UC Berkeley Nuclear Engineering Thermal Hydraulics Laboratory

Current Status of the UCB PB-FHR Mark-1 Commercial Prototype Design Effort

USNIC-Argonne Symposium on Advanced Reactor Economics
January 28, 2014

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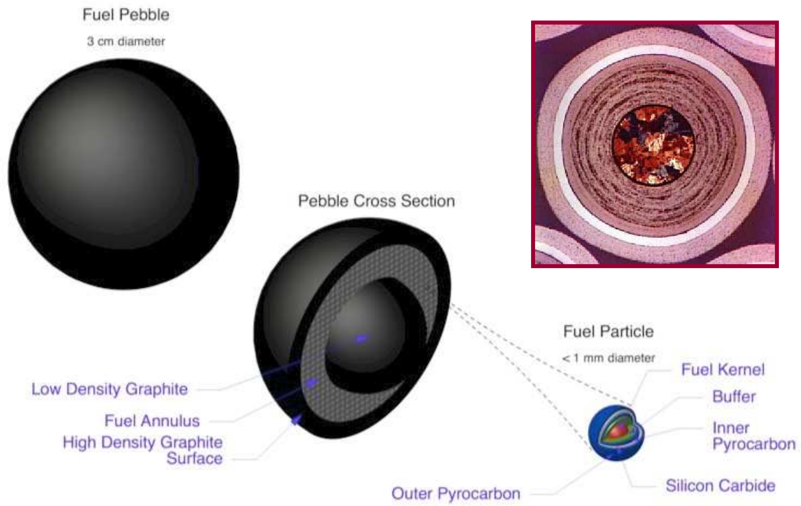
FHR Fluoride Salt Cooled High Temperature Reactor

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

Fluoride Salt-Cooled High-Temperature Reactors (FHRs) Combine Two Nuclear Technologies

Coated Particle Fuel

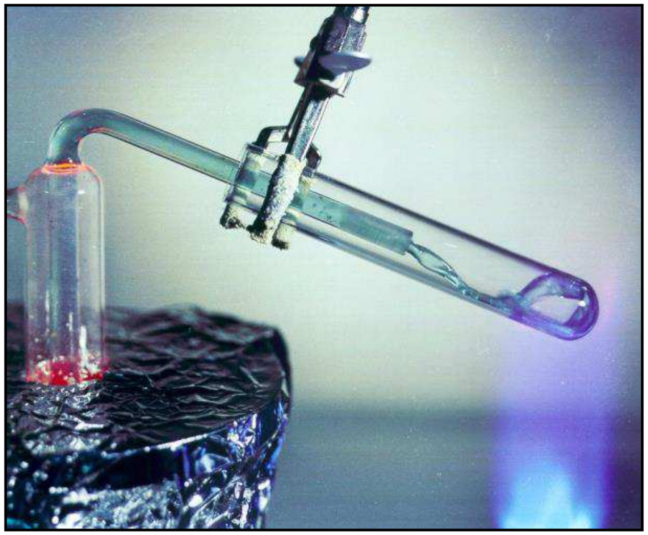


Fission Product Retention > 1600° C

FHRs have <u>uniquely</u> large fuel thermal margins (fuel temp < 1000° C)

BUT need to confirm performance at higher FHR power densities

Fluoride Salt Coolants



Excellent heat transfer properties

Transparent, clean fluoride salt

Boiling point ~ 1400° C

Reacts very slowly in air

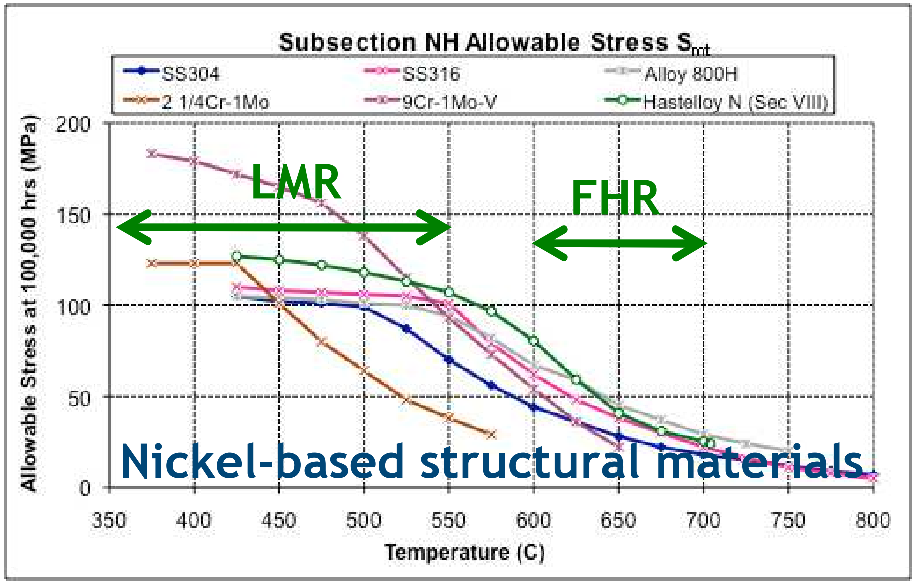
No energy source to pressurize containment

BUT high freezing temperature (459° C)

AND industrial safety for Be control

FHR Design Space Allows for Coupling to Air Cycles

Coolant Temperature	System Pressure Low	High
Low		Light-Water Reactor
Medium	Sodium Fast Reactor	
High	FHR (High Inlet Temperature)	High-Temperature Gas-Cooler Reactor (Low Inlet Temperature)



Current FHR Development Efforts

- DOE Integrated Research Project (IRP)
  - Collaborative university effort with MIT, UCB, and UW
  - Includes commercialization strategy, commercial prototype and test reactor pre-conceptual design effort, and assorted technology development efforts
- Oak Ridge National Laboratory
  - Ongoing FHR development work on technology roadmap and reactor design (plate fuel)
- ANS Standards Committee 20.1
  - Currently developing FHR-specific GDCs and design standards
- Shanghai Institute of Applied Physics (SINAP)
  - Currently developing FHR and MSR technology
  - 10 MW FHR test reactor deployment planned for 2017

Goals for the Compelling FHR Market Case

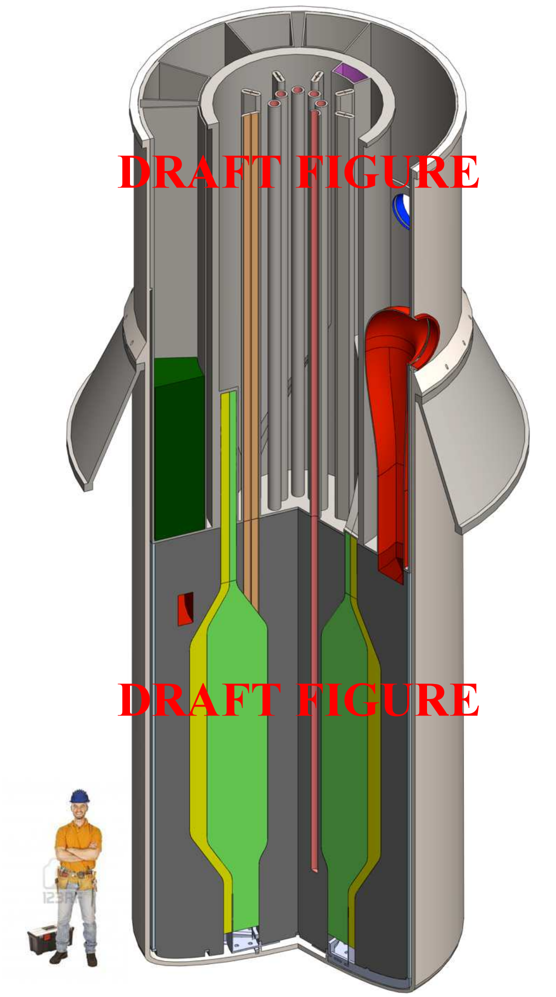
- ENVIRONMENT
  - Enable a low-carbon nuclear-renewable (wind/solar) electricity grid by providing economic dispatchable electricity
- ECONOMIC
  - Increase revenue relative to base load nuclear power plants with natural gas co-firing
- SAFETY
  - No major offsite radionuclide releases even in bounding severe accident cases

PB-FHR Mk1 Design Goals

- Demonstrate a plausible, self-consistent Nuclear Air Combined Cycle (NACC) system design
  - 2 archival articles now accepted to ASME Journal of Engineering for Gas Turbines and Power
- Provide detailed design for decay heat management systems
  - Provide basis for establishing integral effects testing and TH code validation and benchmark exercises
- Develop a credible, detailed annular FHR pebble core design
  - Provide basis for future FHR code benchmarking
- Identify additional systems and develop notional reactor building arrangement
  - "Black-box" level of design for many of these systems
  - Include beryllium and tritium management strategies
- Final Design Report Expected: June 2014
  - Pre-Conceptual Level

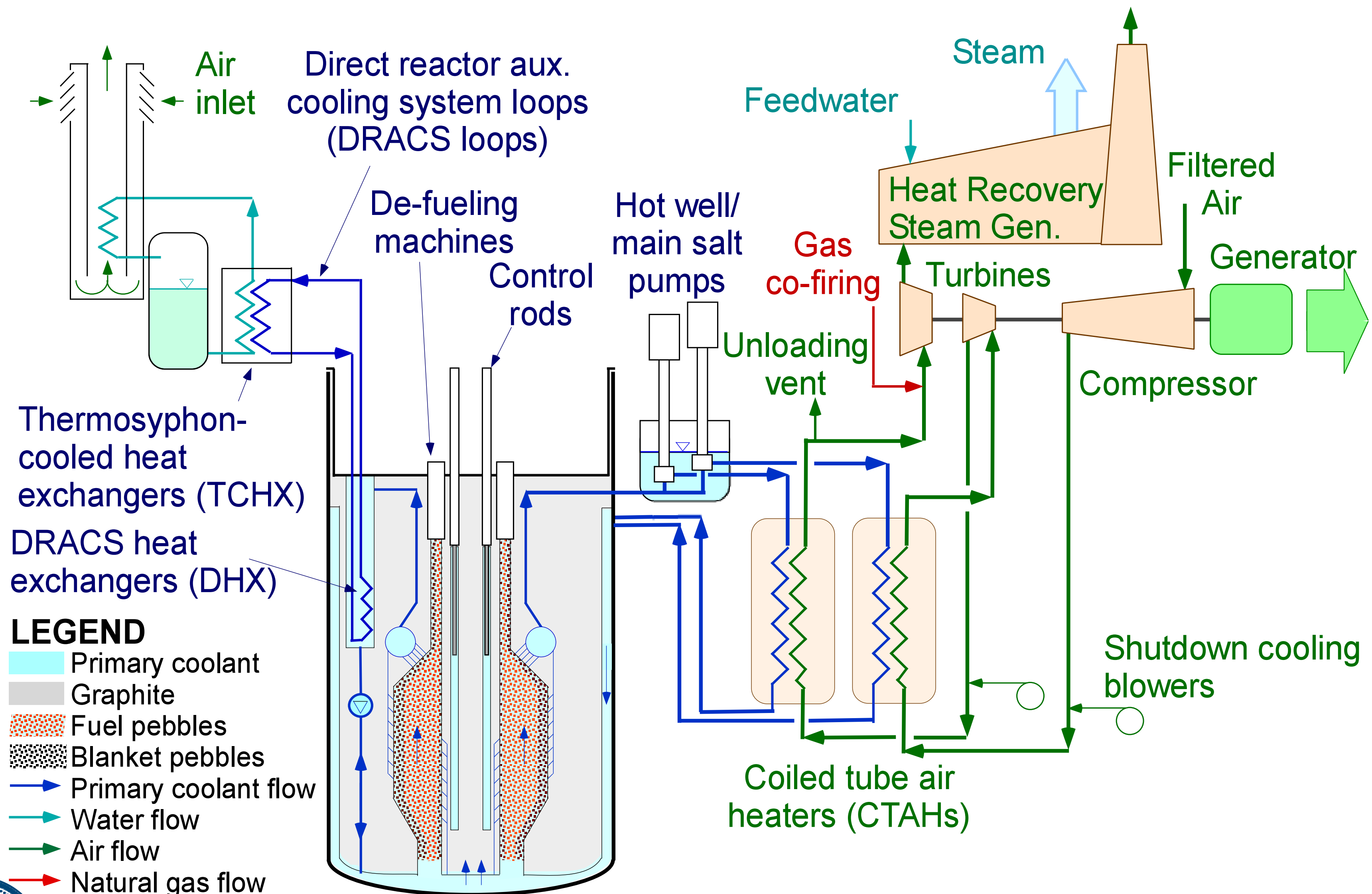
Nominal PB-FHR Mk1 Design Parameters

- Annular pebble bed core with center reflector
  - Core inlet/outlet temperatures 600/700° C
  - Control elements in channels in center reflector
  - Shutdown elements cruciform blades insert into pebble bed
- Reactor vessel 3.5-m OD, 12.0-m high
  - Vessel power density 3 x higher than S-PRISM & PBMR
- Power level: 236 MWth, 100 MWe (base load), 242 MWe (peak w/ gas co-fire)
  - Base load efficiency: 42.4%
  - Natural gas conversion efficiency: 66.4%
- GE 7FB gas turbine w/ 3-pressure HRSG
- Air heaters: Two 3.5-m OD, 10.0-m high CTAHs, direct heating
- Tritium control and recovery
  - Recovery: Absorption in fuel and blanket pebbles
  - Control: Kanthal coating on air side of CTAHs

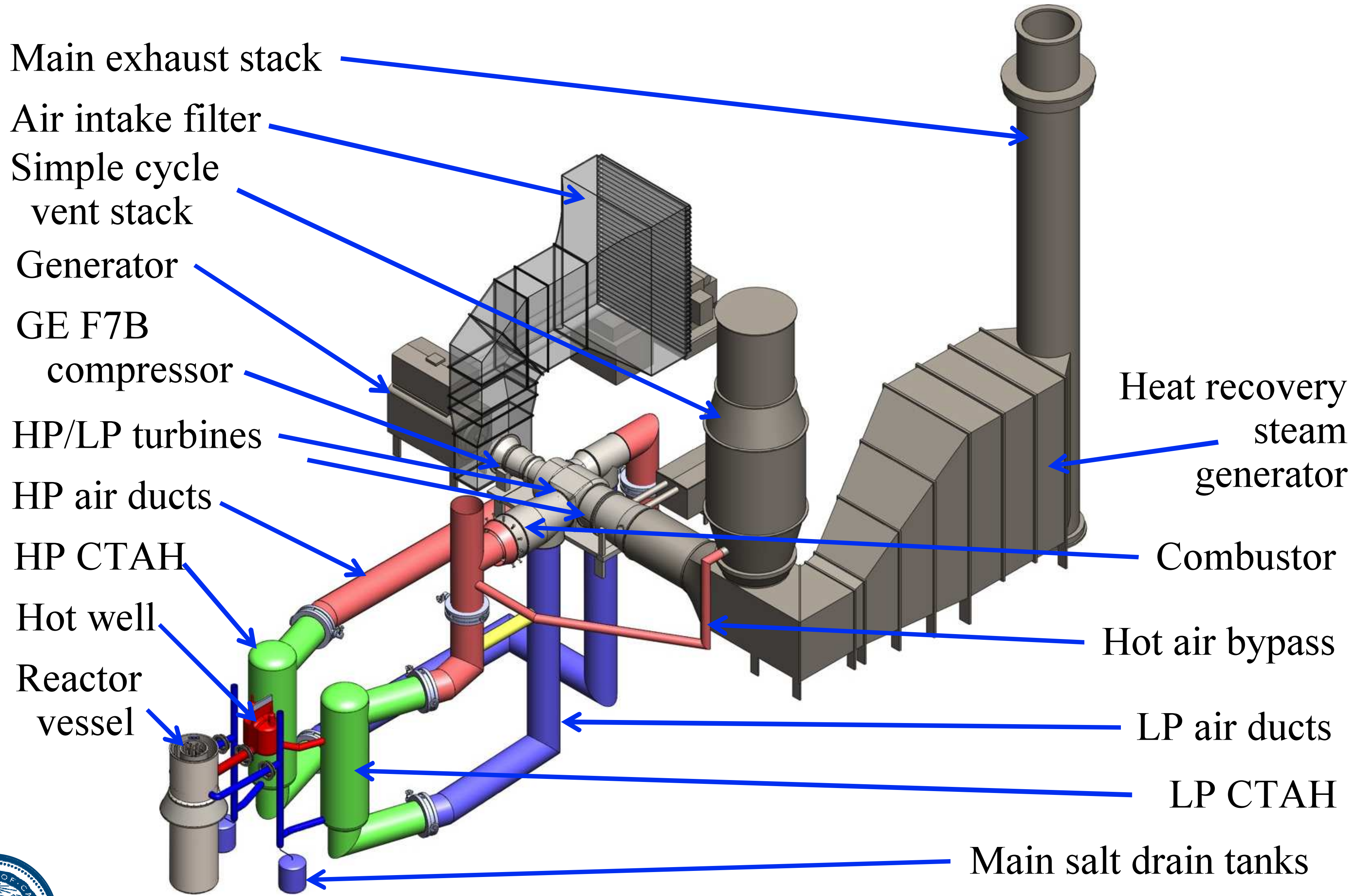


PB-FHR Vessel Cross Section

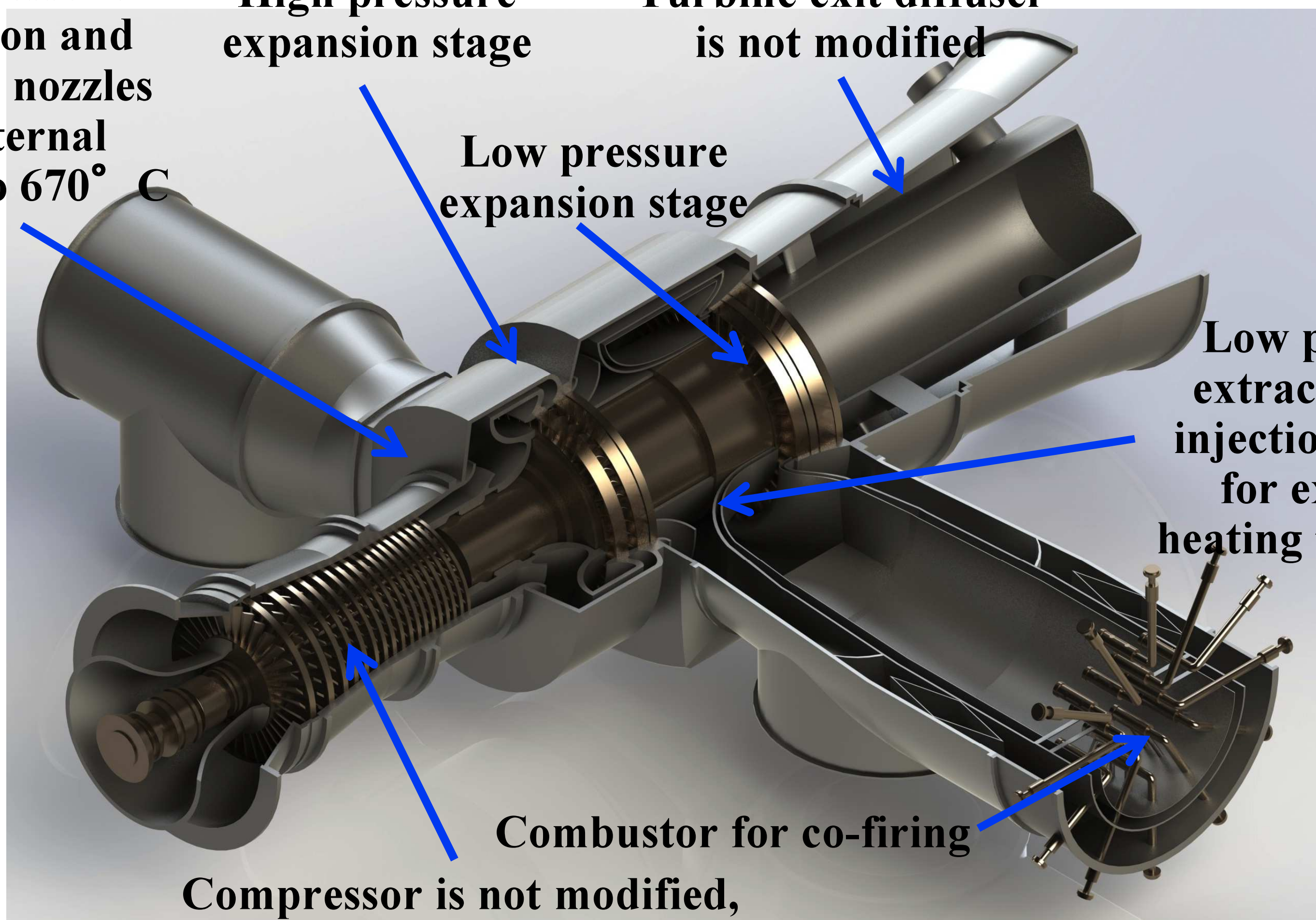
PB-FHR Mk1 Flow Schematic



PB-FHR Mk1 NACC Physical Arrangement



GE 7FB Turbine Modified for External Nuclear Heating



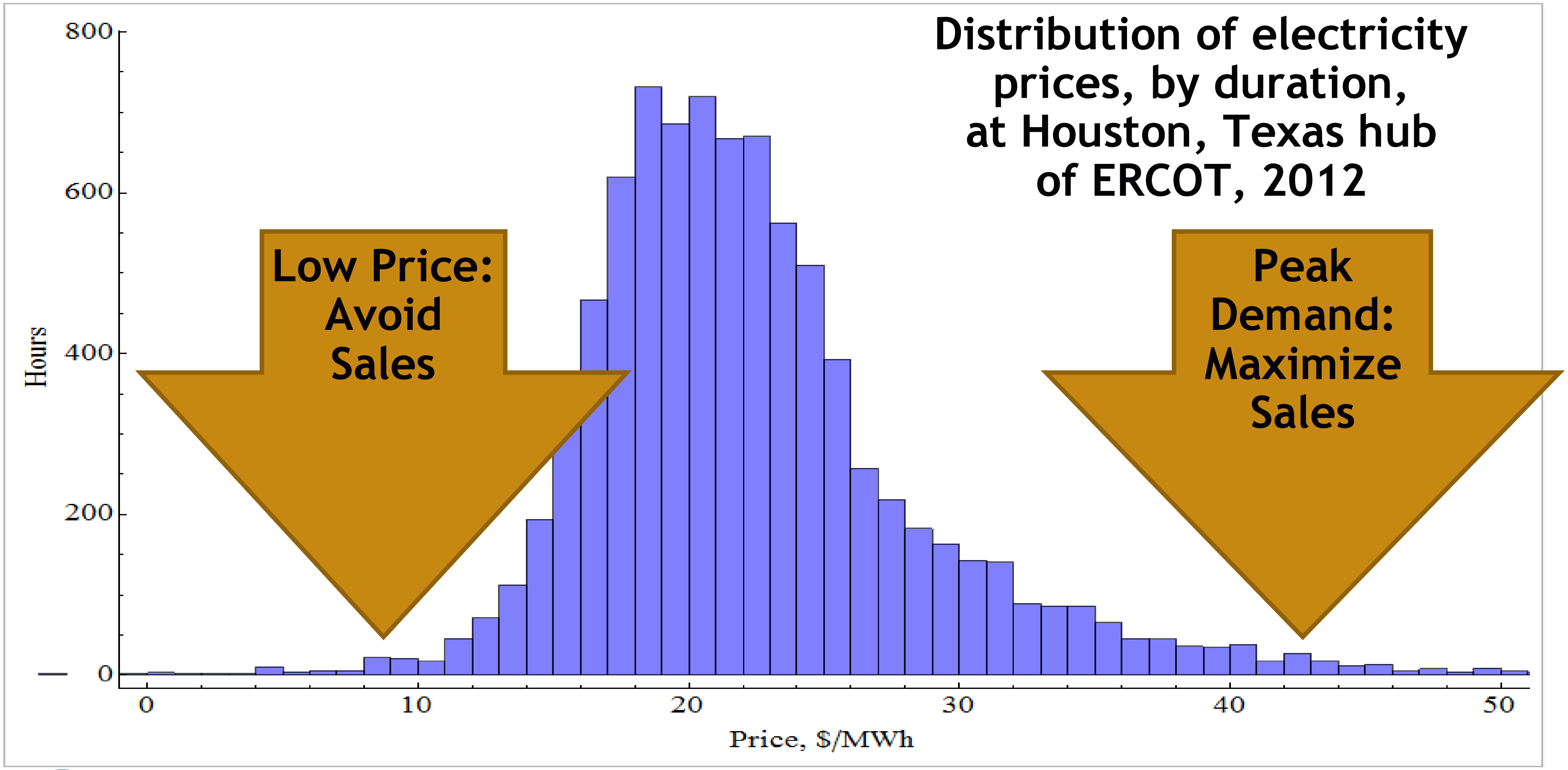
Unique Features of NACC

- Capability to provide peak power with auxiliary fuel
  - Increase revenue after paying for fuel
  - Natural gas today, hydrogen and bio-fuels in future
- Fast response because turbine is always hot and spinning - peak power starts from base-load NACC
- Efficient natural gas to electricity conversion
  - 66.4% heat to electricity efficiency vs. NGCC ~ 60%
- 40% cooling water required of LWR per kW(e)h
- Efficient process heat option
  - No isolation steam generator with capital cost and temperature drop penalty. No tritium concern.
  - High temperature steam

Source: C. Forsberg, "Commercialization Strategy and Challenges for Fluoride-Salt-Cooled High-Temperature Reactors (FHRs). 19 January 2014

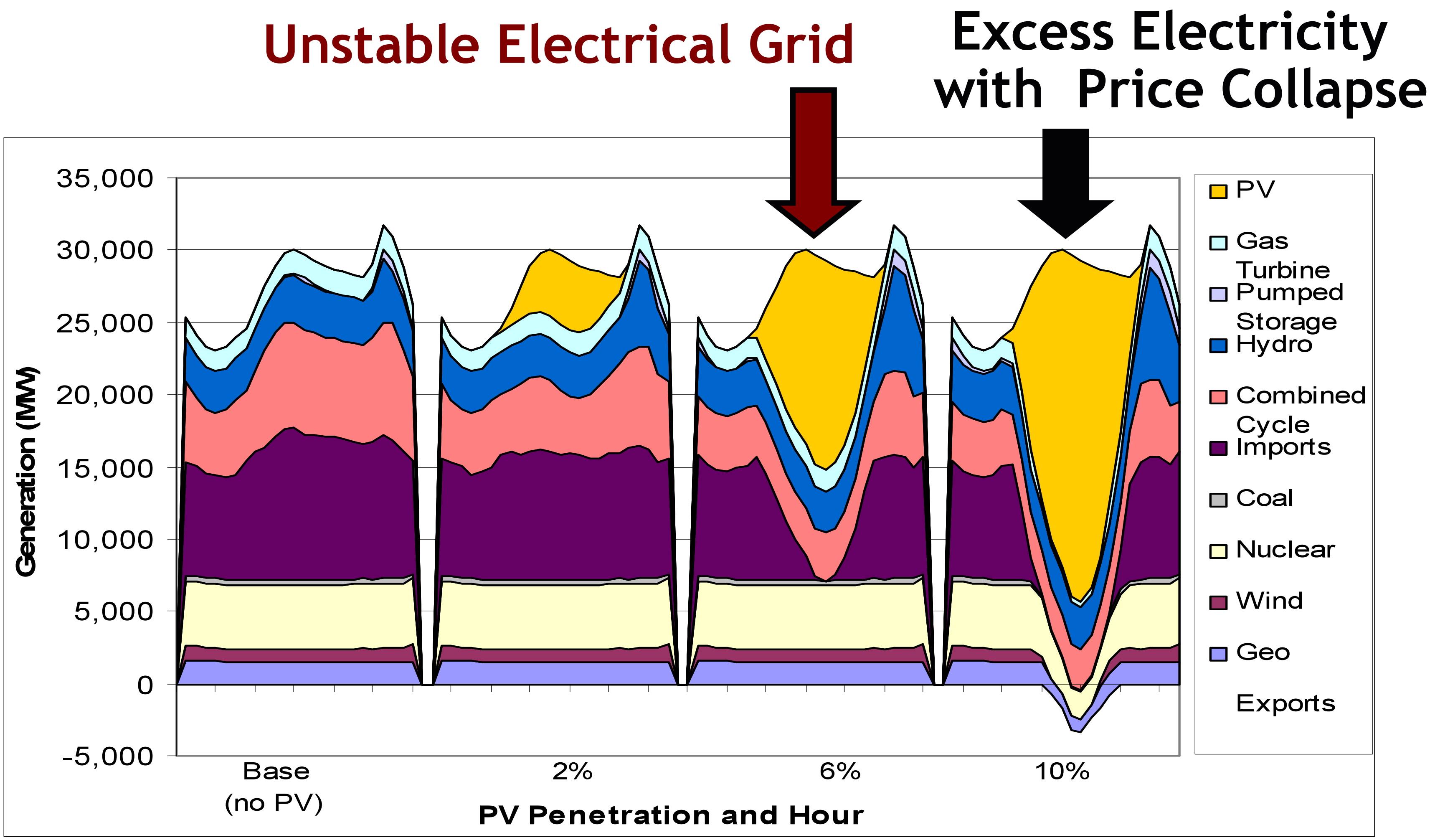
Maximize Revenue By Selling Electricity When the Price is High

Electricity Price Vs Hours Sold at that Price



Source: C. Forsberg, "Commercialization Strategy and Challenges for Fluoride-Salt-Cooled High-Temperature Reactors (FHRs). 19 January 2014

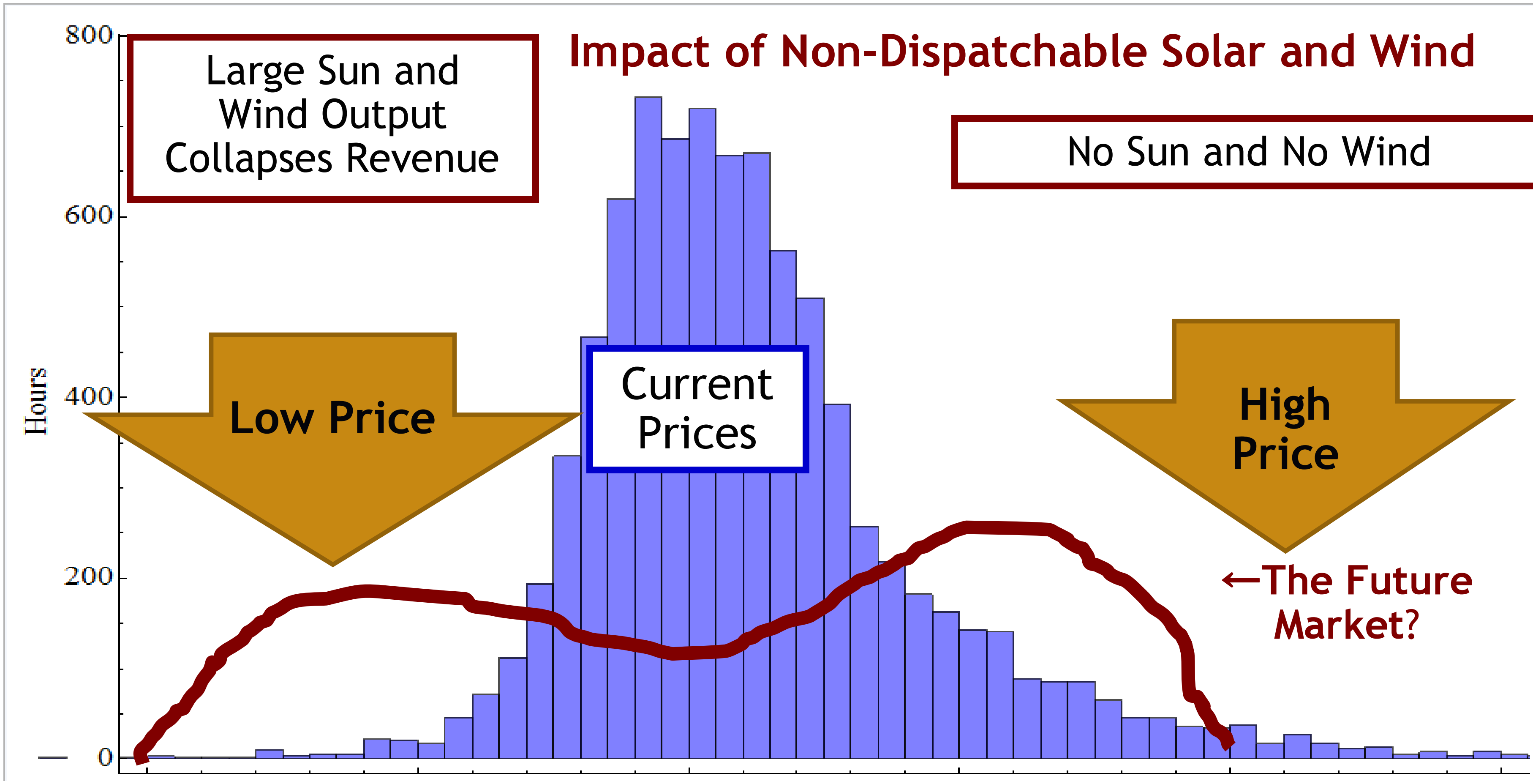
Renewable Deployment Changes the Grid



California Daily Spring Electricity Demand and Production with Different Levels of Photovoltaic Electricity Generation

Source: C. Forsberg, "Commercialization Strategy and Challenges for Fluoride-Salt-Cooled High-Temperature Reactors (FHRs). 19 January 2014

Transition to a Low-Carbon Electricity Market Imply More Hours of Low / High Price Electricity

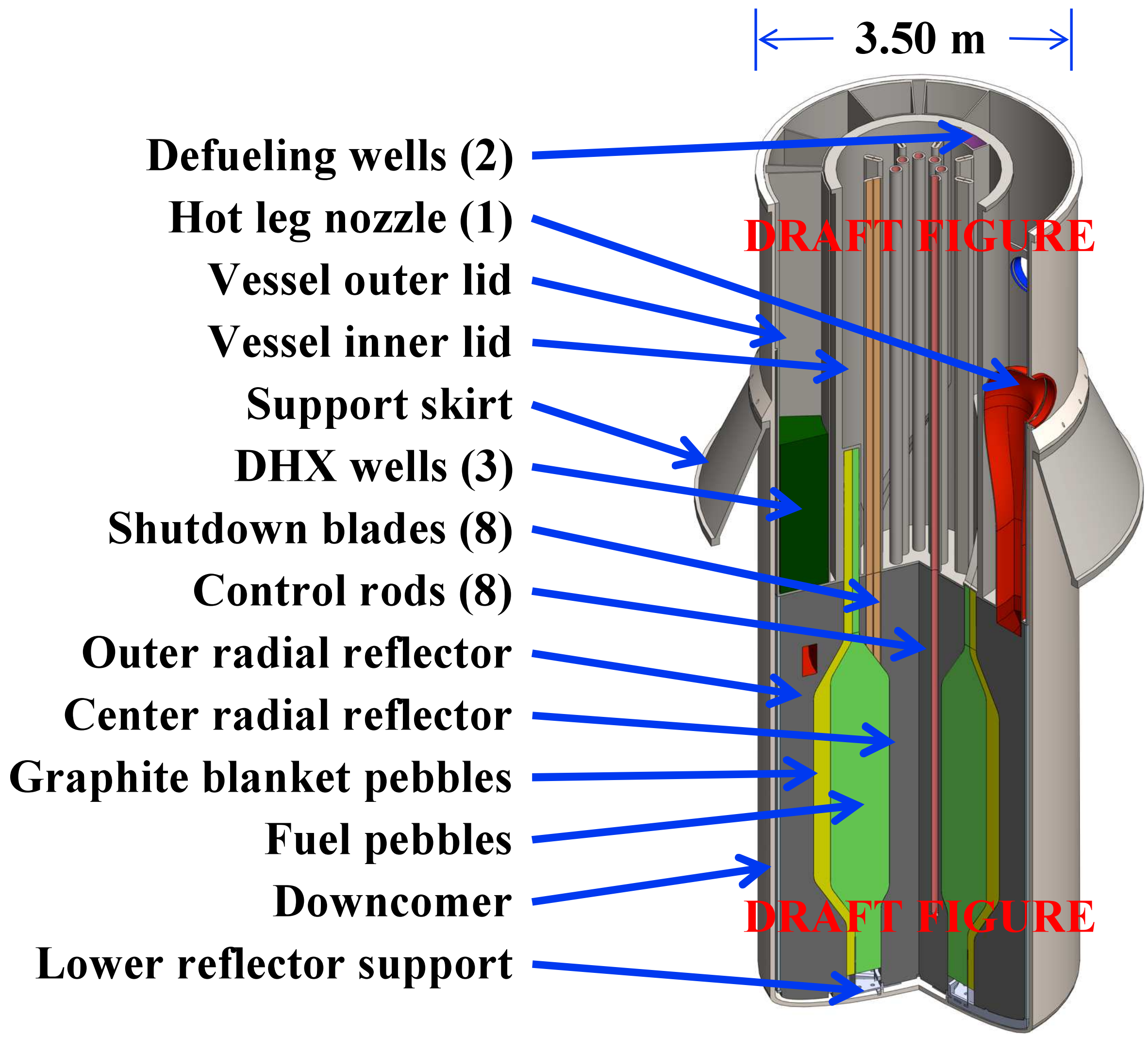


Favors FHR with NACC Economics

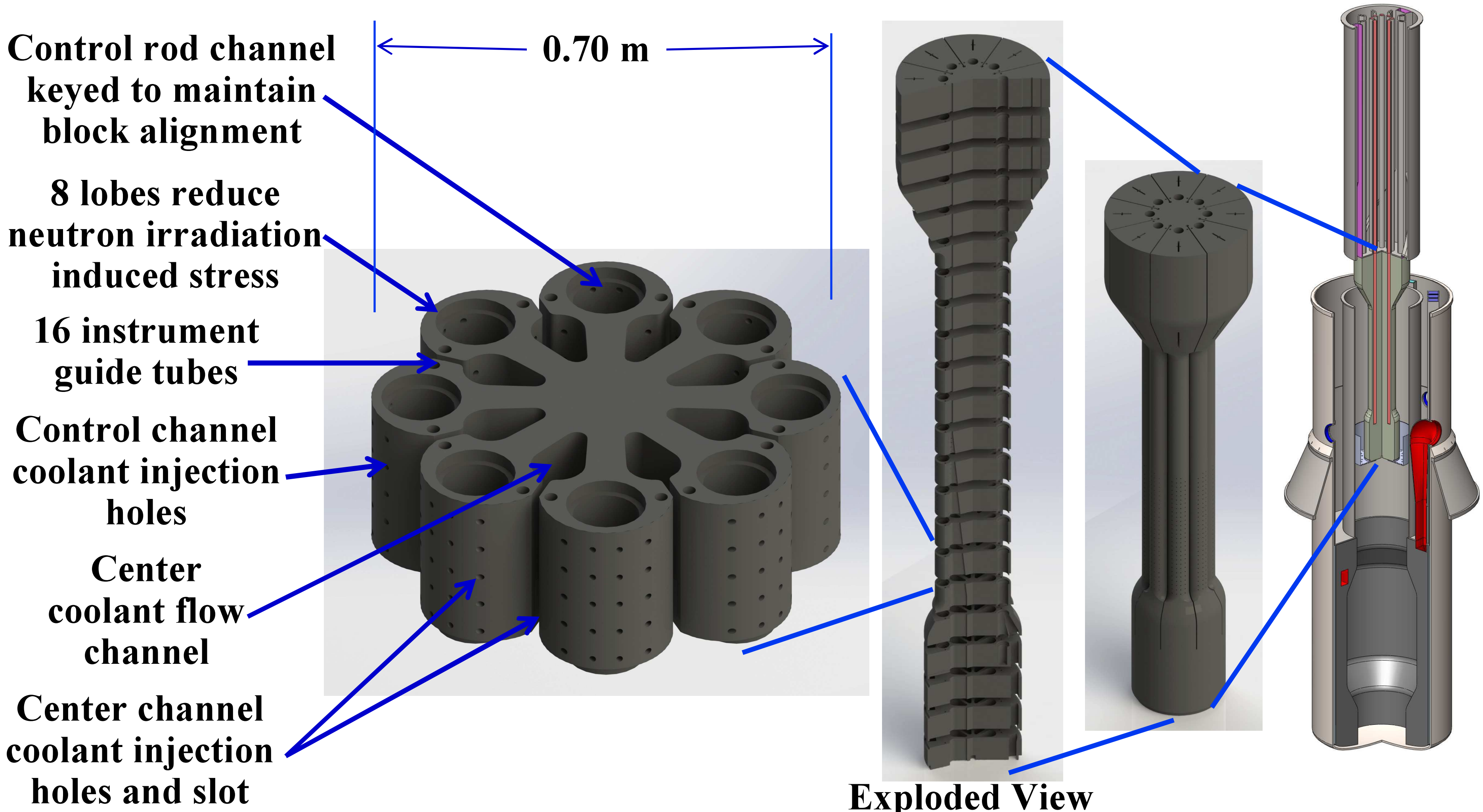
Distribution of electricity prices, by duration, at Houston, Texas hub of ERCOT, 2012

Source: C. Forsberg, "Commercialization Strategy and Challenges for Fluoride-Salt-Cooled High-Temperature Reactors (FHRs). 19 January 2014

PB-FHR Mk1 Reactor Vessel Cross Section

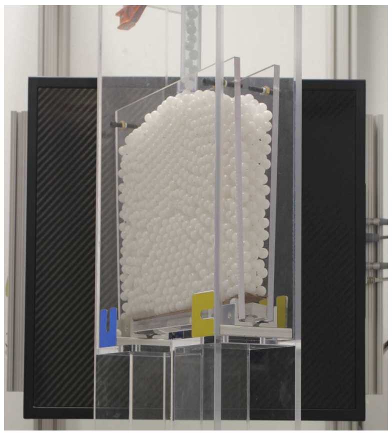


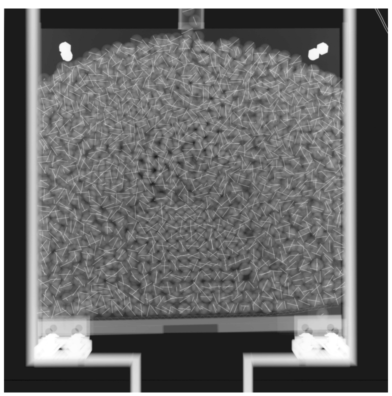
The Mark-1 center reflector block geometry minimizes stresses induced by neutron irradiation

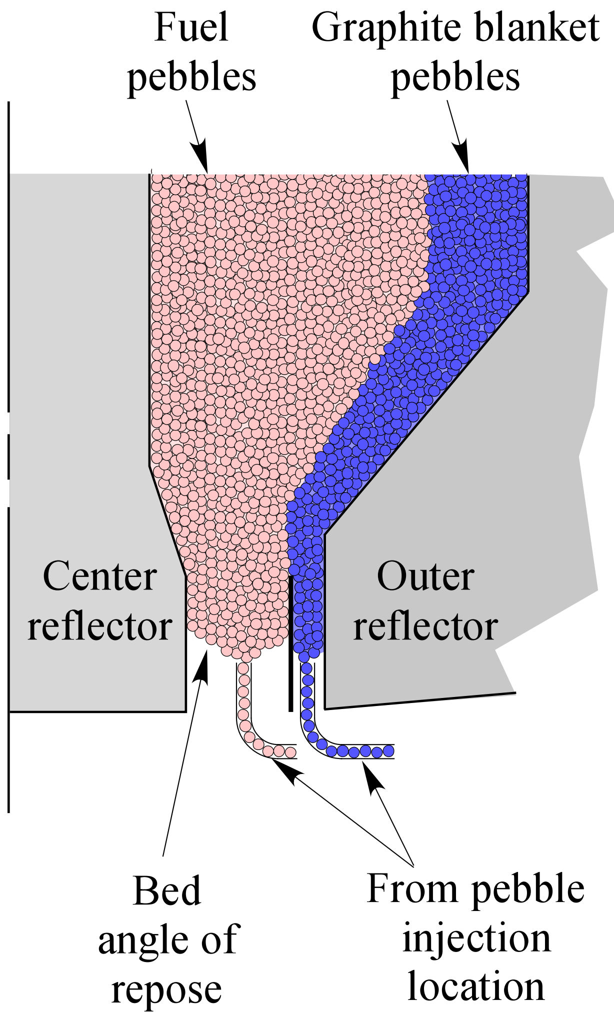


Pebble Injection and Core Flow in PB-FHR Mk1

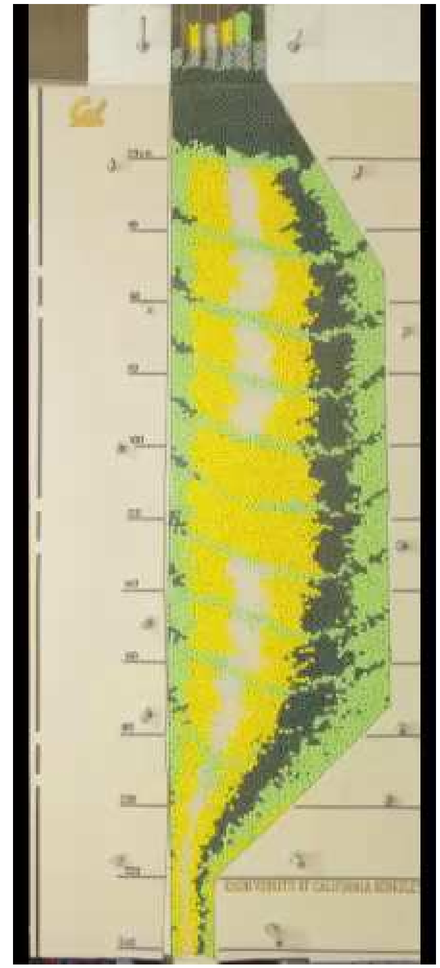
Narrow Slot Heap Structure



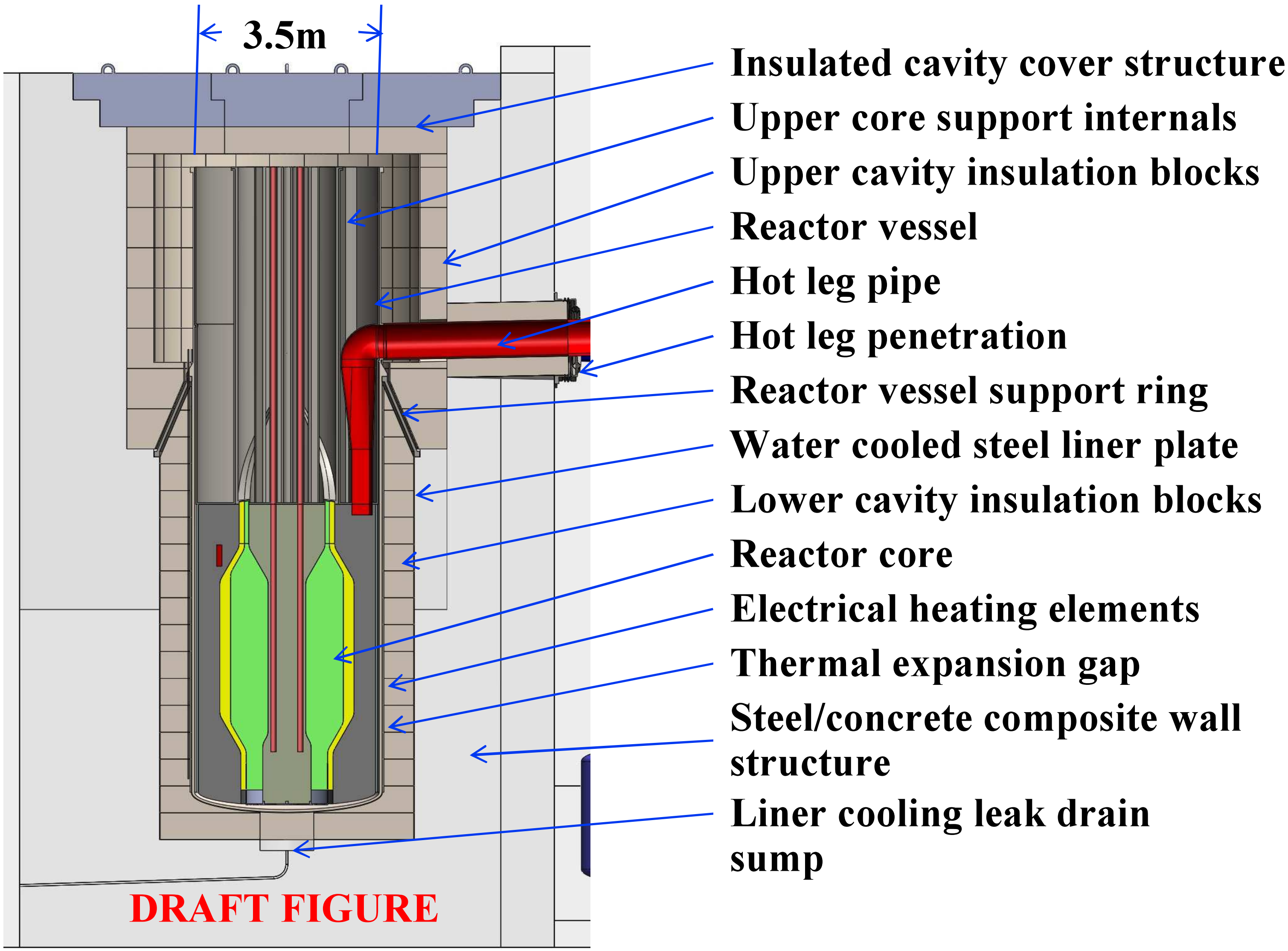




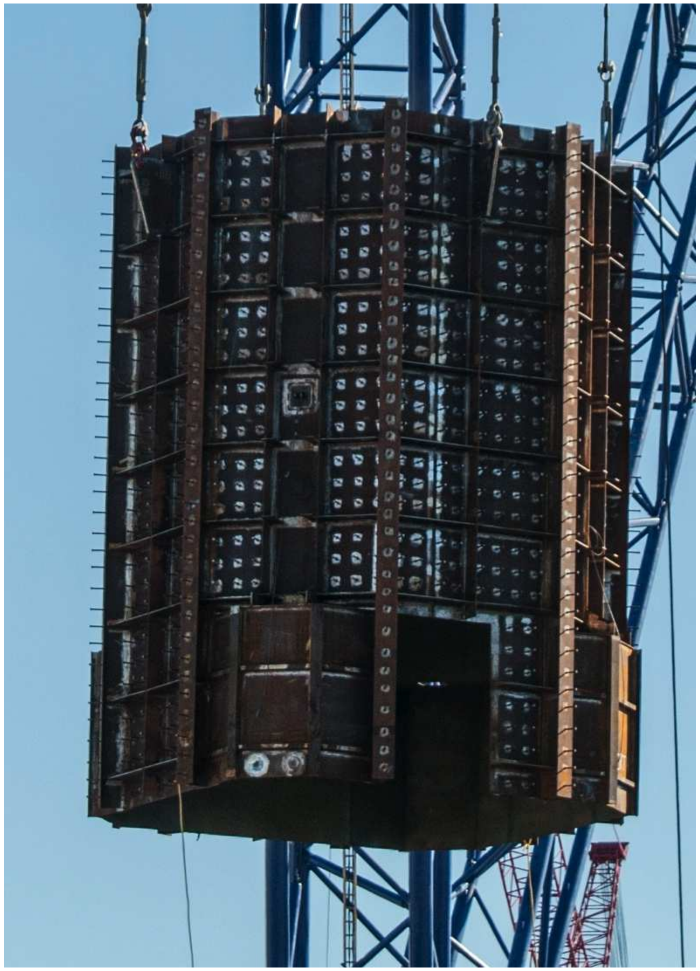
Scaled Pebble Flow (Dry System)



PB-FHR Mk1 Refractory Reactor Cavity Liner System



V.C. Summer Unit 2 Reactor Cavity Module CA04



- **The Mk1 PB-FHR reactor building will use the same modular, steel-plate/concrete composite structures as AP-1000**
- **The Mk1 reactor cavity system will use the a similar stainless steel liner design**

http://www.flickr.com/photos/scegnews/sets/72157629244341909/

Comparison to Other Reactor Designs

	Mk1 PB-FHR	ORNL 2012 AHTR	Westing-house 4-loop PWR	PBMR	S-PRISM
Reactor thermal power (MWt)	236	3400	3411	400	1000
Reactor electrical power (MWe)	100	1530	1092	175	380
Fuel enrichment †	19.90%	9.00%	4.50%	9.60%	8.93%
Fuel discharge burn up (MWt-d/kg)	180	71	48	92	106
Fuel full-power residence time in core (yr)	1.38	1.00	3.15	2.50	7.59
Power conversion efficiency	42.4%	45.0%	32.0%	43.8%	38.0%
Core power density (MWt/m3)	22.7	12.9	105.2	4.8	321.1
Fuel average surface heat flux (MWt/m2)	0.189	0.285	0.637	0.080	1.13
Reactor vessel diameter (m)	3.5	10.5	6.0	6.2	9.0
Reactor vessel height (m)	12.0	19.1	13.6	24.0	20.0
Reactor vessel specific power (MWe/m3)	0.866	0.925	2.839	0.242	0.299
Start-up fissile inventory (kg-U235/MWe) ††	0.79	0.62	2.02	1.30	6.15
EOC Cs-137 inventory in core (g/MWe) *	30.8	26.1	104.8	53.8	269.5
EOC Cs-137 inventory in core (Ci/MWe) *	2672	2260	9083	4667	23359
Spent fuel dry storage density (MWe-d/m3)	4855	2120	15413	1922	-
Natural uranium (MWe-d/kg-NU) **	1.56	1.47	1.46	1.73	-
Separative work (MWe-d/kg-SWU) **	1.98	2.08	2.43	2.42	-

† For S-PRISM, effective enrichment is the Beginning of Cycle weight fraction of fissile Pu in fuel

†† Assume start-up U-235 enrichment is 60% of equilibrium enrichment; for S-PRISM startup uses fissile Pu

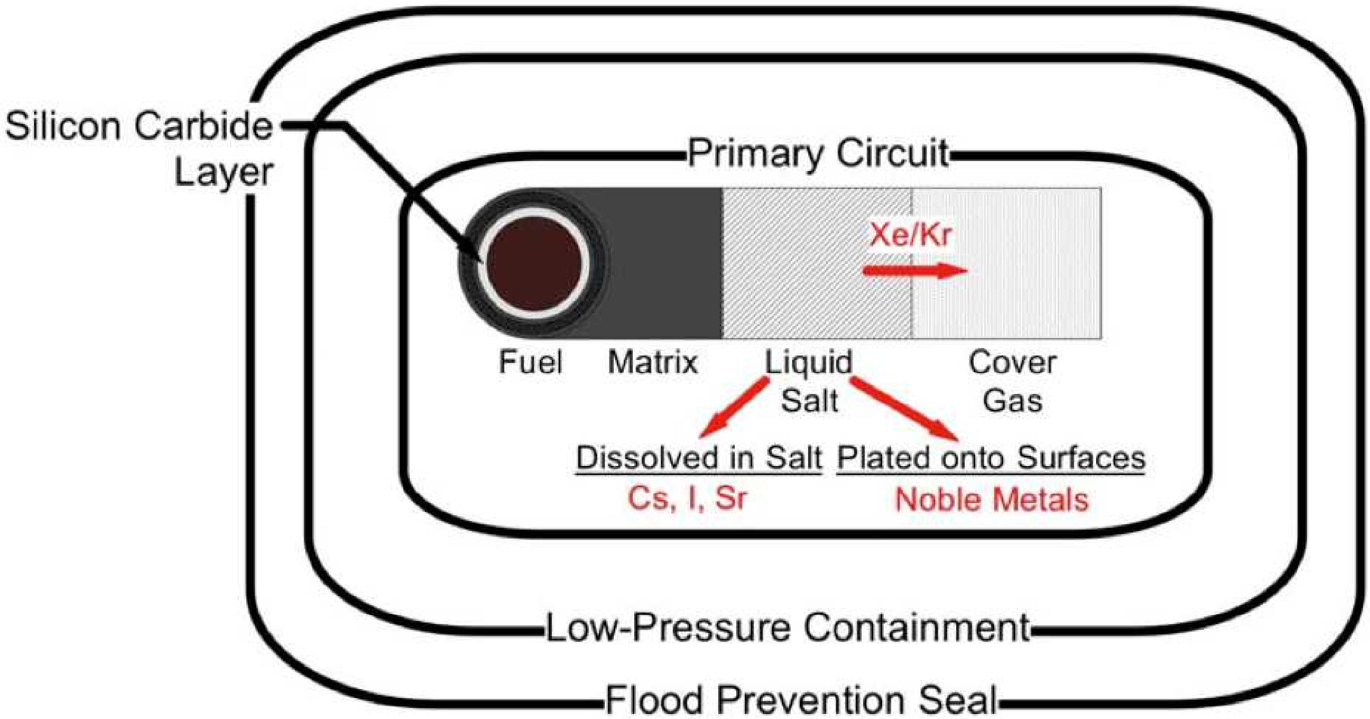
* End of Cycle (EOC) life value (fixed fuel) or equilibrium value (pebble fuel)

** Assumes a uranium tails assay of 0.003.

FHRs Provide Robust Inherent Defense-In-Depth to Retain Radionuclides During Accidents

- Inherent characteristics of the fuel and coolant retain radionuclides:
  - TRISO Fuel
    - Demonstrated FP retention > 1600° C in NGNP Program
    - FHRs operate with 100s° C of fuel temperature margins
    - No incremental fuel failure expected during accidents
      - Need to confirm performance at higher power densities
  - Flibe Coolant
    - Demonstrated retention of solid FPs and iodine in MSRE
      - MSRE ~ FHR Test with 100% Fuel Failure
    - Low pressure coolant reduces stored energy in containment
- Low-pressure low-leakage containment reduces the release of noble gas fission products or their daughter radionuclides
  - Noble gas fission products will be removed under normal operation in the processing of the inert cover gas

FHR Radionuclide Barriers

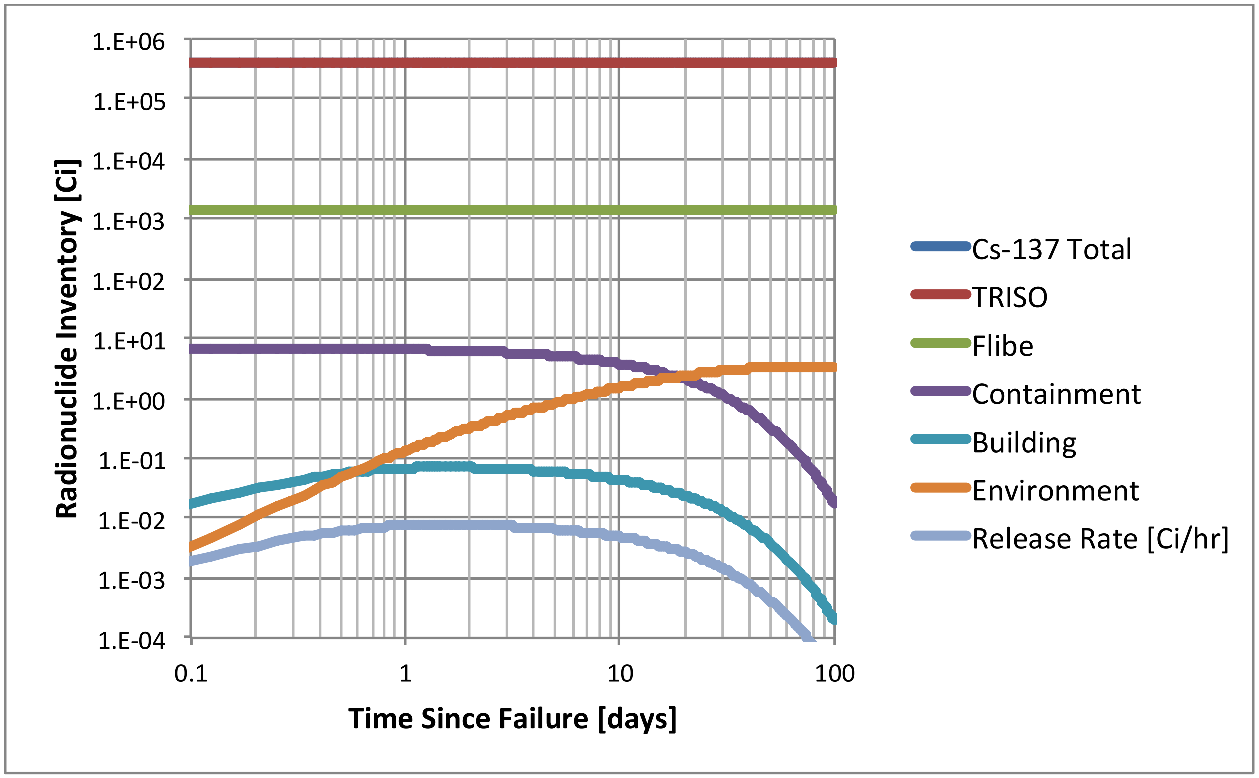


Intrinsic characteristics can provide two key benefits:

1. **Reduce licensing uncertainty with conservative analysis**
2. **Reduce development costs by using best estimate analysis**

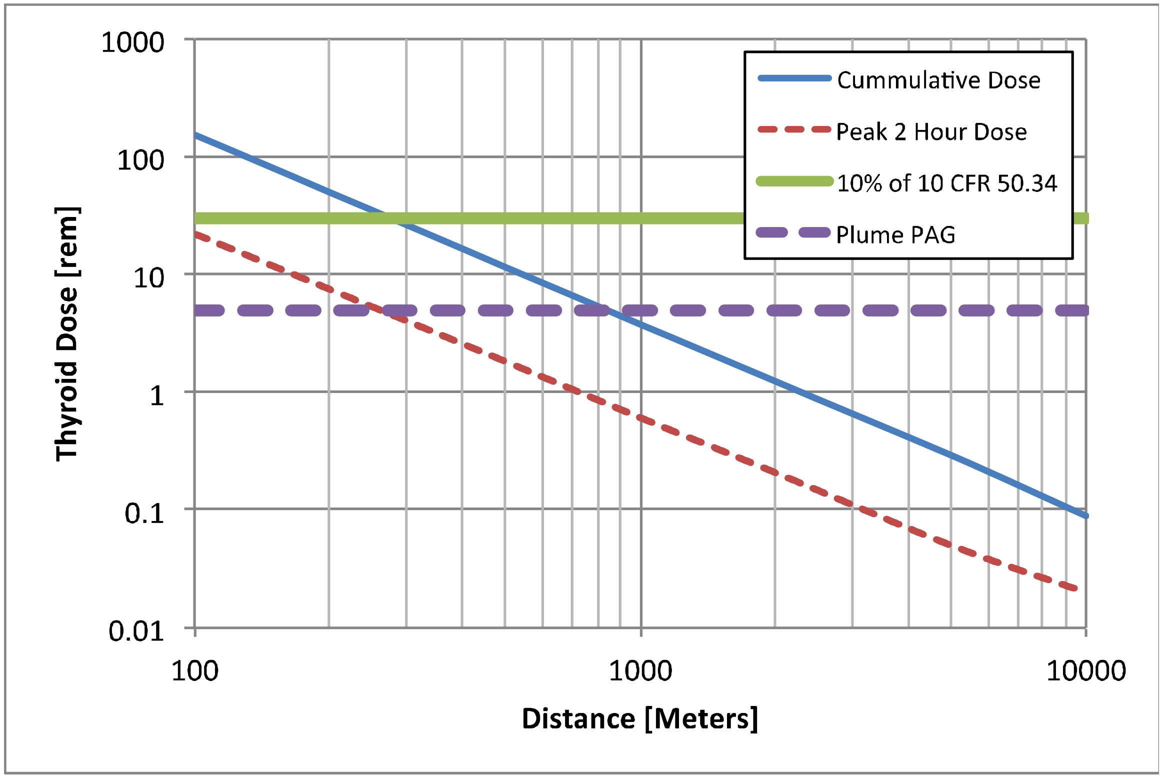
Image Source: ORNL, "AHTR Mechanical, Structural, and Neutronic Preconceptual Design," Oak Ridge National Laboratory, Oak Ridge, TN, ORNL/TM-2012/320, Sep. 2012.

Preliminary Results for PB-FHR Cs-137 Release Bounding Case with 1% Defective Fuel



- **Total release after 100 days is less than 4 Ci**
- **99.998% retention in the fuel and flibe**

Preliminary Thyroid Dose Analysis Bounding Case with 1% Defective Fuel



- PB-FHR Mk1 should meet 10% of the 10 CFR 50.34 dose limits with EAB and LPZ boundaries at 100 and 300 meters
  - Provides margin for multi-module sites
- The Plume EPZ may be set at approximately 850 meters

(Partial) List of PB-FHR Opportunities and Challenges

- Opportunities
  - Simplified Safety Analysis
    - Large fuel temperature margins, low-pressure system, single phase coolant, scaled experiments
  - Flexible operation of NACC
  - Low pressure system with thin-walled components
  - Modular design and construction methods
- Challenges
  - Demonstrate tritium control strategy
  - Procurement of flibe coolant with enriched Li-7
  - Fuel fabrication and qualification
  - High temperature materials with long-term creep
- Future Potential
  - New structural alloys for increased temperature/power
  - Operational experience with salts could benefit MSR efforts