

Neutron Imaging of Lithium Inside a High-Temperature Heat Pipe

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Dedication

To my family. My mom Jo, my dad Kevin, and my sister Krissa have been unequivocally supportive my entire life. Coming home is the best vacation I can ever imagine.

To Miss Susan Reid. You have been with me every step of the way for six brief years, and I am truly honored and fortunate to call you my best friend.

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Thermacore, Inc. provided the heat pipe for this experiment, and I would like to thank them for answering every technical question I could imagine. Sid Kosta, John

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As I look ahead to what lies beyond this Hallowed Hill in Tennessee I am reminded of what so many have given me. My teachers, coaches, friends, and family have taught me more than I will ever truly realize. Life and learning extend beyond books and halls, and I hope I can pay forward the incredible influence of so many fine folks.

Abstract

Neutron imaging of a high-temperature Mo-Li [molybdenum-lithium] heat pipe has been performed to assess Li flow visualization. The high neutron attenuation cross section of Li allows for imaging inside the heat pipe shell structure, which has a lower value of neutron attenuation, making neutron radiography an ideal choice for characterizing Li movement.

The gravity assisted, cylindrical heat pipe was heated to 903°C [degree] using a wire resistance Mo heater operating under vacuum. This Mo-Li heat pipe is 35 cm long with a square internal geometry 2.2 cm per side, utilizing small corner radii as the wicking structure for Li return. The heat pipe is evacuated and back filled with 10 g of Li and has an estimated operational temperature of 900°C. The neutron imaging prototype facility on the CG-1D beamline at Oak Ridge National Laboratory was used to capture 30 s exposures of heat pipe operations from ambient conditions through startup to steady-state and subsequently through two large power fluctuations. Tomographic imaging of the heat pipe was performed using 180 s exposures at 1.5° increments with the heat pipe at ambient conditions.

Time lapse reconstruction of the neutron radiography shows a change in the bulk Li level and the meniscus concavity. A change of 9 mm is measured from ambient conditions to steady-state operation. This is a result of Li density changes as well as Li surface tension changes. As the temperature increases, Li held at the top of the pipe through capillary forces flows towards the evaporator increasing the bulk Li level. A

decrease in the meniscus concavity confirms this. Dynamic movement is seen on one side of the pipe during both power fluctuations. Tomographic reconstruction shows Li held in the corner channels above the bulk Li level.

Subsequent work has been performed to develop a new test platform to house future neutron radiography testing. This new platform will increase efficiency on the neutron beamline by decreasing heat pipe startup time. It utilizes an induction heating system to achieve surface heating of the pipe and can be adapted to different heat pipes and orientations.

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List of Symbols

D	aperture diameter [cm]
I	attenuated neutron flux [$\text{n}/(\text{cm}^2\text{-s})$]
I_o	incident neutron flux [$\text{n}/(\text{cm}^2\text{-s})$]
l	sample thickness [cm]
L	collimation length [cm]
n	neutron flux
N	atomic number density[atoms/ cm^3]
t	temporal resolution
T	transmission
x	spatial resolution
z	sample-to-detector distance [cm]
λ_g	geometric unsharpness [cm]
σ	total neutron attenuation cross section [cm^2]

Chapter 1

Introduction/Literature Review

1.1 High-Temperature Heat Pipe Applications

High-temperature heat pipes are passive cooling devices that deliver high thermal fluxes. They are used in a wide range of applications including leading edge cooling on hypersonic vehicles [Ref. 1, 2], dynamic power conversion in solar and nuclear systems [Ref.3], high-temperature furnaces [Ref. 4], and turbine blade cooling [Ref. 5]. Flow visualization inside high-temperature heat pipes can aid in the design and fabrication to increase operational efficiency and reliability.

1.2 Heat Pipes

Heat pipes are two phase heat transfer devices that rely on the latent heat of vaporization to achieve thermal fluxes greater than comparable solid state conductors. Energy, in the form of heat, is applied to the evaporator region of the heat pipe causing the working fluid to transition from liquid to vapor. Due to a pressure drop associated with the temperature difference across the pipe, vapor travels along the pipe to the condenser. Vapor condenses and is returned to the evaporator through one of many methods including but not limited to gravity and capillary forces, Fig. 1.

Heat pipe designs vary widely based on operational temperature ranges and applications. For high-temperature heat pipes, stainless steel, refractory metals, or refractory alloys are used for the shell and wicking structure. The working fluid is based on the desired operational range with alkali metals and silver generally used for high-temperature applications. Table 1 gives the

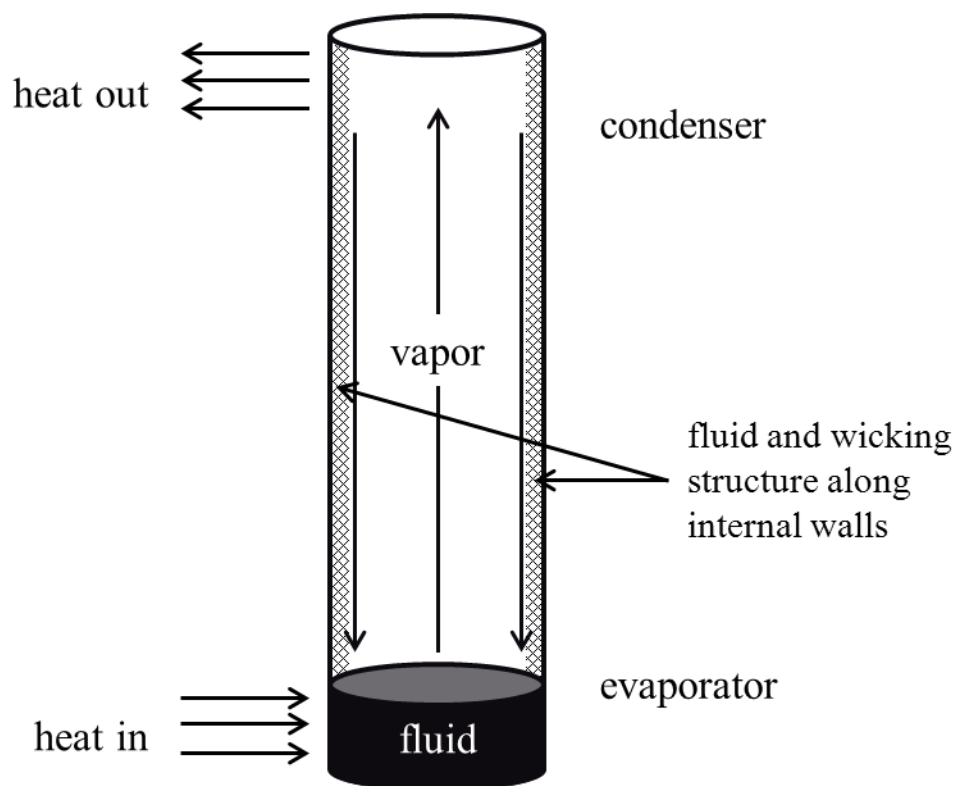


Fig. 1: Heat pipe geometry with working fluid return through capillary forces.

Table 1: Operational temperature range and molecular formula for common heat pipe working fluids [Ref. 6].

Working Fluid	Molecular Formula	Operational Temperature [°C]
Helium	H	-271– -269
Nitrogen	N	-203 – -160
Ammonia	NH ₃	-60 – 100
Ethanol	C ₂ H ₆ O	0 – 30
Methanol	CH ₄ O	10 – 130
Water	H ₂ O	30 – 200
Mercury	Hg	250 – 650
Potassium	K	500 – 1000
Sodium	Na	600 – 1200
Lithium	Li	1000 – 1800
Silver	Ag	1800 – 2300

working fluids. Once fabricated, the heat pipe must be baked out above its desired operational temperature range to remove non-condensable gases, evacuated, and then back filled with the required amount of working fluid. This limits the interior pressure of the heat pipe to the working fluid vapor pressure at a given temperature.

For proper heat pipe operation, liquid must be returned from the condenser to the evaporator. At different stages, the heat flux of the pipe is limited by either the viscous, sonic, entrainment, capillary, or boiling limit. During startup, the viscous, or vapor pressure, limit renders the heat pipe inoperable because the small pressure differential between the evaporator and condenser cannot overcome the viscous effects of vapor flow. As heat input is increased, the pressure differential increases, and the heat pipe begins to operate. The sonic limit intersects with the viscous limit as temperature further increases. The sonic limit results in choked flow along the vapor path essentially limiting the maximum heat transfer rate of the pipe. If the surface tension of the working fluid is not enough to prevent the shear force of the vapor flow from carrying surface droplets along the wicking structure back to the condenser, the heat flux is restricted by the entrainment limit. This prevents adequate liquid return and can result in dry out of the pipe at the evaporator. The heat flux reaches the capillary limit when capillary pressure cannot overcome the pressure differential across the heat pipe limiting the return flow. At the highest operational temperatures, boiling in the wicking structure limits heat pipe operations. Overheating past this point can cause damage to the pipe and can cause two-phase flow to stop. Each limit depends on the working fluid and the structure of the heat pipe; steady-state operation can be achieved within these limits [Ref. 6].

1.3 Neutron Imaging

H. Kallman and E. Kuhn of Germany are credited with the first neutron imaging experiments carried out in 1935 although no results were published and no patents were taken out for many years [Ref. 7]. These tests required nearly four hours to produce one image, but set the stage for future advances in this technology [Ref. 8]. Neutron imaging can be used as a non-destructive testing technique utilizing the volumetric attenuation that is largely independent of atomic number. Unlike x-ray imaging, which interacts with the electron shell of an atom, neutrons interact with the nucleus meaning attenuation coefficients can vary widely across the periodic table and even between isotopes. The relative x-ray and neutron cross sections for some elements are shown in Fig. 2. Note the large neutron cross section for hydrogen, H, which is nearly invisible to x-rays, and the much smaller neutron cross section of deuterium, D, which is an isotope of H. Strong neutron attenuators such as H, boron, B, and Li can be visualized readily even when surrounded by heavier materials [Ref. 7].

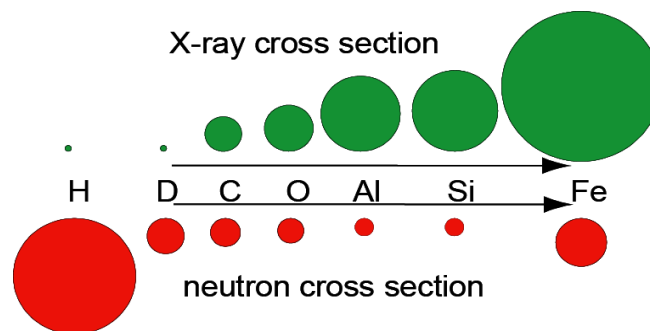


Fig. 2: X-ray and neutron cross sections (courtesy of D. Hussey [Ref. 9]).

There are several ways to produce a neutron beam for use in imaging experiments, including reactors, accelerators, and radioactive decay. The neutron flux of each source can vary, with reactors and large accelerators generally having the highest fluxes, Table 2. Reactor

Table 2: Flux ranges for neutron sources.

Source	Flux [$\text{n}/(\text{cm}^2\text{-s})$]
Reactor	$10^{10} - 10^{15}$
Accelerator	$10^7 - 10^{15}$
Radioactive	$10^5 - 10^9$

based and larger accelerator based sources are non-portable and have dedicated facilities at which neutrons are produced. These will often house additional beamlines dedicated to other neutron sciences, like scattering. Neutrons vary in energy from cold neutrons (< 0.01 eV) to relativistic neutrons (> 20 MeV), but neutrons are generally moderated down to cold and thermal ranges (0.01 to 0.3 eV) for imaging experiments [Ref. 7, 8].

Once the neutrons are moderated, they must be directed towards the sample. This is done using a divergent collimator with an aperture opening from the source, Fig. 3. The collimator is described by the collimation ratio, L/D , with a higher ratio allowing for better spatial resolution. However, this is limited by the desired neutron flux because it is directly related to the aperture size. The collimator is lined with materials that have high neutron absorption characteristics: boron, B; cadmium, Cd; dysprosium, Dy; europium, Eu; gadolinium, Gd; and indium, In. This prevents scattered neutrons from impinging on the sample and detector, which preserves spatial resolution [Ref. 10].

Neutron attenuation of the sample is a result of scattering and absorption which can be described by the Beer-Lambert law of attenuation:

$$I = I_0 e^{-N\sigma l} \quad (1.1)$$

The neutron flux not attenuated in this manner from the beamline must be converted into a recordable signal. For the purposes of this experiment, a lithium fluoride/ zinc sulfide (LiF/ZnS) scintillator screen was used.

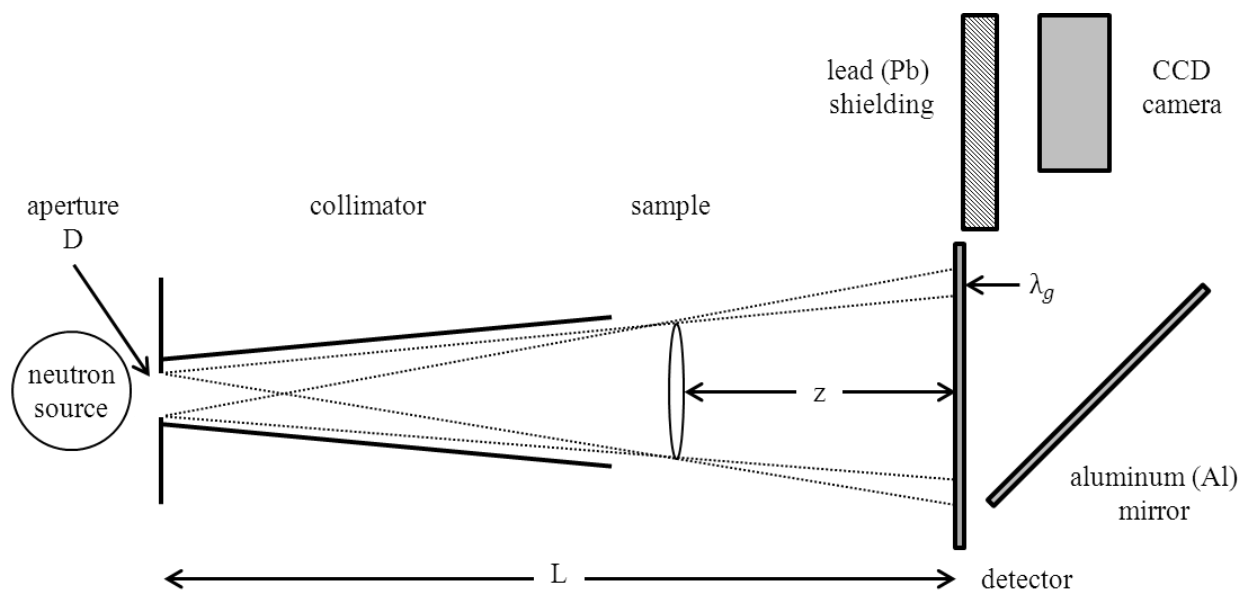


Fig. 3: Neutron imaging setup (not to scale).

Scintillation is the light emitting response of a material when bombarded with “energetic” particles. For neutron imaging, the scintillation screen fluoresces when impacted by a neutron. The visible light is then redirected with the use of a mirror and captured using a charge-coupled device (CCD) camera system. The CCD camera is placed adjacent to the path of incident neutrons to protect it from direct and indirect radiation.

Scintillation screens can be composed of a wide range of materials including liquids, plastics, ceramics, and glasses. Current scintillators are made of Li, B, or Gd and some combination of light elements. The Li, B, and Gd molecules interact with incident neutrons in a nuclear reaction which produces alpha rays and are responsible for creating electron-hole pairs from which light photons escape. The light elements are used to reduce background interference [Ref. 11]. To encourage the emission of light pulses from a scintillator, the base structure is doped with impurities known as an activator. The activator serves to reduce the energy gap between the conduction band, where excited electrons move when exposed to radiation such as incident neutrons, and the valence band, where the hole has been left. A hole will migrate to an activator sight after creation until it is neutralized by a free electron and then emits a photon. Activators can be selected to produce light at a desired wavelength for detection or amplification [Ref. 12].

Current scintillation screens have thicknesses of about 25 - 200 μm with spatial resolutions equivalent to the thickness and thermal neutron efficiencies of 40%; research is ongoing to create thinner scintillators with better resolutions. This is done by limiting a phenomenon known as light blooming, where light produced in the manner previously described is scattered as it travels out of the scintillation screen. However, by reducing the thickness of the scintillation screen, the thermal neutron efficiency decreases [Ref. 13, 14].

Microchannel plates (MCPs) are used as neutron detectors for high resolution neutron imaging. They are manufactured such that thousands or millions of electron multiplier tubes are arranged in parallel to amplify the incoming signal and preserve spatial resolution. For neutron imaging applications, the incoming neutrons must be converted to charged particles to increase the probability of producing an electron avalanche in the MCP. A high voltage is placed across the MCP to support this electron avalanche and to provide amplification. Multiple MCPs can be arranged to increase the overall gain [Ref. 15].

MCPs are manufactured from glass in which straight channels run the length of the MCP. These channels are on the order of 10 μm from the center of one channel to the next with a length-to-diameter ratio of about 100:1 for state of the art designs. Spatial resolution in MCPs is currently limited by glass drawing techniques that produce the channels, but are ultimately limited by the alpha particle range in the channel walls. Reduction in the diameter of the channels will allow for increased performance [Ref. 13, 16]. The channels are often offset by a small angle (about 8°) from the input surface of the MCP although other designs, such as curved channels, have been used [Ref. 15]. At each end of the MCP there is an electrode that has a metallic coating across which the voltage is applied. To convert incident neutrons into charged particles capable of starting an electron avalanche, the MCP glass structure is doped with elements that have high interaction cross-sections for neutrons [Ref.16].

Creating the electron avalanche requires a large potential applied across the MCP to create a strong electric field. When incident neutrons impinge upon the B or Gd particles, reactant particles are released which move through the glass channel walls where the interaction took place, and produce secondary electrons as they move into the open channel. Moreover, upon reaching the other side of the channel, the particles again release secondary electrons. The

secondary electrons move down the channel as a result of the electric field until they reach a wall and release even more electrons [Ref 17]. This process can be seen in Fig. 4 for a single channel inside an MCP.

Although scintillation screens are still considered state of the art in neutron imaging, MCPs promise to increase the spatial resolution while maintaining or increasing thermal neutron detection efficiencies. Currently, MCPs can achieve a reported 40% thermal neutron efficiency while they are expected to reach 50%. The spatial resolution is on the order of 15 μm and still improving [Ref. 18].

The spatial resolution of an imaging detector is a function of the detector itself and of the test setup. Resolution reductions from the setup are referred to as geometric unsharpness. Since the neutron beam is not a point source, but is directed at the sample in a conical beam, the neutrons spread from the aperture and cause the image to blur, as illustrated in Fig. 3. This phenomenon is described by:

$$\lambda_g = \frac{Dz}{L-z} \quad (1.2)$$

$$\text{Assuming } L \gg z \quad (1.3)$$

$$\lambda_g = \frac{z}{L/D} \quad (1.4)$$

Although equation 1.4 cannot be used to calculate the resolution directly, it provides a qualitative understanding that the sample to detector distance should be minimized to provide the best possible spatial resolution [Ref. 13].

A minimum detector exposure time is necessary to produce a high quality image. The required exposure time may be thought of as the detector efficiency which depends on the detector material and type, incident neutron energy, and neutron flux. For a given detector and source, the efficiency can be altered only by changing the flux. For reactor based sources, this is

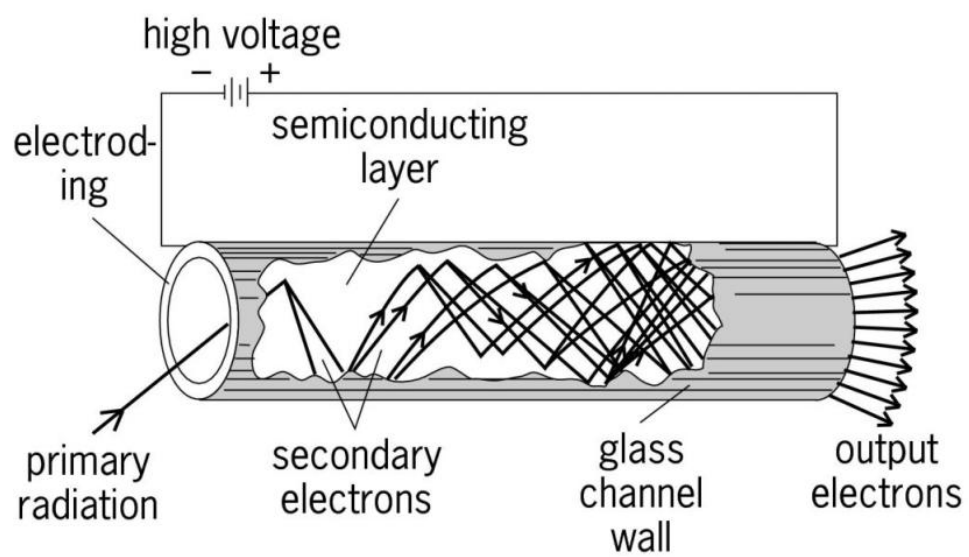


Fig. 4: A straight channel electron multiplier (courtesy J. Wiza [Ref. 15, 19]).

done by changing the aperture size although this inherently changes the geometric blurring. The relationship between spatial resolution, temporal resolution, and neutron flux therefore can be described by:

$$xt \propto n \quad (1.5)$$

Thus, shorter exposures are possible at the expense of spatial resolution [Ref. 20].

1.4 Oak Ridge National Laboratory

Oak Ridge National Laboratory (ORNL) in Oak Ridge, TN is currently home to the cold neutron imaging prototype facility (CG-1D), Fig. 5. CG-1D is a reactor based neutron source at the High Flux Isotope Reactor (HFIR) which is an 85 MW light-water-cooled reactor. Both white and pulsed beam operations are available with a reported white beam flux of 4×10^6 n/cm²/s. A helium, He, filled flight tube is available with aperture settings capable of achieving L/D ratios from 400 to 800. Scintillation detectors are available with resolutions as low as 50 μ m, and an MCP detector is available with 40 μ m spatial resolution. Current capabilities include 1 frame per second detection rates with pixel binning and tomographic scanning capabilities [Ref. 21]. Currently the Spallation Neutron Source (SNS), also on the ORNL campus, is planning to develop an additional neutron imaging facility with neutron energy selection capabilities. This new facility, the Versatile Neutron Imaging Instrument at the SNS (VENUS), is still in the development phase [Ref. 22].

1.5 National Institute of Standards and Technology

The National Institute of Standards and Technology (NIST) Center for Neutron Research is located on the Gaithersburg, MD campus. It houses the Neutron Imaging Facility (NIF) on

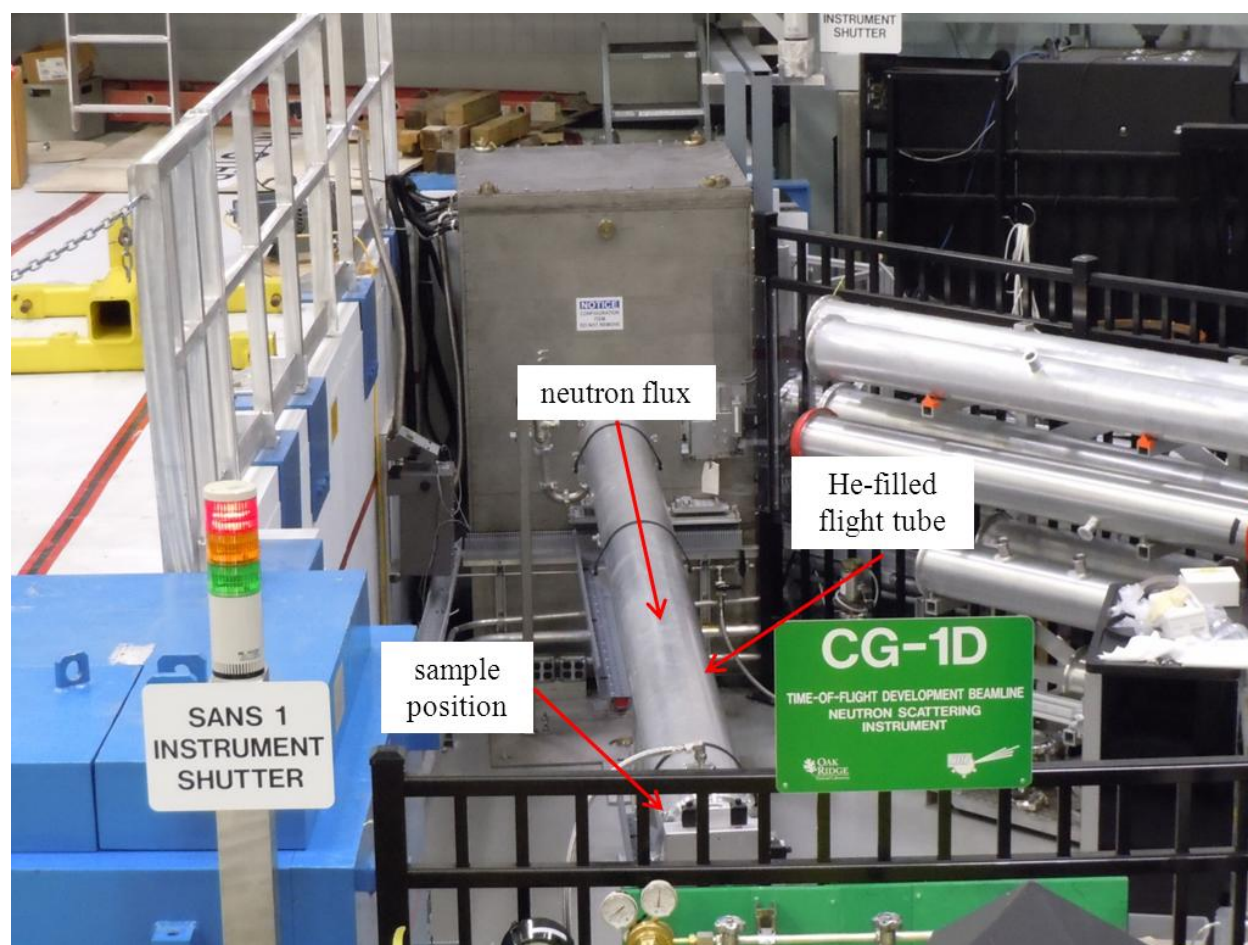


Fig. 5: CG-1D beamline at ORNL with the helium filled flight tube installed.

beamline BT2, which is a thermal beamline attached to a 20 MW heavy-water-cooled reactor. Both MCP and scintillator detectors are available with 30 μm and 50 μm resolution reported, respectively [Ref. 13]. The maximum L/D ratio of 6000 can be achieved using the smallest aperture setting and ranges down to 300. The maximum reported flux for this facility is 3.3×10^7 n/cm²/s utilizing the minimum L/D ratio. Both tomographic and radiographic imaging tests can be performed here, and an emphasis has been placed on in situ imaging of water distribution in fuel cells [Ref. 23].

1.6 Literature Review

Neutron radiography has been employed to study heat pipe operations focusing on two-phase flow distribution in dynamic testing. Liquid vaporization in different wicking structures of stainless steel-water heat pipes has been studied to enhance modeling of this phenomenon [Ref. 24]. Pulsed boiling in a steel-water heat pipe was studied at three different filling quantities and matched with temperature dependence. Three distinct regions were found in the heat pipe corresponding with liquid filled, periodically filled, and constantly vapor filled regions [Ref. 25]. Loop heat pipe operations were the focus of work done by Cimballa et al. [Ref. 26] which utilized ammonia as the working fluid. Results indicate that reverse flow can occur as heating ends and that during unsteady operations vapor is present in the liquid. Fluid flow in oscillating heat pipes (OHP) is seen to achieve higher velocities, amplitudes, and frequencies as heat input is increased [Ref. 27]. This was investigated further to compare water and acetone OHPs with better performance noted at relatively high temperatures with water and at lower temperatures with acetone due to fluid properties. The heat pipe orientation had little impact on test results [Ref. 28]. Volume fraction data of this phenomenon was studied by Yoon [Ref. 29]. Temperature

dependent volume fraction of a water OHP was further investigated [Ref. 30]. Thermal resistance drops for three-dimensional OHPs as a result of higher frequencies when power input is increased. Reducing the filling ratio of the heat pipe also increases the frequency, but acts to effectively reduce heat transfer [Ref. 31]. Experiments focused on localized heating of OHPs found that fluid movement was confined to the heating area, and unlike other OHPs the thermal resistance increases with power input [Ref. 32]. Thompson, Ma, and Wilson concluded that the inclusion of Tesla-type check valves could increase OHP performance with more research needed to optimize the geometry [Ref. 33]. Self-vibrating heat pipes using butane as the working fluid were investigated to match experimental oscillations with those predicted using a mass-spring model with good agreement found in tests with shorter periods [Ref. 34]. A variable conductance heat pipe filled with water and nitrogen was studied to determine the performance effects of filling ratio, heat pipe orientation, and the inclusion of a thin plate. Liquid plug formation, which can be detrimental to performance, was prevented using the insertion of a thin plate. Inverted orientations caused the heat pipe to stop working by blocking the evaporation site by completely filling with liquid [Ref. 35].

Chapter 2

Initial Testing and Fluid Properties

2.1 Ni-Na Heat Pipe Radiography

The initial testing of neutron radiography for high-temperature, liquid metal heat pipes was performed using a nickel-sodium, Ni-Na, heat pipe at NIST, Fig. 6. This nickel alloy heat pipe is 15 cm long with a 3 mm by 10 mm cross section. Testing was performed at ambient conditions to determine if the contrast of Na would allow for dynamic imaging of an operational heat pipe. Although a clear distinction is seen in Fig. 6, a long exposure time of 100 s was required to produce this image. The transmission can be calculated from:

$$T = I/I_o \quad (2.1)$$

and equation 1.1 using a value of 3.81 barn (1 barn = 10^{-24} cm²) for the thermal neutron attenuation cross section and 3 mm for the sample thickness. This results in a 97% transmission, or 3% contrast necessitating long exposures [Ref. 36, 37].

2.2 Torus Mo-Li Heat Pipe

To alleviate the need for long exposures, the working fluid of the heat pipe can be changed to enhance the contrast. The obvious choice for this is Li, as its thermal neutron attenuation cross section is 71.9 barns, much higher than other alkali metals. Also, it is commonly used in high-temperature heat pipes. If the heat pipe in Fig. 6 were filled with Li instead of Na, the contrast would change from 3% to 63% which is beneficial for flow visualization. To ensure the viability of this conclusion, a torus Mo-Li heat pipe partially filled with Li was radiographed at ORNL, Fig. 7. This pipe has an outside diameter of 11.6 cm and a

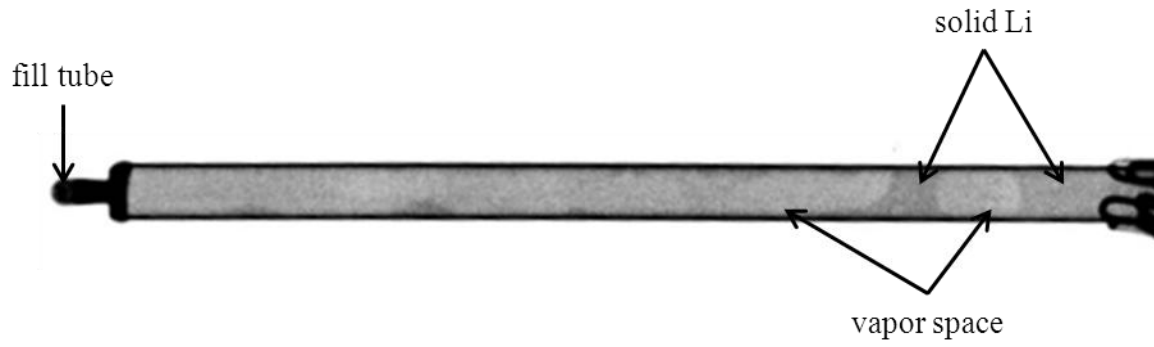


Fig. 6: Ni-Na heat pipe at ambient conditions using a 100 s exposure [Ref. 36].



Fig. 7: Torus Mo-Li heat pipe at ambient conditions on CG-1D [Ref. 38].

tube diameter of 1.9 cm. Solid Li is clearly visible in this 180 s radiograph serving as a proof of concept for future high-temperature testing [Ref. 38].

2.3 Fluid Properties

Because of the higher contrast, Li is a better selection than Na for neutron radiography. Additionally, it is well suited to high-temperature heat pipe applications. Fluid properties for three alkali metal working fluids and water are shown in Table 3. The properties are given at the atmospheric boiling temperatures for each fluid to reflect operational values. The latent heat of vaporization for Li is an order of magnitude greater than that of water and the other alkali metals, increasing the potential heat flux. Li also has the highest surface tension allowing for better wetting of heat pipe wicking structures and higher operational temperatures as seen in Table 1. While water has a higher linear attenuation coefficient at atmospheric boiling conditions, Li flow visualization is possible.

Solid Li will melt at 181°C as the high-temperature heat pipe is heated from ambient conditions to operational temperatures around 900°C. The vapor pressure inside the pipe, limited to the partial pressure, will increase but remain below one atmosphere throughout the test, Fig. 8. The Li density variation with temperature from 200°C to 1200°C is shown in Fig. 9. The decrease in liquid Li density should be evident in neutron radiography tests corresponding to an increase in the occupied volume. Fig. 10 shows the surface tension changes with temperature over the same range. The decrease in surface tension will lower the capillary pressure as the temperature increases [Ref. 39].

Table 3: Fluid properties for H₂O, Li, Na, and K at boiling temperature for atmospheric pressure [Ref. 6, 36].

Working Fluid	Melting Temperature [°C]	Boiling Temperature (at 1 atm) [°C]	Atomic Weight [g/mol]	Liquid Density [kg/m ³]	Liquid Viscosity [mPa-s]	Liquid Surface Tension [N/m×10 ²]	Latent Heat [kJ/kg]	Thermal Neutron Attenuation Cross Section [cm ² ×10 ²⁴]	Linear Attenuation Coefficient [1/cm]
H ₂ O	0	100	18.0	958	0.28	0.59	2258	169	5.42
Li	181	1342	6.94	419	0.23	2.6	19650	71.9	2.61
Na	98	883	23.0	746	0.17	1.1	3913	3.81	0.07
K	63	759	39.1	670	0.12	0.65	1926	4.06	0.04

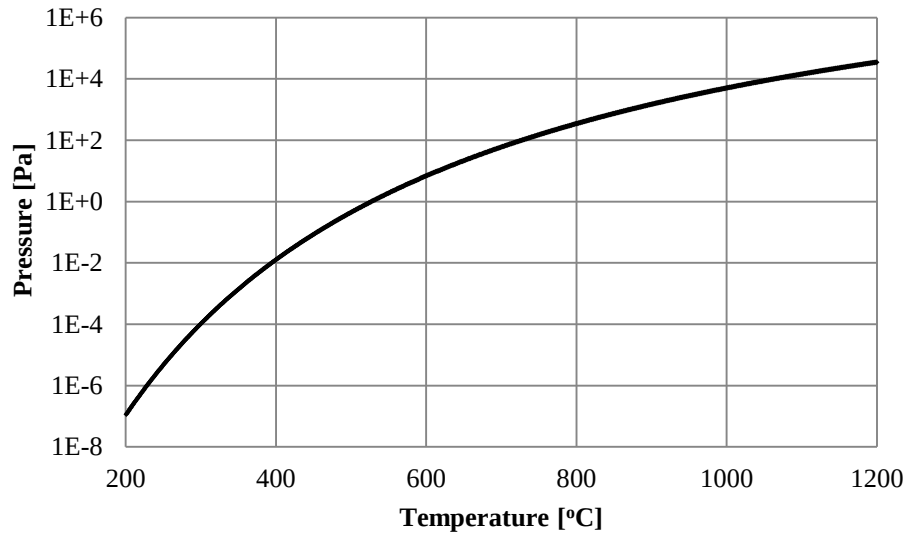


Fig. 8: Vapor pressure of Li vs. temperature.

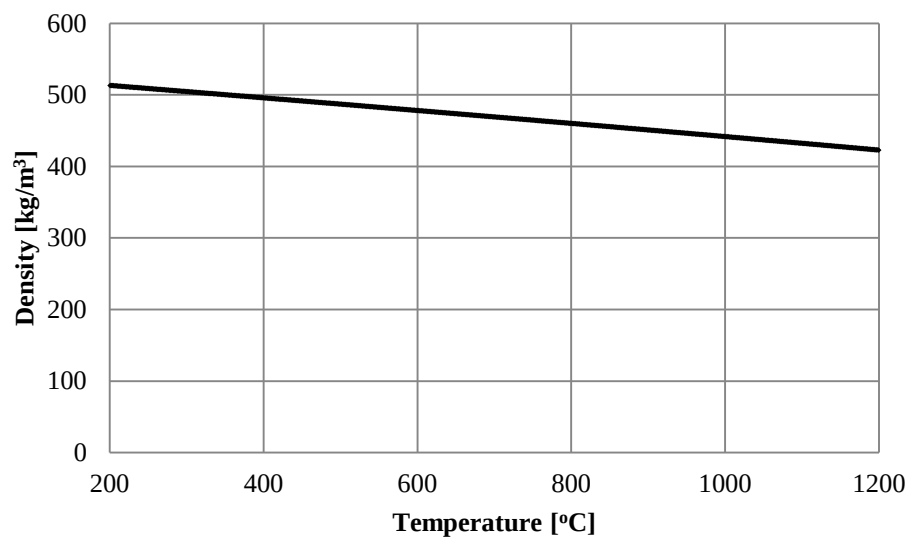


Fig. 9: Liquid Li density vs. temperature.

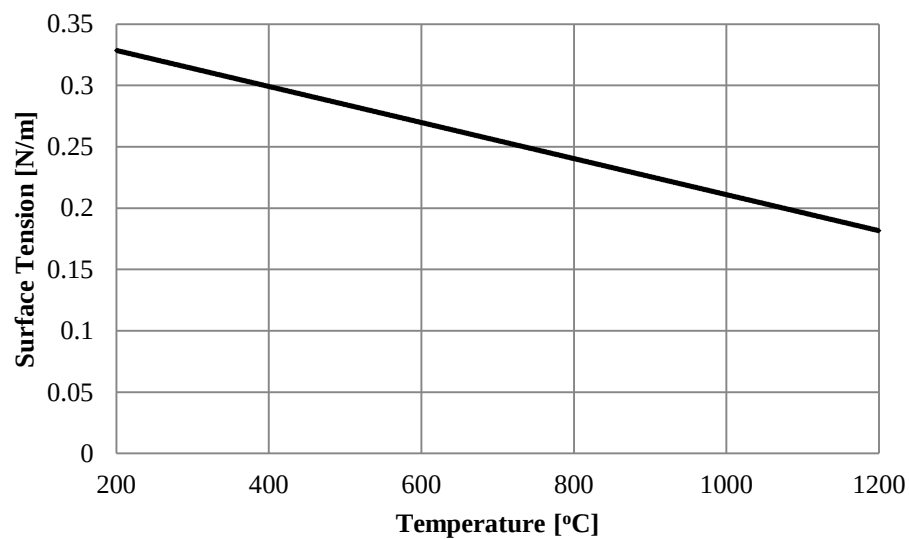


Fig. 10: Surface tension of Li vs. temperature.

Chapter 3

Test Setup and Methods

3.1 Cylindrical Mo-Li Heat Pipe

The first neutron radiographic images of an operational high-temperature heat pipe were performed on a 25 cm long Mo-Li heat pipe with an external diameter of 3.5 cm, Fig. 11, and the results have been accepted for publication [Ref. 38]. The internal geometry is depicted in Fig. 12; it has a square internal cross section with corner radii of 0.125 mm that act as wicking structures. This Mo-Li heat pipe is filled with 10 g of Li and operates as a gravity assisted heat pipe. The estimated operational temperature for this pipe is 900°C.

3.2 Experimental Setup

To prevent oxidation of Mo at high temperatures, a vacuum test platform was used. This was constructed from 1/8" (3.18 mm) stainless steel with feed through ports for a resistance wire heater, four Type K thermocouples, a turbomolecular vacuum pump, and a cold-cathode pressure gauge, Fig. 13. The heat pipe sat at the bottom of the vacuum chamber, oriented 17° from the neutron beam, Fig. 12, on an Al₂O₃ stand to insulate the pipe from the stainless steel thermally. The heat pipe is wrapped in the Mo resistance wire heater, which is insulated electrically from the heat pipe using Al₂O₃ fish spine beads, Fig 14. This covers the bottom 80 mm of the pipe around the evaporator. The four Type K thermocouples were attached 80 mm, 120mm, 161 mm, and 198 mm from the bottom of the pipe and labeled 1 through 4 respectively. Surrounding the resistance heater, thermocouples, and heat pipe were eight layers of Mo foil to serve as radiation shielding. The vacuum inside the test platform, along with the ceramic stand, limited heat loss



Fig. 11: Cylindrical Mo-Li heat pipe.

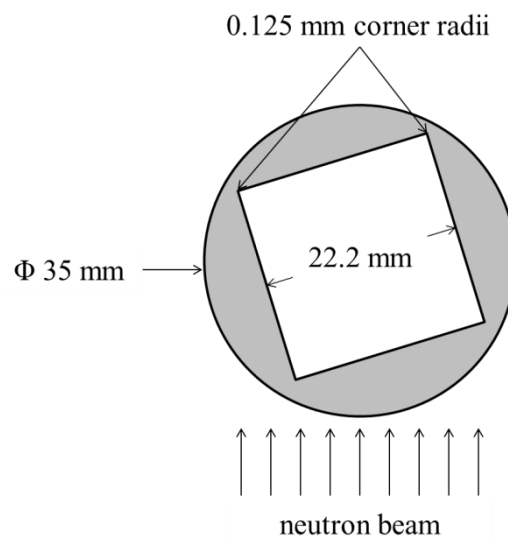


Fig. 12: Internal geometry of Mo-Li heat pipe and orientation to the neutron beam [Ref. 40].

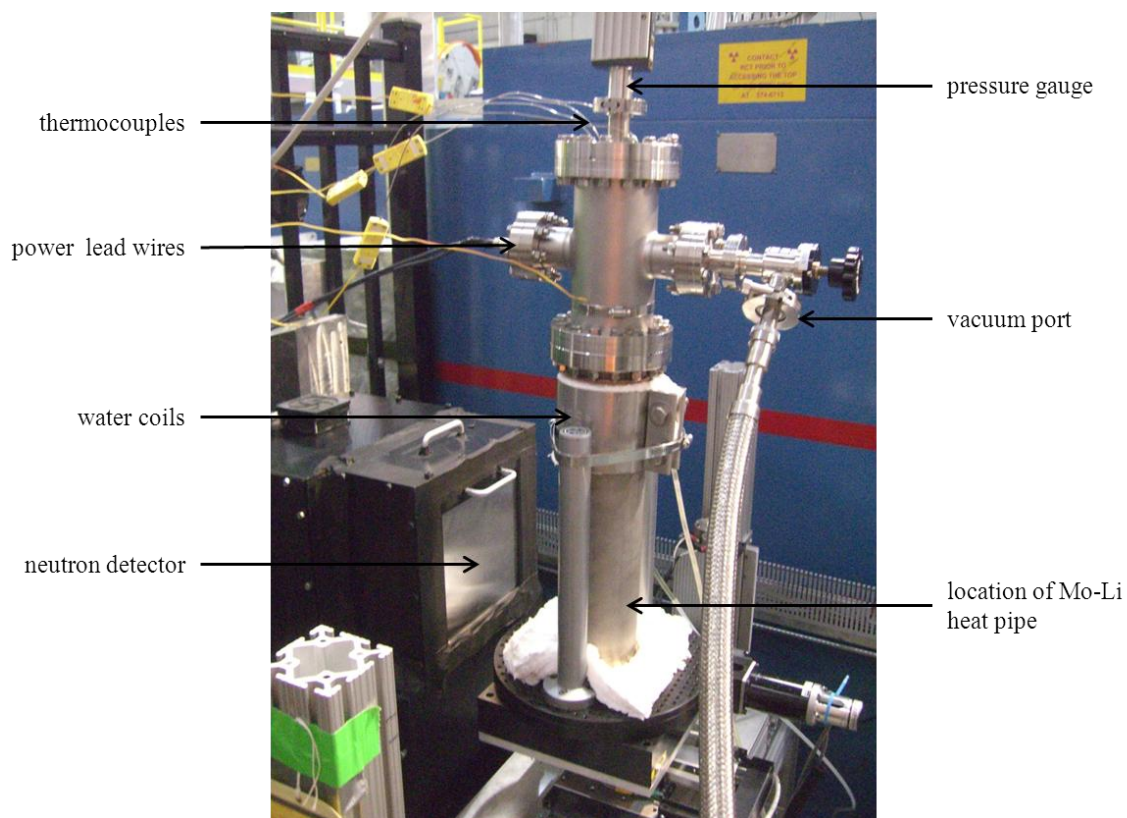


Fig. 13: Test platform at the CG-1D beamline [Ref. 39].

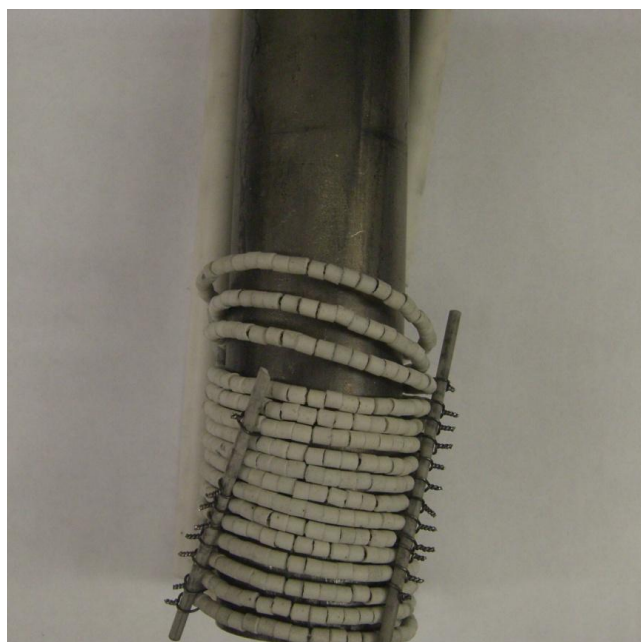


Fig. 14: Mo wire resistance heater wrapped in alumina fish spine beads.

from the pipe to radiation. Temperature measurements were taken from thermocouples 1, 3, 4 and one located on the exterior of the vacuum vessel using a data acquisition system attached to a portable computer. Thermocouple 2 was attached to a temperature controller that feeds into the power supply to shut off power automatically if the temperature exceeded 950°C. Temperature measurements were taken from this thermocouple manually. The vacuum pump was attached to the vessel through a shut-off valve to allow for isolation of the system in the event of heat pipe rupture and Li dispersion. The cold-cathode ion pressure gauge is capable of reading pressures from atmospheric conditions down to 3.8×10^{-10} Torr (51 nPa), and the turbo pump has a base pressure of 1.5×10^{-7} Torr (20 μ Pa). The vacuum vessel below the four-way cross was water cooled using $\frac{1}{4}$ " (6.4 mm) copper tubing attached to a water chiller with a set point temperature at 20°C. The entire test platform was held in place using two steel optical posts, bolted to the imaging table, and two stainless steel hose clamps. The external thermocouple was attached to the vessel using another hose clamp and is located above the heat pipe out of the imaging field of view. A schematic of this entire system is presented in Fig. 15.

3.3 Test Procedure

The testing procedure begins by assembling the test platform and pumping the system down below 10^{-4} Torr (13 mPa). This is the set point to safely operate the heat pipe. Since neutron beam time is expensive, optimization should be done before setup on the imaging line. Therefore, a bake out test is performed prior to setup on the test stand. This is done by heating the pipe above 700°C while maintaining adequate pressure in the vessel. Once this process is completed, the heater power supply is turned off and the heat pipe is allowed to cool to ambient conditions with the turbo pump running. The shut-off valve is closed and the entire testing

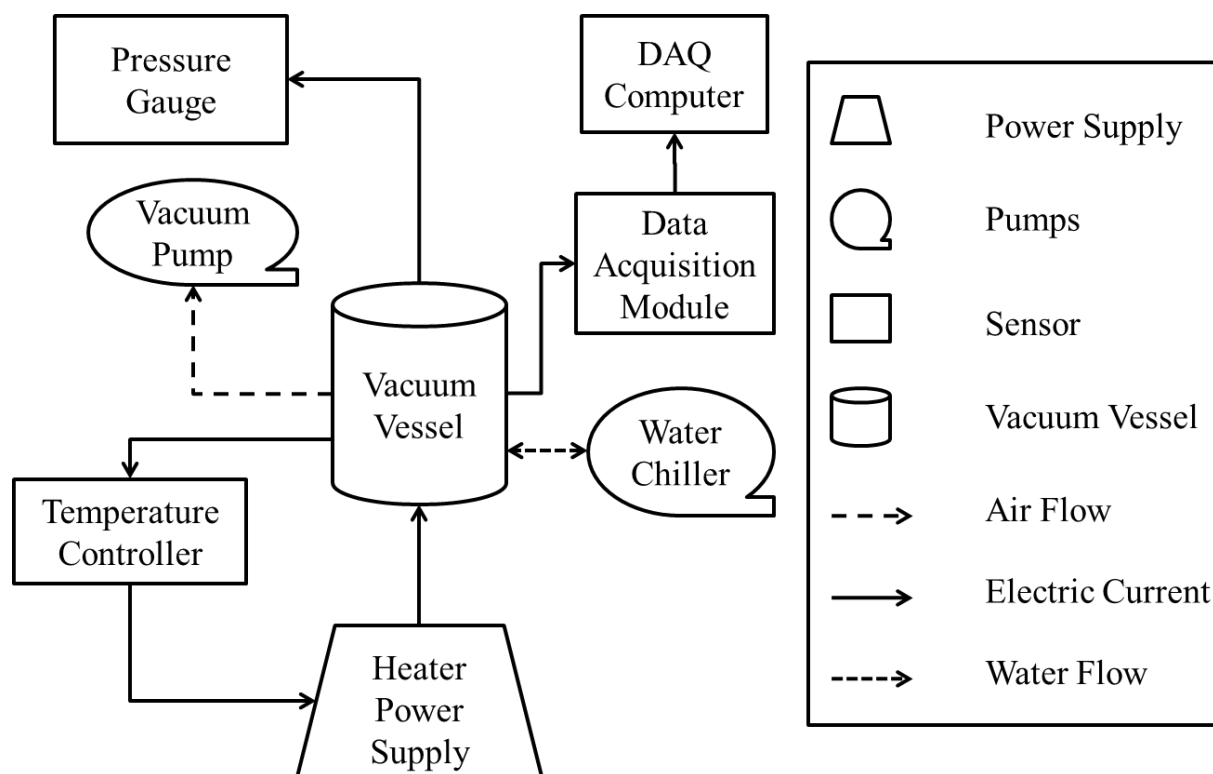


Fig. 15: Schematic of test platform.

platform is moved to the imaging stand on the beamline. Although the system is closed, small leaks in the system will eventually raise the pressure requiring the pump to be restarted as quickly as possible. After all ancillary equipment is connected, the imaging test begins.

Neutron imaging was performed using 30 s exposures from ambient conditions to steady-state at 900°C and through two large power fluctuations. Power was increased by controlling the voltage to the power source. Increases were performed in 1.5 V increments, with current automatically adjusted, for the majority of startup, but were dictated by maintaining pressure. Eleven hours were required to reach the operational temperature where the power was held for five minutes at 323 W. The heater power supply was then turned off and the pipe cooled for 20 min. Subsequently, power was increased to 347 W, held for 10 min, increased further to 471 W, and held for 6 min before being turned off again. After cooling for 14 min, the power was increased again to 467 W and held for 6 min. This was the final power fluctuation to the pipe, and the pipe was allowed to cool afterward.

After reaching ambient conditions, the power supply, vacuum pump, pressure gauge, and thermocouples were removed from the test platform and tomographic imaging began. This was performed using 180 s exposures with each projection 1.5° apart from 0° to 181.5°. Although attenuation from the test platform makes this setup less than ideal, time constraints from the beamline necessitated this method.

Image normalization of the heating test was performed using iMars software developed by ORNL. Tomographic reconstruction was performed using Octopus software by ORNL collaborators [Ref. 41].

Chapter 4

Results and Discussion

4.1 Cylindrical Mo-Li Heat Pipe Temperature and Pressure Performance

The high-temperature radiography test of the cylindrical Mo-Li heat pipe successfully imaged heat pipe operations from ambient conditions to steady-state at a maximum recorded temperature of 903°C and through two large power fluctuations. Fig. 16 is the temperature data recorded through the data acquisition system for thermocouples 1, 3, and 4 and by hand for thermocouple 2. The data acquisition system recorded temperatures in ten second increments, and the hand recorded data was taken immediately preceding power changes. At the maximum temperature, there is a 34.5°C temperature difference between thermocouple 1 and thermocouple 4. Since thermocouple 1 is located at the top edge of the resistance wire heater, it is expected that the maximum temperature actually exceeded 903°C on the exterior of the heat pipe in the middle of the resistance heater. However, the interior temperature gradient should be less, assuming proper heat pipe operation, due to Li evaporation. Temperature readings for the first two hours are not available for thermocouples 1, 3, and 4, but follow the trend from thermocouple 2. This is confirmed from the temperature data recorded for the bake out test, Fig. 17.

The extended testing time is a result of poor pressure performance in the vacuum vessel. Pressures below 10^{-4} Torr (13 mPa) were required to increase power to the resistance heater. The bake out testing achieved a maximum temperature of 703°C in five hours and four minutes under this condition. To achieve this same temperature during radiography, testing required three hours and forty-four minutes. However, to increase the operational temperature the

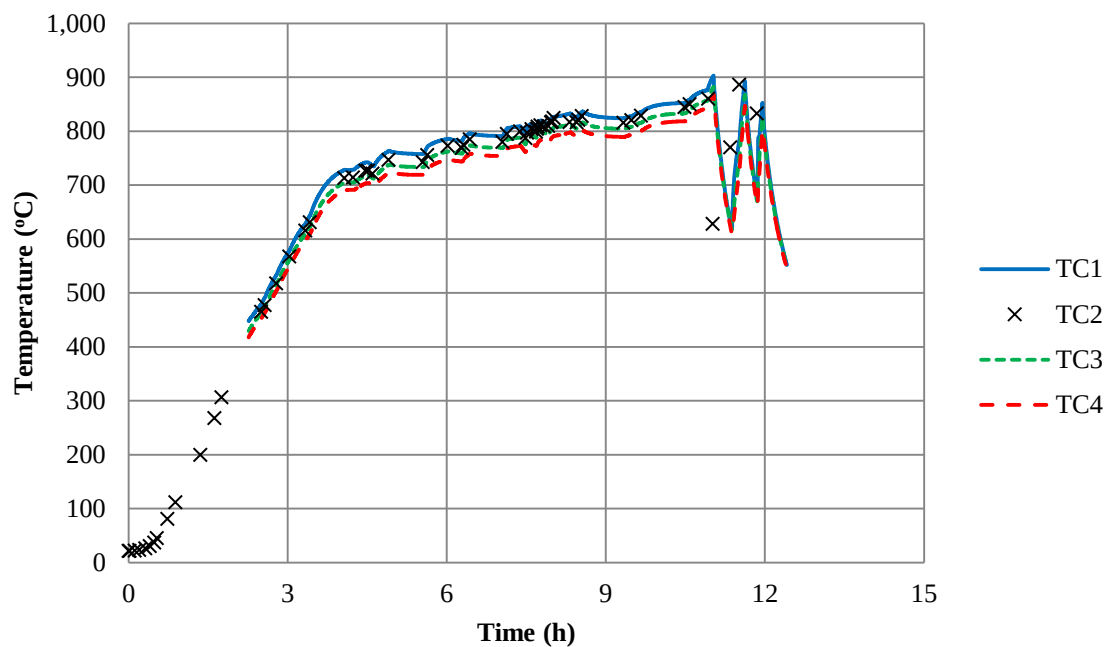


Fig. 16: Thermocouple readings for the high-temperature neutron radiography test.

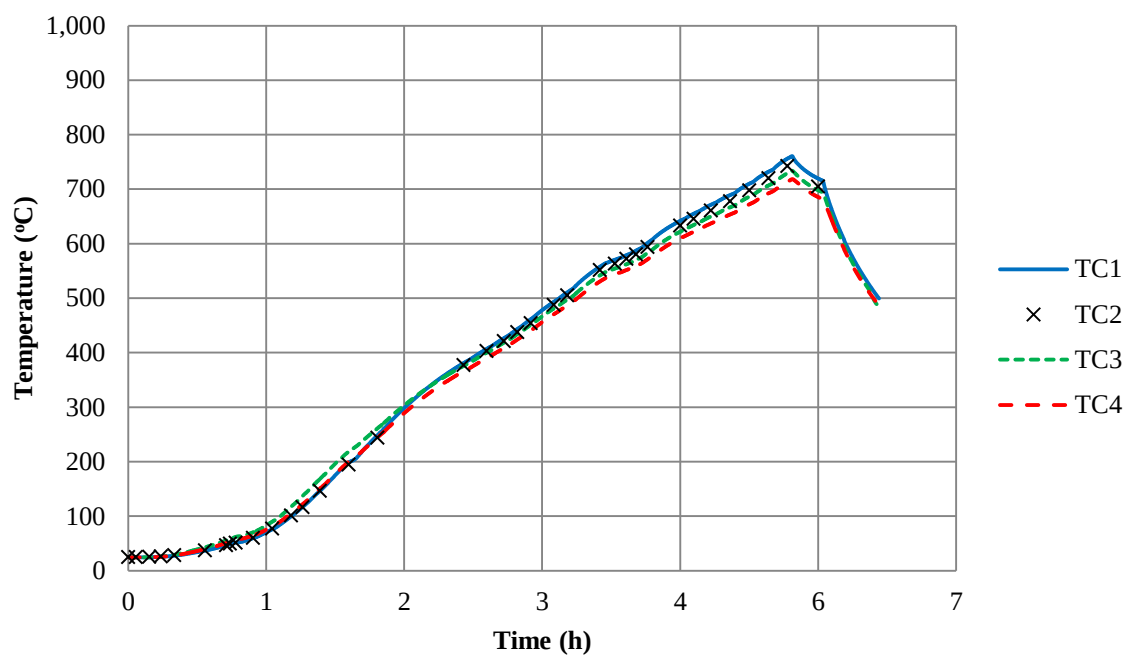


Fig. 17: Thermocouple readings for bake out test.

remaining 200°C, another seven hours and eighteen minutes were needed. Longer bake out tests to the desired operational temperature are needed to alleviate this problem and to maximize time on the neutron beamline. Pressure increases are expected as the temperature of the system increases due to an increase in vapor molecule energy, evaporation of oils caused by material handling, and outgassing. Additionally, leaks from one of the gaskets or feed throughs may have raised the base pressure, increasing the required pump down time. However, since the pressure behaved the same during the two power fluctuations of the radiography testing, it is believed that outgassing from the resistance heater is the main reason for poor vacuum performance. This can be alleviated with the design of a new heating element.

4.2 Cylindrical Mo-Li Heat Pipe Radiography

Li flow visualization was successfully achieved from startup to steady-state operations using the cylindrical Mo-Li heat pipe. Chronological reconstruction of normalized images shows an increase in the bulk Li level with temperature. Fig. 18 (a) and (b) show the normalized images at 22°C and an average temperature of 893°C respectively. Thermocouple 1, the resistance wire heater, and radiation shielding are labeled along with the bulk Li and Li in the corner channels. A time lapse video of each image throughout the radiography test shows few dynamic changes. This is expected since the exposure time for each image is 30 s. Although it is difficult to detect changes in the Li level in this figure, a clear distinction can be seen when taking the difference between (a) and (b). This was done in ImageJ and can be seen in Fig. 19. Light areas represent changes between the two images. A bulk Li rise is evident and has been measured to be 9 mm between ambient condition and 893°C. Additional changes include shifting of the wire heater, movement of the radiation shielding, and slight movement of

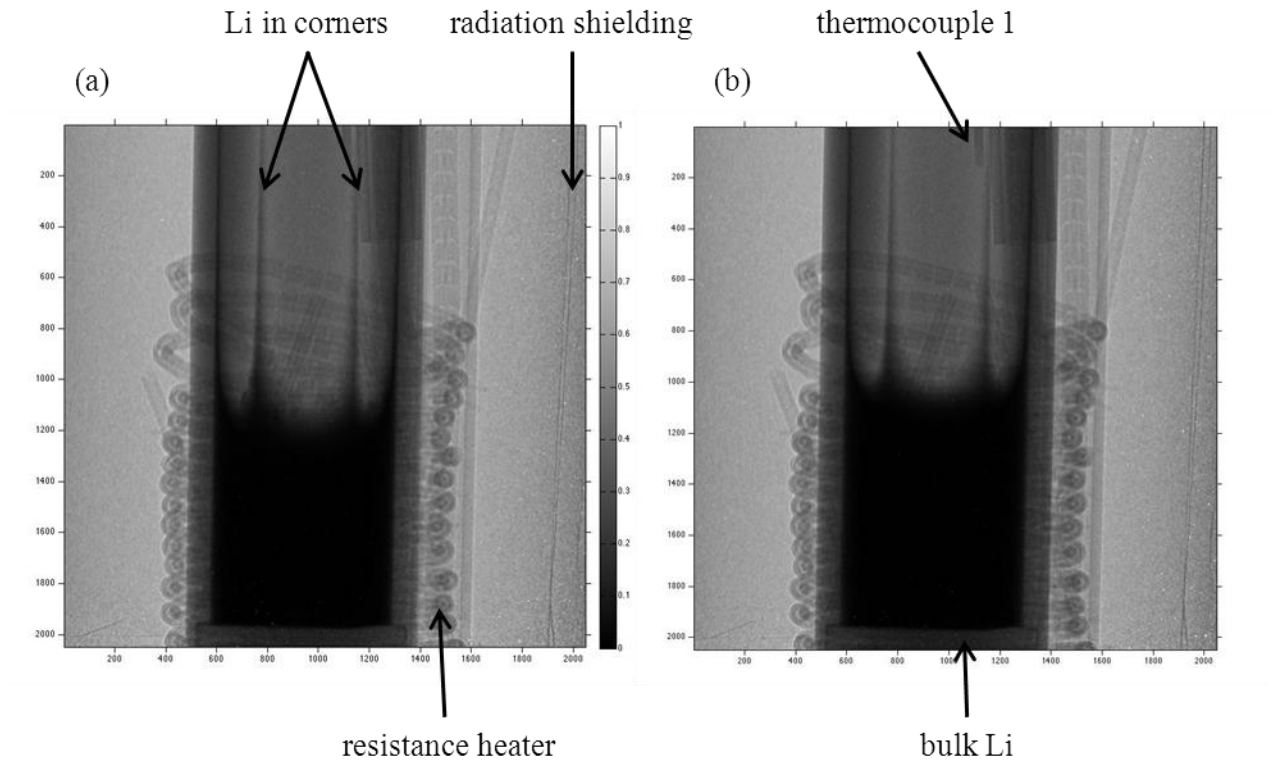


Fig. 18: Cylindrical Mo-Li heat pipe at (a) ambient conditions, 22°C and (b) heated, 893°C [Ref 38].

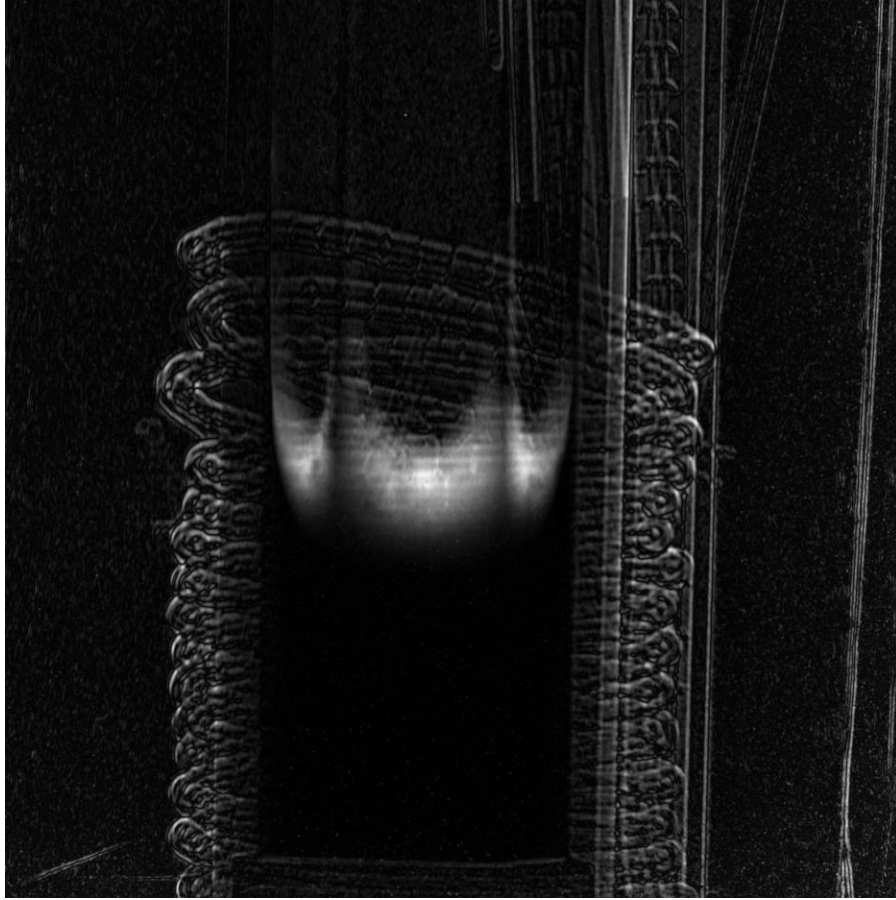


Fig. 19: Image difference between 22°C and 893°C. Lighter areas show changes [Ref. 38].

thermocouple 1. Changes in the bulk Li level are a result of Li density changes with temperature and changes in surface tension. As seen in Fig. 9, the density increases with temperature which causes a volumetric increase. Additionally, since surface tension is inversely related to temperature, Fig. 10, some Li held at the top corners of the pipe by capillary pressure is expected to flow down the pipe. This assumption is confirmed by noting the decreased concavity of the Li meniscus between Fig. 18 (a) and (b). The trends described hold for the duration of the test including the two power fluctuations.

Dynamic movement of Li is seen during the power fluctuations. As power increases to the heat pipe and the temperature rises, a Li slug moves from the condenser to the evaporator region of the heat pipe, Fig. 20. This is restricted to only one side of the heat pipe which can be attributed to a slight lean of the heat pipe, 1.3° , in that direction. This behavior is noted in the same location for both power surges.

4.3 Cylindrical Mo-Li Heat Pipe Tomography

Tomographic reconstruction of Li inside the cylindrical Mo-Li heat pipe shows the Li rise in each of the four corner channels, Fig. 21. Although Li flows down the corner channels while operational, it is expected that capillary forces hold Li in the channels as the heat pipe cools and Li solidifies. Though no operational data can be gained from this procedure, workmanship and Li wetting information can be obtained.

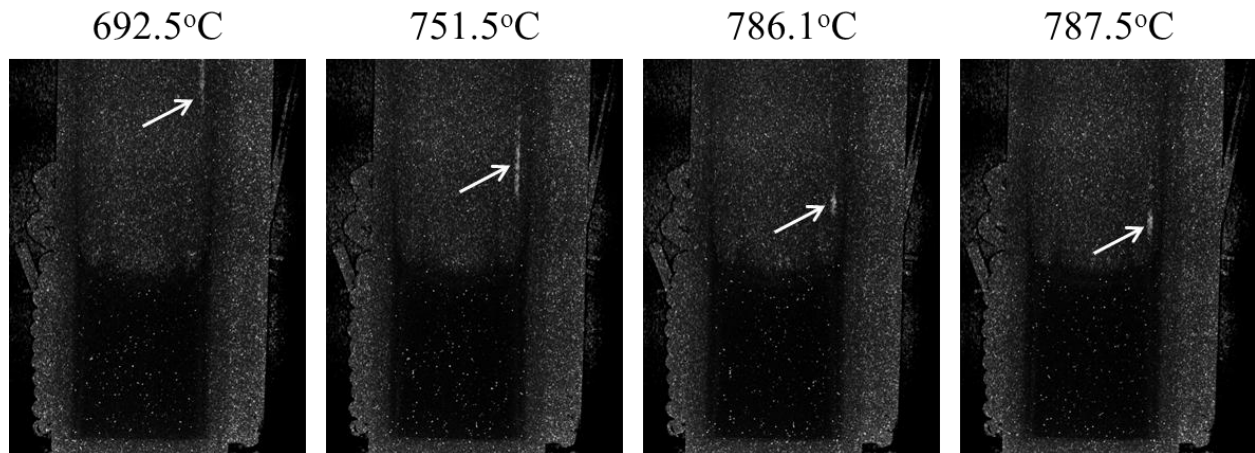


Fig. 20: Dynamic movement of Li as the heat pipe is heated during the second power fluctuation.

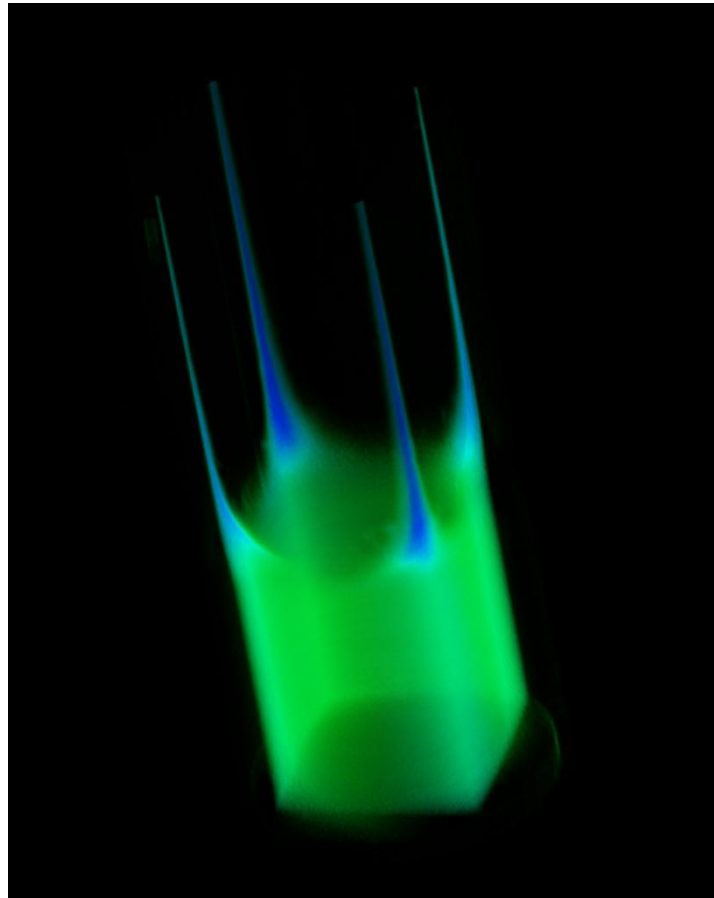


Fig. 21: Tomographic reconstruction of Li inside cylindrical Mo-Li heat pipe [Ref. 38].

Chapter 5

Conclusions and Recommendations

Neutron imaging successfully captured Li level and meniscus concavity changes associated with temperature in a high-temperature heat pipe. This Mo-Li heat pipe is the first operational high-temperature heat pipe to be imaged in this manner. Due to the long exposure period, dynamic changes are only seen during power fluctuations. An emphasis should be placed on decreasing the exposure time to visualize Li flow behavior. Additionally, a heat transfer analysis during neutron radiography will allow for a better understanding of heat pipe operations through a correlation of heat flux and Li movement.

Future testing will focus on Li movement utilizing dynamic imaging on the order of 1 frame per second. New heat pipes will be tested that use refractory metal wire meshes for the wicking structure. The strong capillary force from liquid metals should allow operation in any orientation with minimal effect. Efforts should be made to achieve unsteady operation by increasing the heat flux beyond the operational limits and attempting asymmetric heating. This coupled with heat transfer analyses will provide beneficial insight into high-temperature heat pipe operations. To increase efficiency on the beamline, a new testing platform should be utilized. This should be designed to accommodate the tests previously described.

Chapter 6

Redesigned Test Platform

6.1 Platform

Recent work has been performed to develop a new test platform for future testing. To accommodate different heat pipes, including variable heating orientations, a vacuum bell jar system has been selected. This will allow for visual inspection of heat pipe operations while maintaining the necessary vacuum. A stainless steel service well, constructed with two 2.75" CF flanges (7.00 cm) and two KF40 ports, serves as the base upon which a fused quartz bell jar sits. Fused quartz is used instead of the more common Pyrex type bell jar because Pyrex is a borosilicate glass which is effectively opaque to neutrons. The bell jar is ¼" (0.64 cm) thick, with an internal diameter and height of 12.0" (30.5 cm). The service well has an internal diameter of 11.8" (30.0 cm) and an external sealing flange diameter of 16.0" (40.6 cm). This distance will limit the minimum sample-to-detector distance and cause some geometric blurring but is necessary to house future tests. A drawing of the new test platform is shown in Fig. 22. Imaging will be performed above the top of the service well limiting attenuation to the bell jar. The same turbomolecular pump and pressure gauge will be used from the previous test platform and will be connected by way of the KF40 ports. Four K Type thermocouples will be used to measure temperature data.

6.1 Heating Element

Induction heating is used on the new test platform to alleviate outgassing from the resistance heater and allow for heat pipes of various geometries. Induction heating is caused

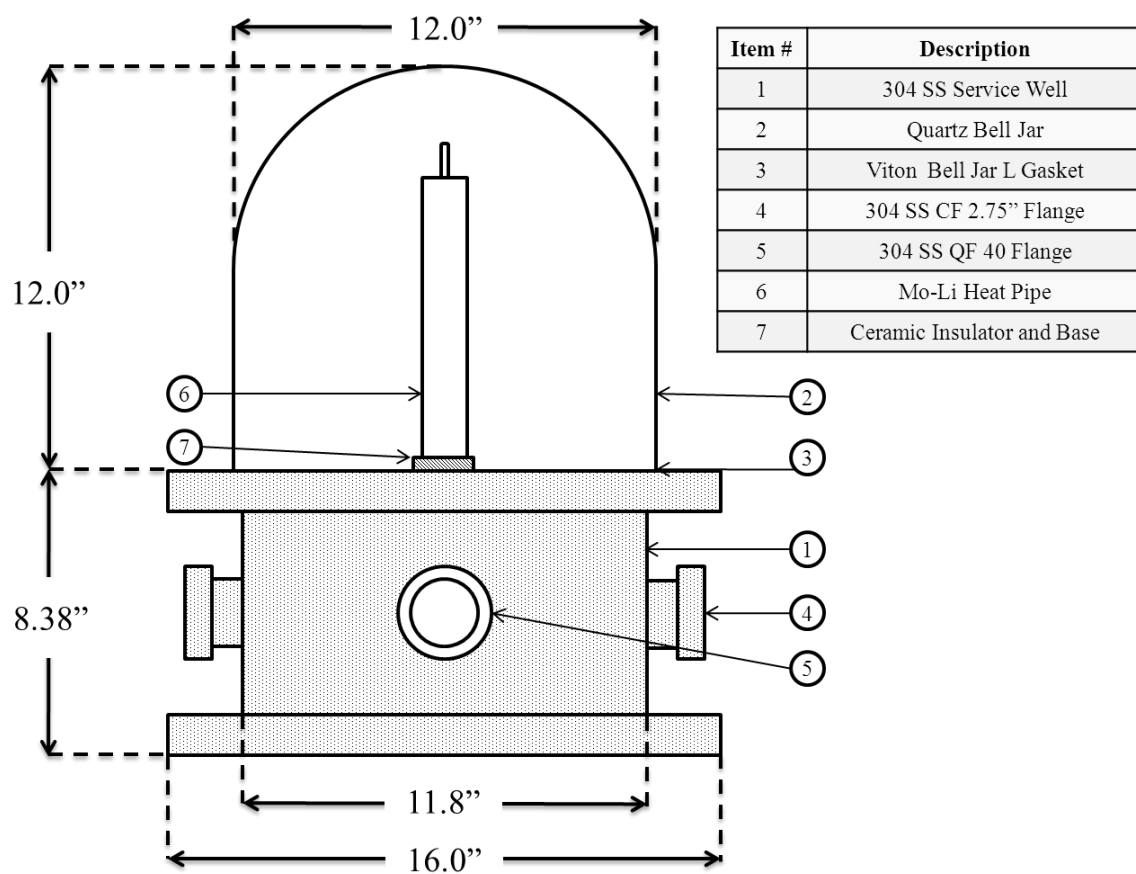


Fig. 22: Bell jar test platform design.

mainly by Joule heating in metals and results from the relationship between electric and magnetic fields. A current passing through a conductor will create a magnetic field aligned 90° from the electric current following the right-hand rule. If a conductor is placed in the induced magnetic field, an electric current is produced. With the application of an alternating circuit across the original conductor, Eddy currents are formed causing Joule heating in the secondary piece, the heat pipe. This can be thought of as a transformer system, meaning the coupling efficiency is proportional to the distance between the primary and secondary conductors. Therefore, the distance between the induction coil and the workpiece should be minimized to achieve the most efficient heating. Moreover, the induction coil geometry must be designed such that magnetic flux lines do not intersect and cancel out [Ref. 42].

Induction coils are generally constructed from copper and may be fabricated to fit any workpiece. The coils are water cooled, which must be taken into account due to the strong neutron attenuation from water. To alleviate this, the coil geometry can be made to completely avoid attenuation, Fig. 23. This coil was designed and fabricated by Ambrell so a heat pipe will sit between the white, u-shaped area of the coil with the neutron beam passing perpendicular to the page. A separate design is to use a helical coil, which has a higher coupling efficiency, with heavy water as the coolant. Because the attenuation from heavy water is significantly less than light water, Fig. 2, Li imaging is possible through this coolant. Both coil types are being used for further high-temperature heat pipe radiography testing. The new test platform is seen in Fig. 24 on the CG-1D utilizing the induction heating system. Testing will continue using this platform, and the incorporation of heat transfer analyses is ongoing.



Fig. 23: U-shaped induction coil fabricated by Ambrell.

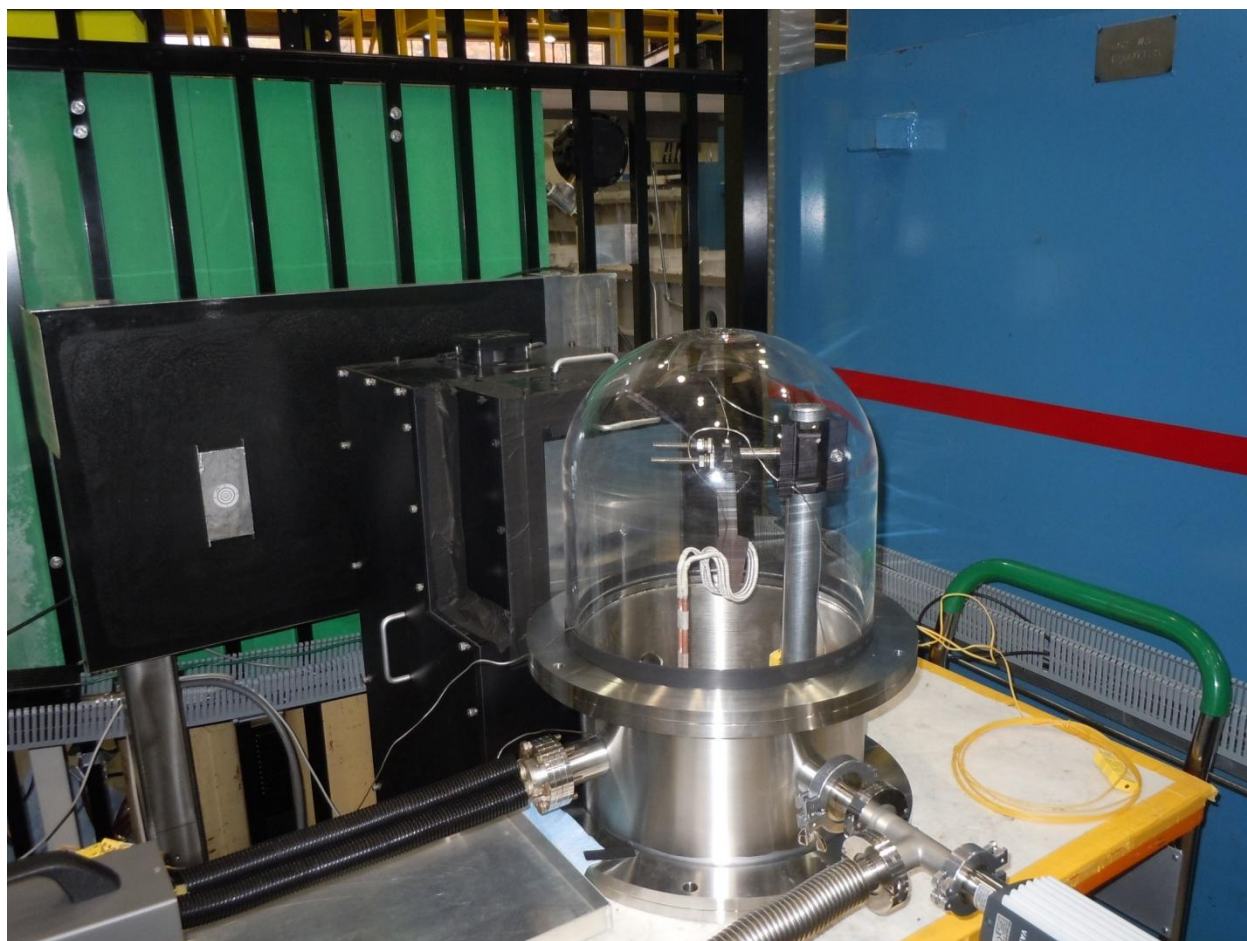


Fig. 24: Redesigned test platform.

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Vita

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