Cryogenic Boiling Team 1

AKA: Team Charlie

Team Members: Felicity Cundiff, Adam Delbow, Evelyn Madewell, and Emi Peterson

Faculty Advisor: Professor Hermanson
TA: Jackson Zhou

Background on Boiling / Heat Flux

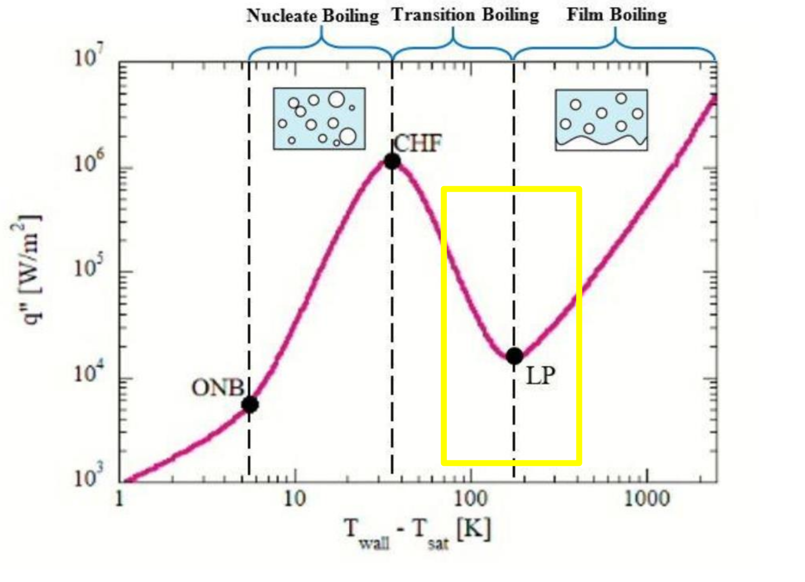


Figure 1: An Example of a Typical Boiling Curve for Water

Boiling Curve:

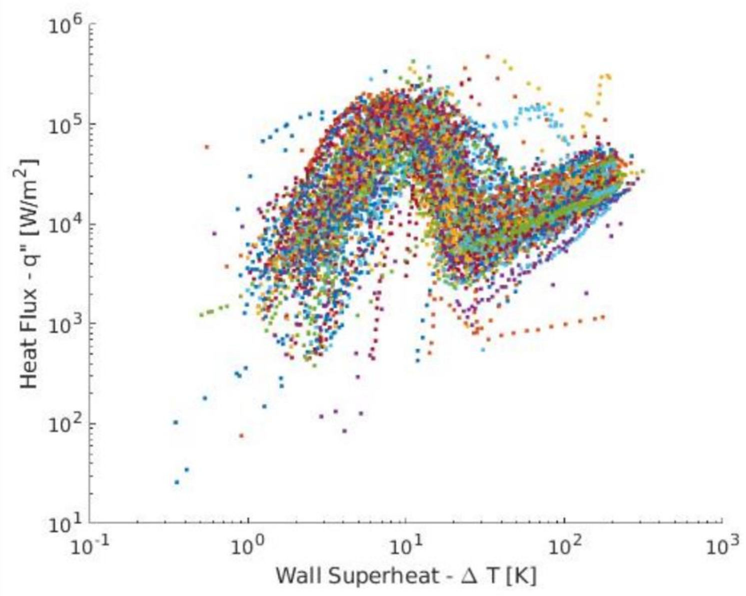
- Fluid moves as liquid heats.
- Transition points for pool boiling
  - Onset of nucleate boiling
  - Critical heat flux
  - Leidenfrost point
- Quenching starts after film boiling.
  - (back down curve)

Heat Flux (for a sphere):

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

- q = heat flux (W/m^2)
- k = thermal conductivity
  - Depends on material
  - Can change in cryogenic temperature
- dT/dr = change in temperature T with respect to radius r

Why Does It Matter?



Spread of q vs T data from Reference 3.

- Hydrogen and Oxygen don't store well.
  - How to reduce boiling off?
  - How does a surface cool down?
- Boiling data is inconsistent: **great uncertainty**
  - What resisto-thermo device is used?
  - What materials?
  - How are sensors inserted into the sphere?
    - No influence from LN?
  - Where to measure temperature?
  - What orientation? (Violent boiling effects)

(Sphere is simplest geometry.)

Goals

- **Reduce uncertainty**
- Improve accuracy of heat transfer methods
- Test hypothesis that temperature measurements taken along the horizontal axis will show less variation than from other orientation

- (Originally planned to change gradients as well, but determined this wouldn't provide new information.)

Challenges

- Sphere material and size
- Thermocouple diameter and availability
- Drilling holes
  - Location
  - Diameter
  - Depth
  - Precision and accuracy
- Thermocouple installation
- Mounting/orientation of spheres

Timeline

Design

Weeks 2-5

- Materials
- Thermocouples
- CADD for Spheres
- Napkin Calculations

Build

Weeks 5-7

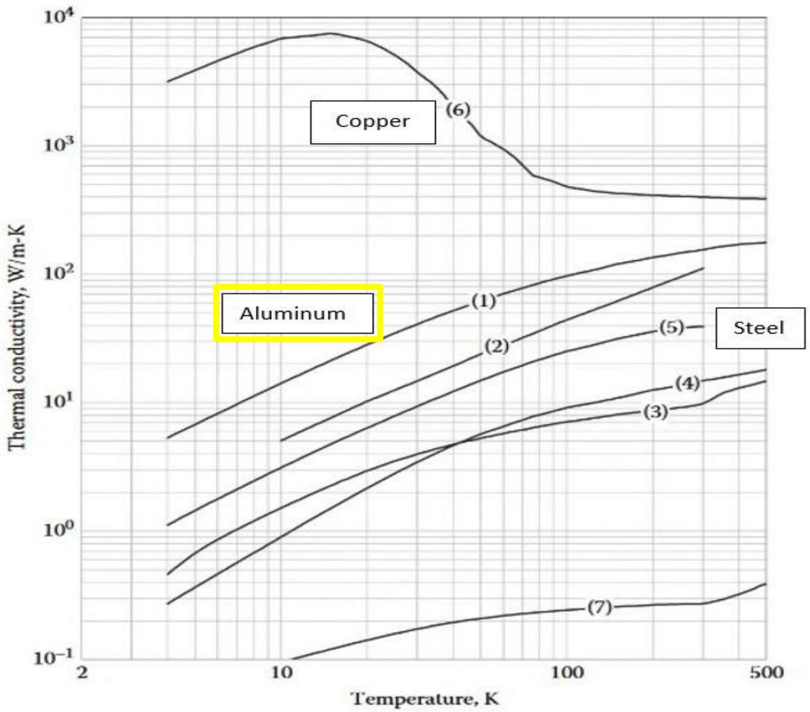
- Mill
- Feasibility
- Adaptations/Improvements
- Assembly

Test

Weeks 7-10

- Safety
- Setup/Checkout
- Experimentation
- Analysis

Materials and Equipment



Considerations

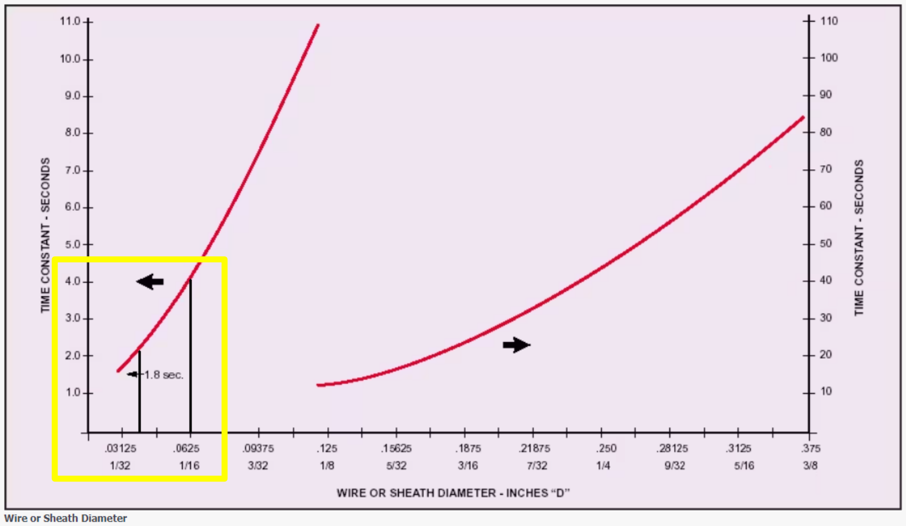
- Cost
- Machinability
- Geometry
- Heat Conduction

Cool-down Time Calculation and Thermocouples

Thermocouple and lead wire.

Calculations:

- From an h value of 198,100 W/m^2 K, Biot number of 10, sphere cool down time ≅ 66.8 seconds
- For 1/25th diameter thermocouples: response time ≅ 2 seconds
- Want greater than one order of magnitude. ✓

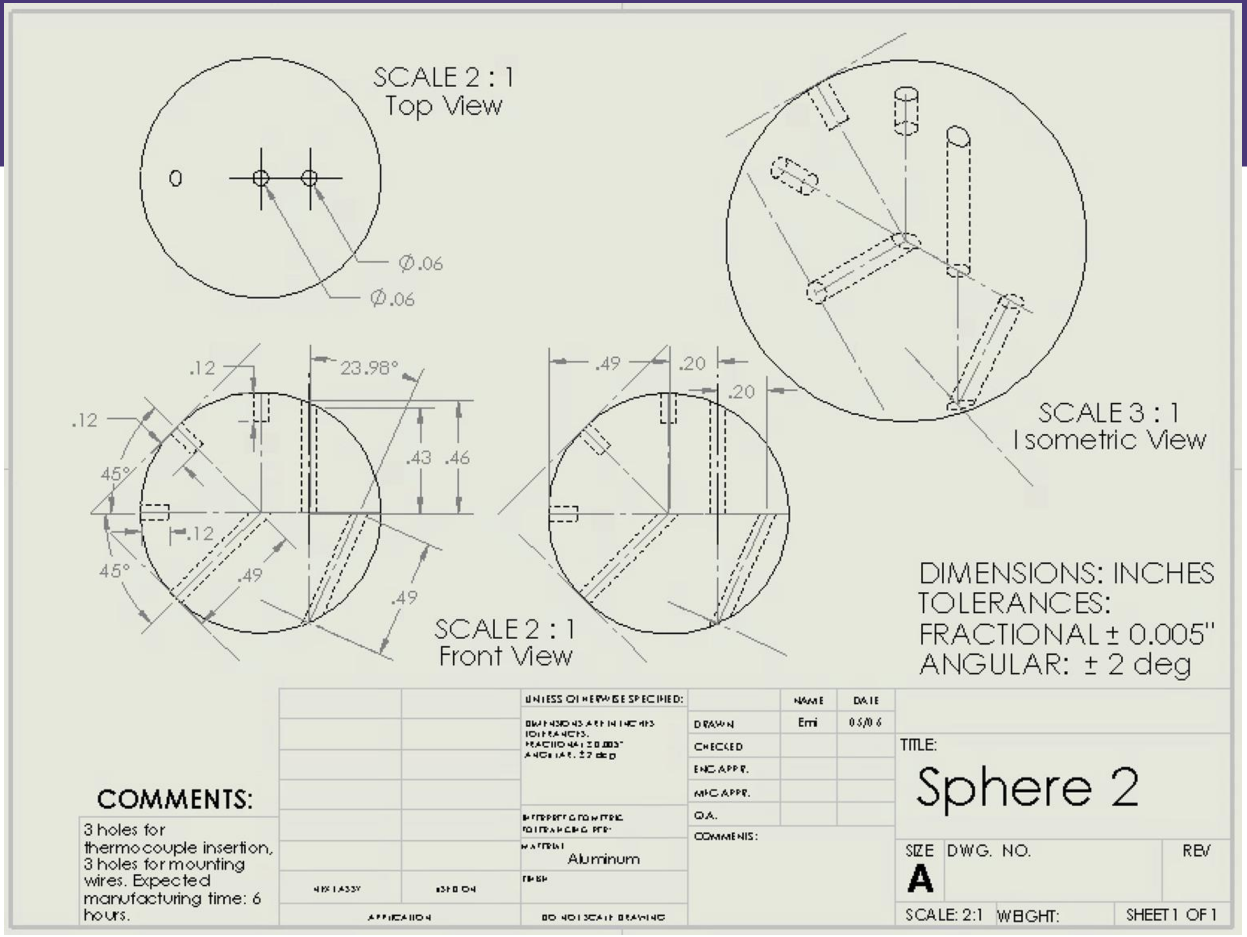


Thermocouple 1-4 second measurement time.

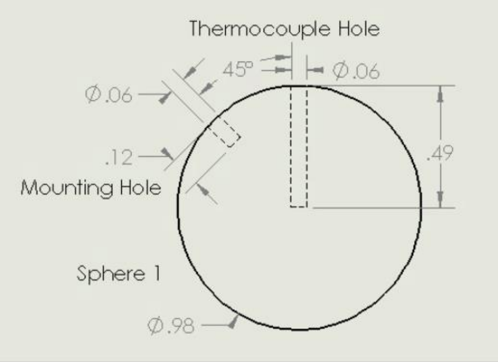
CADD

2 spheres will be drilled for the experiment:

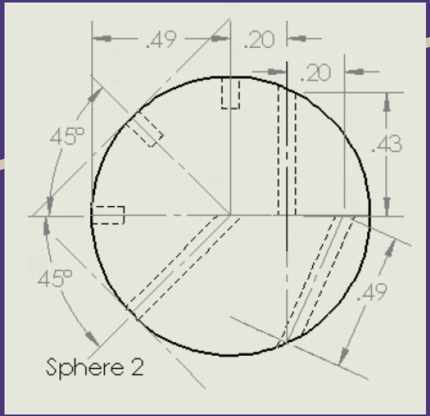
- Sphere 1 with 2 1/16th inch holes, 1 for thermocouples and 1 for mounting wires
- Sphere 2 depicted with 6 1/16th inch holes, 3 for thermocouples and 3 for mounting wires
- Holes ending at 5/10, 7/10, and 9/10 through diameter



Manufacturing and Assembly



Sphere 1

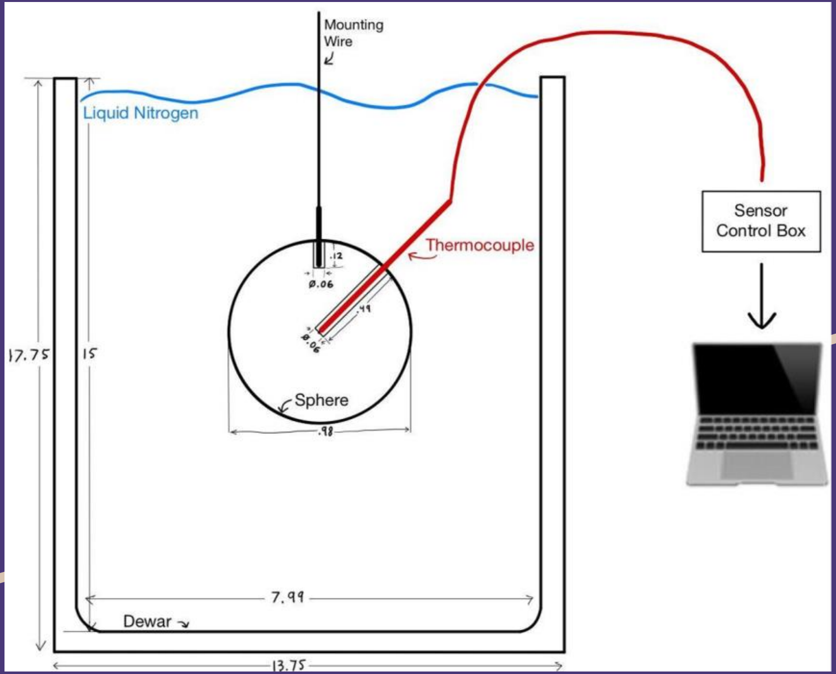


Sphere 2

- Expected to be most difficult and time consuming part of our design.
- Precision:
  - Angle measurements within ± 2 degrees
  - Drill measurements within ± 0.005 inches
- Minimize disturbance effects
- Mounting / suspension
- Mill
  - Accuracy and control
- Vs. watchmaker's drill press
  - Rotational speed
  - Less precise?
- Deeper holes for inserting thermocouples
- Shallower holes for mounting hooks

Safety / Setup

Apparatus:



Safety:

- Lab coats and safety goggles must be worn during experiment.
- Insulated gloves must be worn when working with or near liquid nitrogen.
- Oxygen concentrations must be checked before working with liquid nitrogen (greater than 19.5%).
- Suitable ventilation through air ducts and fume hoods

Setup:

- Calibration of thermocouples with liquid nitrogen, dry ice, and cold water.
- Assembly of thermocouples into sphere
  - Use PTFE tape to ensure seal
- Check thermocouple sealant
  - Compare with results from submerging thermocouple alone
  - Temperature change monitored frequently for drastic variations
- Check drilled holes for cracks or stress due to thermal shock

Experimentation

Constraints:

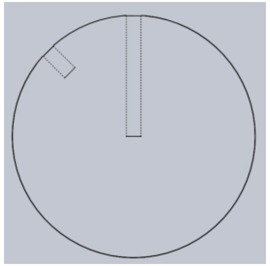
- Liquid nitrogen temperature: 77 K
- Size of spheres: Radius = 12.5 mm (0.5 in.)
- Dewar dimensions: Volume ≅ 17 liters

Test Parameters:

- Room temperature: 290 - 300 K
- Depth of LN: greater than 100mm

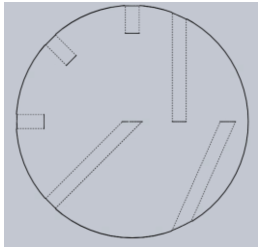
Test Variables:

- Sphere design (Var 1)
  - Sphere 1: center measurement
  - Sphere 2: center, half-way, and surface measurements
- Orientation (Var 3)
  - Horizontal (0 degrees)
  - Angled (45 degrees)
  - Vertical (90 degrees)



Sphere 1

Sphere 2



Measurements:

- 1/2 Sphere temperature (Meas 1)
- 7/10 Sphere temperature (Meas 2)
- 9/10 Sphere temperature (Meas 3)
- Cool down time (Meas 4)

Expected Results

Run	Sphere	Orient.	1/2 Sph.	7/10 Sph.	9/10 Sph.	Cool Time
1 x3	1	any				
2 x3	3	1				
3 x3	3	2				
4 x3	3	3				

Processing:

- 3 channels vs. time for each (repeated) test
- Use Labview to convert voltage to temperature
- Use 3 channels (center, half-way, and surface) to calculate dT/dr
  - $T = a + b \times r^n$, where n should be negative
  - Compare with conductive modeling (Biot #)

Analysis:

- Does the number of drilled holes affect the temperature measurements?
  - Compare to Sphere 1
- Does Orientation 1 (horizontal) provide more consistent results than Orient. 2 and 3?
- Does our data fit into the uncertainty range of previous research?
- Do our results improve uncertainty?
  - vs. previous research

Future Work

Week 7
- Interim Report
- Presentation
- Drill Spheres
- Begin Assembly

Week 8
- Finish Assembly
- Check out Procedure
- First round of testing

Week 9
- Second round of testing
- Third round of testing

Week 10
- Analyze Data
- Final Report

References

1. Barron, R.F., Nellis G.F, “Cryogenic Heat Transfer”, CRC Press, 2016
2. Çengel, Y. A., *Heat Transfer: A Practical Approach*, McGraw-Hill, 2002, Chap. 4: Transient Heat Conduction, pp. 232–241
3. Moore, R. C., and Hermanson, J. C., “Evaluating the Complete Pool Boiling Curve for Liquid Nitrogen,” NASA Grant and Cooperative, 2019-2021.
4. Yee, K., “Liquid Nitrogen Can Cause Severe Burns,” National Capital Poison Center, 2021. URL: [https://www.poison.org/articles/liquid-nitrogen-can-cause-severe-burns-211 Accessed 4/11/23]
5. “Thermocouple Response Time,” Omega Engineering, Inc., 2023. URL: [https://www.omega.com/en-us/resources/thermocouples-response-time Accessed 4/24/23]

Q&A Time

Feel free to ask us any clarifying or in-depth questions about our lab project.