Cryogenic Boiling

Cryogenic Boiling Team 1 (aka Charlie)

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Final Report

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The use of liquid nitrogen as a cryogenic fuel is promising due to it's low freezing and boiling points, abundance in the atmosphere, and the fact that is inert and relatively safe for humans. However, the lack of consistent pool boiling data has made implementation difficult. The boiling of liquid nitrogen can produce dangerously high pressure in storage tanks, and without proper pool boiling data there are not yet any means of safe storage as a fuel. This experiment will investigate the boiling characteristics by immersing cylinders initially at ambient conditions in liquid nitrogen, and then measuring how the temperature changes over time using thermocouples. The results provide clear insight on the cool down time of liquid nitrogen and discuss heat flux and boiling with regards to this experiment and published data, ultimately providing a greater understanding of cryogenic propellants for long-term space travel.

Contents

Nomenclature

A_1 = Constant of initial and boundary conditions of the system
Bi = Biot number
T_i = Initial temperature of the aluminum cylinder
T_s = Subsurface temperature of the cylinder during the cooling process
T_∞ = Ambient temperature (Liquid Nitrogen)
ΔT = Change in temperature
c_p = Specific heat
h = Heat transfer coefficient
k = Thermal conductivity
q = Heat transfer per unit area
r = Radius of cylinder
t = Time
α = Thermal diffusivity
λ_1 = Biot calculation constant
ρ = Density
τ = Time constant

I. Introduction

The motivation for this experiment is to enhance the understanding of heat transfer and cooling properties of cryogenic substances, specifically liquid nitrogen. Efficient storage and transfer of cryogenic propellants, such as hydrogen and oxygen, is crucial for the success of space missions. However, these propellants are prone to boil off, leading to significant loss and inefficiency in propulsion systems. Therefore, the objective of this project is to investigate the boiling characteristics, cool-down time, and heat transfer dynamics of liquid nitrogen by immersing aluminum cylinders into the cryogenic fluid. By conducting a detailed analysis of temperature gradients and heat transfer measurements, the experiment aims to reduce uncertainties and improve the accuracy of data related to boiling in liquid nitrogen. This improved understanding of cryogenics will contribute to the development of more efficient storage and transfer systems.

To prepare for the experiment, Team Charlie utilized a published report from NASA[1] that compiled studies conducted over the past 70 years (see Figure 1). The analysis of these studies revealed significant levels of uncertainty in the heat flux of liquid nitrogen during boiling, with variations exceeding an order of magnitude even at a single wall super-heat level likely due to large fluctuations in the temperature data. The methodologies employed in these studies varied widely, leading to inconsistencies and challenges in comparing the results. To validate the effectiveness of the test procedure, this team plans to utilize the average results from the NASA report as benchmark data. While the NASA report covered a range of geometries, sizes, and materials for quenching substances in liquid nitrogen, this project will specifically focus on studying the quenching process of aluminum cylinders, providing valuable insights into the heat transfer and cooling properties of cryogenic substances.

Team Charlie aims to investigate the heat transfer and cooling properties of liquid nitrogen by examining temperature gradients on two aluminum cylinders. The primary objective of this experiment is to lower the uncertainty of the of heat flux measurements for cylinders immersed in liquid nitrogen by addressing inconsistencies caused by the surrounding nitrogen vapor envelope. This will be achieved by measuring temperatures within the same plane on the cylinder's surface and comparing results across different tests, minimizing uncertainty in the boiling data affected by violent boiling changes. Additionally, precision will be improved by measuring temperature gradients at two different points within the cylinder. The heat transfer equation 1 will be used to quantify heat transfer, taking into account thermal conductivity and temperature gradients ($\frac{dT}{dr}$). The experiment aims to provide more accurate analysis of cylinder quenching, contributing to the development of cryogenic storage and transfer systems for long-term space missions. Quantitative data on heat transfer during quenching in liquid nitrogen will be obtained, with the heat transfer rate (q) measured in watts or joules per second, and the area measured in square meters.

$$q = -k\frac{dT}{dr} \tag{1}$$

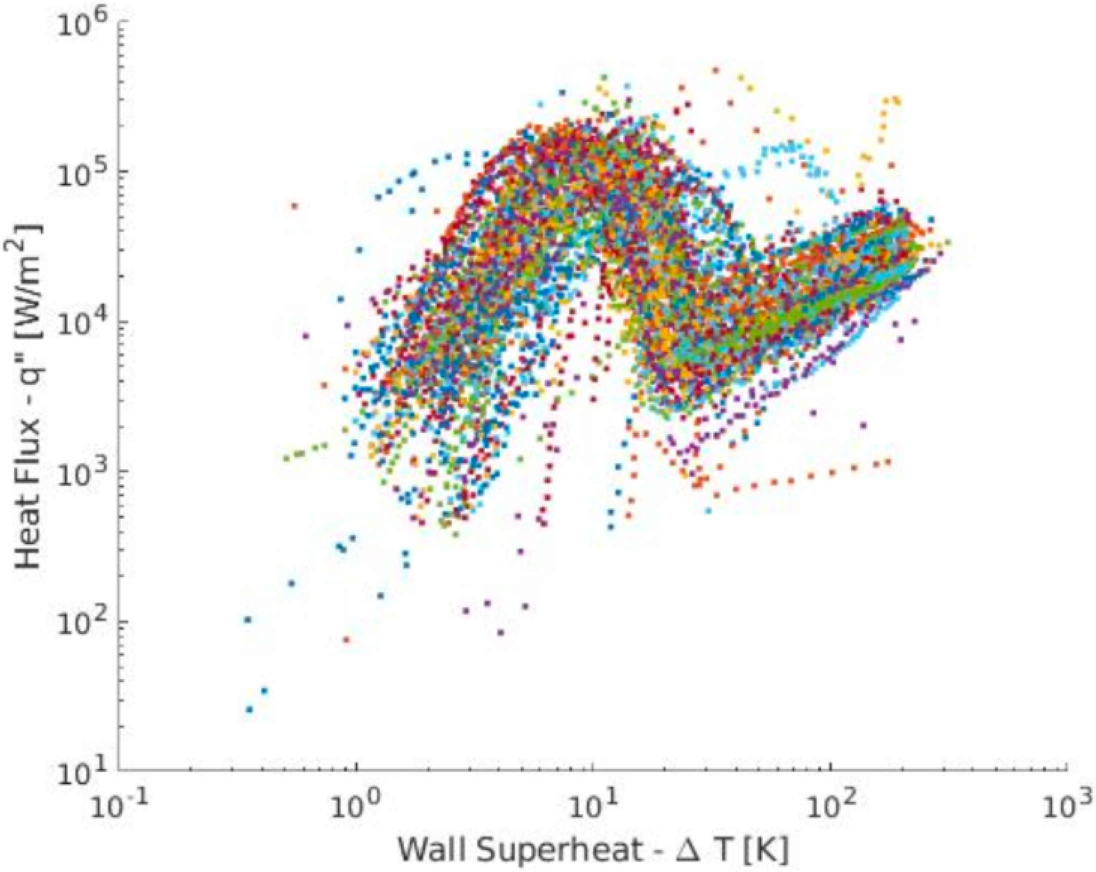


Fig. 1 Published Heat Flux Data

II. Theory / Analysis

This analysis focuses on the heat transfer dynamics and cooling process of aluminum cylinders immersed in liquid nitrogen. The initial temperature of the room is assumed to be approximately 298 K (25°C) while the temperature of the liquid nitrogen is 77 K (-196°C). To determine the appropriate heat transfer coefficient (h) for boiling, which represents the convective heat transfer between the cylinder's surface and the surrounding liquid, the Biot number (Bi) is calculated using Equation 2. The resulting Biot number of 9 indicated that convective heat transfer from the liquid nitrogen fluid significantly influences the temperature of the aluminum cylinder. Referring to Table 4-1 from the book "Heat Transfer: A Practical Approach" by Yunus A. Cengel, the necessary parameters for calculating the cool-down time of the cylinder based on the Biot number can be obtained [2]. Equation 4 represents the relationship between the initial temperature (T_i), the ambient temperature (T_∞), the cylinder surface temperature (T_s), and the time constant (τ). By solving Equation 5, the calculated cool-down time is determined to be 393 seconds or approximately 6.5 minutes.

$$Bi = \frac{hr}{k} = 9 \Rightarrow 9 = \frac{h * 0.03175m}{247 \frac{W}{mK}} \Rightarrow h = 70015 \tag{2}$$

$$\alpha = \frac{k}{\rho c_p} = \frac{247 \frac{W}{mK}}{2710 \frac{kg}{m^3} * 903 \frac{J}{kg*h*K}} \Rightarrow \alpha = 9.7 * 10^{-5} \frac{m^2}{s} \tag{3}$$

$$\frac{T_i - T_\infty}{T_s - T_\infty} = A_1 e^{-\lambda_1^2 \tau} = \frac{221K - 77.35K}{298.15K - 77.35K} = 1.5611 e^{-2.1566^2 \tau} \Rightarrow \tau = 0.18819 \tag{4}$$

$$\tau = \frac{\alpha t}{V} \Rightarrow t = \frac{\tau V}{\alpha} = \frac{0.18819 * 0.457}{9.7 * 10^{-5}} \Rightarrow t = 392.8820s \tag{5}$$

This analysis also provides valuable insights into the heat transfer dynamics involved in the cooling process. The heat transfer during the cooling process of the aluminum cylinders in liquid nitrogen can be described by the heat conduction equation and the convective heat transfer equation. The heat conduction equation (Equation 1), given by Fourier's law, relates the heat flux (q) to the temperature gradient ($\frac{dT}{dr}$) and the thermal conductivity (k) of the material. By considering the convective heat transfer between the cylinder's surface and the surrounding liquid nitrogen, the convective heat transfer equation (Equation 7) can be utilized. The mass (m) of the aluminum cylinder, as well as its volume (v), density (ρ), and specific heat capacity (c_p), play essential roles in the analysis. The mass of the cylinder determines its thermal properties, while the density and specific heat capacity characterize the material's ability to store and transfer heat. Additionally, the maximum heat transfer (Q_{Max}) represents the amount of heat required as time goes onto infinity. The convective heat transfer coefficient (h) represents the effectiveness of heat transfer between the solid and the fluid. The cooling process of the aluminum cylinder can be analyzed by combining the heat conduction equation and the convective heat transfer equation. By solving these equations, the temperature distribution within the cylinder as a function of time can be obtained, providing insights into the cooling behavior.

$$m = \rho \pi r^2 L = (2710 \frac{kg}{m^3}) \pi (0.0635 m^2)(0.1534 m) \Rightarrow m = 5.1835 kg \tag{6}$$

$$Q_{Max} = m c_p (T_i - T_\infty) \Rightarrow Q_{Max} = 674.024 kJ \tag{7}$$

Additionally, the thermal diffusivity (α) of the material plays a crucial role in the cooling process (Equation 3). It characterizes the ability of the material to conduct heat and is defined as the ratio of thermal conductivity (k) to the product of density (ρ) and specific heat capacity (c_p). The thermal diffusivity determines how quickly the temperature within the cylinder changes over time. With the understanding of these fundamental principles and equations, the experimental measurements of temperature gradients on the surface of the aluminum cylinders immersed in liquid nitrogen can be analyzed. The obtained data will be compared with the theoretical predictions based on the heat transfer equations to validate the accuracy of the experimental setup and to refine the understanding of the heat transfer dynamics during the cooling process.

III. Design of Testing Cylinders

A. Approach

When designing the test cylinders the main objective was to make the design as effective as possible while still keeping it practical. Consideration was given to not only how the design would deliver the needed data for evaluating the hypothesis, but also whether the design would be physically possible to manufacture in the shop.

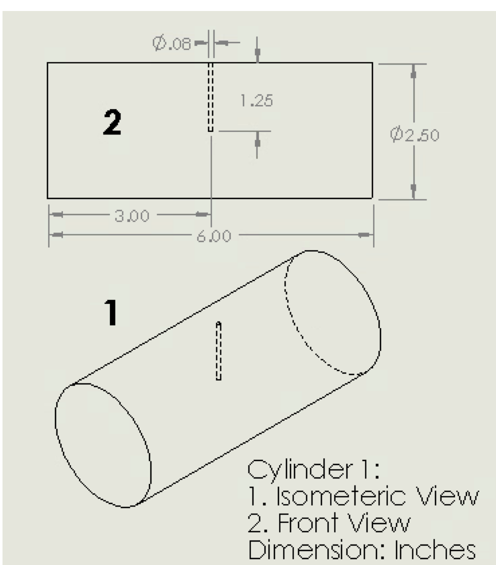
Given the large levels of uncertainty in heat flux data for liquid nitrogen, as well as a lack of clarity in testing procedures, steps were taken to ensure the orientations of measurements are all carefully tracked. In order to accomplish this, the measurements were recorded at points that all lay in the same plane. Knowing where the measurements were being taken within the vapor envelope caused by boiling gave a better understanding of heat flux over the entire cylinder. In order to ensure the orientation of the plane when the cylinder was submerged in the liquid nitrogen, mounting was done using a wire looped through worm-screw style hose clamps. Planar orientation was adjusted by rotating the cylinder within the hose clamps, and a level was used to ensure the exact orientation of the measurement plane was known.

Geometry and material choices were made to simplify the calculations and give more accurate results. Cylindrical geometry was chosen because it offers a circular cross section with a much larger width. This was beneficial because the heat transfer through the circular section will be much faster than through the width, which gives much more consistent heat transfer readings. Taking measurements on a circular cross section is ideal because any sharp corners in the geometry will have an effect on the boiling characteristics of the liquid nitrogen. Aluminum was chosen for its thermal conductivity. Thermal conductivity had to be low enough that the thermocouples were able to get a large number of data points before the cylinders reached equilibrium temperature but also high enough that the change in temperature through the surface would be consistent. Thermal conductivity in all materials varies with temperature, and another benefit of using aluminum was that it's change in thermal conductivity is nearly linear, which will also simplify calculations.

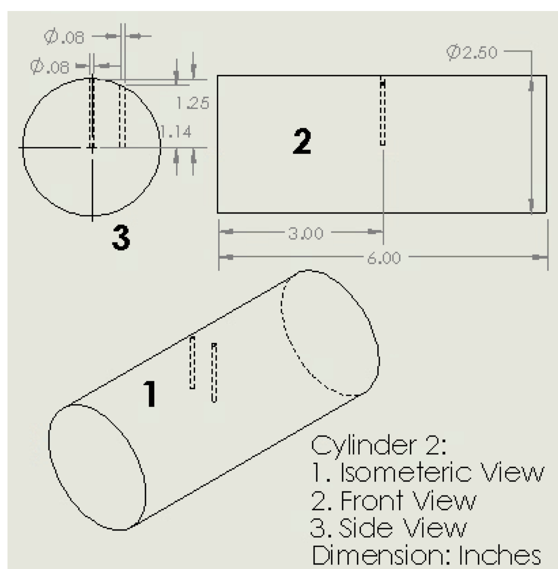
Other factors considered when choosing material were more practical. Using a softer metal like aluminum meant that the manufacturing process would be easier and more accurate. Drilling into harder metals, such as steel, is more difficult to do accurately. Cost was the final consideration as working with a budget means that the materials chosen needed to be affordable.

For a complete Bill of Materials see Appendix C, and for a complete tabulation of budget see Appendix A.

B. Design Description



(a) Diagram of Cylinder 1 once manufactured.



(b) Diagram of Cylinder 2 once manufactured.

Above are two basic drawings of the cylinders as machined. (For more detailed drawings see Appendix B.) On the left (2a) is Cylinder 1, which was used as the baseline measurement. On the right is Cylinder 2 (2b), which was used to measure the heat flux of the liquid nitrogen.

In the drawing of Cylinder 1 (2a), the vertical hole to the center is where the thermocouple probe is inserted.

Measuring there gives data on how the temperature of the center of the cylinder changes when a minimum amount of material has been removed during the manufacturing process.

In the drawing of Cylinder 2 (2b), the two holes are where the thermocouple probes are inserted. There is a hole to the center and 1/2 of the distance from center to surface. Measuring at these locations gives accurate data on the temperature gradient through the surface of the cylinder as it is cooled to 77K.

C. Manufacturing

See Appendix B for detailed CADD drawing of the below manufacturing requirements, and Appendix D for additional assembly instructions.

1. Cylinder 1:

1) Each cylinder must be mounted in a vice in order to hold it stationary to enable drilling of precise holes. Soft jawed clamps are used to protect the surface of the cylinder from damage. The drilling of the cylinders is done using a mill in order to drill accurate, small sized holes. Frequent lubrication of drill bits is necessary to avoid damaging the drill bits and the cylinders.
2) Cylinder 1 only requires one hole drilled where the thermocouple will be installed to measure the temperature at the center of the cylinder. The hole must be located in the center of the 6" length of the cylinder, which is measured out using calipers. The depth of the hole will be 1.25" ±0.005". Depth of drilling is monitored using the depth gauge on the mill, which must be zeroed at the surface of the cylinder before drilling begins. The hole will be perpendicular to the surface of the cylinder (radially), with an angular tolerance of 0° ±2° relative to the horizontal. Hole specifications are verified using a length of wire inserted into the hole and marked where it reaches the surface of the cylinder, and calipers are used to measure how deep the wire went into the cylinder. Angularity is checked by inserting a drill bit into the hole and the angle checked relative to the surface of the cylinder using a carpenter's square.

2. Cylinder 2:

1) Cylinder 2 has two points of measurement requiring two holes to be drilled for thermocouples, both located at the center of the 6" length of the cylinder. The hole for the measurement at the center of the cross sectional area will have the same dimensions and tolerances as cylinder 1. The second hole will be measured 0.562" inches from the central hole. This equates to a distance 0.573", which is measured out on a piece of masking tape which is applied to the cylinder at the central thermocouple hole. These holes are on the same plane, which is accomplished by only moving the table on the mill inward toward the drill head, until the drill bit is lined up with the marking on the tape.
2) The first hole is drilled to a depth of 1.25"±0.005" and an angularity of 0°±2°. Depth is monitored using the depth gauge on the mill.
3) The second hole is drilled to a depth of 1.14"±0.005" and an angularity of 0°±2°. Depth is again monitored using the depth gauge on the mill.
4) Hole specifications will be checked in the manner described for Cylinder 1.

D. Project Management

1. Overview

In the ten week long quarter, the lab group was to design, manufacture, and test an experiment based on a given objective. The given objective was to conduct simple experiments involving a chosen geometry, initially at ambient conditions and suddenly immersed in liquid nitrogen. This ideally would provide better understanding and less uncertainty on cryogenic boiling. Considering the length of the quarter, the group originally decided to spend the first four weeks on design, the next three on manufacturing, two on testing, and a final week on analysis of the experiment. For a more detailed schedule, see the Gantt chart below (III.D.4).

During the design phase, tasks consisted of researching and designing an outline for the manufacturing plan as well as the experiment. This phase was expected to take about four weeks, but took a bit longer since heat transfer and boiling were new topics for all group members. For the first two weeks, focus remained on research and it was not until the end of week three that a very rough experiment was designed. Based on this basic experimental concept, the team worked backwards, wanting to test aluminum spheres (later changed to cylinders) by drilling holes in them and inserting thermocouples to measure heat transfer. By the end of week four, the list of materials was nearly complete, with a few minor modifications to come later. A rough draft CADD model for drilling holes into the cylinders, and a plan complete the manufacturing process by inserting and adhering Type T thermocouples to the cylinders were created. Unfortunately, at this time the team ran into unexpected difficulties, particularly with cool down time calculations and finding thermocouples that would arrive on time and be in-budget. Additionally, the spheres were not available when expected, so the team changed the test geometry to cylinders. These difficulties caused the design phase of the project to extend into week five.

With an overlap as the group began to move into the manufacturing phase during week four and five, three group members completed Mill Training for the purpose of drilling holes for testing in our aluminum cylinders. Purchase requests were sent in, and most parts were received by end of week six. A CADD design drawing was finalized so that manufacturing of test parts could occur shortly. Realizing the aluminum spheres were never shipped, the team went ahead and began cutting and drilling aluminum cylinders during week eight, spending about eight hours in the Machine Shop total.

In week nine and ten, the assembly and testing phases were combined to speed up the experiment. In week nine the team assembled the mounting and thermocouples and conducted three out of six of the test. The rest of the week was spent working on data analysis. In week ten, three more tests were conducted, with some re-assembly required just before testing. This ended the testing phase of the experiment and the project could be finished with more data analysis.

2. Member Specific Roles

1) Adam: Materials Research and Sourcing, Experimental Design
2) Emi: Secretary/Note Taker, Boiling Research (properties, principles)
3) Evelyn: Facilities Liaison, Thermocouple Research, Experimental Design
4) Felicity: Purchasing Officer, Heat Transfer Research (theory, modeling, behavior)

3. Budget

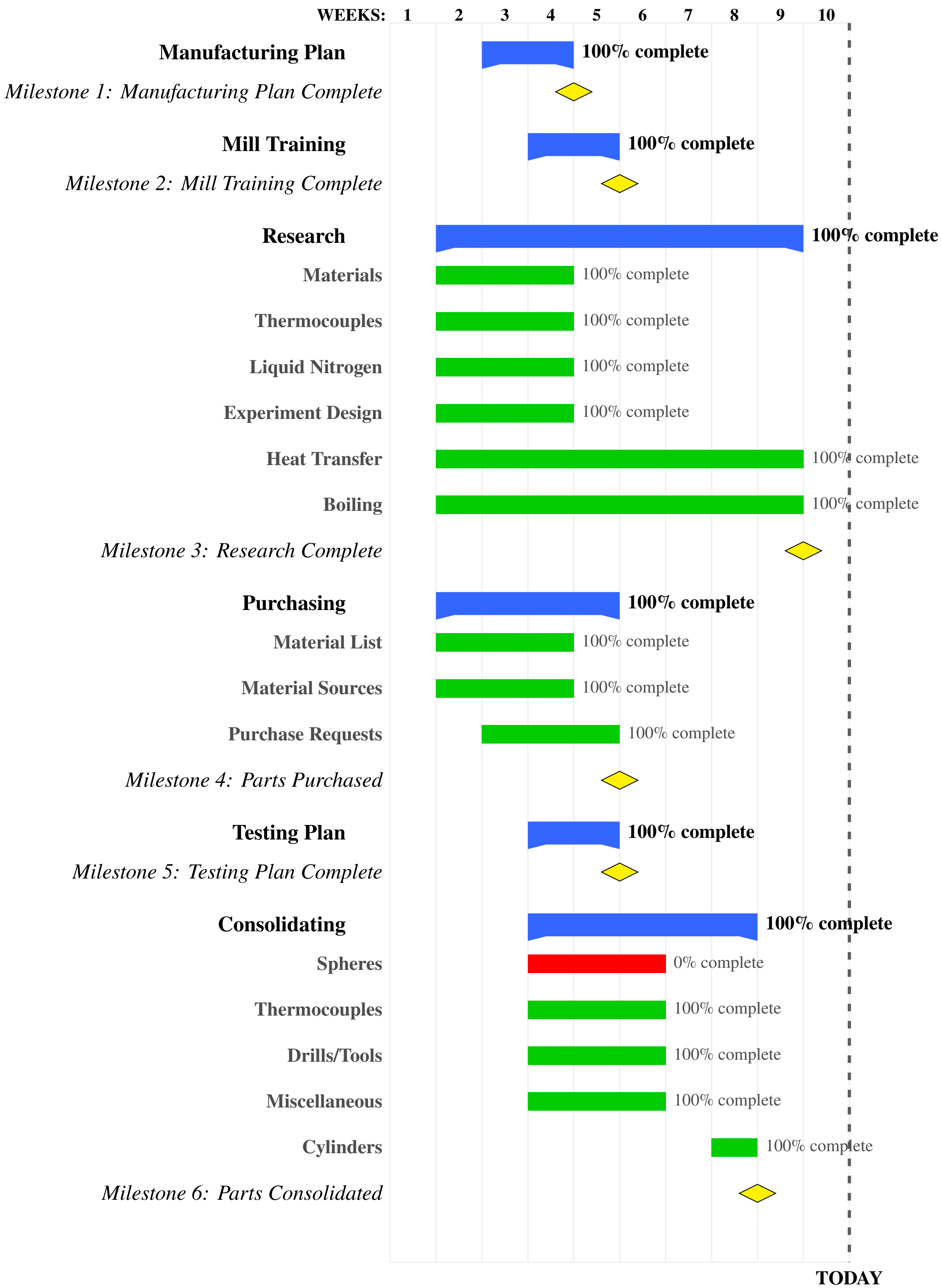
To see the detailed budget reference Appendix A, but expenses and changes to the budget will also be discussed here. The team was given a budget of $300 for this project, which caused a greater amount of conservation and frugality than would ideally be necessary given the assigned task.

The major expense for the project was the Type T thermocouples, which were required due to their ability to withstand the cold temperatures of liquid nitrogen and their both sensitive and short reading times, which in turn provides consistent measurements. These thermocouples cost about $60-70 each, and only two were affordable for purchase instead of the three that would have been more constructive to the project.

The next most expensive part of the project was the liquid nitrogen from the chemistry department, as multiple days of testing were required and needed about ten liters of liquid nitrogen for each testing day. For two days of testing, twenty liters of liquid nitrogen in total was necessary, which cost approximately $90.

These purchases alone put the estimated budget over $200, leaving less room for other items. Luckily, all of the other materials needed were much cheaper; PTFE Tape, eyebolts, drill bits, and taps (some of which would have been needed for the original sphere design), totalled around $50 plus tax and shipping costs. In the end, almost the entire budget of $300 was used.

4. Gantt Chart



WEEKS: 1 2 3 4 5 6 7 8 9 10
Interim Report
100% complete
Milestone 7: Interim Report
Presentation
100% complete
Completing Slides
100% complete
Rehearsals
100% complete
Presented in Class
100% complete
Milestone 8: Presentation Complete
Manufacturing and Assembly
100% complete
Mill Training
100% complete
Receive Materials
100% complete
Drill cylinders
100% complete
Mounting for cylinders
100% complete
Attach Thermocouples
100% complete
Milestone 9: Assembly Complete
Experiment
100% complete
Calibrate Sensors
100% complete
Test cylinder
100% complete
Run All Tests
100% complete
Data Collection
100% complete
Milestone 10: Testing Complete
Final Report
100% complete
Milestone 11: Finishing Project
TODAY

IV. Testing

The process of testing the aluminum cylinders was to immerse them into a dewar full of liquid nitrogen. Thermocouples were used to measure the temperature changes in the cylinder as it reaches an equilibrium temperature with the liquid nitrogen. The first cylinder, Cylinder 1, only collected temperature change at the center in order to give a baseline measurement of how temperature will change with minimal material removed from the cylinder. The second cylinder, Cylinder 2, had two measurements taken along the radius, one in the center, and one at 1/2 of the distance from the center to the surface.

The primary measurements taken were the temperature gradient through the cylinder, and the cool down time of the cylinder. The temperature gradient was used to find the heat flux as the liquid nitrogen transitions through the different boiling regimes using equation 1. Then a comparison was made between the measured cool down time and the calculated cool down time of 393 seconds.

Temperature gradient was measured by drilling two holes in Cylinder 2, one at the center, one at 1/2 distance from center to surface. Thermocouples were used at each of these points to measure how the temperature changed at those points. This data was then used to find the temperature gradient through the radius of the cylinder.

Cool down time was found by measuring the time it took for the cylinder's temperature to change from ambient temperature to within 2% of the liquid nitrogen temperature of 77K using a timer in the LabView program. For a more detailed testing procedure, please see Appendix E.

The main constraints of this experiment were the temperature of the liquid nitrogen, the radius and length of the cylinders, and the dimensions of the dewar. None of these were a significant impediment in the approach to the experiment, but the temperature of liquid nitrogen and radius of the cylinder needed to be considered when analyzing the results.

The main parameters of this experiment were the ambient temperature in the room the experiment was conducted in and the depth of the liquid nitrogen. Room temperature was not controllable for this project, but the cylinders were affected by the room temperature, so the initial temperature of the cylinders was necessarily recorded. The depth of the liquid nitrogen was monitored for the duration of each test, as a cylinder that was not fully submerged in the liquid nitrogen would not give accurate results. Initial volume of liquid nitrogen should be 10 liters which equates to a level of approximately 12 inches in the dewar. Note that the level should not drop below twice the diameter of the cylinder, or 6" above the bottom of the dewar.

The variables of this experiment were the number of holes in the cylinder. Again, Cylinder 1 only had a hole drilled to the center, provided the baseline cool down time, and was tested three times. Cylinder 2 had two measurements taken, and was also tested three times. For a clearer look at constraints, parameters, variables, and measurements, reference Appendix F.

The below diagram shows a sketch of the full testing setup (for Cylinder 1) including dimensions in inches. The type T thermocouple as depicted in red (see Figure 8a for image of actual thermocouple) inserts into the drilled hole so that the sensor end touches the very bottom of the hole and measures the center of the cylinder (within an error of ±0.005"). Both the mounting wire and the thermocouple wire should be draped over the support beam so that the cylinder remains submerged and horizontal and the thermocouple wire is not jostled by the violent boiling of the liquid nitrogen.

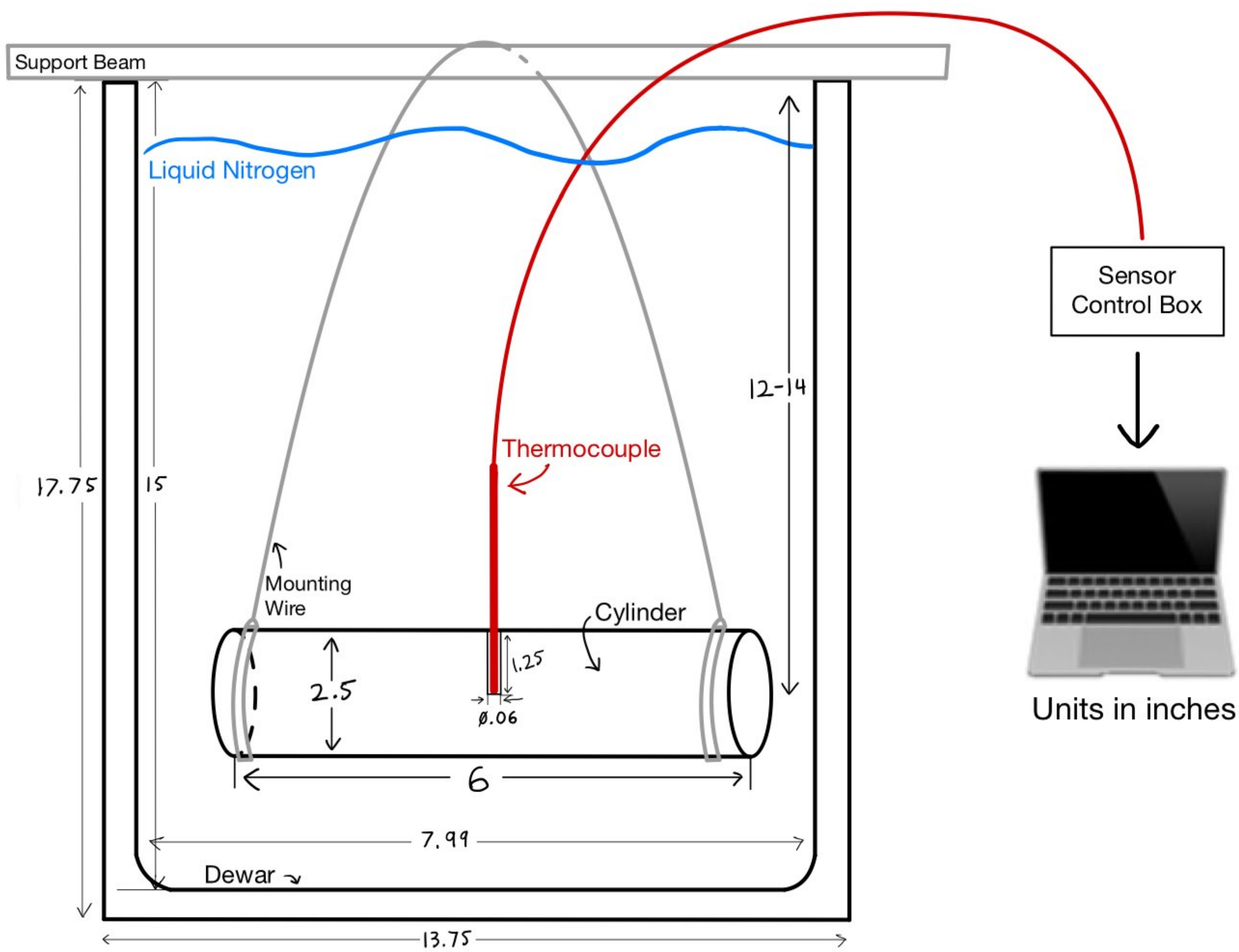


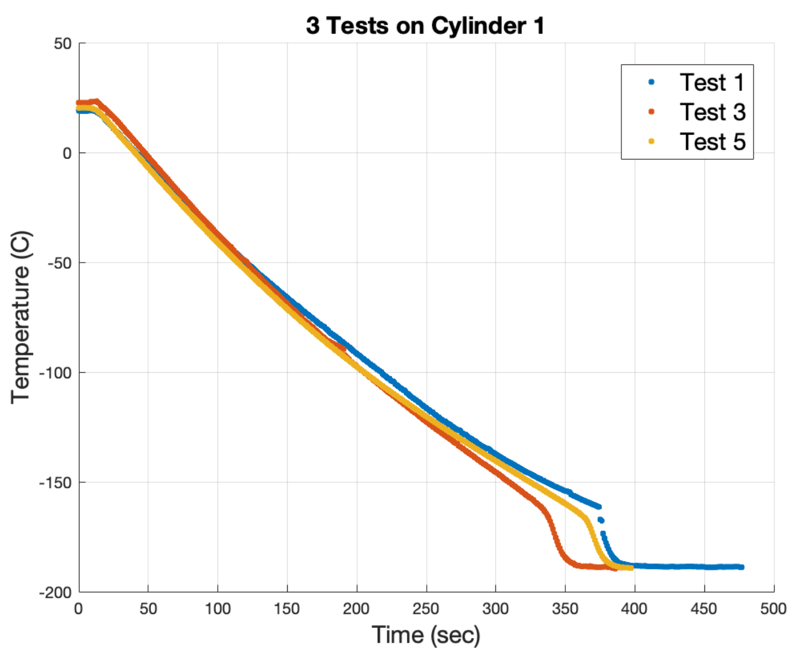
Fig. 3 Apparatus

V. Results and Discussions

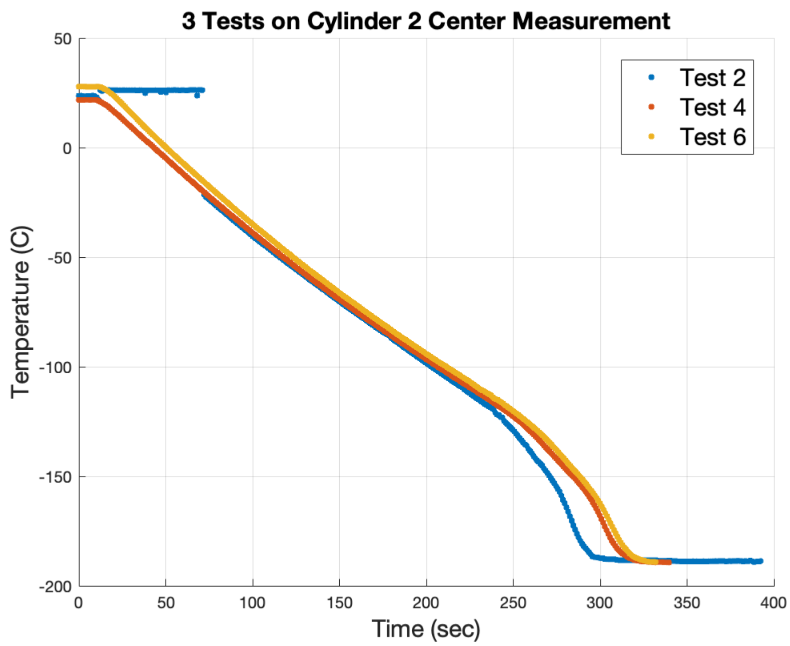
The objective of the experiment was to gain insight on heat transfer and boiling of geometries in cryogenic fluids. The results obtained from the test matrix presented in Appendix C.D list specific cool down times for each test, and plots of temperature versus time for each test can be found in Appendix C.I. Cool down time was calculated as the duration from cylinder submersion to the attainment of -188°C at the central temperature reading. Analyzing the disparities in cool down times across various cylinders and runs allows for a deeper understanding of heat transfer of cyrogenic fluids. From the theory section, the theoretical calculated cool down time was determined to be 393 seconds.

Cylinder 1 was configured with a center drilled hole measuring 1.25 inches in depth and 0.06 inches in width. The thermocouple was inserted into this hole, as depicted in Figure 2a. The results collected from this cylinder were obtained at the center of the 6x2.5" cylinder. Conducting three tests on Cylinder 1 allowed an expectation of similar results for each test, as depicted in 4a. These results provided valuable insights into the accuracy and repeatability of the tests. They also served as a comparison of cool down time and cooling properties to Cylinder 2.

Cylinder 2 had a similar configuration to Cylinder 1, featuring the same center drilled hole and an additional hole drilled to the right at 1.14 inches depth. The respective thermocouples were inserted into these holes, as illustrated in Figure 2b. Similar to Cylinder 1, the pictured results for Cylinder 2 were obtained from the center of the 6x2.5" cylinder. By conducting three tests on Cylinder 2, the team received fairly consistent results across the tests, as evident in 4b. These results provided valuable insights into the heat flux of the cylinder as the radius varies.



(a)

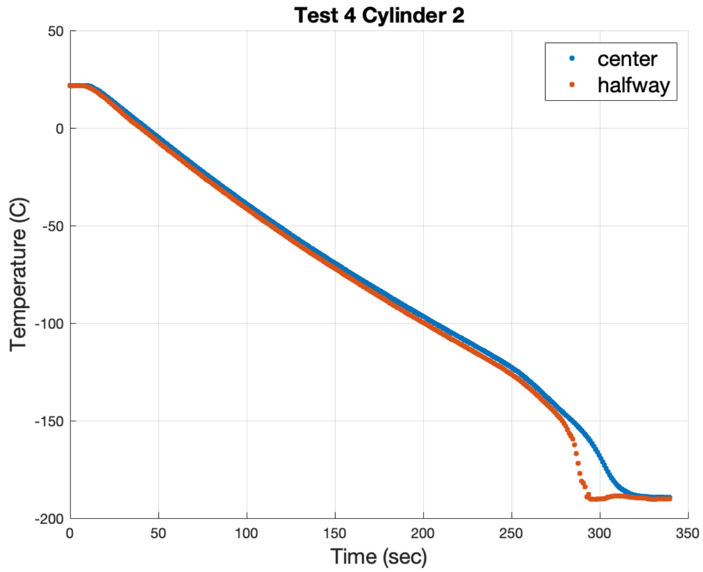


(b)

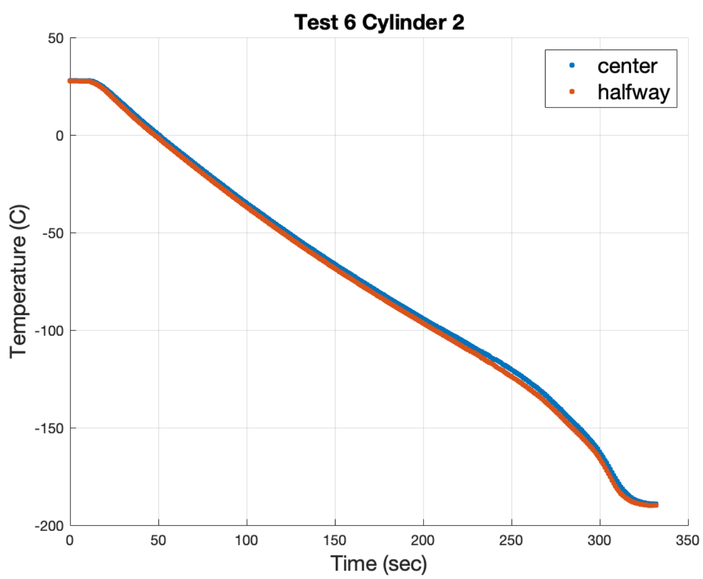
Fig. 4 (a) Plot of Temperature vs. Time for the three tests conducted on Cylinder 1, with limited smoothing of data. (b) Plot of Temperature vs. Time for the three tests conducted on Cylinder 2, with limited smoothing of data. This plot looks at only the center temperature measurement.

Comparing these two plots, both cylinders exhibited a portion of nearly linear cooling from submersion to approximately 250 seconds with a sudden drop off near -150 °C before a level off at -188°C. Nonetheless, there were still clear differences between the two plots. Cylinder 1's cool down time was 382 seconds on average while Cylinder 2's average cool down time was 310 seconds. Cylinder 1's cool time was much closer to the expected 398 seconds calculated from theory, while Cylinder 2's cool time was 21% lower than expected. One explanation for this difference may be that with less material being taken out of Cylinder 1 and a smaller surface disturbed by drilling, the cool time was closer to theory. For Cylinder 2, a greater disturbed surface caused more violent boiling and likely causes the cylinder to cool faster than expected.

After analyzing the cool down times and temperature across the different cylinders and runs, the data seemed to be fairly consistent across all the runs, with the main exception being a longer cool down time for Cylinder 1. With this conclusion, further analysis of temperature gradients and heat transfer dynamics on Cylinder 2 allowed the team to analyze heat flux. Utilizing the heat flux equation (1), Cylinder 2 provided a value for $\frac{dT}{dr}$ as the temperature across the two drilled holes varied. The plots 5a below depict the difference between the measurements at the center and halfway across the radius of the cylinder.



(a)



(b)

Fig. 5 (a) Plot of Temperature vs. Time for Test 4 on Cylinder 2. (b) Plot of Temperature vs. Time for for Test 6 on Cylinder 2.

The temperature measurements closer to the outside of the cylinder (halfway measurement) were slightly colder on average than the temperatures at the center of the sphere. This was as expected, as the center of the cylinder should take the longest to cool to the outside temperature of the liquid nitrogen. Using these different measurements and a radial distance of 0.5625 inches between the two measurements, $\frac{dT}{dr}$ can be obtained. To finish calculating heat flux, a varying thermal conductivity value (k) must be used as temperature changes. The team chose to use a linear approximation of k as it varies with temperature, which can be seen in Appendix GC.I. With k varying and $\frac{dT}{dr}$, the heat flux on Cylinder 2 was plotted and displayed against an average of the published heat flux data 1 as follows in Figure 6.

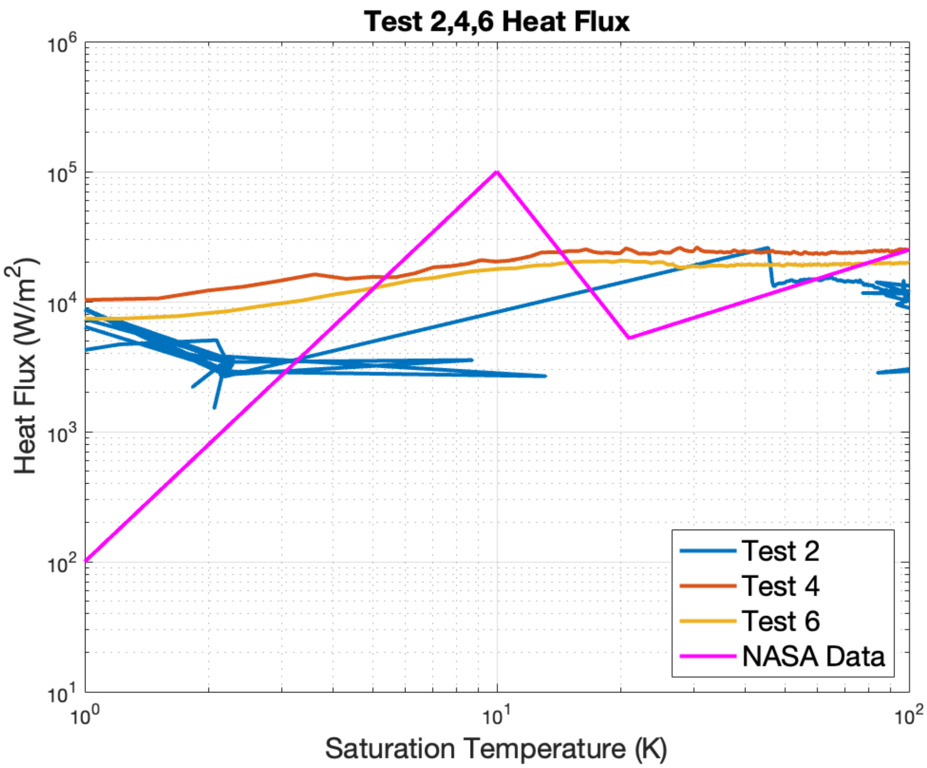


Fig. 6 Plot of heat flux data from experiments compared to data from the NASA report[1].

In the graph above, the magenta line represents the average data for heat flux of geometries submerged in cryogenic liquids [1]. While the published data varied over a magnitude and most tests still reflect this shape, the team's tests do not. Unfortunately, the closest data to the expected heat flux came from test 2, which was a noisy test and produces extraneous lines on the heat flux graph. Although the shape of the group's data does not match, the range of heat flux values recorded was within range of expected values, particularly at a change in temperature above 10 K. Looking only at the right hand half of the data (a temperature change greater than 10 K), the data was closer to expected data, within half an order of magnitude. Increasing accuracy as the change in temperature increases was logical for the tests, as the cylinders' temperatures took less than 15 seconds to change by 10 K. Due to equipment limited by a budget and a Data Acquisition Kit that was in need of maintenance, the readings for this short time period likely were not as accurate as published sources; however, over a longer period of time and temperature change the experimental readings matched theory more closely.

VI. Conclusions

A. Evaluation of Objectives

The objective of this project was to enhance the understanding of heat transfer and cooling properties of cryogenic substances, specifically liquid nitrogen, in order to improve the efficiency of storage and transfer systems for cryogenic propellants. The project aimed to investigate the boiling characteristics, cool-down time, and heat transfer dynamics of liquid nitrogen by immersing aluminum cylinders into the cryogenic fluid. The final approach involved conducting experiments with two cylinders, analyzing the cool down times, and assessing the performance of each cylinder. Two aluminum (6061-T6), 6x2.5" cylinders were manufactured so that Cylinder 1 had a hole directly to the center and

Cylinder 2 had a center hole and another drilled to half-radius of the cylinder on the same horizontal plane as the original hole. Type T thermocouples were inserted so that the temperature change at the location inside the cylinder could be measured as the cylinders were submerged into liquid nitrogen. From the recorded temperatures and corresponding times, the heat flux plot was obtained and analyzed comparing the results to previously published data. Both Cylinder 1 with one measurement location and Cylinder 2 with two decreased linearly from submersion to approximately 250 seconds then the cooling plots exhibited a drastic drop in temperature near $-150°C$ before leveling off as expected at $-188°C$; however, while Cylinder 1's cool down time agreed with the predicted value of 390 seconds, Cylinder 2's time was 21% lower than expected potentially due to surface disturbances on the cylinder from drilling. The experimental heat flux data lay within the expected magnitude, but did not show a reduction in uncertainty nor followed the expected linear zig-zag shape as temperature increased. On the other hand, at greater temperatures the range of the heat flux values matched the expected values more closely, likely due to a smaller change in temperature per time. While this experiment did not improve on the precision and accuracy of quenching data as desired, the results are valid as the heat flux data lay in range of previously published data. The deviation could be due to many sources such as inferior equipment, calibration errors, and fluctuations due to violent boiling and surface imperfections. Though this approximation should have been valid due to the measurements being taken at the center of the length cylinder where the end should not have caused effects, to simplify complex calculations, the heat flux equation for a sphere was also used which may have cause further discrepancies. Therefore, improvement of experimental methods should be considered such as a more exact heat flux equation or testing with equipment with higher accuracy.

B. Future Work

For future work, Team Charlie would recommend repeating the experiment with higher budget equipment and materials, conducting similar tests but with multiple geometries, materials, and orientations of test objects, and improving on the the temperature to heat flux calculations. Since the recorded heat flux data did not match published sources, further analysis of the data obtained may yield better results, or reveal the cause of discrepancies. Additionally, more high-tech mounting set ups that are easy to transfer from test object to test object and a way to quickly warm up test objects would greatly increase the accuracy and efficiency of test results.

A broad overview of a future project may look as follows. Gather three different materials, such as aluminum, copper, and steel, each with a spherical and cylindrical test geometry. Drill three measurement points in each, one at the center, one halfway across the radius, and one nearly at the surface, and insert thermocouples to measure the changing temperature throughout the experiment. Obtain one piece of mounting equipment able to withstand submerging each test object in liquid nitrogen. Conduct 3-5 tests on each test object and compare results for the different geometries and materials, specifically plotting and analyzing heat flux. Compare these results to published data and hopefully obtain clear results near the average heat flux readings.

References

[1] Moore, R. C., and Hermanson, J. C., "Evaluating the Comlete Pool Boiling Curve for Liquid Nitrogen," 2019-2021.

[2] Cengel, Y. A., *Heat Transfer: A Practical Approach*, McGraw-Hill, 2002, Chap. 4: Transient Heat Conduction, pp. 232–241.

Appendix A: Budget

Description	Source	Quantity	Unit	Cost
Liquid Nitrogen (item #7557)	Bagley 36	20	Liter	$90
~~25mm Aluminum Ball (item #1201B83)~~	~~Thomas Scientific~~	~~6~~	~~1~~	~~$35.46~~
Type T Thermocouple (item #TTJ36-CPSS-040G-6-SMPW-M)	Omega	2	1	$66.73 * 2
PTFE Tape (item #3AB55)	Grainger	1	Roll	$0.98
Zinc-Plated Steel Routing Eyebolt (item #9490T1)	McMaster-Carr	1	20	$8.73
Chicago-Latrobe Jobber 1/16" Drill Bit (item #1F489)	Grainger	4	1	$7.72
Chicago-Latrobe Jobber #25 Drill Bit (item #1G965)	Grainger	2	1	$9.62
Cleveland Straight Flute Tap: #10-24 Thread (item #435M19)	Grainger	1	1	$9.13
Estimated Shipping/Tax Costs	General	3	1	$35.98
			Total	$295.62

Appendix B: Detailed Drawings

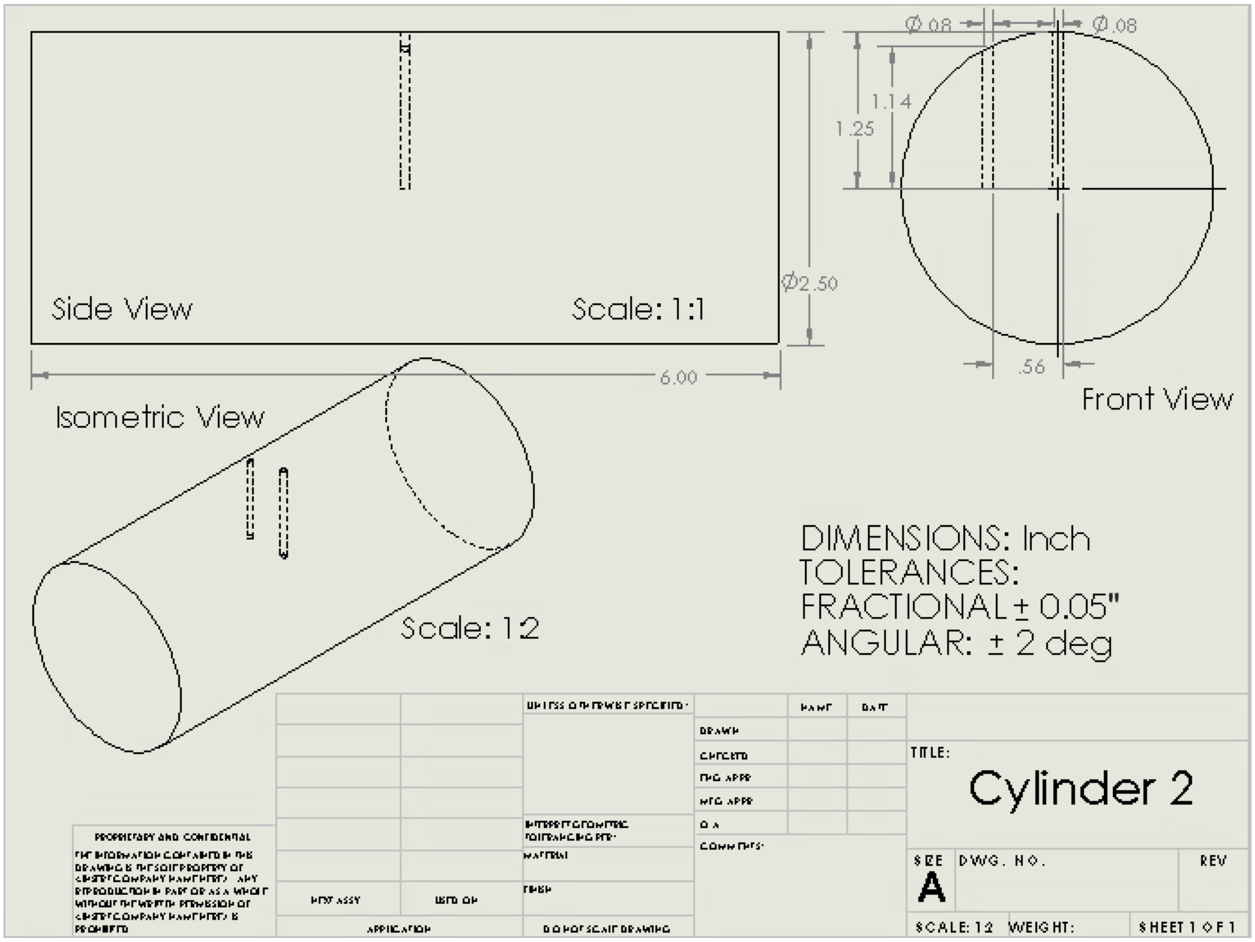


Fig. 7 Drawing of Cylinder 2 to be manufactured. Cylinder 1 is the same except for it only has one drilled hole to the center.

Appendix C: Bill of Materials

A. Purchased

Item	Mfg No	Supplier	Stock No	Quantity	Total Cost	Availability
Type T Thermocouple	TJ36-CPSS-040G-6-SMPW-M	Omega	NA	2	$123.24	Now
Liquid Nitrogen	NA	Bagley 36	7557	20 liters	~$90	As needed
~~Aluminum Spheres~~	~~42014~~	~~Thomas Scientific~~	~~1201B83~~	~~6~~	~~$35.46~~	~~Not Shipped~~
PTFE Thread Sealing Tape	26135	Grainger	3AB55	1	$1.06	Now
Zinc-Plated Eyebolt	NA	McMaster Carr	9490T1	20	$8.71	Now
Chicago-Latrobe #25 Drill Bit	46695	Grainger	1G965	2	$9.62	Now
Chicago-Latrobe 1/16" Drill Bit	44004	Grainger	1F489	1	$7.40	Now
Cleveland Straight Flute Tap #10-24 Thread	54326	Grainger	435M19	1	$9.13	Now

B. Manufactured

Item	Manufacturing Method	Facility	Expected Time	Quantity	Cost
Cylinder 1	Mill or Watchmakers Drill Press	Charlie Bossart Machine Shop	5 Hours	1	NA
Cylinder 2	Mill or Watchmakers Drill Press	Charlie Bossart Machine Shop	10 Hours	1	NA

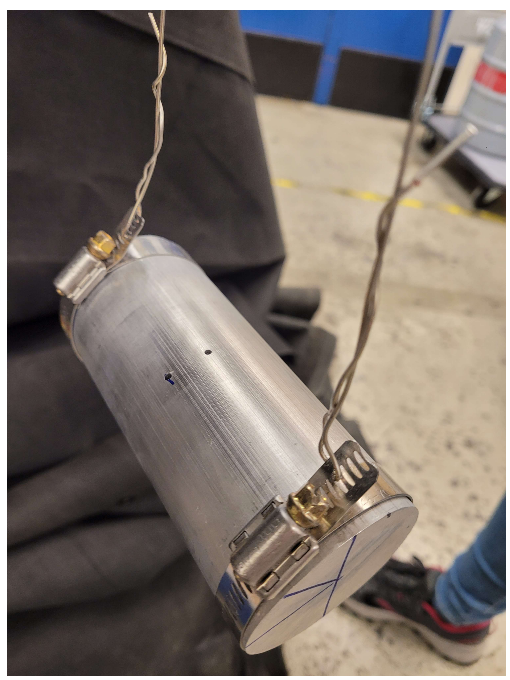
C. Borrowed

Item	Owner	Where to Find It	Quantity	Lend Status
Type T Thermocouples (0.062"x3")	Professor Jim Hermanson	Aerospace Thermal Lab, AERB 223	2	Confirmed and Available
Cryogenic Dewar	Professor Jim Hermanson	Aerospace Thermal Lab, AERB 223	1	Confirmed and Available
Aliant Mill - 48CV - Series 1	Charlie Bossart Mach Shop	Charlie Bossart Mach Shop	1	Confirmed and Available
Watchmakers Drill Press	Charlie Bossart Mach Shop	Charlie Bossart Mach Shop	1	Confirmed and Available
Metal Support Beam (15''x1"x1")	Charlie Bossart Mach Shop	Charlie Bossart Mach Shop	1	Confirmed and Available
Mounting Wire (30")	Charlie Bossart Mach Shop	Charlie Bossart Mach Shop	1	Confirmed and Available
Infrared Thermometer	Adam Delbow	Adam Delbow	1	Confirmed and Available
Hose Clamps	Adam Delbow	Adam Delbow	2	Confirmed and Available

Appendix D: Assembly Plan

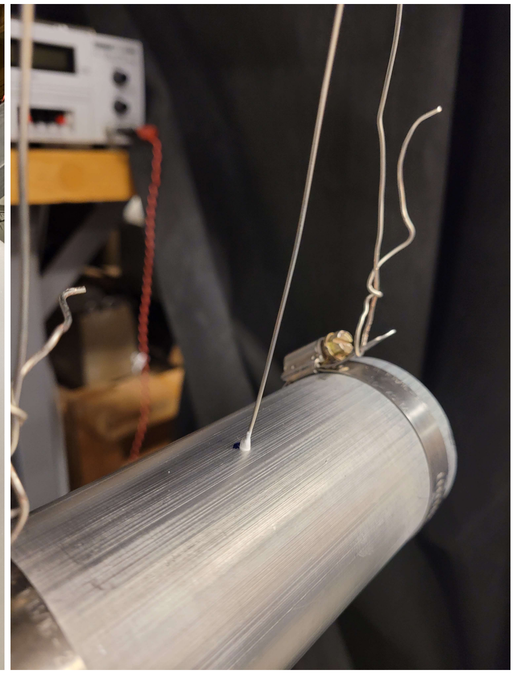
1) Upon completion of drilling the holes, the mounting wires attached to the hose clamps will need to be secured to the ends of the cylinder as shown in Figure 8b. Ensure that the cylinder hangs horizontal from the support beam using a level. (Reference Figure 3 as needed for diagram of full apparatus).
2) Lay the support beam across the top of the dewar with the cylinder inside. Ensure that cylinder is located between 12-14 inches from the top of the dewar. Adjust as necessary (check that cylinder remains level) so that there is a clearance for the cylinder to be completely submerged in the liquid nitrogen during testing.
3) Before assembly, the thermocouples will need to be calibrated. This can be done using known temperature values. The boiling point of liquid nitrogen is 77K, so that will be the lower data point. The freezing point of purified water is 273K, so that can in theory be the upper value. A thermometer will be used to check the actual readings for calibration. If a third data point is needed or desired, the boiling point of water at 373K can be used.
4) After calibration the thermocouples will be inserted into the 1/16" holes in the cylinders. Gently push the thermocouple into the hole until the sensor end touches where the hole ends at the middle of the sphere. Mark the location on the thermocouple at the surface of the cylinder then remove the thermocouple. A single layer of PTFE tape will be wrapped around the thermocouple probe lead at the marked location for the appropriate depth of the hole that the thermocouple is going into. The thermocouple probe will then be inserted into the hole using a gentle twisting motion, taking care to not disturb the sealing tape. The fit should be snug; this can be verified by gently pulling on the thermocouple, which should not move. This will ensure that there is no leakage into the cavity (Figure 8d). Repeat for each cylinder as required.

(a) Part 0: Thermocouple



(b) Part 1: Mounting

(c) Part 2: Clearance



(d) Part 4: Thermocouple Insertion

Cryogenic Boiling Test Procedure

Cryogenic Boiling Team 1 (aka Charlie)

Date: __________ / __________ / __________

Part Number: ______________________________

Serial Number: ______________________________

Initials: ________ , ________ , ________ , ________

Adam Delbow, Emi Peterson, Evelyn Madewell, Felicity Cundiff

Faculty Advisor: Professor Jim Hermanson

AA 322 Aerospace Laboratory II
William E. Boeing Department of Aeronautics
University of Washington
Spring 2023

A. Testing Objectives

Cryogenic Boiling Team 1, aka Charlie, aims to understand heat transfer and cooling properties of liquid nitrogen by measuring the temperature gradients of individual spheres using thermocouples at various points on the same plane along the radius. For long term space travel to be possible, storage and transfer of cryogenic propellants like hydrogen and oxygen are crucial for mission success. Since the propellants are prone to boiling off due to the extreme heat they are exposed to from rocket engine exhaust and air friction in the atmosphere, this can potentially lead to significant losses. To help prevent this, a more thorough understanding of boiling, cool down, and heat transfer characteristics are essential. The objective is to improve the accuracy of heat transfer measurements for cylinder in liquid nitrogen by addressing the inconsistency caused by the nitrogen vapor envelope surrounding the cylinder. This will be achieved by measuring temperature within the same plane of the cylinder's surface and comparing the results across different runs, which is anticipated to help to reduce uncertainty in the boiling data of the cylinder in liquid nitrogen. Another way of improving the precision of the measurements is to measure varying temperature gradients throughout the sphere. The method that will be used to measure heat transfer from the change in temperature is by using the heat transfer equation below, which measures heat transfer using thermal conductivity and temperature gradients ($\frac{dT}{dr}$). Ultimately the objective of this experiment will be to provide improved uncertainty in the analysis of sphere quenching for use in cryogenic storage and transfer systems for long-term space missions by obtaining quantitative data on heat transfer during submersion in liquid nitrogen. The units of q will be measured in watts or joules per second, while the area will be measured in square meters.

$$q = -k\frac{dT}{dr} \tag{8}$$

In preparation for this experiment, the team was given a published report by NASA[1] This report effectively compiled studies from the past 70 years. The data from these studies shows large fluctuations in calculated heat flux, giving rise to high levels of uncertainty. Methodology is also not always clear from study to study, nor is it consistent, so comparing results from the different studies is difficult. In this experiment, Team Charlie hopes to use average results from this paper as guidelines to verify the test procedure is working. The data from this report covered several geometries, sizes, and materials for quenching materials in liquid nitrogen. The focus will be on the quenching of aluminum spheres in particular. In order to reduce uncertainty, the experiment will be conducted with Type T thermocouples calibrated to the freezing point of water (273 K) and the boiling point of liquid nitrogen (77 K). Measurements will be taken at 1/2 and 3/4 of the way across the diameter of the sphere, which will test the heat transfer across radius of the sphere. With these measurements and tests conducted at three different orientations, temperatures across the radius of the sphere and cool down time will be collected and compared across the different tests.

B. Equipment Required

Qty	Description	Specs	Check
20 liters	Liquid Nitrogen (item #7557 from UW Chemistry Stockroom)	N/A	
1	Cylinder 1, tests temperature at the center of the sphere	angle measurements within ±2 degrees, drill measurements within ±0.005 inches	
1	Cylinder 2 (item #1201B83 modified), tests the temperature at 1/2 and 3/4 of the way through the sphere	angle measurements within ±2 degrees, drill measurements within ±0.005 inches	
2	Type T Thermocouples (item #TJ36-CPSS-040G-6-SMPW-M), 1/24 in diameter and 6 inch flexible probe length	calibration is required for greater accuracy at cryogenic temperatures	
1 roll	PTFE Tape (item #3AB55), poly-temp thread sealing, 1/2 in. by 43 ft.	N/A	
1	Cryogenic Dewar, 13.75 in. outer diameter, 8 in. inner diameter, 17.75 in. external height, 15 in. internal height	N/A	

C. Test Procedure

A. Safety

1) Lab coats and safety goggles must be worn at all times during the procedure. Ok? ______
2) Insulated gloves must be worn when working with or near liquid nitrogen (LN). Ok? ______
3) Oxygen concentrations must be checked before working with liquid nitrogen. Though the amount of LN should not cause a great displacement of oxygen, caution and care should still be used. Ensure that there is suitable ventilation through air ducts, fume hoods, and/or open doors and windows.

   Oxygen above 19.5%? ______ | Ventilation? ______

B. Thermocouples

1) Assembly Plan completed? Ok? ______
2) Compare thermocouple reading with ambient temperature from thermometer. Within ±2°? ______
3) Submerge assembled cylinder in liquid nitrogen. Check thermocouple response. If sealed properly, it should take around 60 seconds to reach 77K. Ok? ______
4) Plug thermocouple into a TC module of data acquisition system. Ok? ______

C. System Specific Tests

Prior to each test in the series:

1) Compare thermocouple reading with ambient temperature from thermometer. Within ±2°? ______

Test Procedure:

1) Turn on data acquisition system. Ok? ______
2) Confirm data is being collected. Ok? ______
3) Using insulated gloves and support beam, submerge test cylinder into the center of the dewar at a speed of ten seconds until the support beam can rest on the top of the dewar. Ok? ______
4) When each thermocouple has reached a steady state of around 77K (-196°C) for at least 10 seconds, stop the data acquisition system. Ok? ______
5) Using insulated gloves and support beam, remove test cylinder. Ok? ______
6) Record cool time / time the readings reached steady state. Time? ______ s

D. Shut Down/Maintenance

1) Reseal unused liquid nitrogen in dewar. Ok? ______
2) Verify minimum safe handling temperature of cylinder with infrared thermometer. Above 1°C ______
3) Around the thermocouples, inspect each hole visually for cracks and chips. Ok? ______
4) Around the thermocouples, inspect each hole using fingernail for cracks (should not catch). Ok? ______

Appendix F: Test Plan

E. Test Constraints

Constraint	Description	Value/Range
Liquid Nitrogen Temp	The temperature of the nitrogen in which the cylinders are being submerged, should not change throughout the experiment.	-196°C (77K)
Size of Cylinders	Radius of all cylinders tested, all cut from the same piece of material.	1.25 inch radius
Cryo Dewar Dimensions	Height and diameter of cryo dewar used to hold liquid nitrogen, this will not change.	OD 349.25mm ID 203mm Ext Ht 450.85mm Int Ht 381mm

Table 1 Test Constraints

F. Test Parameters

Parameter	Description	Value/Range
Cylinder Initial Temp	Ambient temperature will likely vary day to day and initial temperature of the cylinder will vary depending on if it has been previously tested that day. Need to measure what temperature cylinder starts at to analyze heat transfer.	20-25°C
Depth of Liquid Nitrogen	Level will decrease as it boils off and need enough depth is needed to conduct each test.	No less than 150mm (or 6in)

Table 2 Test Parameters

G. Test Variables

Variable	Description	Value/Range
Cylinder Tested (Var 1)	We are testing two different cylinders: Cylinder 1 and Cylinder 2. Cylinder 1 tests the temperature at the center of the cylinder and Cylinder 2 tests the temperature at 1/2, and 3/4 of the way through the cylinder's circular center.	1 or 2

Table 3 Test Variables

H. Measurements

Measurement	Description	Value/Range
1/2 Cylinder Temperature (Meas 1)	LabVIEW converts the voltage obtained from the thermocouple throughout the time of the experiment to a temperature (°C), with a 2 second delay time from the thermocouple. These values are saved in an Excel file.	Room Temp to about Cryo Temp (25 to -188°C)
3/4 Cylinder Temperature (Meas 2)	LabVIEW converts the voltage obtained from the thermocouple throughout the time of the experiment to a temperature (°C), with a 2 second delay time from the thermocouple. For Cylinder 2, two thermocouples are inserted and record data simultaneously in the same file, outputting both the 3/4 and 1/2 cylinder temperature measurement.	Room Temp to about Cryo Temp (25 to -188°C)
Cool Down Time (Meas 3)	The time (in seconds) from when the cylinder is submerged in liquid nitrogen til the time its center reaches -188°C (approximately the temperature of liquid nitrogen, which is -196°C). The time from when LabVIEW is turned on until the cylinder is submerged is subtracted out.	1-10 minutes (60-600 seconds)

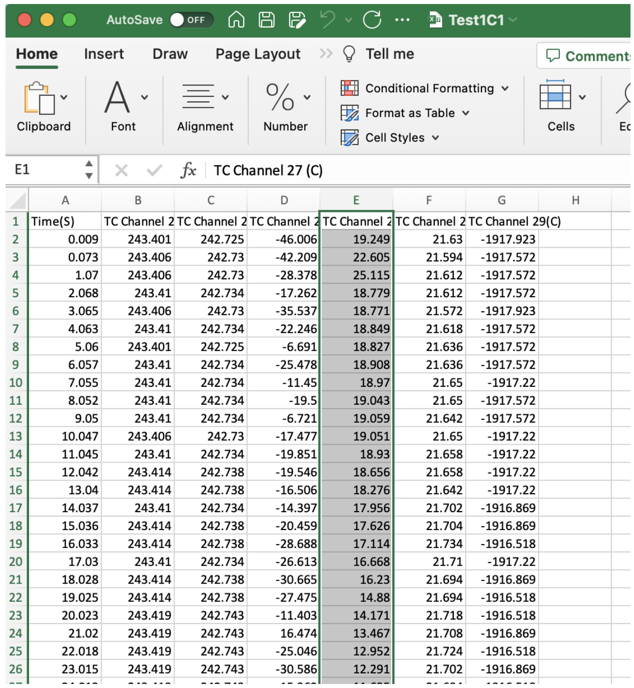
Table 4 Measurements

I. Test Matrix

Run	Cylinder	1/2 cylinder	3/4 cylinder	Cool Time (sec)
1	1	Excel file: Test1C1 (Column 5)	N/A	393
2	2	Excel file: Test2C2 (Column 5)	Excel file: Test2C2 (Column 6)	355
3	1	Excel file: Test3C1 (Column 6)	N/A	350
4	2	Excel file: Test4C2 (Column 2)	Excel file: Test4C2 (Column 3)	312
5	1	Excel file: Test5C1 (Column 2)	N/A	379
6	2	Excel file: Test6C2 (Column 2)	Excel file: Test6C2 (Column 3)	308

Table 5 Test Matrix

The 1/2 cylinder and 3/4 cylinder measurements are taken through LabVIEW and a table of time and temperature measurements are output (see Figure 9 for an example of the readout). These outputs are recorded in an Excel file, and are therefore listed above in Table 5, the Test Matrix, as such. The cool down time is calculated from the file as the time from cylinder submersion until the central temperature reaches -188°C.



	Time(S)	TC Channel 2	TC Channel 2	TC Channel 2	TC Channel 2	TC Channel 2	TC Channel 29(C)
2	0.009	243.401	242.725	-46.006	19.249	21.63	-1917.923
3	0.073	243.406	242.73	-42.209	22.605	21.594	-1917.572
4	1.07	243.406	242.73	-28.378	25.115	21.612	-1917.572
5	2.068	243.41	242.734	-17.262	18.779	21.612	-1917.572
6	3.065	243.406	242.73	-35.537	18.771	21.572	-1917.923
7	4.063	243.41	242.734	-22.246	18.849	21.618	-1917.572
8	5.06	243.401	242.725	-6.691	18.827	21.636	-1917.572
9	6.057	243.41	242.734	-25.478	18.908	21.636	-1917.572
10	7.055	243.41	242.734	-11.45	18.97	21.65	-1917.22
11	8.052	243.41	242.734	-19.5	19.043	21.65	-1917.572
12	9.05	243.41	242.734	-6.721	19.059	21.642	-1917.572
13	10.047	243.406	242.73	-17.477	19.051	21.65	-1917.22
14	11.045	243.41	242.734	-19.851	18.93	21.658	-1917.22
15	12.042	243.414	242.738	-19.546	18.656	21.658	-1917.22
16	13.04	243.414	242.738	-16.506	18.276	21.642	-1917.22
17	14.037	243.41	242.734	-14.397	17.956	21.702	-1916.869
18	15.036	243.414	242.738	-20.459	17.626	21.704	-1916.869
19	16.033	243.414	242.738	-28.688	17.114	21.734	-1916.518
20	17.03	243.41	242.734	-26.613	16.668	21.71	-1917.22
21	18.028	243.414	242.738	-30.665	16.23	21.694	-1916.869
22	19.025	243.414	242.738	-27.475	14.88	21.694	-1916.518
23	20.023	243.419	242.743	-11.403	14.171	21.718	-1916.518
24	21.02	243.419	242.743	16.474	13.467	21.708	-1916.869
25	22.018	243.419	242.743	-25.046	12.952	21.724	-1916.518
26	23.015	243.419	242.743	-30.586	12.291	21.702	-1916.869

Fig. 9 Readout of test data from LabVIEW.

In this readout of test data from LabVIEW, the time and temperature are recorded throughout the test. In the first column of the table, the time (in seconds) is recorded, and in the highlighted column the temperature readout (in Celsius) is depicted, changing with time. From here, the data is read by MATLAB and temperature versus time can be plotted, as seen below Figure 10.

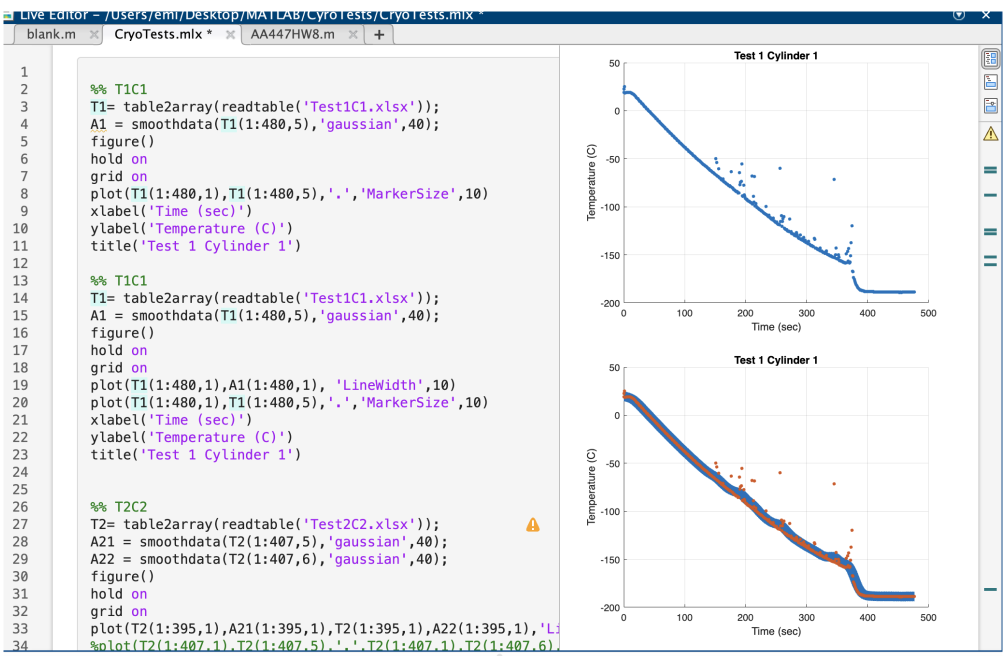


Fig. 10 Example of MATLAB plots generated from readout data.

Appendix G: Data

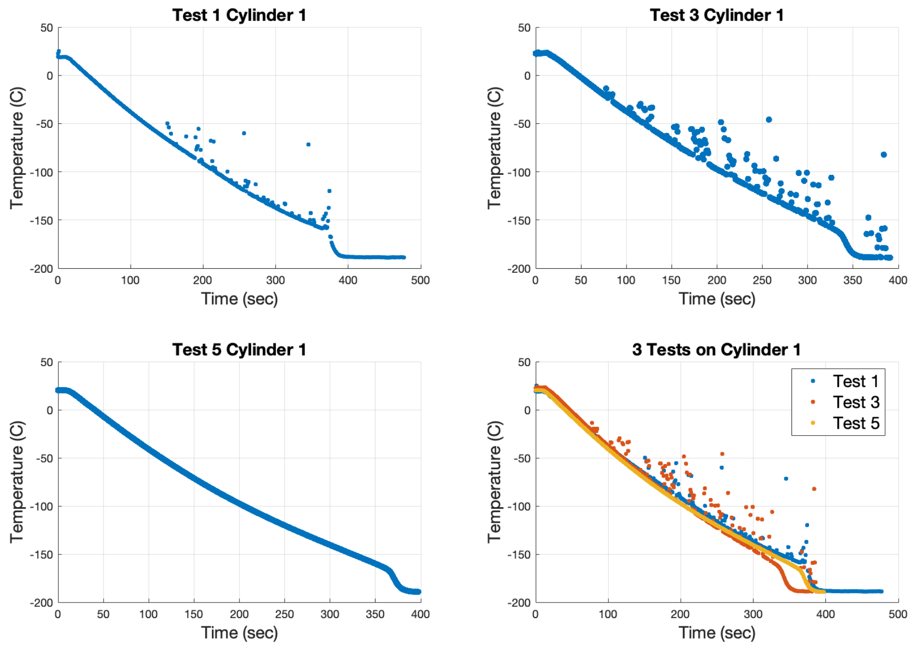


Fig. 11 Separate Plots of Temperature vs. Time for the three tests conducted on Cylinder 1, using the raw data collected.

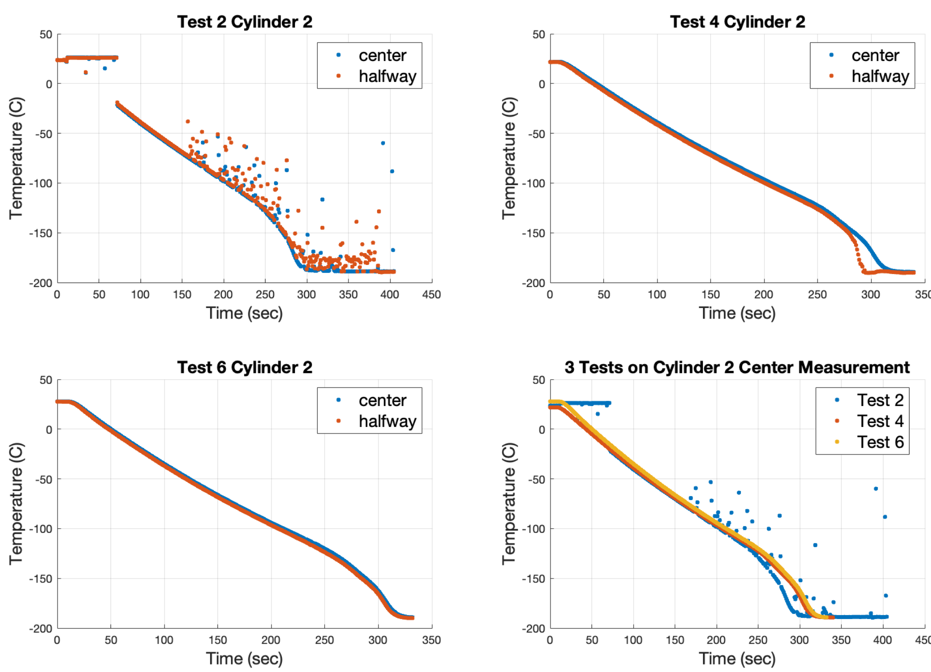


Fig. 12 Separate Plots of Temperature vs. Time for the three tests conducted on Cylinder 2, using the raw data collected.

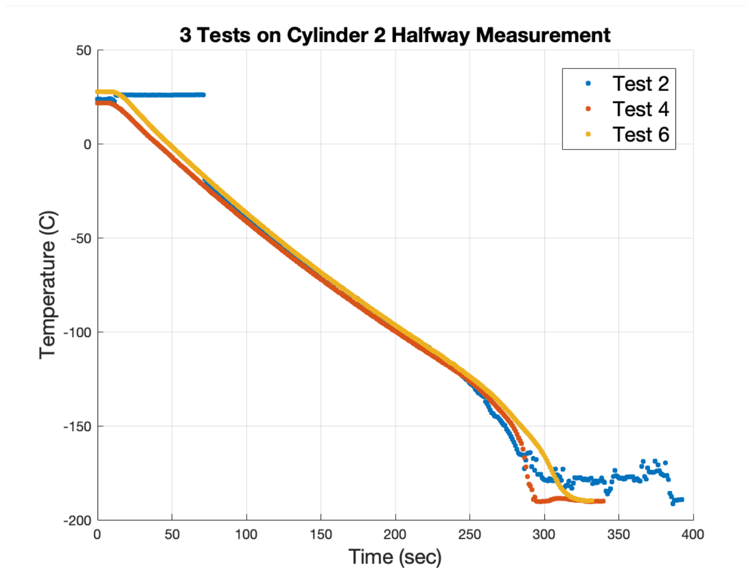


Fig. 13 Plot of Temperature vs. Time for the three tests conducted on Cylinder 2, looking at only the halfway temperature measurement. Data has been smoothed.

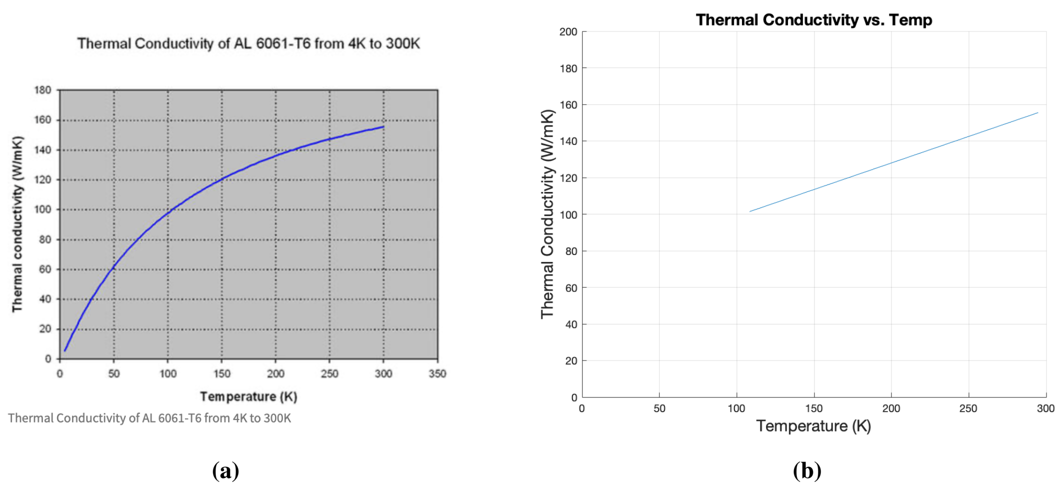


Fig. 14 (a) Plot of thermal conductivity vs. temperature from published data. (b) Linearized plot of thermal conductivity vs. temperature used in this report to calculate heat flux.