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REQUIREMENTS FOR IT SYSTEMS SUPPORTING THE OIL-FILLING PROCESS OF ELECTRIC OIL HEATERS

The oil-filling stage in electric oil heater production is a critical operation impacting product safety, thermal performance, and long-term reliability. Thermal oil acts as both a heat transfer medium and an electrical insulator. Deviations in oil quality or filling conditions may cause latent defects appearing only during operation. Contamination, especially moisture ingress, reduces dielectric strength and accelerates oil degradation. Air entrapment during filling can cause uneven temperature distribution, localized overheating, and premature heating element failure. Variability from manual or poorly controlled filling increases the risk of underfilling or overfilling, affecting compliance with technical standards. This paper examines the main technical issues in oil filling, including risks, process control challenges, and safety concerns. From an IT perspective, the process demands precise measurement, system reliability, and integration of control software, sensors, and data acquisition platforms. Software misconfiguration, communication errors, or inadequate validation may lead to incorrect filling parameters and delayed fault detection. The paper outlines key functional and user-interface requirements for IT systems supporting and stabilizing the oil-filling process.

1. INTRODUCTION

Electric oil heaters (Fig. 1) are widely used for residential and industrial heating applications due to their thermal stability and efficiency. They consist of a metal body filled with thermal oil, whose function is to serve as both a heat transfer medium and an electrical insulating material. The production process of these devices involves several critical steps, among which the filling of thermal oil plays a key role. The oil functions as both a heat transfer medium and an electrical insulating material, directly influencing operational safety and service life [1]. Manufacturing defects related to oil filling are often latent and may only become evident after extended operation. Such failures can result in overheating, insulation breakdown, or leakage, emphasizing the importance of controlled and standardized filling procedures [2]. This paper proposes a structured set of functional, configuration, and human–machine interface requirements for IT systems supporting the oil-filling process in electric oil

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heater manufacturing. The proposed requirements are derived from industrial practice and mapped onto a safety-critical filling workflow integrating PLC, HMI, and data acquisition systems. The paper focuses on the IT systems supporting the manufacturing process, noting that parameters such as theoretical heater volume, compensated volumes of internal components (like the heating unit), and the required air cushion volume are critical inputs for the system. The shortcomings of existing oil heater filling systems, as identified in industrial practice, primarily revolve around the lack of integrated, automated control and the reliance on manual or loosely monitored procedures.

Fig. 1. Electric oil heater (fot. Ganesh.H, CC BY-SA 3.0)

2. LITERATURE REVIEW

Recent literature highlights the critical role of thermal oil quality and filling processes in ensuring the operational safety and longevity of electrical oil heaters. Studies in heat transfer and thermal systems engineering emphasize that the performance of oil-filled heating devices strongly depends on uniform oil distribution and stable thermophysical properties during operation [1]. Even low moisture concentrations can significantly reduce dielectric strength and accelerate oxidation processes in insulating oils. This is consistent with the guidelines of IEEE Std C57.106-2021 [2], which emphasize the importance of strict moisture control during oil handling and filling operations [4]. Process automation and repeatability have been addressed by Groover [3], who emphasizes that manual filling operations are particularly susceptible to variability in mass production environments. Automated filling systems equipped with real-time monitoring significantly reduce deviations in oil volume and minimize human error. Material compatibility between thermal oils and construction components has also received attention in recent studies. Rudnick [5] discusses chemical interactions between lubricants and elastomeric seals, highlighting the risk of long-term degradation when incompatible materials are used, especially under elevated temperatures. From a regulatory perspective, IEC 60335-2-30 defines updated safety requirements for household electrical heaters, including oil-filled room heaters [6]. These standards indirectly address oil-filling issues by defining strict limits for leakage, thermal stability, and electrical insulation performance. Despite the availability of standards and technical guidelines, the literature indicates that oil-filling issues are often addressed indirectly rather than as a dedicated research topic. Most studies focus on transformer oils or general thermal systems, revealing a research gap related to production-specific challenges of electrical oil heaters.

3.CHARACTERISTICS OF ELECTRICAL HEATER OILS

The oils used in electrical heaters are typically highly refined mineral oils or synthetic fluids designed to provide thermal stability, low vapour pressure, and adequate dielectric strength over the entire operating temperature range [1]. Key parameters governing their performance include viscosity, flash point, moisture content, and oxidation resistance, all of which directly influence heat transfer efficiency and electrical insulation properties. Moisture contamination is particularly critical, as even small amounts of water can significantly reduce dielectric strength and accelerate oil degradation and aging processes [2]. In addition, moisture promotes oxidation reactions and may contribute to the formation of corrosive by-products during operation. Maintaining oil purity during storage, handling, and filling is therefore essential to ensure long-term performance, safety, and reliability of electrical oil heaters.

4. CHALLENGES IN THE OIL-FILLING PROCESS

Contamination remains one of the most significant challenges during oil filling. Sources include residual moisture within heater casings, airborne particulates, and improperly cleaned filling equipment. Even trace amounts of water or solid contaminants can compromise insulation performance and increase the risk of electrical breakdown [2]. The duration of process of oil oxidation due to moisture in the air depends on conditions. However, moisture ingress accelerates degradation, often leading to latent defects visible only after extended operation. Proper filling ensures even temperature distribution. The system is designed to achieve uniform and stable oil distribution. Avoiding “insulating pockets” of air is critical to preventing thermal irregularities that lead to component failure. Air pockets formed during filling may impair heat transfer and cause localized overheating. Such thermal irregularities can lead to mechanical stress, material fatigue, and premature failure of heating elements. While there is no single universal volume, even a small air pocket (exceeding 3-5% of the total internal volume, depending on the model) can be critical. The danger is not just the volume itself, but its location. If air accumulates around the heating element, it prevents heat dissipation to the oil, causing a “dry firing” condition. This leads to local temperatures exceeding 300°C within seconds, causing thermal expansion of the steel and potential seal failure. Furthermore, while a properly positioned air cushion at the top of the heater acts as a compressible buffer, an uncontrolled air pocket trapped near the heating element experiences rapid localized thermal expansion due to dry firing. This localized superheating of trapped air, combined with the volumetric expansion of the surrounding oil, generates an internal pressure surge that can deform the radiator casing. In large-scale production, achieving repeatable filling results presents a major challenge. Variations in oil temperature, viscosity, and filling pressure can cause deviations in oil volume. Oil level influences heat transfer efficiency. Inadequate process control may result in under-filled or overfilled heaters, negatively affecting thermal expansion behaviour and safety margins [3]. Oil-filling operations pose risks to both workers and the environment. Oil spills may result in slip hazards and environmental contamination, while exposure to heated oil can cause burns or respiratory irritation. Compliance with occupational health and environmental regulations is therefore mandatory [7].

5. OIL-FILLING PROCEDURE IN ELECTRIC HEATER MANUFACTURING

The oil-filling process is carried out through a defined sequence of stages, each serving a specific physical and functional purpose. The procedure begins with filling the internal reservoir, which provides the basic working medium required for heat transfer. The oil acts as a thermal carrier, absorbing heat from the heating elements and distributing it evenly throughout the heater body. Proper initial filling ensures that all internal components intended for heat exchange are adequately supplied with oil. The next stage involves vacuum generation, which is essential for removing residual air and gases from the internal volume of the heater. The vacuum generation stage serves as a primary method for moisture control. By reducing the internal pressure, the system facilitates the evaporation of residual water at lower temperatures, effectively drying the internal surfaces of the heater. This extraction is vital to ensure the oil maintains its dielectric properties and to prevent long-term corrosion or oxidation of the thermal fluid. Eliminating trapped air prevents the formation of insulating pockets that could reduce heat transfer efficiency or lead to localized overheating. This step also supports the structural integrity of the system by minimizing internal oxidation and pressure-related stress during operation. Following this, controlled oil filling is performed to introduce the oil into the evacuated internal space in a gradual and precise manner. This allows the oil to fully occupy the available volume, including narrow channels and cavities, while avoiding turbulence or air entrapment. The goal of this stage is to achieve a uniform and stable oil distribution inside the heater. After filling, preliminary oil extraction is carried out to remove a defined portion of the oil. This step is necessary to create adequate free volume within the heater, accommodating thermal expansion of the oil during normal operating conditions. By adjusting the oil quantity at this stage, the risk of excessive internal pressure and mechanical stress is significantly reduced. The final stage is air cushion formation, which establishes a controlled volume of air or gas inside the heater. This air cushion functions as a compensating buffer, allowing the oil to expand and contract with temperature changes without compromising the tightness or safety of the enclosure. Proper formation of this cushion is essential for maintaining stable pressure conditions and ensuring long-term durability of the heater.

6. COMPONENTS OF OIL-FILLING MACHINERY

In industrial liquid filling equipment, the fundamental mechanical components that directly support the process of transferring fluid into a product enclosure include a bulk liquid reservoir for storage and supply, pumps that convey and meter the fluid to the target volume, filling nozzles or lances that provide the physical interface for introducing the liquid into the interior of the heater, and an array of valves that control flow direction, start/stop dispensing, and prevent backflow. These elements are interconnected through a network of piping and fittings engineered for sealing integrity and compatibility with the specific fluid properties, and together they constitute the core structural elements of precision filling systems used across a wide range of liquid handling applications, including oils with varying viscosities.

7. IT-SUPPORT OF THE OIL-FILLING PROCESS

The oil-filling process in electric oil heater production is typically executed as a sequence of automated and semi-automated operations supported by industrial control hardware and dedicated IT applications. The integration of programmable logic controllers (PLCs), sensors, actuators, and human-machine interfaces (HMIs) enables precise control of filling parameters, real-time monitoring, and reliable quality evaluation. The process is schematically presented on Fig. 2.

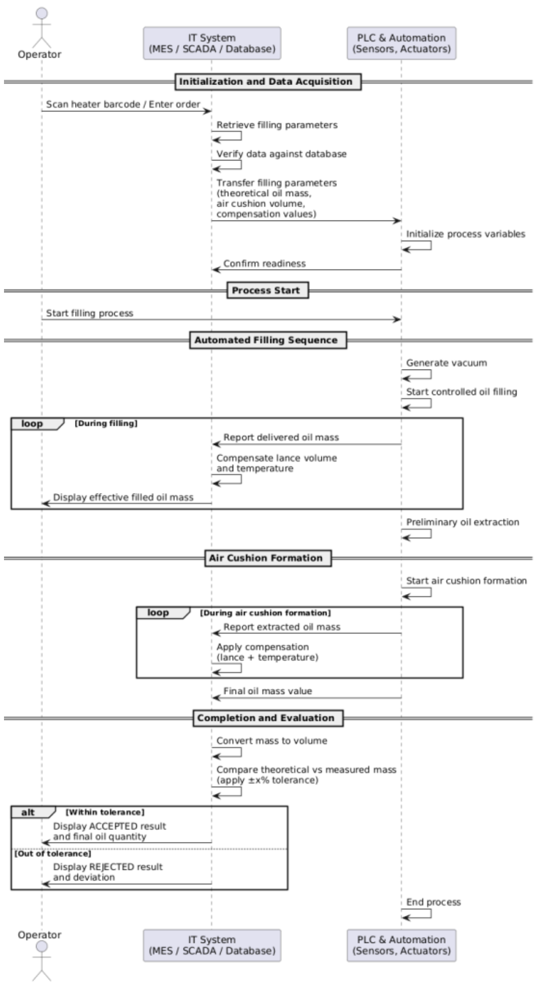

Fig. 2. Schematic structure of the IT-supported oil-filling process

At this point it shall be stated, that chapter 7 presents a first part of the main original contribution of this study by formulating IT system requirements derived from industrial oil-filling applications. The author took part in a pilot development of IT software overlay for the oil-filling system. As such, the author's work was embedded in every step of the control diagram, providing the logic for data acquisition, real-time compensation, and automated process evaluation. This IT layer transforms the hardware station into a fully integrated cyber-physical system.

7.1. INPUT DATA ACQUISITION AND INITIALIZATION

Prior to process initiation, filling parameters are transferred from a supervisory IT system to the PLC. These parameters may be entered manually or retrieved automatically after scanning the heater code. The system may optionally verify received data against a local database to detect inconsistencies before process start. Input data include the required air cushion volume, compensated volumes of internal components (such as lance, heating unit), and the theoretical heater volume (including the lance and lance reservoir) converted to mass using a temperature-dependent oil density model. The theoretical oil mass to be filled is stored as a reference value for subsequent evaluation (to determine the permissible filling time). At this stage, the system calculates and stores the theoretical oil mass to be filled, excluding the heating element volume and air cushion. This reference value is later used for comparison with the measured filled mass at the end of the filling cycle.

7.2. AUTOMATED FILLING SEQUENCE

Once the operator initiates the process, the oil-filling procedure is executed through a predefined sequence of automated steps, already described in chapter 5. Each step is supervised by the PLC and continuously monitored by the IT system to ensure compliance with predefined process limits. During the active filling phase, the PLC continuously reports the mass of oil delivered to the heater. The IT system compensates this value by subtracting the lance volume converted to mass, resulting in the effective filled oil mass. This value is dynamically displayed to the operator throughout the process.

7.3. AIR CUSHION FORMATION CONTROL

During air cushion formation, the system continuously monitors the mass of oil extracted from the heater. As in the filling phase, lance volume compensation and temperature-based mass-to-volume conversion are applied. This ensures precise control of the final air cushion size and prevents deviations that could affect thermal expansion behaviour during operation. After completion of the air cushion formation step, the final filled oil quantity is fixed, converted into volumetric units using the oil temperature compensation model, and presented on the user interface. The conversion is vital because oil density is temperature-dependent. Precise control of the final air cushion size, calculated by the IT system using real-time temperature compensation, prevents deviations in thermal expansion behaviour. The success of the process is determined by comparing the final volume against model-specific configured tolerance ranges (e.g. from 1% to 3% of the nominal volume), ensuring compliance with safety standards regarding internal pressure.

7.4. PROCESS COMPLETION AND EVALUATION

Upon completion of the oil-filling procedure, the system compares the theoretical oil mass with the measured filled mass, considering configurable tolerance limits (±x%). Based on this comparison, the system automatically determines whether the filling process is accepted or rejected. The result, along with the corresponding oil quantities converted to volumetric units, is clearly displayed to the operator. Figure 3 presents the original graphical user interface designed by the author to support the oil-filling process. The information about the final volume of oil poured into the heater, displayed at the end user is used for automated pass/fail final evaluation, quality assurance, ensuring full traceability and compliance analysis with standards as well as providing clear visual feedback to the operator.

8. IT SYSTEM REQUIREMENTS AND CHALLENGES IN SUPPORTING THE OIL-FILLING PROCESS

The increasing automation and digitalization of electrical oil heater production place significant demands on information technology (IT) support functions. While IT systems enable higher process stability, traceability, and quality assurance, they also introduce new challenges that directly affect the oil-filling stage. In Sections 8.1 and 8.4–8.6, this study introduces additional original contributions by defining IT system requirements grounded in industrial oil-filling implementations. The challenges include the integration of PLC/HMI/MES systems, ensuring communication reliability, and eliminating configuration errors, which are the main cause of quality losses. From an IT systems perspective, the oil-filling process in electric oil heater manufacturing imposes strict requirements on measurement accuracy, system reliability, and the tight integration of control software, sensors, and data acquisition platforms. Because oil filling directly influences both electrical safety and thermal performance, IT-supported systems must operate with high precision and robustness under industrial conditions. Recent studies in smart manufacturing emphasize that digitally supported filling processes are safety-critical cyber-physical systems, where software errors or communication failures can directly affect product conformity and operational safety [3]. Software misconfiguration, communication errors, or insufficient system validation may result in incorrect filling parameters, undetected deviations, and delayed fault detection. Recent literature highlights that such failures are among the most common root causes of quality losses in automated liquid-filling processes [8]. This chapter discusses the key functional and user-interface requirements for IT systems designed to support and stabilize the oil-filling process in electric oil heater manufacturing.

8.1. FUNCTIONAL REQUIREMENTS

IT systems supporting oil-filling operations must ensure accurate acquisition and processing of key parameters such as oil volume, temperature, pressure, and filling time. The final filled mass is compared against a theoretical reference value within configurable tolerance limits (±x%) to determine acceptance or rejection. These data are collected via sensors connected to PLC and SCADA systems. Any deviation from predefined tolerance limits should be detected in real time and immediately reported to operators or higher-level control systems. The software must also support automated recipe management for different heater models and oil types, minimizing human error during changeovers. Modern oil-filling systems rely on real-time monitoring of critical parameters including oil volume, temperature, pressure, and filling duration. As noted by Groover [3] and Industry 4.0 research, these must be continuously compared with tolerance windows to maintain process stability. Role-based access control and parameter locking are recognized best practices for preventing unauthorized modifications and reducing operator-induced variability [3]. Functionally, the IT application for the oil-filling process shall provide: fully automated oil filling, step-by-step filling for diagnostics or service, automatic parameter assignment via scanned heater codes, manual parameter entry using local or network heater databases, controlled database modification by authorized users, real-time visualization of valves, pumps, sensors, temperatures, pressures, and oil levels, manual system control for authorized service personnel, configuration of system parameters, communication interfaces, and tolerance limits, as well as comprehensive alarm, warning, and event logging. Operators without elevated privileges must be able to monitor all relevant process variables and component states in real time, ensuring transparency and situational awareness during filling operations (see Fig. 3).

8.2. SYSTEM INTEGRATION AND COMMUNICATION RELIABILITY

Ensuring dependable integration among sensors, programmable logic controllers (PLCs), human–machine interfaces (HMIs), and Manufacturing Execution Systems (MES) remains a major challenge in digitally enabled filling processes. Failures in communication, network instability, or protocol incompatibilities can result in unfinished filling operations or improper parameter execution. To mitigate these risks, IT systems must employ standardized industrial communication protocols and continuous diagnostics for monitoring data integrity and transmission latency. Robust integration architectures are increasingly recognized as a prerequisite for traceability and real-time quality control in automated production lines [9].

8.3. DATA ACQUISITION, TRACEABILITY AND QUALITY SUPPORT

Manufacturing cyber-physical systems increasingly rely on integrated data acquisition and data management architectures to enable real-time monitoring, traceability, and informed decision-making [11]. In oil-filling operations, IT systems must reliably capture and store process parameters such as filling quantities, oil batch identifiers, environmental conditions, timestamps, and test results for each individual unit. These data are essential for quality assurance, root-cause analysis, and compliance with regulatory and audit requirements. Maintaining data integrity throughout the production lifecycle is critical. High-resolution, well-structured, and consistently linked production data significantly enhance process transparency, support continuous improvement initiatives, and strengthen safety and quality compliance [12].

Fig. 3. Author-developed human-machine interface configuration supporting oil-filling operations

8.4. USER INTERFACE AND HUMAN-MACHINE INTERACTION

Despite advanced automation, operators and maintenance staff regularly interact with IT-supported filling systems. A key challenge is providing sufficient training and intuitive interfaces to reduce input errors and misinterpretation of system messages. Poorly designed HMIs or inadequate training can limit the benefits of digitalization and increase the risk of filling defects. User-interface design strongly affects process reliability. HMIs should display filling parameters, system status, and alarms clearly and intuitively [13]. Ambiguous alarm messages or poor layouts may delay operator response and lead to incorrect manual actions [13]. Requirements include role-based access, clear visualization of process trends, and guided workflows supporting both normal operation and fault handling. Proper training and documentation remain essential for effective system use. A typical service interface example is the manual operation window, where component states are shown graphically. Authorized users can manually control system elements (e.g., valves and pumps) after switching from automatic to manual mode. Step-by-step manual control and an oil-draining mode should also be available. All manual actions must be logged. If no database is used for parameter setup, operators can use a manual override mode, which opens a window for entering heater volume and the air-cushion percentage. While the sequence is automated and supervised by a PLC, the dynamic display ensures transparency, situational awareness and allows for a quick response in case of a failure. The presence of the operator is necessary – the operator initiates the process, scans codes, and monitors the system to ensure compliance with process limits.

8.5. CONFIGURATION AND DATA MANAGEMENT

Authorized users shall be able to configure communication parameters, system thresholds, oil temperature compensation models, tank capacity limits, tolerance ranges, and logging behaviour. To ensure system flexibility, authorized users must have access to the following configuration layers:

- Communication Layer: PLC/Scanner port settings, baud rates, and database connection strings.
- Process Layer: Lance and reservoir volumes, temperature compensation coefficients, and air cushion thresholds.
- Quality Layer: Permissible upper and lower process deviations (tolerance limits) and alarm triggers (e.g., "Turn on boiler" threshold).
- Security Layer: User group permissions and access levels.

8.6. REPORTING AFTER COMPLETION

After each completed filling cycle, the system shall generate a result file containing the following minimum data: operator identification, date and time of operation, heater type and parameter source, measured process data, pass/fail result, detected defects and diagnostic messages, as well as alarm descriptions linked to specific automation components. Clear visual feedback indicating successful or unsuccessful completion of the filling process shall be provided also to the operator.

8.7. FAULT DETECTION AND PROCESS STABILIZATION

The system discussed has to include real-time detection of deviations from tolerance limits, comprehensive alarm and event logging, as well as continuous diagnostics for monitoring data integrity and automation components. Advanced IT systems increasingly incorporate trend analysis and condition monitoring to support early fault detection [14].

Empirical studies of Industry 4.0 implementations indicate that systematic analysis of process deviations and trends enables earlier detection of instability, equipment degradation, and quality risks in automated production environments [12]. Such predictive capabilities enable proactive maintenance and process adjustments, reducing scrap rates and unplanned downtime [14]. The integration of data analytics into filling control systems is therefore considered a key enabler of stable and resilient production processes in modern electric heater manufacturing. Timely alerts and diagnostic information allow maintenance and production teams to intervene before defects occur, reducing scrap rates and unplanned downtime.

9. CONCLUSION

The oil-filling stage in the manufacturing of electrical oil heaters constitutes a safety-critical and quality-critical operation whose stability directly affects product reliability, thermal performance, and compliance with regulatory requirements. Failures are often latent, appearing only after extended operation. Risks include insulation breakdown, overheating, leakage, and non-compliance with safety standards such as IEC 60335-2-30. This study has demonstrated that conventional process control approaches are insufficient to manage the combined risks arising from oil contamination, air entrapment, parameter variability, and increasing production complexity in automated manufacturing environments. The primary contribution of this work is the systematic formulation of IT system requirements dedicated to oil-filling operations, derived from industrial practice and structured along functional, integration, data management, and human-machine interaction dimensions. Unlike existing studies that address oil properties or filling phenomena only indirectly, this paper explicitly links process physics, automation logic, and IT system design within a unified manufacturing framework. The presented requirements formalize how PLC-based control, sensor data acquisition, parameter compensation models, and operator-oriented HMIs can be integrated to stabilize the oil-filling process, ensure traceability, and enable early detection of deviations. By treating the oil-filling station as a cyber-physical manufacturing system, the study highlights the role of IT not merely as a monitoring layer, but as an active enabler of process robustness and quality assurance. From a manufacturing engineering perspective, the results provide a reusable reference model for designing and evaluating IT-supported liquid filling processes in safety-relevant products. The proposed approach supports standardization, reduces operator-dependent variability, and strengthens the interaction between automation hardware, software architecture, and organizational procedures. As such, the findings contribute to the broader field of digitally enabled production systems and offer practical guidance for industrial implementation in electric heater manufacturing and related applications.

10. FUTURE WORK

Future research will focus on advancing the presented IT-supported oil-filling framework toward quantitative process optimization and adaptive control in industrial manufacturing environments. One key direction is the integration of data-driven methods for systematic analysis of process variability, enabling the identification of early indicators of instability such as sensor drift, valve wear, oil degradation, or deviations in air-cushion formation. Further work will investigate the development of digital twin models of the oil-filling process, combining physical process models with real-time production data. Such models will enable virtual commissioning, sensitivity analysis of filling parameters, and simulation of fault scenarios without interrupting production, thereby supporting more robust process design and validation. Another research direction concerns the formal integration of oil-filling IT systems with Manufacturing Execution Systems (MES) and quality management platforms. Standardized data models and interfaces will be explored to improve interoperability, traceability, and cross-line comparability in multi-product manufacturing environments. Finally, future studies will include experimental validation of the proposed IT requirements in an industrial production line, with a focus on measurable performance indicators such as process capability indices, defect rates, downtime reduction, and long-term system stability. These investigations will allow quantitative assessment of the impact of IT-supported oil-filling systems on manufacturing efficiency and product quality. Additionally, future research will explore transitioning from semi-automated operations to fully autonomous filling cells. By integrating robotic handling and advanced automated interlocks, the constant presence of an operator could be minimized, shifting the human role strictly to system activation, high-level supervision, and exceptional fault response.

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