Radioisotope Portable Power Unit: A Compact, Long-Duration Radioisotope Power Unit for Autonomous Systems

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ABSTRACT

Long-duration autonomous systems require continuous power where solar illumination is unavailable, battery-only storage is insufficient, and maintenance access is impossible. RPPU-0 is a compact, sealed, decay-driven radioisotope power architecture that directs charged-particle flux from radioisotope decay through a governed extraction topology and regulated DC bus.

The paper defines a governed decay-ionised domain within a static physical enclosure. Dynamic governed topology constraints inherited from IDG-2 define the permitted field-state envelope across the full decay life. Field-assisted extraction, watts-per-curie bus regulation, daughter-product filtering, feedthrough degradation management, inductive energy recovery, safety interlocks, environmental hardening, telemetry, and flight housing are integrated as one sealed RPPU-0 module.

Version 5 extends the long-duration engineering package with two passive, sealed-interface elements. The Metamaterial Boundary Layer (MBL) smooths selected interface gradients, reduces mapped local harmonic content, and reinforces the designed curvature topology. GECDS-IDG is a segmented, electrically isolated governed eddy-current damping shell that manages selected low-frequency transient response around the curvature hardware and structural frame. Curvature remains the primary stability mechanism. DIGSP-IDG coordinates the permitted topology, boundary condition, damping response, extraction state, safety state, and regulated bus through its established supervisory hierarchy.

RPPU-0 is designed as a 24 VDC nominal power architecture in the 5–50 W class. Its platform expressions include lunar and planetary robotics, deep-space micro-probes, surface infrastructure, harsh-environment industrial sensors, emergency autonomous power nodes, and RPPU-Lite battery-sustainment configurations for long-duration UAV and autonomous-system operations. In the RPPU-Lite expression, the sealed core maintains the battery reserve through continuous governed DC delivery while the battery provides propulsion, payload, manoeuvre, and avionics peaks.

The manuscript develops the RPPU-0 system architecture, power-bus specification, environmental hardening, packaging, long-duration control, safety envelope, platform expressions, comparative architecture, and RPPU-1 handoff. Its evidence pathway is defined through the G1–G10 graduation programme, which carries the sealed core through bench integration, vacuum qualification, environmental qualification, and flight-hardware transfer. Version 5 includes a hardware safety layer independent of DIGSP software, a dose-rate term in the feedthrough insulation model, radiation-tolerant Sm2Co17 mirror magnets, and an accelerated-dose qualification gate G10.

RPPU-0 is an author-owned engineering integration architecture. The paper defines the sealed decay-ionised core, extraction, boundary, damping, safety, and bus package required for long-duration autonomous power deployment.

Nomenclature

Symbol	Definition	Source
RPPU	Radioisotope Portable Power Unit (acronym)	IDG-4
Psi_RPPU(t)	Full RPPU topology state vector	IDG-4
R_ins	Feedthrough insulation resistance under cumulative dose (Ohm)	IDG-4
W/C_long	Long-duration watts-per-curie stability metric (W/Ci)	IDG-4
Omega_RPPU	Full RPPU governability envelope	IDG-4
I_recovered	Inductive energy recovered from Class-C transitions (W)	IDG-4
epsilon_crit	Critical back-stream electron threshold	IDG-3/4
epsilon_se	Secondary electron back-stream fraction	IDG-3
q; q/m(t)	q: governed extracted current (A); q/m(t): evolving isotope-vector charge-	IDG-4
eta_long	Long-duration extraction efficiency	IDG-4
Omega_DTG	Dynamic topological governability envelope	IDG-2
chi	Angular-spread compression ratio	IDG-3
rho	Space-charge density in extraction channel (C/m^3)	IDG-3
MBL	Metamaterial Boundary Layer at the RPPU interface	IDG-4 V5
GECDS-IDG	Governed Eddy-Current Damping Shell for RPPU transient management	IDG-4 V5
Boundary	Mapped gradient and harmonic content within selected MBL envelope	IDG-4 V5
Damping	GECDS-IDG transient response within selected decay envelope	IDG-4 V5

MISSION DEFINITION

RPPU-0 (Radioisotope Portable Power Unit) is a compact, governed, decay-driven power unit for autonomous systems operating where solar is unavailable, battery endurance is insufficient, and maintenance is impractical. It is a continuous-power core for long-duration, high-reliability missions.

RTGs convert decay heat to electricity through thermoelectrics; the charged-particle flux produced by decay remains unused. RPPU-0 directs that flux through a governed decay-ionised domain whose constrained field state sets extraction stability and bus performance. The architecture delivers stable, continuous, low-noise DC for decade-scale autonomous operation.

TARGET PLATFORMS

RPPU-0 is platform-agnostic. A single unit design serves multiple mission classes without redesign. Platform adaptation is handled at the mechanical interface and telemetry protocol level.

2.1 Lunar and Planetary Robotics

ATLAS is the primary near-term deployment. The same unit serves autonomous excavators, regolith processors, sample-handling manipulators, crater-shadow robotics, and rover subsystems operating through the 14-day lunar night without solar illumination.

2.2 Deep-Space Micro-Probes

CubeSat-scale probes, outer-planet micro-landers, comet and asteroid micro-platforms, and long-duration sensor nodes all require continuous power at the 5-50 W level in environments where solar flux is negligible.

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2.3 Surface Infrastructure

Lunar night-proof beacons, seismic stations, communications relays, navigation nodes, and autonomous construction modules require power sources that operate continuously for years without servicing.

2.4 Harsh-Environment Industrial Sensors

Deep-borehole instrumentation, offshore monitoring platforms, arctic and antarctic autonomous stations, and volcanic or seismic sensor networks operate in environments where battery replacement is impractical and solar is unreliable.

2.5 Emergency Autonomous Power Nodes

Disaster-zone communications repeaters, autonomous drones, sensor networks, and micro-generators use rapid-deployment, long-duration power. The lightweight Sr-90 RPPU-Lite variant (Section 16) serves the UAV and autonomous-drone segment with a dedicated mass budget, power-scaling tables, and an operating architecture for 5-30 W governed DC at 5.5-8.0 kg.

2.6 Micro-Propulsion Demonstrators

Attitude-control jets, station-keeping units, and micro-thruster experiments can be powered by RPPU-0 as an integrated power and propulsion subsystem when coupled with governed micro-thruster architectures.

2.7 GRFF Power Core (Lunar + Terrestrial)

RPPU-0 provides the primary power core for a single GRFF-class field unit. A 10–30 W governed DC bus runs the GRFF coil drivers, suppression rails, and DIGSP telemetry continuously. On the Moon, the unit carries GRFF operation through the full 14-day lunar night without solar support.

The RPPU-0 bus is stable, low-noise, and compatible with GRFF driver electronics. In graphite-handling plants, battery-material facilities, flare-gas sites, hydrogen plants, and other harsh industrial environments, an RPPU-powered GRFF module provides long-duration EM dust governance without grid power or local generators. RPPU-0 therefore supplies both lunar GRFF power and standalone terrestrial EM-governance power.

2.8 Long-Duration Emergency Battery Support

RPPU-0 functions as a sealed long-duration core for critical battery-backed systems requiring 10–20 years of survival power. The unit supplies continuous governed DC in the 5–50 W class. Batteries supply short-duration peak draw while RPPU-0 sustains battery charge and the emergency bus independent of solar, grid, or generator status.

This configuration serves lunar safemode life-support battery stacks and terrestrial redundant-survival systems. Remote sensor nodes, deep-borehole instruments, emergency communication repeaters, and other battery-backed systems retain a governed charge source after loss of primary power. The emergency bus remains available across the design life of the unit.

Lightweight Long-Duration Emergency Core

RPPU-0 is a compact sealed power module with a mass under 8 kg and a governed output in the 5–50 W class. The unit has no moving parts or consumables and is configured for 10–20 years of unattended operation. This mass and reliability profile defines the RPPU-0 emergency-power class.

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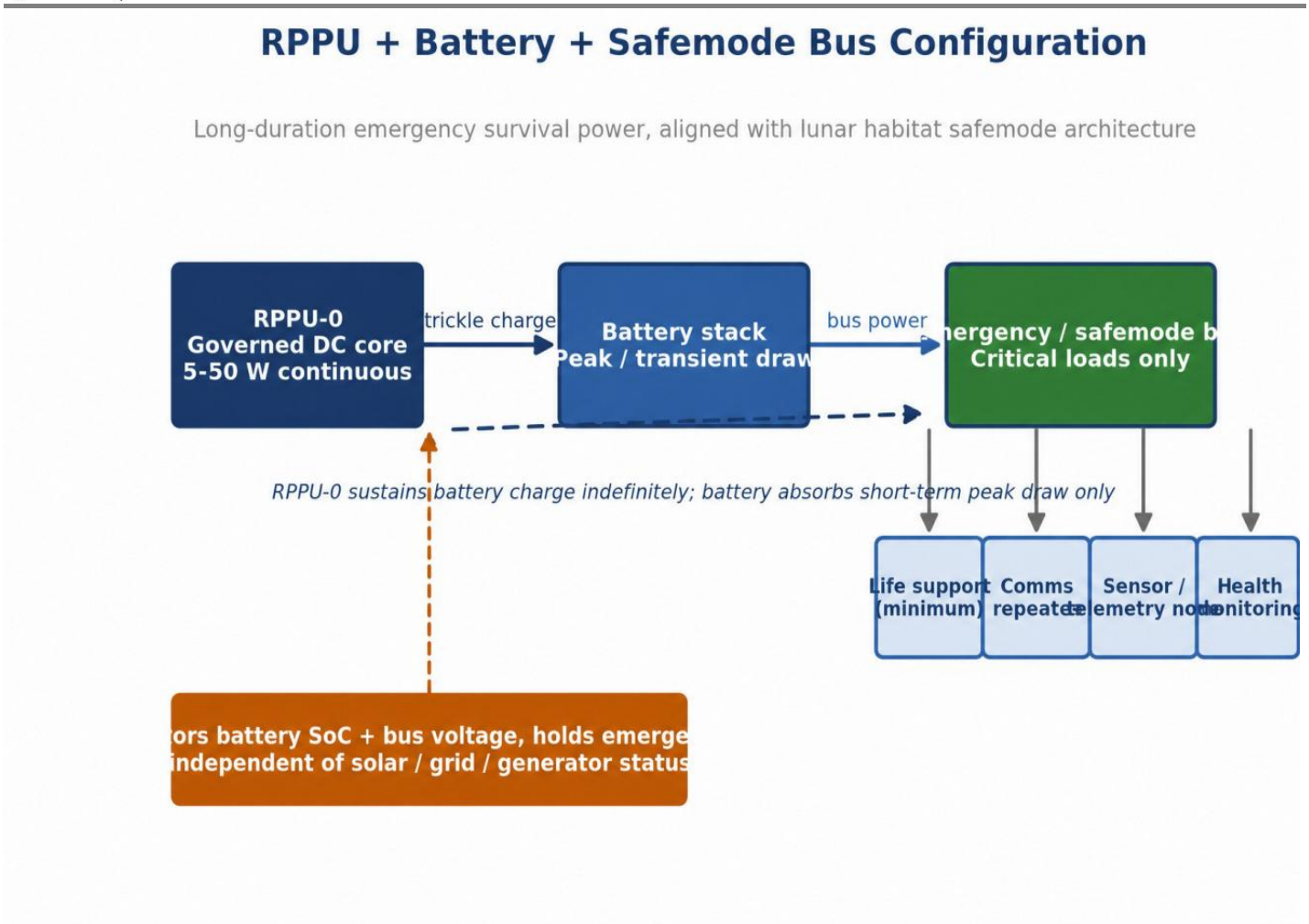


Figure 1. RPPU + battery + safemode bus configuration, aligned with lunar habitat safemode architecture.

Table 1. Target platform summary.

Platform category	Examples	Power	Environment
Lunar/planetary	ATLAS arm, excavators,	10-50 W	Vacuum, night, dust
Deep-space micro-	CubeSats, micro-landers	5-20 W	Deep space, radiation
Surface infrastructure	Beacons, seismic, comm	10-30 W	Surface, thermal cycling
Industrial sensors	Boreholes, offshore, arctic	5-15 W	Terrestrial harsh
Emergency power	Comm repeaters, drones	5-30 W	Rapid deployment
Micro-propulsion	Attitude control, station-keeping	5-10 W	Orbital, vacuum

RPPU-0 SYSTEM ARCHITECTURE

RPPU-0 combines the governed decay-ionised domain of IDG-1, the dynamic governed topology constraints of IDG-2, the field-assisted extraction stack of IDG-3, and the long-duration engineering additions of IDG-4 in one sealed module. IDG-1 through IDG-3 establish the governed domain, topology envelope, and extraction stack. IDG-4 carries that lineage into the long-duration package, safety envelope, power bus, and flight-interface architecture.

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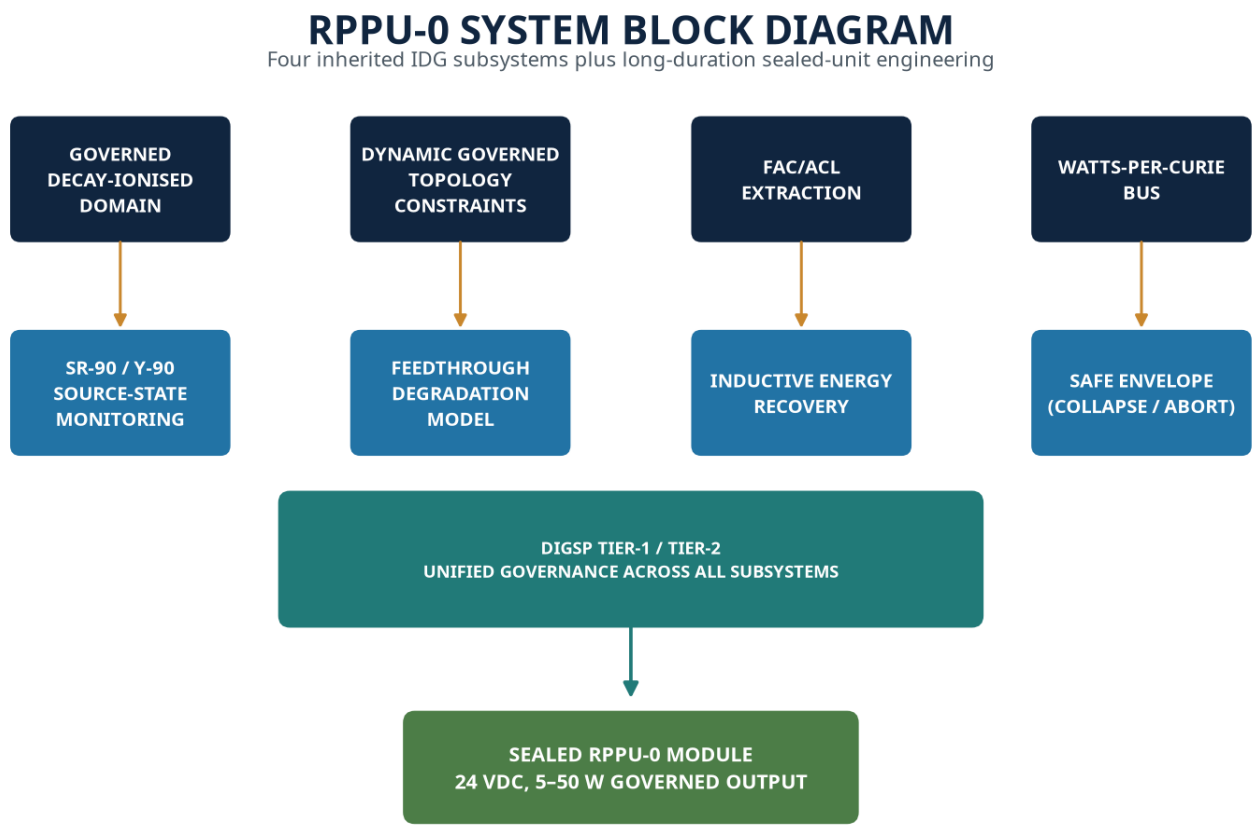


Figure 2. RPPU-0 system block diagram: four inherited subsystems plus six IDG-4 engineering additions.

Table 2. RPPU-0 subsystem architecture.

Subsystem	Source	Engineering Function	Governed By
Governed decay-ionised domain	IDG-1	Sustains decay-ionised domain	DIGSP-Tier-1
Dynamic governed topology constraints	IDG-2	Defines the permitted static RPPU topology envelope	DIGSP-Tier-1
FAC/ACL/SCR extraction	IDG-3	Converts topology into current	DIGSP-Tier-2
Watts-per-curie bus	IDG-3	Delivers governed DC power	DIGSP-Tier-2
Daughter-product filtering	IDG-4	Retunes ACL as q/m evolves	DIGSP-Tier-2
Feedthrough degradation model	IDG-4	Tracks R_ins, derates V_accel	DIGSP-Tier-2
Inductive energy recovery	IDG-4	Captures Class-C EMF	DIGSP-Tier-2
Safety envelope	IDG-4	Collapse and abort protocols	DIGSP-Tier-1/2
Flight housing	IDG-4	Containment, shielding	Passive
Telemetry and bus regulation	IDG-4	Monitoring, interlocks, conditioning	DIGSP-Tier-2
Metamaterial Boundary Layer	IDG-4 V5	Passive EM medium at the RPPU boundary; smooths selected field gradients and reinforces curvature topology	DIGSP-IDG Tier 0/1

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GECDS-IDG	IDG-4 V5	Segmented isolated damping shell; manages selected low-transient distortions without altering the sealed static geometry frequency	DIGSP-G Tier 0/1

3.1 Governed Boundary and Damping Architecture

3.1.1 Metamaterial Boundary Layer

IDG-4 Version 5 places a passive Metamaterial Boundary Layer at the selected RPPU interface. The graded electromagnetic medium smooths selected field gradients, reduces mapped local harmonic content, and reinforces the designed curvature topology. The layer carries no driven current and is integrated with the sealed core geometry.

3.1.2 GECDS-IDG

GECDS-IDG places segmented conductive plates around the RPPU curvature hardware and structural frame. The segments are electrically isolated from one another and from the main support structure.

The shell manages selected low-frequency transient response while preserving the selected static curvature geometry without establishing additional transport paths.

3.1.3 Curvature-Defined Governance and DIGSP-IDG

Curvature remains the primary IDG-4 stability mechanism. MBL and GECDS-IDG reinforce the selected geometry passively. DIGSP-IDG Tier 0 monitors governability, curvature, boundary-map, damping, extraction, safety, and bus-regulation state; Tier 1 maintains the selected equilibrium and curvature-layer envelope; Tier 2 executes bounded correction of the approved field and extraction settings. IDG-4 Version 5 governs through sealed static geometry, passive boundary conditioning, selected damping, and supervised extraction control.

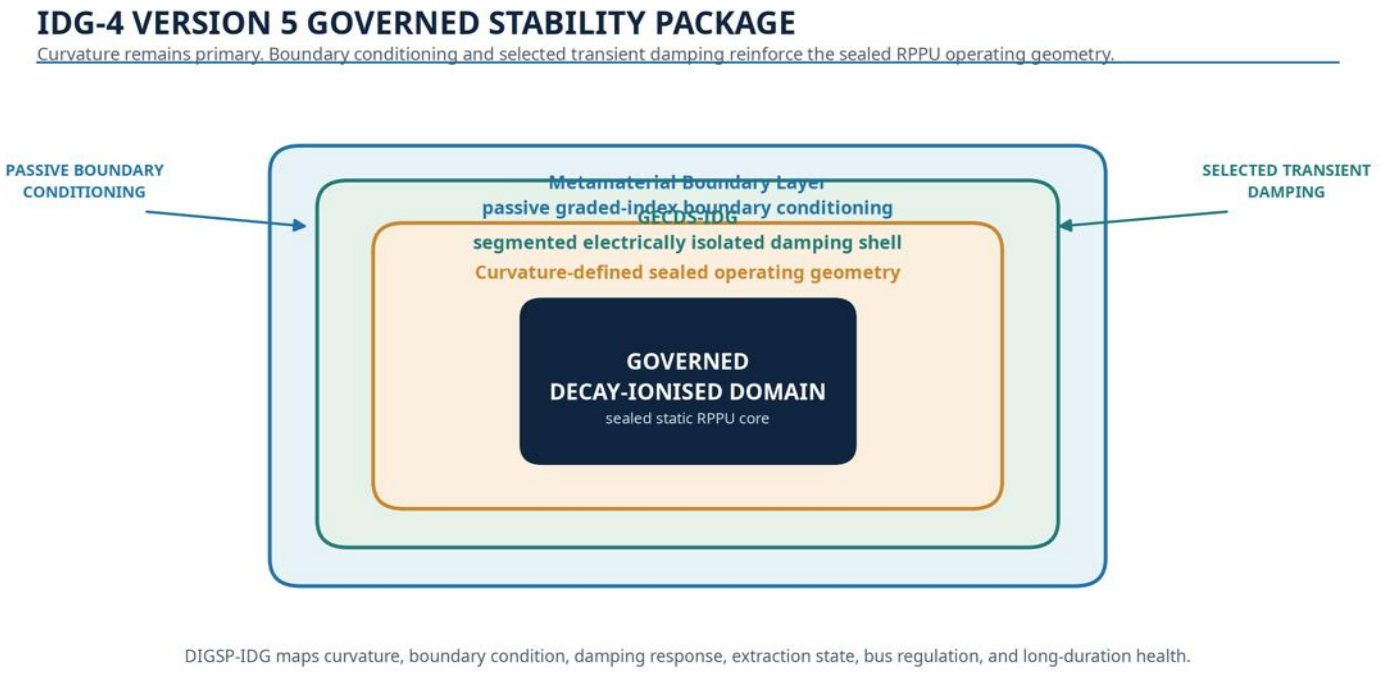


Figure 3. IDG-4 Version 5 governed stability package: curvature topology, MBL, and GECDS-IDG around the sealed governed decay-ionised domain.

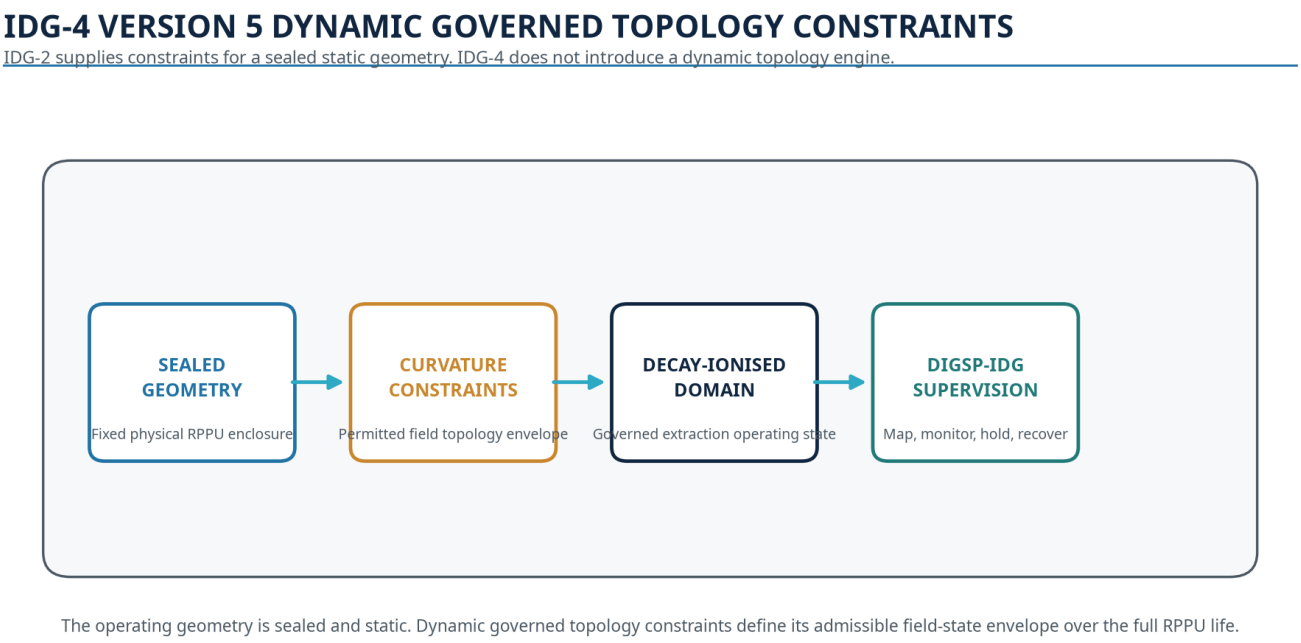


Figure 4. IDG-4 Version 5 dynamic governed topology constraints: a static sealed geometry defines the permitted operating envelope across the RPPU life.

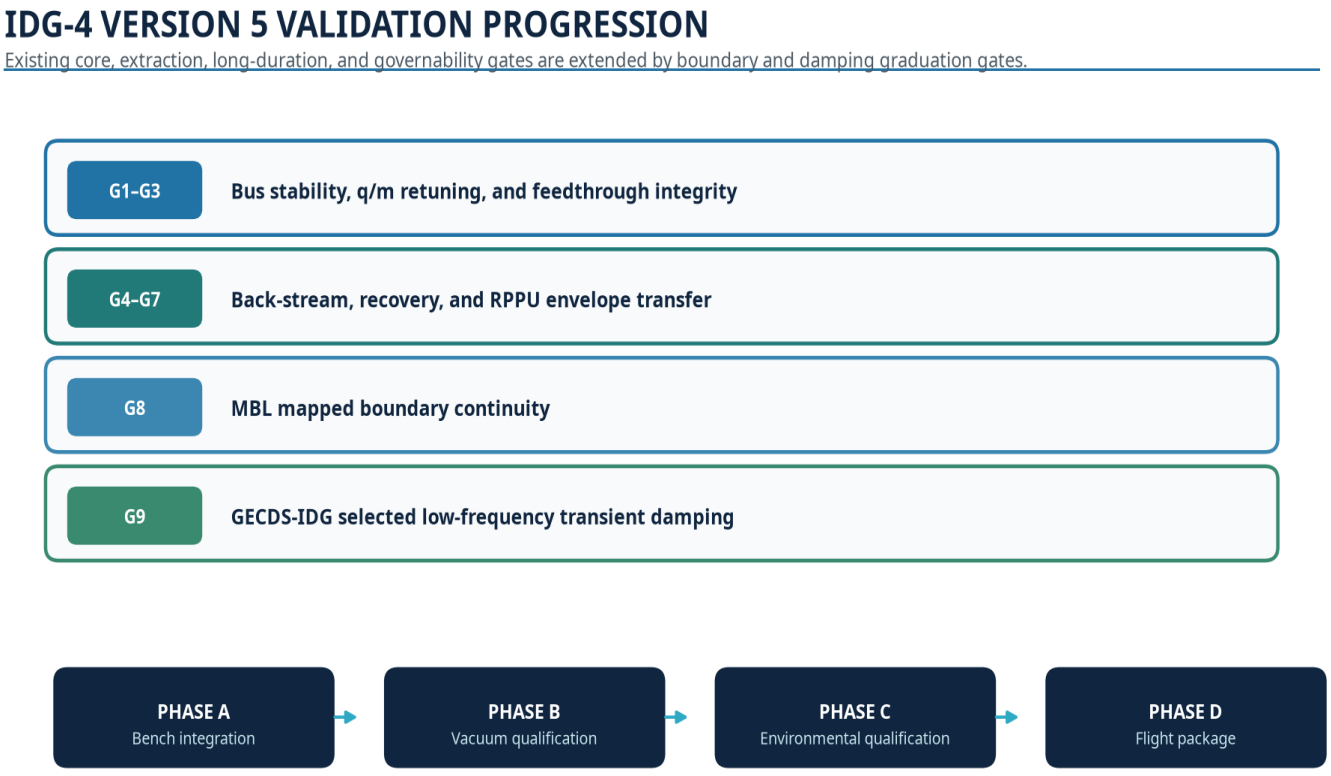


Figure 5. IDG-4 Version 5 validation progression: the retained G1 to G7 programme is extended through MBL and GECDS-IDG graduation gates G8 and G9.

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3.2 Lineage Inheritance

Table 3. Related-work lineage inheritance.

Origin	Contribution to RPPU-0
MPE-1/2	Governance formalism and stability criteria
MPE-5	Topology state vector Psi(t)
MPE-6	Lambda-governance convergence
MPE-8	Dynamic curvature-suppression invariant
IDG-1	Static governed topology, passive confinement, decay-driven
IDG-2	Dynamic governed topology, Omega_DTG envelope
IDG-3	Governed extraction, watts-per-curie scaling, FAC/ACL/SCR
IDG-4	Long-duration engineering, safety envelope, packaging, ConOps

PLATFORM-AGNOSTIC REQUIREMENTS

Table 4. Platform-agnostic requirements.

Requirement	Specification	Rationale
Continuous	5-50 W DC, regulated	Covers all platform power classes
Bus voltage	24 VDC nominal (18-32 VDC	Standard spacecraft/robotics bus
Design life	10-20 years	Exceeds any single mission duration
Bus stability	Low-noise, transient-stable	Actuator and sensor compatibility
Operating	Vacuum-native	Lunar, orbital, deep-space baseline
Radiation	Sr-90 self-shielded, rad-hard	No external shielding dependency
Thermal	Operational across lunar diurnal	Passive thermal management
Maintenance	Zero	Autonomous, sealed, no consumables
Mass	6-8 kg (excluding source capsule)	First-generation unit; RPPU-1 targets
Mounting	Modular flange, vibration-isolated	Platform-agnostic mechanical interface
Boundary	Mapped interface gradient within	MBL preserves selected curvature
Transient	Selected low-frequency response	GECDS-IDG maintains curvature-layer

POWER BUS SPECIFICATION

5.1 Bus Voltage Selection

The RPPU-0 bus voltage is locked at 24 VDC nominal with a regulated band of 18-32 VDC. This selection satisfies compatibility with standard spacecraft power buses, ATLAS robotic arm actuators, CubeSat avionics, and industrial sensor interfaces. The 24 V nominal avoids low-voltage high-current inefficiency while remaining within the safe-touch voltage limit for ground handling. The regulated band provides margin for V_accel derating as feedthrough insulation degrades without requiring the host system to accommodate a voltage step change.

Bus ripple specification. The governed DC bus is specified for less than fifty millivolts peak to peak ripple across the control bandwidth. This is the governed DC-bus engineering requirement carried through the hardware test programme.

5.2 Predicted Bus Power

Source sizing for the RPPU-0 power class is given in Table 19.

Governing equation

W/C_long = [eta(t) * q * V_accel(t) + I_recovered(t)] / A(t)

A(t) is the source activity in curies, so W/C_long is the governed bus power per curie of source.

5.3 Output Connector

The baseline connector is MIL-DTL-38999 Series III for full-scale platforms and Nano-D (MIL-DTL-32139) for mass-constrained platforms. Both are qualified for vacuum, vibration, and radiation. The 9-pin baseline pinout carries DC power (2 pins), telemetry data (4 pins), safety interlock (2 pins), and chassis ground (1 pin). Voltage rating 50 VDC, current rating 3 A continuous.

ENVIRONMENTAL HARDENING

Table 5. Environmental hardening matrix.

Environment	Specification	Qualification path
Lunar vacuum	Sealed micro-cell at 0.5 atm	Thermal-vacuum
Lunar night	14-day continuous without solar	Thermal cycling
Dust exposure	Housing resistant to charged	GRFF-T/RCCA
Radiation	Sr-90 self-shielded; 100 krad TID	Component-level rad
Shock and	Launch loads per GEVS	Random vibe and shock
Thermal cycling	-180 C to +120 C, 1000+ cycles	GEVS Section 2.3.3
Microgravity	No gravity-dependent subsystems	Parabolic flight or ISS

All environmental qualification follows NASA GEVS (GSFC-STD-7000A). Thermal cycling uses Section 2.3.3 with a minimum of 8 cycles at qualification extremes and 4 at acceptance levels. Random vibration uses Section 2.4. Shock uses Section 2.5.

LONG-DURATION ENGINEERING

The long-duration programme focuses on daughter-product evolution, feedthrough radiolysis, and inductive recovery. IDG-1 through IDG-3 establish their physics basis. IDG-4 defines the monitoring, correction authority, intervention triggers, and response for each.

7.1 Daughter-Product Evolution

Sr-90 produces the Y-90 daughter within the sealed source chain. DIGSP-Tier-2 monitors the Faraday-cup profile, thermal state, and governed bus response, then maintains the approved extraction and bias settings within the selected RPPU envelope. Source-state supervision remains within the sealed static geometry and retains the selected transport boundary.

Table 6. Daughter-product parameters.

Parameter	Sr-90	Y-90 daughter	Engineering impact
Source	Sr-90 beta parent	Y-90 beta daughter	Sealed source-chain
Decay	28.8-year parent half-life	Daughter activity follows	DIGSP source-state
Extraction	Beta spectrum enters approved	No dynamic geometry or	Bounded bias and bus
Detectable	2-5 years (source decay, Zr-90	Equilibrium with Sr-90	Continuous DIGSP

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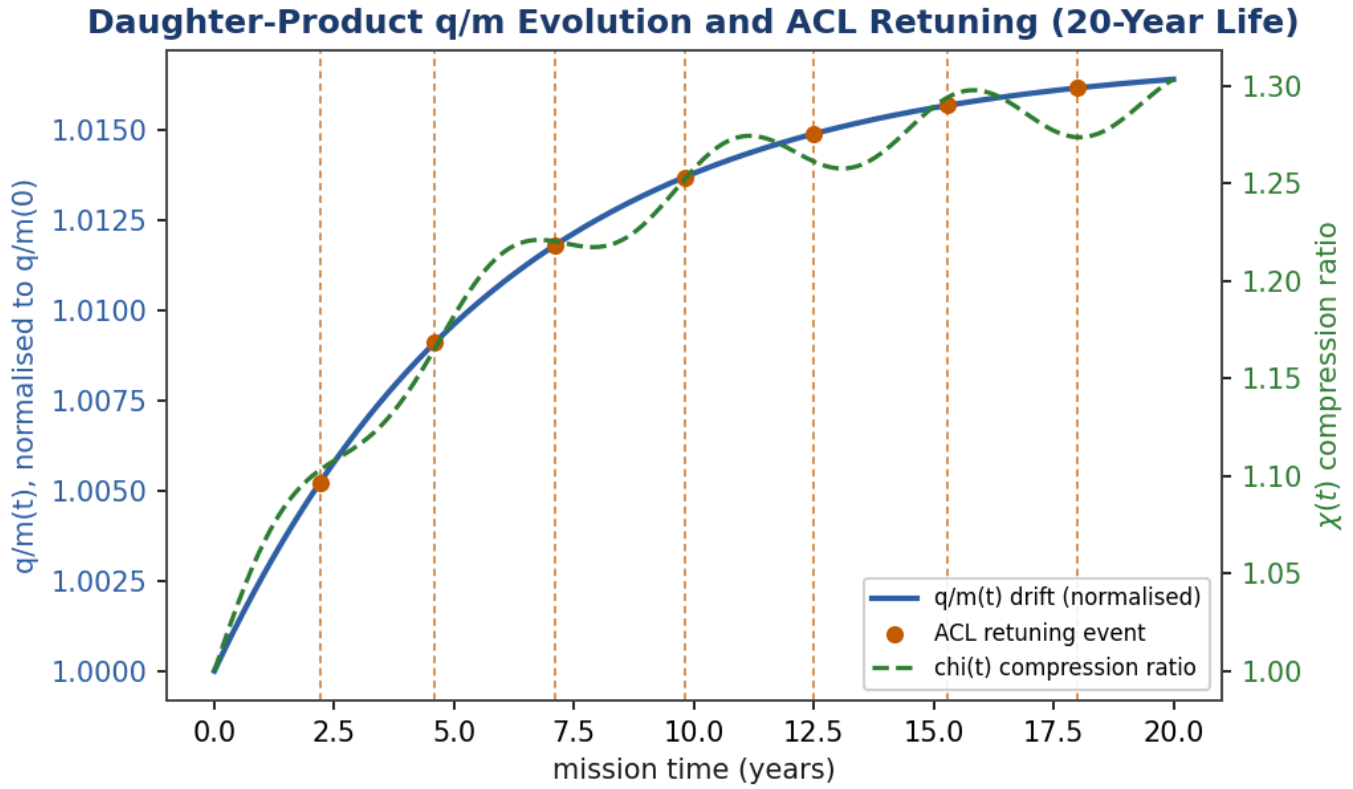


Figure 6. Daughter-product q/m evolution over 20 years with ACL retuning events and chi trajectory.

7.2 Feedthrough Radiolysis

Cumulative dose degrades feedthrough insulation resistance. Insulation leakage has two components: a permanent term that accumulates with total dose, and a radiation-induced conductivity (RIC) term set by the instantaneous dose rate. DIGSP-Tier-2 tracks R_ins via periodic impedance measurement and derates V_accel before leakage current exceeds the bus stability margin.

$$1/R_{ins}(t) = 1/(R_0 - \alpha_{dose} * D(t)) + G_{RIC} * \dot{D}(t)^{\delta}$$

$$V_{accel}(t) = V_0 * R_{ins}(t) / R_0$$

RIC in alumina and sapphire scales with dose rate to the power delta, with delta between 0.7 and 1.0. The dose rate at the feedthrough is set by source activity and shielding geometry and falls with the 28.8-year Sr-90 half-life, so the RIC term is largest at beginning of life and relaxes as the source decays. The permanent term grows with cumulative dose. R_ins,min is therefore checked at both ends of the design life.

Table 7. Feedthrough degradation parameters.

Parameter	Value	Notes
R_0	> 10^10 Ohm	Alumina or sapphire
alpha_dose	10^3-10^5 Ohm/Gy	Measured in Phase A
G_RIC	Material constant	Measured in Phase B under gamma irradiation
delta	0.7-1.0	Alumina or sapphire RIC exponent
Ddot at feedthrough	Set by source activity	Fixed by shielding geometry; decays with Sr-90
R_ins,min	10^7 Ohm	Bus stability limit
Time to R_ins,min	> 20 years (design target)	Validated from alpha_dose measured in Phase A
Monitoring	Periodic impedance	DIGSP-Tier-2 automated

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7.3 Inductive Energy Recovery

Class-C transitions produce dB/dt at the mirror throat. A pickup loop captures the EMF and feeds it into the DC bus via a rectifier. Failure mode: rectifier saturation during fast collapse, triggering Tier-2 abort and rectifier bypass.

I_recovered = k_coupling * dB/dt

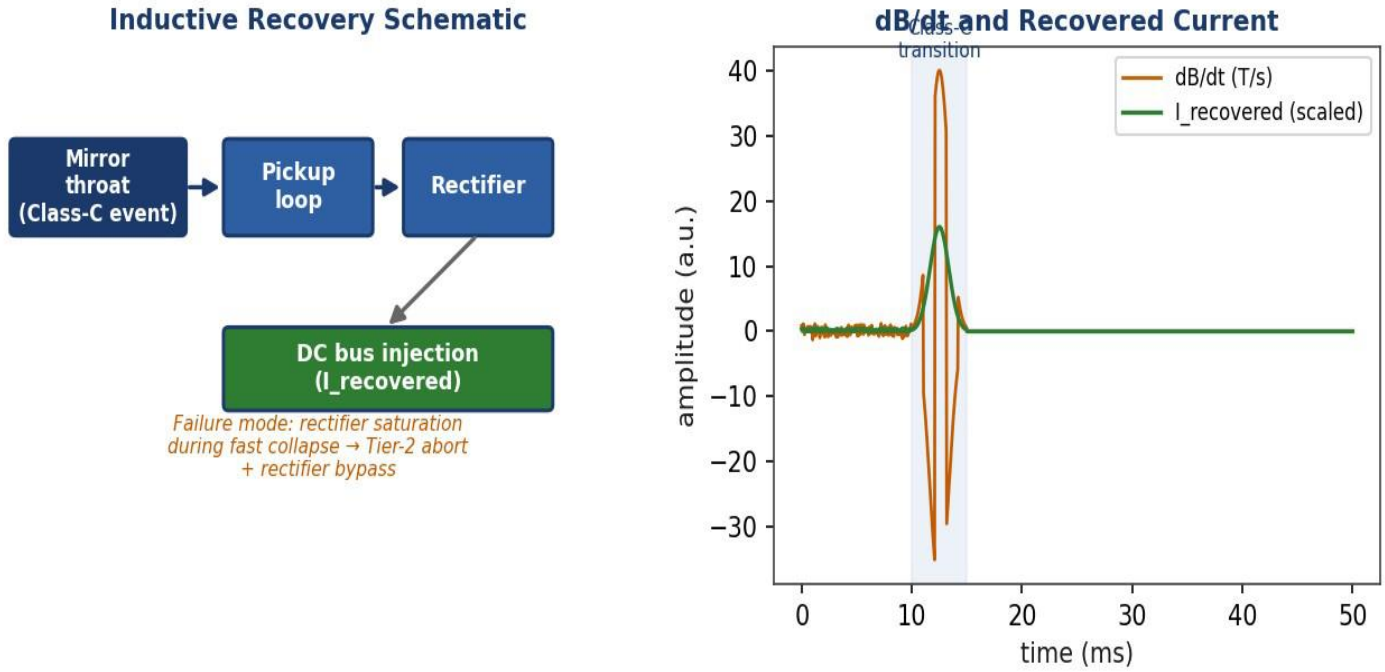


Figure 7. Inductive recovery schematic: pickup loop, rectifier, DC bus injection, dB/dt waveform.

7.4 Magnet Radiation Tolerance

The mirror magnets are samarium-cobalt (Sm2Co17). Sm2Co17 retains remanent flux under cumulative radiation dose with markedly lower loss than NdFeB, and holds its coercivity at elevated temperature. Mirror-field flux is measured by a Hall sensor at the mirror throat and reported in telemetry, so any drift in mirror ratio R_m is detected and compensated by the suppression coils before it reaches the topology constraints.

RPPU GOVERNABILITY ENVELOPE

Omega_RPPU is the intersection of Omega_DTG (IDG-2), extraction constraints (IDG-3), and long-duration constraints (IDG-4). As the system ages, Omega_RPPU contracts. The calendar date at which it reaches zero volume defines end-of-governed-life.

Table 8. Omega_RPPU constraint set.

Domain	Constraint	Source
Topology	kappa at or below kappa_max	MPE-
Suppression	S_f at or above S_f,crit	MPE-8
Bandwidth	tau_dot within tau_dot_max	IDG-2
Extraction	eta, chi, rho in admissible bands	IDG-3
Feedthrough	R_ins at or above R_ins,min	IDG-4
Isotope drift	q/m compensated by ACL	IDG-4
Back-stream	epsilon_se at or below	IDG-3/4

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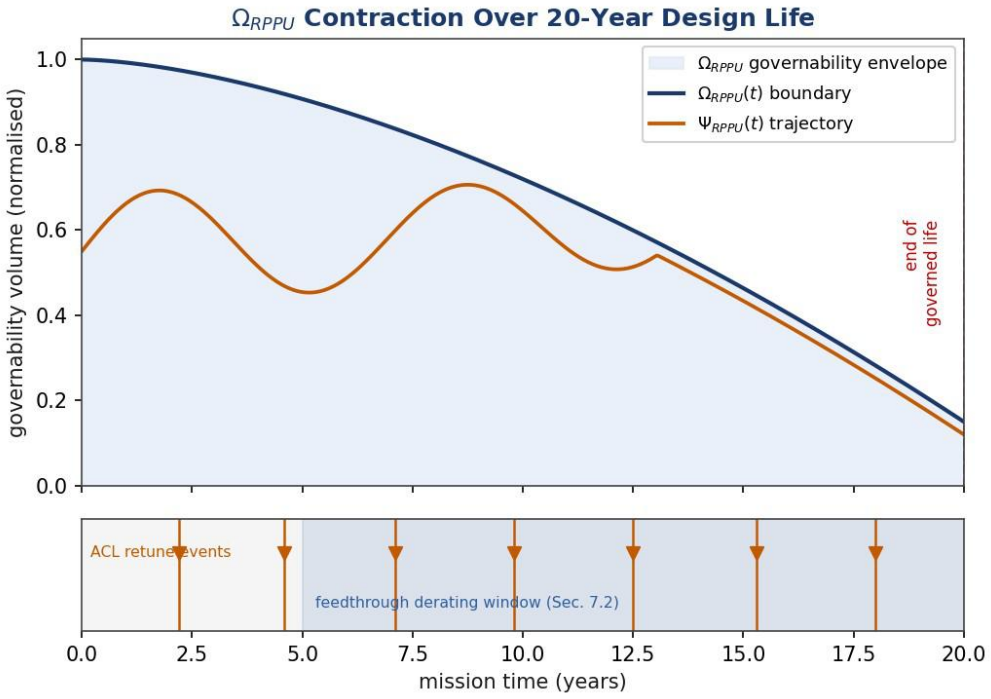


Figure 8. Omega_RPPU contraction over 20-year design life with Psi_RPPU trajectory and margins.

SAFETY ENVELOPE

9.1 Tier-1 Collapse Protocol

Triggers on: Omega_RPPU violation, curvature overshoot, suppression depletion, bandwidth failure, space-charge overload, feedthrough failure, or back-stream surge. Response: controlled shutdown, FAC de-energised, topology relaxes to open-mirror, safe standby. Recovery requires cold restart.

9.2 Tier-2 Extraction Abort

Triggers on: eta drift, chi exceedance, FAC desync, bus droop, or inductive instability. Response: extraction stops, decay-ionised domain retained in sealed governed operation, automated recovery attempted. Escalates to Tier-1 on timeout.

Table 9. Safety trigger matrix.

Trigger	Tier	Response	Recovery
Omega_RPPU violation	1	Shutdown	Cold restart
Curvature overshoot	1	Shutdown	Cold restart
Suppression depletion	1	Shutdown	Cold restart
Space-charge overload	1	Shutdown	Cold restart
Feedthrough failure	1	Shutdown	Replacement
Back-stream surge	1	Shutdown	FAC service
eta drift	2	Abort	Auto retune
chi exceedance	2	Abort	ACL retune
FAC desync	2	Abort	Phase reset
Bus droop	2	Abort	Load shed
Inductive instability	2	Abort	Rectifier bypass
Boundary-map deviation	2	Bounded	Mapped-envelope recovery
Damping-state	2	Extraction hold	GECDS-IDG diagnostic

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9.3 Hardware Safety Layer

A hardware safety layer operates independently of DIGSP software. It uses discrete logic, analogue comparators, and relays that trip without processor involvement. The layer has authority over software: DIGSP cannot override a hardware trip, and every hardware response drives the unit toward the de-energised safe state. Two DIGSP channels run in parallel, and disagreement between them places extraction on hardware hold.

No single software or controller failure can hold extraction or field drive in an unsafe state. On loss of all control power the coils de-energise, the permanent-magnet mirror holds the open-mirror topology, and source decay heat is rejected through the passive thermal path of Section 10.2. The hardware layer is verified by fault injection at G7 and in Phase C environmental qualification.

Table 9A. Hardware safety layer: single-point failures and responses.

Failure	Detection	Hardware response	Recovery
DIGSP lockup or software fault	Independent watchdog timer	Removes FAC drive and extraction enable	Tier-1 cold restart
Corrupted or invalid command	Dual DIGSP cross-check	Hardware hold on disagreement	Tier-2 recovery
Bus overvoltage	Analogue comparator	Crowbar and series disconnect	Load shed, restart
Feedthrough leakage surge	Leakage-current comparator	Removes V_accel	Derated restart
Over-temperature	Hardwired thermal trip	Removes extraction and coil drive	Cold restart
Loss of host interlock	Normally-open relay	De-energises extraction	Interlock restore
Loss of control power	Supply supervisor	Coils de-energise; permanent-magnet mirror holds open-mirror topology; decay heat rejected by passive thermal path	Cold restart
Recovery rectifier saturation	Passive clamp	TVS clamp and bypass	Automatic

RPPU-0 PACKAGING AND MASS BUDGET

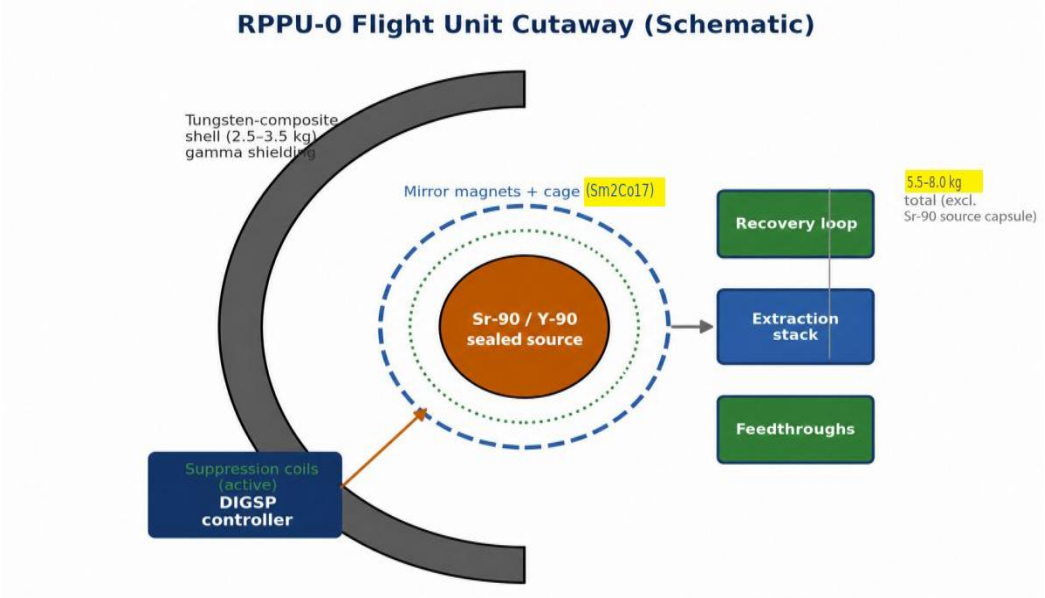


Figure 9. RPPU-0 flight unit cutaway: tungsten shell, micro-cell, mirror assembly, extraction stack, feedthroughs, recovery loop, DIGSP controller.

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Table 10. RPPU-0 mass budget.

Component	Mass (kg)	Notes
Tungsten-composite shell	2.5-3.5	Gamma shielding + structure; nominal design point 3.0 kg
Sealed micro-cell	0.8-1.2	Ti-6Al-4V, 0.5 atm argon
Mirror magnets + cage	0.7-1.0	Sm2Co17, R_m approx 5; radiation-tolerant
Suppression coils	0.3-0.5	Active S_f
Extraction stack	0.4-0.6	FAC/ACL/SCR + ceramics
DIGSP controller	0.3-0.4	Rad-hard electronics
DC bus + feedthroughs	0.2-0.3	Ceramic, bus regulation
Recovery loop	0.1-0.2	Pickup coil + rectifier
Telemetry + harness	0.2-0.3	Monitoring, interlocks
Total	5.5-8.0	Excl. Sr-90 capsule
Metamaterial Boundary Layer	Allocated in Phase A package layout	Passive RPPU interface treatment
GECDS-IDG shell	Allocated in Phase A package layout	Segmented isolated damping hardware

The Version 5 package carries MBL and GECDS-IDG allocations through the Phase A physical layout. The final RPPU-0 mass closes against the selected source activity, shielding design, and sealed interface-package geometry. Shielding configuration remains within the controlled private engineering package.

10.1 External Interfaces

Table 11. External interfaces.

Interface	Type	Specification
DC output	Electrical	24 VDC, 5-50 W, regulated
Telemetry	Data	Psi_RPPU, R_ins, q/m, P_bus, T, B_mirror; 1 Hz
Safety interlocks	Logic	Shutdown command, fault ack
Mechanical	Structural	Flange, vibration standoffs, thermal straps

10.2 Thermal Management

Internal heat spreader. Copper or pyrolytic graphite distributes waste heat from the extraction stack across the shell interior, preventing hot spots on the micro-cell or feedthrough ceramics.

Passive radiator fins. External fins on the shell provide radiative cooling. Fin area is sized for worst-case continuous dissipation. High-emissivity coating on all radiating surfaces.

Conduction straps to host. Flexible copper straps connect the mounting flange to the host thermal bus. Strap conductance is sized so the unit can reject full waste heat through conduction alone if the radiator view factor is obstructed.

Ceramic standoff thermally isolates the Sr-90 source capsule from the extraction stack, so source decay heat does not drive extraction temperature above the governed range.

Higher source activities carry a combined thermal load: extraction waste heat, source self-absorption, and bremsstrahlung generated in the tungsten shielding. Source self-absorption and bremsstrahlung scale with activity independently of extraction efficiency. The radiator and conduction-strap package therefore closes against the total thermal load across the RPPU activity range.

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CONCEPT OF OPERATIONS

11.1 Startup Sequence

The governed decay-ionised domain is established within the sealed RPPU enclosure and carried through the approved static topology constraints. The resulting field state provides the direct operating basis for extraction, damping, safety interlocks, and bus regulation.

11.2 Normal Operation

DIGSP-Tier-2 continuously evaluates Psi_RPPU(t), adjusts extraction, and manages mass filtering, feedthrough derating, and recovery. Telemetry broadcasts a 1 Hz heartbeat containing Psi_RPPU, R_ins, q/m, epsilon_se, P_bus, V_bus, mirror-field flux, and temperature. The host receives state and fault status while DIGSP maintains normal bus operation autonomously.

11.2.1 Boundary and Damping Governance

During normal operation DIGSP-IDG maps the selected curvature, boundary, damping, extraction, safety, and bus-regulation state alongside the existing RPPU topology metrics. MBL maintains the passive boundary treatment and GECDS-IDG maintains selected transient damping. The 1 Hz telemetry heartbeat includes the interface-package state alongside Psi_RPPU, R_ins, q/m, P_bus, V_bus, and temperature.

11.3 Tier-2 Event Handling

On a Tier-2 trigger, extraction stops while the decay-ionised domain remains in sealed governed operation. Telemetry records the fault type, trigger value, and recovery status. A successful recovery resumes extraction and logs the event. An unresolved recovery at the 60-second timeout escalates to Tier-1.

11.4 Tier-1 Shutdown

On a Tier-1 trigger, the unit executes controlled shutdown. Extraction stops, the FAC de-energises, suppression coils ramp down, and topology relaxes. The bus goes to zero and telemetry records the cause and final state. Cold restart proceeds through the host safety interlock.

11.5 End-of-Life

End-of-governed-life is the date Omega_RPPU contracts to zero. DIGSP projects this continuously and reports remaining governed life in telemetry. At zero, DIGSP commands final Tier-1 shutdown. Unit enters permanent safe standby. Sr-90 source remains sealed and shielded indefinitely.

11.6 Redundancy Configuration

Lunar GRFF field envelopes use N+1 redundancy: two RPPU-0 units per envelope, one active and one hot standby. DIGSP performs failover within one control cycle. Terrestrial deployments use either a single unit or N+1 configuration according to the selected safety case.

COMPARATIVE ANALYSIS

Table 12. RPPU-0 vs existing radioisotope power systems.

System	Power	Mass	Lifetime	Moving	Notes
RTG	110-	45-56	20-30 yr	None	Thermal only; discards particle flux
Stirling	130 W	55	14 yr	Yes	Higher eta but mechanical wear
Betavoltaic	uW to	grams	Decades	None	Ultra-low; sensors only
RPPU-0	5-50 W	6–8	10-20 yr	None	Curvature, boundary, and damping-governed

Table 13. Extended comparative metrics.

System	Specific power (W/kg)	Maintenance	Typical application	Primary failure mechanism	Output regulation
RTG (MMRTG, GPHS-RTG)	2–5	Zero	Deep-space and planetary missions (New Horizons, Curiosity, Perseverance-class)	Thermocouple (Seebeck) degradation over decades	None; passive. Output declines with fuel decay
Stirling RPS	2.4	Periodic (piston/bearing service)	Long-duration deep-space missions requiring higher efficiency	Piston and bearing wear	Active; mechanical governor
Betavoltaic	N/A (µW–mW class, gram scale)	Zero	Micro-sensors, implantable and embedded electronics	Semiconductor radiation damage over time	None; passive
RPPU-0	0.6–8.3	Zero	Robotic arms, micro-probes, industrial EM governance, emergency survival power	ACL saturation / chi exceedance (Tier-2 abort); feedthrough insulation degradation (long term)	Active; DIGSP Tier 2 continuous governance

Specific power ranges are computed from the power and mass figures in Table 12; RTG and RPPU-0 ranges reflect the spread across each system's power and mass envelope rather than a single configuration.

RPPU-0 occupies the 5–50 W band between betavoltaic sensor power and conventional radioisotope power systems. It converts decay-particle flux directly through feedback-controlled governed topology into regulated DC power.

Lunar-night radioisotope power is receiving dedicated development investment through NASA Tipping Point activity and independent lunar-generator programmes. RPPU-0 advances the governed extraction route: decay-particle flux is managed through a feedback-controlled field state and delivered through the regulated DC bus.

FALSIFIABILITY GATES

Ten gates graduate the RPPU-0 architecture from the governed decay-ionised domain through the Version 5 boundary and damping package. Each gate supplies a direct measurement condition for the selected operating envelope.

Table 14. IDG-4 falsifiability gates.

Gate	Criterion	Test method	Failure implication
G1	eta_long stable 1000+ hrs	Bus power monitoring	Extraction cannot hold
G2	ACL retunes q/m drift	Faraday cup tracking	Compression failure
G3	R_ins >= R_ins,min	Impedance measurement	Feedthrough failure
G4	epsilon_se <= epsilon_crit	Retarding-field analyser	Core potential collapse
G5	W/C_long within 30%	Bus calorimetry	Scaling law fails
G6	Recovery within 50%	Pickup current vs dB/dt	Transient loss unmodelled

G7	Omega_RPPU holds bench to flight	Progressive testing	Flight invalid
G8	MBL mapped boundary continuity	Field map across selected RPPU interface	Boundary package does not retain selected geometry
G9	GECDS-IDG selected low-frequency transient	Controlled disturbance and field-response	Damping package does not control selected transient response
	damping	measurement	
G10	Feedthrough R_ins and ACL drift within limits at 20-year equivalent dose	Accelerated Co-60 gamma and electron-beam irradiation with in-situ R_ins and actuator measurement	Long-duration envelope not closed

PROGRAMME PLAN

Table 15. RPPU-0 development programme.

Phase	Duration	Scope	Gates	Preliminary Estimate (USD)
A: Bench Integration	6 months	First unit, static extraction, bus power; MBL map and GECDS segmentation	G1, G5, G8	$140k–$220k
B: Vacuum Qualification	9 months	Thermal-vacuum, long-duration, R_ins; boundary and damping response	G1, G3, G5, G7, G8, G9, G10	$280k–$480k
C: Environmental Qualification	12 months	GEVS vibration/shock/thermal testing, q/m drift, recovery; retained sealed interface-package operation	G2, G4, G6, G7, G8, G9	$600k–$1.2M
D: Flight Packaging + RPPU-1	12 months	Flight materials, platform integration, stacking	All G1–G10	$200k–$400k

Total: approximately 39 months from Phase A to RPPU-1 delivery, at a preliminary planning estimate of USD 1.22M–2.3M. This is the Phase A through D planning envelope. Each phase closes its allocation against the established engineering baseline and transfers the selected package into the next qualification stage. Phase A begins on completion of IDG-3 bench validation. This total covers engineering integration, vacuum qualification, environmental qualification, and flight packaging only; nuclear material handling and regulatory licensing (Section 15.1) are outside this budget.

Phase B carries two defined qualification targets: ACL actuator life under cumulative radiation dose across the 10–20 year design life, and the radiolysis rate in the selected micro-cell gas mixture that sets the feedthrough insulation-resistance model in Section 7.2. Phase B and C measure both quantities directly and close the long-duration operating envelope. Gate G10 qualifies feedthrough coupons and ACL actuators to the 20-year equivalent dose by accelerated Co-60 gamma and electron-beam irradiation, with in-situ measurement of R_ins and actuator drift.

14.1 TRL Framework

Technology Readiness Level Summary (Single RPPU Unit). Component TRLs track hardware maturity and schedule the next qualification stage. The ratings are programme values carried into independent qualification through the Phase A to Phase C progression. An independent TRL review is held at each phase gate against NASA NPR 7123.1 and ISO 16290, and a phase closes only on the reviewed rating.

Version 5 hardware maturity is managed as a single sealed RPPU package: MBL and GECDS-IDG enter the Phase A prototype layout, are qualified in the Phase B vacuum programme, and transfer with the selected RPPU-1 interface package through Phase C environmental qualification.

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Component	TRL	Basis
Governed decay-ionised	TRL-3	Bench decay-ionised domain stable; ready for
Dynamic governed topology	TRL-3	Static topology constraints validated in bench
Extraction stack	TRL-3/4	Stable DC output demonstrated in vacuum bench
Long-duration engineering	TRL-2/3	Models validated; requires Phase B/C
Integrated RPPU-0	TRL-3	Architecture complete; ready for first full unit
RPPU-1 flight unit	TRL-5/6	Achieved after environmental qualification and

Table 16. TRL assessment by component, single RPPU unit.

IDG-4 TO RPPU-1 HANDOFF

Table 17. Handoff matrix.

IDG-4 delivers	RPPU-1 adds
RPPU-0 architecture	Flight-grade materials
Long-duration engineering	Lunar vacuum thermal integration
Safety envelope	Robotic arm interface
Falsifiability gates G1-G10	Multi-unit stacking
Packaging and mass budget	Mission-level DIGSP
Power bus specification	Host bus handoff protocol
Platform-agnostic requirements	Platform-specific qualification
Version 5 governed boundary and damping	Flight-qualified boundary and damping

15.1 Regulatory and Licensing

RPPU-0 uses a sealed Sr-90 source. The capsule, transport package, and operating pathway are defined around the applicable radioactive-material controls for the selected deployment. The source remains a sealed, doubly encapsulated engineering package with containment verification and controlled handling through the operating life.

Launch Approval Pathway

US launches carrying radioactive material follow the Nuclear Safety Launch Approval pathway, including NEPA environmental review and Interagency Nuclear Safety Review Panel (INSRP) safety analysis. Missions above the defined risk thresholds proceed to Presidential-level launch decision. The RPPU-1 programme opens this pathway at Phase B entry so the multi-year review proceeds alongside qualification through flight readiness. Regulatory pre-application engagement with the launch-approval and licensing authorities begins in Phase A.

Terrestrial Licensing

Terrestrial deployments in Sections 2.7 and 2.8 operate under an NRC or Agreement State byproduct-material licence covering possession, use, and transfer of the sealed source. The operating package includes the radiation safety officer, leak-test schedule, and security plan across the full deployment life. International deployment follows the equivalent host-nation licence pathway aligned with IAEA guidance.

Transport

Domestic and international transport of the sealed RPPU-0 source follows IAEA SSR-6 and DOT 49 CFR 173 using a Type B(U) package, as the kCi source activities exceed the Type A limit for Sr-90. The doubly encapsulated tungsten capsule is designed toward Special Form certification. Transport documentation,

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placarding, and carrier notification apply to each shipment, including returns for maintenance, requalification, and end-of-life recovery.

End-of-Life Recovery

At end of governed life, the Sr-90 source remains sealed and shielded in permanent safe standby pending its controlled disposition. The disposition pathway returns the source to a licensed facility for sealed-source recycling or storage, or transfers it to a licensed low-level radioactive waste disposal facility. The terrestrial programme includes a source take-back route aligned with established sealed-source vendor practice.

Public Safety

The Special Form, doubly encapsulated design establishes source containment for normal use, handling, and credible accident conditions under ALARA principles. Terrestrial deployments use access control, shielding sized to accessible-surface dose limits, and routine leak-test verification. Flight deployments proceed through the INSRP safety analysis described above.

The INSRP analysis evaluates source containment across credible launch, ascent, and re-entry accident scenarios before launch approval.

Sr-90 is selected for this power class as a beta-emitting source with a defined Sr-90/Y-90 daughter chain and a 28.8-year half-life. The RPPU engineering package manages primary beta shielding, secondary bremsstrahlung control, sealed-source handling, and long-duration governed bus delivery within the selected power envelope.

LIGHTWEIGHT SR-90 RPPU-LITE: UAV AND AUTONOMOUS PLATFORM VARIANT



Figure 10. RPPU-Lite UAV variant: governed Sr-90 power module for long-endurance autonomous platforms.

16.1 Rationale and DARPA Alignment

DARPA's Rads to Watts programme targets lightweight Strontium-90 radioisotope power cells above 10 W/kg with multi-decade endurance. RPPU-Lite works in this Sr-90 power class and delivers 3.8 to 5.5 W/kg in its 30 W configuration. Governance adds variance suppression, predictable endurance, integrated pulse support, and field-safe boundary control carried from RPPU-0.

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16.2 Sr-90 Isotope Properties

Table 18. Sr-90 isotope properties for UAV RPPU-Lite.

Property	Value
Isotope	Sr-90 (+ Y-90 daughter)
Decay mode	Beta (Sr-90: 546 keV max, Y-90: 2.28 MeV
Combined average	1.13 MeV per disintegration
Half-life	28.8 years
Thermal power	~0.007 W/Ci
Encapsulation	SrTiO3 ceramic pellet
Specific activity	~137 Ci/g (pure Sr-90)

16.3 Power Scaling

At ~10% governed EM conversion efficiency, the required source activities are in the kCi regime.

Table 19. Sr-90 UAV power scaling at 10% conversion efficiency.

Activity (kCi)	Sr-90 Mass (g)	P_decay (W_th)	eta	P_bus (W_e)	Platform
7.5	~55	~52	10%	~5	Sensor node
15	~110	~105	10%	~10	Small UAV
22	~160	~155	10%	~15	Medium
45	~330	~315	10%	~30	Large UAV

The Sr-90/Y-90 source chain provides the beta spectrum used by the governed extraction pathway, DIGSP loop, and regulated 24 VDC bus.

16.4 Mass Budget

Table 20. Sr-90 UAV RPPU-Lite mass budget (30 W configuration).

Component	Mass (kg)	Notes
Sr-90 capsule (SrTiO3)	0.15-0.80	55-330 g pure Sr-90
Beta shielding (PMMA/Al)	1.5-2.5	Stops primary betas
Bremsstrahlung shielding	1.0-3.0	Thin Pb or W for secondary X-rays
Governed extraction stack	0.5-0.8	FAC/ACL/SCR and ceramics
DIGSP governance	0.3-0.5	DC regulation, telemetry, bus
Housing + connectors	0.5-0.8	Sealed Al, MIL-spec
Buffer battery (Li-ion)	0.3-0.6	Burst power for manoeuvres
Total (30 W)	5.5-8.0	Tight at 30 W, comfortable at 5-15 W

16.5 Operational Architecture

The UAV RPPU-Lite operates as a continuous trickle-power source charging a buffer battery. Propulsion and avionics run from the battery while the governed isotope replenishes it over months to years. DIGSP provides variance suppression and stable DC routing. The buffer supplies burst-power manoeuvres. The unit has no moving parts or consumables and is configured for 10–20 years of unattended operation.

16.6 Regulatory Context

RPPU-Lite follows the Rads to Watts performance direction: lightweight construction, high specific power, decade-scale life, and autonomous operation where battery depletion sets the mission limit. The governed EM pathway carries this architecture through the RPPU qualification and regulatory programme.

CONCLUSION

RPPU-0 Version 5 defines a complete governed radioisotope power architecture. Curvature establishes the primary RPPU operating geometry; MBL conditions the selected boundary; GECDS-IDG manages selected low-frequency transient response; and DIGSP-IDG coordinates these layers with the governed decay-ionised domain, dynamic governed topology constraints, field-assisted extraction, long-duration engineering, safety, and bus regulation. A hardware safety layer independent of DIGSP software holds the unit safe on any single control failure. The G1 to G10 programme graduates the sealed core, boundary, and damping package into RPPU-1 flight hardware.

RPPU-0 serves robotic arms, probes, surface infrastructure, industrial sensors, emergency survival power, and autonomous systems operating across long-duration mission environments. Version 5 carries one governed topology from the sealed decay-ionised domain through the selected boundary and damping layers, establishing the engineering basis for RPPU-1 integration.

Declaration of AI Use

The concepts, architecture, analysis, and conclusions in this manuscript are the original work of the author. AI tools were used to produce figures, build tables, and format the document. The author reviewed and verified all content and takes full responsibility for it.

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