College of Engineering
Mechanical and Nuclear Engineering

Heat Removal for First Wall Components, Blankets, and Power Conversion

Lane B. Carasik, Ph.D. – Happy Pride Month!

Fluids in Advanced Systems and Technology (FAST) Research Group, Virginia Commonwealth University

Email: lbcarasik@vcu.edu – Group Website: fastresearchgroup.weebly.com

How’d I get here?

ATL - Getty Images

Middle Georgia
State University

Middle Georgia College
Associates in Math

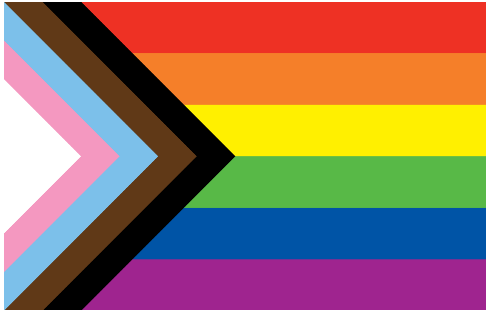
THE UNIVERSITY OF
TENNESSEE
KNOXVILLE

B.S. in Nuclear Engineering
Undergrad research in experimental thermal hydraulics

knoxnews

TEXAS A&M
UNIVERSITY

Ph.D. in Nuclear Engineering
Coursework in Aero, Mech, and Civil



How'd I get here?

Georgia Tech Savannah

Summer REU (NSF CREATE)

The University of Tennessee Knoxville

Undergrad Research

TVA

Summer Intern

Summer Intern

Imperial College London

Visiting Researcher

Lawrence Livermore National Laboratory

Grad Intern

Argonne National Laboratory

Grad Intern

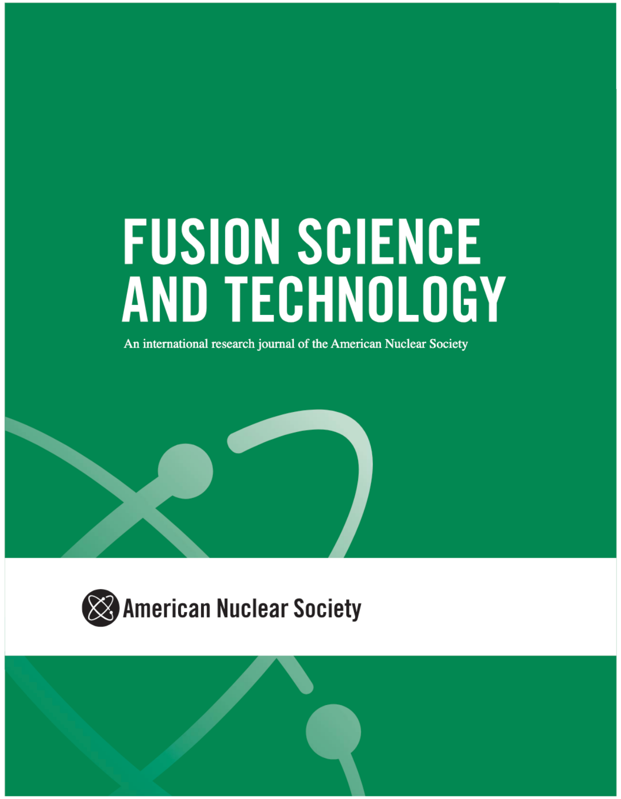
Kairos Power

CFD Engineer

USNC Ultra•Safe•Nuclear

Nuclear Thermal Fluids Engineer

What am I doing in the Fusion Community?



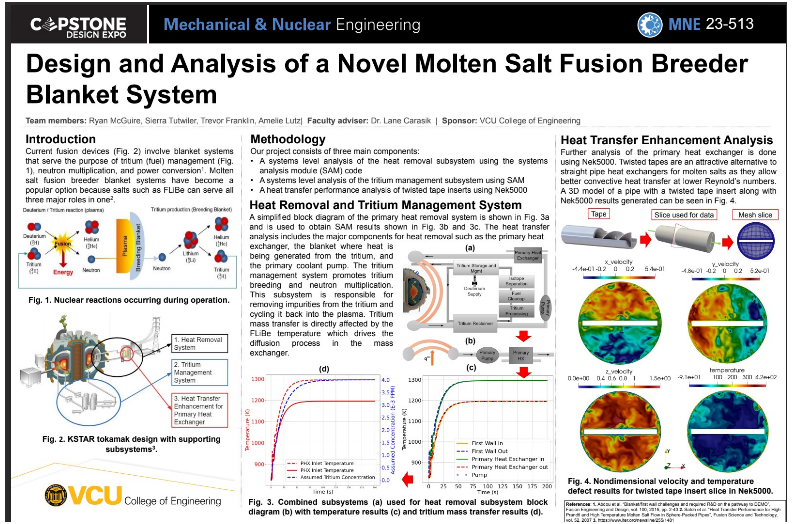
FS&T Associate Editor (2022-Present)

U.S. ITER RESEARCH PROGRAM

2022 Fusion Energy Sciences Research Needs Workshop

Final Report
October 8, 2022

ITER Workshop Participant and [Report] Writing Support (2022)



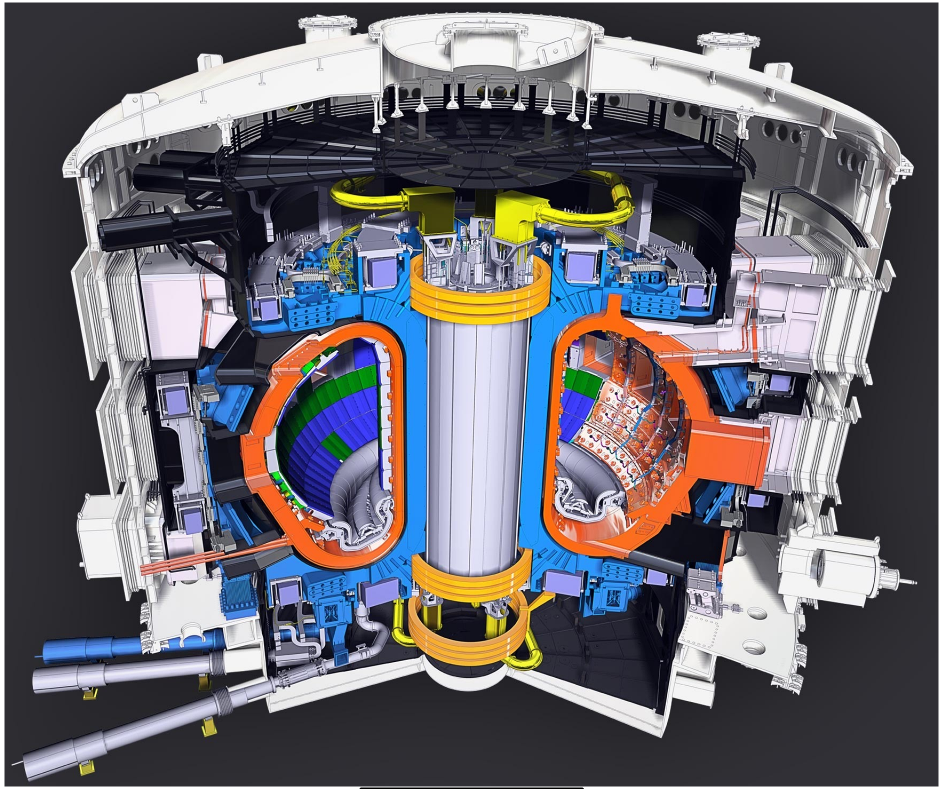
Liquid Immersion Fusion Blanket Senior Design Team!

VCU

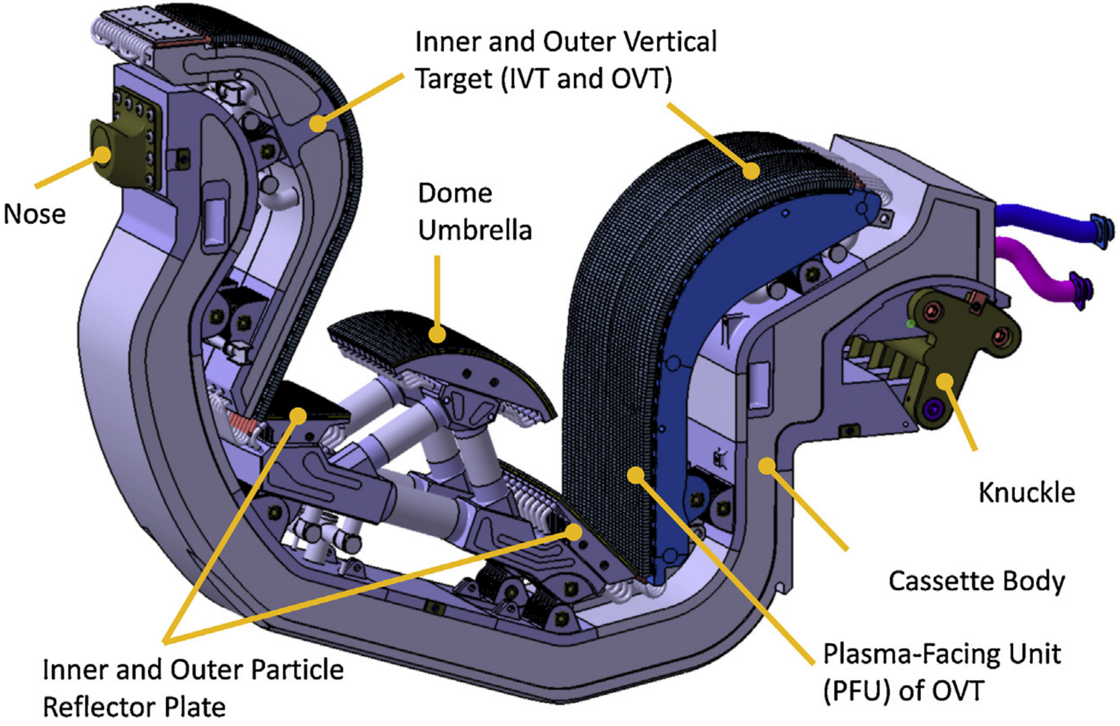
Outline

- First Wall Components within Fusion Devices
- System Level Viewpoint
- Power Conversion Thermodynamic Cycles
- Component Level Heat Removal Mechanisms

First Wall Components within Fusion Devices



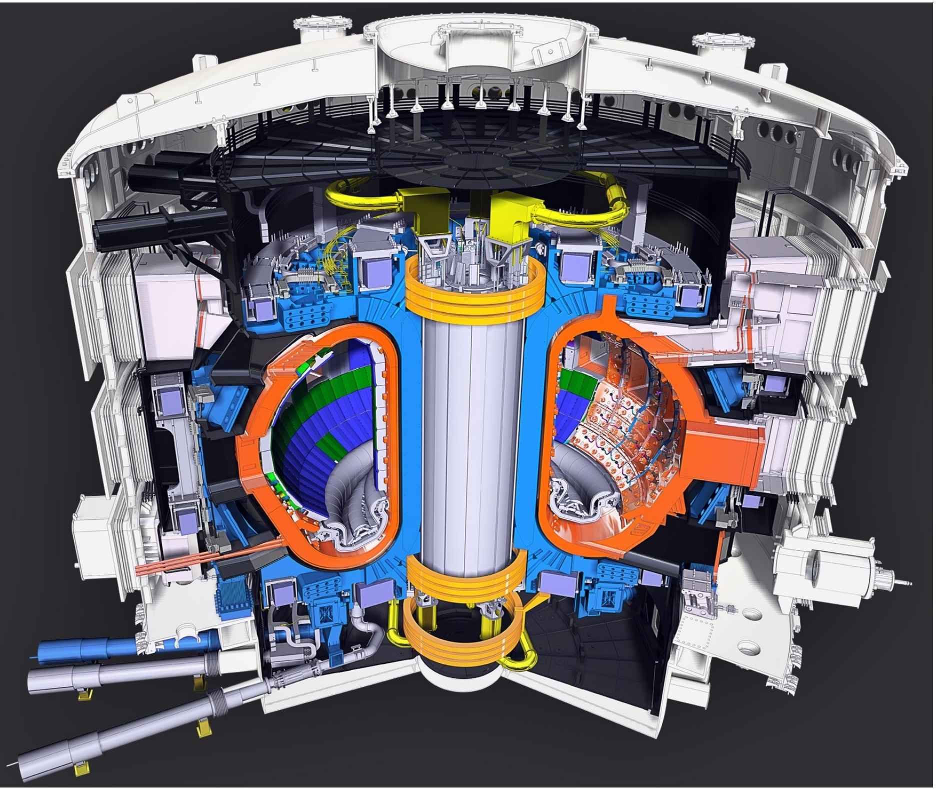
ITER[1]



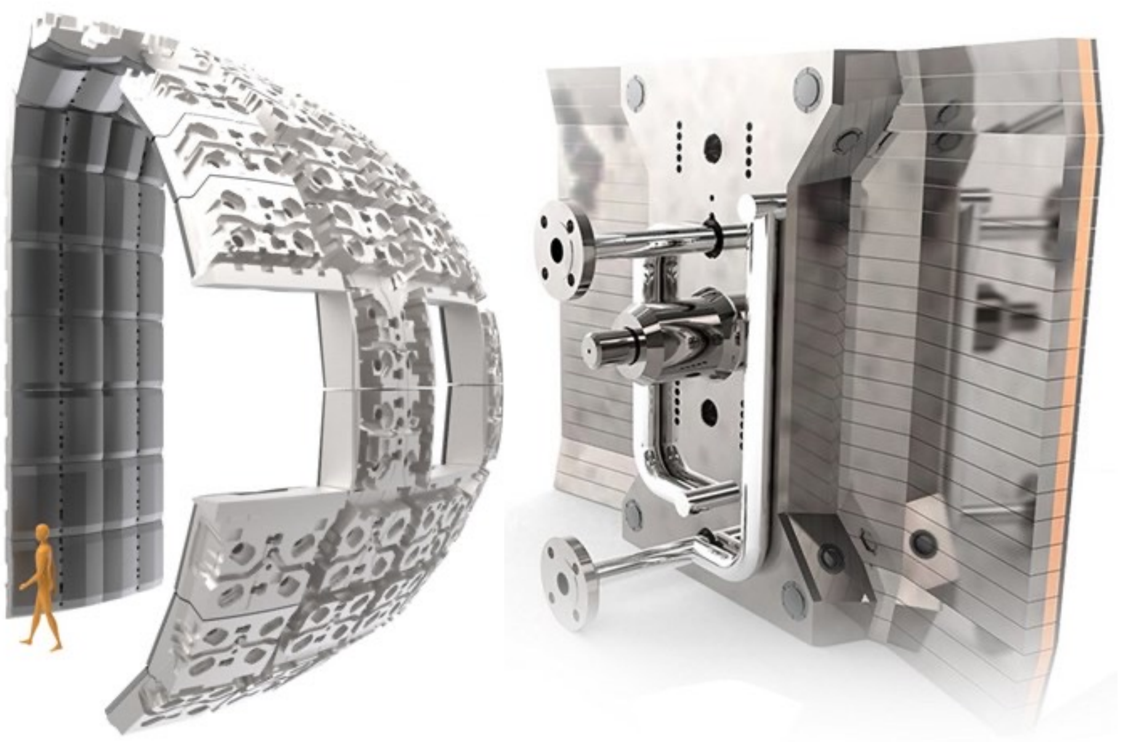
ITER Plasma Facing Component[1]
Divertor (Up to 20 MW/m^2)

[1]ITER Organization, 2021, https://www.iter.org/

First Wall Components within Fusion Devices



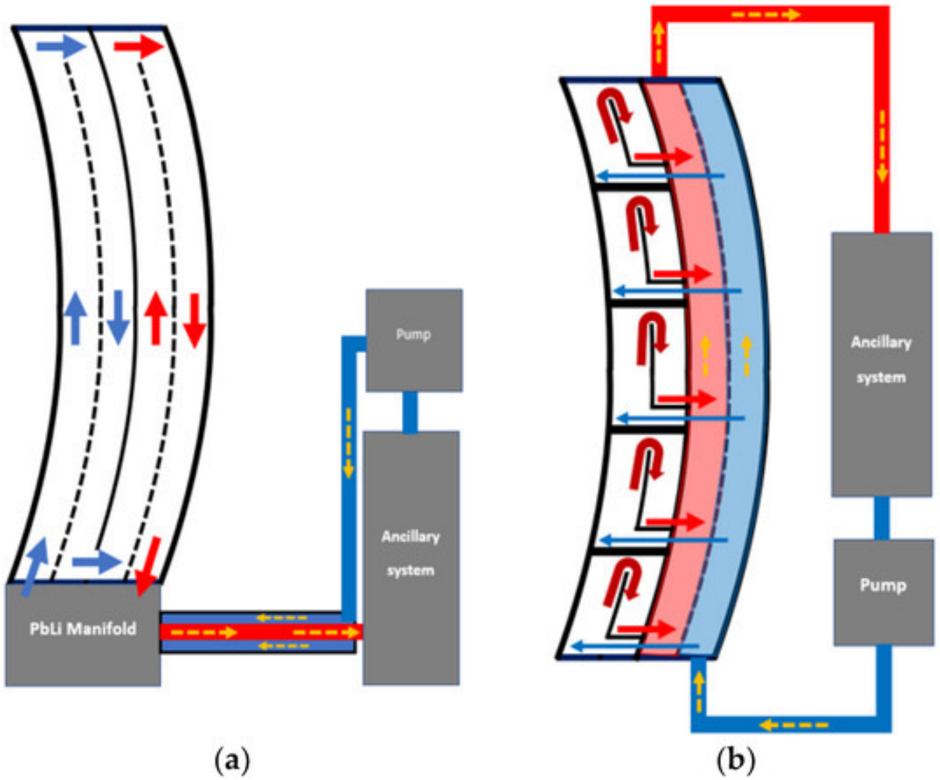
ITER[1]

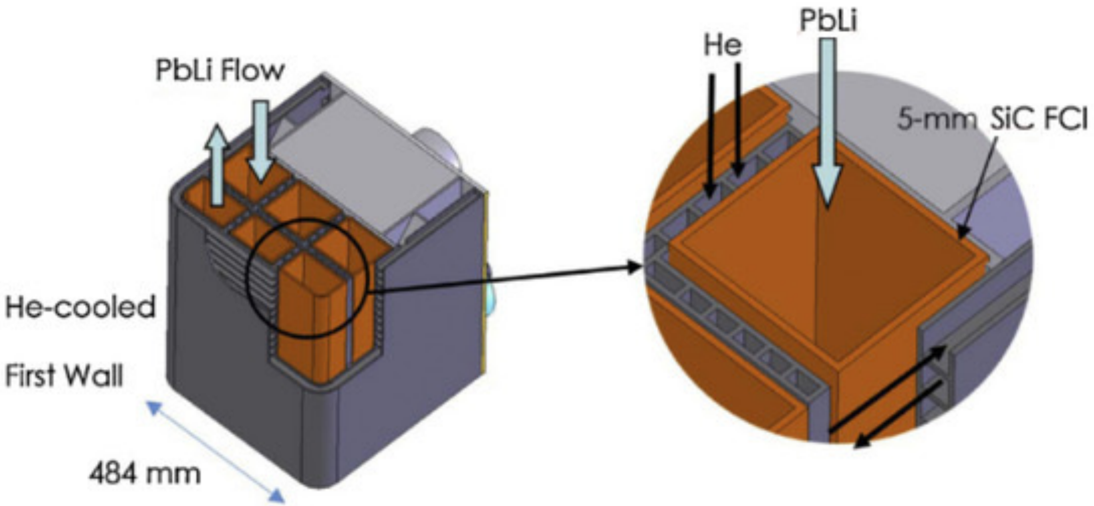


ITER Blanket[1]
(~4.5 MW/m^2)

[1]ITER Organization, 2021, https://www.iter.org/

Dual Cooled Lead Lithium Concept

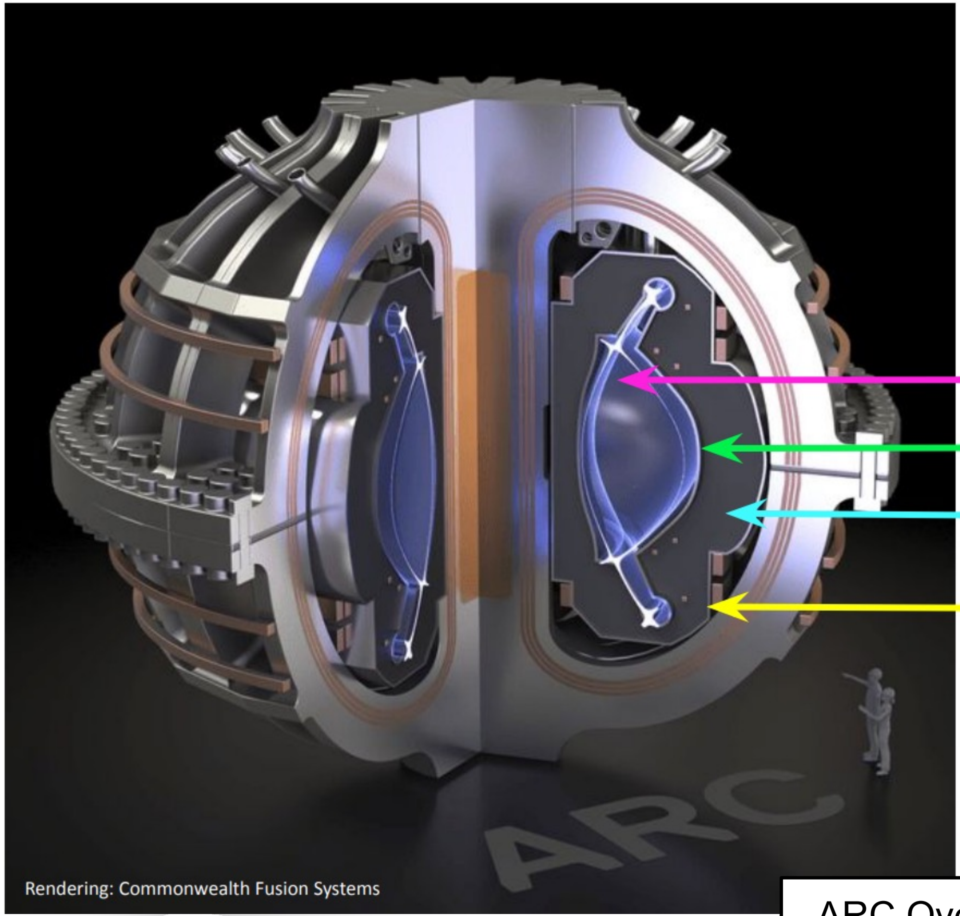




Schematic of the DCLL with PbLi and Helium 1st wall cooling[1]

[1]S. Smolentsev, *Fluids* **2021**, *6*(3), 110; https://doi.org/10.3390/fluids6030110

Liquid Immersion Blanket Concept (ARC)



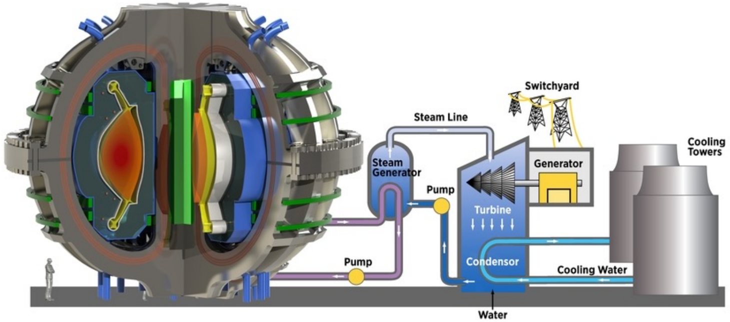
Plasma

Vacuum vessel

LIB (molten FLiBe)

Blanket tank

ARC Overview[1]

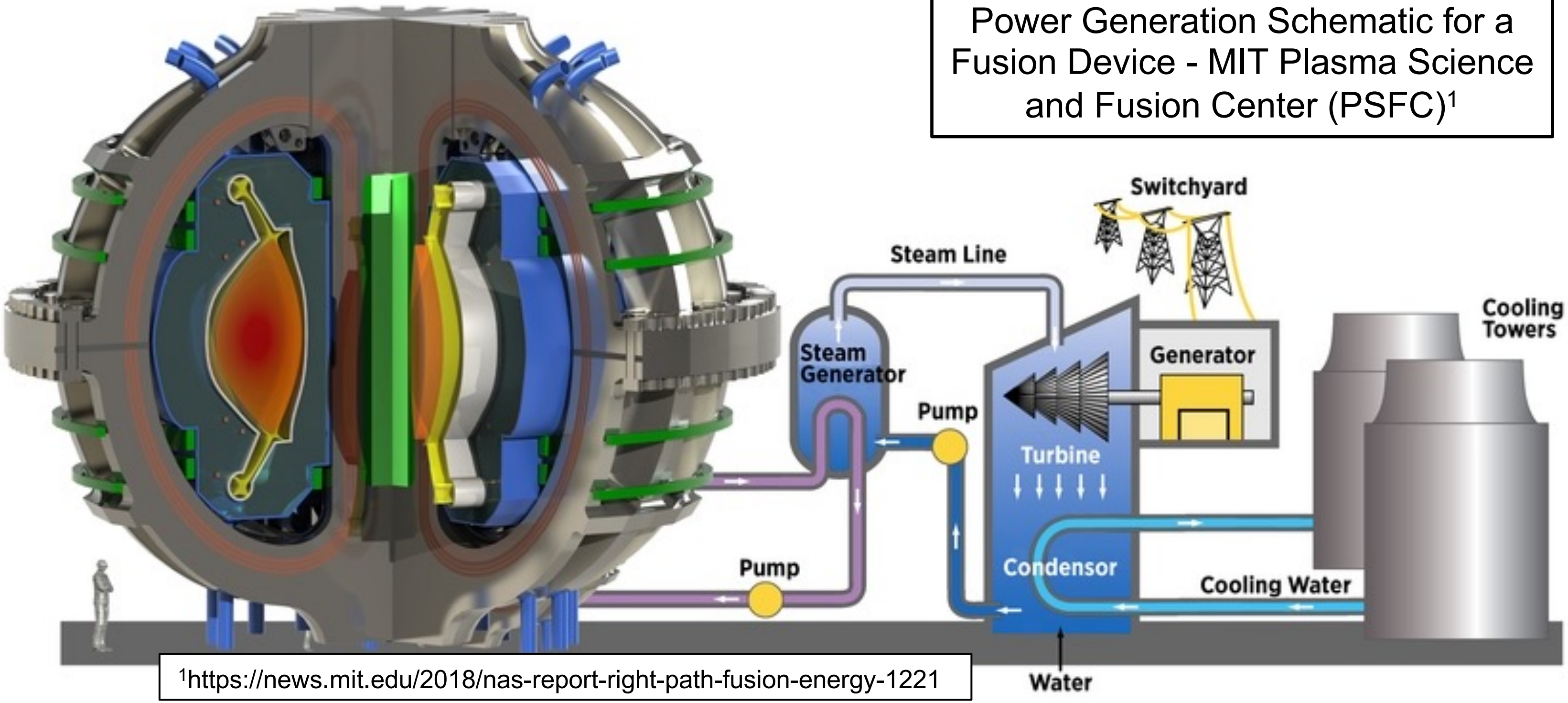


[2]https://news.mit.edu/2018/nas-report-right-path-fusion-energy-1221

[1]S. Ferry, 2023, https://suli.pppl.gov/2023/course/SULI%202023%20presentation.pdf

Why Heat Removal? (System Level)

- Cooling of components to prevent degradation and damage
- Why use fusion devices at all?
  - Power generation

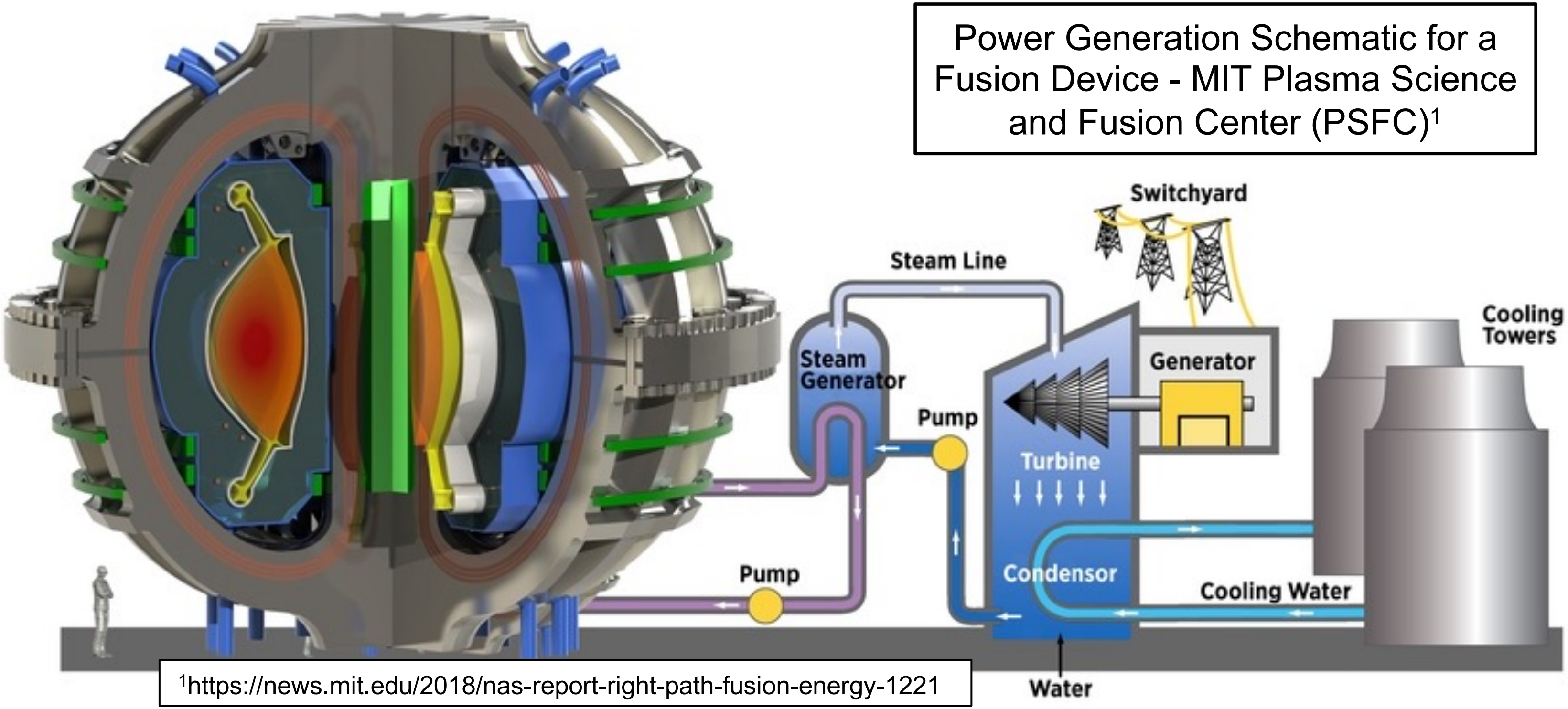


Power Generation Schematic for a Fusion Device - MIT Plasma Science and Fusion Center (PSFC)[1]

[1]https://news.mit.edu/2018/nas-report-right-path-fusion-energy-1221

System Level – Power Cycles

- Based on a Rankine power cycle that is built upon centuries of experience in the power industry



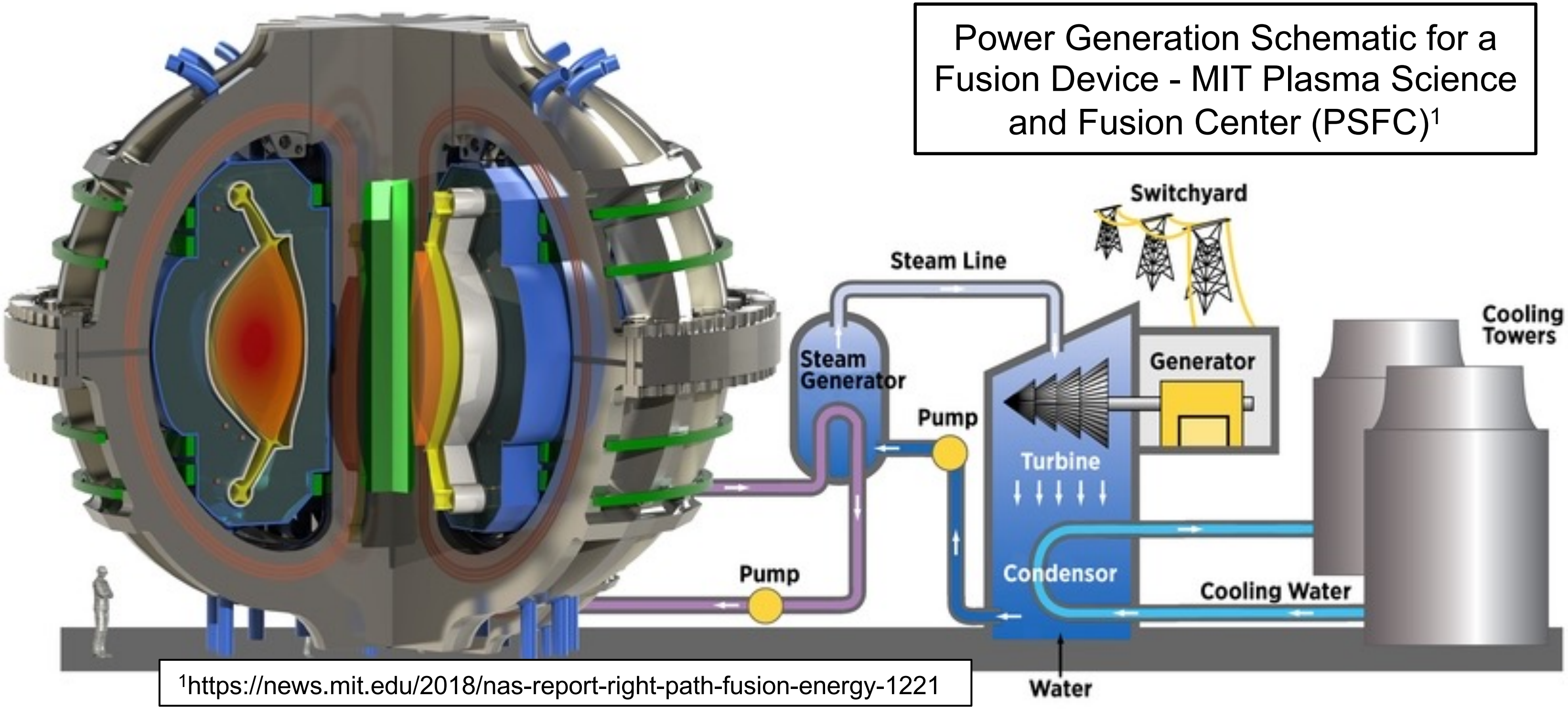
Power Generation Schematic for a Fusion Device - MIT Plasma Science and Fusion Center (PSFC)[1]

[1]https://news.mit.edu/2018/nas-report-right-path-fusion-energy-1221

System Level – Power Cycles

- Regardless of heat source, most power generation results in the same thing, boiling water to spin a turbine that causes a generator to create electricity.

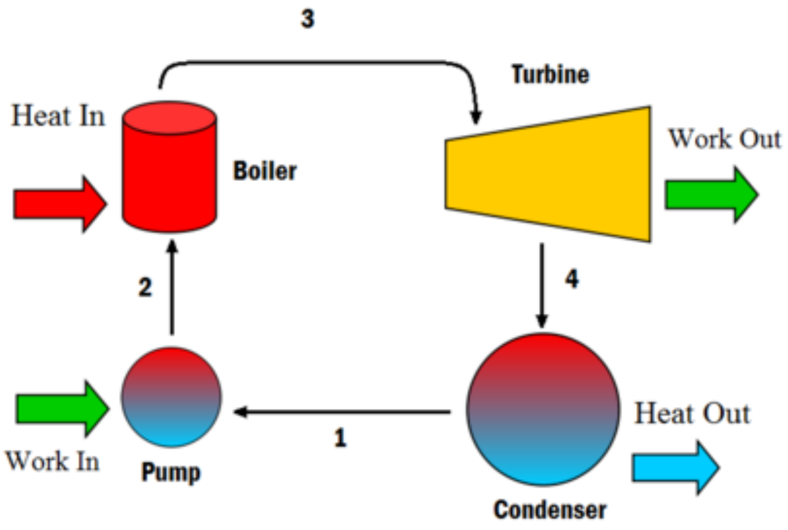
Power Generation Schematic for a Fusion Device - MIT Plasma Science and Fusion Center (PSFC)[1]



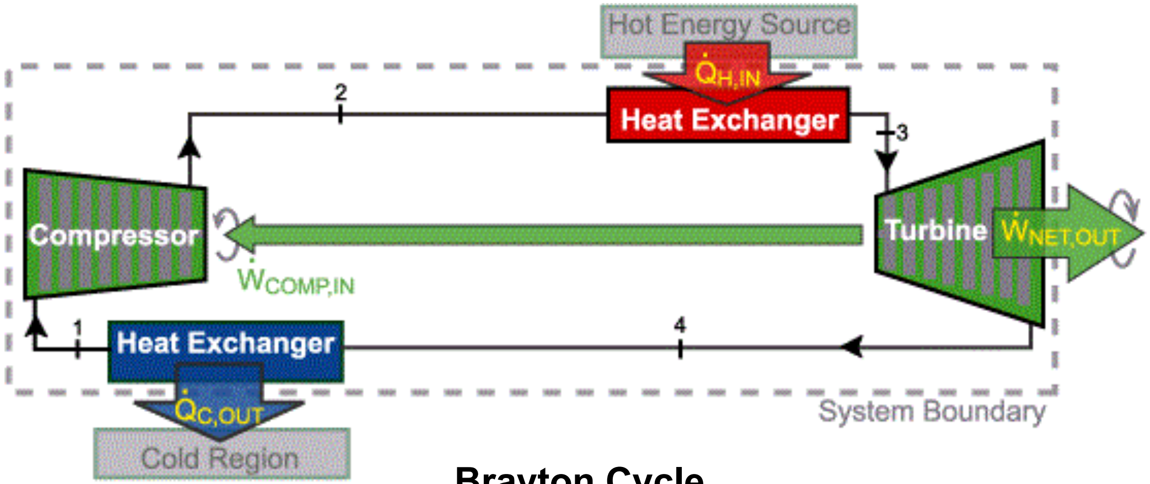
[1]https://news.mit.edu/2018/nas-report-right-path-fusion-energy-1221

System Level – Power Cycles

- There are two common forms of power cycles that could be used:
  - Rankine (Liquid - water based)
  - Brayton (Gas – helium or others based)



Rankine Cycle



Brayton Cycle

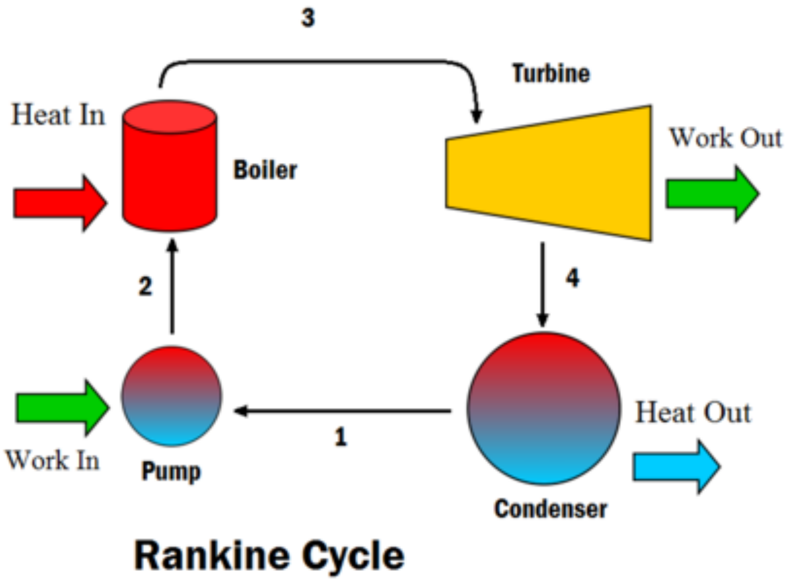
[1]https://energyeducation.ca/encyclopedia/Rankine_cycle
[2]https://energyeducation.ca/encyclopedia/Brayton_cycle

System Level – Power Cycles

- Both cycles can be made more complex with reheating, regeneration, multiple stages, to maximize the amount of useful energy out vs. heat in

$$\eta = \frac{Work\ Out}{Heat\ In} = \frac{W}{Q_H} = \frac{Q_H - Q_C}{Q_H} \text{ or } = \frac{T_H - T_C}{T_H}$$

- In this case, the T_H or T_C are the hottest and coldest reservoir temperatures.



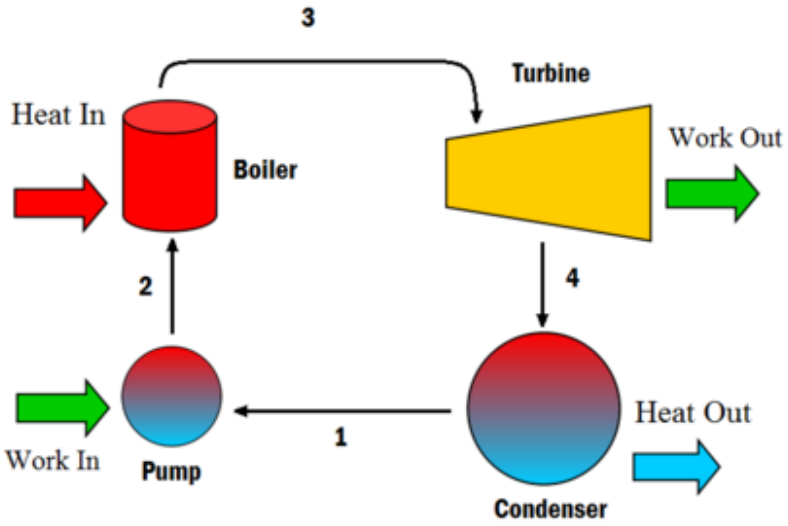
[1]https://energyeducation.ca/encyclopedia/Rankine_cycle

System Level – Power Cycles

- Both cycles can be made more complex with reheating, regeneration, multiple stages, to maximize the amount of useful energy out vs. heat in

$$\eta = \frac{Work\ Out}{Heat\ In} = \frac{W}{Q_H} = \frac{Q_H - Q_C}{Q_H} \text{ or } = \frac{T_H - T_C}{T_H}$$

- We have a few options, lower our final heat sink temperature, raise our operating temperature, but never can reach ideal efficiencies.

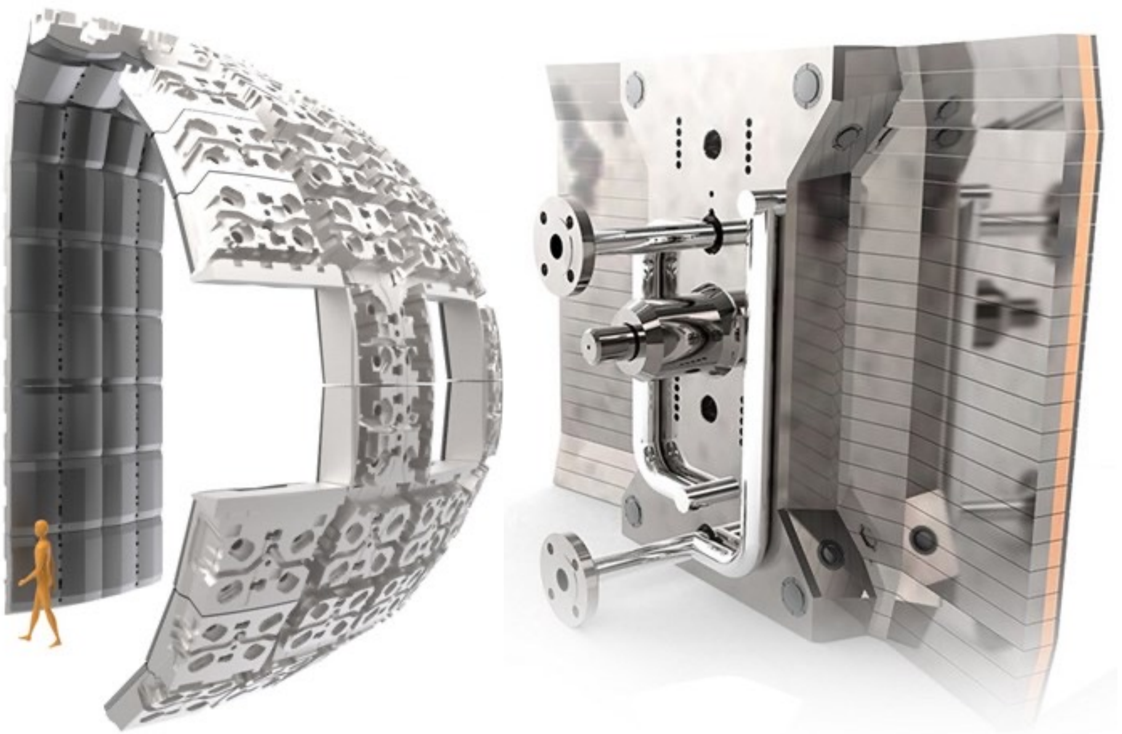


Rankine Cycle

[1]https://energyeducation.ca/encyclopedia/Rankine_cycle

System Level – Heat Removal

- A critical aspect of heat removal is ensuring we understand the heat transfer mechanisms that control our power cycle capabilities, material temperature limits, and instrumentation/control schemes.

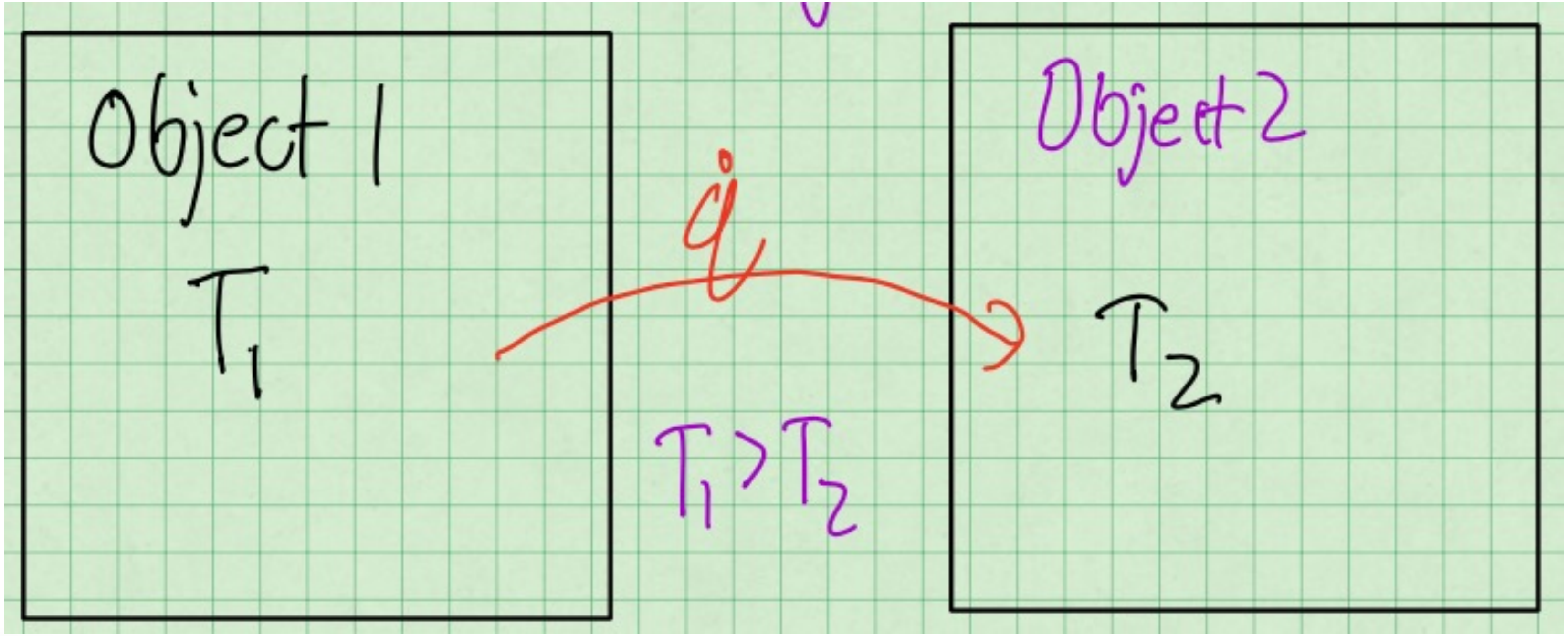


ITER Blanket[1] (~4.5 MW/m^2)

[1]ITER Organization, 2021, https://www.iter.org/

Heat Transfer Mechanisms

- Heat Transfer occurs whenever there is a temperature difference between two objects



Heat Transfer Mechanisms

- Heat Transfer occurs in:
  - Solids – Gases – Fluids – Plasmas - Others?
  - As a continuum (not individual particles)

Very General Conservation of Energy Equation

Enthalpy Formulation

$$\rho \frac{Dh}{Dt} = \nabla \cdot (k \nabla T) + \dot{q}''' + \frac{DP}{Dt} + \mu \Phi$$

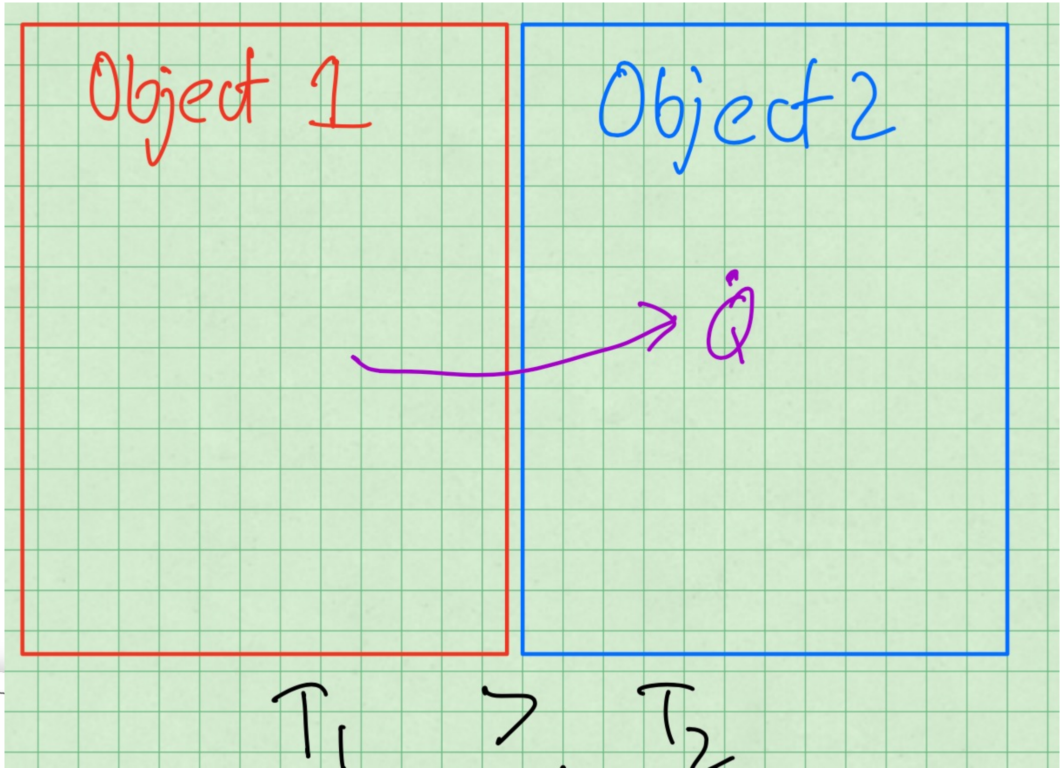
Temperature Formulation

$$\rho c_p \frac{DT}{Dt} = \nabla \cdot (k \nabla T) + \dot{q}''' + \beta T \frac{DP}{Dt} + \mu \Phi$$

VCU

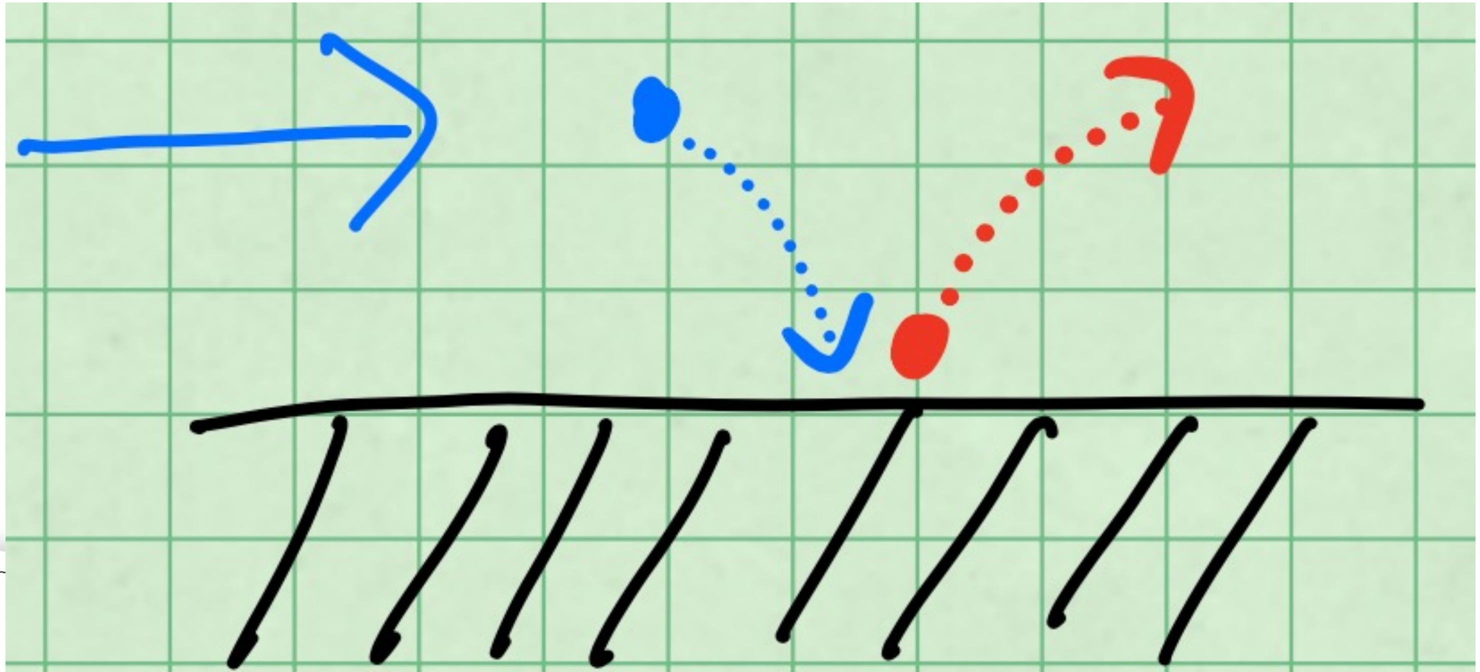
Heat Transfer Mechanisms

- Heat Conduction (Conductive Heat Transfer)+
  - Can occur within an object and between objects in contact
  - Described using diffusion operator ($\nabla k \nabla T$) in the energy equation



Heat Transfer Mechanisms

- Heat Convection (Convective Heat Transfer)
  - Involves a fluid (liquid or gas) that is moving due to mechanical or buoyant forces
  - Described using the advective operator ($\vec{V} \cdot \nabla T$ or $\vec{V} \cdot \nabla h$)



Heat Transfer Mechanisms

- Heat Convection (Convective Heat Transfer)
  - Two forms (Free/Natural and Forced Convection)

$$\dot{Q}_{conv.} = HTC(T_{wall} - T_{bulk})SA$$

$$HTC = \frac{kNu}{D_h}$$

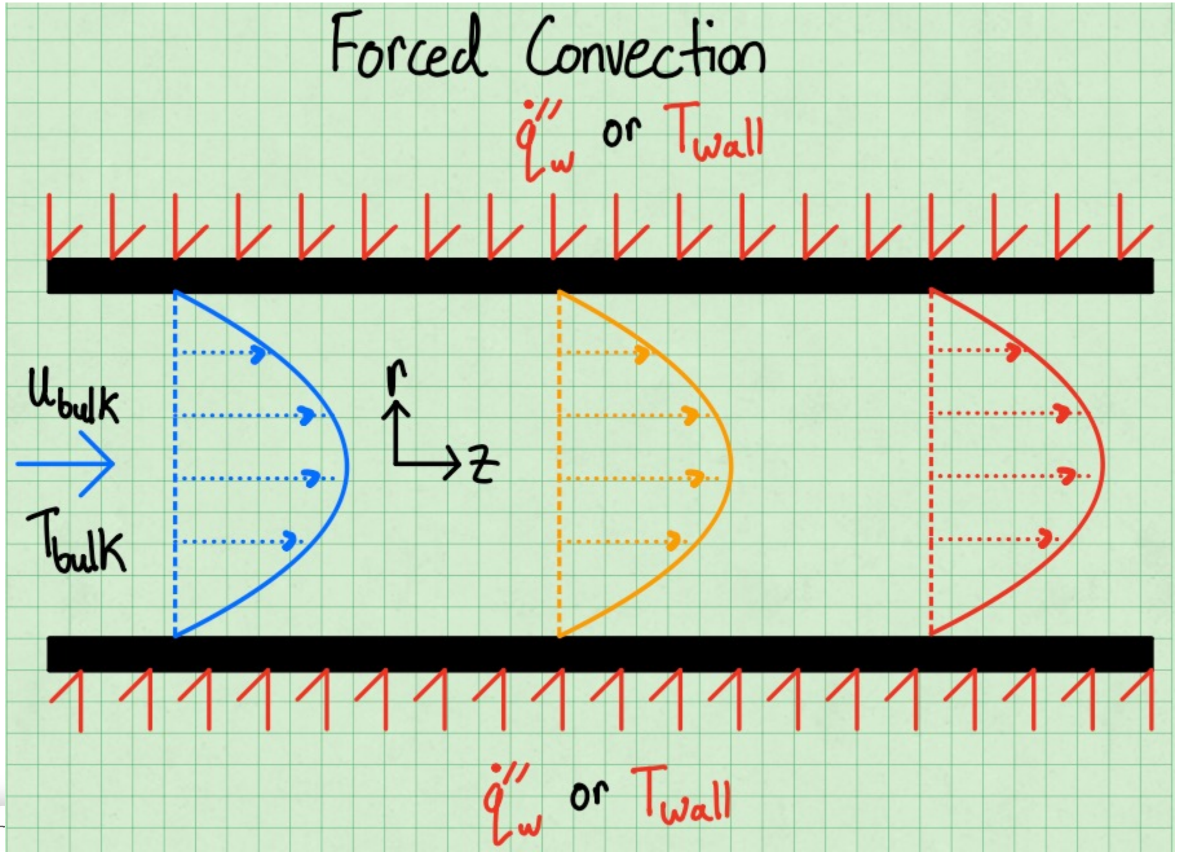
$HTC - Heat\ Transfer\ Coefficient$

$T_{wall} - Wall\ Temperature\ (°C)$

$T_{bulk} - Bulk\ Fluid\ Temperature\ (°C)$

$SA\ - Surface\ Area\ (m^2)$

$Nu - Nondimensional$
$Heat\ Transfer\ Coefficient\ or$
$Nusselt\ Number$



Heat Transfer Mechanisms

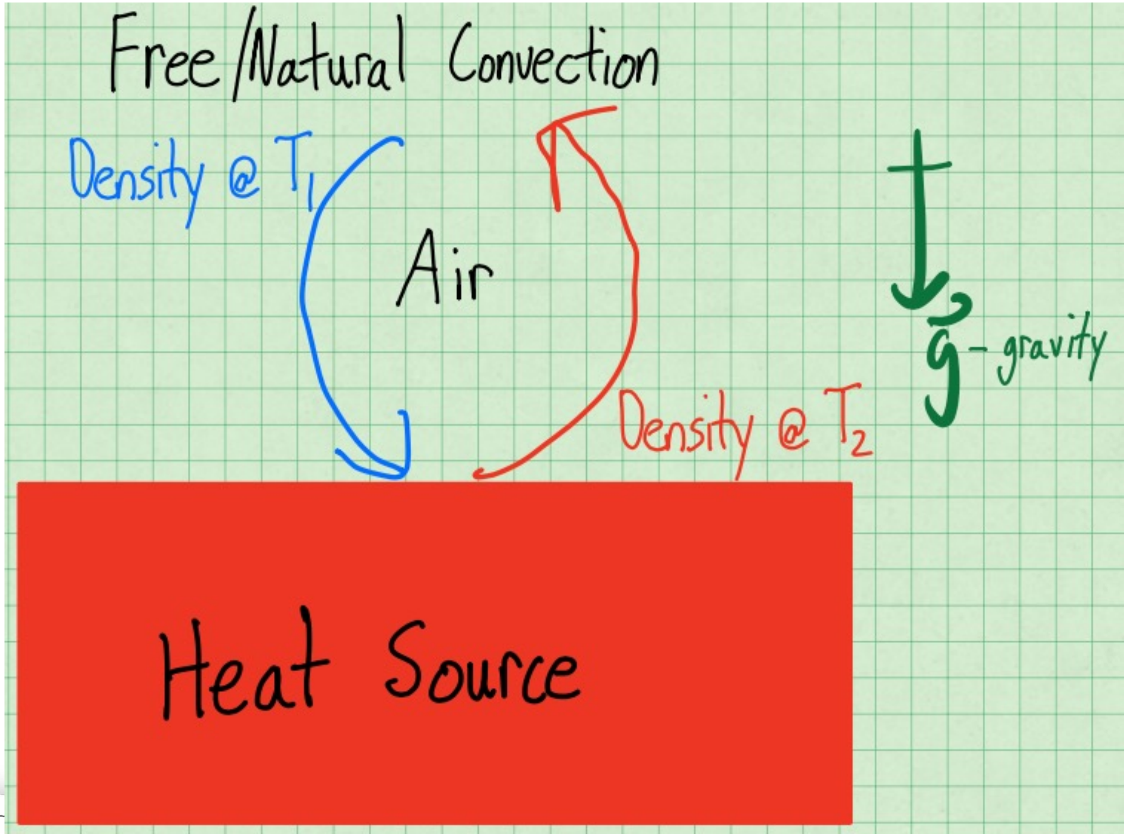
- Heat Convection (Convective Heat Transfer)
  - Two forms (Free/Natural and Forced Convection)

$$\dot{Q}_{conv.} = HTC(T_{wall} - T_{\infty})SA$$

$$HTC - Heat\ Transfer\ Coefficient$$

$$HTC = \frac{kNu}{L_C}$$

$$T_{wall} - Wall\ Temperature\ (°C)$$
$$T_{\infty} - Ambient\ Temperature\ (°C)$$
$$SA\ - Surface\ Area\ (m^2)$$
$$Nu - Nondimensional$$
$$Heat\ Transfer\ Coefficient\ or$$
$$Nusselt\ Number$$



Heat Transfer Mechanisms

- Heat Radiation (Irradiative Heat Transfer)

$$\dot{Q}_{rad} = \varepsilon\sigma\left(T_{Hot}^4 - T_{Cold}^4\right)SA$$

ε $- Emissitivity\ (-)$

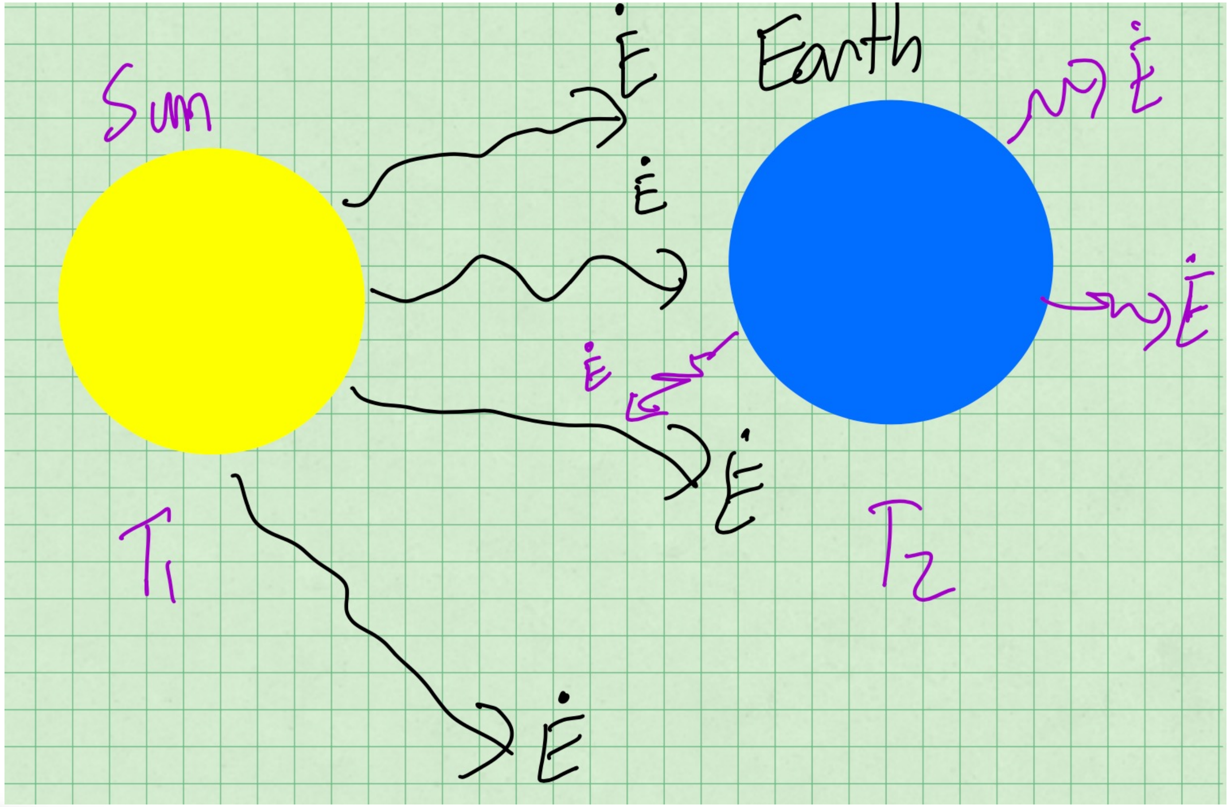
σ $- Stefan - Boltzmann\ Constant$

$- 5.6703x10^{-8}\ \frac{W}{m^2 - K^4}$

$T_{Hot} - Hotter\ Surface\ (K)$

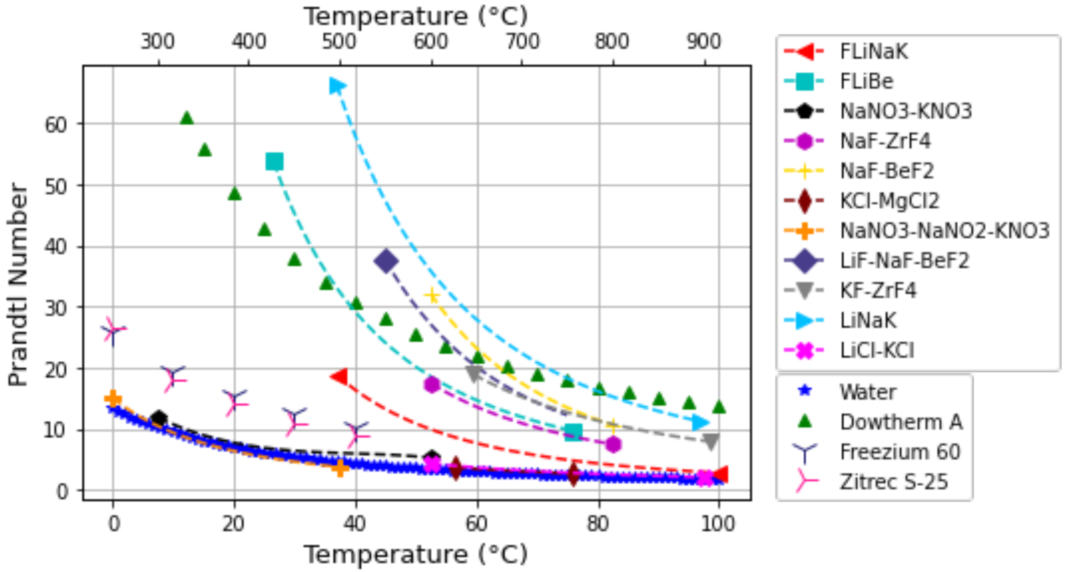
$T_{Cold} - Colder\ Surface\ (K)$

SA $- Surface\ Area\ (m^2)$



Scaling and Similitude for Fusion Device Design

We take advantage of surrogate fluids for molten salts, liquid metals, and gases to do scaled heat transfer and fluid dynamics experiments.



Relevant scaling parameters/non-dimensional numbers:

$$\mathrm{Pr} = \frac{\mu c_p}{k} \qquad Re = \frac{\rho u D_h}{\mu}$$

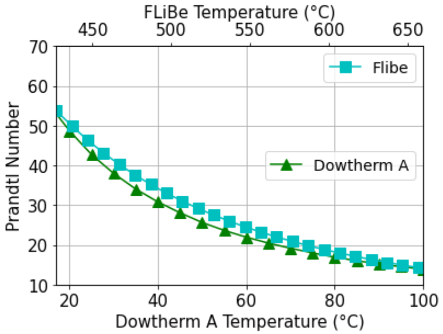
Desired Heat Transfer/Fluid Dynamics Design Information:

$$HTC = f\,(Re, Pr, Geom, BCs)$$

$$dP = f(Re, Geom)$$

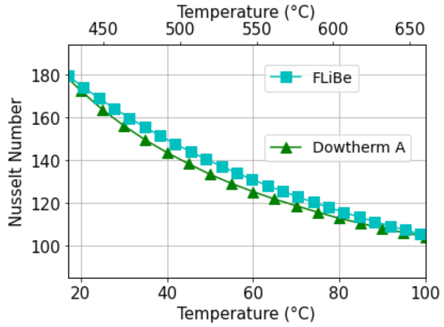
Cabral, A., et al., “Identification of Surrogate Fluids for Molten Salt Coolants used in Energy Systems Applications including Concentrated Solar and Nuclear Power Plants,” Int. J. Energy Res., Vol. 46(3), pp. 3554-3571, 2022

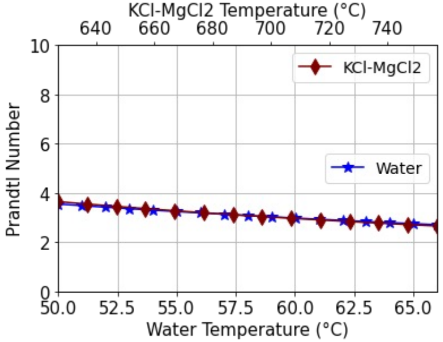
Similitude of Heat Transfer



Fluorides:

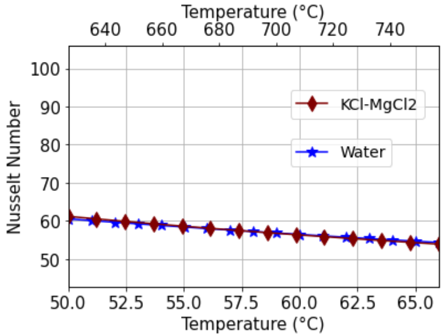
$$Re = \frac{\rho u D_h}{\mu}$$

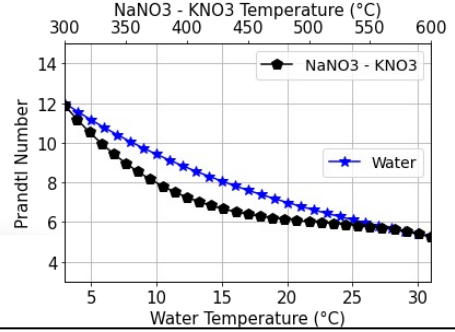




Chlorides:

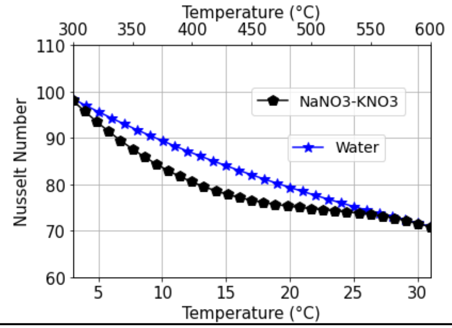
$$\mathrm{Pr} = \frac{\mu c_p}{k}$$





Nitrates:

$$HTC = f\ (Re, Pr, Geom, BCs)$$



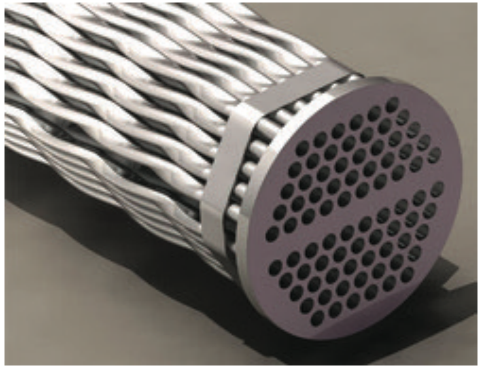
VCU

Cabral, A., et al., "Identification of Surrogate Fluids for Molten Salt Coolants used in Energy Systems Applications including Concentrated Solar and Nuclear Power Plants," Int. J. Energy Res., Vol. 46(3), pp. 3554-3571, 2022

Types of Heat Transfer Enhancements

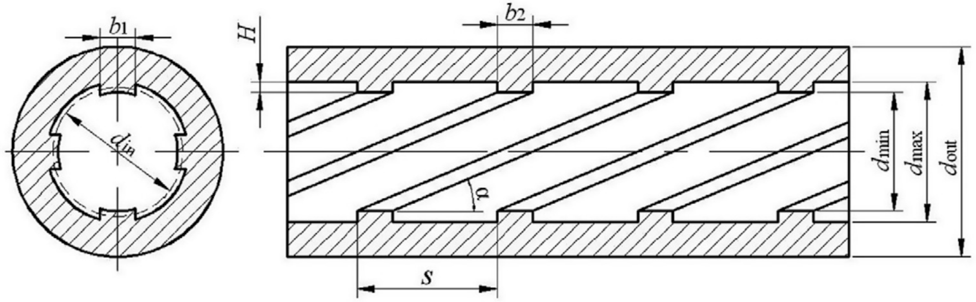
Different forms of heat transfer enhancements exists:

- Swirl flow inserts
- Internal fins
- Rifling/grooves
- Others

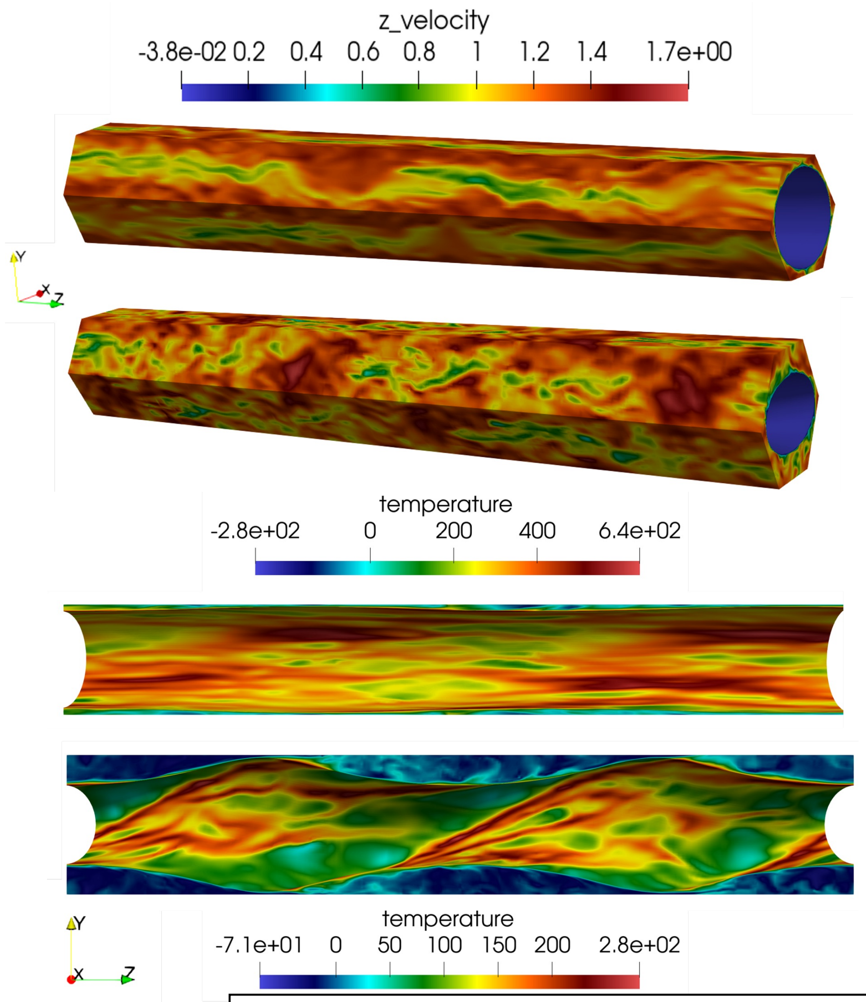


Performance quantified by the
Thermal Performance Factor

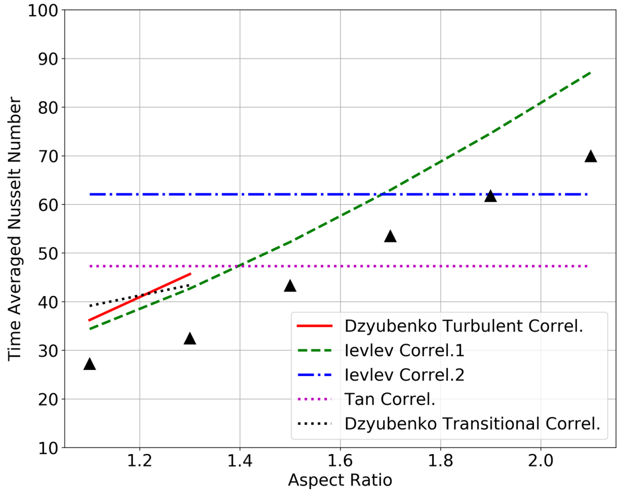
$$T.P.F. = \eta = \frac{\left(\frac{Nu}{Nu_0}\right)}{\left(\frac{f}{f_o}\right)^{1/3}}$$

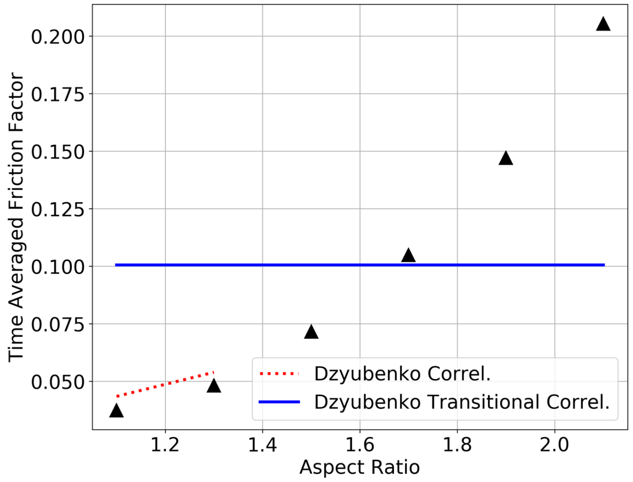


Computational Fluid Dynamics



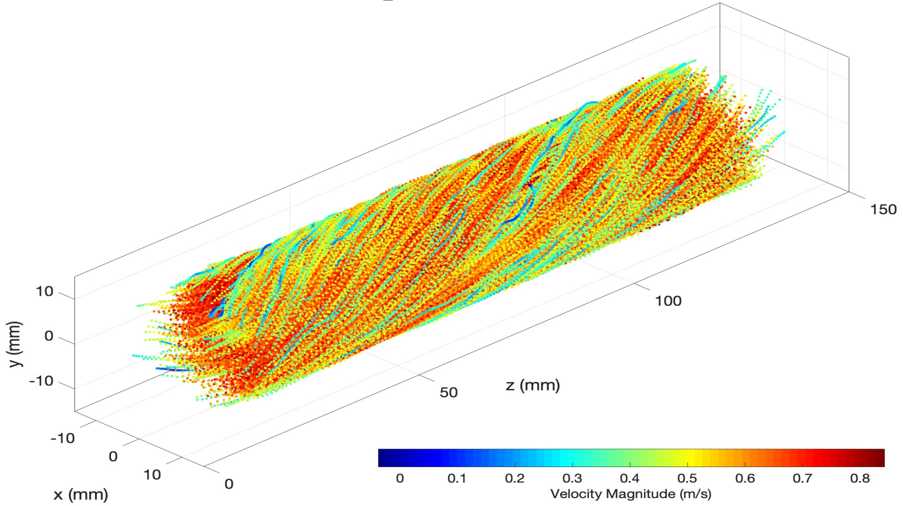
Data Reduction (Triangles are Simulations)

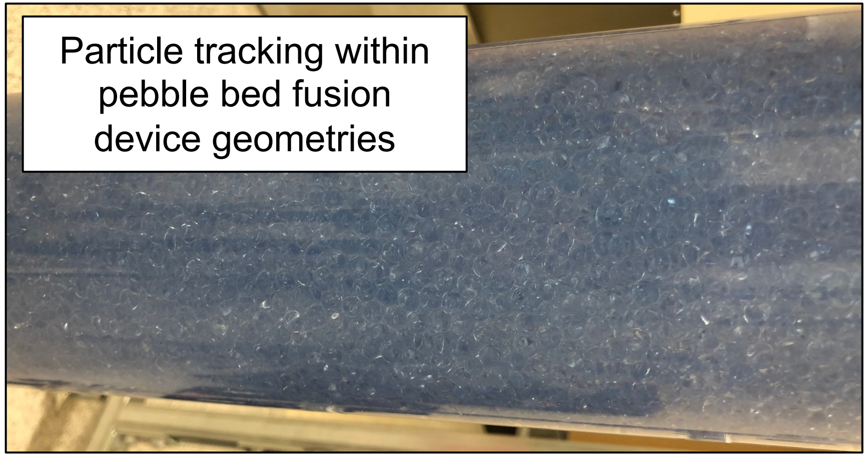


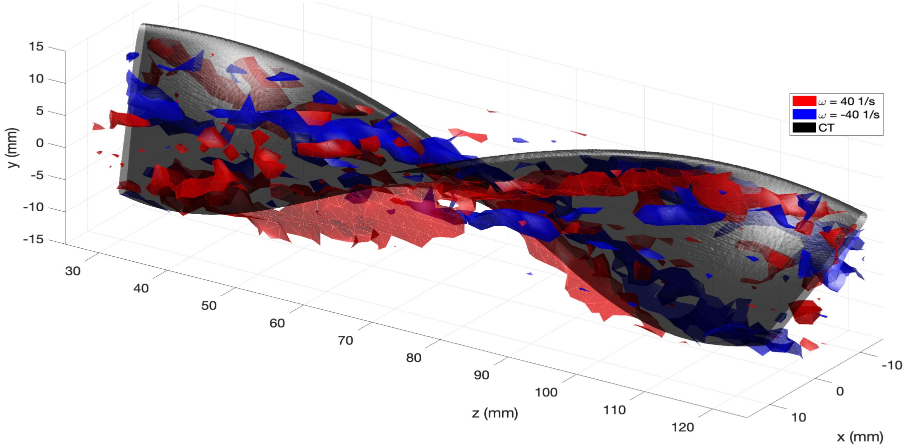


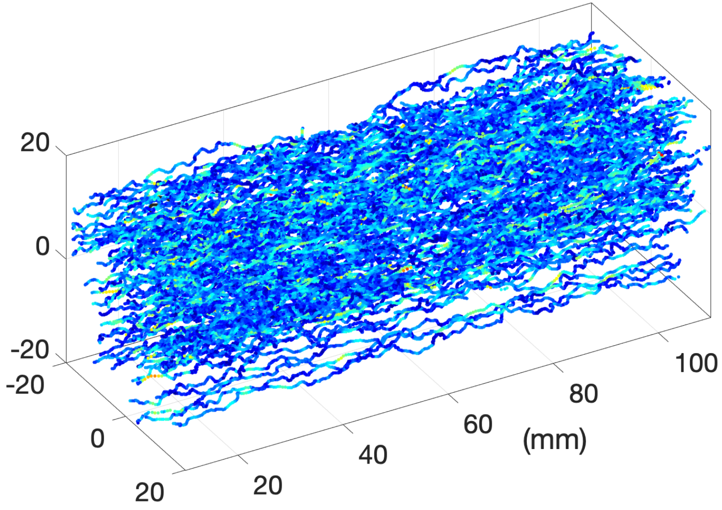
Tutwiler, S., Shaver, D., Carasik, L. B., "Determination of Aspect Ratio Influence on Flow and Heat Transfer Behavior in Twisted Elliptical Tubes for Molten Salt Applications," Adv. In Thermal Hydraulics, 2022

Experimental Fluid Dynamics









Wiggins, C., et al., “Noninvasive interrogation of local flow phenomena in twisted tape swirled flow via positron emission particle tracking (PEPT),” Nuc. Eng. Des., Vol. 387, pp. 1116012022, 2022.

Acknowledgements

Thanks to Dr. Arturo Dominguez, PFURO, DOE FES, US DOE Office of Science, and more for this opportunity!

Thank you!

Additional Resources

Heat Transfer Lectures:

https://www.youtube.com/playlist?list=PLZOZfX_TaWAHZOgn8CRjpqRElp5Dd-GaY

Fluid Mechanics Lectures:

https://www.youtube.com/watch?v=clVwKynHpB0&list=PLZOZfX_TaWAGocs2k5QmTL44OKOl7rn34&ab_channel=CPPMechEngTutorials

https://www.youtube.com/watch?v=PXjZ7xEAqsU&list=PLZOZfX_TaWAH0baRhA8OosWVbEsJK5sPe&ab_channel=CPPMechEngTutorials

https://www.youtube.com/watch?v=kxhTMc8tyEo&list=PLZOZfX_TaWAE7uM59dIBr-rH73WTJCcp_&ab_channel=CPPMechEngTutorials