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Overview of Monitoring Methods for Metalworking Fluids

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Abstract

The article presents a comprehensive review of current methodologies for monitoring the condition of metalworking fluids (MWFs) employed in machining operations. Emphasis is placed on physico-chemical, biological, and electrochemical assessment techniques, including the measurement of pH levels, concentration, contamination, microbial activity, electrical conductivity, and optical characteristics. Particular attention is devoted to the integration of automated and sensor-based monitoring systems capable of real-time data acquisition and analysis. The advantages, limitations, and applicability of these methods within the framework of modern digital and automated manufacturing environments are critically examined. The findings underscore the importance of adopting a multidisciplinary and systematic approach to MWF quality control in order to enhance process efficiency, ensure production stability, and extend the service life of fluids.

Keywords: metalworking fluids (mwfs); condition monitoring; cutting fluid quality; ph measurement; contamination detection; bacterial contamination; sensor technologies; real-time diagnostics; machining processes; smart manufacturing.

Introduction

Metalworking fluids (MWFs) are indispensable to modern machining and metal-forming operations. Their multi-component formulations provide rapid heat dissipation, reduce friction coefficients, suppress corrosion on freshly machined surfaces, and facilitate chip evacuation from the cutting zone. Yet the harsh service environment-characterised by elevated temperatures, pressures, and continuous exposure to air and workpiece debris-accelerates the physical, chemical, and biological degradation of MWFs. Undetected shifts in concentration, pH, particulate load, or microbial activity can quickly erode surface integrity, shorten tool life, increase unplanned downtime, and exacerbate environmental risks.

As industry embraces the paradigms of smart and zero-defect manufacturing [1], [2], the demand for reliable, highly sensitive, and preferably real-time monitoring of coolant condition has intensified. Over the past two decades, researchers have proposed a broad spectrum of approaches, ranging from classical titrimetric and refractometric assays to integrated cyber-physical platforms that blend spectroscopy, electrochemistry, ultrasonics, and machine-learning analytics. Despite promising laboratory results, widespread industrial adoption still faces hurdles such as sensor fouling, frequent recalibration, lack of harmonised standards, and significant capital investment.

This article aims to systematise existing methods for monitoring metalworking-fluid quality, critically evaluate their advantages and limitations within digital-manufacturing environments, and outline future directions for sensor technologies and data-analysis frameworks capable of enabling predictive maintenance and extended coolant life cycles.

1. Classification and functions of metalworking fluids (MWFs)

Metalworking fluids (MWFs) are an indispensable element of most metal cutting and forming technologies. Their multi-component formulations simultaneously address several critical tasks: efficient dissipation of heat from the cutting zone, reduction of friction between the tool and the workpiece, removal of chips, prevention of surface corrosion, and enhancement of dimensional stability in machined parts. As cutting speeds increase, surface-quality requirements tighten, and the range of difficult-to-machine materials expands, the performance demands placed on MWFs have risen correspondingly. Modern fluids must exhibit high thermo-oxidative stability, resistance to microbial growth, compatibility with automated delivery systems, and full compliance with environmental and occupational-safety regulations.

Given the diversity of functions they perform and the variety of operating conditions they face, several fundamentally different classes of MWFs have emerged-from neat mineral and synthetic oils to aqueous solutions and hybrid cryogenic systems. Each group has its own advantages and limitations that define its optimal field of application. The following section provides a structured classification of contemporary metalworking fluids, outlining their typical compositions, key characteristics, and characteristic areas of use, followed by a consolidated list of the core functions they fulfil in industrial machining processes.

Table 1. The classification of metalworking fluids

Main Group	Typical Sub-groups	Key Features	Typical Applications
Neat oils	• Mineral • Refined paraffinic • Vegetable / bio-based oils	• 100 % oil, non-miscible with water • Maximum film strength • High viscosity & thermal conductivity	Slow cutting, deep drilling, threading
Soluble oils (macro-emulsions)	• Mineral emulsions 50–80 % oil + surfactants • Bio-emulsions	• Milky macro-emulsion at 5–10 % in water • Balanced cooling and lubrication	General turning/milling, sawing
Semi-synthetic (micro-emulsions)	• 5–30 % oil dispersed in synthetic matrix	• Transparent micro-emulsion • Enhanced cooling, less foam/odor	High-speed milling, grinding
Synthetic aqueous solutions	• Poly-glycols, borates, phosphates • HWCF	• Clear, oil-free solutions • Maximum heat removal, fire-safe	High-speed grinding, high-pressure die casting
Special / hybrid	• Pastes & gels, MQL mists • Cryogenic (N_2, CO_2) • Ionic liquids	• Minimal consumption • Eco-friendly, localized cooling	Micro-machining, aerospace, hard-to-cut alloys

In summary, the spectrum of metalworking fluids spans from oil-rich neat formulations to fully synthetic, water-based, and even cryogenic systems-each engineered to balance lubrication, cooling, cleanliness, and environmental performance under specific machining scenarios. Selecting the most appropriate fluid therefore requires a holistic evaluation of work-piece material, cutting parameters, tool metallurgy, downstream surface requirements, and regulatory constraints. Continuous advances in additive chemistry, bio-derived base stocks, and minimal-quantity lubrication (MQL) are further widening the toolbox available to process engineers, enabling both higher productivity and lower ecological impact.

Yet, as fluid chemistries become more sophisticated, so too does the need for rigorous monitoring and maintenance practices. Real-time sensing of concentration, pH, microbial activity, and wear metals is rapidly moving from laboratory settings onto the shop floor, supporting predictive maintenance strategies and extending fluid life cycles. Looking ahead, the convergence of smart sensors, data analytics, and environmentally benign formulations is expected to reshape the role of metalworking fluids-from a consumable production aid to an integral, digitally managed component of advanced manufacturing systems.

2. Methods of monitoring metalworking fluids

Main Approaches to Monitoring Metalworking Fluids (MWFs):

1) Comprehensive Analysis of MWF Composition:

Chemical control involves determining the concentration of active components (surfactants, corrosion inhibitors, and biocides), pH levels, as well as quantifying the presence of organic and inorganic contaminants.

Physical control includes measurements of viscosity, density, surface tension, and other parameters that influence the lubricating and cooling performance of the fluid.

2) Assessment of Fluid Contamination:

Control of mechanical impurities is performed using filtration systems and includes the detection and removal of solid particles, metal chips, and abrasive residues.

Microbiological control is carried out using bacteriological methods to determine the quantity of microorganisms (bacteria, molds, etc.) that may cause biodegradation of the fluid. These procedures are regulated by relevant industrial standards and methodologies.

3) Adjustment of Emulsion Concentration

Adjustment of the fluid composition is based on continuous monitoring data, enabling the maintenance of optimal ratios between concentrate and water, depending on material properties, machining conditions, and processing parameters.

To ensure a systematic control approach, it is advisable to implement a regulated monitoring schedule:

Daily monitoring includes visual assessment of the emulsion (color, transparency, foaming) and temperature measurement.

Weekly monitoring includes pH measurement, concentration determination (using refractometric methods), and analysis of mechanical impurities.

Monthly monitoring includes a complete chemical analysis, microbiological testing (in accordance with GOST 9.060–75), and diagnostics of filtration equipment.

A systematic approach to monitoring the operational characteristics of MWFs significantly improves the quality of machined parts, reduces maintenance costs, extends the service life of working emulsions, and minimizes environmental risks associated with their disposal.

Effective MWF monitoring contributes to prolonged equipment lifespan, improved machining quality, and reduced operational expenses at the enterprise level.

One of the most widely used and accessible techniques for MWF condition monitoring is refractometry, performed using refractometers. This method is based on the measurement of the refractive index and its derivative parameters. It is widely used in industrial settings for chemical identification, quantitative and structural analysis, and the determination of physicochemical properties of substances.

A refractometer measures the refraction of light in a fluid, typically expressed in degrees Brix (°Bx), which represents the mass fraction of dissolved solids in a liquid.

The term "refractometer" originates from the Latin word refractus ("bent"), introduced into scientific use by Isaac Newton in the early 18th century. The device evaluates the deviation of light from a straight path when it passes between substances with different optical densities. The ratio of the angle of incidence to the angle of refraction is referred to as the refractive index.

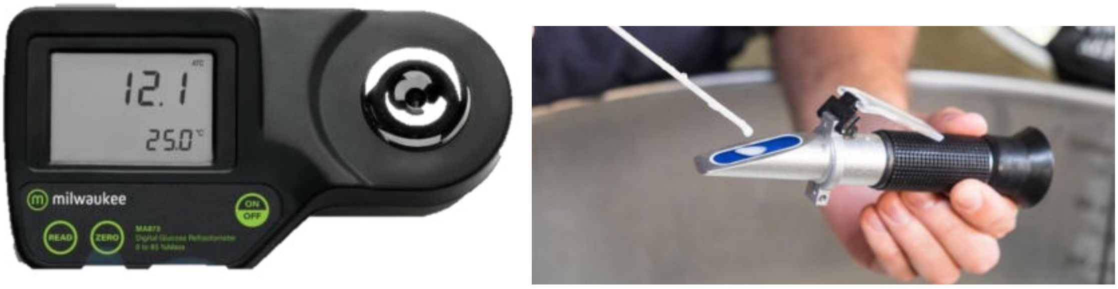

Fig.1. – Refractometer

This value increases proportionally with the fluid's density. The refractometer measures this relative to distilled water, which is used for calibration.

Refractometry (from Latin refractus - 'bent' and Ancient Greek μετρέω - 'to measure') is an analytical method based on the determination of the refractive index (coefficient of refraction) and its related functions. The refractometric method is widely used for the identification of chemical compounds, quantitative and structural analysis, and the determination of the physicochemical properties of substances.

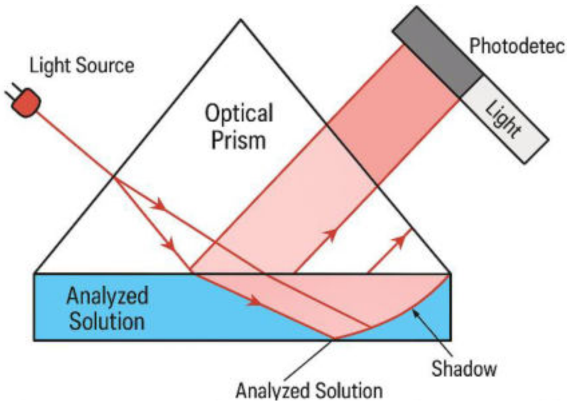

Fig.2. – The operating principle of a refractometer

The relative refractive index n is defined as the ratio of the speed of light in two adjoining media. For liquids and solids, n is typically measured relative to air, while for gases, it is measured relative to vacuum (absolute refractive index).

The value of n depends on the wavelength λ of light and temperature, which are indicated in the subscript and superscript, respectively. For example, the refractive index at 20 °C for the D-line of the sodium spectrum (λ = 589 nm) is written as n_D^{20}. Other commonly used spectral lines include the hydrogen H-line (λ = 656 nm) and F-line (λ = 486 nm).

In the case of gases, the dependence of n on pressure must also be considered, with values either specified or normalized to standard pressure conditions.

In ideal systems (formed without changes in volume or polarizability of components), the dependence of the refractive index on composition is approximately linear when composition is expressed in volume fractions (percentages):

$$n = n_1V_1 + n_2V_2, \tag{1}$$

where n - is the refractive index of the mixture,

n_1 and n_2 - are the refractive indices of the individual components,

V_1 and V_2 - are their respective volume fractions ($V_1 + V_2 = 1$).

The refractometer analyzes the degree to which a light beam deviates from a straight-line path when transitioning from one substance to another. The ratio between the angle of incidence and the angle of refraction at the boundary between two media is referred to as the refractive index. This index increases proportionally with the density of the substance. The relative "weight" of a sample is determined by the refractometer in comparison with distilled water, which is used for preliminary calibration of the instrument.

Refractometry, performed using refractometers, is one of the most widely used methods for the identification of chemical compounds, quantitative and structural analysis, and the determination of physicochemical properties of substances.

The condition of metalworking fluids (MWFs) is also monitored by assessing their acidity levels. Over time, the pH value of the emulsion may decrease due to microbiological activity, such as the growth of fungi and bacteria, which leads to the formation of acids. A pH drop below acceptable limits indicates significant bacterial contamination and necessitates either fluid replacement or the implementation of regeneration measures. Under standard operating conditions, the pH level should remain within the range of 8.5 to 9.5.

To assess the degree of microbiological contamination in MWFs, dip slides are widely used—special indicator devices that allow for visual determination of fungal and bacterial concentrations in the fluid. To obtain reliable results, it is essential to strictly follow the application procedure provided in the manufacturer's instructions.

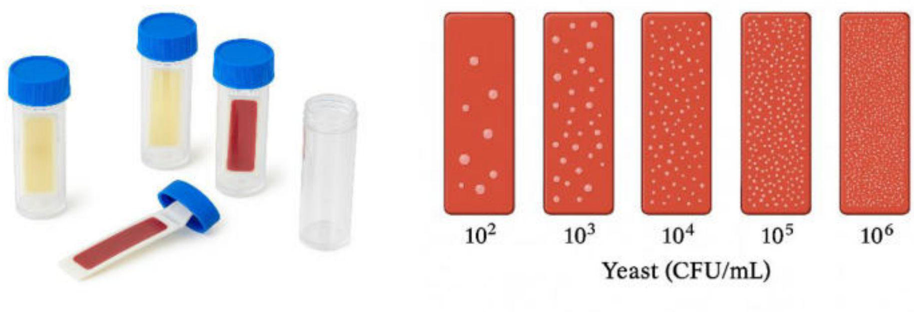

Fig.3. – The dip slides

This issue is also relevant at the global level, and several modern methods for monitoring the quality of metalworking fluids (MWFs) have been proposed to date.

3. Review of the latest metalworking fluid monitoring systems

Many articles on this topic have been analyzed, and we will consider the main scientific directions. Over the last two decades the scientific community has proposed a rich palette of monitoring concepts – from classical titration and refractometry to advanced multi-sensor cyber-physical platforms.

1. Spectroscopic techniques

Optical spectroscopy has evolved into a versatile tool for rapid, non-destructive assessment of MWF quality. Kiefer et al. employed visible and near-infrared (NIR) absorbance signatures to quantify oil concentration and detect emulsion ageing in commercial fluids [3]. Their calibration models ($R^2 > 0.95$) demonstrated that multispectral data outperform single-wavelength refractometry when tramp oils or hard-water salts interfere with refractive index. other researchers expanded this concept by integrating fibre-optic probes directly into machine-tool sumps, enabling continuous spectral acquisition at 1-minute intervals [4]. The authors reported a detection limit of 0.1 % (v/v) for mineral-oil fraction and proposed a rule-based algorithm for coolant make-up control.

Long-path transmission spectroscopy was adopted by another group of researchers to monitor droplet coalescence during accelerated thermal ageing tests [5]. A broadening of the 600 nm peak served as an early indicator (48 h advance) of phase separation. In a complementary study, Schandl et al. embedded a USB-based miniature spectrometer inside a machining centre and successfully tracked concentration fluctuations caused by high-pressure coolant delivery [6]. A fluorescence-based variant was proposed by another study, who exploited native fluorophores (long-chain amides, antimicrobial dyes) for contamination detection; the spectral shift at 350 nm correlated logarithmically with bacterial count [7].

Recent study demonstrated that inline NIR spectroscopy can close the loop in automatic dosing systems; when concentration deviated by ±0.5 % the pump response time was <30 s, maintaining surface finish within Ra 0.8 µm [8]. a group of authors introduced an indirect spectro-thermographic approach: by capturing infrared thermograms of a falling film they reconstructed apparent viscosity maps which agreed with rotational-rheometer data within 6 % [9]. research conducted miniaturised the optical path in a microfluidic chip (total volume 30 µL) suitable for point-of-use analysis on shop-floor carts [10].

Collectively, these works underscore the sensitivity of optical observables – absorbance, fluorescence, NIR overtones and mid-IR fingerprints – to multiple degradation modes (oil depletion, emulsifier breakdown, microbial metabolites). Remaining challenges include light-scattering by swarf, temperature compensation, and standardisation across fluid chemistries.

2. Electrochemical and impedance methods

Electrochemical impedance spectroscopy (EIS) has gained momentum as a multi-parameter probe. investigators established a three-electrode flow-cell that simultaneously predicts droplet size, pH and concentration through radial basis function regression of magnitude-phase spectra [11]. Their root-mean-square error for pH was 0.08 over the industrial range 7–10. Riaz et al. designed thick-film RuO_2 transducers whose open-circuit potential varies quasi-Nernstian with hydrogen ion activity, enabling affordable in-situ pH tracking under high ionic strength [12].

Researchers advanced the concept by fabricating an interdigitated micro-electrode printed on ceramic; the 1 kHz impedance modulus increased linearly with emulsifier depletion ($R^2 = 0.93$) and was robust against tramp-oil fouling [13]. a study tackled chemical by-products: they quantified nitrite accumulation (a corrosion indicator) via square-wave voltammetry with a detection limit of 0.3 mg L^{-1} [14]. The study recommends a 500 mg L^{-1} alarm threshold to mitigate ferritic pitting of machine beds.

Recent investigation merged EIS hardware with machine-learning analytics. Using a dataset of 14 000 spectra they trained a gradient-boosting model that classified coolant age into four maintenance states with 95 % accuracy [15]. The authors emphasise that data-driven techniques compensate for fluid-to-fluid variability and sensor drift. Ultrasonic monitoring, though not electrochemical, also relies on propagation impedance: authors related attenuation coefficients at 5 MHz to solid particle loading (1–50 g L^{-1}) with a 3 g L^{-1} standard error [16].

3. Microbiological assessment

Metalworking fluids have a negative impact on human health [17], [18]; therefore, special attention is given to the control of biological contamination. Unchecked microbial proliferation degrades lubricant efficacy and poses occupational hazards. early studies pioneered culture-based field surveys linking sump colony counts (>10^6 CFU mL^{-1}) to aerosol mist exposure [19]. authors synthesised 60 years of microbiology literature and identified Pseudomonas, Mycobacterium and Candida as dominant taxa in semi-synthetic emulsions [20]. Their review recommends dip-slide screening every 72 h, corroborating earlier ATP bioluminescence work by previous research; the latter reduced test time from 48 h incubation to 5 min swab-to-result [21].

An investigation introduced optical coherence tomography (OCT) to visualise biofilm formation on transparent coupons immersed in coolant; OCT intensity contrasted biofilm thickness with 2 µm depth resolution, triggering sanitisation before biomass exceeded 100 µm [22]. Shen et al. combined fluorescence excitation-emission matrices (EEM) with HPLC to fingerprint dissolved organic matter produced by bacteria, isolating tryptophan-like signals as early spoilage markers [23]. Valuated a novel heterocyclic biocide in 12 industrial sites; microbial counts dropped by three orders of magnitude within 24 h and remained suppressed for four weeks [24].

Researchers broadened the scope to environmental risk, reviewing ISO 14852 and OECD 301 protocols for assessing biodegradability and eco-toxicity of new coolant chemistries [25]. Documented metal leaching (Zn, Fe, Cr) into fresh and used fluids, underscoring the complex interaction between microbiology, corrosion inhibitors and worker dermatitis [26].

4. Physical stability and functional performance

The physical integrity of oil-in-water emulsions is a prerequisite for chip evacuation and thermoregulation. Glasse et al. utilised turbidity spectra (400–900 nm) to determine creaming index; phase inversion was predicted when absorbance at 750 nm exceeded 1.2 AU [27]. earlier researchers provided a macroscopic perspective, coupling tribometer tests with frictional power analysis to link lubricant depletion to tool flank wear, thereby translating laboratory metrics into production economics [28].

Scientists (spectroscopic sensor) and other researchers (automatic titration) both investigated the impact of replenishment strategies on kinematic viscosity and surface tension, whereas research findings demonstrated that inline refractometer feedback prevents under-dilution events that would raise cutting temperature by 40 °C [29]. Infrared thermography by a group of authors further revealed that a 10 % viscosity rise elevated the thermal boundary layer thickness, reducing convective heat transfer coefficients by 12 % [9].

5. Cyber-physical and IIoT integration

Also an Arduino-based prototype was described, combining refractometer, temperature, flow and conductivity sensors; MQTT messaging transmitted data to a cloud dashboard for rule-based alerts [30]. Scientists expanded the architecture to OPC-UA and edge analytics for latency-critical tasks such as pump actuation [31]. Their pilot reduced fluid consumption by 18 % over eight months. research in manufacturing framed coolant monitoring within a zero-defect manufacturing roadmap: sensor fusion, cyber-twins and predictive maintenance loops enabled a 25 % scrap reduction in automotive cylinder-head machining [32].

A recent study as well as a recent investigation (machine learning) illustrate convergence between process control and chemical diagnostics, while research conducted highlight the trend toward miniaturisation for decentralised sampling. Collectively, sources [6], [15], [8], [10] and [32] emphasise the need for open ontologies and standard data models to ensure interoperability.

6. Ultrasonic monitoring

Ultrasound is also employed for monitoring the quality of metalworking fluids, and several up-to-date techniques have been identified. Recent literature highlights three complementary ultrasonic-based strategies for assessing and maintaining metalworking-fluid quality.

Attenuation-based ultrasonic monitoring employs a broadband 5 MHz transducer placed in a flow-through cell; the amplitude decay of the acoustic signal increases quasi-linearly with the volumetric concentration of solid debris between 1 and 50 g L^{-1}, enabling continuous estimation of particle loading without sampling [33]. The method is attractive for its in-line configuration, immunity to oil-content fluctuations and low capital cost, yet its accuracy deteriorates below ≈ 5 g L^{-1}, sensor faces are prone to fouling and the reading must be temperature-compensated.

A second line of research couples fluorescence spectroscopy with ultrasonic stirring to monitor organic contamination. Here, ultrasound is used only to homogenise the coolant and stabilise the optical signal, while the diagnostic variable is the fluorescence intensity of native dye or biocide molecules that correlates with bacterial proliferation and tramp-oil ingress [34]. The approach offers sub-second response and multi-parameter calibration for pH and concentration, but it relies on the presence of a stable fluorophore, is sensitive to light-absorbing impurities and generally involves higher instrument costs than purely acoustic probes.

Ultrasonic cleaning with concurrent turbidity sensing combines high-power cavitation (20–40 kHz) to detach metallic fines from the recirculating coolant with real-time monitoring of the resulting turbidity change as an index of cleaning efficiency [35]. Integrating regeneration and diagnosis in a single loop prolongs fluid life and reduces manual filtration; however, sustained cavitation increases power consumption, may destabilise emulsifiers if over-driven, and requires cavitation-resistant tank materials.

Collectively, the attenuation approach [33] is best suited for tracking solid particulate levels, fluorescence monitoring [34] excels at detecting organic and microbiological spoilage, whereas the cavitation-based system [35] provides a holistic “clean-and-measure” solution. Selection among these techniques should therefore be guided by the dominant failure mode of the coolant, permissible energy budget and instrumentation constraints of the target manufacturing environment. Besides monitoring the quality of metalworking fluids, ultrasound is widely applied in many other fields, where it has proven highly effective [36 - 38].

Conclusions

The reviewed literature evidences a vibrant research landscape moving from periodic laboratory tests toward real-time, in-machine intelligence. Spectroscopic methods dominate due to versatility, but electrochemical and acoustic probes provide complementary selectivity, especially for chemical by-products and particulate fouling. Microbiological diagnostics have benefited from optical and biochemical accelerations, yet incubation-free quantitation remains an open frontier.

Despite promising prototypes, industrial uptake lags behind. Key barriers include sensor fouling, fluid-specific calibration, proprietary communication protocols and unclear cost-benefit justification. Future work should prioritise: harmonised performance benchmarks, adaptive machine-learning models transferable across fluid chemistries, self-cleaning or disposable sensor architectures, and cybersecurity of cloud-connected monitoring platforms. Cross-disciplinary collaboration between mechanical engineers, analytical chemists, microbiologists and data scientists will be essential to unlock the full potential of smart metalworking fluids management.

Pilot trials under real production conditions will be crucial to demonstrate sensor durability and data fidelity over extended machining cycles. Robust economic models that link continuous monitoring data to tangible savings—through reduced fluid consumption, lower tool wear and minimized downtime - can help solidify management buy-in. Standardisation bodies and industry consortia should work together to define clear protocols for sensor interoperability, data encryption and quality assurance. Advances in bio-inspired coatings and novel miniaturised electronics offer promising routes toward self-healing, auto-calibrating probes that require minimal maintenance. Finally, building open-source software platforms and shared data repositories will accelerate innovation, lower entry barriers for small and medium-sized enterprises, and drive widespread adoption of smart MWF monitoring systems.

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