FIREFLY ENERGY

Carbon-foam VRLA batteries for modern energy storage

Technology White Paper (Updated)

Application-led guidance for reliability-first power systems

PREPARED FOR PARTNERS, OEMS, INTEGRATORS, AND END USERS

Executive Summary

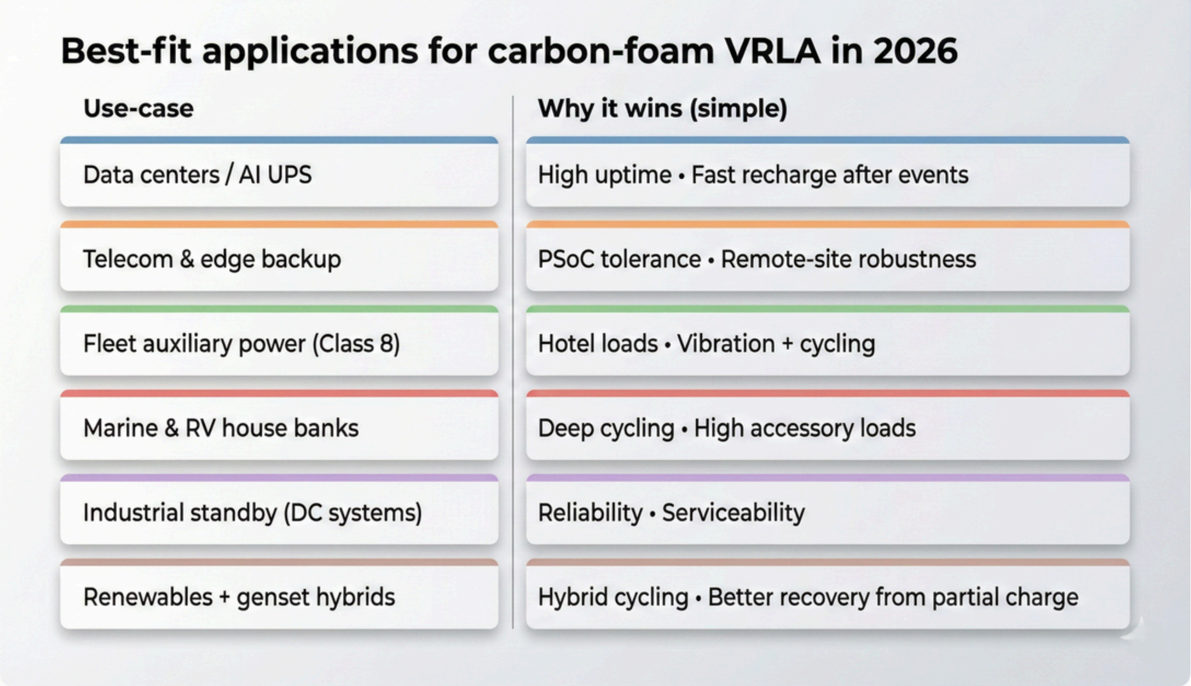
Energy storage buyers in 2026 are optimizing for uptime economics: fast recovery after outages, partial-state-of-charge (PSoC) operation, predictable field service, and safe deployment at scale. Firefly's carbon-foam electrode architecture (Microcell™ 3D²) modernizes the familiar VRLA platform by improving charge transfer, thermal behavior, and cycling robustness - particularly in high-availability infrastructure where reliability and serviceability are non-negotiable.

This paper explains the engineering rationale for carbon-foam VRLA, where it fits relative to conventional VRLA and lithium-ion systems, and how to integrate it (charging, monitoring, and maintenance) across common use-cases: data centers/AI ride-through, telecom and edge backup, fleet auxiliary power, marine/RV house loads, and industrial standby.

What energy storage requires in 2026

Across critical power and mobility-adjacent use-cases, design priorities have converged on:

- Rapid recovery after events (recharge time matters as much as discharge time).
- Tolerance to PSoC duty cycles (especially when generators/alternators top up intermittently).
- Thermal resilience and predictable life in hot engine rooms, outdoor cabinets, and packed UPS rooms.
- Serviceability, safety, and compliance at scale (field swaps, logistics, and recycling).
- Total cost of ownership (TCO), not just upfront price.



Best-fit applications for carbon-foam VRLA in 2026

Use-case	Why it wins (simple)
Data centers / AI UPS	High uptime • Fast recharge after events
Telecom & edge backup	PSoC tolerance • Remote-site robustness
Fleet auxiliary power (Class 8)	Hotel loads • Vibration + cycling
Marine & RV house banks	Deep cycling • High accessory loads
Industrial standby (DC systems)	Reliability • Serviceability
Renewables + genset hybrids	Hybrid cycling • Better recovery from partial charge

Figure 1. Where carbon-foam VRLA can create measurable uptime value.

Technology overview: carbon-foam electrode architecture

Conventional lead-acid plates rely on a metal grid and pasted active material. Under demanding cycling, electrochemical transport limitations and non-uniform reactions can accelerate degradation mechanisms such as sulfation and localized heating. Firefly's approach replaces key current-collection and transport paths with a three-dimensional, conductive carbon-foam scaffold, creating a highly interconnected structure that supports improved charge acceptance and more uniform utilization of active material.

The result is a VRLA-format battery designed to handle higher cycling intensity and PSoC operation while retaining the practical advantages of lead-acid systems: mature safety expectations, broad field familiarity, and well-established recycling streams.

Figure 2. Schematic comparison: conventional grid + paste vs 3D carbon-foam scaffold.

System Integration Guidance

The best battery will underperform if the system is not tuned for its duty cycle. Use the following guidelines to capture cycle life and recharge performance:

- Define the mission profile: outage duration, recharge window, depth of discharge, ambient temperature, and event frequency.
- Set a charger/alternator profile that prioritizes full recovery without excessive overcharge.
- Use temperature compensation where practical and ensure adequate airflow around strings/racks.
- Monitor voltage, current, and temperature; trend internal resistance/impedance as a health indicator.
- Design for safe service: access clearances, lifting/handling, and standard operating procedures for swaps.

Why it performs differently: key mechanisms

1) Charge acceptance and faster recovery

In high-availability systems, batteries are often asked to discharge briefly and then recover quickly. Carbon-foam architecture can support improved charge transfer by providing high surface area and short diffusion paths, enabling faster return to readiness (especially in mid-SOC ranges).

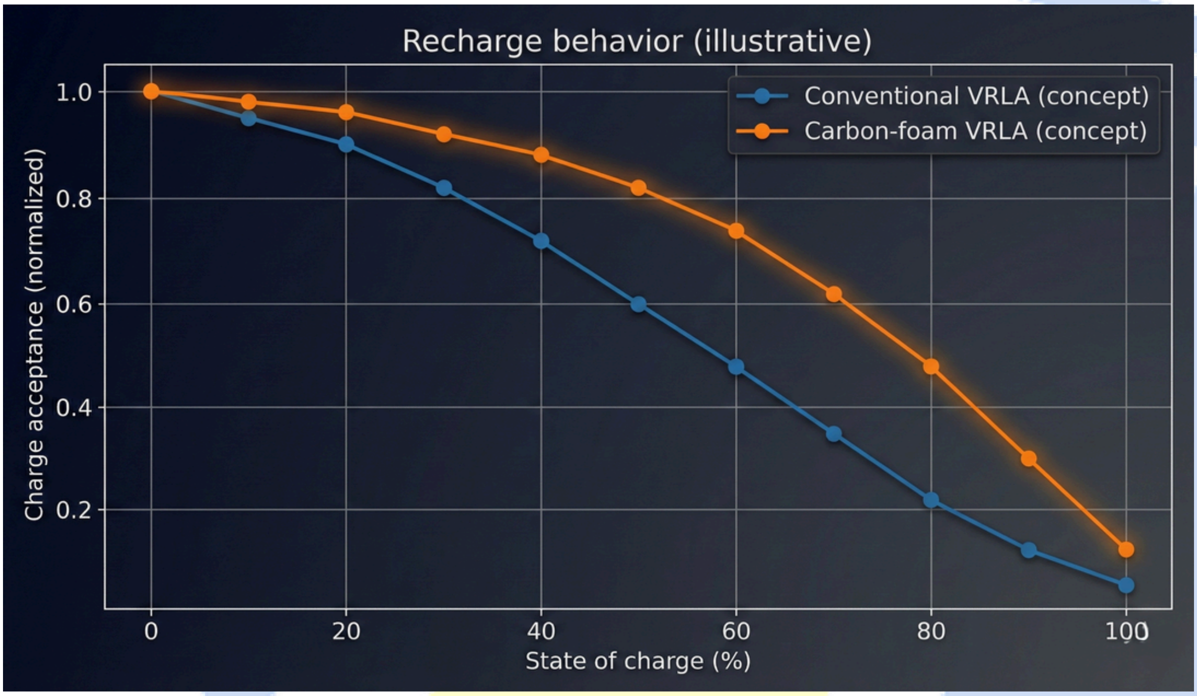


Figure 3. Illustrative recharge behavior (conceptual): charge acceptance vs state of charge.

2) Partial-state-of-charge (PSoC) tolerance

Many real-world duty cycles (telecom, hybrid genset + renewables, fleet auxiliary loads) keep batteries in a partial SOC band. Carbon-foam electrodes are engineered to reduce sensitivity to sulfation and help maintain usable capacity over repeated PSoC cycling.

3) Thermal behavior and reliability in harsh environments

Heat is an enemy of battery life. By improving internal transport and reducing localized reaction hot spots, carbon-foam designs aim to lower thermal stress and support more stable operation in hot cabinets, engine rooms, and tightly packed UPS spaces.

4) Mechanical robustness

For mobile and marine use, vibration and shock contribute to premature failures. A structurally supportive electrode architecture and optimized plate construction help improve resilience in trucking, RV, and marine environments.

Where to deploy: application playbooks

Data centers, AI infrastructure, and UPS ride-through

- Best fit: short-duration ride-through with rapid recovery between events and strict up-time targets.
- Engineering focus: string balancing, thermal management, and monitoring integration.
- Commercial focus: reduced service events and predictable maintenance windows.

Telecom, edge, and remote cabinets

- ·Best fit: PSoC operation with intermittent recharge, mixed loads, and hot outdoor enclosures.
- ·Engineering focus: temperature compensation, enclosure thermal design, and remote monitoring.
- ·Commercial focus: fewer truck rolls and longer field intervals.

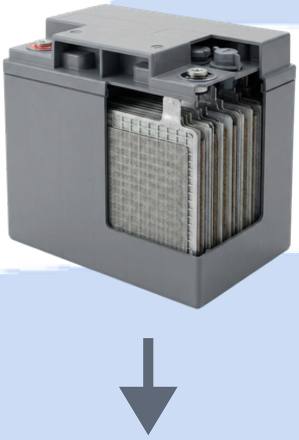
Fleet auxiliary power (Class 8 hotel loads, idle reduction)

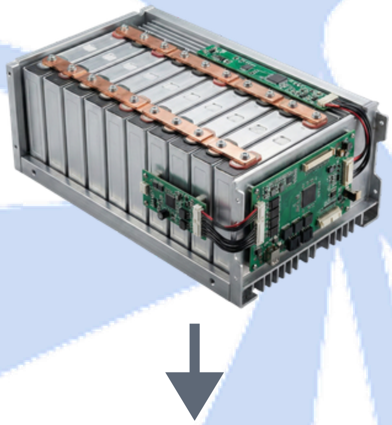
- ·Best fit: repeated cycling with alternator recharge, vibration exposure, and high under-hood temperatures.
- ·Engineering focus: alternator/charger matching and wiring voltage-drop control.
- ·Commercial focus: uptime and reduced downtime due to battery-related failures.

Marine and RV house loads

- ·Best fit: deep cycling, vibration, and mixed charging sources (alternator, shore power, solar).
- ·Engineering focus: charging profile alignment and cable sizing; consider smart chargers and temperature sensing.
- ·Commercial focus: longer usable life and better recovery after deep use.

Positioning: carbon-foam VRLA vs conventional VRLA vs lithium-ion





Attribute that matters in 2026	Conventional VRLA lead-acid	Firefly 3D/3D2 (carbon-foam VRLA)	Typical lithium-ion (system level)
Partial-state-of-charge tolerance	Often limited; sulfation risk grows	Designed to resist and reverse sulfation; better PSoC behavior	Generally strong; behavior BMS-managed
Recharge time after event	Moderate to slow at high SOC	Improved fast-recharge behavior via high surface area and low diffusion lengths	Often fast; charger/BMS dependent
Hot environment resilience	Life drops rapidly as temperature rises	Improved thermal transfer; cooler operation	Cell still temperature-sensitive; needs thermal management
Cold discharge power	Large derating; may need oversizing	Higher available power at low temperature	Varies; low-temp charging limits apply
Serviceability and safety	Mature; simple; low incident energy	Same lead-acid safety model; lower runaway risk	Requires BMS; many chemistries need runaway mitigation
End-of-life / circularity	Best-in-class recycling infrastructure	Recyclable in existing lead-acid streams; foam acts as fuel in smelting	Recycling improving but varies by region

Economics: TCO and operational simplicity

In critical power and fleet applications, the biggest costs often come from service logistics and downtime risk - not the battery purchase price. When evaluating options, model the full stack: installation, monitoring, maintenance labor, replacement frequency, and operational impact of failures.

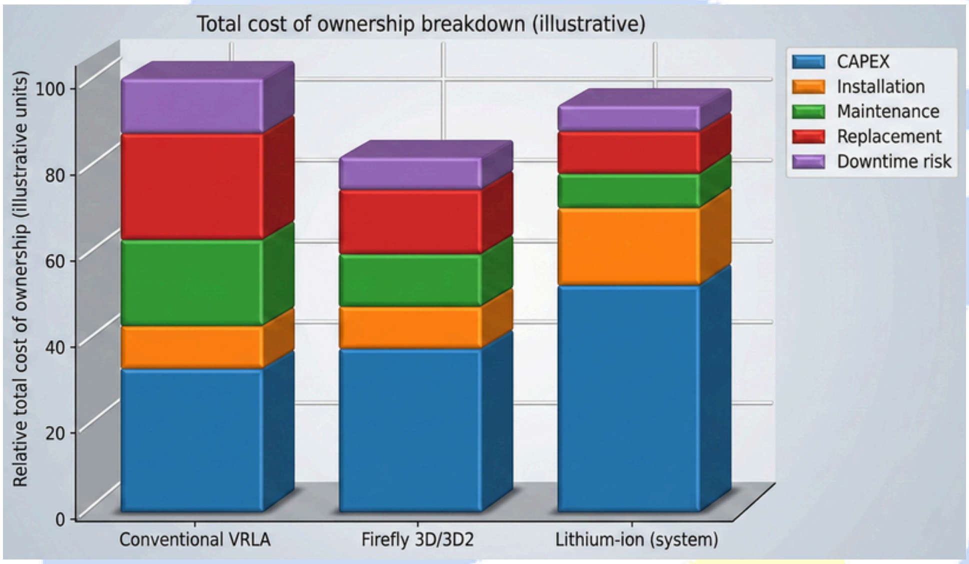


Figure 4. Illustrative TCO stack (conceptual): distribution of ownership costs by category.

Sustainability and circularity

Lead-acid systems benefit from one of the most established closed-loop recycling ecosystems in industrial manufacturing. For many buyers, that translates into practical circularity: predictable collection, high recovery, and established secondary material flows.

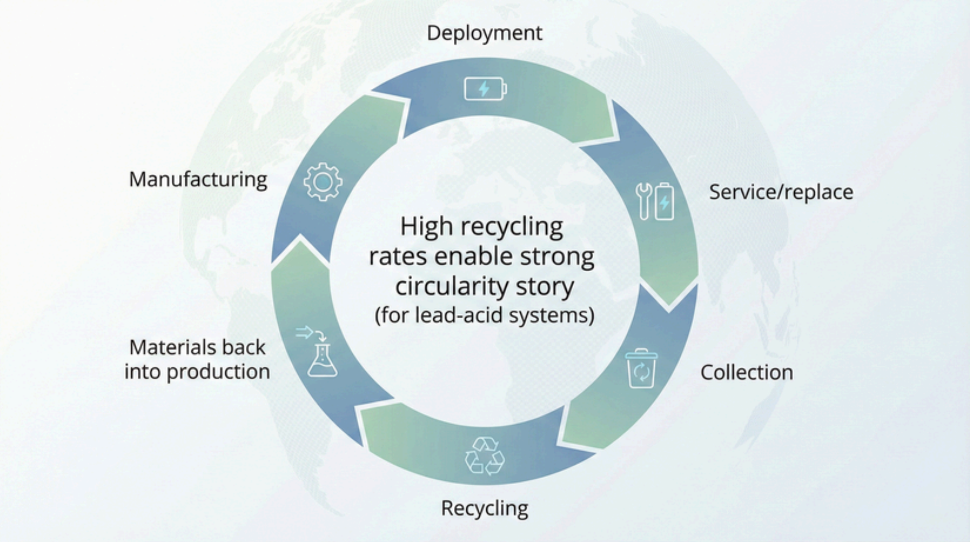


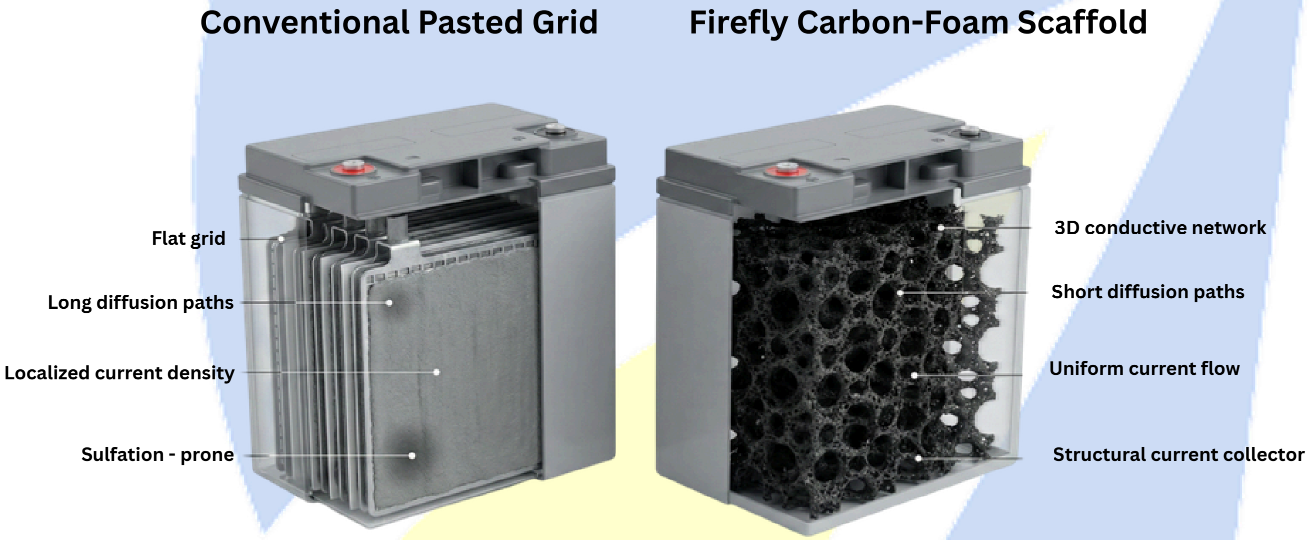
Figure 5. Circularity loop: the lead-acid recycling ecosystem (high-level schematic).

Economics: TCO and operational simplicity

A fast, low-risk adoption path typically follows:

- Sizing workshop: confirm discharge, recharge, temperature, and redundancy requirements.
- Pilot: deploy a limited number of strings or vehicles and instrument for voltage/current/temperature logging.
- Benchmark: compare recharge time, event recovery, and service events against baseline technology.
- Scale: roll out with a standardized commissioning checklist and monitoring thresholds.

Appendix A: Technical Foundations and Legacy Validation



Conventional Pasted Grid

Firefly Carbon-Foam Scaffold

Figure A1. Conceptual comparison of conventional pasted-grid plates and carbon-foam electrode architecture.

A1. Historical Origin of the Carbon-Foam Battery Concept

The carbon-foam lead-acid battery architecture was originally conceived to solve durability and reliability challenges observed in heavy-duty industrial and motive power applications. Traditional lead-acid designs, optimized for cost and short-duration discharge, demonstrated rapid degradation when subjected to partial-state-of-charge operation, vibration, elevated temperatures, and frequent cycling.

Rather than incremental improvements to grid alloys or additives, the original Firefly research program pursued a fundamental architectural change: replacing the conventional negative plate grid with a three-dimensional, electrically conductive carbon scaffold capable of acting as both current collector and structural support.

This work formed the basis of the original Firefly white paper and established the foundation for subsequent commercial development.

A2. Carbon Foam as an Electrode Architecture (Not an Additive)

Unlike carbon black, graphite, or other conductive additives mixed into paste formulations, reticulated carbon foam functions as the electrode framework itself. Lead active material is integrated within the open-cell structure, resulting in:

- Extremely high effective surface area
- Continuous electronic conductivity
- Short ionic diffusion paths
- Mechanical integrity under cycling and vibration

This distinction is central to understanding why carbon-foam VRLA behaves differently from enhanced AGM designs.

A3. Legacy Failure Modes in conventional VRLA Systems

Extensive analysis in the original Firefly documentation identified four dominant degradation mechanisms in conventional VRLA batteries:

- Sulfation accumulation during partial recharge
- Acid stratification under low agitation conditions
- Localized heating caused by uneven current density
- Mechanical shedding and loss of electrical contact

These mechanisms interact and accelerate total capacity fade and resistance growth over time.

A4. Architectural Mitigation Enabled by Carbon Foam

By distributing current flow throughout a three-dimensional network and minimizing diffusion distances, carbon foam fundamentally alters the electrochemical environment of the negative electrode. This results in:

- Reduced sulfation accumulation
- Faster charge recovery
- More uniform thermal behavior
- Improved mechanical durability

Importantly, these benefits arise from geometry and physics rather than chemistry changes.

A5. Validation and Evolution into Modern 3D / 3D2 Designs

The original Firefly white paper documented laboratory and field validation demonstrating improved charge acceptance, cycle life, and resistance to vibration-related degradation. Subsequent generations (3D and 3D2 architectures) refined foam structure, integration methods, and manufacturing consistency while preserving the original architectural principles.

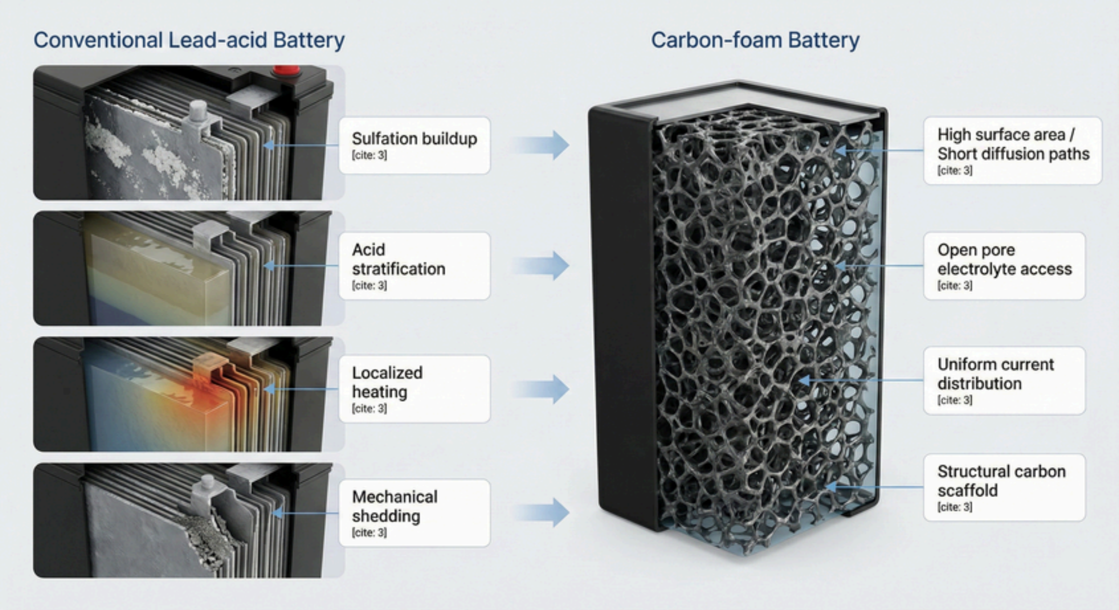
A6. Relevance to Modern Energy Storage Systems

While originally developed for industrial reliability, carbon-foam VRLA architecture is particularly well-suited to modern energy storage environments characterized by:

- Frequent shallow cycling
- Partial-state-of-charge operation
- High accessory loads
- Demand for serviceability and recyclability

This appendix preserves the technical lineage underpinning the updated white paper and ensures continuity between Firefly’s original research and current system-level deployments

How Carbon - Foam Architecture Alters Legacy Failure Modes



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