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# Secondary Carbon-Hydrogen Storage on Transmuted Intercalated Carbon

Secondary carbon-hydrogen storage on transmuted intercalated carbon is a secondary inventive step of the Hydrogen-Aluminum Energy Cell disclosed in U.S. Provisional Application No. 64/055,649. A surface-bond energy storage cell that stores energy as metal-hydrogen surface bonds leaves the carbon it uses for dynamic flake expansion doing only structural work, while that same carbon presents chemically distinct surfaces that could carry charge of their own. The disclosed cell adds a secondary hydrogen storage chemistry on this carbon: carbon species that intercalate into the metal nanoflakes during dynamic expansion undergo a transmutation from gel-resident graphenic configurations to metal-coordinated configurations, and the transmuted carbon presents carbon-hydrogen binding sites that store additional hydrogen alongside the principal metal-hydrogen chemistry. Because this stored hydrogen is released by the mechanical collapse of the carbon as the flake refolds during discharge, rather than by draining electrons through the external circuit, the secondary chemistry discharges at a higher sub-mechanism round-trip efficiency than the principal chemistry and lifts the cell's overall efficiency.

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## The Problem: Carbon That Only Does Structural Work

The disclosed cell stores energy principally as electron-stabilized metal-hydrogen surface bonds on the metal nanoflakes. To raise capacity beyond the static surface area of a contracted flake, the cell uses dynamic flake expansion: carbon species from the gel intercalate into the flake structure under applied bias and wedge the flake layers apart, exposing previously buried surface area for additional metal-hydrogen bonding. In that role the carbon is a structural wedging species. It separates layers and is held there by bonded hydrogen, but it does not itself store charge.

That leaves capacity on the table. The intercalated carbon, once it has migrated into the flake, occupies a chemical environment unlike the surrounding metal lattice, and its surfaces present binding sites that differ from the metal surfaces. The disclosed cell uses those sites to carry a secondary hydrogen storage chemistry, so the carbon both expands the flake and adds capacity of its own.

## Carbon Transmutation Inside the Flake

Carbon enters the flake at the coordination asymmetry boundaries described for the dynamic expansion mechanism, migrating from the gel framework, including the auxiliary carbon reservoir, into the flake interior. Upon that migration the carbon undergoes a transmutation of chemical state: it changes from the gel-resident sp2 and sp3 graphenic configurations it held in the gel to a metal-coordinated configuration within the flake structure.

The specification defines this carbon transmutation as the chemical state change of carbon from a gel-resident sp2 or sp3 graphenic configuration to a metal-coordinated configuration upon migration from the gel framework into the metal nanoflake structure during dynamic flake expansion. Hydrogen binding on carbon surfaces and the formation of metal-coordinated carbon complexes are both established surface chemistry; what the architecture does is put that known chemistry to work in a new role. The state change relocates the carbon into a coordination environment in which the metal-coordinated carbon presents hydrogen-binding surface sites distinct from those of both the surrounding metal lattice and the gel-resident carbon, and the cell harnesses those sites as a second storage population alongside the principal metal-hydrogen chemistry.

## Carbon-Hydrogen Surface Bonds

The transmuted carbon presents surface sites that admit carbon-hydrogen surface bonds. The specification places the binding energies of these sites in the range of approximately 80 to 110 kilojoules per mole, corresponding to typical carbon-hydrogen bond strengths, somewhat exceeding the metal-hydrogen bond energies of the principal surface chemistry.

These carbon-hydrogen bonds are a distinct storage population from the principal metal-hydrogen surface bonds. They occupy the carbon surfaces, not the metal surfaces, and they account for capacity that the metal-hydrogen bonds alone do not admit.

## How the Capacity Scales

The additional capacity from the secondary chemistry is not a fixed offset; it tracks the same event that drives dynamic expansion. The intercalated-carbon surface area scales with the fractal-branch-separation event that admits the metal-surface expansion, so the secondary capacity is multiplicative with the dynamic-expansion factor rather than merely additive.

The specification states the secondary carbon-hydrogen chemistry contributes additional storage capacity beyond the metal-hydrogen bonds in the range of approximately 15 to 22 percent additional capacity at typical engineering implementations without carbon air phase formation, in the range of approximately 22 to 30 percent additional capacity in implementations admitting carbon air phase formation during conditioning, with stretch values up to approximately 30 to 32 percent additional capacity at maximum carbon air utilization in mature engineering implementations. The capacity is further amplified by the surface-area enhancement of the carbon air phase.

## Discharge by Mechanical Collapse

The secondary chemistry discharges by a mechanism distinct from the principal chemistry. The principal metal-hydrogen chemistry releases hydrogen by an electron-drain mechanism through the external circuit. The secondary chemistry instead releases its hydrogen mechanically. As the metal nanoflake refolds during discharge and the intercalated carbon de-intercalates back into the gel framework, the carbon undergoes mechanical compression and release from its metal-coordinated configuration. That mechanical collapse releases the hydrogen atoms bonded to the carbon surfaces as a byproduct of the refolding event, without requiring the electron-drain mechanism that drives the principal discharge.

The specification defines mechanical-collapse hydrogen release as a discharge mechanism in which hydrogen atoms bonded to intercalated carbon surfaces are released as a byproduct of the mechanical refolding of the metal nanoflake during discharge, with the released hydrogen carrying the bond-energy excess as productive proton kinetic energy rather than as dissipated heat.

## Why the Mechanical Pathway Is More Efficient

The mechanical-collapse pathway admits a substantially higher sub-mechanism round-trip efficiency than the electron-drain release of the principal chemistry. The specification attributes this to three factors. First, the absence of the polariton-state coupling and bond-electron-mediated stability that gives the principal chemistry its hysteresis. Second, the mechanical collapse is itself thermodynamically downhill, with the system returning toward its ground state during refolding, so the released hydrogen carries the bond-energy excess as productive proton kinetic energy rather than as dissipated heat. Third, the cooperative timing between mechanical collapse and proton release admits efficient capture of the bond energy as electrical work through the gel's directional flow patterns.

The specification projects the sub-mechanism efficiency for the carbon-hydrogen discharge pathway to approach approximately 95 to 99 percent in mature engineering implementations, in distinction from the approximately 80 to 90 percent round-trip efficiency of the principal metal-hydrogen chemistry.

## Contribution to Overall Cell Efficiency

The cell's overall round-trip efficiency is the capacity-weighted average of the principal-chemistry and secondary-chemistry sub-mechanism efficiencies. With the secondary chemistry contributing approximately 15 to 25 percent of total capacity at typical engineering implementations and approaching approximately 99 percent sub-mechanism efficiency, it contributes a measurable upward shift to the cell's overall round-trip efficiency relative to a configuration without the secondary chemistry.

The specification projects the round-trip energy efficiency for a cell incorporating the secondary storage in the range of approximately 86 to 94 percent, an elevation over the principal-chemistry-only efficiency of approximately 82 to 92 percent. The improvement is most pronounced in deep-discharge applications where the mechanical-collapse pathway dominates total discharge, and is more modest in shallow-discharge applications where the principal-chemistry electron-drain pathway dominates.

## The Transmutation Catalyst

The carbon state change that enables this secondary chemistry is catalyzed in the disclosed cell by a single multifunctional additive at low loading. The additive simultaneously serves two functions: catalysis of the carbon state change from gel-resident graphenic configuration to metal-coordinated intercalated configuration during dynamic flake expansion, which enables the secondary storage; and stress-activated supplementary conduction during peak power events. A single species is preferred over multiple separate additives because multiple additive types introduce parasitic chemical and electronic interference that compromises both functions.

Admissible compositions include, without limitation, MXene nanoflakes of the general formula Mn+1XnTx, with specific compositions including Ti3C2Tx, V2CTx, Nb2CTx, and Mo2CTx; transition metal dichalcogenide nanoparticles of the general formula MX2, including MoS2, WS2, and MoSe2; and functionalized graphene-class composites incorporating Group V/VI heteroatoms and stress-responsive nano-domains. The MXenes catalyze the transmutation through their carbide structure bridging graphenic carbon and metal-coordinated carbon and through their exposed surface metal sites catalyzing C-metal bond formation. The additive loading is in the range of approximately 0.4 to 1.2 weight percent of total gel mass, with preferred loading of approximately 0.6 to 0.9 weight percent; below the range both functions are insufficient, and above it the additive forms percolating conductive networks at rest and over-saturates the transmutation catalytic pathway.

## Disclosure Scope

This article describes subject matter disclosed in U.S. Provisional Application No. 64/055,649. The mechanisms, ranges, and outcome terms stated here, including the carbon-hydrogen binding energies, the additional-capacity percentages, the sub-mechanism and overall round-trip efficiency ranges, the additive loading range, and the named additive compositions, are those recited in that filing. The numerical values disclosed in the provisional are characterized in the specification as projections. Nothing here extends beyond the disclosure of that application.

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## Hydrogen-Aluminum Energy Cell (/h-al-battery)

All 40 steps → (/inventive-steps)

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)
- Hydrogen-Locked Expanded State: Surface-Energy Inversion as a Positive-Feedback Capacity Mechanism (/articles/h-al-battery/hydrogen-locked-expanded-state)
- **Secondary Carbon-Hydrogen Storage on Transmuted Intercalated Carbon (/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)
- Boron Doping of the Carbon Framework as a Multi-Function 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)

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