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Phenomena Identification and Ranking Table (PIRT) for Heat Pipes

Microreactor Program

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ABSTRACT

This Phenomena Identification and Ranking Table (PIRT) report provides an evaluation of key phenomena affecting the performance and operational regimes of heat pipes, particularly in the context of heat pipe microreactors (HPMRs). 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 the heat pipe, including phase change, turbulent transition, and compressibility effects, among others, there is high uncertainty in identifying and ranking the important phenomena affecting the operation of heat pipes and the current knowledge for their modeling and simulation and experimental measurements and instrumentation. 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. The report analyzes phenomena with high importance and low knowledge, such as wick de-wetting, critical heat flux, contact angles, and pressure dynamics, discussing challenges and future research directions for improving their modeling and simulation and experimental measurements. Additionally, the report addresses phenomena with low knowledge that could impact heat pipe operation during non-normal or transient operation, including frozen startup, laminar to turbulent transition, geyser boiling, wick priming, underfilling conditions, surface roughness of the wick, NCGs 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 critical applications such as nuclear reactors, and contributing to the advancement of heat pipe technologies in safety-critical industries.

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CONTENTS

FIGURES

TABLES

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ACRONYMS

ANL	Argonne National Laboratory
ATR	Advanced Test Reactor
DOE	U.S. Department of Energy
DOE-ID	U.S. Department of Energy-Idaho Operations Office
E&I	Experiments and Instrumentation
HPMR	Heat Pipe Microreactor
INL	Idaho National Laboratory
LANL	Los Alamos National Laboratory
MFC	Materials and Fuels Complex
MRP	Microreactor Program
M&S	Modeling and simulation
NASA	National Aeronautics and Space Administration
NCG	Non-condensable gas
NEAMS	Nuclear Energy Advanced Modeling and Simulation
NEUP	Nuclear Energy University Program
NRC	Nuclear Regulatory Commission
PIRT	Phenomena Identification and Ranking Table
PSI	Paul Scherrer Institute
R&D	Research and development
QA	Quality assurance
U.S.	United States
U-M	University of Michigan
UW	University of Wisconsin
V&V	Verification and validation

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Phenomena Identification and Ranking Table (PIRT) for Heat Pipes

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.

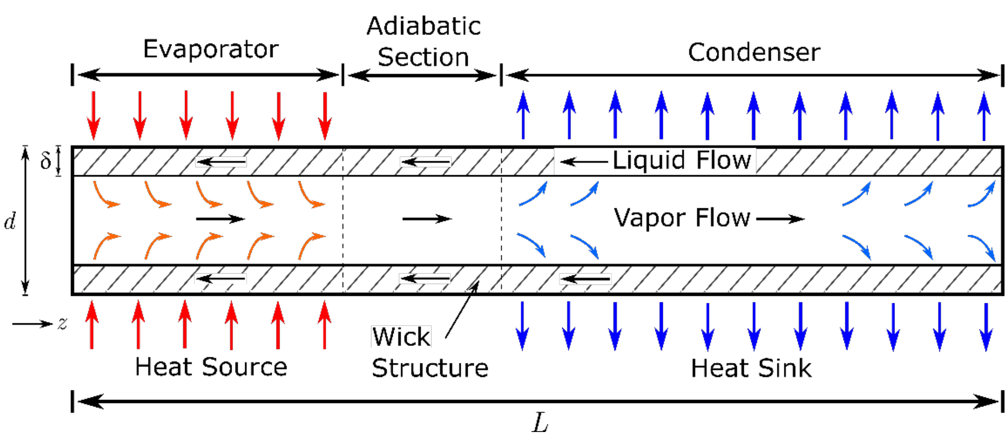

Figure 1. A schematic describing heat pipe operation [5].

The operation of heat pipes results in rather complex multiphase flow and heat transfer phenomena including evaporation, condensation, capillary flow, vapor-liquid entrainment, compressible flow, turbulence, and gravitational effects, among others. The conjugation of these phenomena determines the operational characteristics of the heat pipe and the limits to its performance. Therefore, particularly for safety-critical industries such as nuclear, accurate modeling and simulation of heat pipes that can capture these effects is essential for optimizing performance and assessing safety and reliability. However, factors such as the innate coupling of the phase change and flow phenomena within heat pipes, presence of complex flow structures, as well as interfacial and capillary phenomena create numerous challenges that need to be resolved to develop accurate high-fidelity models. Furthermore, experimental works that can be used for the development and validation of models are lacking, due to the complexities in heat pipe operation, and a variety of difficulties in internal measurements. The need for heat pipe experiments was highlighted in the recent review of experimental works investigating heat pipes for HPMR applications by Yilgor et al [6, 7].

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 [8]. 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 proposed. This PIRT exercise aims at systematically identifying, reviewing, and prioritizing key phenomena affecting heat pipe performance based on importance and knowledge rankings, while considering modeling and experimental challenges. Through this exercise, future avenues for research on the identified phenomena can be determined considering the importance and knowledge levels determined by experts.

The present PIRT exercise is a collaborative effort involving multiple stakeholders, including the DOE MRP, the DOE NEAMS program, the Nuclear Regulatory Commission (NRC), and university partners. This diverse group of participants brings a wealth of expertise, ensuring a comprehensive and balanced approach to the identification and ranking of critical phenomena. The exercise was organized into several phases, each designed to logically build upon the previous one, culminating in the present comprehensive final report that is aimed to serve as a valuable resource for researchers, developers, and industry stakeholders.

The process began with the preliminary identification of phenomena by the DOE MRP at INL. These initial phenomena encompassed fundamental aspects of heat pipe operation, including phase change dynamics, fluid dynamics, thermal dynamics, material properties, and operational conditions. This foundational work set the stage for a thorough review and refinement process, ensuring that all critical phenomena were considered and accurately described. The next phase involved assembling a diverse group of stakeholders who contributed their expertise and insights to the exercise. The preliminary plan outlined specific roles and responsibilities, promoting an organized and collaborative approach. This step was crucial for ensuring that the PIRT exercise benefits from a wide range of perspectives, enhancing the robustness and comprehensiveness of the final document.

Following the invitation of participants, a preliminary PIRT document was circulated for review and feedback, with participants expected to submit their insights. This feedback phase was designed to ensure that the document reflects a consensus among key stakeholders, addressing the completeness, accuracy, and relevance of the identified phenomena and their rankings. The iterative process of integrating feedback and refining the document ensures transparency and thoroughness, ultimately leading to a more robust and reliable PIRT. On March 11, 2025, a full-day hybrid meeting was held. This meeting provided a platform for in-depth discussions and finalization of the PIRT, allowing for real-time collaboration and consensus-building. The meeting was recorded to facilitate a comprehensive write-up, which was distributed to participants. The present final report incorporates all additions and comments from the meeting, resulting in a detailed and expanded document. Following the completion of the report, another round of review was conducted by the participants. This feedback phase provided an opportunity for participants to confirm the accuracy and completeness of the final document, ensuring that it meets the highest standards in order to properly guide R&D and regulatory efforts. The present work will also serve as a valuable resource for researchers, developers, and stakeholders involved, guiding future research and development efforts towards enhancing the heat pipe technologies.

In summary, this PIRT exercise aims to provide a comprehensive and systematic evaluation of key phenomena affecting heat pipe operational regimes and performance with the objective of guiding future R&D efforts that support the focus areas identified by DOE MRP. By involving a diverse group of stakeholders and following a detailed process of identification, review, and prioritization, the PIRT exercise will result in a robust and reliable resource that addresses all critical aspects of heat pipe operation. This report 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 [9-11]. The organizational structure followed by the present PIRT exercise is a nine-step process commonly employed in literature. It should be noted that the present work focuses on investigating heat pipe performance and its effectiveness in transferring energy from the evaporator to the condenser, rather than a particular accident scenario for a specific hardware system or reactor design. The descriptions of all steps employed are provided in the present section.

2.1.1. 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 in the operation of the heat pipes.

Although heat pipes for advanced reactor applications are investigated in particular, it should be noted that 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.

2.1.2. Objectives

A series of objectives are developed for this PIRT considering the identified issue in Section 2.1.1. 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. **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.
3. **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.
4. **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.
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.

2.1.3. Hardware and Scenario

The present exercise broadly considers phenomena related to cylindrical heat pipes using liquid metal coolants, which are employed 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 that are envisioned to be utilized in HPMR applications, which currently are mainly using sodium as the heat transfer fluid. However, the identified phenomena and rationale are also mostly applicable to other wick types.

2.1.4. 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 viscous and sonic limits of the heat pipe are expected to be reached during starup.
- **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 capillary, entrainment, and boiling limits. Accidents beyond these limits can occur that result in an inability to transfer heat, such as mechanical failures. These mechanical failures can include breaches in the heat pipe wall, such as cracks or pinhole leaks, failures in welds or joints,

and structural deformation or damage due to external impacts or internal pressures. Additionally, failures in the wick structure can occur, such as disintegration, blockage, or displacement, which can impede the capillary action necessary for liquid return. Contamination from non-condensable gases (NCGs) or impurities can accumulate in the condenser, creating an inactive length, or get trapped in the wick, leading to dry spots and reduced capillary action. Thermal stresses from sudden temperature changes or thermal cycling can induce cracking, warping, or material fatigue, compromising structural integrity. Overheating and dryout can occur when the heat input exceeds the heat pipe's capacity, resulting in rapid temperature spikes and potential failure. During startup from a frozen state, if the working fluid re-freezes in the condenser or the wick fails to prime properly, the heat pipe may not achieve steady-state operation, leading to localized overheating and potential damage. Loss of coolant in integrated systems can also lead to inadequate heat removal and overheating of the heat pipe. These limits and potential failure modes are crucial, as reaching or exceeding 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. [6]. 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 power (heat energy per unit time) that a heat pipe can transfer. It is constrained by physical limits, which include:
    - *Frozen startup limit*: This limit occurs when the working fluid re-freezes in the condenser during the startup process. As the heat pipe transitions from a frozen state to operational conditions, the working fluid must melt and evaporate. If the vapor re-freezes in the condenser before reaching steady-state operation, it can prevent the establishment of the cyclic evaporation-condensation process, thereby limiting the heat pipe's ability to transfer heat.
    - *Viscous Limit*: During the early stages of startup, the vapor pressure may not be sufficient to overcome viscous losses within the vapor core. This limit is characterized by high viscous resistance to vapor flow, which can restrict the mass flow rate of vapor from the evaporator to the condenser. As a result, the heat transfer capacity is limited until the vapor pressure builds up enough to overcome these viscous losses.
    - *Sonic Limit*: The sonic limit is reached when the vapor flow velocity approaches the speed of sound within the vapor core. At this point, choking occurs, meaning that the vapor cannot travel faster than the speed of sound. This limit constrains the maximum mass flow rate of vapor and, consequently, the overall heat transfer capacity of the heat pipe. The sonic limit is particularly important during startup and transient conditions when vapor velocities can be high.
    - *Capillary Limit*: The capillary limit is defined by the maximum capillary pressure that the wick structure can provide to balance the pressure losses along the working fluid flow path. This limit determines the maximum heat transfer rate that the wick can support without experiencing dryout. If the capillary pressure is insufficient to return the liquid to the evaporator, dryout occurs, leading to a significant reduction in heat transfer efficiency and potential overheating of the evaporator.
    - *Entrainment Limit*: The entrainment limit is caused by interfacial shear forces at the liquid-vapor interface, which can shear off the liquid from the wick and move it towards the condenser. This phenomenon leads to dryout in the evaporator, as the

liquid is no longer available to absorb heat and evaporate. Entrainment can severely limit the heat transfer capacity of the heat pipe and may result in temperature spikes and potential damage to the heat pipe structure.

- *Boiling Limit*: The boiling limit is defined by the onset of nucleate boiling in the liquid return path, which can occur within the wick structure or the annulus. When nucleate boiling begins, vapor bubbles are generated, which can block or displace the liquid, limiting its return to the evaporator. This condition reduces the heat transfer capacity and can lead to rapid heat pipe failure. Boiling in the annulus is just as detrimental as boiling within the wick, as both scenarios inhibit liquid return and disrupt the cyclic evaporation-condensation process.

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: $k_{eff} = \frac{QL}{A\Delta T}$ where:
   - Q is the power (heat transfer rate) transferred by the heat pipe.
   - L is the length of the heat pipe.
   - A is the cross-sectional area of the heat pipe.
   - ΔT is the temperature drop along the heat pipe.

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.

2.1.5. 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. [12] and Yilgor et al. [6, 7], 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 to comprehensively assess the importance of the phenomena from different perspectives.

2.1.6. Phenomena Identification

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

I. Heat transfer mechanisms – *Mainly Performance and Physics Related*,

II. Fluid dynamics – *Mainly Performance and Physics Related,*

III. Liquid-vapor phase change – *Mainly Performance and Physics Related*,
IV. Capillary pumping – *Mainly Performance and Physics Related*,
V. Non-condensable gas effects – *Mainly Performance and Physics Related*,
VI. Startup, shutdown, and transient scenarios – *Mainly Performance and Physics Related*,
VII. Aging and degradation – *Mainly Performance and Physics Related*,
VIII. Environmental factors – *Mainly Performance and Physics Related*,
IX. Materials science – *Mainly Quality-Assurance Related*,
X. Manufacturing variability – *Mainly Quality Assurance Related*.

Each identified phenomenon was grouped under these categories and described in detail, with its impact and potential consequences thoroughly examined. Since each of the phenomenon identified could be related to a physics phenomenon that affects the heat pipe or to issues that deal with the quality assurance process during the fabrication and usage of the heat pipe, a label is added to identify the grouping to which the phenomenon is most closely related. 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.

2.1.7. 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. The importance levels were color coded with gray, green, yellow, and red for insignificant, low, medium, and high importance phenomena, respectively.

Table 1. Definitions of importance level rankings.

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

2.1.8. 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 Level:** 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 Level:** 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.

M&S of heat pipes is a comprehensive subject with various approaches evaluated to predict heat pipe cooling performance during steady-state and operational transients. These approaches range from simple correlation-based methods to higher-fidelity mechanistic models based on Computational Fluid Dynamics (CFD). To streamline the discussion, we will categorize the modeling methodologies into two groups:

1. **Heat-pipe performance codes**: These codes use low-dimensional mechanistic models and closure correlations to predict the cooling performance of heat pipes without detailing their internal workings. An example of such a code is Sockeye, which is being developed under the DOE-NEAMS program.
2. **Higher-fidelity codes**: These codes aim for a comprehensive mechanistic understanding of heat pipe performance, relying on a limited set of correlations primarily for phase change and capillarity forces. These models typically use CFD codes and require significantly more computational resources.

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. The knowledge levels were color coded with green, yellow, red, and gray for H-, M-, L-, and U-knowledge-level phenomena, respectively.

Table 2. Definitions of knowledge level rankings.

Knowledge Level	Definition
H	Known with little or no uncertainty
M	Mostly known; moderate uncertainty
L	Mostly unknown; high uncertainty
U	Limited knowledge; uncertainty cannot be characterized

2.1.9. Documentation

The present report 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.

2.2. Participants

The PIRT exercise included participants from six different institutions, in alphabetical order the are listed as follows: Argonne National Laboratory (ANL), Idaho National Laboratory (INL), Los Alamos National Laboratory (LANL), University of Wisconsin-Madison (UW), University of Michigan, Ann Arbor (U-M), Paul Scherrer Institute (PSI) and the U.S. Nuclear Regulatory Commission (NRC). The names of the participants, the DOE program they support, and their institutions are given in Table 3.

Table 3. Participants in the PIRT exercise.

Participant	Institution
Lise Charlot	DOE-NEAMS / INL
Joshua Hansel	DOE-NEAMS / INL
Elia Merzari	DOE-NEAMS / ANL
Yinbin Miao	DOE-NEAMS / ANL
Jeremy Hartvigsen	DOE-MRP / INL
Piyush Sabharwall	DOE-MRP / INL
Zachary Sellers	DOE-MRP / INL
Mauricio Tano	DOE-MRP / INL
Ilyas Yilgor	DOE-MRP / INL
Katrina Sweetland	DOE-MRP / LANL
Mark Anderson	DOE-NEUP / UW & INL
Victor Petrov	DOE-NEUP / U-M & PSI
Stephen Bajorek	US-NRC
Tarek Zaki	US-NRC

2.3. Discussion Format

The discussion format was determined as a semi-structured exercise guided by moderators from INL. Prior to the discussion, INL identified the issue, objectives, phenomena categories, and pre-identified a preliminary figure of merit and preliminary phenomena within each category. Initially, during the exercise, the figure of merit was discussed and finalized. Then, the pre-identified phenomena were discussed and ranked by their importance and knowledge levels individually. Phenomena or phenomena definitions were added, modified, clarified, or removed as needed during the exercise. Notes were taken during the discussion, and the discussion was recorded and transcribed to ensure no information is lost during the exercise.

3. PHENOMENA IDENTIFICATION AND RANKING

The present section presents the identified phenomena under each category, along with their description, rankings, and rationale, in a tabular format. Any discussion or clarification that is relevant is included in its respective subsection.

3.1. Heat Transfer Mechanisms

This category represents phenomena related to the heat transfer mechanisms of conduction, convection, and radiation, both within the heat pipe and between the reactor core and heat pipe wall. Heat-pipe operation involves all three heat transfer mechanisms.

3.1.1. Radial Heat Conduction (I-01) Performance and Physics Related

3.1.1.1. Importance Rationale

Conduction heat transfer in a cylindrical heat pipe can be evaluated as radial conduction, axial conduction, and azimuthal conduction. Radial conduction is the main heat transfer mechanism in the heat pipe wall and the wick regions during normal operation due to (1) low flow rates in the wick or annulus, (2) high thermal conductivity of alkali metal liquids, and (3) convection being dominant in the vapor region. Radial conduction is important to determine the radial temperature drop across the wall and wick, however, due to the heat pipe wall and wick regions being relatively thin, and made of materials with high thermal conductivities, these temperature drops are minimal. However, radial conduction could be more significant during frozen startup and shutdown conditions where the working fluid circulation is not yet established. For these reasons radial conduction is given a **medium** importance ranking.

3.1.1.2. Modeling and Simulation Knowledge Rationale

The conduction mechanism is well understood due to it being a fundamental principle of heat transfer. Radial heat conduction across the heat pipe wall and wick can be modeled using Fourier's law of heat conduction, which applies well-established mathematical formulations. The radial temperature drops are typically insignificant due to the small thickness of the wall and wick regions, resulting in low thermal resistance in the radial direction. Additionally, the material properties of commonly used heat pipe materials (such as stainless steels) are well documented, facilitating accurate modeling. Based on these factors the knowledge level for M&S is designated as **high**.

In higher-fidelity codes, radial heat conduction can be simulated with high accuracy using finite element or finite volume methods. These methods discretize the heat pipe geometry and solve the heat conduction equations to provide detailed temperature distributions.

In heat-pipe performance codes such as Sockeye, radial heat conduction is typically modeled using simplified thermal resistance networks. These networks approximate the radial temperature drop based on the thermal conductivity and geometry of the heat pipe components. This approach is computationally efficient and provides reasonable accuracy for engineering applications.

3.1.1.3. *Experiments and Instrumentation Knowledge Rationale*

Experimentally it is challenging to measure internal temperatures, hence heat pipe temperature measurements are usually taken at the heat pipe wall, or at a thermowell at the center of the heat pipe if available. This makes it challenging to measure the temperature drops across the wall and wick, also considering that outside wall and thermowell temperature measurements may not be accurate due to heat losses. To address these issues, and to provide high-spatial resolution temperature data, internally placed fiber optic distributed temperature sensors (DTS) are currently being implemented. However, this technique applied to high-temperature heat pipes is still under development, and there exist some concerns regarding its influence on internal flow dynamics and heat transfer. For these reasons, the E&I knowledge for this phenomenon is ranked as **medium**.

Table 4. Ranking of Radial Heat Conduction (I-01).

Importance Level	M
M&S Knowledge Level	H
E&I Knowledge Level	M

3.1.2. Axial Heat Conduction (I-02)

Performance and Physics Related

3.1.2.1. Importance Rationale

Axial heat conduction occurs across the heat pipe wall and wick regions. It is commonly neglected during heat pipe analysis due to (1) the main mode of axial heat transfer in the heat pipe being vapor advection from the evaporator to the condenser, (2) the long axial length of heat pipes, and (3) heat pipes being approximately isothermal. However, during startup or shutdown transients, or under accident conditions where the heat from the evaporator cannot be transmitted to the working fluid due to dryout, axial conduction in the wall could be significant to heat pipe operation. For these reasons the importance for axial heat conduction is designated as **medium**.

3.1.2.2. Modeling and Simulation Knowledge Rationale

Axial heat conduction along the heat pipe length in the heat pipe wall and wick regions is well understood. The same fundamental principles of heat transfer apply as in radial conduction, where Fourier's law can be extended to the axial direction. This makes it straightforward to model using existing methods. The material properties and geometric dimensions required for these models are typically well known, allowing for precise simulations. Furthermore, the axial temperature distribution can be measured and validated against the models, providing a feedback loop that enhances the reliability of the simulations. Given that axial heat conduction is significant only during specific scenarios (e.g., frozen startup, shutdown, or dryout conditions), the ability to model these scenarios accurately further supports the **high** ranking in knowledge.

Higher-fidelity codes can simulate axial heat conduction with high fidelity by solving the heat conduction equations along the length of the heat pipe. These simulations can capture detailed temperature profiles and heat flux distributions, which are critical for understanding the axial heat transfer behavior.

In heat-pipe performance codes, axial heat conduction is solved using finite elements. Each segment is treated as a control volume with its own thermal resistance and capacitance. This approach allows for the efficient simulation of axial heat conduction and temperature gradients along the heat pipe length.

3.1.2.3. Experiments and Instrumentation Knowledge Rationale

Although heat pipe wall temperatures along the axial direction can be measured effectively, it can be difficult to determine axial heat transfer accurately, since the distribution of the working fluid within the wick structure may not be uniform during the frozen startup, shutdown, or accident conditions where axial heat conduction may be significant. For these reasons, the knowledge level for E&I is determined as **medium**.

Table 5. Ranking of Axial Heat Conduction (I-02).

Importance Level	M
M&S Knowledge Level	H
E&I Knowledge Level	M

3.1.3. Azimuthal Heat Conduction (I-03)

Performance and Physics Related

3.1.3.1. Importance Rationale

Azimuthal heat conduction in the wall and wick is neglected under normal operating conditions with approximately uniform evaporator input and condenser cooling powers. However, similarly to axial conduction, azimuthal conduction could be important during frozen startup, shutdown or accident conditions, and/or in the presence of localized hotspots, de-wetted regions, or limit conditions. In addition, the importance of azimuthal conduction can be influenced by the geometry and orientation of the heat pipe. Regardless, it can be deduced that the impact of azimuthal conduction to the predictability of operational regimes and performance is less than radial and axial conduction, especially considering the purpose of the heat pipe is to transfer heat axially. Based on this rationale, the importance level for the phenomena is designated as **low**.

3.1.3.2. Modeling and Simulations Knowledge Rationale

While the conduction mechanism in the azimuthal (circumferential) direction is fundamentally understood and can be modeled using Fourier's law, practical challenges arise in accurately modeling azimuthal conduction in the wick region, particularly during frozen startup or shutdown. Variations in the distribution of the working fluid within the heat pipe can lead to non-uniform thermal properties, which complicates the modeling process. Additionally, the thin wick structure and potential for localized dry spots or hot spots can introduce complexities that are not easily captured by standard modeling techniques. These factors contribute to the **medium** ranking of M&S knowledge in this area, indicating that while basic principles are well understood, practical implementation in specific scenarios remains challenging.

Higher-fidelity codes can model azimuthal heat conduction by discretizing the heat pipe circumference and solving the heat conduction equations in the azimuthal direction. However, capturing the effects of non-uniform fluid distribution and thermal properties requires high-resolution simulations and detailed material characterization.

In heat-pipe performance codes such as Sockeye, azimuthal heat conduction is typically simplified or approximated due to the challenges in capturing non-uniformities. These codes may use empirical correlations or simplified thermal resistance networks to represent azimuthal heat transfer, which may not fully capture the complexities of the phenomenon.

3.1.3.3. Experiments and Instrumentation Knowledge Rationale

As is the case for axial conduction, it is difficult to measure azimuthal conduction in the wall and wick regions, because it requires knowledge on the working fluid distribution in the wick and multiple temperature measurements in the azimuthal direction. It may be helpful to determine the working fluid distribution via X-ray radiography techniques, but due to low amounts of sodium in the wick this may be challenging for certain regions. For these reasons the E&I knowledge level is designated as **medium**.

Table 6. Ranking of Azimuthal Heat Conduction (I-03).

Importance Level	L
M&S Knowledge Level	M
E&I Knowledge Level	M

3.1.4. Thermal Contact Resistance between the Wall and Wick (I-04)

Performance and Physics Related

3.1.4.1. Importance Rationale

Thermal contact resistance between the heat pipe wall and wick is not significant for annular wicks unless localized hot/dry spots or de-wetted regions exist, or the wick has moved to touch the heat pipe wall during operation. This is because the heat transfer is from the heat pipe wall to the working fluid in the annulus. The importance could be higher for crescent wicks or wrapped-screen wicks touching the wall surface. However, considering that the thermal conductivities of alkali metal working fluids are high, and that the annular wicks are the main candidates for reactor applications, the importance of this phenomena was designated as **low**.

3.1.4.2. Modeling and Simulation Knowledge Rationale

The thermal contact resistance between the wick and the wall of the heat pipe is influenced by several factors, including geometric tolerances, surface roughness, and the presence of any gaps or voids. Modeling this contact resistance is challenging because it requires detailed knowledge of the micro-scale interactions between the wick and wall materials. Additionally, the contact resistance can vary along the length of the heat pipe and may change over time due to thermal cycling or mechanical stress. These variations are difficult to predict and incorporate into models with high accuracy. Given these challenges, the knowledge ranking for modeling thermal contact resistance is **low**, reflecting the significant uncertainties and complexities involved.

Higher-fidelity codes can model thermal contact resistance using detailed mesh representations of the interface between the wick and wall. However, accurately capturing the micro-scale interactions and variations in contact resistance requires high-resolution simulations and detailed material properties, which may not always be available. Modeling the thermal dilation of solid materials under mechanical restraints is well developed. However, modeling the thermal expansion of the heat pipe wick can be more complicated due to anisotropy.

Heat-pipe performance codes typically use simplified models or empirical correlations to represent thermal contact resistance. These models may not capture the detailed variations along the length of the heat pipe, leading to uncertainties in the simulations. Contact resistance is commonly determined experimentally and later implemented in models. For wick types where the wick is placed uniformly around the wall or is immobile, data from characterization tests may be used to predict the contact resistance. However, for wick types where the wick may move within the heat pipe, it is challenging to model this effect.

3.1.4.3. Experiments and Instrumentation Knowledge Rationale

Experimentally, it is challenging to know the exact location of the wick as it may move within the heat pipe for annular wick structures. From fabrication tolerances and operating conditions, there may be varying degrees of contact between the wick and wall. Although X-ray radiography techniques can give information on wick location, however the degree of contact may change significantly over the heat pipe length or radius due to a variety of factors. Furthermore, there is no good way to determine the contact force between the wick and wall with current experimental setups. Overall, since the location of the wick can be determined with X-ray radiography, the knowledge level for E&I for this phenomenon is determined as **medium**.

Table 7. Ranking of Thermal Contact between the Wall and Wick (I-04).

Importance Level	L
M&S Knowledge Level	L
E&I Knowledge Level	M

3.1.5. Vapor Advection (I-05) Performance and Physics Related

3.1.5.1. *Importance Rationale*

The flow of vapor from the evaporator to the condenser is important to the function of a heat pipe. As the heat transfer to the working fluid in the evaporator is transferred to the condenser via vapor flow within the vapor core. Therefore, the importance level ranking for this phenomenon is determined as **medium**.

3.1.5.2. *Modeling and Simulation Knowledge Rationale*

The basic mechanics of vapor phase flow (advection) from the evaporator to the condenser are well understood, including the principles of fluid dynamics and heat transfer. However, complexities arise due to turbulence and pressure recovery effects in the condenser, which may require further investigation. The transition between laminar and turbulent flow regimes, as well as the impact of vapor flow characteristics on heat transfer efficiency, are areas that can introduce uncertainties in the models. Advanced higher-fidelity tools can be used to simulate vapor advection, but the need for high-fidelity modeling to capture these effects contributes to the **medium** ranking of knowledge in this area.

Higher-fidelity codes can simulate vapor advection using detailed fluid flow models that account for turbulence, pressure drops, and phase change effects. These simulations can provide insights into the complex flow dynamics and heat transfer mechanisms within the vapor core.

Heat-pipe performance codes such as Sockeye model vapor advection using simplified flow equations and pressure drop correlations. While these models can capture the overall behavior of vapor flow, they may not fully account for the detailed effects of turbulence and pressure recovery, leading to some uncertainties.

3.1.5.3. *Experiments and Instrumentation Knowledge Rationale*

From an experimental perspective, current measurement techniques cannot capture detailed information on vapor advection since measurement of velocities and pressure variations are needed. Outside wall or thermowell temperatures can provide some information on vapor core temperatures via the effective thermal conductivity, yet this approach only describes vapor flow within the heat pipe in a rudimentary way. Therefore, the knowledge level for E&I for this phenomenon is designated as **low**.

Table 8. Ranking of Vapor Advection (I-05).

Importance Level	M
M&S Knowledge Level	M
E&I Knowledge Level	L

3.1.6. Liquid Advection (I-06)

Performance and Physics Related

3.1.6.1. Importance Rationale

Liquid flow from the condenser to the evaporator is important for heat pipe operation and sustaining the working fluid inventory in the evaporator to maintain heat removal from the wall. For this reason, the importance ranking is determined as **medium**.

3.1.6.2. Modeling and Simulation Knowledge Rationale

The flow of the liquid phase (liquid advection) from the condenser to the evaporator within the wick is characterized by slow and laminar flow, which is well understood. The principles of capillary action and laminar flow in porous media are well established, allowing for accurate modeling using existing methods. The properties of the wick material, such as pore size and permeability, are key inputs to these models and are typically well characterized. Given the well-understood nature of the liquid flow mechanisms and the availability of reliable modeling techniques, the knowledge ranking for liquid advection is **high**.

Higher-fidelity codes can model liquid advection using porous media flow models that account for capillary action and laminar flow. These simulations can capture detailed flow patterns and pressure distributions within the wick.

In heat-pipe performance codes, liquid advection is modeled using simplified flow equations and capillary pressure correlations. These models are computationally efficient and provide accurate predictions of liquid flow behavior in the wick.

3.1.6.3. Experiments and Instrumentation Knowledge Rationale

Experimentally, detailed measurements of capillary flow cannot be obtained during heat pipe operation, hence separate effect tests are commonly conducted. Furthermore, wick wetting characteristics can differ spatially. Considering these factors, the E&I knowledge was designated as **low**.

Table 9. Ranking of Liquid Advection (I-06).

Importance Level	M
M&S Knowledge Level	H
E&I Knowledge Level	L

3.1.7. Thermal Contact between the Core and the Heat Pipe (I-07)

Performance and Physics Related

3.1.7.1. Importance Rationale

The thermal contact between the reactor core and the heat pipe is affected by geometric tolerances, thermal expansion, and surface roughness. The evolution of this thermal contact resistance for different operating conditions, especially transients, is critical from proper heat removal from the core. However, the thermal contact resistance should be computed in the reactor design and should not significantly affect the cooling performance of the heat pipe. Therefore, the importance level is designated as **medium**.

3.1.7.2. Modeling and Simulation Knowledge Rationale

Although the physics of thermal contact resistance between the core and the heat pipe are well understood, modeling this phenomenon is challenging. The contact resistance can be influenced by geometric tolerances, thermal expansion, surface roughness, and the presence of any gas gaps. Accurately capturing these factors in numerical models requires detailed knowledge of the mechanical and thermal interactions at the interface. Additionally, the coupling of the heat pipe to the core block numerically can require a large number of fixed-point iterations in a segregated coupling approach, adding to the computational complexity. These challenges contribute to the **medium** ranking of knowledge in this area.

Higher-fidelity codes can model thermal contact resistance using detailed mesh representations of the interface and contact mechanics models. These simulations can capture the effects of thermal expansion, surface roughness, and gas gaps, but require high computational resources and detailed material properties. Higher-fidelity codes can model thermal expansion using thermal-structural coupling models that account for temperature-dependent material properties and mechanical restraints. These simulations can capture detailed thermal expansion behavior and its impact on mechanical performance but require accurate input data for material properties and loading conditions.

Heat-pipe performance codes such as Sockeye use simplified models or empirical correlations to represent thermal contact resistance. These models may not fully capture the detailed interactions at the interface, leading to some uncertainties in the simulations.

3.1.7.3. Experiments and Instrumentation Knowledge Rationale

Experimentally the thermal contact resistance between heater blocks and heat pipes is not well known and can change significantly with thermal expansion and the thermal conductivity of the gas medium if present. Furthermore, changes in heat pipe dimensions due to deformation during operation cause the contact resistance to differ considerably along the heat pipe. Small gas gaps can form between the heater block and the heat pipe which can further cause uncertainties in measurements. For these reasons the E&I knowledge ranking is determined as **low**.

Table 10. Ranking of the Thermal Contact between the Core and the Heat Pipe (I-07).

Importance Level	M
M&S Knowledge Level	M
E&I Knowledge Level	L

3.1.8. Radiation Heat Transfer (I-08)

Performance and Physics Related

3.1.8.1. Importance Rationale

Radiation becomes the primary mode of heat transfer at elevated temperatures due to its dependence on the fourth power of the absolute temperature, making it a significant factor in the heat transfer from high-temperature heat pipes. Specifically, radiation heat transfer is crucial in several areas: (i) from the external surface of the condenser to the secondary heat sink, (ii) across the monolith to heat pipe gap at the evaporator, and (iii) within the heat pipe itself between the working fluid and the internal surfaces. These various pathways highlight the importance of accurately modeling and understanding radiation heat transfer to ensure efficient thermal management. Therefore, this phenomenon is designated as **medium** importance.

3.1.8.2. Modeling and Simulation Knowledge Rationale

Radiation heat transfer becomes significant at high temperatures, and its modeling requires knowledge of the emissivity of the heat pipe materials, which can change due to oxidation and other environmental factors. These changes in emissivity, which can vary from 0.3 to 0.8, have a strong effect on the operating temperature of the heat pipe. The uncertainty in emissivity values and their evolution over time and temperature complicates the modeling of radiation heat transfer. Additionally, the complex interactions between radiation, conduction, and convection in the heat pipe environment add to the difficulty of accurate simulations. These factors lead to the **low** ranking of knowledge in this area, indicating significant uncertainties and challenges in modeling radiation heat transfer for heat pipes.

Higher-fidelity codes can model radiation heat transfer using methods such as the discrete ordinates method (DOM), the finite volume method (FVM), or the Monte Carlo method. These methods require detailed knowledge of the emissivity and absorptivity of the materials, as well as the geometric configuration of the heat pipe. However, the variability in emissivity due to oxidation and environmental conditions adds complexity and uncertainty to these models.

In heat-pipe performance codes, radiation heat transfer is typically modeled using simplified correlations or empirical models that account for radiative heat exchange between surfaces. These models require input parameters such as emissivity, which can be challenging to determine accurately. The lumped parameter approach may not fully capture the spatial variations and dynamic changes in emissivity, leading to uncertainties in the predictions.

3.1.8.3. Experiments and Instrumentation Knowledge Rationale

Challenges exist in accurately measuring emissivity experimentally at high temperatures in present facilities with devices such as reflectometers. A multi-band pyrometer may allow for the emissivity to be measured experimentally but lacks calibration standards. Under well-controlled experiments where oxidation of the surface is not anticipated, the data from reflectometers taken at room temperature may be sufficient. For these reasons, the knowledge level for E&I is designated as **medium**.

Table 11. Ranking for Radiation Heat Transfer (I-08).

Importance Level	M
M&S Knowledge Level	L
E&I Knowledge Level	M

3.2. Fluid Dynamics

Flow dynamics within heat pipes are complex and involve liquid flow in the wick structure driven via capillary forces, along with vapor flow in the vapor core. This category includes fluid dynamic phenomena within the heat pipe, including effects such as turbulence, compressibility, mean free path, and pressure drops, as well as instabilities and disturbances such as geyser boiling, wick de-wetting, excess liquid pooling in the condenser.

3.2.1. Laminar to Turbulent Transition in Vapor Flow (II-01)

Performance and Physics Related

3.2.1.1. Importance Rationale

Predicting the laminar to turbulent transition for the vapor enables the accurate calculation of vapor pressure drops, which in turn results in accurate capillary limit calculations. While it may not be crucial to predict the precise point of transition, understanding that the transition may occur farther downstream as more vapor is generated in the evaporator is important. This phenomenon effectively shifts the pressure drop (delta-P) along the vapor flow path, impacting the overall pressure distribution and capillary limit calculations. Heat pipes commonly operate near the transition region from laminar to turbulent, making this phenomenon significant for operational regimes and ensuring stable and efficient performance. For these reasons, the importance ranking is designated as **medium**.

3.2.1.2. Modeling and Simulation Knowledge Rationale

Modeling of turbulence is complex, especially considering that evaporation and condensation in heat pipes effectively cause vapor mass injection and extraction, to and from the vapor core, respectively. This can result in *(i)* either stabilizing or de-stabilizing effects to the vapor flow, *(ii)* early or late onset of turbulence, and *(iii)* effects on the velocity profiles that are not well understood. For these reasons the M&S knowledge level is designated as **low** for this phenomenon.

Higher-fidelity codes can simulate transitional flows using advanced turbulence models such as the Reynolds-Averaged Navier-Stokes (RANS) models, Large Eddy Simulation (LES), or Direct Numerical Simulation (DNS). However, accurately capturing the transition from laminar to turbulent flow, especially with mass injection and extraction, requires high-resolution simulations and detailed knowledge of the flow conditions.

Heat-pipe performance codes typically use simplified flow models that may not fully capture the complexities of the laminar-turbulent transition. These models rely on empirical correlations or simplified assumptions, leading to uncertainties in predicting the transition behavior.

3.2.1.3. Experiments and Instrumentation Knowledge Rationale

Experiments investigating turbulence in the vapor core of heat pipes are lacking. Work by Haug and Busse in the mid-1980s investigated this phenomenon with some success [13]. It should be noted that it is not possible to visualize vapor flow in alkali metal heat pipes with current methods. For these reasons the E&I knowledge level is designated as **low**.

Table 12. Ranking for Laminar to Turbulent Transition in Vapor Flow (II-01).

Importance Level	M
M&S Knowledge Level	L
E&I Knowledge Level	L

3.2.2. Near-Sonic Compressible Flow and Sonic Limit (II-02)

Performance and Physics Related

3.2.2.1. Importance Rationale

Compressible flow may occur in alkali metal heat pipes, particularly at low operating temperatures due to the low vapor densities. Near-sonic velocities and choking limit the mass flow rate of the vapor, limiting the power throughput of the heat pipe. This operating limit is known as the sonic limit for heat pipes. The sonic limit is commonly the limiting factor at lower temperatures during heat pipe startup and must be considered for developing robust heat pipe startup procedures. However, it should be noted that the sonic limit usually does not create safety risks, i.e. it does not result in sharp increases in wall temperatures at the evaporator. In addition, compressibility effects have a strong impact on the axial pressure and temperature distributions across the heat pipe. For these reasons, this phenomenon is designated as **medium** importance.

3.2.2.2. Modeling and Simulation Knowledge Rationale

Since the theory of compressible flow is well established, the knowledge level is constrained by uncertainties in thermophysical properties. Near sonic velocities (Ma ~ 1) may be observed at the evaporator exit, impacting the sonic limit and transient response during startup. Compressibility effects significantly influence pressure and temperature distribution at low temperatures, even when not near the sonic limit. Properly accounting for these effects is crucial for ensuring safe and efficient operation. For these reasons the knowledge level for M&S is determined as **medium**.

Higher-fidelity codes can simulate compressible flow using the compressible Navier-Stokes equations. These simulations can capture detailed pressure and temperature distributions, as well as shock waves and other compressibility effects. However, accurate thermophysical property data is essential for reliable predictions.

Heat-pipe performance codes (Sockeye): Heat-pipe performance codes model compressible flow using simplified equations of state and flow correlations. These models can provide reasonable predictions of flow behavior but may not fully capture the detailed effects of compressibility, leading to uncertainties.

3.2.2.3. Experiments and Instrumentation Knowledge Rationale

Experimentally, the sonic limit can be inferred indirectly based on axial temperature profiles. Although it is deemed challenging to directly observe compressibility, sonic limit is not a significant concern from an experimental perspective as it does not cause rapid dryout and failure. For these reasons the knowledge level ranking for E&I is designated as **medium**.

Table 13. Ranking for Near-Sonic Compressible Flow and Sonic Limit (II-02).

Importance Level	M
M&S Knowledge Level	M
E&I Knowledge Level	M

3.2.3. Incompressible to Compressible Flow Transition (II-03)

Performance and Physics Related

3.2.3.1. Importance Rationale

Compressibility should be considered for $Ma \in (0.3, 1.0)$ for accurate pressure drop, thermophysical properties, and capillary limit calculations. However, the transition from compressible to incompressible appears to not be of great significance operationally. For these reasons the importance for this phenomenon was designated as **medium**.

3.2.3.2. Modeling and Simulation Knowledge Rationale

Although Mach numbers may be lower than sonic levels, compressibility can be important for accurate pressure drop, thermophysical properties, and capillary limit calculations. Understanding the compressible/incompressible transition helps refine the calculations for vapor flow dynamics, even if the operational impact is not large. For these reasons, the knowledge level is classified as **medium**.

Higher-fidelity codes can model the transition between compressible and incompressible flow using variable density flow models. These simulations can capture the effects of changing flow regimes on pressure drops and thermophysical properties, but require accurate data and high computational resources.

Heat-pipe performance codes use simplified flow models that account for compressibility effects through empirical correlations or equations of state. These models provide efficient and reasonably accurate predictions, but may not capture all the nuances of the transition behavior.

3.2.3.3. Experiments and Instrumentation Knowledge Rationale

Methods for measuring compressibility such as via velocity measurements are unclear for alkali metal heat pipes. Velocity measurements may be possible in low temperature heat pipes where internal instrumentation is less challenging to implement. Low-temperature heat pipe tests may be utilized to better understand the transition from incompressible to compressible flow. Current experimental methods do not allow velocity measurements within alkali metal heat pipes. For these reasons the knowledge level is designated as **limited**.

Table 14. Ranking for Incompressible to Compressible Flow Transition in Vapor Flow (II-03).

Importance Level	M
M&S Knowledge Level	M
E&I Knowledge Level	U

3.2.4. Rarified Flow and the Continuum Flow Front (II-04)

Performance and Physics Related

3.2.4.1. *Importance Rationale*

During heat pipe startup from a frozen state, continuum flow may not be present in the entire heat pipe length as the working fluid evaporates to gradually fill the vacuum. This transition between rarified flow to continuum flow is bound by the so-called continuum flow front, which could be important during frozen startup as the heat pipe enters the viscous limit bound region. However, this transition occurs relatively early during startup where the cyclic evaporation and condensation is not yet established, with temperatures below that of the sonic limit bound region. Therefore, the importance level ranking for this phenomenon is designated as **low**.

3.2.4.2. *Modeling and Simulation Knowledge Rationale*

Some modeling of the propagation of the continuum flow front has been performed in literature with some success [14]. However, uncertainties appear to be relatively significant for the relevant diffusion coefficients. Rarified flow within heat pipes is normally determined using a Knudsen number criterion [15, 16]. The transition between rarified flow to continuum flow is important during frozen startup as the heat pipe enters the viscous limit bound region. Understanding this transition is useful for accurately modeling startup behavior but has limited operational significance once steady-state conditions are reached. For these reasons the M&S knowledge level for this phenomenon is designated as **medium**.

Higher-fidelity codes can model the continuum flow front using variable viscosity and density models. These simulations can capture the transition from rarified to continuum flow but require detailed knowledge of diffusion coefficients and flow conditions.

Heat-pipe performance codes use simplified models to represent the continuum flow front. These models may rely on empirical correlations or approximations, leading to uncertainties in predicting the exact location and behavior of the flow front.

Experiments and Instrumentation Knowledge Rationale

Propagation of the continuum flow front during startup may be inferred experimentally via axial temperature measurements in wall-mounted thermocouples. However, these external measurements would likely not be highly effective, as it would likely be challenging to distinguish between the continuum flow and melt fronts solely with wall temperature measurements. High accuracy power throughput measurements via robust calorimetry setups can enhance the effectiveness of predicting the location of the continuum flow front. Another option could be to place high temperature fiber optic distributed temperature sensors internally for high spatial resolution temperature measurements. Based on these factors, the knowledge level for E&I is designated as **low**.

Table 15. Ranking for Rarified Flow and the Continuum Flow Front (II-04).

Importance Level	L
M&S Knowledge Level	M
E&I Knowledge Level	L

3.2.5. Liquid Flow and Pressure Drops in the Wick (II-05)

Performance and Physics Related

3.2.5.1. Importance Rationale

Liquid flow and pressure drops in the annulus or porous wick are critical to effective capillary pumping in the heat pipe. For annular wicks, the liquid flows in the annulus whereas the screen provides the capillary pressure needed and prevents entrainment due to vapor flow. Liquid pressure drop is a critical component of the resistance to flow along the working fluid path. Viscous and hydrostatic pressure drop components are considered based on the permeability of the wick, and the orientation with respect to gravity, respectively. Since liquid pressure drops are crucial to predicting capillary limits, the importance level is designated as **high** for this phenomenon.

3.2.5.2. Modeling and Simulation Knowledge Rationale

The liquid flow in the annular gap and the porous wick is critical for heat pipe operation. Efficient liquid flow ensures the sustained return of the working fluid from the condenser to the evaporator, maintaining the evaporation-condensation cycle. The liquid flow is slow and laminar, and the pressure drop is captured accurately by analytic relations, semi-empirical relations based on wick parameters, or Darcy flow approximations. These well-established principles allow for reliable modeling. It should be noted that changes in the location of the wick during operation may affect liquid pressure drops and are currently not well known. For these reasons, the current knowledge level is classified as **medium**.

Higher-fidelity codes can model liquid flow within the wick using porous media flow models. These simulations can capture detailed flow patterns, pressure drops, and capillary action within the wick structure. However, accurately capturing changes in wick position and their impact on pressure drops requires high-resolution models and detailed material properties.

In heat-pipe performance codes, liquid flow within the wick is modeled using simplified flow equations and capillary pressure correlations. These models are computationally efficient and provide accurate predictions of liquid flow behavior in the wick. Sockeye provides efficient and reasonably accurate predictions but may not fully capture the effects of changes in wick position.

3.2.5.3. Experiments and Instrumentation Knowledge Rationale

Liquid flow might be visualized with high current X-ray systems in a facility such as the Advanced Photon Source (APS). Despite this capability, it remains challenging to observe the fluid distribution and flow characteristics due to the small pore sizes in the wick. However, the effectiveness of liquid flow within the wick can be inferred based on the effective thermal conductivity of the heat pipe and details from wick characterization tests, such as bubble point tests. In addition, experiments have been conducted on low-temperature heat pipes to measure the pressure drops in the wick. However, the presence of pressure taps, small pressure drops, local disturbances in liquid flow and meniscus shape, and large hydrostatic pressure drops based on orientation can cause significant uncertainties in measurements. Additionally, other phenomena such as entrainment and geyser boiling affect the success of measurements. The use of high-temperature liquid metals introduces further difficulties and complications for these measurements, as the presence of pressure taps may influence heat pipe flow dynamics downstream. For these reasons, the E&I knowledge is designated as **low** for this phenomenon.

Table 16. Ranking for Liquid Flow and Pressure Drop in the Wick (II-05).

Importance Level	H
M&S Knowledge Level	M
E&I Knowledge Level	L

3.2.6. Vapor Pressure Drops (II-06) Performance and Physics Related

3.2.6.1. Importance Rationale

Vapor pressure drops and gains are crucial for calculating axial pressure profiles and capillary limits, as well as for understanding pressure dynamics. Accurate measurement and understanding of these factors are essential for the effective design and operation of systems involving vapor flow. For these reasons the importance level for this phenomenon is designated as **high**.

3.2.6.2. Modeling and Simulation Knowledge Rationale

Pressure drops within the evaporator for laminar flow are well understood, but the pressure drops in the transition/turbulent regime, particularly in the condenser where pressure recovery may occur, are not well known. Existing correlations seem to fail in capturing the necessary physics, and some are not fully validated. This gap in understanding highlights the need for further research and validation to accurately characterize pressure drops in these regimes, since accurate knowledge of these pressure variations is needed for assessing the overall performance and limitations of the heat pipe. For these reasons the M&S knowledge level is designated as **medium**.

Higher-fidelity codes can model vapor pressure drops using detailed flow simulations that account for laminar, transitional, and turbulent regimes. These simulations can capture pressure variations and recovery effects but require high-resolution models and detailed flow conditions.

Heat-pipe performance codes model vapor pressure drops using simplified flow equations and empirical correlations. These models provide efficient predictions but may not fully capture the complexities of transition and pressure recovery effects.

3.2.6.3. Experiments and Instrumentation Knowledge Rationale

Measuring vapor pressure drops is challenging because it requires invasive techniques. Previous experience on low-temperature heat pipes, such as the work conducted by Haug [13], has shown that small pressure drops and the effects of the pressure tap create significant difficulties. Additional experiments on vapor pressure drops are currently underway to address these challenges and improve measurement accuracy. Based on these factors, the E&I knowledge is designated as **low**.

Table 17. Ranking for Vapor Pressure Drops (II-06).

Importance Level	H
M&S Knowledge Level	M
E&I Knowledge Level	L

3.2.7. Geyser boiling (II-07) Performance and Physics Related

3.2.7.1. Importance Rationale

Geyser boiling is a phenomenon affecting vertical heat pipes. Geyser boiling occurs when there is a liquid pool in the evaporator end due to gravitational effects or when the wick is de-wetted by gravity. This phenomenon can happen during startup, depending on the wick structure, and is particularly common under vertical operation. Large wall temperature fluctuations may be observed between geyser boiling stages, which could impact the long-term reliability of the heat pipe. However, geyser boiling is typically not a concern during normal operation and at higher input powers. For these reasons the importance level for this phenomenon is designated as **medium**.

3.2.7.2. Modeling and Simulation Knowledge Rationale

Although some models are available to study geyser boiling, high-fidelity simulations are very challenging due to the complex flow dynamics involved. For these reasons the knowledge level for E&S is designated as **low**.

Higher-fidelity codes can model geyser boiling using two-phase flow models that account for bubble formation, vapor generation, and liquid displacement. However, accurately capturing the complex flow dynamics and interactions during geyser boiling requires high-resolution simulations and detailed flow conditions.

Heat-pipe performance codes use simplified models or empirical correlations to represent geyser boiling. These models may not fully capture the detailed flow dynamics and temperature fluctuations, leading to uncertainties in the predictions.

3.2.7.3. Experiments and Instrumentation Knowledge Rationale

Geyser boiling can be visualized using X-ray radiography, and temperature oscillations during the different stages of geyser boiling can be observed through wall temperature measurements. The geyser boiling frequency follows wall temperature oscillations without a significant lag. Rapid vapor generation at the end of the stagnant pool stage may be studied in more detail using pressure measurements, as temperature measurements are relatively slow due to dampening by the sensor and wall thermal masses. However, as mentioned previously, internal measurements are invasive and challenging to conduct for high-temperature heat pipes. For these reasons the E&I knowledge level is designated as **medium**.

Table 18. Ranking for Geyser boiling (II-07).

Importance Level	M
M&S Knowledge Level	L
E&I Knowledge Level	M

3.2.8. Wick Priming (II-08) Performance and Physics Related

3.2.8.1. Importance Rationale

The heat pipe diameter, wick properties and dimensions, fill ratio, and orientation should be optimized to ensure complete wetting of the wick and that the wick can supply the necessary capillary pressure to prime itself. If regions of the wick are not primed, hot spots may emerge, causing performance degradation. After heat pipe shutdown, the wick is typically already filled with frozen working fluid, in which case priming may not be a concern. Since it has safety implications but is expected to be not a concern for properly designed heat pipe, the importance level is designated as **medium** for this phenomenon.

3.2.8.2. Modeling and Simulation Knowledge Rationale

Current models do not consider wick priming, yet its detailed analysis may not be necessary for effective heat pipe design and analysis tools. Simple calculations of capillary forces may be sufficient to ensure the wick can prime itself during startup. Considering this the knowledge level for M&S is designated as **low**.

Higher-fidelity codes can model wick priming using capillary flow models that account for liquid saturation and capillary forces. However, capturing the detailed interactions and flow dynamics during priming requires high-resolution simulations and detailed material properties.

Heat-pipe performance codes use simplified models or empirical correlations to represent wick priming. These models may not fully capture the detailed flow dynamics and capillary forces, leading to uncertainties in the predictions.

3.2.8.3. Experiments and Instrumentation Knowledge Rationale

The effectiveness of the wick priming process depends on the type of wick, the design of the heat pipe, and the annulus thickness. Orientation can also be significant, as changes in wick location along the heat pipe can result in variations between crescent and concentric annular configurations. These configurations need to be accounted for in design because if the wick is not primed or wetted properly, vapor can fill the annulus. The presence of any hot spots due to wick not priming can be observed after the startup of the heat pipe with wall temperature measurements. Based on these factors, the E&I knowledge is designated as **medium**.

Table 19. Ranking for Wick Priming (II-08).

Importance Level	M
M&S Knowledge Level	L
E&I Knowledge Level	M

3.2.9. Wick De-Wetting (II-09) Performance and Physics Related

3.2.9.1. Importance Rationale

Ensuring the wick remains wetted is critical for maintaining effective heat transfer and preventing hotspots that can degrade heat pipe performance. De-wetting of the wick can result in significant temperature increases at the heat pipe wall in the evaporator. This phenomenon can occur during various operational scenarios, including startup, normal operation, and transient conditions. During startup, if the wick does not prime properly, de-wetting can lead to initial hotspots and uneven heat distribution. During normal operation, changes in orientation due to gravity can cause portions of the wick to become de-wetted, leading to the pooling of the working fluid and diminished heat transfer efficiencies in the evaporator. Additionally, during transient scenarios, such as sudden changes in heat load or power fluctuations, the wick may experience temporary de-wetting, causing large temperature spikes in the evaporator. Experimental observations have documented the occurrence of wick de-wetting under these conditions, highlighting its impact on heat pipe performance. For these reasons, the importance level is designated as **high** for this phenomenon.

3.2.9.2. Modeling and Simulation Knowledge Rationale

Modeling wick de-wetting is challenging considering that the changing meniscus shape, gravitational effects, and capillary effects need to be resolved, resulting in the need for high-fidelity models. Because of these complex effects, the knowledge level for M&S is designated as **low**.

Higher-fidelity codes can model wick de-wetting using two-phase flow models that account for capillary action, gravity, and meniscus dynamics. However, accurately capturing the detailed interactions and flow dynamics during de-wetting requires high-resolution simulations and detailed material properties.

Heat-pipe performance codes use simplified models or empirical correlations to represent wick de-wetting. These models may not fully capture the detailed flow dynamics and capillary effects, leading to uncertainties in the predictions.

3.2.9.3. Experiments and Instrumentation Knowledge Rationale

Temperature measurements, as well as thermal and X-ray imaging, can be utilized to study de-wetting experimentally. In the case of wick de-wetting, temperatures in the evaporator will show sharp increases, while condenser temperatures will show sharp drops. Since the phenomenon can be readily observed with present techniques and was studied in previous investigations, the E&I knowledge is designated as **high**.

Table 20. Ranking for Wick De-Wetting (II-09).

Importance Level	H
M&S Knowledge Level	L
E&I Knowledge Level	H

3.2.10. Excess Liquid Pooling in the Condenser (II-10)

Performance and Physics Related

3.2.10.1. Importance Rationale

Excess working fluid fill ratio reduces the active length of the heat pipe due to subcooled liquid accumulation at the condenser endcap. Depending on the amount of excess fill, the effect may be more significant. This effect can be exploited to achieve a similar function to gas-filled heat pipes. Slight overfilling may be beneficial to avoid low working fluid inventories in the evaporator during startup and to prevent de-wetting due to gravity. Since the phenomena effects operational performance but is normally not a safety concern, the importance level is designated as **medium**.

3.2.10.2. Modeling and Simulation Knowledge Rationale

The presence of the liquid pool may present numerical challenges in simulation due to liquid being present in the vapor space, causing zero void fraction there. In addition, liquid-vapor interaction at the liquid pool may need to be investigated especially under non-horizontal orientations. Resolving the interface between vapor and liquid at the condenser also presents challenges to most numerical methods. For this reason, the knowledge level of this phenomena is classified as **medium**.

Higher-fidelity codes can model excess liquid pooling using two-phase flow models that account for liquid accumulation and vapor-liquid interactions in the condenser. These simulations can capture detailed flow patterns and temperature distributions but require accurate input data and high computational resources. The interface mass and momentum exchange interaction between vapor and liquid that defines the stability of the liquid pool could also be modeled but has not been demonstrated.

Heat-pipe performance codes (Sockeye): Heat-pipe performance codes use simplified models or empirical correlations to represent excess liquid pooling. These models provide efficient predictions but may not fully capture the detailed effects of liquid accumulation and flow dynamics.

3.2.10.3. Experiments and Instrumentation Knowledge Rationale

X-ray imaging can be utilized to directly observe excess liquid pooling in the condenser, along with the axial temperature profile of the heat pipe based on wall measurements. There may be uncertainties when temperature measurements are used since some fluctuations were observed in pooling length in recent simulation experience. Further experiments may be required to study this effect and it evolution if the inactive length with operational conditions especially under vertical or near-vertical conditions. Based on these reasons the E&I knowledge is designated as **medium**.

Table 21. Ranking for excess Liquid Pooling in the Condenser (II-10).

Importance Level	M
M&S Knowledge Level	M
E&I Knowledge Level	M

3.2.11. Under-Filling (II-11) Quality-Assurance Related

3.2.11.1. Importance Rationale

Under-filling can cause serious performance degradation and dry spots in the evaporator due to an insufficient amount of working fluid. In some cases, the heat pipe operation may not even start due to a lack of fluid in the evaporator. Depending on the level of under-filling, the heat pipe might start but reach critical heat flux (CHF) at a lower power. Under-filling can occur in actively controlled heat pipes in the event of an accident or malfunction. Since this phenomenon may be avoided with proper fill ratio, the importance level is designated as **medium**.

3.2.11.2. Modeling and Simulation Knowledge Rationale

Modeling the effects of under-filling is challenging, primarily due to the partial wetting of the wick, and it is usually treated as an invalid input to simulations. Since it can be deemed an error in the design or manufacturing, it may not be necessary to consider under-filling in models. However, the phenomenon may be captured in high-fidelity models resolving partial wetting of the wick. Regardless, the knowledge level for M&S is designated as **low** based on current modeling capabilities.

Higher-fidelity codes can model under-filling using two-phase flow models that account for liquid distribution and capillary action. However, accurately capturing the effects of under-filling requires high-resolution simulations and detailed wick properties.

3.2.11.3. Experiments and Instrumentation Knowledge Rationale

Due to serious performance degradation caused by the early onset of dryout in the evaporator, it is challenging to study the effects of under-filling experimentally. Consequently, the effects of under-filling have not been studied extensively. Therefore, the knowledge level is designated as **low** for this phenomenon.

Table 22. Ranking for Under-Filling (II-11).

Importance Level	M
M&S Knowledge Level	L
E&I Knowledge Level	L

3.3. Liquid-Vapor Phase Change

Phase change category includes phase change phenomena within the heat pipe including evaporation and condensation, nucleate boiling, and critical heat flux (CHF) conditions.

3.3.1. Evaporation and Condensation at the Liquid/Vapor Interface (III-01)

Performance and Physics Related

3.3.1.1. Importance Rationale

Evaporation and condensation at the liquid-vapor interface are the main modes of heat transfer within the heat pipe and are critical to heat pipe function. Therefore, the importance level is designated as **high** for this phenomenon.

3.3.1.2. Modeling and Simulation Knowledge Rationale

There are uncertainties in the accommodation coefficients, especially for condensation, and it is also difficult to infer the meniscus shape for calculating the interfacial area. For these reasons the knowledge level for M&S is designated as **medium**.

Higher-fidelity codes can model evaporation and condensation using phase change models that account for interfacial heat and mass transfer. These simulations can capture detailed flow patterns and temperature distributions but require accurate input data for accommodation coefficients and interfacial properties.

Heat-pipe performance codes use simplified models or empirical correlations to represent evaporation and condensation. These models provide efficient predictions but may not fully capture the detailed effects of interfacial heat and mass transfer, leading to uncertainties in the predictions.

3.3.1.3. Experiments and Instrumentation Knowledge Rationale

Although it is mostly possible to identify liquid/vapor zones using X-ray radiography, it is currently not possible to measure interfacial mass flux with existing methods. Accurate calorimetry measurements and estimates on interface area can enable the indirect calculation of the interfacial mass flux. Separate effects experiments may be useful in experimentally characterizing evaporation and condensation. However, considering techniques currently available, the knowledge level is designated as **low**.

Table 23. Ranking for Evaporation and Condensation at the Liquid/Vapor Interface (III-01).

Importance Level	H
M&S Knowledge Level	M
E&I Knowledge Level	L

3.3.2. Nucleate Boiling at High Heat Fluxes (III-02)

Performance and Physics Related

3.3.2.1. Importance Rationale

Nucleate boiling in the wick structure, by definition, represents the boiling limit. The occurrence of the boiling limit can be severe for alkali metal heat pipes, as nucleating bubbles can prevent liquid return to the evaporator. This phenomenon may be more significant in the presence of non-condensable gases (NCGs) and/or changes in surface characteristics, which can result in higher active nucleation site densities. Since the boiling limit can cause rapid heat pipe failure and damage, it is an important phenomenon that needs to be predicted accurately. Based on this rationale, the importance level for this phenomenon is designated as **high**.

3.3.2.2. Modeling and Simulation Knowledge Rationale

Dedicated correlations for nucleate boiling in heat pipes are not available. Additionally, nucleate boiling phenomena depend on the characteristics of the heat pipe and surface morphologies. Bubbles in the wick create modeling challenges due to capillary forces. This phenomenon may include transient scenarios in which nucleate boiling occurs only at one stage during the transient. While correlations for the boiling limit are rather well known, dynamic modeling of nucleate boiling appears to be not feasible using present techniques. Furthermore, surface properties may change spatially and over time within the heat pipe, affecting properties such as nucleation site densities, resulting in uncertainties in predictions. Considering these factors, the knowledge level for M&S is designated as **low**.

Higher-fidelity codes can model nucleate boiling using two-phase flow models that account for bubble dynamics, heat transfer, and surface properties. These simulations can capture detailed flow patterns and temperature distributions; however, they require high computational resources and accurate input data for surface properties and nucleation site densities.

Heat-pipe performance codes use simplified models or empirical correlations to represent nucleate boiling. These models provide efficient predictions but may not fully capture the detailed effects of bubble dynamics and surface properties, leading to uncertainties in the predictions.

3.3.2.3. Experiments and Instrumentation Knowledge Rationale

As higher-performance wicks are designed, the boiling limit might become the limiting factor for higher temperature heat pipes. Factors related to manufacturing that affect boiling characteristics need to be considered. The boiling limit is also important because it represents a power limit that might result in rapid temperature increases. The temperature fluctuations and superheats could be large, which can be an issue when considering material limits. Vapor generation can block or displace liquid flow near nucleation sites, and the time evolution of active nucleation site densities may require characterization and separate effects testing. Based on these reasons, the E&I knowledge level is designated as **low** for this phenomenon.

Table 24. Ranking for Nucleate Boiling at High Heat Fluxes (III-02).

Importance Level	H
M&S Knowledge Level	L
E&I Knowledge Level	L

3.3.3. Critical Heat Flux (III-03) Performance and Physics Related

3.3.3.1. Importance Rationale

CHF represents 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). Dryout conditions can cause rapid spikes in wall temperatures that may result in immediate damage to the heat pipe body or wick structures. It can be assumed that the heat pipe cannot be operated further after the critical heat flux (CHF) is reached. This phenomenon could be caused by cascading heat pipe failures, reactivity insertion accidents, or other extreme conditions.

Additionally, there is another phenomenon that warrants consideration: a CHF event resulting from a sudden overcooling of the condenser section. This occurrence is particularly significant in reactor operating conditions, where over-operation of the secondary cooling mechanism can lead to an overcooling in the condenser of the heat pipe. Rapid cooling of the condenser section while heat is being applied to the evaporator section can alter the local vapor pressure within the heat pipe or drive the system to the sonic limit, thereby inducing CHF in the evaporator section. This is of critical importance due to the substantial coupling between the condenser and evaporator sections of the heat pipe. Consequently, not only could a spike in the evaporator heat flux induce CHF but maintaining a constant evaporator heat flux while altering the cooling conditions could also precipitate a CHF event.

For these reasons, the importance of this phenomenon is ranked as **high**.

3.3.3.2. Modeling and Simulation Knowledge Rationale

Modeling challenges for this condition are comparable to those for nucleate boiling. The safety-critical nature of the phenomenon requires accurate modeling. Therefore, the M&S knowledge level for this phenomenon is designated as **low**.

Higher-fidelity codes can model CHF using two-phase flow models that account for heat transfer, phase change, and surface properties. These simulations can capture detailed flow patterns and temperature distributions but require high computational resources and accurate input data for surface properties and boiling characteristics.

Heat-pipe performance codes use simplified models or empirical correlations to represent CHF. These models provide efficient predictions but may not fully capture the detailed effects of heat transfer and phase change, leading to uncertainties in the predictions.

3.3.3.3. Experiments and Instrumentation Knowledge Rationale

Designing well-controlled experiments with known nucleation site sizes throughout the heat pipe is difficult. Inspection of the inner surface of long heat pipes can be challenging. Additionally, high temperatures, the possibility of damage to the heat pipe, and safety concerns related to sodium release to the environment pose further challenges to experimentation. Therefore, the E&I knowledge level for this phenomenon is designated as **low**.

Table 25. Ranking for Critical Heat Flux (III-03).

Importance Level	H
M&S Knowledge Level	L
E&I Knowledge Level	L

3.4. Capillary Pumping

The wick structure plays a vital role in the operation of a heat pipe. Where capillary action principle is utilized to pump the liquid from the condenser to the evaporator where it can absorb the heat from the evaporator, facilitating heat transfer. The capillary pumping ability of a wick structure depends on the wick geometry and properties as well as the thermophysical properties of the working fluid. This category includes identified phenomena that is related to the capillary pumping within the heat pipe.

3.4.1. Capillary Action (IV-01) Performance and Physics Related

3.4.1.1. Importance Rationale

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. Due to its critical effects on heat pipe operation, capillary action is designated as **high** importance.

3.4.1.2. Modeling and Simulation Knowledge Rationale

Modeling and simulation of capillary action in heat pipes are well-developed due to the fundamental nature of the underlying principles. Capillary action is primarily governed by the pore size and wettability of the wick material, which can be characterized and incorporated into models with a **high** degree of accuracy.

Higher-fidelity codes can effectively simulate the capillary pressure and liquid distribution within the wick structure, enabling accurate predictions of heat pipe performance. This includes both microfluidics models integrating detailed models for capillary effects in the wick or porous media models, which integrate the capillary force as a volumetric force in the wick region. Given the well-established theoretical framework and the availability of reliable modeling techniques, the knowledge level for modeling and simulation of capillary action is designated as high.

Heat-pipe performance codes can incorporate capillary force by adding the equivalent capillary force to the wick model in two-phase simulations. For this purpose, correlations for the capillary force are needed, which are developed to some extent but still need more information regarding potential gas entrainment and flow distribution in the wick. However, if these correlations are measured, then the integration of the capillary force in the lumped parameter models is straightforward.

3.4.1.3. Experiments and Instrumentation Knowledge Rationale

Although capillary action is a well-known principle, and wick characterization tests can characterize capillary pressures provided by wick structures accurately, the knowledge level is designated as **medium** considering that direct measurements of capillary pressure is not possible within the heat pipe.

Table 26. Ranking for Capillary Action (IV-01).

Importance Level	H
M&S Knowledge Level	H
E&I Knowledge Level	M

3.4.2. Wettability (IV-02) Performance and Physics Related

3.4.2.1. *Importance Rationale*

The contact angle is an indication of the wettability of the surfaces by the working fluid and influences the capillary pressure that can be supplied by the wick, which is crucial for heat pipe operation. Therefore, the importance ranking for this phenomenon is designated as **high**.

3.4.2.2. *Modeling and Simulation Knowledge Rationale*

Factors to consider for the effective modeling of contact angles include conditions of the material, as well as pressure, and temperature effects. The contact angle also depends on the surface morphology of the material and impurities in the working fluid. Considering these complexities, the current knowledge level for M&S is designated as **low** for this phenomenon.

A challenging aspect of contact angles is the distinction between advancing and receding contact angles. The advancing contact angle is observed when the liquid front is moving forward on a solid surface, while the receding contact angle occurs when the liquid front is retreating. These angles can differ significantly due to surface hysteresis, which is influenced by surface roughness, chemical heterogeneity, and dynamic conditions. In the context of a wick, which has a much more complex and porous structure, the situation becomes even more intricate. The wick's structure introduces additional factors such as capillary forces within the pores, the interaction between the liquid and the porous media, and the distribution of pore sizes. Accurate modeling must account for this hysteresis and the complexities of the wick structure to predict the wetting and de-wetting behavior of the working fluid accurately, as well as the overall capillary pressure and liquid distribution within the wick.

Higher-fidelity codes can model contact angle effects using surface tension and contact angle models. These simulations can capture detailed interactions between the working fluid and solid surfaces, but require accurate input data for contact angles, including both advancing and receding values, and surface conditions. Additionally, accurately representing the dynamic nature of contact angles in response to changing conditions remains a challenge.

Heat-pipe performance codes use simplified models or empirical correlations to represent contact angle effects. These models may not fully capture the detailed interactions and variations in contact angle, particularly the differences between advancing and receding angles, leading to uncertainties in the predictions. Consequently, the fidelity of such models is limited when dealing with complex wetting and de-wetting phenomena in heat pipes.

3.4.2.3. *Experiments and Instrumentation Knowledge Rationale*

Contact angles are not well characterized for high temperatures, and changes in surface characteristics with temperature or impurities add further complexity (see IV-01). Therefore, the knowledge level for E&I is designated as **low**.

Table 27. Ranking for Wettability (IV-02).

Importance Level	H
M&S Knowledge Level	L
E&I Knowledge Level	L

3.4.3. Wet Point Location (IV-03) Performance and Physics Related

3.4.3.1. Importance Rationale

The location of the wet point is where the liquid and vapor pressures are equal and the liquid-vapor interface is flat. This location is important to the liquid flow in the wick, since it establishes the liquid flow path to conduct pressure balance along for capillary limit calculations. For this reason, the importance level for this phenomenon is identified as **medium**.

3.4.3.2. Modeling and Simulation Knowledge Rationale

The wet point location is affected by orientation, gravitational effects, and pressure recovery in the condenser. The wet point can be predicted with reasonable accuracy based on the available models. Therefore, the M&S knowledge level is designated as **medium** for this phenomenon.

Higher-fidelity codes can model wet point location using phase change and capillary flow models. These simulations can capture detailed flow patterns and pressure distributions, provided that accurate input data on orientation and pressure conditions are available.

Heat-pipe performance codes use simplified models or empirical correlations to represent wet point location. These models provide efficient predictions of fluid flow behavior, but may not fully capture the effects of orientation and pressure recovery, leading to uncertainties in the predictions.

3.4.3.3. Experiments and Instrumentation Knowledge Rationale

The wet point location can be determined using X-ray radiography, however there may be difficulties encountered with fine resolutions. Considering this the E&I knowledge level is designated as **medium**.

Table 28. Ranking for Wet Point Location (IV-03).

Importance Level	M
M&S Knowledge Level	M
E&I Knowledge Level	M

3.4.4. Wick Fabrication Techniques (IV-04)

Performance and Physics Related

3.4.4.1. Importance Rationale

Wick fabrication techniques can influence wick performance and reliability. Optimization of wick fabrication techniques based on heat pipe performance, reliability, and mass manufacturability is imperative. For these reasons, the importance level is designated as **medium**.

3.4.4.2. Modeling and Simulation Knowledge Rationale

Integrating non-uniform pore sizes and distributions in the wick to simulations is challenging. Sockeye has correlations for the capillary pressure as a function of the pore sizes, but it assumes a flat distribution. If correlations are developed, they may be implemented in Sockeye, although developing these correlations could be challenging. For these reasons, M&S knowledge is designated as **medium**.

Higher-fidelity codes can model the effects of wick fabrication techniques using porous media flow models that account for variations in pore size, permeability, and porosity. These simulations can capture detailed flow patterns and pressure distributions, provided that accurate input data on wick properties and fabrication methods is available.

Heat-pipe performance codes use simplified models or empirical correlations to represent the effects of wick fabrication techniques. These models provide efficient predictions of capillary pumping behavior, but may not fully capture the effects of non-uniform pore sizes and distributions, leading to uncertainties in the predictions.

3.4.4.3. Experiments and Instrumentation Knowledge Rationale

Experimentally, while wicks that perform the expected function can be developed, wick fabrication processes have not yet been optimized. Based on this reason the E&I knowledge is designated as **medium**.

Table 29. Ranking for Wick Fabrication Techniques (IV-04).

Importance Level	M
M&S Knowledge Level	M
E&I Knowledge Level	M

3.5. Non-Condensable Gases

The presence of non-condensable gases (NCGs) in the heat pipe can impact its performance and operating characteristics. These gases may be *(i)* placed by design inside the heat pipe to achieve certain effects such as controlled operating temperatures, *(ii)* created in small amounts within the heat pipe due to chemical reactions in the wall, wick, or working fluid, and *(iii)* introduced inside the heat pipe during filling and sealing processes or leaks. NCGs do not participate in the phase change process and can accumulate in the condenser, causing an inactive length.

3.5.1. Accumulation of NCGs in the Condenser (V-01)

Performance and Physics Related

3.5.1.1. Importance Rationale

Non-condensable gases (NCGs) inside the heat pipe accumulate at the condenser endcap during operation. This accumulation results in an inactive condenser length that expands, and contracts based on the operating pressure, effectively controlling the heat transfer area on the condenser surface. The importance of these phenomena for the operation of the heat pipe is classified as **medium**.

3.5.1.2. Modeling and Simulation Knowledge Rationale

There might be modeling challenges depending on the amount of NCGs and its source. This phenomenon could be used in the design of the heat pipe to achieve a more constant operating temperature, thus should be incorporated in design tools. Current models can effectively model the NCG accumulation in the condenser and the length of the inactive region via a sharp interface model. Therefore, the M&S knowledge is designated as **medium**.

Higher-fidelity codes can model the accumulation of NCGs using multiphase flow models that account for gas-liquid interactions and phase change. These simulations can capture detailed flow patterns and pressure distributions but require accurate input data on NCG properties and accumulation rates.

Heat-pipe performance codes use simplified models or empirical correlations to represent NCG accumulation. These models approximate the inactive length determined by partial pressure balance and mass of NCGs, providing efficient predictions of the impact on heat pipe performance.

3.5.1.3. Experiments and Instrumentation Knowledge Rationale

Determining the amount of NCGs with high accuracy is challenging experimentally. While it is relatively easy to measure the inactive length with axial temperature measurements, the diffusion of working fluid vapor and NCG, as well as wall conduction, can obscure the accumulation area if relatively low amounts of gas are present. Furthermore, it should be noted that small amounts of NCGs may be contained in the wick or vapor spaces (see III-03) that may affect operation. Based on these factors, the knowledge level for E&I is designated as **medium**.

Table 30. Ranking for Accumulation of NCGs in the Condenser (V-01).

Importance Level	M
M&S Knowledge Level	M
E&I Knowledge Level	M

3.5.2. Vapor-NCG Front Location (V-02)

Performance and Physics Related

3.5.2.1. Importance Rationale

The accumulated non-condensable gases (NCGs) form a front with the vapor phase of the working fluid. The location of this vapor-NCG front determines the active and inactive lengths of the heat pipe. Considering that the accumulation of NCGs in the condenser is of high importance, the present phenomenon is designated as **medium** importance as well.

3.5.2.2. Modeling and Simulation Knowledge Rationale

As in the previous phenomenon, the vapor-NCG front location can be well approximated with the assumption of NCG accumulation at the condenser end, with the inactive length determined by the partial pressure balance and the total mass of NCGs. However, diffusion and mixing between the NCG and vapor can lead to uncertainties. Based on these factors, the M&S knowledge is designated as **medium**.

Higher-fidelity codes can model the vapor-NCG front location using multiphase flow models that account for gas-liquid interactions and phase change.

Heat-pipe performance codes use simplified models or empirical correlations to represent the vapor-NCG front location. These models provide efficient predictions of the impact on heat pipe performance, provided that accurate input data on NCG properties and mass balance is available.

3.5.2.3. Experiments and Instrumentation Knowledge Rationale

Similarly, diffusion and mixing between the NCG and vapor can introduce uncertainties in the front location when using the axial temperature profile. High spatial resolution temperature measurements could mitigate this issue. Based on these factors, the E&I knowledge is designated as **medium**.

Table 31. Ranking for Vapor-NCG Front Location (V-02).

Importance Level	M
M&S Knowledge Level	M
E&I Knowledge Level	M

3.5.3. Diffusion and Mixing between Vapor and NCG (V-03)

Performance and Physics Related

3.5.3.1. Importance Rationale

Diffusion or mixing at the vapor-NCG front determines how sharp the transition is and how much the presence of NCGs may affect flow and phase change characteristics in the active region. Additionally, this phenomenon can also affect the liquid flow, as the presence of NCGs in the wick can alter the capillary action and liquid return to the evaporator. The extent to which diffusion and mixing impact the overall performance is also dependent on the wick structure and its ability to manage the distribution of NCGs. For these reasons, the level of importance is designated as **medium**.

3.5.3.2. Modeling and Simulation Knowledge Rationale

The mass diffusion coefficient may not be well known, and condensation effects due to NCGs may be difficult to model near the inactive length. Considering these factors, M&S knowledge is designated as **medium**.

Higher-fidelity codes can model diffusion and mixing between vapor and NCG using multiphase flow models that account for mass transfer and phase change. These simulations can capture detailed flow patterns and concentration distributions, but require accurate input data on diffusion coefficients and NCG properties.

Heat-pipe performance codes (Sockeye): Heat-pipe performance codes use simplified models or empirical correlations to represent diffusion and mixing between vapor and NCG. These models provide efficient predictions of the impact on heat pipe performance, but may not fully capture the detailed effects of mass transfer and phase change, leading to uncertainties in the predictions.

3.5.3.3. Experiments and Instrumentation Knowledge Rationale

Local diffusion and mixing between the NCG and vapor are hard to determine, as internal measurements are needed. Wall temperatures may not provide a detailed account due to the thermal mass and conduction of the wall. For these reasons, the E&I knowledge is designated as **low** for this phenomenon.

Table 32. Ranking for Diffusion and Mixing between Vapor and NCGs (V-03).

Importance Level	M
M&S Knowledge Level	M
E&I Knowledge Level	L

3.5.4. Trapped NCGs in the Wick (V-04) Performance and Physics Related

3.5.4.1. Importance Rationale

Non-condensable gases (NCGs) trapped in the wick can cause dry spots in the wick or annulus, preventing liquid return and creating effects similar to boiling limit and critical heat flux (CHF) conditions. For these reasons, the importance level is designated as **medium**.

3.5.4.2. Modeling and Simulation Knowledge Rationale

This could change boiling limit characteristics and requires an understanding of the behavior of NCGs in the wick under variable pressure and temperature. Modeling transport in the wick is necessary to predict changes to flow dynamics. These factors cause challenges and complexities in model development that are not yet implemented. Therefore, M&S knowledge for this phenomenon is designated as **low**.

Higher-fidelity codes can model NCG trapping in the wick using multiphase flow models that account for gas-liquid interactions and capillary effects. These simulations can capture detailed flow patterns and pressure distributions, but require accurate input data on NCG properties and behavior in the wick.

Heat-pipe performance codes typically do not consider NCG trapping in the wick due to the lack of empirical correlations and data. Simplified models may not fully capture the detailed effects of NCG transport and behavior in the wick, leading to uncertainties in the predictions.

3.5.4.3. Experiments and Instrumentation Knowledge Rationale

The trapping of NCGs in the wick has been documented in previous experiments, but their presence is hard to identify with indirect measurements. X-ray radiography could be used to observe NCG pockets based on their size and distribution. Since further investigations are necessary to better understand this phenomenon, the knowledge level for E&I is designated as **low**.

Table 33. Ranking for Trapped NCGs in the Wick (V-04).

Importance Level	M
M&S Knowledge Level	L
E&I Knowledge Level	L

3.6. Startup, Shutdown, and Transient Scenarios

Heat pipe response to startup, shutdown, and other transient scenarios is critical to ensure proper operation and minimize the risk of failures. Startup scenarios for alkali metal heat pipes involves the process of reaching normal operation from an initially frozen state. Transient scenarios include the response of the heat pipe to changes in heat load, condenser cooling, internal flow instabilities, temperature variations, and accident scenarios including wick dryout.

3.6.1. Frozen Startup (VI-01)

Performance and Physics Related

3.6.1.1. Importance Rationale

Frozen startup involves the startup of the heat pipe from near ambient conditions where the working fluid is fully or partially frozen. The working fluid gradually melts and saturates the wick until the cyclic evaporation-condensation process is established. The frozen startup process is crucial as the heat pipe's working fluid melts and the cyclic evaporation and condensation process is established inside the heat pipe. Startup procedures need to be developed considering the frozen startup limit, where vapor can re-freeze in the condenser at near-frozen startup limits. Orientation can play an important role in the behavior of the melt front. For these reasons, the phenomenon is identified as **medium** importance.

3.6.1.2. Modeling and Simulation Knowledge Rationale

Current models for the melting of the working fluid are not high-fidelity. However, current models do consider melt front progression during startup. Frozen startup modeling is challenging due to extremely low pressures in the vapor, which can be numerically challenging for flow solvers due to the need for vacuum treatment and possibly insufficient equation of state relations. Considering these limitations, the knowledge level for M&S is designated as **medium**.

Higher-fidelity codes can model frozen startup using phase change models that account for melting, evaporation, and the low-pressure vapor phase. These simulations can capture detailed temperature distributions and phase front progression, but require accurate input data and high computational resources.

Heat-pipe performance codes (Sockeye): Heat-pipe performance codes use simplified models or empirical correlations to represent frozen startup. These models provide efficient predictions of the startup process, but may not fully capture the detailed effects of low pressures and phase change, leading to uncertainties in the predictions.

3.6.1.3. Experiments and Instrumentation Knowledge Rationale

This process can be characterized well experimentally with X-rays, but experimental results need to be compared to models. The resolution of the meniscus may not be sufficient depending on the heat pipe and operating conditions. Additionally, it may be difficult to distinguish between solid and liquid sodium in the wick. Considering these challenges, the knowledge level for E&I is designated as **medium**.

Table 34. Ranking for Frozen Startup (VI-01).

Importance Level	M

M&S Knowledge Level	M
E&I Knowledge Level	M

3.6.2. Solidification and Solid Accumulation Post Shutdown (VI-02)

Performance and Physics Related

3.6.2.1. Importance Rationale

As the heat pipe returns to near ambient conditions during shutdown, solidification of the working fluid occurs in the wick. Solidification and solid accumulation in the wick and condenser regions can impact subsequent startups by affecting the distribution of the working fluid. Ensuring controlled solidification helps maintain the heat pipe's readiness for subsequent startups and prevents issues related to non-uniform freezing. It is important that the working fluid solidifies in a manner that enables fast and efficient re-start of the heat pipe. Startup performance could be impacted if the working fluid freezes mostly in the condenser region during shutdown. For these reasons, the importance level for the phenomenon was designated as **high**.

3.6.2.2. Modeling and Simulation Knowledge Rationale

Solidification during shutdown is not currently modeled; however, higher-fidelity codes can model melting and solidification using phase change models that account for latent heat and thermal properties of the working fluid. These simulations can capture detailed temperature distributions and phase front progression but require high computational resources and accurate input data.

Heat-pipe performance codes use simplified models or empirical correlations to represent solidification and solid accumulation. These models provide efficient predictions of the shutdown process but may not fully capture the detailed effects of phase change and thermal properties, leading to uncertainties in the predictions.

Due to these reasons, the knowledge level for this phenomenon is raked as **medium**.

3.6.2.3. Experiments and Instrumentation Knowledge Rationale

To study this phenomenon experimentally, X-ray and CT scans of the heat pipe can be conducted post-shutdown to study the solid accumulation regions. The shutdown procedures can then be modified accordingly. Considering these examinations can be readily conducted with current techniques, the E&I knowledge is designated as **high**.

Table 35. Ranking for Solidification and Solid Accumulation Post Shutdown (VI-02).

Importance Level	H
M&S Knowledge Level	M
E&I Knowledge Level	H

3.6.3. Startup and Shutdown Time Scales (VI-03)

Performance and Physics Related

3.6.3.1. Importance Rationale

The time scales of heat pipe startup and shutdown processes are important for developing operating procedures and establishing operational characteristics. Rapid response of heat pipes during startup may be required for certain reactor designs, making it crucial to characterize the time constant of the heat pipe, which is not a strictly defined parameter in the literature. Since these time scales are parameters describing a variety of factors, the importance level is designated as **medium**.

3.6.3.2. Modeling and Simulation Knowledge Rationale

Modeling these time scales may be possible using a quasi-steady lumped capacitance method with a viscous and frozen startup mode to determine the active length. Lumped capacitance with forward differencing can be unstable with large time steps, but it may be possible to switch to backward differencing. Capturing superheat and subcooling in the system during these transients could be challenging. Based on these challenges the M&S knowledge level is designated as **low**.

Higher-fidelity codes can model startup and shutdown time scales using transient heat transfer and fluid flow models. These simulations can capture detailed temperature distributions and flow dynamics, but require high computational resources and accurate input data.

Heat-pipe performance codes use simplified models or empirical correlations to represent startup and shutdown time scales. These models provide efficient predictions of the transient processes, but may not fully capture the detailed effects of superheat and subcooling, leading to uncertainties in the predictions.

3.6.3.3. Experiments and Instrumentation Knowledge Rationale

Startup and shutdown time scales can be defined based on temperature measurements and measured experimentally. Therefore the knowledge level for E&I is designated as **high**.

Table 36. Ranking for Startup and Shutdown Time Scales (VI-03).

Importance Level	M
M&S Knowledge Level	L
E&I Knowledge Level	H

3.6.4. Successive Startup and Shutdowns (VI-04)

Performance and Physics Related

3.6.4.1. Importance Rationale

Successive startups and shutdowns are important to quantify the effects of thermal cycling and to develop robust operating procedures that consider frozen startup and solidification after shutdown. For these reasons the importance level is designated as **medium**.

3.6.4.2. Modeling and Simulation Knowledge Rationale

Mechanistic thermomechanical models to capture thermal fatigue effects are possible but are likely outside the scope of practical heat pipe models and would require high-fidelity, three-dimensional heat pipe models. Since these simulations can be conducted but are involved and complex to implement, the knowledge rating for M&S is designated as **medium**.

Higher-fidelity codes can model successive startups and shutdowns using transient heat transfer and structural models that account for thermal fatigue and material properties. These simulations can capture detailed temperature distributions and stress interactions, but require high computational resources and accurate input data.

Heat-pipe performance codes use simplified models or empirical correlations to represent the effects of successive startups and shutdowns. These models provide efficient predictions of thermal cycling behavior, but may not fully capture the detailed effects of thermal fatigue and structural interactions, leading to uncertainties in the predictions.

3.6.4.3. Experiments and Instrumentation Knowledge Rationale

This phenomenon has not been studied in detail, but experiments can be conducted with current capabilities to determine its effects. Hence, the E&I knowledge level for this phenomenon is designated as **medium**.

Table 37. Ranking for Successive Startup and Shutdowns (VI-04).

Importance Level	M
M&S Knowledge Level	M
E&I Knowledge Level	M

3.6.5. Thermal Stresses (VI-05)

Performance and Physics Related

3.6.5.1. Importance Rationale

Stresses caused by thermal gradients during transients can occur under limit conditions where the heat pipe ceases to be isothermal and hot spots may be observed, causing increased thermal gradients. While heat pipes respond to normal transients approximately isothermally, system transients and accidents may expose certain heat pipes to harsher conditions, inducing increased thermal stresses to particular heat pipes among the array. Considering these effects, this phenomenon is designed as of **medium** importance.

3.6.5.2. Modeling and Simulation Knowledge Rationale

Mechanistic thermomechanical models are possible but are likely outside the scope of practical heat pipe models and would require high-fidelity, three-dimensional heat pipe models. Considering these complexities, the knowledge level for M&S is designated as **medium**.

Higher-fidelity codes can model thermal stresses using coupled thermal-structural models that account for temperature-dependent material properties and stress interactions. These simulations can capture detailed temperature distributions and stress patterns but require high computational resources and accurate input data.

Heat-pipe performance codes use simplified models or empirical correlations to represent thermal stresses. These models provide efficient predictions of stress behavior but may not fully capture the detailed effects of thermal gradients and material properties, leading to uncertainties in the predictions.

3.6.5.3. Experiments and Instrumentation Knowledge Rationale

Experiments that investigate thermal stresses can be conducted with temperature and strain measurements, including optical fiber sensors for high-resolution measurements of both parameters. Investigations of near-limit conditions are underway but should be advanced further. Based on these factors the knowledge level is designated as **medium** for E&I.

Table 38. Ranking for Thermal Stresses (VI-05).

Importance Level	M
M&S Knowledge Level	M
E&I Knowledge Level	M

3.6.6. Pressure Dynamics (VI-06)

Performance and Physics Related

3.6.6.1. Importance Rationale

Pressure dynamics during startup, shutdown, and thermal power transients are important for the study of flow dynamics, instabilities, transients and limit conditions including viscous and sonic. For these reason the importance level for this phenomenon is designated as **high**.

3.6.6.2. Modeling and Simulation Knowledge Rationale

Current pressure and velocity profile correction factors were presented in the 1980s and assume uniform heating and cooling for heat pipes at steady state. These correlations may not fully capture the pressure dynamics in heat pipes during transients, especially for startups and shutdowns. Therefore, the knowledge level for M&S is designated as **low** for this phenomenon.

Higher-fidelity codes can model pressure dynamics using transient fluid flow models that account for compressibility, phase change, and pressure variations. These simulations can capture detailed pressure distributions and flow dynamics, but require high computational resources and accurate input data.

Heat-pipe performance codes use simplified models or empirical correlations to represent pressure dynamics. These models provide efficient predictions of pressure behavior, but may not fully capture the detailed effects of transients and phase change, leading to uncertainties in the predictions.

3.6.6.3. Experiments and Instrumentation Knowledge Rationale

Internal pressure measurements are hard to conduct due to the interference of the probe with the internal flow, low axial pressure drops, and ambiguities in the interpretation of pressure measurements considering the two-phase flow in the heat pipe and liquid flow in porous media. Due to these limitations, the knowledge level for E&I is designated as **low** for this phenomenon.

Table 39. Ranking for Pressure Dynamics (VI-06).

Importance Level	H
M&S Knowledge Level	L
E&I Knowledge Level	L

3.6.7. Acute Mechanical Damage (VI-07) Performance and Physics Related

3.6.7.1. Importance Rationale

Acute mechanical damage can be caused by breaks in the heat pipe wall, wick, or welds due to external or internal factors. The heat pipe wall or endcaps may be compromised via a failed weld, a pinhole leak, or other mechanical damages. QA processes are being developed to mitigate such issues and ensure long-term reliability. Ingress of non-condensable gases (NCGs) and moisture could occur if the heat pipe is at a lower pressure with respect to the ambient. Considering these effects, the importance level is designated as **medium** as this is a condition that is expected to occur with low probability following the development of QA procedures.

3.6.7.2. Modeling and Simulation Knowledge Rationale

While modeling these failures has not been done before and may be outside the scope of functional modeling, the development of QA processes is expected to mitigate such failures. Therefore, the knowledge level for M&S is designated as **medium**.

Higher-fidelity codes can model acute mechanical damage using coupled thermal-structural models that account for material properties, stress interactions, and damage mechanics. These simulations can capture detailed temperature distributions and stress patterns but require high computational resources and accurate input data.

Heat-pipe performance codes use simplified models or empirical correlations to represent acute mechanical damage. These models provide efficient predictions of damage behavior but may not fully capture the detailed effects of material properties and stress interactions, leading to uncertainties in the predictions.

3.6.7.3. Experiments and Instrumentation Knowledge Rationale

Work is underway to develop mass manufacturing processes for heat pipes through experimental procedures. Considering these efforts, the knowledge level for E&I is designated as **medium**.

Table 40. Ranking for Acute Mechanical Damage (VI-07).

Importance Level	M
M&S Knowledge Level	M
E&I Knowledge Level	M

3.7. Aging and Degradation

The performance and reliability of heat pipes can degrade due to various aging and degradation mechanisms. Over time, heat pipes experience aging due to thermal cycles, mechanical stress, and chemical interactions. This can affect the physical and chemical properties of the working fluid and the structure of the pipe. Aging and degradation mechanisms include factors such as corrosion, oxidation, fatigue, fluid contamination, and wick clogging.

3.7.1. Material Degradation (VII-01) Performance and Physics Related

3.7.1.1. Importance Rationale

Long-term material degradation caused by mechanisms such as corrosion, oxidation, creep, and fatigue is a concern for the long-term reliability of heat pipes. Current experience includes data on long-term material degradation due to these mechanisms for most materials, but novel materials may need further investigation. For these reasons the importance level is designated as **medium** for this phenomenon.

3.7.1.2. Modeling and Simulation Knowledge Rationale

. This phenomenon has not been integrated into functional models before, but it is beneficial for predicting the lifespan and maintaining the performance of the heat pipe over time. Modeling long-term material degradation may be outside the scope of the functional modeling of heat pipes. But effects can be implemented in models if they can be characterized experimentally, therefore the M&S knowledge is designated as **medium**.

Higher-fidelity codes can model material degradation using coupled thermal-structural and chemical reaction models that account for changes in material properties, stress interactions, and environmental conditions. These simulations can capture detailed degradation patterns and their impact on performance, but require accurate input data and high computational resources.

Heat-pipe performance codes can incorporate material degradation using empirical correlations and sensitivity analysis. These models provide efficient predictions of degradation effects, but may not fully capture the detailed interactions and changes in material properties, leading to uncertainties in the predictions.

3.7.1.3. Experiments and Instrumentation Knowledge Rationale

It is important to ensure that long-term or life tests are performed on the materials used. This is a standard procedure for heat pipes but may need to be conducted for novel materials (see category IV). Therefore, E&I knowledge is determined as **medium**.

Table 41. Ranking for Material Degradation (VII-01).

Importance Level	M
M&S Knowledge Level	M
E&I Knowledge Level	M

3.7.2. Fluid Contamination (VII-02)

Quality-Assurance Related

3.7.2.1. Importance Rationale

Fluid contamination in the form of oxides and other impurities can significantly affect working fluid properties and heat pipe longevity. Non-metallic impurities from the structural materials or working fluid, such as oxygen, silicon, or carbon, are of particular concern. Due to the numerous effects of contaminants on heat pipe operation, the importance ranking for this phenomenon is designated as **high**.

3.7.2.2. Modeling and Simulation Knowledge Rationale

Changes in fluid properties and fluid-solid contacts can be integrated into models, provided that measurements are available. However, this phenomenon has not yet been integrated into models, therefore M&S knowledge level is designated as **medium**.

Higher-fidelity codes can model fluid contamination using multiphase flow and chemical reaction models that account for changes in fluid properties and interactions with solid surfaces. These simulations can capture detailed contamination patterns and their impact on performance but require accurate input data and high computational resources.

Heat-pipe performance codes can incorporate fluid contamination using empirical correlations and sensitivity analysis. These models provide efficient predictions of contamination effects but may not fully capture the detailed interactions and changes in fluid properties, leading to uncertainties in the predictions.

3.7.2.3. Experiments and Instrumentation Knowledge Rationale

While it is possible to characterize oxides in working fluids, there are high uncertainties associated with current techniques. Recommended methods were presented by Reid et al. in 2005 [17], but no standard exists. Removing non-metallic impurities such as oxygen and carbon from alkali metal is an important step in ensuring the heat pipe will operate properly over its life. If impurities such as oxygen and carbon get into the alkali metal working fluid, they can lead to undesired effects such as precipitated and clogging wicks, de-wetting, and an increased amount of corrosion. Further recommendations and details can be found in paper at Reid et al [17]. Considering these factors the E&I knowledge level is designated as **low**.

Table 42. Ranking for Fluid Contamination (VII-02).

Importance Level	H
M&S Knowledge Level	M
E&I Knowledge Level	L

3.7.3. Wick Degradation (VII-03) Quality-Assurance Related

3.7.3.1. Importance Ranking

Wick degradation in the form of damage, contamination, or clogging can occur during normal operation due to factors such as corrosion, clogging, or mechanical degradation, which can diminish the performance of the heat pipe. Any break in the continuity of the wick structure could limit its capillary pumping ability. Similarly, any clogs in the wick structure due to corrosion or other contaminants will increase the pressure drop in the wick and could limit its capillary pumping ability. Hence, the importance of this phenomenon is ranked as **high**.

3.7.3.2. Modeling and Simulation Knowledge Rationale

Wick degradation effects may be implemented via correlations in existing models, however developing such correlations could be challenging. Based on this reason the knowledge for M&S is designated as **medium**.

Higher-fidelity codes can model wick degradation using porous media flow and structural models that account for changes in material properties, capillary action, and fluid interactions. These simulations can capture detailed degradation patterns and their impact on performance but require accurate input data and high computational resources.

Heat-pipe performance codes can incorporate wick degradation using empirical correlations and sensitivity analysis. These models provide efficient predictions of degradation effects but may not fully capture the detailed interactions and changes in wick properties, leading to uncertainties in the predictions.

3.7.3.3. Experiments and Instrumentation Knowledge Rationale

A combination of in-operation and post-operation tests may be able to characterize wick degradation, yet the current knowledge remains limited. These tests could include CT scans and destructive testing. Considering the limited knowledge, the E&I knowledge level is designated as **low**.

Table 43. Ranking for Wick Degradation (VII-03).

Importance Level	H
M&S Knowledge Level	M
E&I Knowledge Level	L

3.7.4. NCG Production (VII-04)

Performance and Physics Related

3.7.4.1. Importance Rationale

Non-condensable gases (NCGs) can be produced during operation due to corrosion, non-purified working fluid, or not removing NCGs from all structures in the pipe. Relatively low amounts of NCGs are expected to be produced if QA procedures are properly designed and followed. For these reasons the importance level is designated as **low**.

3.7.4.2. Modeling and Simulation Knowledge Rationale

NCG generation during operation can be estimated via correlations, and corrosion calculations have been performed previously using PNP (physics-based nuclear performance). Some existing corrosion correlations were developed by Sandia in the late 1990s. Based on these factors, E&I knowledge is designated as **medium**.

Higher-fidelity codes can model NCG production using multiphase flow and chemical reaction models that account for gas-liquid interactions and corrosion effects. These simulations can capture detailed NCG production patterns and their impact on performance but require accurate input data and high computational resources.

Heat-pipe performance codes (Sockeye): Heat-pipe performance codes can incorporate NCG production using empirical correlations and sensitivity analysis. These models provide efficient predictions of NCG production effects but may not fully capture the detailed interactions and changes in gas-liquid dynamics, leading to uncertainties in the predictions.

3.7.4.3. Experiments and Instrumentation Knowledge Rationale

However, from an experimental perspective, detecting low amounts of NCGs generated can be difficult. Therefore, the E&I knowledge is designated as **low**.

Table 44. Ranking for NCG Production (VII-04).

Importance Level	L
M&S Knowledge Level	M
E&I Knowledge Level	L

3.7.5. Irradiation Damage (VII-05) Performance and Physics Related

3.7.5.1. Importance Rationale

Irradiation damage under long-term operation inside a reactor core is an area with limited literature. Irradiation effects 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 affect operation. Based on these factors, the importance level is designated as **medium** for this phenomenon.

3.7.5.2. Modeling and Simulation Knowledge Rationale

It may be possible to interpolate from irradiation damage models used for PWRs and SFRs. However, the effects of wick performance degradation due to irradiation are unknown, and embrittlement may be an issue. However, based on the existing knowledge of radiation damage mechanisms, the M&S knowledge level is designated as **high**.

Higher-fidelity codes can model irradiation damage using coupled thermal-structural and radiation damage models that account for changes in material properties, stress interactions, and irradiation effects. These simulations can capture detailed irradiation damage patterns and their impact on performance, but require accurate input data and high computational resources.

Heat-pipe performance codes can incorporate irradiation damage using empirical correlations and sensitivity analysis. These models provide efficient predictions of irradiation damage effects, but may not fully capture the detailed interactions and changes in material properties, leading to uncertainties in the predictions.

3.7.5.3. Experiments and Instrumentation Knowledge Rationale

Irradiation damage experiments are conducted regularly at INL. Heat pipes have been used to make irradiation capsules more isothermal in the past [6]. It appears that sufficient knowledge exists to perform irradiation damage tests on heat pipes if needed. But since the experimental experience is from the last century, the E&I knowledge level is designated as **medium**.

Table 45. Ranking for Irradiation Damage (VII-05).

Importance Level	M
M&S Knowledge Level	H
E&I Knowledge Level	M

3.8. Environmental Factors

Environmental conditions, such as external humidity, motion, and vibrations, can impose significant effects on heat pipe performance. These factors can change the operating conditions and material properties, leading to altered heat transfer dynamics.

3.8.1. Humidity (VIII-01)

Performance and Physics Related

3.8.1.1. Importance Rationale

The effects of environmental humidity on heat pipe operation are expected to be minor, with the possible exception of a relatively slight influence on the contact resistance between the core and the heat pipe. For this reason the importance level is designated as **low**.

3.8.1.2. Modeling and Simulation Knowledge Rationale

These minor effects can be accommodated in models if deemed important following characterization tests. Based on this reason the knowledge level for M&S is designated as **high**.

Higher-fidelity codes can model the effects of humidity on the external surfaces of the heat pipe using fluid flow and heat transfer models that account for moisture interactions and condensation effects. These simulations can capture detailed interactions with the environment but are generally not necessary for the internal performance of the heat pipe.

Heat-pipe performance codes typically do not consider the effects of environmental humidity on the internal workings of the heat pipe. For external effects, simplified models or empirical correlations can be used to represent moisture interactions if necessary, but these effects are generally minor and can be ignored in most simulations.

3.8.1.3. Experiments and Instrumentation Knowledge Rationale

There may be some challenges in safety considerations during experiments due to the use of liquid metal working fluids for experiments, due to the risk of reaction of alkali metals with water. However, this can be accommodated with engineering controls. For these reasons the knowledge level is designated as **high** for E&I.

Table 46. Ranking for Humidity (VIII-01).

Importance Level	L
M&S Knowledge Level	H
E&I Knowledge Level	H

3.8.2. Vibration and Movement (VIII-02)

Performance and Physics Related

3.8.2.1. Importance Rationale

Vibration and movement caused by mobile applications or transport systems can introduce structural issues such as fatigue, considering the frequency and amplitude of oscillations. Flow dynamics may also be affected based on the motion and changes in orientation. Hence, the importance of this phenomenon is classified as **medium**.

3.8.2.2. Modeling and Simulation Knowledge Rationale

These external forces can change the net effect of capillary action and may also be influenced by orientation and subsequent effects on neutronics. Considering these complexities, the knowledge level for E&I is designated as **medium**.

Higher-fidelity codes can model the effects of vibration and movement using coupled fluid-structure interaction (FSI) models that account for external forces, oscillations, and their impact on fluid flow and capillary action. These simulations can capture detailed interactions and variations in performance due to vibration and movement but require high computational resources and accurate input data on vibration characteristics.

Heat-pipe performance codes can incorporate the effects of vibration and movement using simplified models or empirical correlations. These models can provide efficient predictions of the impact on heat pipe performance but may not fully capture the detailed interactions and variations in capillary action and flow dynamics, leading to uncertainties in the predictions.

3.8.2.3. Experiments and Instrumentation Knowledge Rationale

Experimental rigs that simulate motion conditions can be used to study heat piped. Designing such experiments can be challenging, especially for long heat pipes, due to high-temperature operation and other safety concerns. Based on these challenges the knowledge level for E&I is designated as **medium**.

Table 47. Ranking for Vibration and Movement (VIII-02).

Importance Level	M
M&S Knowledge Level	M
E&I Knowledge Level	M

3.9. Materials Science

Materials science category concerns itself with the properties of materials used in heat pipes, including wettability, corrosion resistance, thermal expansion, and creep deformation. Corrosion can degrade materials over time, especially in pH-sensitive environments. The thermal expansion of materials alongside temperature changes can introduce mechanical stresses that impact performance. Wettability is discussed under the Capillary Pumping category in Section 3.6.

3.9.1. Corrosion and Oxidation in Wall and Wick Materials (IX-01)

Quality-Assurance Related

3.9.1.1. Importance Rationale

Corrosion can alter material and surface properties, cause damage to the wick structure, and introduce non-condensable gases (NCGs) in the heat pipe. It can affect the wettability of the wick and diminish capillary pumping. Corrosion can be rapid in heat pipes due to the presence of oxygen or other contaminants. Sodium purity is crucial for the prevention of corrosion, and compatibility between the fluid and wall/wick materials is a concern for novel materials. Understanding and mitigating corrosion is key for maintaining the long-term reliability and performance of heat pipes. Considering its manifold effects on heat pipe operation, the importance level for this phenomenon is designated as **high**.

3.9.1.2. Modeling and Simulation Knowledge Rationale

Interactions between some alloys and working fluids are not well characterized and should be improved. The effects of evaporation and condensation on the materials can cause increased uncertainties in simulations. Therefore, the M&S knowledge ranking is designated as **medium**.

Higher-fidelity codes can model corrosion and oxidation using chemical reaction models that account for material properties and environmental conditions. These simulations can capture detailed interactions and changes in material properties but require accurate input data for corrosion rates and reaction kinetics.

Heat-pipe performance codes use simplified models or empirical correlations to represent corrosion and oxidation effects. These models provide efficient predictions but may not fully capture the detailed interactions and material changes, leading to uncertainties in the predictions.

3.9.1.3. Experiments and Instrumentation Knowledge Rationale

More experiments are needed for materials that are not widely used in high-temperature alkali metal heat pipes, particularly sodium which is the main candidate for HPMR applications. Corrosion has a significant impact on heat pipe operation, particularly wick wettability, making it challenging to characterize its effects. Impurities may accumulate at certain locations within the heat pipe, and wick characterization under corrosion may be necessary to evaluate corrosion rate correlations in the literature. Reid et al. present some information on corrosion caused by non-metallic impurities [17]. Corrosion can be of increased concern in thin-walled heat pipes. Corrosion of wall and wick materials can be investigated with high-resolution X-ray imaging, computed tomography (CT) scanning, and destructive analysis. Considering these factors, the knowledge level for E&I is designated as **medium** for this phenomenon.

Table 48. Ranking for Corrosion and Oxidation in Wall and Wick Materials (IX-01).

Importance Level	H
M&S Knowledge Level	M
E&I Knowledge Level	M

3.9.2. Creep in Wall and Wick Materials (IX-02)

Quality-Assurance Related

3.9.2.1. Importance Rationale

Creep is important to the structural integrity of the heat pipe and should be considered due to the persistent high temperature operation and stresses on the materials. Creep in heat pipes can also be significant for the physical interaction between the wick and wall. Extreme temperatures can result in higher vapor pressures inside the heat pipe that may influence creep. Based on these reasons and potential safety implications, the importance for this phenomenon is designated as **high**.

3.9.2.2. Modeling and Simulation Knowledge Rationale

Models for material creep are well established, provided that stresses and temperatures can be properly characterized. There are creep models available for diverse materials. Based on these factors the knowledge rating for M&S is designated as **high**.

Higher-fidelity codes can model creep using viscoelastic or viscoplastic material models that account for stress, temperature, and time-dependent deformation. These simulations can capture detailed creep behavior, provided that accurate input data is available for material properties and loading conditions.

Heat-pipe performance codes use simplified models or empirical correlations to represent creep effects. These models provide efficient predictions but may not fully capture the detailed time-dependent deformation and stress interactions, leading to uncertainties in the predictions.

3.9.2.3. Experiments and Instrumentation Knowledge Rationale

The significance of creep depends on the material and operating conditions involved. Knowledge about creep is limited due to challenges in internal pressure measurements and long duration experiments required for investigation. This issue becomes more pronounced with extremely high-temperature heat pipes that may experience higher internal pressures. Based on these reasons the knowledge ranking for E&I is designated as **low**.

Table 49. Ranking for Creep in Wall and Wick Materials (IX-02).

Importance Level	H
M&S Knowledge Level	H
E&I Knowledge Level	L

3.10. Manufacturing Variability

Manufacturing variability category encompasses inconsistencies in dimensions, surface roughness, material defects, and assembly methods. Precision in manufacturing is needed to ensure proper heat pipe and wick structure dimensions and effective heat transfer surfaces. Large deviations in fabrication methods can result in performance variations and uncertainties in model predictions.

3.10.1. Dimensional Tolerances (X-01)

Quality-Assurance Related

3.10.1.1. Importance Rationale

Wicks need to be fabricated with the required dimensional tolerances to ensure that the annulus thickness and pore sizes are within the desired ranges. This also ensures that simulations can accurately predict operation based on the fabrication dimensions. Considering these factors, the importance level for this phenomenon is designated as **medium**.

3.10.1.2. Modeling and Simulation Knowledge Rationale

Dimensional tolerances between the heat pipe and wick, as well as tolerances in the wick properties, can impact uncertainties in numerical models. Parameters such as pore size distribution in the wick and wick/wall roughness are crucial. Overall, dimensional tolerances and uncertainties are expected to have a higher impact on the wick structure modeling. These uncertainties can be implemented in simulations considering they are known from QA practices. Based on these factors the M&S knowledge level is designated as **high**.

Higher-fidelity codes can model dimensional tolerances by incorporating variations in geometry and material properties into the simulations. These models can capture the effects of dimensional variations on flow and heat transfer, but require detailed input data on tolerances and manufacturing variations.

Heat-pipe performance codes can incorporate dimensional tolerances using sensitivity analysis and uncertainty quantification methods. These models can provide efficient predictions of the impact of dimensional variations on heat pipe performance, provided that accurate input data on tolerances is available.

3.10.1.3. Experiments and Instrumentation Knowledge Rationale

In terms of experiments and fabrication, maintaining required tolerances for full-length heat pipes (~4 m) may be challenging. Wick spacing and dimensions cannot be characterized with X-rays and should be determined before installation. Additionally, the thermal expansion of the materials needs to be considered when setting tolerances. Based on these factors the E&I knowledge for this phenomenon is designated as **medium**.

Table 50. Ranking for Manufacturing Variability (X-01).

Importance Level	M
M&S Knowledge Level	H
E&I Knowledge Level	M

3.10.2. Surface Roughness of the Wall (X-02)

Quality-Assurance Related

3.10.2.1. Importance Rationale

Surface roughness of the wall affects the wettability and pressure drops in the annulus and wick. It may also influence nucleation-site size and density. Surface roughness of the wall affects the liquid pressure drop in the annulus for annular wicks. Ensuring the correct surface finish during fabrication can enhance the capillary pumping ability of the heat pipe by optimizing the interaction between the working fluid and the pipe wall. Regardless, the importance for this phenomenon is designated as **low**.

3.10.2.2. Modeling and Simulation Knowledge Rationale

Surface roughness can be modeled using standard computational thermal hydraulics methods, such as wall functions. Therefore, the M&S knowledge is designated as **high**.

Higher-fidelity codes can model surface roughness effects using wall functions and detailed surface models. These simulations can capture the impact of surface roughness on flow and heat transfer, but require accurate input data on surface finish and material properties.

Heat-pipe performance codes can incorporate surface roughness effects using empirical correlations and sensitivity analysis. These models provide efficient predictions of the impact of surface roughness on heat pipe performance, provided that accurate input data is available.

3.10.2.3. Experiments and Instrumentation Knowledge Rationale

Surface roughness of the wall can be directly characterized experimentally with well established methods. Therefore, the E&I knowledge is designated as **high**.

Table 51. Ranking for Surface Roughness of the Wall (X-02).

Importance Level	L
M&S Knowledge Level	H
E&I Knowledge Level	H

3.10.3. Surface Roughness of the Wick (X-03)

Quality-Assurance Related

3.10.3.1. Importance Rationale

Surface roughness of the wick can affect vapor core pressure drops and turbulence structures. Proper control of the wick's surface roughness may be necessary to minimize both vapor and liquid pressure losses. Additionally, surface roughness of the wick may change with the presence of the working fluid. A dry wick may exhibit greater surface roughness, acting as a rough wall, while a fully wetted wick may behave more like a smooth wall. However, due to its limited overall effect, the importance level for this phenomenon is designated as **medium**.

3.10.3.2. Modeling and Simulation Knowledge Rationale

Current higher-fidelity or heat-pipe performance codes do not consider this phenomenon. This phenomenon may be challenging to implement for high-fidelity simulations. Therefore, the M&S knowledge level is designated as **low**.

Higher-fidelity codes can model surface roughness of the wick using detailed surface models and porous media flow models. However, accurately capturing the impact of wick surface roughness on flow dynamics requires high-resolution simulations and detailed material properties, which are often not available.

Heat-pipe performance codes typically do not consider wick surface roughness due to the lack of empirical correlations and data. Simplified models may not fully capture the detailed effects of surface roughness on flow and heat transfer, leading to uncertainties in the predictions.

Experiments and Instrumentation Knowledge Rationale

Surface roughness on the wick is normally not specified as a wick parameter; rather, the characterization of the internal structure of the wick is specified. The surface roughness of the wick could influence smooth vs. rough wall assumptions for vapor flow. Surface roughness may change across the length of the heat pipe, as well as with different operational regimes, which may influence the heat pipe's vapor flow. This characteristic is difficult to measure and is influenced by manufacturing methods and wick pore size. Based on these factors the E&I knowledge level is designated as **low**.

Table 52. Ranking for Surface Roughness of the Wick (X-03).

Importance Level	M
M&S Knowledge Level	L
E&I Knowledge Level	L

3.10.4. Manufacturing Defects (X-04)

Quality-Assurance Related

3.10.4.1. Importance Rationale

Unidentified defects in fabrication or large uncertainties can result in failures during operation related to structural integrity or performance. However, with robust QA practices and long-duration testing, this is expected to be an issue that can be minimized. Therefore, the importance level for this phenomenon is designated as **low**.

3.10.4.2. Modeling and Simulation Knowledge Rationale

The ability of the models to target a worst-case scenario, such as needed for safety modeling, can be integrated in current models given that the uncertainty is within the model scope. Therefore, the level of knowledge for this phenomenon is designated as **high** for M&S.

Higher-fidelity codes can model manufacturing defects by incorporating variations in material properties, geometric defects, and bonding quality into the simulations. These models can capture detailed interactions and variations in performance due to manufacturing defects, but require accurate input data on defect characteristics.

Heat-pipe performance codes can incorporate manufacturing defects using sensitivity analysis and empirical correlations. These models provide efficient predictions of the impact of manufacturing defects on heat pipe performance, provided that accurate input data is available.

3.10.4.3. Experiments and Instrumentation Knowledge Rationale

Quality assurance (QA) procedures should be developed and followed, and tolerances and uncertainties should be determined for robust manufacturing practices. LANL has developed an NQA-1 stainless steel wick mass manufacturing process that can produce wicks with a pore size within +/- 3.5 microns per batch. LANL is currently developing processes for filling and sealing heat pipes to allow for mass manufacturing. Based on these factors, the E&I knowledge is designated as **medium**.

Table 53. Ranking for Manufacturing Defects (X-04).

Importance Level	L
M&S Knowledge Level	H
E&I Knowledge Level	M

4. DISCUSSION

This section presents a summary and further analysis of the results of this PIRT exercise. This section is organized as follows. 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. Analysis of 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 and discussed in the present subsection.

The **liquid and vapor pressure drops** represent the flow resistance to capillary pumping along the working fluid path within the heat pipe. It is 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, this 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.

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.

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.

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 buildup of pressure in the wick due to capillary action and the expansion in the evaporator is ultimately compensated by the pressure drop in the vapor core and flow contraction in the condenser. During startup of the heat pipe, the capillary force and expanding flow in the evaporator exceed the others, leading to the activation of the circulation between the wick and the vapor core. The 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 scale. The 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. 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.

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.

Linking these high-importance phenomena, it becomes evident that the efficient operation of heat pipes relies on a delicate balance of multiple interdependent processes. The phase change at the liquid/vapor interface, facilitated by effective vapor and liquid advection, ensures continuous heat transfer within the heat pipe. Robust thermal contact between the reactor core and the heat pipe is essential for transferring heat from the core to the heat pipe efficiently. Corrosion and oxidation must be mitigated to preserve the material properties and structural integrity of the heat pipe over time. Finally, reliable startup and shutdown procedures are necessary to ensure that the heat pipe can consistently transition between operational states without compromising performance.

4.2. Analysis of Select Medium Importance Phenomena with Performance Implications

The current PIRT has mainly focused on ranking with high importance phenomena that is critical for HPMRs operation. However, if transient behavior is analyzed and operational transients are considered, some of the phenomena listed as medium importance could significantly impact the power limit and effective thermal conductivity of the heat pipe. These phenomena are briefly analyzed in the following paragraphs.

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.

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 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.

Underfilling 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, underfilling 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.

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.

The processes of **frozen startup and solidification post-shutdown** are also of medium importance. 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. Similarly, during shutdown, the working fluid must solidify 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.

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 varying 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.

In conclusion, while these phenomena are generally considered medium importance, their impact can escalate during transient operational conditions of the reactor core. 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.

4.3. 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 phenomena with high importance and low level of knowledge for modeling and simulation are analyzed first. Then, other important phenomena with low level of knowledge are analyzed.

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

One phenomenon with low modeling knowledge is **wick de-wetting**. Modeling wick de-wetting is challenging because it involves complex interactions between meniscus shape changes, gravitational effects, mainly in the case of vertical operation of the heat pipe, 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 higher-fidelity simulations, coupled with experimental validation, could provide more accurate predictions of wick de-wetting 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 is another phenomenon with low modeling knowledge, 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 would also be valuable for improving model accuracy.

The **contact angle**, which indicates the wettability of surfaces by the working fluid, 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 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. Higher-fidelity 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.

In summary, addressing the low modeling knowledge for phenomena such as wick de-wetting, critical heat flux, contact angle, and pressure dynamics requires a multi-faceted approach. 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.

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

Although the high-importance, low-knowledge phenomena for modeling and simulation have been provided in the paragraphs above, there are phenomena that have low knowledge and can still impact the operation of the heat pipes in case of operation anomalies or reactor transients. These phenomena are discussed below.

Radiation heat transfer is a phenomenon with low modeling knowledge due to the challenges involved in accurately capturing the effects of emissivity and the interactions between radiation, conduction, and convection at high temperatures. 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 higher-fidelity 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.

The **transition from laminar to turbulent flow** in the vapor phase of heat pipes is another phenomenon with low modeling knowledge. The difficulty in modeling these phenomena 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 higher-fidelity codes to build Reynolds Average Navier Stokes performance models of the whole heat pipe. To develop these closures, techniques such as Large Eddy Simulations or Direct Numerical Simulations can provide detailed insights into the flow dynamics during the transition phase. 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, a phenomenon that is physically characterized by intermittent vapor generation and liquid displacement, also 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. Higher-fidelity 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, also known as wick wetting, is the process of ensuring complete wetting of the wick structure, is another phenomenon with low modeling knowledge. 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 higher-fidelity 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.

The operation of the heat pipe during **underfilling** 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, underfilling 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 underfilling conditions, research should focus on developing high-fidelity multi-phase flow models that can simulate the interactions between liquid distribution, capillary forces, and heat transfer within the wick. Higher-fidelity 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.

The **surface roughness of the wick**, influenced by surface finishing during fabrication, 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 higher-fidelity 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.

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. Higher-fidelity 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.

The **timescales of startup and shutdown** processes are also characterized by 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. Higher-fidelity 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.

The phenomena analyzed in this subsection include radiation heat transfer, laminar to turbulent transition, geyser boiling, wick priming, underfilling 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.

4.4. 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.

4.4.1. 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 [18], and wet-leg vapor core pressure measurements [19] 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 [20, 21]. 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.

4.4.2. Fabrication Techniques

Heat pipe fabrication is rather involved, utilizing several steps and subsystems [14, 20-22]. 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. [17]. 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.

4.4.3. 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.

4.4.4. Proposed Future Research 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. Lastly, 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.

4.5. Discussion of Quality-Assurance Related Issues

This document has analyzed general aspects affecting the operation of heat pipes. However, as previously noted, some of these aspects are physical phenomena affecting the operation of the heat pipes, which should be accounted for in engineering and design, while others can be mitigated via quality assurance (QA) processes in the fabrication of the heat pipes. In this section, we discuss these QA-related issues identified in the PIRT exercise. QA-related phenomena are critical to ensuring the reliability, safety, and performance of heat pipes. The phenomena identified as primarily quality-assurance-related include:

- Under-Filling
- Fluid Contamination
- Wick Degradation
- Corrosion and Oxidation in Wall and Wick Materials
- Creep in Wall and Wick Materials
- Dimensional Tolerances
- Surface Roughness of the Wall
- Surface Roughness of the Wick
- Manufacturing Defects

Under-filling occurs when the heat pipe has an insufficient amount of working fluid relative to its design specifications. This condition can lead to serious performance degradation and the formation of dry spots in the evaporator, as the working fluid is inadequate to maintain continuous heat transfer. The physics behind under-filling involves the capillary action within the wick structure, which is compromised by the lack of sufficient working fluid. This can result in incomplete wetting of the wick, reduced capillary pressure, and ultimately, diminished heat transfer efficiency. QA processes can address under-filling by implementing precise filling procedures, utilizing accurate measurement techniques for the working fluid, and ensuring that the fill ratio is within specified tolerances. Establishing standards for fill ratios and conducting regular inspections can help prevent under-filling and ensure consistent performance.

Fluid contamination involves the presence of impurities such as oxides, non-condensable gases (NCGs), and other contaminants in the working fluid. These impurities can significantly affect the thermophysical properties of the working fluid, leading to reduced heat transfer efficiency, increased corrosion rates, and potential clogging of the wick structure. The physics of fluid contamination includes chemical reactions between the contaminants and the heat pipe materials, which can alter material properties and introduce degradation mechanisms. QA processes can mitigate fluid contamination by ensuring high purity levels of the working fluid, implementing rigorous cleaning and purification methods, and conducting regular quality checks. Standards for acceptable impurity levels and stringent QA protocols can help maintain the integrity of the working fluid and prevent contamination-related issues.

Wick degradation refers to the damage, contamination, or clogging of the wick structure over time. This degradation can occur due to factors such as corrosion, accumulation of impurities, and mechanical wear. The physics behind wick degradation involves the interaction between the working fluid and the wick material, which can lead to changes in the capillary pressure, increased pressure drops, and reduced fluid return to the evaporator. Ensuring the quality and durability of the wick material is essential for maintaining heat pipe performance. QA processes can address wick degradation by selecting corrosion-resistant materials, conducting thorough material testing, and implementing regular maintenance and inspection protocols. Establishing standards for wick material properties and performance can help mitigate degradation and extend the lifespan of the heat pipe.

Corrosion and oxidation are significant concerns for the long-term reliability of heat pipes, particularly due to the high temperatures and reactive environments in which they operate. Corrosion can alter the material properties of the wall and wick, leading to structural damage and the formation of NCGs that impair heat transfer. The physics of corrosion involves electrochemical reactions between the material and its environment, accelerated by impurities such as oxygen. Oxidation can similarly degrade material properties and affect the wettability of the wick. QA processes can address these issues by selecting corrosion-resistant materials, applying protective coatings, and ensuring the purity of the working fluid. Implementing standards for material selection and corrosion resistance, along with regular inspections, can help mitigate the effects of corrosion and oxidation.

Creep deformation occurs under sustained high temperatures and stresses, leading to time-dependent plastic deformation of the heat pipe materials. This can result in permanent changes in the shape and dimensions of the heat pipe components, compromising their structural integrity and heat transfer efficiency. The physics of creep involves the gradual movement of atoms within the material, driven by thermal and mechanical stress. Ensuring that heat pipes are fabricated from materials with high creep resistance is essential. QA processes can address creep by conducting long-term testing of materials, stress analysis, and implementing operational limits to prevent excessive stress. Establishing standards for material properties and operational conditions can help mitigate creep-related issues and ensure the longevity of the heat pipe.

Dimensional tolerances are critical for the proper assembly and operation of heat pipes. Variations in dimensions can lead to inconsistencies in the annulus thickness, wick pore sizes, and overall geometry, impacting the capillary action, flow dynamics, and heat transfer efficiency. The physics involved include ensuring that the wick structure can provide uniform capillary pressure and that the annulus allows for effective vapor and liquid flow without excessive pressure drops. QA processes can ensure precise manufacturing techniques, rigorous inspections, and adherence to strict dimensional specifications to minimize deviations. Implementing standards for dimensional tolerances and conducting regular quality checks can help achieve consistent quality and performance across different heat pipe units.

Surface roughness of the heat pipe wall can influence wettability, pressure drops, and nucleation site density, which in turn affect the overall heat transfer performance. A rough surface can increase frictional losses and alter the liquid-vapor interface dynamics, while a smoother surface can enhance wettability and capillary action. The physics behind surface roughness effects involve the interaction between the working fluid and the wall surface, impacting the formation of the liquid meniscus and the efficiency of heat transfer. QA processes that include surface finishing techniques, regular inspections, and characterization of surface roughness can ensure optimal wall conditions. Establishing standards for acceptable surface roughness levels can help maintain consistent performance and reliability.

The **surface roughness of the wick** can affect vapor core pressure drops and turbulence structures, as well as liquid return efficiency. A rough wick surface can introduce additional resistance to vapor flow and alter the capillary forces within the wick, while a smoother surface can facilitate better fluid flow dynamics. The physics involved include the interaction between the working fluid and the wick structure, influencing capillary action and phase change processes. QA processes that include detailed surface characterization, consistent manufacturing methods, and regular inspections can help control the surface roughness of the wick. Implementing standards for wick surface roughness can ensure that the wick performs its capillary pumping function effectively, maintaining optimal heat pipe performance.

Manufacturing defects, such as voids, cracks, and inconsistencies in material properties, can significantly impact the structural integrity and performance of heat pipes. These defects can introduce weak points that lead to mechanical failures, leaks, and reduced heat transfer efficiency. The physics behind manufacturing defects involve the mechanical and thermal stresses experienced by the heat pipe components during operation. QA processes that include rigorous inspection methods, non-destructive testing, and quality control measures throughout the manufacturing process can identify and eliminate defects before they impact performance. Establishing standards for acceptable defect levels and implementing comprehensive QA procedures can help ensure that heat pipes are manufactured to the highest quality and reliability standards.

In conclusion, addressing QA related issues through the implementation of robust standards and QA processes is paramount for ensuring the reliability, safety, and performance of heat pipes. These phenomena, including under-filling, fluid contamination, wick degradation, corrosion and oxidation, creep, dimensional tolerances, surface roughness of the wall and wick, and manufacturing defects, each present unique challenges that can significantly impact heat pipe operation. The development of standards for heat pipes can help mitigate QA issues as follows:

- By establishing clear standards for fill ratios, we can ensure that heat pipes are filled with the correct amount of working fluid, preventing under-filling and the associated performance degradation. Rigorous QA processes that include precise filling procedures and accurate measurement techniques are essential to maintaining consistent performance.
- Mitigating fluid contamination requires stringent purity standards for the working fluid, along with rigorous cleaning and purification methods. Ensuring high purity levels can prevent the adverse effects of impurities, such as reduced heat transfer efficiency and increased corrosion rates. Regular quality checks and standards for acceptable impurity levels can help maintain the integrity of the working fluid.
- To address wick degradation, selecting corrosion-resistant materials and conducting thorough material testing are crucial. Regular maintenance and inspection protocols can help identify and mitigate degradation, extending the lifespan of the heat pipe. Establishing standards for wick material properties and performance can ensure the durability and efficiency of the wick structure.
- Corrosion and oxidation can be mitigated by selecting materials with high corrosion resistance, applying protective coatings, and ensuring the purity of the working fluid. Regular inspections and standards for material selection and corrosion resistance can help prevent structural damage and maintain heat transfer efficiency.
- Creep deformation can be addressed by using materials with high creep resistance and conducting long-term testing and stress analysis. Establishing operational limits to prevent excessive stress and implementing standards for material properties and operational conditions can mitigate creep-related issues.
- Ensuring precise dimensional tolerances is critical for the proper assembly and operation of heat pipes. Adhering to strict dimensional specifications and conducting regular quality checks can minimize deviations and ensure consistent performance. Standards for dimensional tolerances can help achieve uniform quality across different heat pipe units.
- Surface roughness of the wall and wick can influence heat transfer performance. Implementing surface finishing techniques, regular inspections, and characterization of surface roughness can ensure optimal conditions. Standards for acceptable surface roughness levels can help maintain consistent performance and reliability.
- Addressing manufacturing defects requires rigorous inspection methods, non-destructive testing, and quality control measures throughout the manufacturing process. Identifying and eliminating defects before they impact performance is essential. Establishing standards for acceptable defect levels and implementing comprehensive QA procedures can ensure that heat pipes are manufactured to the highest quality and reliability standards.

5. SUMMARY AND CONCLUSIONS

On March 11, 2025, a PIRT exercise was conducted at INL involving 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 comprehensive list of phenomena was identified, categorized into high, medium, and low importance concerning the FOM. Thirteen phenomena were deemed of high importance, thirty of medium importance, and seven of low importance.

A significant outcome of the PIRT exercise was the distinction between inherently physical phenomena and issues that could be addressed through robust quality assurance and standards. Inherently physical phenomena, such as phase change dynamics, fluid dynamics, and heat transfer mechanisms, require developing modeling techniques and experimental validation to improve understanding and predictive capabilities. Addressing these physical phenomena involves developing high-fidelity models, conducting detailed experiments, and leveraging advanced visualization and measurement techniques, which can then be used to inform heat-pipe performance codes that are most commonly used in reactor engineering calculations. Enhancing our understanding of these phenomena will enable the design of more efficient and reliable heat pipes, ultimately supporting their safer integration into heat-pipe-cooled micro-reactors.

Conversely, several issues identified during the exercise can be effectively mitigated through the implementation of robust QA processes and the establishment of industry standards. Issues such as fluid contamination, under-filling, surface roughness, dimensional tolerances, and manufacturing defects can significantly impact the performance and reliability of heat pipes. By developing and adhering to stringent QA protocols, conducting regular inspections, and implementing rigorous testing procedures, these issues can be minimized. Establishing industry standards for heat pipe fabrication, assembly, and operation will ensure consistent quality and performance, reducing the likelihood of failures and improving overall reliability.

The high-importance phenomena, critical to heat pipe safety, reliability, and performance, included:

Performance and Physics Related	Quality-Assurance Related
• Liquid pressure drops • Vapor pressure drops • Wick de-wetting • Evaporation and condensation • Nucleate boiling • Critical heat flux • Capillary action • Wettability • Pressure dynamics	• Corrosion and oxidation • Creep • 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. Notably, while quality-assurance related issues could be addressed by the generation of procedures and standards, performance and physics related issues should be better understand and addressed by engineering design.

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.

In conclusion, the PIRT exercise successfully identified and prioritized key phenomena affecting the operational regimes and performance of heat pipes. The exercise highlighted critical knowledge gaps in both modeling and experimental techniques, emphasizing the need for advanced research and development to address these gaps. Additionally, the importance of implementing robust QA processes and establishing industry standards was underscored to ensure the consistent quality and reliability of heat pipes. This systematic evaluation and prioritization process serves as a valuable resource for guiding future research efforts, supporting the successful integration of heat pipes into critical applications such as nuclear reactors, and contributing to the advancement of heat pipe technologies in safety-critical industries.

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Appendix A

Phenomena Identification and Ranking Table

Appendix A

A-1. Phenomena Identification and Ranking Table

ID	Phenomena	Description	Imp.	Rationale	Know. (M&S)	Rationale (M&S)	Know. (E&I)	Rationale (E&I)
I-01	Radial Heat Conduction	Radial heat conduction across the heat pipe wall and wick regions	M	Radial heat conduction is important to determine the radial temperature drop across the heat pipe wall and wick, particularly during frozen startup and shutdown in the evaporator section.	H	Conduction mechanism is well known, and the radial temperature drops are not significant due to thin wall and wick regions.	M	It is challenging to accurately measure the temperature difference between the liquid and vapor, since measurements are usually made on the exterior wall surface or in a thermowell. Recent efforts have been made to include optical fibers internally to the heat pipe to get that information. However this is still challenging and could effect the flow in the HP.
I-02	Axial Heat Conduction	Axial heat conduction along the heat pipe length in the heat pipe wall and wick regions	M	Axial heat conduction is not significant in normal operation, yet it could be important for scenarios where heat pipe operation is not established such as frozen startup and shutdown, or under limit or dryout conditions.	H	Conduction mechanism is well known, and can easily be modeled with existing methods.	M	Axial conduction in the wall and wick is difficult to evaluate under normal operation, however not significant. Understanding the distribution of sodium inside the heat pipe during start-up could be difficult. Although can potentially be inferred from temperature measurements under certain conditions, direct measurement of axial conduction is difficult.

ID	Phenomena	Description	Imp.	Rationale	Know. (M&S)	Rationale (M&S)	Know. (E&I)	Rationale (E&I)
I-03	Azimuthal Heat Conduction	Azimuthal heat conduction along the heat pipe circumference in the heat pipe wall and wick regions	L	Azimuthal heat conduction is not significant in normal operation, yet it could be important during frozen startup and/or in the presence of hot spots, de-wetted regions, or limit conditions. Importance may be influenced by the orientation with respect to gravity. Regardless, the effects of azimuthal heat conduction is expected to be less significant during such conditions compared to axial heat conduction.	M	Although the conduction mechanism is well known, and can easily modeled with existing methods, it may be hard to effectively model azimuthal conduction in the wick region during frozen startup or shutdown due to possible variations in the working fluid distribution within the heat pipe.	M	Similar to axial conduction, it is difficult to measure or quantify if the distribution of the sodium in the wick and the annular gap is not known. Information on the sodium distribution in the wick can possibly be obtained from the working fluid distribution from X-ray imaging, albeit, due to the low amount of sodium in this region, capturing it may be complicated.
I-04	Thermal contact b/w wick and wall	Thermal contact resistance between wall and wick for designs where the wick is adjacent to the heat pipe wall, thermal contact resistance between screen layers for screens with multiple wraps	L	Not significant for annular wicks unless hot/dry spots, or de-wetted regions exist, considering that the heat transfer is from the wall to the liquid and that the thermal conductivity of the liquid metal working fluid is high.	L	This is the contact resistance between the wick and the wall of the heat pipe. Modeling may be challenging.	M	Similar to above it is difficult to know where the wick is as it may float within the heat pipe for annular wick structures. There may be varying degrees of thermal resistance between the wall and the fluid or wick. It is possible to see changes with X-ray imaging, however the contact may change significantly across the heat pipe length or radius and may be characterized as random.

ID	Phenomena	Description	Imp.	Rationale	Know. (M&S)	Rationale (M&S)	Know. (E&I)	Rationale (E&I)
I-05	Vapor advection	Vapor phase flow from the evaporator to the condenser within the vapor core	M	Convection of vapor from the evaporator to the condenser is critical to the heat transfer between the evaporator and condenser	M	Basic mechanics are well understood, but turbulence and pressure recovery effects in the condenser may require further investigations.	L	From an experimental point of view, the effective conductivity of the heat pipe can be measured, however the details of the pressure variations or the velocity of the vapor flow are not known.
I-06	Liquid advection	Liquid phase flow from the condenser to the evaporator within the wick	M	Convection of liquid from the condenser to the evaporator is critical to maintaining the working fluid inventory within the wick in the evaporator.	H	Liquid flow is slow and laminar and well understood.	L	We can measure the effective conductivity however experimentally measuring details of the capillary flow is difficult, since it could change as the wick wetting characteristics changes spatially.
I-07	Thermal contact b/w the core and the heat pipe	Contact resistance between the core and the heat pipe due to geometric tolerances, thermal expansion, surface roughness	M	The contact resistance between the core and heat pipe and its evolution over different operating conditions is critical for proper heat removal.	M	Although knowledge of the physics is high, it is challenging to model the phenomena. One consideration is the difficulty in numerically coupling the heat pipe to core block. This has been seen to require a large number of fixed point iterations in a segregated coupling approach.	L	The contact resistance is not very well known and can change with thermal expansion and thermal conductivity. Heat pipes can bend causing contact resistance to differ considerably along the heat pipe. Small gas gaps that form can influence this phenomena significantly.

ID	Phenomena	Description	Imp.	Rationale	Know. (M&S)	Rationale (M&S)	Know. (E&I)	Rationale (E&I)
I-08	Radiation Heat Transfer	Radiation heat transfer to the heat pipe from the core block, and from the heat pipe at the condenser to the surrounding structures and coolant	M	At high temperatures, heat transferred from the core to the evaporator is dominated by radiation rather than conduction.	L	Changes in emissivity due to oxidation as a function of time and temperature, materials, and environmental factors (oxygen levels) for heat pipe operation is not well known. Changes in the emissivity from 0.3-0.8 can have a strong effect on the operating temperature of the heat pipe.	M	The evolution of the emissivity is not well known during operation. Challenges exist in measuring emissivity. Measuring temperature with a multi-band pyrometer may allow for the emissivity to be captured during operation.
II-01	Laminar / turbulent transition in vapor flow	The vapor flow may be under laminar, turbulent, or transition flow regimes based on the geometry and operating conditions	M	Information on the laminar/turbulent transition in the vapor enables the accurate calculation of vapor pressure drops, which is a critical term in the pressure balance in the heat pipe that is used to calculate the capillary limit. Heat pipes usually operate near the transition region, not strictly laminar or turbulent regimes, making the transition region important for understanding the flow dynamics.	L	The phenomena is difficult to model and verify. Vapor generation in the evaporator and condensation in the condenser effectively causes vapor mass injection/extraction to/from the vapor core, respectively. This can cause either stabilizing or de-stabilizing effects on the flow structures and can cause early or late onset of turbulence, as well as disruptions in the velocity profiles that are not well understood.	L	Little data exists for this transition. Viewing the vapor flow past the liquid is difficult and adding viewports can interfere with the phenomena. Work by Haug and Busse in the mind 1980's shows some information but more work needs to be done.

ID	Phenomena	Description	Imp.	Rationale	Know. (M&S)	Rationale (M&S)	Know. (E&I)	Rationale (E&I)
II-02	Near sonic compressible flow	Compressible flow may occur in heat pipes, where near sonic velocities may be observed at the evaporator exit (Ma ~ 1)	M	Phenomena impacts the sonic limit, but it is also important during transient response and startup. Compressibility effects have a significant impact on the pressure and temperature distribution at low temperatures, even when not near sonic limit. Sonic limit is usually the limiting factor during startup and should be considered when designing startup procedures.	M	Since theory is well established, the knowledge level is constrained by uncertainties in thermophysical properties.	M	The sonic limit can be inferred based on the axial temperature profiles. It is difficult to directly observe compressibility but it is typically not of significant concern from an experimental perspective.
II-03	Compressible / incompressible transition in vapor flow	Vapor flow can transition between incompressible and compressible flow based on the flow velocities (~ Ma = 0.3)	M	Although Mach numbers may be lower than sonic levels, compressibility can be important for accurate pressure drop, thermophysical properties, and capillary limit calculations. However, operationally it appears to be not of great significance.	M	Capillary limit calculations may be effected if compressibility is not considered, however the effects may not be very significant.	U	It is unclear how to conduct experimental measurements of the compressibility of vapor within the heat pipe. It may be possible to measure the vapor flow velocity in low temperature heat pipes to better understand the transition. Measuring the velocity in high temperature heat pipes is challenging.

ID	Phenomena	Description	Imp.	Rationale	Know. (M&S)	Rationale (M&S)	Know. (E&I)	Rationale (E&I)
II-04	Continuum flow front	Continuum vapor flow may not be present across the entire heat pipe length during startup or at low operating temperatures	L	Transition between rarified flow to continuum flow is important during frozen startup as the heat pipe enters the viscous limit bound region. However this transition occurs relatively early during the startup where cyclic evaporation condensation is not fully established. Therefore the overall importance was deemed low for the phenomenon.	M	Some modeling of the propagation of the continuum flow front have been performed in the literature with some success; however, some uncertainty exists in the calculation of relevant diffusion coefficients.	L	Could be inferred with the transient temperature profile in wall-mounted thermocouples. However, external measurements would have high uncertainties, as it is hard to distinguish the continuum flow front from the melt front with just temperature measurements. Predictions may be improved with high accuracy power throughput measurements. Another option is the placement of optical fibers internally to the heat pipe that will show the temperature distribution along it and indicate the transition point to continuum flow based on the temperature profile.

ID	Phenomena	Description	Imp.	Rationale	Know. (M&S)	Rationale (M&S)	Know. (E&I)	Rationale (E&I)
II-05	Liquid flow and pressure drops	Liquid phase pressure drops are in the form of viscous losses in the wick and hydrostatic pressure gradients due to heat pipe orientation	H	Liquid viscous and hydrostatic pressure drops are important to effective capillary pumping within the wick and the capillary limit.	M	For a known wick position, liquid pressure drops can be modeled effectively, but changes in the location of the wick during operation may affect the liquid pressure drops and is currently not well known.	L	Experiments have been conducted on low-temperature heat pipes to measure the pressure drops in the wick. However, the presence of pressure taps, small pressure drops, local disturbances in liquid flow and meniscus shape, and large hydrostatic pressure drops based on orientation, can cause large uncertainties in measurements. Other phenomena such as entrainment and geyser boiling also effect the success of measurements. Furthermore, the use of high temperature liquid metals results in further difficulties and complications for these measurements. The presence of pressure taps may influence heat pipe flow dynamics downstream.

ID	Phenomena	Description	Imp.	Rationale	Know. (M&S)	Rationale (M&S)	Know. (E&I)	Rationale (E&I)
II-06	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	H	Vapor pressure drops and gains are important for the calculation of axial pressure profiles and capillary limits and to understand pressure dynamics.	M	Pressure drops within the evaporator for laminar flow are well known, but the pressure drops in the transition/turbulent regime, especially in the condenser where there may be pressure recovery are not well known. Existing correlations appear to not capture the necessary physics, and some are not fully validated.	L	Challenging to measure since the vapor pressure drops must be measured invasively. Experience on low-temperature heat pipes have been conducted by Haug in 1985, but small pressure drops and the effects of the pressure tap creates difficulties. Additional experiments on vapor pressure drops is underway.
II-07	Geyser boiling	Geyser boiling or geyser boiling can occur as generated bubbles rise due to buoyancy while pushing liquid towards the condenser.	M	Geyser boiling occurs when there is a liquid pool in the evaporator end due to gravitational effects, and/or the wick is de-wetted due to gravity. It can occur during startup based on the wick structure and particularly under vertical operation. Large wall temperature fluctuations may be observed. These fluctuations may need to be considered for the long-term reliability of the heat pipe. However, it is usually not a concern during normal operation and at higher input powers.	L	There are some models available, however high-fidelity simulations are very challenging due to complex flow dynamics.	M	Geyser boiling can be visualized with X-ray radiography and temperature oscillations can be observed during the different geyser boiling stages with wall temperature measurements. The geyser boiling frequency follows wall temperature oscillations without a significant lag. Rapid vapor generation at the end of the stagnant pool stage may be studied in more detail with pressure measurements due to the relatively slow nature of temperature measurements arising from dampening by the sensor and wall thermal masses.

ID	Phenomena	Description	Imp.	Rationale	Know. (M&S)	Rationale (M&S)	Know. (E&I)	Rationale (E&I)
II-08	Wick priming	The working fluid needs to prime the wick, i.e. the wick needs to be fully saturated with the working fluid for proper heat pipe operation without hotspots	M	Heat pipe diameter, wick properties/dimensions, fill ratio, and orientation should ensure that complete wetting of the wick can be achieved, and that the wick can supply the necessary capillary pressure to prime itself. If regions of the wick are not primed, hot spots may emerge and cause performance degradation. After shutdown, the wick is typically already filled with frozen working fluid, in which case priming may not be a concern.	L	Current models do not consider this phenomena, yet it may not be necessary for effective heat pipe design and analysis tools. This is because simple calculations of capillary forces may be sufficient in order to ensure the wick can prime itself during startup.	M	This is dependent on the type of wick and the design of the heat pipe and the gap. Orientation can be important. Changes in wick location along the heat pipe can result in changes between crescent and concentric annular configurations. These configurations need to be accounted for in design. If not primed or wetted properly vapor can fill annulus.
II-09	Wick de-wetting	Wick de-wetting in wicks with low capillary pressures can occur due to large gravitational forces pulling the liquid towards the evaporator	H	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.	L	Modeling is challenging considering that the changing meniscus shape, gravitational effects, and capillary effects need to be resolved.	H	Temperature measurements as well as thermal and X-ray imaging can be utilized to study the phenomena. Temperatures in the evaporator will show sharp increases while condenser temperatures will be show sharp drops if the wick is de-wetted.

ID	Phenomena	Description	Imp.	Rationale	Know. (M&S)	Rationale (M&S)	Know. (E&I)	Rationale (E&I)
II-10	Excess liquid pooling in the condenser	Excess fill within the heat pipe can cause liquid pooling on the condenser end	M	Excess filling reduces the active length of the heat pipe due to subcooled liquid accumulation at the condenser endcap. Depending on the amount of excess fill the effect may be more significant. This effect may be exploited to achieve similar function to gas-filled heat pipes. Slight overfilling may be beneficial to avoid low working fluid inventories in the evaporator for startup and de-wetting due to gravity.	M	Thermal expansion of the fluid is easily predicted by an appropriate equation of state; however, the presence of the liquid pool may present numerical challenges in simulation due to liquid being present in the vapor space, as this causes a zero void fraction there.	M	X-ray imaging can be utilized to see these effects along with the axial temperature profile of the heat pipe.

ID	Phenomena	Description	Imp.	Rationale	Know. (M&S)	Rationale (M&S)	Know. (E&I)	Rationale (E&I)
II-11	Under filling	Low working fluid inventory relative to the heat pipe and wick volumes	M	Under-filling can cause serious performance degradation and dry spots in the evaporator due to an insufficient amount of working fluid. The heat pipe operation may not even be started due to a lack of fluid in the evaporator. Depending on the level of under-filling, heat pipe might start but hit CHF at a lower power. Under-filling can occur in actively controlled heat pipes in case of an accident or malfunction.	L	Underfilling effects are challenging to model, mainly due to the partial wetting of the wick, and is usually treated as an invalid input to simulations.	L	Due to serious performance degradation it is challenging to study the effects of under-filling experimentally. Effect of underfilling have not been studied extensively.
III-01	Evaporation and condensation	Evaporation and condensation in liquid metal heat pipes normally occur at the liquid vapor interface within the wick	H	Evaporation and condensation at the liquid-vapor interface is the main mode of heat transfer within the heat pipe.	M	There are uncertainties in the accommodation coefficients, especially for condensation. It is also difficult to infer the meniscus shape for calculating interfacial area	L	Although it is mostly possible to identify liquid/vapor zones with X-ray radiography, it is currently not possible to measure interfacial heat flux with current methods. Separate effects experiments may be useful in experimentally characterizing evaporation and condensation.

ID	Phenomena	Description	Imp.	Rationale	Know. (M&S)	Rationale (M&S)	Know. (E&I)	Rationale (E&I)
III-02	Nucleate boiling at high heat fluxes	Nucleate boiling in the wick structure can occur and limit liquid return to the evaporator	H	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. The phenomena may be more significant in the presence of NCGs and/or changes in surface characteristics can result in a higher active nucleation site densities. Since boiling limit can cause rapid heat pipe failure and damage, it is an important phenomena that needs to be predicted accurately.	L	Dedicated correlations for nucleate boiling in heat pipes are not available. In addition, nucleate boiling phenomena depend on the characteristics of the heat pipe and surface morphologies. Bubbles in the wick create modeling challenges due to capillary forces. This condition may include transient scenarios in which nucleate boiling happens only at one stage during the transient. Correlations for the boiling limit are rather well known. However, dynamic modeling of nucleate boiling is not feasible at the moment. Furthermore, surface properties may change spatially and over time within the heat pipe and can effect properties such as nucleation site densities, resulting in uncertainties in predictions.	L	As wicks with higher performances are designed, boiling limit might be the limiting factor for higher temperature heat pipes. Factors related to manufacturing that affect boiling characteristics need to be considered. Boiling limit is also important because it represents a power limit that might result in rapid temperature increases. The temperature fluctuations and superheats could be large, which can be an issue when considering material limits. Vapor generation can block or displace liquid flow near nucleation sites. The time evolution of active nucleation site densities may require characterization in separate testing.

ID	Phenomena	Description	Imp.	Rationale	Know. (M&S)	Rationale (M&S)	Know. (E&I)	Rationale (E&I)
III-03	Critical heat flux	Dryout of the wick due to boiling which occurs post-boiling limit	H	This is 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). Dryout conditions can cause rapid spikes in wall temperatures that may result in rather immediate damage to the heat pipe body or wick structures. It can be assumed that the heat pipe cannot be operated further after CFH is reached. The condition could be caused by cascading heat pipe failures, reactivity insertion accidents, etc.	L	Modeling challenges are similar to those for nucleate boiling. The safety critical nature of the phenomena could require accurate modeling.	L	It is difficult to design well controlled experiments with known nucleation site sizes throughout the heat pipe. Inspection on the inner surface of long heat pipes can be difficult. Furthermore, high temperatures, possibility of damage to the heat pipe, and safety concerns related to sodium release to the environment pose additional challenges to experimentation.
IV-01	Capillary action	Capillary action due to the small pores within the wick structure	H	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. Due to its critical effects on heat pipe operation, capillary action is designated as high importance.	H	Modeling and simulation of capillary action in heat pipes are well-developed due to the fundamental nature of the underlying principles. Capillary action is primarily governed by the pore size and wettability of the wick material, which can be characterized and incorporated into models with a high degree of accuracy.	M	Although capillary action is a well-known principle, and wick characterization tests can characterize capillary pressures provided by wick structures accurately, the knowledge level is designated as medium considering that direct measurements of capillary pressure is not possible within the heat pipe.

ID	Phenomena	Description	Imp.	Rationale	Know. (M&S)	Rationale (M&S)	Know. (E&I)	Rationale (E&I)
IV-02	Wettability	The angle formed between the working fluid and wick surface	H	The contact angle determines the maximum interfacial curvature, which in turn determines the maximum capillary pressure.	L	Contact angle, conditions of material, pressure, and temperature effects are factors to consider. Contact angle will also depend on the surface conditions of the material and impurities in the working fluid.	L	Contact angles are not characterized well for high temperatures and changes in surface characteristics with temperature or impurities (see IV-01)
IV-03	Wet point location	The location of the wet point where the liquid and vapor pressures are equal, and the liquid-vapor interface is flat	M	Important to the liquid flow in the wick. Establishes the liquid flow path to conduct pressure balance along.	M	Wet point is effected by orientation/gravitational effects, and pressure recovery in the condenser	M	Wet point location can be determined with X-ray radiography
IV-04	Wick fabrication techniques	Influence of wick fabrication methods on the capillary pumping ability of the wick	M	Wick fabrication techniques influence wick performance and reliability. Optimization of wick fabrication techniques based on heat pipe performance, reliability, and mass manufacturability is imperative.	M	Hard to integrate non-uniform pore sizes and distributions in the wick. Sockeye has correlations for the capillary pressure as a function of the pore sizes, but assuming a flat distribution. If correlations are developed they may be implemented in Sockeye. Development of these correlations could be challenging.	M	We can develop wicks that perform the expected function, but have not yet optimized wick fabrication processes.

ID	Phenomena	Description	Imp.	Rationale	Know. (M&S)	Rationale (M&S)	Know. (E&I)	Rationale (E&I)
V-01	Accumulation of NCGs in the condenser	Non-condensable gasses inside the heat pipe accumulate at the condenser endcap during operation	M	Accumulation of NCGs in the condenser during operation results in an inactive condenser length which expands and contracts based on the operating pressure, effectively controlling the heat transfer area on the condenser surface.	M	There might be modeling challenges depending on the amount of NCG and the source. Could be used in the design of the heat pipe to achieve a more constant operating temperature	M	Difficult to determine the exact amount of NCG. It is relatively easy to measure the inactive length with axial temperature measurements but diffusion of working fluid vapor and NCG as well as wall conduction can obscure the accumulation area if relatively low amounts of gas are present.
V-02	Vapor-NCG front location	The accumulated NCGs form a front with the vapor phase of the working fluid	M	The location of the vapor-NCG front determines the active and inactive lengths of the heat pipe.	M	Well approximated with assumption of buildup at the condenser end, inactive length determined by partial pressure balance and mass of NCGs	M	Could be difficult if there is diffusion between the NCG and vapor. More uncertainty than VII-01.
V-03	Diffusion /mixing b/w vapor and NCG	Diffusion and mixing between the gasses across the vapor-NCG front	M	Diffusion or mixing at the vapor-NCG front determines how sharp the transition is, and how much NCG presence may affect flow and phase change characteristics in the active region.	M	Mass diffusion coefficient may not be well known, and condensation effects due to NCGs may not be easy to model	L	Local diffusion and mixing between the NCG and vapor is hard to determine, as internal measurements are needed. Wall temperatures may not provide a detailed account due to the thermal mass and conduction of the wall.
V-04	NCG getting trapped in the wick	NCGs getting trapped in the wick	M	NCGs getting trapped in the wick can cause dry spots in the wick or annulus, preventing liquid return and creating similar effects to boiling limit and CHF conditions.	L	Could change boiling limit characteristics. Requires understanding behavior of the NCG in the wick under variable pressure and temperature. Need to model transport in the wick to predict changes in flow dynamics.	L	Occurrence documented in previous experiments, but NCG presence in the wick is hard to identify with indirect measurements. Could be observed with X-ray radiography based on the NCG pocket size and distribution.

ID	Phenomena	Description	Imp.	Rationale	Know. (M&S)	Rationale (M&S)	Know. (E&I)	Rationale (E&I)
VI-01	Frozen startup	Frozen startup involves the startup of the heat pipe from near ambient conditions where the working fluid fully or partially frozen. The working fluid gradually melts and saturates the wick until cyclic evaporation-condensation is established	M	Frozen startup process is crucial as the heat pipe working fluid melts and the cyclic evaporation and condensation process is established inside the heat pipe. Startup procedures need to be developed considering the frozen startup limit.	M	Frozen startup is challenging due to extremely low pressures in the vapor, which can be numerically challenging for flow solvers due to the need for vacuum treatment and possibly insufficient equation of state relations.	M	Can be characterized well experimentally with X-rays, but experimental results need to be compared to models, and the resolution of the meniscus may not be sufficient depending on the heat pipe and operating conditions. May also be hard to distinguish between solid and liquid sodium in the wick.
VI-02	Solidification and solid accumulation post-shutdown	As the heat pipe returns to near ambient conditions during shutdown, solidification of the working fluid occurs in the wick. Solid accumulation in certain regions may occur based on the orientation of the heat pipe	M	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.	M	Heat pipe models will need to allow arbitrary initial frozen working fluid distributions; current modeling approaches typically assume the working fluid is uniformly distributed in the wick, but generalization should be achievable.	H	X-ray and CT scans of the heat pipe can be conducted post-shutdown in order to study the solid accumulation regions. The shutdown procedures can then be modified accordingly.

ID	Phenomena	Description	Imp.	Rationale	Know. (M&S)	Rationale (M&S)	Know. (E&I)	Rationale (E&I)
VI-03	Startup and shutdown time scales	The time scales of heat pipe startup and shutdown processes	M	Time scales of heat pipe startup and shutdown are important to develop operating procedures and to establish operational characteristics. Rapid response of heat pipes during start-up may be required for certain reactor designs, in which case it becomes important to characterize the time constant of the heat pipe, which is not a strictly defined parameter in literature.	L	May be able to model using quasi steady lumped capacitance method with a viscous and frozen start up mod to determine active length. Lumped capacitance with forward differencing is unstable with large time steps but it may be possible to switch to backwards differencing. Capturing superheat and subcooling in the system during these transients could be challenging.	H	Startup and shutdown time scales can be defined based on temperatures and measured experimentally.
VI-04	Successive startups and shutdowns	Effects of successive startups and shutdowns on heat pipe operation	M	Successive startups and shutdowns are important to quantify the effects of thermal cycling and to develop robust operating procedures that consider frozen startup and solidification after shutdown.	M	Mechanistic thermomechanical models to capture thermal fatigue effects are possible but are likely outside the scope of practical heat pipe models and would require high-fidelity, three-dimensional heat pipe models.	M	This phenomenon has not been studied in detail but experiments can be conducted to determine its effects.

ID	Phenomena	Description	Imp.	Rationale	Know. (M&S)	Rationale (M&S)	Know. (E&I)	Rationale (E&I)
VI-05	Thermal stresses	Stresses caused by thermal gradients during transients	M	Thermal stresses can occur during limit conditions where heat pipe ceases to be isothermal and hot spots may be observed, causing increased thermal gradients. Heat pipes respond to normal transients approximately isothermally, however system transients and accidents may expose certain heat pipes to harsher conditions that may induce thermal stresses amongst the array.	M	Mechanistic thermomechanical models are possible but are likely outside the scope of practical heat pipe models and would require high-fidelity, three-dimensional heat pipe models.	M	Experiments that investigate thermal stresses can be conducted with temperature and strain measurements, including optical fiber sensors for high resolution measurements of both parameters. Investigations of near limit conditions are underway but should be advanced.
VI-06	Pressure dynamics	Pressure dynamics during startup and shutdown as the internal pressure increases in the heat pipe	M	Pressure dynamics during startup, shutdown, and thermal power transients are important for the study of flow dynamics and viscous and sonic limit conditions.	L	Current pressure and velocity profile correction factors were presented in the 1980s and assume uniform heating and cooling for heat pipes at steady state. These correlations may not be fully capturing the pressure dynamics in heat pipes during transients or throughout startups and shutdowns.	L	Internal pressure measurements are hard to conduct due to interference of the probe with the internal flow, low axial pressure drops, and ambiguities in the interpretation of pressure measurements considering the two-phase flow in the heat pipe and liquid flow in porous media.

ID	Phenomena	Description	Imp.	Rationale	Know. (M&S)	Rationale (M&S)	Know. (E&I)	Rationale (E&I)
VI-07	Acute mechanical damage	Acute mechanical damages can be caused by breaks in the heat pipe wall, wick, or welds due to external or internal factors	M	The heat pipe wall or endcaps may be compromised via a failed weld, a pinhole leak, or other mechanical damages. QA processes are being developed to mitigate such issues to ensure long term reliability. External ingress of NCGs and moisture could occur if the heat pipe is at a lower pressure with respect to the ambient.	M	Have not been done before, but may be out of scope of what we expect from functional modeling.	M	Development of QA processes is expected to result in the mitigation of such failures. Work is under way to develop mass manufacturing processes of heat pipes.
VII-01	Material degradation	Long-term material degradation caused by mechanisms such as corrosion, oxidation, creep and fatigue	M	Material degradation due to aging is a concern for the long-term reliability of heat pipes. Current experience includes data on long term material degradation due to the listed mechanisms for most materials. However novel materials may need further investigation	M	Have not been done before, but may be out of scope of what we expect from functional modeling.	M	It should be ensured that long-term or life tests are performed on the utilized materials. This is standard procedure for heat pipes but may need to be conducted for novel materials (see category IV)
VII-02	Fluid contamination	Fluid contamination in the form of oxides and other impurities	H	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.	M	Changes in the fluid properties and fluid-solid contacts can be integrated into the models provided that measurements are available. This phenomena has not been integrated in the models before.	L	Could be done, but characterization of oxides in working fluids have high uncertainties. Recommended methods presented by Reid et al in 2005, but no standard exists.

ID	Phenomena	Description	Imp.	Rationale	Know. (M&S)	Rationale (M&S)	Know. (E&I)	Rationale (E&I)
VII-03	Wick degradation	Wick degradation in the form of damage, contamination, or clogging	H	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. Any break in the continuity of the wick structure could limit the capillary pumping ability of the wick. Similarly, any clogs in the wick structure due to corrosion or other contaminants will increase the pressure drop in the wick and could limit its capillary pumping ability.	M	Effects may be implemented via correlations, however developing such correlations can be challenging.	L	A combination of in- and post-operation tests may be able to characterize the wick degradation yet the current knowledge remains limited.
VII-04	NCG Production	NCGs are produced during operation due to corrosion for non-purified filling liquid or not removing NCGs from all structures int he pipe	L	Relatively low amounts of NCGs are expected to be produced as long as QA procedures are followed.	M	This can be computed via correlations, and corrosion calculations have been performed via PNP. There are some existing corrosion correlations developed by Sandia in late 90s.	L	Difficult to detect low amounts of NCGs generated.

ID	Phenomena	Description	Imp.	Rationale	Know. (M&S)	Rationale (M&S)	Know. (E&I)	Rationale (E&I)
VII-05	Irradiation damage	Irradiation damage under long term operation inside reactor core	M	There is limited literature on this issue. Irradiation effects on materials such as SS316 and Na are known. Non-heat-pipe tests may be utilized to study effects. Phase change coupled with irradiation can result in differing effects. Impurities accumulation due to transmutation could also affect operation.	H	May be able to interpolate from irradiation damage models used for PWRs and SFRs. Effects of wick performance degradation due to irradiation is unknown. Embrittlement may be an issue.	M	Irradiation damage experiments are conducted regularly at INL. Heat pipes have been used to make irradiation capsules more isothermal in the past. It appears that sufficient knowledge exists to perform irradiation damage tests on heat pipes if needed.
VIII-01	Humidity	Humidity of the surrounding ambient atmosphere	L	The effects of environmental humidity are expected to be minor on heat pipe operation except perhaps minor influence to the contact resistance between the core and the heat pipe	H	The effects are minor and can be accommodated if deemed important.	H	There may be some challenges in safety considerations during experiments due to the use of liquid metal working fluids.
VIII-02	Vibration and movement	Vibration and movement caused by mobile applications or transport systems	M	Structural issues such as fatigue may arise considering the frequency and amplitude oscillations. Flow dynamics may also be effected based on the motion.	M	Introduces external forces that can change the net effect of the capillary action. May also be affected by orientation and subsequent effects on neutronics.	M	Experimental rigs which can simulate motion conditions can be conducted on heat pipes. Designing experiments can be challenging especially for long heat pipes considering high temperature operation and other safety concerns.

ID	Phenomena	Description	Imp.	Rationale	Know. (M&S)	Rationale (M&S)	Know. (E&I)	Rationale (E&I)
IX-01	Corrosion and oxidation in wick and wall materials	Corrosion and oxidation in the wick and wall materials	H	Corrosion can alter material and surface properties, cause damage to the wick structure, and introduce NCGs in the heat pipe. It can affect the wettability of the wick and diminish capillary pumping. Corrosion can be rapid in heat pipes due to the presence of oxygen or other contaminants. Sodium purity is crucial for the prevention of corrosion. Compatibility b/w fluid and wall/wick materials is a concern for novel materials.	M	Interactions between some alloys and working fluids are not well characterized, Effects of evaporation and condensation on the materials can cause uncertainties.	M	More experiments are needed for materials that are not widely used in sodium heat pipes. Corrosion has large impact on heat pipe operation and wettability in particular, making it challenging to characterize effects. Impurities may accumulate at certain locations within the heat pipe. Wick characterization under corrosion may be needed to evaluate corrosion rate correlations in literature. Reid et al. presents some information of corrosion caused by non-metallic impurities. Additionally corrosion can be of concern in thin walled heat pipes. Corrosion on the wall can be seen with high resolution X-ray and destructive analysis.
IX-02	Creep in wall/wick materials	Creep in wall/wick material	H	Important to the structural integrity of the heat pipe and should be considered. Creep is influenced by temperature differences and the physical interaction b/w the wick and wall. Extreme temperatures can result in higher vapor pressures inside the heat pipe.	H	Models for material creep are very well known, provided that stresses and temperature can be properly characterized. There are creep models for diverse materials.	L	Significance depends on the material and temperatures involved, knowledge is low considering challenges in internal pressure measurements. This becomes a larger problem with extremely high temperature heat pipes that experience higher internal pressures.

ID	Phenomena	Description	Imp.	Rationale	Know. (M&S)	Rationale (M&S)	Know. (E&I)	Rationale (E&I)
X-01	Dimensional tolerances	Dimensional tolerances between heat pipe and wick, dimensional tolerances in the wick properties	M	Wicks need to be fabricated with the required tolerances such that the annulus thickness and pore sizes are in the desired ranges.	H	Impacts uncertainties in the numerical models through parameters such as the pore size distribution in the wick, wick/wall roughness. Overall dimensional tolerances and uncertainties are expected to have a higher impact in the wick. These uncertainties can be implemented in simulations as long as they are known.	M	Tolerances for full-length heat pipes (~4 m) may be challenging. Wick spacing and dimensions cannot be characterized with X-rays and should be measured before installation. Thermal expansion of the materials needs to be considered when determining tolerances.
X-02	Surface roughness of the wall	Surface roughness of wall based on their surface finishes during fabrication	L	Surface roughness of the wall affects the wettability and pressure drops in the annulus/wick. Surface roughness may also influence nucleation-site size.	H	Can be modeled via standard computational thermal hydraulics methods, e.g., wall functions.	H	Can be directly characterized experimentally.
X-03	Surface roughness of wick	Surface roughness of wick based on their surface finishes during fabrication	M	Surface roughness of the wick can effect vapor core pressure drops and turbulence structures	L	Current higher-fidelity or heat-pipe performance codes do not consider this phenomenon.	L	Surface roughness on the wick is normally not specified. Rather the characterization of the internal structure of the wick is specified. The surface roughness of the wick could influence smooth vs rough wall assumptions for vapor flow. Surface roughness may change across the length of the heat pipe, as well as with different operations regimes which may influence the heat pipes vapor flow. This is difficult to measure and will also relate to the each

ID	Phenomena	Description	Imp.	Rationale	Know. (M&S)	Rationale (M&S)	Know. (E&I)	Rationale (E&I)
								manufacturing method and wick pore size.
X-04	Manufacturing defects	General uncertainties and defects in manufacturing processes that may cause failures during operation	L	Unidentified defects in fabrication or large uncertainties can result in failures during operation.	H	The ability of the models to target a worse case scenario, e.g., as needed for safety modeling, can be developed easily as long as the uncertainty is within the model scope.	M	QA procedures should be developed and followed, and tolerances/uncertainties should be determined. LANL has developed a NQA-1 stainless steel wick mass manufacturing process that can produce wicks that have a pore size within +/- 3.5 microns per batch. LANL is currently developing processes for filling and sealing heat pipes to allow for mass manufacturing.

Appendix B

References for Phenomena Categories

A-2. References for Phenomena Categories

Heat Transfer Mechanisms:

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