VCU College of Engineering
Mechanical and Nuclear Engineering

What is the Fusion Fuel Cycle (Inner and Outer)?

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

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But first, Who am I, What is my background?

Lane B. Carasik, Ph.D.
Assistant Professor
Associate Editor,
Fusion Sci. Tech Journal
linkedin.com/in/lane-Carasik

Fluids in Advanced Systems and Technology (FAST) Research Group:

- Advanced thermal hydraulics (fusion, fission, and solar)
- Advanced instrumentation
- Medical isotope production

Professional Background:

- Virginia Commonwealth University, Assistant Professor, 2019 – Now
- Idaho National Laboratory, (No-Cost) Joint Appointment, 2022 – Now
- Ultra Safe Nuclear Corporation, Nuclear Thermal Engineer, 2018-19
- Kairos Power LLC., CFD & Thermal Fluids Engineering, 2017-18

Academic Background:

- Texas A&M University, Doctorate of Nuclear Engineering, 2017
- University of Tennessee, Knoxville, Bachelors of Nuclear Engineering, 2012
- Middle Georgia State University, Associates of Mathematics, 2010

TEXAS A&M UNIVERSITY

THE UNIVERSITY OF TENNESSEE KNOXVILLE

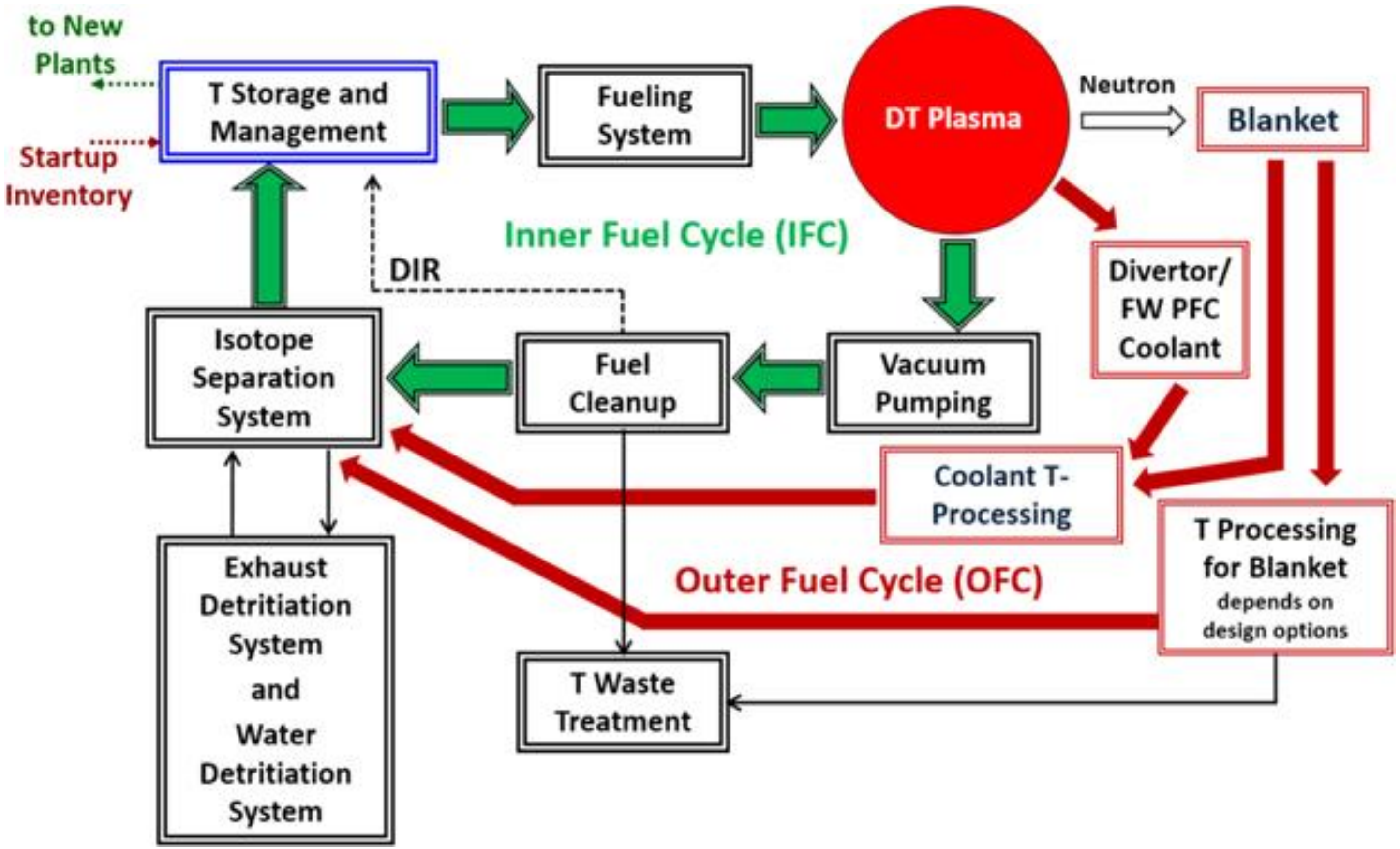
Middle Georgia State University

VCU

What are the learning objectives?

1. What is the fusion energy system fuel cycle?
2. What are the differences between inner and outer fuel cycles?
3. What is a breeding blanket and what are the different kinds of blankets?
4. What is a power conversion system and how can it tie to the outer fuel cycle?

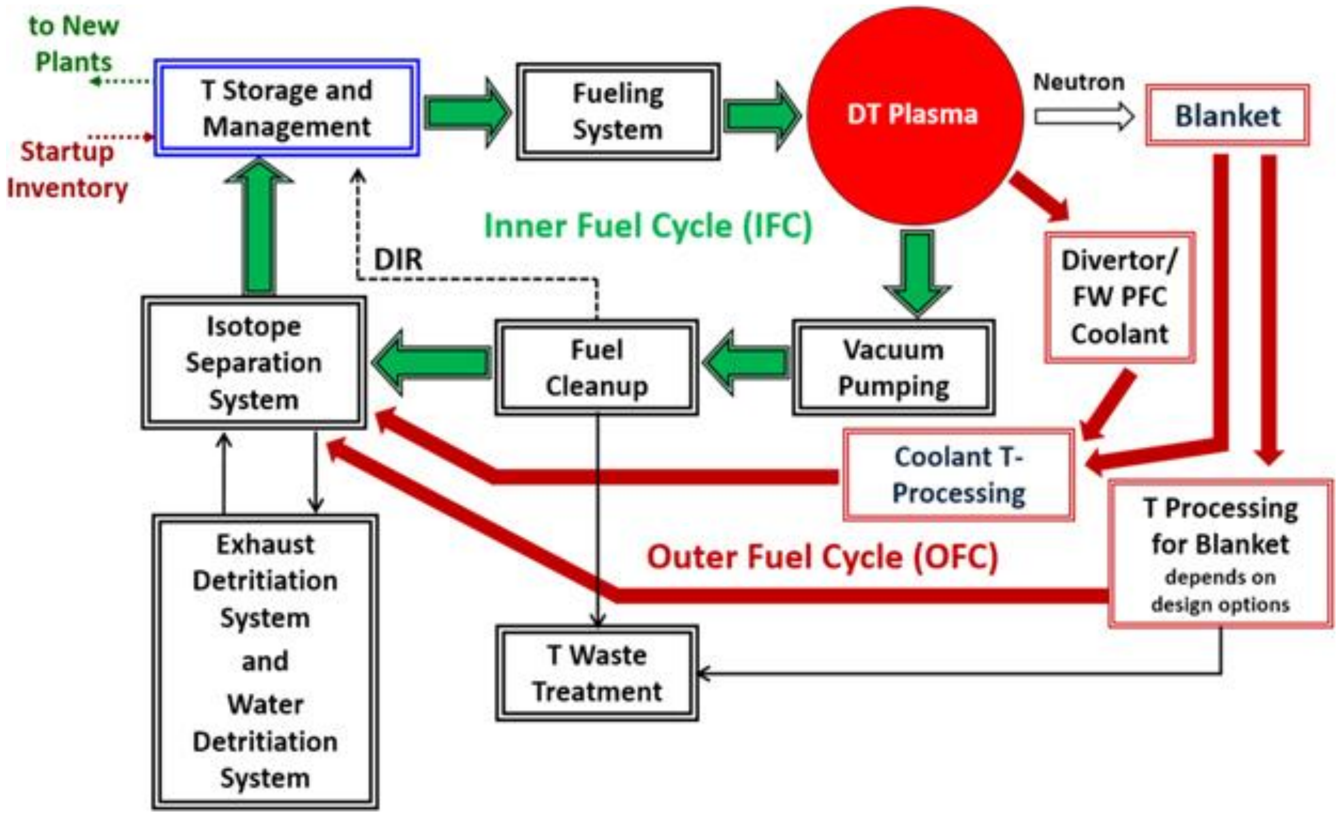
What is the fusion energy system fuel cycle?



Generic Deuterium-Tritium Fuel Cycle[1]

[1]M. Abdou et al., "Physics and technology considerations for the deuterium–tritium fuel cycle and conditions for tritium fuel self sufficiency", https://iopscience.iop.org/article/10.1088/1741-4326/abbf35

What is the fusion energy system fuel cycle?



Generic Deuterium-Tritium Fuel Cycle[1]

- The current terminology of "fuel cycle" includes two features:
  - Fuel management
    - **Inner** Fuel Cycle
  - Heat transport
    - **Outer** Fuel Cycle

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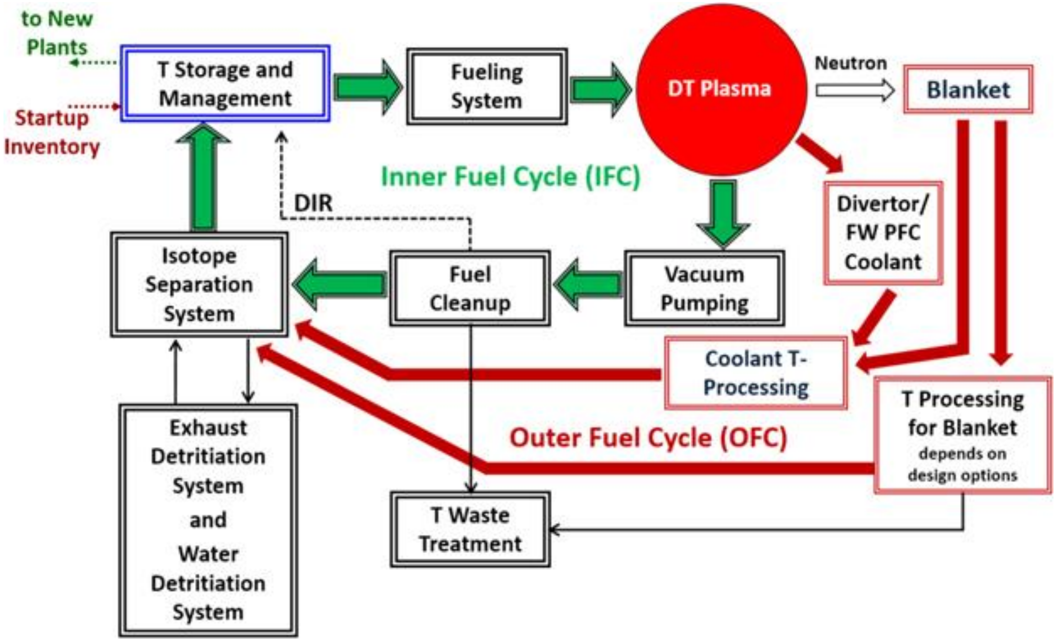
What is the fusion energy system fuel cycle?

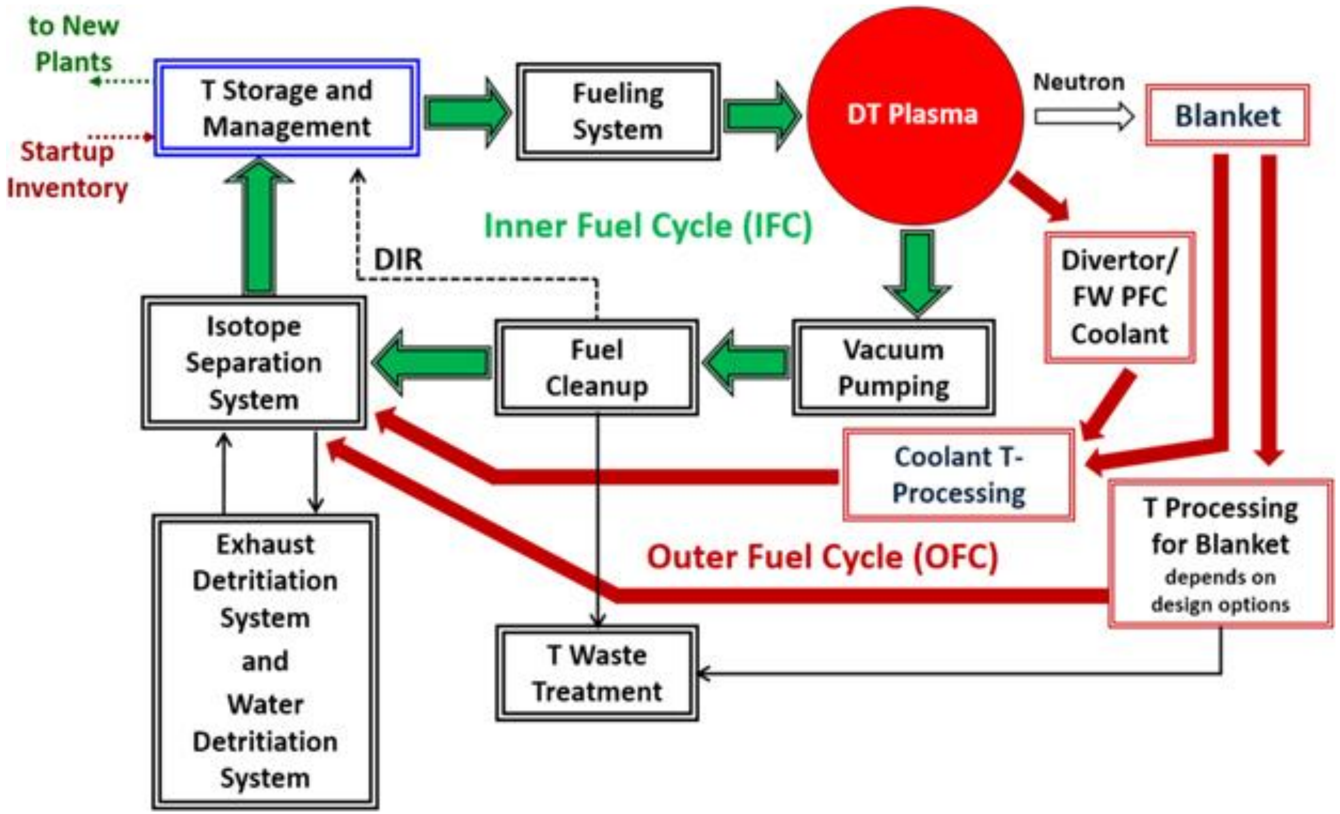


Generic Deuterium-Tritium Fuel Cycle[1]

- The current terminology of ”fuel cycle” includes two features:
  - Fuel management
    - **Inner** Fuel Cycle
  - Heat transport
    - **Outer** Fuel Cycle
- What is the real difference?
  - Inner (Fuel)
  - Outer (Heat Transfer)

[1]M. Abdou et al., “Physics and technology considerations for the deuterium–tritium fuel cycle and conditions for tritium fuel self sufficiency”, https://iopscience.iop.org/article/10.1088/1741-4326/abbf35

What is the fusion energy system fuel cycle?

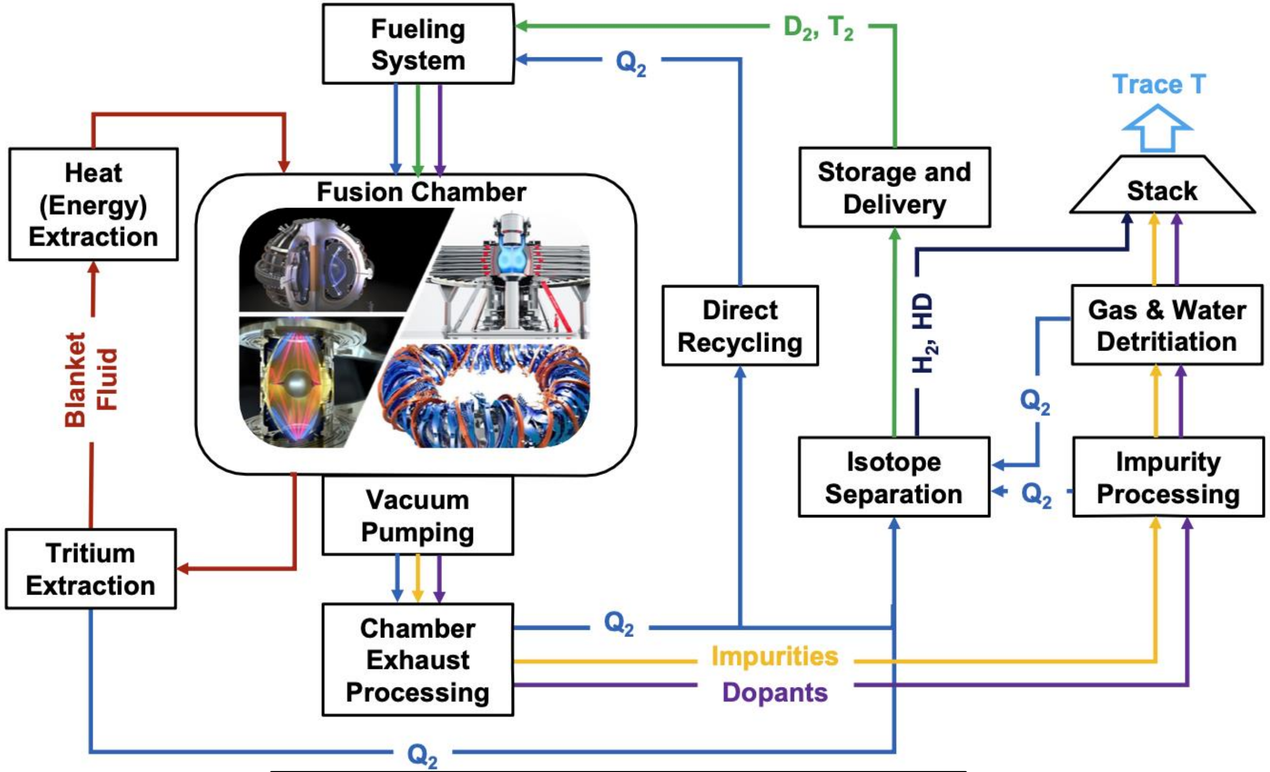


Generic Deuterium-Tritium Fuel Cycle[1]

- The current terminology of "fuel cycle" includes two features:
  - Fuel management
  - Heat transport
- The differences in the fuel cycle can depend on:
  - Plasma configuration (ex: MFE vs. IFE)
  - Fuel type (tritium vs. others)
  - Blanket breeder technology
  - Heat transfer fluids

[1]M. Abdou et al., "Physics and technology considerations for the deuterium–tritium fuel cycle and conditions for tritium fuel self sufficiency", https://iopscience.iop.org/article/10.1088/1741-4326/abbf35

What are differences between the inner and outer fuel cycle?

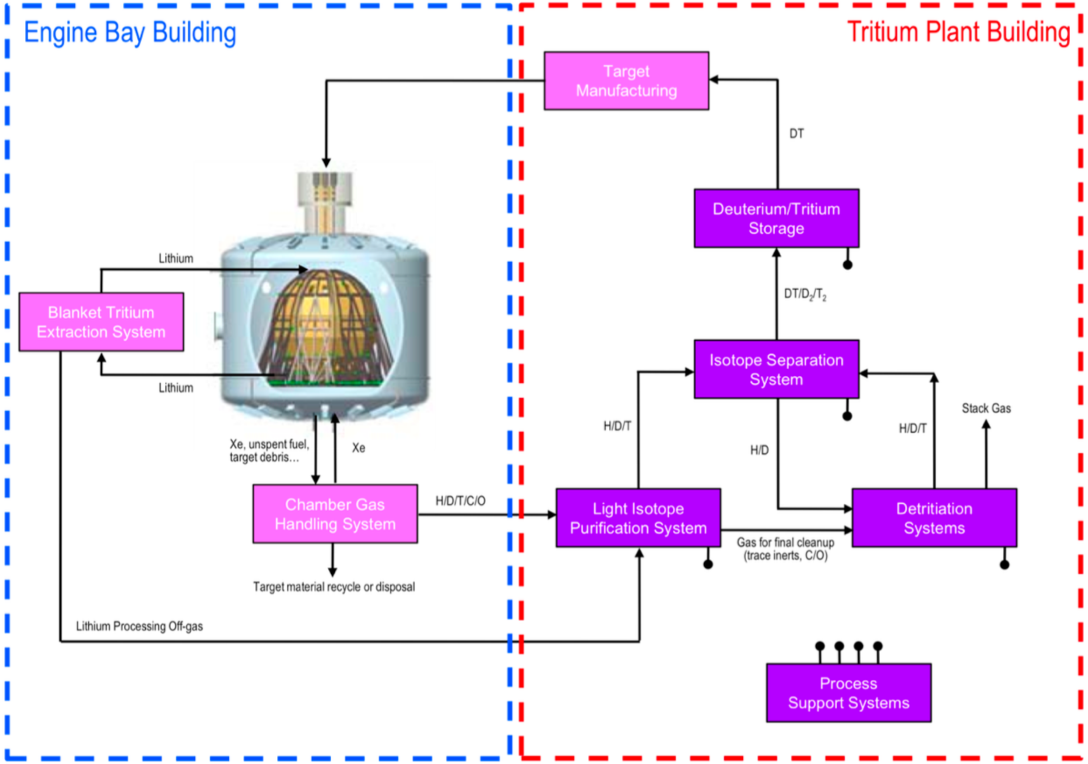


(Semi-Generic) Inner Fuel Cycle[1]

- The differences in the fuel cycle can depend on:
  - For MFE, there are different approaches, but:
    - Fuel injection
    - Fuel extraction from blanket/others
    - Purification
    - Storage
    - Not all encompassing*

[1]B. Garcia-Diaz, "Fusion Fuel Cycle", https://suli.pppl.gov/2024/course/Garcia-Diaz%20-%20Fuel%20Cycle.pdf

What are differences between the inner and outer fuel cycle?

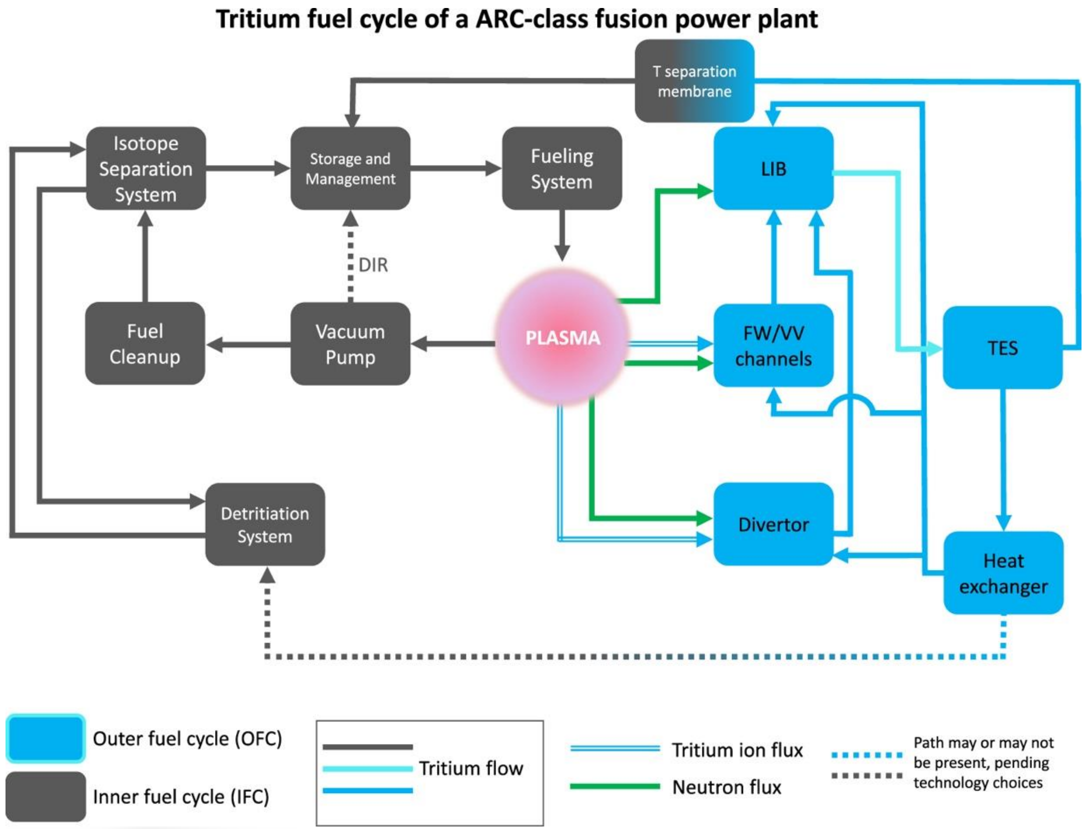


(Semi-Generic) Inner Inertial Fusion Energy Fuel Cycle[1]

- The differences in the fuel cycle can depend on:
  - For IFE, there are different approaches, but:
    - Fuel injection
    - Fuel extraction from blanket/others/chamber gas
    - Purification
    - Target manufacturing
    - Storage
    - Not all encompassing*

[1]B. Garcia-Diaz, “Fusion Fuel Cycle”, https://suli.pppl.gov/2024/course/Garcia-Diaz%20-%20Fuel%20Cycle.pdf

What are differences between the inner and outer fuel cycle?



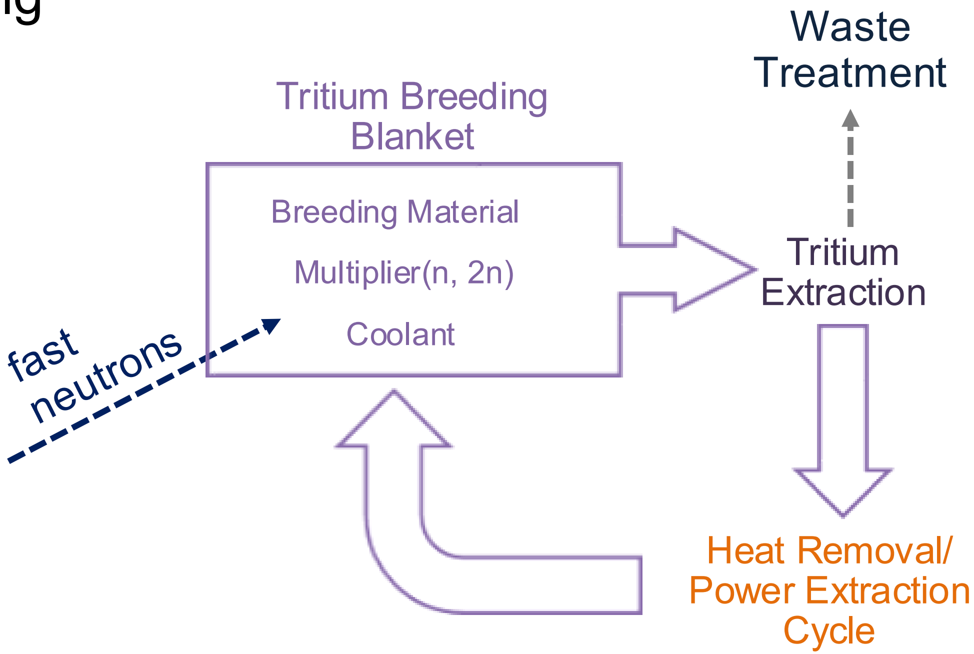
ARC Inner and Outer Fuel Cycle Schematic[1]

- Regardless of inner fuel cycle, the outer fuel cycle has to:
  - Remove heat from the blanket and divertors
  - Transfer heat to primary heat exchanger and the power conversion system
  - Remove tritium from coolant and transfer to inner fuel cycle

[1]Samuele Meschini et al 2023, Nucl. Fusion 63, 126005, https://iopscience.iop.org/article/10.1088/1741-4326/acf3fc/

What is a breeding blanket and what are the different kinds of blankets?

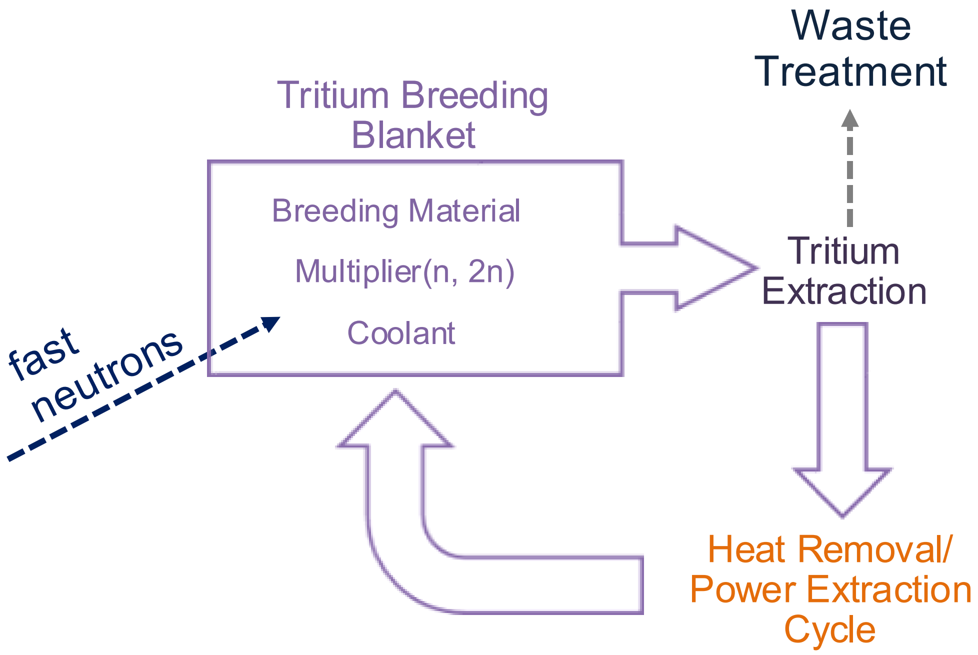
- The breeder blanket is used for:
  - Creating new tritium (breeding)
    - Multiplication of neutrons for breeding
  - Generating heat and removing
  - Shielding of
    - Magnets
    - Diagnostics
  - Provide structural support



M. Gehrig " Tritium Breeding Blankets for Nuclear Fusion Reactors" https://suli.pppl.gov/2024/course/Blanket_presentation_2024-06-18.pptx

What is a breeding blanket and what are the different kinds of blankets?

- The different options of blankets are classified in different ways:
  - Single (self) vs. dual cooled
  - Solid vs. liquid breeders
  - Material used for breeding



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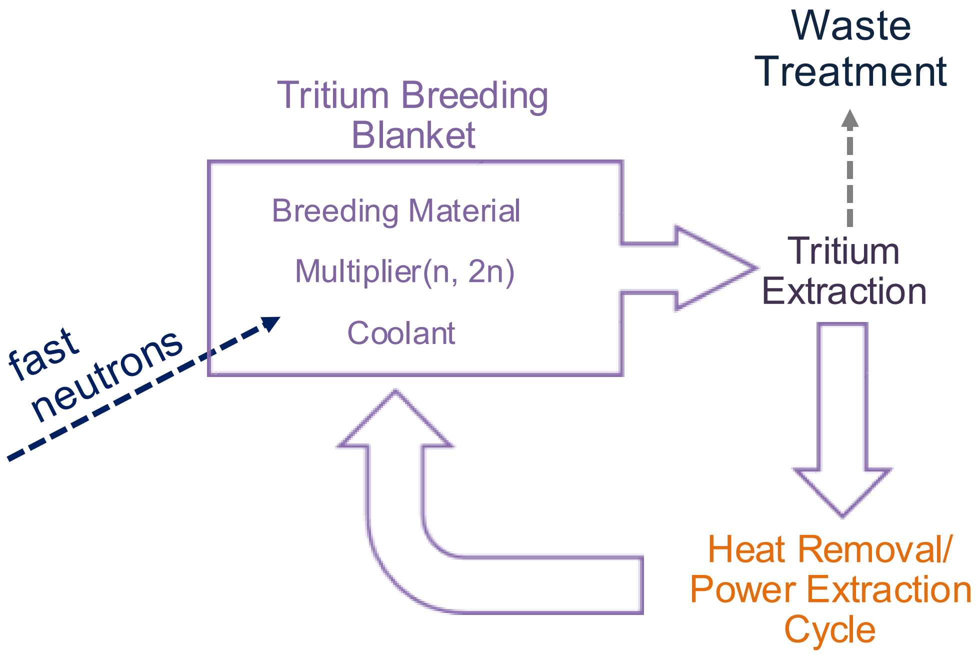
What is a breeding blanket and what are the different kinds of blankets?

- The different options of blankets are classified as:
  - Single Cooled:
    - Water-Cooled Ceramic Breeder (WCCB)
    - Helium-Cooled Ceramic Breeder (HCCB)
    - Self-Cooled Lead Lithium (SCLL)
    - Liquid Immersion Blankets (LIB), molten salt
  - Dual cooled:
    - Water-Cooled Lithium-Lead (WCLL)
    - Dual-Cooled Lead Lithium (DCLL) - (Helium)
  - Others



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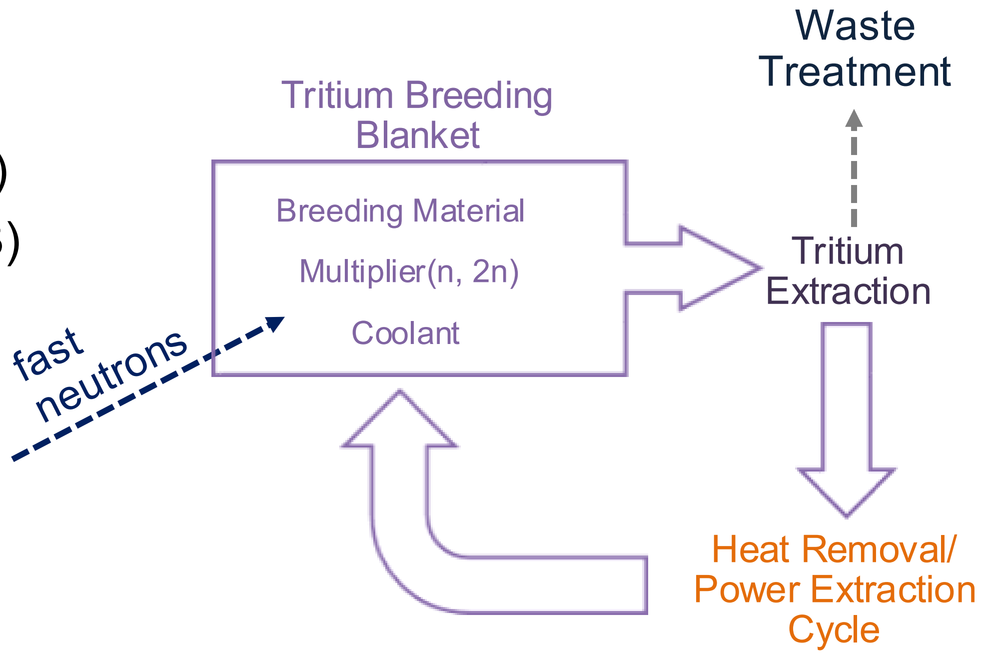
What is a breeding blanket and what are the different kinds of blankets?

- The different options of blankets are classified as:
  - Solid breeders (Gas or Water)
    - Water-Cooled Ceramic Breeder (WCCB)
    - Helium-Cooled Ceramic Breeder (HCCB)
  - Liquid breeders (Liquid Metal or Molten Salt)
    - Liquid metal (SCLL/DCLL or WCLL)
    - Molten Salts (LIB)
  - Others



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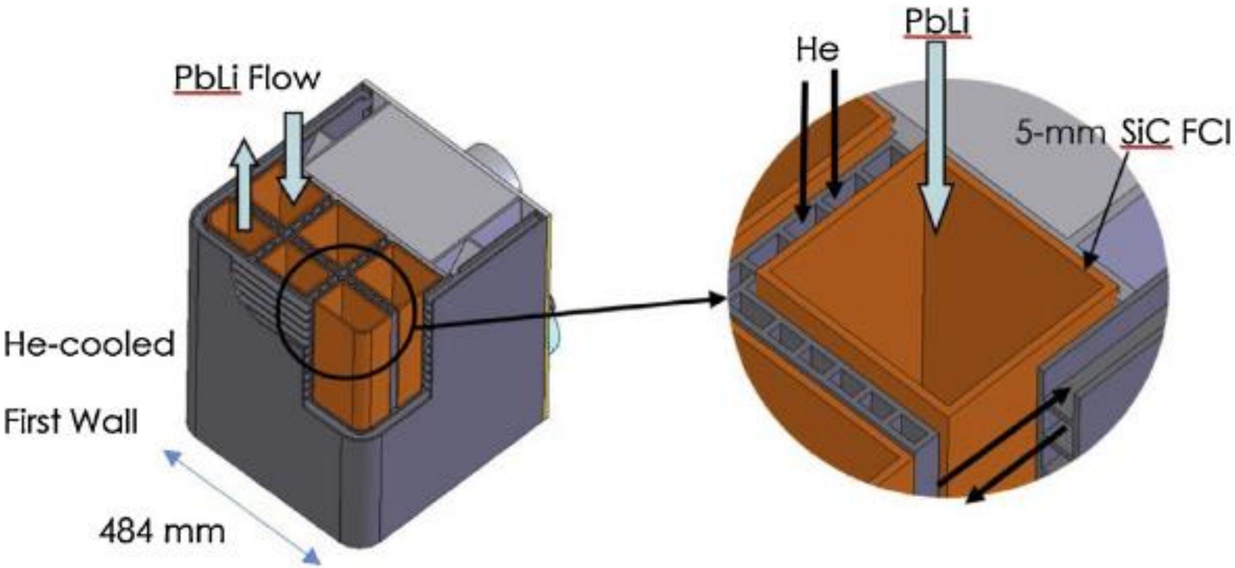
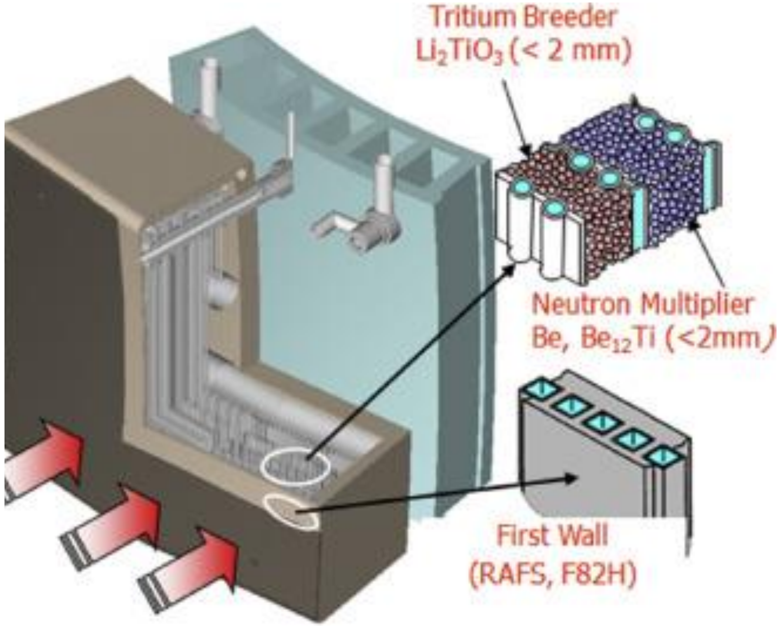
What is a breeding blanket and what are the different kinds of blankets? Examples



M. S. Tillack and S. Malang, "High performance PbLi blanket," *17th IEEE/NPSS Symposium Fusion Engineering*



M. Abdou (2015). Blanket/first wall challenges and required R&D on the pathway to DEMO. Fusion Engineering and Design.

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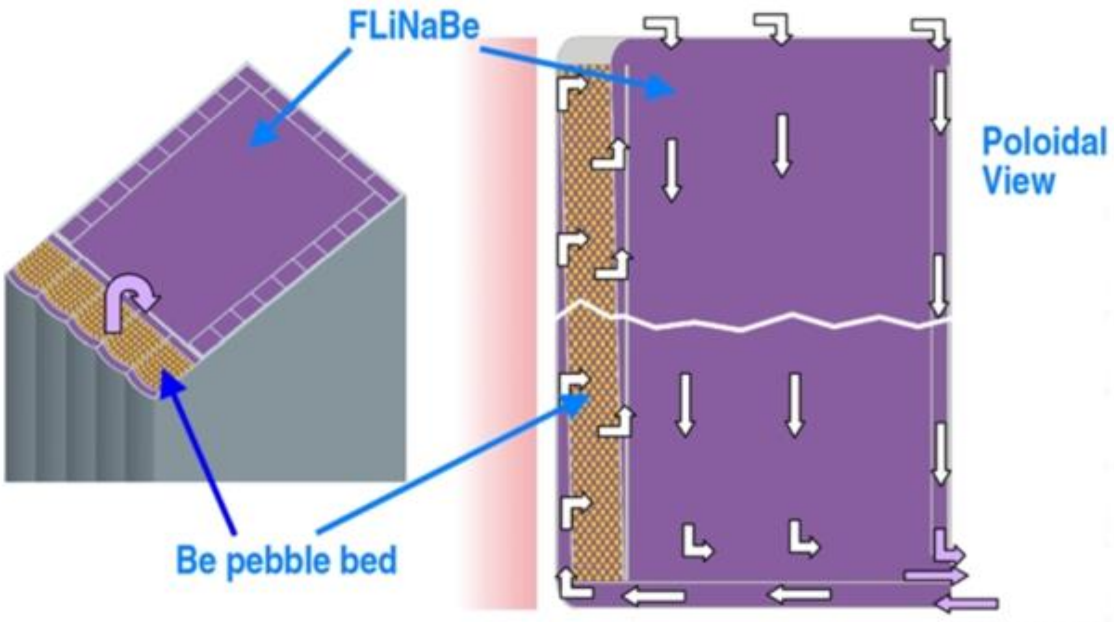
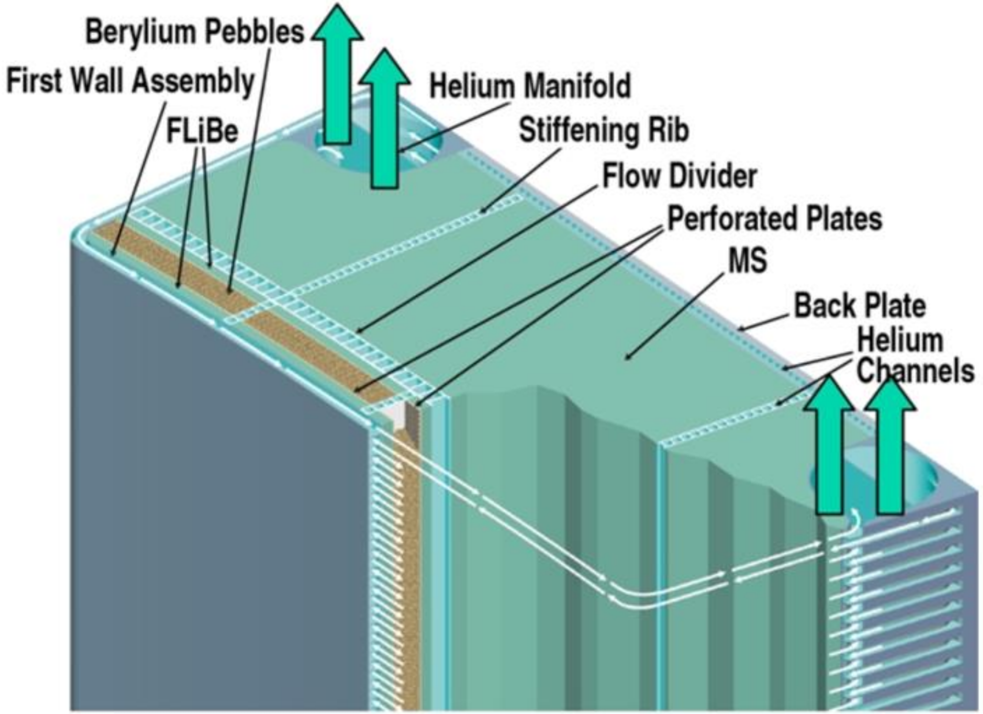
What is a breeding blanket and what are the different kinds of blankets? Examples



C. Wong, *Fusion Sci. Technol.* **47:3** (2005) 502-509



C. Wong, *Fusion Eng. Des.* **72** (2004) 245-275.

What is a breeding blanket and what are the different kinds of blankets?

Liquid Metal (Li)

- Good TBR; may not need ^{6}Li enrichment
- Low T_{melt} = 180 °C
- Traditionally paired with Vanadium alloy or RAFM steel structure
- Very high chemical reactivity with H_2O and air (safety issue)
- High tritium solubility/inventory, different extraction techniques needed
- Electrical insulators required for MFE

Liquid Metal (PbLi)

- Good TBR, but with ^{6}Li enrichment
- Low T_{melt} = 235 °C
- Traditionally paired with RAFM steel or SiC structure
- Much lower chemical reactivity than pure Li
- Low T/high T design options
- Material compatibility at high T may require coatings
- Electrical insulators required for MFE

Solid Ceramic

- Good TBR requires Be multiplier addition,
- Traditionally paired with RAFM steel structure and He or H_2O coolant
- Better material compatibility than liquids
- Simpler & more mature tritium extraction
- Require replacement
- Evolution under irradiation important

Molten Salt (FLiBe)

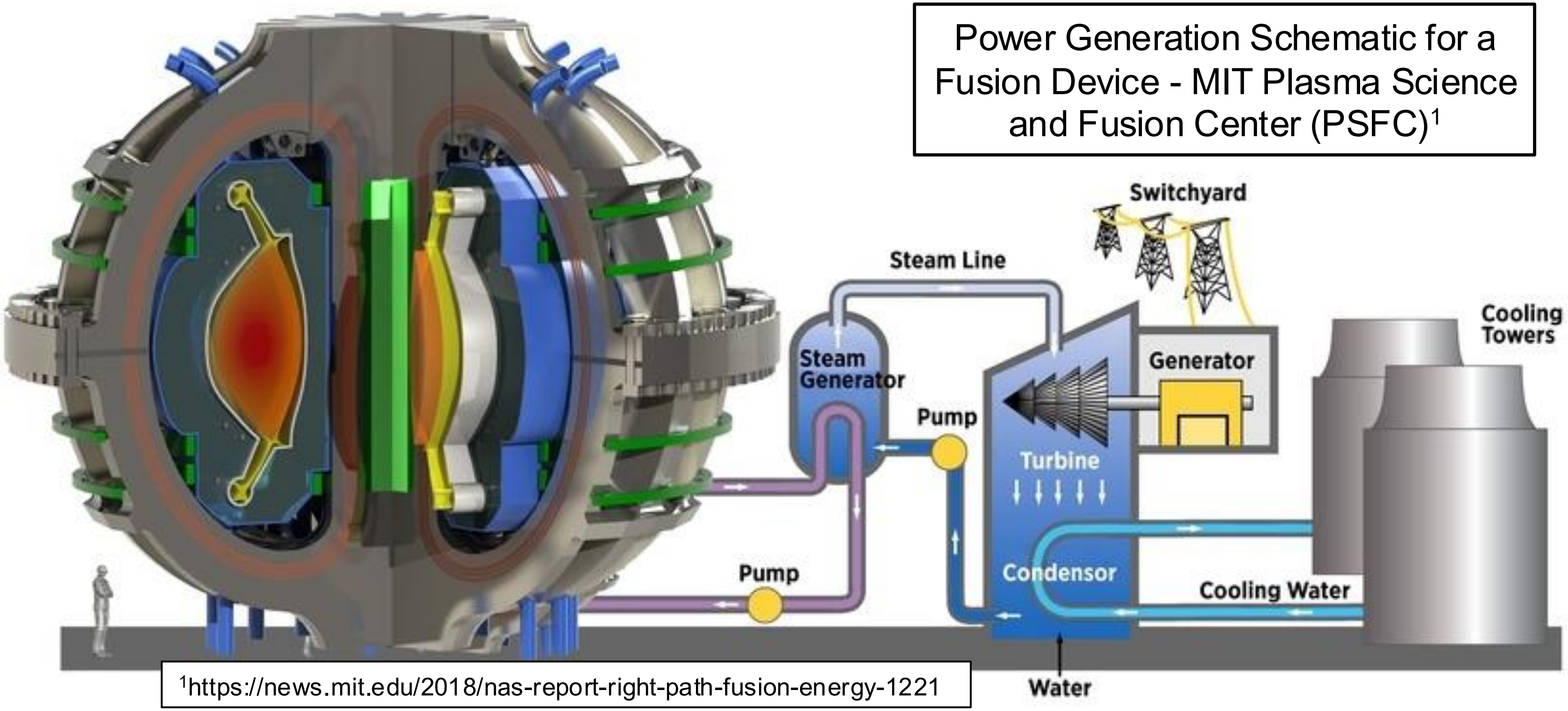
- Good TBR may require Be multiplier addition
- High T_{melt} = 460 °C
- Structural material solution unclear
- Corrosion a significant concern
- Low electrical conductivity
- High heat capacity
- Low thermal conductivity
- High viscosity

M. Gehrig " Tritium Breeding Blankets for Nuclear Fusion Reactors" https://suli.pppl.gov/2024/course/Blanket_presentation_2024-06-18.pptx

What is a power conversion system and how can it tie to the outer fuel cycle?

- Based on a Rankine or Brayton 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]

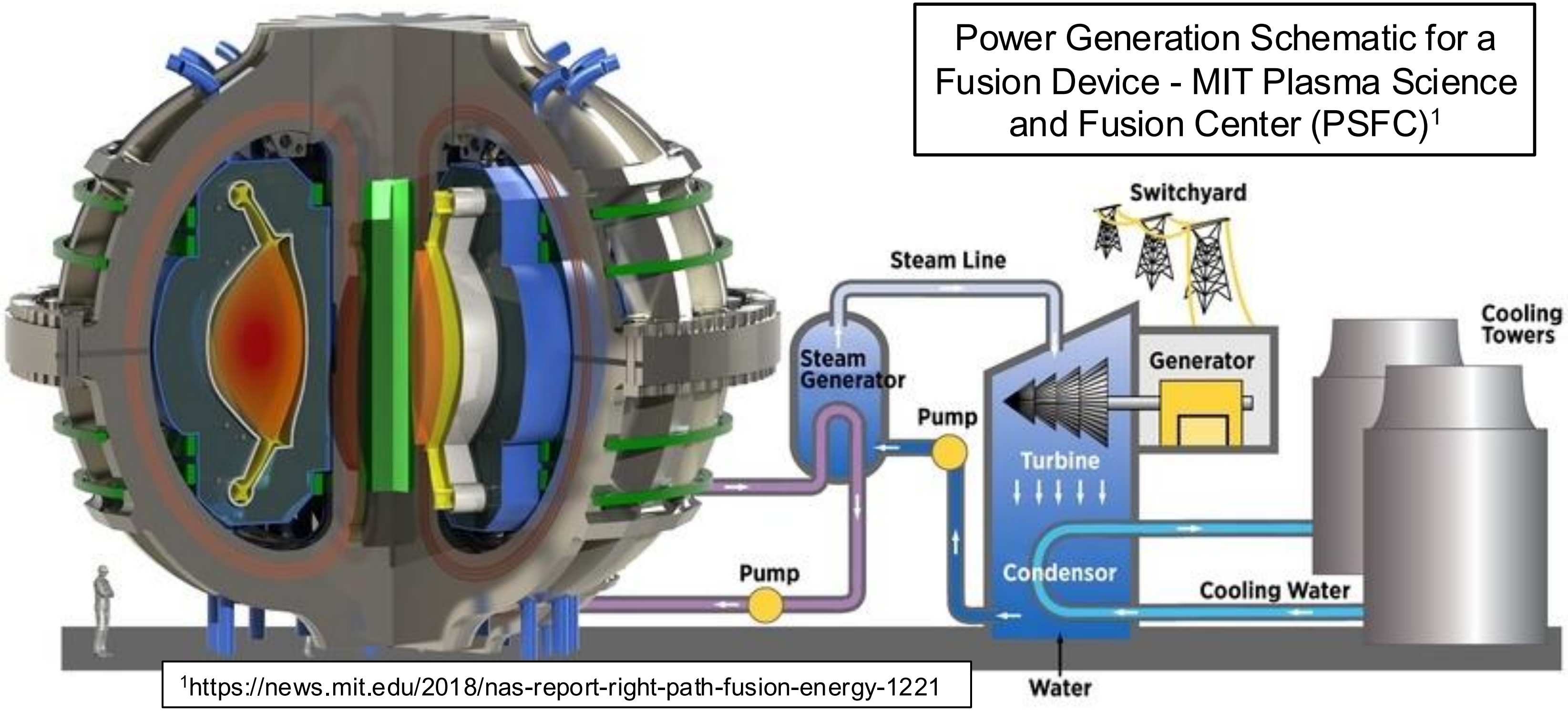


[1]https://news.mit.edu/2018/nas-report-right-path-fusion-energy-1221

What is a power conversion system and how can it tie to the outer fuel cycle?

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

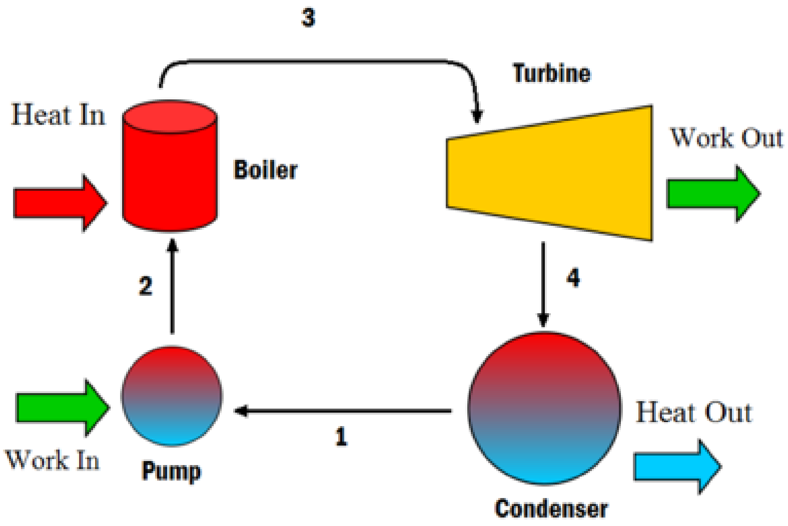
Power Generation Schematic for a Fusion Device - MIT Plasma Science and Fusion Center (PSFC)[1]



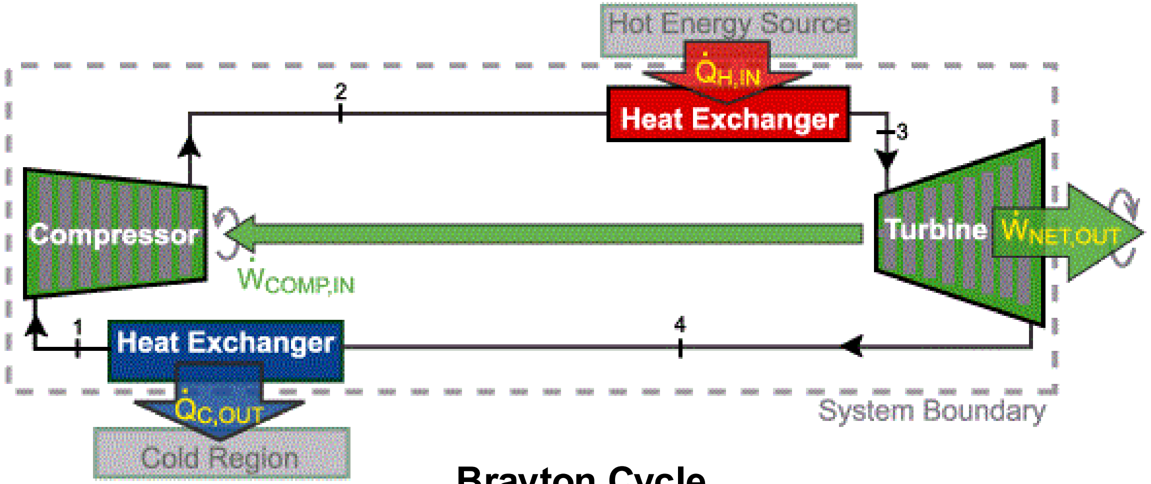
[1]https://news.mit.edu/2018/nas-report-right-path-fusion-energy-1221

What is a power conversion system and how can it tie to the outer fuel cycle?

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



Rankine Cycle



Brayton Cycle

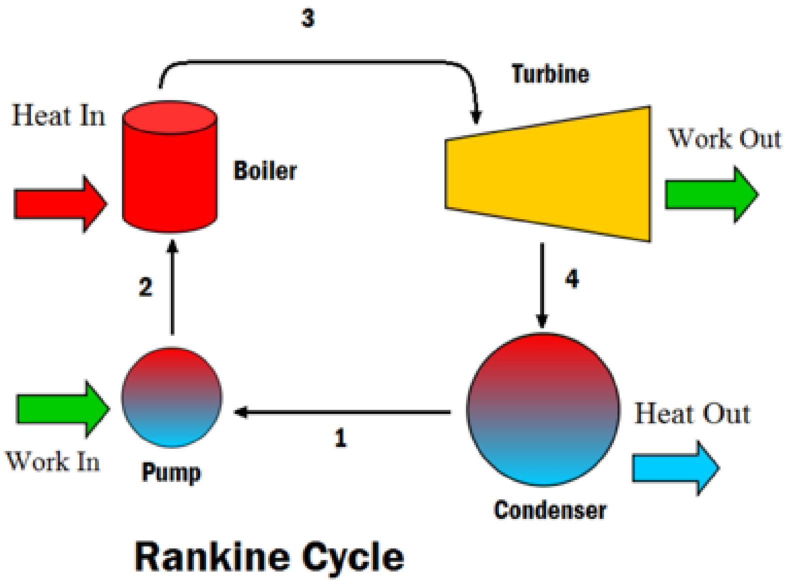
[1]https://energyeducation.ca/encyclopedia/Rankine_cycle
[2]https://energyeducation.ca/encyclopedia/Brayton_cycle

What is a power conversion system and how can it tie to the outer fuel cycle?

- 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.



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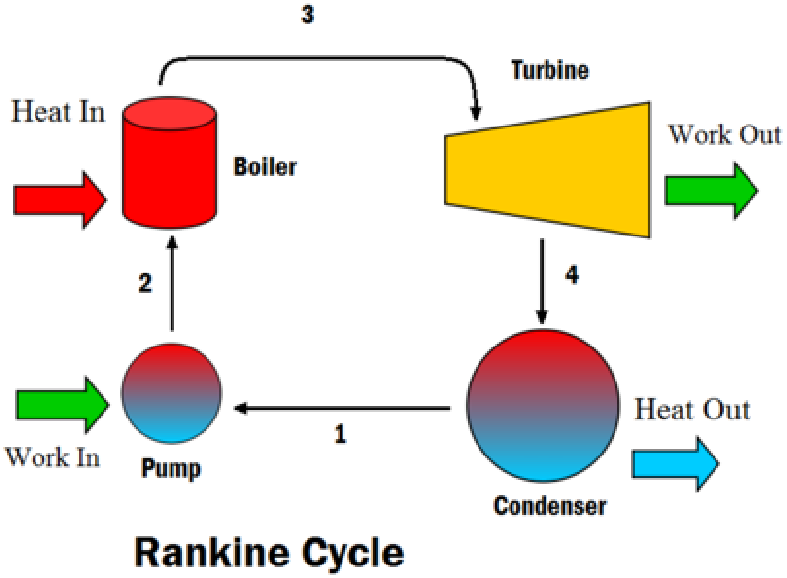
- We have a few options, lower our final heat sink temperature, raise our operating temperature, but never can reach ideal efficiencies.



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What is the FAST Research Group?

Lane B. Carasik, Ph.D.
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Fluids in Advanced Systems and Technology (FAST) Research Group:

- Advanced thermal hydraulics (fusion, fission, and solar)
- Advanced instrumentation
- Medical isotope production

Alexander Coxe, Ph.D.
Post Doctoral Researcher

Graduate (PhD) Students (*NSF/+NEUP/^VCU Fellowship/>Industry)

Theodore Chu

James Vulcanoff

Sierra Tutwiler*,+

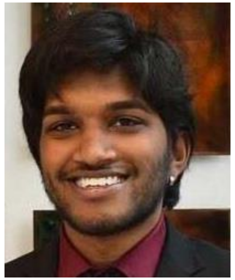
Ryan McGuire+

Trevor Franklin*,+

Jerel Houston^

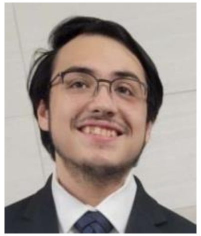
Andrew Hutsell+

Jesse East>



Dilan Kurukulasuriya

Undergraduate Students (@McNair Fellow)



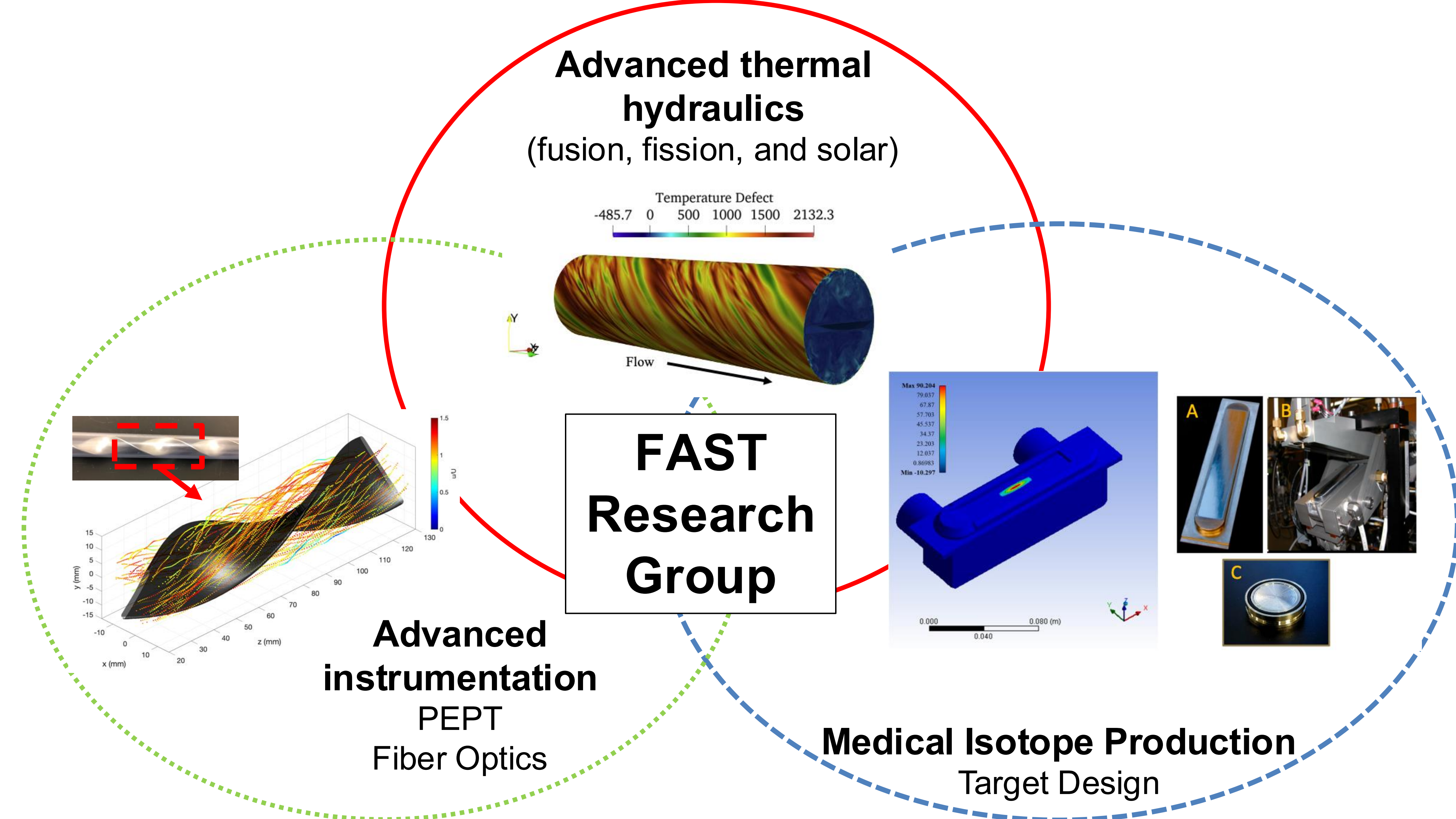
Ethan Villarreal

Jeremy Lopez

Gavin Standish

Eisha Langlia

VCU



Advanced thermal hydraulics
(fusion, fission, and solar)
Temperature Defect
-485.7 0 500 1000 1500 2132.3
Y
Flow
FAST Research Group
Advanced instrumentation
PEPT
Fiber Optics
Medical Isotope Production
Target Design
Max 90.204
79.037
67.87
57.703
45.537
34.37
23.203
12.037
0.86983
Min -10.297
0.000
0.040
0.080 (m)
A
B
C
u/U
y (mm)
x (mm)
z (mm)

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