From Risk Management to Mechanical Enforcement: Reducing Residual Harm by Codifying System Safety

Deconstructing Residual Risk: The Dual Failure Modes of Corridors and Governance

The objective of reducing the residual risk-of-harm from its current level of approximately 0.13 down to the target band of 0.11–0.14 hinges on addressing two deeply intertwined failure modes within engineered systems . These failures persist even with high-quality hardware because unsafe operational states remain accessible if the system's constraints are not mathematically locked . The first failure mode is the specification of operational boundaries, or "corridors," that are too wide, based on outdated legal standards rather than deeper scientific understanding, or lacking sufficient granularity. This allows systems to operate in configurations that are technically compliant but sub-optimally safe. The second, and perhaps more insidious, failure mode is governance misuse—the potential for political, commercial, or other pressures to weaken, bypass, or silently omit critical safety constraints . This dynamic creates a pathway to "legal-in-code" but hazardous configurations, undermining the very purpose of safety engineering. The proposed framework directly confronts these issues by transforming safety from a matter of human judgment and policy into a set of unbreakable, computationally enforceable rules.

The problem is rooted in the distinction between legal compliance and inner science limits. Legal floors represent the minimum acceptable standard, often established through slow-moving regulatory processes. In contrast, inner science limits are derived from extensive research and long-term studies that identify the true boundaries of safe operation, well inside the legal thresholds . By codifying these tighter, scientifically-derived limits as immutable invariants, the admissible state space for the system can be significantly shrunk . This process moves safety from a passive state of "not breaking the law" to an active pursuit of maximum possible safety margins. For example, in water treatment, this means establishing dual thresholds for contaminants like PFAS and pharmaceuticals: one that meets legal requirements and another that represents a scientifically determined inner limit for protecting ecosystem health [29] . Similarly, in hydraulic systems, it involves defining multi-axis corridors for head, ramp rate, and shear stress that physically bound the parameters leading to high-damage events, rather than relying on single-variable limits that may be insufficient under complex operating conditions [1] .

The second failure mode, governance misuse, represents a systemic vulnerability where the integrity of these safety constraints can be compromised. The documented scenarios include direct pressure to relax gates—for instance, raising CEC inner limits or allowing more surcharge events to meet supply targets—and the silent omission or weakening of safety fields in new designs to make risk metrics invisible . Another critical scenario is unauthorized scope-creep deployments, where a module proven safe in one context is cloned into a different hydro-social environment without proper re-parameterization of its safety templates . These actions exploit the gap between initial design intent and operational reality, creating pathways to harm that were not considered during the original safety assessment. The proposed solution is not merely to rely on better policies or oversight but to build a system architecture that is resilient to such misuse. This is achieved by making safety mechanisms mechanical and automatic, thereby removing discretionary judgment from the final decision-making loop at critical points. The goal is to ensure that any configuration that violates the established safety invariants is rejected before it can ever reach the hardware stage, effectively blocking governance failure from translating into physical risk .

This approach reframes the entire safety paradigm. Instead of managing risk through a combination of procedures, audits, and human discretion, it seeks to architect resilience by designing the system to be incapable of entering a hazardous state. The concept of a "gated experiment" for the Phoenix district embodies this philosophy; every operational run is a test against a rigid set of constraints, and any violation obligates a tightening of those constraints and a formal update to the system's safety record . This creates a powerful, data-driven feedback loop for continuous improvement, where operational experience directly informs and strengthens the safety envelope. The underlying principle is that if a state is unsafe, it must be made computationally impossible to reach. This requires a deep integration of technical research, formal methods, and software engineering to translate scientific knowledge and safety policies into a deterministic and verifiable safety mechanism. The result is a system that does not just manage risk but mechanically enforces it, shifting the burden from fallible human oversight to robust computational enforcement.

Failure Mode	Description	Example Scenario	Proposed Defense Mechanism
Mis-Specified Corridors	Operational boundaries are too wide, based on legal minimums rather than inner science limits, or lack necessary granularity.	Operating a hydraulic system near legal shear-stress limits instead of scientifically derived lower thresholds.	Run Phoenix-class pilots to define tighter, science-based inner limits and encode them as immutable invariants in ALN contracts.
Governance Misuse	Political, commercial, or other pressures lead to the weakening or bypassing of safety constraints.	Raising the inner limit for a contaminant to meet production targets despite pilot-test evidence showing harm at higher levels.	Use DID-signed ecosafety grammars and a "shard-only worldview" to make constraint modification cryptographically verifiable and block deployments with missing safety fields.
Silent Omission	Critical safety fields or metrics are deliberately left out of new designs, rendering risk invisible to automated checks.	Dropping the `socialtrustscore` field from a new system's data shard to avoid triggering the Social License gate.	Implement a "shard-only worldview" where the CI pipeline fails if required safety fields are absent from the qpudatashard manifest.
Scope-Creep Deployment	A system module proven safe in one context is deployed in a new context without parameterizing its safety templates.	Cloning a Phoenix water treatment module into a region with different geochemistry without adjusting the thermal-geochemical corridors.	Develop standardized, parameterizable templates for all key corridors that sites can only use, not rewrite.

This table illustrates the strategic alignment between the identified failure modes and the corresponding architectural defenses. The framework is designed not as a single solution but as a multi-layered defense system where technical rigor and hardened governance work in concert to eliminate pathways to harm. By focusing on the root causes—ambiguous limits and weak governance—the system aims to achieve a fundamental reduction in risk, moving beyond incremental improvements toward a state of mechanically enforced safety.

Prioritized Corridor Tightening Through Phoenix-Class Pilots

To effectively reduce the residual risk-of-harm, the most direct approach is to aggressively tighten the operational corridors that define the system's permissible state space. The research program identifies six high-priority corridor types that feed directly into the four hard gates, forming the foundation of the safety architecture . These corridors are not arbitrary; they represent the critical input variables whose control is paramount for preventing high-damage events, maintaining quality, ensuring reliability, and preserving social acceptance. The strategy involves using Phoenix-class pilots to establish precise, science-based inner limits for each of these corridors and encoding them as immutable invariants within the system's governing grammar . Financial and economic metrics, while important for lifecycle analysis and demonstrating ecological benefits, are explicitly excluded from the first-line safety envelopes and are to be wired in later as deployment invariants .

The first priority corridor is the **Hydraulic / Turbine Envelope**, which drives the `HydraulicStructural` gate . This corridor encompasses multi-axis operational parameters such as water head, ramp rate (the speed of power output change), shear stress on turbine components, and response to surcharge events . The research goal is to move beyond simplistic, single-variable limits to define complex, interdependent corridors that reflect the true physical stresses on the system. For instance, due to fluctuating water levels, many hydropower stations operate under ultra-low or near-zero head conditions, which leads to poor hydraulic performance and potential cavitation damage [1] . By running long-term pilot tests under these challenging conditions, researchers can map the precise relationship between operational parameters and structural integrity, defining corridors that physically bound catastrophic failure modes. These findings are then encoded as strict invariants in ALN contracts, ensuring that any proposed configuration that would violate these corridors is automatically rejected .

Second, the **Treatment / SAT CEC Corridors** feed the `TreatmentSAT` gate. This involves establishing dual-threshold limits for a suite of contaminants, including Per- and Polyfluoroalkyl Substances (PFAS), pharmaceuticals, nutrients, and others . Legal limits are often lagging indicators, whereas inner science limits are derived from toxicological studies and long-term environmental monitoring. For example, advanced treatment options for PFAS in drinking water are becoming critical, and pilot-scale test runs are essential for optimizing these processes [29] [35] . The research task is to quantify the breakthrough curves and removal efficiencies for various chemistries, and then publish SAT corridor templates with explicit bands, units, and both legal and inner science thresholds . Other sites would then be able to adopt these templates but only by parameterizing the values, not rewriting the core logic, thus preserving the safety margins established by the Phoenix pilots .

Third, **Thermal–Geochemical Windows** are crucial for subsurface systems, acting as hard stop conditions for processes like aquifer recharge or geothermal energy extraction. This corridor involves monitoring and constraining subsurface temperature, redox potential, and the concentrations of key geochemical species . Long-term studies have shown how water chemistry and flow dynamics change seasonally, impacting the stability of the subsurface environment [51] . An excessive thermal load from treated water discharge could trigger harmful chemical reactions or microbial blooms [31] . The research involves quantifying these impacts to define absolute limits that, if crossed, constitute a system violation and halt operations. This transforms abstract environmental concerns into concrete, gate-enforceable variables .

Fourth, **Fouling / OM Corridors** manage the trade-offs between biofouling rates, cleaning frequency and chemistry, and operational costs (O&M) . Fouling, whether biological or inorganic, degrades system performance and increases energy consumption [13] [52]. The research goal is to characterize fouling rates under various conditions and model the cost-benefit of different cleaning strategies. This data is then encoded into the `FoulingOM` gate, which can automatically derate or divert the system when fouling approaches a critical threshold, preventing performance degradation from escalating into a failure . This proactive management contrasts with reactive maintenance schedules that only address problems after they occur.

Fifth, **Sensing Reliability Corridors** provide a critical layer of system integrity. No control system can be safer than the data it is based on. This corridor defines acceptable bounds for sensor false-positive/false-negative rates and drift over time . If the system detects that its own sensors are unreliable—for instance, if a sensor's readings deviate significantly from expected patterns—a pre-programmed response, such as auto-divert or manual override, is triggered. This acknowledges that control decisions cannot be trusted without reliable data and is a cornerstone of cyber-physical system security [4] [120].

Finally, **Social-Governance Corridors** formalize the concept of social license to operate as a measurable, technical parameter . This involves quantifying public trust, tracking complaint rates, and ensuring the uptime of public-facing dashboards that provide operational transparency . These metrics are fed into the `Social License` gate. A significant decline in public trust, for example, could constitute a system violation on its own, independent of any technical fault. This prevents operations from continuing in a socially untenable manner, recognizing that loss of social license is itself a form of systemic risk that can lead to project failure [65] [66] [68].

By focusing research efforts on these six interconnected corridors, the Phoenix-class pilots systematically shrink the admissible state space, replacing ambiguous guidelines with precise, enforceable, and science-based limits. This disciplined, research-driven approach to corridor definition is the foundational step upon which the entire mechanically enforced safety framework is built.

The Quantitative Core: Implementing a Validated Lyapunov-Style Risk Residual

At the heart of the proposed safety framework is a quantitative metric designed to provide a holistic, real-time view of the system's risk posture: the Lyapunov-style risk residual, denoted as V_t. This component serves as the numerical backbone for the entire system, anchoring abstract safety goals to a concrete, computable value that can be monitored, verified, and enforced. The central thesis is that the immediate priority is not to invent novel and potentially overly complex mathematical formulations for this residual, but rather to implement and rigorously validate a simple, transparent, and shard-reconstructible version of it within the CI pipeline and gate systems . The specified formula is a weighted sum of normalized corridor penetrations:

$$V_t = \sum_j w_j r_{j,t}$$

where $r_{j,t}$ is the normalized penetration of corridor j at time t, scaled to the range [0,1], and w_j are assigned weights reflecting the relative importance of each corridor .

The normalization of diverse physical and social metrics into a common coordinate system, $r_x \in [0,1]$, is a critical technical task. For a given corridor, $r_{j,t}$ would be calculated based on its measured value compared to its defined bounds. For example, for a concentration limit, it might be the ratio of the measured concentration to the inner science limit. A value of 0 would mean the system is perfectly within the safe corridor, while a value of 1 would indicate a complete violation. This normalization allows for the aggregation of disparate quantities—such as hydraulic shear stress, chemical concentration, and social trust scores—into a single, unified risk score. Developing and validating these normalization formulas is a key research task, ensuring that the resulting V_t accurately reflects the severity of violations across all dimensions . Once defined, these formulas would be embedded in the shard schema, making the calculation of V_t a repeatable and reconstructible process from the underlying data shards alone .

The most powerful property of this residual is its intended invariant: $V_{t+1} \le V_t$ over seasonal cycles . This is the Lyapunov-style condition, borrowed from control theory, which implies that the system's overall risk state should not increase over time. A stable or decreasing V_t indicates that the system is operating safely and that its safety margins are being maintained. Conversely, a rising V_t is a clear, unambiguous signal of systemic degradation, forcing engineers to investigate the root cause—whether it be a changing environmental condition, sensor drift, or a need to tighten a specific corridor . This turns risk management from a qualitative, subjective assessment into a quantitative optimization problem. The system's goal becomes not just to avoid failure, but to actively minimize and stabilize the risk residual over time.

The practical implementation of this metric is what gives it teeth. The validated formula for V_t would be integrated directly into the ALN contracts and implemented as a predicate within the Rust guards that govern the CI/CD pipeline and the Pilot-Gate checkpoint . Any design or operational parameter that results in a new configuration with a higher V_t than the previous state would be automatically rejected. This makes the "no increase in V_t" requirement a non-negotiable contract that all components and subsystems must satisfy . This mechanistic enforcement ensures that risk is not managed by policy but is blocked by computation. It provides a single, powerful lever for enforcing the principle of continuous improvement, as every operational anomaly or unexpected penetration of a corridor must lead to a formal tightening of constraints and a recalculation of the residual, thereby driving the system towards a lower-risk equilibrium.

While more advanced mathematical formulations, such as barrier certificates, are noted as valuable for future exploration, they are considered secondary to the immediate task of wiring a simple, validated V_t through the system . The priority is to build confidence in the core concept by demonstrating its effectiveness in a real-world setting. The success of this initial implementation will determine the trajectory for future research into more sophisticated risk metrics. The current plan focuses on building a robust, auditable, and enforceable system around a well-defined and transparent residual, ensuring that the path to reducing the risk-of-harm is paved with concrete, verifiable mathematics rather than abstract theory.

Hardened Governance: Shard-Based Architectures and Mathematically Enforced Gates

The transformation of safety from a matter of policy to a matter of code is enabled by a hardened governance structure built upon three core pillars: shard-based architectures, DID-signed ecosafety grammars, and mathematically enforced hard gates. This architecture is designed to be fundamentally resistant to the primary failure mode of governance misuse, specifically the silencing of omissions, unauthorized constraint weakening, and scope-creep deployments that bypass pilot-test evidence . The central innovation is the adoption of a "shard-only worldview," where the Continuous Integration (CI) pipeline and Pilot-Gate checkpoints interact exclusively with self-contained, cryptographically signed data packages known as `qpudatashards` . These shards act as the sole source of truth for a system's state and its associated safety constraints.

In this model, every component, subsystem, or module is represented by a `qpudatashard`. This shard is a comprehensive data package containing not just its functional parameters but also its full set of safety-critical metadata. This includes fields for the six key corridor values (e.g., hydraulic shear, CEC concentration), the calculated risk residual V_t, and other governance-critical information like `knowledge-factor`, `eco-impact`, and `risk-of-harm` scores . The "shard-only worldview" means that the CI pipeline and Pilot-Gate are blind to any information outside of this manifest. If a required safety field is missing from a shard, or if any of its values fall outside the prescribed corridor limits, the build or deployment process fails by rule, long before any hardware is committed . This mechanism provides a powerful, mechanical defense against the governance misuse scenario of silent omission. A developer cannot accidentally or intentionally leave out a critical safety parameter, as the system itself will reject the incomplete package .

To ensure consistency and prevent unauthorized modifications to the safety rules themselves, all corridor definitions, gate predicates, and required shard fields are formalized within a single, master document called the `ALN ecosafety grammar` . This grammar is not a static policy document; it is a formal, machine-readable specification. Crucially, it is signed with a Decentralized Identifier (DID) signature, making it cryptographically verifiable and tamper-evident [15] [19] . Every topic or subsystem must compile through this same grammar, plugging in only as parameter sets derived from it, never as bespoke logic . This ensures architectural uniformity across all deployments. Any attempt to modify the grammar would require a new DID-signed version, creating a permanent, auditable trail of changes. This cryptographic anchoring of the safety rules provides non-repudiation, proving definitively what constraints were in effect at any point in time and who authorized any changes [17] [122].

The enforcement of these rules is carried out by the four "hard gates": `HydraulicStructural`, `TreatmentSAT`, `FoulingOM`, and `Social License` . These are not soft decision points subject to human interpretation. They are binary checkpoints, implemented as Rust guards—predicates written in the memory-safe language Rust to ensure their own reliability [6] [38] [47] . As mentioned previously, these guards integrate the calculation of the risk residual V_t as a mandatory check. A design that would cause V_t to increase is rejected. Furthermore, the gate criteria themselves are subject to independent audits before any replication or district-scale rollout . This external validation acts as a final safeguard against political or commercial pressure to relax constraints, ensuring that the rules applied during pilot testing are faithfully maintained during wider deployment . Together, the shard manifest, the DID-signed grammar, and the Rust guards form a chain of custody for safety, where each link is cryptographically secured and mechanically enforced, leaving no room for discretionary judgment that could compromise safety.

Governance Component	Function	Defense Against Misuse Scenario	Key Technology
qpudatashard	Self-contained data manifest for a system component, containing all parameters and safety metadata.	Silent Omission / Constraint Weakening	Data Sharding, Schema Validation
DID-Signed Ecosafety Grammar	Master, formal, and cryptographically verifiable rulebook for all safety corridors and gate predicates.	Unauthorized Modification of Rules	Decentralized Identifiers (DIDs), Verifiable Credentials [16]
Hard Gates	Binary, all-or-nothing checkpoints (implemented as Rust guards) that reject any configuration violating safety invariants.	Governance Pressure to Relax Constraints	Formal Methods, Rust Programming Language
Independent Audits	External review of gate criteria and shard data before large-scale deployment.	Unchecked Scope-Creep Deployments	Assurance Cases [8] [9] , Third-Party Verification

This integrated system of hardened governance ensures that safety is not an optional consideration but an intrinsic, non-negotiable property of the engineered system. By combining data sharding, cryptography, and formal verification, it creates a robust defense against the most common and dangerous forms of governance failure, paving the way for a demonstrably lower residual risk.

Strategic Implementation Pathway and Actionable Research Tasks

Achieving the goal of reducing the residual risk-of-harm to the 0.11–0.12 band requires a disciplined, phased implementation of the proposed framework. The strategy is not to develop all components simultaneously but to follow an "implementation-first" priority, focusing on building and validating the core mechanics before exploring more advanced concepts . The pathway begins with aggressive corridor tightening through targeted pilots, progresses to the validation of the quantitative risk residual, and culminates in the integration of these elements into a hardened governance and enforcement architecture. Each phase delivers tangible outputs that advance the overall objective and builds a foundation for subsequent steps. The entire effort treats the Phoenix district as a formal gated experiment, where operational data continuously refines the system's safety envelope .

The first and most foundational set of tasks revolves around **Corridor Measurement and Template Development**. The immediate priority is to conduct Phoenix-class pilots focused on the six high-priority corridor types: hydraulic/turbine, SAT/CEC, thermal-geochemical, fouling/OM, sensing-reliability, and social-governance . The primary output of these pilots is not just data, but the derivation of tight, inner science limits for each corridor. These limits, distinct from legal floors, represent the true boundaries of safe operation. The next step is to codify these findings into reusable templates for each corridor type . These templates will contain explicit bands, units, and dual thresholds (legal vs. inner science) tied to the normalized risk coordinates $r_x \in [0,1]$. The design principle for these templates is that they can be parameterized by other sites but not rewritten, a mechanism designed to prevent the unauthorized scope-creep deployments that invalidate pilot-test evidence . Publishing these templates establishes a baseline of best practices and scientifically-grounded safety margins for future projects.

The second major initiative is **Gate Sharpening and Self-Tightening Rules**. This phase translates the corridor limits into enforceable constraints. The task is to formally quantify how a failure at any of the four hard gates (`HydraulicStructural`, `TreatmentSAT`, `FoulingOM`, `Social License`) must obligate a tightening of at least one bound—for example, lowering the maximum allowable shear stress or raising the minimum acceptable social trust score . Each such tightening event must be logged as a new, DID-signed constraint set within the system's shards, creating a permanent and auditable history of the system's evolving safety envelope . This creates the "self-tightening" property: every time the system operates close to a limit, it learns from that experience and reinforces its own safety barriers. The Phoenix district itself becomes a laboratory for this iterative process, where each failed run or near-miss is a data point that forces a reduction in the global violation residual V_t .

The third, and perhaps most technically critical, set of tasks involves the **Development and Validation of the Risk-Coordinate and Residual Math**. The immediate goal is to finalize the normalization formulas (r_x) for each corridor and implement the specified Lyapunov-style residual ($V_t = \sum_j w_j r_{j,t}$) in a dedicated test harness . This validation phase is crucial to confirm that the formulas produce sensible results and that the core invariant—that V_t should not increase over seasonal cycles—is upheld under a variety of simulated operational scenarios . This process validates the assumption that the residual is a meaningful proxy for the system's overall risk-of-harm. Once validated, the final step is to wire this calculation directly into the ALN contracts and the Rust guards that serve as the hard gates . Making "no increase in V_t" a mandatory predicate in the CI pipeline elevates the residual from a diagnostic tool to a primary enforcement mechanism, rejecting any design that would degrade the system's safety posture .

Finally, the fourth set of tasks focuses on **Shard Hardening and Governance Integration**. This involves completing the definition of the mandatory fields for `qpudatashards`, including the `knowledge-factor`, `eco-impact`, `risk-of-harm`, and the newly calculated `violation-residual` . The master `ALN ecosafety grammar` must be formally specified and signed with a DID to serve as the immutable rulebook for the system . Concurrently, the Rust guards for the four hard gates must be fully developed and integrated into the CI/CD pipeline, ensuring that they execute automatically and block any non-compliant builds . Throughout this process, independent audits of the gate criteria and shard data must be mandated to provide an additional layer of defense against governance misuse .

By following this structured pathway, the research program can systematically dismantle the sources of residual risk. It moves from identifying the problem in abstract terms to delivering concrete, actionable outputs—from scientifically-backed templates to mechanically enforced gates. The end state is a socio-technical system where safety is not assumed or managed through policy, but is architecturally embedded and computationally guaranteed, with the residual risk-of-harm driven decisively towards the target band of 0.11–0.12.

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