Fluoride-Salt-Cooled High-Temperature Reactors (FHR): From Lunch to Kairos Power with Three IRPs

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Molten Salt Reactor Workshop
Oak Ridge National Laboratory

5 November 2024
Knoxville, Tennessee

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The First FHR Journal Paper in 2003 in Nuclear Technology

MOLTEN-SALT–COOLED ADVANCED HIGH-TEMPERATURE REACTOR FOR PRODUCTION OF HYDROGEN AND ELECTRICITY

FISSION REACTORS

KEYWORDS: *molten salt, high-temperature reactor, hydrogen production*

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Received August 6, 2002
Accepted for Publication May 29, 2003

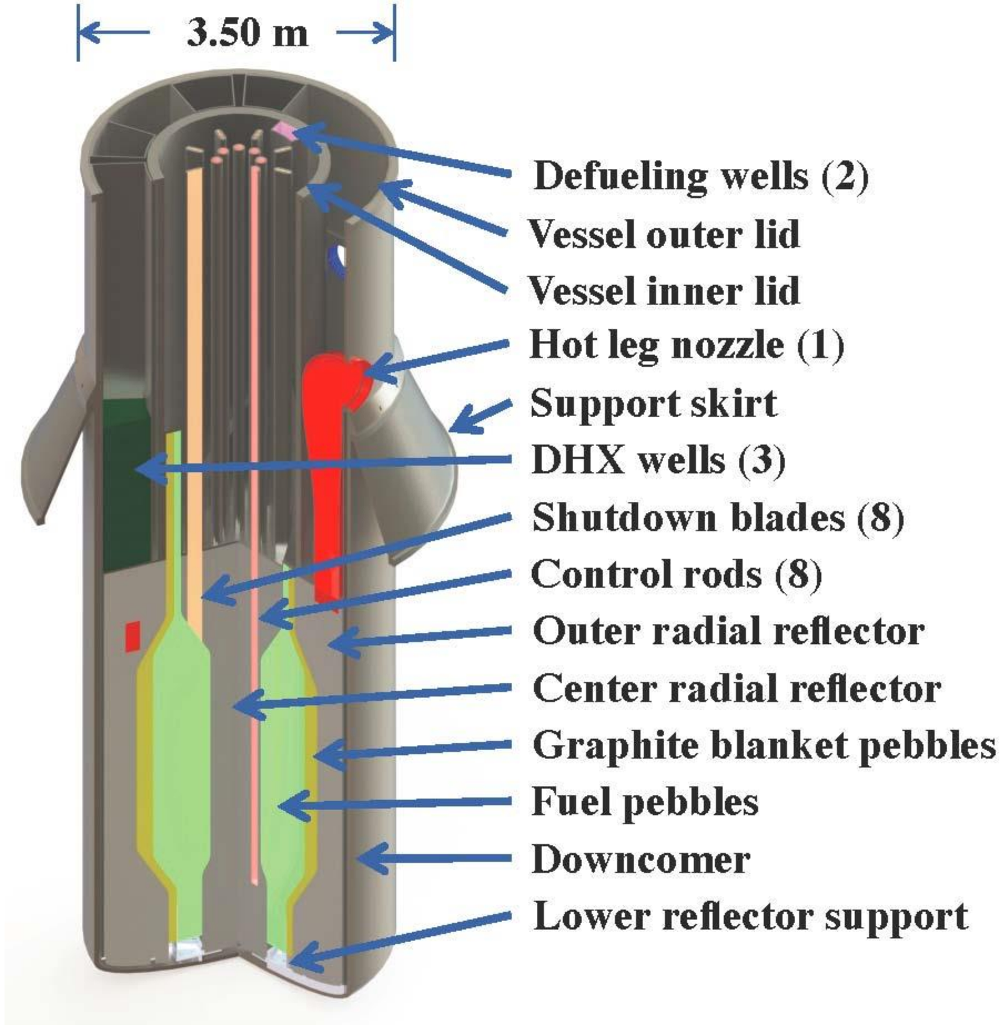
Initial concept developed over lunch at GenIV meeting, subpanel on alternative reactor concepts

- Charles Forsberg: ORNL (now MIT)
- Per Peterson: U. of California at Berkeley (also Kairos)
- Paul Pickard: Sandia (now retired)

- HTGR fuel with high-temperature performance
- Clean salt coolant
  - Higher power density than gas-cooled reactor
  - Absorb most fission products
- Low pressure
- Half way point to fueled MSR and molten salt blankets for fusion

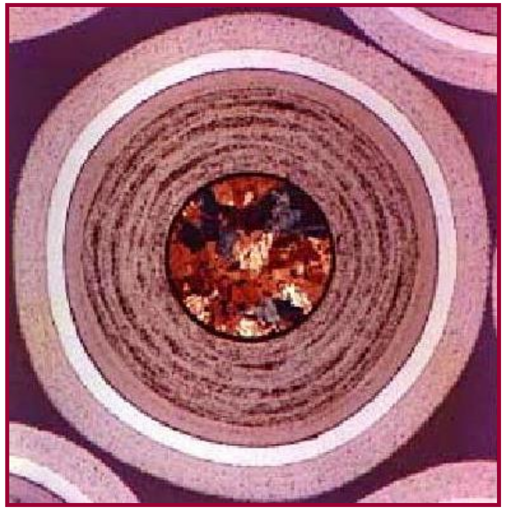
First Conference Paper: C. W. Forsberg and P. L. Pickard, “Advanced High-Temperature Reactor: Molten-Salt Coolant and Graphite Fuel”, American Nuclear Society 2001 Winter Meeting, Reno, November 11-15, 2001

IRP Pebble-Bed FHR with Flibe Salt Coolant



FHR IRP MK1 PB-FHR

Fuel: High-Temperature Coated-Particle Pebble-Bed Fuel Developed for High-Temperature Gas-Cooled Reactors (HTGRs)



Coolant: High-Temperature, Low-Pressure Flibe ($^7Li_2BeF_4$) Salt Coolant originally chosen for molten salt reactors

C. ANDREADES et al., "Design Summary of the Mark-I Pebble-Bed, Fluoride Salt-Cooled, High-Temperature Reactor Commercial Power Plant", *Nuclear Technology*, **195** (3), 223-238 (September 2016): DOI: 1013182/NT16.2

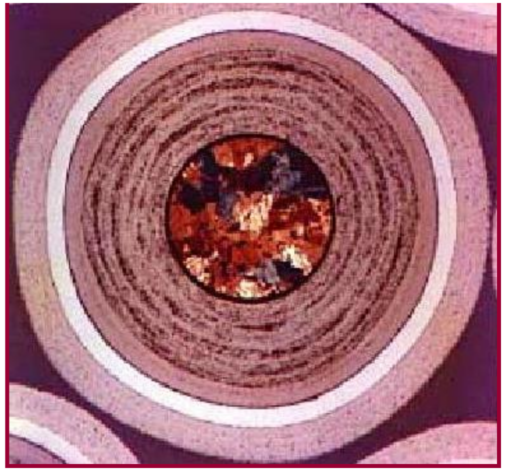
Economic Basis for Salt Reactors I: Higher-Temperature Heat to Power Cycles and Industry

Coolant	Average Core Inlet Temperature (˚C)	Average Core Exit Temperature (˚C)	Ave. Temperature of Delivered Heat (˚C)
Water	270	290	**280**
Sodium	450	550	**500**
Helium	350	750	**550**
Salt	**600**	**700**	**650**

C. W. Forsberg. Market Basis for Salt-Cooled Reactors: Dispatchable Heat, Hydrogen, and Electricity with Assured Peak Power Capacity, *Nuclear Technology*, 206 (11), 1659-1685, November 2020. https://doi.org/10.1080/00295450.2020.1743628

Economic Basis for FHRs II: Safety Case that Minimizes Capital Costs (To be Demonstrated)

- Fuel can withstand high-temperatures (>1700˚C) with high boiling point coolant (>1400˚C) that traps fission products
- No accidents in core—vessel fails first
- Low-pressure system, no high-pressure or gas-generation to release radionuclides
- Confinement building rather than containment building
- Simple decay heat removal because of high temperature fuel and coolant



FHR History: ORNL, MIT and Berkeley

2024

	Electrified Thermal Solutions (MIT Startup) (Nuclear Air Brayton Combined Cycle)
Integrated Research Project III	MIT, Berkeley, NCSU, and ORNL
Kairos Power (UCB Startup)	Parallel Development Using Salt: Commonwealth Fusion (MIT Startup)
Integrated Research Project II	MIT, Berkeley, Wisconsin, U. New Mexico
Integrated Research Project I	MIT, U.C. Berkeley, U. Wisconsin
Oak Ridge National Laboratory	Included work at U.C. Berkeley and SNL

Concept of FHR (Forsberg, Peterson and Pickard)

FHR Initial Development at ORNL (Pre-IRP) with U.C. Berkeley and Sandia National Laboratory

- ORNL has a long history of working on molten salt reactors and high-temperature gas-cooled reactors
- **People knew both technologies**
- Indicated economic potential

D. Ingersoll, C. W. Forsberg, L. J. Ott, D. F. Williams, J. P. Renier,, D. F. Wilson, S. J. Ball, L. Reid, W. R. Corwin, G. D. DelCul, P. F. Peterson, H. Zhao, P. S. Pickard, E. J. Parma, and M. Vernon, Status of Preconceptual Design of the Advanced High-Temperature Reactor (AHTR), ORNL/TM-2004/104, May 2004

First Integrated Research Project (2011: DOE/NE)

Fluoride-salt-cooled High-temperature Reactors (FHRs)
for Power and Process Heat

C. W. Forsberg (MIT)
Lin-wen Hu (MIT)
Per F. Peterson (U. of California at Berkeley)
Kumar Sridharan (U. of Wisconsin)

Charles Forsberg, Lin-wen Hu, Kumar Sridharan, and Per F. Peterson, Fluoride-salt-cooled High-temperature Reactor (FHR) for Power and Process Heat: Final Project Report, MIT-ANP-TR-157, Massachusetts institute of Technology, Cambridge, Massachusetts, December 2014. https://www.osti.gov/servlets/purl/1183687

Major IRP-I Outcomes

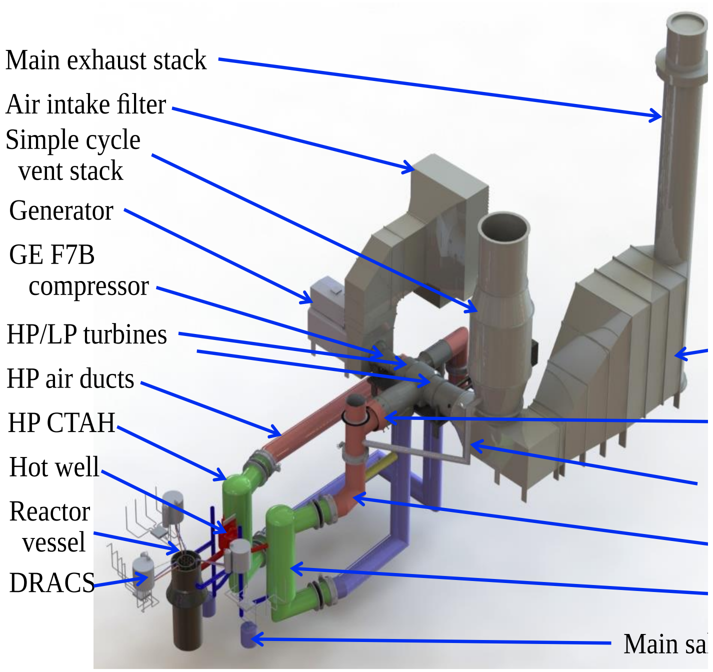
Analytical Studies

- Commercial basis: FHR with Nuclear Air Combined Cycle (NACC) to boost revenue by 50% over traditional reactors: base-load reactor with dispatchable electricity (MIT)
- Point design of FHR (UCB)
- Test reactor strategy

Experimental

- Thermal hydraulics test loop with organic simulants (UCB)
- Salt corrosion tests, non-radioactive (UW)
- Materials irradiation in flibe salt (MIT reactor)

Activities from First FHR IRP



Commercial Strategy and Markets (MIT)

↓

Commercial Reactor Point Design (UCB)

↓

Test Reactor Goals, Strategy and Design (MIT)

↓

Technology Development (MIT/UCB/UW)

a.

b.

c.

Salt Materials ←Irradiations (MIT)

Dowtherm Hydraulic→ Experiments (UCB)

Second Integrated Research Project (DOE/NE)

Integrated FHR Technology Development: Tritium Management, Materials Testing, Salt Chemistry Control, Thermal Hydraulics and Neutronics, Associated Benchmarking and Commercial Basis

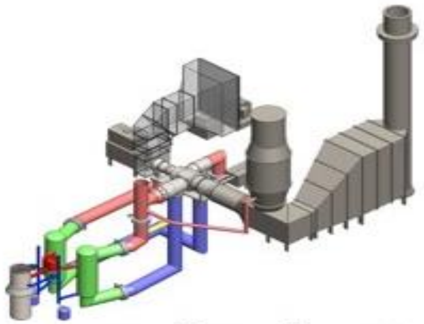
C. W. Forsberg and Lin-wen Hu (MIT)
P. F. Peterson and M. Fratoni (U. of California at Berkeley)
K. Sridharan (U. of Wisconsin)
A. Kant Prinja (U. of New Mexico)

- C. W. Forsberg, P. F. Peterson, K. Sridharan, Lin-wen Hu, M. Fratoni, A. Kant Prinja, Integrated FHR Technology Development: Tritium Management, Materials Testing, Salt Chemistry Control, Thermal Hydraulics and Neutronics, Associated Benchmarking and Commercial Basis (IRP report), Massachusetts Institute of Technology, MIT-ANP-TR-180 (October 2018) https://www.osti.gov/servlets/purl/1485415/

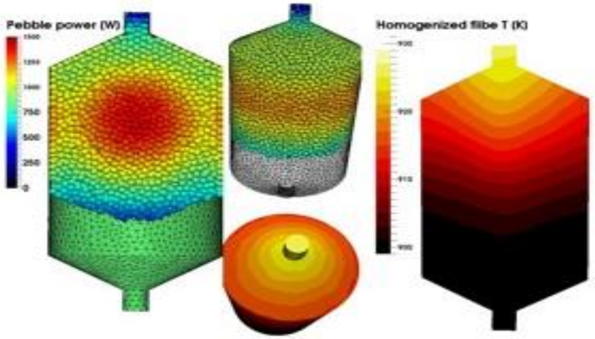
Major IRP-2 Outcomes

- Experiments and tritium systems model (MIT)
- Thermal hydraulics integrated tests: Dowtherm (UCB)
- Flibe corrosion testing: external and in-reactor (UW/MIT)
- Benchmarking
- Commercialization (Kairos Power)

Activities from Second FHR IRP



Conceptual Design Studies



Coupled Neutronics and Thermal Hydraulics

Separate and integral effect tests

Corrosion Test Loops

In Reactor Materials Testing

Benchmarking

Kairos Power formed in 2016 to Commercialize FHR

University of California Berkeley Spinout

- Design, build, test development strategy
- Building Hermes test reactor in Oak Ridge (35 MWt)
- Kairos Power / Google Agreement for first 5 commercial reactors

Hermes Test Reactor Under Construction in Oak Ridge, Tennessee

Third Integrated Research Project (DOE/NE)

Molten Salt Reactor Test Bed with Neutron Irradiation (Underway)

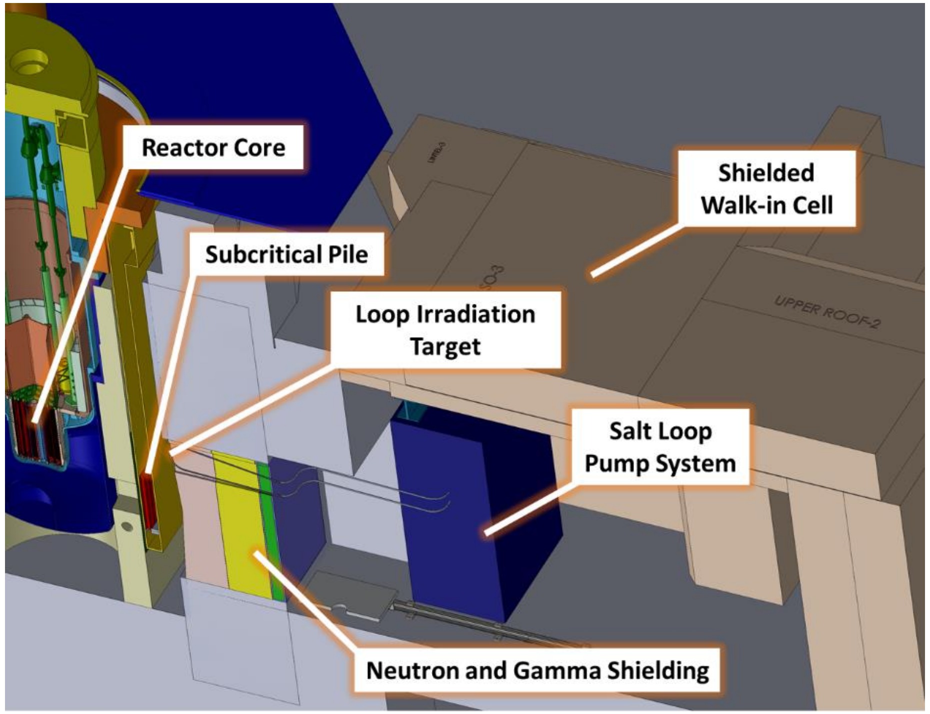
C. W. Forsberg and D. Carpenter (MIT)
R. O. Scarlat (U. of California at Berkeley)
A. Hawari (North Carolina State University)
K. Robb (Oak Ridge National Laboratory)

MIT Has Initiated the Design and Construction of a Flowing Salt Loop at MIT Reactor: Operational 2025

- **Goal is forced circulation salt loop for the MIT reactor (6 MWt)**
  - Neutron & gamma irradiation
  - Heated and cooled
  - Fully instrumented
  - 1000 hours operation
- **Instrumentation for salt loops, experiments and power reactors**
  - U.C. Berkeley developing redox sensors
  - NCSU developing off-gas sensor system for MSR-salt with uranium (Irradiating uranium in salt for realistic off-gas at NCSU)

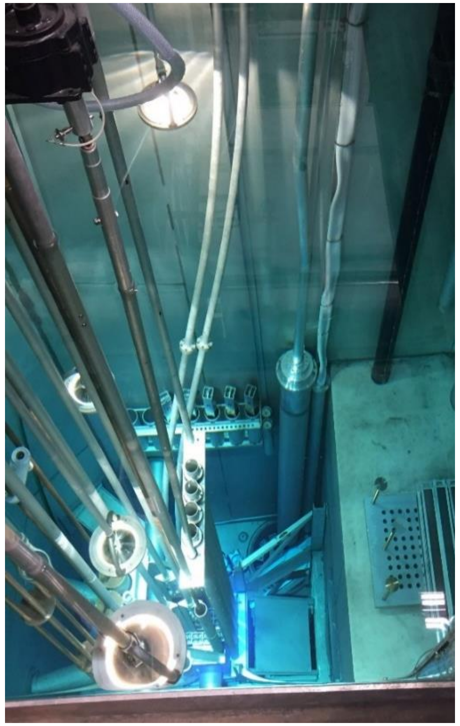
Activities for Third IRP

Flowing Salt Loop in the MIT Reactor



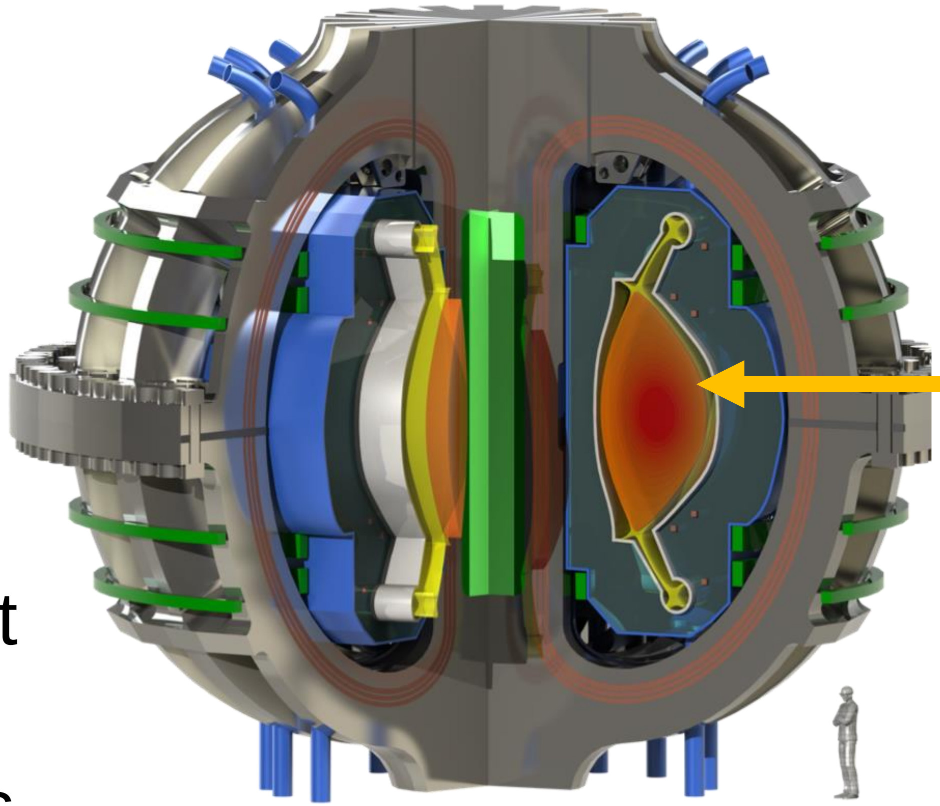
On-Line Instrumentation for Salt Loops at U.C. Berkeley

Molten Salt with Uranium Off-gas Measuring System at NCSU Pulstar Reactor

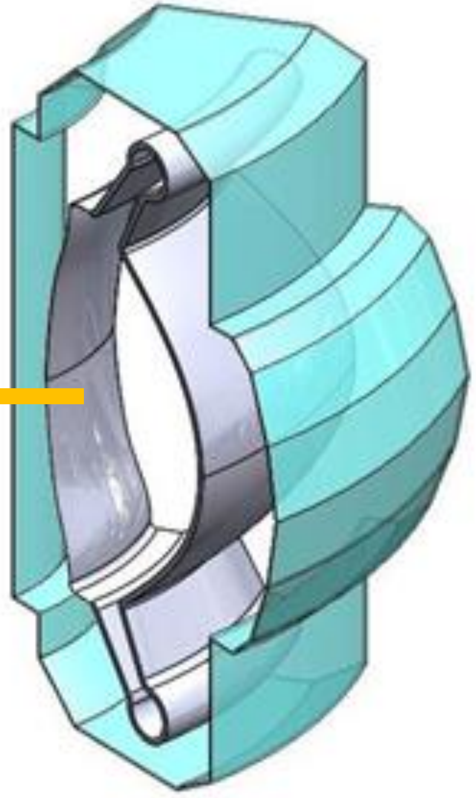


Parallel Development: MIT Spinout: Commonwealth Fusion formed in 2018 to Commercialize Fusion with Flibe Salt Blanket

- MIT develops ARC fusion system based on REBCO superconductor with flibe salt blanket
- MIT and Commonwealth Fusion (spin-out company from MIT) start development
- Creates massive incentives to develop flibe salt systems for fusion



ARC



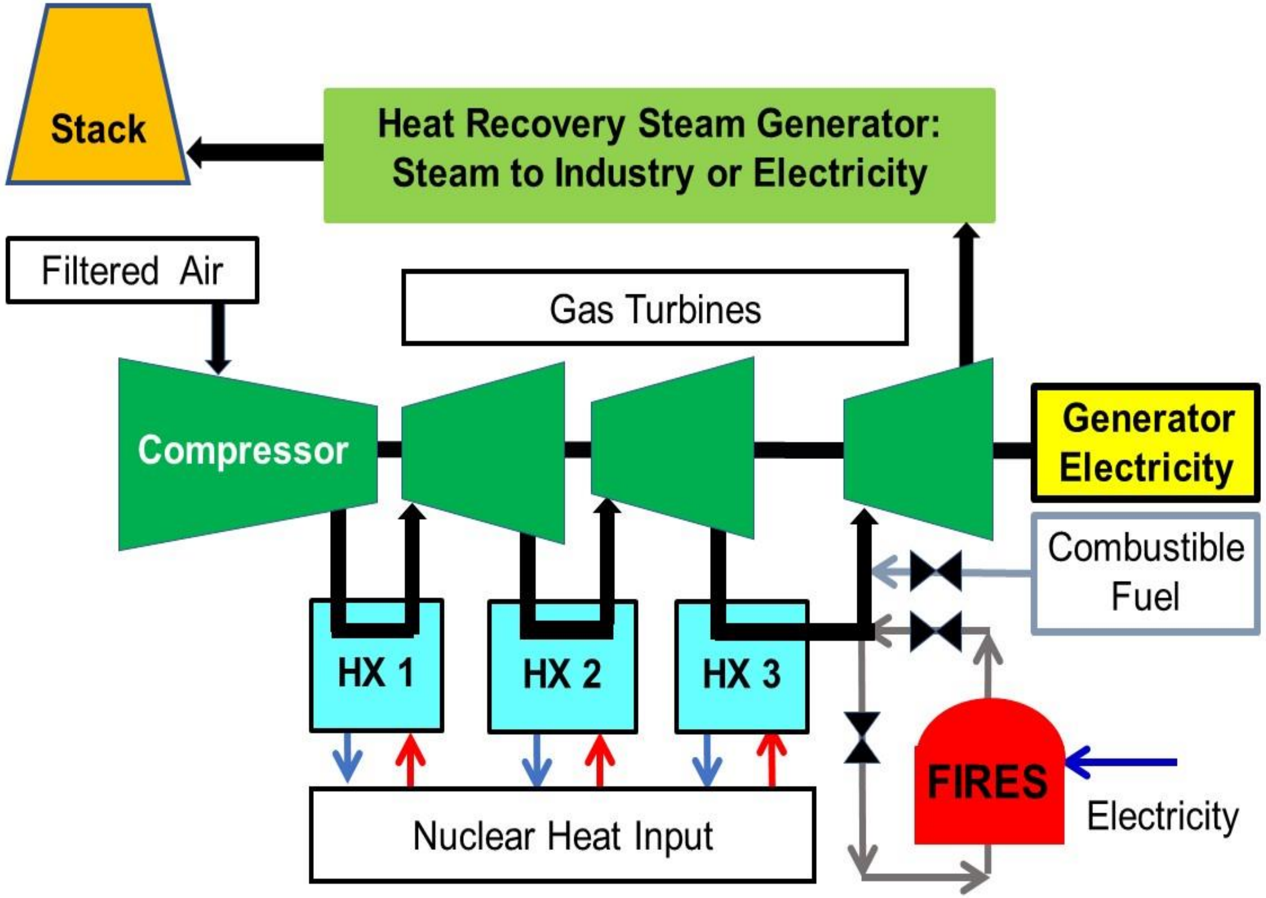
Flibe Salt Blanket

https://www.newyorker.com/magazine/2021/10/11/can-nuclear-fusion-put-the-brakes-on-climate-change

Electrified Thermal Solutions: MIT Spinout

Electrically Conductive Firebrick to Heat Firebrick to 1800˚C (Forsberg & Stack)

- Electricity-to-heat storage temperature match natural gas combustion temperature.
- Developed to enable Nuclear Air-Brayton Combined Cycle with high temp. heat storage
- Variable electricity to the grid with base-load salt reactor and high high-temperature stored heat to maximize revenue



1. C. Forsberg and D. C. Stack, *Electrically Conductive Firebrick System*, U.S. Patent: 11,877,376 B2. January 16, 2024. https://image-ppubs.uspto.gov/dirsearch-public/print/downloadPdf/11877376; 2. Electrified Thermal Solutions, https://electrifiedthermal.com/

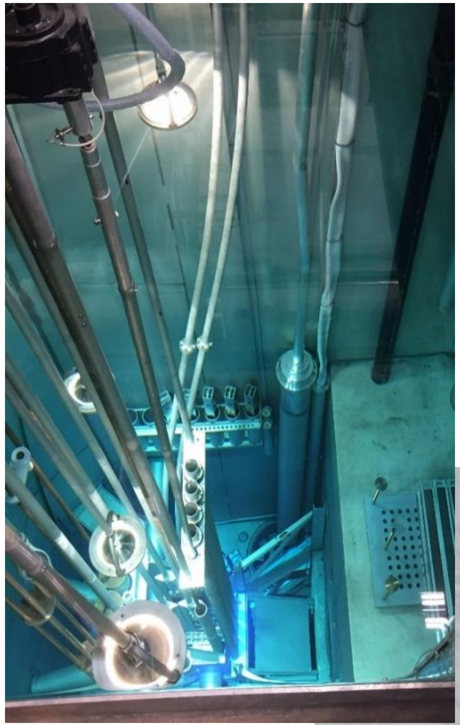
3. C. W. Forsberg, P. J. McDaniel, and B. Zohuri, Nuclear Air-Brayton Power Cycles with Thermodynamic Topping Cycles, Assured Peaking Capacity and Heat Storage for Variable Electricity and Heat, *Nuclear Technology*, 207 (4), 543-557, April 2021.; https://doi.org/10.1080/00295450.2020.1785793

Observations From Developing the FHR and IRPs

E

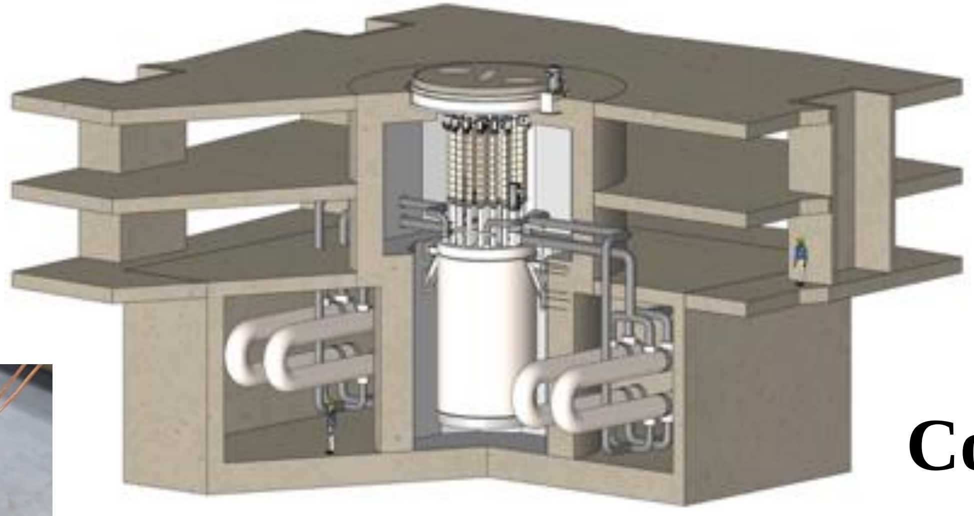
- **Economics must be considered from the beginning**
- It takes a lot of good people to succeed and multiple institutions (ORNL, SNL, MIT, Berkeley)
- Random events have major impacts. Nobody would buy a movie script of FHR development history because so many "not credible" events occurred
- Need to document what worked and equally important what does not work to reduce development costs and time

Questions

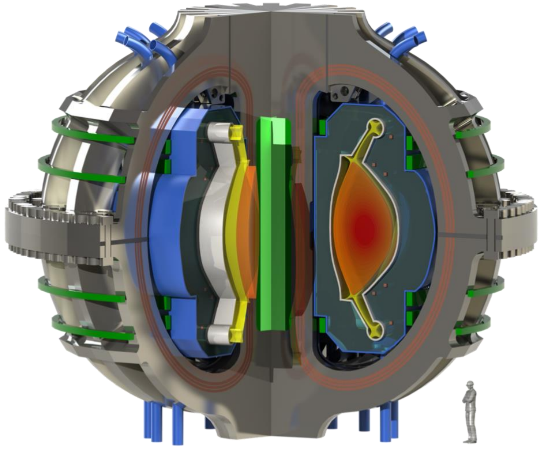


NCSU

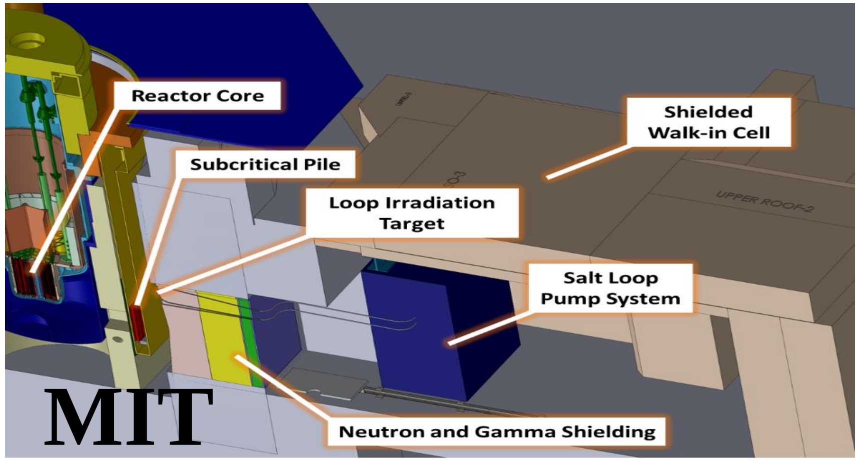
UCB



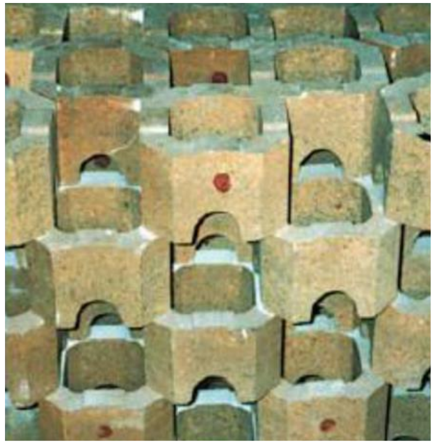
Kairos Power



Commonwealth Fusion



MIT



Electrified Thermal Solutions

Added information (backup): Pebble bed UNF fuel safeguards lower than LWR SNR, Reducing waste management cost and Fissile fuel production options