The current status of Fluoride salt cooled High temperature Reactor (FHR) technology and its overlap with HIF target chamber concepts

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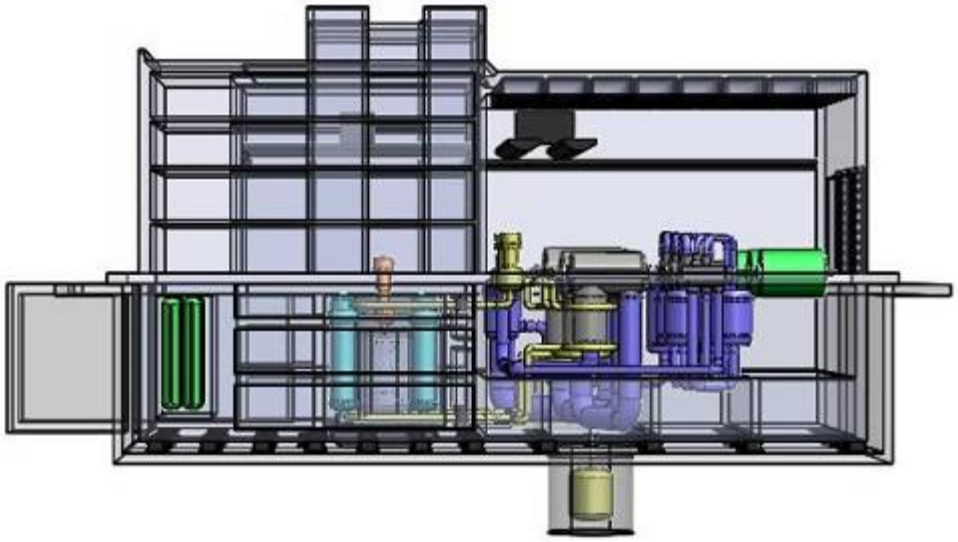


900 MWth, 410 MWe PB-AHTR

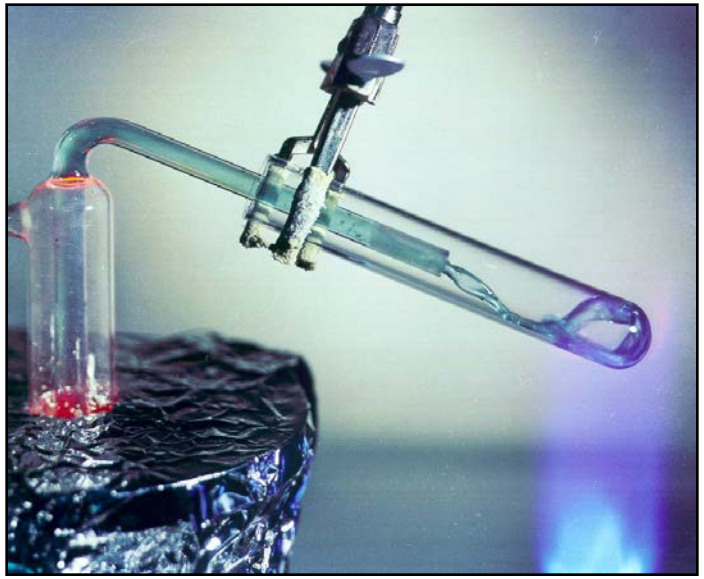
Outline

1. **FHR Overview**
2. **Overlap with HIF target chamber concepts**
3. **Technology Development Status**
4. **Experimental facilities at UC Berkeley**

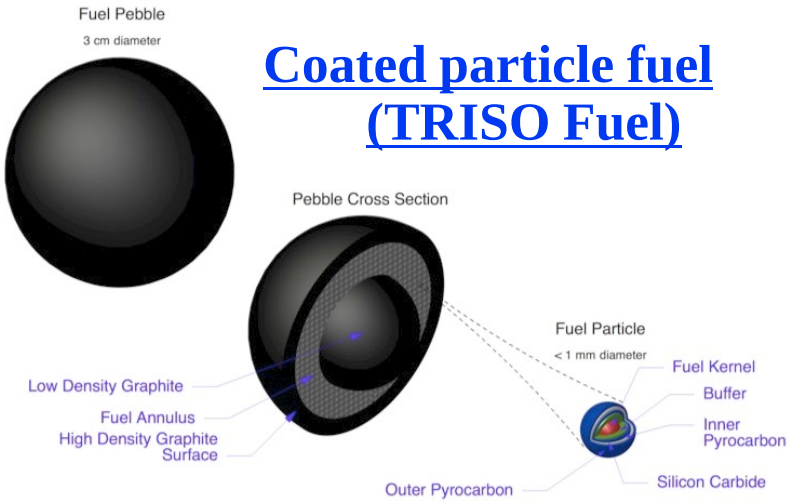
Fluoride salt cooled High Temperature Rectors (FHRs) Combine Two Older Technologies

Liquid fluoride salt coolants

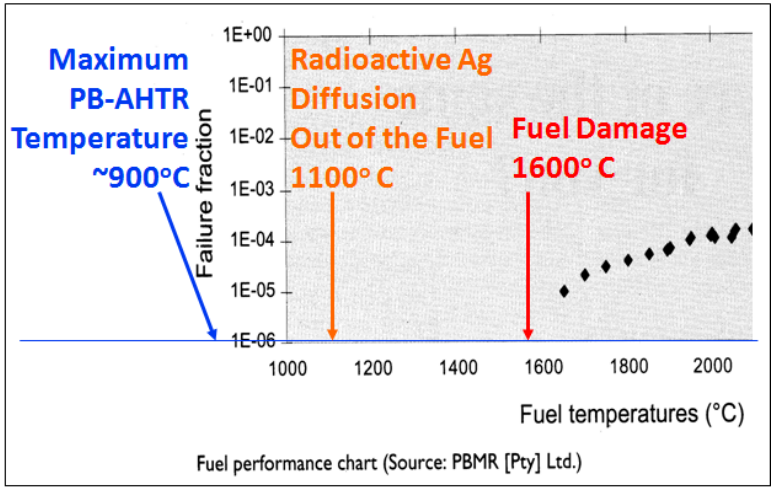
Excellent heat transfer
Transparent, clean fluoride salt
Boiling point ~1400°C
Reacts very slowly in air
No energy source to pressurize containment
But high freezing temperature (459°C)
And industrial safety required for Be



Coated particle fuel (TRISO Fuel)

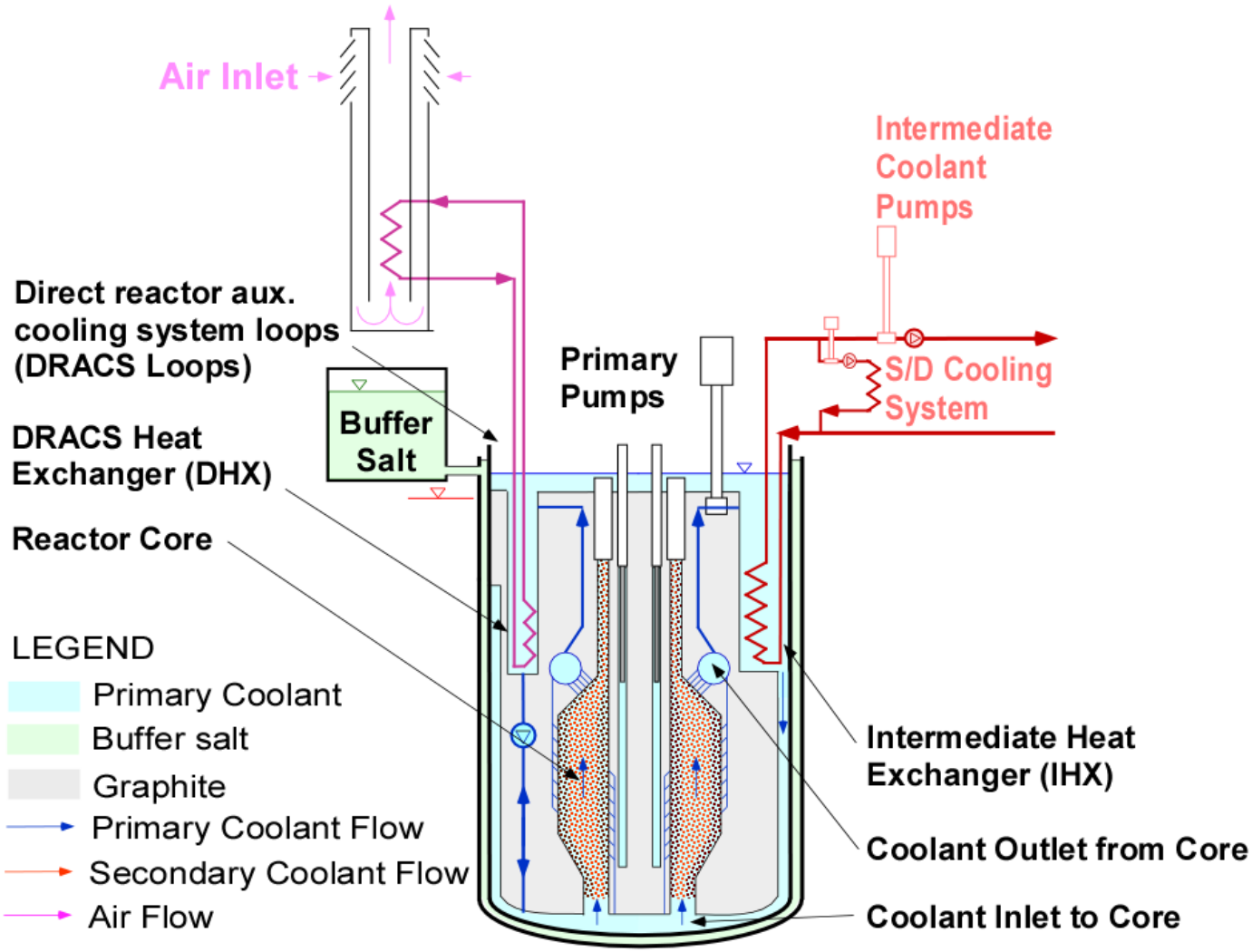


FHRs have uniquely large fuel thermal margin



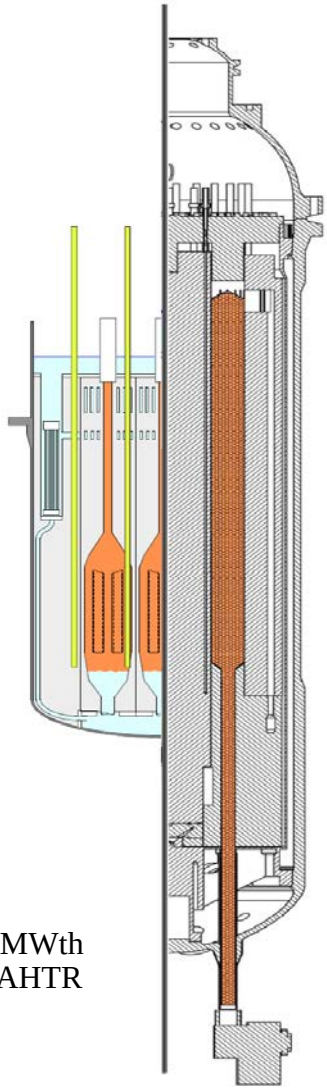
Fuel performance chart (Source: PBMR [Pty] Ltd.)

The baseline PB-FHR is a modular pool-type reactor with passive decay heat removal



Modular PB-FHR Economics

Much more compact equipment than Gas Cooled Reactors

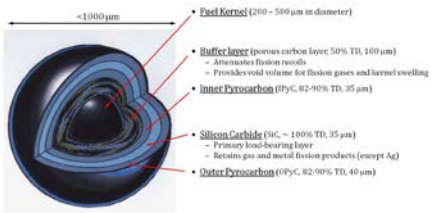


900 MWth
PB-AHTR

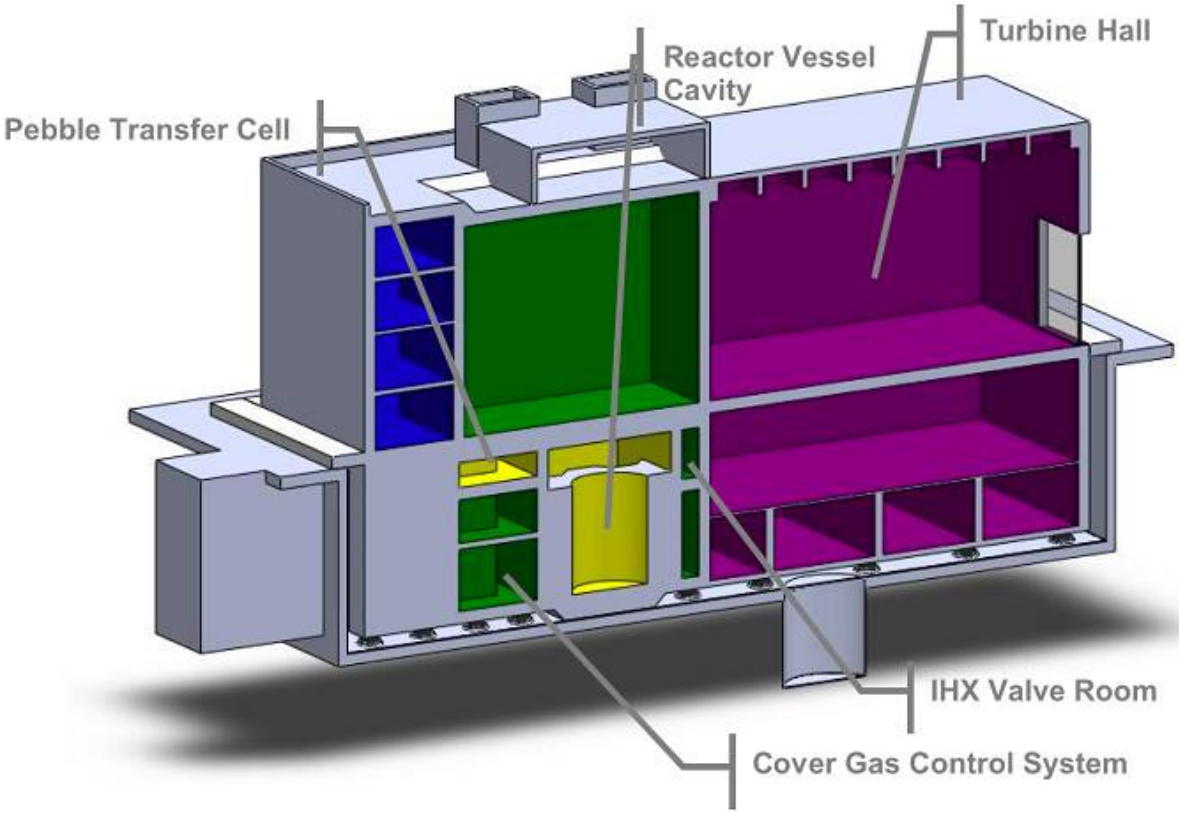
400 MWth
PBMR

1. D. T. Ingersoll, et al., "Status of Preconceptual Design of the Advanced High-Temperature Reactor (AHTR)," ORNL/TM-2004/104, pp. 69, 2004.

Reactor Safety: PB-FHR Defense in Depth



TRISO Particles
Micro-containment vessels (>10,000 per fuel element)



HVAC Zones

1 - Reactor cell (Low-Leakage Inerted Containment)

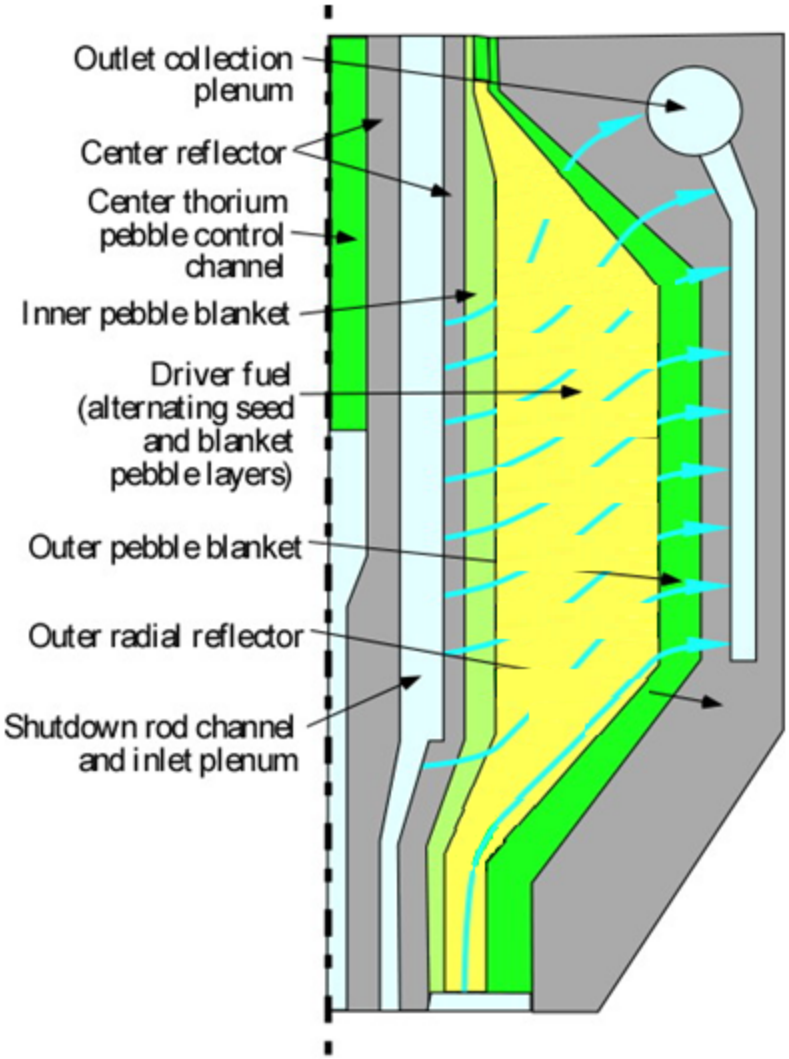
2 - Reactor citadel (Filtered Confinement)

3 – Reactor quipment hallways (Ambient air)

4 - Turbine hall (Ambient air) – additional hold-up

Potential Benefits of Radially-Zoned, Annular Seed/Blanket Core Configuration

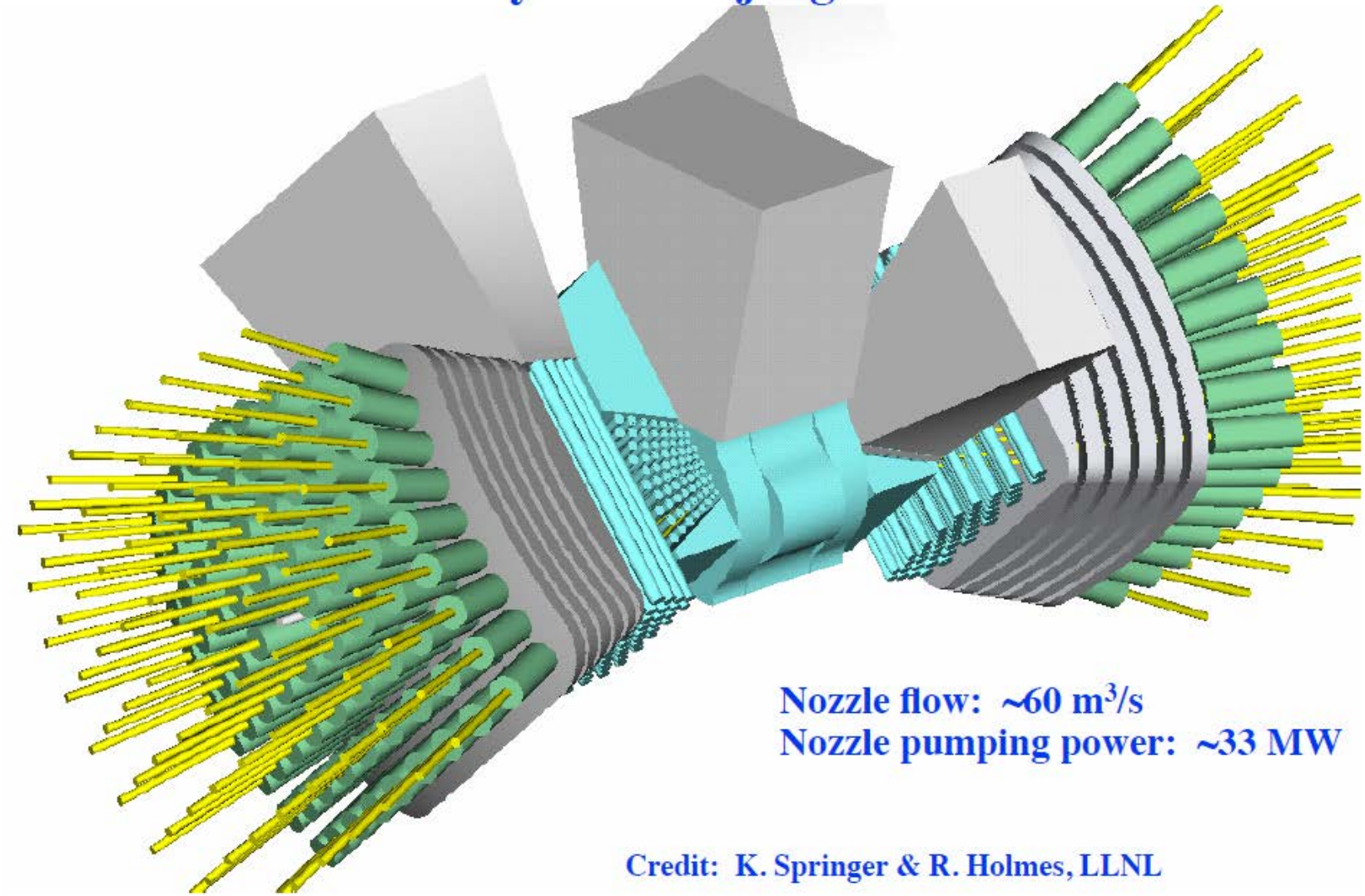
- **Zoning allows use of thorium blanket pebbles**
  - **External Pa-233 decay storage**
  - **Closed and once-through seed-blanket fuel cycles being studied**
- **Effective neutron shielding of outer radial reflector**
- **Greatly reduced core pressure drop (using a combination of axial and radial flow)**



Outline

1. FHR Overview
2. Overlap with HIF target chamber concepts:
   thick liquid layers for schielding reaction chamber walls
   - Cylindrical fluid jets
   - Large scale vortex flow
3. Technology Development Status
4. Experimental facilities at UC Berkeley

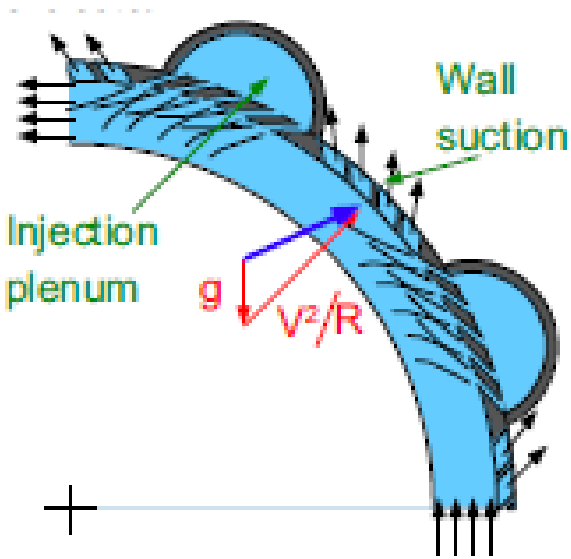
A 160-beam configuration has been developed using a cylindrical jet grid

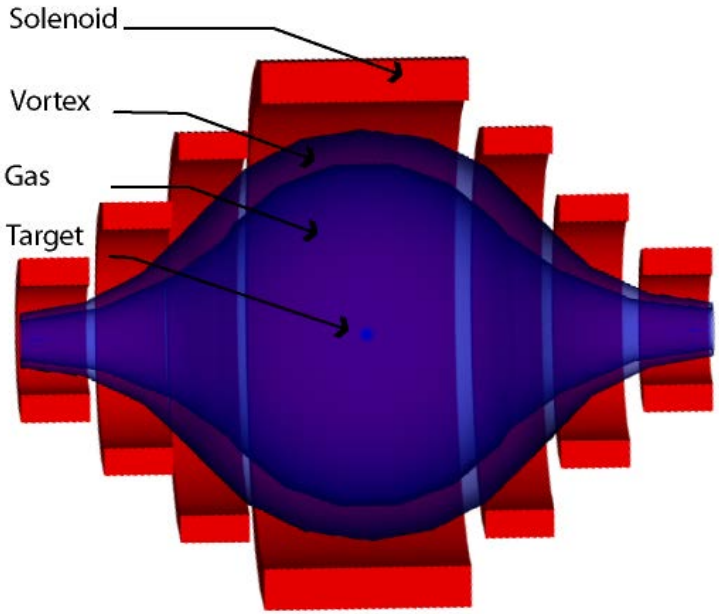


Credit: K. Springer & R. Holmes, LLNL

Modular solenoid HIF chamber could potentially use a large-scale vortex flow

- **Issues:**
  - **Using injection and suction to maintain vortex flow on substrate with non-uniform radius**
  - **Response of liquid layer to x-ray ablation (surface waves, substrate stresses, droplet ejection)**
  - **Effects of turbulent surface renewal on surface temperature and condensation**



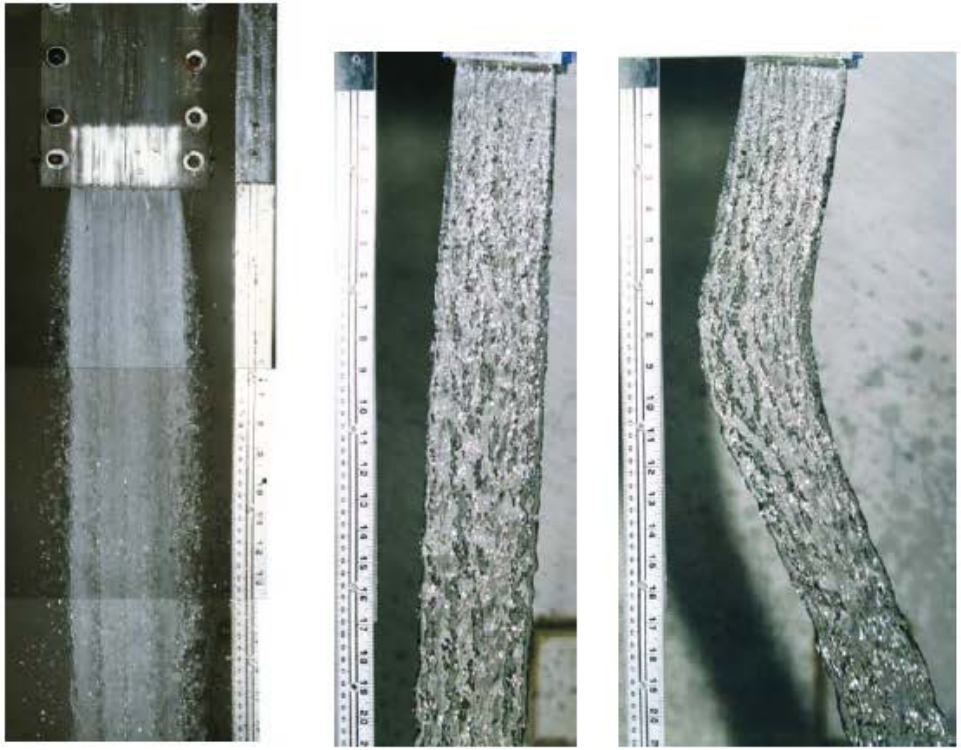


IFE system phenomena cluster into distinct time scales

- **Nanosecond IFE Phenomena**
  - **Driver energy deposition and capsule drive (~30 ns)**
  - **Target x-ray/debris/neutron emission/deposition (~100 ns)**
- **Microsecond IFE Phenomena**
  - **X-ray ablation and impulse loading (~1 μs)**
  - **Debris venting and impulse loading (~100 μs)**
  - **Isochoric-heating pressure relaxation in liquid (~30 μs)**
- **Millisecond IFE Phenomena**
  - **Liquid shock propagation and momentum redistribution (~50 ms)**
  - **Pocket regeneration and droplet clearing (~100 ms)**
  - **Debris condensation on droplet sprays (~100 ms)**
- **Quasi-steady IFE Phenomena**
  - **Structure response to startup heating (~1 to 10^4 s)**
  - **Chemistry-tritium control/target fabrication/safety (10^3-10^9 s)**
  - **Corrosion/erosion of chamber structures (10^8 sec)**

Principal focus for IFE Technology R&D…

Single-jet experiments provide jet geometries for constructing integrated pockets



Bad: Breaks up | **Stationary** | **Oscillating**

Better: No Droplets

UCB Stationary Jets (1.6 cm x 8.0 cm, view from flat side, Re = 160,000, We = 29,000)

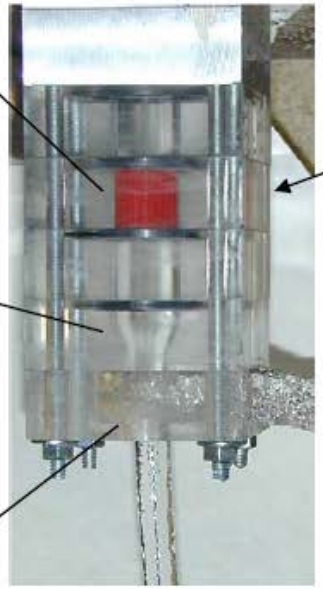
Recent experiments show that cylindrical jets can be sufficiently smooth for beam-line protection

Flow Conditioning

honeycomb

screen/nozzle

cutter blade



Jet with 1.5 : 1.0 nozzle contraction ratio

Re = 100,000

Re = 186,000

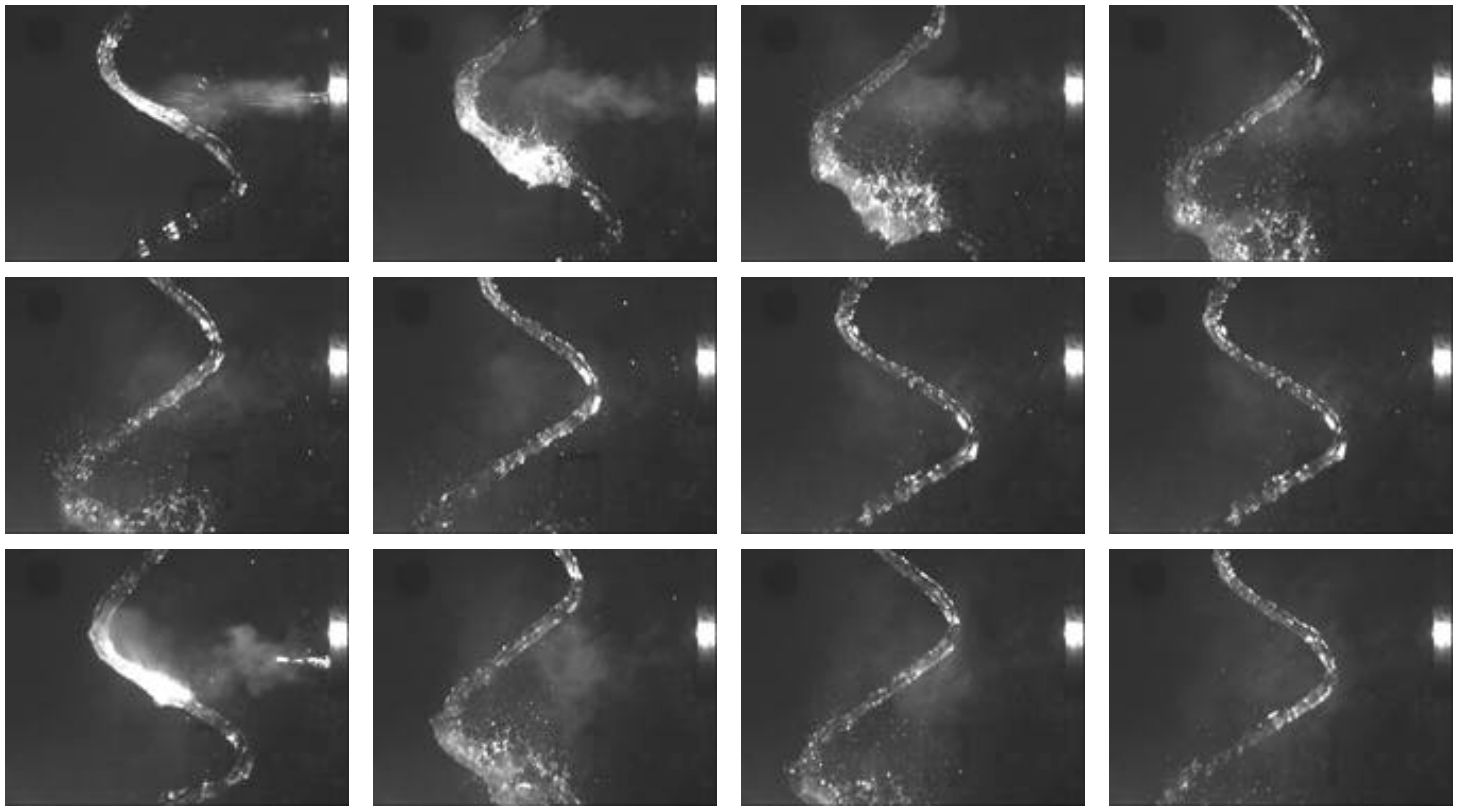
Re = 70,000 (no conditioning)

Phase-I hydraulics experiments can be performed in university-scale facilities

- **Example: UCB facility studies single jets and few jets (partial pockets).**
- **Transient flow into large vacuum vessel**

Water used to simulate Flibe (allows Re, Fr and We number matching at 1/2 to 1/4 geometric scale)

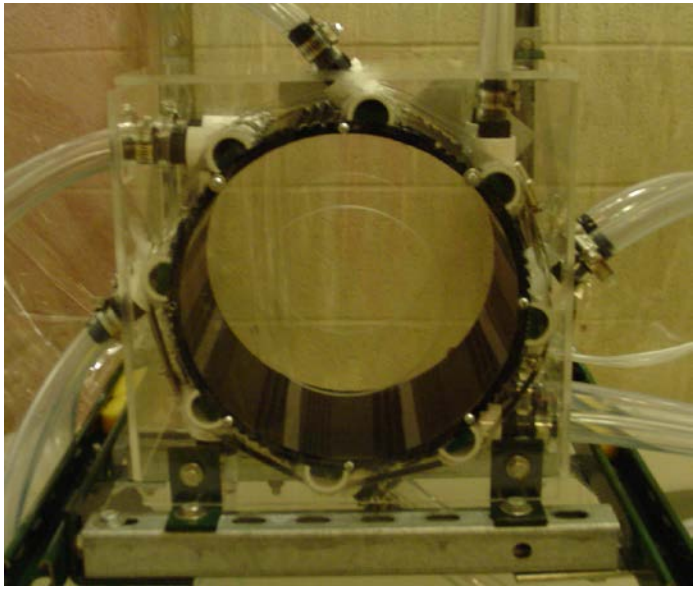
Cartridges can provide required impulse loading

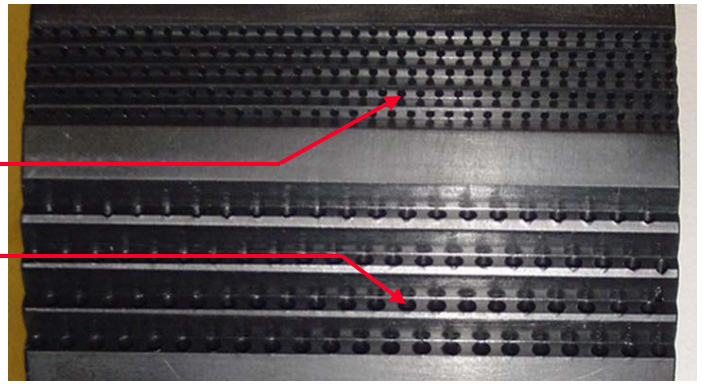


Single-jet disruption at 10.3 Hz

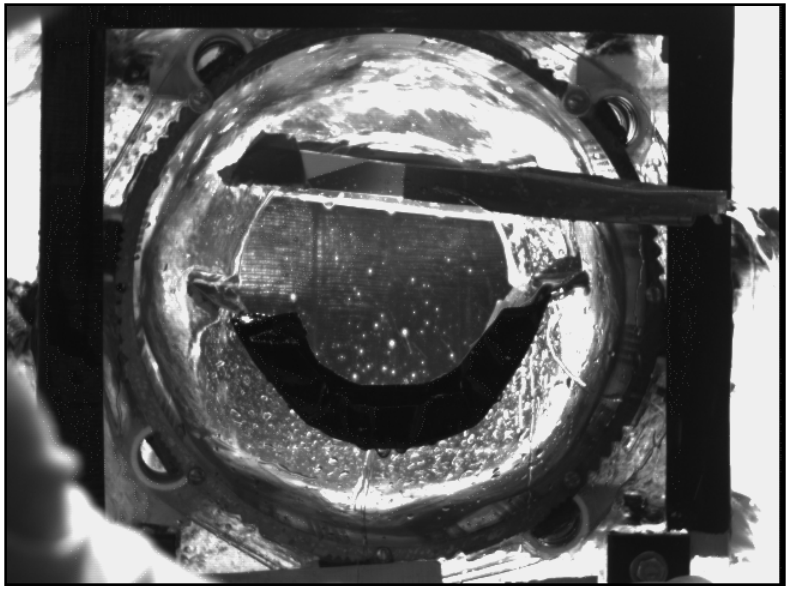
An improved device was constructed, based on the previous experiment

- **A test device was fabricated from a segment of cylindrical pipe (25.4-cm diameter, 14-cm wide)**
- **Injection and suction holes were fabricated with precision**
- **Eight pressurized plenums provided blowing flow**
- **Perforations between injection plenums provided suction**
  - $A_{suction} = 2A_{injection}$
- **End walls produced modest non-ideality**

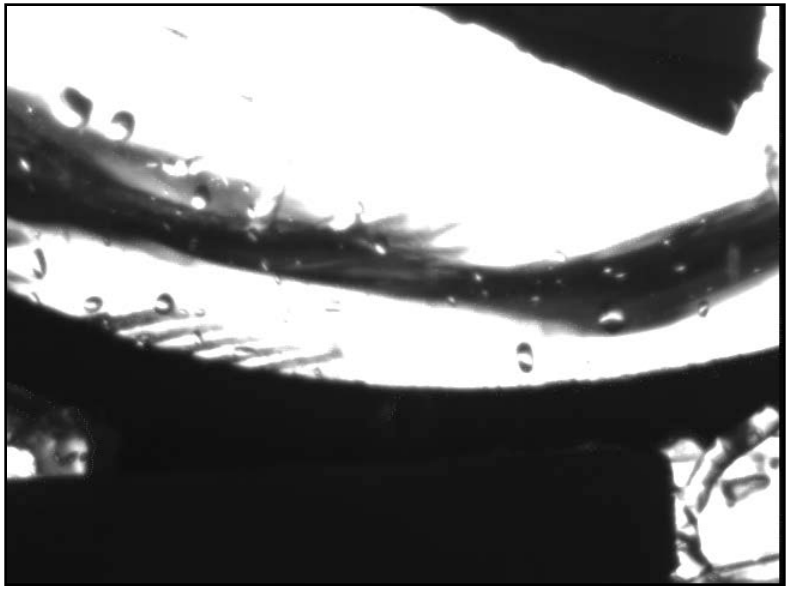




Different layer thicknesses have been obtained with Froude number as low as 3



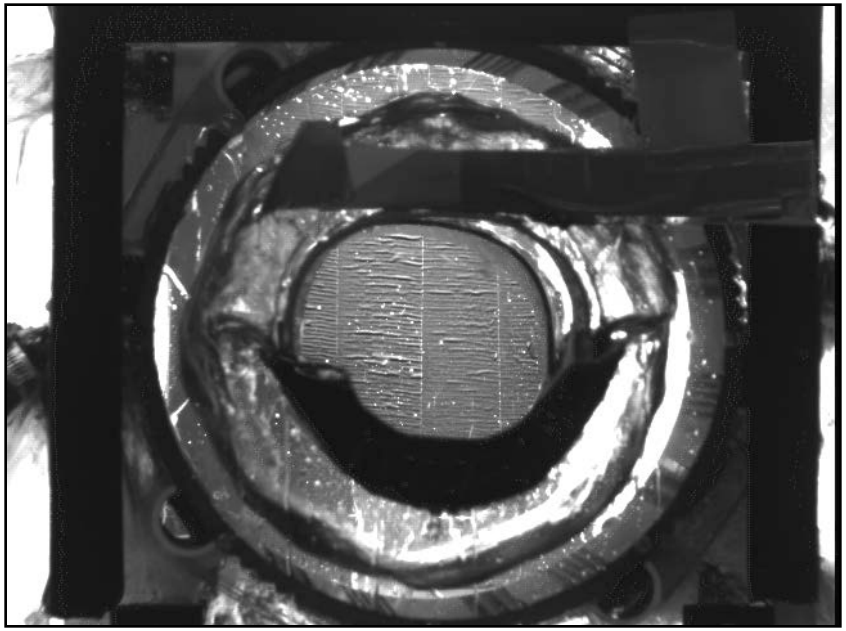
- $\delta/R = 5\%$
- $Fr = U^2/gR = 13.6$
- $Re = UR/\nu = 5 \cdot 10^5$



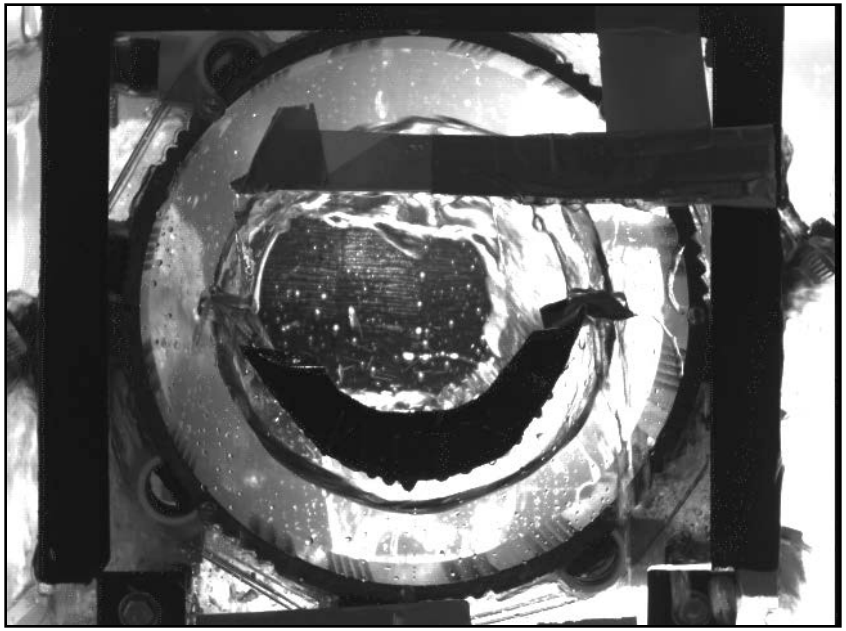
- the layer is inhomogeneous, due to sharp angle of injection

hexagon shape layer

Different layer thicknesses have been obtained with Froude number as low as 3, cont



- $\delta/R = 20\%$
- $Fr = 3.6$
- $Re = 3 \cdot 10^5$ (~20% of prototype)



- $\delta/R = 28\%$
- $Fr = 3.7$
- $Re = 3 \cdot 10^5$ (~20% of prototype)

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The FHR Development Program has three phases

Viability Phase (nominally 3 to 4 years)

- Simulant Fluids SET and IET Experiments performed

Major end products:

- Conceptual design for a 16-MWth Test Reactor
- NRC pre-application review submittal

Performance Phase (nominally 4 years)

- Component Test Facility operates, and Fuel Qualification underway

Major end products:

- Construction authorization for a 16-MWth Test Reactor
- Submittal of NRC Design Certification Application for a commercial prototype

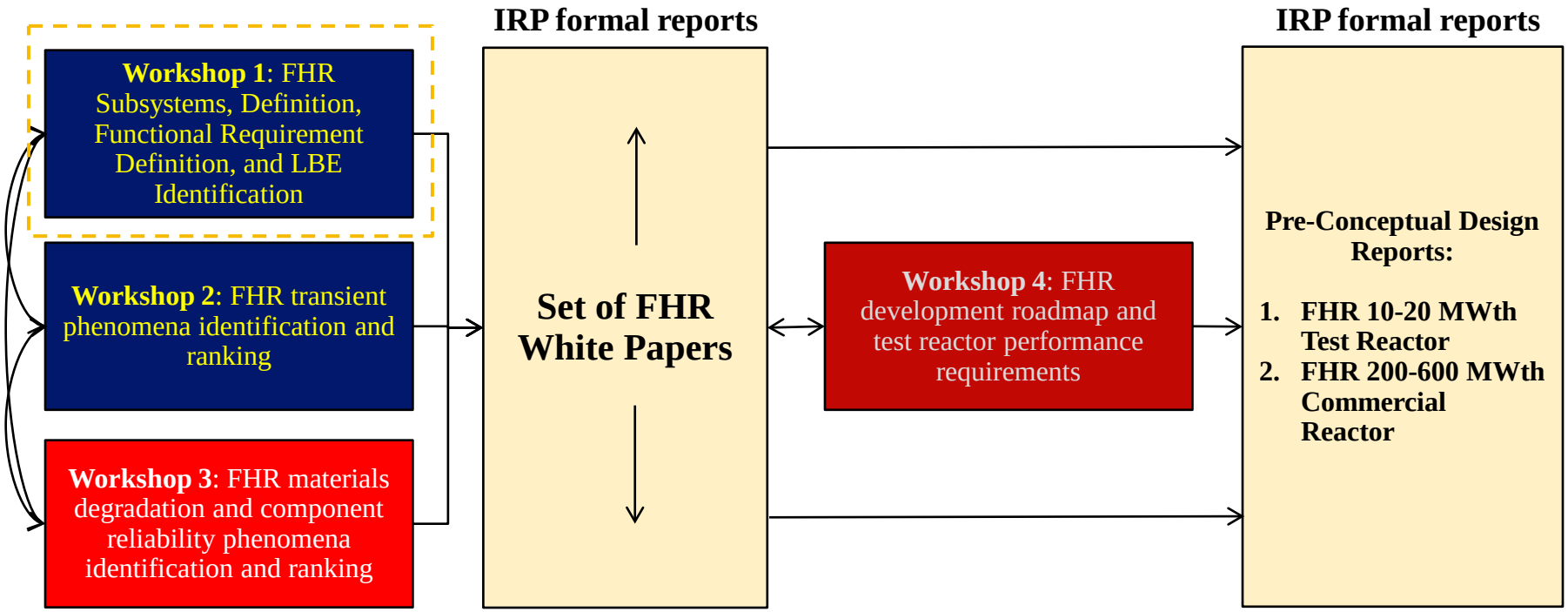
Demonstration Phase (nominally 5 years)

- 16-MWth AHTR Test Reactor operates

Major end products:

- NRC Design Certification
- NRC Combined Construction and Operating License for a commercial-scale PB-AHTR Pilot Plant

FHR Technology Development and IRP Integration



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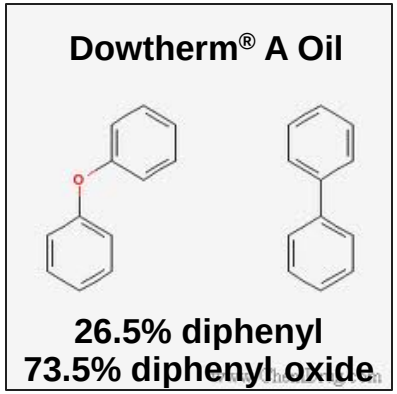
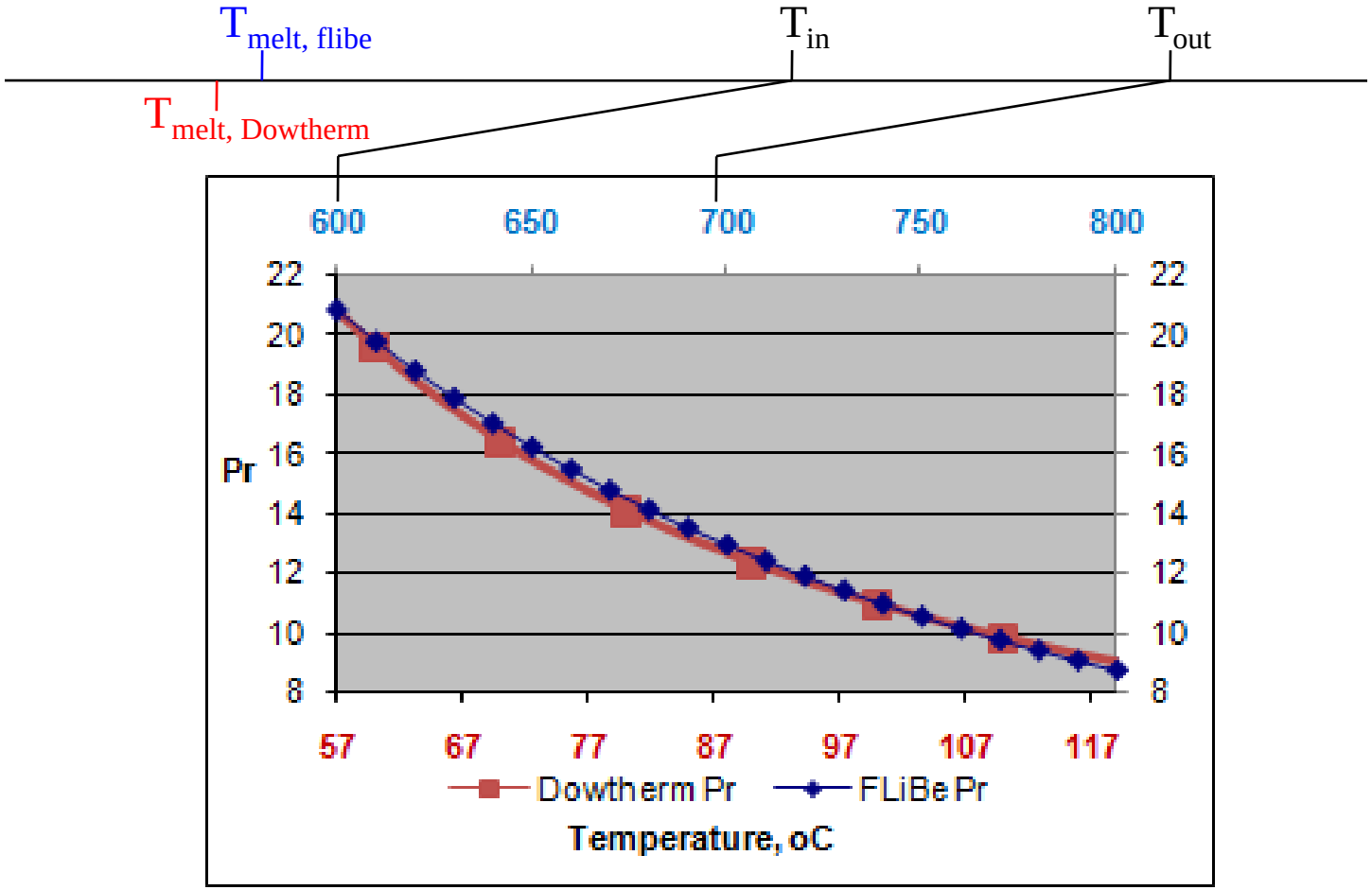


Major FHR Experimental Program Elements

- **Integral Effects Tests**
  - **Compact Integral Effects Test (CIET) facility**
    - » **Scaled simulant fluid IET to study system response to LOFC, ATWS, and other transients**
  - **Pebble Recirculation Experiment**
    - » **Scaled simulant fluid IET to study pebble recirculation hydrodynamics**
  - **Czech EROS zero power critical tests (w/ salt) (Viability phase)**
    - » **Validate predictions for negative coolant void reactivity**
- **Separate Effects Tests**
  - **Scaled High Temperature Heat Transfer (S-HT^2) facility**
    - » **Heat transfer coefficient measurements using simulant fluids**
  - **Fuel irradiation and post-irradiation examination**
  - **Other SET experiments**
    - » **Materials corrosion test loop**
    - » **Pebble friction coefficients**
    - » **Confirmatory data during component test experiments**

Dowtherm A is a useful simulant fluid for fluoride salts

Prandtl Number for flibe and Dowtherm A

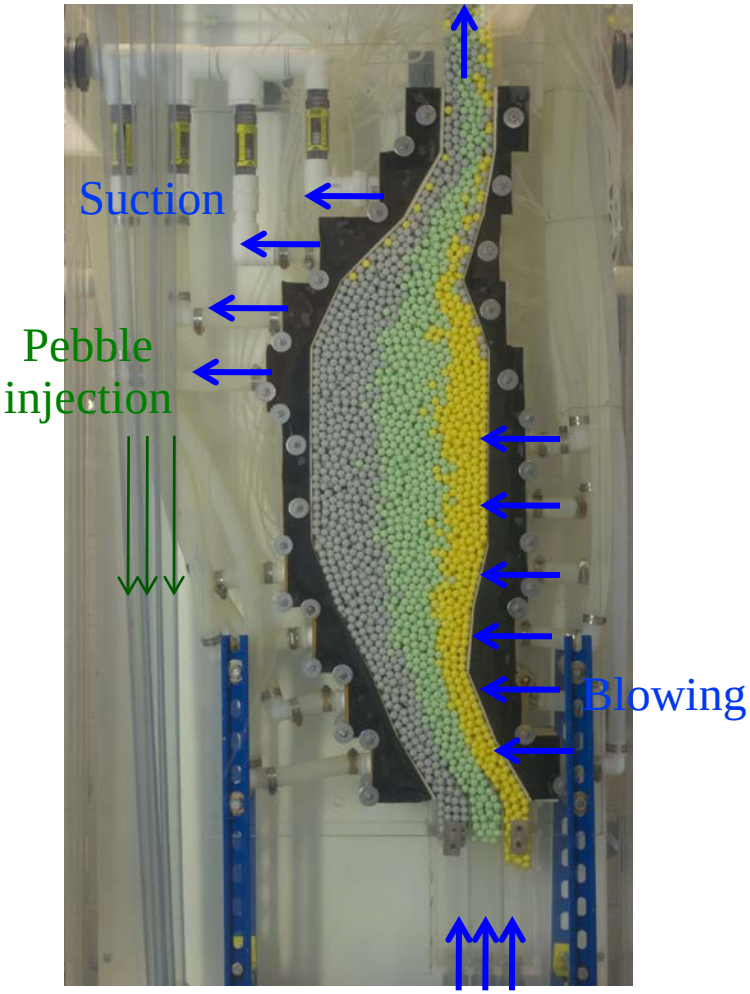


Dowtherm A is an excellent simulant coolant fluid for flibe molten fluoride salt.

Salt hydrodynamics can be replicated using water

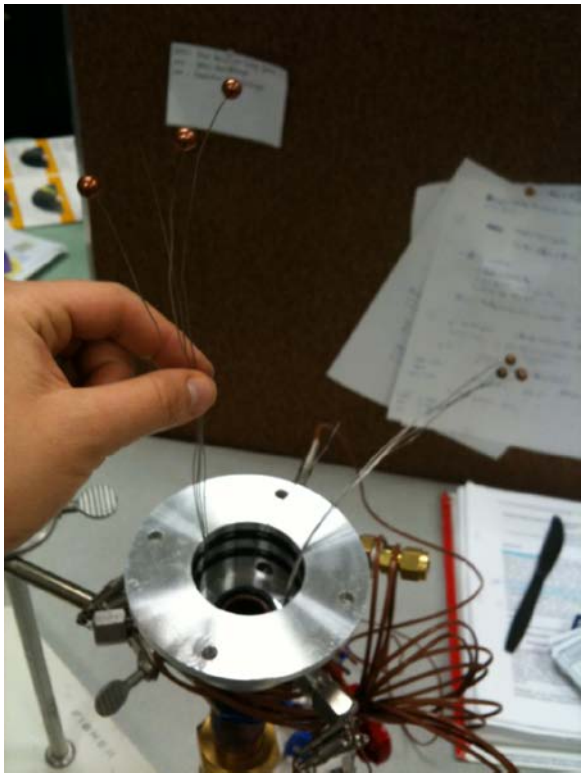
- **Reynolds number and Froude number can be matched at 40% geometric scale using water**
- **Forces acting on fuel pebbles, and pebble bed dynamics, can be replicated in room temperature experiments**
  - **Friction coefficient of HDPE on acrylic is similar to graphite lubricated with fluoride salt**

PREX 3.1

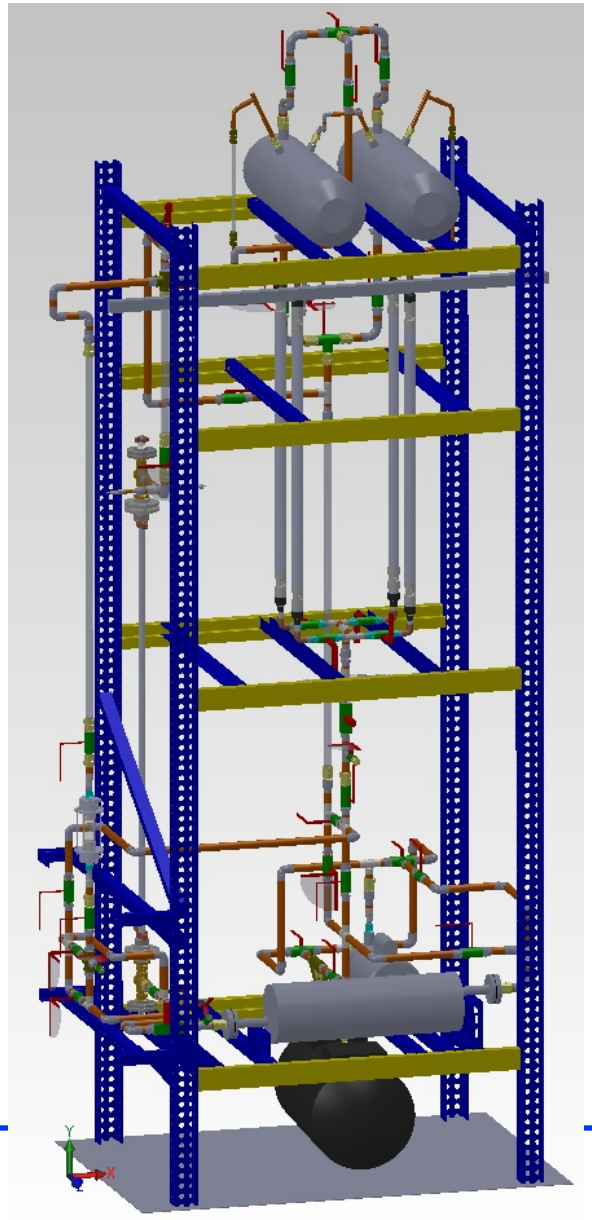


Wet experiment scaled to match Re and Fr

Convective heat transfer in pebble beds



CIET Test Bay for SETs and IETs



Summary
PB-AHTR Technology and the Path Forward

- **AHTR achieves substaintial reduction in capital cost compared to ALWRs, primarily through compact size, no high pressure, and higher temperature/power conversion efficiency**
- **PB-AHTRs maintain uniquely large thermal margins for damage to fuel, and Coolant temperature limit is established by thermal limits on primary loop metallic structures**
- **Fluoride salts can be used to from thick liquid layers for schielding reaction chamber walls**
- **Excellent simulant fluids for molten fluoride salts allow for obtaining experimetal data at much lower costs than using prototypical fluids**
- **Development path involves pre-application review and subsequent Design Certification by NRC, and it has clear roles for national laboratories, universities, and industry**

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