UC BERKELEY NUCLEAR ENGINEERING Thermal Hydraulics Laboratory

FHR and MSR Thermal Hydraulics Research at UC Berkeley


12-Unit Mk1 PB-FHR Site

ORNL MSR Workshop
Per Peterson, UC Berkeley
October 5, 2016

NUCLEAR TECHNOLOGY INNOVATION LABORATORY
University of California, Berkeley

NEUP Nuclear Energy University Programs
U.S. Department of Energy

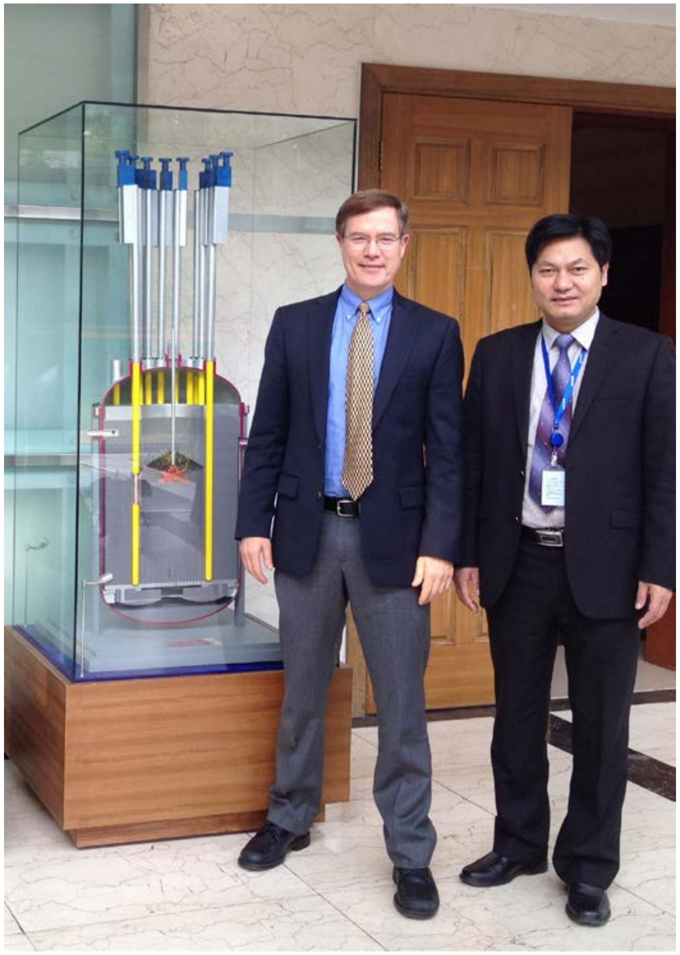
Overview: Simulant fluid TH experiments

- Thermal hydraulics experiments with simulant fluids have important advantages.
  - Low temperatures and ability to use transparent structural materials allows very high fidelity experimental measurements with simulant fluids
  - Experiments can be constructed rapidly and at low cost
  - Key issues involve validating principals of similitude and identifying/quantifying sources of distortion
- Examples presented here:
  - Granular flows of pebble beds: Pebble Recirculation Experiments (PREX)
  - Separate effect tests for convective heat transfer: PB-HTX
  - Integral effect tests: Compact Integral Effects Test (CIET)

Pebble Recirculation Experiments (PREX)

Early scaled experiments in 2006 confirmed ability to recirculate pebbles in FHRs

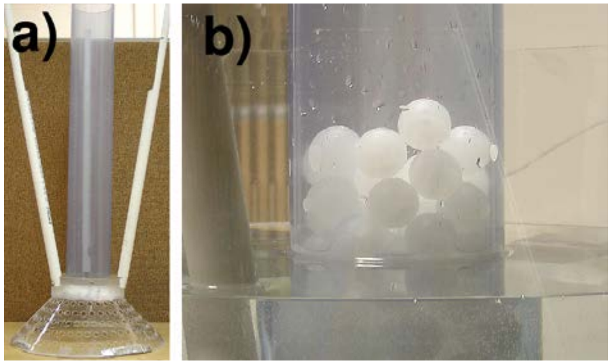
2006: UCB Pebble Recirculation Experiment (PREX)



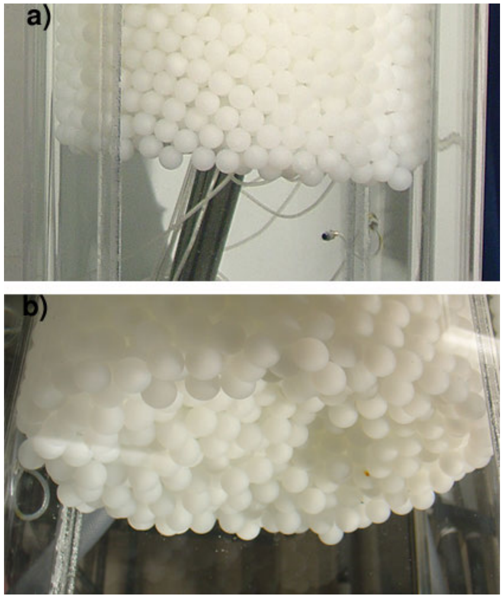
2014: Model for SINAP 10-MW TMSR-SF1 Test Reactor

PREX-1 studied key issues for pebble recirculation

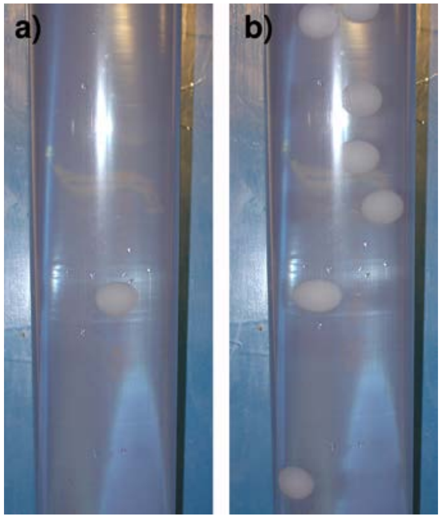
PREX-1, 8300 pebbles



Scaled defueling chute

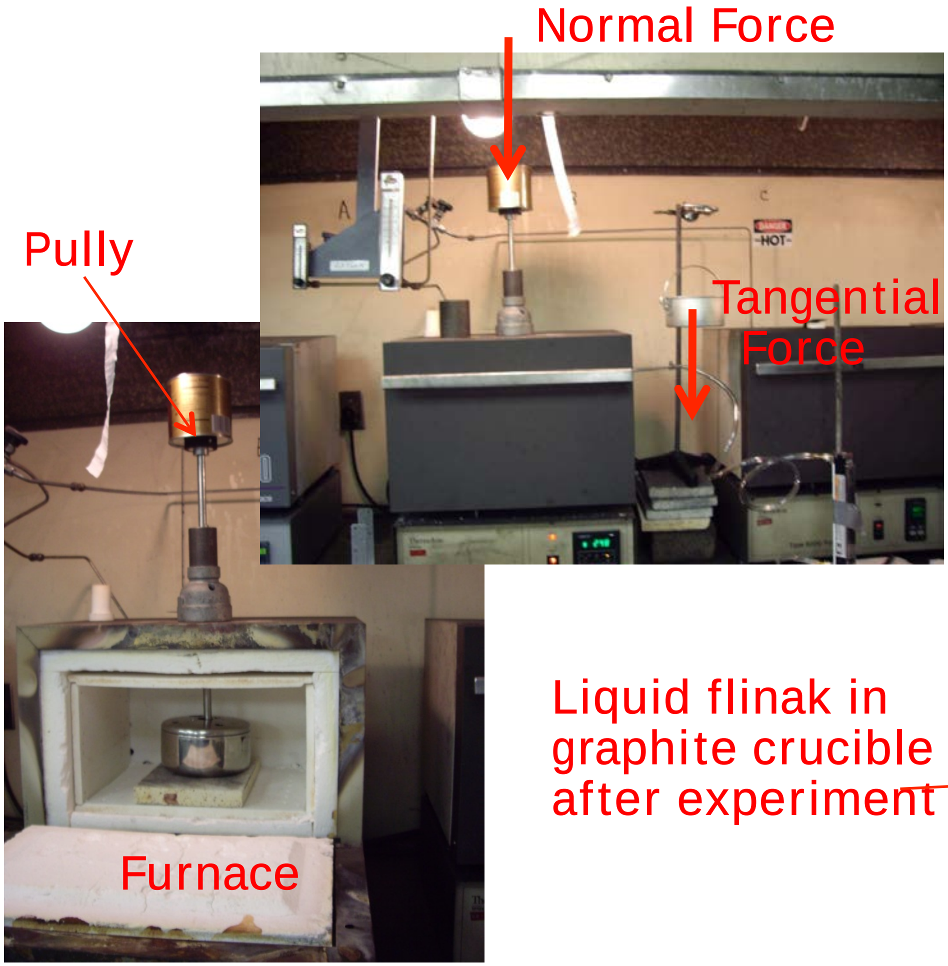


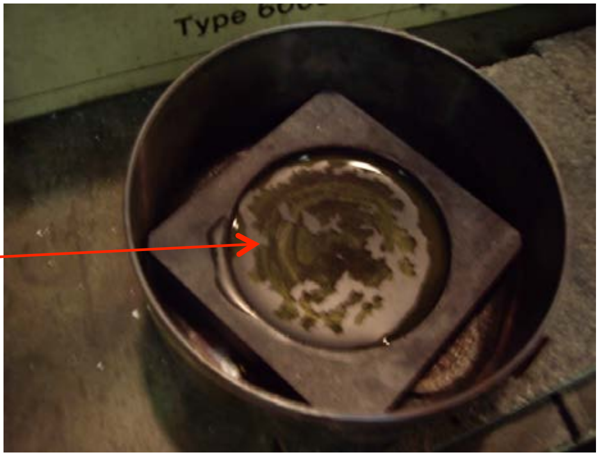
Pebble bed bottom



Pebbles injected and carried downward in cold leg

Validating similitude of friction coefficients required testing with molten salt





Friction coefficient measurement with flinak (simulant for flibe)

Credit: Patrick Purcell, 2009 NE 170 senior design class

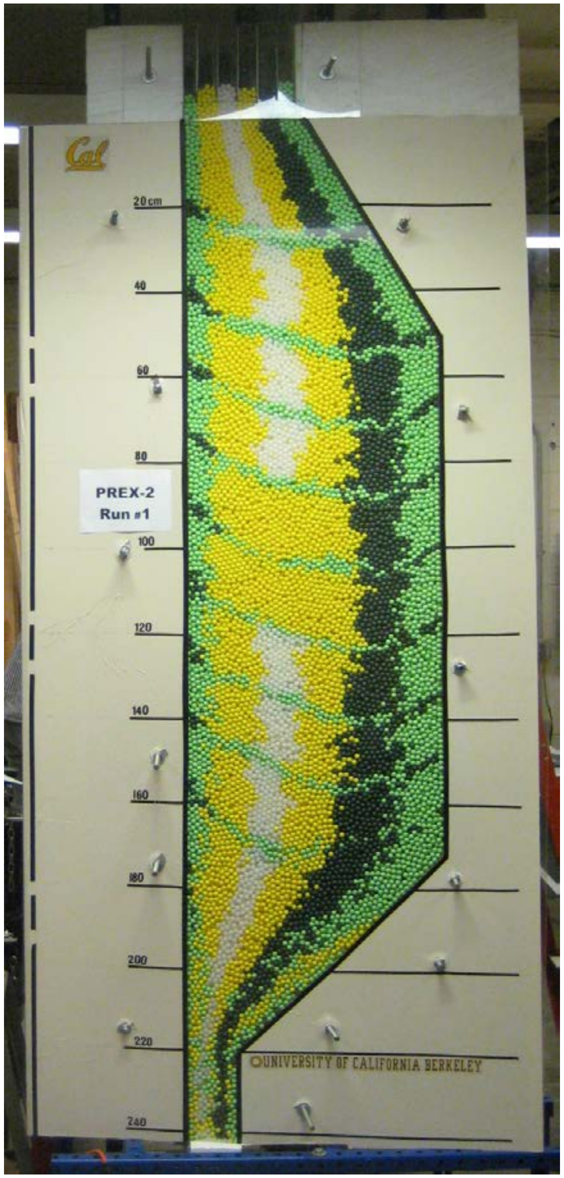
Graphite pebble friction measurement results

Temperature (°C)	Normal Mass (kg)	μ_d	μ_s
492	.915	.237	.273
	1.39	.190	.256
	1.86	.180	.253
525	.915	.224	.260
	1.39	.189	.253
	1.86	.182	.255
559	.915	.215	.251
	1.39	.187	.251
	1.86	.177	.250

- Friction coefficients are reduced to less than half that measured for dry helium operating conditions prior to flinak addition
- Compare to friction coefficient for HDPE on acrylic with water lubrication, ~0.3

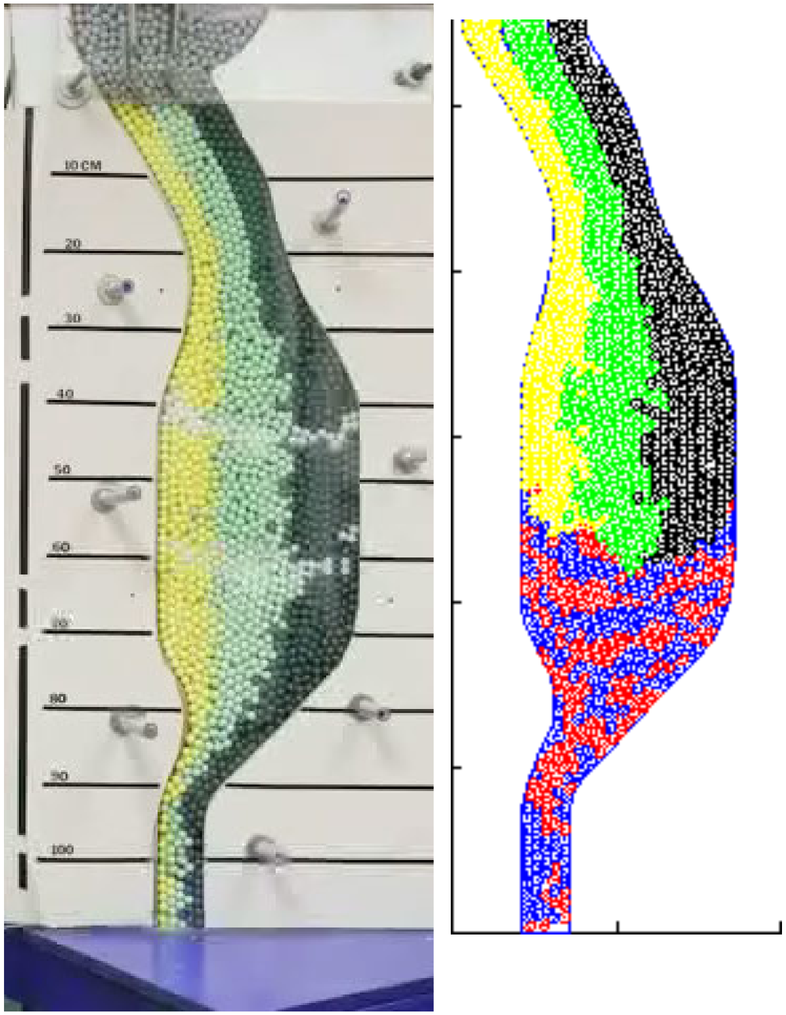
PREX-2 (dry) confirmed radial zoning capability

- 15° sector PREX-2 experiment simulating 900-MWth annular core
  - 129,840 colored 1.28-cm diameter HDPE pebbles in 15° sector
  - Average of 9460 + 1260 pebbles in each axial layer
- For simplicity PREX-2 was a dry experiment (unlike PREX-1), so pebbles are added to the top of the core and removed from the bottom
  - Hydrodynamic forces on pebbles neglected; were studied in PREX 3.1



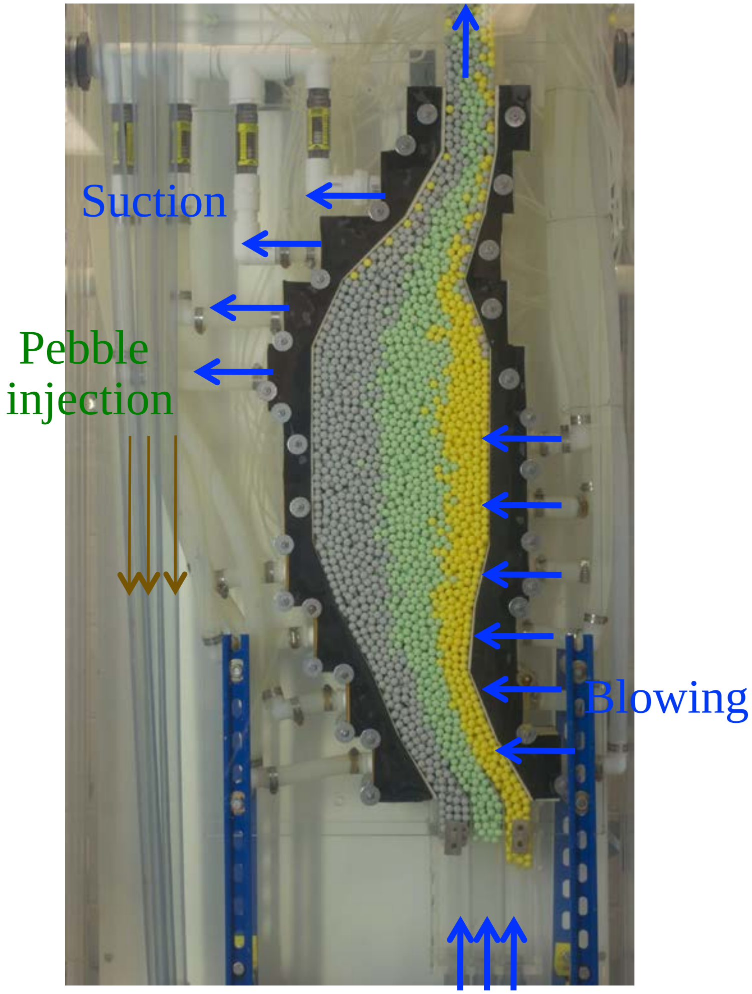
PREX-2 Run#1

PREX 3.0



Dry experimental/simulation demonstration for radially-zoned pebble motion

PREX 3.1

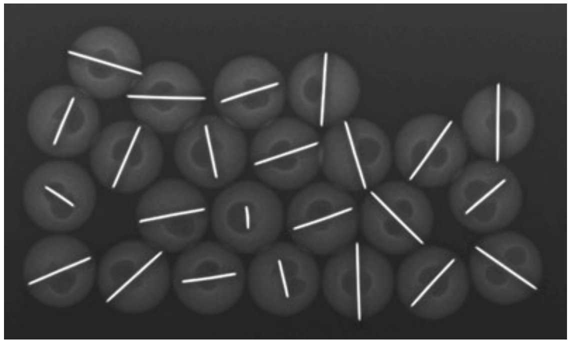


Wet experiment scaled to match Re and Fr

X-PREX now enables x-ray tomography for granular flow of packed sphere beds

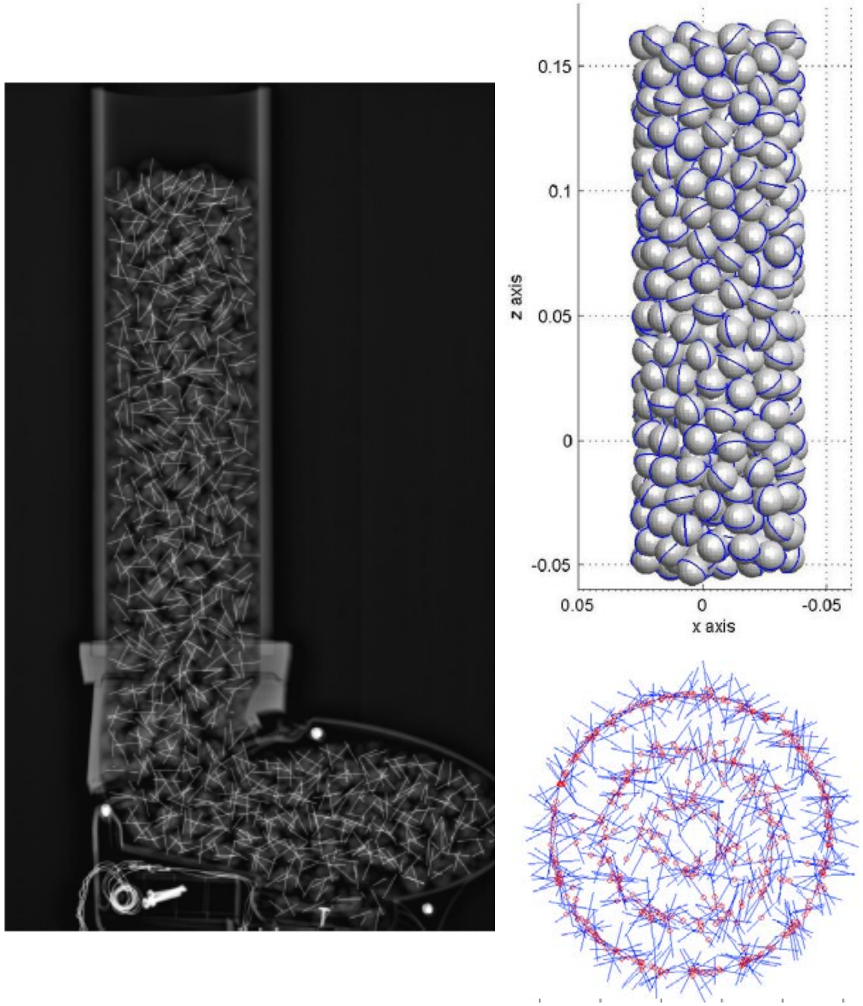
- X-Ray Pebble Bed Recirculation Experiment (X-PREX) research objective:
  - Generate validation data for discrete element simulations (DEM) for slow, dense granular flow
- Instrumented polypropylene pebbles with tungsten wire inserts
- Digital x-ray tomography will generate translation and rotation motion data for ALL pebbles

X-PREX Facility

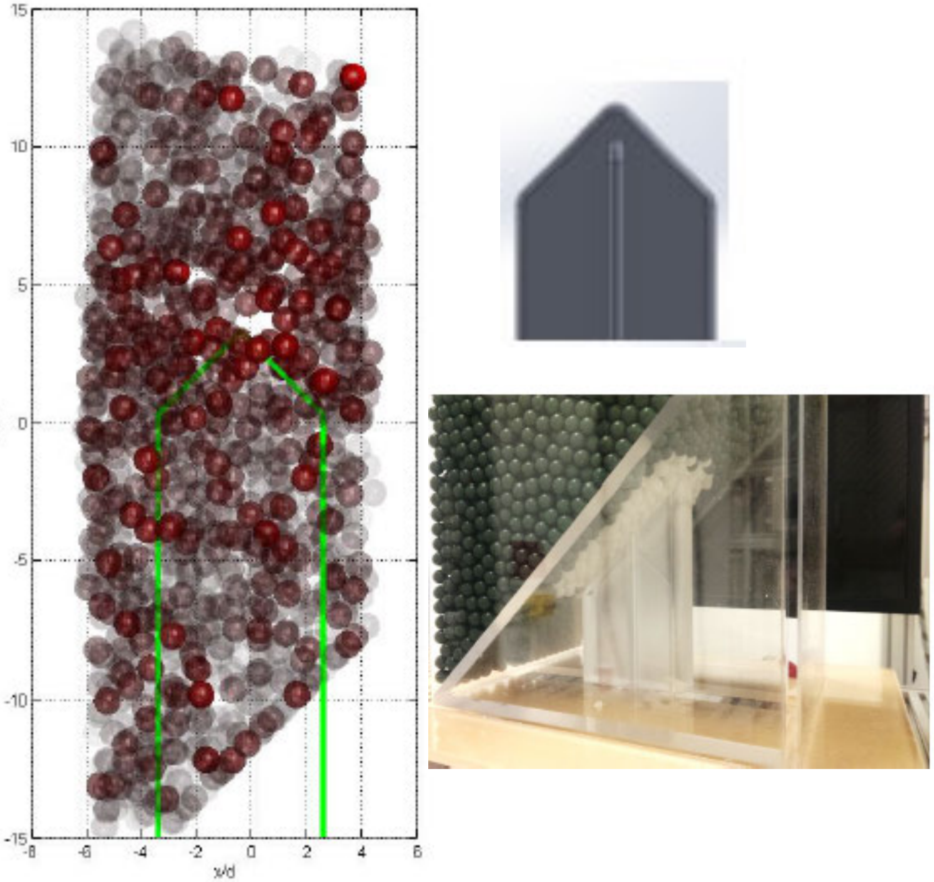


X-Ray Image of Pebbles with Wire Insert

Example X-PREX results



Defueling Chute
Channel Flow



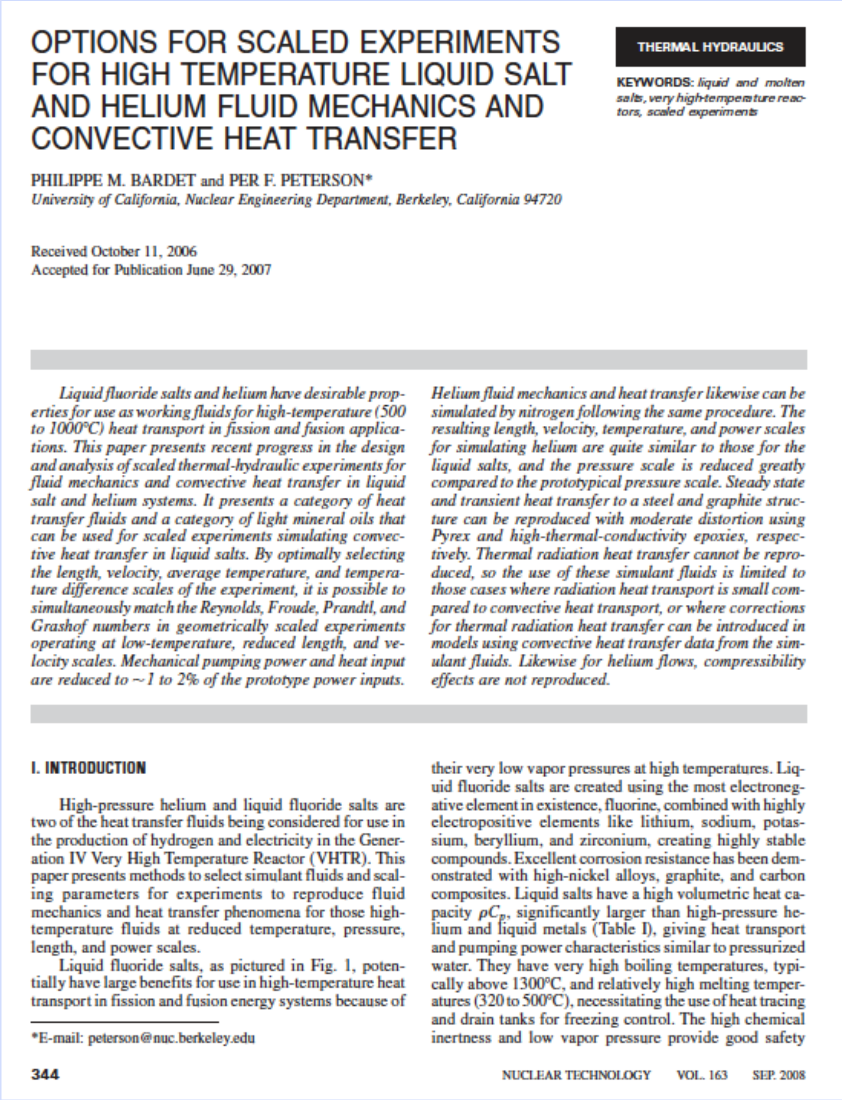
Control Blade Insertion in
Pebble Bed

FHR Separate Effects Tests

A few examples

The similitude of convective heat transfer in oil and molten salts was discovered in 2005

- Reynolds, Froude, Prandtl, and Grashof numbers can be matched simultaneously.
- Mechanical pumping power and heat input reduced to 1 to 2% of prototype power inputs.



OPTIONS FOR SCALED EXPERIMENTS FOR HIGH TEMPERATURE LIQUID SALT AND HELIUM FLUID MECHANICS AND CONVECTIVE HEAT TRANSFER

THERMAL HYDRAULICS

KEYWORDS: *liquid and molten salts, very high-temperature reactors, scaled experiments*

PHILIPPE M. BARDET and PER F. PETERSON*
University of California, Nuclear Engineering Department, Berkeley, California 94720

Received October 11, 2006
Accepted for Publication June 29, 2007

Liquid fluoride salts and helium have desirable properties for use as working fluids for high-temperature (500 to 1000°C) heat transport in fission and fusion applications. This paper presents recent progress in the design and analysis of scaled thermal-hydraulic experiments for fluid mechanics and convective heat transfer in liquid salt and helium systems. It presents a category of heat transfer fluids and a category of light mineral oils that can be used for scaled experiments simulating convective heat transfer in liquid salts. By optimally selecting the length, velocity, average temperature, and temperature difference scales of the experiment, it is possible to simultaneously match the Reynolds, Froude, Prandtl, and Grashof numbers in geometrically scaled experiments operating at low-temperature, reduced length, and velocity scales. Mechanical pumping power and heat input are reduced to ~1 to 2% of the prototype power inputs.

Helium fluid mechanics and heat transfer likewise can be simulated by nitrogen following the same procedure. The resulting length, velocity, temperature, and power scales for simulating helium are quite similar to those for the liquid salts, and the pressure scale is reduced greatly compared to the prototypical pressure scale. Steady state and transient heat transfer to a steel and graphite structure can be reproduced with moderate distortion using Pyrex and high-thermal-conductivity epoxies, respectively. Thermal radiation heat transfer cannot be reproduced, so the use of these simulant fluids is limited to those cases where radiation heat transport is small compared to convective heat transport, or where corrections for thermal radiation heat transfer can be introduced in models using convective heat transfer data from the simulant fluids. Likewise for helium flows, compressibility effects are not reproduced.

I. INTRODUCTION

High-pressure helium and liquid fluoride salts are two of the heat transfer fluids being considered for use in the production of hydrogen and electricity in the Generation IV Very High Temperature Reactor (VHTR). This paper presents methods to select simulant fluids and scaling parameters for experiments to reproduce fluid mechanics and heat transfer phenomena for those high-temperature fluids at reduced temperature, pressure, length, and power scales.

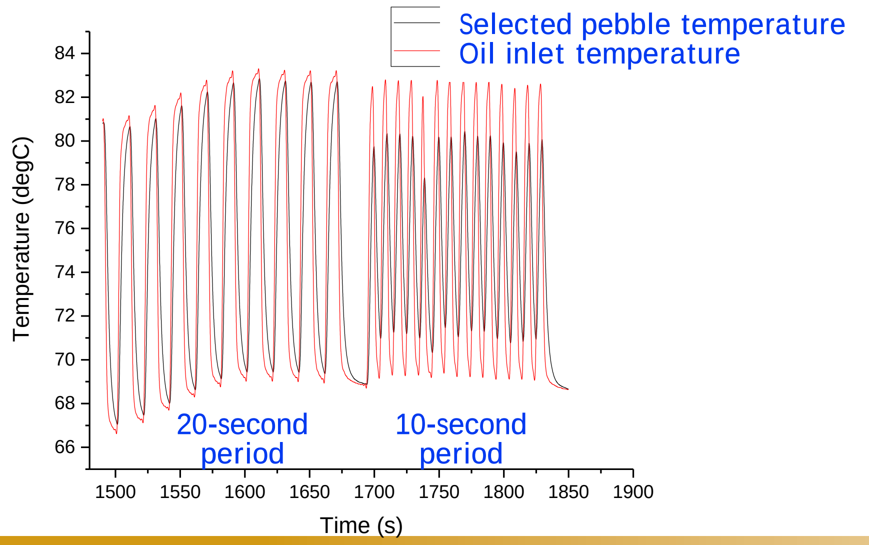
Liquid fluoride salts, as pictured in Fig. 1, potentially have large benefits for use in high-temperature heat transport in fission and fusion energy systems because of their very low vapor pressures at high temperatures. Liquid fluoride salts are created using the most electronegative element in existence, fluorine, combined with highly electropositive elements like lithium, sodium, potassium, beryllium, and zirconium, creating highly stable compounds. Excellent corrosion resistance has been demonstrated with high-nickel alloys, graphite, and carbon composites. Liquid salts have a high volumetric heat capacity ρC_p, significantly larger than high-pressure helium and liquid metals (Table I), giving heat transport and pumping power characteristics similar to pressurized water. They have very high boiling temperatures, typically above 1300°C, and relatively high melting temperatures (320 to 500°C), necessitating the use of heat tracing and drain tanks for freezing control. The high chemical inertness and low vapor pressure provide good safety

---

*E-mail: peterson@nuc.berkeley.edu

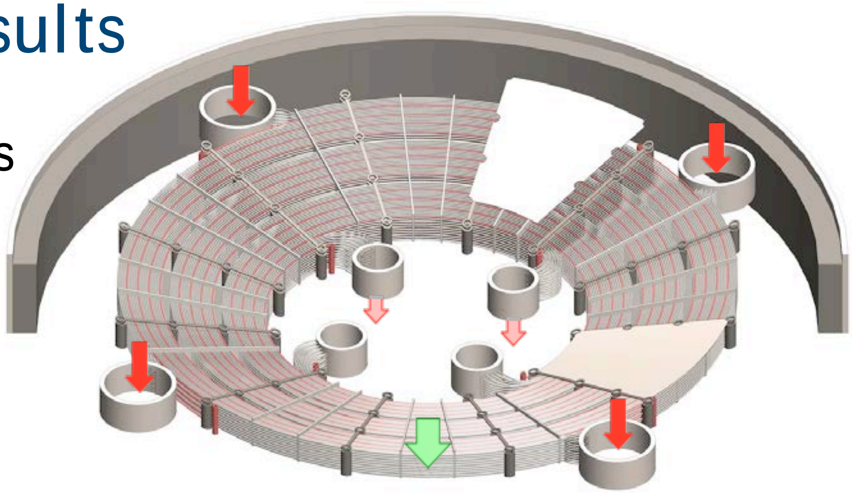
PS-HT^2: Experimental facility for capturing heat transfer data in pebble beds

- Test section filled with 0.00635 mm (1/4“) diameter copper spheres
- 7 instrumented pebbles and 4 thermocouples measuring bulk fluid temperature
- Drakesol 260AT working fluid
- Measure heat transfer coefficient using transient temperature method

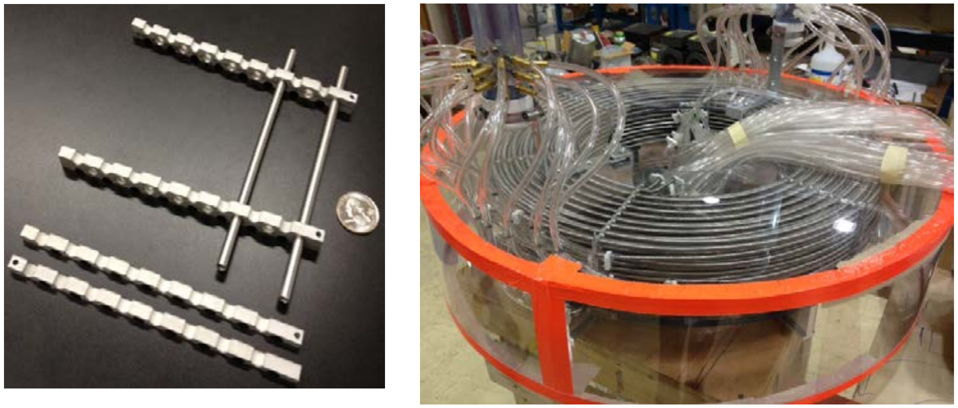


CTAH Test bundle experients are validating THEEM simulation results

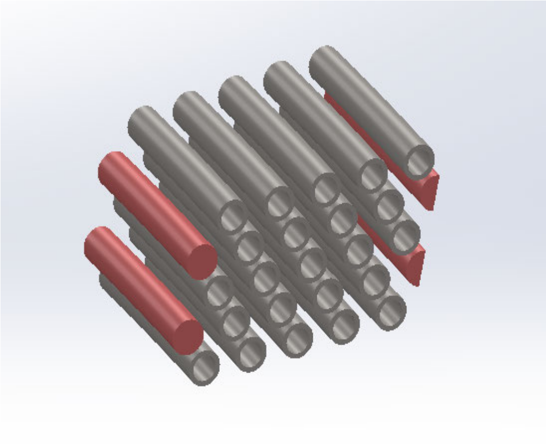
- Transverse Heat Exchange Effectiveness Model (THEEM)
  - 2-D Finite Volume Simulation
  - Calculates
    - Effectiveness
    - Heat Transfer
    - Temperature Distribution of Liquid and Gas
    - Pressure drop of Liquid and Gas



Mk1 CTAH Subbundle



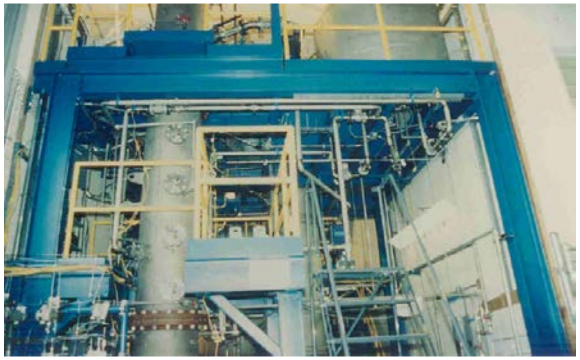
CTAH Heat Transfer Test Bundle



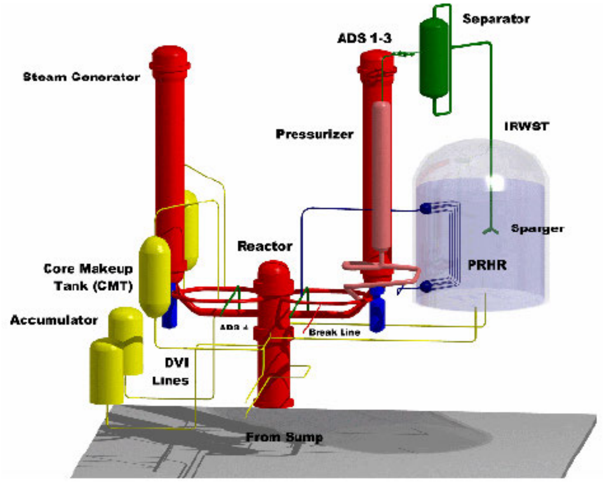
Typical THEEM control volume

FHR Integral Effects Tests

Reduced height, reduced area, integral effect test (IET) facilities have played a central role in passive safety system licensing



PUMA IET facility, Purdue University, Reduced height (1/4), reduced area (1/400 volume), 0.45 MW (SBWR/ESBWR)



APEX IET facility, Oregon State University, Reduced height (1/4), reduced area (1/192 volume), 1.0 MW (AP1000)

MASLWR IET facility, Oregon State University, Reduced height (1/3), reduced area (1/255 volume), 0.60 MW (NuScale)

The CIET Facility

Research objectives:

- Predict the transient thermal hydraulic response of liquid-salt-cooled reactor systems, including integral transient response for forced and natural circulation operation (two coupled loops)
- Use experimental data to validate numerical models

Experimental configuration:

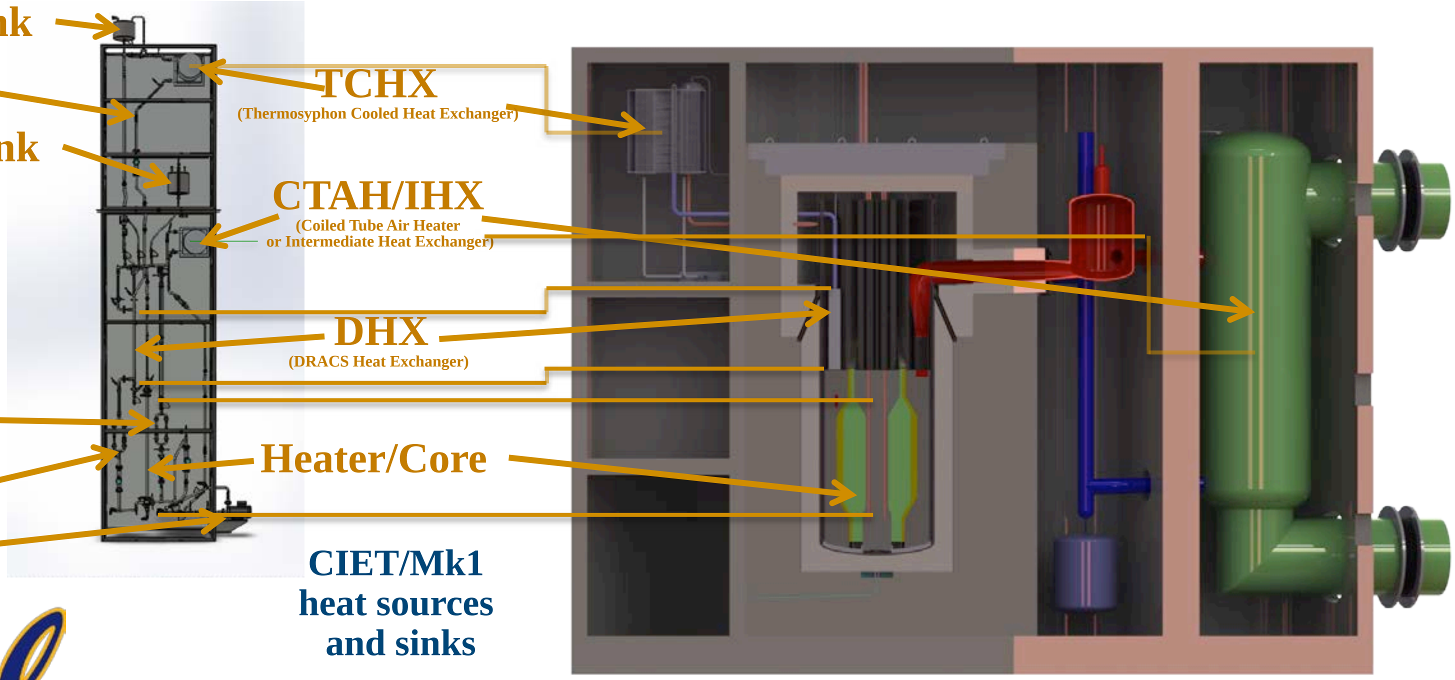
- Coupled square loops (primary and DRACS) with pump, vertical heater, “fluidic diode”, heat exchangers
- All branches equipped with needle valves to vary friction factor
- Shell-in-tube oil-to-oil DHX, with modularity to switch to twisted tubes heat exchanger

All CIET research falls under the facility-specific quality assurance program.

The UCB Compact Integral Effects Test (CIET) facility scaling matches the Mk1 reactor design

UC Berkeley CIET
(50% Height)

Mk1 PB-FHR
(100% Height)



DRACS Head Tank

DRACS Loop

Primary Head Tank

Core bypass

DHX flow diode

Primary Pump

TCHX
(Thermosyphon Cooled Heat Exchanger)

CTAH/IHX
(Coiled Tube Air Heater
or Intermediate Heat Exchanger)

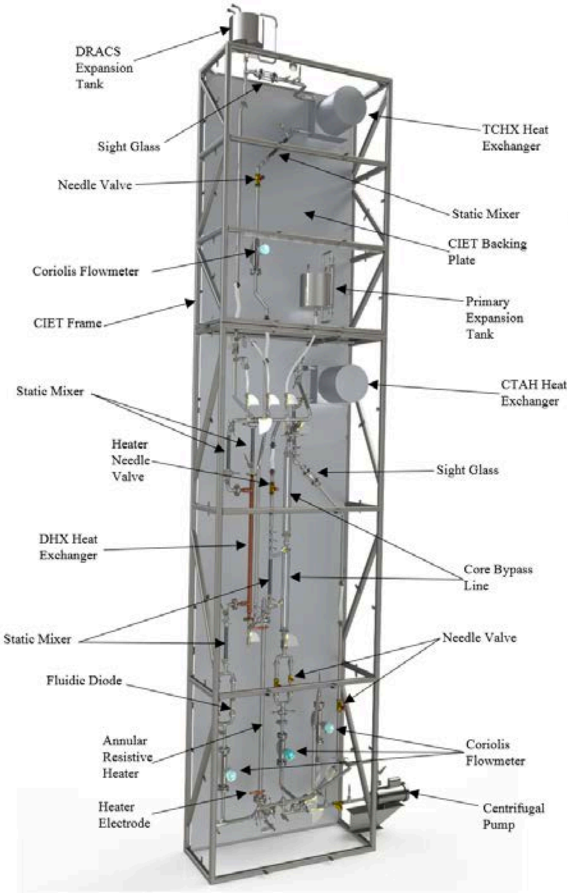
DHX
(DRACS Heat Exchanger)

Heater/Core

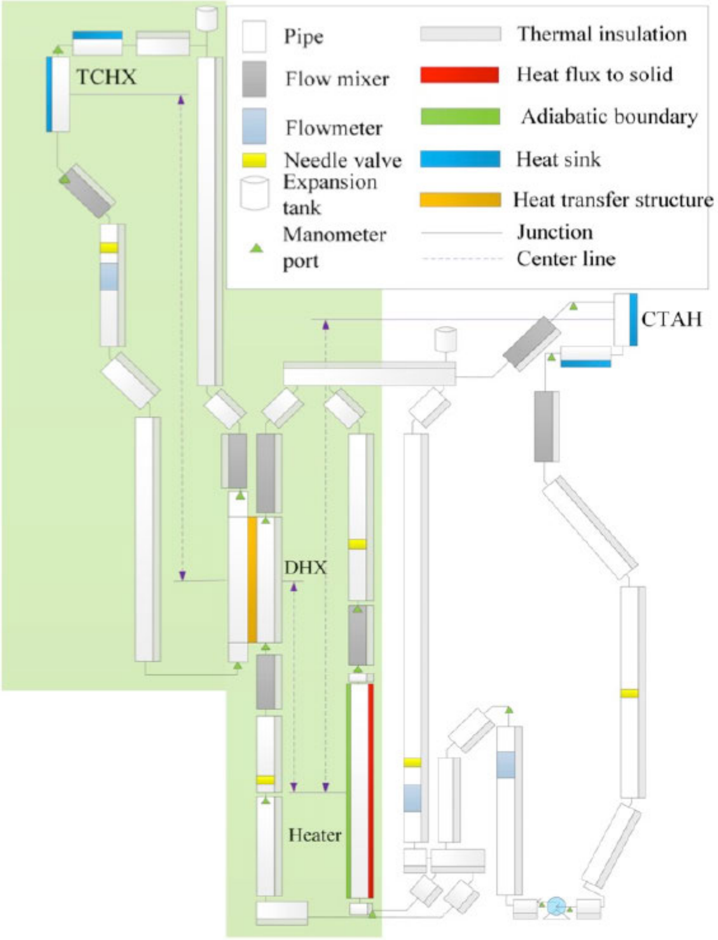
**CIET/Mk1
heat sources
and sinks**

CIET is validating FHR transient models

CIET In Operation

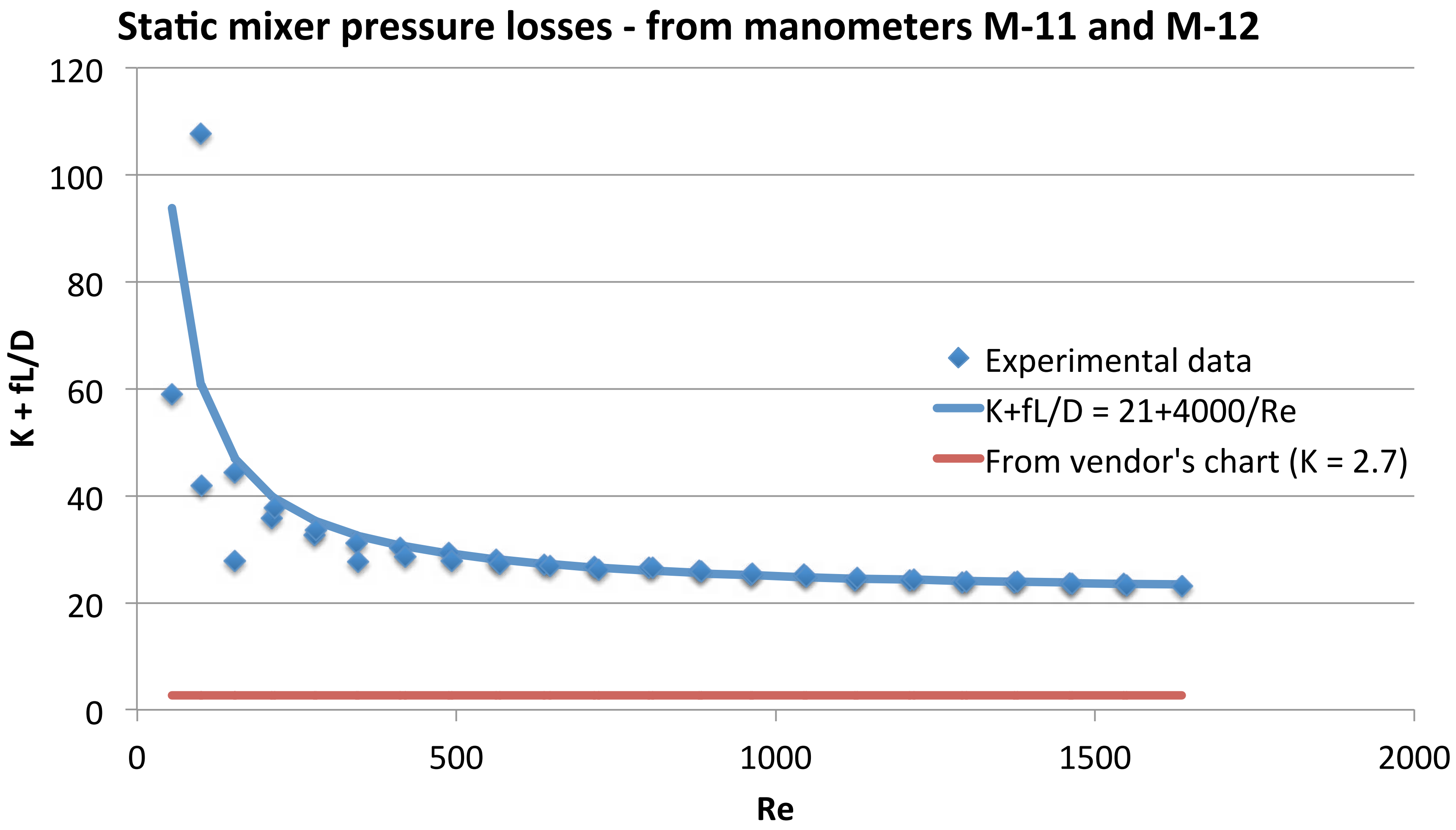


CIET Front View



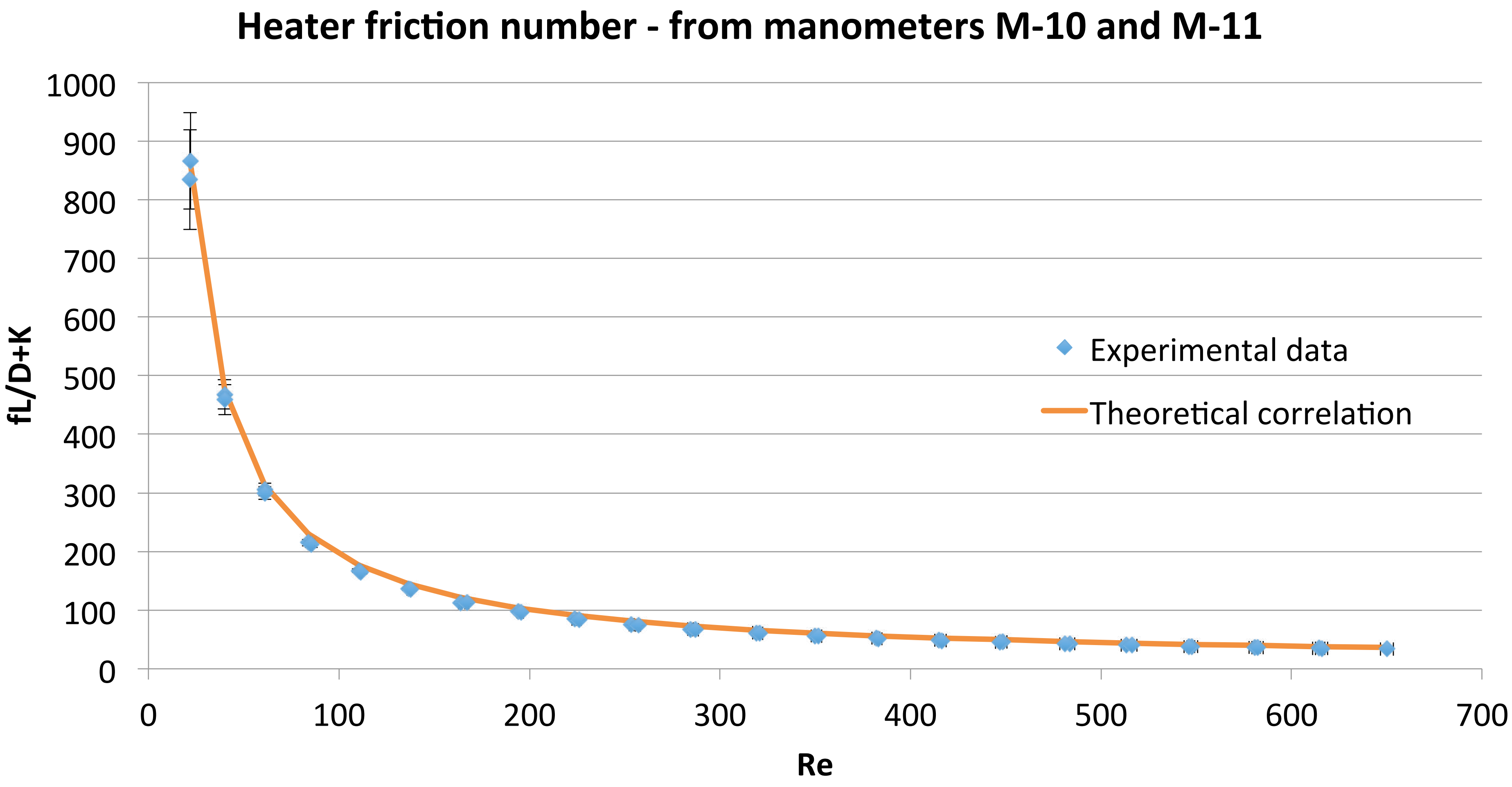
Nodalization for CIET/FHR simulation

Example: Calibration of Friction Number Correlation--Static Mixers



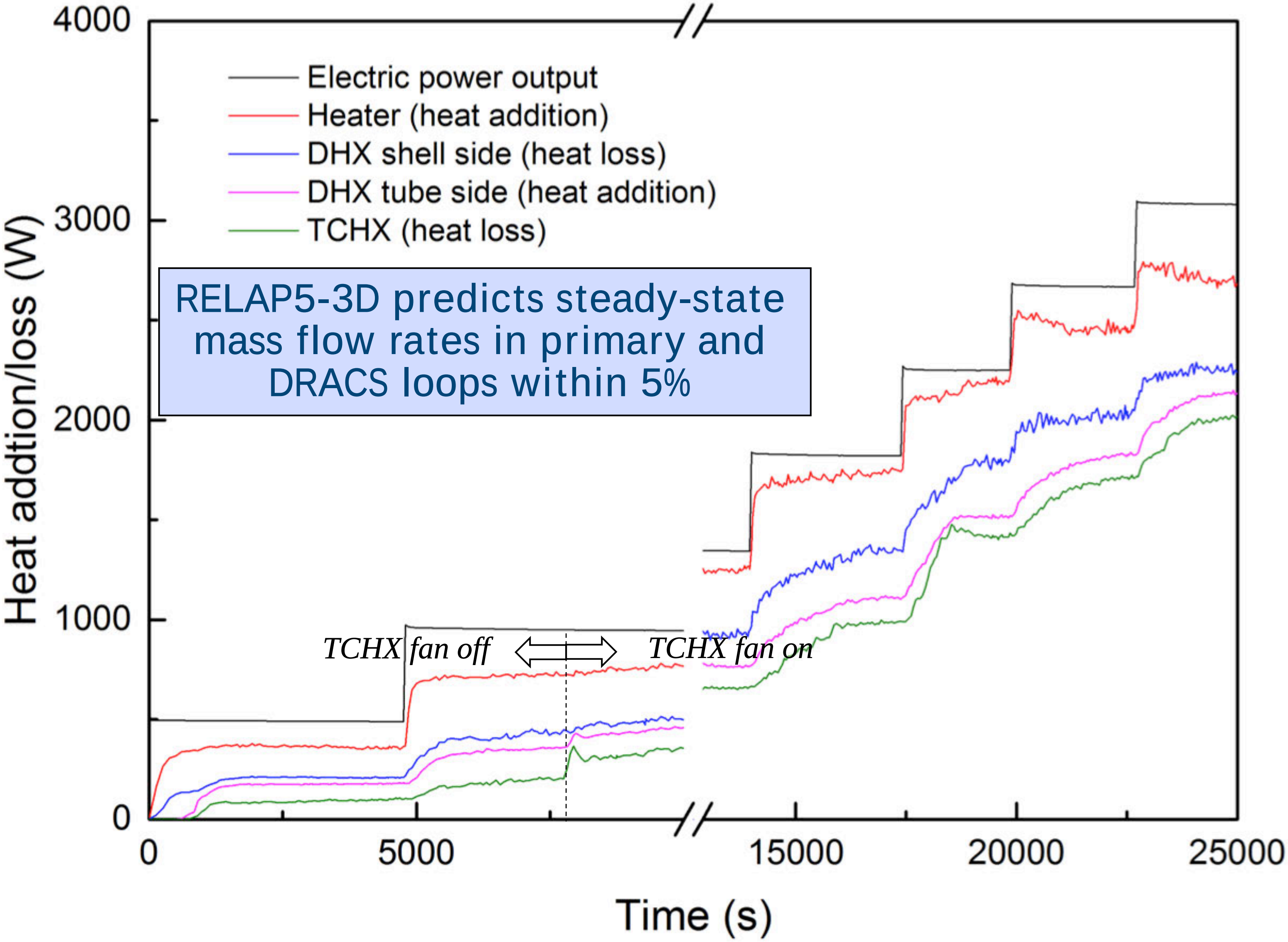
Measured friction losses are higher than vendor's chart.
Potentially due to flow inlet conditions.

Example: Friction Number Correlation Validation—Heater



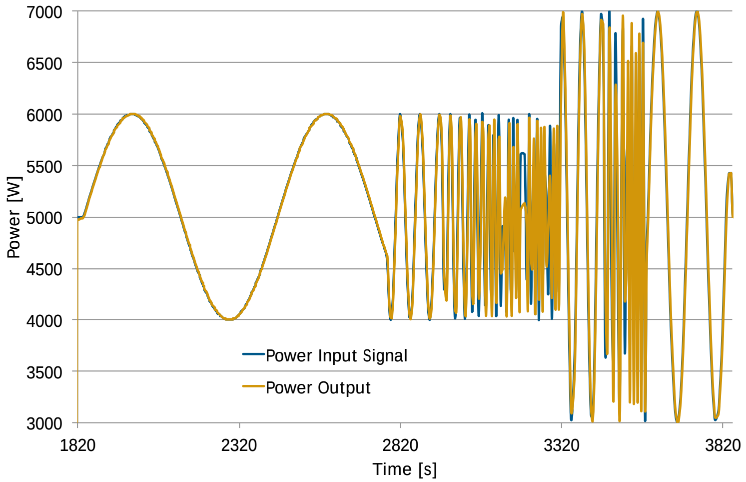
Theoretical correlation for annular channels is valid for the CIET electrical heater. This confirms that as-built geometry is identical to design geometry.

Steady-State, Coupled Natural Circulation Results

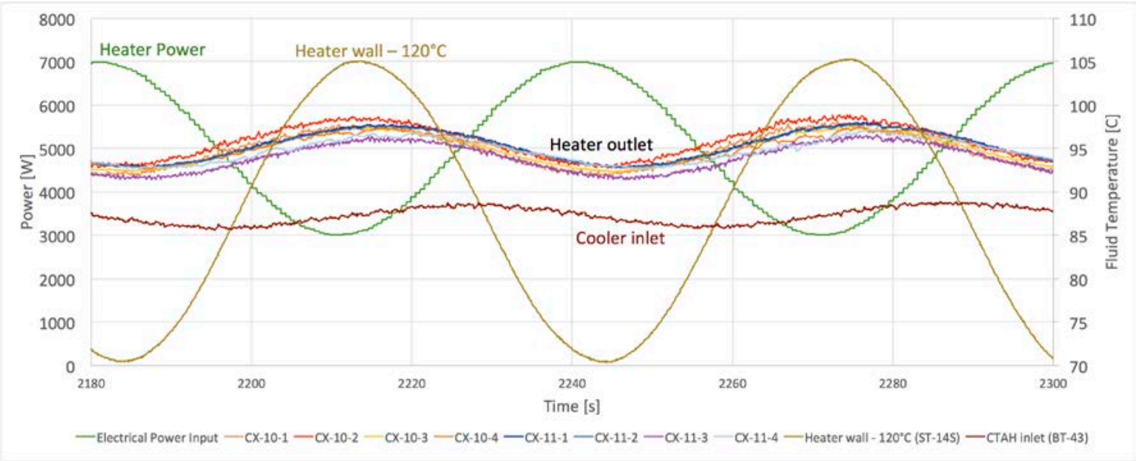


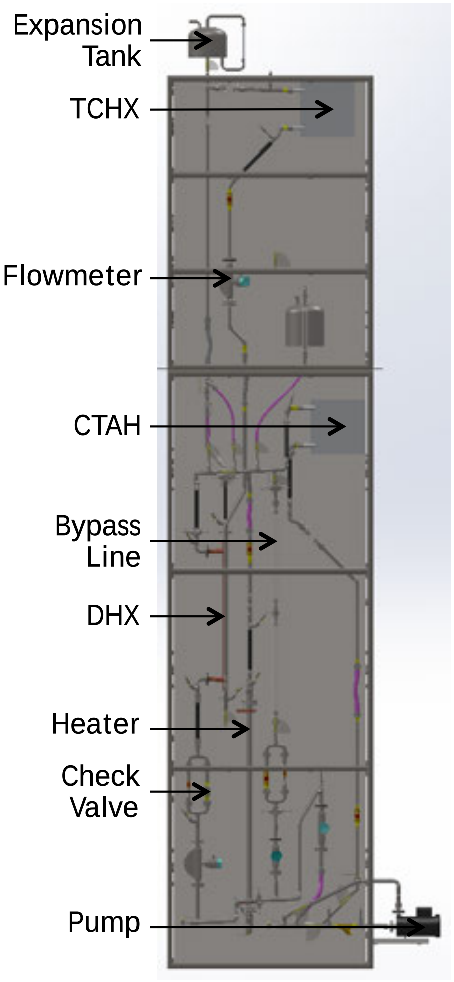
RELAP5-3D predicts steady-state mass flow rates in primary and DRACS loops within 5%

The current CIET test program is now studying response to dynamic forcing



- **Power oscillation in CIET is enabling study of transient thermal response of heat structures**
- **Future work will add power feedback to mimic core reactivity feedback phenomena, and will study the design of FHR control systems**

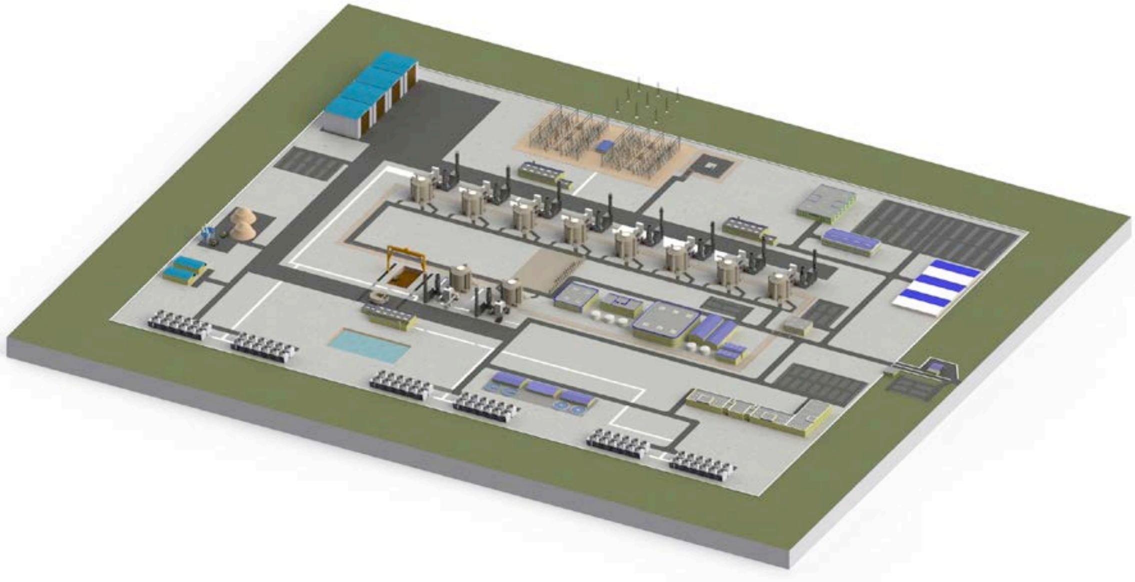




Key next steps for simulant fluid IETs for FHRs/MSRs involves scaling methodology

- Three-step scaling methodology to systematically identify and quantify
  - Sources of scaling distortion-study using SETs
  - Sources of measurement uncertainty-quantify uncertainty distributions
- Major steps:
  1) Design hypothetical molten salt (HMS) IET
     - » Conventional reduced area, reduced height, electrically heated IET scaling (similar to APEX, PUMA, MASLWR)
     - » Identify HMS-specific sources of scaling distortion
  2) Design scaled simulant fluid IET
     - » Scaled to match HMS IET forced and natural circulation
     - » Identify simulant-fluid-specific sources of scaling distortion
  3) Assess and characterize measurement uncertainty
     - » Credit higher measurement accuracy for low-temperature simulant fluids

Questions?



For more info: http:// fhr.nuc.berkeley.edu