empirical base includes conjunctural market reviews, calculations of effective demand, economic reports of the household magnetic recording equipment system, internal quality analyses, and related documentary materials. Quantitative indicators such as production volume, inventory levels, defect losses, and warranty repair costs are analyzed to reconstruct the relationship between technological constraints and everyday user experience.

Results and Discussion.

Production, Planning, and Structural Imbalance.

The development of household magnetic recording technology in the late socialist period unfolded within a centrally coordinated industrial system in which technological change was determined primarily by planning priorities rather than market competition. Planning materials conceptualized recording technology as part of an integrated technological complex encompassing tape production, recording equipment, and distribution infrastructure. At the same time, persistent shortages of electronic components and reliance on externally supplied micro-motors constrained technological modernization and affected key performance parameters, including noise level, mechanical stability, and durability (Sopostavitel'nyi analiz i prognozirovanie…, 1980, pp. 151–152). Contemporary industrial analyses stressed that technological quality depended not only on engineering design but also on patterns of resource allocation and institutional priorities. In practice, modernization generated uneven results, while technological reliability remained unstable under systemic industrial constraints, forming the structural conditions that shaped the everyday use of recording technology.

Conjunctural reviews of the household magnetic recording industry reveal a structural contradiction between planned production and actual consumer demand. The conjunctural review for the first half of 1975 reported continued expansion of output, with 1,226 thousand tape recorders produced, representing a 28.5% increase compared to the same period in 1974 (Kon'iunkturnyi obzor…, 1975, p. 5). Despite this growth, the document simultaneously emphasized a persistent shortage of desirable models and an insufficient assortment structure. Production plans continued to prioritize outdated reel-to-reel and low-quality cassette models, even as consumer demand shifted toward high-quality devices (see Figure 2).

This shift reflected not only a preference for improved sound quality but also changing patterns of use, including the increasing importance of portability, ease of duplication, and compatibility with recorded media circulation. This imbalance between production structure and consumer demand produced a paradoxical coexistence of shortage and surplus. While high-demand models were scarce in retail networks, inventories of technologically obsolete devices accumulated in both wholesale and retail distribution channels. The same review noted that total retail sales remained below supply, leading to the growth of inventories in trade networks, a phenomenon measured through the category of *tovarodni* (inventory days) (Kon'iunkturnyi obzor…, 1975, p. 5).

From an infrastructural perspective, inventory accumulation functioned as a diagnostic indicator of systemic misalignment rather than a temporary logistical issue. Centralized planning prioritized quantitative output indicators, while regional demand structures remained insufficiently reflected in production decisions. As a result, the circulation of tape recorders through the planned economy followed uneven temporal patterns: short periods of market presence for high-demand models alternated with long phases of scarcity. The conjunctural review further indicated that the production plan for 1976 was lower than the targets previously established by governmental decree, while the rate of model renewal remained insufficient (Kon'iunkturnyi obzor…, 1975, p. 80). This evidence suggests that structural shortage was embedded within planning mechanisms themselves, rather than resulting solely from supply disruptions.

Figure 2. Final adjustment section of "Mayak-305" tape recorders at the Kyiv "Mayak" plant (Kyiv, 1982), illustrating final calibration and preparation of devices prior to distribution within the late socialist production system (Central State Audiovisual and Electronic Archive, n. d.).

Demand, Distribution, and Technological Constraints.

The analysis of commodity flows reveals how centralized distribution shaped the material availability of recording technology. Internal reports repeatedly emphasized that the relationship between supply and retail sales was characterized by uneven temporal distribution. Even when production increased, retail availability remained unstable due to delays in distribution, logistical bottlenecks, and assortment mismatches. Documentary materials from the late 1970s provide further evidence of this phenomenon. A market analysis report noted that tape recorders with high consumer demand were often sold out within hours or days, while the assortment available in retail networks was frequently limited to three or four models, often those with declining demand (Analiz otechestvennogo i zarubezhnogo rynkov…, 1978,

p. 14). This pattern indicates that the effective availability of tape recorders was determined not only by production volume but by distribution structure and assortment composition. In practical terms, the temporal instability of retail presence transformed acquisition into a socially mediated process. Consumers relied on personal networks, informal information channels, and opportunistic purchasing rather than predictable market availability. From an infrastructural perspective, the distribution system thus functioned as a mechanism shaping access to technology and structuring patterns of consumption. Oral testimonies confirm that these structural constraints were directly experienced at the level of everyday use. Respondents consistently emphasized the unpredictability of access to recording devices and the necessity of adapting to available models rather than preferred ones. Taken together, these patterns indicate that availability was not a direct function of production volume but of structural alignment between planning priorities, distribution mechanisms, and consumer expectations.

The calculation of effective consumer demand for tape recorders in 1976 provides a detailed quantitative framework linking production resources, retail supply, and household monetary resources (see Figure 3). The report forecast a substantial increase in retail turnover for tape recorders (approximately 2.5 times higher than in 1971) reflecting growing consumer demand for recording technology (Otchet. Raschet platezhesposobnogo sprosa …, 1975, p. 8). However, statistical tables in the same report reveal a structural gap between the growth of consumer demand and the expansion of production capacity. While production was projected to increase modestly, retail sales were expected to grow significantly faster, indicating the persistence of systemic imbalance within the planned economy. The report also identified two principal barriers to acquisition: the absence of desired models in retail and insufficient household financial resources (Kon'iunkturnyi obzor…, 1975, p. 80). This dual constraint demonstrates that shortage in late socialist economies operated simultaneously as a commodity shortage and as a constraint of purchasing power. Access to recording technology therefore varied across social groups, producing differentiated acoustic environments.

The problem of assortment imbalance was a recurring theme in industrial documentation. Conjunctural reviews emphasized that the continued production of technologically obsolete models generated inventory accumulation and reduced efficiency within distribution networks. Price reductions were frequently used to stimulate sales of outdated devices, but this mechanism produced only partial stabilization, as demand increasingly shifted toward higher-class models (Kon'iunkturnyi obzor…, 1975, p. 5). From an infrastructural perspective, assortment imbalance influenced not only economic performance but also the technological characteristics of domestic sound environments. Lower-class devices offered reduced recording fidelity, higher noise levels, and shorter durability, thereby shaping the sonic quality of domestic recording practices. Survey data from the mid-1970s further indicate that unmet demand resulted not only from a lack of financial resources but also from the absence of preferred models. (Kon'iunkturnyi obzor: "Sostoianie vnutrennego rynka…, 1974, pp. 4-15). This evidence suggests that consumers increasingly differentiated between technological classes, indicating a shift from basic acquisition toward qualitative evaluation of recording technology.

Figure 3. Radio equipment technicians at the Kyiv "Mayak" plant testing the operation of tape recorders on a testing bench (Kyiv, October 24, 1979), illustrating functional testing procedures within the industrial quality control process (Central State Audiovisual and Electronic Archive, n. d.).

Analytical materials from the late socialist period repeatedly linked technological limitations to shortages of electronic components and dependence on imported parts. Reports on technological development emphasized that the lag of domestic recording equipment behind international standards was primarily due to the absence of a modern electronic component base and long development cycles (Sopostavitel'nyi analiz i prognozirovanie…, 1980, p. 151). This dependence shaped key technological parameters such as mechanical stability, noise level, and durability. As a result, quality constraints were systemic rather than isolated technical failures. The documentary record indicates that technological modernization occurred unevenly, producing cycles of improvement followed by renewed deterioration.

Quality and Social Accessibility.

Economic reports of the household magnetic recording industry indicate that "quality" functioned as a measurable economic category linking technological reliability with financial performance. Internal documentation consistently evaluated quality through three interconnected indicators: defect losses during production, warranty repair expenses after distribution, and post-production costs associated with logistics and servicing. These indicators formed what may be described as the "economy of quality," in which technological limitations were translated into financial outcomes and institutional performance metrics.

The economic review for 1980 recorded a significant increase in defect-related losses at the Mayak plant, rising from 321.7 thousand rubles in 1979 to 428.7 thousand rubles in 1980 (Ekonomicheskii obzor…, 1980, p. 82). This growth indicates a deterioration in technological stability despite ongoing modernization efforts. Simultaneously, warranty repair expenses increased, reflecting both the expansion of production and the growing proportion of more complex stereophonic models. The same report linked rising warranty costs to higher technical complexity and adjustments in repair tariffs following the State Price Committee decree of September 7, 1979 (Ekonomicheskii obzor…, 1980, p. 56). From an infrastructural perspective, the expansion of technological functionality did not automatically improve reliability. On the contrary, increasing complexity under conditions of limited electronic component quality often produced higher rates of malfunction. Internal quality analyses confirmed that defect losses and warranty repair constituted a significant share of production-related costs, demonstrating the systemic nature of technological instability (Analiz sostoianiia kachestva…, 1981, pp. 147–149, 163). User accounts further indicate that perceptions of quality were shaped not only by technical parameters but by practical usability, including reliability, ease of repair, and stability in everyday operation (see Figure 4).

Figure 4. Quality inspection of a Mayak tape recorder at the Kyiv Scientific-Production Association “Mayak.” Technician Vitalii Solovei is shown calibrating a Mayak-001 tape recorder (Kyiv, March 17, 1976), illustrating factory-level testing and adjustment procedures in Soviet audio equipment production (Central State Audiovisual and Electronic Archive, n .d.).

Economic reports from the late 1970s reveal cyclical fluctuations in quality indicators, suggesting that technological stability was shaped not only by engineering factors but also by institutional interventions. The economic review for 1979 recorded a nationwide increase in defect losses of 40.2% compared to 1978, while the Ministry of Communications Equipment Industry reported a reduction of 26.2%, including a substantial decrease at the Mayak plant (Ekonomicheskii obzor …, 1980, p. 72). This temporary improvement likely reflects intensified quality-control campaigns rather than structural technological stabilization. Subsequent reports documented renewed growth in defect losses, indicating that quality management functioned as a cyclical process influenced by resource constraints, workforce discipline, and production pressures. From an institutional perspective, quality was not a stable technical parameter but a dynamic outcome shaped by administrative priorities and planning pressures.

Analytical and forecast materials consistently identified the limited electronic component base as a primary factor constraining technological quality. Reports emphasized that the technological lag of domestic recording equipment behind international standards resulted from shortages of modern electronic components and long development cycles (Sopostavitel’nyi analiz…, 1980, p. 151). These constraints affected core performance parameters such as noise level, mechanical stability, and durability. The reliance on imported micro-motors and critical components created additional vulnerabilities, linking technological performance to external supply conditions. Efforts at import substitution were initiated but produced uneven results, further contributing to cyclical quality fluctuations.

Economic reviews provide quantitative insight into the relationship between technological constraints and economic performance. The 1980 report recorded a reduction in average production cost per tape recorder by 5.4% compared to 1979 (Ekonomicheskii obzor…, 1980, p. 56). From the perspective of industrial policy, this reduction represented an apparent success in cost optimization. However, consumer accessibility was determined not only by production cost but by the interaction of retail price, availability, and household purchasing power. Documents repeatedly emphasized that acquisition was constrained both by absence of desired models and by insufficient financial resources (Kon'iunkturnyi obzor…, 1975, pp. 34–39). This dual constraint demonstrates that technological accessibility was socially differentiated and structurally embedded within the planned economy.

The economy of quality redistributed technological risk across the production-consumption chain. Defects and malfunctions increased warranty repair costs, while dependence on repair infrastructures affected the continuity of user experience. Documentary materials indicate that the average lifespan of a tape recorder was estimated at approximately ten years, with repair systems playing a critical role in maintaining long-term functionality (Kon'iunkturnyi obzor...., 1975, p. 36). From an infrastructural perspective, repair networks constituted an essential component of the technological system, extending device lifespan and stabilizing domestic recording practices despite systemic technological instability.

The documentary evidence suggests that technological quality in late socialist industry cannot be reduced to engineering design alone. Instead, it emerged from the interaction of multiple structural factors: component shortages, production pressures, institutional quality campaigns, and planning priorities. As a result, quality functioned as a dynamic institutional variable linking technological constraints with financial and social outcomes. Calculations of effective consumer demand reveal that access to tape recorders in late socialist Ukraine was shaped by the interaction of commodity availability and household purchasing power. The demand forecast for 1976 projected substantial growth in retail turnover for tape recorders, increasing approximately 2.5 times compared to 1971 (Otchet. Raschet platezhesposobnogo sprosa …, 1976, p. 8).

However, the same report emphasized that rising household income did not eliminate structural constraints on acquisition. Statistical tables demonstrated that projected growth in retail sales exceeded planned production growth, implying persistent shortage embedded within the planning system (Otchet. Raschet platezhesposobnogo sprosa …, 1976, p. 13). Consequently, technological access was constrained simultaneously by commodity scarcity and uneven income distribution. Internal conjunctural reviews identified two primary obstacles to acquisition: the absence of preferred models in retail networks and insufficient financial resources among households (Kon'iunkturnyi obzor…, 1975, p. 39). These dual constraints indicate that shortage operated both as a material limitation and as a socio-economic filter, producing differentiated access to recording technology across social groups.

Distribution reports repeatedly documented persistent assortment imbalances within retail networks, where lower-demand devices accumulated while preferred models remained scarce (Analiz otechestvennogo i zarubezhnogo rynkov…, 1978, p. 14). As a result, the retail availability of tape recorders remained unstable, reinforcing periodic shortages of the most desirable models.) This pattern produced a distinctive temporal structure of technological availability: brief windows of market presence alternated with extended periods of scarcity. Acquisition therefore depended on timing, personal networks, and informal access rather than predictable market supply. From an infrastructural perspective, the distribution system functioned not merely as a logistical mechanism but as a structure shaping social practices of acquisition and technological access.

Price adjustments constituted one of the principal administrative tools used to manage inventory imbalances. Price reductions were applied to technologically obsolete models in order to stimulate sales and reduce accumulated inventories (Kon'iunkturnyi obzor…, 1975, p. 5). While this mechanism improved circulation of outdated devices, it also contributed to differentiated technological access. Lower-cost models became more widely available but often provided lower recording fidelity, higher noise levels, and reduced durability. Consequently, price regulation influenced not only economic efficiency but also the acoustic characteristics of domestic recording environments.

Repair, Substitution, and the Continuity of Technology.

Oral testimonies in this study are not used merely as illustrative material but as analytical evidence of user interaction with technological systems. They provide insight into how technological instability was experienced, interpreted, and practically managed in everyday contexts. Survey data indicate that consumers adapted to shortage through substitution and improvisation. When preferred models were unavailable, households often purchased alternative devices of lower class or relied on secondary markets, repair networks, and collective access arrangements (Kon'iunkturnyi obzor…, 1975, pp. 35–36). From an infrastructural perspective, these adaptive strategies represent forms of technological mediation. Access to recording technology was shaped not only by industrial production but also by social networks, repair infrastructures, and informal circulation. The resulting acoustic environments varied across households depending on technological class, reliability, and recording quality (see Figure 5).

Within the structural conditions of a shortage economy, malfunction and repair formed an intrinsic phase in the life cycle of technical artefacts rather than an exceptional breakdown. This situates Soviet household electronics within a regime of permanent technical negotiation, where reliability was not guaranteed by design but achieved through continuous user intervention. Practices commonly associated with do-it-yourself culture can therefore be interpreted as a historically specific mode of late Soviet subject formation, in which technical competence operated as a stabilizing response to unstable material and industrial environments (Golubev & Smolyak, 2013, pp. 519–521, 532–540). The acts of assembling, adjusting, and repairing devices functioned simultaneously as technological practice and as a form of everyday adaptation to systemic uncertainty.

Figure 5. Adjustment and testing section of tape recorders at the Kyiv "Mayak" plant (Kyiv, 1980), illustrating the organization of calibration and quality control procedures in late socialist industrial production (Central State Audiovisual and Electronic Archive, n. d.).

Repair systems played a critical role in stabilizing domestic recording practices. Documentation indicates that the average operational lifespan of tape recorders was approximately ten years, with maintenance and repair extending functional use despite technological instability (KNPO "Maiak", 1975, p. 43). The economic significance of repair is evident in warranty repair expenses, which formed a substantial share of production-related costs. From a socio-technical perspective, repair infrastructures constituted an essential component of the recording system, ensuring continuity of domestic recording practices and shaping user experience.

The persistence of technical instability in serially produced equipment was partially mitigated by the extensive circulation of specialized technical literature devoted to Soviet magnetic recording technology (Anisimov, 1986). Manuals and technical handbooks issued between the 1960s and the 1980s provided detailed circuit diagrams, calibration data, functional descriptions of core assemblies, and procedural instructions for maintenance and modification (Samodurov, 1971; Kolosov, 1974; 1977; Pochepa, 1979; Vasilevskii, 1989). Importantly, this corpus addressed not institutional repair services but technically literate users capable of direct engagement with device operation. In this technical discourse, the tape recorder appeared not as a closed consumer commodity but as an open and adjustable system whose performance depended on user-mediated calibration and modification. Such representations contributed to the formation of a distinct operational culture in which the user simultaneously occupied the roles of consumer, technician, and partial designer. Domestic repair, experimentation with recording parameters, substitution of components, and fabrication of auxiliary devices became normalized elements of everyday technological practice.

A key mediating role in this configuration was played by the Massovaia radiobiblioteka series, which functioned as a distributed infrastructure of technical knowledge. Rather than producing professional repair specialists, these publications equipped users with practical competencies for diagnosing faults and stabilizing device performance in domestic settings. Alongside general explanations of tape recorder construction and operating principles, they provided detailed guidance on correcting typical malfunctions, fine tuning tape transport and recording circuits, and constructing supplementary modules and attachments (Bozdekh, 1981; Shiyanov, 1988). Through this literature, technical literacy was standardized and embedded in everyday practice, effectively extending the site of technological maintenance from institutional workshops into the domestic sphere.

Oral testimony reveals how this domestically embedded regime of technological competence operated in practice. A recurring feature in user narratives is the necessity of continuous intervention in the functioning of tape recorders. In these accounts, the tape recorder rarely appears as a finalized and self-sufficient technical object but rather as a device existing in a state of ongoing modification, ranging from routine cleaning of recording heads to replacement of mechanical assemblies and rewiring of circuits. Respondents describe these actions as ordinary and expected components of use: "you replace the heads, replace the tape transport mechanism… you did it for your own goals and tasks" (Interview with Respondent No. 1 (2025), DELS Archive, Fond 61, Opys 3, Sprava 42, fol. 22); "with reels you had to clean the head so that the sound would be good" (Interview with Respondent No. 1 (2025), DELS Archive, Fond 61, Opys 3, Sprava 42, fol. 23). At the same time, technically experienced users emphasized the structural limits of improvement. One informant directly associated the instability of household electronics with the quality of the civilian component base and the selective allocation of higher-grade elements to the military sector: "we made some improvements, but still it never improved to the level of branded equipment, which cost tens of times more at the time; it was still not that. Our component base, especially the capacitors, was of very low quality. That was in all devices except military ones, where there was military acceptance and different parts. For household equipment, everything went that wasn't used for the military, everything that got rejected. That's why it wasn't as reliable" (Interview with Respondent No. 2 (2025), DELS Archive, Fond 61, Opys 3, Sprava 42, fol. 7).

Technological Quality, Use, and Social Construction.

The empirical evidence presented above suggests that technological quality in late socialist industry should be understood as a relational category shaped by institutional and social contexts. From an STS perspective, qualities such as reliability, fidelity, and functionality may be interpreted as affordances rather than inherent properties of devices. This perspective highlights a reciprocal dynamic: while industrial planning and resource allocation structured technological possibilities, everyday practices of use contributed to redefining what counted as acceptable performance. Users adapted to noise, instability, and mechanical limitations, integrating them into normalized listening practices. Oral testimonies demonstrate that users actively interpreted and redefined technological limitations, integrating them into routine practices and thereby contributing to the social construction of technological quality. At the same time, demand for specific functionalities (portability, reproducibility, ease of circulation) shaped expectations toward recording technologies.

Consequently, technological development did not follow a linear trajectory of improvement but unfolded through continuous negotiation between institutional production regimes and socially embedded practices of use. This interpretation is supported by the empirical evidence presented in the preceding sections, which demonstrates that fluctuations in quality indicators, uneven distribution, and reliance on repair infrastructures directly shaped user experience. In this context, technological limitations were not simply constraints but conditions that structured patterns of use, adaptation, and evaluation. From a broader perspective, this case suggests that late socialist consumer technologies should be understood as dynamic socio-technical systems in which institutional structures and everyday practices were mutually constitutive. Such an approach contributes to bridging the gap between industrial history of technology and studies of everyday life in socialist societies.

Mayak as a Socio-Technical Infrastructure.

The expansion of domestic recording technologies facilitated informal sound circulation beyond official media channels. Home recording enabled copying of radio broadcasts, duplication of phonograph records, and circulation of recorded materials through personal networks. These practices formed part of the broader phenomenon often described as magnitizdat (informal circulation of audio recordings through privately copied magnetic tapes), in which magnetic recording technologies supported decentralized sound distribution. Documentary evidence suggests that shortage and uneven technological access reinforced the importance of informal circulation. When desired recordings were unavailable through official channels, domestic recording provided alternative means of access. From an infrastructural perspective, the tape recorder functioned not only as a consumer device but as a medium enabling decentralized sound exchange (see Figure 6).

Figure 6. Tape recorder adjustment section at the Kyiv "Mayak" plant (Kyiv, October 24, 1979), illustrating calibration and fine-tuning procedures within the industrial production process (Central State Audiovisual and Electronic Archive, n. d.).

The interaction of technological access, distribution mechanisms, and domestic recording practices contributed to the emergence of individualized acoustic environments. The personal acoustic environment may be understood as the configuration of listening, recording, and reproduction practices within domestic space, shaped by technological capabilities and social conditions. In this context, the Mayak tape recorder functioned as an infrastructural device mediating access to sound, memory, and social communication. The acoustic characteristics of domestic environments (noise levels, recording fidelity, durability, and continuity of access) were determined by technological parameters shaped by industrial planning and systemic constraints.

The documentary record allows Mayak tape recorders to be interpreted not merely as consumer devices but as components of a broader socio-technical infrastructure linking industrial production, distribution systems, maintenance networks, and everyday sound practices. Within this framework, the tape recorder functioned simultaneously as a planned commodity and as a medium structuring private sonic life. Industrial documentation repeatedly demonstrates that technological parameters (mechanical stability, durability, and noise level) were shaped by systemic constraints of centralized planning and component shortages. These parameters directly influenced user experience, determining the reliability of recording, the continuity of device use, and the quality of reproduced sound. Consequently, technological characteristics cannot be understood independently of institutional and economic structures (Sopostavitel'nyi analiz i prognozirovanie…, 1980, p. 151). The infrastructural perspective highlights the interconnectedness of production, quality, distribution, and consumption. Technological instability increased warranty repair and defect losses, while uneven distribution shaped patterns of acquisition and access. Together, these factors formed a system in which industrial organization significantly structured everyday auditory experience, without fully determining it, as users actively adapted technologies to their needs and contexts of use.

Documentary evidence indicates that the relationship between industrial production and domestic recording was reciprocal. Industrial planning shaped technological availability, while patterns of use influenced institutional responses. Conjunctural reviews repeatedly emphasized the importance of aligning production structure with consumer demand, noting that insufficient assortment and slow model renewal generated both shortage and inventory accumulation (Kon'iunkturnyi obzor…, 1975, pp. 56-58). The shift toward higher-class and stereophonic models reflected both technological modernization and changing consumer expectations. However, increased technological complexity often produced higher rates of malfunction, reinforcing the cyclical nature of quality fluctuations. From a socio-technical perspective, technological modernization did not eliminate instability but reconfigured its forms. Domestic recording practices further shaped technological meaning. Tape recorders were used not only for listening but for recording broadcasts, copying music, preserving speech, and circulating sound through personal networks. These practices transformed the tape recorder into a medium of everyday communication and memory, extending its function beyond industrial design.

Informal Networks and Social Mediation.

The infrastructural analysis of distribution and repair reveals that technological access followed specific temporal rhythms. Short periods of availability in retail networks alternated with longer phases of scarcity, while repair cycles interrupted and restored device functionality. These rhythms shaped the continuity of domestic recording practices and contributed to the formation of individualized acoustic environments. Repair networks played a stabilizing role within this temporal system, extending the operational lifespan of devices and mitigating technological instability.

From this perspective, technological access was not a static condition but a dynamic process structured by production cycles, distribution flows, and maintenance networks.

The scarcity of desired models and uneven distribution encouraged the development of informal acquisition networks (Analiz otechestvennogo i zarubezhnogo …, 1978, pp. 29–30). Consumers relied on personal connections, opportunistic purchasing, and secondary circulation when preferred devices were unavailable. These informal networks constituted an extension of the technological infrastructure, mediating access to devices and recordings. The tape recorder thus became embedded within social relations, functioning as both a technological object and a social resource (see Figure 7).

Figure 7. Mentor of young workers, Mayak plant employee A. B. Yurkevych, sharing work experience with junior workers (Kyiv, 1982), illustrating the transmission of technical skills and workplace knowledge in Soviet industrial production (Central State Audiovisual and Electronic Archive, n. d.).

The material characteristics of tape-recording technology shaped everyday sonic experience, while evolving patterns of use simultaneously influenced how these characteristics were perceived, evaluated, and normalized. Noise levels, mechanical instability, and variability in recording quality influenced listening practices and user perception of sound. Documentation demonstrates that these characteristics were shaped by systemic industrial constraints, linking sensory experience with institutional and economic structures. In this sense, the personal acoustic environment cannot be understood solely in cultural or psychological terms. It emerged from the interaction of technological materiality, industrial organization, and social practice. The Mayak tape recorder functioned as a mediator between these domains, structuring the sonic conditions of everyday life in late socialist Ukraine.

The combined analysis of production, quality, distribution, and everyday use suggests that Mayak tape recorders constituted a key infrastructural element of late socialist domestic life. Their technological trajectory was shaped by systemic constraints rather than linear innovation, producing a dynamic interplay between technological instability and everyday adaptation. From a broader perspective, the study demonstrates that socialist consumer technologies cannot be understood solely through production statistics or cultural analysis. Instead, they must be examined as socio-technical systems linking industrial organization with everyday practice.

Conclusions.

This article has approached Mayak tape recorders not simply as consumer devices but as a socio-technical infrastructure formed at the intersection of centralized planning, technological constraint, and everyday practices of domestic sound recording in late socialist Ukraine. By combining industrial documentary materials with an infrastructural perspective, the study shows that the trajectory of Mayak technology cannot be explained through technical evolution alone. It must be understood within the broader institutional and economic environment of late socialist industry, where production, distribution, and use were closely interwoven. The analysis demonstrates that shortage was not a temporary disturbance but a structural feature of the planned economy. Conjunctural reviews consistently recorded the coexistence of scarcity and surplus, where high-demand models remained unavailable while technologically outdated devices accumulated in storage. This imbalance reflected the dominance of quantitative production targets over demand sensitive assortment planning and shaped not only the volume of available technology but also the timing and rhythm of its acquisition.

Our study highlights the importance of what may be described as an economy of quality. Economic reports reveal that technological reliability functioned as a measurable financial category expressed through defect losses, warranty repair expenditures, and post-production costs. In this framework, quality was not a fixed technical attribute but a variable outcome shaped by component shortages, production pressures, and institutional quality campaigns. Engineering limitations were thus translated into economic and administrative decision making. The findings show that technological accessibility was determined by the combined effects of commodity scarcity and uneven purchasing power. Demand calculations and conjunctural reviews indicate that access to tape recorders varied significantly across social groups, producing differentiated domestic acoustic environments. Recording technology was therefore distributed not only through production systems but also through broader social and economic structures.

The article demonstrates the infrastructural role of distribution and repair networks. Uneven commodity flows generated temporal scarcity, while repair systems extended the operational life of devices and stabilized everyday recording practices. From a socio-technical perspective, repair was not a secondary service but a constitutive component of the recording system, enabling technological continuity under conditions of instability. The spread of domestic recording technologies facilitated decentralized forms of sound circulation. In an environment shaped by limited official media access and material shortage, home recording enabled copying, preservation, and exchange of sound, contributing to the formation of informal sonic networks and everyday media practices. Tape recorders thus functioned as infrastructures of communication and memory as much as tools of reproduction.

Taken together, these findings support a systemic interpretation of Mayak tape recorders as infrastructural devices linking industrial organization with everyday auditory experience. Their development was shaped by the interaction of planning mechanisms, resource constraints, and user adaptation. More broadly, the study suggests that late socialist consumer technologies should be understood as dynamic socio-technical systems in which technological materiality, institutional structures, and everyday practices were mutually constitutive. The Mayak tape recorder illustrates how industrial planning influenced not only production and distribution but also the sensory, temporal, and cultural dimensions of everyday life. At the same time, this relationship was not unidirectional. Everyday practices of recording, listening, and circulation contributed to shaping technological expectations and, indirectly, production priorities. The Soviet tape recorder thus functioned within a reciprocal socio-technical dynamic in which industrial systems and user practices continuously interacted.

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Conflicts of Interest.

The author declare no conflict of interest.

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Магнітофони "Маяк" у пізньосоціалістичній Україні: Промислове планування, технологічні обмеження та повсякденні практики звукозапису

Анотація. *У статті реконструйовано життєвий цикл магнітофонів «Маяк» у радянській Україні як соціотехнічної інфраструктури, яка формувалася під впливом централізованого промислового планування, пріоритетів оборонного сектору та повсякденних практик домашнього звукозапису у 1970–1980 х роках. Дослідження спирається на широкий комплекс внутрішньої міністерської та заводської документації. Використано кон'юнктурні огляди ринку, розрахунки платоспроможного попиту населення, економічні звіти галузі побутового магнітного звукозапису та внутрішні аналізи якості. Окрему групу джерел становлять матеріали опитувань і усних свідчень користувачів радянської побутової техніки, що дозволяють відтворити повсякденний досвід експлуатації магнітофонів. У роботі застосовано інфраструктурний аналіз, джерелознавчу критику та історичну реконструкцію статистичних даних. Це дало змогу простежити взаємозв'язок між організацією промисловості та повсякденними звуковими практиками. Архівні матеріали показують, що технологічна якість функціонувала як економічна категорія. Вона вимірювалася втратами від браку, витратами на гарантійний ремонт і післявиробничими витратами, поєднуючи технологічні обмеження з фінансовими та інституційними результатами. Результати дослідження свідчать, що структурний дефіцит, нерівномірність асортименту та залежність від ремонтної інфраструктури формували практики домашнього слухання. Вони також сприяли неформальній циркуляції звуку, включно з домашнім копіюванням і магнітіздатом. Зроблено висновок, що магнітофони «Маяк» функціонували одночасно як планова продукція і як медіаінфраструктура приватного звукового життя. Вони визначали матеріальні умови формування персонального акустичного середовища в пізньосоціалістичній Україні. Аналіз також демонструє взаємозв'язок між технологічними системами та практиками користувачів, показуючи, як повсякденне використання технологій запису сприяло переосмисленню понять якості, функціональності та доступності в умовах пізньосоціалістичної промислової системи.*

Ключові слова: *магнітний звукозапис; магнітофони «Маяк»; планова економіка; дефіцит; домашній звукозапис; персональне акустичне середовище*

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From *Pelita* to electric lamp: An evolutionary study of lighting technology in Kuala Lumpur, 1880s–1940

Abstract. *This article aims to examine the transformation of lighting systems in Kuala Lumpur, a major town in Selangor, Malaya from the late 19th century to the early 20th century. This study analyses how the process of illuminating the home at night shifted from a laborious hand-on task to a significantly more convenient and efficient system as a result the development of science and technology-based infrastructure particularly the provision of electricity. In additional, this article explores how exactly lighting technology has been introduced and integrated into homes in Kuala Lumpur. To investigate these questions, the study applied qualitative and historical research methods. Most of the information and statistics used in this article were collected from primary sources, including archives and official documents of the Electrical Department and the Selangor Secretariat Files published in the late 19th century to the first half of the 20th century. The study demonstrated that the provision of electricity as a domestic energy source by the Electrical Department played a significant role in advancing lighting technology in homes. The need to illuminate homes at night which was traditionally met through the use of the pelita, a container filled with kerosene that produces light through a lit wick has shifted to the use of electric lighting which provides illumination with just the flick of a switch. The development of lighting technology meant that the process of illuminating homes was no longer managed entirely by homeowners but also became the responsibility of the Electrical Department. Starting with the generation and distribution of electricity to consumers, the Electrical Department was subsequently responsible for managing household wiring systems and ensuring that the installation of electric lighting was properly carried out before it was used by consumer. Therefore, the evolution of lighting technology in Kuala Lumpur from oil lamp to modern electric lamp not only widened the nocturnal living spaces within homes but also afforded users with an enhanced sense of safety and comfort.*

Keywords*: lighting; electricity; Kuala Lumpur; home; electrical department; urban modernization*

Introduction.

By the end of the 19th century, Kuala Lumpur experienced a very significant development, with its transformation from a small village into a major city in Malaya. The development of the tin mining sector and its selection as the British administrative centre led to large-scale migrations to Kuala Lumpur. In 1880, the population of Kuala Lumpur was estimated to be around 3,000 residents, before increasing to 4,054 residents in 1884 (Gullick, 1955, p. 40). By 1890, the population showed a sharp increase to 19,000 residents, and within the next five years this number shot up to 25,000 (Rus, 2005, p. 102). By the dawn of the 20th century, Kuala Lumpur had 30,000 residents (Ismail, 2015, p. 259). The drastic population increase, especially of European and Chinese communities, turned Kuala Lumpur into a high population density area. At the same time, many houses were erected, leading to an unorganised settlement, and causing a congested and unclean environment. This situation indirectly affected the residents' security, comfort, and health. To accommodate the ever-growing population, each house was built close to one another, and only separated by a 10- to 12-foot-wide road. The small distances between houses and the use of building materials such as wood posed a safety risk to the residents in the event of a fire (Jackson, 1963, p. 119). Meanwhile, the neglected sewage and garbage disposal system and untreated water supply also facilitated the spread of diseases such as malaria, tuberculosis, and dysentery. Therefore, it was clear that the population increase in Kuala Lumpur posed major security and health risks.

To ensure the residents' well-being, the government paid special attention to professional urban governance and sought to design a liveable urban environment. Thus, the Sanitary Board was established in May 1890, responsible for management of urban affairs (Rus, 2001, p. 45). They took steps to improve the sewage system, provide clean water, control the spread of disease, and prevent fires to ensure the survival of Kuala Lumpur as a liveable city. In addition, there is one other important feature of the development of Kuala Lumpur, namely illumination. Although lighting was only used for night-time, the government realised the necessity of an efficient lighting system for crime prevention. Kuala Lumpur, a commercial city of shophouses, clubs, and elite residential areas consequently exposed it to the risk of burglaries, robberies and other crimes. For example, in 1895, there was the Li Choi Gang, involved in robberies and murders (Gullick, 2017, p. 105). In another incident, ten robbers armed with revolvers broke into a shop owned by one Chong Yew. The incident resulted in the owner deprived of $400 and his life (Gullick, 2007, p. 622). Aside from shops and residents' homes, government and private offices were also targeted by criminals. Around 1894, a number of cases of theft were reported to have occurred at the Government Printing Office, the Residency Surgeon, and the Selangor Club (Gullick, 2007, p. 623). Therefore, lighting was very important to ensure the safety of Kuala Lumpur residents. The emphasis on this aspect coincides with the Crime Prevention through Environmental Design (CPTED) model by Newman (1972). Through this model, crime prevention can be implemented by paying attention to urban designs such as roads, buildings, housing, and residential lifestyles. The construction of business and residential premises with a good lighting system can potentially reduce or prevent crimes, thereby increasing the level of residential security. Aside from crime, illumination with efficient and safe energy sources such as electricity can also reduce fire hazards.

Although studies on the history of Kuala Lumpur's 20th century urbanisation received scholarly attention, most discussions do not emphasise on urban illumination. Gullick (2017), who studied the history of Kuala Lumpur between 1856 and 1939, discusses the various aspects of urbanisation, but barely focused on the development of the lighting system. Both Rus (2001) and Ismail (2015) discuss the role of the Sanitary Board in managing aspects of urbanisation in Kuala Lumpur. Although both studies concentrated on the Engineering Department under the Sanitary Board, the ensuing discussions only focused on the sewerage system and clean water supplies. Even Rus (1996; 2006), in his other studies, evidently still focused on the same aspects, namely administration, urban hygiene, and disease control. The latest study by Arbi, Zainol, and Ahmad (2025) on aspects of Kuala Lumpur's urban planning also skipped discussing lighting as one of the important features for city life.

Based on this observation, studies on the implications of western scientific and technological advancements on Kuala Lumpur in particular and Malaya in general have yet to be explored in depth. In fact, when viewed even in the context of Singapore, an important colonial port-city in the "Far East" of the British Empire, research is still lacking (Goh, 2013, p. 3). Although Goh (2013) focuses on technological developments in Singapore, discussion on electricity remains superficial and cursory. Instead, the discussion is more focused on technology in regards to ports, agriculture, sanitation, and public health. Ditto for Yeoh (2003) who only focuses on technology in Singapore's urbanisation such as sanitation and housing. Both of these studies ignored urban illumination, even though in the late 1920s, the government paid attention to the provision of electricity for street lighting and residential uses in Singapore. India, another British colony, saw the development of electrical facilities as a new energy source (Sarkar, 2018). However, based on several studies by Sarkar (2015; 2017; 2020), his discussion only framed this energy source within the economic and technical knowledge development.

Based on existing studies, illumination has yet to receive its due attention within the writing of the history of colonial-era Kuala Lumpur in particular and Malaya in general, even though a good lighting system has become an important feature in the growth of Kuala Lumpur as a modern city. The presence of Chinese and European communities in Kuala Lumpur with their distinctive lifestyles has led to the emergence of a new culture, namely nightlife. Night-time social activities in clubs and hotels, including illicit pastimes such as gambling and prostitution, necessitated illumination. In addition, the process of developing electrification facilities in Kuala Lumpur by the

1920s showed progress, thus providing a stable source of lighting for the population. Therefore, this article aims to study the development of the lighting system in Kuala Lumpur by focusing on residential homes from the late 19th century to the early 20th century. This study analyses the changes that occurred in the process of illuminating the home at night as a result of electrification, and identifies how exactly the progress in lighting technology was introduced and integrated into the homes in Kuala Lumpur. The discussion highlights illumination as one of the important features in ensuring the security and comfort of the residents of Kuala Lumpur. Furthermore, this study provides a new perspective on the history of Kuala Lumpur's urbanisation, namely the development of lighting technology, previously overlooked by researchers.

Research Methodology.

In line with the research objective which aims to examine the transformation of the illumination system in Kuala Lumpur and the integration of modern lighting technology in the process of lighting homes in the past, this study uses the historical and qualitative research methods. Starting with the heuristic method, primary sources such as the Annual Reports of the Electrical Board and the Annual Reports of the Electrical Department were collected. The use of both of these sources is very important and suitable to the focus of the study on electrification facilities. As the department responsible for managing electricity supply services, the Electrical Department has recorded various information and statistics related to this energy source. Furthermore, although the Sanitary Board was established to manage urbanisation in Kuala Lumpur, the development and provision of electricity was the purview of the Electrical Department. Other primary sources used in this study are the Selangor Annual Reports and the Selangor Secretariat Files. These sources contain information about Kuala Lumpur as one of the districts in Selangor. Although these sources do offer information to explain the process of providing electricity in Kuala Lumpur, there are limitations in the information, and it is difficult to determine its development in detail. Some important information such as the number of residential houses that receive electricity, and user groups according to ethnicity, class, or area are not stated. Therefore, it is difficult to analyse the implications of electrification and its utilisation as a source of lighting on the socio-economic aspects of the population. In addition, these sources only explain the services provided by the government, and ignore information on the private companies involved. To compensate for this deficiency, newspapers are also used to obtain information about private companies. In addition to primary sources, secondary sources such as books and articles are also consulted. Therefore, the use of primary and secondary sources ensures the relevant information is collected and adapted to the discussion. After collection, the next method is criticism to confirm the suitability of the sources for the study. After collecting relevant information and statistical data from primary and secondary sources, the next step is interpretation. This step aims to identify appropriate information and statistical data to support the arguments presented in the discussion. The final step is writing, whereby all the collected facts are systematically arranged according to set objectives to ensure the proper flow of ideas. The three objectives are a historical review of traditional illumination systems to identify methods and problems in their utilisation, the provision of efficient and stable energy sources through the development of electrification facilities and then the process of introducing and integrating modern lighting technology in residential homes. The chronological arrangements of these three objectives aim to present a historical narrative on the evolution of the lighting system in Kuala Lumpur from the end of the 19th century to the beginning of the 20th century.

Results and Discussion.

Kuala Lumpur was designed and constructed at the tail-end of the 19th century to function as the administrative centre for the Federated Malay States (a combination of four states, namely Perak, Selangor, Negeri Sembilan and Pahang) as well as the centre of commercial economic activities. With this position, Kuala Lumpur became a focal point for the population. To balance the function of Kuala Lumpur and its ever-increasing population, the government focused on local affairs by developing various modern basic facilities. The provision of these basic facilities has not only transformed the physical structure of Kuala Lumpur, but more importantly has added value to the daily lives of residents in terms of security. In this context, the provision of electricity has led to significant changes in the process of night-time illumination in residential homes. The adaptation of technology such as electricity and electric lamps as a source of lighting has made the night-time atmosphere brighter, further increasing the level of security. Although this lighting technology is something new and involved engineering, the integration process was facilitated by government support, especially its Electrical Department.

Lighting the Pre-electric Home.

Traditionally, for residents of Kuala Lumpur before the arrival of the British, the largest source of lighting in residential homes usually came from fire. This source of lighting was produced through the combustion process, using fuels such as coconut oil or kerosene. The need to provide this source of lighting was the sole responsibility of each homeowner. Therefore, the source of lighting was obtained and managed with local knowledge, which was then adapted with simple nature-based technology to illuminate the house at night. Residents used coconut shells or bamboo as containers, filled with oil and placed a wick at the top to light it. The simple technology used to generate light was described by an English traveller, Isabella Lucy Bird, who travelled to Malaya in the late 19th century, who recorded that the local residents used a "nutshell filled with palm-oil and containing a pith wick" as an *pelita* (oil lamp) (Bird, 1883, p. 24).

Urbanisation and the development of social activities necessitated night-time illumination. Hence, the increase in the demand for oil lamps. Since there was no lamp manufacturing industry in Kuala Lumpur in particular and Malaya in general, oil lamp supplies had to be imported. By the beginning of the 20th century, many companies emerged that became importers and distributors of oil lamps with more modern designs and made of pewter. It was discovered that the import value of lamps and lampware in 1908 increased to $74,036 compared to $73,287 in the previous year (Selangor Administration Report for the year 1908, 1909). The John Little and Company Limited was among the companies involved in importing and marketing oil lamps in Kuala Lumpur (Malaya Tribune, 1916, p. 2).

In general, the provision of oil lamps has brought about changes to the night spaces of residents in Kuala Lumpur, including in residential homes. However, oil lamps produced dim light, smoke, and soot in addition to being a fire hazard. Undoubtedly, oil lamp manufacturing companies were always making improvements to reduce the risk of fire for users. For example, the Kitson Company introduced safer oil lamps because they have glass covers to prevent other objects from catching fire, as well as an adjuster that could control the intensity and use of fuel (Selangor Secretariat File 3981//1920). However, these oil lamps still used liquid fuels such as kerosene and petroleum, which were potential fire hazards. In January 1881, a fire occurred as an oil lamp fell over in an opium shop. The incident resulted in 500 residents becoming homeless and three casualties (Rus, 2001, p. 19). In another incident, four victims died due to an explosion that occurred when one of the victims was filling kerosene to light the lamp (Selangor Secretariat File 875/1899). Furthermore, the use of oil lamps required users to ensure fuel supplies availability at home. Therefore, residents needed to properly prepare and manage space and storage of the fuel to prevent accidents. In other words, residents were fully responsible for providing lighting to their homes at night.

Advent of Electricity: The Modern Lighting Source.

As early as the 1890s, the government had planned to develop electrification facilities in Kuala Lumpur as a source of lighting (Selangor Secretariat File 3921/1901). Thus, Charles Edwin Spooner as state engineer was responsible for drawing up an electrification scheme. Based on Spooner's scheme, a hydroelectric station using the flowing Gombak River was built in 1899, and it was completed and started its operation in 1905 (Selangor Secretariat File 1577/1909). However, the electricity generated was still limited to public use such as street lighting and government buildings. This was because the process of developing electrification facilities in Kuala Lumpur was still in its early stages and only on a small scale. In addition, residents' homes were not equipped with an electrical wiring system, and electrical goods were not yet widely marketed in Kuala Lumpur.

By the early 1920s, the government recognised the fact that electricity needed to be explored and capitalised. Frederick Bolton, who had experience as a hydro-electrical engineer and involved in several projects in Britain and South Africa, was appointed as electrical adviser to design a more efficient supply scheme for Kuala Lumpur and several other cities in the Federated Malay States (Tate, 1989, pp. 58–75). As a result of his report, the Electrical Board was established in 1921 before being restructured in 1927 and known as the Electrical Department. The establishment of the Electrical Department led to the development of properly planned electrification facilities, and managed by professional electrical engineers supported by science and technology-based infrastructure. However, the government's main goal in developing electrification facilities was to provide a source of manpower to meet the needs of the tin mining sector. As the largest contributor to government revenue, the provision of an efficient source of power for the tin mining sector was paramount. Furthermore, by the early 1920s, the tin mining sector in Kuala Lumpur was facing a shortage of manpower (Ken, 1965). Thus, in 1927 began a construction work on a power station in Bangsar with a capacity of 9,000 kW (Selangor Secretariat File 363/1924). The Bangsar Power Station, completed and began its operations in July 1927, supplied most of the electricity for the tin mining sector (Annual Report and Accounts of the Electrical Department for the year 1927, 1928).

The construction of Bangsar Power Station with its large generating capacity indirectly became the starting point for the expansion of electrification involving domestic users. Based on Table 1, it is clear that the use of electricity for the domestic sector in general recorded an increase since 1927. In 1930, the initiative taken by the Electrical Department by adding a 10,000-kW generator set to meet the increasing demand also further increased the Bangsar Power Station's electricity generation capacity to 19,000 kW (Annual Report and Accounts of the Electrical Department for the year 1930, 1931; Selangor Administration Report for the year 1927, 1928, p. 10). The installation of this additional generating set allowed more electricity to be generated and supplied to domestic users. In addition, around the 1930s there was a lot of information about electricity published in newspapers showing its advantages as an energy source. For example, an article titled "Benefits of Electricity" explained the advantages of electricity as a brighter and less risky source of illumination compared to gas, oil, and spirits (Malaya Tribune, 1932, p. 2). The publication of articles about electricity indirectly contributed to the increase in electricity use for the domestic sector. Based on an article published by the Malaya Tribune (1934), it is clear that the use of electricity for lighting purposes has become the go-to choice of the population. Only in 1933 did the use of electricity for the domestic sector recorded a decrease due to the downturn economic situation that had yet to recover from the effects of the world economic recession. This decrease also affected the use of electricity in the economic sector. This situation caused domestic consumers to return the electrical appliances rented from the Electrical Department (Annual Report and Accounts of the Electrical

Department for the year 1933, 1934, p. 11). In fact, the total number of consumers connected to the system in 1933 also showed a decrease from 6,529 consumers to 6,868 consumers in 1932 (Annual Report and Accounts of the Electrical Department for the year 1933, 1934, p. 10; Annual Report and Accounts of the Electrical Department for the year 1932, 1933, p. 11). When the economic situation improved in 1934, the use of electricity for the domestic sector showed an uptick, due to the increase in consumers connected to the system, to 6,945 consumers (Annual Report and Accounts of the Electrical Department for the year 1934, 1935, p. 11).

Table 1. Electrical Energy Unit Usage In Kuala Lumpur, 1927–1937 (Source: Author's reconstruction based on data from *Annual Report and Accounts of the Electrical Department*, from 1934 to 1937).

Year	Domestic	Industry
1927	10,571	654,511
1928	138,194	7,620,295
1929	387,915	14,974,268
1930	795,162	15,155,908
1931	1,003,137	11,152,065
1932	1,043,376	8,395,499
1933	958,195	9,789,535
1934	1,244,330	20,207,889
1935	1,515,388	33,223,588
1936	2,076,321	53,767,591
1937	3,587,825	59,444,880

To ensure that domestic users were connected to the electrification system, two aspects were given due attention by the Electrical Department, namely the building of substations and the connection of transmission lines. The construction of substations functioned as a distribution centre for electricity from Bangsar Power Station to consumers by residential areas. In addition, substations are also built to ensure that the electricity supplied to residential homes were at a lower voltage to suit the level of home use and ensure safety. Many substations were built by the Electrical Department for suitable use for residential areas in Kuala Lumpur. Among them were at Brickfields Road, Ampang Road, Circular Road, Imbi Road, Hospital Road (Annual Report of the

Electrical Board for the year 1926, 1927, p. 3), Sungei Besi Road, Bungsar Road (Annual Report and Accounts of the Electrical Department for the year 1928, 1929, p. 6), Batu Road, Pudu Road, Maxwell Road, and Rodger Street which were equipped with low tension switchgears (Annual Report and Accounts of the Electrical Department for the year 1929, 1930, p. 5).

Table 2. The Extension of Transmission Line Connections in Kuala Lumpur 1928–1939 (Source: Author's reconstruction based on data from *Annual Report and Accounts of the Electrical Department,* from 1928 to 1939).

Year	Overhead Mains (Miles)	Underground Mains (Miles)
1928	135.00	45.00
1929	162.00	50.00
1930	210.75	62.00
1931	227.00	64.60
1932	224.36	67.28
1933	269.61	65.77
1934	285.02	67.94
1935	298.14	68.04
1936	326.06	68.22
1937	382.43	73.12
1938	393.13	76.48
1939	463.35	83.07

With the increase in the number of substations, the Electrical Department also carried out transmission line connection works to channel the electricity generated from Bangsar Power Station to each substation before they were supplied to the end-users. Table 2 shows the increase in the distance of transmission line connections made by the Electrical Department between 1928 and 1939. There were two types of transmission line connections used by the Electrical Department to supply electricity to consumers, namely the overhead mains and underground mains. The connection of these transmission lines shows that the electricity supply in Kuala Lumpur had been expanded. In other words, more residents in Kuala Lumpur have access to electricity.

In 1928, 4,109 users have access to electricity. This number increased to 12,546 users by 1939 (Annual Report and Accounts of the Electrical Department for the year 1928, 1929, p. 7; Annual Report and Accounts of the Electrical Department for the year 1939, 1940, p. 62). Behind the development of electrification facilities, it also shows that the residents of Kuala Lumpur now have a more stable and guaranteed modern lighting source. The transition to the use of electricity as a lighting source subsequently caused the development of illumination technology in the context of residential homes in Kuala Lumpur.

Bringing Electric Light into the Home.

Undoubtedly, the idea of encouraging homeowners in Kuala Lumpur to use electric lights had been around since the late 1890s. At that time, the private companies involved in providing electrical engineering services and supplying electrical goods had influenced the especially elite segment of the population. For example, Mr Sanderson, a representative of Riley, Hargreaves and Company, took the initiative to organise an electric light show in his quarters in High Street (Gullick, 2007, p. 413). In addition, the company also installed electric lights in workshops and invited several Chinese investors to witness the efficiency and advantages of their use (Gullick, 2007, p. 416). However, it is difficult to obtain information on the use of electric lights among the people of Kuala Lumpur around the late 19th century and early 20th century. Although the electrification facilities provided by the government began in 1905, there is no information on its use as a source of lighting in homes. In fact, the Annual Reports of the Public Works Department and the Annual Reports of the Electrical Board also did not clearly state the use of electric lights. Only after 1927 was the use of electricity for lighting started to be recorded in the Annual Report of the Electrical Department. However, the information only referred to electric lights provided by the Electrical Department, and did not mention private companies or other suppliers. The use of electricity as a source of lighting was also not categorised by ethnicity or social class. However, as a new energy source, electricity was seen as a symbol of prestige and modern identity for its consumers. Therefore, it can be concluded that the use of electricity in the early stages was only concentrated among the elite, such as European and Chinese capitalists. Viewed within the context of Singapore, electricity as a source of lighting at home was also only concentrated among foreign capitalists (Edwards, 2017, p. 105). In addition, electricity usage was also not stated in detail for lighting sources, but was instead included under the domestic sector category.

The construction of the Bangsar Power Station and the connection of the transmission line have provided a very important foundation for the modernisation of lighting in homes. However, one issue requirement management by the government, especially the Electrical Department, which was to integrate the electricity into residents' homes. This posed a huge challenge to the Electrical Department because existing homes in Kuala Lumpur were still not equipped with an electrical wiring system. The Electrical Department took steps by installing an electrical wiring system in residents' homes, which included electrical points, sockets, and electrical wires on the wall to be connected to fans, cookers, water heaters, and lamps. In 1928, the Electrical Department installed 1,480 electrical point installations for lights, fans, and cookers (Annual Report and Accounts of the Electrical Department for the year 1928, 1929, p. 7). Within a year, there was an increase of 1,766 electrical points installed by the Electrical Department for new users, which further increased to 1,874 electrical points in 1930 (Annual Report and Accounts of the Electrical Department for the year 1929, 1930, p. 6; Annual Report and Accounts of the Electrical Department for the year 1930, 1931, p. 8). This increase marked the inclination of residents in Kuala Lumpur to switch to the use of electrical goods, including electric lights. To further expedite the process of installing electrical points in residents' homes, the Electrical Department authorised contractors or companies involved in electrical services to manage the installation process. However, to ensure the safety of residents while using electricity, the Electrical Department set regulations that every installation must be handled by certified workers. This regulation, as stipulated in The Electricity Enactment (1914), states:

> *No installation or electrical plant or apparatus shall be worked or operated except by or under the control of persons possessing such qualifications and holding such certificates as may be prescribed, and no person not possessing such qualifications or holding such certificate shall work or operate any installation or electrical plant or apparatus except under such control as aforesaid.*

At the same time, the Electrical Department held examinations that awarded certificates as wireman, chargeman and engineer to passing candidates. For example, 187 candidates sat for the examination in Kuala Lumpur, Ipoh, and Seremban in 1927, and from that number, 25 people passed the test as wireman, while 29 candidates passed as chargeman (Annual Report and Accounts of the Electrical Department for the year 1927, 1928, p. 17). The number of candidates taking the examination to become wireman and chargeman showed a continued increase. In 1928 alone, 63 candidates obtained certification as wireman, and another 36 candidates as chargeman (Annual Report and Accounts of the Electrical Department for the year 1928, 1929, p. 19). This increase enabled the Electrical Department to hand over the work of installing electrical points in homes to contractors. In 1929, 1,383 electrical point installations were carried out by contractors (Annual Report and Accounts of the Electrical Department for the year 1929, 1930, p. 7). By the 1930s, the need to equip residential homes with electric lights was increasingly well-received by the residents of Kuala Lumpur. For instance, 6,073 applications were submitted by users who had received electricity so that the Electrical Department could install a wiring system to be connected to electric lights (Annual Report and Accounts of the Electrical Department for the year 1932, 1933, p. 12). It was discovered that between 1933 and

1938, no less than 6,500 consumers who were supplied with electricity had applied for wiring systems to be fitted at their home for electric lights and several other electrical items.

Table 3. Table Lamp Rental in Kuala Lumpur, 1927–1939 (Source: Author's reconstruction based on data from *Annual Report and Accounts of the Electrical Department,* from 1928 to 1939).).

Year	Table Lamp (Unit)
1927	43
1928	39
1929	29
1930	36
1931	22
1932	19
1933	18
1934	16
1935	16
1936	18
1937	13
1938	12
1939	11

After the installation of the electrical wiring system, the final process that completed the transformation of illumination technology in homes in Kuala Lumpur was to encourage residents to use electric lights. To facilitate the transition process from oil lamps to electric lights, the Electrical Department once again played an important role by establishing the Hiring Department (Annual Report and Accounts of the Electrical Department for the year 1927, 1928, p. 10). There were two main functions of the Hiring Department, namely (i) disseminating information on the benefits of using electrical goods and teaching residents how to use them, and; (ii) providing electrical goods for rent or sale to consumers. They took the initiative by holding an electric light show with the slogan "Better Light-Better Sight", during the Malayan Agri-Horticultural Association Show (Annual Report and Accounts of the

Electrical Department for the year 1937, 1938, p. 5). The interest shown by visitors led the Hiring Department to build a showroom in Gombak Lane to expose residents to better lighting in the home (Annual Report and Accounts of the Electrical Department for the year 1938, 1939, p. 6).

Meanwhile, for the rental of electrical goods, the Hiring Department only provided table lamps with a small number of units compared to other household appliances such as fans and cookers. Table 3 shows the number of rented table lamps for each year. This figure only represents the rental of table lamps because the Electrical Department did not provide the type of electric lamps hung from the ceiling. Instead, those types of lamps were brought in and marketed by agents who were awarded tenders, such as Aktiebolaget Lux Company and Kitson Empire Lighting Company Limited (Selangor Secretariat File 1749/27; Selangor Secretariat File 3981/1920). In addition, several other companies also sold electric lamps. For example, the Huttenbach, Brothers and Company Company supplies 500- and 1,000-candlepower lamps to consumers (Wright, 1908, p.789; Nasution, 2006, p. 61–65). The imported lamps consisted of several international lamp brands with a proven reputation in lighting technology such as Philips, Osram, and Mazda. For example, The General Electric Company Limited, with sales representatives in Singapore, Kuala Lumpur, and Ipoh, sold Osram brand electric lamps that followed the specifications set by the British Engineering Standards Association (The Straits Times, 1932, p. 13). The company also supplied various types of lamps with a power ranging from 15 watts to 100 watts, thus providing many choices to consumers (The Straits Times, 1932, p. 16). Meanwhile, Robinson and Company Limited and William Jacks and Company (Malaya) Limited were both suppliers of Philips brand lamps, which gave out brighter lighting while avoiding high electricity consumption costs (The Straits Times, 1933, p. 6; The Straits Times, 1935, p. 1). The Borneo Company Limited supplied Mazda brand electric lamps by the British Thomson-Houston Company Limited in Kuala Lumpur, Singapore, Ipoh, and Penang (The Straits Times, 1930, p. 14). Apart from selling electrical appliances, the private companies also offered services for the installation of wiring systems and electrical appliances in consumers' homes.

The businesses run by these companies provided more choices for residents in Kuala Lumpur to access electric lighting. Thus, the decrease in table lamp rentals (Table 3) did not reflect the residents' rejection of the use of electric lighting, but instead influenced by the increasingly widespread marketing of domestic lighting, due to the role of private companies as suppliers of electric lighting. In other words, consumers could obtain electric lighting from these companies, which offered more modern models and designs that suited the lifestyle of the elite community in Kuala Lumpur. Furthermore, the light bulbs sold was cheap, around 50 cents to $1.19 (The Straits Times, 1932, p. 16). The emergence of these companies as distributors or suppliers of internationally-branded electric lighting gave the impression that the business of electrical goods, including lighting, has sound and profitable economic prospects. This situation indirectly shows that the use of electric lighting was indeed in demand among the residents of Kuala Lumpur. In fact, there was also an increase in the revenue collected by the Electrical Department for the sale of electricity for lighting purposes. In 1936, the revenue from the sale of electricity units for lighting was $633,755 (Annual Report and Accounts of the Electrical Department for the year 1936, 1937, p. 60), before increasing to $693,134 the following year (Annual Report and Accounts of the Electrical Department for the year 1937, 1938, p. 64). By 1939, the total income recorded was $823,979 (Annual Report and Accounts of the Electrical Department for the year 1939, 1940, p. 44).

Conclusions.

The period between the end of the 19th century and the beginning of the 20th century saw major changes in the illumination of homes in Kuala Lumpur. The need to illuminate homes at night, which was originally a laborious hand-on task and required residents to be involved in every step, was later simplified by the end of the 1920s. The establishment of the Electrical Department was a very important turning point in the transformation of lighting technology in Kuala Lumpur. The electrification facilities, provided through the construction of the Bangsar Power Station, supplied energy for the domestic sector and provided a more efficient and safer source of lighting. Simultaneously, the Electrical Department paid attention to home mechanisation through the installation of wiring systems, electrical points, and sockets to enable residents to utilise electricity in their daily lives at home. Furthermore, the involvement of private companies as distributors of electrical appliances, including lamp, further accelerated the transition toward a modern lighting system in Kuala Lumpur. Thus, electric lamps began to become the residents' choice to improve their lighting. The transition from oil lamps to electric lamps marked the beginning of modern illumination in Kuala Lumpur. This modernisation has further improved user safety. Undeniably, the use of electricity and electric lamps also has risks to residents. However, at least the risks could be managed with the installation and monitoring by trained and skilled technicians from the Electrical Department. This entire process, starting from the generation and supply of electricity to consumers, to the installation of wiring systems and electrical goods, managed by the Electrical Department, has indirectly led to government involvement in providing light in residents' homes. This situation meant that illuminating the house was no longer the responsibility of the homeowner, but the Electrical Department. Residents no longer have to bother with the hard work, as the need to illuminate their homes at night with brighter light became easier just by simply flipping a switch.

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Від гасових до електричних ламп: Еволюція технологій освітлення в Куала-Лумпурі, 1880–1940 роки

Анотація. *У статті розглядається трансформація систем освітлення в Куала-Лумпурі – одному з головних міст штату Селангор (Малайя) – від кінця XIX до початку XX століття. Дослідження аналізує, як процес освітлення житла в нічний час перейшов від трудомісткої ручної праці до значно більш зручної та ефективної системи внаслідок розвитку науково-технічної інфраструктури, зокрема впровадження електроенергії. Крім того, у статті досліджується, яким саме чином технології освітлення були запроваджені та інтегровані в домогосподарства Куала-Лумпура. Для вивчення цих питань застосовано якісні та історичні методи дослідження. Більшість інформації та статистичних даних, використаних у статті, зібрано з першоджерел, зокрема архівних матеріалів і офіційних документів Електричного департаменту та секретаріату штату Селангор, опублікованих наприкінці XIX – у першій половині XX століття. Дослідження показало, що забезпечення електроенергією як джерелом побутової енергії з боку Електричного департаменту відіграло важливу роль у розвитку технологій освітлення в домівках. Потреба освітлювати житло вночі, яка традиційно задовольнялася за допомогою пеліти – посудини, наповненої гасом і оснащеної гнотом, що давала світло під* *час горіння, – поступово змінилася використанням електричного освітлення, яке забезпечує світло простим натисканням вимикача. Розвиток технологій освітлення означав, що процес освітлення домівок більше не контролювався повністю лише власниками житла, а також став відповідальністю Електричного департаменту. Починаючи з виробництва та розподілу електроенергії споживачам, департамент згодом відповідав за управління системами внутрішньої електропроводки та забезпечення належного встановлення електричного освітлення перед його використанням споживачами. Отже, еволюція технологій освітлення в Куала-Лумпурі – від гасової лампи до сучасної електричної – не лише розширила можливості нічного життя в домівках, а й забезпечила користувачам підвищений рівень безпеки та комфорту.*

Ключові слова: *освітлення; електроенергія; Куала-Лумпур; житло; електричний департамент; урбаністична модернізація*

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Healing the eyes of the Indies: Circulating and localizing European ophthalmological knowledge and technology in twentieth-century Yogyakarta

Abstract. *This research explores the emergence of ophthalmological practices in Yogyakarta, specifically within the realm of hospital practice. By focusing on the Prinses Juliana Gasthuis voor Ooglijders, this study analyzes the circulation and localization of European ophthalmological knowledge and technology within a colonial context. The investigation involved a thorough review of archival documents, including colonial and hospital reports, alongside an examination of the brands and origins of medical devices currently preserved at the Museum of Dr. Yap Prawirohusodo. The analysis utilizes David Arnold's framework, which highlights* *intercultural exchange, regional circulation, and the hybridization of European knowledge and technology within a colony. The Prinses Juliana Gasthuis voor Ooglijders (Princess Juliana Hospital for Eye Disease Patients) was established in 1923 by Dr. Yap Hong Tjoen, a Chinese-Indonesian ophthalmologist who earned his doctorate from the University of Leiden. For this reason, his European education integrated him into a global network of medical expertise. He played a pivotal role in circulating ophthalmological knowledge and technology upon returning to the Dutch East Indies to work at the hospital. While he applied standardized European diagnoses and treatments for eye care, he simultaneously adapted this knowledge to local contexts by translating unfamiliar Western concepts for indigenous patients. Furthermore, the analysis of medical devices reveals a significant influx of imported equipment from Europe to Yogyakarta, underscoring the existence of a robust transnational network. Interestingly, the research also uncovers evidence of modification and self-fabrication, particularly regarding Snellen charts, wheelchairs, and medicine-compounding equipment. Such adaptations provide insight into how technology was tailored to suit local needs shaped by social, cultural, and physical factors. Ultimately, this study contributes to the historiography of medicine in the Dutch East Indies by examining the role of local agencies and the materiality of medical technology. It also underscores the significance of indigenous environments in the global dissemination and practical application of European medical science.*

Keywords: *Prinses Juliana Gasthuis voor Ooglijders; colonial medicine; medical knowledge; medical technology; local adaptation; Museum of Dr. Yap Prawirohusodo*

Introduction.

This article examines the circulation and localization of European medical knowledge and technology in the Dutch East Indies, now modern-day Indonesia, by focusing on a specific case study of ophthalmology in Yogyakarta. This process began with the arrival of European influence, which fundamentally altered medical practice. Although these medical advancements initially served as a means of asserting colonial power and safeguarding military and government personnel (Boomgaard, 1993), they eventually introduced innovative approaches to disease diagnosis and therapeutic practices. Established through medical institutions (Baha'uddin, 2005; Boomgaard, 1993; Kurniawan & Agustia, 2021; Pols, 2018; van Bergen, 2024), medical education (Hesselink, 2011; Pols, 2024), and public health policy (Baha'uddin, 2005, 2006; van Bergen et al., 2017), European medicine effectively reshaped medical practice throughout the colonial setting.

The dynamics of European medicine in the Dutch East Indies have received considerable scholarly attention. Previous studies by Baha'uddin (2005), Boomgaard (1993), Kurniawan & Agustia (2021), Van Bergen (2024), and Zondervan (2016) provide a comprehensive historical overview of medical institutions. These organizations originated with the Military Medical Services (MMS) in the early 19th century. Subsequently, the Civil Medical Services (CMS) was established as a separate entity from the MMS in 1911, eventually transitioning into the Public Health Services (PHS) in 1925. Furthermore, Baha'uddin (2005) analyzes how shifts in medical policy directly affected healthcare delivery. He notes that discriminatory public health policies in the 19th century led to substandard care for the general population. Conversely, early 20th-century reforms and the CMS introduced systematic care through subsidies and the construction of new hospitals. Additionally, Bergen et al. (2017) studied regional healthcare services by examining the archives of *Geneeskundig Tijdschrift voor Nederlandsch-Indie* (the Medical Journal of the Dutch East Indies) from 1852 to 1942. Their research details the political and socioeconomic influences on healthcare, the organization of medical services, hospital development, key medical figures, and various disease treatment methods utilized during that era.

While the aforementioned studies focused on how European influence affected various aspects of medicine in this region, other research has concentrated on the interaction between European and traditional medicine. Boomgaard (1993) examined the development of colonial healthcare in Java and the confrontation between Western and indigenous medical practices. This investigation reveals a new medical phenomenon that is neither fully Western nor fully Eastern, as exemplified by the evolution of nursing. Similarly, research by Pols (2024) investigated the development of medical education in the Dutch East Indies and Indonesia by focusing on the establishment of medical courses for indigenous students. The study reveals the rise of a culturally hybrid Indonesian medical profession that closely mirrored its European counterpart, thereby occupying a liminal position within colonial society (Pols, 2024, p. 181). Accordingly, these two works highlight how interactions between European and non-European actors produced a hybrid culture within medical institutions. Nevertheless, the study of interconnection regarding the dissemination of medical knowledge and technology remains underexplored.

At the same time, the study of medical knowledge and technology within post-colonial countries warrants particular attention due to its significant implications. Arnold (2005) asserts that the interconnection of technological history in colonial and post-colonial contexts outside Europe demonstrates that technological development cannot be comprehended as a mere extension of the West (p. 98). This research emphasizes the need to acknowledge long-standing exchange, adaptation, and innovation involving non-European societies. Furthermore, it highlights the role of these interactions in shaping the global technological landscape (Arnold, 2005, pp. 98–99).

This article addresses the academic gap by examining the dynamics of European ophthalmological knowledge and technology in Yogyakarta. Ophthalmology stood as a vital branch of colonial medicine, primarily because eye diseases had been a major concern in this region since the late 19th century (Sari & Nurdiana, 2024, p. 437). Statistics from 1890 indicate that eye diseases ranked as the fifth most prevalent disease among the population (Koningh, 1891, p. 204). Despite this high prevalence, the history of eye care in this region has received limited scholarly attention. Previous research remains focused on the general development of ophthalmology hospitals (Zondervan, 2016), the evolution of ophthalmology as a formal science (Sari & Nurdiana, 2024), the treatment of trachoma (Albar, 2025; ten Doesschate, 2017), and biographies of key medical figures (Hesselink, 2011; ten Doesschate, 2017).

By focusing on a case study of the *Prinses Juliana Gasthuis voor Ooglijders* (the Princess Juliana Hospital for Eye Disease Patients), this study explores the circulation and localization of European ophthalmological knowledge within hospital settings. The investigation specifically seeks to determine the role this institution played in the treatment of eye diseases. Furthermore, it analyzes how the hospital participated in the active circulation and localization of European ophthalmological knowledge and technology.

Methods.

This research employs historical analysis and medical material culture analysis within Arnold's (2005) framework, which highlights intercultural exchange, regional circulation, and the hybridization of European technology within a colony. The historical analysis was conducted through archival research to examine the development of the *Prinses Juliana Gasthuis voor Ooglijder* and eye care practices during the colonial period. Primary sources consisted of colonial and hospital reports. These documents provided empirical data on institutional dynamics, medical practices, and the distribution of health services, while also documenting the circulation of knowledge. Concurrently, the study examined the medical material culture of the hospital currently preserved in the Museum of Yap Prawirohusodo. By analyzing the brands and origins of these devices, the research evaluated them as evidence of the circulation of European technology and its dynamics in Yogyakarta. Furthermore, Arnold's (2005) framework served to demonstrate how ophthalmological knowledge and technology did not merely transfer linearly. Instead, these elements underwent constant exchange, negotiation, and adaptation through interactions between European and local actors.

Results and Discussion.

The Role of *Prinses Juliana Gasthuis voor Ooglijders* in Treating Eye Diseases.

The early 20th century represented a significant period of transformation for ophthalmology in Yogyakarta, characterized by the emergence of specialized medical personnel, dedicated hospitals, and advanced medical instruments. Initially, the dissemination of ophthalmological care in this region and Java in general began with the appearance of *Doekoen Mata*, indigenous eye specialists trained by European physicians during the 1900s (Wilkens, 1913, p. xl). Subsequently, eye care entered a more formal phase of development in the 1920s with the establishment of clinics and hospitals that eventually evolved into permanent medical institutions.

The creation of these medical facilities was inextricably linked to the efforts of Dr. Yap Hong Tjoen. Born in Yogyakarta on March 30, 1885, this Chinese-Indonesian ophthalmologist pursued his higher education at the University of Leiden in the Netherlands, where he earned his doctorate in ophthalmology on January 24, 1919. While studying abroad, Dr. Yap developed a strong ambition to open a hospital dedicated to assisting impoverished individuals suffering from eye diseases. He clearly recognized the urgent lack of specialized medical services available to the general population of the Dutch East Indies (Sundari et al., 2023, p. 30; Wibowo, 2000, p. 19).

Fortunately, Dr. Yap received substantial backing from G. Vissering, the president of the Dutch bank, who formed a fundraising committee in 1919 alongside several other prominent figures to finance the hospital’s construction. Additional support came from E.A. Zeilinga, president of the Java Bank, who founded the Central Association for the Promotion of Ophthalmology in the Dutch East Indies (*Centrale Vereeniging tot Bevordering der Oogheelkunde in Nederlandsch-Indie*). Furthermore, the late Mayor Oei Tiong Ham, a renowned philanthropist from Semarang, contributed significant funds to the cause. The Yogyakarta Department of the Agricultural Association of Vorstenlandsche (*Vorstenlandsche Landbouwvereeniging*) also played a vital role by covering annual operational costs. Simultaneously, the Sultanate of Yogyakarta provided the necessary land at no cost, while the colonial government offered subsidies and technical assistance through the Public Health Services (PHS) and the Domestic Administration (*Binnenlandsch Bestuur*) (Tjoen, 1926, p. 144).

While preparations for the hospital’s construction were underway, Dr. Yap Hong Tjoen opened the *Polikliniek voor Ooglijders* (the Outpatient Clinic for Eye Patients) on June 20, 1921. Situated within a rented house in Gondolajoe, the clinic quickly became crowded with patients seeking specialized care. Subsequently, Sultan Hamengku Buwono VIII held a formal groundbreaking ceremony on November 21, 1922 (Tjoen, 1926, p. 144). The facility was designed by the renowned Dutch architect Eduard Cuypers, who worked under the company *NV Architecten en Ingenieursbureau Fermont te Weltevreden en Ed. Cuypers in Amsterdam*; Suhartono *et al.*, 2020, p. 5). The hospital eventually opened on May 29, 1923, with an initial capacity to accommodate sixteen patients. Governor-General D. Fock conducted the inauguration and officially named the institution the *Prinses Juliana Gasthuis voor Ooglijders* (Tjoen, 1926, p. 144) (see Figures 1 and 2).

Figure 1. The Inauguration of *Prinses Juliana Gasthuis voor Ooglijders* in 1923, attended by Hamengku Buwono VIII and L.F. Dingemans, resident of Yogyakarta (left), and the hospital building (right) (Source: Bruggen & Wassing, 1998, pp. 42, 148).

Figure 2. The hospital ward (left) and patients from the hospital (right) (Source: Tjoen, 1926, p. 144).

The hospital building underwent continuous expansion to keep pace with growing patient demands. By May 1925, the facility provided 96 beds for those receiving free care, 12 beds for third-class patients, and approximately six beds for first- and second-class patients. Because the entire facility was fully operational by the end of that year, the average daily patient count reached 43 (Tjoen, 1926, p. 144). Hospital reports indicate that the number of clinical consultations increased steadily from 1921 to 1925 (see Table 1). During this timeframe, a total of 18,022 patients were treated, accounting for an impressive 217,905 consultations. These figures strongly suggest a high frequency of repeated visits and long-term care. Notably, the vast majority of those treated were indigenous individuals, totaling 16,514 people or 92% of the patient base. This was followed by 1,085 Chinese patients (6%) and 432 European patients (2%). Such statistics underscore the pivotal function of the hospital in providing specialized eye care, particularly to the indigenous community.

Table 1. Number of patients treated in *Polikliniek voor Ooglijders* and *Prinses Juliana Gasthuis voor Ooglijders* 1921–1925 (Tjoen, 1926, p. 144).

Year	Number of Patients	Number of Consultations
1921	2,132	21,149
1922	3,887	53,835
1923	3,863	45,318
1924	3,574	46,432
1925	4,566	51,171
Total	18,022	217,905

During the Japanese occupation, the *Prinses Juliana Gasthuis voor Ooglijders* was renamed *Rumah Sakit Mata dr. Yap* (Dr. Yap Eye Hospital), which remains its official designation today. Concurrently, the arrest and detention of Dr. Yap Hong Tjoen significantly disrupted hospital operations. Even upon his eventual return to the facility, formidable challenges persisted due to a drastic reduction in staff numbers and acute shortages of essential supplies, including medications, medical tools, and clothing. Furthermore, the patient count decreased during this turbulent era, forcing the hospital to function strictly within its limited remaining capacity. In 1949, Dr. Yap Hong Tjoen departed for the Netherlands, officially passing the leadership of the institution to his son, Dr. Yap Kie Tiong, who served until 1969 (Wibowo, 2000, p. 60). The hospital directors through the years are listed below.

- Dr. Yap Hong Tjoen (1923–1949)
- Dr. Yap Kie Tiong (1949–1969)
- Prof. R. Pramono (1969–1970)
- Dr. Gunawan (1970–1971)
- Dr. Basarodin Kusniomalebari (1971–1993)
- Dr. Tri Sutartin Radjiman (1973–2003)
- dr. Nunuk Mara Ulfah, Sp.M., M.Kes. (2004–2014)
- dr. Emy Tjahjani Permatasari, Sp.M., M.Kes. (2014–2020
- dr. Alida Lienawati, M.Kes (MMR)., FISQua (2020–present).

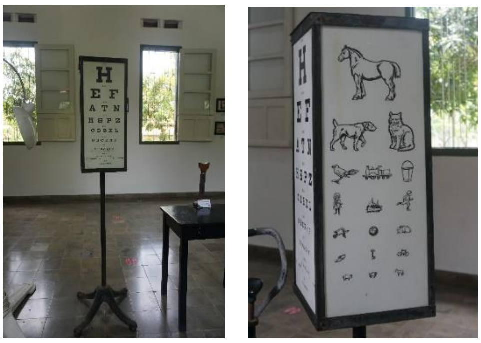
Circulating and Localizing Ophthalmological Knowledge and Technologies in Hospital Practice.

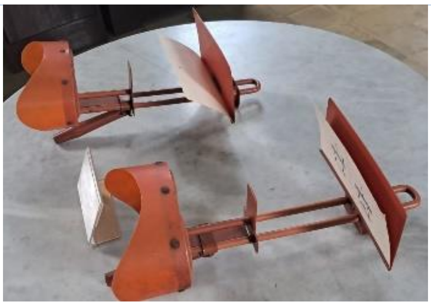
The circulation and localization of ophthalmological knowledge and technology in hospital practice can be understood through two interrelated contexts. Firstly, regarding knowledge, Dr. Yap's formal education in Europe, where he trained under esteemed European physicians, positioned him within a global network of medical expertise. Upon his return to the Dutch East Indies, he utilized this specialized training to facilitate the delivery of advanced eye care. Throughout his professional endeavors, he demonstrated the transfer of this expertise through clinical practice and institutional leadership. Accordingly, he applied standardized approaches to diagnosis and treatment for his patients, effectively demonstrating the circulation of European ophthalmological knowledge far beyond its original geographical and social boundaries.

Nevertheless, the knowledge acquired by Dr. Yap was not applied without modification within local social settings. He frequently encountered patients who continued to rely on traditional indigenous understandings of illness and healing. Under these circumstances, he played a pivotal role in translating unfamiliar European medical concepts into forms that indigenous patients could comprehend. Thus, Dr. Yap became a recipient and an intermediary of European ophthalmological knowledge and technology. Therefore, global science was practiced effectively at a local level.

Secondly, the physical presence of technology is clearly observable in the hospital's medical devices. Various instruments used since the founding of the *Prinses Juliana Gasthuis voor Ooglijders* are currently preserved in the Museum of Dr. Yap Prawirohusodo. This museum was established in 1997 through the initiative of Dr. Tri Sutartin R., Sp.M., who served as the Director of Dr. Yap Eye Hospital from 1993 to 2003, alongside Dr. Basarodin, Sp.M., Dr. Wasisdi Gunawan, Sp.M., Ignatius Rudhyanto, J. Handoyo, and Mrs. Maghdalena. Their goal was to commemorate the legacy of Dr. Yap Hong Tjoen (Handayaningsih et al., 2020, pp. 100–101). The museum was officially inaugurated on May 29, 1988, by the Governor of Yogyakarta, Sri Sultan Hamengku Buwono X. It was initially named *Museum Rumah Sakit Mata Dr. Yap* (Dr. Yap Museum of Eye Hospital) and was located within one of the original hospital buildings. Subsequently, in 2013, management of the facility was transferred to the Dr. Yap Prawirohusodo Foundation, and the name was changed to the Museum of Dr. Yap Prawirohusodo. The collection is organized into three distinct categories, namely medical devices, household items, and private collections. This analysis focuses specifically on the medical devices as tangible evidence of the development and professionalization of ophthalmology in Yogyakarta.

Table 2. Ophthalmological medical devices formerly used at the *Prinses Juliana Gasthuis voor Ooglijders*, currently in the collection of the Museum of Dr. Yap Prawirohusodo (Photographs by authors, 2025).

No.	Medical Devices	Photo
1	Snellen Chart It is a device utilized to measure visual acuity. This instrument determined whether a patient suffered from refractive errors, such as nearsightedness, farsightedness, or astigmatism. This specific chart is a product of John Weiss & Son (United Kingdom). Modified Snellen chart. Developed by Dr. Yap Hong Tjoen, this version employed animal images to replace the standard Latin letters found on conventional charts.	 (a) (b)

No.	Medical Devices	Photo
2	Corrective and Trial Lens Set Used to determine the necessity for eyeglasses, this comprehensive set consists of various lens types and sizes ranging from 3 cm in diameter to larger dimensions. The lenses are categorized by shape into square and round varieties. These sets include convex and concave lenses, as well as a range of magnifying glasses, examination spectacles, and specialized eyewear for post-operative recovery.	
3	Ophthalmoscope This instrument is utilized to examine the anterior segment of the eye. The museum maintains several ophthalmoscopes from various prestigious brands, including Carl Zeiss Jena (Germany), Keeler (United Kingdom), Keeler Vizta Diagnostic (United Kingdom), Heine Beta 200 (Germany), and W. Walg Machf Heidenberg. The collection also features models produced in the 1960s by Neitz Instrument BX and Neitz B (Japan).	
4	Stereo Campimeter This device is employed in ophthalmological examinations to measure a patient's central field of vision. It is particularly effective for detecting scotomas (blind spots) or damage to the optic nerve. Accordingly, the collection of stereo campimeters at the museum is highly diverse, featuring examples constructed from leather, wood, plastic, and iron.	 
5	Perimeter It is a specialized device utilized to examine the visual field, assess overall visual function, and detect serious conditions like glaucoma. The museum's collection features two distinct types, namely wooden and metal. The wooden perimeter represents an earlier version of the instrument, although its exact place of manufacture remains unidentified. It operates by positioning paper markers at fixed	 (a)

No.	Medical Devices	Photo
	points that are rotated to create a full 360° field of vision for the patient. The Goldmann perimeter was developed by Hans Goldmann in Bern, Switzerland, in 1945. This device uses controlled light stimuli projected at specific locations to measure the visual field with high precision.	 (b)
6	Slit Lamp It is a specialized binocular microscope used to examine ocular structures, including the cornea, iris, vitreous, and retina. It supports a wide range of diagnostic examinations, laser treatments, and ocular imaging. The specific collection item was manufactured by Haag Streit Liebefeld Bern in Switzerland. This model features a fixation lamp that was introduced in 1945 and produced until 1959, when it was eventually replaced by the Model 900. Based on these characteristics, the instrument is estimated to date from the period between 1945 and 1958, most likely originating in the 1950s.	
7	Sollux It is a therapeutic device utilized to manage bleeding in the eye without the need for invasive surgery. The museum's collection includes several prestigious brands, including Eleitz Wetzlar, Leitz Focomat I C, and Hanau. Accordingly, these instruments were manufactured in Germany during the 1950s.	

No.	Medical Devices	Photo
8	Sterilization Equipment It clearly demonstrates how antiseptic principles were applied in early 20th-century medical procedures. The current set includes a hand-washing station equipped with a sterilization table, two heating burners, a container opening, a foot pedal, and a sterilization basin. Furthermore, it contains a Maison Luer autoclave, which features a pressure regulator on top and a drain pipe on the side. This autoclave was primarily used to sterilize surgical gowns and delicate instruments.	
9	Microscope The museum preserves several microscopes used by Dr. Yap throughout his clinical career. These include models from Eleitz Wetzlar, Carl Zeiss, and Isamy Batavia-C, which utilized Carl Zeiss Jena lenses. Additionally, the collection features a Reichert Wien unit from Austria.	
10	Incubator It is a device specifically designed for cultivating microbes at precise, adjustable temperatures. The museum's collection includes several units manufactured by Koninklijke Fabriek Interim (Netherlands) and Luer Wulfing-Luer (France).	
11	The equipment includes a wide array of devices utilized for ophthalmological examinations and surgical procedures, encompassing various types and international brands. This category contains tonometers, lamp holders of diverse dimensions, C. Davis Keeler flashlights, and cysto-urethroscopes. Furthermore, the collection features polarimeters and thermocontex iontophoresis units along with an assortment of spare components. Most of this specialized equipment was imported from abroad.	 

No.	Medical Devices	Photo
12	Surgical Equipment Operating Table This table features metal legs and supports, while the top surface consists of a sponge layer wrapped in clean white cloth. Operating Light This instrument supported medical and surgical procedures by providing optimal illumination within the operating field. The lamp is an Original Hanau product (Germany), produced during the 1950s. Electromagnetic Corporeal The primary function of this device is to attract and remove ferromagnetic foreign objects, such as metal or iron shards, from within the body. It is particularly vital for reaching difficult areas like the deep intraocular space inside the eye. This specific tool was manufactured by John Weiss & Son (United Kingdom).	 (a)  (b)  (c)
13	Wheelchair This custom-built three-wheeled wheelchair was fabricated directly by hospital staff to meet specific patient needs. The uniqueness of the device lies in its unconventional wheel system, which features two large wheels on the sides and a smaller stabilizing wheel at the rear. Interestingly, the design is equipped with springs shaped like those found on the traditional carriages of the Yogyakarta Royal Palace. Such a feature reflects the successful incorporation of local technology into the design of a medical aid. Consequently, the size and ergonomics of the chair were carefully adapted to suit Indonesian anthropometric conditions.	

No.	Medical Devices	Photo
14	Equipment for Compounding Medicine Dr. Yap personally formulated and mixed medicines for his patients when treating various eye diseases. The various devices used in this pharmaceutical process are still preserved in the museum, including measuring cups of different sizes, porcelain bowls, medicine scales, and mortars and pestles. Additionally, the collection includes medicine molds and spatulas. These tools consist of imported items and locally produced materials, such as wooden spatulas and custom medicine molds.	

The collection of medical devices provides substantial evidence regarding the historical practice of ophthalmology in Yogyakarta. These instruments offer profound insight into the application of diagnostic and therapeutic eye care to address a variety of conditions, including trachoma, glaucoma, strabismus, and other prevalent diseases. Significantly, the use of these tools marked a clear transition toward clinical medicine predicated on scientific observation and experimentation.

As demonstrated throughout this study, identifying the brands and manufacturers of these devices indicates that the vast majority originated in Europe, particularly within Germany, the United Kingdom, the Netherlands, Austria, France, and Switzerland. This finding highlights the existence of a robust transnational network of medical material culture connecting Europe and the Dutch East Indies. In addition to European instruments, several devices from Japan and America were also identified. Nevertheless, these items were produced later, around the 1960s, and therefore did not constitute the primary focus of this specific investigation.

Beyond the linear transfer of medical knowledge and technology, the findings also reveal the intentional modification of medical devices. A prime example is the Snellen chart (see Table 2, No. 1), which utilizes animal symbols instead of the Latin alphabet. Within the social context of Yogyakarta during that era, access to formal education was largely restricted to the nobility, leading to pervasive illiteracy among the broader community. Consequently, the standard Snellen chart proved to be an ineffective diagnostic method for many patients. In order to facilitate more precise eye examinations, the substitution of Latin letters with easily recognizable animal symbols was implemented. Thus, this finding underscores the adaptation of European medical technology to address specific social challenges, particularly the low literacy rate within the community.

Another noteworthy discovery involves the unique wheelchair fabricated by hospital staff (see Table 2 No. 13). Historical reports suggest that the hospital initially imported wheelchairs from Europe, but these were eventually deemed unsuitable because their dimensions conformed strictly to European physical standards.

Accordingly, Dr. Yap initiated the fabrication of custom wheelchairs adapted specifically to the posture and needs of the indigenous community. This instance demonstrates a successful technical adaptation to address challenges caused by physiological differences between populations.

Furthermore, hospital treatment was inseparable from the role Dr. Yap played in independently dispensing eye medications. The discovery of various compounding devices supports this conclusion (see Table 2, No. 14). Such a practice reveals that, despite his extensive training in European pharmacology, Dr. Yap did not rely entirely on imported pharmaceuticals. Instead, he prepared medications using local ingredients and equipment. Consequently, this reflects a strategic attempt to reduce dependence on European supplies while ensuring a consistent stock of medication for patient care.

Conclusions.

The development of ophthalmological practices in Yogyakarta was shaped by continuous processes of knowledge and technological circulation and localization. *Prinses Juliana Gasthuis voor Ooglijders* not only played a crucial role in the treatment of various eye diseases during the colonial period but also served as key sites for the transmission and adaptation of medical knowledge and technology. These developments were facilitated by transnational networks that connected Europe with hospitals in the Dutch East Indies. Through his extensive education in Europe, Dr. Yap acquired scientific knowledge and clinical skills while gaining exposure to advanced medical technologies. This experience allowed him to engage with a global network of medical expertise, which he subsequently integrated into the local context of Yogyakarta.

Furthermore, the utilization of medical equipment imported from Europe underscores the presence of transnational networks that connected industrial production centers with colonial territories. However, when this knowledge and technology were applied within the hospital, they frequently underwent significant modifications and adaptations. These changes addressed various sociocultural, physiological, and resource-related challenges, as exemplified by the custom Snellen charts, specialized wheelchairs, and equipment for compounding medicine. Thus, this analysis highlights the necessity of studying medical material culture to fully comprehend the dynamics of medical technology.

By analyzing these developments in Yogyakarta, the study implies that knowledge and technology were circulated and localized rather than simply transferred from colonial centers to the periphery. These findings reinforce the notion that medical advancement in post-colonial regions involves active local adaptation and the participation of indigenous communities. Consequently, the process was far more complex than a passive, one-way transfer of ideas. The study highlights the cross-border dissemination of medical expertise within a global context. Contemporaneously, this research illuminates how medical knowledge and technology continue to globalize in the post-colonial era. The findings regarding localization provide important lessons for current health practices, particularly in developing countries with limited resources. Ultimately, the success of medical technology depends not only on access to transnational networks but also on the ability of local communities to adapt, modify, and integrate these tools to meet their specific social and cultural needs.

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Conflicts of Interest.

The authors declare no conflict of interest.

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Лікування очей в Індонезії: Поширення та локалізація європейських офтальмологічних знань і технологій у Джок'якарті XX століття

Анотація. *У цьому дослідженні розглядається становлення офтальмологічної практики в Джок'якарті, зокрема в контексті медицини. Зосереджуючись на лікарні «Лікарня принцеси Юліани для пацієнтів із захворюваннями очей», робота аналізує процеси поширення та локалізації європейських офтальмологічних знань і технологій у колоніальному середовищі. Дослідження передбачало ґрунтовний аналіз архівних документів, зокрема колоніальних і лікарняних звітів, а також вивчення марок і походження медичного обладнання, що нині зберігається в Музеї доктора Япа Правірохусодо. Аналіз базується на концептуальному підході Девіда Арнольда (2005), який акцентує увагу на міжкультурному обміні, регіональній циркуляції та гібридизації європейських знань і технологій у колоніальному контексті. Лікарню принцеси Юліани для пацієнтів із захворюваннями очей було засновано у 1923 році доктором Япом Хонг Тьоеном — китайсько-індонезійським офтальмологом, який здобув докторський ступінь у Лейденському університеті. Саме завдяки європейській освіті він став частиною глобальної мережі медичних знань і відіграв ключову роль у поширенні офтальмологічних знань і технологій після повернення до Голландської Ост-Індії для роботи в лікарні. Хоча він застосовував стандартизовані європейські методи діагностики та лікування хвороб очей, водночас адаптував ці знання до місцевих умов, перекладаючи незрозумілі західні концепції для корінних пацієнтів. Крім того, аналіз медичного обладнання свідчить про значний приплив імпортованих із Європи приладів до Джок'якарти, що підкреслює існування розгалуженої транснаціональної мережі. Водночас дослідження виявляє приклади модифікації та самостійного виготовлення обладнання, зокрема таблиць Снеллена, інвалідних візків і пристроїв для приготування лікарських засобів. Такі адаптації дають змогу зрозуміти, як технології пристосовувалися до місцевих* *потреб, сформованих соціальними, культурними та фізичними чинниками. Це дослідження робить внесок у історіографію медицини Голландської Ост-Індії, висвітлюючи роль місцевих агентів і матеріальний аспект медичних технологій. Воно також підкреслює значення локального середовища в глобальному поширенні та практичному застосуванні європейської медичної науки.*

Ключові слова: *лікарня принцеси Юліани для пацієнтів із захворюваннями очей; колоніальна медицина; медичні знання; медичні технології; локальна адаптація; музей доктора Япа Правірохусодо*

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Compartmentalization and system ranking as fundamental design requirements for armored vehicles: Ukraine, Switzerland

Abstract. *The proliferation of low-cost FPV drones has fundamentally altered the threat landscape for main battle tanks, elevating crew survivability to the primary design criterion and necessitating a reassessment of historical protection concepts. This study, through a comparative analysis of archival materials from the Swiss Federal Archives, declassified Soviet-era thematic publications, and the personal diaries of development participants, traces the independent emergence of the compartmentalization principle (Ukrainian term – division of the vehicle into compartments isolated from one another) within the Swiss and Ukrainian schools of tank design during the 1970s–1980s. The results demonstrate that both engineering schools, responding to the catastrophic tank losses during the 1973 Yom Kippur War, independently arrived at nearly identical solutions despite complete informational isolation. In the Swiss NKPZ project, «Kompartimentierung» was formally established as a mandatory evaluation criterion, with only two concepts ensuring complete physical separation of the crew, ammunition, and power pack. Concurrently, Kharkiv designers developed a compartmentalized layout based on the quantitative ranking of systems by their contribution to survivability, assigning the highest protection coefficient to the crew, who were placed in the most protected compartment. Both schools independently converged on three fundamental principles: locating the crew in an isolated rear capsule, utilizing the engine compartment as an additional protective barrier, and equipping ammunition compartments with blow-off panels to vent explosive energy outward. This developmental parallelism demonstrates that compartmentalization and system ranking represent an objective regularity in the evolution of specialized vehicles, rather than localized inventions. The timeliness of this research is underscored by the fact that the principles of compartmentalization and layered crew protection, developed in the 1970s as a response to the challenges of their era, are gaining renewed relevance today in light of the widespread use of FPV drones, which once again bring the issues of armored vehicle survivability and the prevention of catastrophic losses to the forefront.*

Keywords: *compartmentalization; tank design; engineering schools; armored vehicles; Cold War*

Introduction.

Commercial FPV drones have emerged as a critical threat to main battle tanks and other specialized military vehicles due to their low cost, effectiveness, accessibility, and low observability. They are capable of striking vehicles in their most vulnerable areas, causing fires in fuel and ammunition stowage. This necessitates a revision of protection concepts and the integration of new countermeasures (Lavers, 2025). Technological advancements promise further cost reductions and increased reliability, solidifying the role of FPV drones as a standard anti-armor means, radically altering the battlefield balance (Sumlenny, 2024). At the same time, main battle tanks are likely to retain a key role on the battlefield, as their significant combat power allows forces to maintain mobility in direct contact with the enemy, despite growing concerns regarding their vulnerability (Reynolds, 2023).

This study examines research aimed at enhancing the protection of specialized vehicles conducted during the 1970s by the Swiss Eidgenössische Konstruktionswerkstätte (K+W) and the Kharkiv KB-60M (KMDB) design bureau. The key finding of this research was the necessity for a radical increase in survivability, as the experience of combat operations, particularly the 1973 Yom Kippur War, vividly demonstrated the vulnerability of existing vehicles. Hits to ammunition or fuel caused catastrophic losses, as vividly demonstrated during the 1973 war. This prompted designers to pursue the concept of compartmentalization (German: Kompartimentierung) – the strict separation of the internal volume into isolated compartments: engine, transmission, weapon and ammunition stowage, a rear crew compartment, and others. This solution, intended to provide the crew with a chance of survival even after armor penetration, fire, or ammunition detonation, became the decisive factor in the selection of advanced layouts.

Of the numerous concepts developed by K+W (30 in total), only two met the stringent compartmentalization and technical requirements: the turretless (casemate) variant 13f with a twin gun and rear engine placement, and variant 23a with a front engine and a turret featuring a limited traverse angle (+130°). Both variants envisioned the use of an autoloader, placement of the entire ammunition load in an isolated compartment near the gun, and a three-man crew always oriented in the direction of travel. However, each concept possessed its own strengths and weaknesses (Bundesarchiv, 1976d).

Kharkiv designers, independently from their Swiss colleagues, arrived at similar solutions (Mazurenko, Morozov, & Nazarenko, 1987).

The relevance of researching compartmentalization as a fundamental principle for designing specialized vehicles has not diminished since the 1970s; rather, it has gained critical importance in light of the analysis of modern armed conflicts. The experience of combat operations in recent decades irrefutably demonstrates that ammunition stowage hit remains one of the primary causes of the irreversible loss (catastrophic kill) of armored vehicles along with their crews, negating any advancements in firepower, protection, and mobility.

Research Methods.

This study, based on an analysis of archival materials from the Swiss Federal Archives (Bundesarchiv) in Bern, an examination of the technical documentation of the NKPZ projects, the personal diaries of A. A. Morozov, industry literature, and a retrospective overview of the development of global tank design during the 1970s–1980s, attempts to objectively determine the conceptual similarity of engineering solutions developed by two leading schools of vehicle engineering that evolved in conditions of mutual informational isolation. Key aspects of implementing the principles of compartmentalization and system ranking by survivability into the practice of designing specialized vehicles are identified.

A comparative analysis of the design solutions and layout schemes of the vehicles under investigation is conducted. The comparative analysis of conceptual similarity is based on six operational criteria derived directly from the primary sources: (1) functional compartmentalization into mutually isolated volumes, (2) location of the crew in a rear armored capsule, (3) use of the engine compartment as an additional ballistic barrier, (4) incorporation of blow-off panels for ammunition compartments, (5) ranking of systems by their contribution to survivability, and (6) alignment of the direction of travel with the primary direction of fire. Each criterion was assessed using a binary scale (present/absent) or a three-level scale (fully/partially/not present). The possibility of direct knowledge transfer was examined by comparing the timelines of the Swiss and Soviet/Ukrainian projects and by checking archival evidence of any technical exchange. The complete absence of such evidence, combined with the identical sequence of conceptual decisions, supports the hypothesis of parallel independent evolution.

Comparing the implementation of compartmentalization concepts in Europe and Ukraine reveals the distinctive characteristics of national engineering schools while simultaneously confirming the convergent nature of global tank development, where similar tactical-technical challenges generate isomorphic technical solutions irrespective of political boundaries. The comparison of the development stages of the prospective tank protection concept in Switzerland and Ukraine is carried out with mandatory consideration of the specific developmental context of their respective industrial complexes. Collectively, this allows for a well-reasoned rejection of the hypothesis of direct borrowing and substantiates the thesis of a parallel, independent formation of an identical protective paradigm.

Results and Discussion.

The concept of compartmentalizing the internal volume of a combat vehicle as a fundamental principle for ensuring survivability was first proposed in the U.S. Army Ordnance Corps technical report «New Tank Main Armament System», in connection with the introduction of completely combustible cartridge cases. Developers encountered a fundamentally new threat: the use of combustible cases, while effectively solving the problem of ejected spent cases inside the turret, created a critical danger of catastrophic fire and detonation of the entire ammunition stowage upon armor penetration. The report explicitly stated that «*a perforated hit which results in a propellant fire is a holocaust*», a circumstance demanding fundamentally new approaches to ammunition stowage and protection (Watervliet Arsenal, 1959).

American engineers proposed placing the entire ammunition load in a turret bustle, separated from the crew compartment by an armored bulkhead. This solution, as emphasized in the document, would "isolate the fire hazard" and minimize the probability of crew casualty in the event of detonation. The design stipulated that in case of ammunition ignition, overpressure would be vented through special blow-off panels, directing the explosive energy outward rather than into the fighting compartment. This concept, first documented in the 1959 report, became the foundation for the subsequent development of the compartmentalization idea.

What is Compartmentalization?

The core requirement of compartmentalization mandates the strict separation of the crew, weapon system/ammunition, and engine/fuel into isolated compartments. As noted by K+W, a tank being developed for service entry by 1985 must no longer be subject to the destructive consequences of a projectile hit resulting in crew loss and the catastrophic kill of the vehicle. Participants (Bundesarchiv, 1976c) were shown a photograph of a T-54 tank from the 1973 Yom Kippur War, its turret separated from the hull by an ammunition hit. All tanks currently in service or being accepted for service, including the Leopard 2, are susceptible to such catastrophic failures. Such an ammunition hit also has a devastating effect on the morale of other tank crews. This is arguably the most significant weakness of modern tanks, and the pursuit of its mitigation substantially influenced the approach to selecting the final vehicle concepts.

The primary objective was to enhance the tank's combat effectiveness, but only in aspects that would not lead to a significant increase in cost. Studies indicated that the greatest increase in combat value regarding protection could be achieved by dividing the internal space into isolated compartments (compartmentalization). This involves partitioning the tank into, for example, three compartments: the engine compartment, the weapon and ammunition compartment, and the crew compartment. The crew is isolated from all elements that could threaten them upon a hit, such as ammunition, fuel, and hydraulic fluid (Fig. 1, 2).

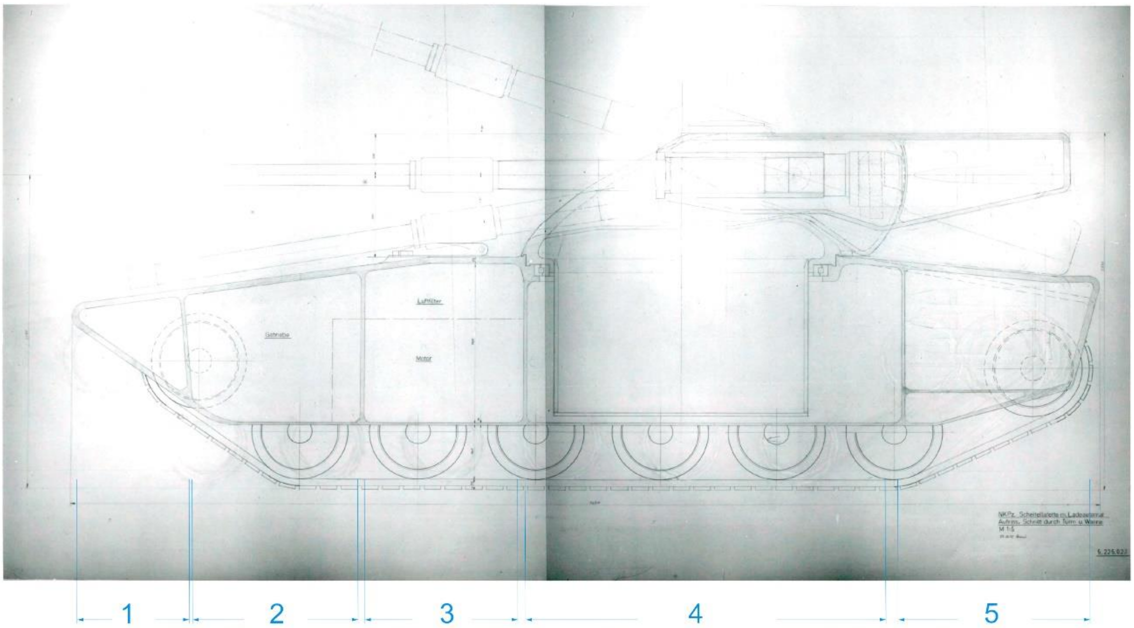


Figure 1. Example of NKPZ chassis compartmentalization (Bundesarchiv, 1976b). 1 – fuel compartment, 2 – transmission compartment, 3 – engine and auxiliary systems compartment, 4 – crew compartment, 5 – ammunition compartment.

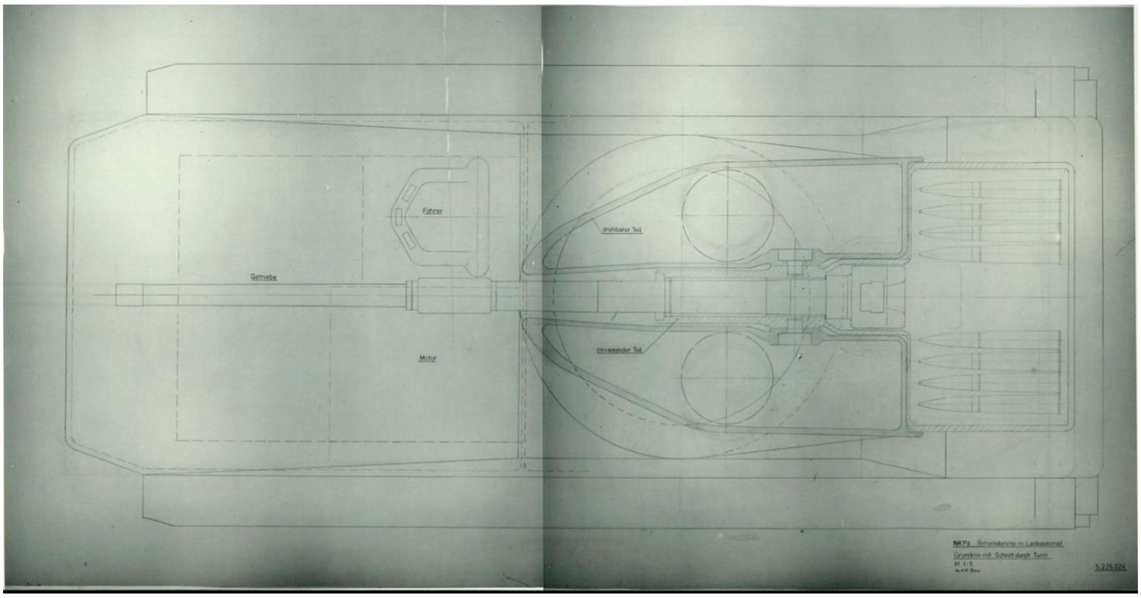


Figure 2. Example of NKPZ chassis compartmentalization, top view (Bundesarchiv, 1976b).

Compartmentalization ensures the maximum possible protection against even current and future munitions. It simplifies the loading process, as ammunition is stowed near the gun. Compartmentalization gives the crew the necessary confidence in their weapon system, as they perceive a chance of survival in combat even against a numerically superior enemy. All these considerations led to the formulation of the Basic Requirements and General Technical Specifications; among all the investigated variants, only two concepts satisfied these criteria.

An example illustrating the advantages of compartmentalization is the use of diesel fuel as a filler in composite armor. It was established that a two-layer armor array with a diesel fuel interlayer not only effectively attenuates a shaped charge jet (with a jet attenuation factor of K = 2.7) but also provides a significant weight saving in protection – approximately 71% compared to monolithic steel (Gadzhibalaev Lubert, Fenenko, & Chernomurov, 1982).

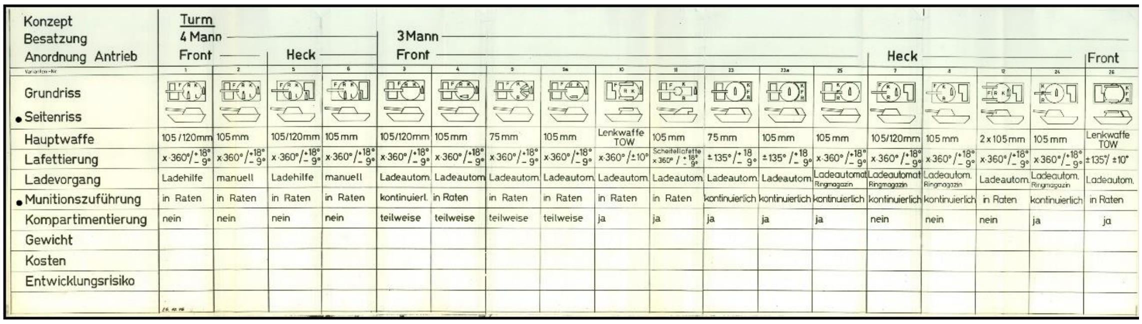
Concept Selection to Maximize the Advantages of Compartmentalization. Description of the Turretless (Casemate) Tank Concept with Twin Guns (Variant 13f).

Variant 13f represented a turretless (casemate) layout with a rear-mounted power pack and a twin-barreled gun system. In this concept, the main armament was rigidly attached to the hull, lacking the ability for independent horizontal traversal – a fundamental departure from the classic turreted configuration. The twin-gun system, in turn, was viewed by the developers as a means to radically increase the probability of target engagement through salvo firing, theoretically offering a 10–20% advantage in target kill probability compared to single-gun systems. The K+W designers also identified other advantages in this solution: if one gun was disabled, combat effectiveness could be maintained with the second barrel, thus providing a degree of redundancy; the alignment of the direction of travel and the direction of fire simplified crew orientation on the battlefield. However, this particular variant generated the greatest number of unresolved technical issues, which ultimately predetermined its rejection in favor of the alternative Concept 23a. Critically unresolved problems included the compatibility of the turretless configuration with Switzerland's hilly terrain, the difficulty of maneuvering a unit of such vehicles due to the inability to rapidly re-target the guns without turning the entire hull, and the requirement for high-precision stabilization of the twin weapon system in elevation, which demanded the development of fundamentally new and costly fire control systems.

The persistence of these problems, combined with the opportunity to examine a functioning full-scale mock-up of a similar turretless vehicle, the VT 1-1, in West Germany (Hilmes, 2021, p. 34) – which demonstrated the practical difficulties of implementing the concept – led the developers to favor the more conservative yet more realistic partially-traversable turret variant. Nevertheless, the very fact that the turretless configuration was explored in such depth testified to the readiness of Swiss engineers to fundamentally rethink established tank design paradigms in favor of maximizing crew protection – the primary priority underpinning the NKPZ project.

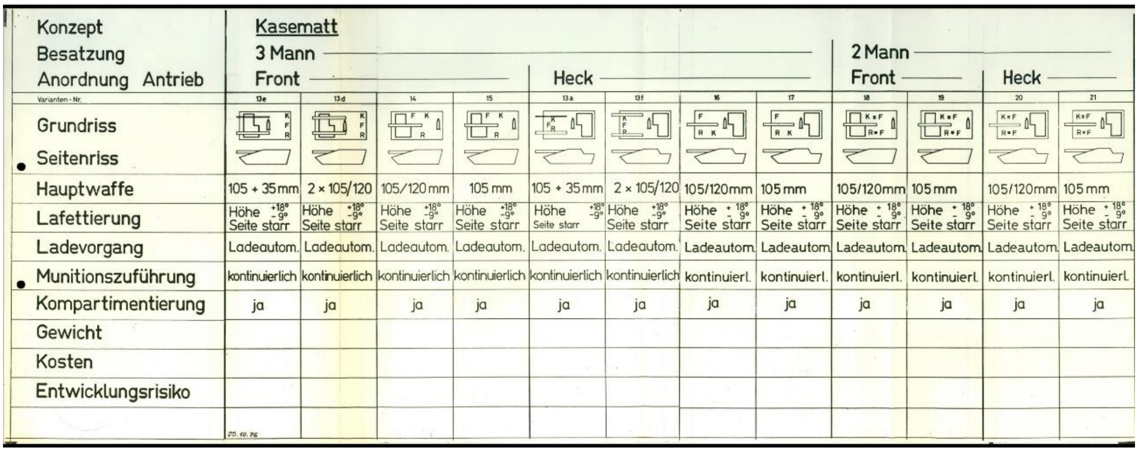
However, the concept had critical drawbacks. The most technically challenging problem was the need for highly precise vertical stabilization of the weapon system. Tactically, questions remained unresolved regarding the suitability of the turretless layout for Switzerland's hilly terrain, the lack of established tactics for maneuvering units of such vehicles (due to the hull-mounted guns), and doubts about the feasibility of target tracking procedures. A significant disadvantage was the near-complete loss of combat effectiveness if the chassis was damaged, as well as the necessity of maneuvering the vehicle to bring suppressive fire from secondary weapons to bear.

Compartmentalization (Fig. 3, 4) is used as one of the key evaluation parameters in the design and assessment of the new tank. This requirement appears both in the list of basic troop requirements and in the evaluation tables for each specific variant (including Variant 23a), featured as a separate line item among the tank's combat characteristics (Fig. 3, 4). For each variant, the Kompartimentierung line indicates "ja" (yes), "nein" (no), or for some, "teilweise" (partially).



Konzept	Turm																	
Besatzung	4 Mann				3 Mann													
Anordnung Antrieb	Front		Heck		Front									Heck				Front
Varianten-Nr.	1	2	5	6	3	4	9	9a	10	11	23	23a	25	7	8	12	24	26
Grundriss																		
• Seitenriss																		
Hauptwaffe	105/120mm	105mm	105/120mm	105mm	105/120mm	105mm	75mm	105mm	Lenkwaffe TOW	105mm	75mm	105mm	105mm	105/120mm	105mm	2x105mm	105mm	Lenkwaffe TOW
Lafettierung	x·360°/+18°/−9°	x·360°/+18°/−9°	x·360°/+18°/−9°	x·360°/+18°/−9°	x·360°/+18°/−9°	x·360°/+18°/−9°	x·360°/+18°/−9°	x·360°/+18°/−9°	x·360°/±10°	Scheitellafette x·360°/+18°/−9°	±135°/+18/−9°	±135°/+18/−9°	x·360°/+18°/−9°	x·360°/+18°/−9°	x·360°/+18°/−9°	x·360°/+18°/−9°	x·360°/+18°/−9°	±135°/±10°
Ladevorgang	Ladehilfe	manuell	Ladehilfe	manuell	Ladeautom.	Ladeautom	Ladeautom	Ladeautom.	Ladeautom	Ladeautom	Ladeautom.	Ladeautom.	Ladeautomat Ringmagazin	Ladeautomat Ringmagazin	Ladeautom. Ringmagazin	Ladeautom.	Ladeautom. Ringmagazin	Ladeautom.
• Munitionszuführung	in Raten	in Raten	in Raten	in Raten	kontinuierl.	in Raten	in Raten	in Raten	in Raten	in Raten	kontinuierlich	kontinuierlich	kontinuierlich	kontinuierlich	kontinuierlich	in Raten	kontinuierlich	in Raten
Kompartimentierung	nein	nein	nein	nein	teilweise	teilweise	teilweise	teilweise	ja	ja	ja	ja	ja	nein	nein	nein	ja	ja
Gewicht																		
Kosten																		
Entwicklungsrisiko																		

Figure 3. Comparative tables of characteristics for the 30 vehicle concepts considered (Bundesarchiv, 1976d). In the tables comparing dozens of tank concepts, "Kompartimentierung" is listed as a separate evaluation criterion.



Konzept	Kasematt											
Besatzung	3 Mann								2 Mann			
Anordnung Antrieb	Front				Heck				Front		Heck	
Varianten-Nr.	13e	13d	14	15	13a	13f	16	17	18	19	20	21
Grundriss												
• Seitenriss												
Hauptwaffe	105 + 35mm	2 × 105/120	105/120mm	105 mm	105 + 35mm	2 × 105/120	105/120mm	105mm	105/120mm	105mm	105/120mm	105mm
Lafettierung	Höhe +18°/−9° Seite starr	Höhe +18°/−9° Seite starr	Höhe +18°/−9° Seite starr	Höhe +18°/−9° Seite starr	Höhe +18°/−9° Seite starr	Höhe +18°/−9° Seite starr	Höhe +18°/−9° Seite starr	Höhe +18°/−9° Seite starr	Höhe +18°/−9° Seite starr	Höhe +18°/−9° Seite starr	Höhe +18°/−9° Seite starr	Höhe +18°/−9° Seite starr
Ladevorgang	Ladeautom.	Ladeautom.	Ladeautom.	Ladeautom.	Ladeautom.	Ladeautom.	Ladeautom.	Ladeautom.	Ladeautom.	Ladeautom.	Ladeautom.	Ladeautom.
• Munitionszuführung	kontinuierlich	kontinuierlich	kontinuierlich	kontinuierlich	kontinuierlich	kontinuierlich	kontinuierl.	kontinuierl.	kontinuierl.	kontinuierl.	kontinuierl.	kontinuierl.
Kompartimentierung	ja	ja	ja	ja	ja	ja	ja	ja	ja	ja	ja	ja
Gewicht												
Kosten												
Entwicklungsrisiko												
	25.10.76											

Figure 4. Comparative tables of characteristics for the 30 vehicle concepts considered (Bundesarchiv, 1976d). In the tables comparing dozens of tank concepts, "Kompartimentierung" is listed as a separate evaluation criterion.

Description of the Partially-Traversable Turret Tank Concept (Variant 23a). The overall concept is characterized by the strict division of the internal space into three compartments: Engine compartment at the front – Weapon and ammunition compartment in the center – Crew compartment at the rear. This results in a limitation of the turret's horizontal traverse sector from the conventional ±360° to ±130°, which was considered acceptable given the vehicle's equal mobility in forward and reverse.

The front engine placement also provided additional protection for the weapon system, ammunition, and crew (Fig. 5).

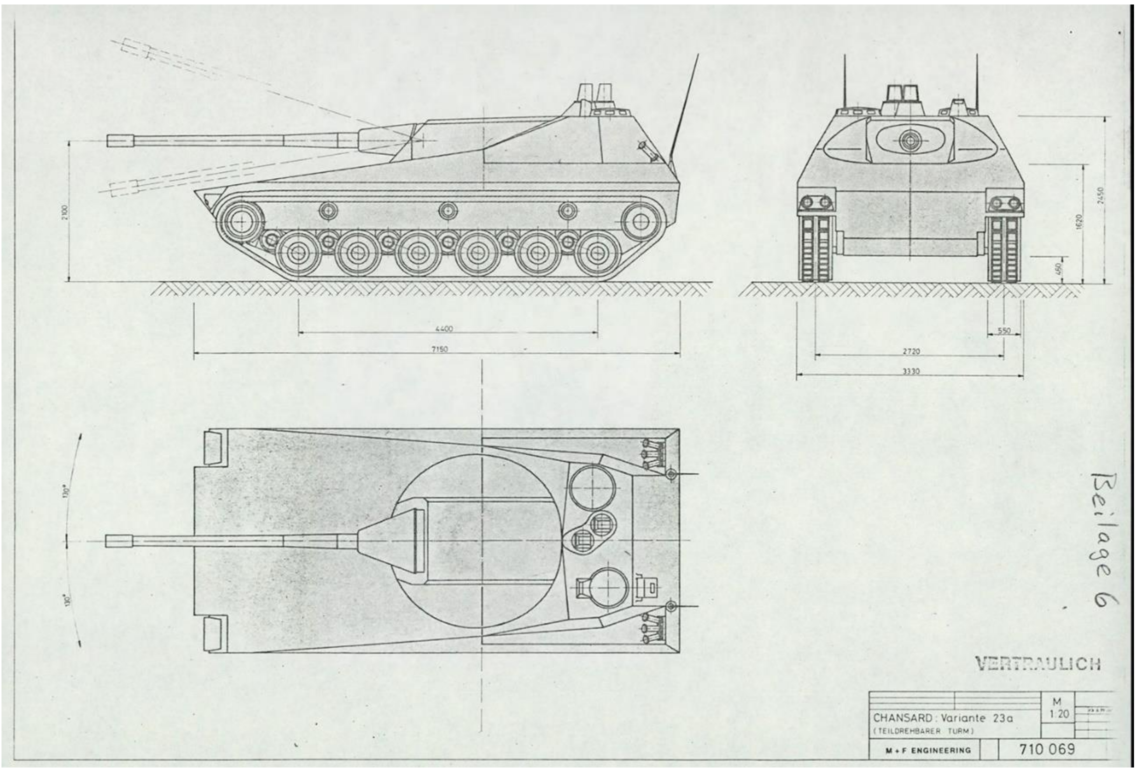


Figure 5. NKPZ Chansard Variant 23a (Teildrehbarer Turm - partially traversable turret).

Placing the entire ammunition load in the weapon and ammunition compartment allows for a relatively simple and reliable autoloader. The enclosed weapon and ammunition compartment is equipped with blow-off panels (covers) on the top and bottom to vent explosive pressure. In the event of an ammunition hit, these panels open under the resulting overpressure, which should practically prevent the destruction of both the crew compartment and the engine compartment. The entire 3-man crew, consisting of the commander, gunner, and driver, is housed together in the crew compartment.

This arrangement also simplifies crew interaction and consolidates crew protection systems (psychological advantages, NBC protection and air conditioning). Furthermore, the driver's placement allows for unlimited forward movement (in combat) and reverse movement (during redeployment) without direction from the commander, so that even in a delaying action, the most heavily protected side can always be presented to the enemy (Bundesarchiv, 1976a). Since the entire crew is in a single compartment, NBC protection and sound insulation are simplified. Additionally, there is no need to extract propellant gases, and there are no fire-prone elements, such as hydraulics, within the compartment.

Table 1. Comparison of Characteristics for NKPZ Variants 13f and 23a (Based on Bundesarchiv, 1976d)

Characteristic / Criterion	Variant 13f (Turretless/Casemate)	Variant 23a (Partially-Traversable Turret)
Overall Layout	Turretless (casemate)	Partially-traversable turret (±130°)
Engine Location	Rear	Front
Crew Compartment Location	Front/Center	Rear
Armament	Twin guns (rigid hull mounting, vertical stabilization)	Single gun (in traversable mount)
Crew Size & Orientation	3, in hull facing direction of travel	3 (commander, gunner, driver together in rear capsule), facing direction of travel
Ammunition Stowage	Isolated compartment near guns	Isolated compartment in center, equipped with blow-off panels (top/bottom)
Autoloader	Yes	Yes
Compartmentalization	Yes	Yes
Protection Philosophy	Maximize crew protection via isolation; engine at rear reduces frontal vulnerability	"Schutz durch Motor" (protection by engine); front engine acts as additional barrier; crew receives maximum protection in rear
Mobility Characteristics	Equal forward/reverse mobility	
Key Advantages	- 10-20% higher hit probability with twin guns - Gun redundancy - Simplified orientation (direction of travel = direction of fire) - Simplified layout with rear engine - Reduced thermal signature (engine at rear)	- Uses conventional turret tactics - Immediate target engagement without turning hull (within ±130°) - Frontal protection enhanced by engine compartment - Simplified crew communication and NBC protection (all in one compartment) - Simple ammunition resupply via rear hatch
Key Disadvantages / Challenges	- Unsuitable for hilly terrain (cannot engage without turning hull) - Complex and costly vertical stabilization required - Difficult unit-level tactics (all guns point same direction) - Loss of chassis = loss of combat effectiveness - Complex target tracking	- Driver placement in rear (unconventional) - Thermal signature at front - Crew requires protection from rear attacks - Limited turret traverse - Front armor must be partially dismantled for engine access - Thermal disturbance affecting observation/sighting

Historical analysis of the Swiss projects shows that by the mid-1970s a stable consensus had emerged among military and technical experts regarding the vulnerability of classical armored vehicle designs. The Swiss projects examined here became indicators of a shift in tank design philosophy: from focusing on firepower and frontal armor to the problem of crew survivability. Turning to procedural aspects, by November 1976 the Swiss NKPz project already had a formalized list of "Basic Requirements" (Bundesarchiv, 1976d), in which the principle of "Separation of crew, weapons/ammunition, and engine/fuel" was placed first. Compartmentalization in Switzerland proved not to be an engineering abstraction but a direct consequence of a military veto on a "simple tank": "The troops need a counter-strike tank that is technically equal or superior to the enemy. A simple battle tank, even if there were more of them, is rejected by the troops." The priority of crew protection was elevated to an inviolable tactical principle precisely under pressure from the end users, not from the developers. The significance of the NKPz lies in the fact that Swiss engineers translated the survivability problem into formal tactical-technical requirements. The strict ranking of protection (crew – ammunition – armament) recorded in the "Military Framework Requirements Specification" remained unchanged throughout the entire project period, marking a transition from the paradigm of "impenetrable armor" to the paradigm of structural survivability: the main task becomes not to prevent a hit, but to localize its consequences.

Compartmentalization in Ukrainian Vehicles Designs Incorporating the Concept of Ranking Primary Systems by Contribution to Survivability.

During approximately the same time period, the idea of compartmentalization was first proposed in the former Soviet Union at the Kharkiv Design Bureau by A. A. Morozov. It is appropriate here to quote an entry dated 1972:

> «*In our opinion, one of the main shortcomings of the existing 'classical scheme' of the tank, which essentially creates all the obstacles to the further enhancement of its tactical-technical characteristics, is the imperfection of its fighting compartment design. It resembles a very cramped one-room apartment or a soldier's duffel bag, in which the crew is squeezed in among the weapons, fuel tanks, ammunition stowage, various mechanisms, linkages, wiring, and numerous other devices and components, some of which pass through en route to the engine-transmission compartment. Furthermore, all of this moves, rotates, emits smoke, is a source of noise and injury, presents an explosion and fire hazard, creates crew isolation, complicates crew evacuation from the tank, fails to provide basic conditions for work and habitability, and much more.*
>
> *In the proposed layout, the so-called fighting compartment of the tank is subjected first and foremost to a fundamental change, by dividing it into separate, mutually isolated, independent compartments: fuel, ammunition, armament, crew compartment, and engine-transmission compartment.*

Thus, while the layout of a modern tank of the "classical scheme" essentially divides the tank into two separate compartments – the engine-transmission compartment and the fighting compartment – the proposed layout scheme already provides for 5 sealed compartments: engine-transmission compartment, ammunition compartment, crew compartment, fuel compartment, and armament» (Chernyshev, 2007).

Within the design criteria of the ideology described above, a preliminary design for the tank «Object 450» was developed. Work continued in the second half of the 1970s by A. I. Mazurenko, E. A. Morozov, and others.

Ukrainian engineers, analyzing the experience of World War II and post-war conflicts, concluded that a fundamental revision of the classical layout, which had dominated global tank design for decades, was necessary (Gnedash, Mazurenko, & Morozov, 1991). In their view, the critical flaw of the traditional scheme was the lack of logic in the distribution of vulnerable volumes: ammunition and fuel were dispersed throughout the hull, making their involvement nearly inevitable upon armor penetration, leading consequently to catastrophic detonation or fire. The solution was seen in creating a layout where tank systems would be ranked according to their contribution to combat effectiveness, and their level of protection would correspond to this rank (Mazurenko, Morozov, & Nazarenko, 1987).

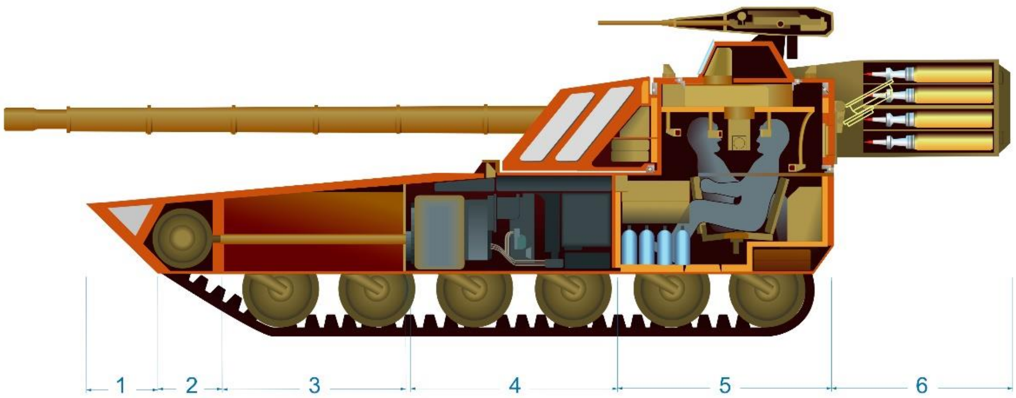


Figure 6. Variant of a non-traditional tank layout scheme with two guns. Author's reconstruction based on source (Apukhtin, Mazurenko, Morozov, & Nazarenko, 1980): 1 – hull armor, 2 – transmission compartment, 3 – fuel compartment, 4 – engine compartment, 5 – crew compartment, 6 – ammunition compartments with loading mechanism.

Description of the Turreted Tank Concept with Two Guns.

Structurally, the tank follows an unusual scheme featuring division into isolated compartments and a rotating weapon platform. The hull is divided into transmission, fuel, engine, and crew compartments. The main feature is the placement of the two-man crew in a stationary armored capsule in the rear part of the hull. Around this capsule rotates a platform with heavy frontal armor and two guns. This not only removed the crew from the "carousel" of rotation but also eliminated the main weakened zone of the classical turret – the gun mounting apertures, which traditionally constitute the most poorly protected area of the frontal aspect (Hilmes, 2021, p. 29).

Beyond firepower superiority, the proposed layout, with guns and autoloaders located in side compartments, fundamentally solves the problem of tank survivability and crew safety. In this scheme, the ammunition load is completely isolated from the crew and located outside the main armored volume. Even in the event of ammunition detonation in one compartment, the explosion energy is directed outward, preventing the catastrophic loss of the vehicle and crew fatalities. Moreover, the disablement of one of the two independent autoloaders does not deprive the tank of its ability to fire – engagement can continue from the undamaged gun, ensuring high combat resilience.

Considerable attention in the project was devoted to crew working conditions and control automation. Both crew members (commander-gunner and driver) are seated in an ergonomic capsule with enhanced radiation protection and air conditioning. They are always facing the front of the vehicle, maintaining spatial orientation regardless of turret position. Fire and mobility controls are duplicated and integrated into unified consoles with displays, allowing either operator to perform the other's functions. All-around vision is provided by screen-type devices based on fiber optics. Reducing the crew to two, combined with locating armament and ammunition outside the habitable compartment, not only reduces vehicle weight and dimensions but also creates prerequisites for a fully automated combat system of the future.

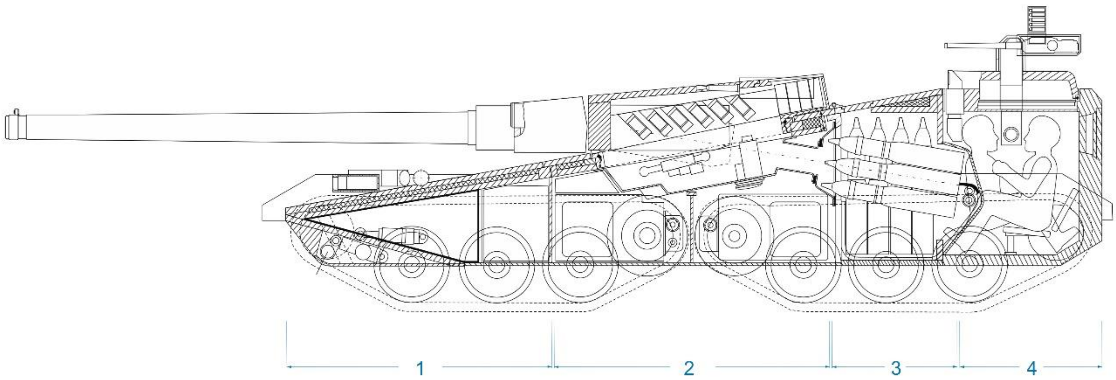


Figure 7. Variant of a non-traditional tank layout scheme. Author's reconstruction based on source (Gnedash, Mazurenko, & Morozov, 1991).
1 – fuel compartment, 2 – engine-transmission compartment, 5 – ammunition compartment with loading mechanism, 6 – crew compartment.

Description of a Turreted Tank Concept with a Non-Traditional Layout Based on Combat Property Ranking.

Analysis of the evolution of tank design shows that the layout scheme first implemented in the T-34 tank became classic for decades. Its key features – front location of the driver's station, central placement of the fighting compartment in a rotating turret, and rear location of the engine-transmission compartment – provided a successful balance of firepower, protection, and mobility for its time. However, the constant growth in tactical-technical characteristics has exacerbated the internal contradictions of the classical scheme. Increased mass negatively affects mobility, caliber growth complicates ammunition and crew placement in the turret, and the pursuit of enhanced protection conflicts with volume and weight constraints. This necessitates the search for fundamentally new layout solutions departing from established canons.

> «*Over 10 years, I understood the weak points, or rather the 'dead-end' points of the modern tank, which cannot be 'cured' through modernization, but which are amenable to 'treatment' through a fundamentally new layout scheme*,» noted the project developer (Mazurenko, 2015).

As one possible direction for overcoming these contradictions, a non-traditional layout scheme is proposed, based on the longitudinal division of the tank hull into five functionally isolated compartments. From front to rear, they are arranged in the following sequence: fuel compartment, power pack compartment, main armament compartment (turret with gun), autoloader compartment with ammunition stowage, and finally, the crew compartment. This linear arrangement allows for the implementation of the layered protection principle, where each subsequent compartment is shielded by the preceding ones, and their armor protection level increases in proportion to the combat significance of the components housed within.

The key advantage of this scheme is the radical enhancement of tank survivability (Hilmes, 2021, p. 41). The fuel compartment, with minimal protection, absorbs the initial impact of the most prevalent weapon types, shielding the power pack. The placement of two engines with independent transmissions for each of the four track runs allows the vehicle to retain mobility even if part of the power pack or running gear is damaged. The autoloader, protected by three front compartments, is fitted with blow-off panels in the floor in case of ammunition detonation to vent explosive energy, minimizing hull damage. The crew compartment, located in the most heavily protected rear section, receives 2-2.5 times thicker armor than the front compartment, ensuring an unprecedented level of personnel survivability even upon hull penetration.

Thus, the proposed layout provides a differentiated level of protection in strict accordance with the significance of each element: the least critical systems (fuel) shield the more important ones (engine, ammunition), while the crew receives the maximum possible protection. This approach allows for a high probability of maintaining tank combat effectiveness under intense fire without a proportional increase in armor mass. Implementing this scheme requires an integrated design approach from the earliest stages; however, it is precisely this departure from classical solutions that opens the path to resolving accumulated problems and creating a tank with a fundamentally new level of combat effectiveness and survivability.

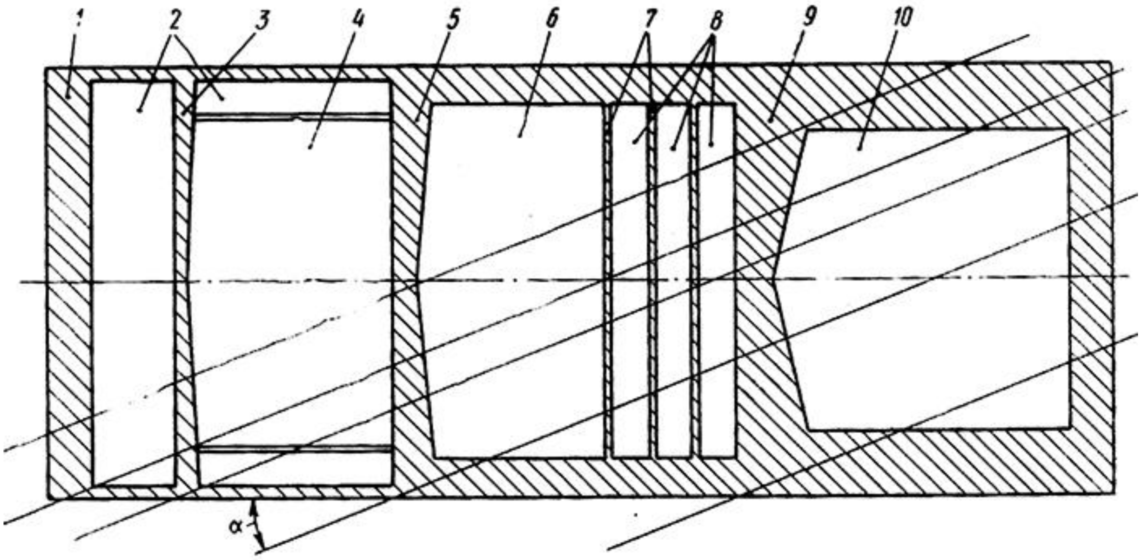


Figure 8. Schematic diagram (plan view) of a tank with sequentially arranged compartments (Mazurenko, Morozov, & Nazarenko, 1987)
1 – front plate; 2 – fuel compartment; 3 – fuel bulkhead; 4 – engine compartment; 5 – engine bulkhead; 6 – fighting compartment; 7 – ammunition stowage bulkheads; 8 – ammunition stowage compartments; 9 – crew compartment bulkhead; 10 – crew compartment; 11 – engagement angle for the most powerful weapons α.

The concept proposed by the Kharkiv designers was based on a strict ranking of systems in descending order of their importance for maintaining combat effectiveness. According to this approach, the highest priority (protection coefficient K=1.0) was assigned to the crew, whose incapacitation meant the total loss of the tank. Following this were the ammunition stowage (K=0.9), whose detonation led to catastrophic loss; the weapon system (K=0.8); the engine-transmission unit (K=0.6); and finally, the fuel (K=0.5) (Mazurenko, Morozov, & Nazarenko, 1987). Based on this ranking, a layout scheme was developed in which five isolated compartments were arranged sequentially along the vehicle's longitudinal axis, with protection levels increasing from the front to the rear: the fuel compartment, the power pack compartment, the autoloader compartment with ammunition stowage, and finally the crew compartment in the rear (Gnedash, Mazurenko, & Morozov, 1991). This configuration, a form of "layered protection," ensured that more important systems were shielded by less important ones. Fuel, having the lowest priority, acted as an additional barrier to protect the engine, while the engine and autoloader shielded the crew. Furthermore, the design incorporated blow-off panels in the floor of the ammunition compartment to vent pressure during detonation, directly echoing American developments from the late 1950s (Watervliet Arsenal, 1959).

The historical analysis conducted demonstrates that the principles of compartmentalization and layered protection, developed in the 1970s–1980s, represent not a random historical phenomenon but a fundamental regularity whose significance only increases in the context of modern armed conflicts. Thus, T. Giurgiu and colleagues (Giurgiu, Virca, Grigoraș, & Năstăsescu, 2023) directly point to the evolution of the protection concept: from the classic «iron triangle» (armor – firepower – mobility) to the primacy of survivability in the face of fundamentally new threats. The widespread use of unmanned aerial vehicles has transformed traditional all-around protection into hemispherical protection, where top cover is critically important. This fully aligns with the main conclusion of our study: it was precisely the threat of crew casualties and catastrophic vehicle loss, demonstrated by the Yom Kippur War, that became the driver for the appearance of isolated compartments in the K+W and Kharkiv design bureau projects.

Moreover, the critical importance of crew survivability, foundational to the Swiss and Ukrainian layouts, today acquires new, deeper economic and operational justification. A. Kumar and S. Sahu (Kumar & Sahu, 2025), using India as an example, demonstrate the paradox of the modern arms race: attempts to protect 50-ton vehicles from swarms of cheap drones and tandem warheads lead to a disproportionate increase in tank cost. Resources are spent not on enhancing lethality but on survivability, calling into question the operational value of heavy armored vehicles. This conclusion directly resonates with the key requirement of the NKPZ project – increasing combat effectiveness without a significant cost increase – where compartmentalization was seen as the most effective way to achieve this. The principle articulated by the Kharkiv designers gains even greater significance today: the loss of a trained crew in the conditions of a "transparent battlefield" becomes even more critical than the loss of the most expensive vehicle.

Finally, the conceptual similarity between the Swiss and Ukrainian solutions, identified in our study, finds confirmation in contemporary forecasts for the development of tank design. A. Gat (Gat, 2023) asserts that ground forces stand on the threshold of a revolution – a transition from kinetic protection (heavy armor) to electronic protection, where active protection systems become the foundation. He draws a direct analogy with the decline of the era of heavy battleships, which gave way to aircraft carriers. However, our historical analysis shows that this transition would not have been possible without conceptual groundwork. It was the principle of compartmentalization that first allowed the engine, fuel, and ammunition to be considered not merely as vulnerable points, but as part of a layered protection system that absorbs the impact and gives the crew a chance of survival. In this sense, Gat's ideas about the inevitability of implementing active protection systems are not a rejection, but a direct continuation and development of the philosophy that originated in the 1970s in Switzerland and Ukraine. Passive compartmentalization, supplemented by active threat interception, represents the synthesis that will enable the creation of a specialized vehicle combining high protection with operational flexibility, as also discussed by Kumar & Sahu (2025), who advocate for the development of lighter and more networked systems.

The conceptual breakthroughs achieved by the Swiss and Kharkiv design schools in the 1970s were not isolated events. They reflected a broader and growing recognition within the international military-technical community that the traditional layout of armored vehicles had reached a fundamental impasse. As explicitly stated in the U.S. Army Test and Evaluation Command document *Armored Vehicle Vulnerability to Conventional Weapons* (TOP 2-2-617, 1975), "the three major concerns in vulnerability analysis are: protection of the crew, protection of vehicle mobility, and protection of firepower. Of particular concern in this regard is protection against detonation of stowed ammunition and uncontrolled burning of the fuel, for if either occurs, the results could be catastrophic" (p. 2). Compartmentalization, as developed in Switzerland and Kharkiv projects, directly addressed this threat. By isolating the crew in a rear capsule, separating the ammunition stowage with blow-off panels, and using the engine and fuel compartments as additional barriers, the new layout made it possible for a vehicle to suffer a mobility or firepower kill without inevitably progressing to a catastrophic kill.

This logic resonates with the observation that "when damaged, it is desirable to repair those components that are fairly vulnerable and, when damaged, have a serious effect upon the firepower or mobility of a vehicle" (TOP 2-2-617, p. 5). The ability to survive a hit, evacuate the crew, and possibly repair the vehicle became a deliberate design goal rather than an afterthought. The continuity of this engineering philosophy is demonstrated by the later development of ammunition compartmentation in the U.S. Abrams tank. As reported by Conant (2013), "the U.S. Army Research Laboratory, then the Ballistics Research Laboratory, developed effective ammunition compartments in the past, to include the development of the Abrams bustle compartment back in the 1980's. This success was achieved primarily through extensive test and evaluation" (para. 2). The fundamental principle remained unchanged: separating the ammunition from the crew and providing venting for explosive pressure. Conant further notes that "when hit with large hostile fire weapons, internally stowed ammunition may react resulting in catastrophic loss of life and system" (para. 1). This statement echoes almost verbatim the concerns raised by Swiss and Ukrainian designers a decade earlier. Moreover, the 21st-century research described by Conant demonstrates a direct methodological lineage from the compartmentalization experiments of the 1970s. The Army Research Laboratory is now "developing modeling and simulation methodologies to improve the survivability of combat fighting vehicles beginning with hypotheses synthesis and phenomenology studies underpinned by experimentation" (Conant, 2013, para. 4). The enduring relevance of compartmentalization is further underlined by the observation that "as the Army modernizes its fleet, effective ammunition compartmentation will again be needed to ensure vehicles and crew members survive hostile fires" (Conant, 2013, para. 3).

Conceptual Similarity of Solutions from Two Leading Engineering Schools. The comparative analysis conducted of design materials from the Kharkiv KB-60M and the Swiss K+W during the period of the 1970s–1980s reveals not a mere coincidence of individual technical solutions, but a profound conceptual kinship of engineering thought that emerged under conditions of complete informational isolation and the absence of direct experience exchange. Both schools, starting from the analysis of the same tragic lessons of the Yom Kippur War (1973) – where ammunition hits led to the catastrophic destruction of vehicles along with their crews – independently arrived at the conclusion that a change in the layout paradigm was necessary. The similarity is evident on three key levels: protection philosophy, structural implementation, and functional ranking of internal systems.

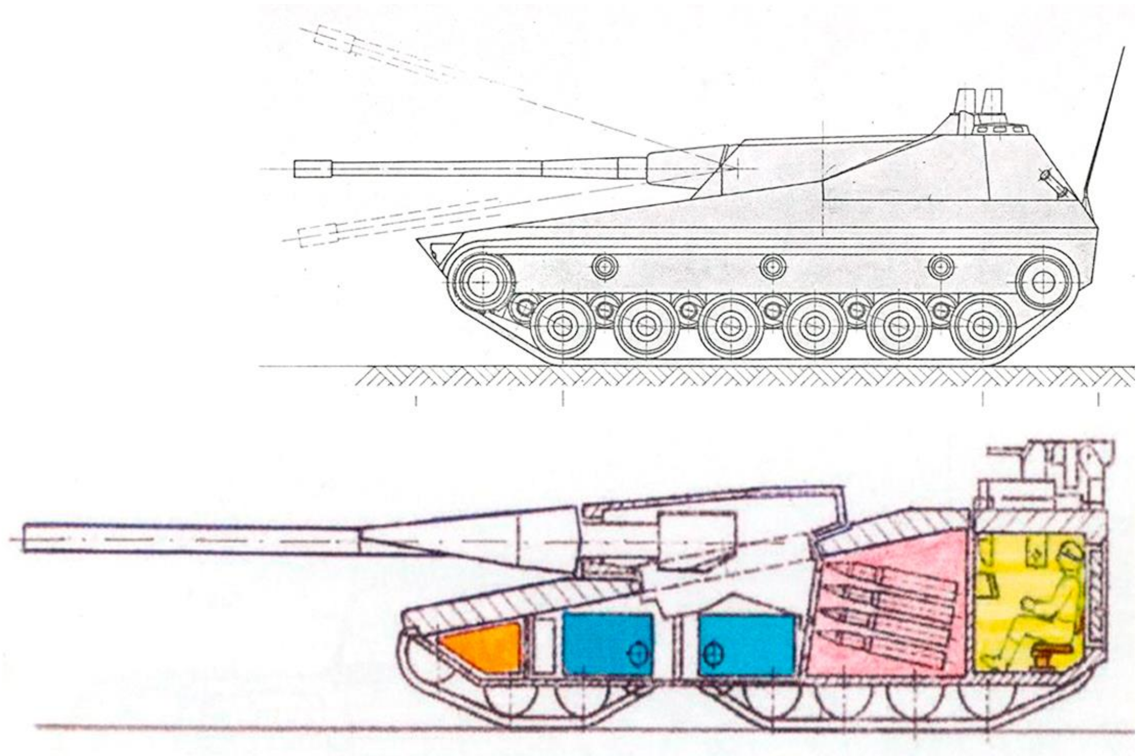


Figure 9. Comparison of side profiles of the Chansard variant 23a (Switzerland) and the tank with a non-traditional layout scheme based on combat properties ranking (Ukraine).

First, both engineering schools rejected the traditional augmentation of frontal armor thickness as the sole or primary means of enhancing protection. Instead, they adopted the principle of compartmentalization as the foundation – that is, the strict functional division of the vehicle's internal volume into sealed and mutually isolated compartments. In the K+W documentation, this principle is established as a separate mandatory criterion for evaluating combat characteristics ("Kompartimentierung: ja/nein"), while in A. A. Morozov's diaries, it is justified by the necessity to abandon the traditional cramped fighting compartment, where the crew is confined among explosive and fire-prone elements. Both Swiss and Ukrainian designers aimed to ensure that a fire or ammunition detonation in one compartment would not lead to the guaranteed destruction of the crew and the catastrophic loss of the entire vehicle.

Second, a structural similarity is observed in the arrangement of key elements. This is most strikingly evident when comparing the Swiss Chansard 23a variant and the line of Ukrainian designs (from the preliminary design «Object 450» to later concepts documented in articles by A. I. Mazurenko. Both concepts place the crew (three in the Swiss design, two in the Ukrainian scheme) in an isolated compartment in the rear of the vehicle. The rear location of the crew compartment was deemed optimal, as it provided maximum protection from the main direction of combat (the front) due to shielding by the power pack and fuel compartments, and also facilitated evacuation. In both cases, the engine (in Switzerland – at the front; in the Ukrainian concept – in the center or front) serves not only as a power source but also as an additional barrier (German: Schutz durch Motor), absorbing penetrating elements. Both solutions stipulated that a mobility kill was preferable to a catastrophic kill.

Third, and most importantly, a unified approach to handling the ammunition load is evident. The Swiss variant 23a provided for the placement of the entire ammunition load in an isolated weapon compartment, separated from the crew by an armored bulkhead, with this compartment being mandatorily equipped with blow-off panels (covers) to vent explosive pressure outward. Ukrainian developments went even further in detailing this principle. In the concepts based on combat property ranking, the ammunition load (K=0.9 in significance) is not merely isolated but is also layered in accordance with the concept of ranking primary systems by their contribution to survivability: it is positioned behind the engine (K=0.6) and fuel (K=0.5), which absorb the primary impact. At the same time, in the Ukrainian projects, the ammunition compartment is also equipped with blow-off panels, representing a direct development of ideas first documented in the American Watervliet Arsenal report (Watervliet Arsenal, 1959).

Finally, both schools arrived at an understanding of the need to synchronize the direction of travel and the primary direction of fire to simplify crew operations. In the Swiss variant 23a, the driver, commander, and gunner are located in the rear compartment and are always oriented in the direction of travel (forward), regardless of the turret's position. In the Ukrainian twin-gun concept with a rotating platform, the crew in the stationary capsule is also always facing the front of the vehicle, preserving spatial orientation and reducing psychophysiological load. This similarity demonstrates a shared understanding of combat ergonomics: personnel should not become disoriented when the turret rotates or when firing to the rear.

Thus, the commonality of engineering thought manifested in the developments of two isolated schools convincingly demonstrates that the principles of compartmentalization and layered protection are not a random or localized invention, but an objective regularity in the evolution of armored vehicles. The prioritization of crew survivability over firepower and mobility, achieved through volume separation and system ranking, became the conceptual bridge connecting Swiss pragmatism and the Ukrainian engineering school in the quest for the tank of the future. Ignoring these principles when defining requirements for the development of advanced vehicles, as occurred with the «Boxer» R&D project in 1979 (The State Archive of Kharkiv Region, 1979), ran counter to the conclusions already reached by the science of the industry.

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The author declare no conflict of interest.

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Компартменталізація та ранжування систем як фундаментальні вимоги до проєктування спеціальних машин: Україна, Швейцарія

Анотація. *Поширення дешевих FPV-дронів докорінно змінило характер загроз для основних бойових танків, висунувши живучість екіпажу як головний критерій проєктування та зумовивши необхідність перегляду історичних концепцій захисту. У цьому дослідженні на основі порівняльного аналізу архівних матеріалів Швейцарського федерального архіву та розсекречених тематичних видань радянського періоду, а також щоденникових записів учасників розробок простежено незалежне виникнення принципу компартменталізації (поділення машини на ізольовані один від одного самостійні відсіки) у швейцарській та українській школах танкобудування в 1970–1980-х роках. Результати демонструють, що обидві інженерні школи, реагуючи на катастрофічні втрати танків у війні Судного дня 1973 року, незалежно одна від одної дійшли практично ідентичних рішень, незважаючи на повну інформаційну ізоляцію. У швейцарському проєкті NKPZ «Kompartimentierung» була офіційно закріплена як обов'язковий оціночний критерій, і лише дві концепції забезпечували повне фізичне розділення екіпажу, боєприпасів та силової установки. Водночас харківські конструктори розробили розділену на відсіки компонувальну схему, засновану на кількісному ранжуванні систем за внеском у живучість, із присвоєнням найвищого коефіцієнта захисту екіпажу, розміщеному в найбільш захищеному відсіку. Обидві школи незалежно дійшли трьох фундаментальних принципів: розміщення екіпажу в ізольованій кормовій капсулі, використання моторного відділення як додаткового захисного бар'єра та оснащення відсіків* *боєприпасів вишибними панелями для відведення енергії вибуху назовні. Даний паралелізм розвитку доводить, що компартменталізація та ранжування систем є об'єктивною закономірністю еволюції спеціальної техніки, а не локальними винаходами. Своєчасність дослідження зумовлена тим, що розроблені в 1970-х роках принципи компартменталізації та ешелонованого захисту екіпажу, будучи відповіддю на виклики свого часу, сьогодні набувають нового звучання у світлі масового застосування FPV-дронів, які знову висувають проблему живучості бронетехніки та запобігання безповоротним втратам.*

Ключові слова: *компартменталізація; танкобудування; інженерні школи; броньовані машини; Холодна Війна*

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