Technical Overview of Challenges and Feasibility in Scaling Heat Pipe-Cooled Reactors to Megawatt Power Levels

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1. Introduction

Heat pipes are efficient heat transfer devices that operate through a two-phase process—boiling and condensation—which allows for significant heat transfer with minimal temperature difference between the heat source and the heat sink. These simple, sealed systems ensure no exchange of fluid or interfacing with external systems, making them ideal for various industrial applications, such as electronics and energy systems.

The application of heat pipes in nuclear reactors was first pioneered by NASA in the 1960s, largely because heat pipes function effectively in zero-gravity environments. Additionally, the passive nature of heat pipes makes them well-suited for space applications where maintenance is highly challenging. NASA's research initially focused on reactors in the kilowatt (kW) range, providing sufficient power for spacecraft and satellites. One significant project in this field is the KiloPower program, which developed compact space nuclear reactors. Its key achievement was the KiloPower Reactor Using Stirling Technology (KRUSTY), which used sodium heat pipes at 800ºC. A 1-kWe test reactor was successfully built and operated between 2017 and 2018, marking the first U.S. space reactor test since the 1960s [1].

Recently, efforts to scale up heat pipes to the megawatt (MW) range have increased, driven by the need for stable power in military bases, remote areas, and other critical infrastructure, as well as for passive cooling in spent nuclear fuel pools. This study provides an overview of heat pipe technology and examines the ongoing development in MW-scale heat pipes within the nuclear industry. It also highlights the technical challenges associated with scaling heat pipe-cooled systems.

2. Results and Discussions

2.1 Heat pipe Technology in Nuclear Industry

Heat pipes operate using a two-phase closed thermosyphon system that leverages phase change within a sealed loop, where a wick structure helps return the condensed fluid to the evaporator. The term "heat pipe" was first introduced in 1964 by Grover, who developed capillary-driven liquid-metal stainless-steel heat transfer devices intended for high-temperature applications, particularly space reactors. A key advancement in space reactor technology came in 1983 with the SP-100 reactor, which utilized Mo-13% Re (Rhenium) heat pipes with lithium as the working fluid. This was followed by the development of the SAFE-400 in the early 2000s, a 400-kWt reactor designed to work with a 100-kWe Brayton power system using Na/Mo heat pipes [2]. In 2018, the KRUSTY experiment successfully demonstrated a 1-kWe test reactor using sodium heat pipes. Table 1 shows the design specification of space heat pipe-cooled reactor being developed conceptually.

Table 1. Design specification of space heat pipe-cooled reactor [3, 4].

Reactor	*HP Fluid*	*# of HP*	*Thermal Power (kWt)*	*Electric Power (kWe)*	*HP Temp. (K)*
HOMER -15/25	Na/K	19 / 61	15 / 93.4	3/25	1,100 / 880
SAFE-400	Na	127	400	100	1,200
SP100	K	330	2,400	100	850
SAIRS	Na	60	407 ~ 487	110	1,100 ~ 1,200
MSR	Li	127	1,200	100	1,800
LEGO	Na	43	20 ~ 24	5 ~ 6	-
HP-STMCs	Li	126	1,600	110	1,500
KRUSTY	Na	8	5	1	1,050

Heat pipes are categorized into cryogenic, low-temperature, moderate-temperature, and high-temperature types, with each category defined by its temperature range and heat transport capability as shown in Table 2. High-temperature heat pipes, using sodium, potassium, or lithium, are commonly used in nuclear reactor cooling due to high melting and boiling temperatures, with transport capacities much higher than cryogenic and low/moderate-temperature heat pipes. Low temperature heat pipes, using ammonia or water, are effective in applications such as spent fuel pool cooling.

Table 2. Temperature range of working fluid in heat pipes [5].

Temperature Range Category	**Working Fluid**	**Applicable Temperature Range (K)**
Cryogenic	Helium	2 ~ 4
	Hydrogen	14 ~ 31
	Nitrogen	63 ~ 77
	Argon	84 ~ 116
	Oxygen	73 ~ 119
	Methane	91 ~ 150
Low	Freon-21	233 ~ 360
	Ammonia	213 ~ 373
	Acetone	273 ~ 395
	Water	303 ~ 550

Moderate	Naphthalene	408 ~ 523
	Dowtherm	423 ~ 668
High	Mercury	523 ~ 923
	Cesium	723 ~ 1,173
	Potassium	775 ~ 1,273
	Sodium	873 ~ 1,473
	Lithium	1,273 ~ 2,073
	Silver	2,073 ~ 2,573

2.2 MW-range Heat Pipe-Cooled Nuclear Systems

2.2.1 MegaPower (LANL)

The MegaPower Reactor developed by Los Alamos National Laboratory (LANL) is a mobile, heat pipe-cooled nuclear reactor concept designed for remote applications. It can produce 2 MW of electricity and 2 MW of process heat for up to 12 years. It uses uranium dioxide fuel enriched to 19.5% and incorporates 1224 potassium-filled heat pipes, operating at about 677°C to transfer heat efficiently without active cooling [6]. The reactor, measuring approximately 3.6 meters in length and 1.8 meters in diameter, is designed for high reliability and simplicity, making it ideal for challenging environments [6]. It is intended to be transportable by air or highway, operational within 72 hours of arrival, and housed in an armored cask for protection, with shutdown and relocation possible within seven days [6].

2.2.2 eVinci (Westinghouse)

The eVinci Micro Reactor by Westinghouse is a transportable energy generator designed to deliver combined heat and power ranging from 200 kWe to 5 MWe, with a process heat capability of up to 150°C. This reactor is fully factory-built, fueled, and assembled, with a design intended for a lifespan of 8 or more years. It employs TRISO fuel enriched to 19.75%, which is more resistant to neutron irradiation, corrosion, oxidation, and high temperatures than traditional fuels. Additional safety mechanisms include shutdown rods for defense-in-depth capabilities, control drums that adjust reactivity and passively rotate to a shutdown state, and a passive heat removal system that removes decay heat via natural convection and radiation. The reactor also features remote monitoring through an advanced Instrumentation and Control system. However, detailed technical specifications and reactor design for the eVinci reactor are not publicly available.

2.2.3 Passive Cooling System in Spent Fuel Pool

Several studies have been conducted on applying heat pipes to spent fuel pool (SFP) in China, particularly focusing on passive cooling systems. Key research designed a system to remove 16MW of decay heat from SFP of CAP 1400 nuclear power plant using a loop-type heat pipe, where water circulates by natural convection with phase change under vacuum [7]. In their study, it was found that total 1,594 heat pipes can remove the targeted decay heat of 16 MW. Following this conceptual design, Xiong et al. tested a full-scale prototype of a single loop-type heat pipe [8]. It validated that each heat pipe could remove up to 10.5 kW of heat under optimal conditions.

2.3 Technical Challenge in Scaling on Heat Pipe

Among the published work, only LANL explicitly described and analyzed the scaling issues of heat pipes for MWe scale applications. According to LANL, a major challenge is the practical limit on the number of heat pipes that can be integrated into a single reactor block [6]. As the reactor's power output increases, more heat pipes are needed to manage the thermal load. However, current manufacturing techniques limit this number to approximately 200 heat pipes per block, posing a significant constraint on scalability [6]. Figure 1 shows the heat transport capacity of single heat pipes used in nuclear-related industries. This indicates that few heat pipes can transport over 10 kWth, which means that 300 or more heat pipes would be required to produce 1 MWe for thermal efficiency around 33%.

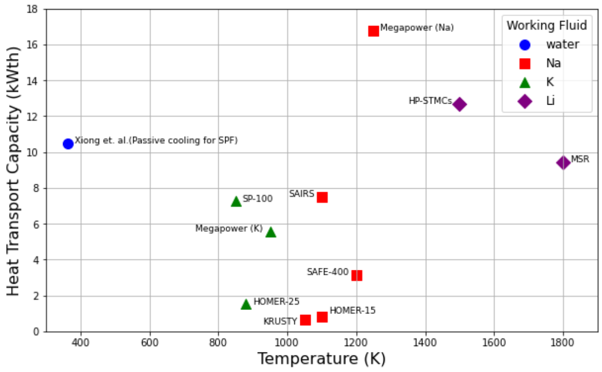

Fig 1. Heat transport capacity of single heat pipe being applied to nuclear industry with respect to operating temperature.

The limitation on the number of heat pipes is closely tied to the risk of cascade failure. Cascade failure is a significant risk in heat pipe reactors, where the failure of one pipe can trigger a domino effect, leading to the failure of adjacent pipes and compromising the reactor's cooling capacity. This risk increases as more heat pipes are integrated into the reactor. Such failures can result in severe accidents, similar to steam generator tube rupture in a pressurized water reactor (PWR), causing fuel or cladding swelling, monolith failure, and core damage [9]. Designing for the failure of a few pipes without catastrophic consequences is crucial, but the challenge grows with the number of heat pipes [6].

Another challenge is the operation limits of heat pipes, which depend on the working fluid and pipe design. Each heat pipe has specific thresholds that affect its heat transfer capability as shown in Figure 2. The sonic and viscous limits are important during startup, while the entrainment and capillary limits determine the maximum heat transport capacity once the pipe heats up and reaches its steady-state operating temperature. The boiling limit is crucial during accidents. These limits make it hard for a single heat pipe to handle large amounts of heat, which is the major challenge in reaching megawatt power levels.

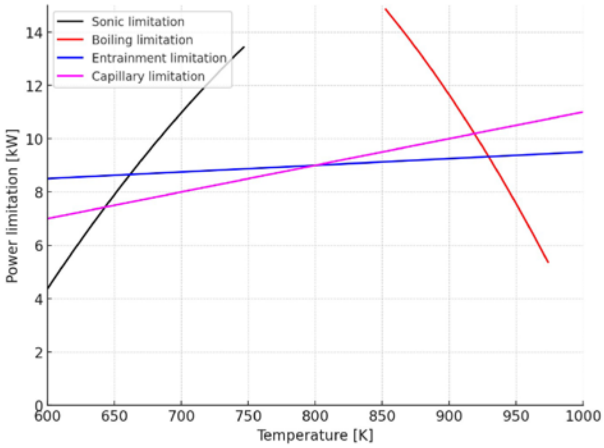

Fig 2. An example of heat pipe operation limits with Na.

The selection of materials for the reactor core and heat pipes introduces further constraints. Materials must not only withstand high temperatures and radiation but also perform reliably under the mechanical stresses imposed by normal operation and potential accidents [6].

3. Summary

This study provides an overview of heat pipe technology in the nuclear industry, focusing on the challenges of scaling heat pipe-cooled systems to megawatt power levels. Heat pipes, first applied in space reactors by NASA, are efficient heat transfer devices operating through a two-phase process. However, scaling them for higher power applications, such as in remote nuclear reactors or spent fuel pool cooling, presents significant challenges. A key issue is the practical limit on the number of heat pipes that can be integrated into a single reactor block, which increases the risk of cascade failure—a domino effect where the failure of one heat pipe triggers the failure of adjacent ones, like steam generator tube rupture in PWRs.

Each heat pipe also has operational limits, influenced by the choice of working fluid and pipe design, that restrict its maximum heat transfer capacity. These constraints make it difficult to achieve megawatt power levels. Overcoming these challenges will necessitate technological advancements, including the optimization of heat pipe internal designs such as wick structures, the development of materials capable of withstanding extreme conditions, and comprehensive research into heat pipe failure mechanisms. Such innovations are crucial for enhancing the reliability and scalability of heat pipe-cooled reactors.

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