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Interdisciplinary Review of Advances in Micro Nuclear Reactor Technology: Design & Deployment, Radiation-Tolerant Materials, Electromagnetic Systems, And Therapeutic Applications

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Abstract- This review synthesizes and critically evaluates four scholarly works spanning the full technological breadth of contemporary micro nuclear reactor (MNR) research. The first work provides a comprehensive general overview of MNR classification, design principles, fuel technologies, safety philosophy, global development programs, and economic considerations, establishing the contextual framework for all subsequent studies. The second study presents the conceptual design of the ZAN4e — a 10 MW(thermal) lead-cooled, graphite-moderated, Stirling-engine microreactor developed for Canadian Arctic communities — and demonstrates its neutronic and thermal-hydraulic viability through analytical and computational analysis. The third study characterizes the micro-mechanical response of four Gen-IV candidate structural alloys to high-dose ion irradiation, establishing that nanocrystalline and oxide-dispersion-strengthened microstructures confer exceptional radiation tolerance through grain-boundary and nanocluster defect sinking. The fourth contribution, encompassing two interconnected papers, addresses the component-level engineering challenges of the MicroURANUS small modular reactor and a research reactor, analyzing electromagnetic pump thermal management and a novel remote-controlled fuel locking mechanism respectively. Together these works chart a coherent trajectory from macro-level technology assessment to system-level reactor design, materials qualification, and precision therapeutic application of nuclear reactions. This review examines the scientific context, methodological rigor, principal findings, limitations, and cross-cutting engineering implications of each contribution, and identifies priority directions for future research.

Index Terms- micro nuclear reactor; small modular reactor; ZAN4e; lead-cooled reactor; HALEU; TRISO fuel; structural alloys; irradiation hardening; ODS steel; nanocrystalline T91; MicroURANUS; electromagnetic pump; LBE coolant; fuel locking mechanism; BNCT; CBE factor; passive safety; Gen-IV reactors

I. INTRODUCTION

The global imperative to decarbonize energy systems while ensuring reliable, distributed power access has propelled micro nuclear reactors to the forefront of energy technology research. Unlike their gigawatt-scale predecessors, micro nuclear reactors — generally defined as fission systems producing less than 20 MWe — are engineered for factory fabrication, passive safety, long-duration operation without refueling, and deployment in environments ranging from Arctic wilderness to military forward operating bases, space missions, and industrial facilities. This convergence of nuclear physics, advanced materials engineering, precision manufacturing, and digital instrumentation represents one of the most interdisciplinary challenges in modern engineering.

The scholarly works reviewed here collectively illuminate four dimensions of this challenge. At the broadest level, the general MNR review establishes the technological landscape: the taxonomy of reactor types, the physics and engineering principles governing their design, the fuel systems that enable long core lives, the safety philosophy underpinning their walk-away-safe credentials, and the global ecosystem of development programs that ranges from NASA's kilowatt-scale Kilopower reactor to Russia's seabed-mounted SHELF. Within this landscape, the ZAN4e conceptual design study by Crowell and Nichita (2023) demonstrates how these principles translate into a concrete, site-specific reactor design for Canadian Arctic communities, integrating neutronic analysis, thermal-hydraulic modeling, and Stirling engine power conversion into a coherent engineering solution.

The structural materials study by Prasitthipayong et al. (2018) addresses a foundational enabling challenge: without structural materials that can withstand decades of intense neutron irradiation without unacceptable degradation, advanced reactors cannot achieve their design lifetimes. By employing micro-mechanical testing on four candidate alloys following ion irradiation to 20.68 displacements per atom, this work provides quantitative evidence that nanocrystalline and oxide-dispersion-strengthened microstructures offer dramatically superior radiation tolerance compared to conventional austenitic and ferritic-martensitic steels.

Finally, the two component-level engineering studies — Kang and Kim (2024) on electromagnetic pump cooling for MicroURANUS, and Lee et al. (2023) on a remote-controlled fuel locking mechanism for plate-type research reactor fuel — illustrate how system-level safety and reliability depend on innovative solutions to specific engineering problems that must be addressed at the component design stage. Together, these four contributions span from technology survey to conceptual reactor design, materials science, and precision mechanical engineering, forming a coherent and mutually reinforcing body of knowledge.

II. OVERVIEW OF REVIEWED WORKS

2.1 General Review: Micro Nuclear Reactor Technology Landscape

The foundational document reviewed here provides a comprehensive academic synthesis of micro nuclear reactor technology, establishing the definitional, technical, and strategic context within which all subsequent studies can be understood. The International Atomic Energy Agency classifies reactors with outputs between 1 kWe and 20 MWe as micro nuclear reactors, distinct from small modular reactors (10–300 MWe) and large nuclear plants (greater than 700 MWe). Within the MNR category, five principal reactor types are identified: heat-pipe reactors using alkali metal working fluids such as sodium or potassium; molten salt reactors dissolving fissile material directly in fluoride or chloride salt coolants; gas-cooled reactors using helium or CO_2 for high-temperature applications; liquid-metal-cooled reactors using lead-bismuth eutectic or sodium; and sealed battery reactors designed for decade-scale operation without refueling.

The safety philosophy of MNRs represents a genuine paradigm shift relative to conventional large reactors. Three interlocking safety layers are described: inherent safety through negative temperature and void reactivity coefficients that automatically suppress power excursions; passive safety systems relying on natural forces such as gravity, thermal expansion, and natural convection rather than powered components; and defense-in-depth through multiple independent fission product barriers from the TRISO particle kernel outward through the reactor pressure vessel and containment. The concept of walk-away safety — where the reactor can be abandoned in an emergency with no risk of core damage — is presented as achievable in MNR designs in ways that are physically infeasible for large conventional reactors, owing to the small thermal mass and robust fuel forms involved.

The global development landscape is extensive and strategically significant. In the United States, Oklo's Aurora (1.5 MWe metallic-fueled fast reactor), Westinghouse's eVinci (0.2–5 MWe heat-pipe reactor), NASA/DoE's demonstrated Kilopower system, and the DoD's Project Pele represent a portfolio of commercial and government-driven programs at various licensing stages. Russia's RITM-200 and SHELF, China's HTR-PM and ACPR50S, and multiple European programs including the UK's Rolls-Royce SMR collectively indicate that MNR development is a globally strategic priority. Canada, with abundant uranium resources and large remote communities, is positioned as both a technology developer and early adopter.

2.2 ZAN4e Microreactor: Conceptual Design for Arctic Communities

Crowell and Nichita (2023) present the conceptual design of the ZAN4e (Zero-degree Arctic Natural-circulation 4-MW electric) reactor, a 10 MW(thermal) system specifically engineered for

Canadian Arctic off-grid communities where electricity costs can reach 1.14 Canadian dollars per kilowatt-hour — approximately ten times the urban rate — due to diesel fuel transportation over remote terrain. The reactor's core concept addresses two fundamental constraints of the Arctic deployment context: the unsuitability of water-cooled systems (due to freezing risks and steam circuit complexity) and the need for minimal maintenance staffing given limited technical personnel availability.

The reactor employs liquid lead as its coolant — a chemically inert material that contracts on solidification (preventing pressure vessel damage if the coolant freezes), has a boiling point of 1,737 degrees Celsius far above any credible accident temperature, and eliminates the exothermic air-water reaction risk associated with sodium-cooled designs. The core is a 1.7-meter graphite cylinder moderated to a near-thermal neutron spectrum, pierced by 13 fuel channels at the CANDU-proven 28.575 cm pitch. Each channel employs a 37-element annular fuel assembly using HALEU fuel enriched to 10%, achieving a core life of 2.75 years without refueling. The large temperature differential between coolant inlet (400°C) and outlet (900°C) drives passive natural convection without mechanical pumps, and 13 Stirling engines mounted in the annular space between inner and outer vessel walls directly convert thermal energy to approximately 3.4 MWe, with the remaining ~6.6 MW available as district heating.

Neutronic analysis confirmed adequate reactivity over the full core lifetime, with a combined power peaking factor of 2.34 — lower than the theoretical bare-core value of 3.64. Thermal-hydraulic analysis demonstrated that the available thermosyphon driving pressure of 19,769 Pa comfortably exceeds the total flow circuit pressure drop of 5,258 Pa, confirming the adequacy of natural convection cooling with substantial margin. Fuel centerline temperatures remain well below the uranium dioxide melting point throughout the core life. The total reactor mass of approximately 264 tonnes is compatible with heavy-lift air freight, enabling deployment without road infrastructure.

2.3 Micro-Mechanical Testing of Gen-IV Structural Alloys Under Irradiation

Prasitthipayong et al. (2018) address a materials challenge foundational to all advanced reactor programs: the qualification of structural alloys that can withstand high-dose neutron irradiation without unacceptable embrittlement, swelling, or creep degradation. Four candidate alloys were selected to span the space of structural material approaches: austenitic 800H (high-nickel stainless steel, 204 μm average grain size), offering excellent high-temperature creep resistance; ferritic-martensitic T91 (9Cr-1Mo steel), combining swelling resistance with good creep performance; nanocrystalline T91 (NCT91) produced by equal-channel angular pressing to a grain size of approximately 320 nm, dramatically increasing grain boundary area as defect sinks; and oxide-dispersion-strengthened 14YWT steel containing yttrium-rich nanoclusters approximately 560 nm in size that simultaneously strengthen the matrix and absorb radiation-induced point defects.

All alloys were irradiated at Lawrence Livermore National Laboratory using 70 MeV Fe9+ ions at 452°C to a dose of 20.68 displacements per atom — conditions simulating a decade or more of Gen-IV service — producing a damage layer approximately 6.2 μm deep. The microscale of this damage layer necessitated small-volume mechanical testing methods: nanoindentation (quasi-static and continuous stiffness measurement), in-situ micro-pillar compression using a picoindenter in a dual-beam FIB-SEM, and X-ray diffraction with CMWP analysis for dislocation density and crystallite size determination.

Results revealed striking contrasts between conventional and advanced microstructures. Austenitic 800H showed a hardness increase of 1.31 GPa after irradiation (from 2.32 to 3.63 GPa), and its yield stress more than doubled from 253 to 593 MPa. Ferritic-martensitic T91 exhibited even larger absolute hardening of 1.76 GPa, with yield stress rising from 778 to 1,263 MPa. In sharp contrast, NCT91 and 14YWT showed negligible hardening — only 0.15 and 0.14 GPa respectively — with yield stresses remaining essentially unchanged. CMWP analysis of X-ray diffraction profiles confirmed the mechanistic explanation: T91 underwent a 5-fold increase in dislocation density after irradiation, while NCT91 showed essentially no increase despite its higher pre-irradiation dislocation density, because its high-density grain boundary network provides continuously available defect sinks that annihilate incoming point defects before they accumulate into damaging clusters. The 14YWT nanoclusters similarly promote defect recombination with minimal net accumulation.

2.4 Electromagnetic Systems for MicroURANUS and Research Reactor Fuel Management

The fourth body of work encompasses two closely related papers addressing component-level engineering challenges in liquid-metal cooled SMRs and research reactors. Kang and Kim (2024) analyze the thermal management of the extra vessel electromagnetic pump for MicroURANUS — a 20 MWe pool-type fast reactor cooled by lead-bismuth eutectic, designed for marine deployment. The EVEMP follows the annular linear induction pump architecture, generating LBE flow through Lorentz forces driven by a three-phase AC current in copper coils wound on silicon steel cores. While mechanically elegant, this design generates substantial Joule heating in coil and core materials, requiring effective cooling to maintain temperatures below the 575 K permissible coil limit.

COMSOL Multiphysics thermal simulations comparing air and water cooling strategies at the design operating point (4,196 kg/s flow rate, 73 kPa developed pressure, 1,250 A coil current at 5 Hz) demonstrated that air cooling yields a maximum coil temperature of 641 K — exceeding the permissible limit by 66 K — while water cooling at 300 K reduces the maximum temperature to 372 K, well below both the coil limit and the boiling point of water, eliminating any requirement for cooling circuit pressurization. The vacuum gap between the inner reactor vessel and the outer EVEMP structure acts as a natural thermal insulator, enabling the water cooling to function without interference from the hot primary circuit.

Lee et al. (2023) address the complementary challenge of fuel safety in upflow pool-type research reactors, where coolant drag forces can eject fuel assemblies from the core during operation, necessitating reliable fuel locking mechanisms. A novel single-electromagnet, dead-weight-actuated FLM was developed for plate-type nuclear fuel with a 50 mm diameter constraint imposed by coexisting reactivity control mechanisms. ANSYS Maxwell electromagnetic field optimization over 175 geometric parameter combinations established the optimal electromagnet window length (120 mm) and stator position (S = 24 mm relative to the electromagnet center), achieving a holding force exceeding 60 N at 5 A — three times the minimum requirement. ANSYS CFX flow analysis quantified a maximum drag force of 1,050 N on the fuel assembly at maximum design flow — 13 times the fuel assembly weight in water — confirming drag as the dominant structural load. Finite element structural analysis verified ASME B&PV Code Section III compliance across all components, with minimum design margins of 50% at the governing ball-lock joint. Prototype testing confirmed operability at 2.5 A withholding forces 10–17% above analytical predictions.

III. METHODOLOGICAL FRAMEWORKS

3.1 Neutronic and Thermal-Hydraulic Analysis (ZAN4e)

The ZAN4e design process employed the DRAGON lattice transport code for fuel cell neutronics and the DONJON core diffusion code for full-core reactivity calculations, a validated Canadian-developed toolchain widely used for CANDU and research reactor analysis. The thermal-hydraulic analysis was performed analytically using natural convection thermosyphon principles, computing driving pressure from the coolant density differential across the heated core height and comparing it against the summed pressure losses across all flow circuit components. This analytical approach is well-suited for the conceptual design phase but will require replacement by multi-dimensional CFD analysis as the design advances to detailed engineering.

3.2 Ion Irradiation and Small-Scale Mechanical Testing (Gen-IV Materials)

The ion irradiation methodology exploits the ability of heavy ion beams to deliver neutron-equivalent displacement damage in laboratory timescales, enabling dose levels of 20.68 dpa within weeks rather than the decades required for neutron irradiation. The SRIM Monte Carlo code was used to predict damage depth profiles, and cross-sectional nanoindentation across the ~6 μm damage layer validated these predictions. The combination of nanoindentation, in-situ micro-pillar compression, and CMWP X-ray diffraction line profile analysis provides a multi-scale mechanical and microstructural characterization framework that is becoming standard practice for small-volume irradiated material testing. The agreement between nanoindentation-derived and microcompression-derived yield stresses across all four alloys strengthens confidence in both techniques as mutually validating approaches.

3.3 Multi-Physics Computational Design (MicroURANUS Components)

Both MicroURANUS component studies employ commercial multi-physics simulation platforms — COMSOL Multiphysics for coupled electromagnetic-thermal analysis and ANSYS Maxwell/CFX/Mechanical for electromagnetic optimization, fluid drag quantification, and structural integrity analysis respectively. These platforms provide validated solvers for each physical domain and enable systematic parametric optimization. The thermal simulation was validated against analytical heat transfer calculations, while the electromagnetic field analysis was validated against prototype tests that consistently exceeded analytical predictions by 10–17%, confirming conservative analytical models. The use of the ASME B&PV Code Section III as the structural acceptance criterion ensures that the FLM design is held to internationally recognized nuclear safety standards.

IV. KEY FINDINGS AND COMPARATIVE RESULTS

4.1 MNR Technology: State of Development and Enabling Challenges

The general MNR review establishes that the technology is at a pivotal inflection point. Multiple first-of-a-kind demonstrations are expected to enter operation in the late 2020s, representing the transition from conceptual design to commercial reality. The Levelized Cost of Electricity for MNRs — estimated at 50–200 USD per MWh under current projections — is not yet competitive with utility-scale generation, but is highly attractive in the remote settings for which these systems are primarily designed, where diesel generation costs of 300–500 USD per MWh prevail. Three enabling challenges are identified as the critical bottlenecks for commercialization: establishment of a reliable HALEU supply chain independent of Russian sources; adaptation of regulatory frameworks designed for large light-water reactors to novel technology classes; and demonstration of long-duration materials performance under realistic operating conditions.

4.2 ZAN4e Design: Key Performance Parameters

ZAN4e Design Parameter	Value / Specification
Thermal Power	10 MW(thermal)
Electrical Output (Stirling)	~3.4 MWe
District Heating Output	~6.6 MW
Primary Coolant	Liquid Lead (unpressurized)
Moderator	Nuclear-grade Graphite (sealed in stainless steel vessel)
Fuel Enrichment (HALEU)	10 wt% U-235
Coolant Inlet / Outlet Temperature	400°C / 900°C (ΔT = 500°C)
Core Lifetime (no refueling)	2.75 years
Combined Power Peaking Factor	2.34 (vs. 3.64 bare-core theoretical maximum)
Thermosyphon Driving Pressure	19,769 Pa (vs. 5,258 Pa total circuit pressure drop)
Total Reactor Mass	~263,651 kg (air-freightable by heavy-lift aircraft)
Stirling Engine Thermal Efficiency	~34% at hot cylinder 650°C / cold cylinder 75°C

Table 1. Summary of principal design parameters for the ZAN4e Arctic microreactor (Crowell & Nichita, 2023).

4.3 Irradiation Hardening: Comparative Alloy Performance

Alloy	Type	Pre-Irr. Hardness (GPa)	Post-Irr. Hardness (GPa)	ΔH (GPa)	Yield Stress Change (MPa)
800H	Austenitic SS	2.32	3.63	1.31 ▲	253 → 593
T91	Ferritic-Martensitic	3.01	4.77	1.76 ▲	778 → 1263
NCT 91	Nanocrystalline FM (ECAP)	4.13	4.28	0.15 ✓	865 → 890
14YWT	ODS Steel	6.90	7.04	0.14 ✓	1759 → 1815

Table 2. Nanoindentation hardness and microcompression yield stress before and after 20.68 dpa ion irradiation at 452°C. Green shading indicates near-zero irradiation hardening (Prasitthipayong et al., 2018).

4.4 EVEMP and FLM: Component Engineering Results

Aspect	EVEMP Thermal Study (Kang & Kim, 2024)	FLM Design (Lee et al., 2023)
Primary challenge	Joule heating threatens coil integrity at >575 K	Coolant drag (13× fuel weight) risks fuel ejection
Core method	COMSOL coupled EM-thermal simulation	ANSYS Maxwell + CFX + Mechanical FEA
Key result — thermal	Air: 641 K max (exceeds limit); Water: 372 K (safe, no pressurization needed)	Water cooling at 300 K maintains all components within limits
Key result — structural	All SUS316 components within permissible temperature envelope	Min. design margin 50% (ball-lock joint); compliant with ASME NG
Experimental validation	Analytical $Q=Cm\Delta T$ vs. COMSOL: ~372 K consistent	Prototype: min. operating current 2.5 A (vs. 2.7 A predicted) — conservative model
Safety significance	Water cooling prevents coil performance degradation enabling sustained SMR operation	Fail-safe design: power failure cannot unlock fuel; remote operation eliminates operator exposure

Table 3. Comparative engineering results for MicroURANUS electromagnetic pump thermal management and research reactor fuel locking mechanism.

V. CROSS-CUTTING THEMES AND INTEGRATED ANALYSIS

5.1 Passive Safety as a Unifying Design Philosophy

Passive safety — the design of systems whose safety functions are fulfilled by natural physical laws without powered components or operator action — is the single most pervasive engineering philosophy across all reviewed works. In the MNR technology overview, passive safety is identified as the primary distinguishing characteristic that enables walk-away-safe operation and legitimizes the goal of deploying reactors in remote locations without full-time licensed operators. In the ZAN4e design, passivity manifests concretely through natural convection cooling (driven by the 500°C temperature differential across the core), the chemical inertness and solidification behavior of lead coolant, and the absence of any pressurized steam circuit. In the structural materials domain, NCT91 and 14YWT exhibit a form of intrinsic passivity: their microstructures continuously self-heal irradiation damage through grain-boundary and nanocluster defect sinking without any active maintenance intervention, providing progressive radiation tolerance over decades of service. Even in the FLM design, the dead-weight actuation principle ensures that the fuel remains locked in its default power-off state, with unlocking requiring deliberate electromagnetic activation — a passively safe default condition.

The consistent application of passive safety principles across scales, from the reactor system level down to the material microstructure and individual mechanical component, reflects a maturation of nuclear engineering philosophy that distinguishes advanced MNR designs from the complex active safety systems of first-generation large reactors.

5.2 Computational Simulation as the Primary Engineering Instrument

All four bodies of work demonstrate the centrality of computational simulation as both a design tool and a validation instrument in contemporary nuclear engineering. The DRAGON/DONJON neutronic toolchain, COMSOL Multiphysics, ANSYS Maxwell, ANSYS CFX, ANSYS Mechanical, and SRIM/Monte Carlo ion range calculations collectively represent the multi-physics computational ecosystem within which modern nuclear component development is conducted. This ecosystem enables systematic parametric optimization — the 175-case ANSYS Maxwell sweep for FLM electromagnet geometry and the frequency/diameter optimization for EVEMP design — that would be prohibitively costly using physical prototypes alone.

Critically, all studies pair computational results with experimental validation at appropriate scope: the ZAN4e thermal-hydraulic predictions are validated by internal consistency between neutronic and thermal results; the irradiation hardening simulations are validated by the excellent spatial correspondence between SRIM-predicted damage profiles and cross-sectional nanoindentation hardness maps; and the electromagnetic analyses are validated by prototype tests consistently yielding 10–17% higher holding forces than predictions, confirming conservative analytical models. This bidirectional coupling of computation and experiment defines the credibility standard for modern nuclear component design.

5.3 The HALEU Supply Chain as a Systemic Constraint

Both the general MNR review and the ZAN4e design study identify the availability of High-Assay Low-Enriched Uranium fuel as a critical systemic constraint for the deployment of advanced MNRs. Enrichments of 5–19.75% U-235 are required by most advanced designs to achieve the compact cores, long fuel cycles, and improved neutron economies that make MNRs technically attractive. However, HALEU production at commercial scale is currently limited, with significant dependence on Russian enrichment capacity representing both a supply chain risk and a geopolitical vulnerability for Western reactor development programs. The ZAN4e's selection of 10% HALEU enrichment — exactly the level that requires the HALEU supply chain to be functional — means that this design's commercial viability is directly coupled to the resolution of this challenge. The general review notes that the U.S. Department of Energy and allied nations are actively investing in domestic HALEU enrichment capacity, but the timeline for achieving commercial-scale production remains uncertain.

5.4 Microstructural Heterogeneity as a Performance-Governing Parameter

Across the reviewed works, heterogeneity at the microscale emerges repeatedly as a fundamental determinant of system performance. In the ZAN4e reactor, radial and axial neutron flux gradients across the heterogeneous fuel-moderator geometry produce power peaking factors that determine maximum fuel temperature; graphite and lead reflectors are deliberately exploited to flatten these gradients to an overall factor of 2.34. In the structural materials study, the contrast between the coarse-grained, homogeneous microstructure of 800H and T91 versus the high-density grain boundary network of NCT91 and the nanocluster-rich structure of 14YWT directly governs whether irradiation damage accumulates as hardening defect clusters or is continuously dissipated. This microstructural design principle — engineering heterogeneity at the nanoscale to create functional properties at the engineering scale — represents one of the most promising frontiers in radiation-tolerant materials development.

VI. CRITICAL ASSESSMENT: LIMITATIONS AND RESEARCH GAPS

6.1 ZAN4e Conceptual Design: Gaps Requiring Resolution

- Reactivity coefficients — temperature, void, and burnup — have not yet been calculated, leaving dynamic stability and inherent safety characteristics unvalidated for the specific ZAN4e geometry.
- The thermal-hydraulic analysis uses one-dimensional analytical models; three-dimensional CFD is needed to characterize flow distribution, local hot spots, and natural convection behavior during transient and accident conditions.
- Lead-stainless steel corrosion compatibility at the high outlet temperature of 900°C has not been quantified; this is a known engineering challenge that could require material substitution or protective coatings.
- Stirling engine performance at the proposed scale and temperature range has not been experimentally demonstrated; commercial Stirling units have not previously been coupled to nuclear-heated circuits.
- Licensing pathway under the Canadian Nuclear Safety Commission Vendor Design Review process is not addressed; novel features including HALEU fuel, unpressurized lead coolant, and Stirling engine integration each require individual regulatory justification.

6.2 Structural Materials: Limitations of Ion Irradiation Surrogates

- Ion irradiation differs from neutron irradiation in cascade morphology, dose rate, and the absence of transmutation-produced helium and hydrogen gases that significantly affect long-term embrittlement behavior; qualification for Gen-IV service will ultimately require neutron irradiation data.
- High-temperature creep behavior following irradiation — a co-dominant failure mode alongside embrittlement in Gen-IV service — has not been assessed for NCT91 or 14YWT.
- The long-term stability of the nanocrystalline grain structure in NCT91 under simultaneous thermal and radiation loading is a critical open question; grain growth at elevated temperatures could eliminate the beneficial radiation resistance.
- Stress corrosion cracking behavior in relevant coolant environments (lead, LBE, molten salt) has not been characterized for these candidate alloys.

6.3 Micro URANUS Component Studies: Scope Boundaries

- The EVEMP thermal study is steady-state only; transient thermal loading during startup, shutdown, pump power fluctuations, and accident scenarios has not been analyzed, leaving thermal fatigue and thermal shock as uncharacterized failure modes.
- Long-term performance degradation of the copper coil insulation (BTTZ MI cable) and silicon steel magnetic properties under the combined neutron/gamma irradiation field adjacent to the reactor vessel has not been addressed.
- The FLM flow analysis models only two fuel assemblies and one CAP out of the full core, potentially underrepresenting inter-assembly flow interaction effects; full-core flow

analysis would improve drag prediction accuracy.

- Seismic qualification, endurance testing under thermal and radiation cycling, and underwater performance validation — all required for nuclear safety qualification — are identified as future work rather than completed demonstrations.

VII. BROADER SIGNIFICANCE AND SOCIETAL IMPLICATIONS

The four bodies of work reviewed here collectively contribute to one of the most consequential technology transitions of the coming decade: the deployment of micro nuclear reactors as a scalable, distributed, carbon-free energy source for communities and applications that are currently dependent on fossil fuels. The ZAN4e design directly addresses energy poverty in remote Arctic communities, demonstrating the technical feasibility of a concept that could transform energy access for populations that pay ten times urban electricity rates while enduring the environmental consequences of diesel combustion. More broadly, the design principles demonstrated in ZAN4e — passive lead cooling, Stirling engine conversion, HALEU fuel — are representative of a design space being explored by multiple development programs worldwide, meaning that the engineering lessons from this concept have wider applicability.

The structural materials study by Prasitthipayong et al. addresses an enabling constraint for all advanced reactors: without structural materials that maintain their properties under intense neutron irradiation, no reactor can achieve its design lifetime. The demonstration that nanocrystalline and ODS microstructures can reduce irradiation hardening by an order of magnitude relative to conventional alloys provides a compelling roadmap for materials selection in future Gen-IV reactors. The micro-mechanical testing methodology demonstrated in this work has already been adopted as a standard approach in the nuclear materials community, amplifying its impact beyond the specific alloys studied.

The MicroURANUS component engineering studies demonstrate the critical importance of subsystem-level innovation in enabling reactor-level safety and reliability. The water-cooling solution for the EVEMP resolves a thermal management challenge that, if unaddressed, would prevent the pump from operating at the flow rates required for reactor safety. The remote-controlled FLM eliminates a radiation exposure risk and operational uncertainty that has historically been accepted in research reactor fuel handling, providing a foundation for safer and more efficient isotope production and neutron irradiation facilities worldwide. The combined LCOE advantage of MNRs in remote settings and the safety improvements enabled by research reactor innovations collectively support the broader case for expanded nuclear power in the global energy mix.

VIII. PRIORITY DIRECTIONS FOR FUTURE RESEARCH

Drawing from the limitations and implications identified across all reviewed works, the following priority research directions are recommended to advance the field.

8.1 Integrated Reactor Demonstration and Safety Analysis

The ZAN4e and similar lead-cooled microreactor concepts require progression beyond conceptual design to engineering design, including three-dimensional CFD analysis of natural convection and thermal stratification, full reactivity coefficient calculation, transient and accident analysis, and lead corrosion characterization at design temperatures. A systematic safety analysis report addressing all design basis and beyond-design-basis events is required before licensing engagement. Parallel development of Stirling engine prototypes at nuclear-representative temperatures and power levels should be pursued in collaboration with established Stirling technology developers.

8.2 Neutron Irradiation Testing of Promising Materials

The extraordinary radiation tolerance of NCT91 and 14YWT demonstrated under ion irradiation must be confirmed under prototypic neutron irradiation conditions, including the transmutation products (helium and hydrogen) absent from ion experiments. Available neutron irradiation test capacity in research reactors should be prioritized for these materials alongside creep testing of irradiated specimens and evaluation of liquid metal corrosion behavior under simultaneously thermally and radiation-loaded conditions. Accelerated testing protocols exploiting the micro-mechanical methods demonstrated by Prasitthipayong et al. should be extended to larger dose ranges and more complex stress states.

8.3 Full Qualification of Nuclear Component Designs

The MicroURANUS EVEMP and FLM designs require progression through the full nuclear component qualification pathway: transient and fatigue analysis, irradiation testing of electrical and magnetic materials, seismic qualification, endurance testing under underwater conditions, and regulatory review against applicable codes. The validated multi-physics simulation platforms established in both studies provide a credible computational infrastructure for these analyses, but experimental programs at increasing fidelity are required to close the gap between analytical prediction and nuclear qualification.

8.4 HALEU Supply Chain and Regulatory Framework Development

Both the ZAN4e and MicroURANUS reactor programs, along with essentially all advanced MNR concepts identified in the general review, depend on reliable HALEU supply and adapted regulatory frameworks. Research contributions to establishing the technical basis for risk-informed and technology-neutral licensing of novel reactor concepts — particularly regarding emergency planning zone sizing, passive safety qualification methodologies, and remote monitoring and control approaches — would substantially accelerate the commercialization pathway for the entire MNR sector.

IX. CONCLUSIONS

This review has synthesized four scholarly works representing the breadth of contemporary micro nuclear reactor technology — from macro-level technology assessment through conceptual reactor design, structural materials qualification, and precision component engineering. The following principal conclusions emerge from this integrated analysis.

The general MNR technology landscape is at a pivotal transition: multiple demonstration projects approaching operation in the late 2020s will determine whether the promising performance projections of micro nuclear reactors can be translated into reliable, commercially viable systems. The enabling challenges are well-defined — HALEU supply, regulatory adaptation, and materials qualification — and are the subject of active investment by governments and private sector developers worldwide.

The ZAN4e conceptual design by Crowell and Nichita demonstrates that a 10 MW(thermal) lead-cooled, naturally circulating, Stirling-engine microreactor is technically feasible for Canadian Arctic communities, with adequate neutronic safety margins, natural convection driving pressure exceeding circuit pressure losses with comfortable margin, and a total reactor mass compatible with air freight deployment. The design concept is compelling, but important technical and regulatory validation steps remain before it can be considered a mature engineering design.

Prasitthipayong et al. establish unequivocally that nanocrystalline and oxide-dispersion-strengthened microstructures confer exceptional radiation tolerance relative to conventional austenitic and ferritic-martensitic alloys at 20.68 dpa, through grain-boundary and nanocluster defect sinking mechanisms that suppress the dislocation accumulation responsible for irradiation hardening and embrittlement. This finding has direct implications for materials selection in all advanced reactor programs and provides a quantitative micro-mechanical characterization framework applicable to future materials qualification.

Kang and Kim confirm that water cooling is thermally necessary and sufficient for the MicroURANUS EVEMP, reducing maximum coil temperature from a damaging 641 K under air cooling to a safe 372 K without requiring cooling circuit pressurization — a practically significant simplification. Lee et al. demonstrate that a single-electromagnet, dead-weight-actuated fuel locking mechanism can meet all structural and functional requirements for remote plate-type fuel management in upflow research reactors within tight spatial constraints, with prototype testing confirming conservative analytical models.

Together, these works chart the pathway from MNR technology concept to deployed reality: macro-level technology validation establishes the design space; conceptual design studies demonstrate system-level feasibility; materials qualification validates the enabling physical infrastructure; and component engineering delivers the specific technical solutions that make safe and reliable reactor operation achievable. Progress along this pathway, sustained by the multi-physics computational and experimental methodologies exemplified in all four studies, will determine the pace at which micro nuclear reactors fulfill their potential as transformative energy technologies for the 21st century.

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