# Fluoride-Salt-Cooled High-Temperature Reactors (FHRs)

## Base-load Reactor Operation with Variable Output, Electricity Storage (as Heat) and Grid Management


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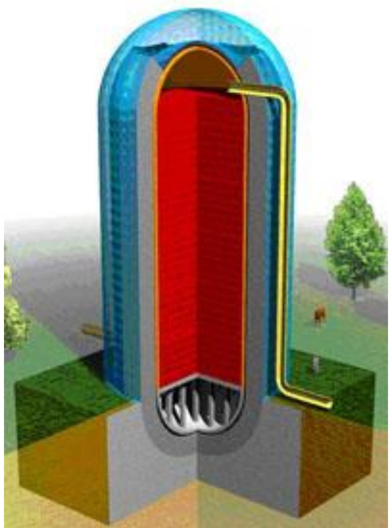
# Abstract

The Fluoride-salt-cooled High-Temperature Reactor (FHR) with a Nuclear Air-Brayton Combined Cycle (NACC) and Firebrick Resistance Heated Energy Storage (FIRES) is a new reactor concept. It is designed to (1) increase revenue relative to base-load nuclear power plants by 50 to 100%, (2) enable a zero-carbon nuclear-renewable electricity grid, and (3) eliminate the potential for major fuel failures in severe accidents. With the reactor operating at base-load the plant can (1) deliver base-load electricity to the grid, (2) deliver peak electricity to the grid using auxiliary natural gas or stored heat at times of high electricity prices, or (3) buy electricity when electricity prices are below that of natural gas and store as heat for peak power production at a later time. The system may provide grid electricity storage to replace pumped hydro storage, batteries, and other devices. These capabilities are a consequences of (1) coupling the FHR (high-temperature gas-cooled reactor fuel and liquid salt coolant) to a gas turbine, (2) advances in gas turbine technology, and (3) advances in high-temperature fuels. MIT leads a university consortium with the University of California at Berkeley and the University of Wisconsin to develop the reactor. The Chinese Academy of Science plans to start up a 10 MWt test reactor by 2020. As a new reactor concept there are significant uncertainties and major development work is required.

# The Base-Load FHR Produces Variable Electricity to Match Market Needs

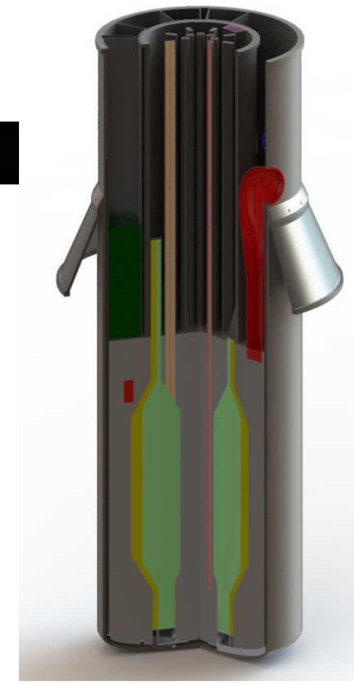
FIRES for
Peak Electricity
Stored Heat

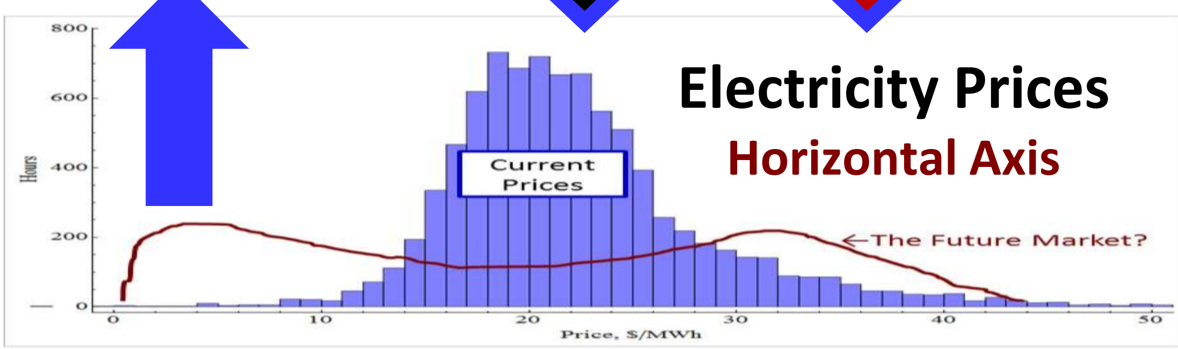


Combustible Fuels
for Peak Electricity

Gas-Turbine (NACC)

Constant High-Temperature Heat
(600 to 700 C)
Reactor (FHR)






Electricity Prices
Horizontal Axis

# FHR: A New Type of Reactor

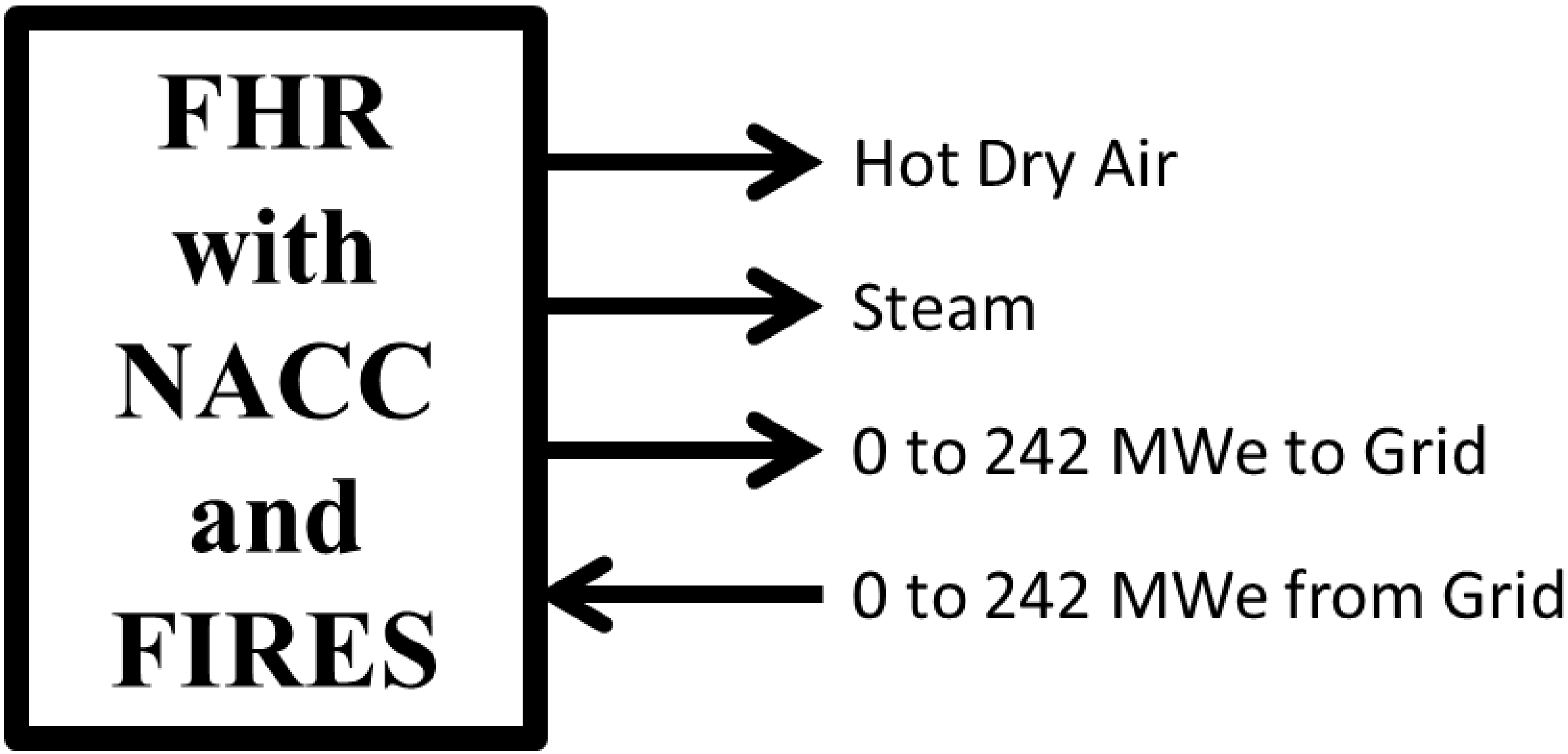
## Fluoride-salt-cooled High-temperature Reactor (FHR) with Nuclear Air-Brayton Combined Cycle (NACC) and Firebrick Resistance-Heated Energy Storage (FIRES)

# The FHR Is About a Decade Old

- **Enabled by two advancing technologies**
  - Natural-gas-fired combined cycle technology
  - Graphite-matrix coated-particle nuclear fuel
- Rapidly growing interest because of different capabilities versus other nuclear reactors
  - Expanding R&D
  - Chinese Academy of Science decision two years ago to build first FHR test reactor by 2020: 10 MWt

# Modular FHR as a Black-Box

## Can be Built in Different Sizes




**NACC: Nuclear Air-Brayton Combined Cycle**
**FIRES: Firebrick Resistance-Heated Energy Storage**

**Not Your Traditional Nuclear Reactor**

# Modular FHR as a Black-Box

## Can be Built in Different Sizes

- Average electricity prices: 100 MWe baseload to grid
- High electricity prices: 242 MWe to grid
  - Peak power using auxiliary natural gas or stored heat
  - 66% NG or stored heat-to-electricity efficiency
- Low or negative electricity prices: Buy 242 MWe
  - Buy when electricity prices less than natural gas
  - Electricity from FHR and grid into heat storage
  - Round-trip electricity-to-heat-to-electricity efficiency: 66%
- Implications
  - Increase plant revenue relative to base-load electricity
  - Enable zero-carbon nuclear-renewable grid (May replace hydro pumped storage, batteries, back-up gas turbines)

**Not Your Traditional Nuclear Reactor**

# FHR Goals

**Economics: 50 to 100% Increase in Revenue**
**Environment: Zero-Carbon Electricity Grid**
**Safety: No Major Fuel Failures**

# The United States Has Successfully Commercialized only One Reactor Type

## Light Water Reactor

- Basis for LWR commercialization
  - Developed LWR because it would revolutionize submarine warfare
  - Requirements for submarine propulsion close to utility power-plant requirements
- **Need compelling case for any new reactor**

# The Commercialization Strategy is Central to Developing a New Reactor

## FHR Integrated Research Project Strategy

Commercial Strategy and Markets (MIT)
Definition of Near-term and Long-term Goals

↓

Commercial Reactor Point Design (UCB)

↓

Test Reactor Goals, Strategy, and Design (MIT)

↓

Technology Development (MIT/UCB/UW)

# Goals for the Compelling FHR Market Case

- **Economic**: Increase revenue 50% to 100% relative to base-load nuclear power plants with capital costs similar to LWRs
- **Environment**: Enable a zero-carbon nuclear-renewable (wind / solar) electricity grid by providing economic dispatchable (variable) electricity
- **Safety**. No major fuel failures if beyond-design-basis accident (BDBA)

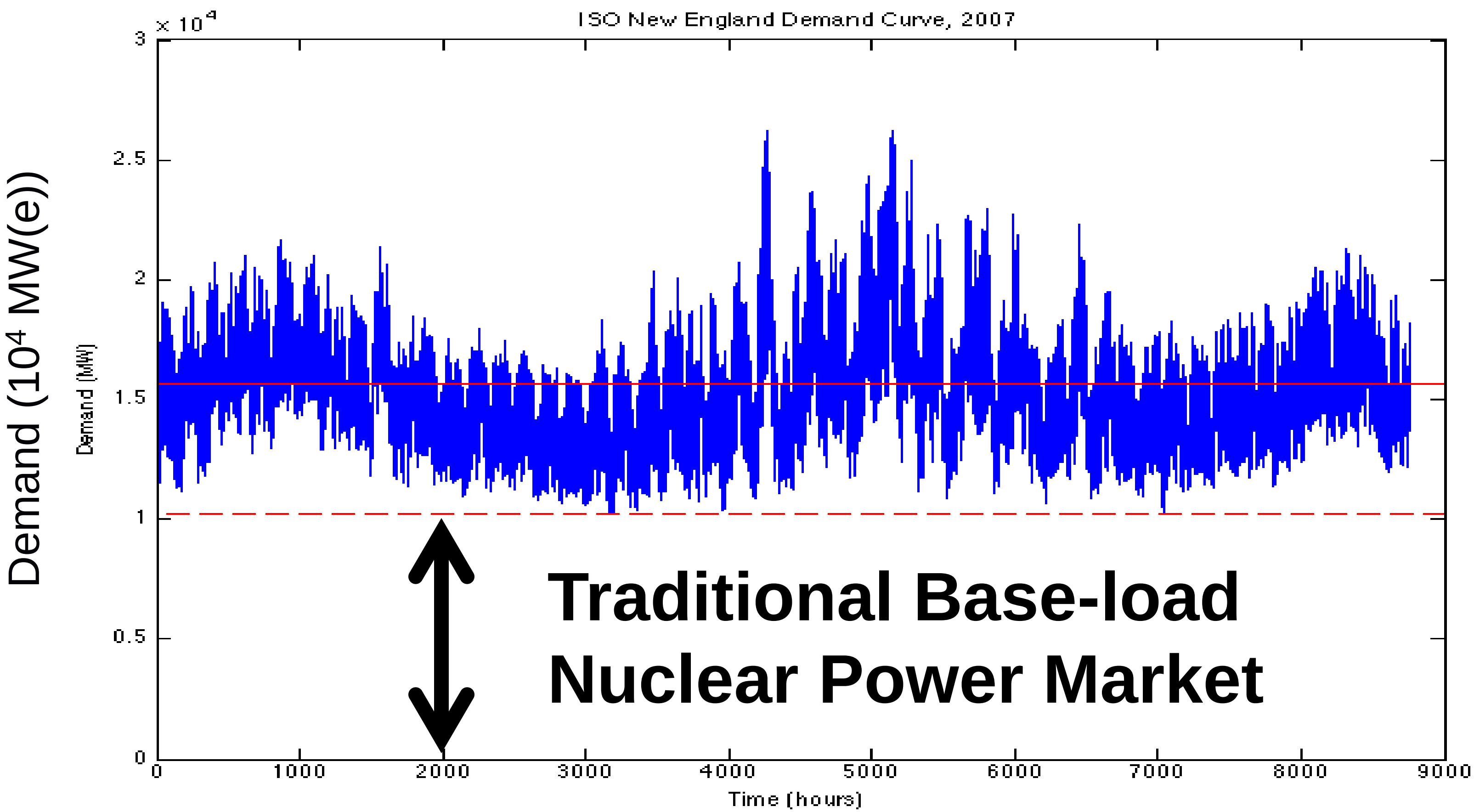
Common Solution

Using California and Texas 2012 hourly price data and the 2012 Henry Hub natural gas at $3.52, 50% gain in revenue relative to base-load nuclear plant. If increase natural gas prices, all nuclear is more economic and FHR with NACC revenue is about double that of a base-load nuclear plant. Most of that economic gain occurs when natural gas prices double. Does not include FIRES.

# The Electricity Market

# Electricity Demand Varies With Time

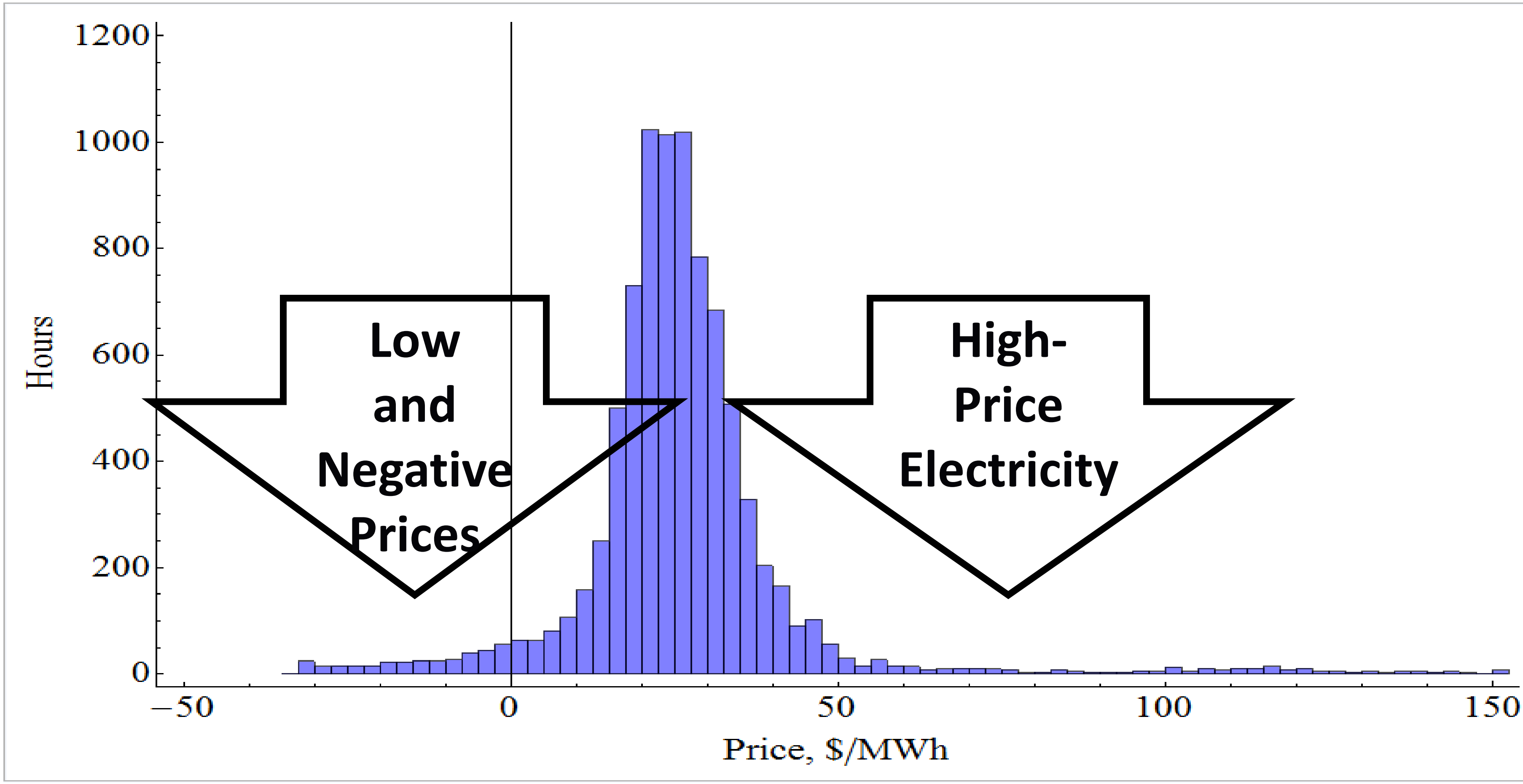
## What Provides Variable Electricity If No Fossil Fuels?




Time (hours since beginning of year)

# In a Free Market Electricity Prices Vary

## Shape of Price Curve Reflects Fossil-Fuel Dominated Grid



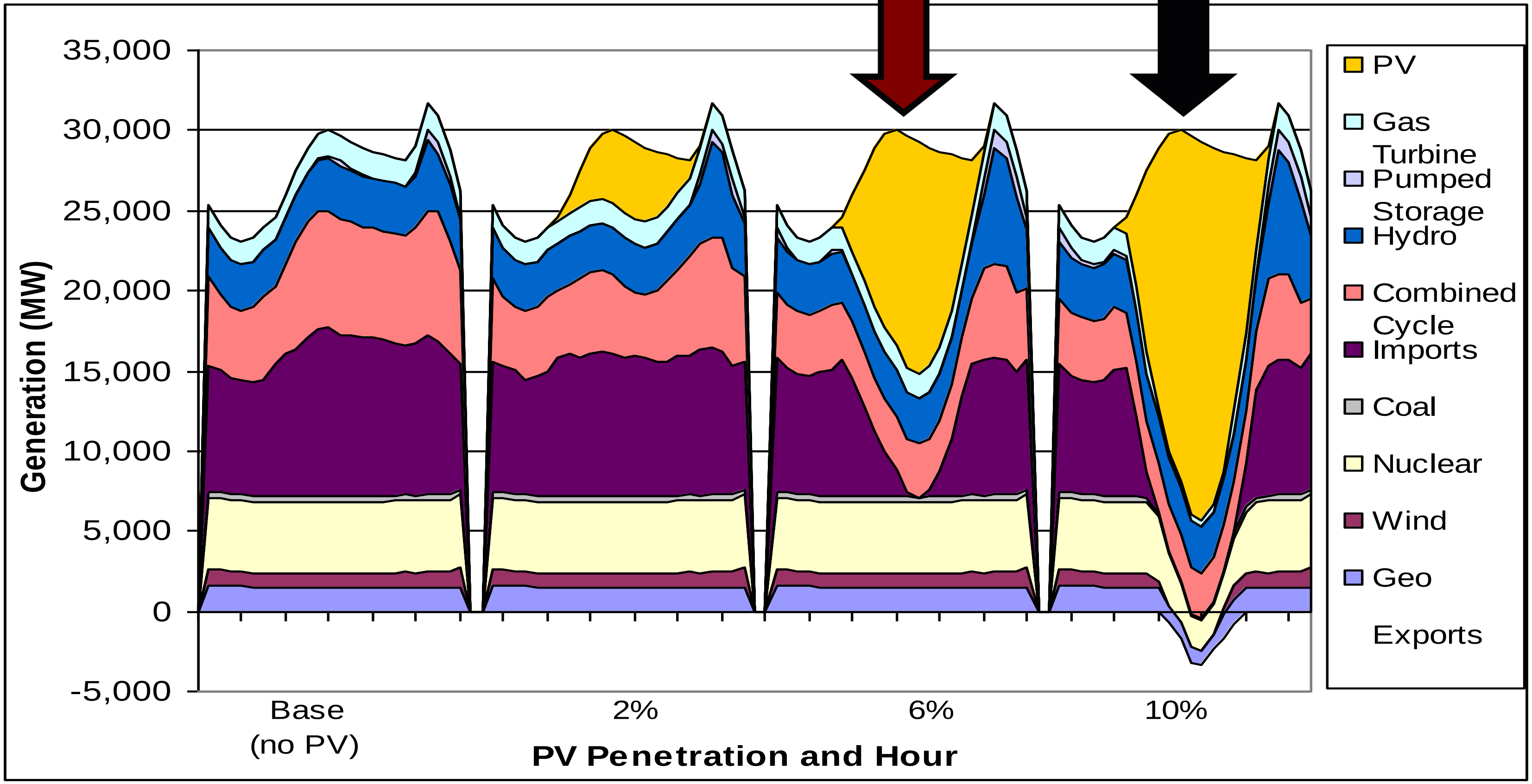



2012 California Electricity Prices

# Adding Solar and Wind Changes Electricity Prices & Price Structure

**Unstable Electrical Grid**

**Excess Electricity with Price Collapse**



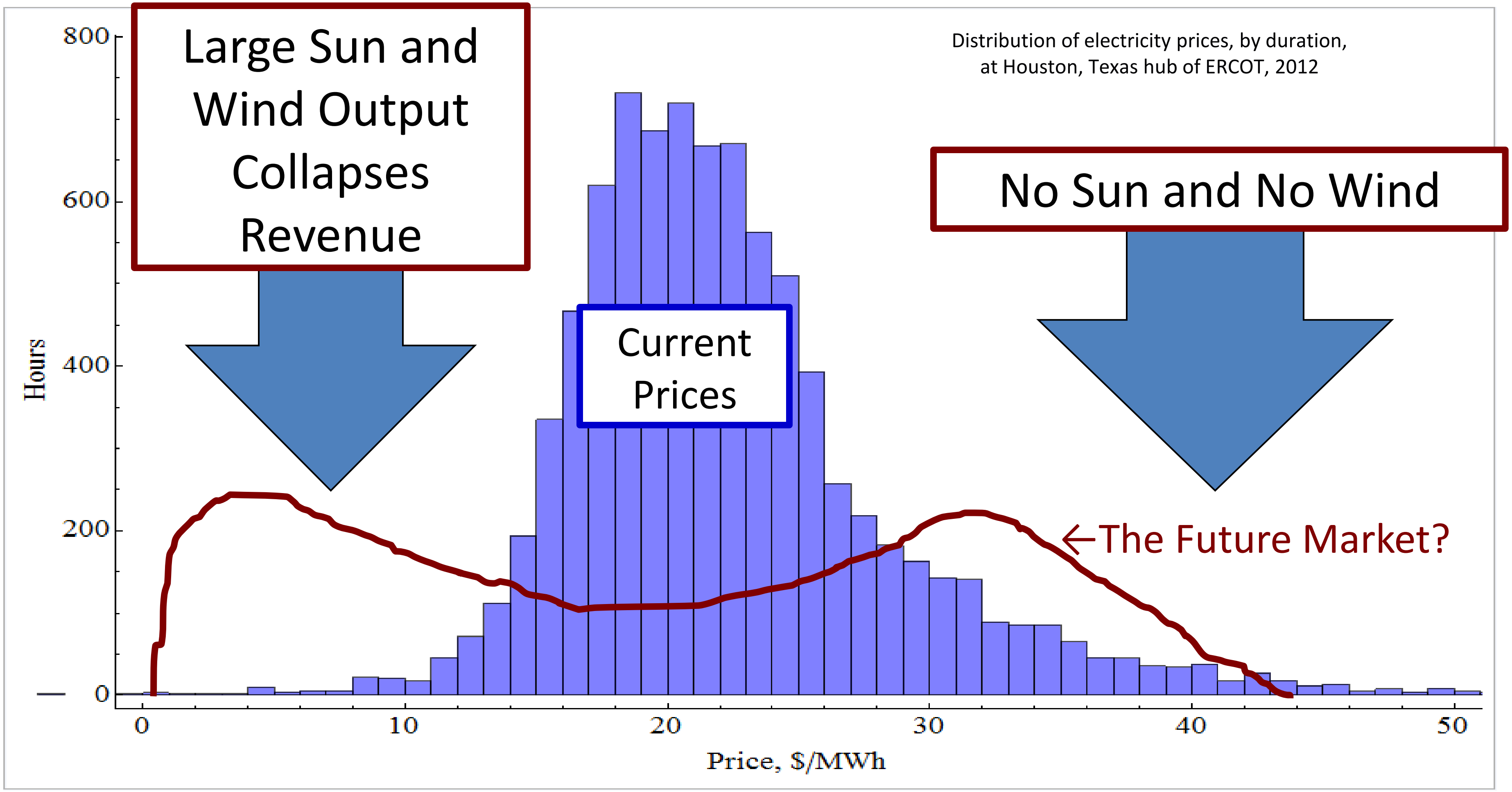

**California Daily Spring Electricity Demand and Production with Different Levels of Annual Photovoltaic Electricity Generation**

# Notes on California Solar Production



- Far left figure shows mix of electricity generating units supplying power on a spring day in California. The figures to the right shows the impact on grid of adding PV capacity assuming it is dispatched first—low operating cost.
- Percent PV for each case is the average yearly fraction of the electricity provided by PV. The % of power from PV is much higher in late June in the middle of the day and is zero at night. Initially PV helps the grid because PV input roughly matches peak load. Problems first show up on spring days as shown herein when significant PV and low electricity load.
- With 6% PV, wild swings in power supply during spring with major problems for the grid. By 10% PV on low-electricity-demand days PV provides most of the power in the middle of many spring days.
- In a free market PV and other producers with zero production costs will accept any price above zero. As PV grows, revenue to PV begins to collapse in the middle of the day. Collapsing revenue limits PV new build. Same happens if lots of wind is built. Large-scale PV or wind also damages base-load electricity market while increasing market for peak power when no sun or wind. In the U.S. that variable demand is getting filled with natural-gas-fired gas turbines with increases in greenhouse gas emissions.
- The revenue problem with renewables is similar to selling tomatoes in August when all the home-grown tomatoes turn red and the price collapses to near zero
- The other part of the story is the need for backup power when low wind or solar. For example, in Texas only 8% of the wind capacity can be assigned as dispatchable. That implies in Texas for every 1000 MW of wind, need 920 MW of backup capacity for when the wind does not blow—almost a full backup of wind. In the Midwest grid, only 13.3% of the wind capacity can be assigned as dispatchable. Consequently, with today's technologies large scale renewables assures large-scale fossil fuel usage

# Low-Carbon Electricity Free Market Implies More Hours of Low / High Price Electricity




**Future Reactor Economics: Make and Buy Low-Price Electricity and Sell High-Price Electricity**

# FHR Economic Strategy

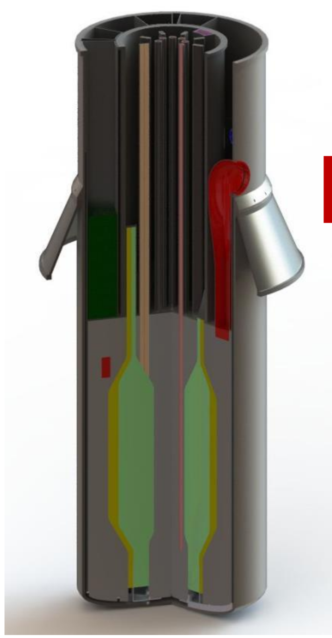
## Reactor Core Operates Base-Load
## Power Cycle Has  Variable Output to Grid
## Increase Revenue Relative to Base-load Plants

# Base-Load FHR with NACC and FIRES Produces Variable Electricity

NACC: Nuclear Air-Brayton Combined Cycle: FIRES: Firebrick Resistance-Heated Energy Storage

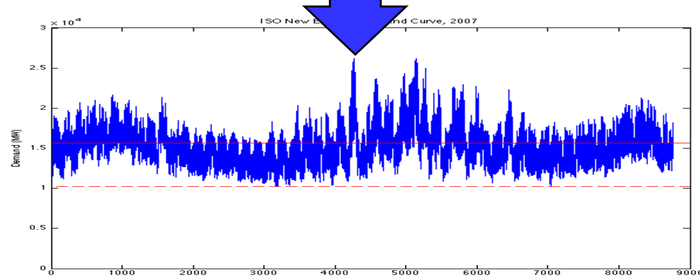
Constant High-Temperature Heat (600 to 700 C)

Reactor (FHR)



Combustible Fuels

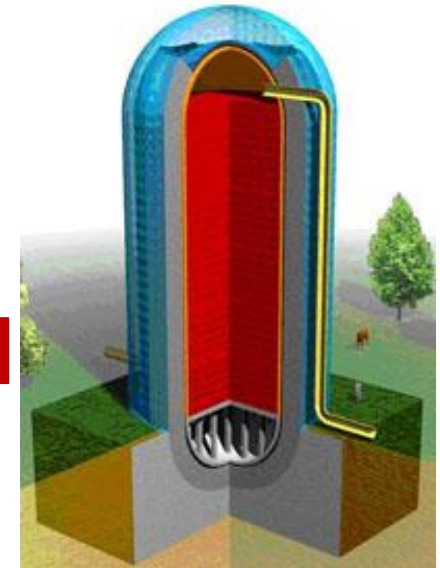
Gas-Turbine (NACC)




Variable Electricity

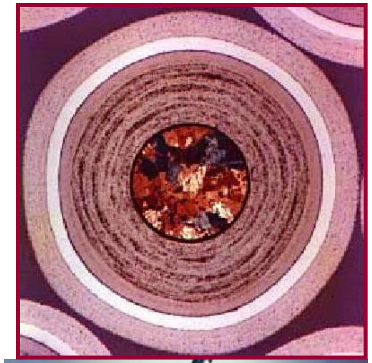
FIRES

Stored Heat

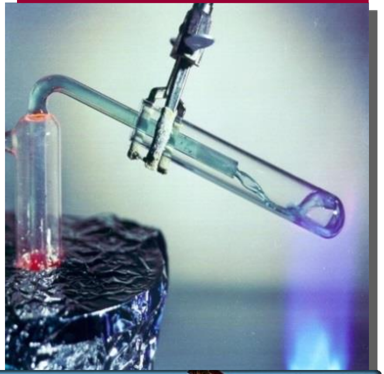


Buy Electricity When Price is Low, Store as High-Temp. Heat

# FHR Combines Existing Technologies



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

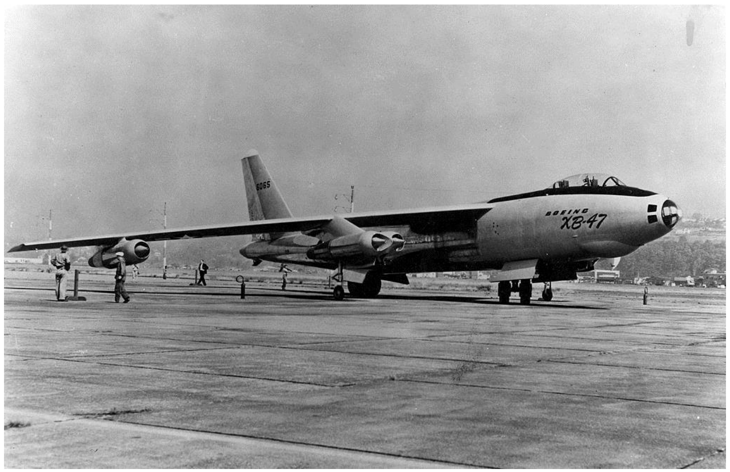


**Coolant:** High-Temperature, Low-Pressure Liquid-Salt Coolant ($^{7}Li_2BeF_4$) with freezing point of 460°C and Boiling Point >1400°C (Transparent)

**Power Cycle**: Modified Air Brayton Power Cycle with General Electric 7FB Compressor

# Fluoride Salt Coolants Were Developed for the Aircraft Nuclear Propulsion Program

## Salt-Cooled Reactors Designed to Couple to Jet Engines



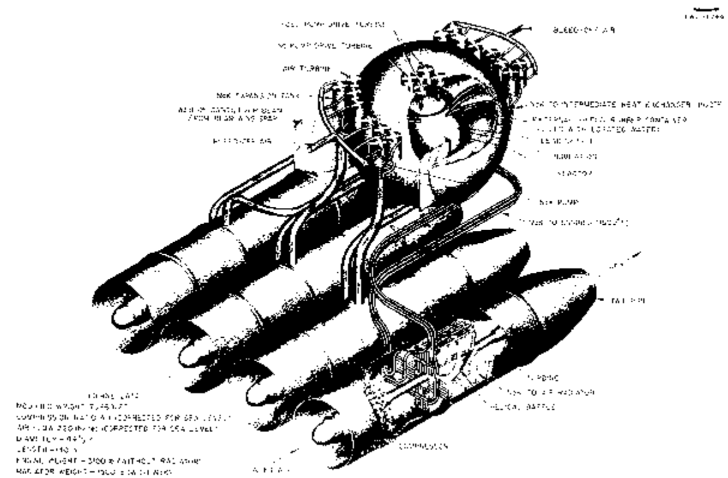
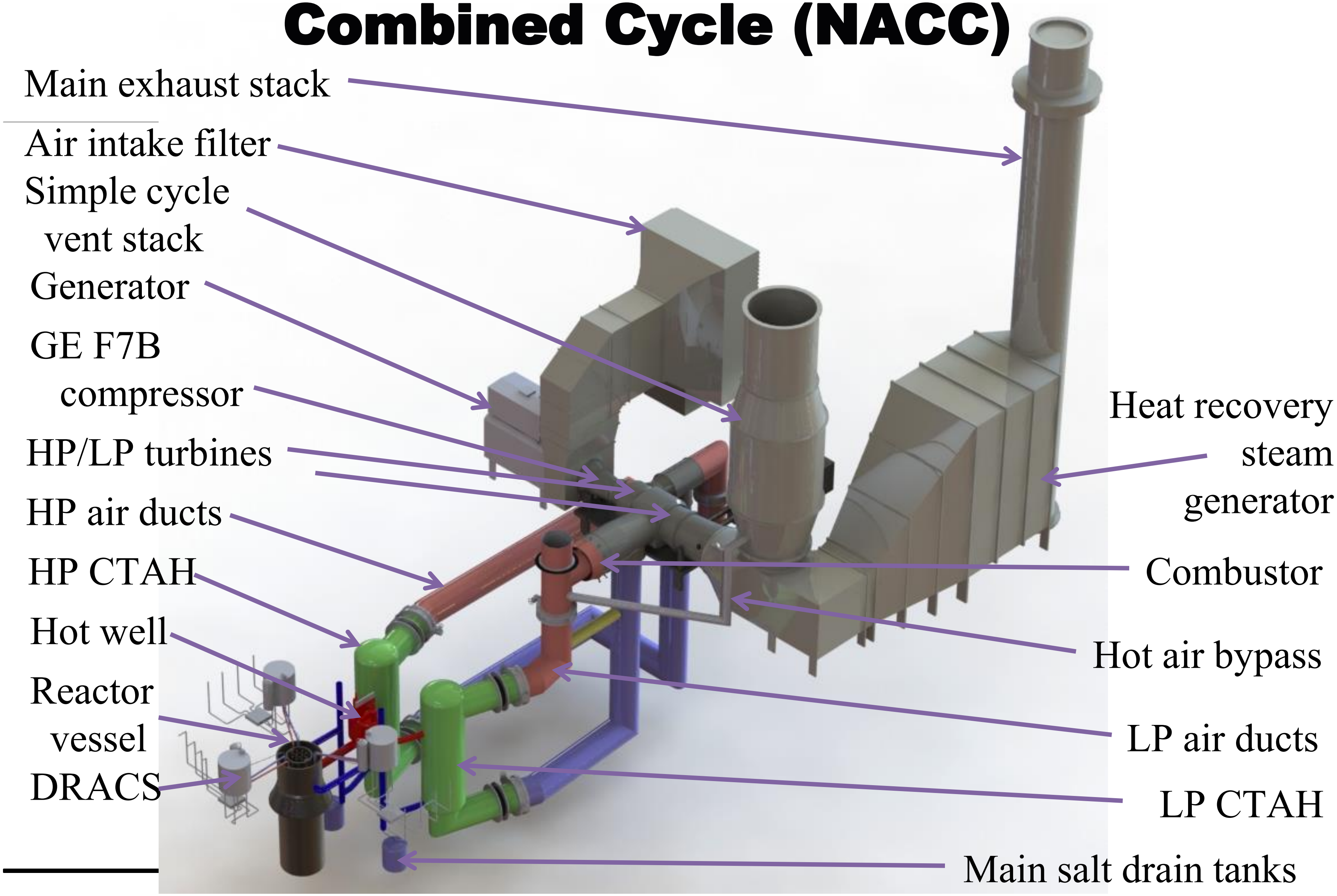



Fig. 4.33. Aircraft Power Plant (200 Megawatt).

**It Has Taken 50 Years for Utility Gas Turbine Technology to Mature Sufficiently to Enable Coupling with an FHR**

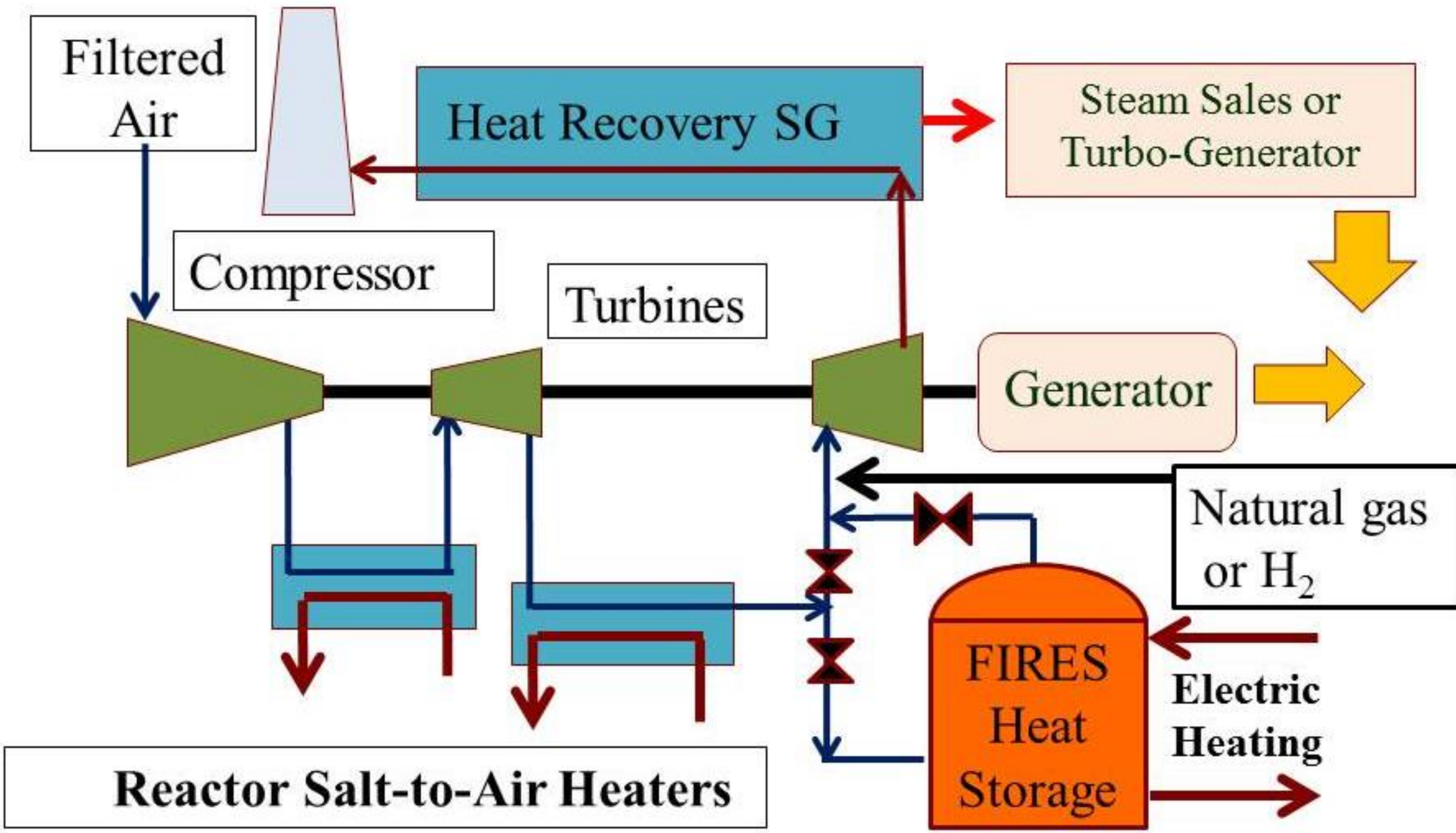
# FHR with Nuclear Air-Brayton Combined Cycle (NACC)




**Reactor** ← **Power Cycle** →

# NACC Power System

## Base-load and Peak Electricity (Auxiliary Natural Gas or Stored Heat)



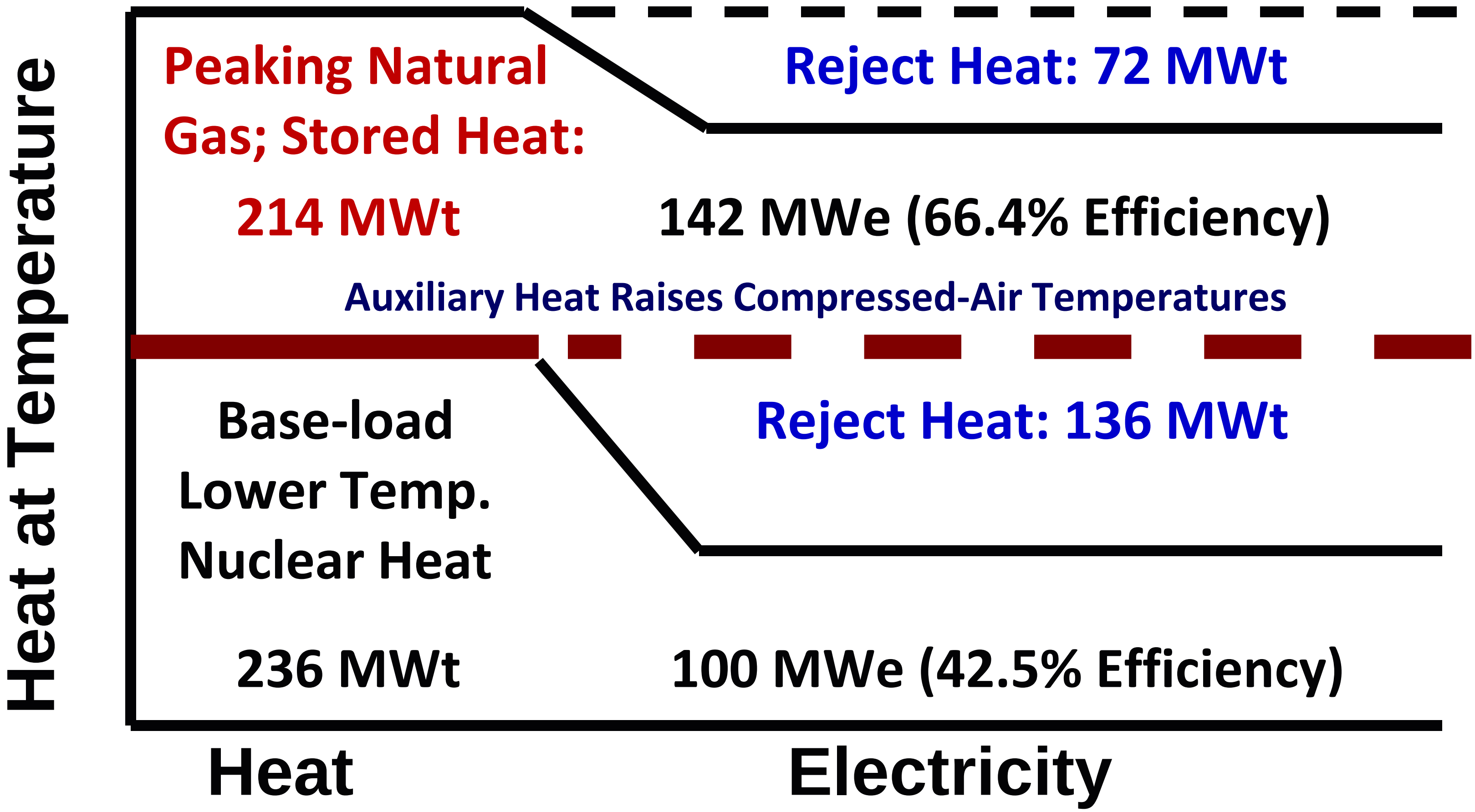
# Notes on NACC

- With base-load operation, air is compressed, heated using heat from the FHR, sent through a turbine to produce electricity, is reheated using heat from the FHR to the same temperature (670C), sent through a second turbine to produce electricity and exhausted at low pressure to a heat recovery steam generator (HRSG)
- In the HRSG the warm air is used to produce steam to produce added electricity or steam for industrial sale.
- The base-load operations are very similar to a natural-gas fired combined cycle plant. The efficiency is ~42%. The cooling water requirements are about 40% of a conventional light water reactor. That is partly because of the higher efficiency and partly because some of the heat rejection is via warm air—similar to stand alone combined cycle natural gas plants.
- For peak power, after second reheat using nuclear heat, natural gas is injected into the hot air stream to raise compressed air temperatures. This increases electricity production from the second turbine and the HRSG.
- The system may also contain a Firebrick Resistance-Heated Energy Storage (FIRES) System. The firebrick is heated with electricity when the price of electricity is below that of natural gas. At times of high prices, compressed air after the second reheat is sent through FIRES to increase its temperature. This results in higher power output from the second turbine and the HRSG
- Peak heat to electricity efficiency is above 66% because it’s a topping cycle above the lower-temperature 700C nuclear heat

# Base-Load Nuclear With Peak Power

## High Natural Gas/ Stored Heat-to-Electricity Efficiency

Base load: 100 MWe; Peak: 241.8 MWe

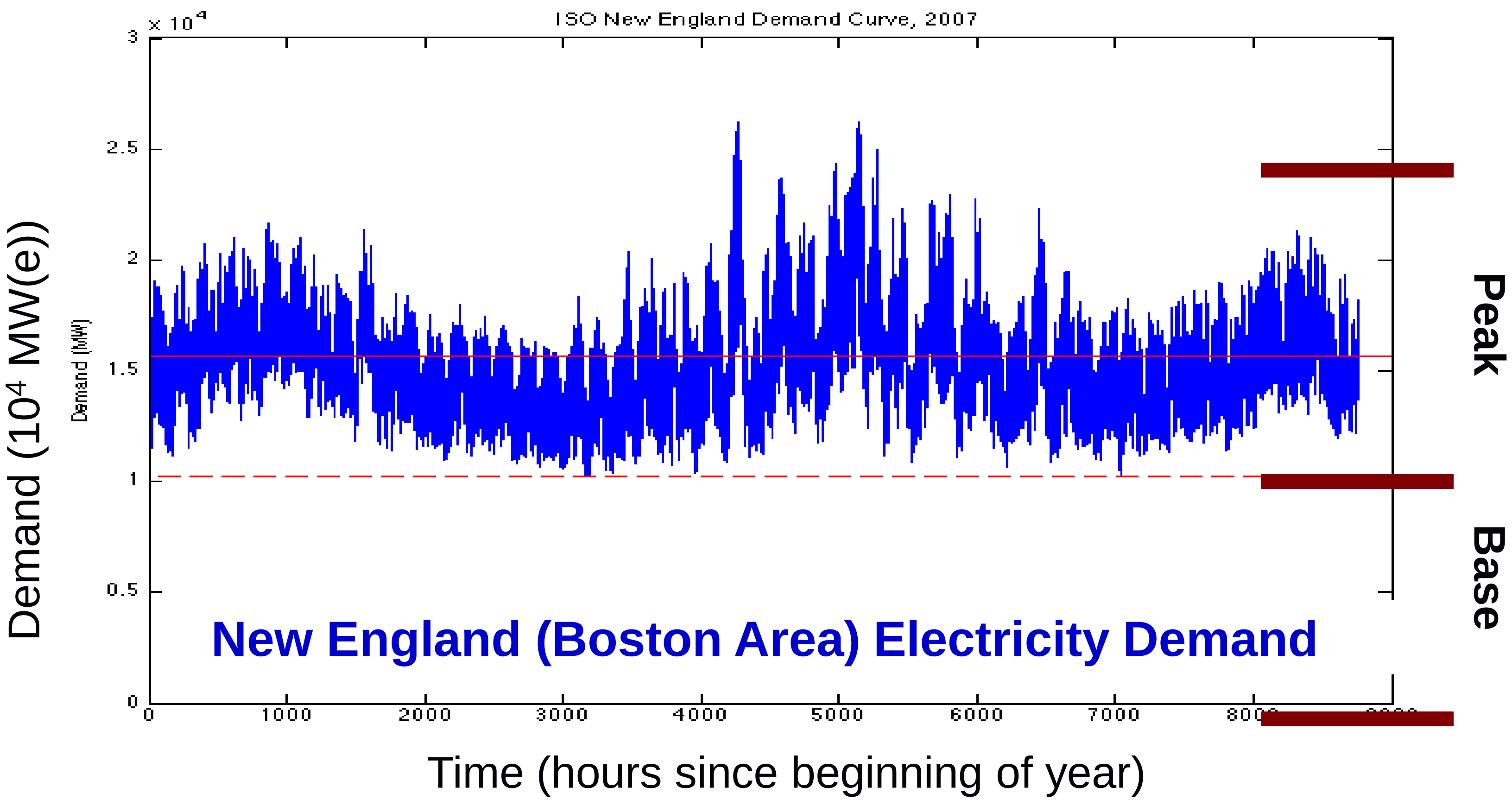





C. Andreades et. al, "Reheat-Air Brayton Combined Cycle Power Conversion Design and Performance under Normal Ambient Conditions," *J. of Engineering for Gas Turbines and Power*, **136**, June 2014

# FHR with NACC Can Meet Variable Electricity Demand

## For Every GW Base load, 1.42 GW of Peaking Capability



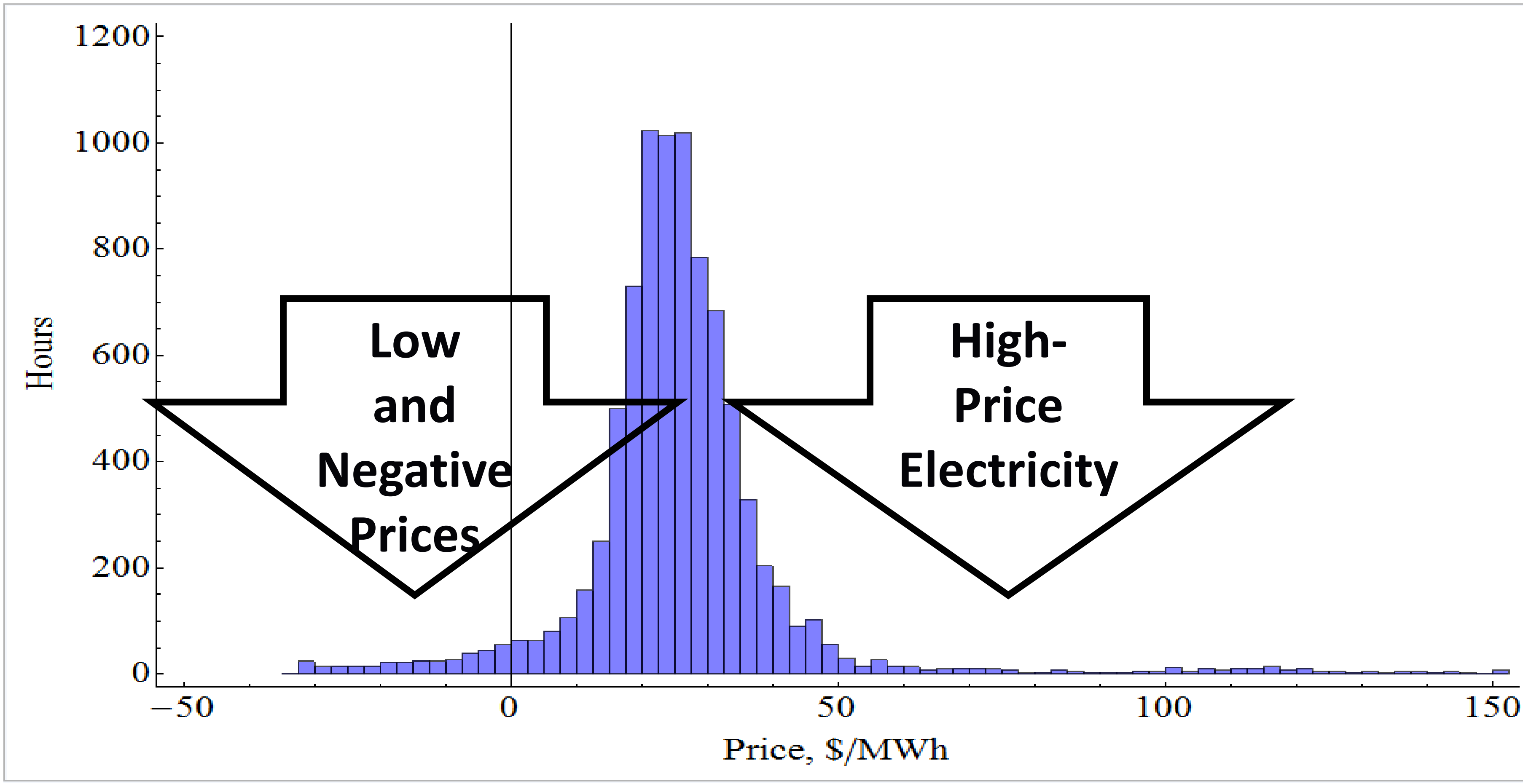

**Dispatchable Nuclear Electricity Option for Zero-Carbon Electricity Grid with Base-Load Reactor Operations**

# Implications of FHR with NACC

- Meet variable electricity demand
  - Most efficient method (66%) to covert combustible fuels (natural gas/hydrogen) or stored heat to peak electricity
  - Stand-alone natural gas plant efficiency is ~60%
  - High efficiency implies FHR/NACC peaking power dispatched before stand-alone gas turbines to meet variable electricity demand
- Cooling water requirements 40% of LWR per MWe (characteristics of combined cycle plant)

# Natural Gas Peaking Boosts Revenue

## Base-load When Low Electricity Prices; Natural Gas Peaking When High Electricity Prices




Massachusetts Institute of Technology

2012 California Electricity Prices

# FHR Revenue Using 2012 Texas and California Hourly Electricity Prices

## After Subtracting Cost of Natural Gas: NACC (no FIRES)

| Grid→ Operating Modes | Texas Percent (%) | California Percent (%) |
|---|---|---|
| Base-Load Electricity | 100 | 100 |
| Base With Peak (NG) | 142 | 167 |

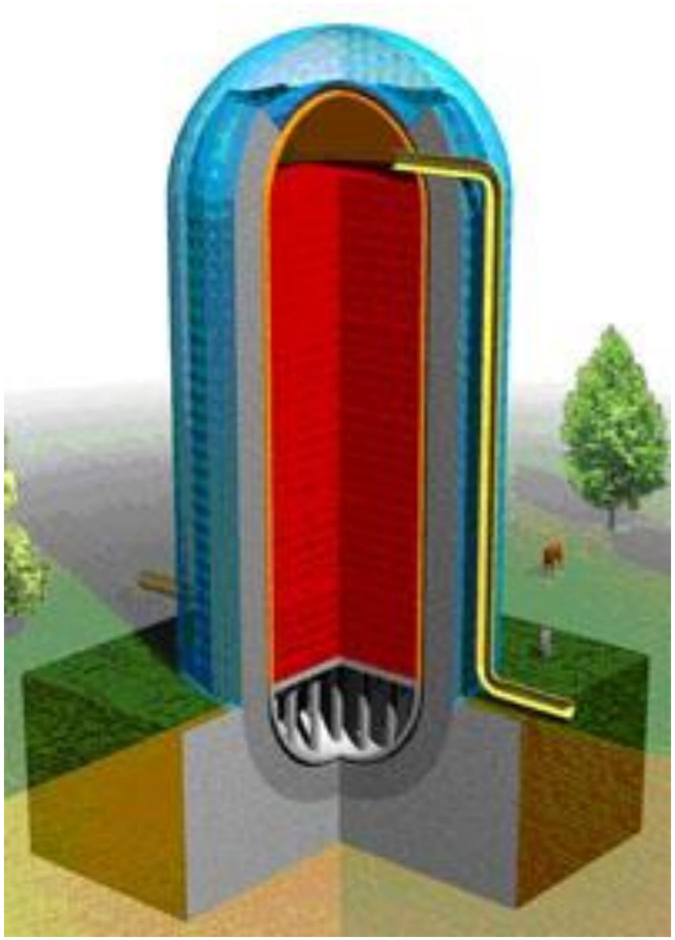
1. Base on 2012 Henry Hub natural gas at $3.52.
2. Methodology in C. W. Forsberg and D. Curtis, "Meeting the Needs of a Nuclear-Renewable Electrical Grid with a Fluoride-salt-cooled High-Temperature Reactor Coupled to a Nuclear Air-Brayton Combined Cycle Power System," *Nuclear Technology*, March 2014
3. Updated analysis in D. Curtis and C. Forsberg, "Market Performance of the Mark I Pebble-Bed Fluoride-Salt-Cooled High-Temperature Reactor, *American Nuclear Society Annual Meeting*, Paper 9751, Reno, Nevada, June 15-19, 2014

# FHR Revenue Increases Rapidly With Increased Natural Gas Prices

- Economics of all nuclear options improve with rising natural gas (NG) prices
- FHR with NACC revenue doubles relative to base-load nuclear as NG prices increase
  - Assumed stand-alone NG plants control electricity prices
  - As prices rise, FHR higher efficiency of incremental NG-to-electricity versus stand-along NG plants improves FHR revenue
  - Most of the increase occurs as NG prices double

1. Base on 2012 Henry Hub natural gas at $3.52.
2. Methodology in C. W. Forsberg and D. Curtis, "Meeting the Needs of a Nuclear-Renewable Electrical Grid with a Fluoride-salt-cooled High-Temperature Reactor Coupled to a Nuclear Air-Brayton Combined Cycle Power System," *Nuclear Technology*, March 2014
3. Updated analysis in D. Curtis and C. Forsberg, "PB-FHR Nuclear Air-Brayton Combined Cycle Natural Gas Price Sensitivity", *American Nuclear Society Annual Meeting*, Anaheim, California, November 9-13, 2014

# Peak Electricity Using Firebrick Resistance-Heated Energy Storage (FIRES)

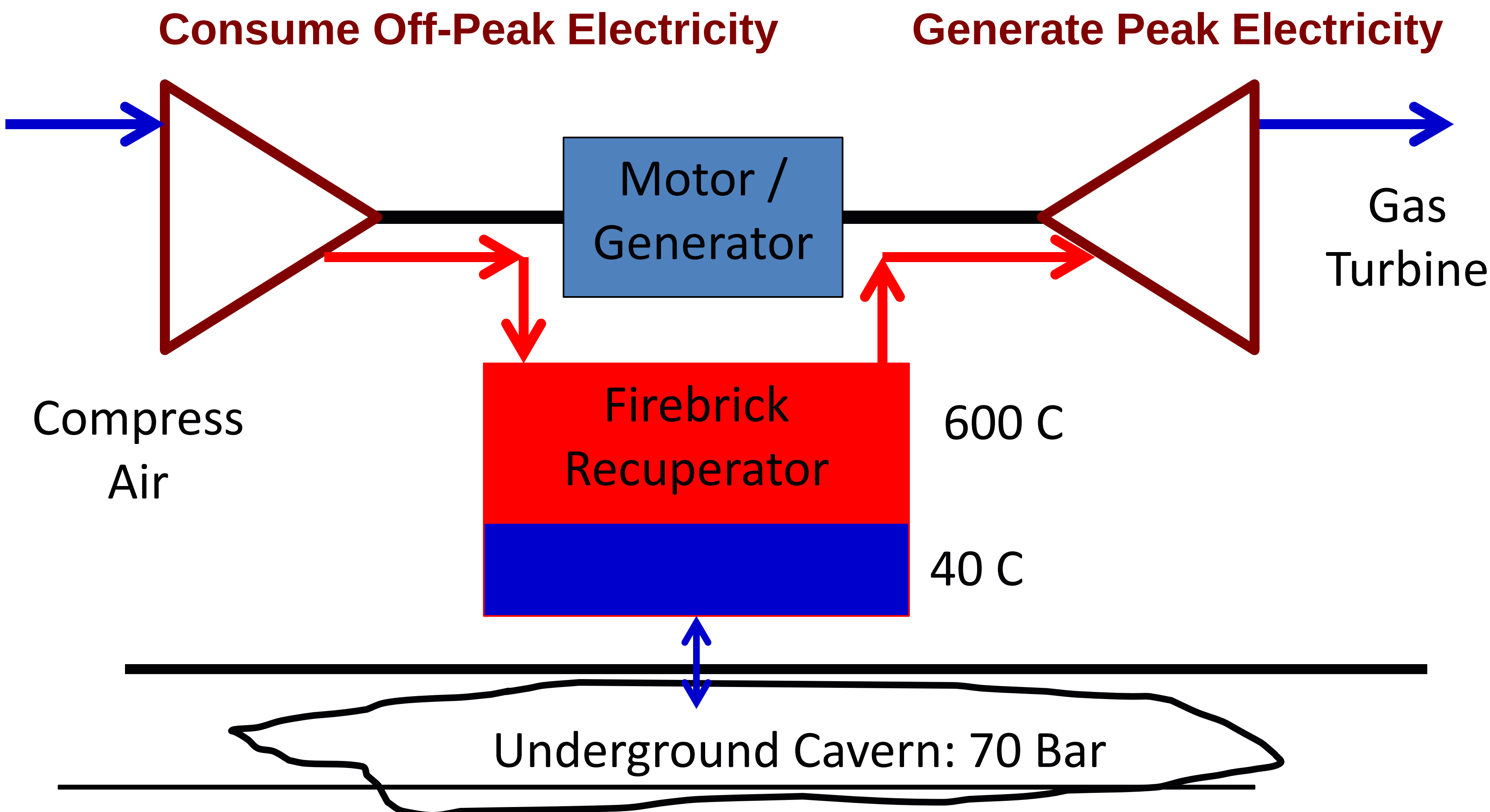


- Electrically heat firebrick in pressure vessel
- **Firebrick heated when low electricity prices; less than natural gas**
  - Electricity from FHR
  - Electricity from grid
- Use hot firebrick as substitute for natural gas peak electricity
- Reasonable round-trip efficiency
  - 100% electricity to heat
  - 66+% heat-to-electricity efficiency (peak power)



**Figure courtesy of General Electric Adele Adiabatic Compressed Air Storage Project**

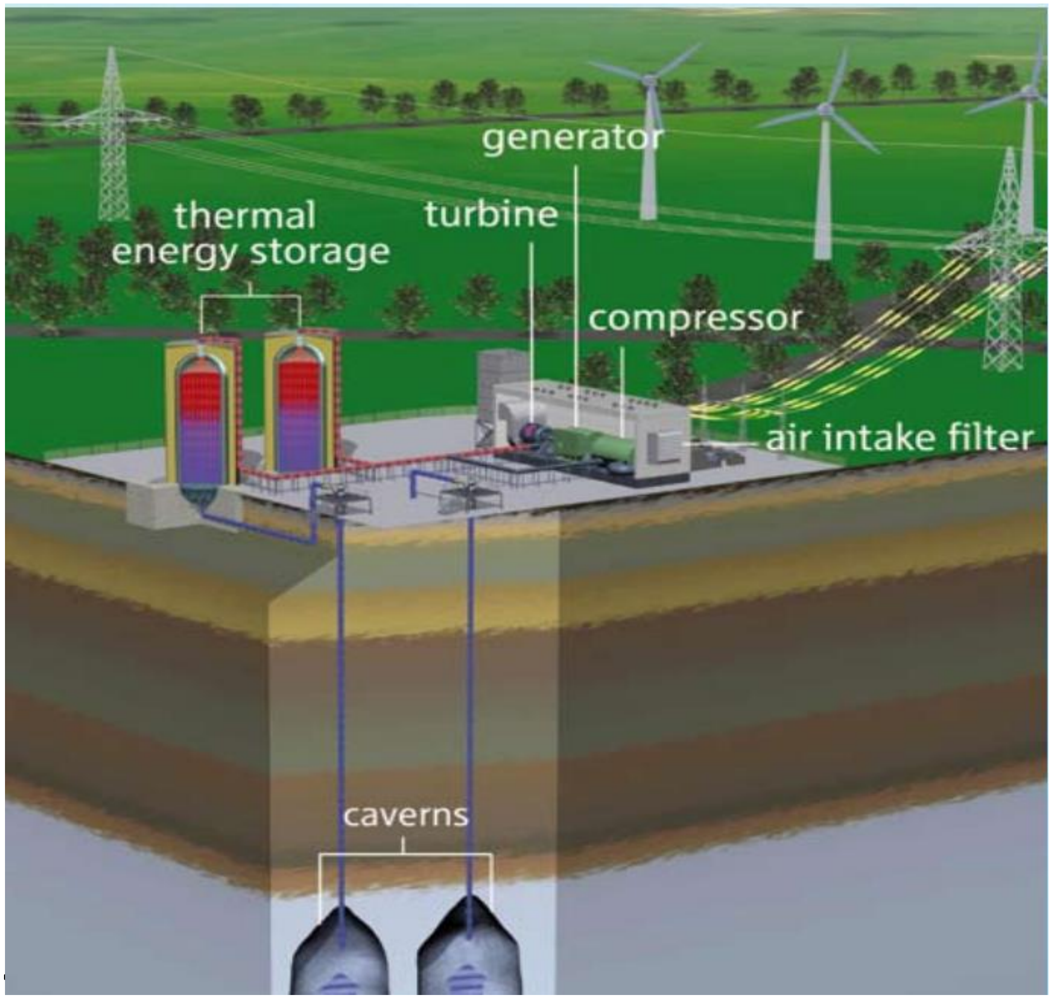
# Gas-Turbine Firebrick Heat Storage Is Being Developed by GE/RWE for Adiabatic Compressed Air Storage Systems



# General Electric - RWE Adiabatic Compressed Air Storage (Adele) Project



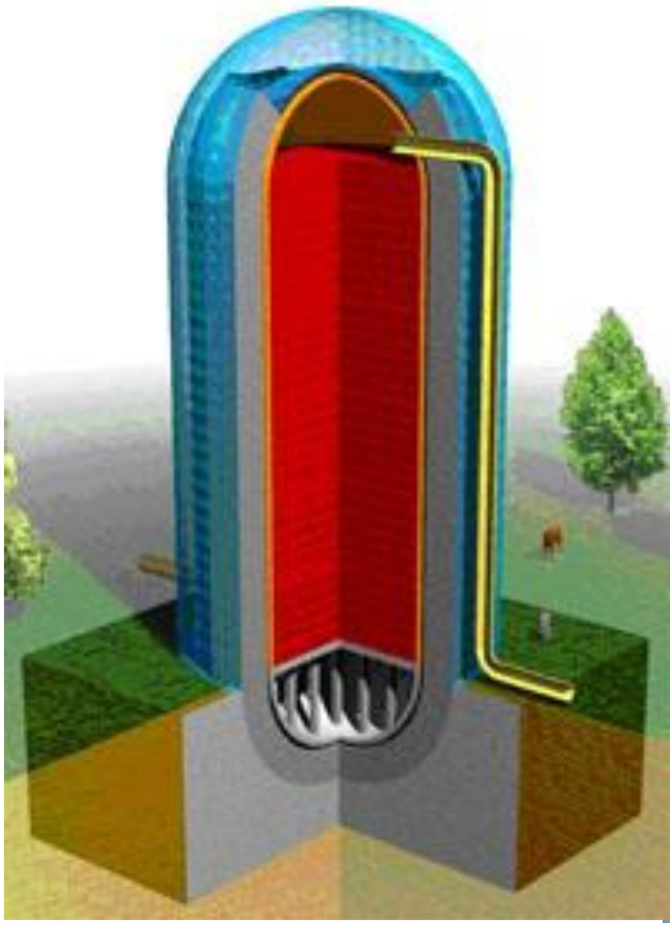
## Developing Most of the Technology Required for FHR Heat Storage




- Grid Electricity into Storage
  - Compress air to 70 bar and 600° C
  - Cool air to 40° C by heating firebrick
  - Compressed air to underground storage
- Electricity from Storage to Grid
  - Heat compressed air with firebrick
  - Turbine produces electricity

# Adele Storage Vessel Testing Underway

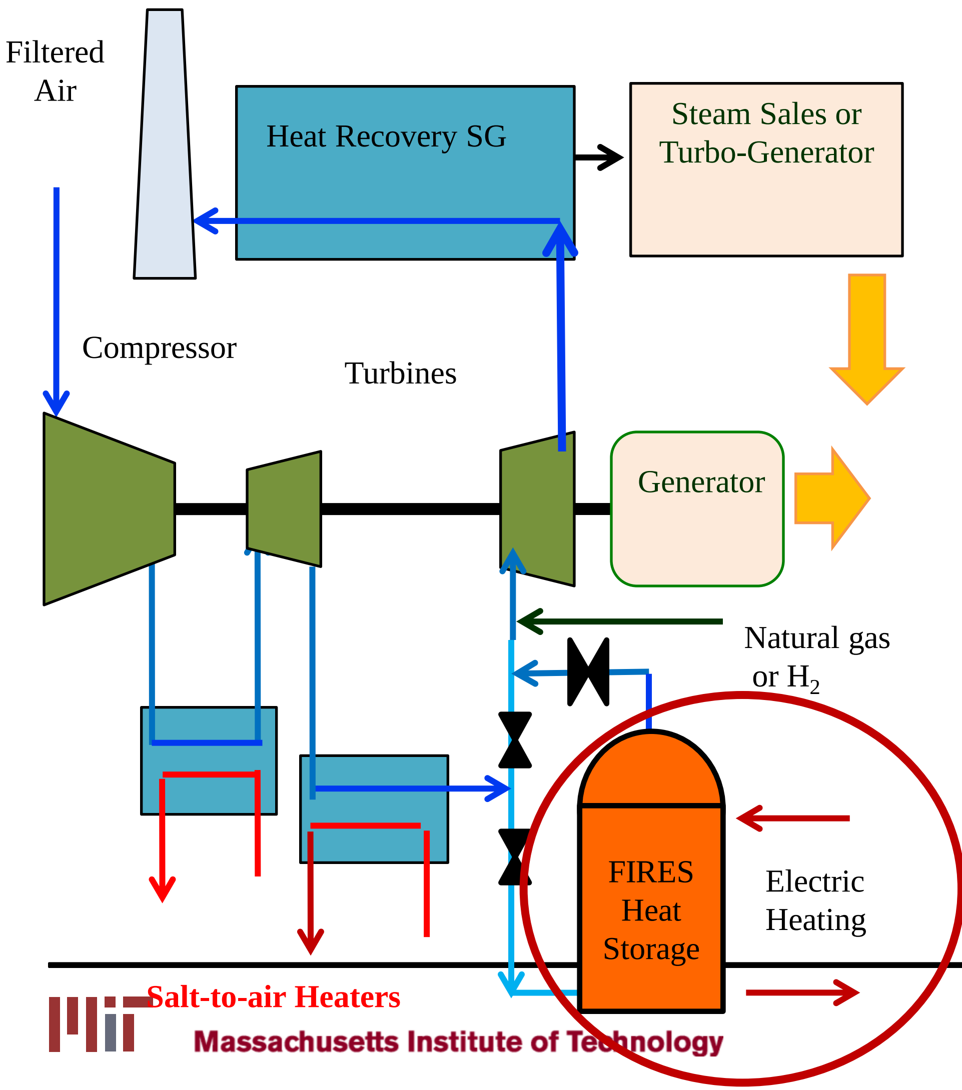
## GE is Integrating Heat Storage and Gas Turbine Technology



**FHR NACC with Stored Heat Differences:**
**Lower Pressure, Higher Temperature and Electric Heating**

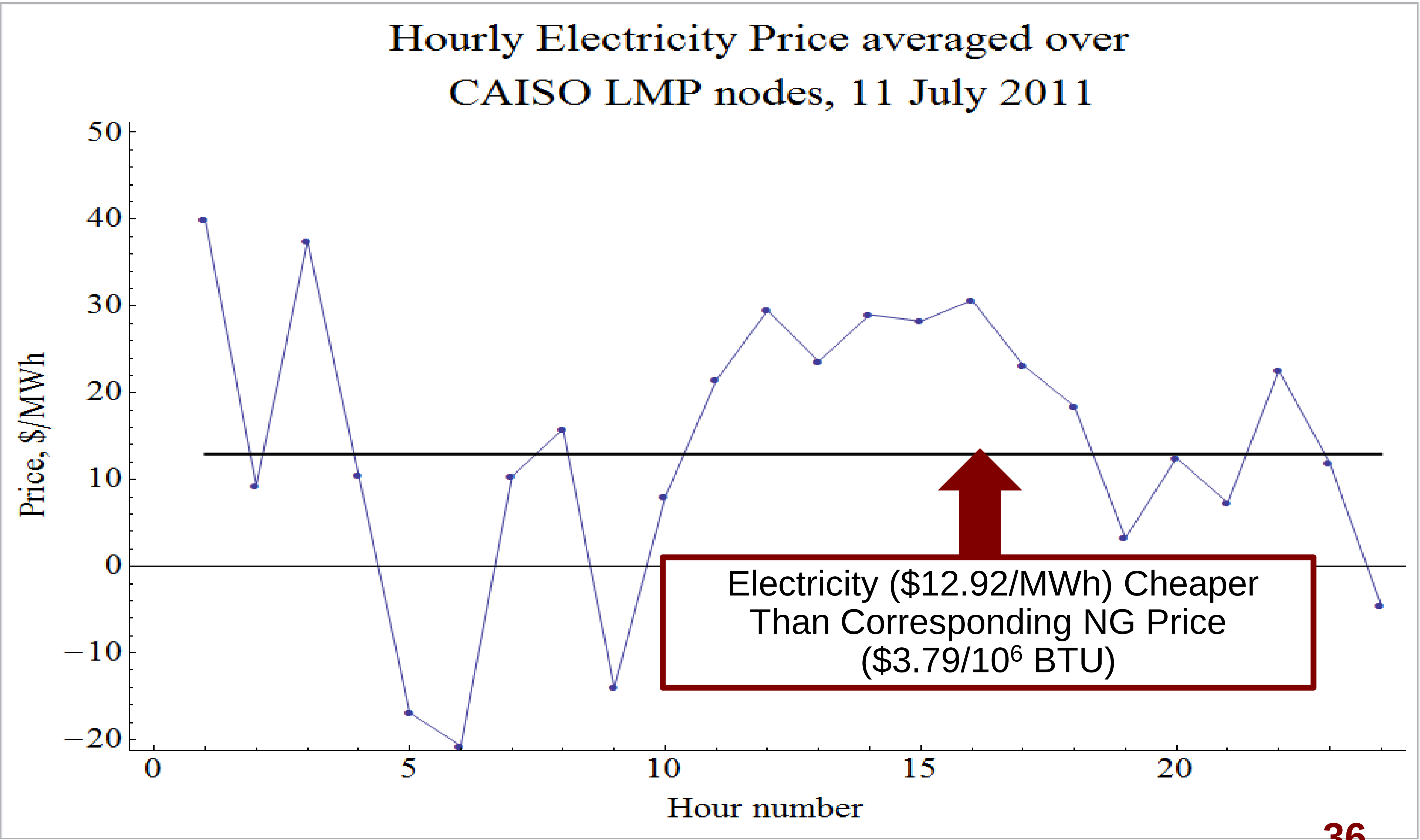
# FHR FIRES Operating Strategy

## For Markets With Significant Electricity Less than the Price of Natural Gas




- Store heat when electricity prices less than natural gas
  - 100 MWe baseload to storage
  - Buy 242 MWe from grid for storage (equal max plant output)
- Use stored heat for peak electricity (242 MWe) output replacing natural gas

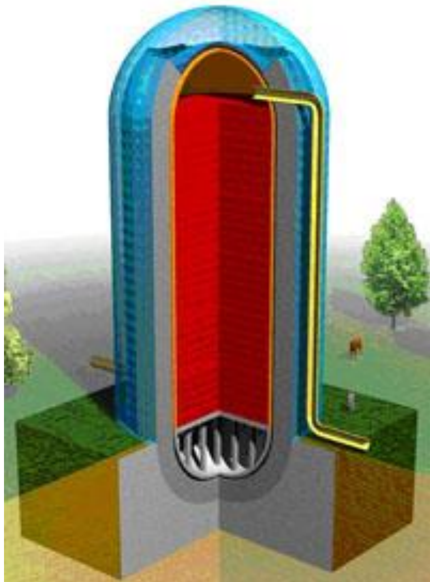
# California Price Curve Shows Times When Electricity Cheaper then Natural Gas



# FHR with NACC and FIRES Produces Variable Electricity to Match Market

## Base-load Nuclear Reactor, Buy and Sell Electricity

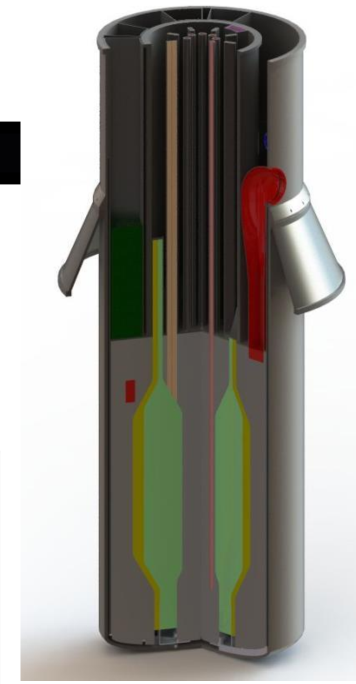
**FIRES**
Stored Heat

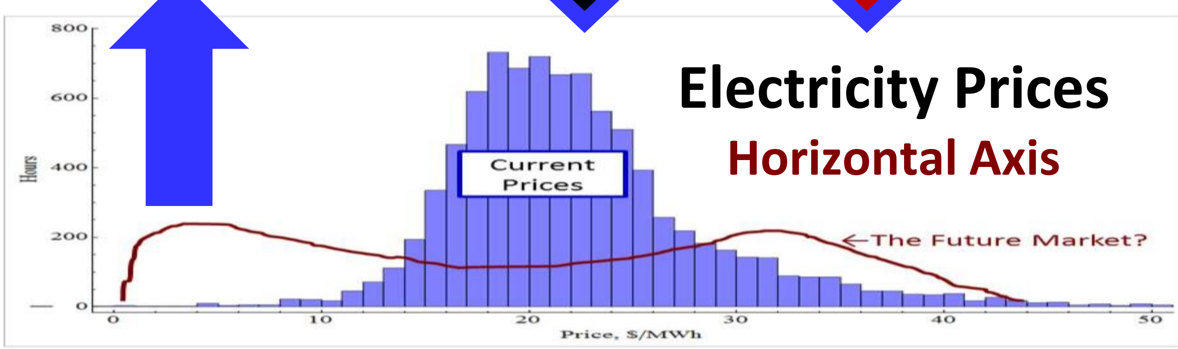


**Combustible Fuels for Peak Electricity**

Gas-Turbine (NACC)

**Constant High-Temperature Heat (600 to 700 C)**
Reactor (FHR)






Electricity Prices
**Horizontal Axis**

# FHR Near-Term and Zero-Carbon Operational Modes

- Most existing markets: FHR with NACC using natural gas for peak power
- Existing markets with low-priced electricity: FHR with NACC using natural gas and FIRES
- Zero-carbon world: FHR uses using FIRES (daily) and hydrogen (seasonal) for peak power
  - FIRES: 66% electricity-to-heat-to-electricity energy storage option—too expensive for long-term storage
  - Hydrogen peak power
    - Electrolysis or equivalent to make electricity
    - Less than 50% electricity-to hydrogen-to-electricity efficiency—but cheap seasonal storage underground like natural gas

# Comparison of FHR Materials with Other Power Generating Systems

## Normalized to FHR Base-load (100 MWe), Not Peak Power (242 MWe)

| | Carbon Steel (1000 kg/MWe) | High Alloy and Stainless Steel (1000kg/MWe) | Concrete (1000 kg/MWe) |
|---|---|---|---|
| Mk1 PB-FHR (100 MWe) | 69.9 | 9.5 | 383.9 |
| ORNL 1970's PWR (1000 MWe) | 36.1 | 2.1 | 179.5 |
| CRS nuclear plant range | 26 to 72 | § | 198 to 685 |
| GE ABWR (1380 MWe) | 46.0 | § | 332.7 |
| GT-MHR | 26.9 | § | 183.1 |
| NGCC plant (620 MWe) | 0.20 | 2.2 | 47.8 |
| CRS NGCC plant range | 34 to 56 | § | 53 to 108 |
| Coal steam plant (1000 MWe) | 62.2 | § | 178.3 |
| CRS coal plant range | 24 to 56 | § | 175 to 354 |

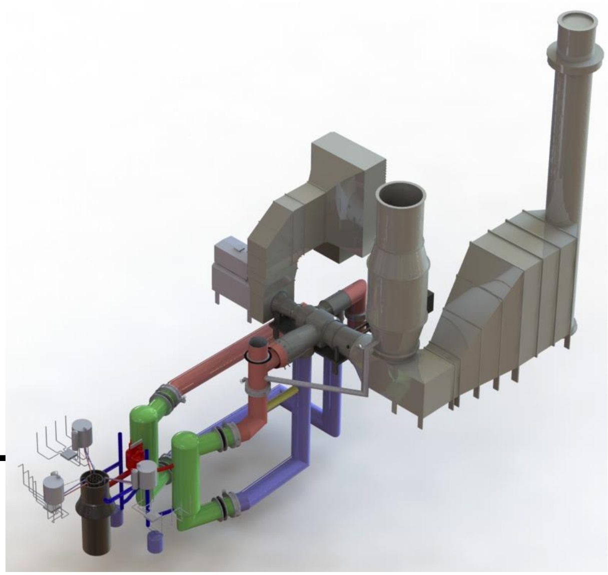
**FHR materials estimates based on site with 12 modular 100 MWe FHRs. No design studies have been completed on larger FHR designs that may have significantly lower materials requirements. Other estimates for larger plants.** § : Not Known

# Commercial Fluoride-salt-cooled High-Temperature Reactor Design

## U. of California--Berkeley

# FHR Commercial Case Defines FHR Technical Requirements

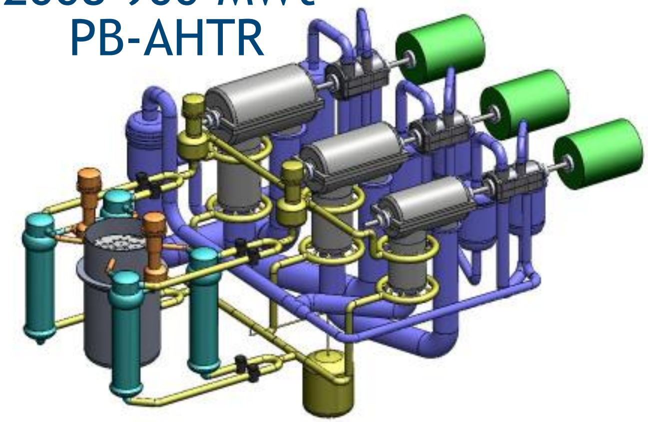
- Front-end air compressor exit temperature between 350 and 500°C—Nuclear heat must be at higher temperatures
- Nuclear heat delivery temperatures: 600-700°C
- FHR matches NACC requirements—what salt coolants were designed for



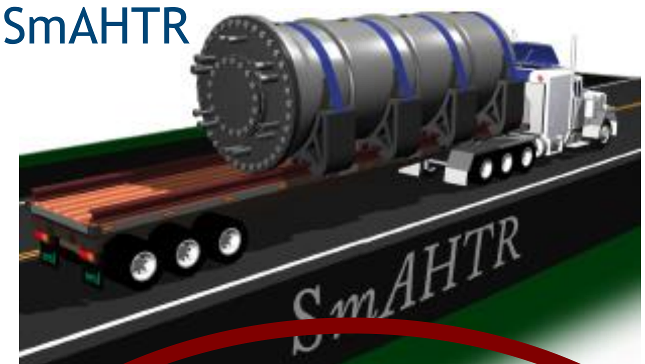
# Alternative FHR Designs Can Be Coupled to NACC

**Base-line UCB/MIT/UW in Oval**

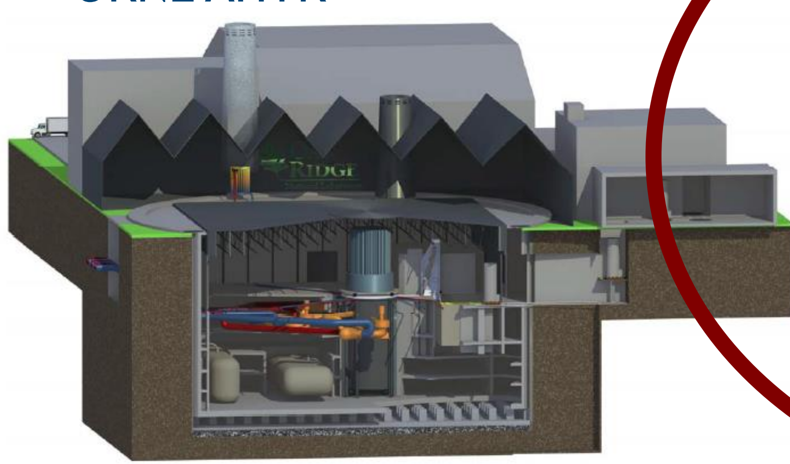
2008 900 MWt
PB-AHTR



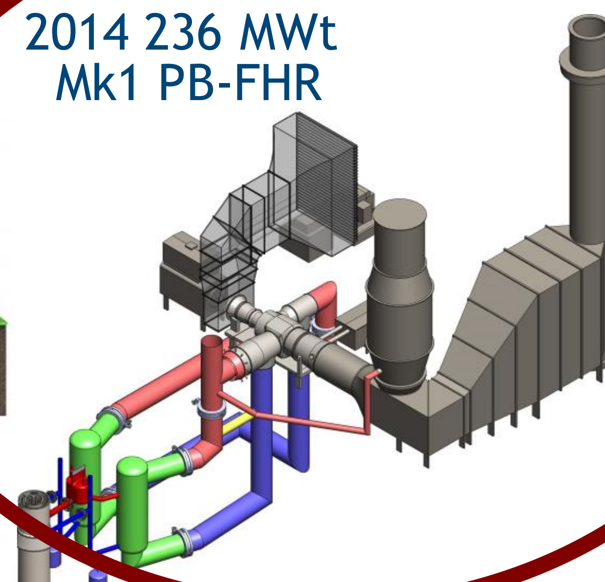
2010 125 MWt
SmAHTR



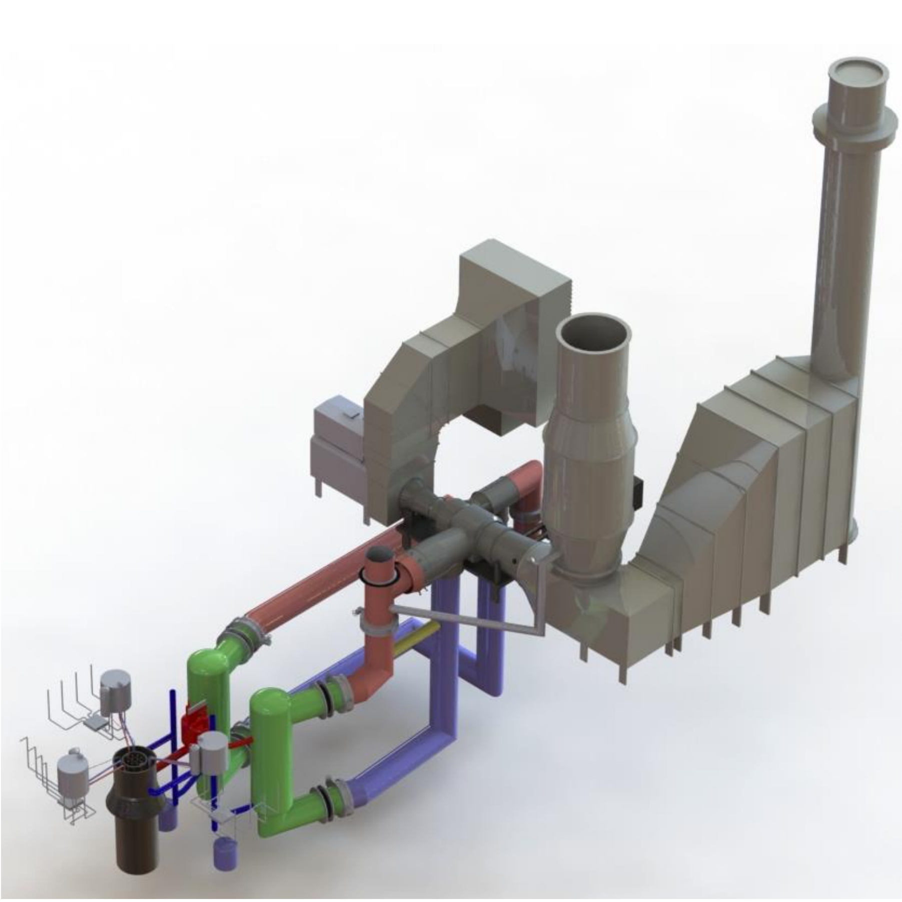

2012 3600 MWt
ORNL AHTR



2014 236 MWt
Mk1 PB-FHR



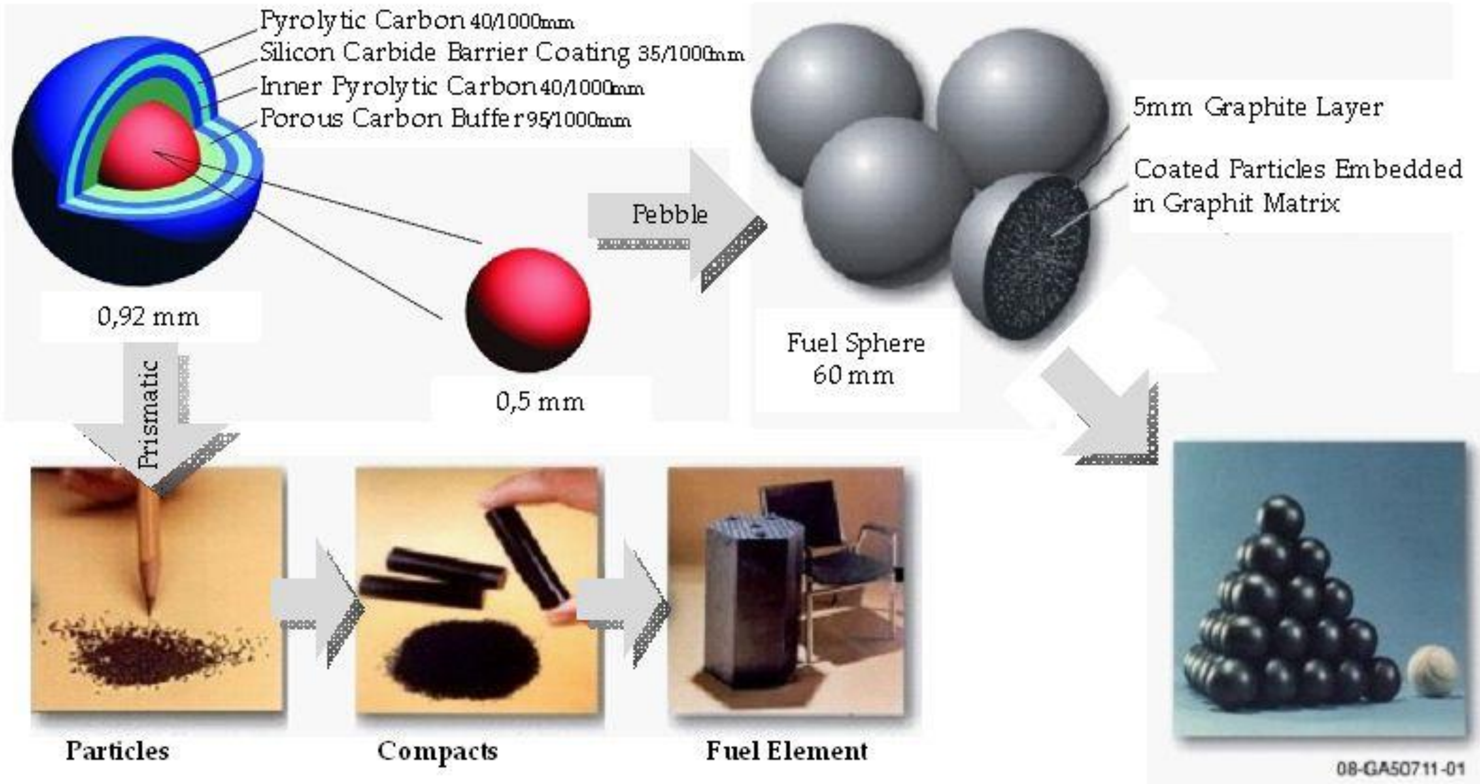
# Characteristics of Modular MK1 FHR Design



- Next-step scale-up from an FHR test reactor
- Modular FHR
  - All components rail shippable
  - Factory manufacture
  - Potential market with multi-reactor site option
- Uses existing technology where possible
- Matches GE 7FB gas turbine size
- Future options
  - Scale to larger size
  - Multiple NACC power units per reactor

# FHR Uses HTGR Pebble-Bed Graphite-Matrix Coated-Particle Fuel

## Several Alternative Fuel Geometries; Same Fuel as NGNP




## Pebble-Bed FHR with 3-cm Diameter Pebbles

# Base Case Salt is $^7Li_2BeF_4$ (Flibe)

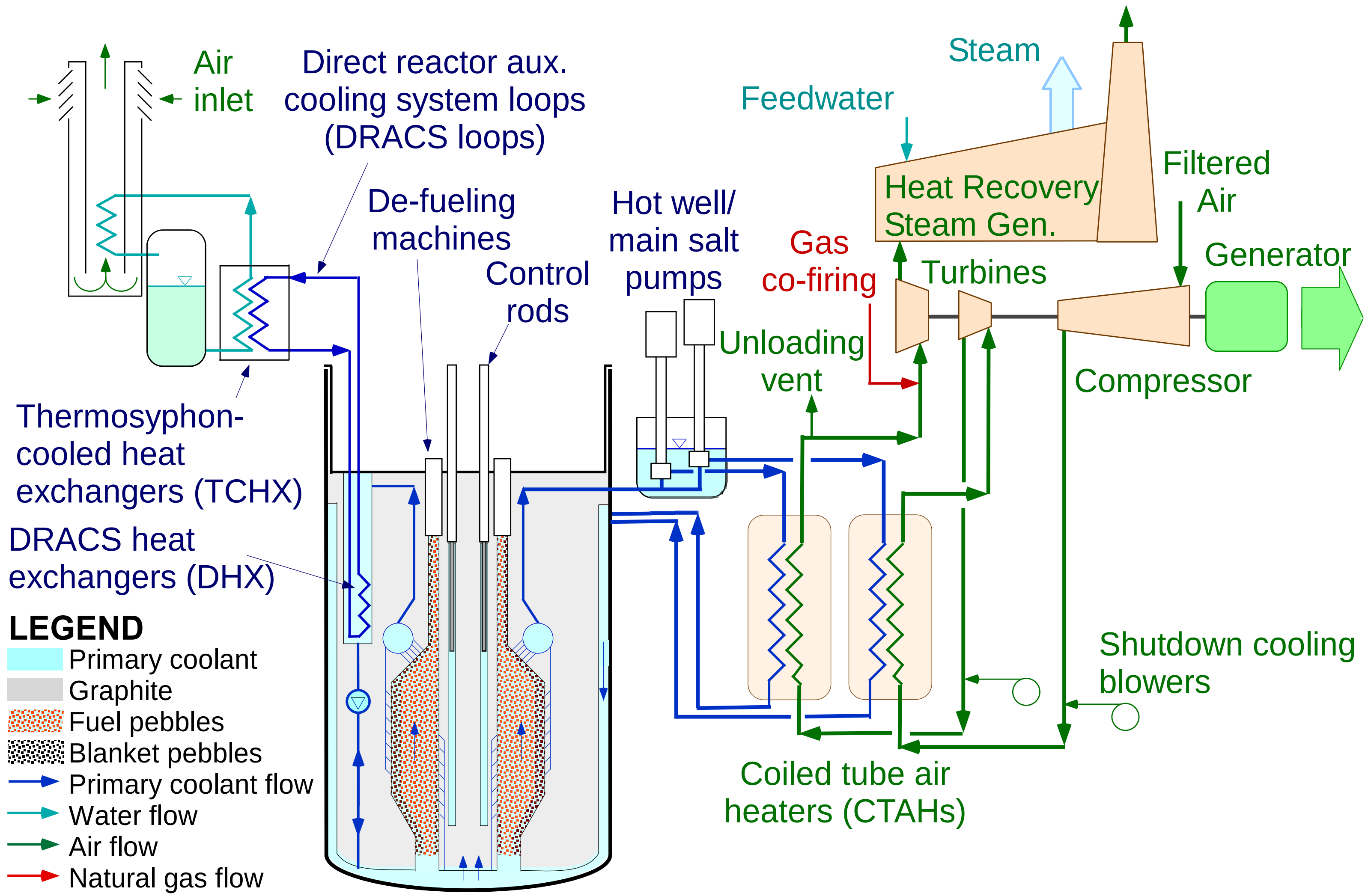
## Other Options are Available

| Coolant | $T_{melt}$ (°C) | $T_{boil}$ (°C) | $\rho$ (kg/m$^3$) | $\rho C_p$ (kJ/m$^3$ °C) |
|---|---|---|---|---|
| **$^7Li_2BeF_4$ (Flibe)** | **459** | **1430** | **1940** | **4670** |
| 59.5 NaF-40.5 $ZrF_4$ | 500 | 1290 | 3140 | 3670 |
| 26 $^7$LiF-37 NaF-37 $ZrF_4$ | 436 | | 2790 | 3500 |
| 51$^7$ LiF-49 $ZrF_4$ | 509 | | 3090 | 3750 |
| Water (7.5 MPa) | 0 | 290 | 732 | 4040 |

Salt compositions are shown in mole percent. Salt properties at 700ºC and 1 atm. Sodium-zirconium fluoride salt conductivity is estimated—not measured. Pressurized water data are shown at 290°C for comparison.

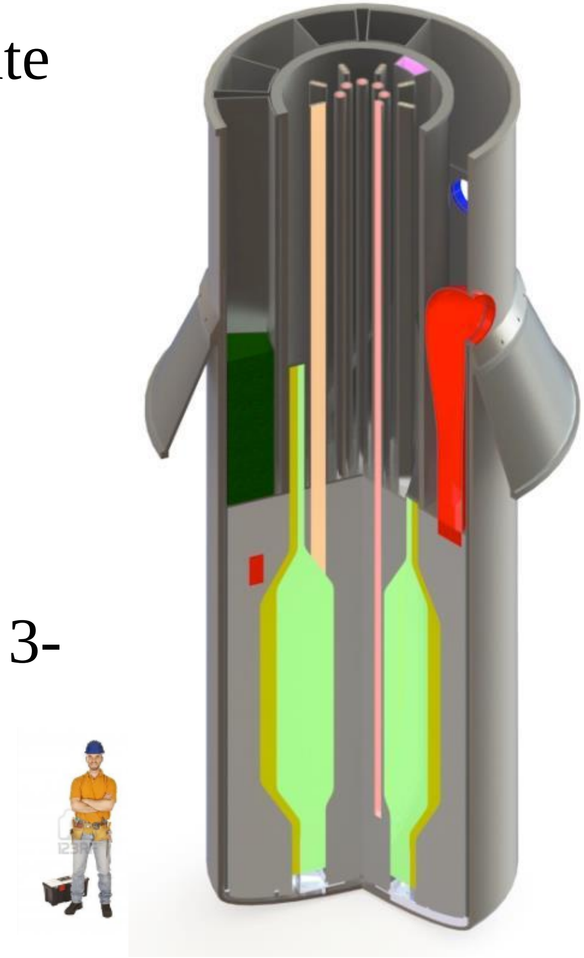
# Mk1 PB-FHR Flow Schematic

## Incorporates Safety Systems from HTGRs and SFRs



# Nominal Mk1 PB-FHR Design

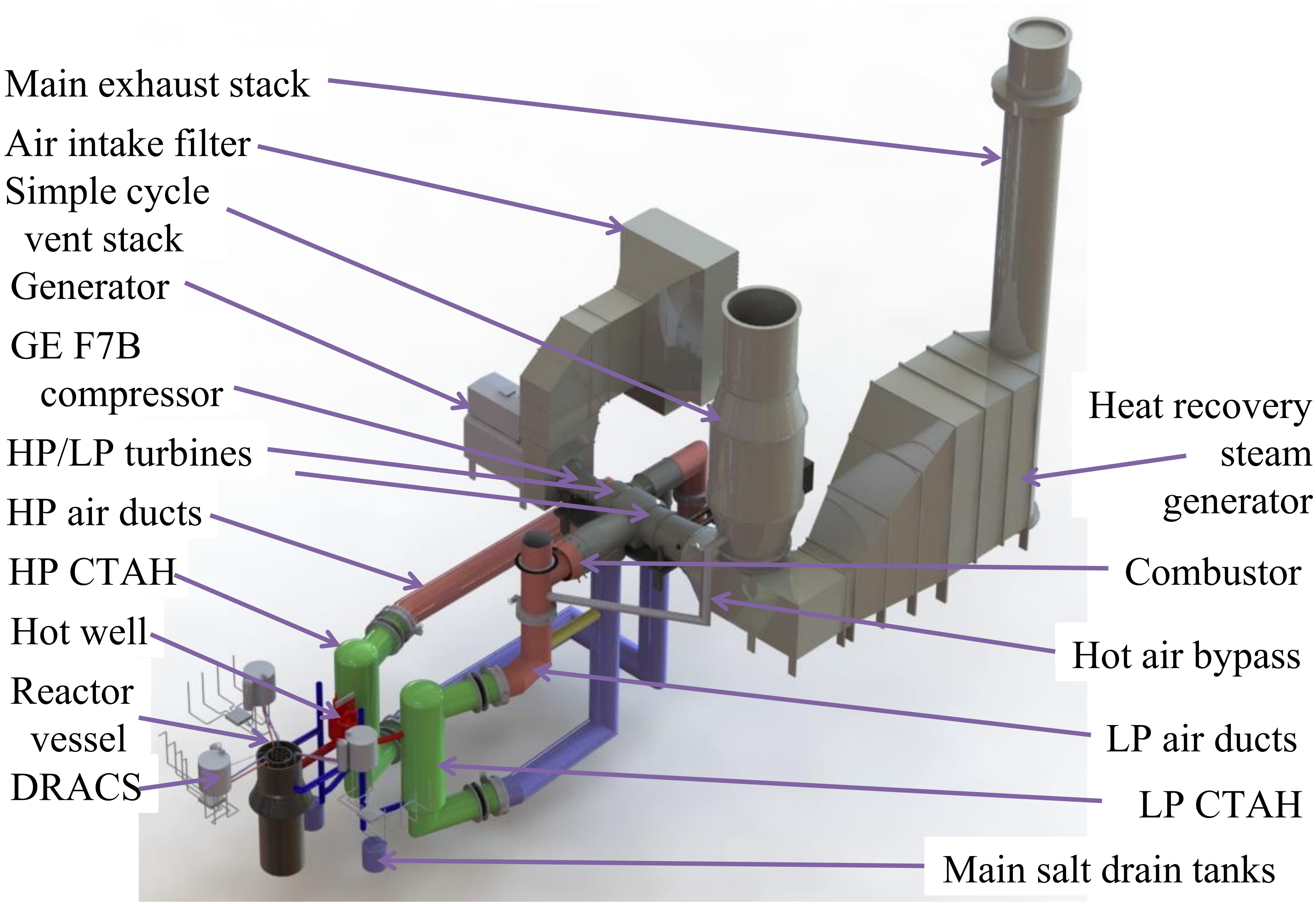
- Annular pebble bed core with center graphite reflector
  - Core inlet/outlet temperatures 600°C/700°C
  - Control elements in center reflector
- Reactor vessel 3.5-m OD, 12.0-m high
- Power level: 236 MWt, 100 MWe (base load), 242 MWe (peak w/ NG)
- Power conversion: GE 7FB gas turbine w/ 3-pressure HRSG
- Air heaters: Two 3.5-m OD, 10.0-m high salt-to air, direct heating



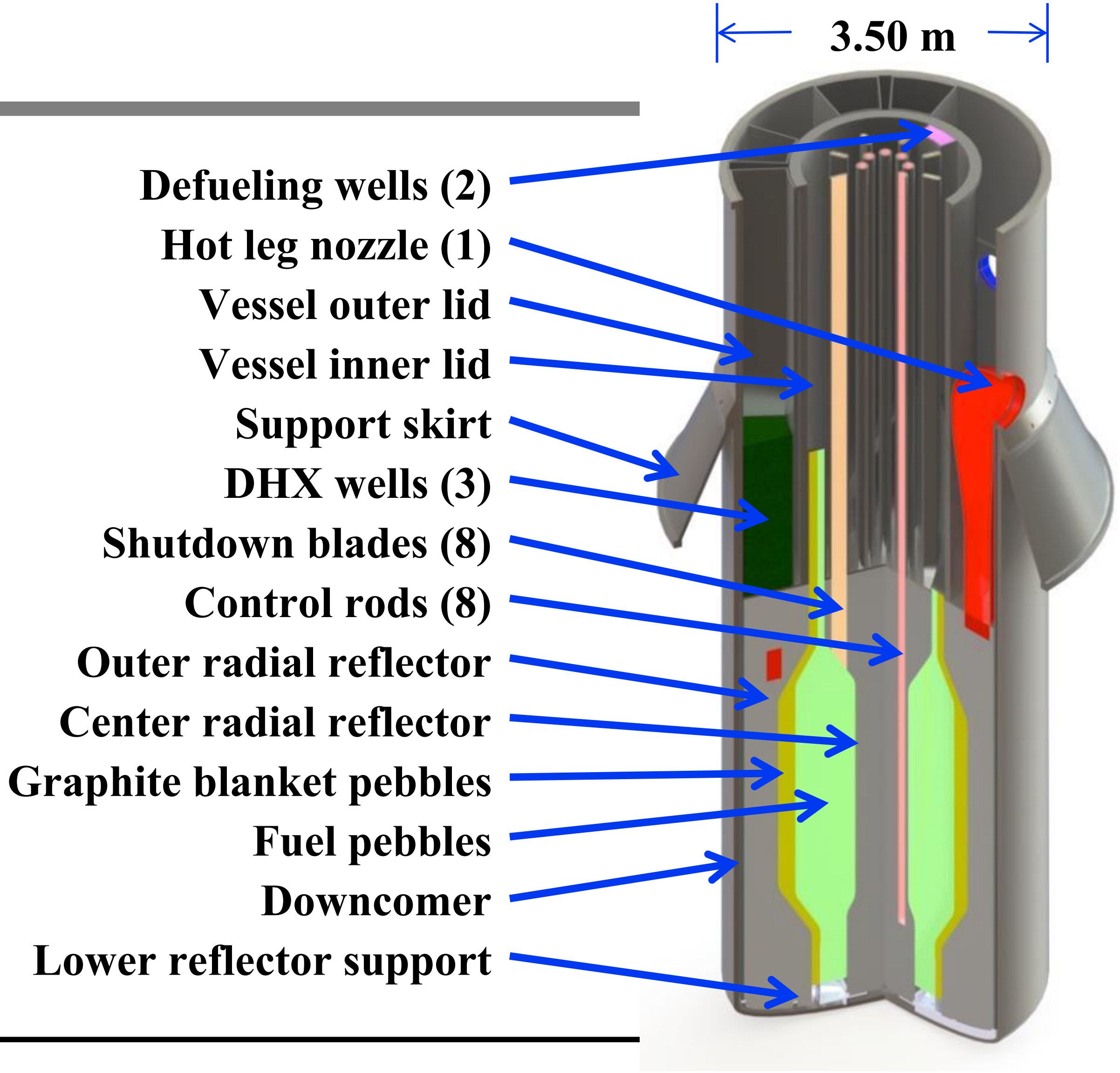
PB-FHR cross section

# Modular MK1 FHR Plant Layout





# Mk1 Reactor Cross Section



# Mk1 CTAHs Have 36 Annular Sub-bundles

## CTAH: Coiled Tube Air Heat Exchangers

Baffle plate

Tube spacer bars w/ tie rod holes

Hot salt manifold

Electric heater electrode

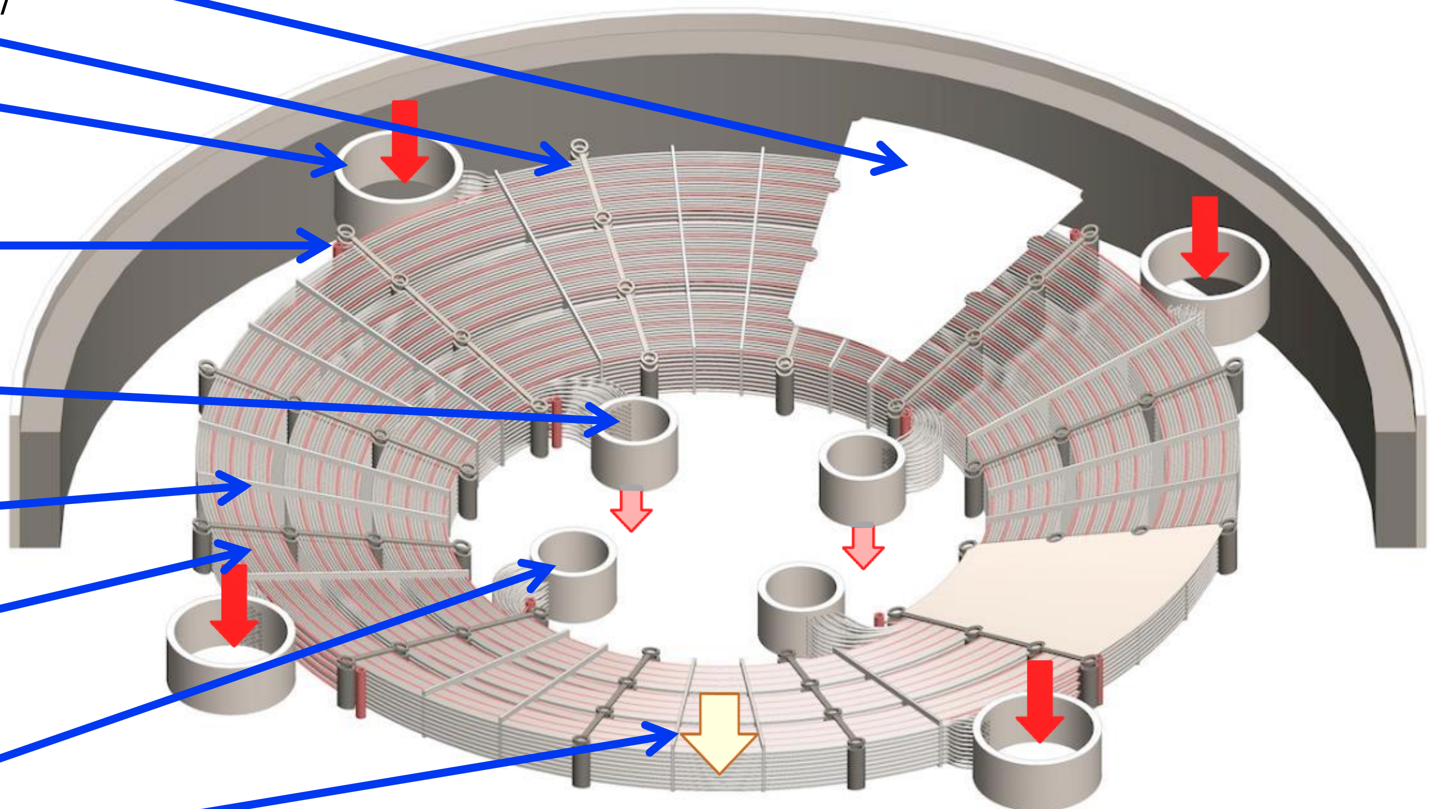
Tube to tube-sheet joints

Anti-vibration supports

Tube lanes (5x4= 20 tubes across)

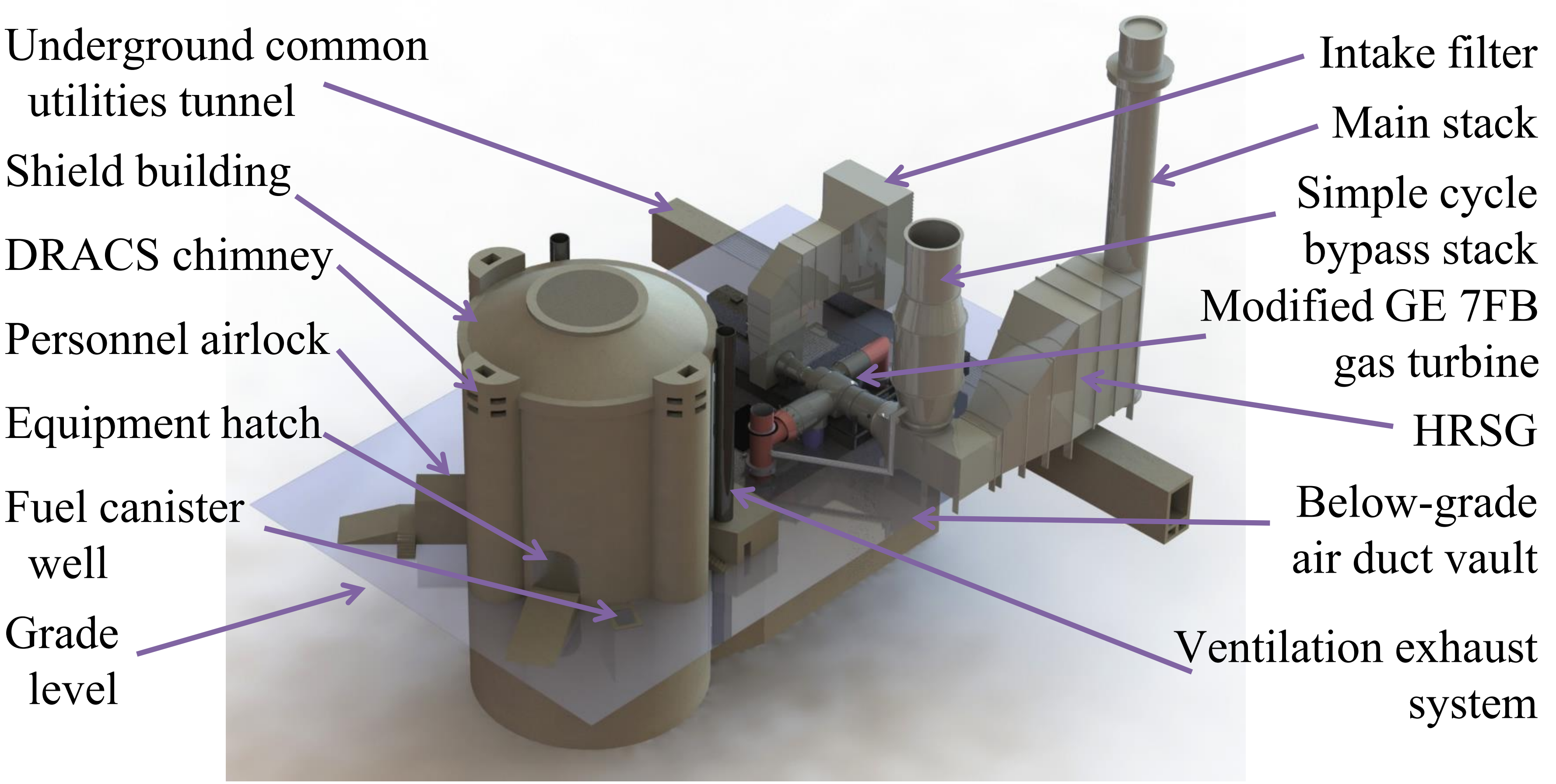
Cool salt manifold

Air flow direction



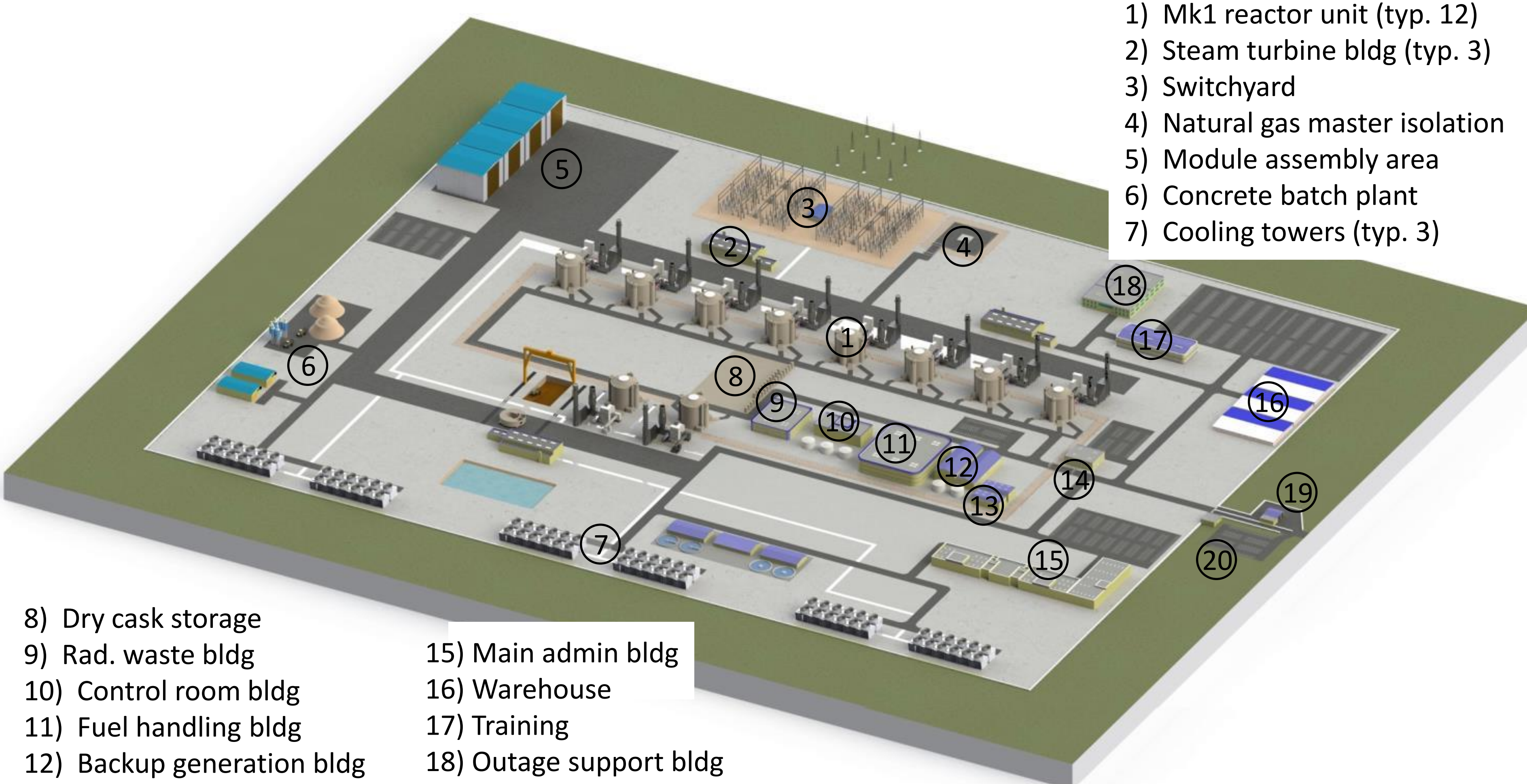
Mk1 CTAH Tube Sub-bundle Model

# The Mk1 Structures are Designed for Modular Construction



# Notional 12-unit Mk1 station

## 1200 MWe base load; 2900 MWe peak

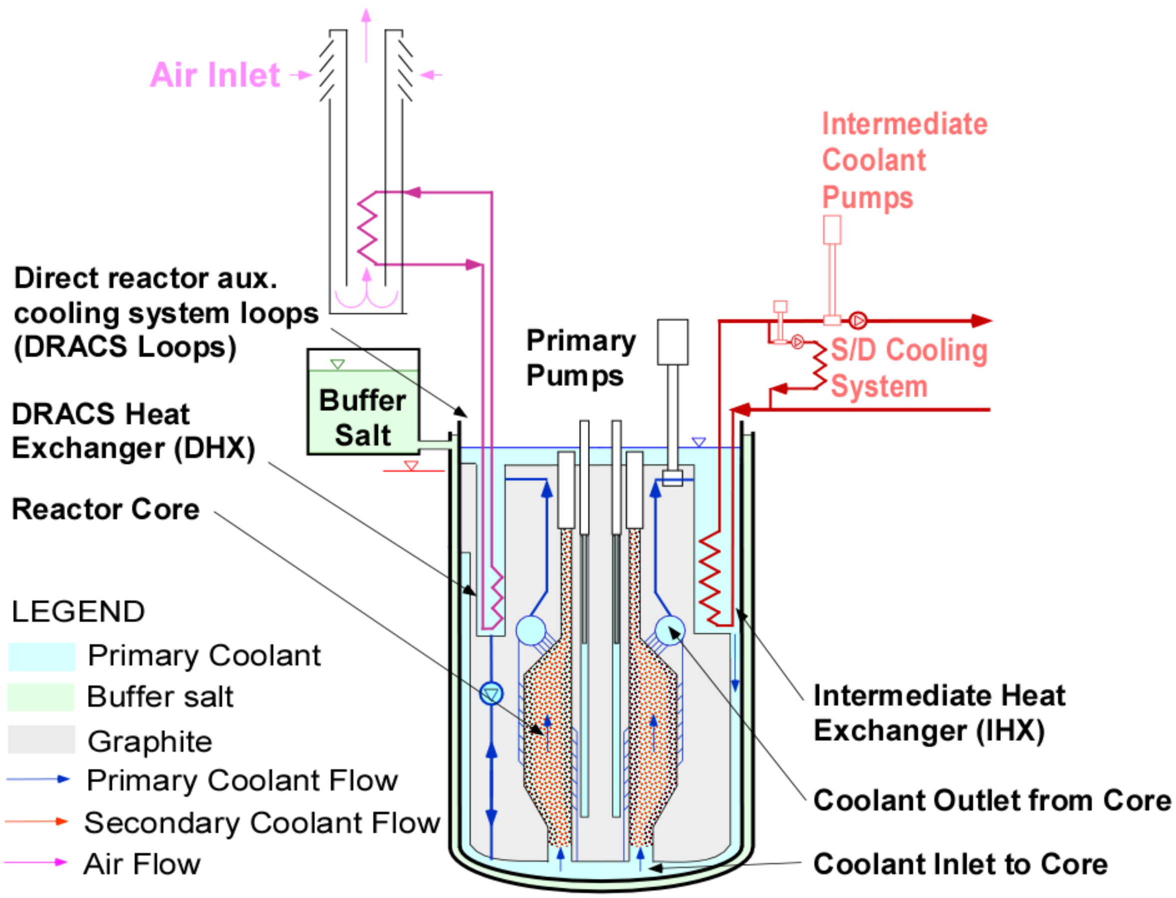



1) Mk1 reactor unit (typ. 12)
2) Steam turbine bldg (typ. 3)
3) Switchyard
4) Natural gas master isolation
5) Module assembly area
6) Concrete batch plant
7) Cooling towers (typ. 3)
8) Dry cask storage
9) Rad. waste bldg
10) Control room bldg
11) Fuel handling bldg
12) Backup generation bldg
13) Hot/cold machine shops
14) Protected area entrance
15) Main admin bldg
16) Warehouse
17) Training
18) Outage support bldg
19) Vehicle inspection station
20) Visitor parking

# Accident and Beyond-Design Basis Accident Strategy

# FHR HEAT REMOVAL SYSTEMS

## Adopted from SFRs and HTGRs




1) **Intermediate HX (for power production)**
2) **DRACS (Passive Decay Heat Removal System)**
3) **<u>BDBA Heat Removal System</u> (for complete system failure)**

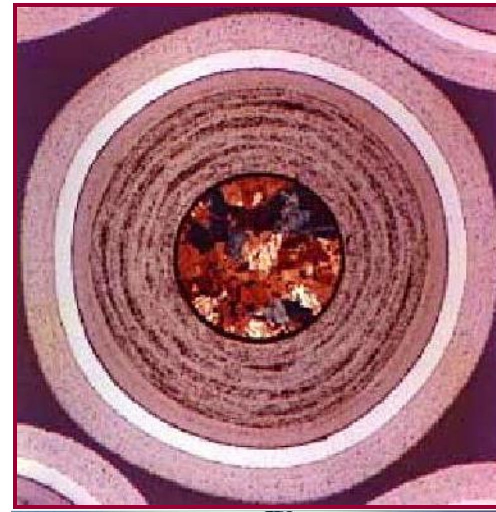
# Beyond Design Basis Accident (BDBA) Goal Is to Prevent Large-Scale Fuel Failures

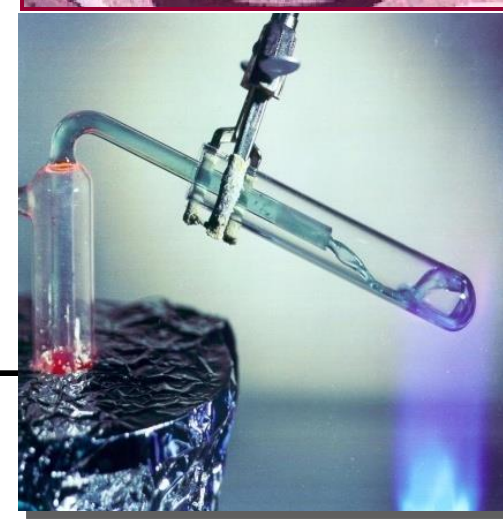
- If peak fuel temperatures below fuel failure temperatures, no major releases
- System design to prevent fuel overheating
- Shutdown fuel temperature depends upon heat generation rate (decay heat) versus heat removal rate
  - Generation rate use ANS decay heat rate curve
  - Heat removal depends upon:
    - Temperature drop to drive heat to environment
    - Resistance to decay heat flow to environment

**Heat Removal = Heat Conductivity · Δ Temperature**

# FHR Fuel And Coolant Provide Very Large ΔT To Drive Decay Heat to Environment in a Severe Accident

- Fuel failure >1650° C
  - Iron melts at 1535° C
  - Nominal peak: ~800° C
- Coolant boiling ~1430° C
  - Nominal peak ~700° C
- Vessel failure: <1200° C
- Different than any other reactor

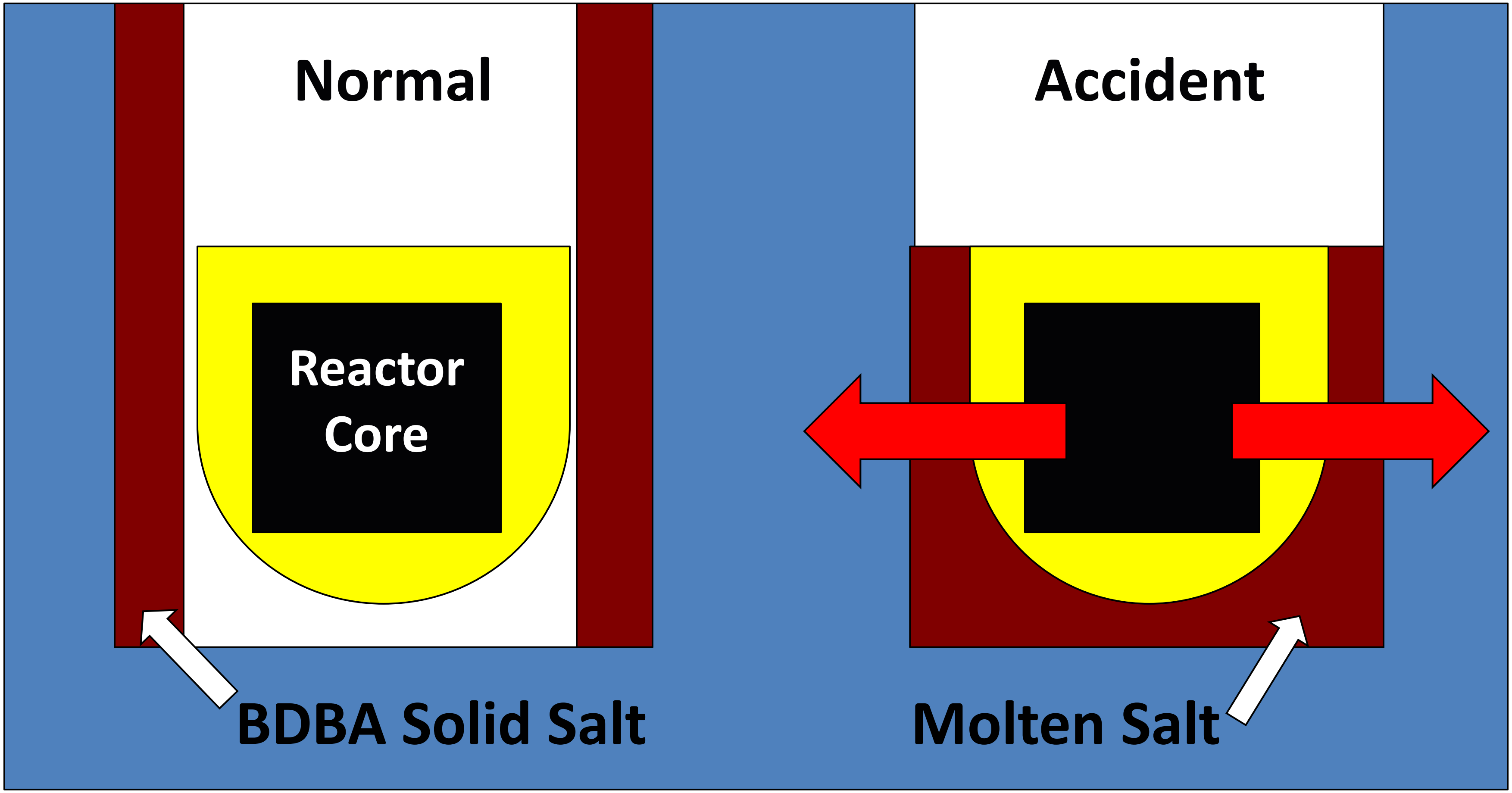




In core feedback: higher temperatures yield negative Doppler with power drop, lower salt viscosity with higher flows and $T^4$ radiation heat transfer

# BDBA Design Maximizes Thermal Conductivity to Environment

**High Accident Temperatures Used to Fail Vessel Insulation and Melt BDBA Salt to Minimize Accident Temperature Drop from Fuel to Silo Wall to Provide Added ΔT To Drive Decay Heat to Environment**



# FHRs Have Small Cs-137 inventories

## Reduced Accident Source Term Because Fuel In Core for 12-18 Months

| Implies unique safety characteristics | 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 | - |

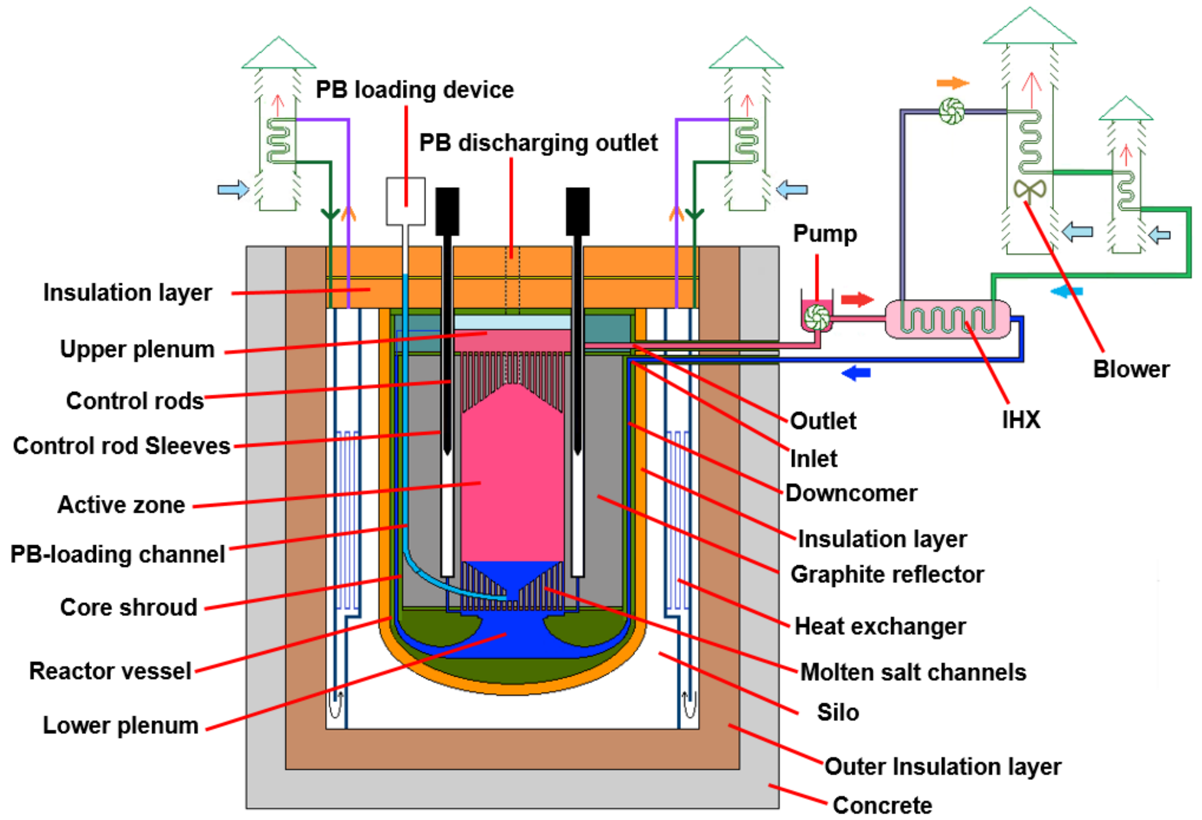
† For S-PRISM, effective enrichment is the Beginning of Cycle weight fraction of fissile Pu in fuel

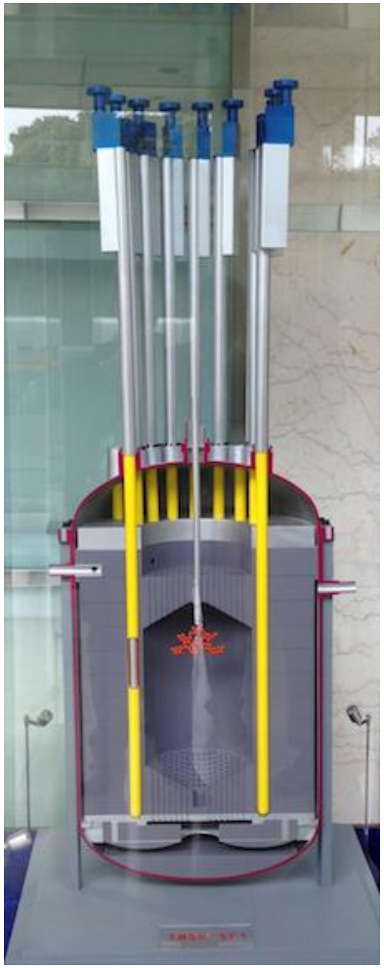
†† Assume start-up U-235 enrichment is 60% of equilibrium enrichment; for S-PRISM startup uses fissile Pu

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

** Assumes a uranium tails assay of 0.003.

# Chinese Academy of Science to Build 10MW TMSR-SF1 (Pebble bed) By 2020



# CAS Work Underway for Test Reactor

## Welding, Machining, Pumps, Graphite, Fuel

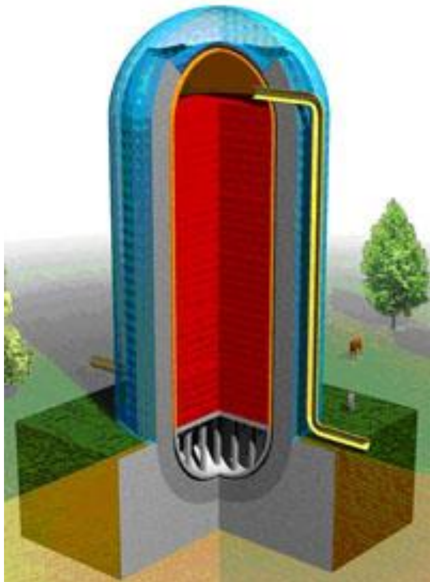
# FHR Conclusions

- The case for any new reactor must be compelling
  - Match electricity need with base-load and peak power using auxiliary natural gas and stored heat
    - Increase in plant revenue over base-load plants
    - Enabling technology for zero-carbon nuclear renewable electricity grid with storage
  - Eliminate major fuel failures with offsite consequences
- New concept—need to explore options (size, fuel geometry, etc.) to define most economic FHR
- Economics built upon (1) changing market and (2) coupling to advanced gas turbines

# Questions

**FIRES**

**Stored Heat**

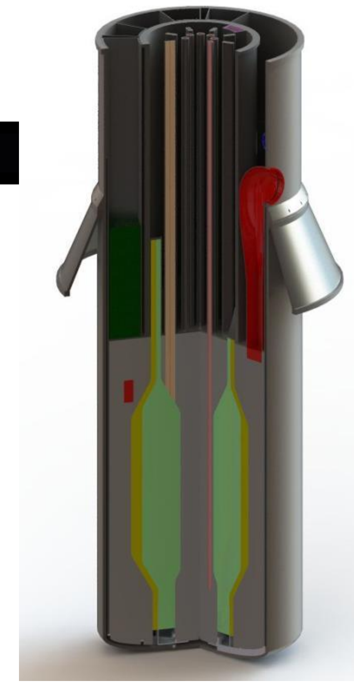


**Combustible Fuels for Peak Electricity**

**Gas-Turbine (NACC)**

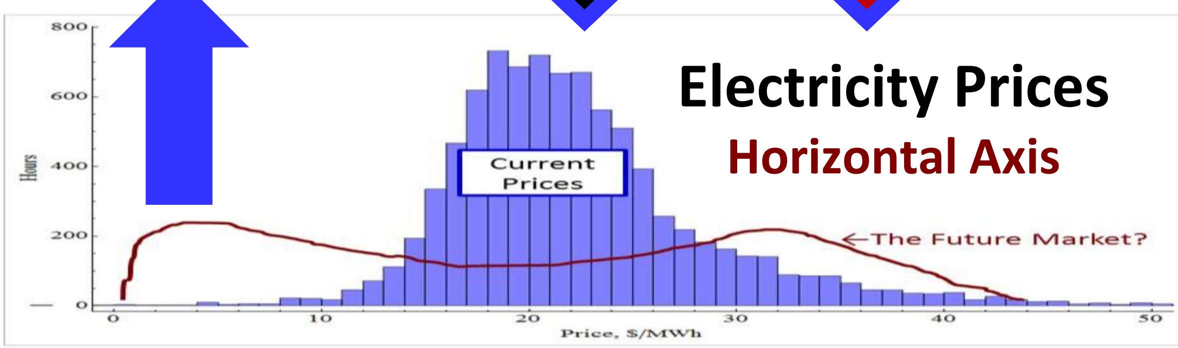
**Constant High-Temperature Heat (600 to 700 C)**

**Reactor (FHR)**



**Electricity Prices**

**Horizontal Axis**



# Added Information

# Biography: Charles Forsberg

Dr. Charles Forsberg is the Director and principle investigator of the High-Temperature Salt-Cooled Reactor Project and University Lead for the Idaho National Laboratory Institute for Nuclear Energy and Science (INEST) Nuclear Hybrid Energy Systems program. He was the Executive Director of the Massachusetts Institute of Technology Nuclear Fuel Cycle Study. Before joining MIT, he was a Corporate Fellow at Oak Ridge National Laboratory. He is a Fellow of the American Nuclear Society, a Fellow of the American Association for the Advancement of Science, and recipient of the 2005 Robert E. Wilson Award from the American Institute of Chemical Engineers for outstanding chemical engineering contributions to nuclear energy, including his work in hydrogen production and nuclear-renewable energy futures. He received the American Nuclear Society special award for innovative nuclear reactor design on salt-cooled reactors and the ANS 2014 Seaborg Award. Dr. Forsberg earned his bachelor's degree in chemical engineering from the University of Minnesota and his doctorate in Nuclear Engineering from MIT. He has been awarded 11 patents and has published over 200 papers.

http://web.mit.edu/nse/people/research/forsberg.html

# The FHR Integrated Research Project Has Three Major Reports

- Commercial Strategy: C. Forsberg et al, *Fluoride-salt-cooled High-Temperature Reactor (FHR) Commercial Basis and Commercialization Strategy*, MIT-ANP-TR-153, Massachusetts Institute of Technology, Cambridge, MA., Dec. 2014
- Commercial Reactor Point Design: C. Andreades et. al., *Technical Description of the "Mark 1" Pebble-Bed Fluoride-Salt-Cooled High-Temperature Reactor (PB-FHR) Power Plant*, UCBTH-14-002, Department of Nuclear Engineering , University of California, Berkeley, Sept. 30, 2014
- Test Reactor Goals, Strategy, and Design: C. Forsberg et. al., *Fluoride-salt-cooled High-temperature Test Reactor (FHTR): Goals, Options, Ownership, Requirements, Design, Licensing, and Support Facilities*, MIT-ANP-TR-154, Massachusetts Institute of Technology, Cambridge, MA, Dec. 2014.

**Commercial Strategy and Markets (MIT)**

↓

**Commercial Reactor Point Design (UCB)**

↓

**Test Reactor Goals, Strategy and Design (MIT)**

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**Technology Development (MIT/UCB/UW)**