INL/JOU-25-84333-Revision-0

Phenomena Identification and Ranking Table (PIRT) for Heat Pipes

July 2025

Changing the World's Energy Future

Ilyas Yilgor, Mauricio Eduardo Tano Retamales

Idaho National Laboratory

INL/JOU-25-84333-Revision-0

Phenomena Identification and Ranking Table (PIRT) for Heat Pipes

Ilyas Yilgor, Mauricio Eduardo Tano Retamales

July 2025

Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

Phenomena Identification and Ranking Table (PIRT) for Heat Pipes

Ilyas Yilgor[a,*], Mauricio Tano[a], Katrina M. Sweetland[b], Joshua E. Hansel[a], Piyush Sabharwall[a], Mark H. Anderson[a,c], Zachary D. Sellers[a], Lise Charlot[a], Jeremy L. Hartvigsen[a], Victor Petrov[d,e], Yinbin Miao[f], Stephen Bajorek[g], Tarek Zaki[g]

[a] *Idaho National Laboratory, Idaho Falls, ID, USA*
[b] *Los Alamos National Laboratory, Los Alamos, NM, USA*
[c] *University of Wisconsin, Madison, WI, USA*
[d] *Paul Scherrer Institute, 5232 Villigen PSI, Switzerland*
[e] *University of Michigan, Ann Arbor, MI, USA*
[f] *Argonne National Laboratory, Lemont, IL, USA*
[g] *Nuclear Regulatory Commission, Washington, D.C., USA*

Abstract

Heat pipes are advanced passive thermal management devices that utilize phase change and capillary action to achieve efficient heat transfer. However, due to the complexity of the phenomena coupled in heat pipes, including capillary, phase change, turbulence, and compressibility effects, there are high uncertainties in the predictability of their operational regimes and performance. This PIRT exercise, conducted as a collaborative effort involving the Department of Energy (DOE) Microreactor Program (MRP), the Nuclear Regulatory Commission (NRC), and university partners systematically identifies, reviews, and prioritizes critical phenomena affecting the operation of heat pipes based on their importance and knowledge levels. Additional analyses and discussions are provided for phenomena with high importance and low knowledge, such as wick de-wetting, critical heat flux, contact angles, and pressure dynamics. The discussions include recognizing challenges and proposing future research directions for both modeling/simulation and experimental efforts. Additionally, the article addresses phenomena with medium importance and low knowledge that could impact heat pipe operation during non-normal or transient conditions, including frozen startup, laminar to turbulent transition, geyser boiling, wick priming, under-filling conditions, surface roughness of the wick, non-condensable gases trapped in the wick, and the timescales of startup and shutdown. This comprehensive evaluation serves as a valuable resource for guiding future research and development efforts, supporting the successful integration of heat pipes into nuclear reactors, and contributing to the advancement of heat pipe technologies in safety-critical industries.

1. Introduction

Heat pipes are advanced passive thermal management devices that utilize phase change and capillary action to achieve efficient heat transfer between the evaporator and condenser. Their applications cover a broad spectrum, from electronics cooling to space systems and nuclear reactors. Heat pipe microreactor (HPMR) concepts have recently been developed by NASA [1,2], LANL [3], and Westinghouse [4], where heat pipes are used to transfer core heat to the power conversion system efficiently, exploiting the extremely high effective thermal conductivities of heat pipes compared to solid materials. This approach yields simple, compact, and mobile reactor designs with passive core cooling, eliminating coolant pumping systems for increased reliability and low maintenance. A schematic describing heat pipe operation can be seen in Figure 1, where the working fluid evaporates from the wick in the evaporator and into the vapor core, flows to the condenser, where it condenses, re-enters the wick, and returns to the evaporator via capillary forces provided by the wick structure. For nuclear applications, the investigated working fluids are mainly alkali metals such as sodium and potassium, which allow high operating temperatures, enabling efficient power conversion and process heat capabilities.

The Department of Energy (DOE) Microreactor Program (MRP) has designated four focus areas to support microreactor development: (i) System integration and analyses, (ii) technology maturation, (iii) demonstration capabilities, and (iv) microreactor applications [6]. Considering these areas, research and development (R&D) support for HPMRs is needed to:

- Better understand heat pipe normal and degraded operation, particularly during transients and accident scenarios,
- Develop design and analysis tools for heat pipes and HPMRs,
- Verify and validate models used in heat pipe and reactor design,
- Enhance heat pipe performance and reliability through novel wick designs, and fabrication techniques,
- Establish regulatory requirements.

To better guide and manage R&D efforts, the present phenomena identification and ranking table (PIRT) exercise was

*Corresponding author
Email address: ilyas.yilgor@inl.gov (Ilyas Yilgor)

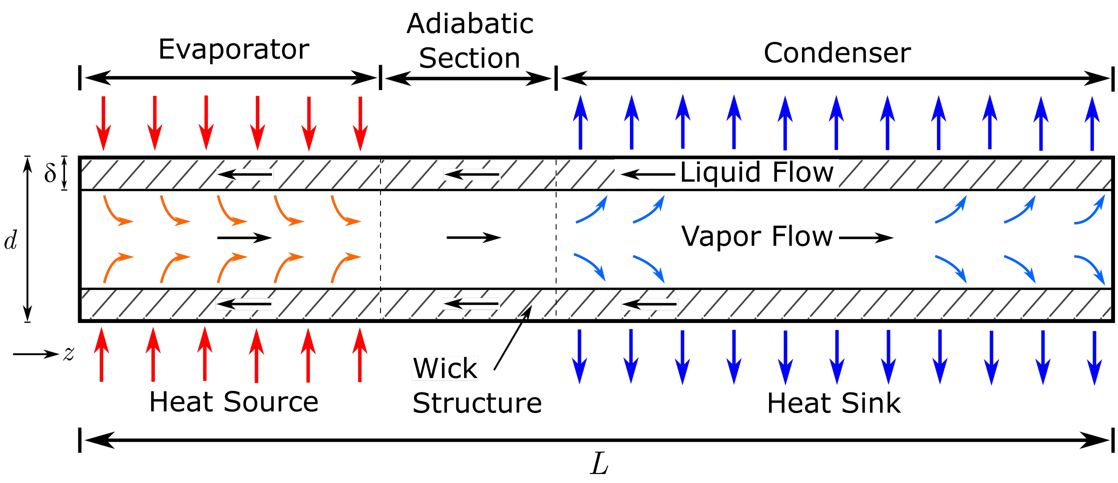

Figure 1: A schematic showing heat pipe operation [5].

proposed. This PIRT exercise aims at systematically identifying, reviewing, and prioritizing key phenomena affecting heat pipe operational regimes and performance based on importance and knowledge rankings, while considering modeling and experimental challenges. Through this exercise, future avenues for R&D on the identified phenomena can be determined considering the importance and knowledge levels determined by experts. The exercise was organized into several phases, each designed to logically build upon the previous one, culminating in the present paper that is aimed to serve as a valuable resource for researchers, developers, and industry stakeholders. By involving a diverse group of stakeholders and following a detailed process of identification, review, and prioritization, the PIRT exercise resulted in a robust and reliable resource that addresses all critical aspects of heat pipe operation. This article is thus expected to be a reference for heat pipe R&D in a variety of fields including nuclear.

The present work is organized as follows: Section 2 describes the organization of the exercise including a list of participants, the PIRT plan including various steps for logical progression, the discussion format, and the ranking system; Section 3 presents the identified phenomena and their descriptions grouped into ten categories, and gives the rankings and rationale for each phenomena as agreed upon during the PIRT meeting; Section 4 includes discussions on the PIRT findings and proposed steps for future R&D efforts; and lastly Section 5 presents a summary and conclusions.

2. Organization

2.1. PIRT Plan

PIRT development process has been employed in the nuclear industry by various institutions [7,3,8]. The organizational structure followed by the present PIRT exercise is a nine-step process commonly employed in literature. This process is shown schematically in Figure 2. It should be noted that the present work investigates heat pipes, rather than a particular accident scenario for a certain hardware system or reactor design. The descriptions of all steps employed are described in the present section.

2.2. Issue

The issue driving the PIRT exercise are the uncertainties in phenomena impacting heat pipe operational regimes and performance in HPMRs and other advanced reactor applications. These uncertainties and knowledge gaps hinder the development of heat pipe technologies and thus HPMR deployment since stakeholders could have difficulties distinguishing critical phenomena that needs to be investigated.

It should be noted that, although the operational regimes and heat transfer performance of heat pipes for advanced reactor applications are investigated in particular, most identified phenomena are also relevant to low-temperature heat pipes that may be employed for R&D for V&V and separate effect tests purposes.

2.3. Objectives

A series of objectives are developed for this PIRT considering the issue defined in the previous step. The main objectives which are supported as a result of this PIRT exercise can be itemized as follows:

1. **Improve modeling accuracy:** Enhance the accuracy of lumped parameter and computational fluid dynamics models for heat pipes by systematically identifying and prioritizing critical phenomena that influence heat pipe performance and ranking their impact.
2. **Optimize heat pipe design:** Enable the design of more efficient and reliable heat pipes by understanding the impact of different phenomena on heat transfer efficiency and operational stability.
3. **Guide experimental research:** Guide experimental research efforts towards the most impactful and uncertain phenomena for heat pipe operation, thereby optimizing resource allocation and experimental design.

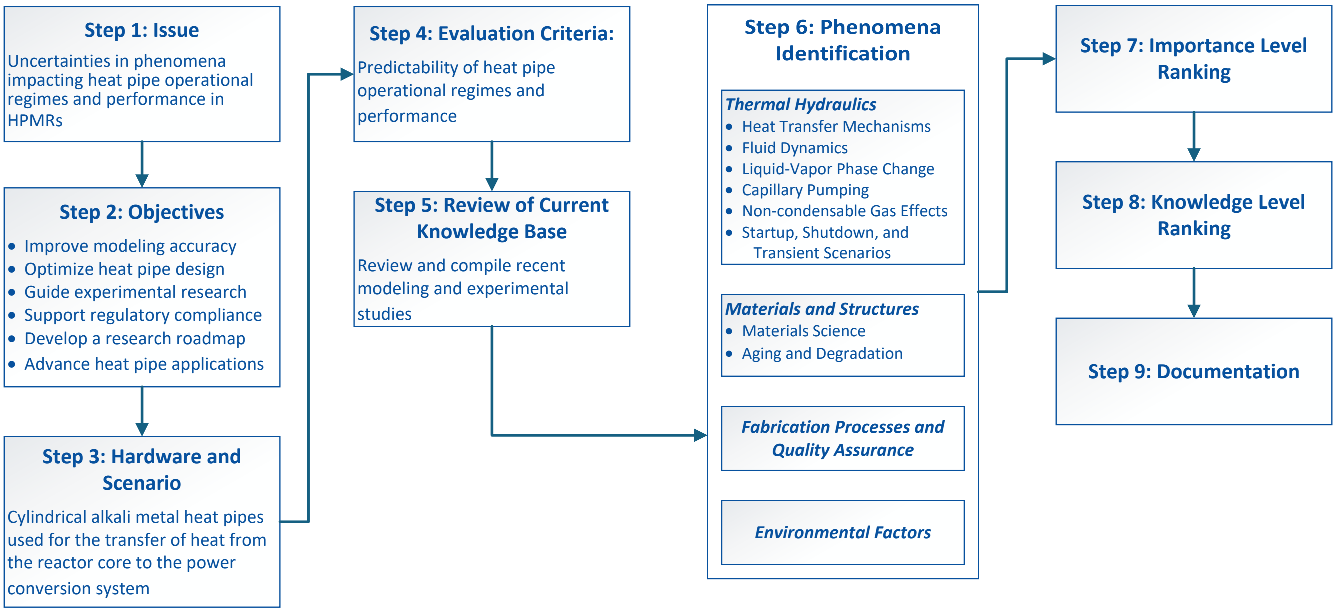

Figure 2: A schematic description of the PIRT process employed in the present work.

4. **Support regulatory compliance:** Provide a scientifically robust foundation for regulatory assessments and approvals by nuclear regulators, e.g., the U.S. NRC, and other stakeholders.
5. **Develop a research roadmap:** Create a prioritized research roadmap that addresses the most critical and uncertain aspects of heat pipe technology, guiding future R&D activities.
6. **Advance heat pipe applications:** Support the development and deployment of advanced heat pipe technologies for nuclear reactors applications by providing a detailed understanding and ranking of their underlying physics affecting heat pipe operation.

2.4. *Hardware and Scenario*

The present exercise broadly considers phenomena related to cylindrical alkali metal heat pipes used for the transfer of heat from the reactor core to the power conversion system. Alkali metals are the main type of working fluid being considered for HPMR applications mainly due to their high operating temperatures. However, it should be noted that there is significant overlap in the important phenomena for all types of heat pipes due to their common operating principles. Furthermore, the rankings and rationale focus on annular (annulus-screen) wicks and sodium working fluids that are envisioned to be utilized in HPMR applications, however the identified phenomena and rationale are also mostly applicable to other wick types.

2.5. *Evaluation Criteria*

Considering the identified issue and objectives, the figure of merit (FOM) for the PIRT is identified as the “predictability of heat pipe operational regimes and performance”. This figure of merit represents the level of impact that a phenomenon has on determining the heat pipe operational regimes and its performance under these regimes. It should be noted that the figure of merit is not a direct quantitative parameter by design, such that the general scope of the present PIRT is maintained and a wide range of phenomena can be identified. This also enables the use of the PIRT for developing a research roadmap. The task of defining the operation of a heat pipe is challenged by multiple regimes that are expected during its lifetime in an HPMR. For alkali metal heat pipes in microreactor applications, the different operational regimes or states identified are the following:

- **Startup:** The working fluid, which is initially at a fully or partially frozen state, gradually melts and then evaporates, to later travel toward the condenser section. The heat pipe is assumed to be under the startup regime until it reaches nominal operating conditions. Since reactor startups are not conducted frequently, phenomena solely affecting startup conditions are not considered critical for the FOM. The occurrence of viscous and sonic limits are normally expected during startup.

- **Normal operation:** A heat pipe that is under normal operating conditions sustains cyclic evaporation and condensation of the working fluid and exhibits nearly isothermal operation across its active length. Since this is the condition mostly expected during the operation of HPMRs, accurate prediction of this condition is paramount. Therefore, phenomena significantly affecting the normal operation of heat pipes including steady states and transients will be considered of high importance in this work.

- **Degraded performance:** Heat pipe performance may degrade over its operating life due to factors such as corrosion, gradually decreasing its heat transfer efficiency. By design, significant degrading of performance should be prevented for heat pipes. Therefore, this operating condition is considered to occur with relatively low frequency and its importance on heat pipe operation is not considered fundamental.

- **Shutdown:** The shutdown process involves the heat pipe operating temperatures reducing to near ambient values and the working fluid solidifying within the wick. This is the condition from the normal operation of the heat pipe up until the working fluid circulation ceases within the heat pipe. Similar to startups, the frequency of occurrence for shutdowns is low, therefore this condition is not considered critical for the FOM.
- **Accident and limit conditions:** The heat pipe power throughput is bound by operating limits that include viscous, sonic, capillary, entrainment, and boiling limits. These limits are crucial, as reaching these limits will either bound or impair the operation of the heat pipe. Hence, phenomena considerably affecting the operational limits and causing safety concerns will be considered of high importance in this work.

A more detailed description of these regimes is described in Yilgor et al.[9]. The reader is directed to this report for future reference.

In addition, the following performance metrics are identified for the definition of the figure of merit:

1. **Power Limit:** This metric represents the maximum thermal power (heat energy per unit time) that a heat pipe can transfer. It is constrained by physical limits, which include:
    - *Frozen Startup Limit:* Working fluid re-freezing in the condenser during frozen startup can result in the frozen startup limit due the failure of the liquid to return to the evaporator.
    - *Viscous Limit:* The vapor pressure not being sufficient to overcome viscous losses during the early stages of startup at low operating temperatures results in the viscous limit.
    - *Sonic Limit:* Choking near the evaporator exit limits the mass flow rate of the vapor and therefore the axial power throughput, resulting in the sonic limit.
    - *Capillary Limit:* The capillary pressure supplied by the wick structure not being sufficient to overcome the losses along the working fluid flow path results in the capillary limit.
    - *Entrainment Limit:* The dryout of the wick due to interfacial shear forces causing the liquid to be entrained into the vapor core results in the entrainment limit.
    - *Boiling Limit:* The onset of nucleate boiling in the wick or annulus is defined as the boiling limit since the nucleated bubbles can diminish liquid return to the evaporator.
2. **Effective Thermal Conductivity:** This metric is an analogous measure to thermal conductivity found in solid materials and quantifies the heat transfer efficiency of a heat pipe. Higher effective thermal conductivity indicates better performance and efficiency of the heat pipe in transferring heat. It is defined using the following formula:

$$k_{eff} = \frac{QL_{eff}}{A\Delta T} \tag{1}$$

   where Q is the thermal power transferred by the heat pipe, L_{eff} is the effective length of the heat pipe, A is the cross sectional area of the heat pipe, ΔT is the temperature drop along the effective length of the heat pipe. The effective length of the heat pipe is defined as:

$$L_{eff} = \frac{L_e}{2} + L_a + \frac{L_c}{2} \tag{2}$$

3. **Response Time:** This metric indicates how quickly a heat pipe responds to transients. Response time is critical for applications where rapid changes in thermal load occur, as it affects the stability and safety of the system. It is typically measured as the time taken for the heat pipe to reach a new steady-state temperature after a sudden change in heat input. A shorter response time signifies a more responsive and adaptive heat pipe under dynamic conditions.

It should be noted that these metrics were chosen to broadly represent heat pipe performance and are more significant under certain operational regimes than others.

2.6. Review of Current Knowledge Base

Current knowledge base was established previously by review studies supported by INL and the DOE-MRP, including the work by Wahlquist et al.[10] and Yilgor et al.[11,12,9], who investigated heat pipe experimental work in literature. The PIRT panel members are all subject matter experts who are already versed in heat pipe technologies and have recently contributed to heat pipe research funded by the DOE and the NRC. The panel included experts in modeling and simulations, experiments, heat pipe fabrication, and licensing, in order to comprehensively assess the importance of the phenomena from different perspectives.

2.7. Phenomena Identification

Defining broader categories and subcategories of phenomena affecting heat pipe operational regimes and performance was deemed important for the organization of the PIRT exercise. These categories and subcategories are:

1. Thermal-hydraulics,
    - Heat transfer mechanisms
    - Fluid dynamics
    - Liquid-vapor phase change
    - Capillary pumping
    - Non-condensable gas effects

- Startup, shutdown, and transient scenarios

2. Materials and structures
   - Materials science
   - Aging and degradation
3. Fabrication processes and quality assurance
4. Environmental factors

Each identified phenomenon was grouped under these categories and described in detail, with its impact and potential consequences thoroughly examined. This comprehensive approach ensures that all critical aspects of heat pipe operation are considered, providing a solid foundation for future research and development efforts. It should be noted that, due to the coupled nature of the phase change, heat transfer, and flow dynamics within heat pipes, there may exist some overlap between different categories or phenomenon. However, these cases involve similar phenomena evaluated from a different perspective and may differ in their importance or knowledge rankings.

2.8. Importance Level Ranking

The importance level of each phenomenon considering its effect on the FOM was determined following the criteria shown in Table 1. The importance levels for all phenomena were determined by consensus during the exercise and by written iteration with participants after the exercise.

2.9. Knowledge Level Ranking

Two knowledge levels for each phenomenon are identified for "modeling and simulation" (M&S) and "experiments and instrumentation" (E&I), such that knowledge levels may be better characterized for each of these disciplines:

- M&S knowledge measured the extent and accuracy to which current modeling and simulation capabilities can capture the phenomena, e.g., high knowledge means that current tools can fully model the phenomenon with relatively high accuracy, while low knowledge means that current models cannot significantly capture the phenomenon or the uncertainty of models in capturing the phenomena is significantly high.

- E&I knowledge evaluates the knowledge level on experimental techniques and the measurement of parameters related to the phenomena, e.g., high knowledge means that experimental methods to measure or characterize the phenomena are well known and with relatively low error, while low knowledge means that the experimental methods cannot effectively measure or characterize the phenomena, and techniques are either underdeveloped or have high uncertainties.

The knowledge levels were evaluated following importance level rankings shown in Table 2. The knowledge levels for all phenomena were determined by consensus during the exercise and by written iteration with participants after the exercise.

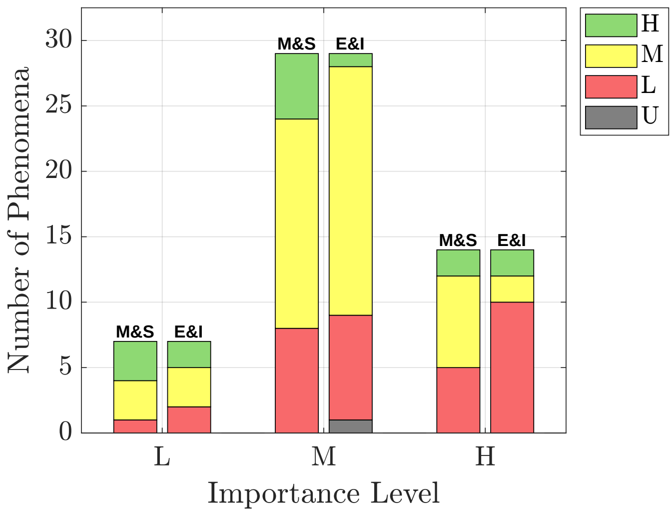

Figure 3: Number of phenomena for each importance level categorized by their knowledge levels for modeling and simulation (M&S) and experiments and instrumentation (E&I).

2.10. Documentation

The present article and the accompanying technical report[13] serves as the main document for this purpose, describing the PIRT process, identified phenomena, importance and knowledge rankings, as well as discussion on future research directions.

3. Phenomena Identification and Ranking

The identified phenomena and their importance and knowledge rankings are shown in Tables 3 to 6 for thermal-hydraulics, materials and structures, fabrication and QA processes, and environmental factors related phenomena, respectively. A full description of the individual phenomena and their importance and knowledge rationales can be found in the accompanying technical report[13]. The present work discusses all high-importance and select medium-importance phenomena that were identified in the exercise for conciseness.

In total, 50 phenomena were identified of which 14 were of high importance, 29 were of medium importance and 7 were of low-importance. The number of phenomena for each importance level categorized based on their knowledge level for M&S and E&I are shown in Figure 3. It can be seen from the Figure that the knowledge levels are consistently lower for E&I compared to M&S, considering a smaller number of phenomena were identified as high-knowledge across the different importance levels.

3.1. High-Importance Phenomena

The PIRT exercise has identified several phenomena as having high importance on heat pipe operation due to their critical impact on safety and performance. These phenomena are summarized in Table 7 and discussed more detail in the present subsection.

Importance Level	Definition	Outcome
High (H)	High impact on FOM	Critical to safety, as well as the design, performance, and modeling of the system
Medium (M)	Moderate impact on FOM	Moderately important to the design, performance, and modeling of the system,
Low (L)	Low impact on FOM	Relatively low importance to the effective design and modeling of the system
Insignificant (I)	Little to no impact on FOM	Minimal or negligible importance to the effective design and modeling of the system

Table 1: Definitions of importance level rankings.

Knowledge Level	Definition
High (H)	Fully known, low uncertainty
Medium (M)	Mostly known, moderate uncertainty
Low (L)	Mostly unknown, high uncertainty
Unknown (U)	Limited knowledge, uncertainty cannot be characterized

Table 2: Definitions of knowledge level rankings.

3.1.1. Thermal-Hydraulics

A majority of high-importance phenomena are in the thermal hydraulics category. These phenomena include **liquid and vapor pressure drops**, which represent the flow resistance to the fluid circulation within the heat pipe. They are thus critical to heat pipe operation, as capillary limits are often the limiting factor for alkali metal heat pipes under nominal operating conditions. These pressure drops should be minimized through effective wick and heat pipe designs to achieve high power throughputs.

Wick de-wetting is a phenomenon that can seriously degrade heat pipe performance, causing rapid increases in wall temperatures at the evaporator followed by de-coupling at the condenser. Ensuring that the wick remains wetted is crucial for maintaining effective heat transfer and preventing hotspots. During transients or changes in orientation, portions of the wick may become de-wetted due to gravity, leading to pooling of the working fluid and diminished heat transfer efficiency in the evaporator. This can result in significant temperature spikes, which may damage the heat pipe or reduce its operational lifespan. Accurate modeling and experimental characterization of wick de-wetting are therefore vital to preventing these adverse effects during transient conditions.

The process of **evaporation and condensation** at the liquid/vapor interface is central to the heat transfer mechanism of heat pipes, as it enables the transfer of heat from the evaporator to the condenser. The efficiency and effectiveness of this phase change process directly influences the overall power output and effective conductivity of the heat pipe. Consequently, improving the understanding and modeling of evaporation and condensation is essential for enhancing heat pipe performance predictions and ensuring reliable operation in various applications.

The boiling limit for heat pipes is characterized by **nucleate boiling at high heat fluxes** in the annulus or wick. Due to the high wall superheats involved during boiling for liquid metals, the process can cause large wall temperature fluctuations. Furthermore, the generated bubbles can prevent liquid return in the evaporator, potentially creating a positive feedback mechanism through which the liquid in the evaporator may be depleted. Certain conditions such as the presence of NCGs within the heat pipe or changes in surface characteristics can reduce the heat flux at which the onset of nucleate boiling occurs. This condition can result in rapid heat pipe failure and must be addressed by lowering the input power. If the heat flux is increased past boiling limit (onset of nucleate boiling) conditions, **critical heat flux** can be reached. This condition can cause serious damage to the heat pipe body or wick structures. It can be assumed that the heat pipe cannot be operated further once it reaches CHF. Such conditions can occur during system-scale accidents such as cascading heat pipe failure, or reactivity insertion accidents. CHF may be used to define the absolute heat transfer capacity of heat pipes above which heat pipes will be rendered obsolete.

Capillary action is the mechanism that enables the transfer of liquid from the condenser to the evaporator via a capillary pressure difference between the vapor and liquid supplied by the pores in the wick structure. Therefore, this phenomenon is crucial for the liquid return to the evaporator to sustain the heat transfer function of the heat pipe. An optimized wick structure should be designed in such a way to supply high capillary pressures through small pores, while minimizing viscous losses due to the permeability of the wick structure. In addition, **wettability** of the wall and wick materials directly affect the capillary pressure that can be supplied by the wick. Good wettability enables higher maximum capillary pressures and enhances heat pipe performance by increasing the capillary limit.

Solidification and solid accumulation post-shutdown is important as the heat pipe returns to near-ambient conditions. The working fluid must solidify in the wick uniformly in a manner that allows for efficient re-start. Improper solidification can result in uneven distribution of the working fluid, leading to performance degradation during subsequent startups.Therefore, developing robust startup and shutdown procedures that account for these phenomena is crucial for maintaining heat pipe performance and reliability.

Internal **pressure dynamics** in the heat pipe during startup, shutdown, and transients such as limit conditions or power fluctuations can have significant effects on safe and stable operation. A heat pipe is ultimately a pressure-driven device, where the capillary pressure provided by the wick is ultimately compensated by the pressure drops in the wick and vapor core. During startup of the heat pipe, the capillary force and expanding flow in the evaporator exceed losses, leading to the activation of the circulation along the wick and the vapor core. The time scale of the startup transient is regulated by the buildup of flow friction in the wick and vapor core. During shutdown, the phenomena are reversed, and the friction forces usually dictate the shutdown time scale. Pressure fluctuations due to evaporation and condensation usually show nonlinear behavior, which results in a nonlinear response of the heat pipe under evaporator and condenser load changes. Therefore, understanding the pressure dynamics is critical to predict the power output of the heat pipe, its effective thermal conductivity, and the timescale of its response.

3.1.2. Materials and Structures

Corrosion and oxidation of heat pipe materials represent another critical phenomenon due to their potential to diminish the long-term reliability of heat pipes. Corrosion can alter material properties, damage the wick structure, and introduce non-condensable gases into the heat pipe. These effects can diminish the capillary pumping ability of the wick, reduce heat transfer efficiency, and ultimately lead to heat pipe failure. Given the high operating temperatures and harsh environments often encountered in heat pipe applications, selecting corrosion-resistant materials and implementing protective measures are essential for ensuring the longevity and reliability of heat pipes.

Creep deformation is important to the structural integrity of heat pipes, considering they must withstand extreme temperatures and physically interact with core structures. Therefore, creep should be considered in both heat pipe and reactor design.

Fluid contamination during fabrication or operation due to impurities from structural materials or oxides can influence working fluid properties and useful life. Since the heat pipe is a closed system, such contamination should be avoided during fabrication with effective QA practices. Contaminated working fluids can cause increased corrosion and the formation of NCGs within the heat pipe, affecting reactor safety and reducing performance.

Long-term operation can result in **wick degradation** because of fluid contamination, corrosion, clogging, or mechanical damage. This is highly important as any breaks or irregularities in the continuity of the wick structure can reduce the capillary pressure supplied by the wick or create increased pressure drops. Considering this, heat pipe fabrication techniques should ensure the wick and wall is clean, free of any contaminants, and are compatible with the working fluid.

		Knowledge	
Phenomenon	**Importance**	**M&S**	**E&I**
Radial heat conduction	M	H	M
Axial heat conduction	M	H	M
Azimuthal heat conduction	L	M	M
Thermal contact b/w wick and wall	L	L	M
Vapor advection	M	M	L
Liquid advection	M	H	L
Thermal contact b/w the core and the heat pipe	M	M	L
Radiation heat transfer	M	L	M
Laminar/turbulent transition in vapor flow	M	L	L
Near-sonic compressible flow	M	M	M
Compressible/incompressible transition in vapor flow	M	M	U
Rarefied flow and continuum flow front	L	M	L
Liquid flow and pressure drops	H	M	L
Vapor pressure drops	H	M	L
Geyser boiling	M	L	M
Wick priming	M	L	M
Wick de-wetting	H	L	H
Excess liquid pooling in the condenser	M	M	M
Evaporation and condensation	H	M	L
Nucleate boiling at high heat fluxes	H	L	L
Critical heat flux	H	L	L
Capillary action	H	H	M
Wettability	H	L	L
Wet point location	M	M	M
Accumulation of NCGs in the condenser	M	M	M
Vapor-NCG front location	M	M	M
Diffusion /mixing b/w vapor and NCG	M	M	L
NCG getting trapped in the wick	M	L	L
Frozen startup	M	M	M
Solidification and solid accumulation post-shutdown	H	M	H
Startup and shutdown time scales	M	L	H
Successive startups and shutdowns	M	M	M
Thermal stresses	M	M	M
Pressure dynamics	H	L	L

Table 3: Identified and ranked thermal-hydraulics phenomena and rankings.

		Knowledge	
Phenomena	**Importance**	**M&S**	**E&I**
Corrosion and oxidation in wick and wall materials	H	M	M
Creep in wall/wick materials	H	H	L
Acute mechanical damage	M	M	M
Material degradation	M	M	M
Fluid contamination	H	M	L
Wick degradation	H	M	L
NCG Production	L	M	L
Irradiation damage	M	H	M

Table 4: Identified and ranked phenomena related to materials and structures.

		Knowledge	
Phenomena	**Importance**	**M&S**	**E&I**
Dimensional tolerances	M	H	M
Surface roughness of wall	L	H	H
Surface roughness of wick	M	L	L
Under-filling	M	L	L
Wick fabrication techniques	M	M	M
Manufacturing defects	L	H	M

Table 5: Identified and ranked phenomena related to fabrication processes and QA.

		Knowledge	
Phenomena	**Importance**	**M&S**	**E&I**
Humidity	L	H	H
Vibration and movement	M	M	M

Table 6: Identified and ranked phenomena related to environmental factors.

3.2. Select Medium Importance Phenomena with Performance Implications

Ensuring that heat pipes can effectively manage transients is essential for their successful integration into critical systems, such as nuclear reactors, where stability and reliability are paramount. If non-normal scenarios are analyzed, operational transients are considered, or high-performance heat pipe operation is desired, some phenomena listed as medium importance could significantly impact the power limit and effective thermal conductivity of the heat pipe. These phenomena are reported in the following subsections based on their category.

3.2.1. Thermal-Hydraulics

Efficient **thermal contact between the reactor core and the heat pipe** is essential for the effective transfer of heat from the core to the heat pipe, which in turn is crucial for maintaining safe and stable reactor operation. Poor thermal contact can lead to localized hotspots and reduced heat transfer efficiency, potentially compromising the reactor's performance and safety. Consequently, ensuring robust thermal contact through proper design, fabrication, and assembly methods is a key focus area for heat pipe development.

Liquid and vapor advection within the heat pipe enable the axial transfer of heat along the heat pipe length after the working fluid's latent heat is exchanged in the evaporator and condenser. Vapor advection involves the movement of vapor from the evaporator to the condenser within the vapor core, while liquid advection refers to the return of liquid from the condenser to the evaporator via the wick. Both processes are needed for maintaining the cyclic operation of heat pipes and ensuring continuous heat transfer. Any disruptions or inefficiencies in these processes can lead to performance degradation. Therefore, accurate modeling and experimental characterization of vapor and liquid advection are vital for optimizing heat pipe designs and improving their reliability.

Near-sonic compressible flows occur at low operating temperatures during heat pipe startup and can limit the mass flow rate of the vapor due to choking. Although this condition is a limiting condition known as the sonic limit, it does not cause heat pipe failure but rather serves as an operational bound. Therefore, the phenomenon should be considered when designing efficient startup procedures but does not pose safety risks. However, it should be noted that compressibility effects are important for internal pressure dynamics, pressure and temperature distributions, and transient response.

Geyser boiling phenomenon occurs when there is a liquid pool in the evaporator end due to gravitational effects or when the wick is de-wetted by gravity. These phenomena could be of high importance for HPMR cooling using vertical heat pipes. Geyser boiling can cause significant wall temperature fluctuations, which could impact the long-term reliability of the heat pipe. Although it is typically not a concern during normal operation and at higher power inputs, during transient conditions or startup, geyser boiling can pose a serious threat to the stability and performance of the heat pipe. Understanding and mitigating this phenomenon is essential to ensure reliable operation under varying conditions.

The process of **frozen startup** occurs normally in alkali metal heat pipes. During frozen startup, the working fluid gradually melts and evaporates to establish the cyclic evaporation-condensation process within the heat pipe. The establishment of this process is critical for ensuring reliable startup and preventing damage to the heat pipe. Therefore, developing robust startup procedures that account for this phenomena and the sonic limit is crucial for maintaining heat pipe performance and reliability.

Successive startups and shutdowns are important to quantify the effects of thermal cycling on heat pipe performance. Repeated thermal cycles can lead to material fatigue, changes in thermal contact resistance, and degradation of the wick structure. These effects are particularly pronounced during transient conditions, where rapid temperature changes can induce thermal stresses and impact the long-term reliability of the heat pipe. Developing robust operating procedures that account for the effects of successive startups and shutdowns is essential to ensure the durability and performance of heat pipes under vary-

Phenomena	Description	High Importance Rationale
Liquid flow and pressure drops	Liquid phase pressure drops in the form of viscous losses in the wick and hydrostatic pressure gradients due to orientation	Liquid viscous and hydrostatic pressure drops are important for effective capillary pumping within the wick and the capillary limit.
Vapor pressure drops	Vapor pressure drops can be in the form of viscous losses, inertial pressure drops in the evaporator, and inertial pressure gains in the condenser	Vapor pressure drops and gains are important for the calculation of axial pressure profiles and capillary limits and to understand pressure dynamics.
Wick de-wetting	De-wetting in wicks with low capillary pressures occurs due to large gravitational forces pulling the liquid towards the evaporator	De-wetting of the wick can result in significant temperature increases at the heat pipe wall in the evaporator. As portions of the wick is de-wetted due to gravity, pooling of the working fluid could diminish heat transfer efficiencies.
Evaporation and condensation	Evaporation and condensation in liquid metal heat pipes normally occur at the liquid-vapor interface within the wick	Evaporation and condensation at the liquid-vapor interface is the main mode of heat transfer within the heat pipe.
Nucleate boiling at high heat fluxes	Nucleate boiling in the wick structure that occurs at high operating temperatures and wall superheats	Nucleate boiling in the wick structure by definition represents the boiling limit. The boiling limit occurrence can be severe for alkali metal heat pipes. Nucleating bubbles can prevent liquid return to the evaporator.
Critical heat flux	Dryout of the wick due to boiling which occurs post-boiling limit	The condition in which the heat flux to the heat pipe is high enough to reach dryout in a post-nucleate boiling regime (after the boiling limit is reached).
Capillary action	Capillary action due to the small pores within the wick structure	Capillary action is the phenomenon that is the driving force that enables liquid return to the evaporator from the condenser. The capillary pressure supplied by the wick is governed by the pore size and wettability.
Wettability	The angle formed between the working fluid and wick surface	The contact angle determines the maximum interfacial curvature, which in turn determines the maximum capillary pressure.
Solidification and solid accumulation post-shutdown	Solid accumulation in certain regions may occur based on shutdown characteristics and orientation	It is important that the working fluid solidifies in a manner which enables fast and efficient re-start of the heat pipe. Startup performance of the heat pipe could be impacted if the working fluid freezes mostly in the condenser region during shutdown.
Pressure dynamics	Pressure dynamics during startup and shutdown as the internal pressure increases in the heat pipe	Pressure dynamics during startup, shutdown, and thermal power transients are important for the study of flow dynamics and viscous and sonic limit conditions.
Corrosion and oxidation in wick and wall materials	Corrosion and oxidation in the wick and wall materials	Corrosion can alter material and surface properties, cause damage to the wick structure, introduce NCGs in the heat pipe, and diminish the wettability of the wick.
Creep in wall/wick materials	Creep in wall/wick material	Important to the structural integrity of the heat pipe and should be considered.
Fluid contamination	Fluid contamination in the form of oxides and other impurities	Non-metallic impurities from the structural material or working fluid such as oxygen, silicon, or carbon can significantly effect working fluid properties and heat pipe longevity.
Wick degradation	Wick degradation in the form of damage, contamination, or clogging	The wick could get altered or damaged during normal operation due to factors such as corrosion, clogging, or mechanical degradation, which can diminish the performance of the heat pipe.

Table 7: Phenomena ranked high importance and their rationales.

ing operational conditions.

Thermal stresses induced by transient conditions can also have significant implications for heat pipe performance. During normal transients and accidents, certain heat pipes may be exposed to harsher conditions, resulting in increased thermal gradients and mechanical stresses. Although heat pipes are designed to respond approximately isothermally, extreme conditions can induce localized hotspots, leading to thermal stresses that may compromise the structural integrity of the heat pipe. Accurate modeling and experimental characterization of thermal stresses are therefore crucial to ensure the safety and reliability of heat pipes during transient scenarios.

3.2.2. Materials and Structures

Irradiation damage mechanisms on common materials such as SS316 and sodium (Na) are known, and non-heat-pipe tests may be utilized to study irradiation damage on heat pipes. Phase change coupled with irradiation can result in differing effects, and impurities accumulation due to transmutation could also influence operation. Regardless, heat pipes have been successfully used to make irradiation capsules more isothermal in the past, where they operated under reactor conditions for irradiation times averaging 6,000 hours and up to 23,000 hours [9,14].

3.2.3. Fabrication Processes and QA

Dimensional tolerances and fabrication methods, although generally considered medium importance, can also have heightened significance during transient operations. Variations in dimensions and inconsistencies in fabrication can result in performance deviations and uncertainties, which can be exacerbated during transient scenarios. For instance, minor deviations in the annulus thickness or wick pore sizes can impact the capillary pumping ability of the wick, especially under varying heat loads or orientations. Ensuring tight dimensional tolerances and robust fabrication methods is crucial to maintaining consistent performance and reliability of heat pipes during transients.

Under-filling of the heat pipe indicates that working fluid inventory inside the heat pipe is not sufficient to wet the entire wick in the active region with liquid. This can cause the heat pipe to be unable to start, or the CHF condition being reached at a lower heat flux than anticipated. Therefore, setting the correct fill ratio in the heat pipe is critical to high-performance operation and safety. However, under-filling can be mitigated with proper design or fabrication methods. It should be noted that more working fluid than the wick volume may be needed based on orientation due to possible de-wetting of the wick.

4. Discussion

This section presents a discussion and further analysis of the results of this PIRT exercise. First, the high importance phenomena identified in the PIRT exercise are analyzed. Then, the main modeling and simulation needs identified in this PIRT exercise are studied. Finally, key experimental needs are analyzed.

4.1. Identification of Modeling and Simulation Needs

The modeling and simulation of heat pipes includes several areas where knowledge gaps have been detected in this PIRT exercise. The complex nature of the phenomena involved and the present efforts towards the high-fidelity modeling of heat pipes can require unique capabilities to capture the desired physics. Therefore modeling and simulation needs are described for each high-importance phenomena and select medium importance phenomena on a phenomenon-by-phenomenon basis.

4.1.1. Analysis of High-Importance, Low-Knowledge Phenomena

Developing advanced multi-phase and multi-scale models, coupled with high-resolution simulations and detailed experimental validation, will enhance our understanding and predictive capabilities for these critical phenomena. By improving the accuracy of these models, we can ensure the reliable and efficient operation of heat pipes under various conditions, ultimately supporting their successful integration into critical applications such as nuclear reactors. Considering these efforts, the following M&S needs are identified for high-importance, low-knowledge phenomena.

Wick De-Wetting. Modeling wick de-wetting is challenging because it involves complex interactions between meniscus shape changes, gravitational effects, and capillary forces. The high-fidelity models required to resolve these interactions are not yet fully developed, and current modeling techniques struggle to capture the detailed dynamics of wick de-wetting. To improve modeling of this phenomenon, research should focus on developing advanced multi-phase flow models that can accurately represent capillary action and meniscus dynamics. High-resolution CFD simulations, coupled with experimental validation, could provide more accurate predictions of wick dewetting behavior. Additionally, incorporating anisotropic properties of the wick material and its interactions with the working fluid into models would enhance the accuracy of predictions.

Critical Heat Flux. Low modeling knowledge for CHF is primarily due to the complexities involved in capturing the post-nucleate boiling regime and dryout conditions. The transition to CHF involves rapid vapor generation, which can create significant temperature spikes and potential damage to the heat pipe. Current models lack the capability to dynamically simulate these transitions and the associated heat transfer mechanisms. To better model CHF, research should focus on developing detailed phase change models that can simulate the nucleation, growth, and collapse of vapor bubbles within the wick structure. High-fidelity simulations, possibly using large eddy simulation or direct numerical simulation techniques, could provide insights into the multi-scale interactions occurring during CHF. Experimental studies to characterize nucleation site densities and surface properties under high heat flux conditions are also be valuable for improving the accuracy of models.

Wettability. The wettability of surfaces by the working fluid quantified using contact angles is another phenomenon with low modeling knowledge. The contact angle depends on various factors, including surface morphology, temperature, pressure, and impurities in the working fluid. Current models struggle to account for these dependencies and their impact on capillary pressure and fluid distribution within the wick. To enhance modeling of the contact angle, research should focus on developing multi-scale models that can capture the interactions between surface roughness, fluid properties, and environmental conditions. Advanced surface characterization techniques, combined with molecular dynamics simulations, could provide detailed insights into the factors influencing the contact angle. Incorporating these detailed characterizations into larger-scale models would improve the accuracy of predictions for capillary pumping and fluid distribution.

Pressure Dynamics. Pressure dynamics during startup, shutdown, and thermal power transients also have low modeling knowledge due to the dynamics involved in capturing the interactions between pressure variations, flow dynamics, and phase change processes. Current models often rely on simplified correlations that do not fully account for the transient behavior of heat pipes. To better model pressure dynamics, research should focus on developing high-fidelity transient models that can simulate the coupled interactions between pressure, temperature, and flow within the heat pipe. CFD simulations, using techniques such as unsteady Reynolds-averaged Navier-Stokes or Large-Eddy Simulations, could provide detailed insights into the pressure variations during different operational scenarios. Additionally, experimental validation of pressure measurements under transient conditions would help refine and validate these models, leading to more accurate predictions of heat pipe behavior.

4.1.2. Analysis of Medium Importance Phenomena with Performance Implications for Non-Normal Conditions

There are phenomena that were designated as medium importance yet can still impact the operation or performance of heat pipes in case of operational anomalies or transients. They also may need to be considered for the optimization of heat pipe performance. The phenomena analyzed in this subsection thus include medium-importance, low M&S knowledge phenomena of radiation heat transfer, laminar to turbulent transition, geyser boiling, wick priming, under-filling conditions, surface roughness of the wick, NCGs trapped in the wick, and the timescales of startup and shutdown processes. Addressing these knowledge gaps requires a concerted effort to develop advanced modeling techniques, such as high-fidelity multi-phase and multi-scale models, coupled with detailed experimental validation. By focusing on improving our understanding and predictive capabilities for these critical phenomena, we can enhance the reliability and efficiency of heat pipes under various conditions. This will support their successful integration into critical applications, such as HPMRs, ultimately contributing to the advancement of heat pipe technologies and their deployment in safety-critical industries.

The phenomena analyzed in this subsection include radiation heat transfer, laminar to turbulent transition, geyser boiling, wick priming, under-filling conditions, surface roughness of the wick, NCGs trapped in the wick, and the timescales of startup and shutdown processes. Addressing these knowledge gaps requires a concerted effort to develop advanced modeling techniques, such as high-fidelity multi-phase and multi-scale models, coupled with detailed experimental validation. By focusing on improving our understanding and predictive capabilities for these critical phenomena, we can enhance the reliability and efficiency of heat pipes under various conditions. This will support their successful integration into critical applications, such as HPMRs, ultimately contributing to the advancement of heat pipe technologies and their deployment in safety-critical industries.

Radiation Heat Transfer. Challenges involved in accurately capturing the effects of emissivity and the interactions between radiation, conduction, and convection at high temperatures introduces modeling challenges. Additionally, ill-defined radiation boundary conditions can significantly influence experiments leading to challenges in model validation. Surface conditions and termination also play a fundamental role in radiation heat transfer; emissivity values can vary significantly based on oxidation and surface conditions, and these changes are difficult to predict and incorporate into models. To improve the modeling of radiation heat transfer, research should focus on developing thermal radiation transport models that can account for dynamic changes in emissivity and surface properties over time. Implementing detailed spectral radiation models and coupling them with CFD simulations would provide a more accurate representation of the heat transfer processes. These effective heat transfer models can then be used to inform faster-running lumped parameters models as the ones in the Sockeye code. Additionally, experimental studies to measure emissivity at high temperatures and under different environmental conditions would help refine these models and reduce uncertainties.

Laminar to Turbulent Transition in Vapor. Difficulties in modeling the laminar to turbulent transition arise from the need to accurately capture the onset of turbulence, especially with mass injection and extraction due to evaporation and condensation. Current models are believed to fail to predict the early or late onset of turbulence and its effects on velocity profiles. To enhance the modeling of laminar to turbulent transition, research should focus on developing turbulence closures that can simulate the effects of mass injection and extraction. Then, these closures can be leveraged by CFD codes to build Reynolds Average Navier Stokes performance models of the whole heat pipe. To develop these closures, techniques such as Large Eddy Simulations (LES) or Direct Numerical Simulations (DNS) can provide more detailed insights into the flow dynamics during the transition phase. However, it should be noted that difficulties in the implementation of such high-fidelity techniques to study the complex turbulence structures in heat pipes may dictate the use of simpler models for developing closures. Additionally, incorporating machine learning algorithms to identify patterns and predict transitions based on simulation data could improve the accuracy of these models. Machine-learned models can also be used to develop the effective parameters for vapor conduction used in the lumped-parameters codes. Experimental validation of turbulence onset and flow characteristics using advanced flow visualization techniques would further refine these models.

Geyser Boiling. The intermittent vapor generation and liquid displacement during geyser boiling has low modeling knowledge due to the complex flow dynamics involved. High-fidelity simulations are challenging because they must capture the rapid changes in temperature and pressure during geyser boiling stages. To better model geyser boiling, research should focus on developing two-phase flow models that can accurately represent bubble formation, vapor generation, and liquid displacement. CFD simulations using volume-of-fluid or level-set methods can provide detailed insights into the flow patterns and interactions during geyser boiling. Experimental studies using high-speed imaging and temperature measurements can help validate these models and improve our understanding of the behavior of geyser boiling under different conditions.

Wick Priming. Current models do not adequately consider the detailed dynamics of capillary forces and liquid distribution required for effective priming and hence, cannot provide substantial guidance to define and numerically evaluate priming strategies. To improve the modeling of wick priming, research should focus on developing capillary flow models that can simulate the interactions between liquid saturation, capillary forces, and wick geometry. High-resolution CFD simulations that consider surface tension forces, coupled with experimental validation, can provide more accurate predictions of wick priming behavior. Additionally, studies on the effects of orientation, gravitational forces, and varying wick properties on priming efficiency would enhance our understanding and modeling capabilities. Experimental techniques such as X-ray imaging and high-resolution temperature measurements can help characterize the priming process and validate the developed models.

Under-Filling. The operation of the heat pipe during under-filling conditions is characterized by low modeling knowledge due to the challenges involved in capturing the partial wetting of the wick and the resulting changes in heat transfer dynamics. Although the physics is technically present in the models used for heat pipes, under-filling can lead to serious performance degradation and dry spots in the evaporator, making it challenging to model accurately using existing techniques. To better model the operation of heat pipes under under-filling conditions, research should focus on developing high-fidelity multiphase flow models that can simulate the interactions between liquid distribution, capillary forces, and heat transfer within the wick. CFD simulations, coupled with experiments designed to characterize the behavior of heat pipes under varying fill ratios, would provide valuable insights. Additionally, incorporating detailed wick geometry and material properties into models would improve the accuracy of predictions and help identify optimal fill ratios for different heat pipe designs.

Surface Roughness of the Wick. Influenced by surface finishing during fabrication, surface roughness of the wick is another phenomenon with low modeling knowledge. Current models do not adequately account for the effects of surface roughness on vapor pressure drops and flow pattern perturbation within the wick. To improve the modeling of surface roughness, research should focus on developing detailed surface characterization techniques and incorporating these measurements into CFD simulations, which could be then utilized for developing effective conduction parameters for lumped-parameters codes. High-resolution surface scanning and imaging methods can provide accurate representations of wick surface morphology, which can then be used to refine flow and heat transfer models. Additionally, experimental studies to investigate the impact of different surface finishing techniques on wick performance would help validate these models and guide the optimization of fabrication processes.

Trapped NCGs in the Wick. NCGs trapped in the wick present another modeling challenge due to their potential to cause dry spots and disrupt liquid return, similar to boiling limit conditions. The behavior of NCGs in the wick under varying pressure and temperature conditions is not well understood, making it difficult to accurately predict their impact on heat pipe performance. To better model NCGs trapped in the wick, research should focus on developing multi-phase flow models, with detailed modeling of the capillarity force distribution in two phases, that can simulate gas-liquid interactions within the wick structure. CFD simulations, combined with experimental validation using techniques such as X-ray radiography and high-resolution temperature measurements, would provide valuable insights into the behavior of NCGs and their impact on heat pipe operation. Additionally, incorporating the effects of material properties and fabrication techniques on NCG trapping into models would enhance the accuracy of predictions.

Startup and Shutdown Time Scales. The timescales of startup and shutdown processes are designated as low modeling knowledge due to the interaction of different phenomena involved in capturing the transient behavior of heat pipes. Current models often rely on simplified assumptions that do not fully account for the dynamic interactions between heat transfer, fluid flow, and phase change during these processes. To improve the modeling of startup and shutdown timescales, research should focus on developing high-fidelity transient models that can simulate the coupled interactions between pressure, temperature, and flow within the heat pipe. CFD simulations using unsteady Reynolds-averaged Navier-Stokes or large eddy simulation techniques can provide detailed insights into the transient behavior of heat pipes. This mechanistic understanding can then be utilized for evaluating lumped-parameters models and tunning thermal inertias. Experimental studies to measure temperature and pressure variations during startup and shutdown, coupled with high-resolution data acquisition systems, would help validate these models and improve their accuracy.

4.2. Identification of Experimental and Instrumentation Needs

The PIRT exercise identified several experimental and instrumentation knowledge gaps that should be addressed to (i) support technology demonstration and maturation capabilities, (ii) improve the accuracy of experimental techniques to improve their applicability to design optimization, as well as the validation of models, and (iii) improve instrumentation accuracies or fidelities to improve the quality of experimental results and the understanding of heat pipe operation. The present section investigates identified phenomena that have been ranked as high-importance, low-knowledge; and medium-importance and low-knowledge. An analysis of phenomena that have been identified as low knowledge for E&I reveals commonalities between the challenges associated with experiments and instrumentation. These challenges can be identified as those that require internal measurements, the development and optimization of fabrication and QA methods, and safety constraints.

4.2.1. Internal Measurements and Visualization

The main limitation of current experimental capabilities is that internal measurements are challenging to obtain for alkali metal heat pipes operating at high temperatures, which generally prevents the study of the phenomena that have been identified as low knowledge. Internal measurements create a variety of complexities with heat pipe experimentation.

Firstly, internal measurements interfere with heat pipe flow structures. These include any temperature or pressure probes that may be placed inside the heat pipe. In the case of pressure probes, the use of wet legs can introduce significant uncertainties due to local disturbances and capillary effects. Furthermore, it is hard to interpret pressure measurements as it is usually unclear what pressure is being measured considering the two-phase flow inside heat pipes with the liquid located in the wick region and the vapor being in the vapor core. In addition, pressure drops for both vapor and liquid are usually small enough that they are prone to errors and uncertainties related to the instrument itself and its placement. Hydrostatic pressures can also cause uncertainties, especially for non-horizontal setups. Recent work on wet leg pressure and pressure drop measurements at the inside wall [11,15], and wet-leg vapor core pressure measurements [16] reveal that due to these complexities it may be more beneficial to use pressure measurements for the characterization of instabilities and operating limits.

In addition to introducing uncertainties and ambiguities, internal instruments also introduce breaks in the heat pipe boundary due to instrument leads or pressure legs. The increase in the interior space that the fluid can occupy can result in changes to operating characteristics. Furthermore, the presence of breaks in the heat pipe boundary can prevent the use of similar fabrication procedures as those used in prototypic heat pipes, possible introducing uncertainties that may need to be characterized for the extrapolation of results to model validation and design optimization.

The state-of-the-art X-ray radiography techniques for flow visualization are challenging, expensive, and require radiation safety protocols. Recent studies have shown significant developments in this regard, with obtained images clearly showing distinctions between liquid and vapor, as well as the accumulation of excess fill in the condenser and the surface waves [17,18]. It would be beneficial if these visualization techniques can be improved to be sufficiently fine resolution such that the wick structure and the liquid-vapor interface due to the presence of the wick structures can be resolved. Another limitation is that, due to the complexities involved, X-ray imaging is normally conducted in a single direction only, rendering the 3-D reconstruction of the interior flow infeasible.

4.2.2. Fabrication Techniques

Heat pipe fabrication is rather involved, utilizing several steps and subsystems [19,17,20]. Fabrication and assembly methods should ensure minimal impurities and good wick bonding. Impurities in the working fluid or wick and wall structures can affect operational characteristics. Longer heat pipes face additional fabrication challenges. Experimental characterization of the effectiveness of fabrication and assembly methods is somewhat developed. Wick fabrication techniques are improving, and wick integrity can be tested using various methods assembly. Measuring oxygen concentration in sodium can be challenging, but methods were proposed previously by Reid et al. [21]. Fabrication experience suggests that surface finishing tolerances can be specified and met by manufacturers. Bonding specifications depend on the manufacturing method and material, but the impact of poor bonding is well understood. Since there is still room for improvement, the E&I knowledge for this phenomenon is designated as medium.

The fill level has a strong impact on the internal flow dynamics of a heat pipe, so the variability in the fill ratio due to filling methods should be determined. Depending on the working fluid and geometry, relatively small variability in the mass of the working fluid filled into the heat pipe can cause large variation in the fill ratio based on volume. In addition, the sealing process should ensure minimal non-condensable gases (NCGs) in the heat pipe, as their presence may affect operational characteristics. The filling process for heat pipes is not standardized, leading to varying levels of uncertainties in the fill ratio depending on the filling system and heat pipe dimensions. While there are developed procedures for the filling process, they are not yet optimized. Both vendors and institutions are still working to optimize these processes for fabrication, where the introduction of NCGs remains a concern. For stainless steel, the sealing process is well characterized, but there may be increased variability for other materials. Filling processes for long or large heat pipes may have more uncertainty. Considering these factors, the E&I knowledge level was designated as medium.

Overall, minimization of manufacturing variabilities through the development of robust QA procedures and standards are required both for the accuracy and repeatability of experiments and for the development of mass manufacturing processes for heat pipes. Optimization of fabrication techniques for heat pipe performance and economics are also needed.

4.2.3. Safety Constraints

Experimentation with alkali metal fluids requires the implementation of a series of engineering controls that significantly increase operational costs. Although such experiments are routinely conducted in national laboratories and universities, experimentation at high temperatures or near limit conditions for heat pipes may require the development of additional safety protocols due to the possibility of damage to the heat pipe causing leakage of the working fluid. It may be beneficial to design and operate facilities that can investigate capillary and boiling limit conditions for heat pipes such that the data can be used for model validation of such conditions.

4.2.4. Proposed Future Directions

From the PIRT exercise it is evident that reliable techniques that can enable internal temperature, pressure, or velocity measurements would be immensely valuable to address knowledge gaps associated with the complex flow dynamics and heat transfer within heat pipes. Most importantly, reliable vapor pressure drop measurements would be extremely valuable for improving the understanding of vapor flow dynamics such as turbulence and compressibility, and for model validation. In addition, the extension of current X-ray radiography techniques to resolve the wick can enable the study of the evaporation and condensation mechanisms during operation.

Low knowledge levels on the safety-related phenomena dictate the investigation of such conditions experimentally. Since these tests can cause heat pipe failure, experimental setups with robust engineering controls are required. Destructive testing and examinations of heat pipes may be beneficial for the investigation of severe accident scenarios. Additional experiments on factors that affect the life of heat pipes such as corrosion, oxidation, and wick degradation would be beneficial in establishing heat pipes as effective cooling solutions for nuclear applications.

Further operational experience with heat pipes are needed to improve and optimize designs and fabrication processes. As heat pipe technology improves, it will be necessary to develop codes and standards related to heat pipe design, fabrication, and QA. These codes and standards can in turn enable the more broad adoption of heat pipe technologies in the nuclear industry. This is deemed to be a logical progression of the work being conducted within the DOE national laboratory systems.

5. Summary and Conclusions

On March 11, 2025, a PIRT exercise was conducted at INL involving thirteen experts from national laboratories, university partners, and the NRC. This semi-structured session, guided by moderators, commenced with the establishment of the figure of merit (FOM): the predictability of operational regimes and performance of heat pipes. Various operational regimes and performance metrics were subsequently defined. Following the FOM identification, a comprehensive review of pre-identified phenomena was carried out, with necessary additions and modifications made. A total of 50 phenomena were identified, categorized into high, medium, and low importance concerning the FOM. Fourteen phenomena were deemed of high importance, twenty-nine of medium importance, and seven of low importance. The high-importance phenomena, critical to heat pipe safety, reliability, and performance, included:

- Liquid pressure drops
- Vapor pressure drops
- Wick de-wetting
- Evaporation and condensation
- Nucleate boiling
- Critical heat flux
- Corrosion and oxidation
- Creep
- Capillary action
- Wettability
- Solidification and solid accumulation post-shutdown
- Pressure dynamics
- Fluid contamination
- Wick degradation

Most of these high-importance phenomena exhibited low knowledge levels in either modeling and simulation (M&S), experiments and instruments (E&I), or both, with the exceptions of corrosion and oxidation, and capillary action. Detailed discussions followed, focusing on phenomena with high and medium importance that had low knowledge levels. This led to the identification of both modeling and experimental needs, aimed at guiding future research and development efforts.

Acknowledgements

The work presented here was supported by the DOE Office of Nuclear Energy under the Advanced Reactor Technology portfolio's Microreactor Program (MRP). This content reflects the current status of and technical gaps in heat pipe technology. This information was prepared as an account of work sponsored by an agency of the U.S. government. Neither the U.S. government nor any agency thereof, nor any of their employees, makes any warranty, expressed or implied, or assumes legal liability or responsibility for the accuracy, completeness, or usefulness, of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. References herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement recommendation, or favoring of the U.S. government or any agency thereof. The views, opinions and recommendations of authors expressed herein do not necessarily reflect those of the U.S. government or any agency thereof.

References

[1] D. I. Poston, M. A. Gibson, T. Godfroy, P. R. McClure, Krusty reactor design, Nuclear Technology 206 (sup1) (2020) S13–S30. doi:10.1080/00295450.2020.1725382.
URL https://doi.org/10.1080/00295450.2020.1725382

[2] D. I. Poston, M. A. Gibson, R. G. Sanchez, P. R. McClure, Results of the krusty nuclear system test, Nuclear Technology 206 (1) (2020) S89–S117. doi:10.1080/00295450.2020.1730673.
URL https://doi.org/10.1080/00295450.2020.1730673

[3] J. W. Sterbentz, J. E. Werner, M. G. McKellar, A. J. Hummel, J. C. Kennedy, R. N. Wright, J. M. Biersdorf, Special purpose nuclear reactor (5 mw) for reliable power at remote sites assessment report, Report, Idaho National Lab. (INL), Idaho Falls, ID (United States) (2017). doi:10.2172/1410224.
URL https://www.osti.gov/biblio/1410224

[4] M. M. Swartz, W. A. Byers, J. Lojek, R. Blunt, Westinghouse evinci™ heat pipe micro reactor technology development, in: 28th International Conference on Nuclear Engineering, Vol. Volume 1: Operating Plant Challenges, Successes, and Lessons Learned; Nuclear Plant Engineering; Advanced Reactors and Fusion; Small Modular and Micro-Reactors Technologies and Applications, V001T04A018, 2021. doi:10.1115/icone28-67519.

[5] I. Yilgor, S. Shi, Scaling laws for two-phase flow and heat transfer in high-temperature heat pipes, International Journal of Heat and Mass Transfer 189 (2022) 122688. doi:https://doi.org/10.1016/j.ijheatmasstransfer.2022.122688.
URL https://www.sciencedirect.com/science/article/pii/S0017931022001703

[6] J. H. Jackson, P. Sabharwall, Foreword: Special issue on the u.s. department of energy microreactor program, Nuclear Technology 209 (sup1) (2023) iii–v. doi:10.1080/00295450.2022.2134723.
URL https://doi.org/10.1080/00295450.2022.2134723

[7] G. E. Wilson, B. E. Boyack, The role of the pirt process in experiments, code development and code applications associated with reactor safety analysis, Nuclear Engineering and Design 186 (1) (1998) 23–37. doi:https://doi.org/10.1016/S0029-5493(98)00216-7.
URL https://www.sciencedirect.com/science/article/pii/S0029549398002167

[8] X. Sun, G. L. Yoder, R. N. Christensen, S. Shi, H.-C. Lin, X. Wu, S. Zhang, Thermal hydraulics phenomena identification and ranking table (pirt) for advanced high temperature reactor (ahtr), Report, Nuclear Engineering University Program (NEUP) (2017).

[9] I. Yilgor, Z. Sellers, J. L. Hartvigsen, P. Sabharwall, K. Sweetland, Heat pipe cooled microreactors, Report, Idaho National Laboratory (2024).

[10] S. Wahlquist, J. Hansel, P. Sabharwall, A. Ali, A critical review of heat pipe experiments in nuclear energy applications, Nuclear Science and Engineering 197 (5) (2023) 719–752. doi:10.1080/00295639.2022.2082230.
URL https://doi.org/10.1080/00295639.2022.2082230

[11] I. Yilgor, Investigation of transients important for heat pipes in microreactor applications, Thesis, Rensselaer Polytechnic Institute (2024).

[12] I. Yilgor, S. Z. D., H. J. L., S. K. M., H. Pei-Hsun, A. Taehwan, S. Joseph, M. Annalisa, P. Victor, A. Mark, H. Yassin, S. Shanbin, , P. Sabharwall, Recent developments and findings of heat pipe experiments for microreactor applications, Nuclear Technology (2024) 1–35Doi: 10.1080/00295450.2024.2375488. doi:10.1080/00295450.2024.2375488.
URL https://doi.org/10.1080/00295450.2024.2375488

[13] M. Tano, I. Yilgor, K. M. Sweetland, J. Hansel, P. Sabharwall, M. H. Anderson, Z. Sellers, L. Charlot, J. Hartvigsen, E. Merzari, Y. Mao, V. Petrov, S. Bajorek, T. Zaki, Phenomena identification and ranking table (PIRT) for heat pipes, Report INL/RPT-25-84171, Idaho National Laboratory (2025).

[14] W. A. Ranken, Irradiation of high temperature heat pipes (1987).

[15] I. Yilgor, S. Shi, Operational characteristics and oscillatory phenomena in two-phase closed thermosyphons, Applied Thermal Engineering 265 (2025) 125401. doi:https://doi.org/10.1016/j.applthermaleng.2024.125401.
URL https://www.sciencedirect.com/science/article/pii/S1359431124030692

[16] D. Orea, N. K. Anand, Y. A. Hassan, Experimental analysis of temperature and vapor core pressure for an annular heat pipe, Physics of Fluids 35 (9) (2023). doi:10.1063/5.0156589.
URL https://doi.org/10.1063/5.0156589https://pubs.aip.org/aip/pof/article-abstract/35/9/092117/2913087/Experimental-analysis-of-temperature-and-vapor?redirectedFrom=fulltext

[17] E. M. Tillman, G. F. Nellis, M. H. Anderson, X-ray imaging of flow phenomena within sodium heat pipes for microreactor applications (2023).

[18] L. M. Gaspar, D. A. Giordano, N. A. Greenfield, S. J. Kim, F. A. Kubic, M. R. Middlemas, A. J. Pizarro, W. J. Saeger, K. M. Sweetland, R. S. Reid, eblock37 microreactor electrical demonstration unit, Nuclear Technology 209 (1) (2023) S73–S91. doi:10.1080/00295450.2021.1997540.
URL https://doi.org/10.1080/00295450.2021.1997540

[19] R. S. Reid, K. M. Sweetland, M. J. Ward, Advances in microreactor fabrication, Report, Los Alamos National Laboratory (2023).

[20] E. M. Tillman, T. A. Moreira, G. F. Nellis, M. H. Anderson, High-resolution internal temperature measurements and x-ray imaging of sodium heat pipes, Applied Thermal Engineering (2025) 126296doi:https://doi.org/10.1016/j.applthermaleng.2025.126296.
URL https://www.sciencedirect.com/science/article/pii/S1359431125008889

[21] R. Reid, J. Martin, G. Schmidt, Method for determination of less than 5 ppm oxygen in sodium samples, Report, Los Alamos National Laboratory (2005).