Conceptual Core Design Study of a Pipe Type Transportable Molten Salt Fast Reactor

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1. Introduction

The development of micro nuclear reactors has gained attention recently, particularly for their potential use in forward operating bases and other remote installations. One innovative approach is the development of transportable reactors, which necessitates consideration of constraints related to weight and space limits for container loading and transport. As one of a solution, a molten salt reactor (MSR) with a pipe-shaped configuration suggested as a promising candidate. This design utilizes the advantages of molten salt reactors such as efficient flow distribution and reduced system weight due to simplification.

A preliminary study investigated the feasibility of such a pipe-shaped MSR design. Several conceptual designs have been examined from the perspective of nuclear core design as well as the technical challenges associated with implementing these concepts.

OpenMC, a program developed at the Massachusetts Institute of Technology, was used for all calculations, utilizing the ENDF/B-VII.1 cross-section library for iterative K-eigenvalue calculations. The analysis considered only stationary fuel and steady-state conditions, focusing on KCl-UCl_3 with HALEU (high-assay low-enriched uranium), which contains approximately 19.75% enriched U-235.

2. Pipe reactor

The primary advantage of a pipe reactor lies in the reduction of additional structural components required for flow field formation, thereby simplifying the design and development of the flow field. An unstable flow field can result in stagnant flow areas and localized temperature increases, requiring more support structures and a larger system volume overall. Managing the residence time of delayed neutron precursors is crucial because their behavior has a considerable impact on reactivity and reactor dynamics, whereas prompt neutrons are very modestly affected by flow. In MSR designs, which are aimed at low power generation with a compact core, narrow flow areas, and low velocities, achieving a uniform flow field becomes increasingly challenging.

In order to simplify system design and lower overall weight, a parametric study was carried out to analyze different inlet and outlet pipe designs and identify the ideal pipe thickness.Additionally, the feasibility of achieving sufficient excess reactivity by optimizing reflector efficiency was assessed.

2.1 Linear pipe design

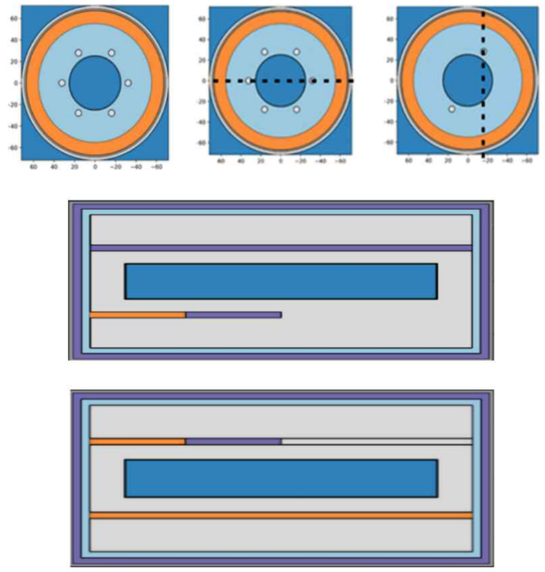

Fig. 1. Radial and axial schematic views of a linear pipe reactor.

The linear pipe design consists of a transversely extended cylindrical active core surrounded by concentric layers; a BeO reflector, CaH_2 shielding, and B_4C absorber. With a horizontal container length of approximately 12 meters, the design facilitates the implementation of a straightforward linear pipe concept. To prevent direct contact between the molten salt and the reflector, a nickel structural material coated with

SS316H is employed at the interface between the heat generation region and the reflector.

The three X-Y cross-sectional views in Figure 1 show the design configurations of the four control rods and two shutdown rods, which perform the respective functions of control and shutdown. Below the center of active corer height, only the two shutdown rods are able to be inserted. The purple region in Figure 1 represents the space available for the insertion of control rods, while the orange region illustrates the configuration with the control rods inserted. Shutdown rods can be fully inserted (100%), providing complete reactivity reduction. In contrast, control rods can be partially inserted (up to 50%), allowing for finer reactivity adjustments. During transport, all six rods are fully inserted to ensure the reactor remains in a subcritical state.

Table I: Evaluation of linear pipe control system's reactivity worth

Condition		Control rods	Safety rods	Keff(std)	Rod worth [pcm]
Normal operation	At 635℃	60 (Partial)	60 (Partial)	1.02573(11)	ITC (-1.21)
	At 735℃	60 (Partial)	60 (Partial)	1.02452(12)	
Normal Shutdown	4 CRs	110	60 (Partial)	0.98825(13)	3748
	3 CRs	110	60 (Partial)	0.99474(12)	3099
Emergency Shutdown	2 SRs	110	220	0.94841(14)	7732
	1 SRs	60 (Partial)	220	0.98687(13)	3886
All Rods In		110	220	0.91545(12)	11025

2.2 U shaped Pipe Reactor

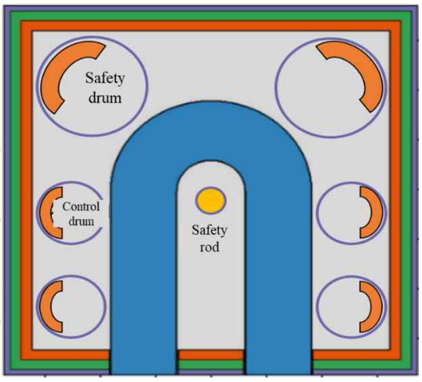

Fig. 2. Schematic drawing of a U-shaped pipe reactor.

In a linear pipe reactor, significant neutron leakage requires a larger fuel volume to achieve criticality and causes shielding issues, especially for compact cores. As a potential solution to these problems, a horizontal U-shaped reactor design with the inlet and outlet pipes arranged on the same plane has been investigated. This design allows the reflector to cover both inlet and outlet pipes simultaneously, resulting in a smaller reflector volume and weight than conventional linear pipe designs.

To take advantage of both devices, the control drum and control rods have been combined into a single control system. Control drums positioned vertically in the empty spaces of the reflector continuously introduce neutron absorbers without penetrating the vessel. Shutdown rods are strategically positioned in the central region where heat generation is highest.

Table II: Sensitivity evaluation U shaped pipe control system's reactivity worth

Control drum	Safety drum	Safety rod	Keff (std)
In	In	In	0.93995(13)
In	Out	In	0.95967(14)
In	Out	Out	0.97292(14)
Out	In	In	0.99874(12)
Out	Out	In	1.01739(13)
Out	Out	Out	1.03211(12)

2.3 Fork shaped pipe reactor

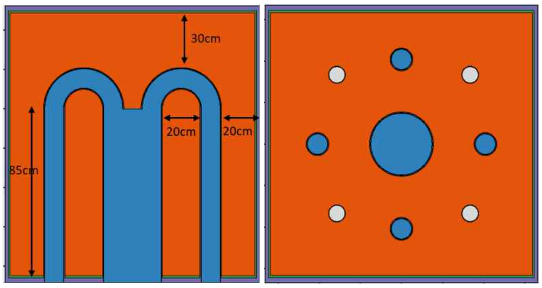

Fig. 3. Radial and axial schematic views of a fork-shaped pipe reactor.

The fork-shaped configuration directs molten salt from a single inlet pipe into multiple branched outlet pipes. This design improves reflector efficiency by increasing overlap between adjacent pipes compared to a U-shaped layout, while also reducing inlet pipe thickness. With a fixed flow rate, the outlet pipe thickness decreases proportionally as the number of branches increases. Control mechanisms, including control rods and drums, are implementedin a manner similar to the U-shaped pipe design.

Table III: Sensitivity evaluation of Fork shaped pipe control system's reactivity worth

Case	Keff (std)
4ea CR In	0.95757(13)
3ea CR In	0.97692(13)
2ea CR In	0.99674(12)
1ea CR In	1.01639(13)
All Rod Out	1.03451(12)

2.4 Spring shaped pipe reactor

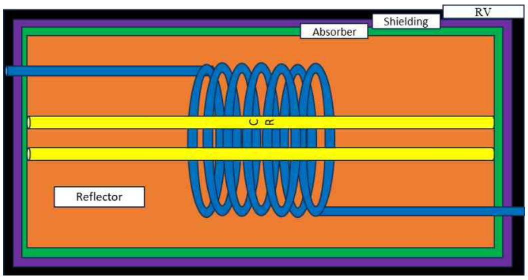

Fig. 4. Schematic drawing of a spring shaped pipe reactor.

The spring-shaped configuration features a coiled pipe concept positioned between a single inlet and outlet pipe, creating a compact heat generation section. The spiral piping acts as an effective reflector, reducing both the critical mass and the overall size of the heat generation section. Additionally, this design facilitates easy access for control rods to the central reflector region of the coiled pipe, where nuclear fission chain reactions are actively occurring. This accessibility enables precise reactivity control, offering the advantage of fine-tuning the reactor's reactivity.

3. Conclusions

This study presents a novel reactor design that moves from traditional upright cylindrical configurations to a horizontally elongated shape with thin-walled pipes. This design facilitates easier transportation and secure reactor fixing while maintaining efficient molten salt flow within the active core.

The development of a compact, container-friendly reactor is achieved by optimizing reflector efficiency and integrating effective control mechanisms. The horizontal reactor configuration, which uses the container’s length rather than its height, improves subsystem integration and vibration management during transportation.

The use of U-shaped and spring-shaped pipe layout significantly reduces overall fuel loading while boosting reflector performance. Furthermore, the design provides flexibility by allowing for reactor length extentions to meet increased power requirements, ensuring adaptability and operational efficiency.

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