Integrated Research Project FHR Overview for DOE Nuclear Energy Advisory Committee

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

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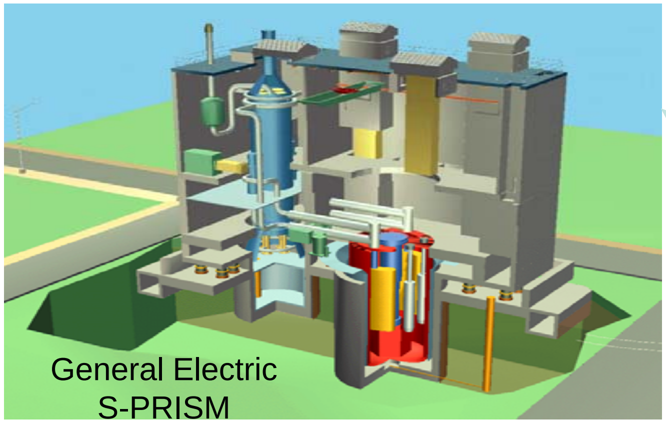
Fluoride Salt-Cooled High-Temperature Reactor (FHR)



Passively-Safe Reactor

GE Power Systems 7FA Gas Turbine

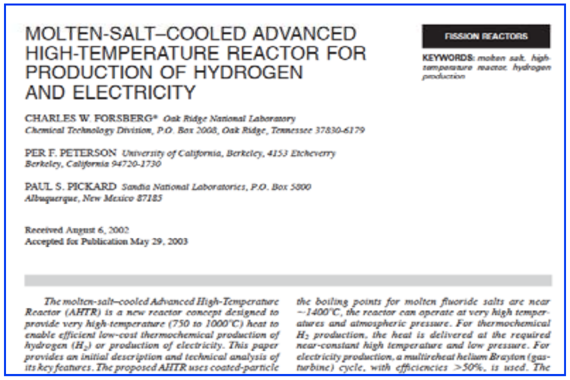
Nuclear Air-Brayton Combined Cycle

High-Temperature Coated-Particle Fuel

High-Temp., Low-Pressure Liquid-Salt Coolant (Transparent)

FHR Historical Timeline

- Original concept: 2000
- Early studies: 2000-2010
  - ORNL (Forsberg), Peterson (UCB), INL
- UW salt work initiated 2006
- IRP Proposal: Early 2011
- **Fukushima: March 2011**
- **Chinese Academy of Science: 2012**
  - **Decision to build 2-MWt FHR test reactor by 2017**
  - **Technical staff >400 people**
  - **Project management team built Chinese version of ANL Advanced Light Source**
- **American Nuclear Society ANS 20.1 FHR safety standard working group formed: 2012**



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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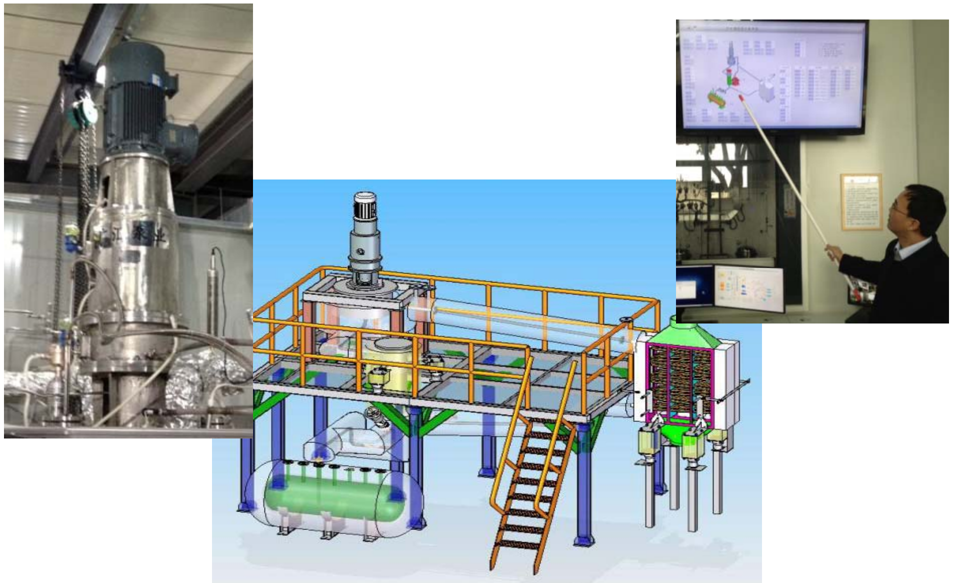
The molten-salt–cooled Advanced High-Temperature Reactor (AHTR) is a new reactor concept designed to provide very high-temperature (750 to 1000°C) heat to enable efficient low-cost thermochemical production of hydrogen (H_2) or production of electricity. This paper provides an initial description and technical analysis of its key features. The proposed AHTR uses coated-particle

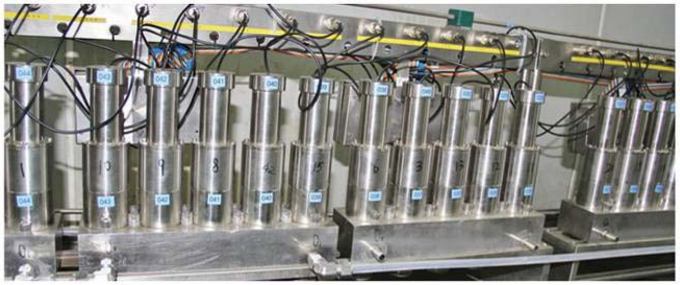
the boiling points for molten fluoride salts are near ~1400°C, the reactor can operate at very high temperatures and atmospheric pressure. For thermochemical H_2 production, the heat is delivered at the required near-constant high temperature and low pressure. For electricity production, a multireheat helium Brayton (gas-turbine) cycle, with efficiencies >50%, is used. The

SINAP is Developing a 2-MWth FHR Experimental Reactor by 2017

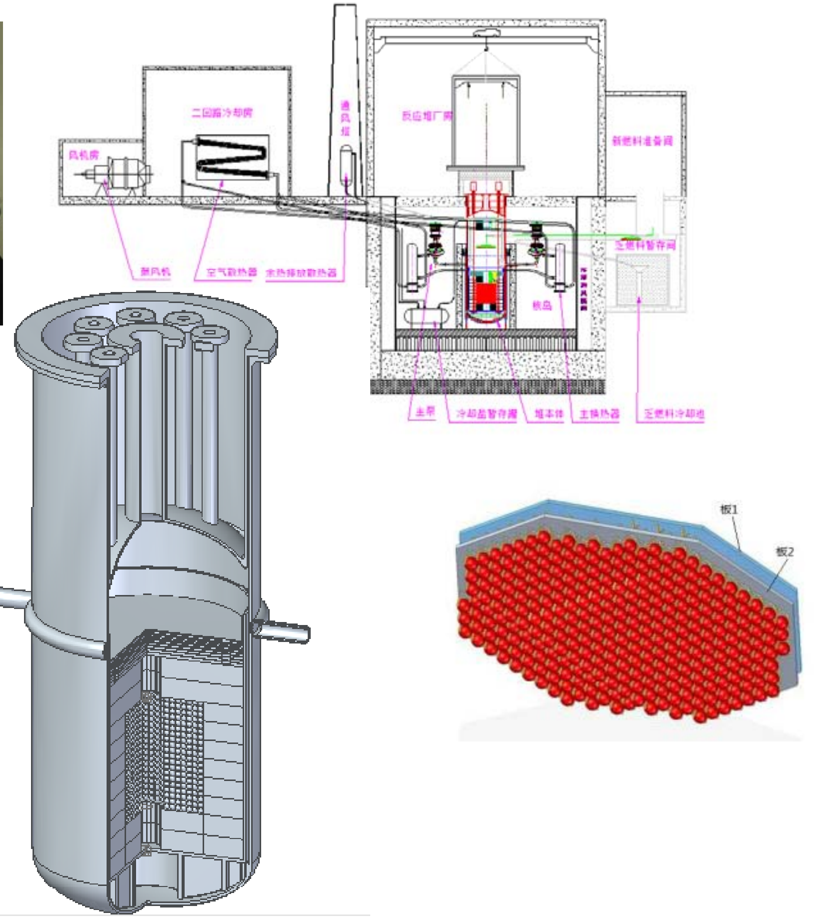
Uses solid pebble fuel, plans fluid fuel for subsequent reactors



SINAP Flinak loop (2013)



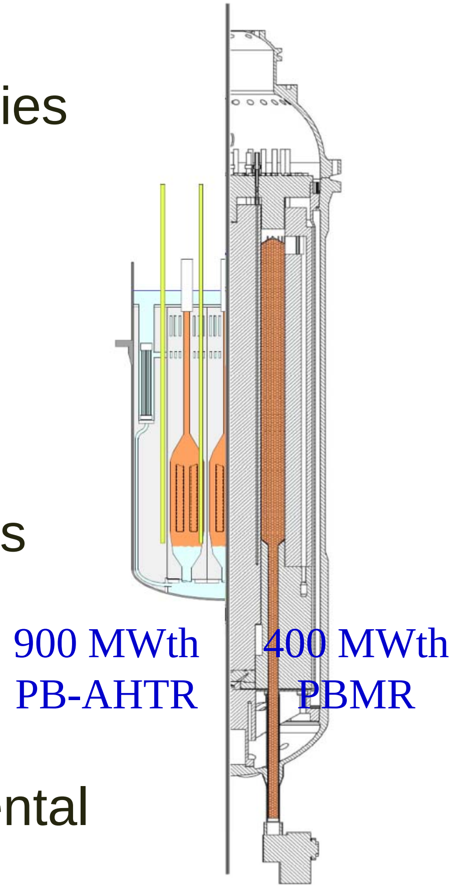
Crown-ether Li-7 enrichment demonstrated (2013)



Intermediate term (2017): TMSR-SF1 experimental reactor w/ ordered pebble bed

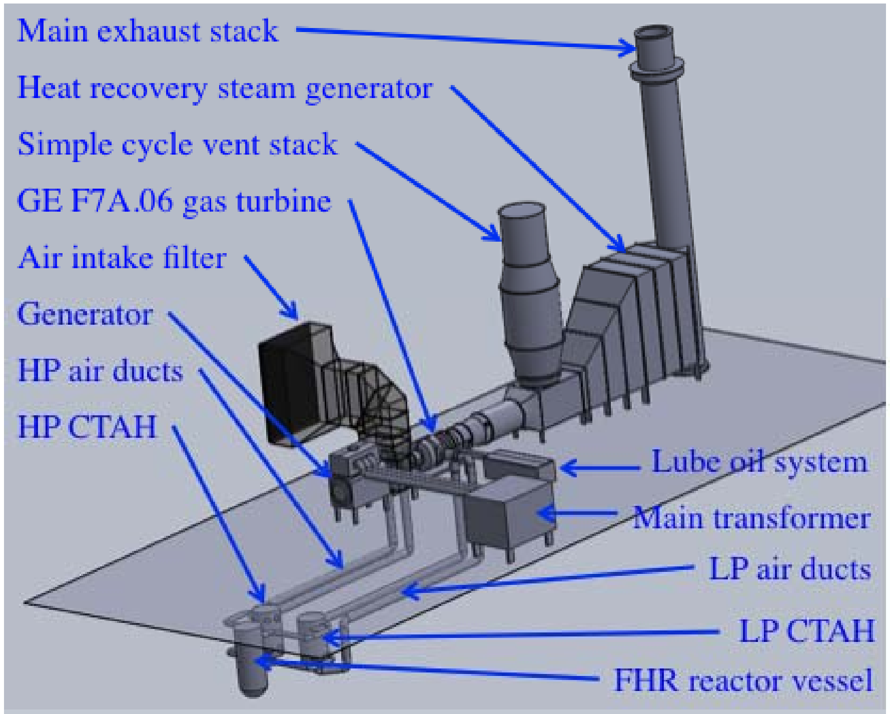
The motivation to study FHRs

- Low pressure/high power density address key issues for helium-cooled HTRs
  - Leverages existing U.S. fuel and materials capabilities
- Low pressure/high temperature enable potential improvement vs. ALWRs
  - Design and license using same codes as ALWRs
  - Low pressure gives compact reactor buildings
  - High temperature enables use of gas Brayton cycles
- Key learning experience for young U.S. researchers
  - Opportunities to design and simulate new experimental facilities, including the CAS TMSR-SF1
  - Opportunity to learn fundamental principals for reactor safety



IRP FHR Uses a Nuclear Air-Brayton Combined Cycle (NACC) Power System

- Similar to natural-gas combined cycle plants
- Only FHRs couple to NACC because of 350 to 500°C exit temperature from standard air compressor
- Current baseline:
  - GE F7A.06 gas turbine
  - Conventional heat recovery steam generator
  - 245 MWth reactor power
  - 104 MWe baseload
  - 240 MWe peaking (with gas co-firing)



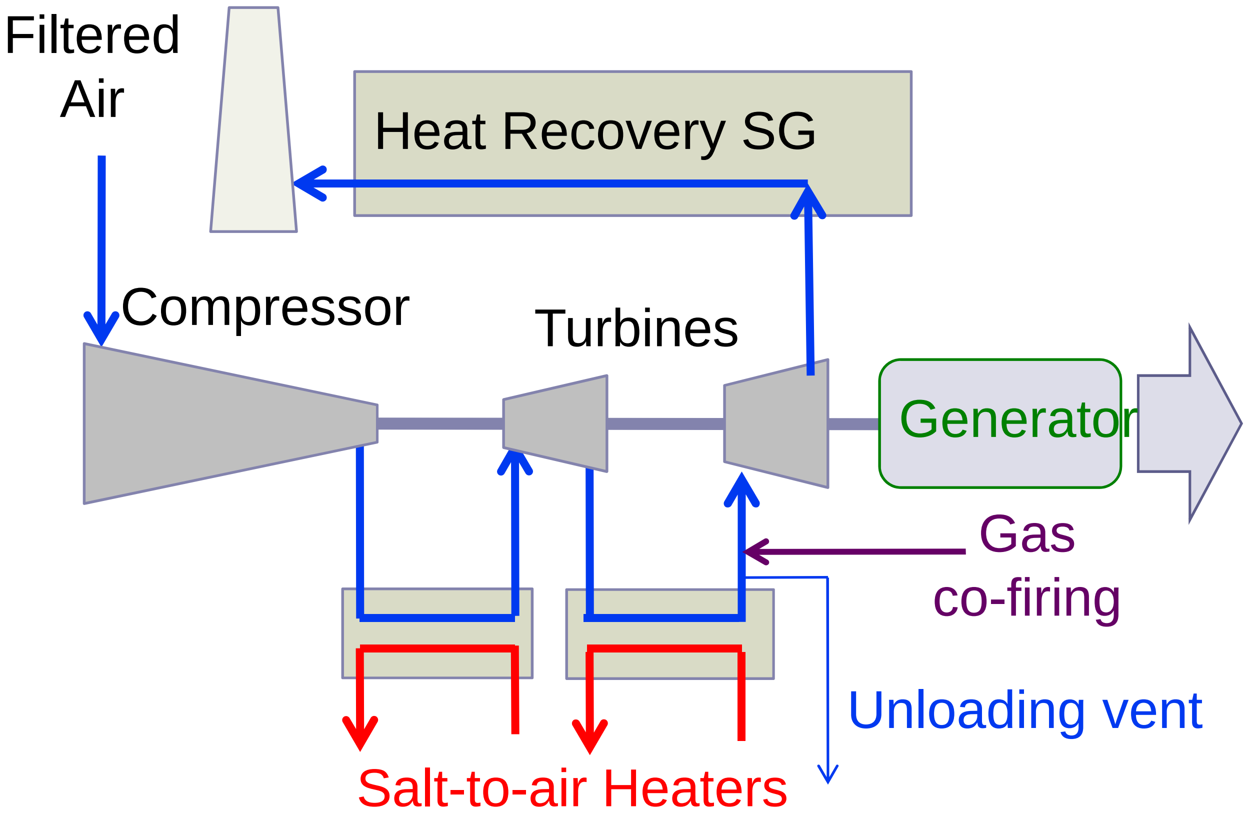
FHR Couples to NACC, Super-Critical CO_2 and Steam: NACC Baseline Chosen to Meet Goals and Boost Revenue

Commercial Basis for FHR

MIT Lead

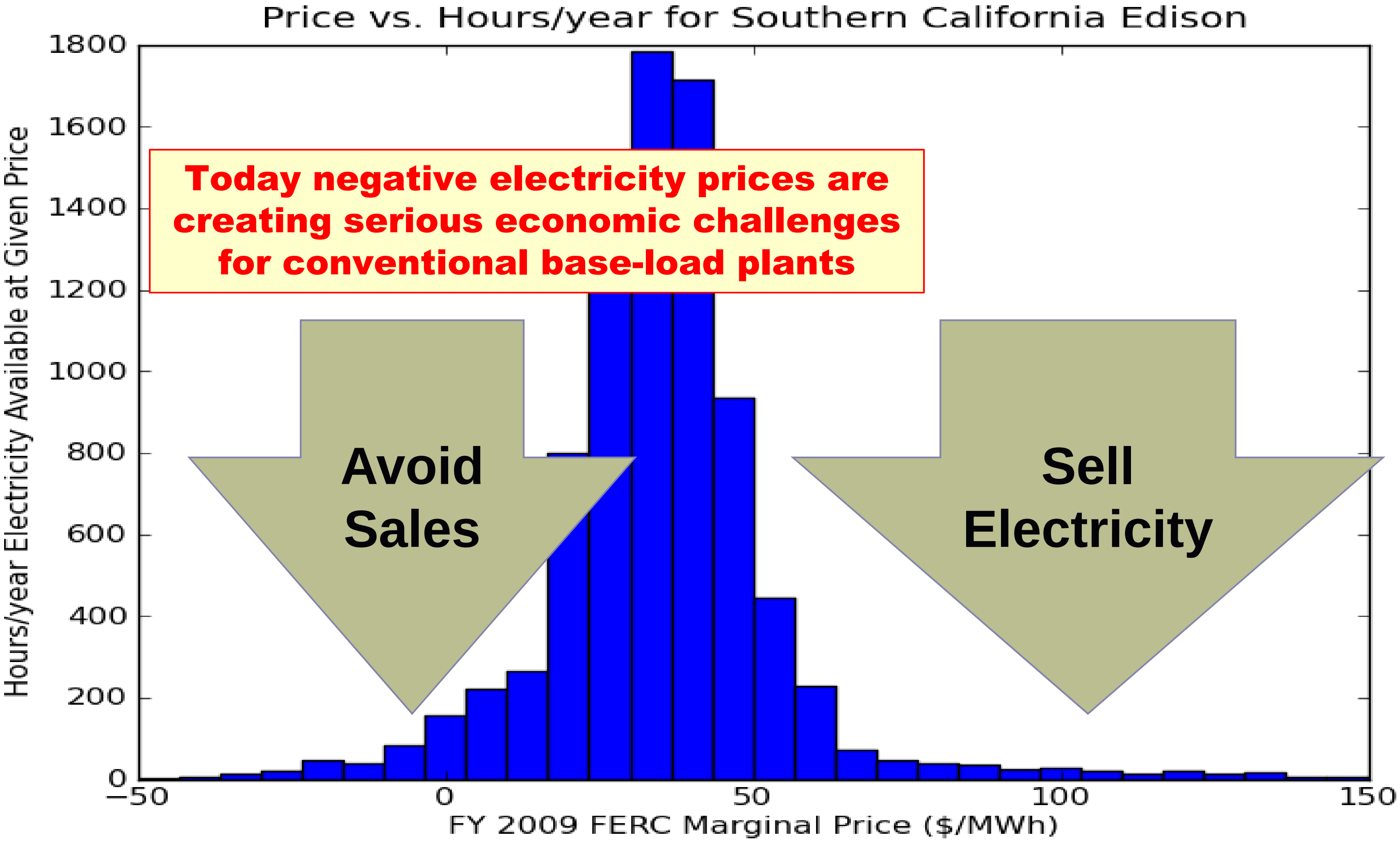
(More details in May 7 NEAC NRT Subcommittee briefing)

NACC Power System Maximizes Revenue in a Low-Carbon Nuclear-Renewable Future



- **Base-load electricity**
- **Peak electricity with natural gas assist**
- **Sell steam if low electricity prices**
- **Stabilize grid with rapid response**

>50% Increase in Plant Revenue With NACC Versus Base-Load Plant



Today negative electricity prices are creating serious economic challenges for conventional base-load plants

Avoid Sales

Sell Electricity

UW-MIT Materials Testing

(More details in May 7 NEAC NRT Subcommittee briefing)

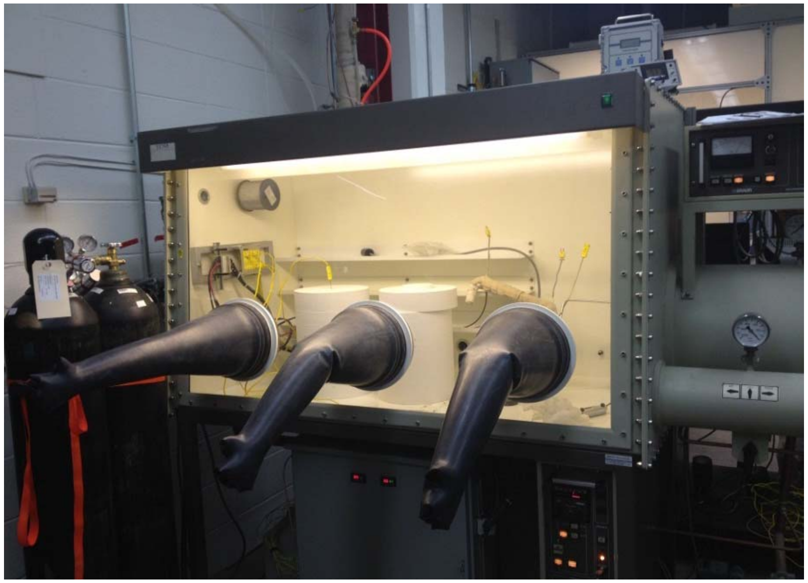
MIT and UW Division of Work

Identical Experiments with/without Neutrons to Sort Out Chemical Effects from Radiation Effects at 700°C

Wisconsin	MIT
Corrosion Models	Primary Systems Models
Out of Reactor Test Loops	In-core MIT research reactor irradiations at temperature
Small and Large Tests (No reactor limits)	Small tests: Volume Constraints in Reactor
No Radiation	Full Neutron Flux

UW and MIT Completed Work for Starting Flibe Salt Experiments

Experiments starting following delivery of DOE flibe salt



UW Out-of-Reactor Experiments

MIT In-Reactor Experiments

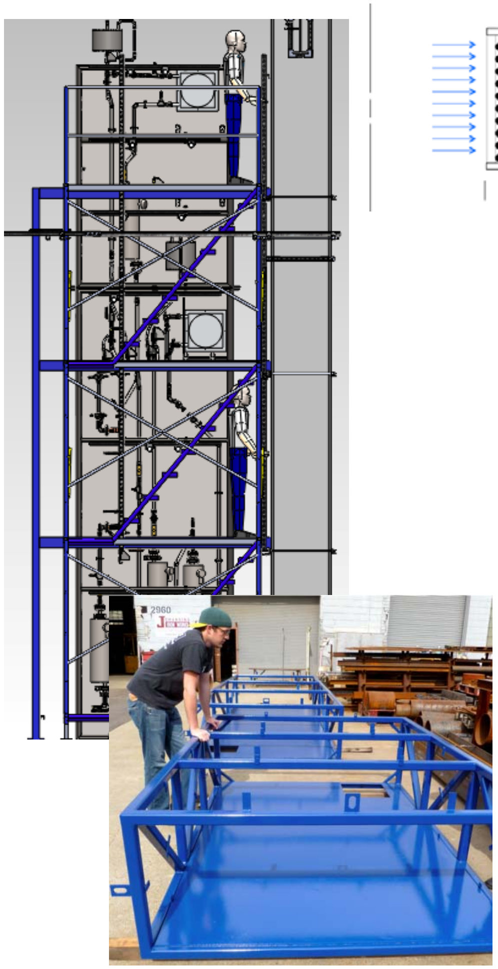
←MIT Irradiation Capsule

UCB FHR Thermal Hydraulics and Neutronics

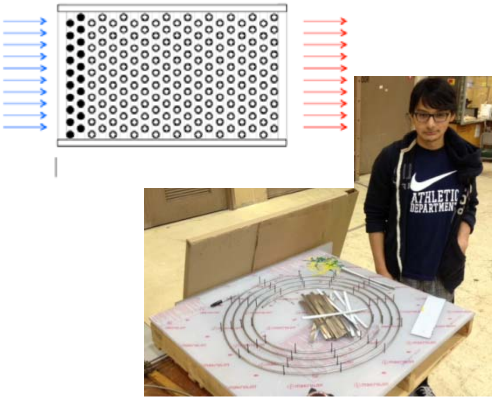
(More details in May 7 NEAC NRT Subcommittee briefing)

UCB work includes TH experiments

Pebble Recirculation Experiments



Compact Integral Effects Test (i.e. “APEX” for FHR)



Coiled tube air heaters

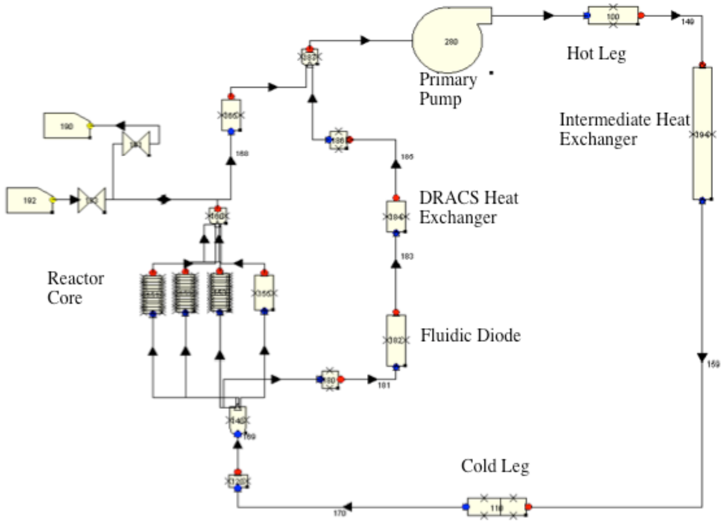
Pebble friction

Pebble heat transfer

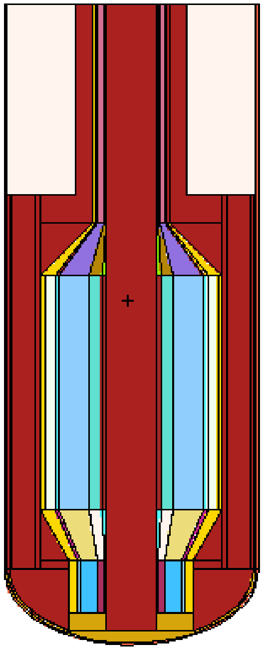
Natural circulation

Various Separate Effects Tests

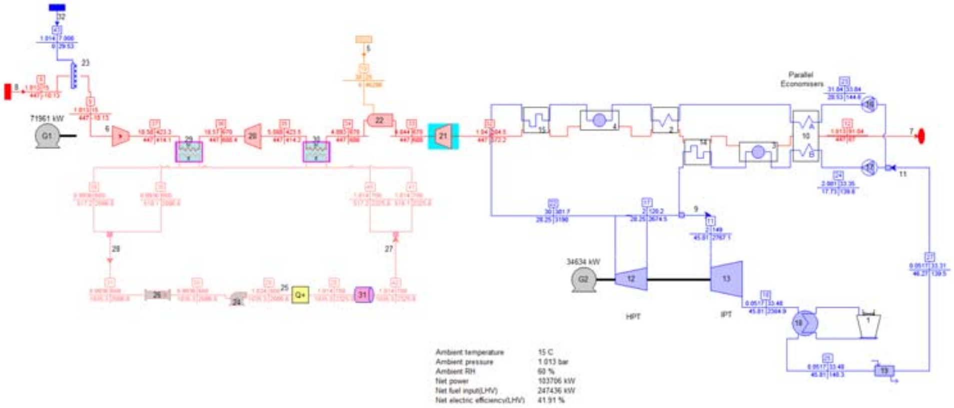
UCB Modeling and Simulation



RELAP/Flownex (Reactor Thermal Hydraulics)



MCNP/Origen/BEAU
(Neutronics/Depletion)



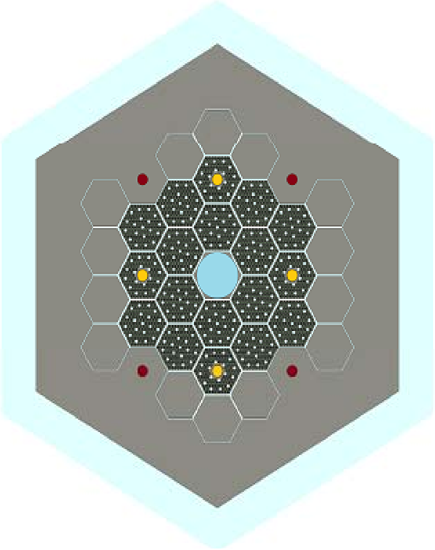
Thermoflex (Power Conversion)

Fluoride-salt-cooled High-temperature Test Reactor: FHTR

(MIT Lead)

The FHTR Equivalent of Dragon:
The First HTGR
20 MWt: United Kingdom
1964-1975

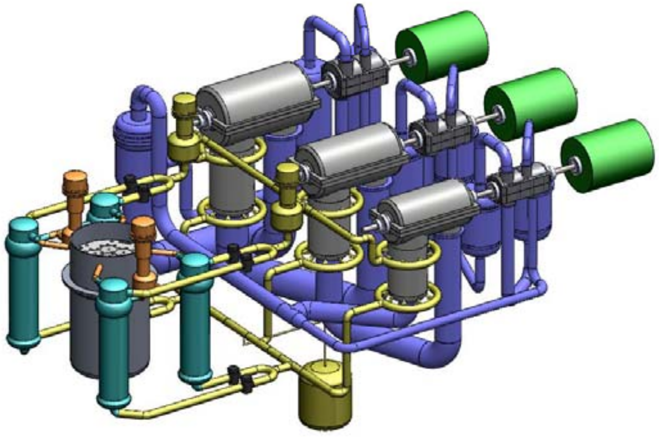
Current FHTR Design Requirements



- Peak flux 3X maximum commercial FHR
- Minimum cycle length of 0.5 y
- Negative power and void coefficients of reactivity
- Capability to operate with either FLiBe or NaF-ZrF_4 coolant
- Full assembly-sized in-core irradiation position for fuels testing for multiple fuel types (pebble, plate, other): a minimum of 40 L total volume in this position
- Multiple additional test positions for high-temperature materials irradiations
- Less than 20% U-235 enrichment with TRISO fuel

Commercial Reactor Design

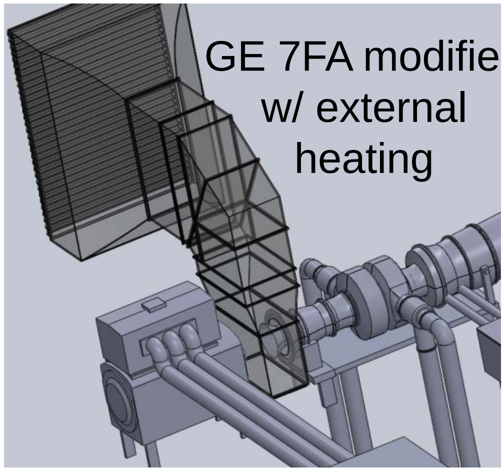
UCB Lead



Goal is to update the
2008 UCB point design

High-Level Functional Requirements for UCB PB-FHR Commercial Prototype Design

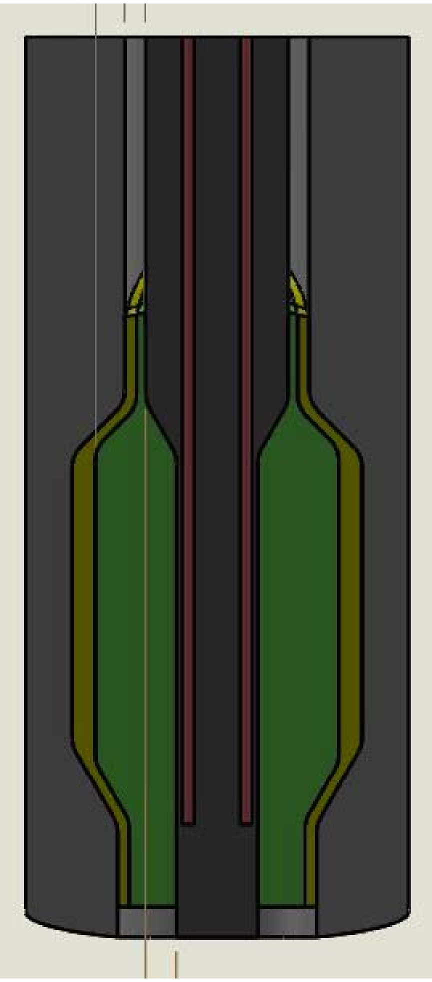
- Have capability to provide additional grid support services besides reliable nuclear base-load generation
  - Design to drive a credible nuclear air Brayton combined cycle (NACC) w/ natural gas co-fire
  - No alternative off-site power required
  - Capable to black-start grids
  - Use GE 7FA gas turbine
  - Validate performance predictions w/ Thermoflex


GE 7FA modified w/ external heating

- All components rail shippable
- Maximize the simplicity and credibility of the baseline design
  - Have credible strategies for:
    - In-service inspection and maintenance
    - Safety analysis and licensing
    - Materials and component development and procurement
  - Carry forward design alternatives where warranted

Nominal PB-FHR Design Parameters

- Annular pebble bed core with center reflector
  - Core inlet/outlet temperatures 600°C/700°C
  - Control elements in channels in center reflector
  - Shutdown elements cruciform blades insert into pebble bed
- Reactor vessel 3.5-m OD, 10.0-m high
  - Power density 3.5 x higher than S-PRISM
- Power level: 247 MWth, 103 MWe (base load), 240 MWe (peak w/ gas co-fire)
- Power conversion: GE 7FA gas turbine w/ HRSG
- Air heaters: Two 3.5-m OD, 8.0-m high CTAHs, direct heating
- Tritium control and recovery
  - Control: Kanthal coating on air side of CTAHs
  - Recovery: Compact flibe spray column



PB-FHR core and reflectors

Preconceptual design description by August, 2013

Path Forward

IRP Will Continue Engaging Students and Professors

- ~15 students working on IRP (masters and PhDs)
- Non-project students engaged
  - Part of design classes at MIT and UCB
  - Students in other departments with related projects
  - Workshops and other IRP projects involve other students
- Multiple professors beyond IRP principals
- **Key Question: What FHR Activities after 2014?**

4th FHR Workshop, MIT, Oct. 2012

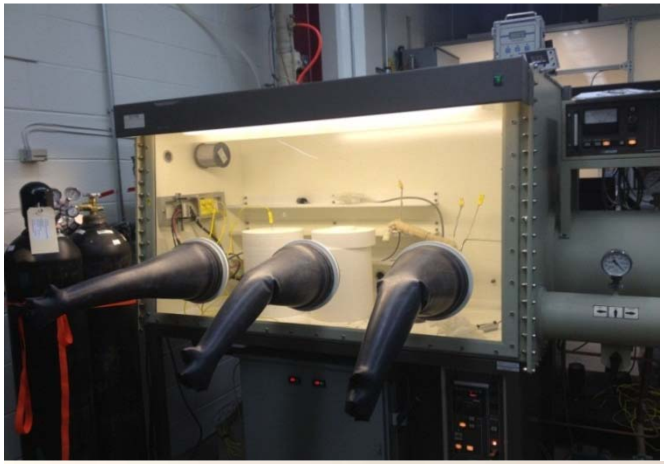
Large Incentive for the U.S. to Work With CAS

Selection soon for new SINAP campus for TMSR

- IRP working with CAS under DOE MOU
- Need for approval of TMSR/ORNL CRADA
- Plan for 2014 TMSR Summer School in Shanghai
  - Model on successful INL/ORNL MeV Summer School
- **Large incentive for agreement to exchange test reactor data for each side to validate their safety codes**

We Believe Strong Case to Continue DOE investment in FHR R&D Efforts

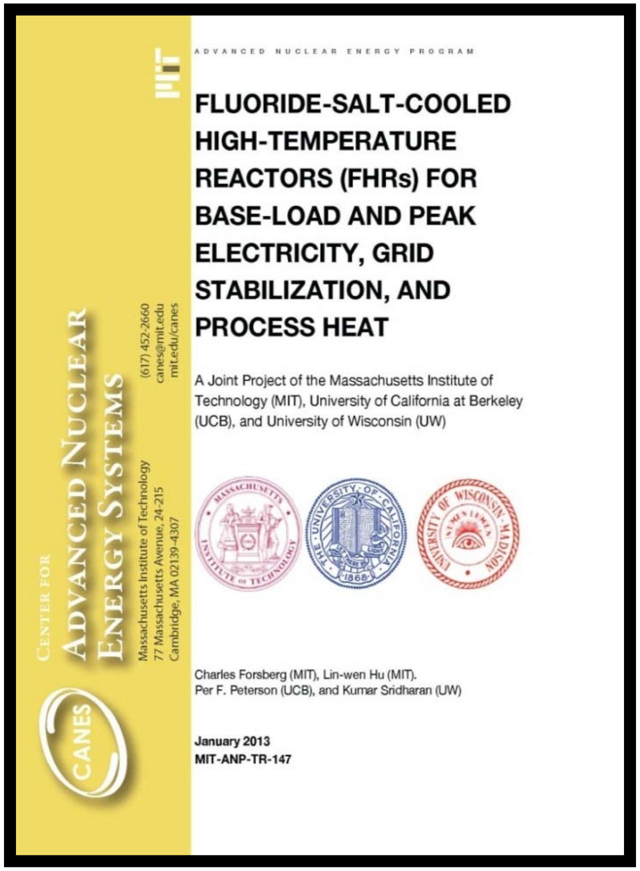
Major Facilities Being Built But Limited Data by End of IRP; More Time Required for Test and Irradiation Data



Includes Procedures, Approved QA plans, and Safety Analysis (Such MIT Reactor for 700°C Experiments)

Conclusions

- Developed strong and unique FHR market case
- Major experiments to begin this year
- ANS 20.1 FHR Safety Standard under development
- Engagement of universities, national laboratories, vendors and international collaborators
- Opportunities for students to study a new technology



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ADVANCED NUCLEAR ENERGY PROGRAM

FLUORIDE-SALT-COOLED HIGH-TEMPERATURE REACTORS (FHRs) FOR BASE-LOAD AND PEAK ELECTRICITY, GRID STABILIZATION, AND PROCESS HEAT

A Joint Project of the Massachusetts Institute of Technology (MIT), University of California at Berkeley (UCB), and University of Wisconsin (UW)

Charles Forsberg (MIT), Lin-wen Hu (MIT).
Per F. Peterson (UCB), and Kumar Sridharan (UW)

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Need to Work with DOE on the Actions Beyond the IRP