FHR Benchmarking Workshop 2

Integral Effects Test (IET) Research Program

Mohamed Abou Dbai (UW), Karl Britsch (UW),
James Kendrick (UCB), Christopher Poresky (UCB)

Clark Kerr Campus; April 14, 2016

Overview

1. FHR IET Program Purpose
2. IET Background
3. UCB Progress and Plans
4. UW Progress and Plans
5. Benchmarking Strategies
6. Looking Forward: TMSR

FHR IET Program Purpose

Develop understanding and competence in SETs and IETs for FHR research

Verify and validate evaluation models that can be used for FHR design and analysis

Support understanding of FHR performance under licensing basis events of concern to the NRC for licensing

Ultimately: To Commercialize

IET Background

Purpose of IETs:

- **Reproduce the integral behavior of the system of interest under a wide range of initial and boundary conditions**
- **Produce test data to compare against evaluation model results for the scaled system**

Examples from OSU:

- **Advanced Plant Experimental (APEX) Facility**
- **Multi-Application Small Light Water Reactor (MASLWR)**

MASLWR Facility at OSU

IET Background

Discussion Points:

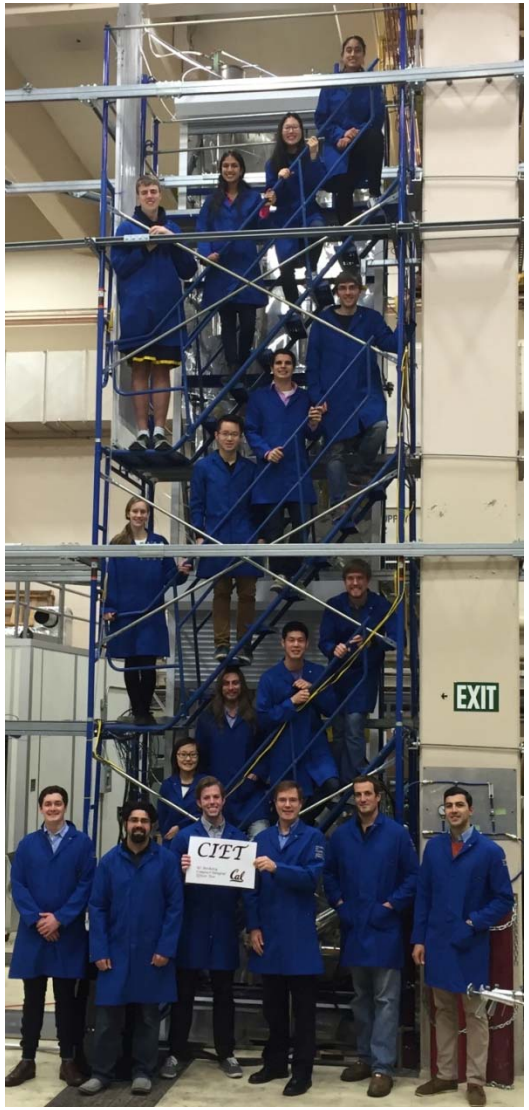
Is this the best direction for IET development within this IRP to support FHR/MSR understanding and development?

Can IETs be useful in other areas of FHR/MSR research? Training facility for personnel? Etc.?

Is there something missing that is restricting progress or limiting the application of IET research?

UCB Progress and Plans

Compact Integral Effects Test (CIET 1.0) Facility



Progress:

- Completed basic steady-state natural circulation validation for single- and coupled-loop configurations
- Completed basic steady-state power step change validation for single-loop configuration
- Preliminary results for Loss-of-Forced-Circulation transient scenario verification and validation

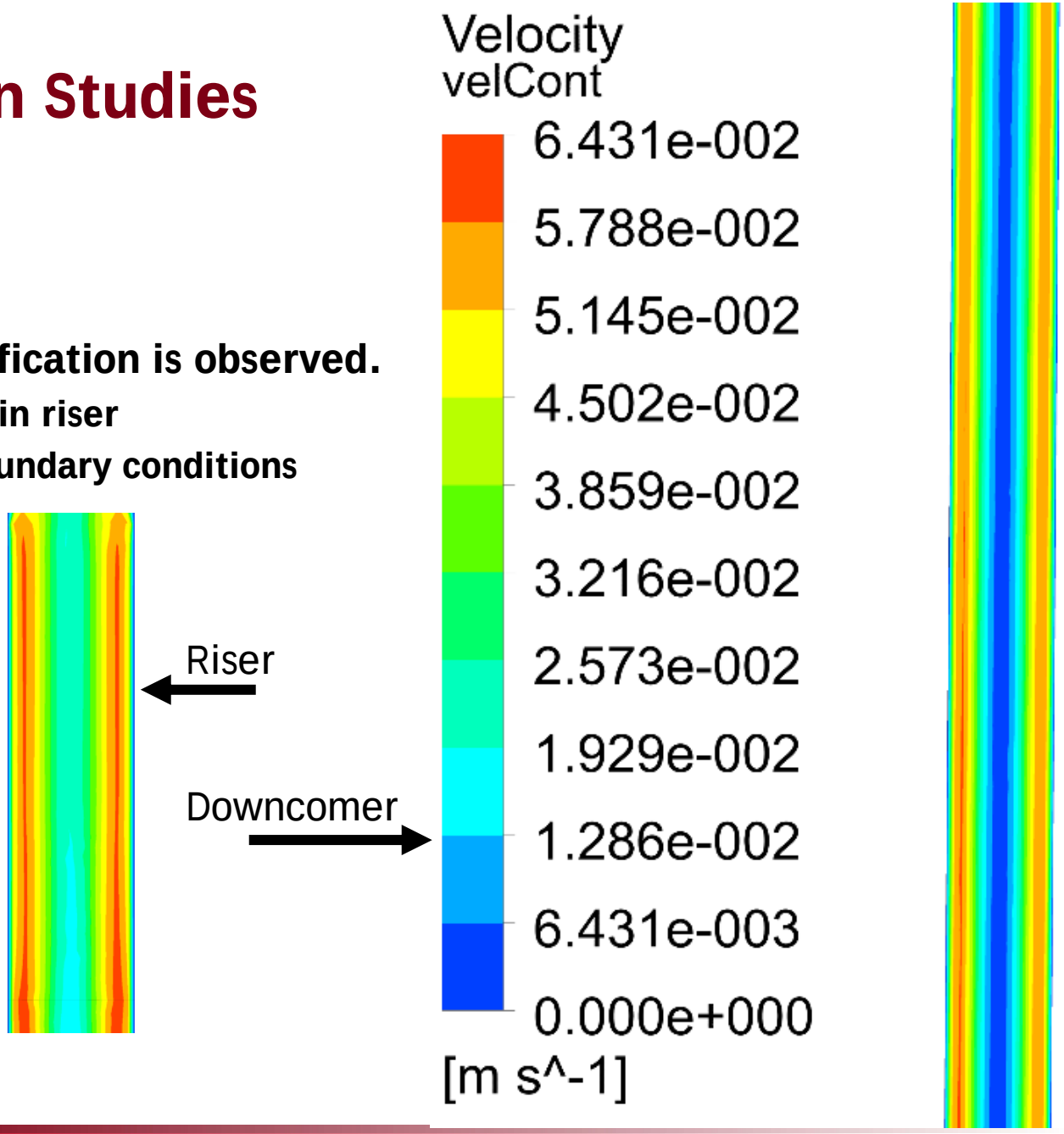
Plans:

- Upgrade instrumentation and control system for dynamic inputs (controlled oscillation, reactor dynamic models, power conversion models)
- Complete Loss-of-Forced-Circulation and Loss-of-Heat-Sink scenario verification and validation

Flow Loop Design Studies

CFD Simulation

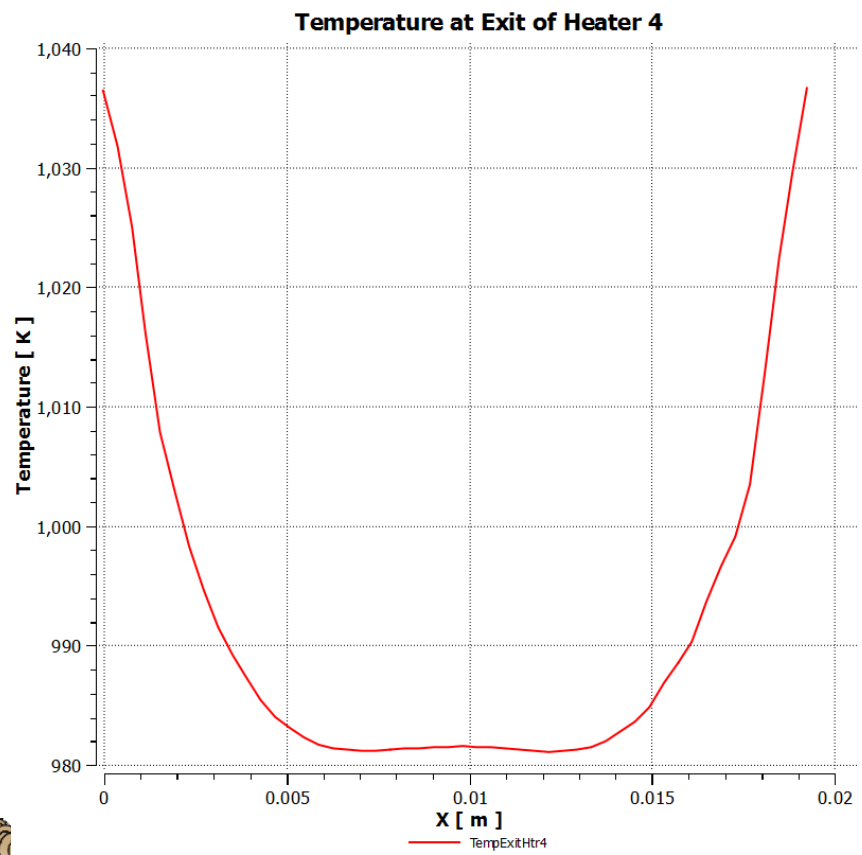
- **2D, Steady state**
- **Significant flow stratification is observed.**
  - **Potential back flow in riser**
  - **Dependent upon boundary conditions**
    - » **Temperature**
    - » **Heat flux**

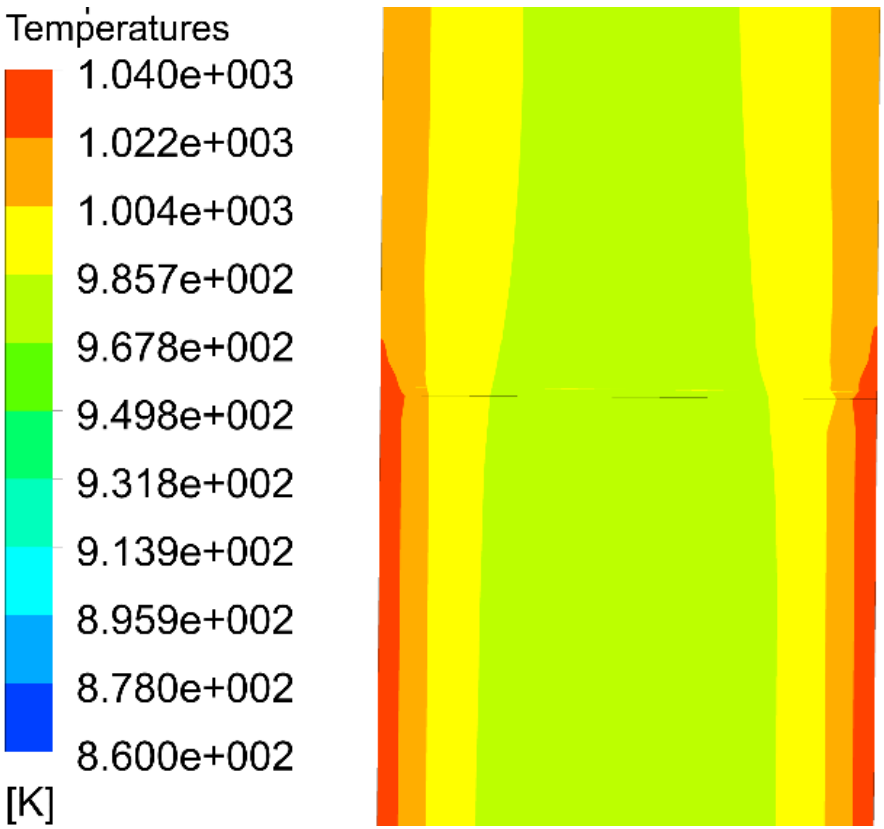


Flow Loop Design Studies

- **Large Temperature gradient also observed**
  - **Tube ID: 0.76 inches**
  - **Salt has poor thermal conductivity and large heat capacity but this seems extreme**

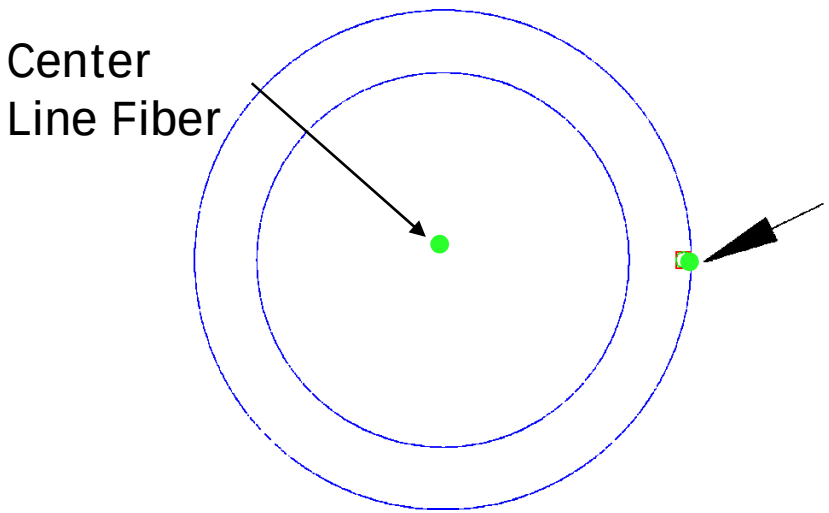
- Is this important to FHR?
- If so, what need we measure?

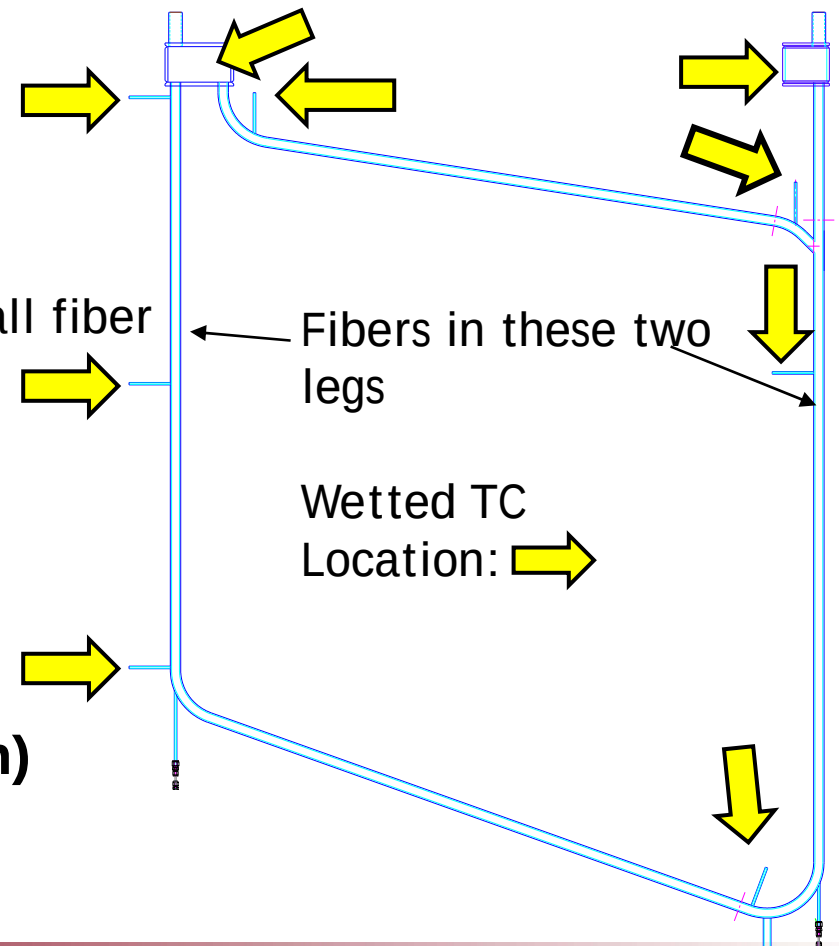




Measurement Capabilities

- **Wetted Thermocouples**
  - **Accuracy may be as low as ± 10 ℃**
- **Fiber-optic temperature sensors down outside of wall and pipe centerline**





- **Redox with UW Probe (corrosion)**
- **Time**

Discussion Points

- **How can the TH measurements from the flow loop be put to best use for the FHR project?**
  - **Particular tests we can run?**
  - **Particular measurements we need to take?**
  - **Is there interest in scaling this loop to oils? If so, are additional experiments needed?**

- **In the limited time available before corrosion testing, what sorts of tests should be prioritized vs. what would be nice to have if there is enough time?**

UW Progress and Plans

Progress:

- **Verification of a simple natural circulation loop model in COMSOL Multiphysics that uses FLiBe as the coolant with temperature-dependent thermo-physical properties**
- **Preliminary results for a 1-D linear stability analysis on the natural circulation loop**

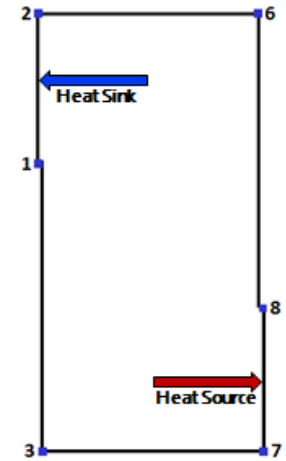
Plans:

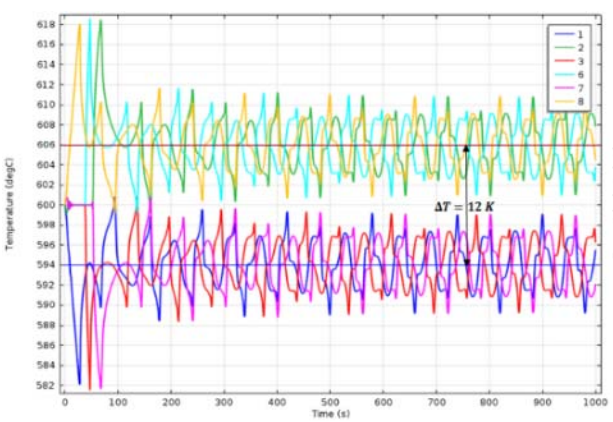
- **Continue the work on the stability behavior of a single-phase molten salt natural circulation loop**
- **Include the effect of freezing in the stability analysis of the natural circulation**
- **Present different transient scenarios for the benchmarking studies of the CIET facility (startup/shutdown, power step changes, loss of forced cooling)**

Natural Circulation Loop Model in COMSOL

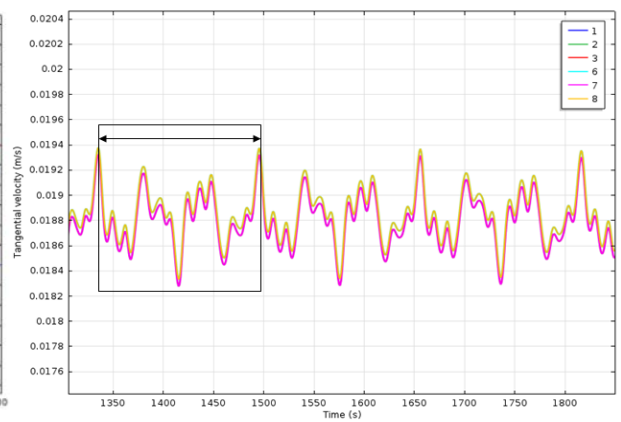
COMSOL Simulations

- 1-D, Transient study
- Boundary conditions: uniform heat flux at the cooled and heated regions
- System reaches a periodic-steady-state condition
  - The period is equal to the time it takes for the salt to complete one loop
- Changing the boundary condition at the cooled region to a constant convective boundary condition has an attenuating effect on the cyclic behavior of the flow/temperature in the system

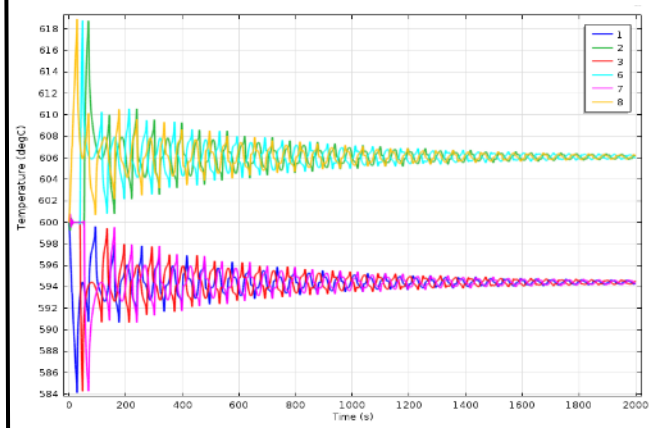




Temperature versus time



Velocity versus time



Temperature versus time

Scaling Analysis for the Freezing of Liquid Inside a Pipe

From the thermal energy balance equations on the flow inside the pipe, the solid layer and the solid-liquid interface, the following scaling arguments are identified for the scaling analysis of the freezing of liquid inside a pipe

- **Boundary and initial conditions: constant pipe wall heat flux, inlet temperature, and velocity**

Table 1: Non-dimensional quantities

Parameter	Expression
Reynolds	$Re = \frac{2\rho_L \bar{u}_o R}{\mu}$
Prandtl	$Pr = \frac{c_L \mu}{k_L}$
Stefan	$Ste = \frac{c_S(T_o - T_f)}{H_f}$
Heat Flux Parameter	$\Pi_Q = \frac{\dot{q}''_w}{k_S(T_o - T_f)/R}$
Thermal Conductivity Ratio	$\Pi_k = \frac{k_L}{k_S}$
Aspect Ratio	$\Pi_R = \frac{R}{L}$

Table 2: Mk1 design parameters for a single tube for CTAH, DHX and TCHX

Parameter	CTAH	DHX	TCHX	Unit
Minimum Temperature	600	526	526	°C
Mass Flow Rate	0.0351	0.0121	0.051	kg/s
Inlet Velocity	1.08	0.0641	0.27	m/s
Inside Diameter	0.00457	0.0109	0.0109	m
Tube Length	18.47	24.0	24.0	m
Pipe Wall Heat Flux	25.37	24.08	10.54	kW/m^2
Reynolds	1189	119.0	500.5	-
Prandtl	18.64	27.88	27.88	-
Stefan	0.452	0.215	0.215	-
Reynolds at freezing point	562.9	81.38	342.2	-
Ptandtl at freezing point	42.15	42.15	42.15	-

Discussion Points

- **For our 1-D NC model, what transient scenarios can we investigate with our model that are applicable to the benchmarking studies of the CIET facility? (For example, heat input step changes, loss of forced cooling)**

- **For our NC stability studies, how the 1-D model can be extended to relax some of the assumptions, for example, consideration for a mixed boundary condition (radiation and convection)?**

- **For our freezing studies, where can we find the temperature-dependent thermo-physical properties (k, c_p, ρ, μ, H_f) for FLiBe and FLiNaK at and near their freezing points?**

UW/OSU/SINAP Progress and Plans

UW: Natural circulation flibe test loop

OSU: DRACS test facilities

SINAP: Multiple salt loops, TMSR-SF0

Benchmarking Strategies

Is there something missing that is restricting progress or limiting the application of IET research?

Are there aspects of one facility that can be complementary to another facility?

Can results from different studies be compared with one another?

What PIRT exercises are needed? How can this be coordinated with the Georgia Tech IRP?

What modeling tools and codes need to be benchmarked?

Looking Forward: SINAP TMSR

For what modes of operation and scenarios should the evaluation models be verified and validated in advance of TMSR-SF0? In advance of TMSR-SF1?

Are there other experimental facilities (IETs) needed for TMSR modeling and study?

- **Are scaled, simulant fluid loops needed?**

Thank you for your attention!