Effects of Heat Pipe Failures in Microreactors

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Abstract

Microreactors provide new opportunities for nuclear reactor applications given their long-lived fuel source, compact size, portability, reliability as it relates to safety and their self-regulating nature. To take advantage of these opportunities there are technological challenges that need to be overcome. One advancing technology often used in conjunction with microreactor designs are heat pipes, which are used for heat removal from the reactor core to the power conversion system. Heat pipes are a substitute for the traditional system in which the same fluid used as coolant in the reactor is then used as the working fluid in the power conversion system. This document describes how heat pipes operate, what happens when a heat pipe fails, and what codes can be used to simulate the results. Our analyses show that a single/double heat pipe failure results in a temperature increase of 15-50°C respectively in surrounding heat pipes. Heat pipe microreactors could be easily designed such that this increase is within the maximum parameters allowable for safety and does not result in cascading heat pipe failure. Thus, such failures do not lead to severe degradation of the reactor.

1.0 Introduction

Thermosyphons are passive, isothermal heat exchangers. They exploit the liquid/vapor phase change in a fluid that is selected based on the source and sink temperatures. In microreactor applications, the source is the reactor and the sink is the power conversion system. A heat pipe (Figure 1) is a specific form of thermosyphon that has a wick. The wick is a physical porous media to hold the liquid, drive its flow through capillary force, and separate it from the vapor. In a heat pipe, vapor and liquid coexist but on opposite flow paths. The fundamental heat pipe is a cylinder containing three radial regions and three axial regions. From the heat pipe core outwards, the radial regions are the vapor core, the liquid wick, and the liquid annular gap. From the bottom up, the axial regions are the evaporator, adiabatic region, and condenser. An adiabatic region does not need to be present as it serves to increase the distance across which the heat can be transferred. Exceptionally long adiabatic regions can decrease the efficiency of heat transfer and are thus avoided if not needed. Only one liquid region is required, with various possible wick configurations. The annular wick includes a wick with a diameter less than the inner diameter of the heat pipe, leaving a gap between it and the wall. Through computational modeling, it has been shown to be very efficient at all temperature ranges, particularly so at the higher end.

2.0 Operation of a Heat Pipe

As mentioned in the introduction, there are three axial regions in each heat pipe: evaporator, adiabatic, and condenser. The evaporator of a heat pipe is in contact with the heat source and experiences an inward incident heat flux. The adiabatic region has no heat flux in or out. The condenser is in contact with the heat sink and experiences an outward heat flux. The incoming heat in the evaporator vaporizes the liquid in the outer regions, which are thin enough that the vaporization can be said to occur at the inner surface of the wick, where the new vapor merges into the core. The pressure drop between evaporator and condenser drives the pressure towards the heat sink, where it deposits its energy,

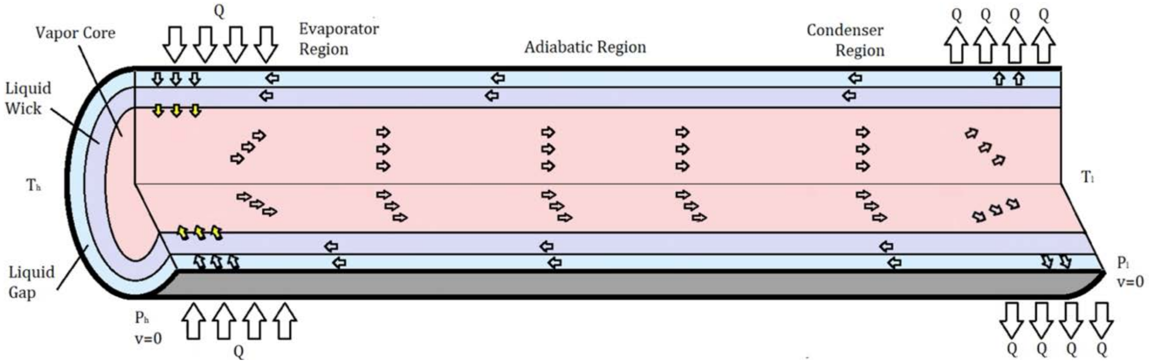

Figure 1 Heat Pipe Operation

condenses, and the liquid merges back into the wick and annulus. It then flows back to the evaporator due to capillary force driven by the small pores in the wick, and gravity if it is present. To make use of gravity, the heat pipe must be oriented with the condenser at the top and the evaporator at the bottom. If gravity is present but intended to minimally affect heat pipe operation, the heat pipe can be oriented horizontally. To be in equilibrium, the total heat entering the evaporator must equal the total heat expelled from the condenser, therefore the operational conditions of the heat pipe are externally driven but also dependent on the design, including working fluid, shell material, and wick configuration. The fluid is an especially important design parameter as it is firmly limited to a pressure-dependent range around the fluid's boiling point.

Heat pipes are a common heat removal technology in modern electronics. These heat pipes predominantly utilize water, but microreactors deal with significantly higher temperatures. Alkali metals are used as working fluids in these high-temperature applications, particularly potassium, sodium, a mixture of the two, and lithium. Alkali metals have many unique properties as liquid/vapor working fluids, particularly their propensity to become superheated and remain in the liquid state prior to evaporating. The most commonly-used alkali working fluid is sodium due to its useful boiling point of 1155K at 1 atmosphere, at which it can move more heat than any of the other fluids. Heat pipes generally operate in sub-atmospheric pressures, which makes this an ideal range for microreactor designs. Sodium also has chemical stability benefits as potassium can be quite reactive. Lithium is an exceptional choice with over double the heat transfer capability, but at a much higher temperature with its boiling point of 1615K. When the appropriate fluid is selected for the operational conditions, heat pipes work exceptionally well. However, if the conditions change a heat pipe can encounter a functional limit.

There are five major heat pipe limits: boiling, entrainment, sonic, viscous, and capillary, all except the viscous limit shown in Figure 2. The boiling limit occurs when the incident heat flux exceeds the heat pipe's heat transfer capabilities, resulting in a buildup of heat in the evaporator. In this condition, boiling can occur where vapor bubbles exist in the liquid regions on the outer wall of the heat pipe. These bubbles are impeded by the wick from entering the vapor core, and as the heat rises, the bubble population increases until film boiling occurs. The vapor has much lower thermal conductivity than the liquid, so when the liquid can no longer reach the heated surface due to the vapor, even less heat can be transferred to the vapor core and ultimately through the heat pipe to the heat sink. This condition of liquid loss in the wick is called dryout, and ultimately results in the heat pipe's failure, which means that the heat pipe can no longer remove heat from the core. The entrainment limit occurs when a wick is not present to separate the liquid and vapor flowing in opposing directions and the significantly faster vapor pulls droplets of liquid with it to the condenser, where the liquid then pools. When enough liquid is constrained to the condenser, it causes a dryout in the liquid region and can cause failure. Heat pipe failure can occur by any of the described mechanisms, or fail due to manufacturing defects (juvenile failure). In this document a failed heat pipe indicates a heat pipe which no longer has any heat removal capabilities.

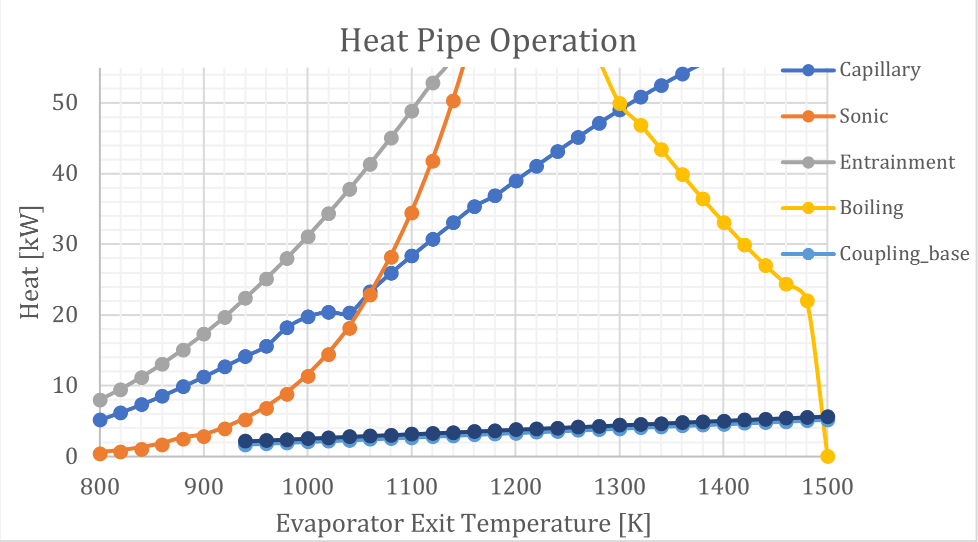

Figure 2 Heat Versus Temperature Results for a Nominal Reactor-Sized Heat Pipe

The sonic limit occurs when the vapor velocity approaches the local speed of sound and experiences a shock due to choked flow. The shock self-corrects this limit and it therefore does not result in failure, but is less efficient than operating below this limit. The viscous limit occurs during startup and at very low vapor pressures when the viscous forces opposing the vapor flow exceed the pressure drop driving it. In a fully melted heat pipe, this limit is not observed. The capillary limit occurs when the capillary pressure driving the liquid flow cannot overcome the opposing pressures. Capillary pressure allows a liquid to creep up a surface based on its surface tension and contact with another fluid at that location. In a wick, this requires the presence of a small amount of tiny vapor bubbles to pull the liquid along the wick. If the wick becomes saturated entirely with liquid, there is no capillary pressure to drive the flow and the liquid cannot move without gravity assistance. This is ultimately self-correcting with some vapor returning to the wick as a result of the liquid slowdown, and then the motion can resume. For this and the other self-correcting limits, the input heat must be reduced or the heat pipe will continue to alternate between the quasi-failure mode and corrected transient operation. However, to reach the boiling and entrainment limits, the heat pipe will be permanently damaged and is considered lost. When plotted together, these limits form an intersecting curve. A functional heat pipe is designed to operate generously below the lowest limit curves, but if a neighboring heat pipe fails, the external temperature and incident heat may increase and move towards an intersection along the curve.

3.0 Heat Pipe Failure

In a heat pipe based microreactor design, a single heat pipe failure does not necessarily cause the entire system to fail. Each heat pipe is an individual, closed system that externally couples to the reactor and power conversion system. In the sample reactor design given in Figure 3, each unit element contains heat pipes contained by a structural matrix and surrounded by fuel elements. Failure of a single heat pipe doesn't physically impact surrounding heat pipes, but its lack of heat removal thermally impacts its neighbors. In a monolithic microreactor design, the surrounding heat pipes experience increased heat flux corresponding to that which was previously being removed by the now-failed heat pipe. Should this cause additional heat pipes to fail, one must examine how many more heat pipes might fail and whether or not that creates cascading heat pipe failure. The design of the system should be such that every heat pipe can handle increases of at least 100-200°C before failing. The results of analysis in this section show that even upon two heat pipe failures, temperature increases in the areas surrounding heat pipes do not exceed 100°C. Planned heat pipe nonnuclear testing will verify the temperature and power increases that heat pipes can handle safely.

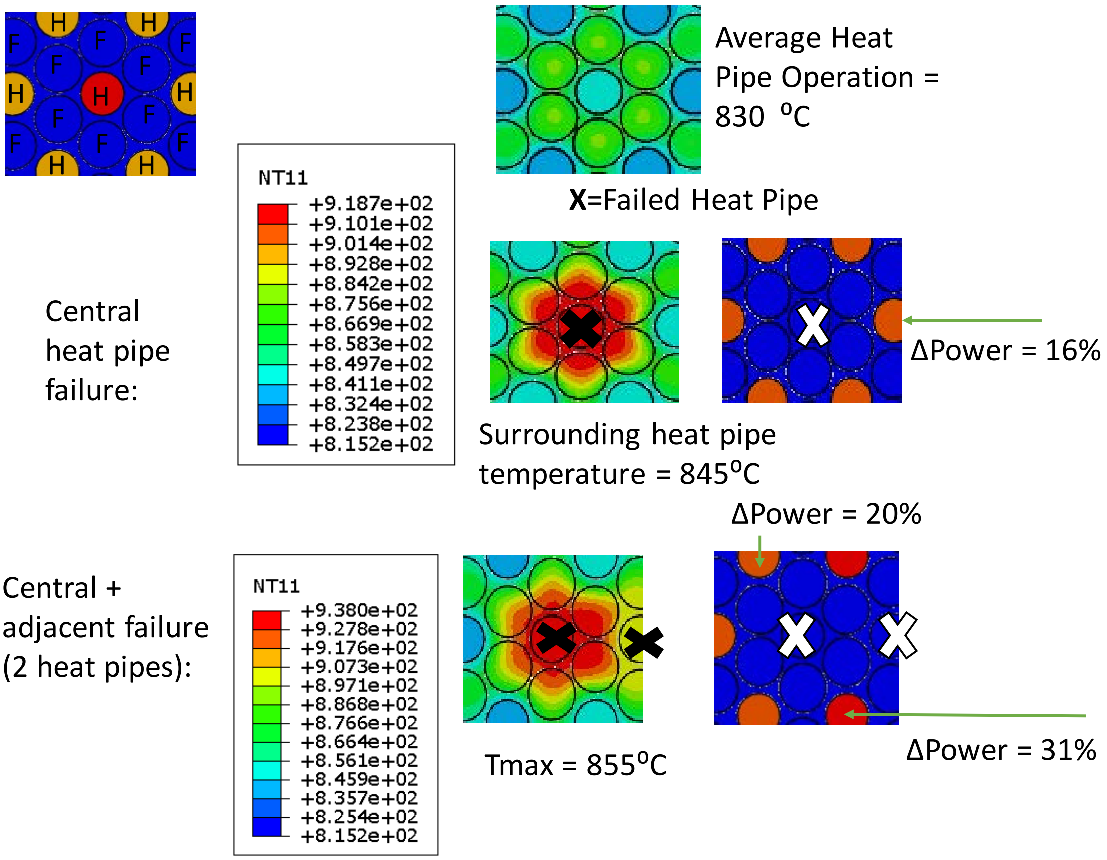

Figure 3 Abaqus Simulation of Microreactor Unit with Normal and Failed Heat Pipe Conditions

Top left in Figure 3, a fuel rod, monolith, and heat pipe configuration are shown, with results of both a single heat pipe and double heat pipe failure as calculated by a coupled Abaqus [Dassault]/MCNP simulation. In this model the heat pipe boundary condition is set to a heat flux corresponding to desired heat pipe throughput. In a failed heat pipe scenario this heat flux is set to 0, mimicking the loss of heat sink condition when a heat pipe fails. In the case of a single heat pipe failure corresponding to the central heat pipe, a temperature increase in the surrounding heat pipes of 15°C (Figure 3 "Central heat pipe failure"). The bottom of Fig. 3 ("Central + adjacent failure") shows a simulation of a case in which two heat pipes failed, producing an increase in the temperature of nearby heat pipes of about 25°C. The change in power output to surrounding heat pipes is about 16% with one failed heat pipe, and the change to nearby heat pipes is 31% when two fail; with a lower 20% increase in power to heat pipes further away. Thus, heat pipes should nominally be operated below 70% capacity to account for this scenario. However, without predictive heat pipe transient modeling capabilities, it is difficult to assess the true response of a heat pipe to adjacent failures, which requires additional conservatism in the reactor design to accommodate the uncertainty.

The heat pipe team at LANL has investigated the effect of heat pipe failure on its neighbors using a parameter, xi (ξ). This parameter represents the ratio of incident heat on a heat pipe after one of its neighbors fails to the incident heat that heat pipe would otherwise experience in normal operating conditions. This method demonstrates that the heat increase on a neighbor heat pipe is dependent on the number of heat pipes neighboring the failed one. For example, consider a heat pipe located on the periphery of a reactor. In this worst case geometry the failed heat pipe is neighbor to fewer heat pipes, with thermal communication depending on the various material compositions inherent to the reactor design. The residual heat that is no longer being transferred would have to be absorbed by the neighboring heat pipes and would likely be divided fairly evenly between the neighbors. This peripheral heat pipe failure could be a limiting event. Multiple failed heat pipes would lead to higher temperatures in surrounding heat pipes as given in the "Central + adjacent failure" case in Figure 3. However, these increases in temperature in adjacent heat pipes are about 25°C, which the surrounding heat pipes should be able to handle without failing. If unacceptable temperature increases are observed, reactor design adjustments are required.

3.1 Heat Pipe Operation in an Example Microreactor

Shortly after heat pipes were developed and optimized, reactor designs emerged to utilize these high-temperature heat exchangers in reactors. Between the needs for efficient design and analysis of a solitary heat pipe and an entire reactor system including many heat pipes, researchers began work experimenting on heat pipes and creating simulations based on what they learned. The first robust simulation tool is still used today, HTPIPE [Woloshun]. It is considered the fundamental heat pipe analysis tool and although simplistic, is considered so due to its accurate representation of the internal physics. HTPIPE provides information on the heat-dependent operating limitations and pressure and temperature along the length of a heat pipe at a single point in time. It offers six wick options (however, not the crescent annular wick often used in high temperature designs), 17 different fluids, and multiple input options, including power and various temperatures. Three of the fluids are the high-temperature alkali metals useful for microreactors. The major limitation for reactor assessment, though, is its steady-state solution, an input interface that would pose difficulties in coupling to a thermal analysis tool modeling the surrounding heat pipe, and most relevantly, the 1-dimensional assessment which inhibits the consideration of a nonuniform heat flux, as would be present in the case of a neighboring heat pipe's failure. In 1-dimensional models, the neighboring heat pipe failure is modeled by increasing the incident heat by the ξ factor as previously described, trading accuracy for increased safety margin (assuming ξ is conservatively justified). These nonuniform heat distributions are important to address in predictive heat pipe simulations. Figure 4 shows the axial temperature and pressure profile for the SAFE-30 experiment as predicted by HTPIPE.

More recently, INL and LANL have collaborated to create the multiphysics tool suite, the MOOSE [Gaston] herd where many different physics simulation codes are built on the MOOSE framework. These simulation codes can be used independently or in conjunction for a coupled analysis, while MOOSE solves the associated partial differential equations. MAMMOTH, Rattlesnake, Bison, and Sockeye are the individual codes that model a microreactor's reactor physics, radiation transport, heat transfer and thermal expansion, and heat pipe operation, respectively. Although Sockeye was still in early-stage development upon the evaluation of MOOSE capabilities for microreactors, its initial absence was accounted for by the current means of approximating heat pipe effects in a larger system-replacing the heat pipe with a temperature boundary condition. The boundary can be either isothermal with a very large heat transfer coefficient, or constant heat flux. A failed heat pipe condition is modeled by turning off these boundary conditions on the failed heat pipe, allowing no heat transfer through the heat pipe.

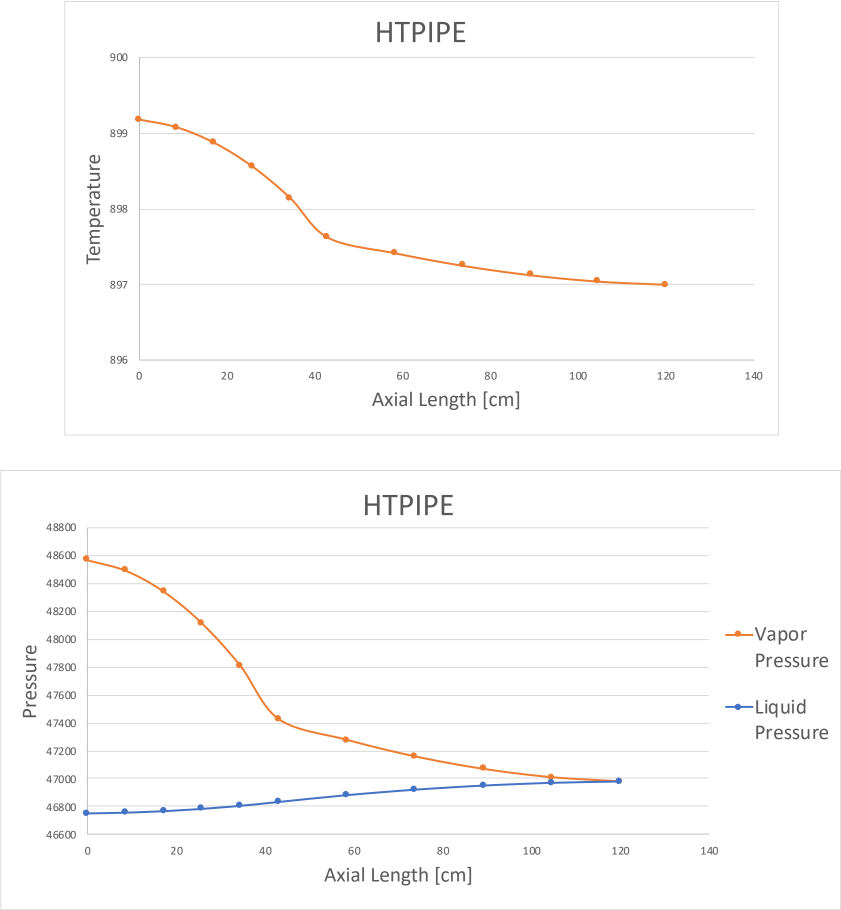

Figure 4 HTPIPE Pressure Profile Results for SAFE-30 Experiment [Reid]

Figure 5 shows an example of a unit in a potential microreactor core layout along with the equilibrium state following a heat pipe failure. In this case, the isothermal condition is used, making the operational heat pipes appear blue, excluding the failed heat pipe. The reactor's average temperature is nearly the same, but the temperature of the fuel rods in neighboring heat pipes increase as shown in Fig. 5.. This analysis does not account for the response of neighboring heat pipes.

3.2 Impact of Failed Heat Pipes on Nearby Heat Pipes, and the Potential for Cascade

An important concern for a heat pipe reactor is the potential for a random failure of one heat pipe to propagate to adjacent heat pipes. One goal for designing a heat pipe system is to build enough safety margins on average heat pipe temperatures such that if a single or double heat pipe failure occurs, nearby heat pipe conditions will not exceed the maximum allowable temperatures and power, hereby preventing all heat pipes to fail, or cascade heat pipe failure. This section displays results of heat pipe failure simulations that have been performed for a variety of designs. Heat pipe failure for a particular design would have to undergo all of the following analysis along with experimental testing to understand the limits, temperatures, and powers that the particular design could withstand.

The failure of an individual heat pipe will cause an increase in the thermal load of the neighboring HPs, as well as increase the operating temperature of those heat pipes for the reactor to reject the same amount of power to the heat exchanger. This could increase the probability of the adjacent heat pipes failing because their operating margin is reduced; i.e. the heat pipes are operating closer to their limits. In some cases the throughput limits will increase enough with higher temperature, blunting the impact of the failed heat pipe on adjacent heat pipes. Increased power and temperature will also increase the potential for corrosion or mass transfer effects that might damage the wick, wall, or welds. In all cases, the increased probability of failure will depend on how well the nominal heat pipe is designed and manufactured to provide margin to these failure mechanisms. Quantification of the failure probability as a function of temperature and power will depend on the specific heat pipe design, and ultimately a testing program. It should be noted that in most cases, juvenile failure (due to manufacturing defects) will be the most likely mechanism of heat pipe failure, which would not impact the probability of a cascade occurring to the same degree a failure by exceeding operational limits would.

The level of increase in power and temperature of heat pipes adjacent to a failure is dependent on several factors. The change in heat pipe load is significantly influenced by the location of the pipe in the core and the number of adjacent HPs available to take up the load (in many cases a peripheral heat pipe location will be worse than a central location). Another important factor is the thermal conductance from one heat pipe location to the next, which impacts how well the power can spread beyond the heat pipes closest to the failure. The type of heat exchanger, and potential orificing of the gas-flow to match nominal power, also plays major role in how much a heat pipe must warm up to reject the additional power; the more the heat pipe needs to warm up, the more that power will spread to heat pipes further from the failure. All of these factors are highly dependent on the reactor design. Then if two adjacent heat pipes fail, this would cause a greater increase in power and temperature of the working heat pipes nearby. Systems should be designed such that all heat pipes can handle the temperature and power increases possible if multiple surrounding heat pipes fail.

Calculation of the increase in power and temperature of nearby heat pipes was performed for an unmoderated SS/U10Mo 5-MWt Megapower [McClure] reactor. In this design, U10Mo fuel pellets are placed in holes in an SS316 monolith, with a 2 fuel-pin-to-heat-pipe ratio. The heat pipes are 1.59 cm (5/8") OD with a potassium working fluid. Potassium is used because of the relatively low operating temperature of 925 K. The effect of a heat pipe failure on the nearest adjacent heat pipe is a relatively small increase in temperature of surrounding heat pipes as shown in Table 1.

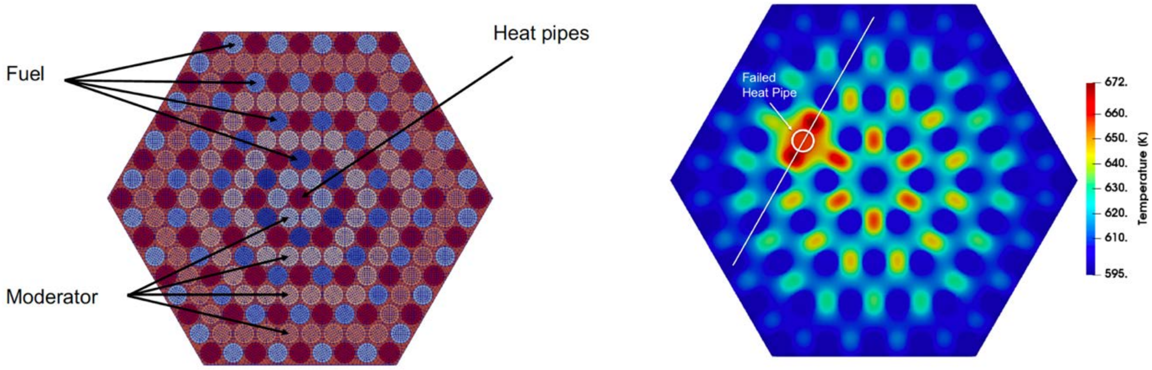

Figure 5 Bison/MAMMOTH/Rattlesnake Temperature Results for Microreactor Fuel, Moderator, and Webbing [Matthews]

Table 1. Effect of Heat Pipe Failure on Nearest Adjacent Heat Pipe

	T-vapor	T-wall	Q total	q-axial	q-radial
	(K)	(K)	(kW)	(kW/cm2)	(W/cm2)
nominal HP	925.0	934.1	5.6	5.7	10.3
adjacent to 1 failed HP	949.4	963.3	6.1	6.2	16.1
adjacent to 2 failed HP	983.1	999.7	6.7	6.9	19.2

The parameters in the above table could ultimately be used to estimate the probability of failure for a specific heat pipe, ideally in a correlation that expresses failure probability as a function of power, temperature, and lifetime. In some cases, the radial heat flux might be of particular interest because of the azimuthal non-uniformity of power entering the heat pipe (i.e. more power is entering on the sides facing the failed heat pipes).

Once a design becomes relatively mature, then a computational model that predicts behavior can be developed. In the past this has been done with Monte Carlo analysis based on a probability function assigned to heat pipe failure as a function of power, temperature, and age. This model will not only predict the probability of cascade, but also the expected number of failures during reactor lifetime, and the chance of exceeding design temperature due to several adjacent failures.

An example of how to model cascade potential in a larger geometry (greater than a single hex fuel unit) is demonstrated. The coupled thermal-neutronic transient analysis code FRINK [Poston] was used to estimate the impact of failed heat pipes on system performance. This simulation used a subset of sample microreactor units together to analyze failed heat pipes without effectively failing one nearby to all other heat pipes in the model, as occurs in unit cell simulations. Figure 6 shows a representative geometry used to simulate several heat pipe failure scenarios.

The model equates to 54 effective heat pipes, so a failure of an internal (non-symmetric) heat pipe approximates 1 failure in every 54 heat pipes in the core, at the same relative position in each reflected segment (see Figure 6). Modeling in this fashion allows a comparison to see how far apart failures need to be in order to be relatively independent; to determine how far the thermal effects of a heat pipe failure travel. Heat pipe wall temperatures in Table 1 show a ~30 °C temperature rise for a single failed heat pipe indicating the impact on heat pipes beyond the those six closes is minimal . Results given in Figure 7 and Figure 8 show the changes in temperatures of the fuel, heat pipe (hp), monolith (mono), and heat exchanger (gas out) relative to the average in the situation where one or two heat pipes fail in a sample microreactor system. In Figure 7 at two hours of operation, a heat pipe fails, then at three hours, the power draw is increased by 10% as a potential action to bring system electrical power back to nominal, given the drop in mixed-mean gas outlet temperature (noting that 10% is likely too much for one or two

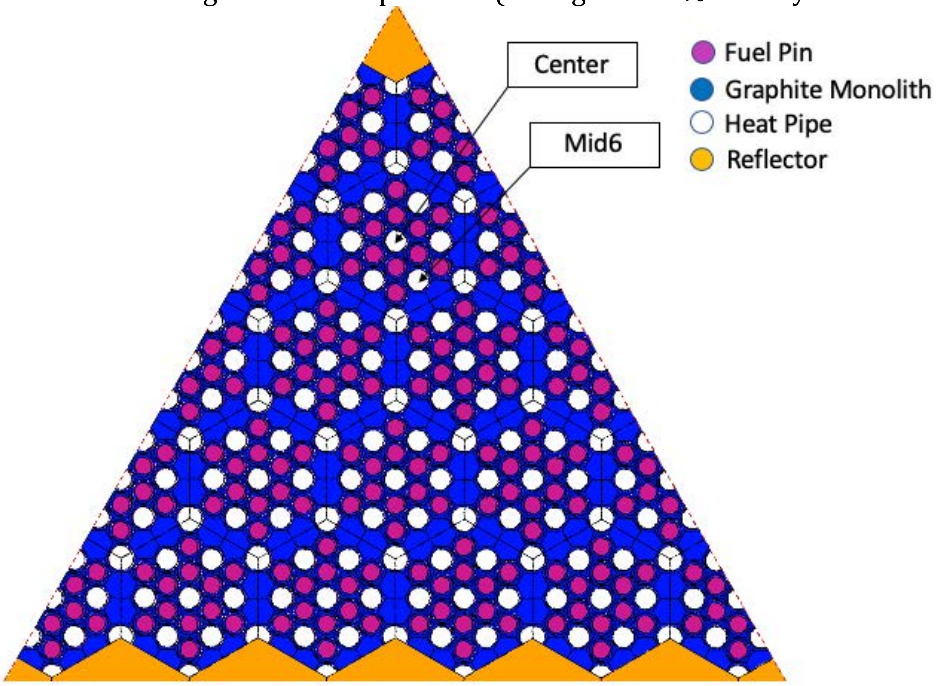

Figure 6 Picture of 1/6th Core Geometry for Failed Heat Pipe Scenarios Design (protected under patent 1620.0121P)

failed heat pipes, depending on the drop in power conversion efficiency). The "Center" heat pipe is in the center of the lattice surrounded by fuel. The "Mid6" heat pipe is one of the 6 heat pipes that surrounds the center heat pipe. In the case of the single, center, heat pipe failure (Figure 7) the maximum temperature of the monolith and maximum temperature of the heat pipe coincide, where the maximum heat pipe temperature is defined as the temperature in the failed heat pipe. Maximum fuel temperature rise is ~30 °C, maximum monolith temperature rise is ~40 °C, and the maximum heat pipe temperature rise is ~120 °C corresponding to the failed heat pipe. Average fuel and monolith temperatures are seen to effectively hold constant, while the average heat pipe temperature has a slight increase. Analyzing the results for two failed heat pipes (Figure 8) show similar trends with more dramatic temperature increases. One difference is that the maximum monolith temperature is higher than the maximum heat pipe temperature, expected as the monolith between the two failed heat pipes will see even greater temperature increases. Given many modeling simplifications (e.g., 2.5 mil airgaps, infinite HP conductance, no axial peaking, adiabatic core, and graphite conductivity– see Ref. Trellue) plus various uncertainties, significantly more margin would likely be needed. The other parameter to note is the gas outlet temperature, corresponding to the temperature of the gas exiting the heat exchanger. Not only does it decrease due to the failed heat pipes (because some flow channels have no heat), but it also decreases when power increases (power increase at 3 hours in Figure 7) due to the integral reactivity balance caused by higher temperature gradients. The information obtained for various failed geometries, center and/or mid6, along with assumptions of single or multiple heat pipe failures, provides information regarding the temperature increase in adjacent heat pipes. This information would then inform the heat pipe failure model as a function of the heat pipe power, temperate and age yielding an expected failure frequency that informs the likelihood of further heat pipe failures.

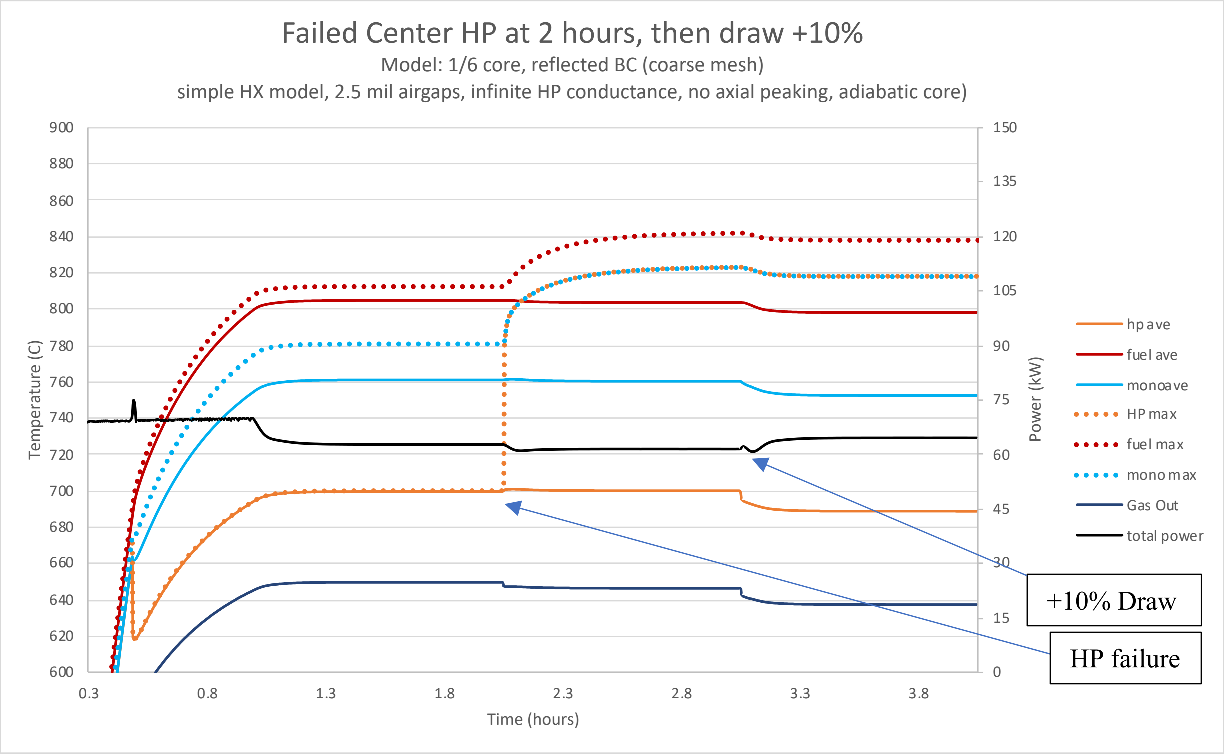

Figure 7 Changes in Temperature with One Failed Heat Pipe (HP)

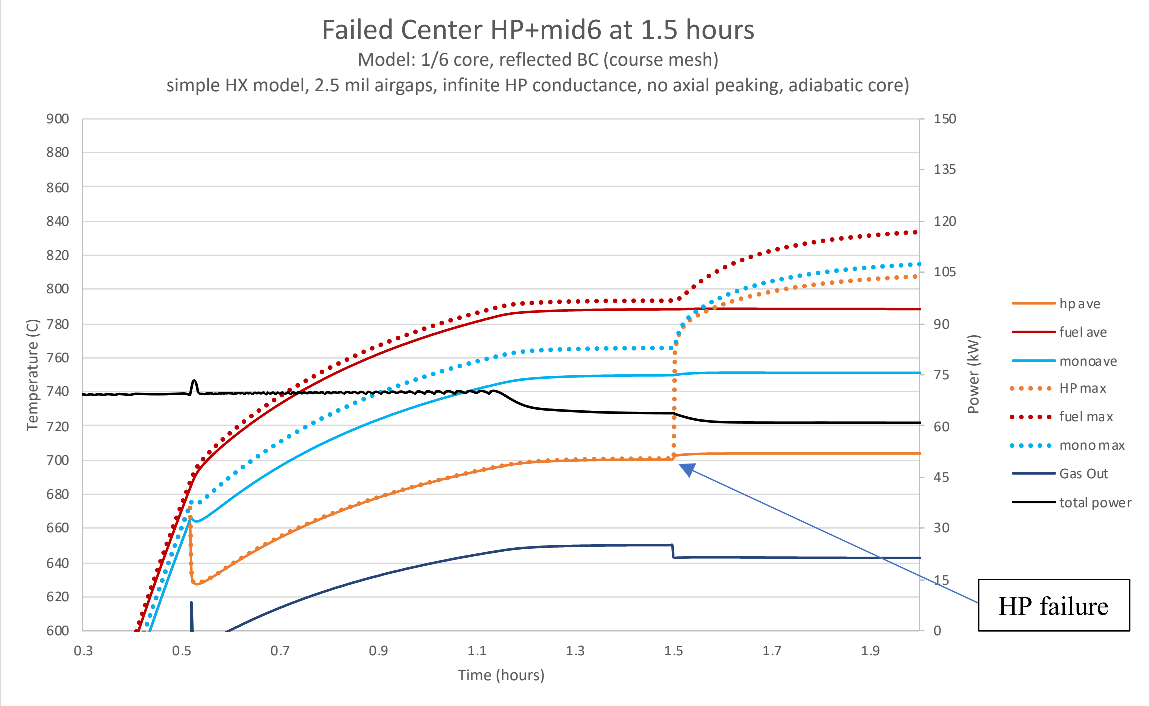

Figure 8 Changes in Temperature with Two Failed Heat Pipes (HP)

The most important aspect of modeling heat pipe (HP) reactor reliability is the impact of adjacent HP failures on individual HP reliability. The following reliability analysis does not predict the reliability of HPs; instead, it provides information as to what range of HP reliability might be necessary to produce a reliable reactor system. It also serves as a tool to evaluate how the reliability of various HP-reactor concepts may compare with each other and what system parameters (e.g., the number of HPs, peaking factor, and performance margin) impact reliability the most. Analysis and results are separated into three sections that correspond to reliability —stochastic failure, conditional failure, and performance-based failure. In the simulations, “adjacent” is defined with respect to a specific HP location; in a triangular mesh, each HP has six HPs adjacent to it (except on the edges or next to safety rods). If HP failures are adjacent to a working HP, the failure probability of the working HP is expected to increase by some amount. The magnitude of this amount depends on several factors, including how the HPs are coupled to the power conversion system. If the HPs are designed and qualified to a sufficient margin to failure, the increased probability caused by one adjacent or two adjacent failures will be small. However, there is the possibility for a significant increase in HP failure probability if several adjacent HPs fail; thus, the possibility of a cascading failure must be considered and analyzed. One-adjacent failure assumes that the “central” HP has already failed and that one HP has failed next to it (therefore, two HPs have failed next to each other). Three adjacent failures indicates that the central HP plus three adjacent HPs have failed.

To assess reliability, a metric of success and failure must be established. To facilitate this analysis, two scenarios are defined as “failure”. Any simulation that doesn’t end in one of the “failure” modes is counted as a “success”.

1. Three adjacent failures (potential cascade). To simplify this study, it is assumed that if any HP location is surrounded by three failed-HPs, this condition will lead to the failure of the central HP (if it has not already failed) and will have significant potential to initiate a cascade. The potential for a cascade would depend on the HP conditions and margins, and it would be possible to design a reactor that could survive this condition; however, for the sake of this study, this scenario is chosen simply as a metric to demonstrate reliability.

2. A delta pattern of HP failures. In this scenario, all three HPs surrounding a specific fuel-pin location have failed (which are in the form of a delta pattern). This condition would produce very high temperatures and stresses in the core. This condition can occur without a three-adjacent-failures scenario; thus, it is more limiting than the previous criteria. Again, no analysis indicates that this scenario would lead to system failure—it was chosen simply as a metric to demonstrate reliability.

Representative results for stochastic and conditional failure scenarios are provided below and are not intended to predict the reliability of HPs; instead, the results provide information as to what range of HP reliability might be necessary to produce a reliable reactor system. The results also serve as information to evaluate how the reliability of various HP-reactor concepts may compare with each other and what system parameters impact reliability the most.

Stochastic Failure

The simplest form of analysis is to set a fixed reliability for all HPs and record how often system failure occurs. A stochastic tool was developed to run 10 million histories with 6 different HP reliability values: 0.95, 0.98, 0.99, 0.995, 0.998, and 0.999. A sample geometry was used with a 6-row hex of 127 HPs. Results are summarized in Table 2 where FHP stands for failed heat pipe. Note that a "Delta" heat pipe failure configuration is one where three heatpipes surrounding a fuel element all fail.

The results in Table 2 indicate that if HP failure is independent of adjacent failures, then HP core reliability is very high (even if the individual HP failure rate approaches 5%). Also, the reliability in this case is a linear function of the number of HPs, i.e., a core with twice the HPs would have twice the failure rate and vice-versa.

Table 2. Stochastic Failure Scenario Probabilities for a Generic 127 HP Core

Stochastic, 127 HP Core	**Nominal Individual HP Failure Probability**					
	0.001	0.002	0.005	0.01	0.02	0.05
Zero failed HPs (FHPs)	0.88074	0.77537	0.52821	0.27748	0.07520	0.00130
Worst case, isolated FHPs	0.11894	0.22329	0.46347	0.69030	0.80587	0.48590
Worst case, one adjacent FHP	0.00033	0.00133	0.00817	0.03115	0.11088	0.41057
Worst case, two adjacent FHPs	0.00000	0.00001	0.00014	0.00106	0.00781	0.09410
Three or more adjacent FHPs	0.00000	0.00000	0.00000	0.00002	0.00024	0.00813
"Delta" FHP configuration	0.00000	0.00000	0.00003	0.00021	0.00166	0.02467
Probability of "Success"	**1.00000**	**1.00000**	**0.99997**	**0.99979**	**0.99831**	**0.97438**

Predefined Conditional Failure

In most cases the failure probability of a HP will be impacted by the state of the surrounding HPs. The analysis tool was used to execute the same set of cases as listed in Table 1, but in this case the failure probability was conservatively multiplied by two for every adjacent failed HP (i.e., 2× for one adjacent FHP, 4× for two-adjacent FHPs, 8× for three adjacent FHPs, etc). These results are listed in Table 3.

Table 3. Dependent Failure Scenario Probabilities for a Generic 127 HP Core

Dependent (2x), 127 HP Core	**Nominal Individual HP Failure Probability**					
	0.001	0.002	0.005	0.01	0.02	0.05
Zero FHPs	0.88074	0.77537	0.52821	0.27748	0.07520	0.00130
Worst case, isolated FHPs	0.11826	0.22061	0.44718	0.62968	0.61393	0.12354
Worst case, one adjacent FHP	0.00099	0.00392	0.02299	0.08054	0.22493	0.22468
Worst case, two adjacent FHPs	0.00001	0.00010	0.00151	0.01070	0.06348	0.20754
Three or more adjacent FHPs	0.00000	0.00000	0.00011	0.00160	0.02246	0.44295
"Delta" FHP configuration	0.00001	0.00004	0.00069	0.00583	0.04807	0.54073
Probability of "Success"	**0.99999**	**0.99996**	**0.99930**	**0.99413**	**0.95158**	**0.45766**

As expected, if HP failure probability increases due to adjacent failures, the core HP reliability decreases. This can be seen by comparing the results in Table 2 with Table 3. The actual conditional probability is most likely not well represented by a constant multiplier of 2. Adjacent HP failures will not impact reliability significantly until the performance margin is closely approached. Thus, the failure probability increase will most likely be small, with one and perhaps two adjacent failures, but relatively large for several adjacent failures, depending on the design margin.

3.3 Heat Pipe Transient Calculations

In addition, heat pipe transient simulations can be performed using the code Thermal Hydraulic Response Of Heat Pipes Under Transients code, THROHPUT [Hall]. The THROHPUT code was designed with the purpose of modeling transient heat pipe operation within a space reactor with radiative transfer to a heat sink. The developers sought to improve on limitations of previous heat pipe codes, particularly the lack of transient start-up modeling and time step requirements or instability due to explicit solution schemes employed on a system with such large velocity gradients. It is therefore fully implicit and can quickly solve the system of 1-dimensional partial differential equations, state equations, and interphase linkage equations that are used in it to define a heat pipe. It solves for the flow and thermal properties along the length using the 1-dimensional partial differential equations. Terms such as the heat transfer between the liquid and vapor due to conduction or phase change are included in these equations to account for the radial components of mass and heat transfer, and are solved simultaneously in the radial model's interphase linkage equations. It also incorporates noncondensible gases, an advanced option for more control over a heat pipe. It can model time-dependent incident heat fluxes, but also requires the use of the ξ factor to assess nonuniform incident heat fluxes. THROHPUT was modified and updated in 1994 in conjunction with the top heat pipe researchers at LANL. Six new working fluids and one new wall material were added along with modifications to the surface model. Like HTPIPE, THROHPUT is a stand-alone heat pipe code, but it has been integrated into a computational physics development environment to allow for computational enhancements to the algorithms and the code itself. Four of the final plots from a THROHPUT simulation of a single experimental molybdenum heat pipe are shown in Figure 9. The plots were generated via a standalone heat pipe simulation performed during the design phase of heat pipe development, not in conjunction with reactor design.

4.0 Future Work

An accurate cascade heat pipe failure analysis depends heavily upon design parameters of interest. More extensive analysis with the both the reliability analysis tool mentioned in Section 3.2 and the code THROHPUT, coupled with neutronic/thermal analyses needs to be performed for representative microreactor geometries. Such detailed analyses should include heat pipe-specific transients and effects of heat pipe failures on generic microreactor systems and particular demonstration units proposed for measurements. Bracketed ranges of required heat pipe reliability, and the assumptions under which

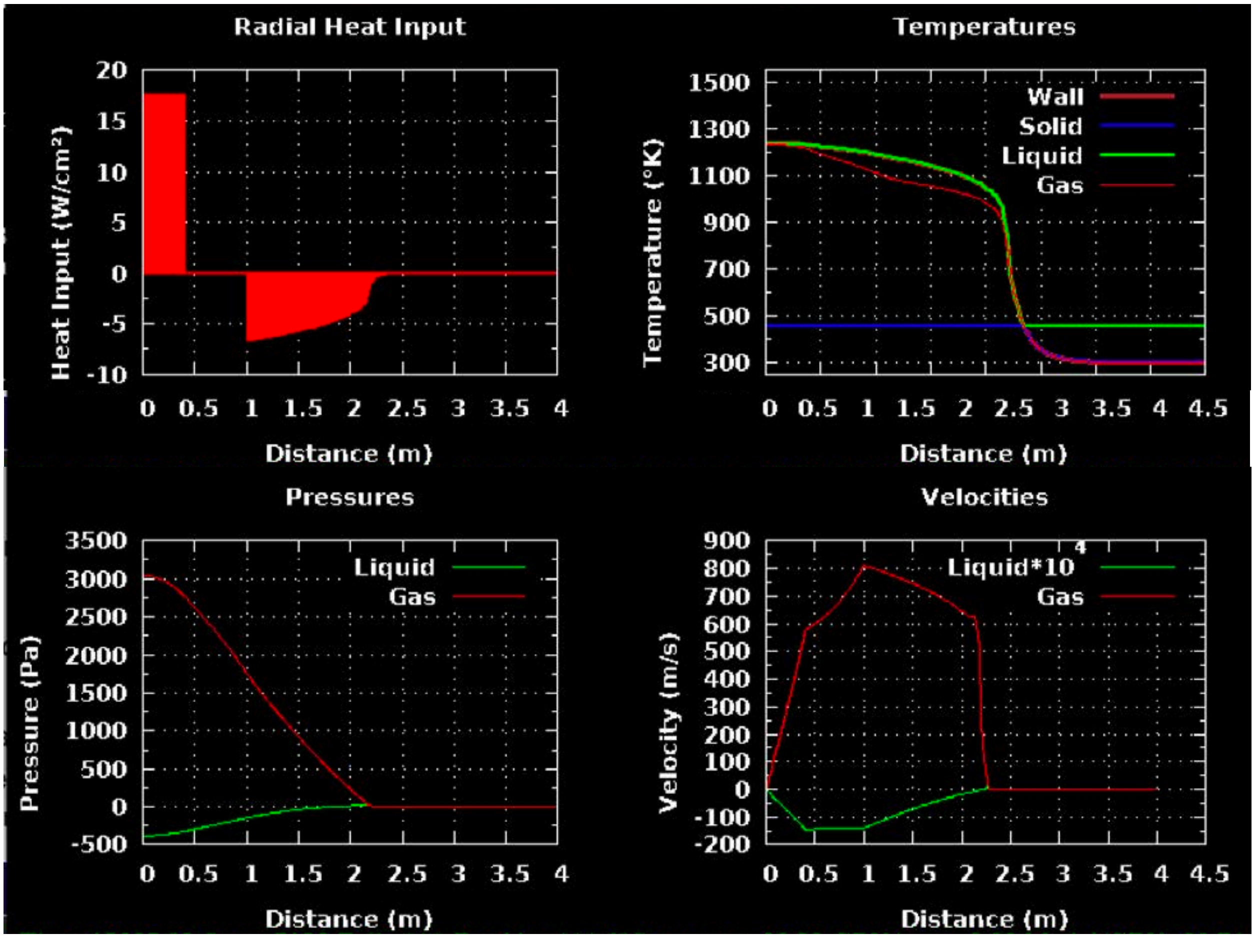

Figure 9 THROHPUT Results for Lithium Heat Pipe Experiments

those heat pipe reliability requirements were obtained should be developed and justified for evolving microreactor design concepts.

5.0 Conclusions

Heat pipe failure concerns as it relates to reactor designs can be classified into two aspects: individual heat pipe failure mechanisms, and broader implications of a single heat pipe failure. Regarding the failure mechanisms for an individual heat pipe, failure can occur if dryout conditions occur in the heat pipe by exceeding either the boiling or entrainment design limits of the heat pipe. Additionally, manufacturing defects can cause abnormal heat pipe operation and failure. The knowledge and modeling of heat pipe failure is heavily informed by experimental observations on heat pipes, with historical transient modeling performed using the THROHPUT code to estimate time dependent behavior. Implications of asymmetric heat distributions surrounding heat pipes have little historical investigation and are of importance when considering the implications of heat pipe failures in a nuclear reactor context.

While cascade heat pipe failure has been studied in the past, there is no official documentation on results and/or high-fidelity analysis performed to simulate core performance in such an event. The main impact of heat pipe failures is an increase in the temperatures of/resulting heat produced by other materials/heat pipes in the core, with representative studies highlighted in this document. However, preliminary calculations in representative microreactor designs show that the temperatures rise appreciably as expected but not significantly enough to shut down reactor operation in the reactor configurations studied. The maximum temperature rise in adjacent heat pipes is well within prototypical operating temperatures associated with the associated heat pipe design indicating that heat pipe failure propagation is unlikely and that there is sufficient margin in the reactor design to accommodate the loss of heat removal. Results from the calculations are highly reactor dependent where conclusions will be different according to differing designs and are associated with many simplifications and assumptions. As vendor designs evolve, the assumptions and models will need to be re-examined.

While heat pipe failure results in this document focused primarily on the likelihood of the failure of adjacent heat pipes by focusing on the increase in heat pipe operating temperature due to the required increased heat removal, detailed responses would be highly reactor dependent. Heat pipe failure would cause a local increase in all surrounding materials, and the degree to which they heat up depends on thermal conductivities of individual materials. An assessment of the temperature increase of all surrounding materials would need to be compared to acceptable limits, both in melt temperature and mechanical considerations. Further, any reactor design that has a strong reactivity feedback as a function of temperature would also require confirmation of neutronic stability in a heat pipe failure event.

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