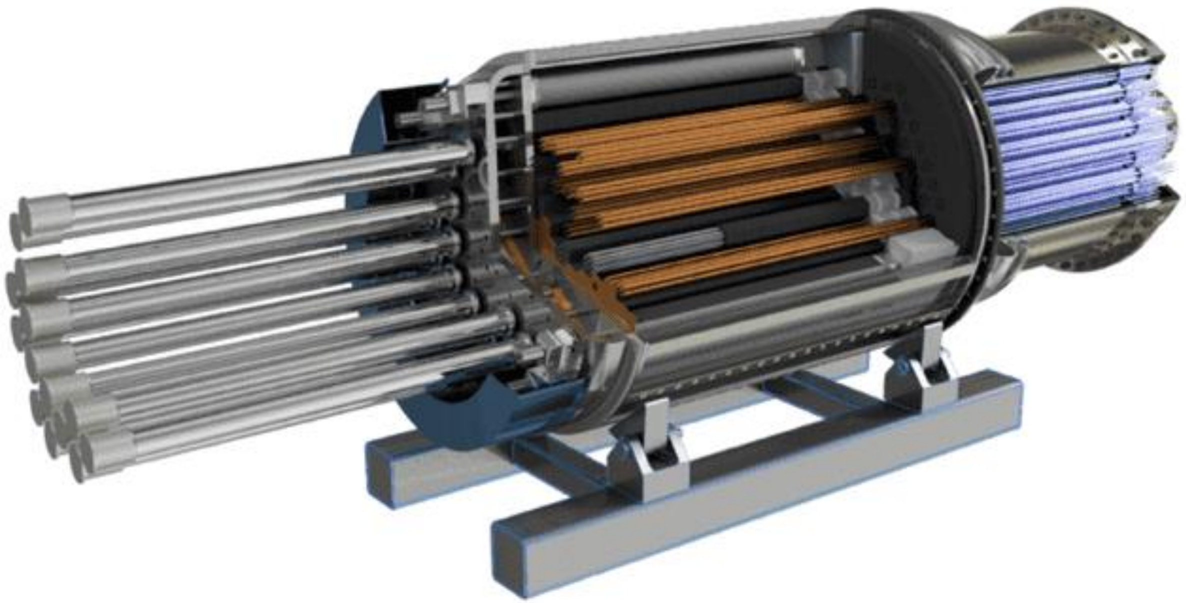
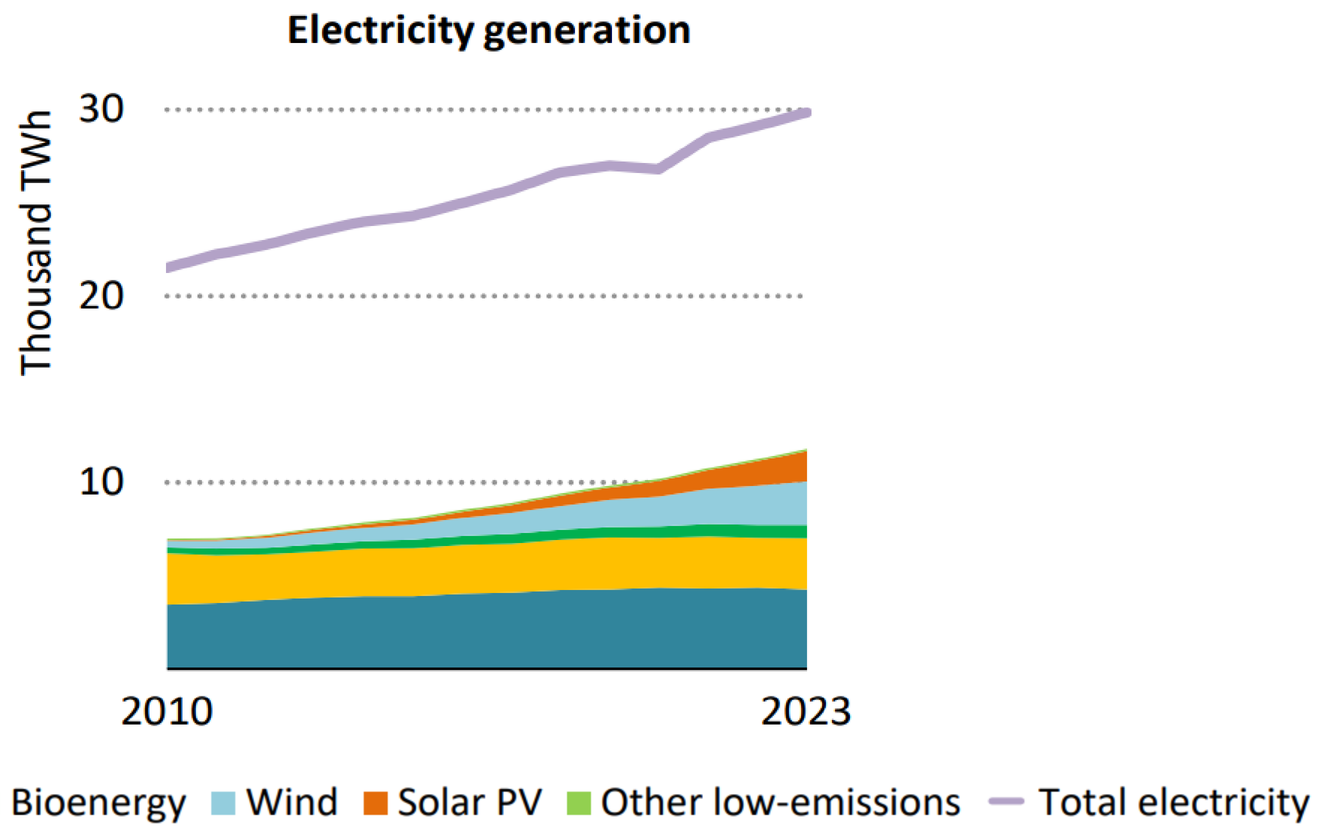
Swanson School of Engineering
Mechanical Engineering and Materials Science (MEMS) Department
University of Pittsburgh

Heat Exchanger Insulation Design for eVinci™



TEAM 8: PAIGE DILLON, JESSICA NIZNIK, EVAN PELUSO, KRZYSZTOF RADZISZEWSKI, ROBYN STRAZISAR, AND AIDEN ZURCHER

Global energy demand is increasing faster than renewable energy can be installed to meet it.



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Nuclear energy can provide electricity without emissions, but it requires investment of time, money, and space.

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Westinghouse is designing the eVinci microreactor to meet the energy demands of remote, critical energy areas.

Military bases

Industrial Sites

Remote Communities

Data Centers

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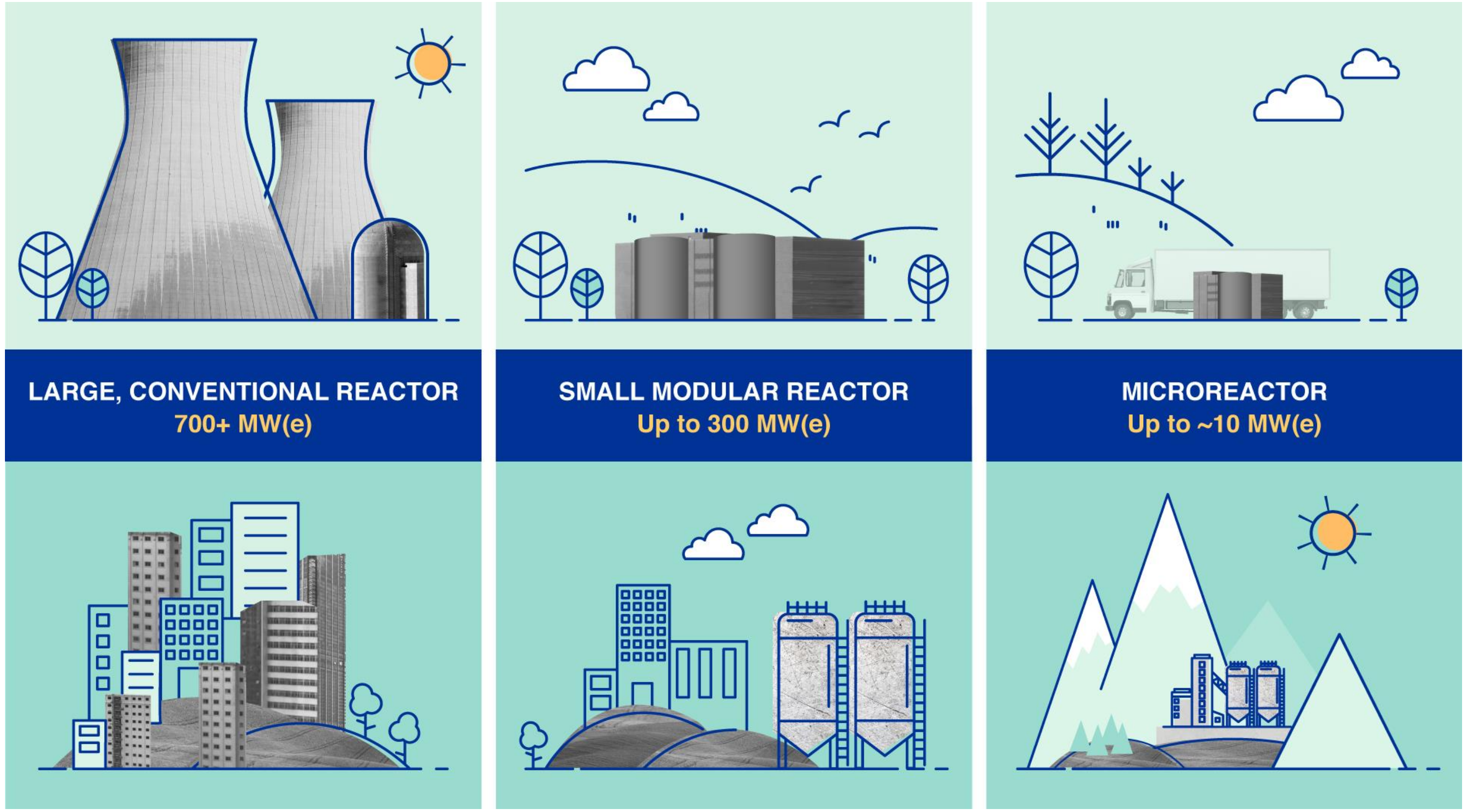
The eVinci microreactor is easier to manufacture, transport, and operate than a traditional nuclear reactor.



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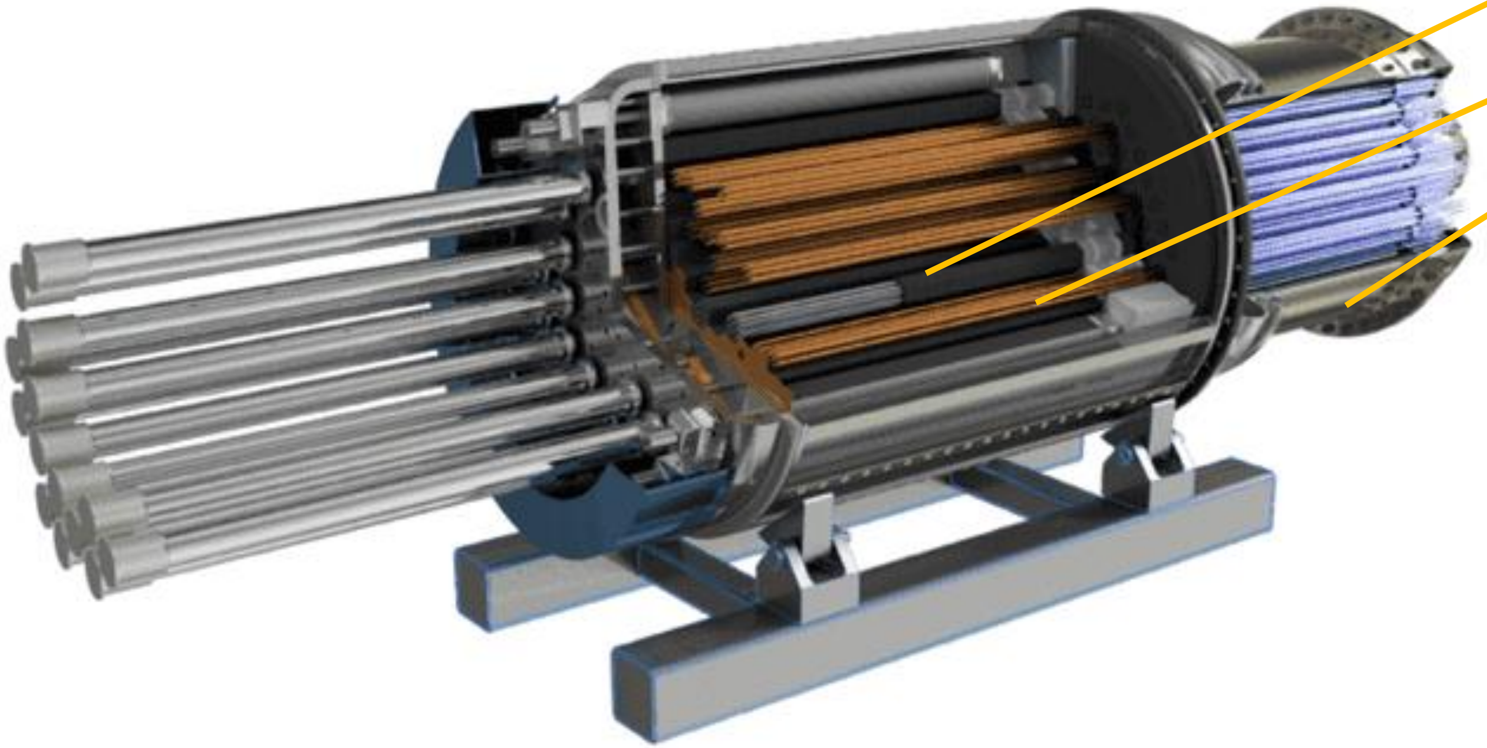
Heat generated in the core of the eVinci is transferred to the primary heat exchanger using heat pipes.



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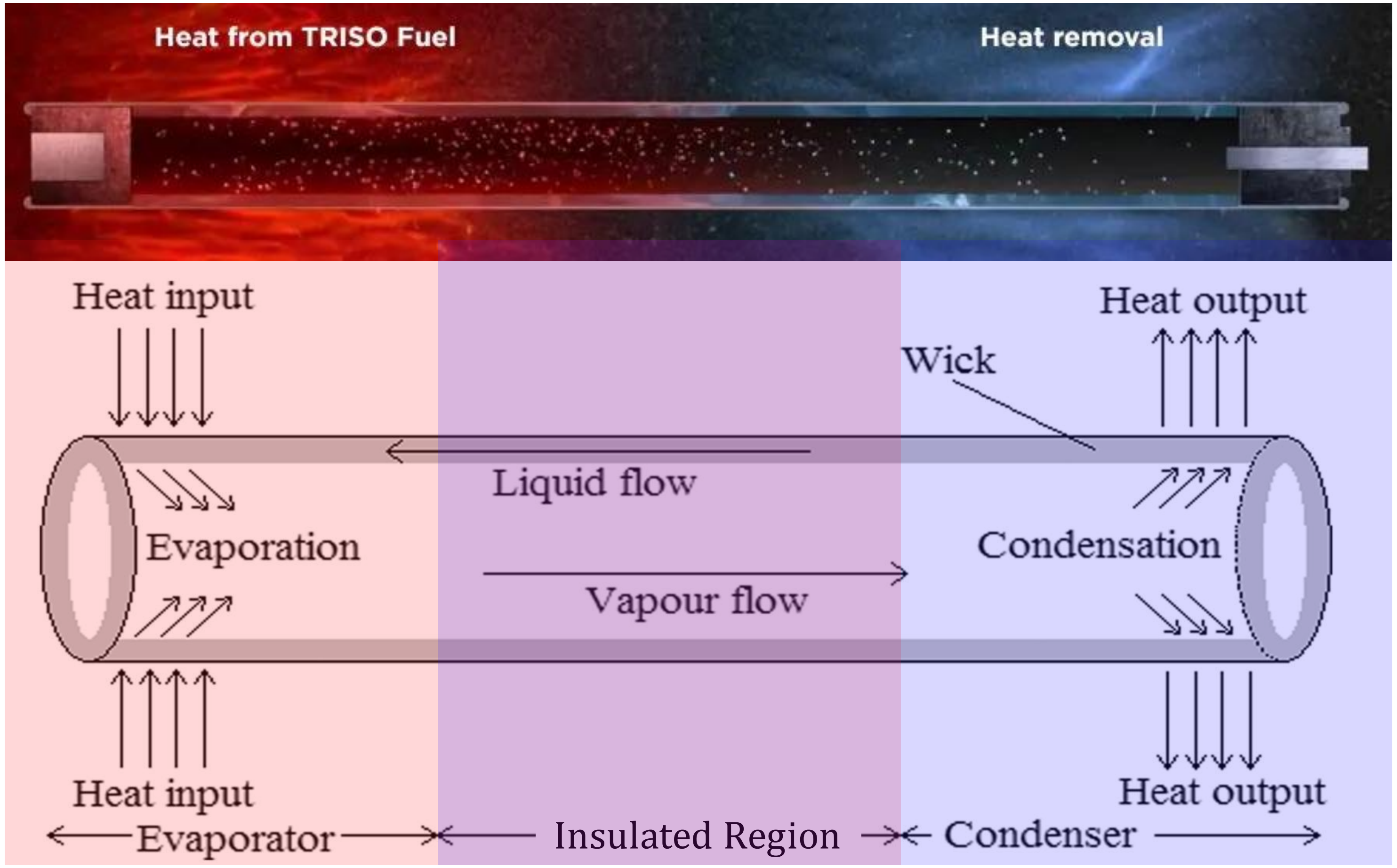
Efficient operation of the eVinci reactor requires effective insulation of the heat pipes.



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Project Goal and Deliverables

Design an insulation package that meets given requirements in the helium environment

Thermal Simulation of Heat Pipe System

- Temperature profile of the system
- Heat flux through surface of the insulation

Material Datasheet

- Material properties (Composition, grade, operating temperature, conductivity, strength, cost, etc).

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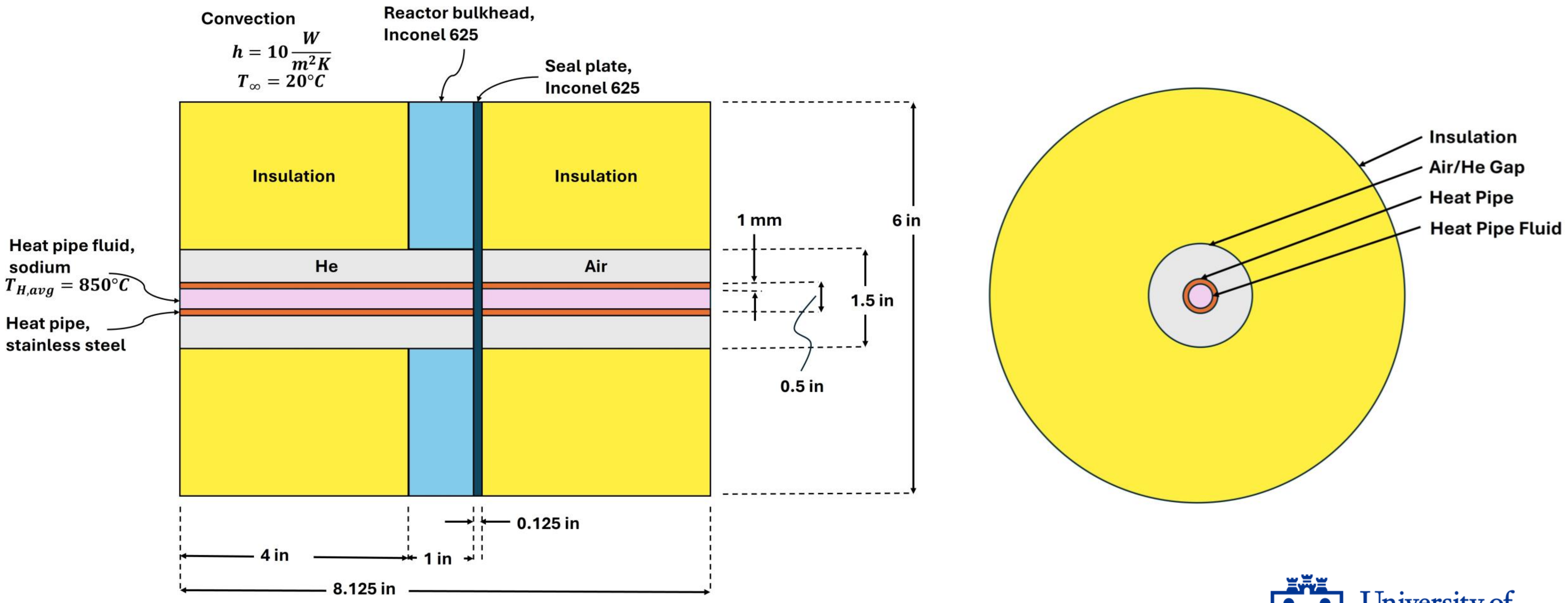
We designed a schematic to model the heat transfer conditions reflecting the future testing environment.



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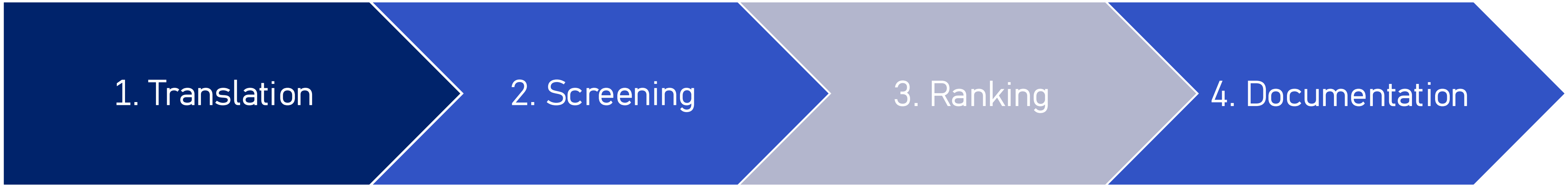
Different insulation materials show variation in thermal and mechanical properties, requiring a structured material selection approach.

ALL MATERIALS **FINAL MATERIAL**



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Translation - converting design requirements into constraints, objectives, and free variables.

CONSTRAINTS	**Design life** – 12 years **Environment** - Helium (1 atm) and air (7 atm) **Structure** – Rigid, fully contained, thickness ≤ 2.25 in. **Thermal Performance** – Max surface heat flux (5 kW/m) and max surface temperature (400°C)
OBJECTIVES	**Minimize** – surface heat flux and surface temperature, balance with cost
FREE VARIABLES	**Material** – thermal conductivity and emissivity

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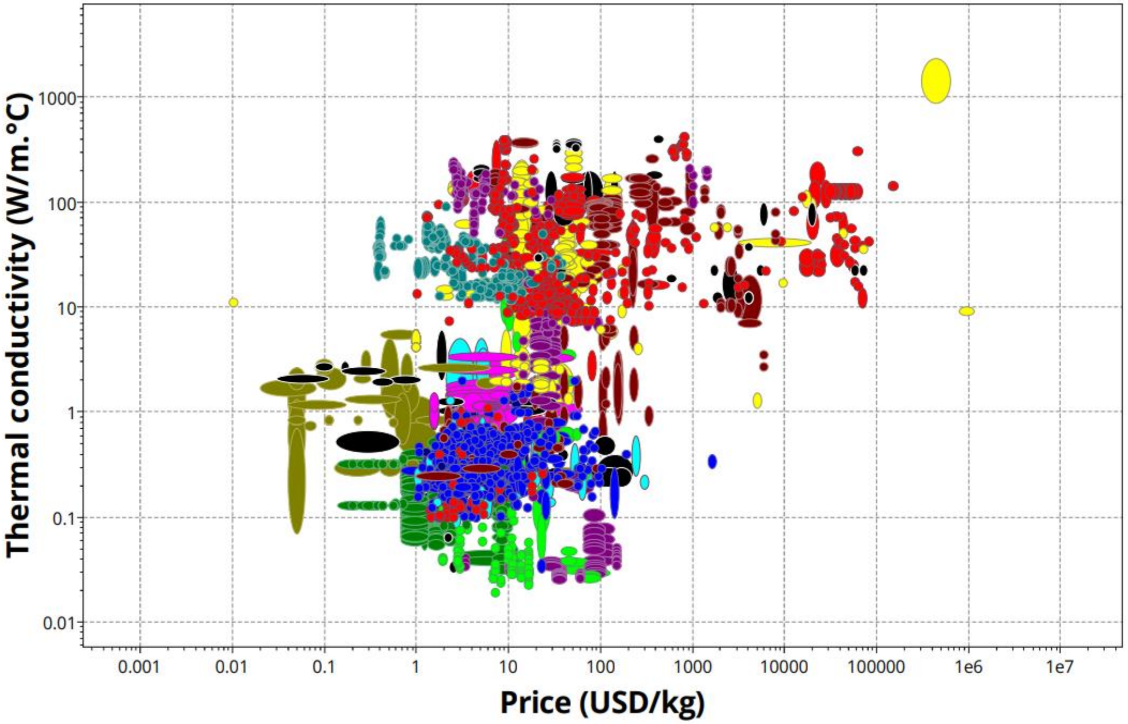
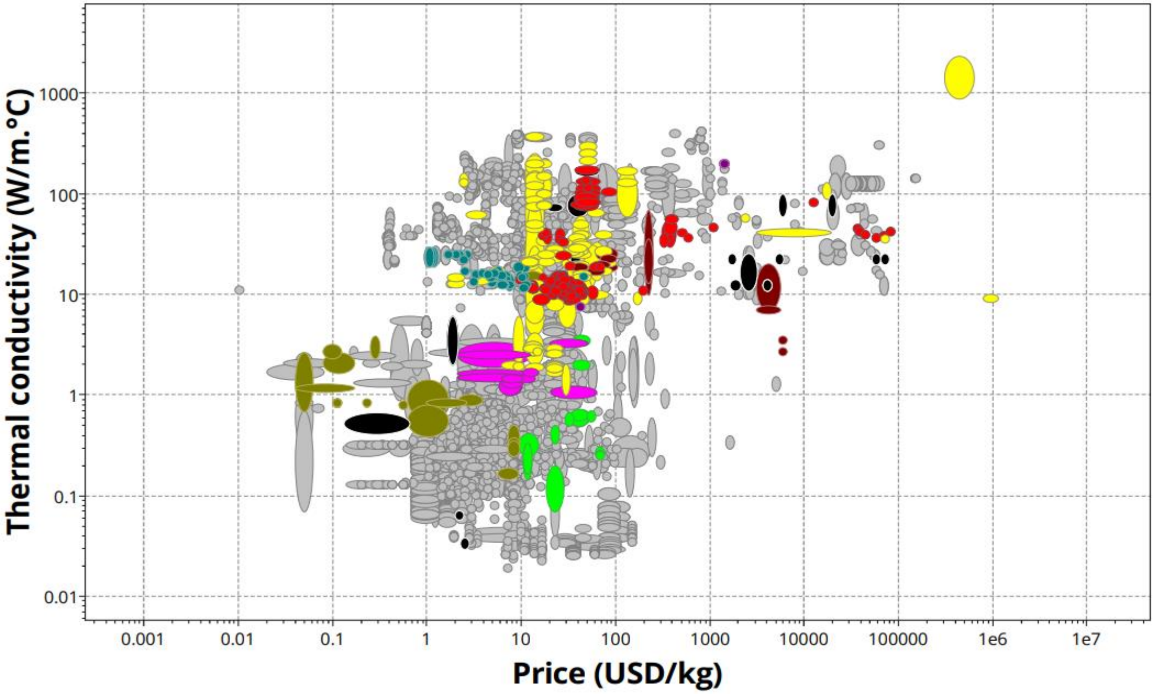
Screening – Apply constraints to remove materials that don't meet minimum requirements.





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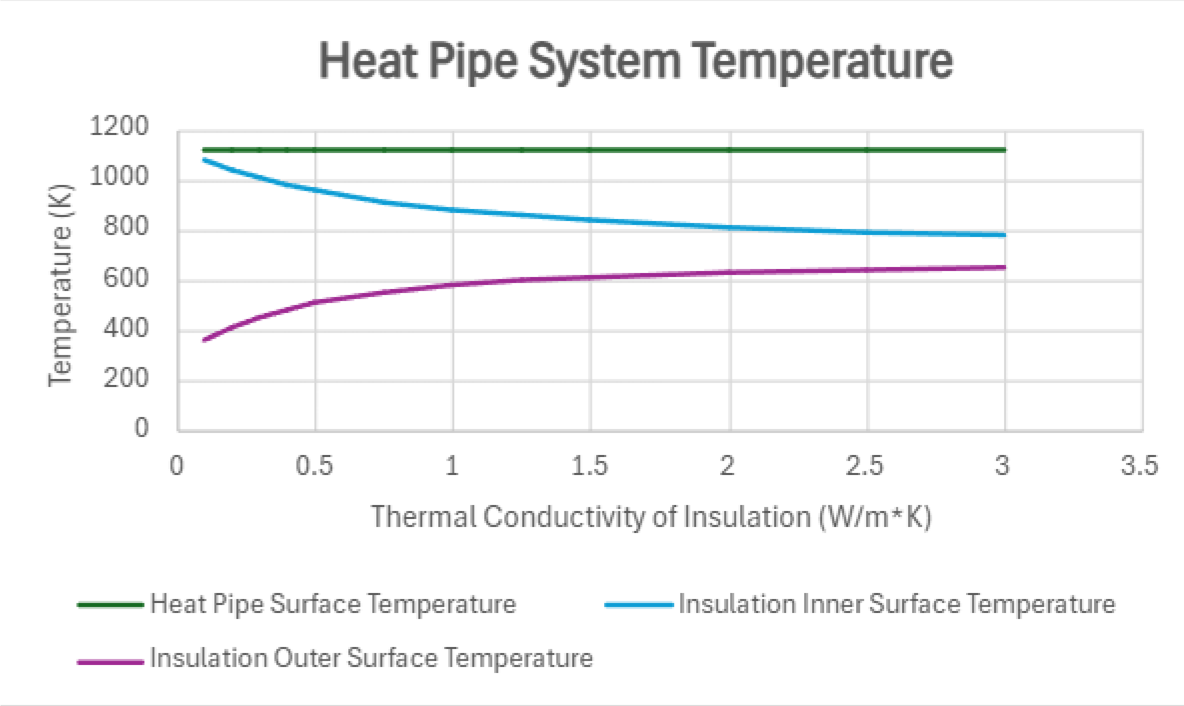
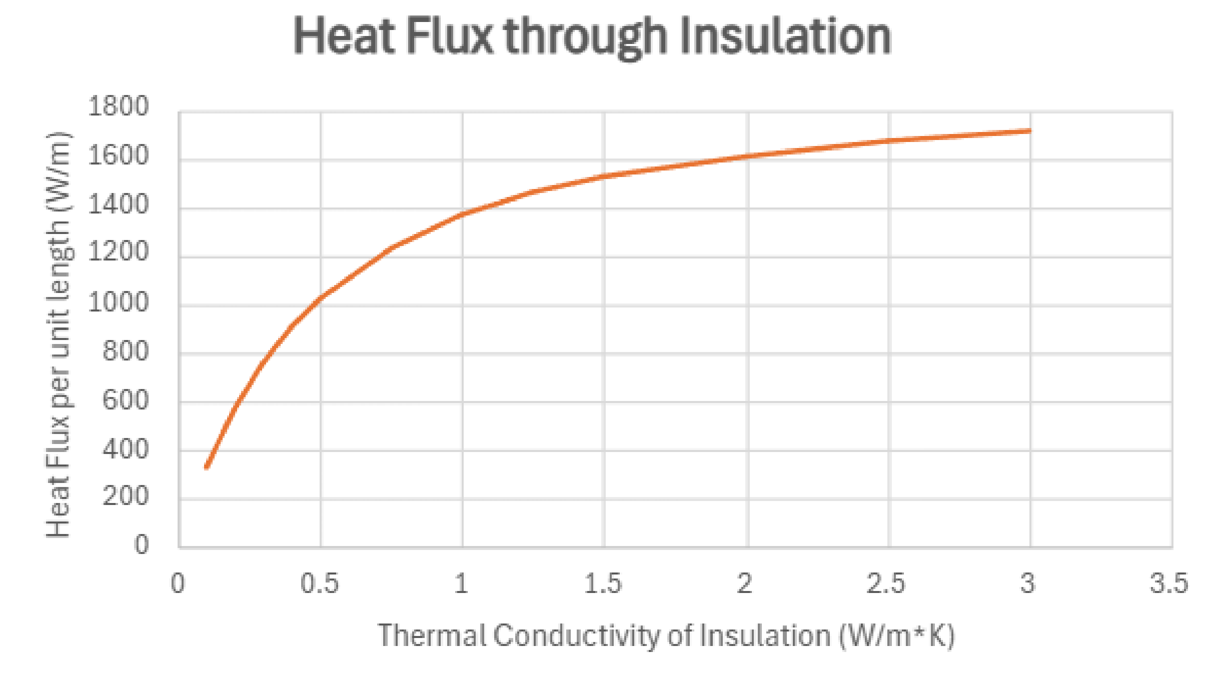
Ranking – Quantitatively identify which materials are the best for the job.





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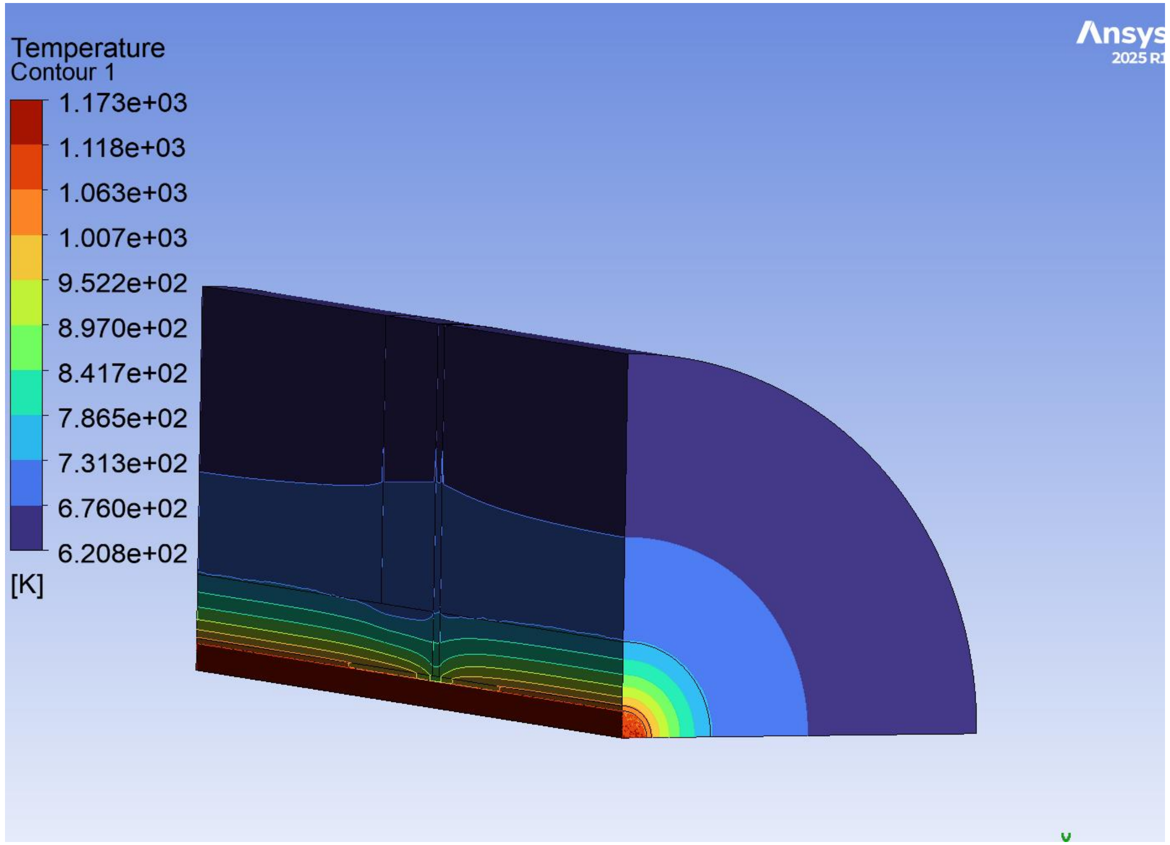
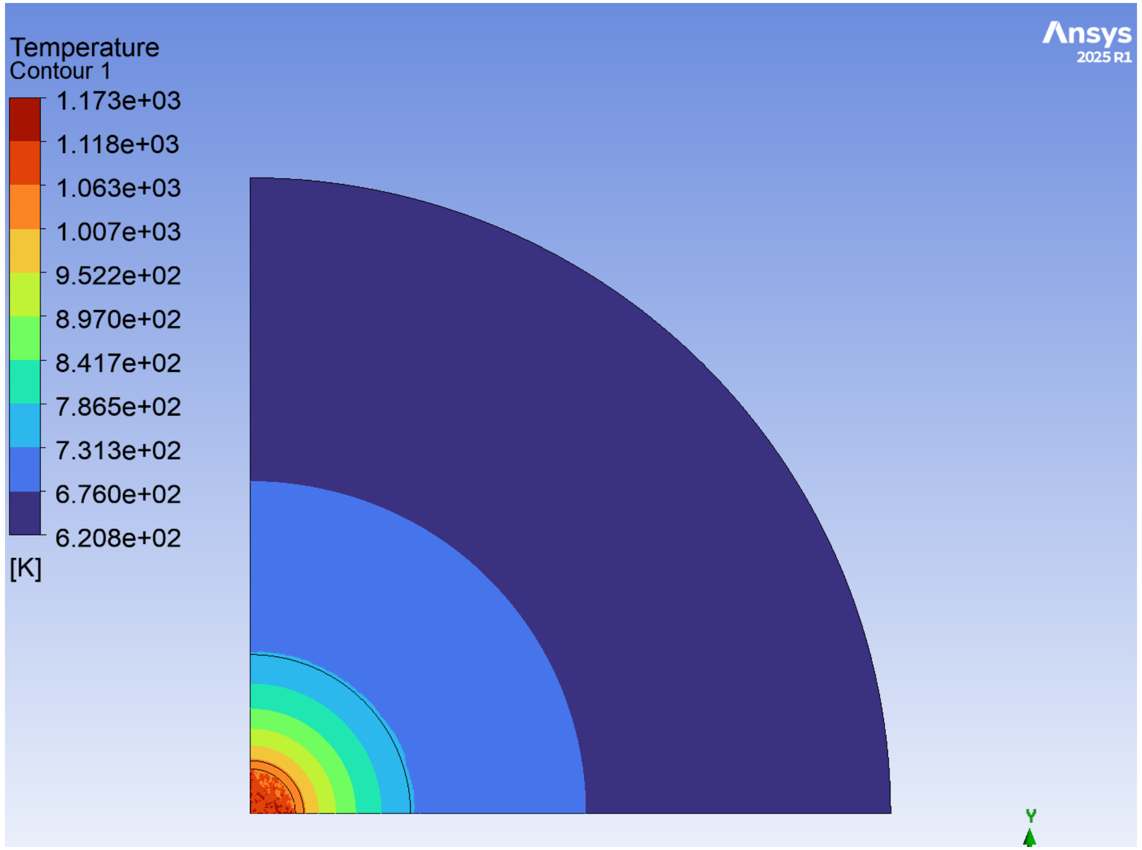
A simulation was performed to validate the hand calculation and material choice.





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Documentation – Consider higher order properties to determine feasibility of implementation.

Hot Face Environment	Exposed to helium; inert gas
Structural Loading	Minimal loading with pressure up to 7 atm (~0.7MPa)
Thermal Cycling	Insulation section is ideally isothermal
Cost vs Performance	Balance between optimizing performance vs. cost
Manufacturing	Machinability, testable sizes, and multiple supplier options
Safety	Minimize risk to reactor components

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Refractory Ceramic Fibers (RFCs)

Aerogels

Dense Refractory Brick

University of Pittsburgh

Documentation – Consider higher order propertiesto determine feasibility of implementation.

Refractory Ceramic Fibers (RFCs)

Safety Risk: Fiber debris can damage reactor components and cause failures, as shown in documented case studies

Aerogels

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Aerogels

Safety Risk: Gel is contained in a fiber matrix; same risk as RFCs

Cost / Temperature Limit: Standard silica aerogels rated ≤650 °C; high-temperature variants cost ~$300–$500 per roll

Dense Refractory Brick

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Dense Refractory Brick

Thermal Performance: Weaker insulation with high thermal conductivity (1–3 W/m·K); cost-to-performance ratio is poor

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Based off each stage of the material selection process, Insulation Fire Bricks (IFB) were selected.

Insulation Fire Brick (IFB) - IN 23	
Classification Temperature ASTM C 155	1260 [C]
Composition	$Al2O3$–45%, $SiO2$-50%, $Fe2O3$-0.9%, $TiO2$-1.2% CaO-1.5%, Alkalis-0.4%
Density ASTM C134	618 [kg/m]
Modulus of Rupture ASTM C133	1.20 [MPa]
Thermal Conductivity ASTM C 182	0.14-0.26 [W/m-K]
Brick Size	9"x4.5"x2"
Cost per Brick	$4.15

Achieves...

Outer surface temperature:

88°C - 178°C

Surface heat flux:

325 W/m – 757 W/m

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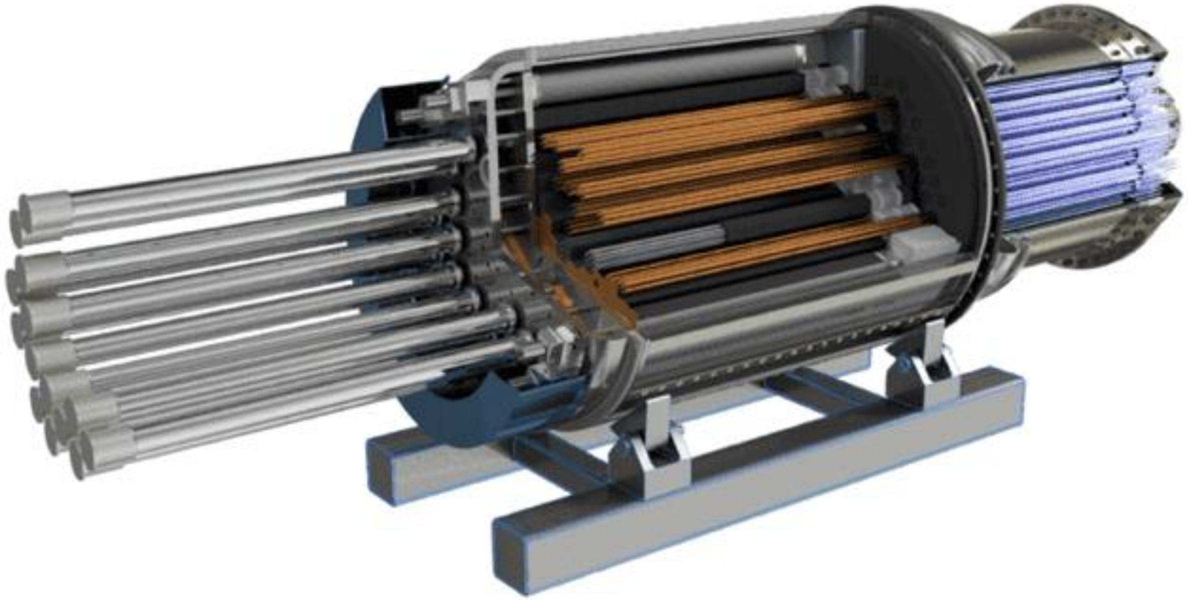
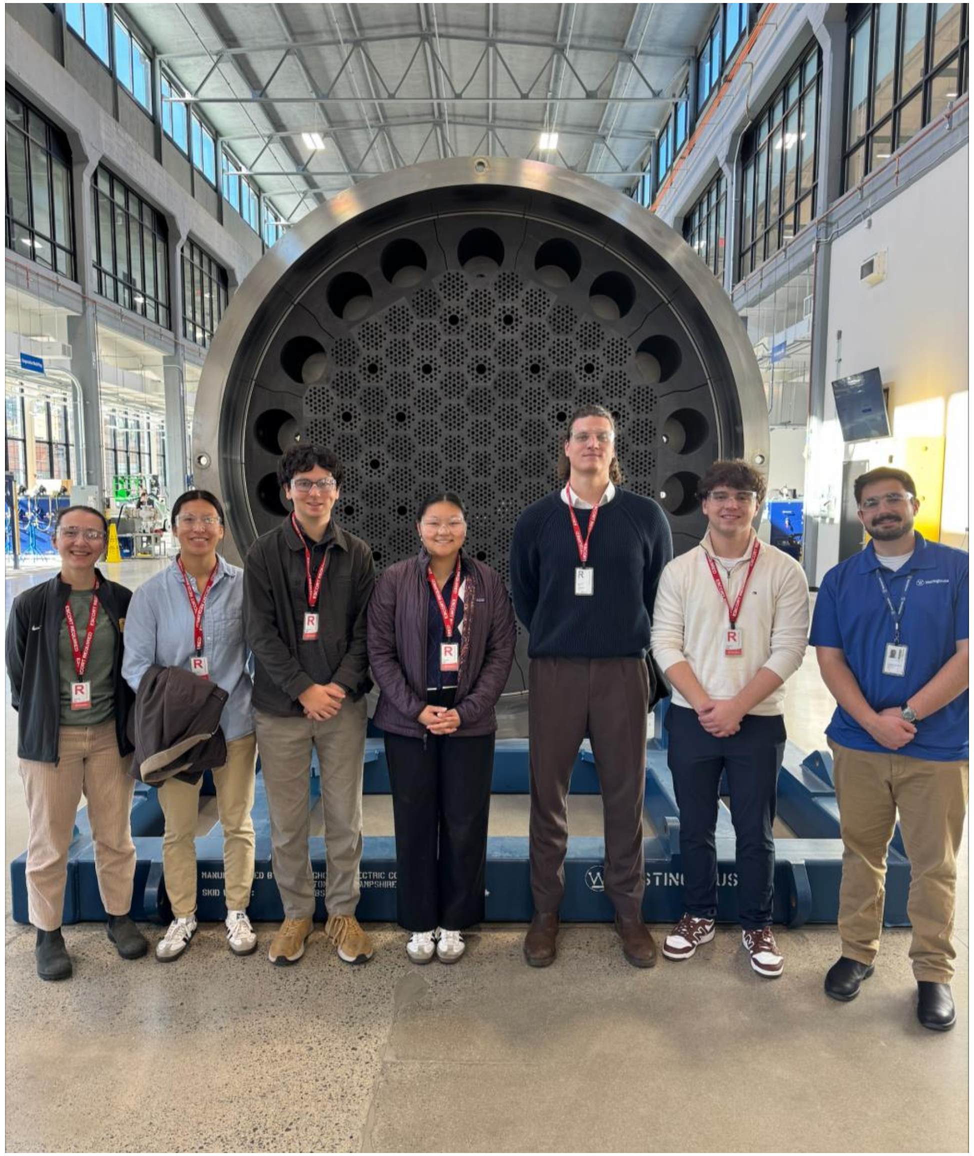
Conclusion and Summary





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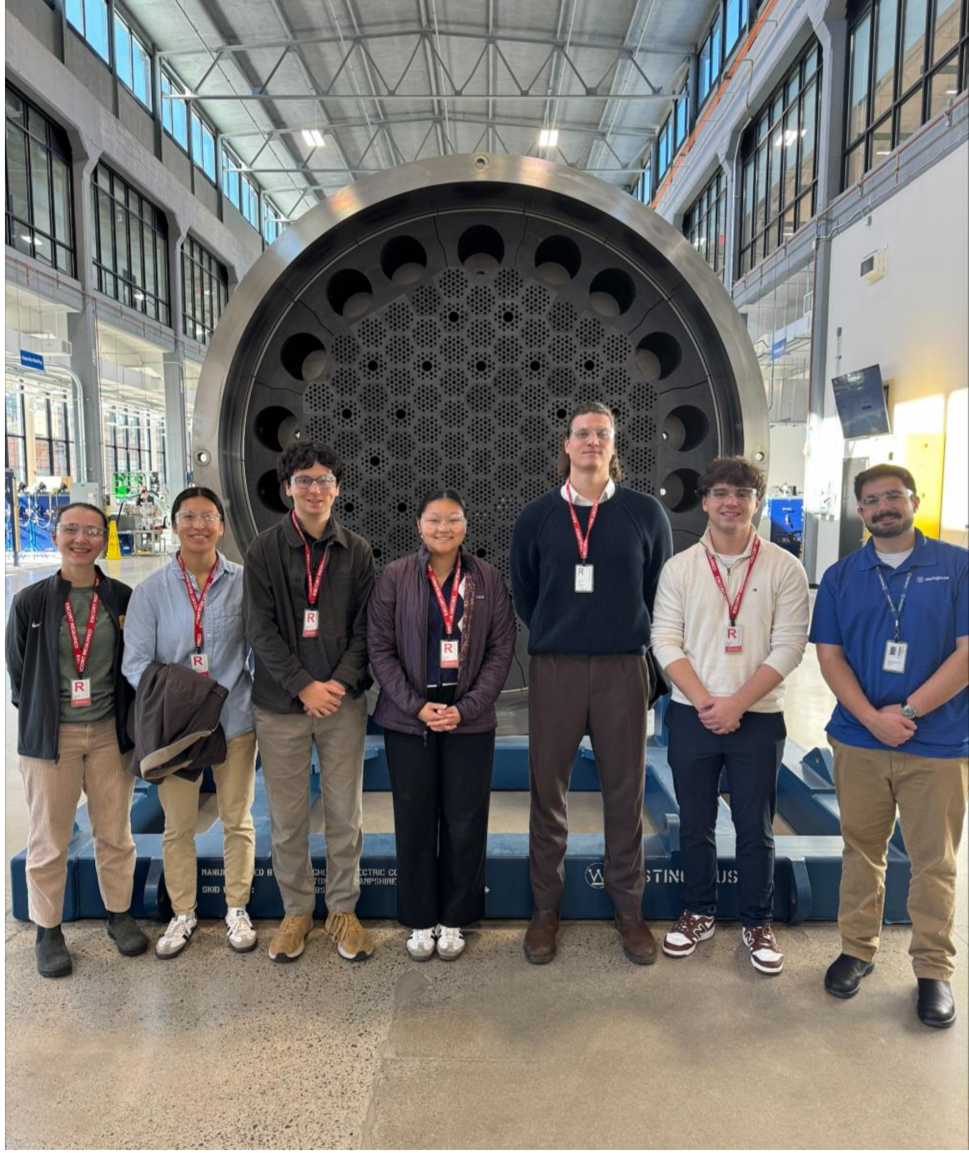
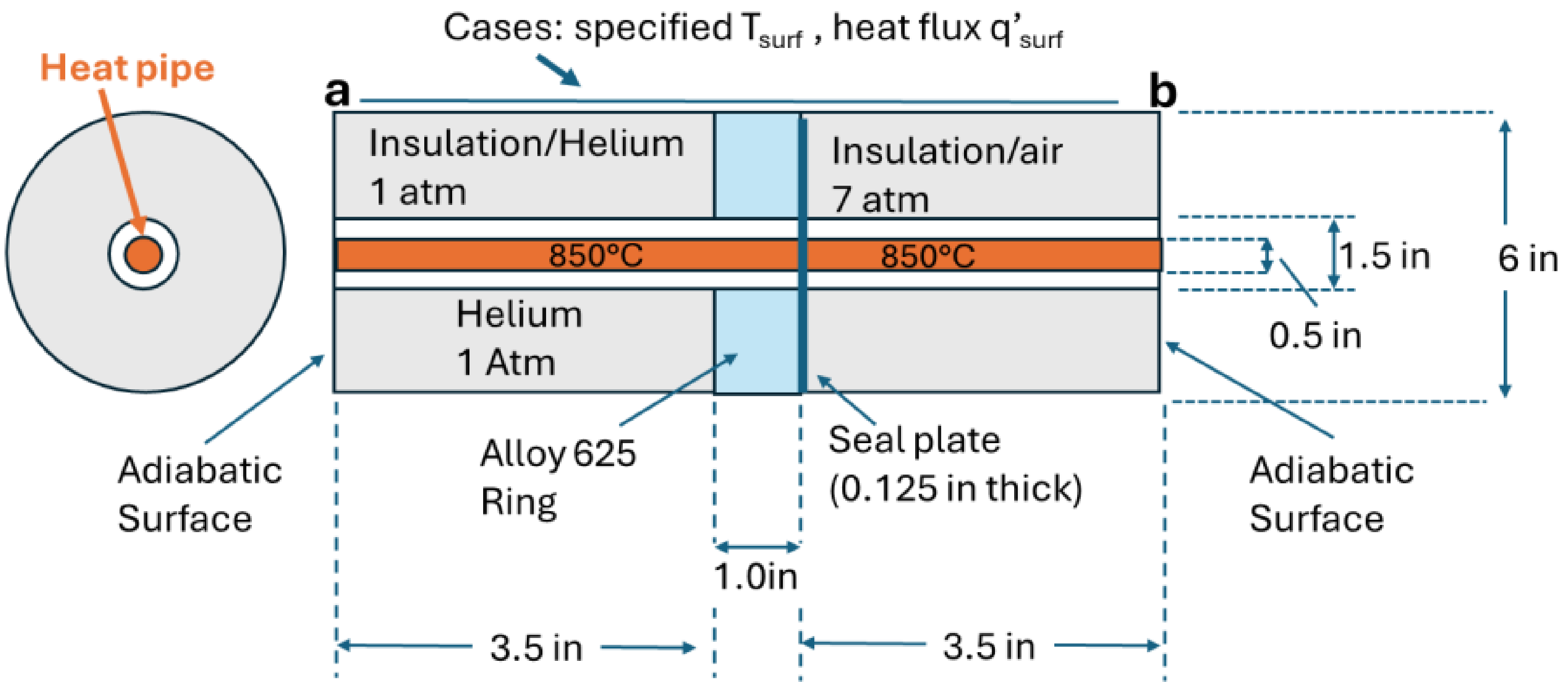
Westinghouse site tour to discuss heat loss roadblocks

- Viewed full-scale Modular Design Unit (MDU) of reactor core
- Met with the Westinghouse eVinci design team
- Gathered counsel on how to proceed
- Left with an alternative project description of the insulation package



Heat loss analysis could not be conducted based on provided requirements.



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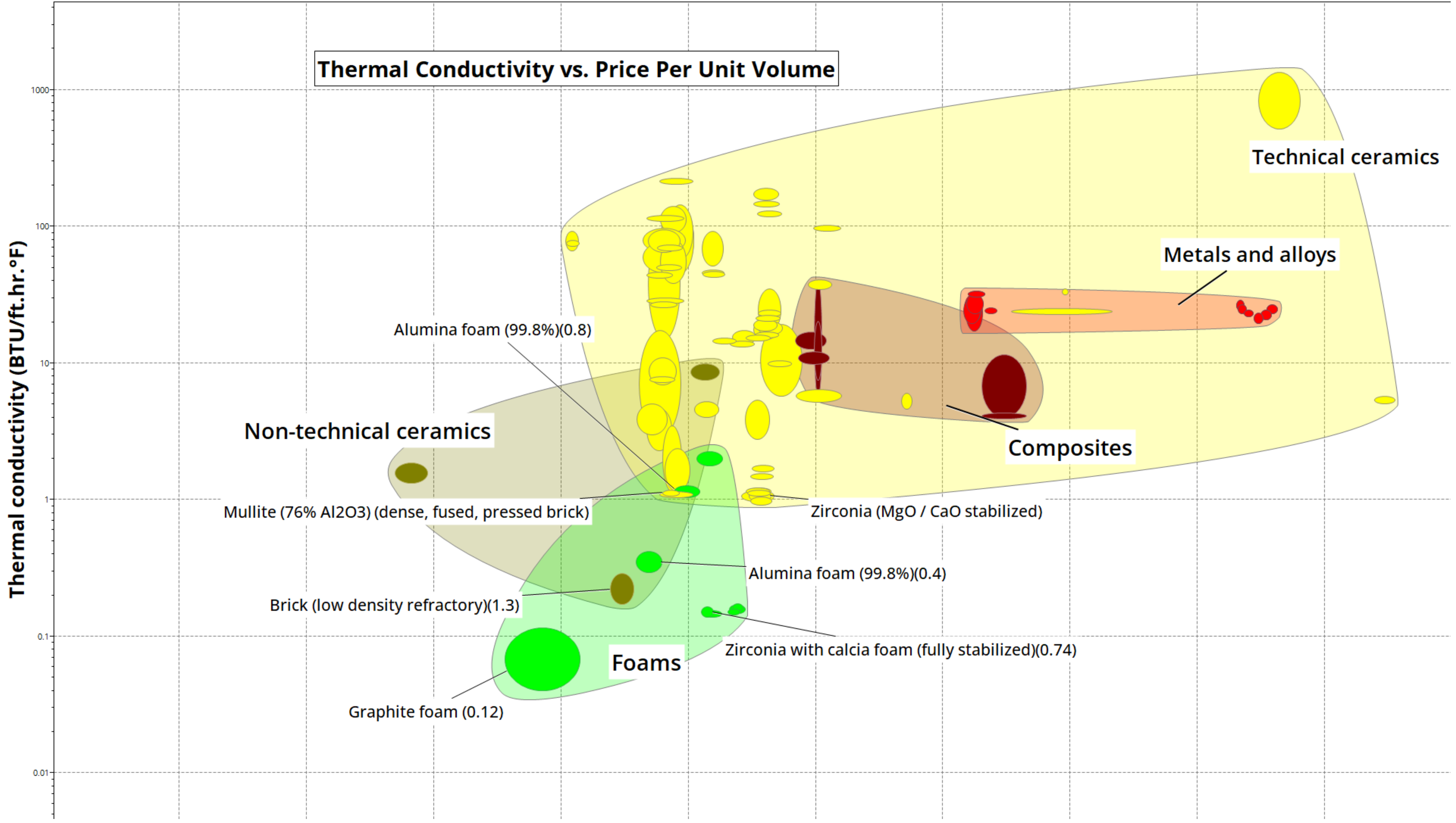

Thermal Conductivity vs. Price Per Unit Volume
Thermal conductivity (BTU/ft.hr.°F)
1000
100
10
1
0.1
0.01
Technical ceramics
Metals and alloys
Composites
Non-technical ceramics
Foams
Alumina foam (99.8%)(0.8)
Mullite (76% Al2O3) (dense, fused, pressed brick)
Zirconia (MgO / CaO stabilized)
Alumina foam (99.8%)(0.4)
Brick (low density refractory)(1.3)
Zirconia with calcia foam (fully stabilized)(0.74)
Graphite foam (0.12)

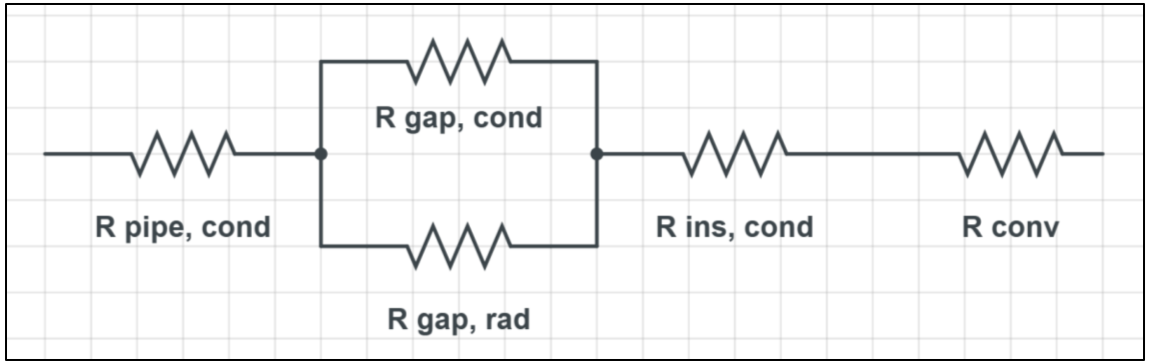
Heat Transfer Hand Calculations

$$R_{cond} = \frac{\ln(\frac{r_2}{r_1})}{2\pi k}$$

$$R_{rad} = \frac{(T_2 - T_1)(\frac{1}{\epsilon_1} + \frac{1-\epsilon_2}{\epsilon_2}\left(\frac{r_1}{r_2}\right))}{2\pi r_1 \sigma (T_2^4 - T_1^4)}$$

$$R_{conv} = \frac{1}{2\pi r h}$$

$$q' = \frac{\Delta T}{R}$$



4 Equations

1. $q' = \frac{T_{pipe,outer} - T_{pipe,inner}}{R_{pipe,cond}}$
2. $q' = \frac{T_{ins,\,inner} - T_{pipe,outer}}{(\frac{1}{R_{gap,cond}} + \frac{1}{R_{gap,rad}})^{-1}}$
3. $q' = \frac{T_{ins,outer} - T_{ins,inner}}{R_{ins,cond}}$
4. $q' = \frac{T_{\infty} - T_{ins,outer}}{R_{conv}}$

4 Free Variables

1. q'
2. $T_{pipe,outer}$
3. $T_{ins,inner}$
4. $T_{ins,outer}$

Heat Transfer Hand Calculation

- K_{SS316} = 25.4 W/m-K
- K_{He} = 0.067 W/m-K
- ε_{ins} = 0.7
- ε_{SS316} = 0.8

k [W/m*K]	Rcond,ins	q'	Heat Pipe Surface Temp [K]	Insulation Inner Surface Temp [K]	Insulation Outer Surface Temp [K]	in c
0.1	2.206356002	325.1	1122	1078	361	88
0.2	1.103178001	569.6	1122	1040	412	139
0.3	0.735452001	757.5	1122	1008	451	178
0.4	0.551589	904.9	1122	981	482	209
0.5	0.4412712	1022.6	1122	958	507	234
0.75	0.2941808	1231.1	1122	912	550	277
1	0.2206356	1365.2	1122	879	578	305
1.25	0.17650848	1457.3	1121	855	597	324
1.5	0.1470904	1523.8	1121	835	611	338
2	0.1103178	1612.9	1121	808	630	357
2.5	0.08825424	1669.2	1121	789	642	369
3	0.0735452	1707.9	1121	775	650	377

Insulation Fire Bricks (IFBs)

What They Are

- Lightweight refractory bricks engineered for thermal insulation at high temperatures
- Common commercial compositions:
  - Alumina–silicate (most widely used)
  - Silicate-based IFBs (lower temperature grades)
  - Lightweight corundum (high-alumina, higher strength, higher service temperature)
- Microstructure: high porosity, fine cellular pores, and lightweight crystalline phases
- Higher alumina content + higher firing temperature → higher classification temperature
  - Max operating temperature typically ~100 °C lower than classification temperature
- Classified under ASTM C155 into 4 groups based on density, composition, and service temperature
- Cast IFBs generally show better uniformity and thermal performance than cement-bonded IFBs

ASTM C-155 Guidelines

IFB Classification Groups	Shrinkage < 2% after 24hrs at °F	°C	Maximum Density lb/ft³	kg/m³
Group 16	1550	845	34	545
Group 20	1950	1065	40	641
Group 23	2250	1230	48	769
Group 26	2550	1400	54	865
Group 28	2750	1510	60	961
Group 30	2950	1620	68	1089
Group 32	3150	1730	95	1522
Group 33	3250	1790	95	1522

Table 2: Guideline example: An IFB 23 may not exceed a density of 769 kg/m3 (48lb/ft3) and must have a shrinkage below 2 percent, after 24 hours of firing at 1,230°C (2,250°F) to be classified in group 23.

Insulation Fire Bricks (IFBs)

Advantages

- High operating temperature capability, suitable for >1000 °C applications
  - Higher alumina IFBs can support up to 1400–1600 °C depending on grade
- Cost-effective
  - Typical price range $4–$22 per brick; Lower-temp grades (adequate for our design) are inexpensive
- Low thermal conductivity
  - Typical k = 0.14–0.48 W/m·K (varies with density and grade)
  - Fine pore structure disrupts solid conduction and reduces gas conduction
  - Closed-cell porosity lowers radiative heat transfer at high temperature
- Lightweight
  - Densities commonly 0.6–1.2 g/cm³, much lower than hard refractory bricks
- Chemically stable in oxidizing environments
  - Stable in air and helium (helps for sealed R&D setups)
- Easy to work with
  - Can be cut, shaped, and drilled using simple tools (hacksaw, bandsaw, drill press)
  - Allows custom fits for cylindrical assemblies or test articles

Disadvantages

- Higher thermal conductivity compared to ceramic fiber blankets or aerogel materials
- Lower mechanical strength
  - High apparent porosity → reduced compressive strength
  - Acceptable for our design due to low mechanical stresses
- Poor wear resistance
- Not suited for environments with erosion, abrasion, or high gas velocities

IFB Properties

Properties	Unit	IN-23	IN-26	IN-28	IN-30
Classification Temperature	°F	2300	2600	2800	3000
ASTM C 155	°C	1260	1427	1538	1649
Density	lb/ft^3	39	50	55	65
ASTM C 134	kg/m^3	618	801	881	1036
Modulus of Rupture	lb/in^2	124	247	290	450
ASTM C 133	MPa	0.85	1.70	2.0	3.10
Cold Crushing Strength	lb/in^2	174	377	435	609
ASTM C 210	MPa	1.20	2.60	3.00	4.20
Percent Linear Change	°F | °C				
24hrs @ Soaking Temp.	2250 | 1232	0.0 %	-	-	-
ASTM C 210	2550 | 1399	-	-0.4 %	-	-
	2750 | 1510	-	-	-0.7 %	-
	2950 | 1621	-	-	-	-0.7 %
	3150 | 1732	-	-	-	-
Thermal Conductivity	Btu-in/ft²,hr,°F (W/mk)				
ASTM C 182	°F | °C				
	500 | 260	1.0 (0.14)	1.6 (0.23)	2.3 (0.33)	2.8 (0.40)
	1000 | 538	1.3 (0.19)	1.9 (0.27)	2.4 (0.35)	2.9 (0.42)
	1500 | 816	1.6 (0.23)	2.2 (0.32)	2.6 (0.37)	3.1 (0.45)
	2000 | 1093	1.8 (0.26)	2.6 (0.37)	2.7 (0.39)	3.3 (0.48)
Chemical Composition	Al_2O_3	45	51	64	72
*%	SiO_2	50	43	33	26
	Fe_2O_3	0.9	0.8	0.7	0.5
	TiO_2	1.2	1.3	0.9	0.5
	CaO & MgO	1.5	1.5	1.0	0.3
	Alkalies, as Na^2O & K_2O	0.4	0.4	0.4	0.2

Refractory Ceramic Fibers (RCFs)

What It Is

- Man-made aluminosilicate fibers (ASW: aluminum silicate wool)
  - Produced by melting + blowing/spinning calcined kaolin or Al_2O_3–SiO_2 mixes (≈50/50 wt%)
- AES wool (alkaline-earth silicate) = biosoluble, made from CaO–MgO–SiO_2 formulations
  - Safer for lungs; dissolves more easily in the body
  - Lower chemical resistance; prone to recrystallization
  - ~1150 °C continuous-use rating

Forms

- Blankets (most common): high porosity, binder-free, flexible
- Also available as modules, papers, boards, textiles, foams, adhesives, and coatings

HIGH TEMPERATURE INSULATION WOOL (HTIW)

HTIW Grades		Chemical Composition	Acid / Alkaline	Max Temp.	Continuous Use Temp.	Typical Service Temp.	Melting Point	Mean Fiber Length	Thermal Shock Sensitivity	Bulk Density
	AES Wool	CaO 27 - 32 % MgO 2 - 6 % SIO_2 61 - 68 %	- / +	1260°C 2300°F	1150°C 2102°F	< 1000°C < 1832°F	≈ 1300°C ≈ 2372°F	1 - 4.5 µm	+	64-128 kg/m^3 4 - 8 lb/ft^3
RCF	Aluminum Silicate Wool	Al_2O_2 47 - 49% SIO_2 50 - 52%	+ / -	1260°C 2300°F	1180°C 2156°F	< 1150°C < 2102°F	≈ 1760°C ≈ 3200°F	1 - 4.5 µm	++	64-160 kg/m^3 4 - 10 lb/ft^3
		Al_2O_2 35 - 40% SIO_2 38 - 50% ZrO_2 15 - 17%	+ / -	1427°C 2600°F	1343°C 2450°F	< 1300°C < 2372°F	≈ 1760°C ≈ 3200°F	1 - 4.5 µm	++	96-160 kg/m^3 6 - 10 lb/ft^3
PCW	Polycrystalline Wool	Al_2O_2 72 - 80% SIO_2 20 - 28%	+/+	1649°C 3000°F	1600°C 2912°F	< 1600°C < 2912°F	≈ 1871°C ≈ 3400°F	1 - 4.5 µm	++	96-160 kg/m^3 6 - 10 lb/ft^3
		Al_2O_2 95 - 97% SIO_2 3 - 5%	+/+	1800°C 3272°F	1650°C 3002°F	< 1650°C < 3002°F	≈ 2000°C ≈ 3600°F	1 - 4.5 µm	++	96-160 kg/m^3 6 - 10 lb/ft^3

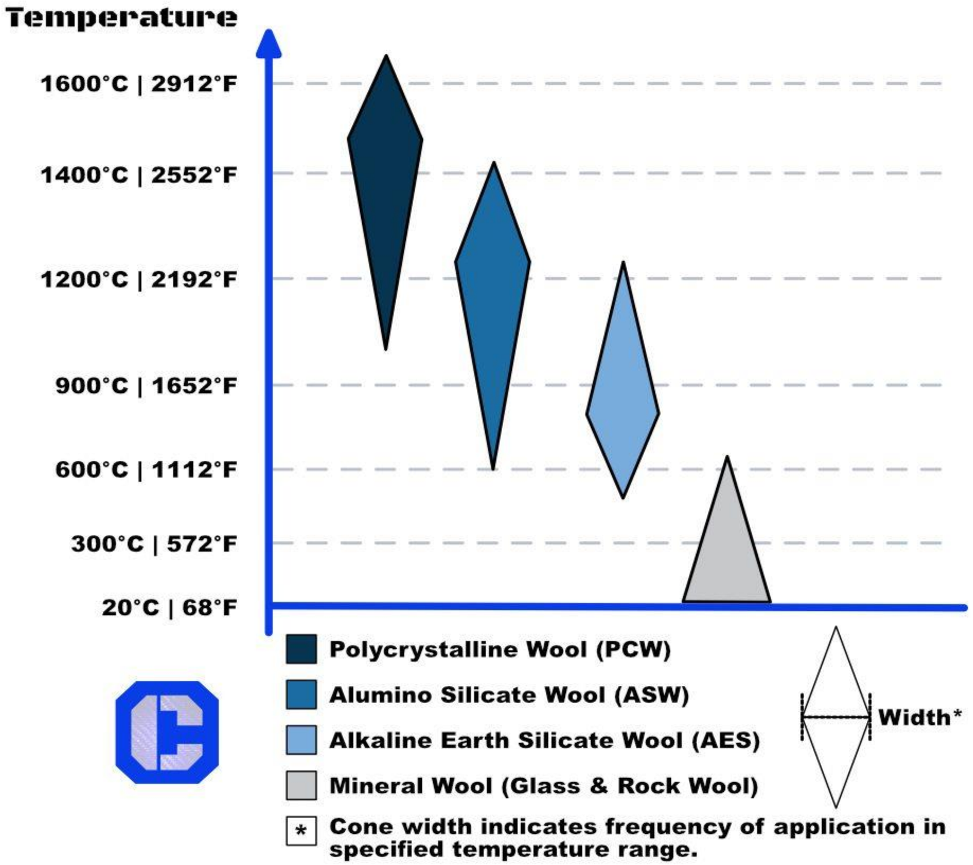
Refractory Ceramic Fibers (RCFs)

Advantages

- Lightweight
- Excellent thermal shock + good chemical resistance
- Very low thermal conductivity at high temp (k ≈ 0.10–0.275 W/m·K at ~850 °C)
  - High porosity → disrupts solid conduction paths
  - Fibrous structure → strong phonon scattering (reduces solid conduction)
  - Large fiber surface area → reduces radiative heat transfer
- Easy to shape around cylinders
- High service temperature (≈1100–1600 °C)
  - Most common "high-purity" grade: ~1180 °C continuous use

Disadvantages

- Fibers shed → can damage reactor components, clog systems
- Health/safety hazard if fibers burn or become airborne
- Requires additional mechanical support/containment



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Aerogels

What They Are

- Ultra-lightweight, highly porous solids made from sol-gel derived networks (most commonly silica aerogels).
- Typical structure: 90–99% air, nanoscale pores (10–100 nm), and a continuous silica or oxide network.
- Extremely low density (0.03–0.2 g/cm³) and extremely low solid conduction due to thin silica "struts."
- Variants include:
  - Silica aerogels (most common for insulation)
  - Composite aerogel blankets (silica aerogel embedded in fiberglass mats → flexible + durable)
  - High-temperature aerogels (alumina, mullite, SiC-modified, or doped silica for >1000 °C stability)

How They're Made

- Sol–gel process: precursor (e.g., TEOS, sodium silicate) → hydrolysis → gel formation
  - Gel is "aged" to strengthen the network
- Drying step is critical:
  - Supercritical CO_2 drying → classic monolithic aerogels
  - Ambient pressure drying + surface modification → cheaper composites used in commercial blankets
- Commercial insulation products are typically aerogel particles impregnated into fiber blankets, giving flexibility and toughness.

Aerogels

Advantages

- Extremely low thermal conductivity
  - Typical k (room temperature): 0.012–0.020 W/m·K and even at high temperature: 0.03–0.05 W/m·K
  - Outperforms IFB and ceramic fiber at equal thickness
- Suppress all heat-transfer modes
  - Nanoscale pores limit gas conduction
    - Very low solid volume → minimal solid conduction
  - High scattering of IR radiation (especially opacified and composite aerogels)
- Very lightweight
  - Much lighter than IFBs; similar or lighter than ceramic fiber
- Flexible (as blankets)
  - Conforms easily around cylindrical pipes
  - Thin layers (2.5–10 mm) achieve performance equivalent to much thicker fiber or brick insulations

Disadvantages

- Cost
  - Blanket prices typically $10–$40 per ft², depending on thickness
  - High-temperature grades (Pyrogel XTE, Pyrogel HPS) can be $500+ per roll
- Temperature limitations (for silica aerogels)
  - Pure silica aerogels start to shrink or sinter above ~600–800 °C
  - Stabilized/modified high-temp aerogels can handle 1000–1200 °C, but at even higher cost
- Fragility (in monolithic form)
  - Pure aerogels are brittle; crumble under mechanical load
  - solve this by embedding aerogel into fibrous matrices
- Dust generation during cutting
  - Similar to ceramic fibers: particles can irritate skin and lungs
  - PPE recommended
- Hydrophilicity (unless treated)
  - Moisture absorption can reduce insulation performance
  - Commercial products usually include hydrophobic surface modification

Dense Refractory Brick

Properties	Unit	High Duty	Super Duty	High Alumina
Classification Temperature	°F °C	2900 1593	3000 1650	3254 1790
Density ASTM C 134	lb/ft^3 | g/cm^3	130-139 | N/A	141 | 2.26	161 | 2.58
Modulus of Rupture ASTM C 133	lb/in^2 MPa	900 -1500	900 - 1500 6.2 - 10.3	1970 13.6
Cold Crushing Strength ASTM C 210	lb/in^2 MPa	2500-4000	3000 - 5000 20.7 - 34.5	9000 62.1
Apparent Porosity ASTM C 830	%	13-18	14-19	15.5
Chemical Composition %	Al_2O_3 SiO_2 TiO_2 Fe_2O_3 CaO MgO P_2O_5 Alkalies, as Na_2O & K_2O SiO	38.40 - 2.80 - .21 .61 - .98 55.20	41.5 52.8 2.86 1.89 0.03 0.20 0.00 0.93 -	67.3 26.2 2.50 1.40 0.20 0.30 1.60 0.50 -

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An overview of insulating firebricks | Thermal Processing Magazine

A Review of High-Temperature Aerogels: Composition, Mechanisms, and Properties

An overview of refractory ceramic fibers | Thermal Processing Magazine

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K-Aerogel-Ht-i-Flyer.pdf

Emissitivity of Common Materials