FHR MIT-IRP Overview

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

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Integrated Research Project Workshop
Berkeley, California
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For Public Distribution

IRP Objectives

The objective of our proposed new Integrated Research Project (IRP-2) is to address major challenges in the development of commercial Fluoride-salt-cooled High-temperature Reactor (FHR) technology: tritium control; fluoride-salt corrosion control and materials selection; thermal-hydraulics and neutronics; and evaluation model benchmarking

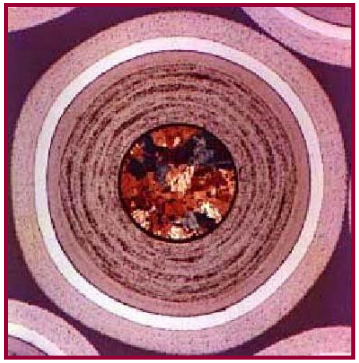
This talk also includes related developments at the four universities not part of the IRP

IRP Base-Case Design

Fluoride-Salt-Cooled High-Temperature Reactor

Nuclear Air-Brayton Combined Cycle and Firebrick Resistance-Heated Energy Storage

FHR Combines Existing Technologies



Fuel: High-Temperature Coated-Particle Fuel Developed for High-Temperature Gas-Cooled Reactors (HTGRs) with Failure Temperatures >1650°C

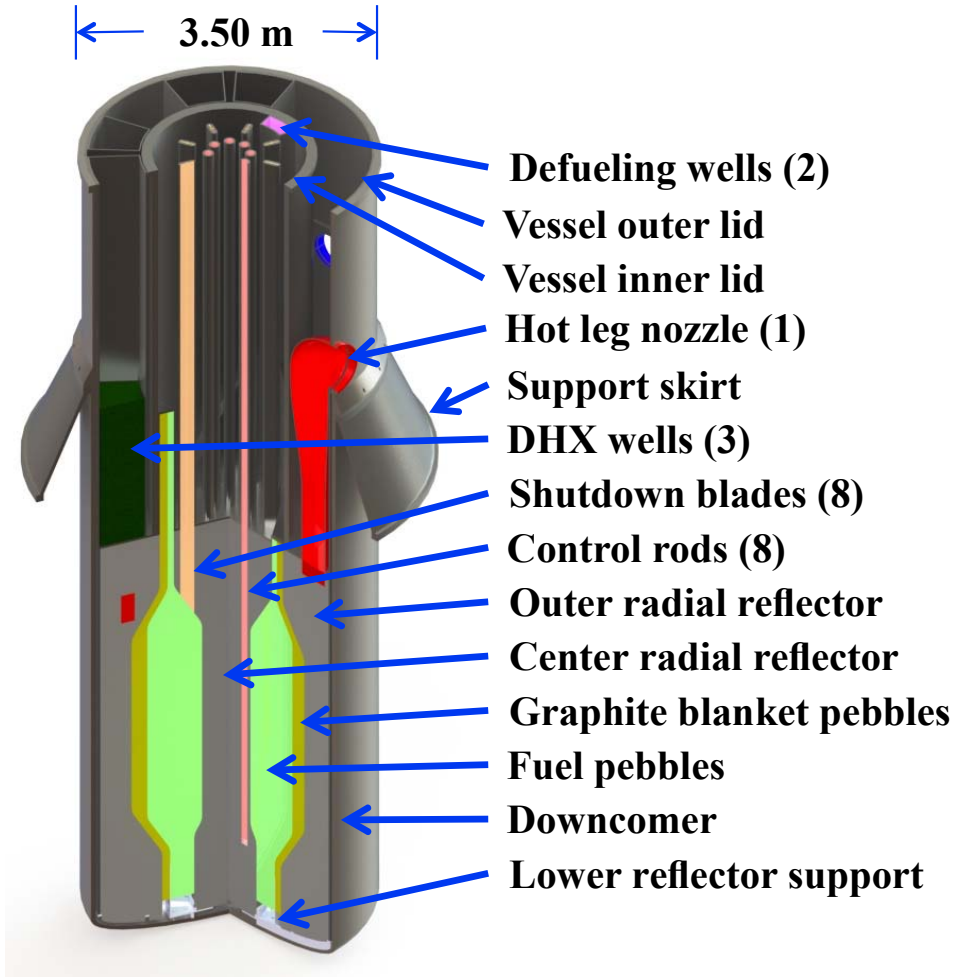
Coolant: High-Temperature, Low-Pressure Liquid-Salt Coolant ($^{7}Li_2BeF_4$) with freezing point of 460°C and Boiling Point >1400°C (Transparent)

Power Cycle: Modified Natural-Gas Air Brayton Power Cycle with General Electric 7FB Compressor

Base-line IRP FHR Design

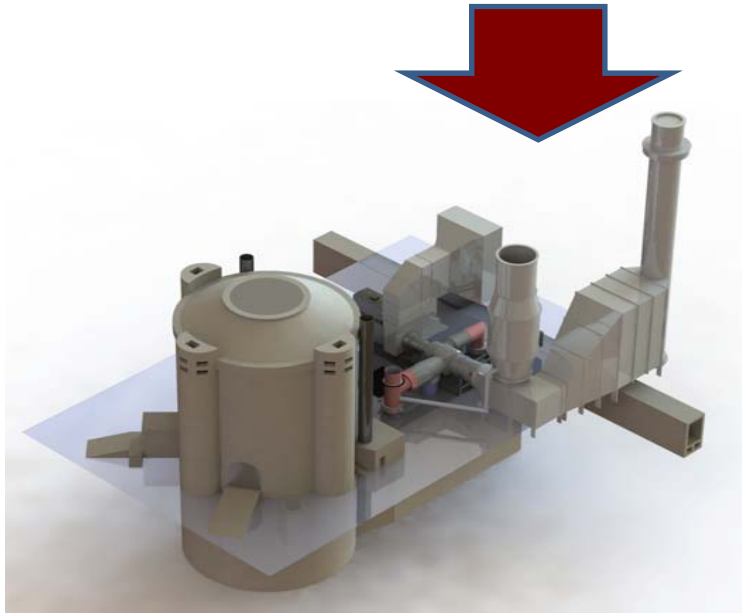
Alternatives Exist for Each Major Design Choice

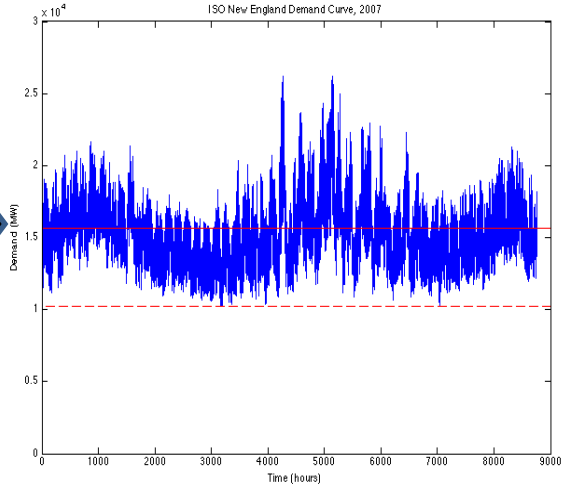
- Pebble bed graphite-matrix coated-particle fuel
- Clean flibe salt ($^7Li_2BeF_4$) coolant
- Nuclear Air-Brayton Combined Cycle (NACC)



Salt-Cooled Reactors With NACC Match Market Requirements

Stored Heat and/or Natural Gas





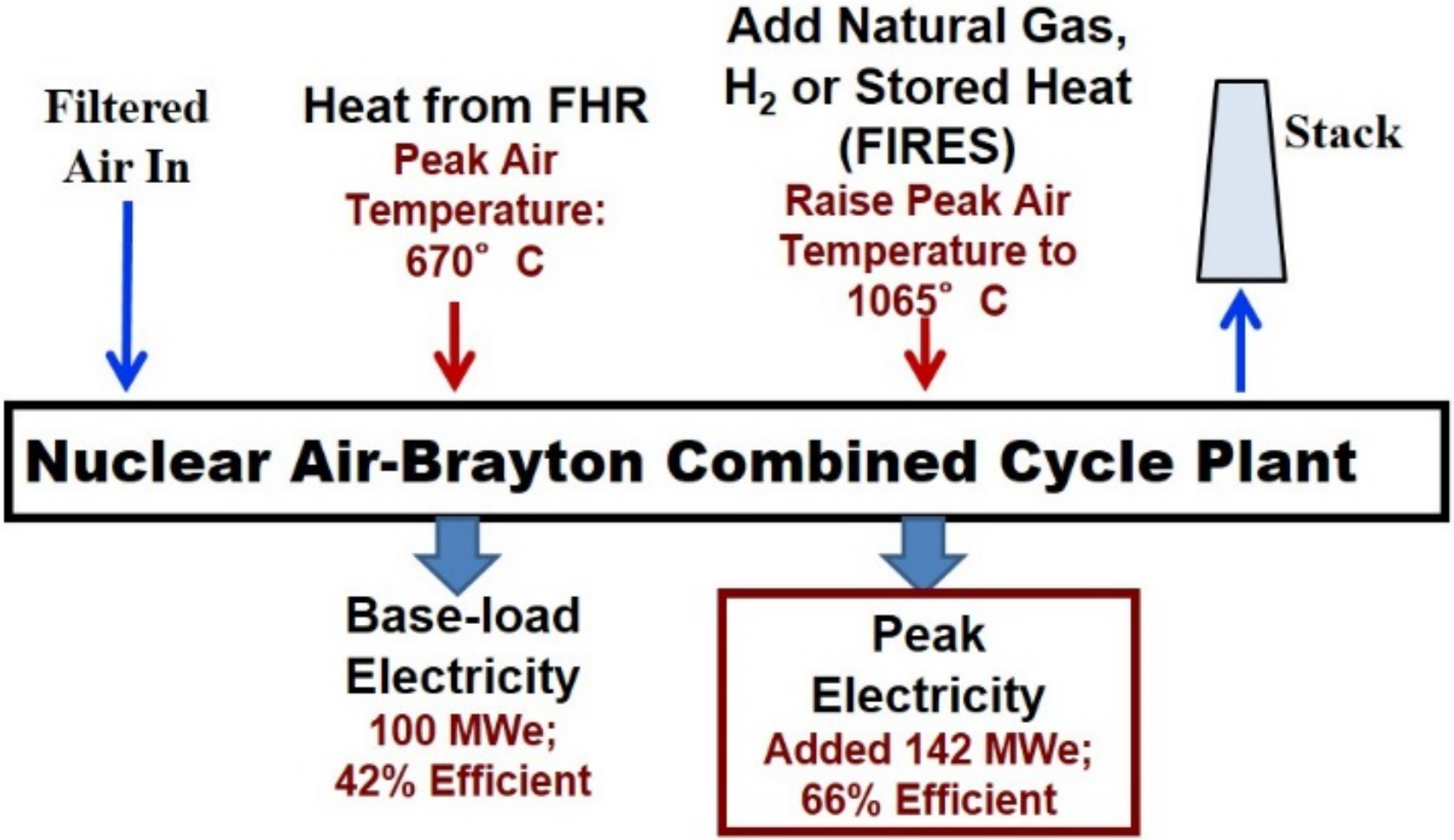
Base-Load Reactor

Gas Turbine

Variable Electricity And Steam

- **50 to100% Greater Revenue than Base-Load Plant**
- **Enable Zero-Carbon Energy System when Coupled to Heat Storage**

NACC for Variable Electricity Output



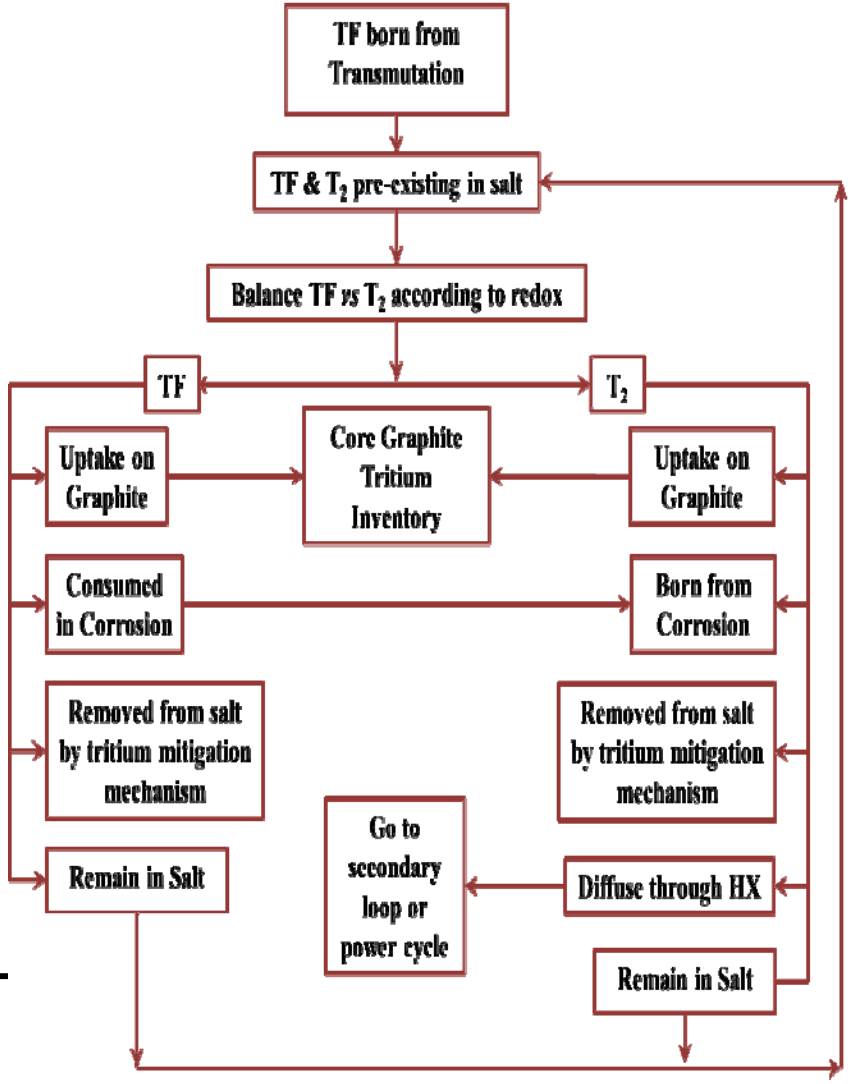
Topping Cycle: 66% Efficient for added Heat-to-Electricity: Stand-Alone Natural Gas Plants 60% Efficient

FHR Tritium Control

MIT and Wisconsin

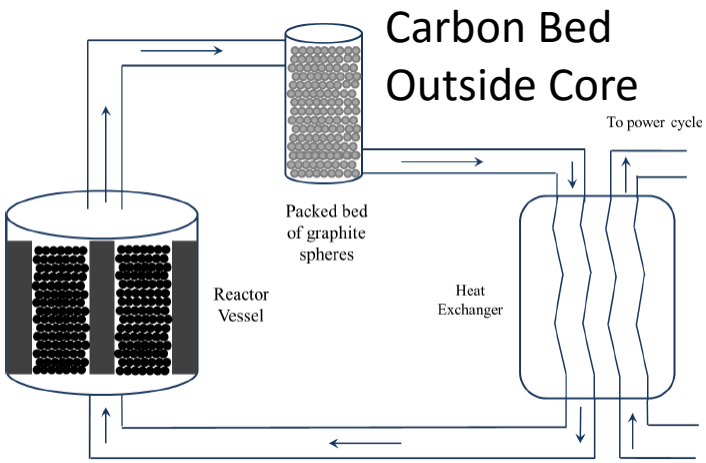
Work on Tritium Control Strategies

- Tritium Working Group (FHR, MSR, Fusion)
  - Integrate work across FHR, MSR, and fusion for tritium in 700°C salt
  - Salt Lake Workshop Oct. 2015 (Proc. available) on $^3H_2$ generation and control.
  - April 2016 Meeting at UCB
- Developed TRIDENT Model (Right)
- Experimental work underway
  - H_2 absorption on carbon at <1 Pa (MIT)
  - H_2 characterization on carbon (Wisconsin)
  - Materials Irradiation and $^3H_2$ sorption on multiple materials (MIT)
- Summary paper on Workshop website



Two Developments in Tritium Control

- Carbon has the potential to control tritium efficiently
  - Can remove tritium using nuclear-grade carbon bed
  - Nuclear-grade carbon designed to withstand neutron flux
  - If carbon bed outside core, different requirements allow use of other carbon forms that may improve tritium removal efficiency by orders of magnitude
- Carbon forms developed for fuel cells and catalysts that have nickel or noble metal particles
  - Faster tritium sorption
  - Expected to remove noble metals—a major challenge for MSRs



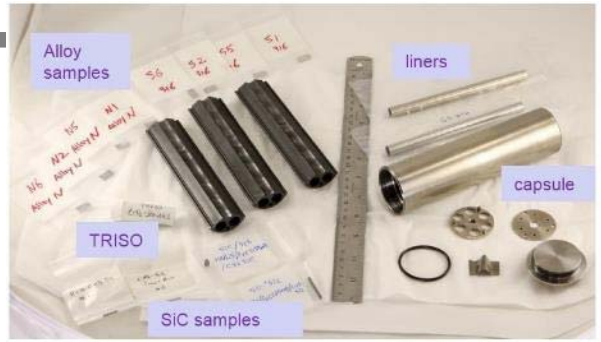
Platinum on Carbon (Courtesy of Tanaka, http://pro.tanaka.co.jp/en/products/group_f/f_5.html)

Fluoride-salt Corrosion Control and Materials Selection

MIT and Wisconsin

University of Wisconsin Focus: Materials Salt, Chemistry, and Electrochemistry, Materials Corrosion, and Flow Loop: FLiBe Salt

FLiBe Purification System



Picture of components for corrosion tests

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Purified FLiBe

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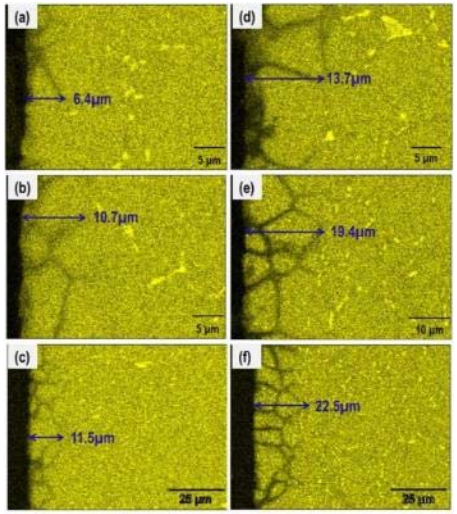
Assembled Capsule

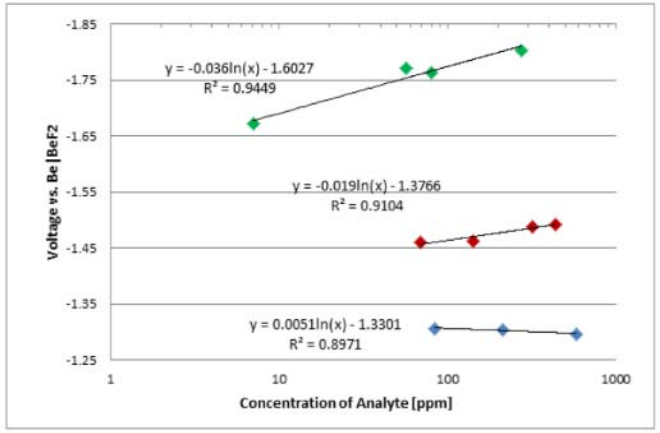


1000 hours

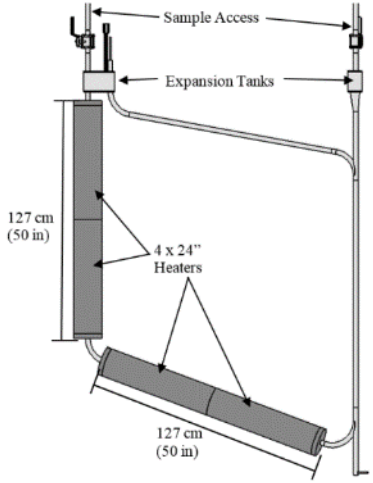
2000 hours

3000 hours

Materials Corrosion: 316 stainless steel



Electrochemistry: Changes in redox potential with impurity additions

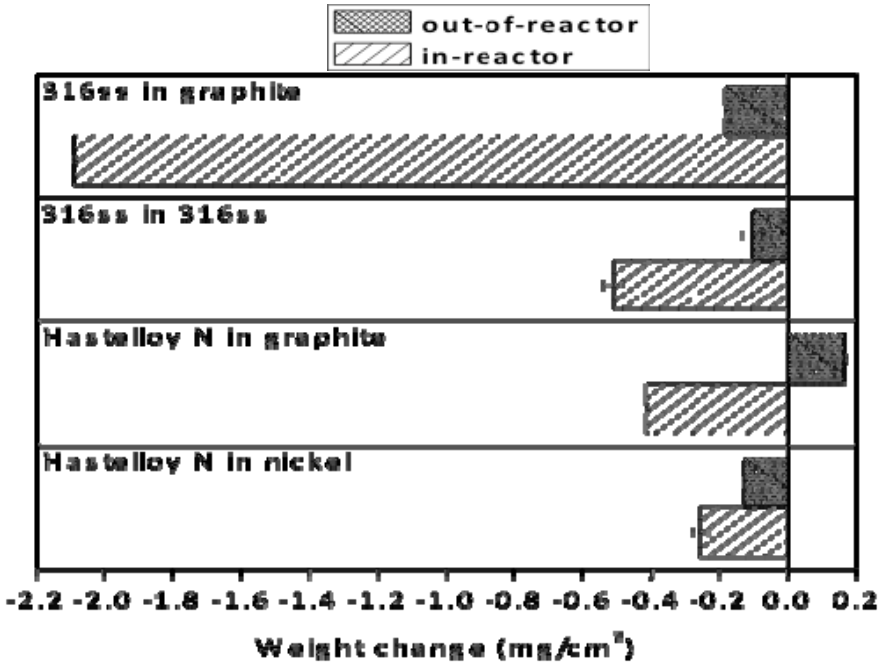


Molten FLiBe Salt Flow Loop: (under construction)

Massachusetts Institute of Technology

MIT Preparing Third Round of Integrated FLiBe Irradiation & Materials Exposure Tests

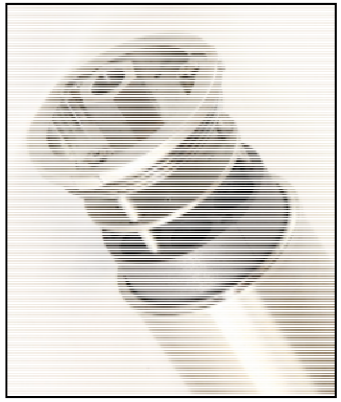
- MIT research reactor performed irradiations at 700°C. New irradiation facility with active heating is developed.
- New MIT lab space dedicated for handling irradiated flibe, FHR materials, and tritium.
- New custom-built tritium desorption and capture system can measure tritium in irradiated graphite.



Initial results indicated accelerated corrosion in in-reactor experiments compared to out-of-reactor experiments performed at UW.

Upcoming MITR FHR Irradiations

- Three types of experiments planned for IRP-2
  - Release of tritium and activation product gasses from flibe
  - Tritium uptake on graphite
  - Tritium diffusion through metals



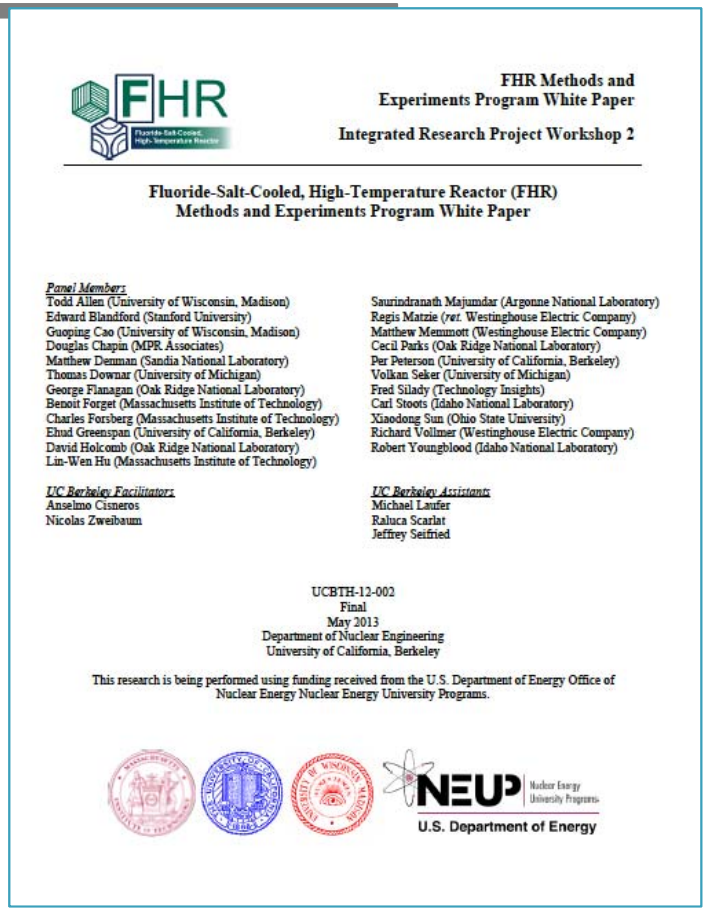
- Designing new experimental facilities based on lessons learned from the first two flibe irradiations
  - Control of salt condensates to prevent accumulation in gas lines
  - Off-gas holdup for short half-life decay (N^{16} and O^{19})
  - Avoiding <200°C radiolysis (fluorinated compound production)

Thermal-Hydraulics and Neutronics

Berkeley and U. of New Mexico

UCB is Developing the Technical Basis to Validate FHR Neutronic and Thermal Hydraulics codes

- FHRs differ from LWRs due to large thermal margin to fuel damage during design-basis accidents
  - LWR operating limits established by fuel-damage limits
  - FHR operating limits established by primary coolant boundary limits
- FHRs operate with lower coolant volumetric flow rates
  - Flow regimes commonly in transition or laminar regime
  - Single-phase flow unless gas entrainment occurs
- But LWR thermal hydraulics codes appear to work well for FHRs
  - Can leverage well established USNRC licensing approach for passive safety



FHR Methods and Experiments Program White Paper

Integrated Research Project Workshop 2

Fluoride-Salt-Cooled, High-Temperature Reactor (FHR)
Methods and Experiments Program White Paper

Panel Members
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Douglas Chapin (MPR Associates)
Matthew Denman (Sandia National Laboratory)
Thomas Downar (University of Michigan)
George Flanagan (Oak Ridge National Laboratory)
Benoit Forget (Massachusetts Institute of Technology)
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University of California, Berkeley

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U.S. Department of Energy

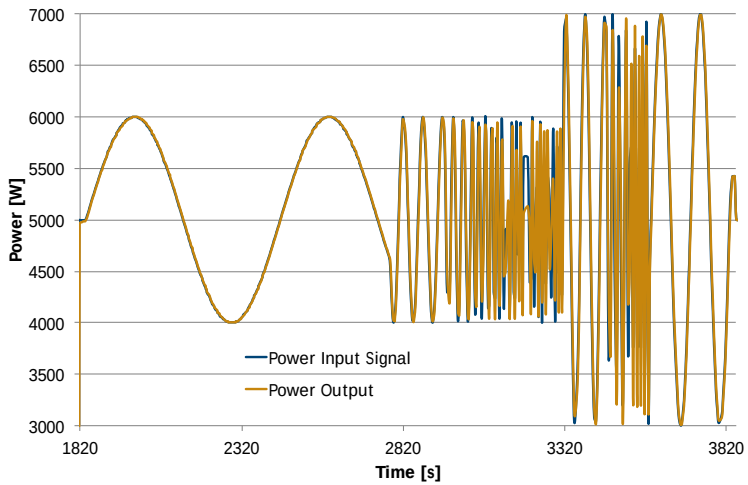
IRP-1 expert workshops in 2012 developed recommendations for thermal hydraulics methods and validation for FHRs

UCB: Thermal Hydraulics

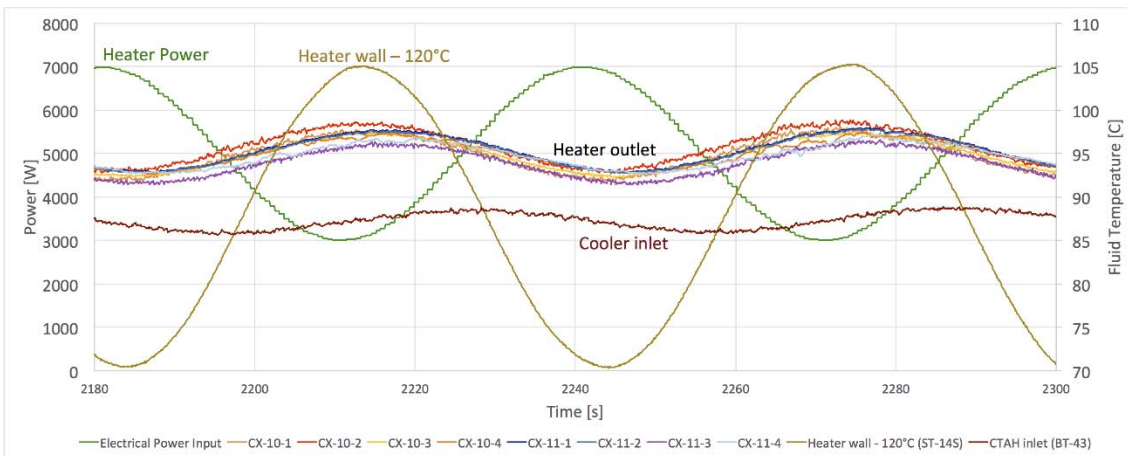
University of California at Berkeley

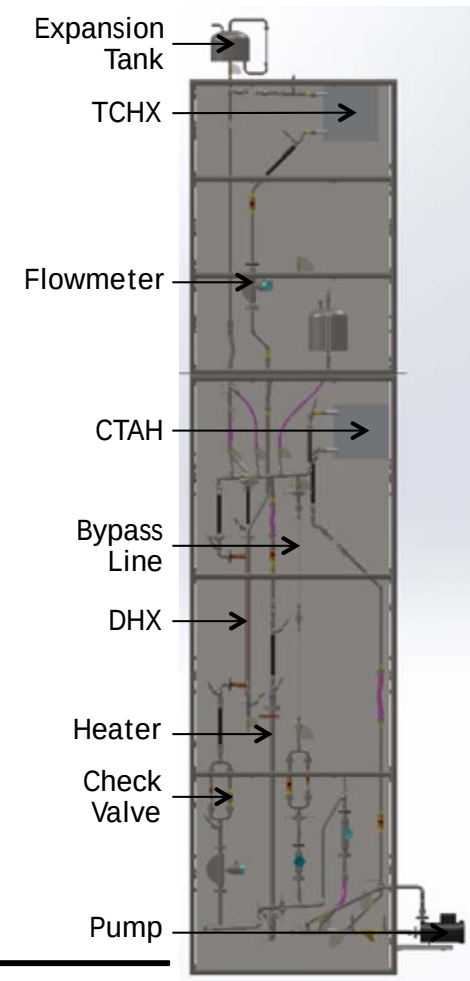
- New Capabilities
  - Dowtherm-A thermal hydraulics loops
  - NACC heat exchanger development
- Experimental basis for lower-cost validation of FHR thermal hydraulics codes

UCB Integral Effects Tests are now studying response to dynamic forcing



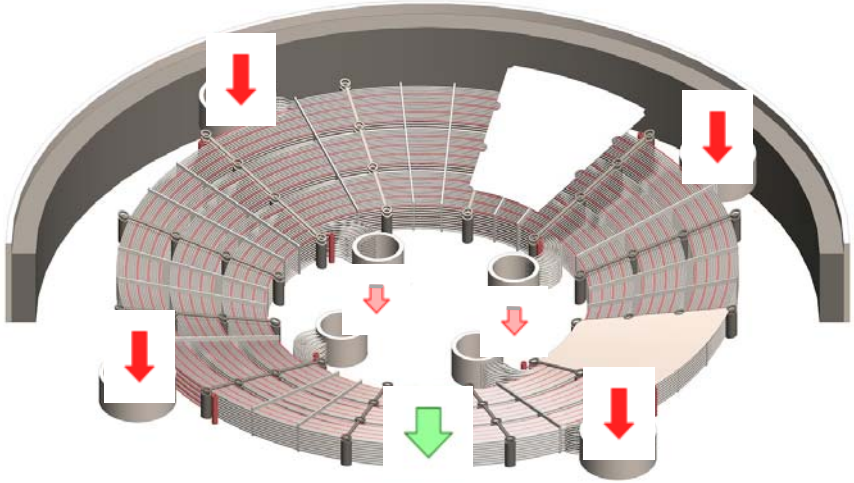
- Power oscillation in CIET is enabling study of transient thermal response of heat structures
- Future work will add power feedback to mimic core reactivity feedback phenomena, and will study the design of FHR control systems



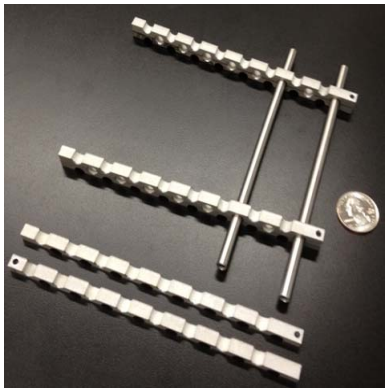


THEEM 1.0 is being developed to model CTGHs

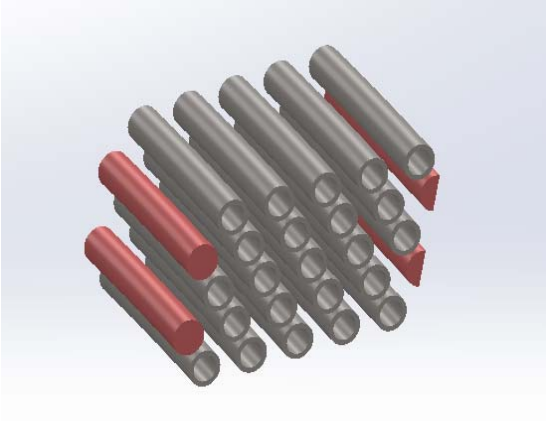
- Transverse Heat Exchange Effectiveness M
  - 2-D Finite Volume Simulation
  - Calculates
    - Effectiveness
    - Heat Transfer
    - Temperature Distribution of Liquid and Gas
    - Pressure drop of Liquid and Gas



Mk1 CTAH Subbundle

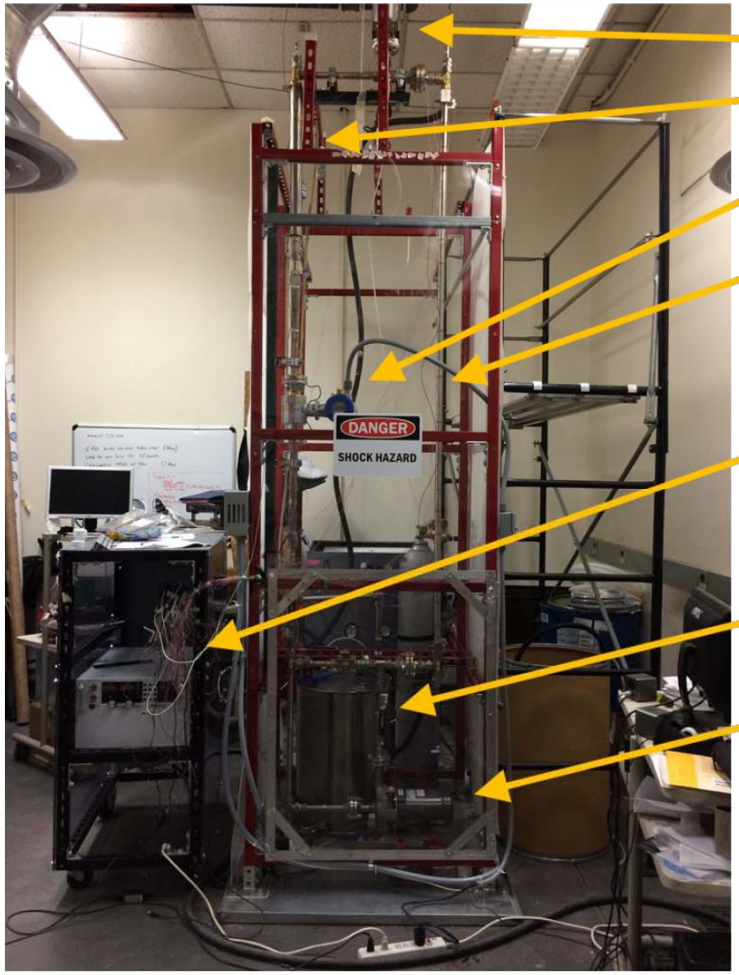


CTAH Heat Transfer Test Bundle



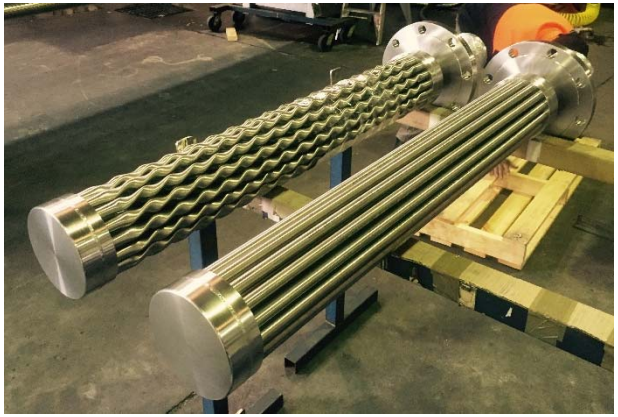
Typical THEEM control volume

University of New Mexico Experimental Heat Transfer Loop



Expansion Tank
Heat Exchanger
Flow Meter
Heated Section
Programmable Power Supply and DAQ Housing
Drain Tank
Pump

- Focus on heat transfer Separate Effects Tests using Dowtherm
  - Plain versus twisted tubes
  - Directional DRACS heat exchanger
  - Double-wall twisted-tube heat exchanger



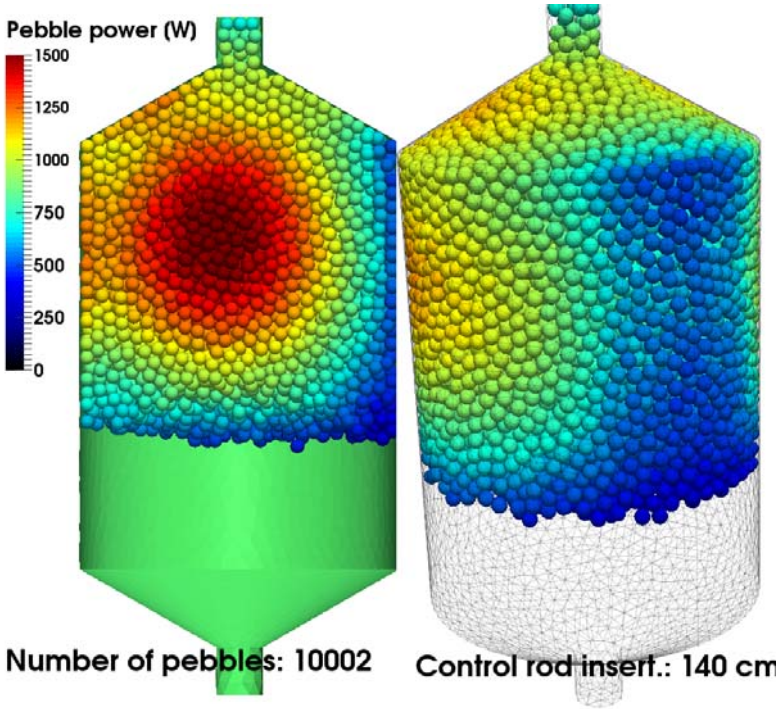
Twisted and straight tube test DHXs

MIT Examining Impact of Salt Property Uncertainties on Reactor Design

Coolant	Property	Value/Correlation	Uncertainty
$^{7}LiF\text{-}BeF_2$ (Flibe) Composition: 66.6% LiF 33.3% BeF_2	Density, ρ (kg/m^3)	2413 – 0.488*T[K]	2%
	Viscosity (Pa-s)	0.000116*exp(3755/T[K])	20%
	Heat Capacity (J/kg-K)	2386	3%
	Thermal Conductivity (W/m-K)	1.1	10%
$NaF\text{-}ZrF_4$ (Nafzirf) Composition: 59.5% NaF 40.5% ZrF_4	Density (kg/m^3)	3829.7 – 0.889*T[K]	5%
	Viscosity (57% - 43%) (Pa-s)	0.0000767*exp(3977/T[K])	20%
	Heat Capacity (J/kg-K)	1172	10%
	Thermal Conductivity (W/m-K)	0.49	15%

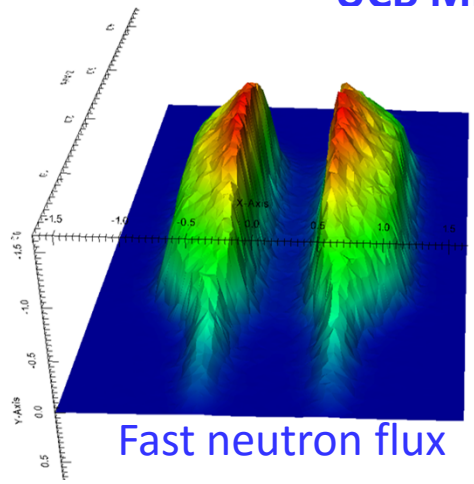
UC Berkeley Neutronics

SINAP TMSR-SF1

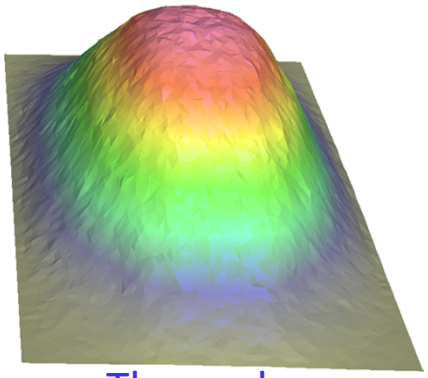


Control rod worth (single rod, 10,002 discrete fuel pebbles)

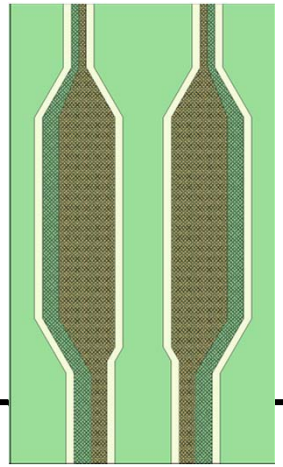
UCB Mk1 PB-FHR



Fast neutron flux



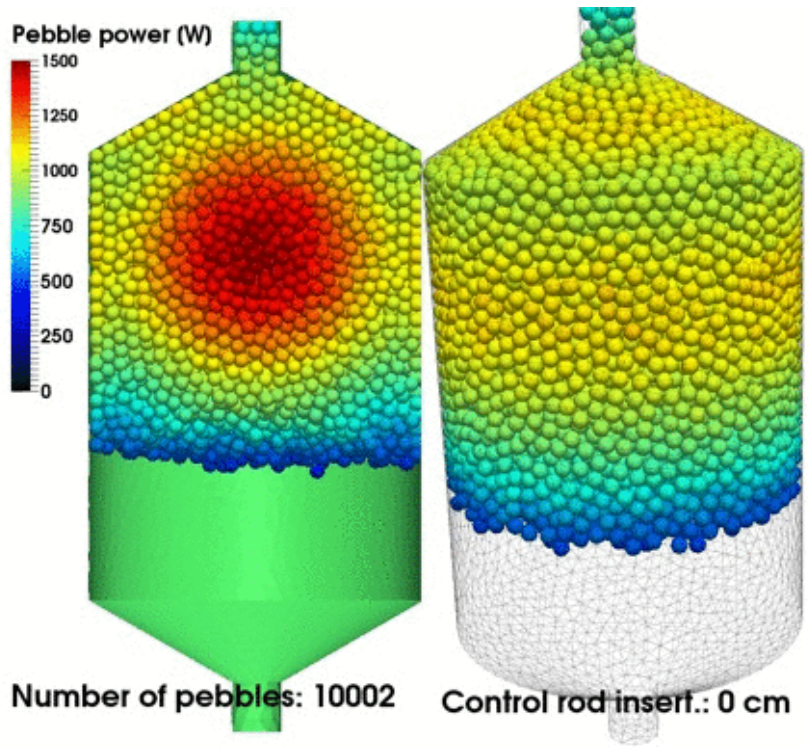
Thermal neutron flux



Mk1 Serpent geometry representation

Berkeley Neutronics: multi-physics modeling

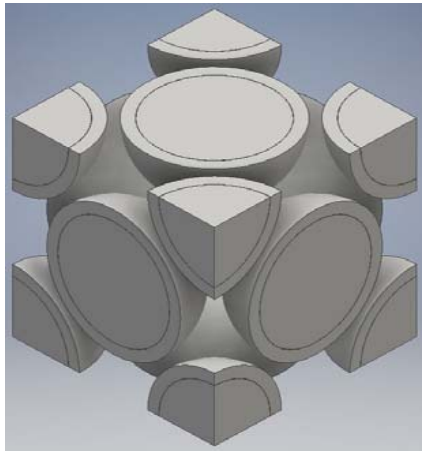
- Developing capabilities for multi-physics modeling
  - Coupled Monte Carlo/CFD/DEM (Serpent-OpenFOAM)—high fidelity, time consuming method
  - Point kinetics/unit cell heat transfer model and deterministic/CFD model (COMSOL)—low fidelity, fast method
- Transient simulations based on the TMSR core

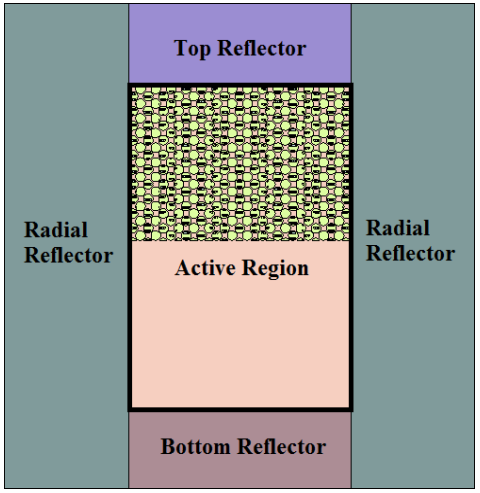


Example: power distribution as a function of insertion of two adjacent control rods in the TMSR

Berkeley Neutronics: benchmark

- Developing code-to-code comparison for FHRs
  - Phase 1: criticality calculations for unit cell and full core from uniform composition to double-heterogeneity
  - Completed benchmark specifications for Phase 1
  - Completed calculations using MCNP, Serpent, and SCALE (KENO, NEWT)
  - Phase 2 under development





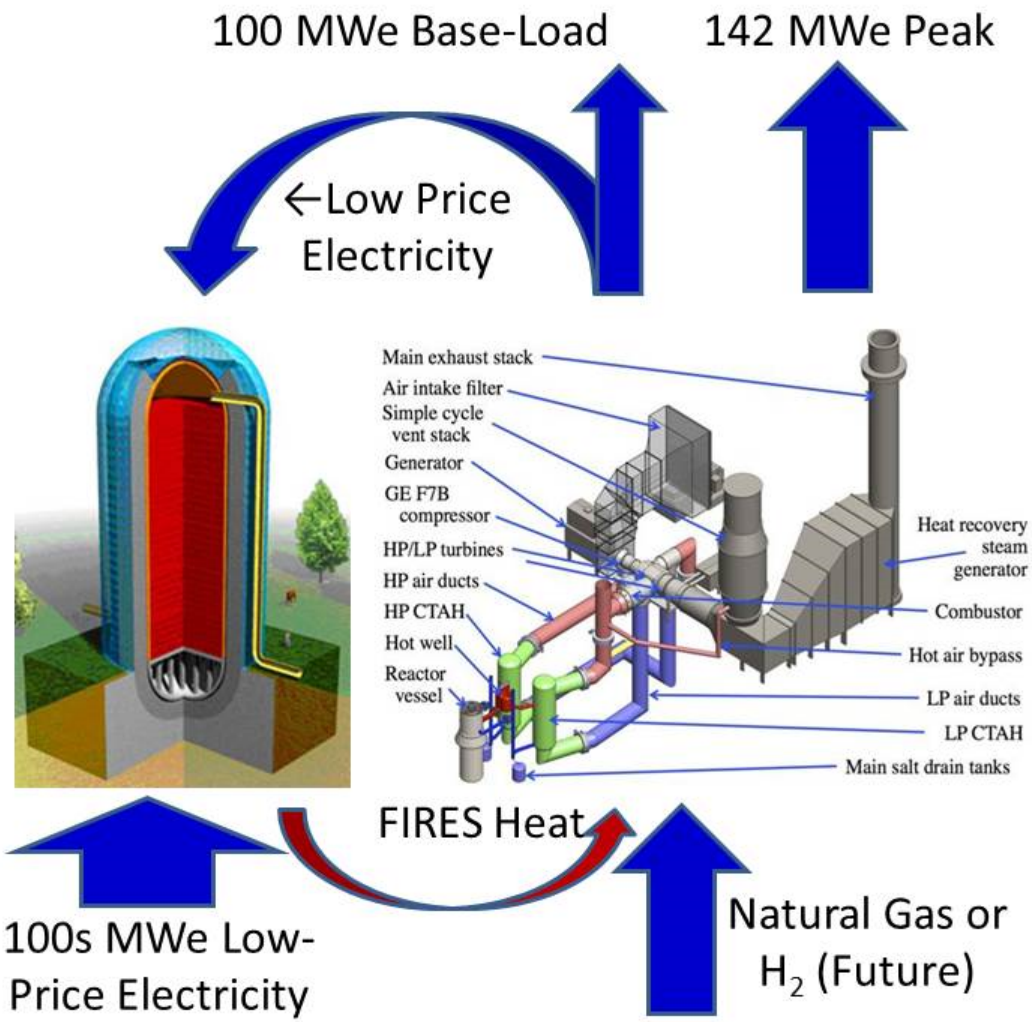
Unit cell (left) and full core model (right) as defined in the benchmark specifications

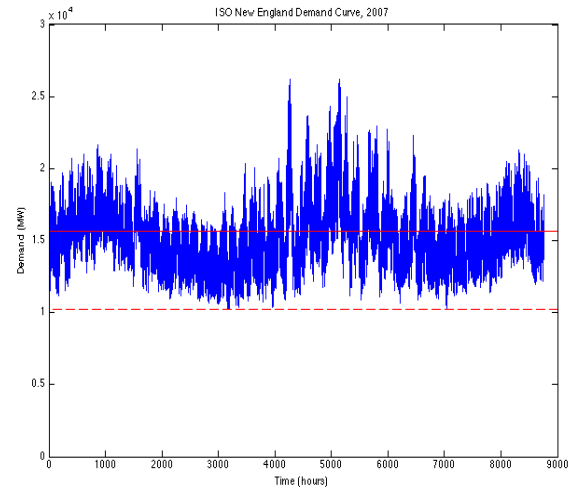
Impact of FHR with NACC On a Low-Carbon Grid

MIT

FHR and Power System

Base-load Electricity, Peak Electricity, Heat Storage



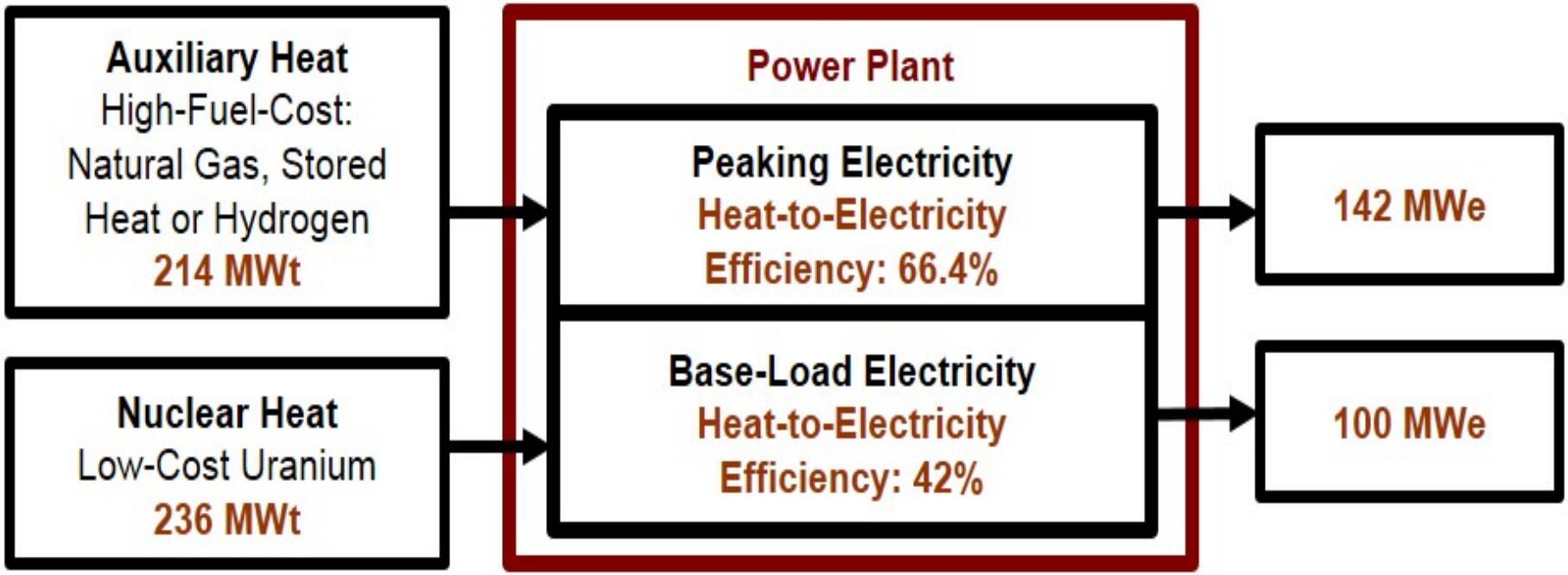


Base-Load Reactor, NACC and FIRES

Variable Electricity And Steam

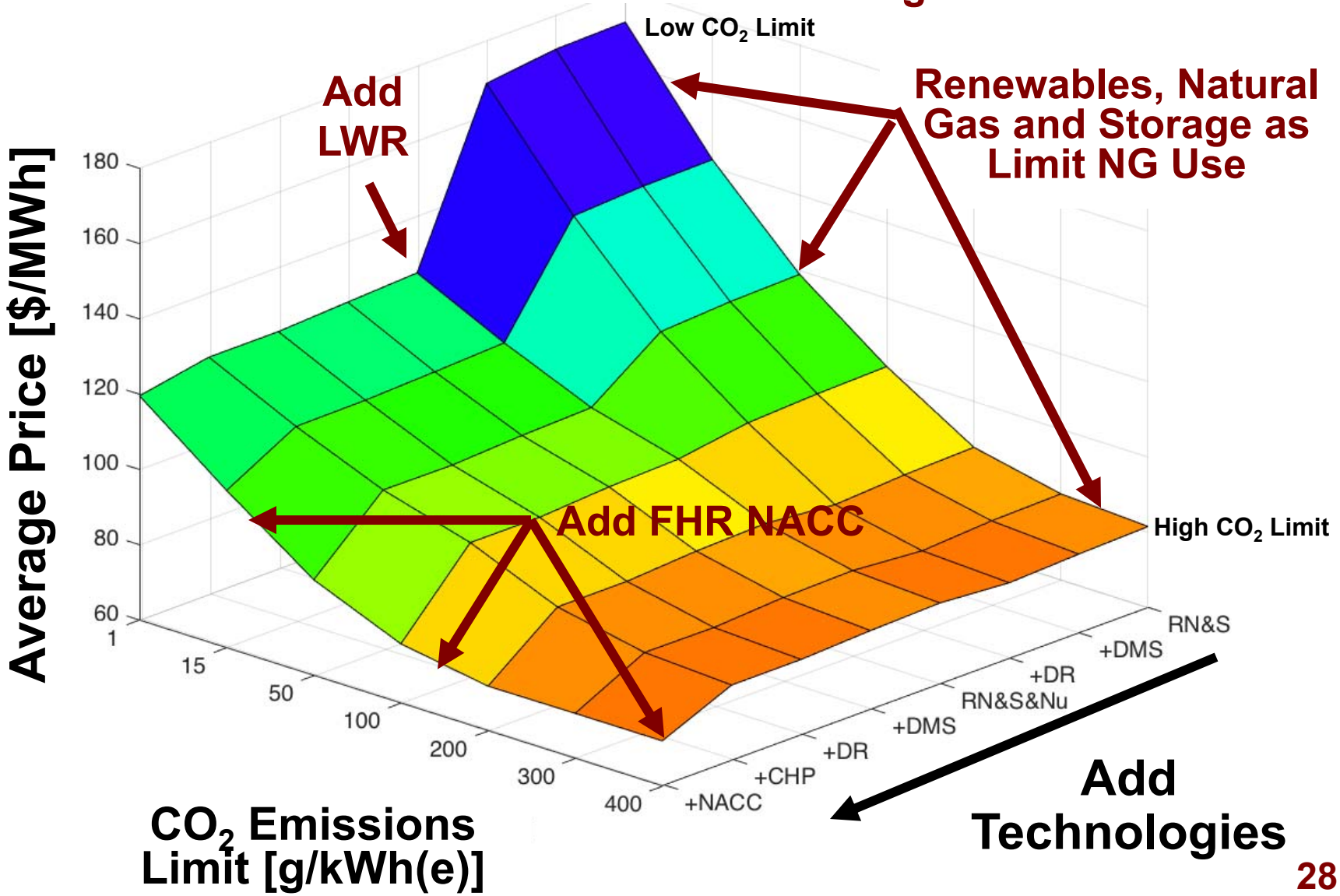
Gas Turbine Cycles Enable Nuclear Topping Cycles

- Heat exchangers limit peak nuclear temperatures to ~700° C
- Gas turbines can go to 1400° C with natural gas or stored heat
- Peaking efficiency exceeds stand-alone natural gas plants

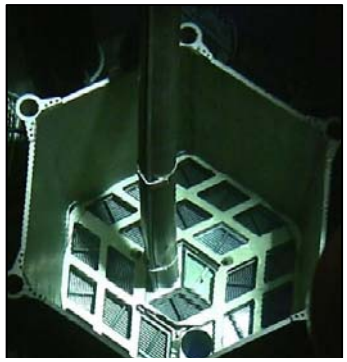


2050 Minimum-Cost Texas Grid Versus Added Technologies and CO_2 Limits

Addition of FHR/NACC/FIRES Lowers Average Electric Prices



Questions



MIT Sample Holder, Capsule, Reactor Core

Wisconsin Salt Purification Facility

UNM Heat Exchangers

Berkeley CIET Facility

Acknowledgements

We Would Like to Thank the Following Organizations

- U.S. Department of Energy, Office of Nuclear Energy for their financial support
- Westinghouse Electric Company
- FHR IRP Advisory Panel: Regis Matzie Chair
- Oak Ridge National Laboratory
- Idaho National Laboratory
- Numerous other individuals and organizations

Preliminary Grid Analysis

Maximizing Social Welfare by Minimizing Cost of Electricity with a Low-Carbon Constraint

Long-Term Impact of FHR/NACC/FIRES Deployment on Electricity Prices

Nestor Sepulveda, Charles Forsberg and Richard Lester

Grid Analysis Assumptions/Methodology-1

- Greenfield 2050 generating mix with 1% yearly growth from 2015 to 2050
- Real hourly data for demand and wind/solar capacity factors
- No deployment capacity constraints (Land, etc.)
- Model solves for optimal investment and operation considering
  - Unit commitment, startup, shutdown, and startup costs
  - Ramp rates for up and down between consecutive hours
  - Up and down efficiencies for storage charge and discharge
  - Minimum stable output and maximum output
- Cost assumptions
  - IEA and NEA 2015 report on cost generation
  - FIRES: $15//kwh
  - FHR cost per kWe identical to LWR plus adjustment for peaking gas turbine capability

Grid Analysis: Technologies Available

- Combined cycle gas turbine (natural gas)
- Open cycle gas turbine (natural gas)
- Nuclear (LWR)
- Solar (PV)
- Wind (on shore)
- Pumped hydro
- Batteries
- Demand-side Management (shift load in time)
- Demand response (Curtail load)
- Heat Storage (FIRES)
- Advanced Nuclear (FHR with NACC)*

***FHR with NACC and FIRES can operate on nuclear with peaking using stored heat or natural gas depending upon economics and allowable CO_2 emissions. In terms of capacity, treated as buying base-load but has peaking capacity that comes with that base load—does not fit any of the usual categories.**