Review of Transportable Nuclear Reactor Development and Establishment of Preliminary Design Requirements

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1. Introduction

Mobile nuclear systems have gained increasing attention as the demand for remote communities, military installations, and other locations where conventional grid infrastructure is unavailable. Various terms have been used to describe mobile nuclear systems. In this study, the term Transportable Nuclear Reactor (TNR) is adopted to represent a reactor designed for transportation, removal, and repeated installation at different sites.

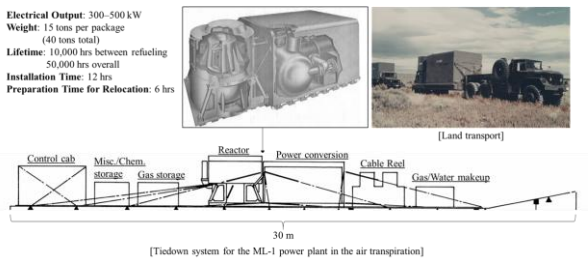
TNRs have been investigated since the early development of compact nuclear power systems. As shown in Fig. 1(a), the ML-1 represented an early attempt to develop a reactor system that could be transported and rapidly installed at remote sites. Recent concepts, such as Project Pele and related BWXT's designs shown in Fig. 1(b), extend this approach through compact reactor technologies, modularization, and factory fabrication. The basic operational concept of a TNR is transported to the operating site, installed and connected to the required balance-of-plant systems, and operated for the intended period. After operation, the reactor is shut down, disconnected from the site infrastructure, and prepared for removal. The reactor system can then be transported to another site for subsequent installation and operation.

Because TNR concepts differ in how they are transported, operated, removed, and reused, they can be classified according to their mobility characteristics. The mobility classification adopted in this study is summarized in Table I. M1 denotes a mobile reactor module designed for repeated relocation. M2 denotes transportable reactor designed for long-term operation, followed by factory return for refueling. M3 denotes a module transported to and permantely installed at the site.

Table I: Definition of Mobility Type

Class	Definition	Relocation time	Site
M1	Repeated relocation with the reactor	Hours-Weeks	Temporary
M2	Planned relocation after long-term operation	Weeks-Months	Prepared
M3	Delivery to a permeant site	Not applicable	Permanent

Various TNR concepts are currently under research and development. Regulatory agencies are developing new design criteria and licensing processes to support the commercialization of TNPs. However, dedicated design requirements for TNRs have not yet been fully established [2]. Therefore, this study assumes a reference TNR and defines preliminary design requirements for its development.



(a)



(b)

Fig. 1. (a) ML-1 reactor design characteristics [1] (b) Project pele and related design by BWXT

2. Review of technology designs

The ML-1 was the first nitrogen cooled, water moderated reactor with a nitrogen turbine energy conversion system. They were adopted to minimize system size and weight, enabling transport by truck or aircraft. Since around 2018, research and development of TNRs has regained momentum, driven by advances in microreactor technologies. Various TNR concepts are currently under development with different reactor types, power levels, transport configurations, and technology maturities. Table II summarizes representative TNR designs selected based on their reactor type and development maturity.

Each TNR concept has been developed for a different objective and operating environment. Project Pele places the emphasis on mobility and rapid deployment. The primary objective is to provide resilient power to military bases and other mission-critical locations. The eVinci microreactor is a heat-pipe-cooled reactor developed for reliable power and heat supply in remote and

Table II: Summary of Current TNR Designs and Technical Specifications

Developer (Name)	Reactor type	Power	Fuel	Refueling Interval	Mobility type	Transport configuration	Status	Figure
BWXT (Project Pele)	HTGR	1.5 MWe	TRISO	3 years	M1	Four 20 ft containerized module	Prototype reactor fabrication	
Westinghouse (eVinci)	Heat Pipe	5.0 MWe	TRISO	8 years	M2	Containerized module	Pre-demonstration	
Radiant (Kaleidos)	HTGR	3.5 MWth	TRISO	5 years	M2	40 ft containerized module	Preparing for reactor testing	
Antares Nuclear (R1)	Heat Pipe	1.0 MWe	TRISO	6 years	M2	-	Zero-power criticality experiment	
NANO Nuclear Energy (ZEUS)	Solid-Core Battery	4.0 MWth	HALEU	10 years	M2	Contrainerized module	Engineering development	
Copenhagen atomics	MSR	100 MWth	Thorium fuel salt	breeder	M3	40 ft Containerized module	Non-fission prototype testing	

infrastructure-limited locations. Its passive heat-pipe system eliminates the need for a conventional primary coolant loop and associated pumps, contributing to a compact and simplified system suitable for transport and rapid installation. Kaleidos is intended primarily as a direct replacement for diesel generators, emphasizing rapid installation, minimal site preparation, air cooling, and factory-based refueling for remote and emergency power applications.

The Antares R1 is more strongly oriented toward strategic applications, including defense-critical assets and operations in remote or austere environments, and therefore emphasizes compactness, passive heat transport, and simplified deployment. Similarly, ZEUS is being developed as a robust "nuclear battery" for infrastructure-limited locations, with an emphasis on passive safety, minimal operator intervention, and a sealed transportable configuration. In contrast, the Copenhagen Atomics reactor applies transportability primarily to factory production and rapid site installation rather than frequent relocation. Its development objective is large-scale production of modular molten-salt reactors for industrial heat and electricity, with the longer-term potential for thorium breeding and utilization of transuranic from spent nuclear fuel.

3. Reference Transportable Nuclear Reactor

The reference reactor concept is established through a comparative assessment of TNR designs currently under development. PWR technologies benefit from qualified fuels, established materials, and extensive operating experience. Nevertheless, high-pressure boundaries, water inventory, steam systems, and associated safety equipment impose substantial mass and deployment-time penalties. These characteristics are more compatible with permanent installation under M3 conditions.

Heat-pipe-cooled reactors offer compact geometry and simplified primary systems. However, their limited representation among M1 concepts and insufficient full-scale validation under heat-pipe failure, transport loading, and long-term operation preclude their selection as the reference technology.

Molten-salt reactors provide low-pressure operation, high-temperature heat, and fuel-drain capability. Their application to an M1 system remains constrained by fuel-salt redistribution during transport, freeze–thaw management, corrosion control, salt chemistry, and fission-product handling. The technology is therefore retained as a long-term research alternative.

The prevalence of HTGRs in TNR development is primarily driven by the robustness of TRISO fuel and its compatibility with compact, long-life power systems. Accordingly, a helium-cooled prismatic-block HTGR was selected as the reference TNR. Its power rating, transport envelope, and mobility classification are summarized in Table III.

Table III: Reference TNR

Parameter	Reference	Remarks
Reactor Type	Helium-cooled prismatic-block HTGR	HTGRs account for 40.5% of all actively developed concepts and 85.7% of the M1 candidates.
Refueling Interval	5 EFPY	6 years at an assumed 90% capacity factor
Power Output	3.5 MWth / 1.0 MWe	Typical of thermal power under active development; 28.6% gross efficiency
Transport Envelope	20 or 40 ft reactor modules	Single-container reactor module with separate power-conversion and auxiliary modules.
Mobility Class	M1—repeated road transport and relocation	M2/M3 requiring extended cool-down or permanent site infrastructure are excluded.

Table IV: Summary of Preliminary Design Requirements for TNR system

Requirement ID	Reference Requirement	Basis
Minimum Transport Configuration	Reactor system	-
	Power Conversion System	Prevents the reactor transport package from exceeding its mass and dimensional limits
	Auxiliary Equipment	Consolidates I&C, electrical distribution, startup equipment, and service systems
	Operational Site Shielding	Full-power neutron and gamma fields require substantially more shielding than post-shutdown transport conditions
Transport Subcriticality	$k_{eff} \leq 0.95$	Maintains an adequate subcriticality margin following package deformation, flooding, or geometric rearrangement
Transport Package	No release of radioactive material under normal and hypothetical accident conditions of transport	10 CFR Part 71 containment requirement
Hypothetical Accident Conditions	Package shall withstand 1 m puncture drop, 800°C fire for 30 min, and water immersion	10 CFR 71.73 hypothetical accident conditions
Module Package Size	20 ft or 40 ft ISO-equivalent	Common M1 reactor concepts
Module Package Mass	$\leq$ 22.7 tonnes	U.S. highway gross-vehicle mass limit after accounting for a tractor-trailer tare mass
Installation and Startup	$\leq$ 3 days	Consistent with the Project Pele requirements (Report No. PNNL-31867)
Disassembly and transport readiness	$\leq$ 7 days after shutdown	
Extended Passive Cooling	Minimum 72 hr without external power	Based on the Project Pele requirement (PNNL-36380 Rev. 1) and the NRC requirement (NRC Proposed Part 57, 57.30(b))
Package Surface Temp. During Transport	$\leq$ 85°C	10 CFR Part 71 requirement for exclusive-use transport
Transport Dose Rate	$\leq$ 2 mSv/h at the package surface	Conservative package-surface dose-rate criterion based on 10 CFR Part 71 [3]
Road Transport Vibration	Package shall withstand MIL-STD-810G Category 4 random vibration over 5–500 Hz	Conservative military wheeled-vehicle transport environment [4]

4. Preliminary Design Requirements

Table IV summarizes the preliminary top-level design requirements established for the reference TNR system. The requirements were derived by integrating nuclear-safety functions with the dimensional, mass, deployment, and environmental constraints associated with repeated road transport. The reactor is allocated to a dedicated transport package, while the power-conversion system, auxiliary equipment, and operational shielding are transported separately to maintain compatibility with the ISO-equivalent envelope and the 22.7-tonne roadway payload limit.

Transport safety is governed by the preservation of subcriticality, containment, shielding, and decay-heat removal under normal and hypothetical accident conditions, with 10 CFR 71.73 adopted as the bounding saccident basis. The deployment and removal times are aligned with the Project Pele requirements, while the package temperature, dose rate, and passive-cooling criteria ensure transport readiness following shutdown. Road-transport durability is addressed using the MIL-STD-810G Category 4 vibration environment. These preliminary requirements provide the design and verification baseline for subsequent structural, criticality, shielding, thermal, and transport-package assessments.

5. Conclusions

This study reviewed representative TNRs currently under active design, licensing, or prototype development. Most concepts remain at the engineering-design or prototype stage, and only a few target repeated relocation. Published data are also incomplete and inconsistent, particularly for package mass, transport configuration, cooling time, and relocation procedures. Nevertheless, HTGRs were prevalent among the repeatedly relocatable concepts. Accordingly, a helium-cooled prismatic-block HTGR is selected as the reference reactor. It provides 3.5 MWth and 1.0 MWe with a fuel cycle of 5 EFPY.

Preliminary requirements are established by combining the surveyed design characteristics with nuclear-safety and road-transport constraints. They address module size and mass, transport subcriticality, containment, accident resistance, passive cooling, radiation protection, and random vibration. Installation and startup shall be completed within 3 days, while transport preparation shall be completed within 7 days after shutdown. The reference configuration and principal requirements are summarized in Fig. 2.



Fig. 2. Reference TNR and design requirements

However, these requirements represent a preliminary design basis rather than a validated design specification. Some criteria adopted from existing regulations and standards may be overly stringent for a TNR The requirements may therefore need to be revised as the design objectives and system configuration are further defined.

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