Triply Periodic Minimal Surface Heat Exchangers for SMR and Microreactor Applications

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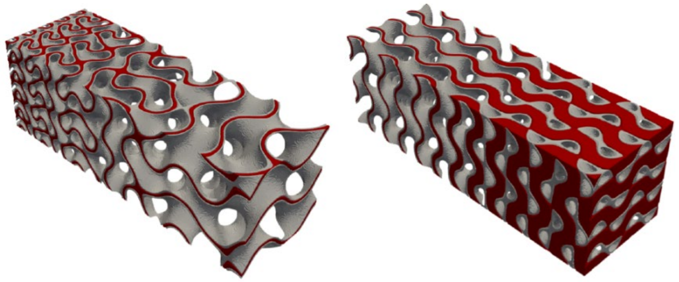

INL Idaho National Laboratory

Oak Ridge National Laboratory

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Los Alamos National Laboratory

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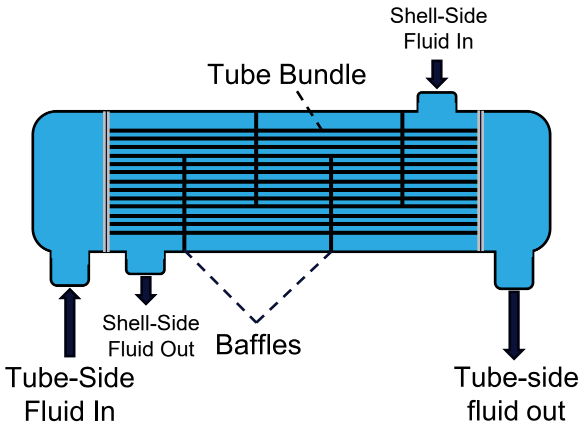
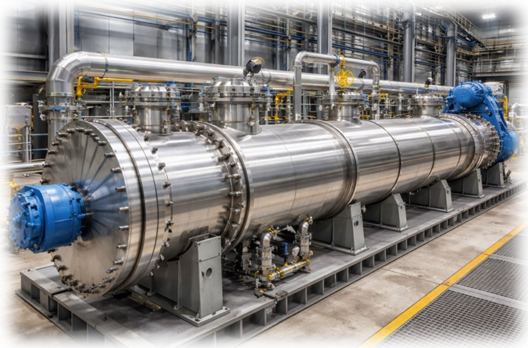
Heat Exchangers in Nuclear

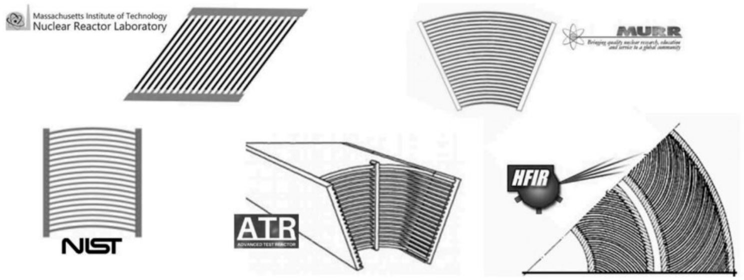


- Two types of heat exchangers exist in nuclear reactors.
  - In-core: Nuclear fuel
  - Ex-core: Heat exchangers

- Innovation in heat exchangers for nuclear energy technology is heavily outdated.
  - Traditional HX are inexpensive but have a large footprint (Shell and tube HX, plate HX etc.).
  - Mainstream nuclear HX designs utilize simple tube, and/or rectangular channel designs to increase heat transfer surface area.

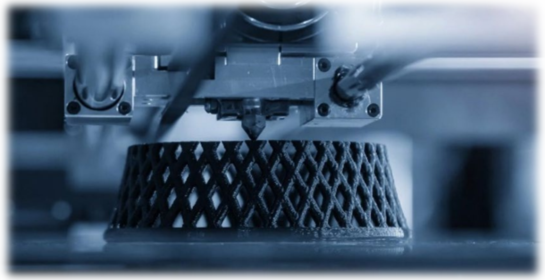
- Current microreactors and SMRs need to downsize their heat extraction systems.
  - Advances in additive manufacturing have opened the door to more intricate, novel heat exchanger designs.

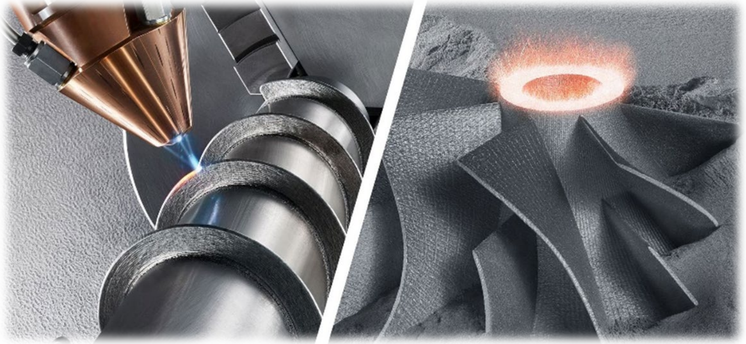


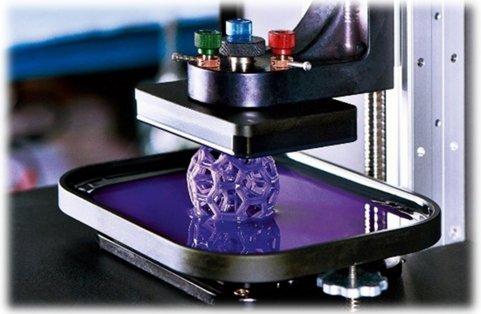


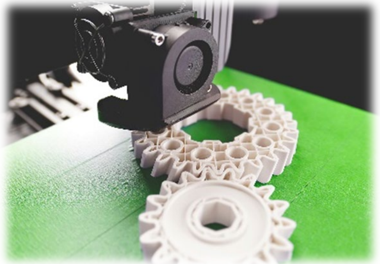
Additive Manufacturing

- **Conventional Manufacturing:** casting (shape in mold) or machining (remove material)
  - Cost driven by tooling (cast) or amount of material removed (machining).
- **Additive Manufacturing:** Another category of machine tools with unique capabilities and limitations
  - No part-specific tooling; builds layer-by-layer.
  - Requires controlled feedstock (e.g., powders, resins, filaments).
  - Surface finish and anisotropic properties require special consideration.
  - Size limited by build chamber (~1m^3 maximum).
  - Cost driven by material added, rather than removed.
  - **Key Advantage:** AM can create complex geometries that are otherwise impossible (biological growth).









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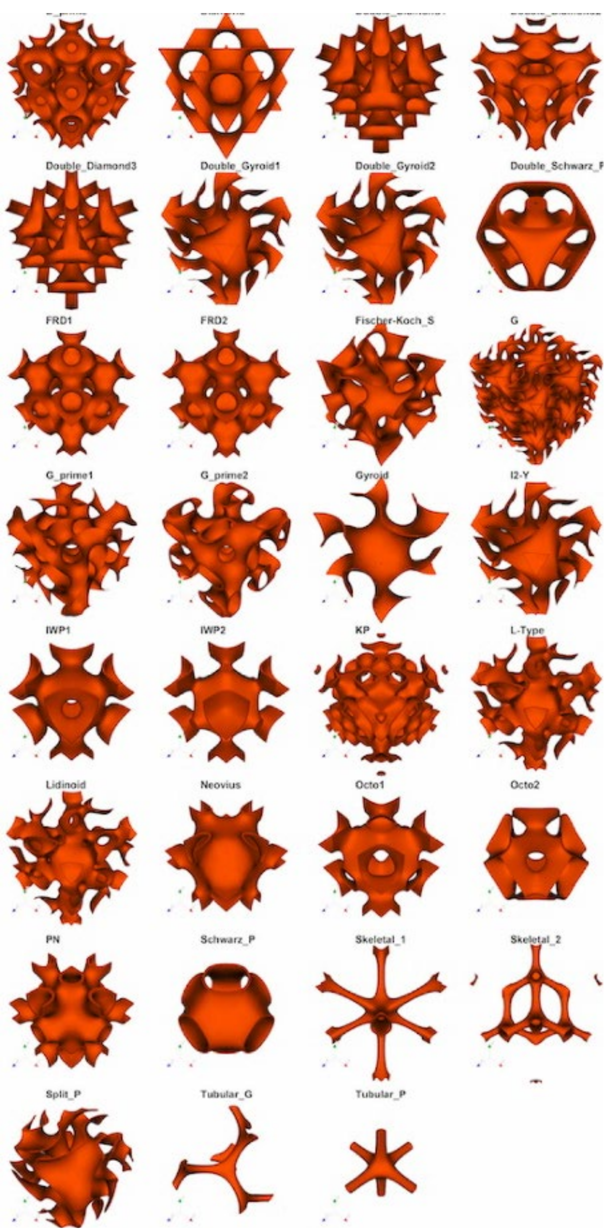
Triply Periodic Minimal Surface (TPMS) Heat Exchangers

- Mathematically derived set of equations that creates a unique, continuously curved surface that is periodic in all three dimensions.
- Many different “families” of TPMS equations with countless more being worked on.
  - Diamond, Gyroid, Primitive, Fischer-Koch, etc.
- Large number of parameters can be modified to custom fit a TPMS geometry for specific system needs.
  - Geometries can be as complex, or as simple as is needed.
  - Multi-fluid capability.
  - Easy to design with a third “air-gap” for dissimilar working fluids.

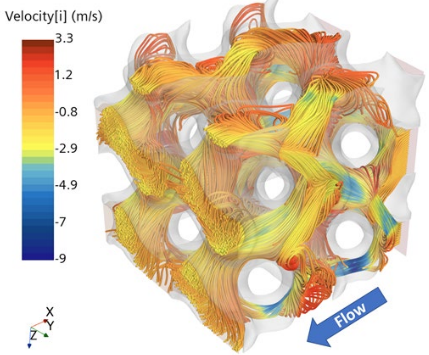


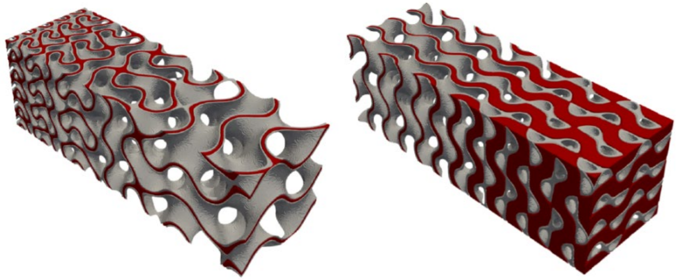
Why Triply Periodic?

- **Compact** – More heat transfer in a smaller form factor, especially important for small reactors.
- **Robust** – Continuously curved intertwined lattice, extremely tolerant of thermal gradients, transients, and vibrations.
- **High Temperature** – AM is one of the most viable methods for ceramics and refractory alloys.
- **Fluid Isolation** – Straightforward to include 3rd domain to isolate incompatible fluids.
- **Manufacturable** – Potential for easier manufacture than chemical-etched diffusion-bonded printed circuit heat exchangers.
- **Hydraulics** – Rather manageable hydraulic resistance, larger open channels less sensitive to small debris, fouling, or build-up.
- **Optimizable** – Math driven AM architecture amendable to optimization via spatial grading
- **Marketable** – Cool looking! The SR-71 of heat exchangers

TPHE (oil cooler for combat helicopters)

Triply Periodic AM Silicon Carbide Lattice





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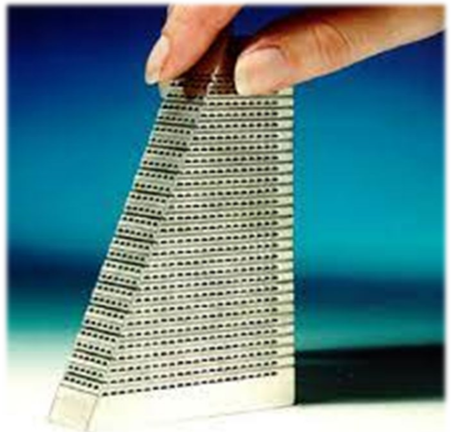
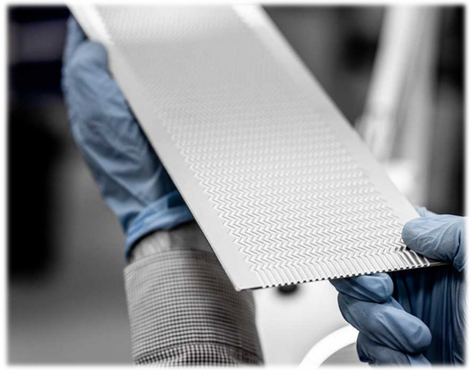
Competition for Compact HX PCHE vs. TPHE

- Printed Circuit Heat Exchangers are currently viewed as the gold standard for compact heat exchangers.
- PCHEs and TPHEs are comparable in compactness and vibration resistance.
- TPHEs are more tolerant of thermal gradients/transients due to their continuously curved 3-D lattice structure.
  - Excellent fluid mixing.
- TPHEs show better resistance to fouling, build-up and plugging.
  - Large interconnected channels.
  - Customize design to reduce pressure drop.
- TPHEs can match or exceed thermal performance of PCHEs.
  - Designs can be tailored to specific thermal/hydraulic needs.





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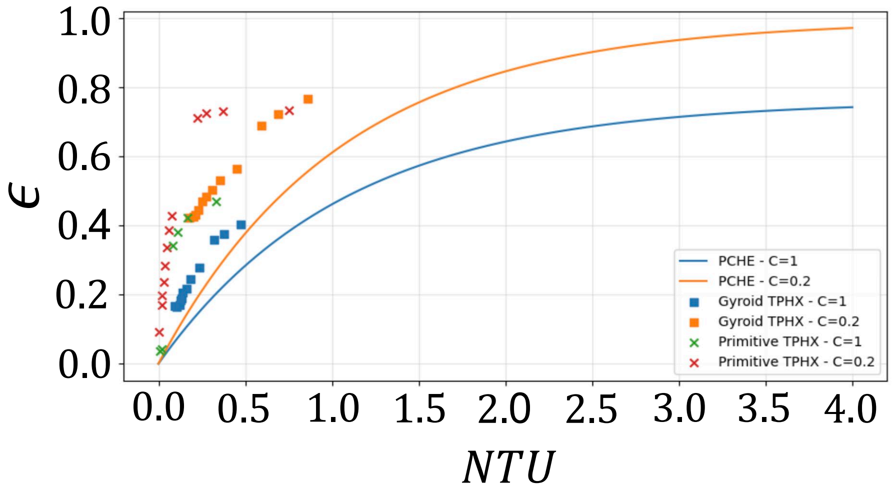
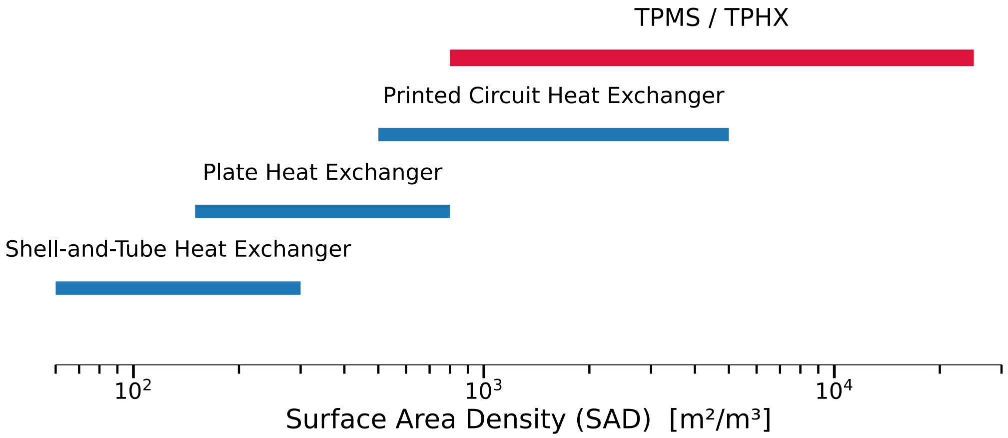
Comparison of PCHE to TPHE

- When compared head-to-head, TPHEs consistently outperform PCHEs.
  - Higher surface area density (same Dh).
  - Lower pressure drop for a given flow geometry.
- The most studied (Schwarz equations) have 15%-120% better heat transfer per pumping power than PCHE.
- Recent research shows that newer types (Fisher-Koch equations) can be 23%-356% better than the highest performing Schwarz structures [1].
- In the advent of AM technology, TPHEs may be easier to manufacture and cheaper over the lifetime of the HX.



Theoretical effectiveness vs number of transfer units for PCHE and TPHE designs. Data from [2]-[3].



Comparison of surface area density for different HX designs, provided from Lorenzo Mazzocco and [3].

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[1] Dharmalingam, Lalith Kannah; Aute, Vikrant; and Ling, Jiazhen, "Review of Triply Periodic Minimal Surface (TPMS) based Heat Exchanger Designs" (2022). International Refrigeration and Air Conditioning Conference. Paper 2393. https://docs.lib.purdue.edu/iracc/2393

[2] Alteneiji, Moza, et al. "Heat transfer effectiveness characteristics maps for additively manufactured TPMS compact heat exchangers." *Energy Storage and Saving* 1.3 (2022): 153-161.

[3] Yoon, Su-Jong, Piyush Sabharwall, and Eung-Soo Kim. *Analytical study on thermal and mechanical design of printed circuit heat exchanger*. No. INL/EXT--13-30047. Idaho National Lab.(INL), Idaho Falls, ID (United States), 2013.

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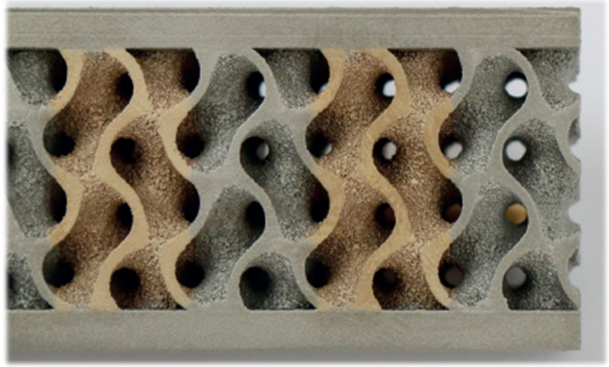
So, what's the catch?

- **New Frontiers (Technology Maturity):**
  - Design, analysis, and testing exist today to create TPHE's, but requires some niche expertise (TPHE's do not yet show up in the heat transfer textbooks)
  - Current commercial options focus on PBF with nickel, iron, or titanium-based alloys
  - Exotic materials require specialized powder, machines and process development.
- **Size Limitations:**
  - Commercial L-PBF machines build chamber.
    - Example Velo Sapphire XC 1MZ 1000 m tall X 600 mm
  - TPHEs much more efficient per volume than conventional heat exchangers, but high capacities will require bigger AM machines or multiple TPHE's
- **AM only beginning to emerge in ASME B&PV Code:**
  - First edition published just over 100 years ago and was only 114 pages long
  - ASME special committee on AM currently creating DED and PBF code cases, goal to include requirements in 2025 edition [2] (probably with some limitations)
  - One could place TPHE's within a wrought/welded vessel as stop gap, or when using non-code materials

Sample 3-domain lattices produced specialized L-PBF process (INL with StarHagen LLC)



Example multi-material L-PBF lattice (Aerosint company)

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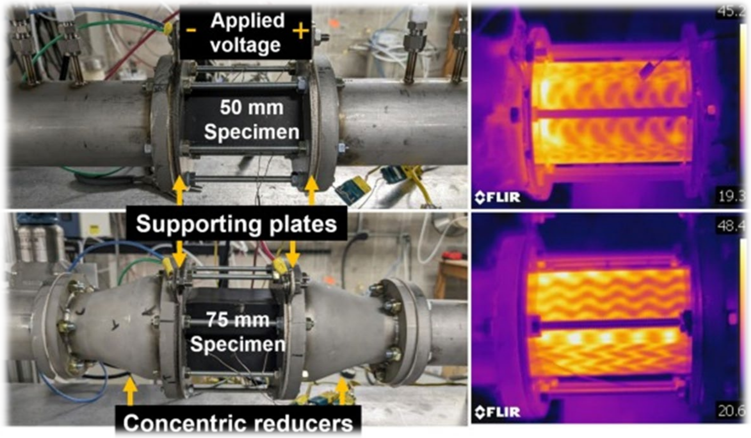
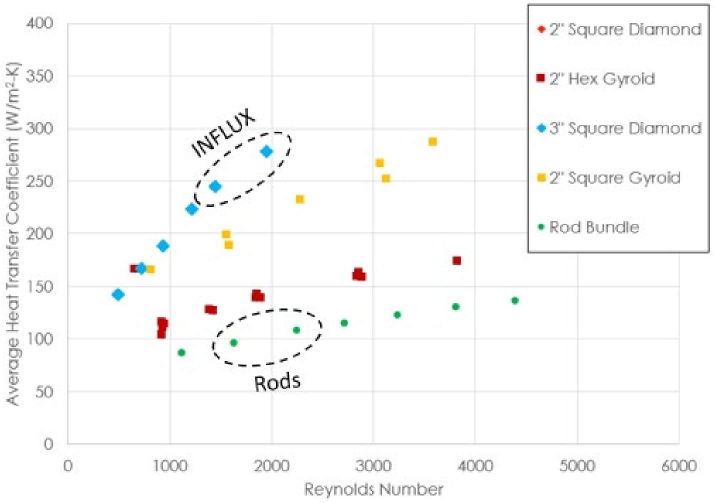
[2] George Rawls and Teresa Melfi, "ASME Additive Manufacturing Codification Workshop on Advanced Manufacturing Technologies for Nuclear Applications" October 26, 2023, Rockville, Maryland

What have we been up to?

- INL has been exploring the use of TPMS geometries for several years now.
- INL awarded 3-year internally funded research project to research biomimicry in advanced heat transfer geometries for nuclear fuel.
  - Research into TPMS geometry as a novel nuclear fuel is actively being funded through the Advanced Fuels Campaign.
- The use of AM nuclear heat exchangers has yet to receive a considerable amount of attention.
- Research collaborations with the University of Wisconsin, MIT, and Oregon State University provided significant contributions to understanding TPMS thermal-hydraulics.
- Developed novel methods to calculate heat transfer in 3-D printed specimen.
  - Created reliable friction factor and Nusselt number correlations.
    - 3x Nusselt number in comparison to rod bundle.
  - Data is limited to lower Reynolds number flows.



Experimental testing facility at the University of Wisconsin.



Average heat transfer coefficients for various TPMS lattices compared to a rod bundle calculated at the University of Wisconsin.

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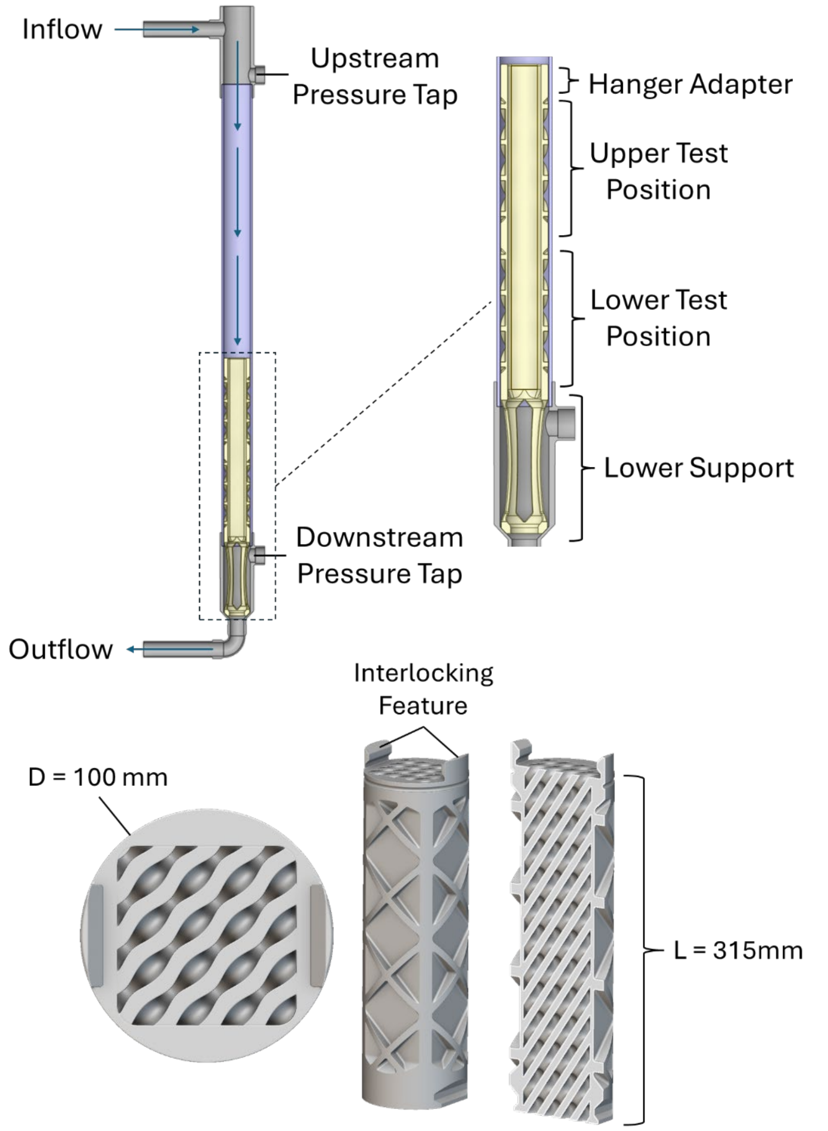
Flowing Loop for INFLUX Pressure Drop (FLIP)

- Current dataset from literature only reaches Reynolds numbers of ~8k.
  - Initial INL test loop (“Home Depot Loop”) was only able to achieved flow rates of ~10gal/min.
- **F**lowing **L**oop for **I**NFLUX **P**ressure Drop (**FLIP**) was designed to bridge the data gap to high Reynolds number flow regimes in TPMS structures.
  - Capable of flow rates up to ~100 gal/min
  - Provide data for pressure drop and friction factors at prototypic reactor conditions (50k for single UC).
  - 4” diameter modular test sections.
- Large axial length allows for detailed interrogation of DP/L correlations.
  - Investigation into “lattice stretching” to reduce pressure drop.



Schematic of the FLIP facility and a 35mm unit cell test article used for testing.

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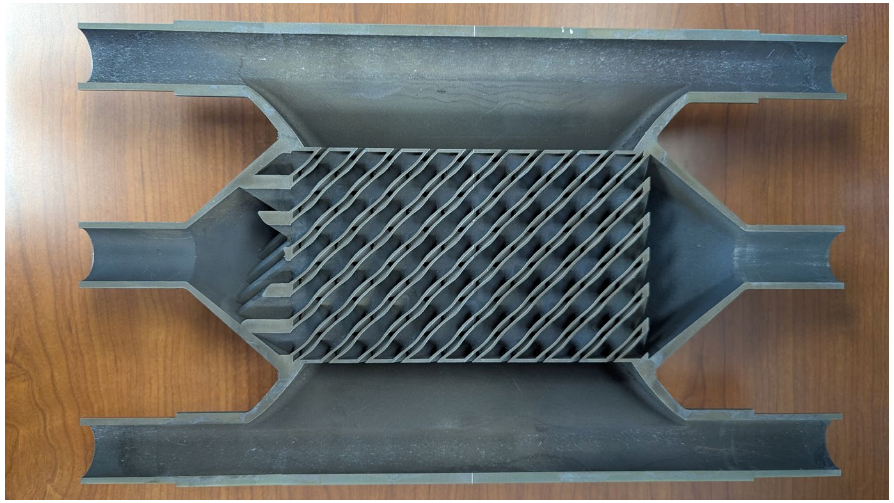
MAGNET Heat Exchanger Test

- The MAGNET facility is a thermal-hydraulic test bed used to facilitate microreactor designs and components.
  - Capable of testing specimens at high temperatures, pressures and flow rates.
  - Instrumented for flow rate, pressure drop and temperature measurements.
- First “real-world” test for TPHEs with prototypic conditions and materials.
  - Preliminary test using 3-D printed Inconel specimen (not optimized, designed to test).
  - Temperature measurements in flow domain, inlet/outlet and total pressure drop.
  - Provides critical baseline for modeling efforts and future.

MAGNET testing facility at INL.



3-D printed Inconel TPHE designed for testing in the MAGNET facility.

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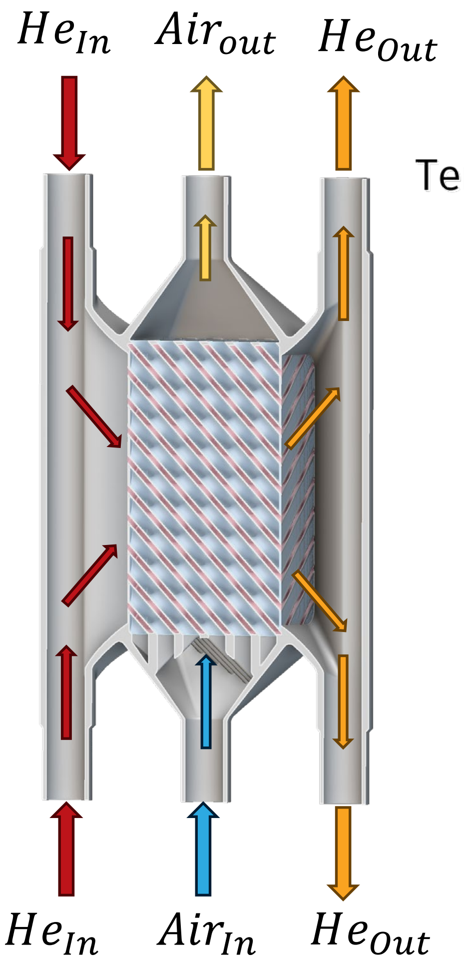
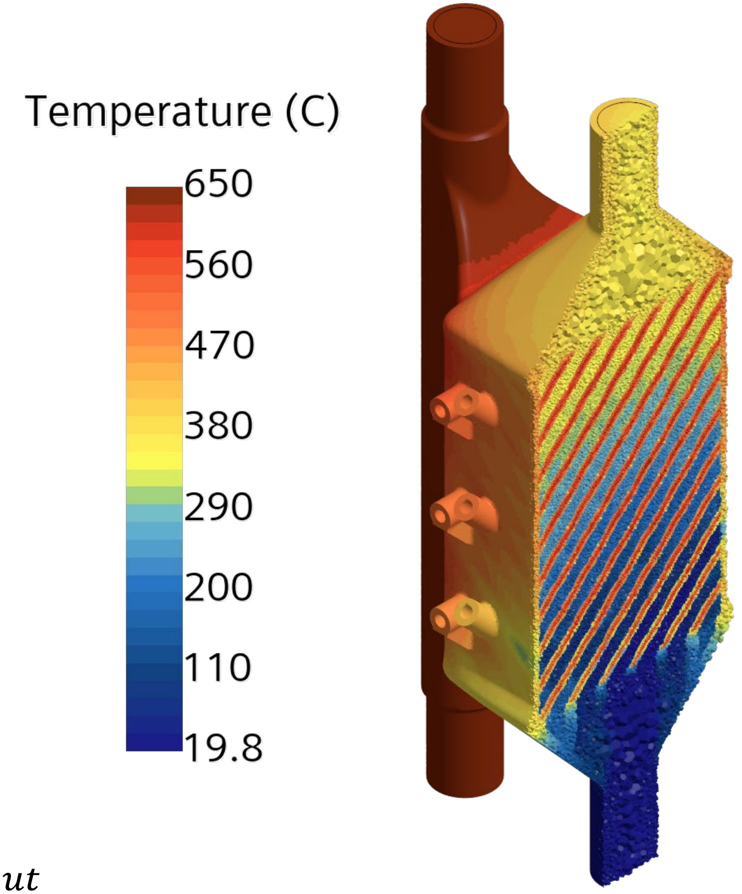
MAGNET Heat Exchanger Test

- Scoping CFD analyses were run for the MAGNET test to determine possible testing conditions.
  - Helium was used for the hot side.
    - $T_{In} = 650°C$
    - $\dot{m}_{He} = 70g/s$
  - Compressed dry air used for the cold side.
    - $T_{In\_Air} = 19.8°C$
    - $\dot{m}_{Air} = 150g/s$

- Heat exchanger efficiency, ϵ, calculated at 56%.
  - Average outlet temperature of the helium side was $501°C$.
  - Average outlet temperature of the air side was $373°C$.



Schematic for the CFD model of the MAGNET test.



Preliminary temperature results from the CFD model of the MAGNET test at expected conditions.

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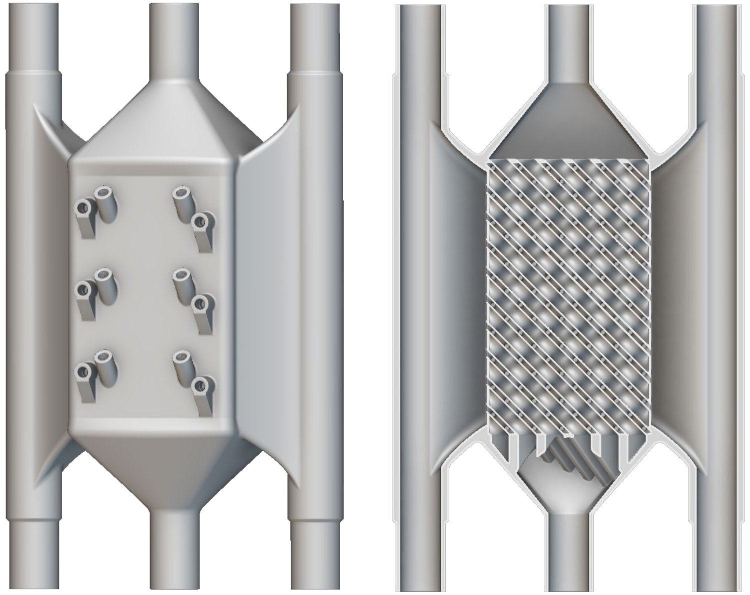
Ongoing and Upcoming work at INL

- Research on TPHEs is expected to ramp up in the coming FY.
  - **1st Quarter of FY-26:**
    - Heat exchanger testing in MAGNET.
  - **2nd- 4th Quarter of FY-26:**
    - Design and optimization studies on TPHE for microreactor application.
    - Fabrication studies on TPHE for microreactor applications.
    - Comparison case study with HTGR-style microreactor.
  - **1st Quarter FY-27:**
    - Fabricate optimized TPHE.
  - **2nd Quarter FY27:**
    - Test optimized microreactor TPHE in MAGNET.

- Ongoing research on TPMS geometries as novel fuel form through the Advanced Fuels Campaign.



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