The Formidable Power of TRIZ x AI (Theme: Decommissioning the Fukushima Daiichi Nuclear Power Plant and Neutralizing Debris/Contaminated Water)

We applied a systematic approach combining TRIZ and AI to structure ideas for addressing one of the most difficult challenges in human history. Taking into account the trade-offs between "timeframe" (short-term vs. long-term) and "technical hurdles" (feasibility), we categorized our proposals into three stages: [Short-term/High Feasibility] (measures that can be strengthened immediately) through to [Long-term/Fundamental Solution] (ultimate neutralization and system transformation).

1. [Short-term/High Feasibility] Maximizing existing resources and spatial isolation (1-3 year timeframe)

This approach begins by flipping existing "negative resources" to their advantage, aiming to isolate and stabilize the situation without altering the current macro-system.

① Transition to "self-healing" water infrastructure (Substance-Field Analysis / Inventive Principle 25: Self-service)

·Challenge: Aging of piping and containment vessels in the cooling water circulation system; risk of micro-leaks.

·Idea: Introduce "fluid self-healing materials" (such as adsorbent polymers or fine ceramic particles) into the cooling water; these materials autonomously seal micro-cracks in response to specific radiation levels or temperature changes.

·TRIZ Explanation: To counter the "harmful effect" of leakage, the substance (water) itself is endowed with a functional capability, thereby eliminating the need for external access for repairs (Self-service).

② Localized adsorption using a dynamic zeolite curtain (Resource Utilization / Inventive Principle 35: Parameter Change)

·Challenge: Groundwater inflow into building basements and the resulting increase in contaminated water.

·Idea: Position a "dynamic trench" inside the frozen soil wall (a static barrier); this trench is filled with a "fluid zeolite slurry" that is permeable and possesses high selective adsorption capabilities for radioactive cesium and strontium. Instead of physically blocking the groundwater, the system allows it to pass through while converting it into "harmless water" before discharging it externally.

·TRIZ Explanation: Alters material properties such as "phase" (solid to fluid) or "permeability," utilizing natural energy (groundwater hydrostatic head pressure) as the driving force.

③ "Pre-sampling" of debris characteristics using flexible micro-crawlers (Inventive Principle 15: Dynamism / Evolution Trend: Segmentation)

·Challenge: Work delays caused by insufficient understanding of conditions inside the reactor, debris hardness, and criticality risks.

·Idea: Instead of deploying a single large robotic arm, deploy an ultra-small, highly radiation-resistant "daisy-chain" (segmented) swarm robot system. These units enter through narrow gaps and make contact with the debris surface to non-destructively map thermal conductivity and composition.

·TRIZ Explanation: Maximizes adaptability to environments filled with unknown obstacles by evolving from a rigid body to a flexible body, and ultimately to a "powder/swarm (multi-agent)" system.

2. [Medium-term / Medium Feasibility] Debris Removal and Transitional Stabilization (3-10 year timeframe)

This phase involves modifying parts of the system to safely extract solid materials while neutralizing or controlling harmful effects (radiation and re-criticality risks).

④ "Underwater" laser excavation using heavy liquid/fluid stuffing (Substance-Field Analysis / Inventive Principle 39: Inert Environment)

·Challenge: Scattering of radioactive fine particles (dust) during debris cutting and insufficient shielding associated with operations in air.

·Idea: Fill the containment vessel not with "pure water," but with a "heavy fluid" (such as an aqueous cesium formate solution or a special inert gel) that suppresses dust suspension and offers extremely high neutron shielding capability. A high-power fiber laser ablates (cuts) the debris through this fluid, and the resulting dust is fully collected along with the fluid using a filter.

·TRIZ Explanation: An intermediate substance (a third substance mediating the field) with shielding or trapping functions is introduced between the harmful "debris dust" and the "working environment" to block the harmful effects.

⑤ In-situ debris "casting" (encapsulation) using a phase-change matrix (Inventive Principle 36: Phase Transition / Inventive Standard Solution: Elimination of Harmful Effects)

·Challenge: Attempting to grasp the debris directly poses risks of structural collapse or criticality.

·Idea: Pour a "low-melting-point alloy" or "special flowable glass" containing neutron-absorbing material (such as boron) around the target debris to solidify it into a single unit (encapsulate it) on-site. The solidified block is then cut out as a "safe product."

·TRIZ Explanation: By flowing into gaps in a liquid state and then solidifying (phase transition), an unstable object is transformed into and constrained within a stable matrix.

⑥ Self-consumption of "thermal resources" via thermoelectric conversion (Seebeck effect) (Resource Utilization / Inventive Principle 19: Periodic Action)

·Challenge: Energy and water are continuously consumed to cool the decay heat generated by the debris.

·Idea: Incorporate high-efficiency, radiation-resistant thermoelectric conversion elements (such as Cella-Roots) into the outer shell of an isolation container placed in contact with or near the debris. Decay heat is converted into electricity on-site and "self-consumed" to power the system's own cooling fans and monitoring sensors.

·TRIZ Explanation: "Decay heat" (unwanted energy)—normally a troublesome byproduct requiring disposal—is inverted into an "internal resource" (power source) to maintain the system. 3. [Long-term/Fundamental Solution] Ultimate "Detoxification" of Materials and System Transformation (10 years and beyond)

These ideas represent the culmination of TRIZ evolutionary trends, involving the transformation of the material's intrinsic properties or the radical restructuring of macro-scale systems.

⑦ Shortening the half-life of long-lived nuclides using an Accelerator-Driven System (ADS) (Material-Field Analysis: Field Transformation / Inventive Principle 2: Separation)

·Challenge: It takes tens of thousands of years for the radioactivity of debris and waste to decay.

·Idea: Chemically separate long-lived elements—such as minor actinides (MA)—from the retrieved debris. Construct a compact "proton accelerator-driven subcritical system (ADS)" on-site or nearby to irradiate the material with high-energy neutrons, thereby "transmuting" (eliminating) them into nuclides that are either stable (non-radioactive) or have extremely short half-lives.

·TRIZ Explanation: Evolve the approach from thermal or mechanical methods (macro-scale) to the atomic nucleus level (micro-scale/field transformation). Control the time parameter (half-life) using an external "field" (neutron flux).

⑧ Structural micro-encapsulation and geological "harmonious" disposal (Evolutionary Trend: Mono → Bi → Multi)

·Challenge: Difficulty in selecting final disposal sites and the risk of leakage over ultra-long timeframes.

·Idea: Trap the residues (whether post-transmutation or remaining waste) within the crystalline structure of nano-scale artificial Synroc (synthetic rock-mimicking ceramics) and further micro-encapsulate them in multiple layers of silicon carbide (SiC). Disperse these capsules within a matrix possessing properties equivalent to the surrounding natural bedrock.

·TRIZ Explanation: Instead of relying on protection by a "massive concrete structure (Mono)," disperse and integrate the waste into "countless tiny capsules (Multi)" to harmonize the system with the Earth's geological cycles (resources).

Summary: Choosing an Approach

If the priority is a short-term, feasible solution, contamination risks can be minimized by altering the characteristics of existing water or trenches, as described in approaches ① and ②.

However, achieving fundamental "neutralization" requires transitioning to the "transformation of the medium (transmutation)" described in approach ⑦. The most rational path forward is a roadmap that transforms the form of the debris—progressing through the stages of solid, powder, solution, and capsule—in alignment with TRIZ trends of evolution.