TITLE OF THE INVENTION

Adaptive Automation Cartridge Systems for Autonomous Maintenance of Fluid, Thermal, Structural and Corrosion Conditions in Defense Platforms

DESCRIPTION

[0001] FIELD

The invention relates to **adaptive, consumable-based cartridges** that autonomously detect and correct anomalous conditions in hydraulic, cryogenic, seawater, lubricating-oil, structural, or thermal subsystems of aircraft, spacecraft, naval vessels, land vehicles, and launch ground equipment.

[0002] BACKGROUND

Mission-critical defense platforms rely on fixed inspection intervals, manual sampling, and static filters. Contamination, corrosion, micrometeoroid puncture, or thermal spikes often escape detection until damage occurs, causing extended downtime, safety risks, and high life-cycle cost.

[0003] SUMMARY

An **autonomous cartridge** (apparatus), a corresponding **method** of anomaly detection and consumable deployment, and a **system** of networked cartridges are disclosed. Each cartridge includes:

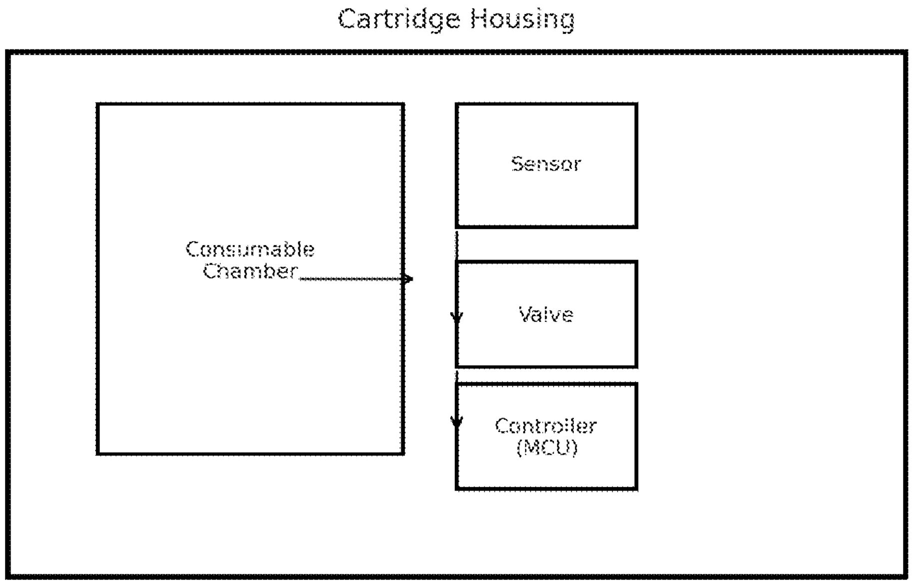
- a **housing** configured for inline or surface mounting;
- at least one **consumable medium** (filter, sealant, phase-change material, inhibitor, additive, anode, or sorbent);
- one or more **sensors** that monitor local parameters; and
- a **controller** that meters the consumable in response to sensed anomalies, then verifies closure and reports status via the platform data bus.

Advantages include real-time correction, reduced unscheduled maintenance, and extended subsystem life.

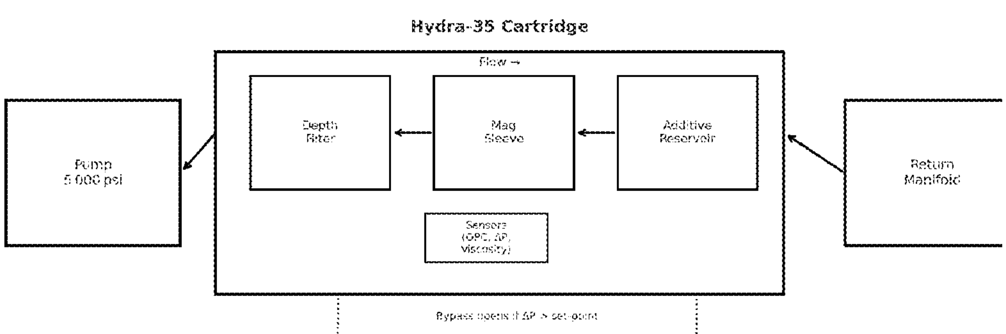
[0004] BRIEF DESCRIPTION OF DRAWINGS

INSERT FIGURES

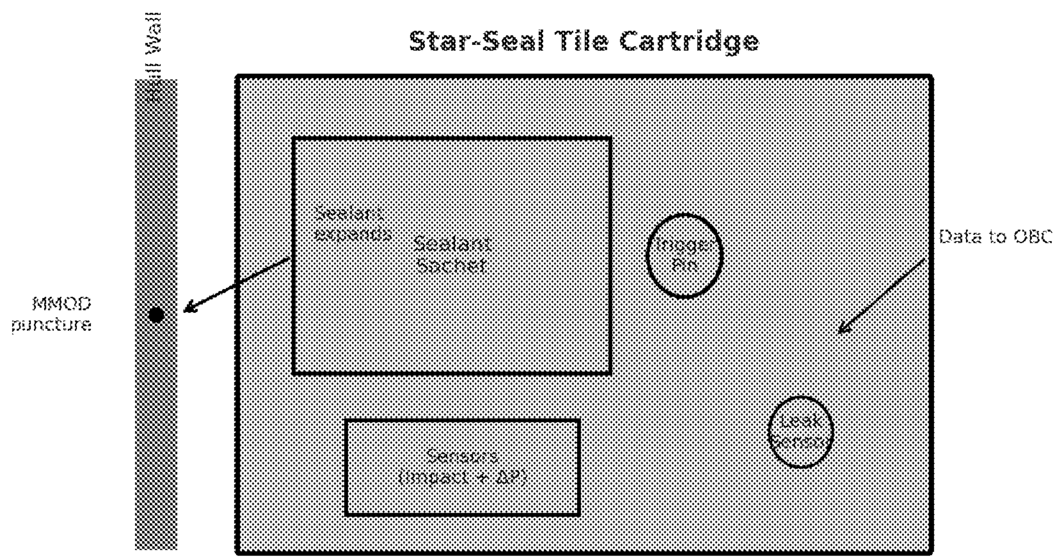
Fig. No.	*Caption / Explanation*



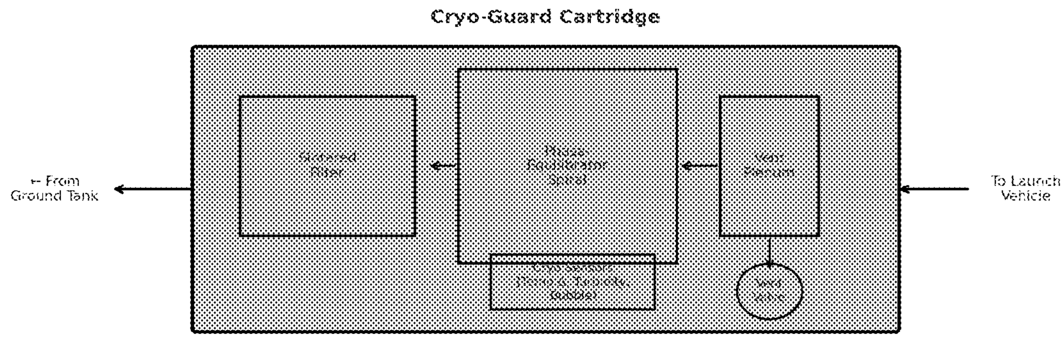
1 **Generic Adaptive Cartridge Cross-Section.** *A cylindrical or prismatic housing (100) encloses: a consumable chamber (110); an inlet port (102) and outlet port (104); an array of embedded sensors (120) such as pressure, temperature, particle count and viscosity; a normally-closed metering valve or micro-pump (130); and an on-board controller board (140). The controller receives real-time data from the sensors, decides whether an anomaly exists, doses the consumable through the valve, and transmits status over the platform data bus.*



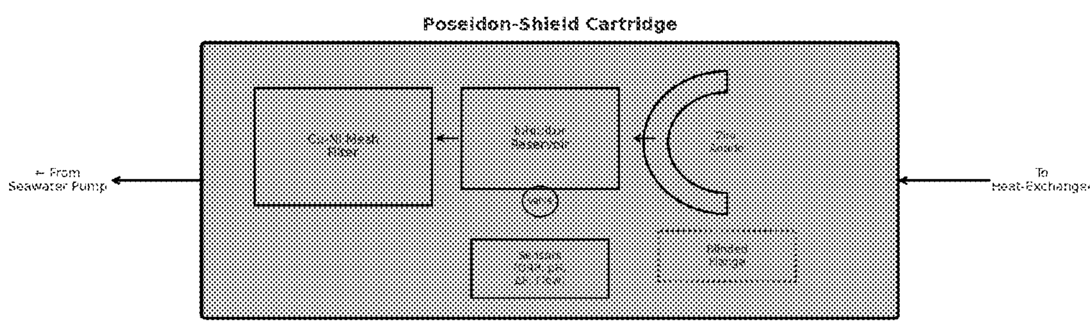
2 ***Hydra-35 High-Pressure Hydraulic Cartridge (Inline Layout).*** *Hydraulic fluid from the aircraft pump (200) enters the cartridge housing (210), passes through a multi-layer depth filter (212) and a high-flux magnetic sleeve (214), then over an additive reservoir outlet (216) before returning to the manifold (220). A sensor block (230) measures differential pressure, particle cleanliness and viscosity; a spring-loaded bypass (222) opens if ΔP exceeds a set point. Flow direction is left-to-right; additive is injected only when contamination or ΔP thresholds are exceeded.*



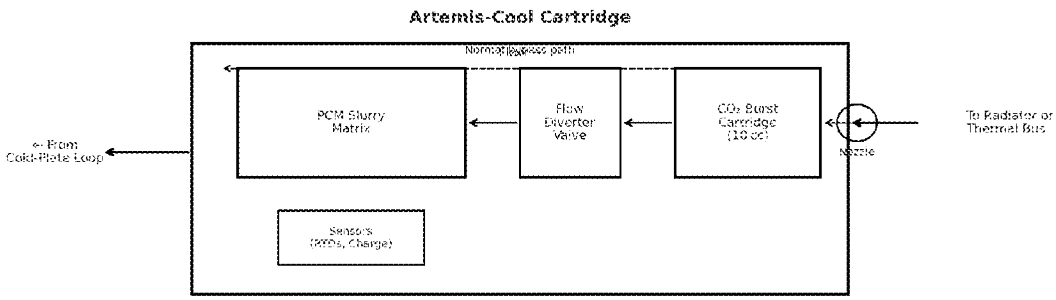
3 ***Star-Seal MMOD Self-Healing Tile.*** *The stack comprises an outer aluminum or CFRP hull plate (300), a silicone sealant sachet (310) held in a frangible foil bladder, an impact trigger pin (320) driven by a miniature voice-coil, and an acoustic + pressure-drop sensor pair (330). Upon micrometeoroid impact and pressure loss, the pin pierces the bladder, sealant extrudes through the breach and cures within seconds, re-establishing hull integrity.*



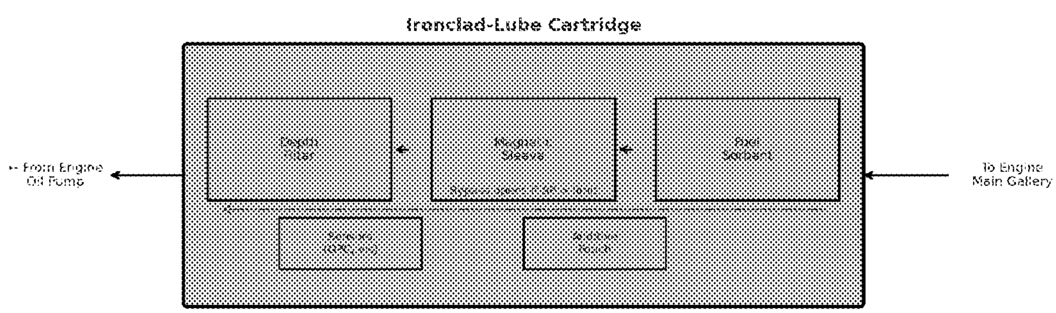
4 ***Cryo-Guard Cryogenic Filter / Phase-Equilibrator Spiral.*** *Liquid oxygen (LOX) from the ground umbilical enters a sintered-metal filter disk (400) that removes sub-micron ice and rust, then flows through a helical phase-equilibrator channel (410) that destratifies temperature gradients. Fiber-optic turbidity (420) and Cernox® temperature probes (422) feed a controller that vents gas pockets through a cryo-rated needle valve (430) if bubbles or ΔT exceed limits.*



5 ***Poseidon-Shield Duplex Corrosion Cartridge.*** *A seawater service pipe couples to a duplex housing (500) containing parallel flow shells: the primary path with a sacrificial zinc anode (510) and an inhibitor injection ring (520); and a standby shell (502) that can be brought on* *line by rotating a blinded flange (530) during hot-swap. An ORP probe and pH sensor (540) trigger inhibitor dosing shots when corrosion potential drifts negative.*

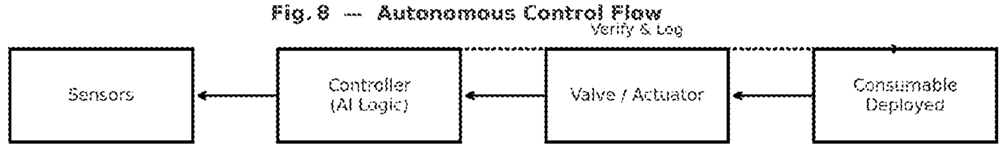


6 ***Artemis-Cool Thermal Spike Cartridge (Vertical Stack Version).*** *Hot fluid first encounters a PCM slurry matrix (600) that absorbs transient heat. A two-way flow valve (610) diverts flow through or around the matrix. If temperature rise rate (dT/dt) still exceeds threshold, a* CO_2 *burst cartridge (620) discharges through an internal nozzle (630) to flash-cool the loop. RTD and tribo-charge sensors (640) supply data to the controller; a dashed bypass line (650) illustrates the normal closed-valve path.*

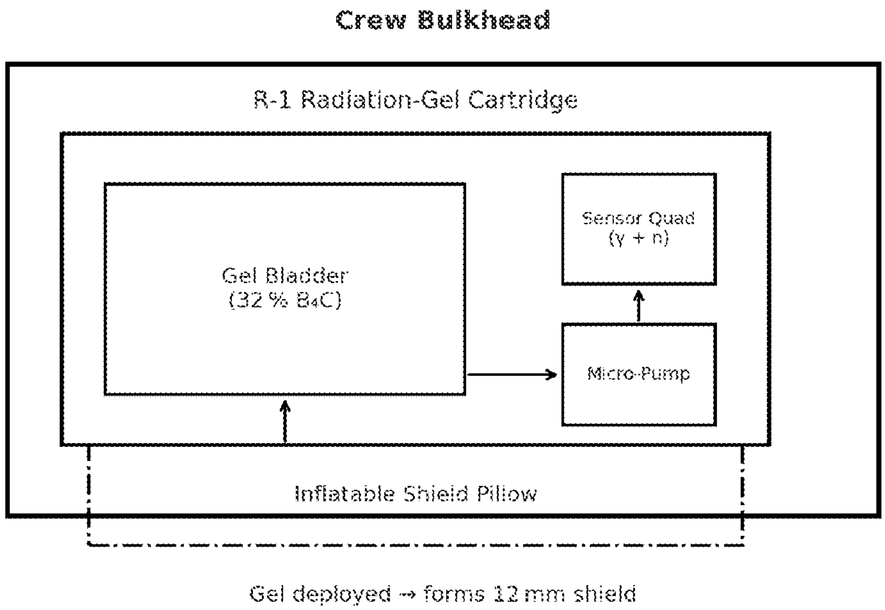


7 ***Ironclad-Lube Engine-Oil Purifier (Horizontal Layout).*** *Dirty oil enters at the left, passes sequentially through a micro-glass depth filter (700), a radial neodymium magnetic sleeve (710) that captures ferrous wear particles, and a fuel-sorbent ring (720) that removes diesel dilution. A sensor module (730) measures ISO cleanliness, ΔP and permittivity; an additive pouch (732) delivers friction-modifier when total-base-number prediction drops. A dotted arrow denotes a spring bypass that protects flow if ΔP exceeds 0.8 bar.*

Fig. 8 — Autonomous Control Flow



8 ***Autonomous Control-Flow Diagram.*** *Sensors (800) stream raw telemetry to a predictive AI controller (810). The controller commands a valve / actuator block (820) to meter consumable or reposition flow. After deployment, a verification loop (dotted arrow 830) feeds success/fault codes back to the controller, which logs the event and updates parameters for the next cycle.*



9 ***Radiation-Shielding Gel Cartridge (Embodiment R-1)***

A flat, panel-type cartridge (710) is bonded to an interior bulkhead (700).

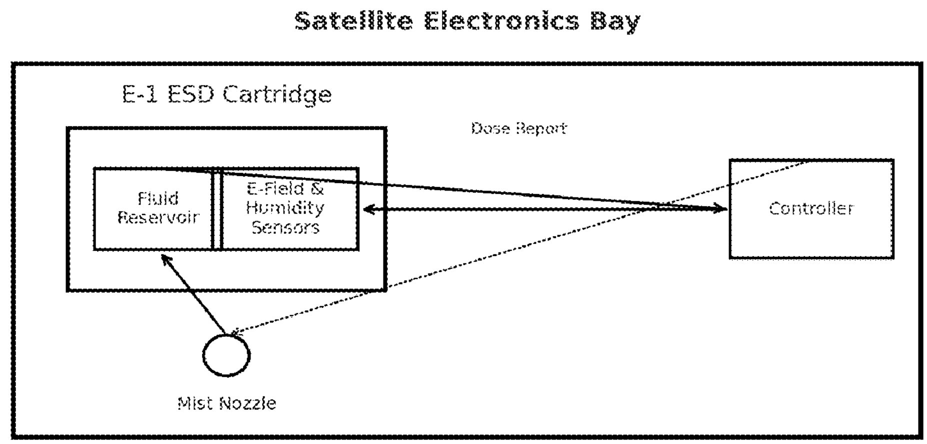
Inside the FR-4 housing a flexible bladder (712) stores ~1.9 L of boron-loaded silicone gel.

A sensor-quad board (720) carries two solid-state gamma dosimeters (722) and two Li-glass neutron probes (724).

Dose data feed a dual-stage piezo micro-pump module (730).

Stage 1 inflates an external Kevlar® shield pillow (740) to ~45 kPa; Stage 2 meters gel through outlet line (742) until a 12 mm barrier coats the crew compartment.

Thermistor 726 supervises gel temperature; all events are logged over the spacecraft CAN-FD bus (750).



Aerosol neutralises charge on boards

10 ESD-Neutraliser Cartridge (Embodiment E-1)

Within a satellite electronics bay (800), a cuboid ESD cartridge (810) is secured via a MIL-DTL-38999 connector.

The left half of the housing contains a 650 mL conductive-fluid reservoir (812); the right half carries an electro-static field sensor (820) and humidity probe (822).

Telemetry is passed to an on-board controller (830) mounted on the backplane.

When $|E| > 10$ kV m^{-1} or $dE/dt > 5$ kV m^{-1} s^{-1}, the controller energises a piezo mist-nozzle (840) that atomises the fluid toward printed-circuit cards.

A capacitive level gauge (814) reports remaining volume; the controller returns "dose count" and "fluid %" every 60 s via SpaceWire (850) for ground logging.

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5. DETAILED DESCRIPTION

5.1 Definitions

"**Consumable**" includes any deployable medium such as filtration media, sealant, phase-change material, corrosion inhibitor, sacrificial anode, sorbent, lubricant, or coolant.

"**Anomaly**" means a deviation of any sensed parameter – pressure, temperature, particle count, acoustic impact, oxidation-reduction potential (ORP), etc. – beyond a threshold.

"**Controller**" encompasses microcontrollers, FPGAs, ASICs, or equivalent logic executing stored instructions.

5.2 Generic Cartridge (Fig. 1)

Housing materials may include aluminum, stainless steel, titanium, carbon-fiber composite, or polymer rated for the operating temperature and pressure ranges (−200 °C to +150 °C; vacuum to 70 MPa).

Sensors may be optical particle counters (≥0.5 µm), pressure transducers (±0.5 %), thermistors/RTDs (±0.1 °C), acoustic sensors (>5 kHz impact spike), ORP probes (−1 V to +1 V), or inductive metal-debris counters.

Valves may be piezoelectric, solenoid, MEMS micro-orifices, or rupture pins.

The controller stores cryptographically signed firmware and communicates via **MIL-STD-1553B, CAN/J1939, SpaceWire, Ethernet, or 10Base-T1**.

Representative Control Logic (pseudocode):

```
IF sensor_value > threshold THEN
   open_valve(duration_ms)
ELSE IF rate_of_change > roc_threshold THEN
   bypass_path()
ENDIF
IF consumable_remaining < reserve
   transmit_replenish_flag()
ENDIF
```

5.3 Embodiment H-1: Hydra-35 (High-Pressure Hydraulic)

1 Hydra-35 Hydraulic Cartridge (Aircraft Example)

Embodiment H-1 (Fig. 2). A replaceable inline cartridge is inserted in a 12.7 mm (½ in) titanium hydraulic line operating between 21 MPa and 55 MPa (3 000–8 000 psi) and temperatures from -54 °C to +135 °C.
The housing is machined from Ti-6Al-4V or 15-5 PH stainless steel, burst-tested to 2.4 × maximum operating pressure.
Internally, fluid first passes through a multi-layer micro-glass depth filter ($\beta_{10} \geq 2\,000$) followed by a >1 T magnetic sleeve that captures ferrous particles ≥ 5 µm.
A 20–50 mL additive reservoir holds an aviation-approved anti-static/lubricity package (e.g., MIL-PRF-87257 type), metered through a normally-closed piezo valve in 100 µL increments.

Sensors include an optical particle counter (4–100 µm, ±1 ISO code), a pair of thin-film pressure transducers (0–70 MPa, ±0.5 %), and a MEMS resonant viscosity sensor covering 1–50 cP.
When the controller detects ΔP > 0.5 bar or NAS 1638 class drift > 2 grades, it doses 1 mL additive and logs the event over MIL-STD-1553B. A spring-loaded bypass opens at 0.8 bar ΔP to guarantee flow.
The cartridge is exchanged every 400 flight hours or 12 months, using the existing filter cavity and ¼-turn retaining nut.

5.4 Embodiment S-1: Star-Seal (MMOD)

2 Star-Seal MMOD Tile (Spacecraft Example)

Embodiment S-1 (Fig. 3). A self-healing tile measuring 150 mm × 150 mm × 10 mm is bonded to the interior face of an aluminum 2219 pressure shell.
The tile contains a vacuum-compatible two-part silicone elastomer (Shore A < 35) held in a foil sachet, with water-activated exothermic particles that accelerate cure below 50 torr.
A voice-coil–driven impact pin ruptures the sachet when both an acoustic piezo sensor (> 5 kHz spike) and a MEMS absolute-pressure sensor (drop > 1 kPa within 50 ms) trigger.
The sealant expands to fill punctures up to 3 mm in diameter and cures in ≤ 30 s at temperatures from -20 °C to +40 °C.
A downstream micro-pressure sensor verifies residual leak ≤ 5 Pa/s; status is uplinked via SpaceWire (10 Mbit/s).
Tiles add < 200 g mass and draw < 0.5 W standby from the 28 Vdc cabin bus.

5.5 Embodiment C-1: Cryo-Guard (Cryogenic Propellant)

3 Cryo-Guard Propellant Cartridge (Launch Pad Example)

Embodiment C-1 (Fig. 4). A cylindrical cartridge, 76 mm internal diameter × 350 mm length, is installed in the LOX umbilical whip.
The double-walled housing is 316L or Inconel 625 with a 10^{-6} mbar-l-s^{-1} vacuum jacket.
Incoming liquid oxygen at -183 °C flows through a 0.2–1.0 µm sintered-metal filter (porosity ≈ 35 %) and a helical phase-equilibrator machined with 4-mm pitch to mix boundary layers.
A fiber-optic turbidity probe (1 ppm detection), dual Cernox® RTDs (ΔT ±0.05 K), and a capacitance bubble detector feed a RISC-V MCU that issues *GO/NO-GO* on Gigabit Ethernet.
If a gas pocket is detected, a cryo-rated needle vent valve opens for 100–500 ms at 10–20 cc s^{-1} mass-flow.
The module is rated to 2 MPa MAWP, weighs < 8 kg, and adds < 0.5 °C pressure-drop equivalent at 250 L s^{-1} flow.

5.6 Embodiment P-1: Poseidon-Shield (Seawater Corrosion)

4 Poseidon-Shield Corrosion Cartridge (Naval Example)

Embodiment P-1 (Fig. 5). A duplex cartridge mounts on an ANSI 150-lb, 6-in flange in a ship's seawater service loop (flow 75–300 m^3 h^{-1}, 20 °C).
The body is Cu-Ni 90/10 lined with a thin alloy-625 overlay to resist pitting.
A cylindrical zinc-based sacrificial anode (100–300 g) is monitored by a Hall-effect depletion sensor.

The consumable chamber holds 150–250 mL of filming-amine inhibitor (e.g., corrosion-rate target < 2 mpy) metered via a magnetically latched plunger at 1–5 mL shots when ORP < -200 mV or pH < 7.2.
Pressure drop is < 0.1 bar at nominal flow; inhibitor cartridge hot-swaps through a blinded flange without draining the system.
Electronics conform to MIL-STD-461G EMI and output J1939 frames to the ship's IPMS.

5.7 Embodiment T-1: Artemis-Cool (Thermal Spike)

5 Artemis-Cool Thermal Cartridge (Satellite / HALE UAV)

Embodiment T-1 (Fig. 6). A flat plate module 120 mm × 80 mm × 25 mm, mass < 250 g, is plumbed into a PAO-based liquid loop (−40 °C to +60 °C, 0.5–1.5 L min^{-1}).
The phase-change medium is a nano-encapsulated paraffin/graphene slurry (latent heat 150–250 kJ kg^{-1}) contained in a porous aluminum foam core.
When dT/dt > 0.5 °C s^{-1} *and* ΔT > 3 °C, a piezo-valve diverts flow through the slurry path, absorbing up to 500 W for 30 s.
If temp overshoot exceeds +10 °C, a 10 cc CO_2 micro-cartridge vents through a Laval nozzle to flash-cool the plate, dropping temperature ≥ 12 °C in 5 s.
Twin Class-A platinum RTDs (±0.1 °C) and a tribo-charge sensor report over CAN-Open; a 1 W heater regenerates the PCM each orbit.

5.8 Embodiment L-1: Ironclad-Lube (Engine Oil)

6 Ironclad-Lube Oil Purifier (Armored-Vehicle Diesel / Turbine)

Embodiment L-1 (Fig. 7). A spin-on cartridge 155 mm × 210 mm, steel shell burst-rated 10 bar, processes engine oil at 60 L min^{-1} and 80–130 °C.
Element stack: micro-glass depth filter (β_{10} ≥ 2 000), 1 T radial neodymium magnetic sleeve, and a fuel-sorbent ring (nitrile-resin, capacity ≥ 20 % own mass).
An inductive particle counter (0.5–15 µm, ±10 %) and a MEMS permittivity/viscosity probe (fuel dilution accuracy ±0.5 vol %) feed a 32-bit MCU.
Additive pouch (friction-modifier + TBN booster) holds 20 mL; controller doses 1 mL when base-number prediction < 5 mg KOH g^{-1}.
Cartridge bypass opens at 0.7 bar ΔP. Data logged on SAE J1939 CAN; swap interval 500 h or 12 months via top-hatch access.

5.9 Embodiment R-1 (Radiation-Shielding Gel Cartridge)

7 Radiation-Shielding Gel Cartridge

A flat, panel-form cartridge (overall 460 mm × 260 mm × 28 mm; mass ≤ 1.8 kg) is bonded to the interior bulkhead of a crewed spacecraft or lunar lander. The FR-4 composite housing (710) encloses a 1.9 L bladder (712) pre-filled with a boron-loaded silicone gel (32 ± 4 wt % B_4C powder; density 1.2–1.3 g cm^{-3}). Four solid-state dosimeters—two CMOS γ sensors (100 mrad to 50 rad, ±5 %) and two Li-glass neutron probes (0.01–20 mSv h^{-1}, ±10 %)—form a sensor quad (720). When any sensor reports dose rate > 25 mSv h^{-1} or a cumulative 100 mSv over 24 h, the controller (730) energises a dual-stage piezo micro-pump: Stage 1 inflates an external Kevlar fabric pillow (740) to 45 kPa in ≤ 10 s; Stage 2 meters gel at 8 mL s^{-1} until a 12 mm thick shielding layer surrounds the crew station. A thermistor (±0.2 °C) ensures gel temperature remains between −30 °C and +60 °C; if not, the pump halts and signals fault code 7 via CAN-FD. Cartridge service life is 5 years standby or three full discharges; replacement is tool-less via two quarter-turn fasteners.

5.10 Embodiment E-1 (ESD-Neutraliser Cartridge)

8 ESD-Neutraliser Cartridge

A cuboid cartridge (95 mm × 85 mm × 40 mm; 420 g) mounts to a 28 V satellite electronics bay using a MIL-DTL-38999 connector and four M4 standoffs. The CFRP shell (810) contains a 650 mL reservoir of aerospace-qualified anti-static fluid (surface resistivity ≤ 1 × 10^6 Ω sq^{-1}, viscosity 3–5 cP at 20 °C). A tri-axis electrostatic field sensor (-50 kV m^{-1} to +50 kV m^{-1}, ±3 %) and a humidity probe (0–100 % RH, ±2 %) form the sensor suite (820). When field strength exceeds ±10 kV m^{-1} or dE/dt > 5 kV m^{-1} s^{-1}, the controller (830) opens a piezo-actuated mist nozzle (835) (orifice dia (e.g., 0.15 mm) enables fluid atomisation) for 120 ms bursts, creating a 50 µm conductive aerosol that dissipates charge within 300 ms. Deployment is permitted only if humidity < 80 % RH and bay pressure > 50 kPa. Dose count, remaining fluid volume (±5 mL by capacitive level gauge), and peak E-field are logged locally and broadcast over SpaceWire every 60 s. Cartridge capacity supports ≈ 400 bursts; the unit is swapped at the next service interval or when fluid falls below 10 % reserve.

5.11 Manufacturing & Installation

Cartridge housings may be CNC-machined, additive-manufactured, hot-isostatic-pressed, or molded. Installation uses standard connectors: **MIL-DTL-38999** electrical; flareless tube, bayonet cryo couplers, ANSI flanges, or NATO thread adapters as applicable.

5.12 Lifecycle & Maintenance

Each cartridge stores a non-volatile "health log" updated on actuation. Replacement intervals may be flight hours, engine hours, or calendar months. Spent units are refurbished by replacing consumable packs; housings are reused, enabling circular logistics.

5.13 Cybersecurity

Firmware images are SHA-256 hashed; bootloaders verify signatures before execution. Data traffic may be encrypted using TLS 1.3 or BACN-compliant link encryption.

5.14 Alternative Consumables

Sealant may be silicone, polyurethane, or UV-curable acrylate; PCM may be paraffin, hydrated salt, or metallic eutectic; inhibitor may be filming amine or molybdate; sorbent may be nitrile, zeolite, or hyper-cross-linked polymer.

5.15 Industrial Applicability

The cartridges reduce unplanned maintenance, extend component life, lower hazardous-waste generation, and improve mission availability across air, sea, land, and space platforms.

[0009] CLAIMS