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Design and Optimization of an Enhanced Ultrasonic Rifle Cleaning Machine Gunguard Ultra with Self-Draining, Thermal Balancing and Even Cleaning

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Abstract

Ultrasonic cleaning has become a preferred approach for removing carbonaceous fouling and metallic residues from firearm components because it can reach complex geometries without mechanical abrasion. Nonetheless, commercially available small-to-medium ultrasonic cleaners were not engineered for defence-grade throughput and repeatability. Typical 22 L class cleaners suffer from spatially uneven cavitation, thermal stratification, and reliance on aggressive chemicals paired with manual maintenance, which together produce inconsistent results and high operational costs. This paper presents the engineering design and validation plan for Gunguard Ultra, an ultrasonic rifle cleaning machine specifically developed to address these issues. The system integrates a phase-modulated, multi-frequency transducer array; rotating and reciprocating fixturing with through-bore purge; zonal heating with controlled low-shear circulation; inline solids separation and magnetic filtration; and an automated drain/flush/regeneration routine controlled by turbidity/conductivity thresholds. A rigorous test program—combining acoustic finite element modeling, thermal CFD, hydrophone mapping, and a fractional factorial DOE—is proposed to demonstrate targets of ≥95% cleaning across bore length in ≤10 minutes, ±2 °C thermal uniformity, bath life ≥5× baseline, and preserved surface integrity. The design also discusses operational integration for specific weapon platforms (AK-47, INSAS, AR-platform rifles, and bolt-action sniper rifles), safety, environmental controls, and an economic assessment that supports adoption in high-usage armouries.

Keywords: **ultrasonic cleaning, cavitation uniformity, thermal balancing, self-draining, rifle maintenance, transducer array, hydrophone mapping.**

1. INTRODUCTION

Firearms maintenance is a fundamental activity in defence, law enforcement, and precision shooting communities. Fouling—arising from burnt propellant residues, lead, copper, and carbon—diminishes accuracy, interferes with gas systems and extraction, and accelerates component wear. Manual cleaning methods, including brushes and solvents, remain widespread but are operator-dependent, time-consuming, and sometimes damaging to finishes. Ultrasonic cleaning offers a non-contact mechanism where cavitation events dislodge contaminants even in occluded geometries such as rifling grooves, chamber shoulders, and gas ports. When the process is properly controlled, it enables repeatable cleaning without abrasive action.

However, many commercially available ultrasonic cleaners are adapted from jewellery and laboratory markets and lack the system-level design necessary for rifle maintenance at scale. Primary shortcomings include uneven cavitation fields that leave localized residues, heater configurations that produce thermal stratification and degrade consistency, and dependence on strong solvents and frequent bath replacement. These limitations are particularly problematic in high-tempo armoury contexts where throughput, repeatability, safety, and regulatory compliance are critical.

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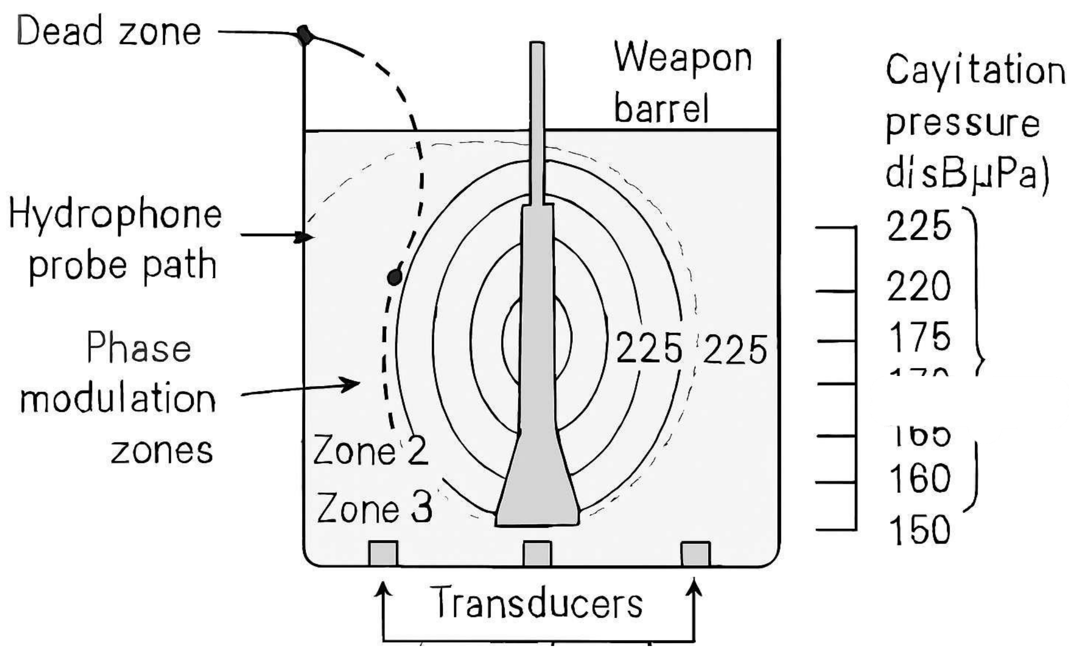

Figure 1. It is showing the combinations of drive modes, rotation, purge settings, temperature levels, and surfactant concentrations, along with the key response metrics like residue removal, hydrophone pressure CV, and surface integrity.

Gunguard Ultra is conceived to fill this gap by addressing acoustic, thermal, mechanical, and maintenance subsystems simultaneously. Its objective is to provide armouries and field maintenance teams with a robust, repeatable, low-maintenance cleaning platform engineered specifically for small arms—optimizing cleaning effectiveness while minimizing chemical exposure and maintenance labour.

2. BACKGROUND AND LITERATURE REVIEW

Ultrasonic cleaning leverages alternating pressure fields to nucleate and collapse microbubbles in a liquid, producing localized microjets and shockwaves that mechanically disrupt contaminants attached to surfaces. The strength and spatial distribution of cavitation depend on acoustic pressure amplitude, frequency, liquid properties (viscosity, vapor pressure), temperature, dissolved gas content, and the geometry of the tank and parts present. Lower frequencies (≈20–40 kHz) generate larger cavitation events suitable for bulk removal of heavy debris, while higher frequencies (>80 kHz) produce more numerous smaller events that can remove fine residues with less risk of surface erosion.

Acoustic field shaping has been actively studied in industrial ultrasonics. Distributed transducer arrays, deliberate phase offsets, frequency sweeping, and multi-frequency operation are proven strategies to reduce standing wave patterns and mitigate dead zones. Mechanical motion (rotation and axial translation) and induced through-part flow additionally improve exposure of all surfaces and assist in purging trapped gasesâ€”especially critical for long bores where air pockets become persistent obstacles. Temperature is another key lever: moderate heating reduces fluid viscosity and vapor pressure, which can lower the cavitation threshold and accelerate contaminant removal. However, non-uniform heating creates gradients that produce location-dependent cavitation behaviour and hence inconsistent cleaning. Literature supports the use of zonal heating combined with controlled low-shear circulation to homogenize temperature without significantly damping cavitation during the active cleaning phase. Regarding chemistry and bath maintenance, aggressive caustic cleaners and organic solvents can improve removal of metal fouling but introduce significant operator hazards and waste management challenges. Recent research emphasizes solvent minimization through the use of biodegradable surfactants at low concentrations, combined with mechanical and acoustic optimization. Inline filtration, centrifugation, and magnetic traps are established approaches for extending bath life, and automated drain/regeneration routines significantly reduce operator maintenance burden and contamination risk. In defence contexts, compliance with waste disposal regulations and limiting volatile organic compounds (VOCs) are especially important.

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3. PROBLEM STATEMENT AND OBJECTIVES

When conventional commercial ultrasonic cleaners—typified by a 22 L tank, single-frequency transducers, and base heating—are tasked with firearm maintenance, three major deficiencies become operationally limiting. First, acoustic non-uniformity manifests as dead zones inside long bores and chamber areas where standing waves and lack of direct coupling prevent adequate cavitation. This results in partial cleaning and necessitates manual brushing or repeated cycles. Second, thermal non-uniformity arises from heater placement and inadequate circulation, causing spatial variations in cavitation thresholds and inconsistent process performance. Third, the reliance on aggressive solvent chemistries, combined with the absence of automated maintenance features such as continuous filtration or auto-drain, creates environmental, safety and lifecycle cost problems.

The objectives for Gunguard Ultra are therefore to: (1) achieve consistent cleaning across full bore lengths and complex geometries with a target of ≥95% residue removal within a 10-minute cycle under standard presets, (2) maintain bath thermal uniformity within ±2 °C across the active cleaning zone, (3) minimize solvent usage by enabling aqueous surfactant operation at
≤500 ppm while preserving cleaning efficacy ≥90% of solvent baselines, and (4) extend usable bath life by at least fivefold via inline solids separation and automated drain/regeneration routines.

These objectives are framed to be measurable and verifiable by hydrophone mapping, image- based residue quantification, ICP metal analysis, thermal logging, and bath contamination metrics (turbidity and conductivity).

4. SYSTEM DESIGN — GUNGUARD ULTRA

Gunguard Ultra's system architecture integrates multiple engineered subsystems to address acoustic uniformity, thermal balance, mechanical fixturing, filtration and automated maintenance. The design is intended to optimize cavitation exposure while preserving surface integrity and ensuring operator safety.

4.1 Mechanical and Structural Layout

The cleaning tank is fabricated from AISI 316L stainless steel for corrosion resistance and to meet defence hygiene standards. Reinforcing ribs and an acoustic isolation mount minimize external vibration transmission and improve transducer coupling. The tank volume is chosen between 25–28 L to provide sufficient headspace for diverse weapon fixtures while maintaining acoustic energy density. A robust lid with mechanical interlock and a sealed viewing port enables safe operation and observation during runs.

Fixtures are modular and ergonomic. A rotating cradle with a stepper motor provides controlled slow rotation (0–5 RPM) and optional low-amplitude axial reciprocation to ensure every segment of rifling is exposed to active cavitation. Quick-connect plumbing interfaces enable through-bore purge for barrels and allow rapid swapping between weapon families.

4.2 Acoustic Subsystem

The acoustic subsystem uses a distributed multi-frequency transducer array consisting of low- frequency (30–40 kHz) high-power modules for bulk removal and mid/high-frequency (80– 120 kHz) modules for micro-scale residue removal. Transducers are arranged on both long sides and the base to create overlapping acoustic fields. Each transducer is mounted in a potted replaceable cartridge to improve serviceability and protect against delamination.

Drive electronics provide independent channel control, allowing several drive modes: single frequency, dual-frequency simultaneous operation, frequency sweep, and phase-modulated sequences. Phase modulation—small intentional phase offsets between groups—breaks standing wave patterns and promotes a more uniform pressure field. The drives include current and temperature monitoring for each channel and an auto-tune routine that adjusts amplitude and frequency for optimal coupling depending on bath loading.

4.3 Thermal Management and Circulation

To eliminate base-only heater stratification, the system employs zonal heating with multiple heater elements positioned around the tank perimeter and a midplane manifold. Each heater zone is controlled with a PID loop using dedicated thermocouples to maintain ±2 °C uniformity within the active cleaning volume. A low-shear circulation pump draws fluid through baffles and a heat exchange manifold, operating in a time-sequenced manner to preserve cavitation efficacy: circulate (homogenize) → settle (acoustic steadiness) → ultrasonic active (clean). Carefully designed manifolds minimize flow rates near the parts during active cavitation to avoid suppression of bubble activity.

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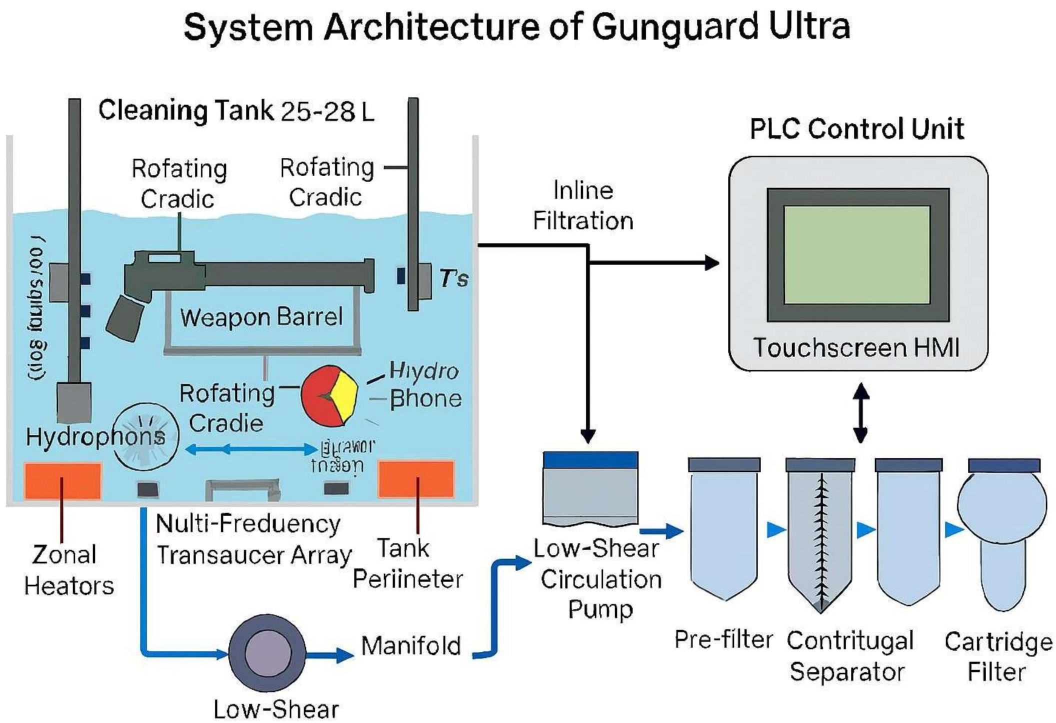

Figure 2 System Architecture of Gunguard Ultra

4.4 Filtration, Solids Handling and Auto-Drain

Filtration is a multi-stage process. A course prefilter captures large particulates, a centrifugal separator removes dense metal filings and sludges, and a cartridge filter provides sub-micron particulate capture. A magnetic trap upstream collects ferrous fines, preventing premature cartridge clogging. Turbidity and conductivity sensors monitor bath contamination and trigger an automated drain and flush routine when thresholds are exceeded. The automated drain sequence includes draining into a settling tank, controlled fresh water rinse with a short ultrasonic flush, and a passive or forced drying phase using heat. Collected sludge is stored in a sealed container for compliant disposal.

4.5 Control Architecture and Instrumentation

A PLC hosts cleaning recipes, monitors sensors, logs data, and provides a touchscreen HMI. Recipe presets for common weapon families (pistols, carbines, rifles, bolt-action rifles) simplify operator workflows. Hydrophone ports allow commissioning acoustic mapping without disassembling the system. Instrumentation includes hydrophones (20–200 kHz) for pressure mapping, Type K thermocouples at multiple axial and radial locations, turbidity and conductivity probes, flow sensors, and current monitors for each transducer channel. Safety features include lid interlock, earth leakage detection, emergency stop, and venting for any volatile emissions.

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5. MODELING AND SIMULATION

Successful implementation requires validated predictions of acoustic and thermal behaviours. Acoustic finite element analysis (FEA) is used to model pressure fields for candidate transducer placements and drive strategies. The models incorporate tank geometry, material acoustic impedances, fluid properties, and the presence of a cylindrical bore as a perturbation within the fluid domain. Simulations compare single-frequency operation against dual-frequency and phase-modulated patterns, optimizing transducer groupings to minimize spatial pressure variance along the bore axis.

Direct microbubble dynamics models are computationally expensive; therefore, predicted acoustic pressure fields are combined with empirical cavitation threshold models—based on fluid properties and temperature—to estimate cavitation active regions. Regions below threshold can be addressed by adding transducer elements, increasing local drive amplitude for a transient period, or using mechanical motion to shift nodes.

Thermal CFD evaluates zonal heater placement, circulation manifold geometry, and heating power requirements to achieve the ±2 °C uniformity target without flows that suppress cavitation. Structural finite element analyses verify tank integrity under cyclic thermal loading and transducer vibration; transducer mounts are designed to decouple undesirable structural resonances while preserving acoustic energy transfer efficiency.

6. PROTOTYPE FABRICATION AND INSTRUMENTATION PLAN

The prototype stage fabricates a single instrumented unit using the described mechanical and acoustic design. Transducer cartridges are assembled and potted off-line; each module includes a temperature sensor and current tap. The tank is laser-cut, welded, and passivated to ensure corrosion resistance. The control cabinet contains the multi-channel amplifiers, PLC, HMI, power distribution, and safety relays.

Instrumentation for prototype testing includes a hydrophone probe capable of measuring pressure amplitude across frequencies from 20 kHz to 200 kHz, an array of thermocouples at least six in number across the active volume, turbidity and conductivity sensors, flow meters, and a high-resolution power logger. A bore hydrophone probe is designed to traverse through test barrels, providing axial acoustic profiles. The data acquisition system synchronizes sensor streams and logs at rates appropriate for each variable (1 Hz for slow thermal/turbidity data, higher burst rates for acoustic characterization during commissioning).

7. EXPERIMENTAL METHODOLOGY AND TEST MATRIX

A rigorous experimental campaign is designed to correlate acoustic field properties and thermal uniformity with cleaning performance across representative fouling scenarios. Test barrels are standardized to consistent alloy, finish, and rifling and are fouled using controlled firing sequences (to generate realistic carbon and metal fouling) or chemical deposition protocols for copper/lead layers where firing is impractical. Test specimens include barrels up to 900 mm in length, bolt carriers, gas blocks, and other critical parts.

The DOE includes the following primary factors: drive mode (multi-frequency phase- modulated vs single-frequency baseline), rotation (on/off), through-bore purge (on/off), temperature setpoint (40 °C, 50 °C, 60 °C), and surfactant concentration (0, 200, 500 ppm). A fractional factorial design limits experimental runs while enabling estimation of main effects and two-way interactions. Each condition is replicated five times to provide statistical confidence. Responses include % area residue removal (from calibrated image analysis), ICP quantification of dissolved metals in bath samples, profilometry (ΔRa) for surface integrity, hydrophone pressure CV along the bore, energy consumption per cycle, turbidity change, and bath contamination trajectory.

Measurement techniques include high-resolution photography of bore cross sections with automated segmentation to compute percentage cleaned, ICP-OES for dissolved metal quantification, optical and stylus profilometry for roughness analysis, and hydrophone mapping with axial traverses to create pressure profiles. Turbidity and conductivity monitoring provide real-time contamination indices used to evaluate the effectiveness of inline filtration and to set automated drain thresholds.

Acceptance criteria are pre-defined: ≥95% residue removal along bore length under recommended preset within ≤10 minutes; acoustic CV ≤±10% across bore axis; thermal uniformity ±2 °C; bath life increased ≥5× compared to baseline; and no evidence of pitting or unacceptable surface roughness changes post-cleaning.

8. EXPECTED PERFORMANCE, DATA ANALYSIS AND STATISTICAL TREATMENT

Based on acoustic modeling and literature precedent, it is expected that a phase-modulated multi-frequency drive combined with timed rotation and through-bore purge will substantially reduce acoustic dead zones and produce a near uniform pressure field (target CV ≤±10%). Zonal heating with low-shear circulation conducted in a circulate-settle-clean sequence is predicted to keep the active zone temperature within ±1–2 °C. These mechanical and acoustic optimizations, when combined with a low-ppm biodegradable surfactant, should achieve cleaning efficiencies approaching solvent baselines (≥90–95% for typical carbon and metal fouling), while dramatically reducing hazardous waste.

Statistical analysis will use ANOVA to test factor significance and interactions; response surface methodology (RSM) may be employed to find optimal operating points balancing cleaning efficiency, energy consumption, and bath life. Repeatability and reproducibility assessments quantify process variance and support acceptance criteria. Correlations between hydrophone pressure maps and localized residue removal will help refine transducer placement and drive sequences in subsequent prototype iterations.

9. SAFETY, ENVIRONMENTAL AND OPERATIONAL CONSIDERATIONS

Safety is paramount for defence applications. The machine will include earth leakage protection, emergency stop circuits, lid interlocks that disable ultrasonics and hydraulics when opened, and thermal shutdowns for heater failures. Adequate ventilation is required in facilities where elevated temperatures or occasional solvent use might create airborne contaminants. Additionally, PPE protocols and training are necessary to manage handling of contaminated parts and collected sludge.

Environmental management prioritizes biodegradable surfactants and minimal ppm dosing to reduce VOC emissions and hazardous waste. Concentrated sludges and spent cartridges are collected in sealed containers and disposed of under local hazardous waste regulations;
partnering with licensed disposal services ensures compliance. Automated drain and capture routines reduce operator contact with contaminated fluid and minimize spillage risk.
From an operational standpoint, recipe management in the HMI simplifies the process for armoury technicians while logging supports traceability and preventive maintenance scheduling. Cartridgeized transducers and modular filters reduce mean time to repair and simplify field servicing.

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10. APPLICATION USE CASES — WEAPON PLATFORMS AND OPERATIONAL INTEGRATION

To demonstrate applicability across typical defence small arms, this section integrates platform-specific procedures and fixture considerations for AK-47 series, INSAS, AR-platform rifles (AR-15/M4 family), and bolt-action sniper rifles commonly used in precision roles.

AK-47 and variants. AK-type rifles often have non-removable fixed barrels on some models and gas systems that incorporate significant carbon deposition in the gas port and carrier. For AK platforms, Gunguard Ultra's modular cradle supports the receiver and allows the barrel to be exposed so that through-bore purging can be applied. The fixturing secures the barrel and uses a low-shear axial flow to purge trapped gases while the transducer array provides uniform cavitation. The rotating cradle primarily aids in exposing chamber and trunnion surfaces to cavitation and helps dislodge carbon from gas block areas. A short, high-power burst mode with purge activated is often effective for carbon build-up in AK gas systems.

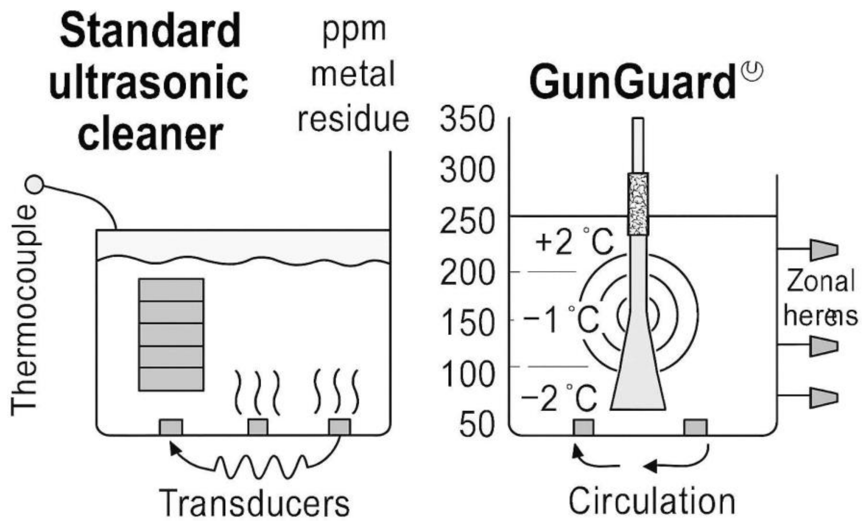

Figure 3 This figure visually contrasts the Gunguard Ultra with a Standard Ultrasonic Cleaner, focusing on cleaning efficiency and system design.

INSAS (Indian Small Arms System) and similar service rifles. INSAS platforms present similar cleaning challenges: tight gas systems, long barrel lengths for some variants, and finish sensitivity. The Gunguard Ultra presets include temperature and surfactant recipes tuned for typical INSAS fouling characteristics, with a moderate temperature setpoint and a conservative surfactant dosing policy to preserve factory finishes. When handling INSAS upper receivers or gas blocks, fixtures allow orientation changes to ensure trapped pockets see the cavitation field.

AR-platform rifles (AR-15 / M4 family). AR platforms commonly use upper receivers with free-floating barrels and differ in barrel lengths and materials. The Gunguard Ultra docking adapters include AR-specific cradles for upper receivers and bolt carriers, enabling complete cleaning without disassembly beyond removal of the upper. The through-bore purge is particularly effective for a variety of AR barrel lengths; presets are available for standard barrel lengths (10.5", 14.5", 16", 20") and provide optimized rotation/purge timing to account for rifling pitch. Gas key and gas block cleaning routines use a combination of low-frequency bulk removal and mid-frequency polishing sequences.

Bolt-action sniper rifles and precision platforms. These systems demand the highest degree of surface integrity preservation while removing heavy fouling. For precision barrels, Gunguard Ultra employs a cautious approach: a lower amplitude mid-to-high frequency stage to avoid micro-erosion, controlled temperature setpoints optimized for the barrel's finish, and a final low-amplitude polish stage. Rotational speeds are kept minimal, and profilometry checks before and after long-term trials ensure no deterioration of accuracy-critical surfaces. For sniper maintenance, the optional mild chelating additive (at very low ppm and only when required) can be enabled as a last resort; preference is always given to mechanical/acoustic removal to protect barrel harmonics and surface coatings.

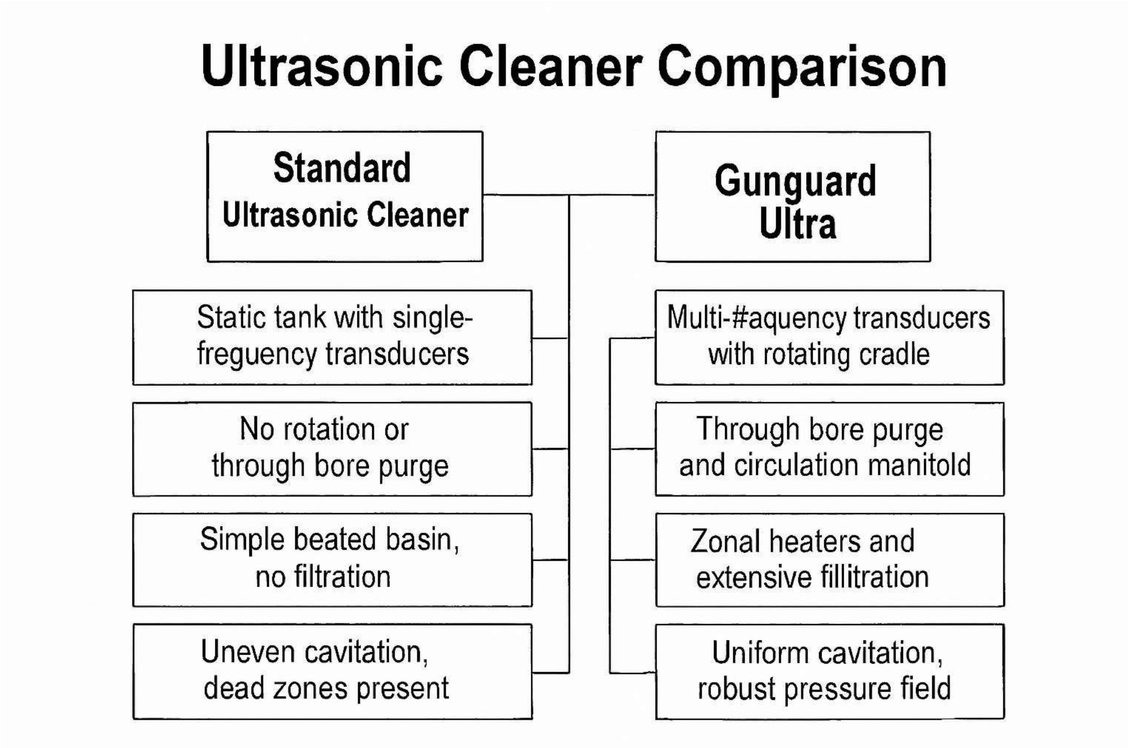

Figure 4 comparing your Gunguard Ultra with a Standard Ultrasonic Cleaner

Across all platforms, operator procedures emphasize pre-inspection, correct orientation to avoid trapped air, and post-cycle drying and light lubrication as required. Recipes stored in HMI include platform-specific notes: fixture position, purge coupling, rotation speed, and recommended surfactant ppm.

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11. ECONOMIC ASSESSMENT AND OPERATIONAL IMPACT

The capital expenditure for Gunguard Ultra prototype and production units will be higher than consumer grade ultrasonic cleaners due to multi-channel electronics, additional pumps, filtration systems, and precision fixtures. However, operational benefits—reduced labour time, fewer repeat cycles, lower solvent purchases and disposal costs, extended bath life, and improved turnaround—yield a favourable total cost of ownership for high-usage armouries. A conservative ROI model for a medium-sized defence facility processing dozens to hundreds of weapons per week anticipates a payback horizon of 12–24 months depending on utilization and local disposal costs.

Maintenance strategies should be built around cartridgeized transducers and replaceable filter elements. Predictive maintenance leveraged from logged power and temperature data enables proactive servicing, reducing unscheduled downtime. The system's modular design supports different procurement strategies: fully rugged military builds for field depots and lower-cost factory versions for civilian armouries.

12. RISKS AND MITIGATION STRATEGIES

Key technical risks include transducer failure (thermal/mechanical stress), cavitation suppression due to improper flow, and incomplete removal of aggressive metallic fouling without solvent chemistries. Transducer reliability is mitigated with redundancy, thermal monitoring, potting materials with adequate mechanical resilience, and conservative duty cycles. Flow-induced cavitation suppression is addressed by the circulate-settle-clean strategy and manifold design that provides homogenous temperatures with minimal active flow near the part during ultrasonics. When aqueous surfactant protocols are insufficient for specific heavy metallic deposits, the system allows an exception path for a short solvent-assisted maintenance cycle under controlled conditions; this is framed as an exception rather than a design reliance. Environmental risk is minimized with sealed waste capture and engagement with licensed disposal vendors.

13. CONCLUSION

Gunguard Ultra proposes a systems engineering approach to ultrasonic rifle cleaning that explicitly addresses the band of challenges encountered when repurposing conventional small- scale ultrasonic cleaners for defence maintenance. By synthesizing acoustic field control (multi-frequency, phase modulation), mechanical motion (rotation, axial reciprocation), fluidic engineering (through-bore purge and low-shear circulation), zonal thermal management, and automated maintenance (filtration + drain/flush), the design targets measurable improvements in cleaning uniformity, cycle time, safety, and lifecycle cost. The experimental plan combining modeling, instrumentation, and a statistically rigorous DOE provides the framework to validate these claims. Platform-specific procedures for AK-type rifles, INSAS, AR platforms, and bolt- action precision rifles demonstrate operational applicability, while safety, environmental, and economic analyses support sustainable deployment in defence contexts.

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