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Review of Micro-Reactor shielding: Addressing transportability and lightweighting challenges

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1. Introduction

Micro-Reactors have recently attracted considerable attention in various applications such as distributed energy and remote power generation. As shown in Figure 1 and Table 1, unlike conventional large-scale nuclear power plants or Linear Accelerator (LINAC) facilities, micro-reactors must be compactly integrated for transport in confined environments such as International Organization for Standardization (ISO) containers[1].

Fig 1. Examples of nuclear system: large-scale NPP (left), LINAC (center), micro-reactor (right) [1,2,3].

Table 1. ISO container dimensions [4].

ISO 1	Length (m)	Height (m)	Width (m)
Low Cube	6.058	2.438	2.438
Standard	6.058	2.591	2.438
High Cube	6.058	2.896	2.438

Consequently, the weight and volume of the overall system are critical design constraints. For example, Table 2 shows the test results of loading the ML-1 package developed for the US military onto an M-172 trailer. The reactor and power conversion package were transported as a single unit for rapid deployment and operational simplicity.

The test results shows that the additional weight due to shielding exceeded the limits set by U.S. highway transport regulations. [2] As a result, additional load distribution and vibration absorption systems had to be introduced. Transportability and lightweighting issues are key challenges to be addressed in micro-reactor design.

[1] The U.S. government prefers to use standard containers because of shipping regulations, infrastructure, ease of handling, and system integration [4].

Table 2. ML-1 and U.S highway standard: size [5].

	ML-1 Package	U.S. Highway Regulations
Size (L×W×H,m)	Reactor: 2.8 ×2.7 ×2.4 Power conversion: 4.3 ×2.9 ×2.4	16.15 ×2.6 ×4.1 Total trailer length
Tandem axle load (kg)	Combined total: 28,000 Each module approx. 14,000	15,400 Total weight: 36,000
Note	- Partially exceeded the height limit (lowering tire pressure) - Exceeds tandem axle limit	Axle load and total weight limit need to be met

In addition, micro-reactors are characterized by modular design, high power density and light safety construction, with a variety of fuel forms being used. In particular, fast reactor designs such as the Oklo Inc.'s Aurora and NASA's KRUSTY, which use highly enriched fuel and minimal moderator, exhibit neutron spectral energy peaks significantly higher than those observed in thermal reactors such as Pressurized Water Reactor (PWR).

As a result, conventional shielding materials alone are not sufficient to achieve the required attenuation within the imposed weight constraints, so it is essential to identify an optimal combination of materials that simultaneously satisfies both lightweighting and shielding efficiency requirements.

Meanwhile, the High-Temperature Gas-cooled Reactor (HTGR) design used in the Pele project uses Tri-structural isotropic (TRISO) fuel to ensure high resistance to the release of radioactive materials, and the selection of shielding materials compatible with high-temperature operating conditions has emerged as a critical design element.

The objective of this study is to analyze the unique aspects of micro-reactor shielding and review current research trends, including evaluations of the ML-1 reactor. The goal is to develop an optimal shielding design that reduces system weight, maintains efficiency, and meets operator safety regulations.

2. Micro-Reactor shielding characteristics

2.1 The need for transportability and lightweight

The transportability of the micro-reactor is closely

[2] The weight of the shielding was not specified, but the increased load due to the shielding was analyzed as the main reason [5].

related to the weight reduction of the overall system. The Army Nuclear Power Program (ANPP), a joint effort between the U.S. Department of Defense and the Atomic Energy Commission, included the Aircraft Nuclear Propulsion (ANP) program which began in 1946 and led to the development of the Aircraft Shield Test Reactor (ASTR).

As shown in Figure 2, ASTR was designed as a radiation source to provide shielding information not available from ground facilities. The ASTR and its shield weighed 15,900 kg, which limited the weight of the reactor on board an aircraft, so testing was carried out by modifying aircraft.

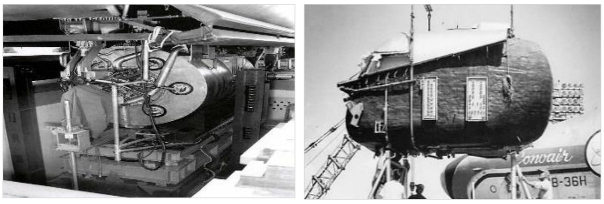

Fig 2. The ASTR (left), Convair NB-36H and the shielded crew compartment [5].

In addition, as shown in Figure 3, to assess the transportability of the 3.3 MW ML-1 studied in the 1960s, a mock-up was built and tested in the U.S. The reactor package and power conversion package weigh approximately 28,000 kg, and when shielding materials are included, the additional weight exceeds the allowable range for transport on U.S. highways. For this reason, the use of shielding materials requires additional measures such as load distribution and vibration absorption systems, and may require changes in means or methods of transportation or special design.

Fig 3. ML-1 concept (left) and transport mock-up (right) [6, 7].

Therefore, the shielding design of micro-reactors requires not only consideration of radiation attenuation performance, but also an integrated design approach to ensure the transportability of the entire system.

2.2 Advanced reactor characteristics shielding

While the transportability and lightweight requirements of micro-reactors present significant challenges, another equally important aspect is the radiation field characteristics produced by these reactors. Although micro-reactors are compact, they can be based on various advanced reactor designs, which inherently influence their neutron and gamma-ray spectra. For example, some micro-reactor designs derive from HTGR technology, resulting in a thermal neutron spectrum, whereas others are based on fast reactor principles, which yield a harder, higher-energy spectrum. These differences in spectral characteristics necessitate distinct shielding strategies. Optimizing micro-reactor shielding involves both ensuring effective radiation attenuation within a compact, lightweight structure and adapting the shielding to the unique spectral properties of various advanced reactor types.

HTGRs use multi-layer TRISO fuel particles in graphite moderators. As shown in Figure 4, Graphite efficiently slows down neutrons, producing a predominantly thermal spectrum that enhances safety. Although PWRs also produce a thermal neutron spectrum, the use of light water as the moderator leads to subtle differences in the spectrum. Table 2 shows that, even though HTGRs use inert coolants like helium, the gamma-ray energy of fission products remains high; however, the overall neutron energy distribution is largely thermal allowing effective attenuation with relatively lightweight shielding materials. The high operating temperatures of HTGRs require that shielding materials not only attenuate gamma rays and neutrons effectively but also possess superior thermal stability, durability, and efficient heat transfer capabilities.

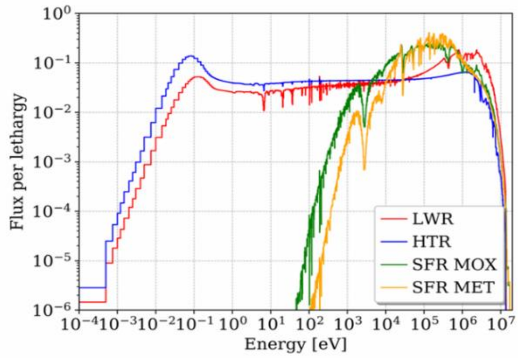

Fig 4. Neutron energy spectrum by reactor type [8].

Table 3. Characteristics of advanced reactor type [10].

Type	Neutron spectrum	Coolant	Outlet Temp (°C)
HTGR	Thermal	Helium	700 - 950
SFR	Fast	Sodium	500 – 550
LFR (Lead-cooled Fast)	Fast	Lead	480 – 570
MSR (Molten Salt)	Thermal / Fast	Fluoride Salt	700 -800

In contrast, fast reactors use fuel with higher enrichment than the thermal reactor and minimal moderation, which results in neutrons retaining high energy levels. As a result, the neutron spectrum in the core of a fast reactor is dominated by fast neutrons. Figure 5 shows that the gamma rays produced from sodium in a fast reactor have also relatively high energy.

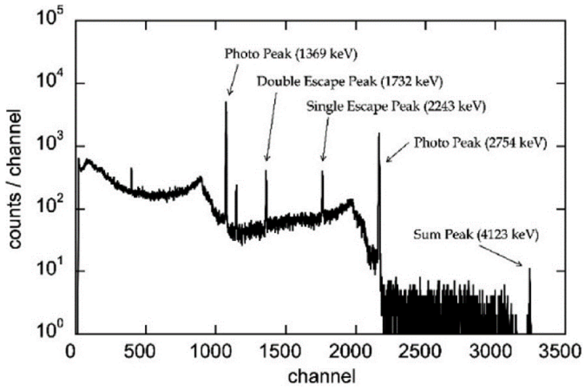

Fig 5. Gamma-ray spectrum of ^{24}Na decay activation [11].

As shown in Table 3, in sodium-cooled fast reactors (SFRs), the coolant sodium is exposed to a high neutron flux, leading to the formation of radioactive isotopes such as ^{24}Na that emit additional gamma rays.[3] To absorb these high-energy neutrons and gamma rays, thicker layers or multilayer structures must be considered, making optimized material arrangement and density control.

Table 4. Nuclear Data and Production Reactions of ^{24}Na [12,13].

Isotope	Half Life	Decay Mode	Radiation used for detection	Producing reaction
^{24}Na	14.977h	β-	γ 1368.6 keV (99.994%)	^{23}Na (n, γ) ^{24}Na ^{24}Mg (n, p) ^{24}Na ^{27}Al (n, α) ^{24}Na

Due to the inherent characteristics of fast reactors, where high energy gamma rays and fast neutrons dominate, effective shielding design is essential. As shown in Figure 6, NASA's KRUSTY, which is based on a fast reactor, uses shielding materials such as lithium hydride and tungsten to address high-energy gamma rays and fast neutrons.

Fig 6. Conceptual NASA KRUSTY Reactor Shielding Design [14].

In summary, the thermal reactor design of HTGRs and the fast reactor design of SFRs require different shielding approaches due to differences in their neutron and gamma-ray energy spectra and operating temperature ranges. HTGRs emphasize material safety at high operating temperatures and use thermal neutron-based shielding. In contrast, fast reactors must address fast neutron and high-energy gamma-ray shielding, along with the extra gamma radiation from ^{24}Na activation in the sodium coolant. These differences critically affect the overall safety, transportability and economic viability of advanced reactors.

3. Current research trends

3.1 INL's Pele project: NGSC Design study

Idaho National Laboratory (INL), as part of the U.S. Department of Defense (DOE) Pele Project, proposed a Nuclear Grade Sandwich Composite (NGSC)[4] as a solution to provide optimum gamma and neutron flux attenuation within a limited weight constraint of 76,100 kg. The NGSC integrates the reactor vessel and the containment building into a single composite structure.

The NGSC design proposed by INL is a multi-layer composite structure. Experiments were conducted using tungsten tetraboride (WB_4) and boron carbide (B_4C). WB_4 is known for its excellent gamma-ray attenuation due to its high density and atomic number. B_4C is effective for neutron attenuation because of boron's high thermal neutron absorption cross section. These tests aimed to determine the optimal arrangement of these materials so that effective radiation shielding can be achieved while maintaining transportability.

INL's study used simulation tools such as Monte Carlo N-Particle Transport Code (MCNP) to evaluate the attenuation of gamma and neutron fluxes through the NGSC within acceptable limits, as shown in Table 3.

Table 5. Objective functions for the NGSC optimization problem [15].

Objective Function	Allowable Range
Neutron Current (n/㎠)	$0.0 – 1.0×10^3$
Gamma-ray Current (γ/㎠)	$0.0 – 5.0×10^6$
Linear Mass (kg/㎠)	0.0 – 190.0

The INL project indicates that a layered configuration incorporating both WB_4 and B_4C, rather than relying on a single material, is the most effective approach. This strategy achieves a significant reduction in overall system mass while still providing adequate neutron and gamma attenuation. In summary, employing multiple shielding materials offers a balanced compromise between radiation protection and weight reduction.

[3] ^{23}Na, the coolant used in SFRs, is irradiated with neutrons to produce the nuclide ^{24}Na, which emits high-energy gamma rays.: ^{23}Na (n, γ) ^{24}Na [9].

[4] NGSC is a concept that integrates reactor pressure vessel and biological shielding into a single composite structure [15].

3.2 CPS Technologies: Composite radiation shielding research

In the U.S, CPS Technologies has recognized the need for effective simultaneous shielding of gamma rays and neutrons within the limited weight and volume constraints of micro-reactors. CPS uses an aluminum-based matrix to address fast neutrons and gamma rays, selectively incorporating tungsten, boron and other alloys to achieve the desired shielding performance. As shown in Figure 9 and Table 5, integrating high-density gamma shielding materials and neutron absorbers within an aluminum matrix yields a tailored material configuration. This configuration enables a single structure to effectively attenuate both gamma rays and neutrons under the transport and operational conditions of micro-reactors.

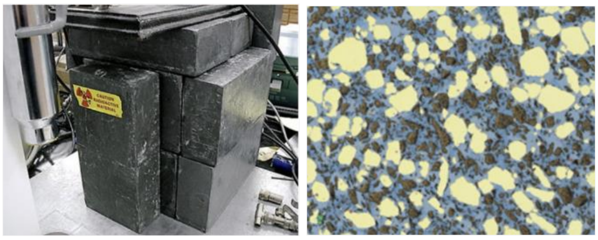

Fig 7. CPS Technologies' Proposed Micro-Reactor Shielding [16].

Table 6. Characteristic Co^{60} shielding of various materials [16].

Material	Co^{60} Half-Value-Layer (mm)	Density (g/㎤)	Half-Value-Mass (g)
Concrete	60.5	2.5	15.125
Steel	21.6	8	17.28
Lead	12.5	11.34	14.175
Tungsten	7.9	19.3	15.247
Al- WB_4	9	6.7	6.03

4. Discussion / Summary

Micro-Reactor shielding design is a complex task that must simultaneously address transportability and lightweighting requirements, as well as the challenges of high energy gamma and neutron emissions during full power operation. The ML-1 reactor transport evaluation revealed that the combined weight of the reactor, power conversion package, and shielding materials surpassed US highway transport limits. Consequently, additional load distribution and vibration absorption systems had to be introduced.

To address these issues, the INL Pele project proposed the NGSC an integrated structure combining the reactor pressure vessel and biological shielding. The NGSC consists of six core layers and seven skin layers, using WB_4 for superior gamma attenuation and B_4C for effective neutron absorption. Pareto analysis has shown that increasing the number of WB_4 layers improves gamma attenuation but also increases the overall mass of the system, thus identifying an optimal material configuration.

However, current research focuses primarily on flux attenuation without conversion of the results to Total Effective Dose Equivalent (TEDE)[5] under full power conditions. This suggests that the NGSC alone may not provide the ultimate safety required for worker protection; additional external biological shielding must be incorporated to meet regulatory standards.

In conclusion, future research should combine internal NGSC optimization with comprehensive dose conversion and external shielding evaluation to ensure safe operation, effective transportation, and adequate radiation protection for operators and the public. In addition, further research is needed to optimize the design through detailed simulations of NGSC and external shielding components, including cost-effectiveness analyses to establish economic feasibility.

[5] TEDE is a concept used in radiation protection and regulatory that serves as an index to comprehensively evaluate the overall effective dose that the human body may receive upon exposure to radiation [17].

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