

Marine and Rail Energy Storage: A Bulk-Equipotential Hydrogen-Aluminum Cell for Mass-Tolerant Heavy Transport

Ships and trains carry their energy storage in spaces where a few hundred extra kilograms barely register, yet they still inherit automotive battery chemistries optimized for the opposite constraint, paying for them in fire risk, self-discharge during long layups, and disposal at end of life. This application describes how heavy marine and rail platforms can be served by a cell built on the Hydrogen-Aluminum Energy Cell, disclosed in U.S. Provisional Application No. 64/055,649, whose bulk-equipotential charge retention, non-flammable breach behavior, and centralized cradle-to-cradle remanufacturing map directly onto duty cycles where volume and mass headroom are generous but uptime, safety, and lifetime cost dominate.

What This Application Specifies

This is an application note. It describes how the architecture disclosed in U.S. Provisional Application No. 64/055,649, referred to here as the Hydrogen-Aluminum Energy Cell, would be configured and deployed for heavy transport, specifically marine vessels and rail rolling stock. The underlying materials science (hydrogen chemisorption on aluminum surfaces, proton conduction in sulfonated carbon gels, electrochemical exfoliation of metal nanoflakes, boron doping of graphene) is

established prior art. What the provisional discloses, and what this note applies, is the architecture: the particular combination and governance of those known effects into a sealed cell that retains charge without an internal separator and stores energy as electron-stabilized hydrogen bonds on a population of aluminum nanoflakes suspended in a dual-domain proton-conducting carbon gel.

The disclosed cell omits the internal separator that defines conventional rechargeable cells. As described in the provisional, the gel is itself both electronically and ionically conductive, and charge is retained not by insulating two electrodes from each other but by holding the entire flake population at a single equipotential. In that condition there is no internal potential gradient and therefore no internal driving force for self-discharge; the cell discharges only when an external circuit closes and establishes an asymmetric electron path between the two terminals. For heavy transport, where assets routinely sit idle (a ferry overnight, a freight consist in a yard, a reserve-power bank between port calls), this retention-by-saturation property is the central reason the architecture is interesting.

Marine and rail are treated together here because they share a defining condition: the platform has room. A vessel's machinery space and a locomotive's carbody or a battery tender car offer mass and volume budgets that an automobile cannot. That headroom is exactly what lets a designer favor the disclosed architecture's other properties (safety behavior, retention, recyclability, lifetime) without being forced to optimize first for the gravimetric and volumetric figures that dominate automotive design.

Why It Matters

Heavy transport electrification is constrained less by how much a battery weighs than by three other things: fire safety in confined or remote settings, energy availability after long idle periods, and the total cost of owning storage that may need to last as long as the hull or the chassis.

Fire is the governing concern at sea and in tunnels. A battery fire aboard a vessel underway, or in a locomotive in a long rail tunnel, is a worst-case event because suppression and evacuation options are limited. The provisional discloses a breach response that is chemically distinct from conventional lithium-ion thermal runaway. As disclosed, on mechanical breach the cell admits atmospheric oxygen and rapidly oxidizes its stored chemical energy into water vapor, aluminum oxide solid particulates, and carbon dioxide, all non-flammable, in contrast to the flammable organic-solvent vapors released by a conventional cell in runaway. The provisional also discloses a heat-triggered discharge stall: above an engineering-tunable temperature window, controlled framework failure outpaces self-healing, internal resistance climbs, and the cell drops into a high-resistance stalled state from which it recovers on cooling. The provisional frames this as a reversible safety interlock, expressly contrasted with the irreversible runaway of conventional cells.

Idle availability matters because heavy transport duty cycles include long rests. Conventional chemistries lose roughly one to five percent of capacity per year at rest through degradation processes that run whether or not the cell is cycled. The disclosed architecture has no internal separator to breach and, as disclosed, no internal potential gradient at rest to drive redistribution; the provisional projects calendar self-discharge well below one percent per year, with the actual value to be determined empirically. A reserve bank that holds its charge through a seasonal layup is worth more to a vessel operator than one rated for a marginally higher energy density.

Lifetime and recyclability matter because marine and rail assets are capital that depreciates over decades, not years. The provisional discloses an end-of-life path of centralized cell remanufacturing with electrochemical and spectroscopic material separation, recovering the aluminum, the boron-doped carbon fractions, the current collectors, and the aluminum enclosure layer for reincorporation into new cells. The provisional estimates end-of-life durations in the range of decades for mature implementations, with actual values to be determined empirically.

How It Composes With the Domain

A marine or rail energy-storage system is an assembly of cells governed by a battery management system, not a single cell, and the disclosed architecture composes into such a system through ordinary engineering interfaces.

System voltage is reached by series stacking. The provisional discloses a single-cell upper voltage bound set by the onset of irreversible carbon-framework oxidation, and prescribes series stacking with inter-cell isolation, mechanical support, thermal management, and per-cell monitoring to reach arbitrarily high bus voltages. Marine DC distribution buses and traction voltage links are both reachable this way, and per-cell monitoring fits the redundancy and isolation practices these domains already require.

Duty profiles map onto the disclosed operating modes. The provisional describes a standard charge-discharge mode, a high-rate mode admitting brief bursts at very high C-rates, and a long-term storage mode. In rail service, the high-rate mode aligns with the transient demands the provisional itself names, motor starting, acceleration, regenerative braking energy capture, and the bulk-equipotential architecture means current can be drawn from anywhere in the cell rather than from a localized electrode. In marine service, the long-term storage mode aligns with reserve and emergency-backup banks held charged between calls, while standard mode covers harbor maneuvering, hotel loads, and short zero-emission transits.

State estimation and health monitoring use properties the provisional discloses directly. The smooth, gradually declining discharge voltage profile admits state-of-charge estimation from open-circuit voltage, which simplifies the battery management system relative to flat-plateau chemistries. For state-of-health, the provisional discloses non-invasive microwave and radar dielectric spectroscopy performed by external instrumentation without opening or interrupting the cell, supporting predictive maintenance scheduling, a natural fit for the planned dry-dock and shop-cycle maintenance regimes of ships and trains.

Thermal integration leans on the disclosed enclosure. The aluminum equipotential extension layer that lines the enclosure interior is disclosed to provide thermal coupling between interior and exterior, supporting heat dissipation during high-rate operation, and to act as a Faraday cage shielding the cell interior from external electromagnetic fields, relevant in the electrically noisy environment around traction inverters and shipboard switchgear.

Embodiment range gives the designer room. The provisional discloses aluminum as the preferred active metal but admits magnesium, zinc, iron, titanium, nickel, palladium, platinum, and alloys; flake loading from roughly five to sixty weight percent spanning high-cycle-life to high-capacity configurations; and fractal flake generation counts that trade synthesis effort for accessible surface area. A mass-tolerant marine or rail application can sit toward the high-cycle-life, robust end of these ranges rather than chasing the synthesis-intensive high-capacity end that a weight-critical application would demand.

What This Enables

Configured for heavy transport, the disclosed architecture enables several deployment patterns:

- Shipboard reserve and emergency-power banks that hold charge through long layups and whose breach products are non-flammable, addressing the dominant fire concern in confined machinery spaces.
- Hybrid and battery-electric locomotive or battery-tender storage sized for regenerative braking capture and acceleration boost, using the disclosed high-rate mode and the bulk-equipotential ability to source current from the whole cell.
- Harbor-craft, ferry, and short-sea propulsion packs where generous hull volume lets the design favor the high-cycle-life, robust end of the disclosed embodiment range.

- Rail and port stationary storage for peak shaving, regenerative energy buffering, and grid-frequency support at depots and terminals, using the long-term storage and high-rate modes.
- Fleet-scale ownership models built on the disclosed decades-scale lifetime and centralized cradle-to-cradle remanufacturing, in which storage is treated as semi-permanent infrastructure recovered and rebuilt rather than disposed.
- Predictive maintenance integrated into existing dry-dock and shop schedules using the disclosed non-invasive dielectric state-of-health monitoring.

These follow from properties the provisional attributes to the architecture. They are deployment scenarios, not new physics.

Boundary Conditions

This is a provisional disclosure of an architecture, not a built or benchmarked product. The underlying materials science is prior art; novelty resides in the disclosed combination, architecture, and governance, and in the resulting cell category, not in any single material, bond, or effect. Nothing here should be read as a claim that a cell has been fabricated, validated, or measured.

No performance figures are asserted in this note. Energy density, cycle life, calendar life, round-trip efficiency, charge and discharge voltages, power, and cost are undisclosed at the level of validated results; the provisional's own quantitative ranges are presented there as estimates and prophetic examples subject to empirical verification, and several depend on synthesis parameters (such as fractal flake generation count and boron doping precision) that are themselves engineering variables. The calendar-retention, lifetime, and self-discharge advantages described above are mechanisms and projections, not measurements.

Domain-specific qualification is required and external to the disclosure. Marine and rail energy storage are governed by classification-society and regulatory regimes (for example flag-state and recognized-organization rules for shipboard batteries, and national rail-safety authorities for rolling-stock energy storage). Any real deployment depends on type approval, fire and abuse testing, and certification under those regimes. The favorable breach chemistry and reversible thermal-stall behavior disclosed in the provisional are properties of the architecture as described, not a substitute for that testing. The provisional also notes that under-sized installations may experience the thermal stall as an operational limit, so system sizing must account for it.

Finally, the heat-stall interlock and the controlled breach response are disclosed as engineered behaviors with tunable thresholds; realizing them in a marine or rail product is an engineering and qualification task, and their protective value in any specific installation is a function of that engineering, not an inherent guarantee.

Disclosure Scope

The technology described in this application note is disclosed in U.S. Provisional Application No. 64/055,649, which discloses the Hydrogen-Aluminum Energy Cell architecture: a sealed bulk-equipotential electrochemical cell with hydrogen-activated metal nanoflakes in a dual-domain proton-conducting carbon gel, together with its charge-retention principle, surface-bonded hydrogen storage chemistry, asymmetric ingress and egress paths, flake-flake electrostatic isolation, dynamic flake expansion, mechanochemical self-healing, boron-doping precision multiplication, safety behaviors, and end-of-life remanufacturing. The marine and rail framing in this note, including vessel and rolling-stock deployment scenarios, classification and regulatory references, maintenance-regime fit, and ownership models, is external domain context provided to illustrate an enabling application of the disclosed architecture. That framing is not part of the patent claims, and references to standards, classification societies, and regulators describe the real-world environment in which such a cell would be qualified, not

features of the disclosed invention. Nothing in this note should be construed as a representation that the disclosed cell has been built, tested, or shown to meet any particular standard or performance level.

Hydrogen-Aluminum Energy Cell ([/h-](#) [All 40 steps → \(/inventive-steps\)](#)

al-battery)

Sealed electrochemical cell storing energy as reversible covalent hydrogen bonds on carbon electrodes.

Provisional application

PRIMARY TECHNICAL DISCLOSURE

- [A Hydrogen-Aluminum Surface-Bond Storage Cell with Bulk-Equipotential Charge Retention \(/articles/a-hydrogen-aluminum-surface-bond-storage-cell-with-bulk-equipotential-charge-retention\)](#)

SECONDARY TECHNICAL

- [Charge Retention by Bulk-Equipotential Saturation Without an Internal Separator \(/articles/h-al-battery/bulk-equipotential-charge-retention\)](#)
- [Storing Energy as Electron-Stabilized Metal-Hydrogen Surface Bonds Formed by Proton-Coupled Electron Transfer \(/articles/h-al-battery/hydrogen-metal-surface-bond-storage\)](#)
- [Electron-Mediated Bond Stability: The Kinetically Trapped Idle State Behind Indefinite Calendar Life \(/articles/h-al-battery/electron-mediated-bond-stability\)](#)
- [Hot-Proton Charging Versus Cold-Proton Discharge: The Bias-Gated Asymmetry That Blocks Self-Charge and Self-Discharge \(/articles/h-al-battery/hot-cold-proton-asymmetry\)](#)
- [Asymmetric Dual-Domain Proton Paths: Separate Ingress and Egress Routes in a Hydrogen-Aluminum Storage Gel \(/articles/h-al-battery/asymmetric-dual-domain-paths\)](#)
- [Hydrophobic Gating: Rejecting Neutral and Molecular Hydrogen While Admitting Only Biased Protons \(/articles/h-al-battery/hydrophobic-gating\)](#)
- [The Storage Gel as a Polarized Electrochemical Switch: Coherent Alignment, Equipotential Locking, and Load-Proportional Discharge \(/articles/h-al-battery/gel-polarized-switch\)](#)
- [Flake-Flake Electrostatic Isolation: DLVO Repulsion as a Self-Discharge Barrier in a Separator-Free Hydrogen-Aluminum Cell \(/articles/h-al-battery/flake-electrostatic-isolation\)](#)

- [Dynamic Flake Expansion: Carbon-Intercalation Wedging to Expose Buried Metal Surface Under Bias \(/articles/h-al-battery/dynamic-flake-expansion\)](/articles/h-al-battery/dynamic-flake-expansion).
- [Hydrogen-Locked Expanded State: Surface-Energy Inversion as a Positive-Feedback Capacity Mechanism \(/articles/h-al-battery/hydrogen-locked-expanded-state\)](/articles/h-al-battery/hydrogen-locked-expanded-state).
- [Secondary Carbon-Hydrogen Storage on Transmuted Intercalated Carbon \(/articles/h-al-battery/secondary-carbon-hydrogen-storage\)](/articles/h-al-battery/secondary-carbon-hydrogen-storage).
- [Mechanochemical Strain Self-Healing and Use-Positive Aging in a Bulk-Equipotential Hydrogen-Aluminum Cell \(/articles/h-al-battery/mechanochemical-self-healing\)](/articles/h-al-battery/mechanochemical-self-healing).
- [Boron Doping of the Carbon Framework as a Multi-Function Precision Multiplier \(/articles/h-al-battery/boron-doping-precision-multiplier\)](/articles/h-al-battery/boron-doping-precision-multiplier).
- [The Floating Aluminum Equipotential Extension Layer: A Multifunctional Inner Case for the Bulk-Equipotential Cell \(/articles/h-al-battery/aluminum-equipotential-extension-layer\)](/articles/h-al-battery/aluminum-equipotential-extension-layer).

APPLICATIONS · GENERAL

- [Grid-Scale and Renewable-Firming Storage with the Hydrogen-Aluminum Energy Cell \(/articles/h-al-battery/grid-scale-storage\)](/articles/h-al-battery/grid-scale-storage)
- [Building-Integrated and Behind-the-Meter Storage: Putting Energy Cells Inside the Structure With the Hydrogen-Aluminum Energy Cell \(/articles/h-al-battery/building-integrated-storage\)](/articles/h-al-battery/building-integrated-storage).
- [Stationary Backup and UPS Reserve Power for Data Centers, Hospitals, and Telecom \(/articles/h-al-battery/backup-and-ups\)](/articles/h-al-battery/backup-and-ups).
- [Storage for Microgrids, Islands, and Off-Grid Sites: A Stationary Cell Built From Abundant Materials \(/articles/h-al-battery/microgrid-and-off-grid\)](/articles/h-al-battery/microgrid-and-off-grid)
- [Electric Mobility and Transport: How a Hydrogen-Aluminum Cell Architecture Maps to Vehicle Constraints, and Where It Does Not \(/articles/h-al-battery/ev-and-mobility\)](/articles/h-al-battery/ev-and-mobility).
- **[Marine and Rail Energy Storage: A Bulk-Equipotential Hydrogen-Aluminum Cell for Mass-Tolerant Heavy Transport \(/articles/h-al-battery/marine-and-rail\)](/articles/h-al-battery/marine-and-rail)**
- [Supply-Chain-Resilient Field Power: An Abundant-Material Energy Cell for Defense and Expeditionary Operations \(/articles/h-al-battery/defense-and-field-power\)](/articles/h-al-battery/defense-and-field-power).

[Hydrogen-Aluminum Energy Cell overview → \(/h-al-battery\)](/h-al-battery)