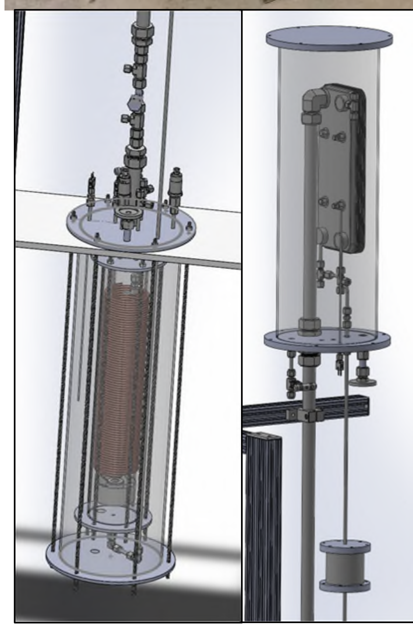
Recent Advancements

- **System-Level SWaP Optimization**: Transitioned from idealized thermodynamic modeling to scale-agnostic sizing routines that prioritize power-to-weight ratios (kW/kg) over simple thermal efficiency.
- **Direct-Heating Architecture Evolution**: Documented a strategic pivot from indirectly-heated cycles to directly-integrated scavenging architectures, significantly reducing total system volume and mass for high-power (10's to 100's of kWe) applications.
- **Zeotropic Mixture Characterization**: Successfully developed a high-accuracy experimental methodology to map the enthalpy changes of sCO_2-zeotropic mixtures, moving beyond theoretical libraries to empirical validation in the near-critical region.
- **Multi-Domain Validation Frameworks**: Advanced the capability to predict localized heat transfer coefficients and pressure drops under transient conditions, enabling the identification of stable operating envelopes for compact heat exchangers.
- **HTD Predictive Capability**: Developed advanced modeling and experimental frameworks to identify safe operating envelopes by predicting the onset of Heat Transfer Deterioration (HTD) near the critical point under dynamic conditions.
- **High-Power Scaling Validation**: Verified internal component sizing models against industrial benchmarks to ensure accuracy when scaling from kilowatt-level laboratory experiments to multi-megawatt aircraft-scale requirements.

Facilities

Currently at AFRL

- A precision controlled rotating table capable of inducing 15 G+ of dynamic gravitational loads
  - Investigate the multi-physics behavior of sCO_2 under dynamic acceleration. This allows researchers to empirically observe Heat Transfer Deterioration (HTD) and buoyancy effects that are critical for maneuvering high-speed platforms.
- A custom, vacuum-insulated flow calorimeter
  - Empirically measure the thermodynamic properties and enthalpy changes of sCO_2-zeotropic mixtures with high precision. It provides a high-fidelity "ground truth" to validate REFPROP predictions and characterize complex phase behavior near the critical point.



In Development

- High-Pressure Recapture Blowdown Facility
  - A specialized test cell focused on the thermomechanical characterization of sCO_2 subsystems. Unlike traditional open-loop facilities, this system integrates a closed-loop fluid recovery system, allowing for the sustainable evaluation of complex, expensive zeotropic mixtures without atmospheric venting.
- Modular Hardware-in-the-Loop Integration
  - Infrastructure designed to support the testing of subscale, university-developed components such as microtube heat exchangers or compact turbomachinery within representative high-pressure flow environments.

Proposed Future Opportunity

- High-Performance Brayton Cycle Emulator
  - A facility capable of inputting megawatt-level thermal power at very high turbine inlet temperatures and pressures. This infrastructure would be optimized for characterizing flight-like, compact energy conversion hardware rather than stationary terrestrial systems, providing the high-energy density environment necessary for de-risking advanced aerospace power and thermal subsystems.

Collaboration Topics: The Path to Weight-Agnostic Energy Scavenging

- **Advanced Material Science (Seals & Compatibility)**: Investigating long-term chemical and mechanical interactions between CO_2 and supercritical zeotropic mixtures and advanced polymers, elastomers, or metallurgy, especially at elevated temperatures and pressures. University microscopic analysis coupled with AFRL high-pressure/temperature test environments can establish critical compatibility maps for bearings and seals.
- **Thermophysical Characterization of Zeotropes**: Empirical mapping of enthalpy changes, phase behavior, and transport properties including density, viscosity, and thermal conductivity for CO2 mixtures near the critical point. Data generated via facilities like the flow calorimeter can validate university-led development of next-generation Equations of State to improve modeling accuracy for heat exchanger and turbine/compressor designs where traditional libraries currently fail.
- **Flight-Weight Heat Exchanger Architectures**: Designing and testing advanced structures, such as microtubes or additive-manufactured fractal geometries, to maximize heat transfer density and/or conformal shapes to maximize heat transfer density and volumetric integration. This research focuses on minimizing wall thicknesses to the limits of structural feasibility to maximize SWaP and minimize weight. These efforts aim to move beyond rigid "off-the-shelf" industrial components to minimize mass and optimize the internal spatial envelope for high-power systems.
- **Dynamic Modeling & Charge Management**: Developing control algorithms and fluid management systems capable of active "charge management" to facilitate the real-time adjustment of working fluid inventory. This research addresses the critical need for system stability and resiliency during rapid fluctuations in thermal load or ambient conditions, where supercritical fluid properties exhibit highly non-linear behavior.
- **System-Level Multi-Domain Analysis**: Extending modeling toolsets to evaluate a wide array of systems and operating conditions, identifying the specific "break-points" where active cycles outperform discrete energy storage or alternative power generation and thermal management technologies.