Renewables, Reactors, and the Electricity Grid

Competing with Stand-Alone Natural Gas and Enabling Zero-Carbon Electricity Grid

Characteristics of the Low Carbon Grid
Nuclear Air-Brayton Combined Cycles (NACC)
Salt Cooled Reactors: FHR, MSR, and Fusion

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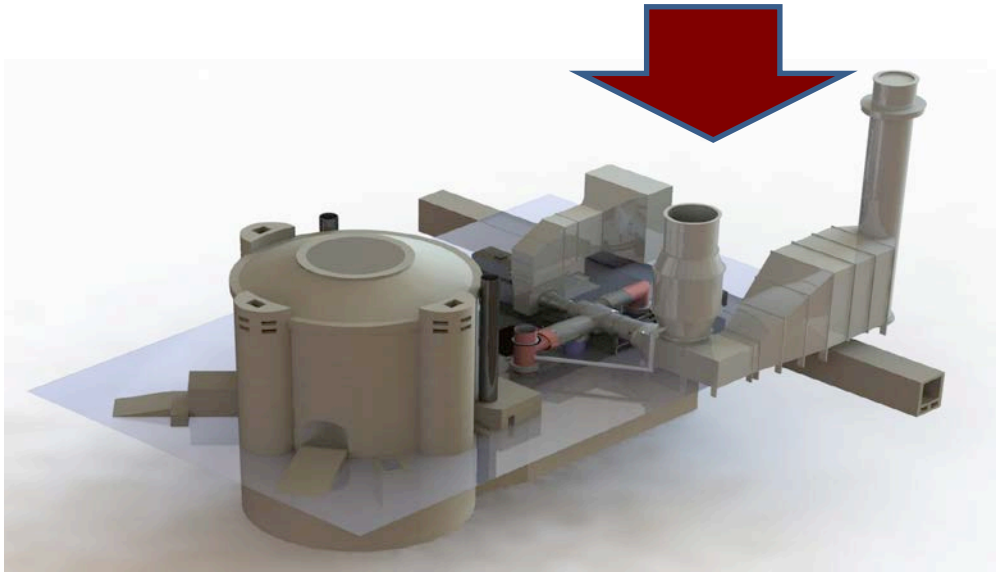
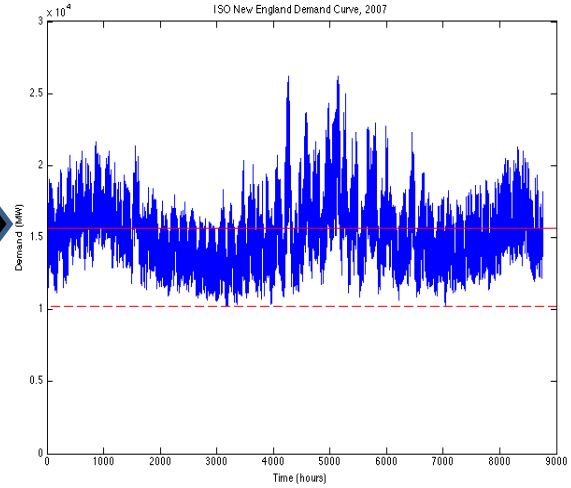
Oak Ridge National Laboratory
October 16, 2015

Salt-Cooled Reactors Enable <u>Base-Load</u> Reactors to Deliver Variable Electricity to the Grid

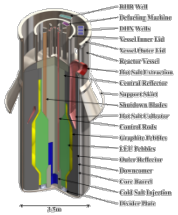
Stored Heat and/or Natural Gas



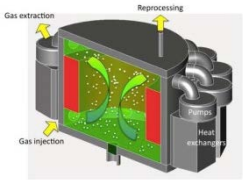


Base-Load Reactor **Combined Cycle Gas Turbine** **Variable Electricity**

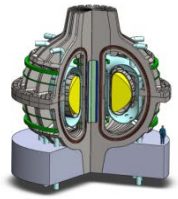
FHR/AHTR



MSR



Fusion



Market Defines Reactor Strategy

Understand 2030 Market

Base-load Electricity, Variable Electricity, Heat to Industry

↓

Power Conversion System to Meet Market Requirements

Rankine (Steam), Supercritical CO_2, Brayton

↓

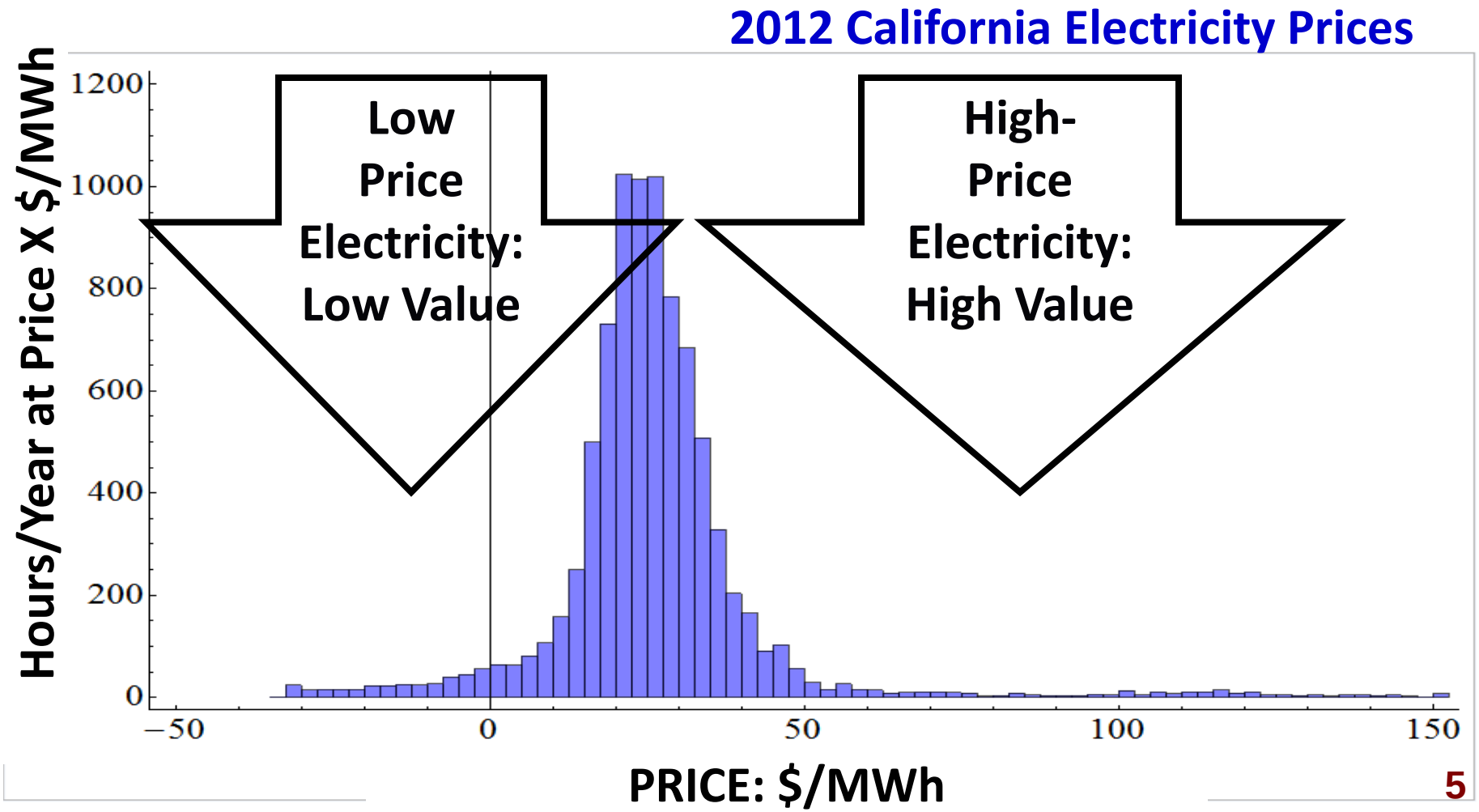
Reactor Design

The Electricity Market

Starting Point for Designing Nuclear Plant

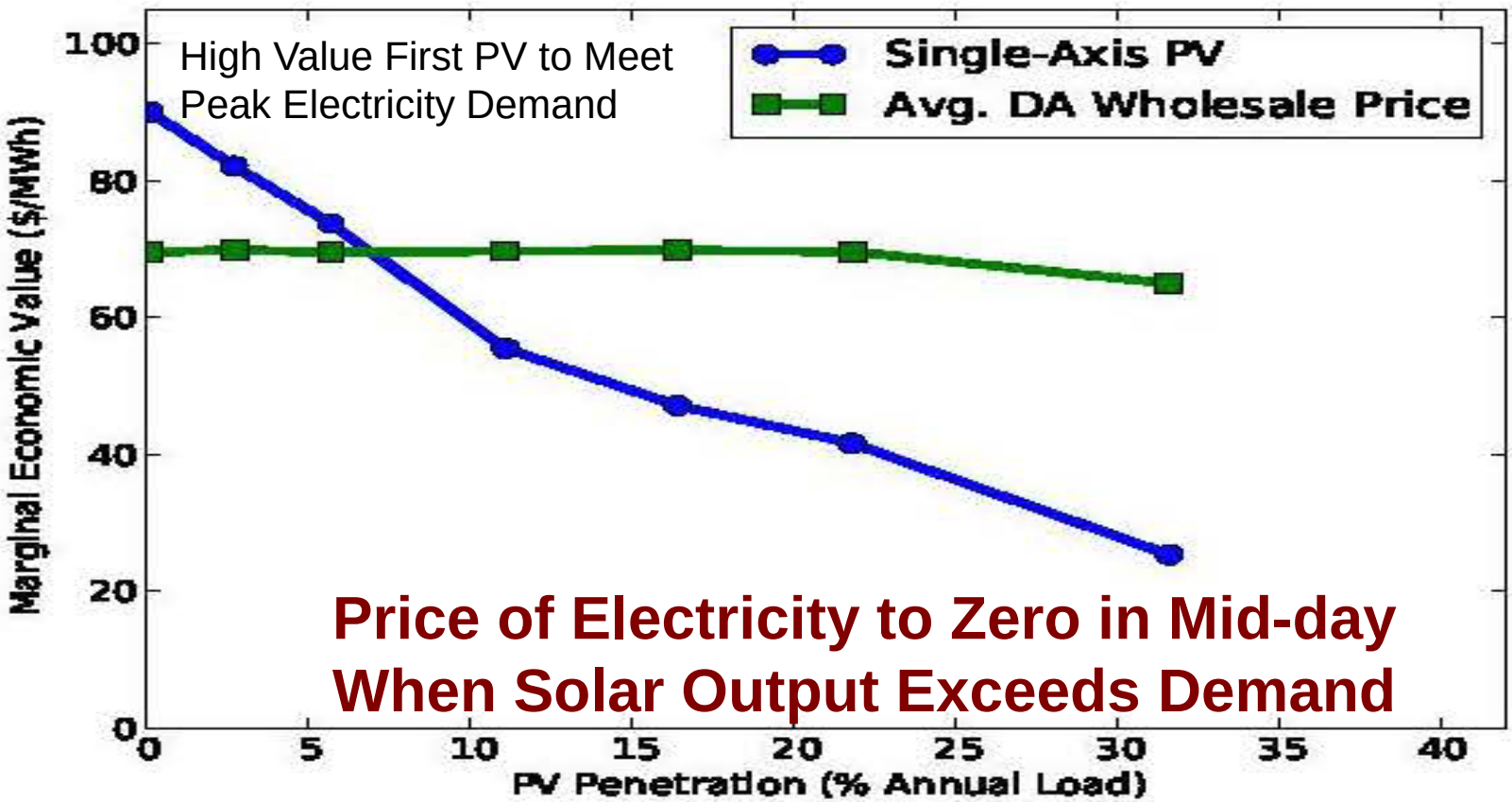
Electricity Prices Vary Over Time

Sell More Electricity When Maximum Need for Electricity and High Electricity Prices



If Add Large-Scale Solar, Electricity Price Collapse at Times of High Solar Input

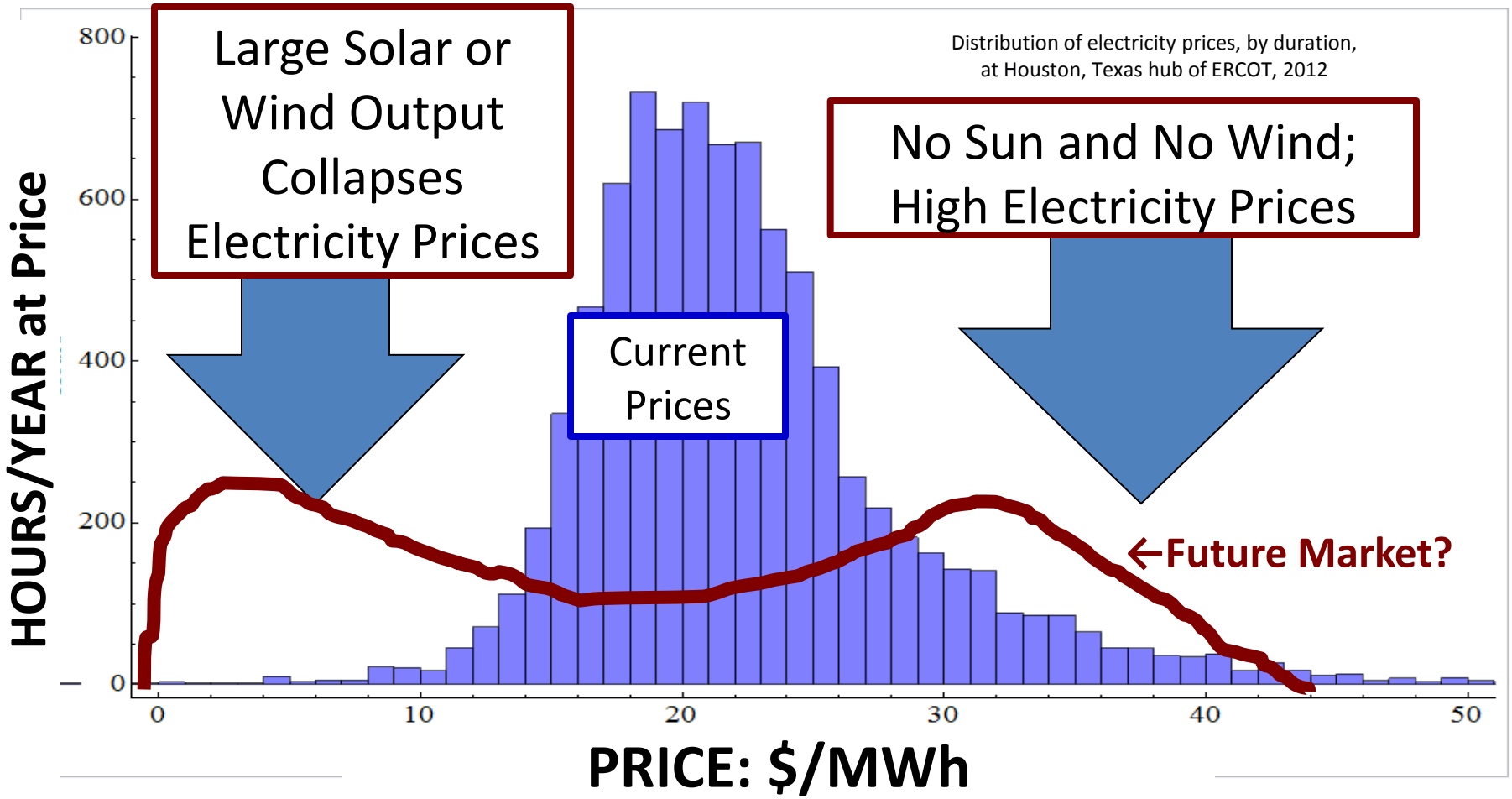
Same if Large-Scale Additions of Wind



Source: A. Mills & R. Wiser (2012) "Changes in the Economic Value of Variable Generation at High Penetration Levels: A Pilot Case Study of California" Technical Report: LBNL-5445E

Increased Renewables or Low-Carbon Goals Result in More Low and High Priced Electricity

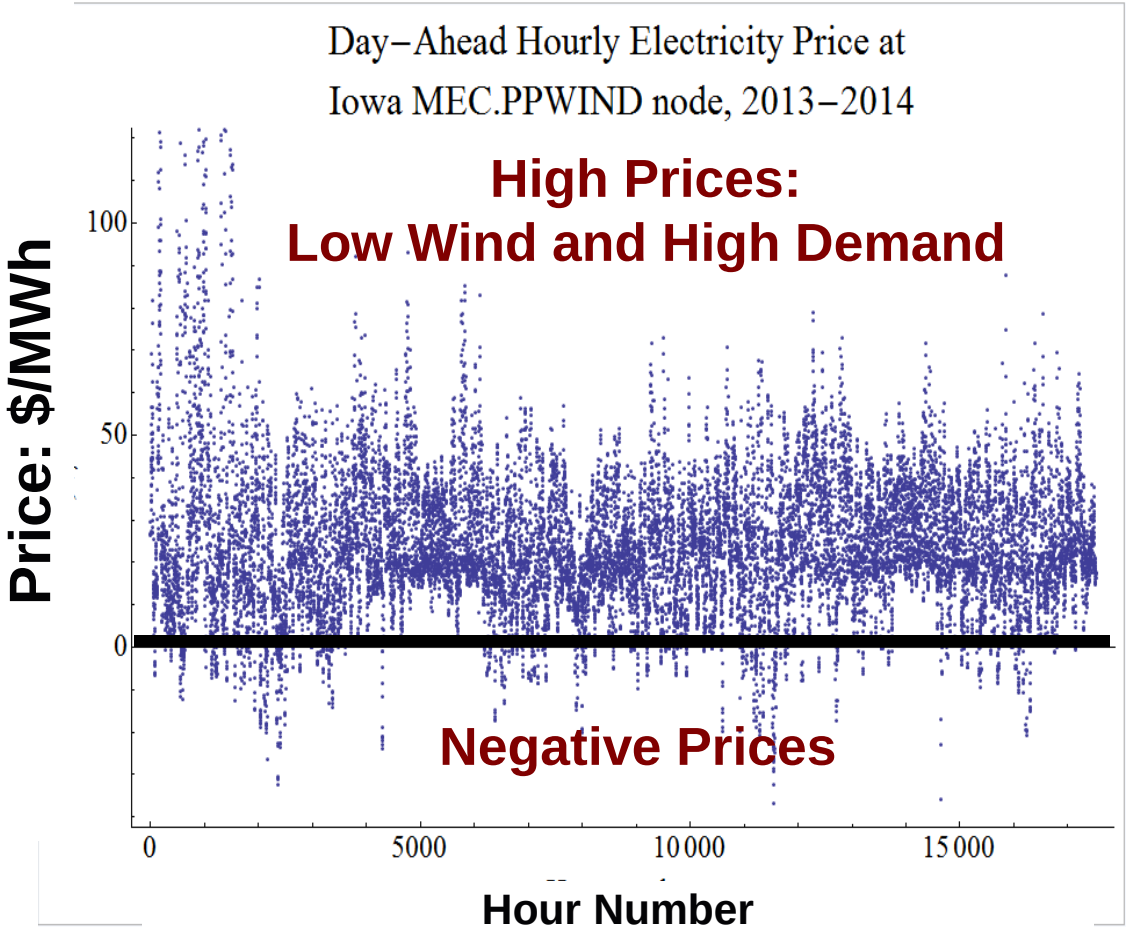
Change from High-Operating-Cost Low-Capital-Cost Fossil System to High-Capital-Cost Low-Operating-Cost Nuclear / Renewable System



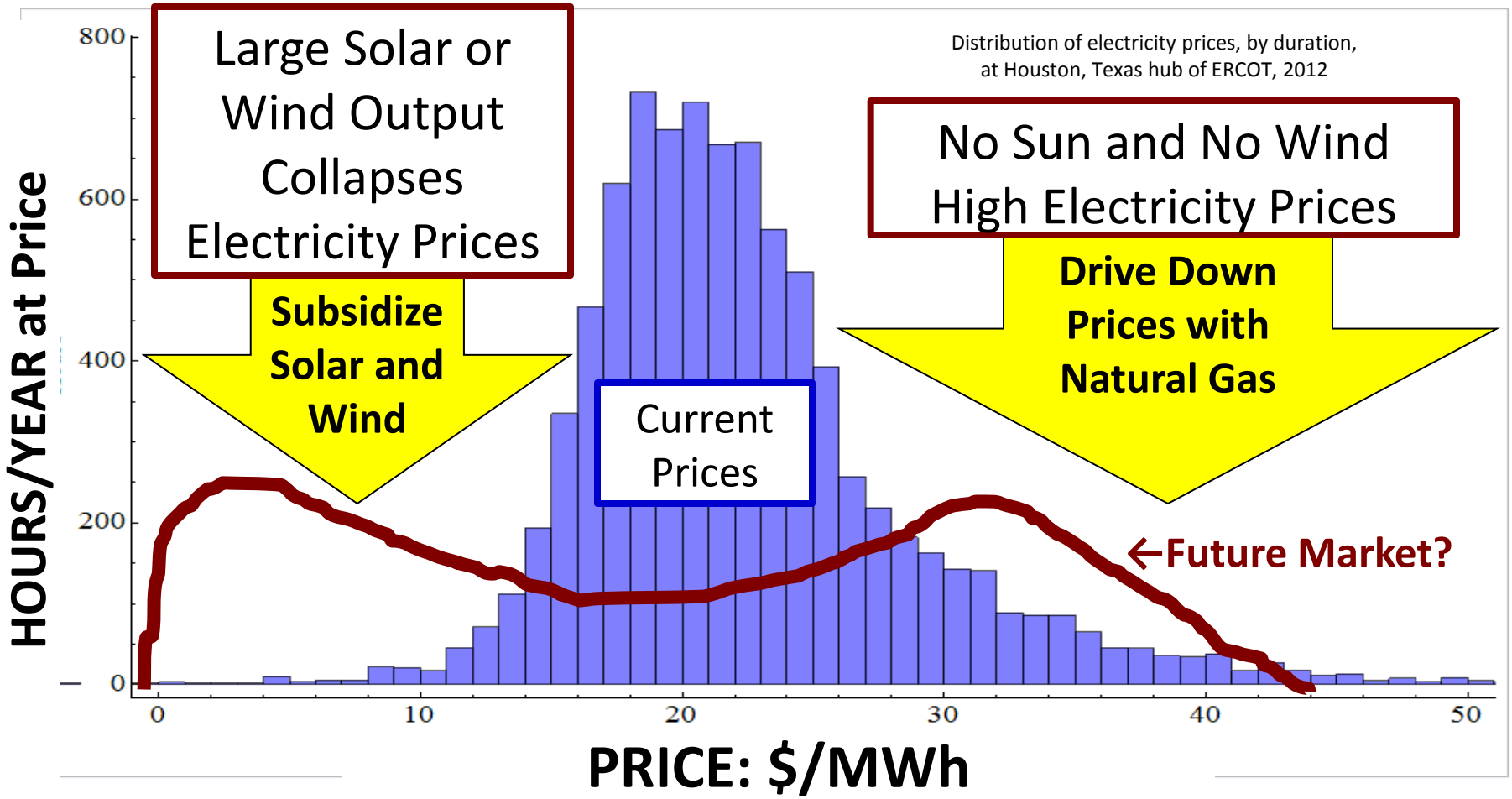
Need Base-Load Reactors with Variable Plant Output

Iowa Early Example of Market Effects of Renewables (Wind)

- High wind deployment
- Negative price about 5% of hours both years.
- High prices when low-wind and high demand
- Price collapse bad for wind and nuclear economics, good for natural gas



Current Solution Is Highly Subsidized Renewables and Natural Gas



This Strategy Increases Total Cost of Energy and Has Limited Impact on Greenhouse Gas Emissions

Nuclear Air-Brayton Combined Cycle (NACC)

Enable a zero-carbon electricity grid

Base-load reactor with variable power output

Fluoride Salt Coolants Were Developed for the Aircraft Nuclear Propulsion Program

Salt Coolants Designed to Couple Reactors to Jet Engines

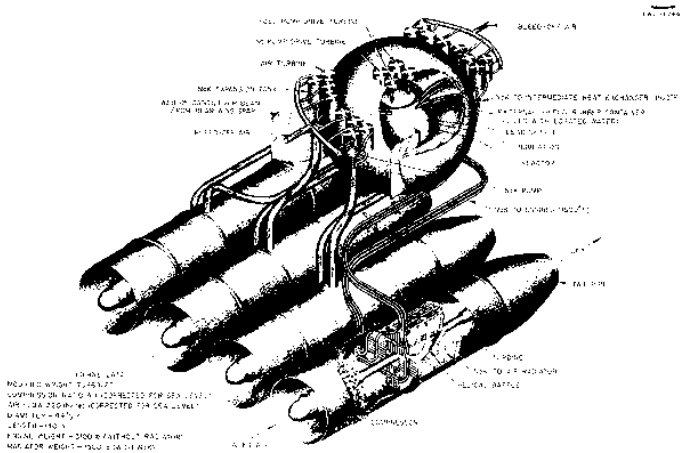
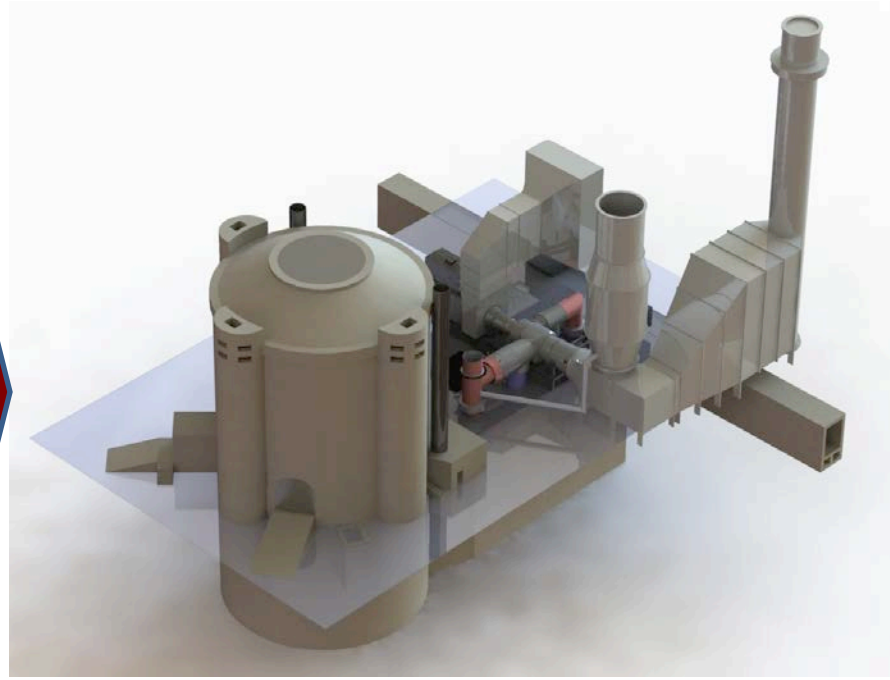


Fig. 4.33. Aircraft Power Plant (200 Megawatt).

It Has Taken 50 Years for Utility Gas Turbine Technology to Mature Sufficiently to Enable Coupling to a Reactor

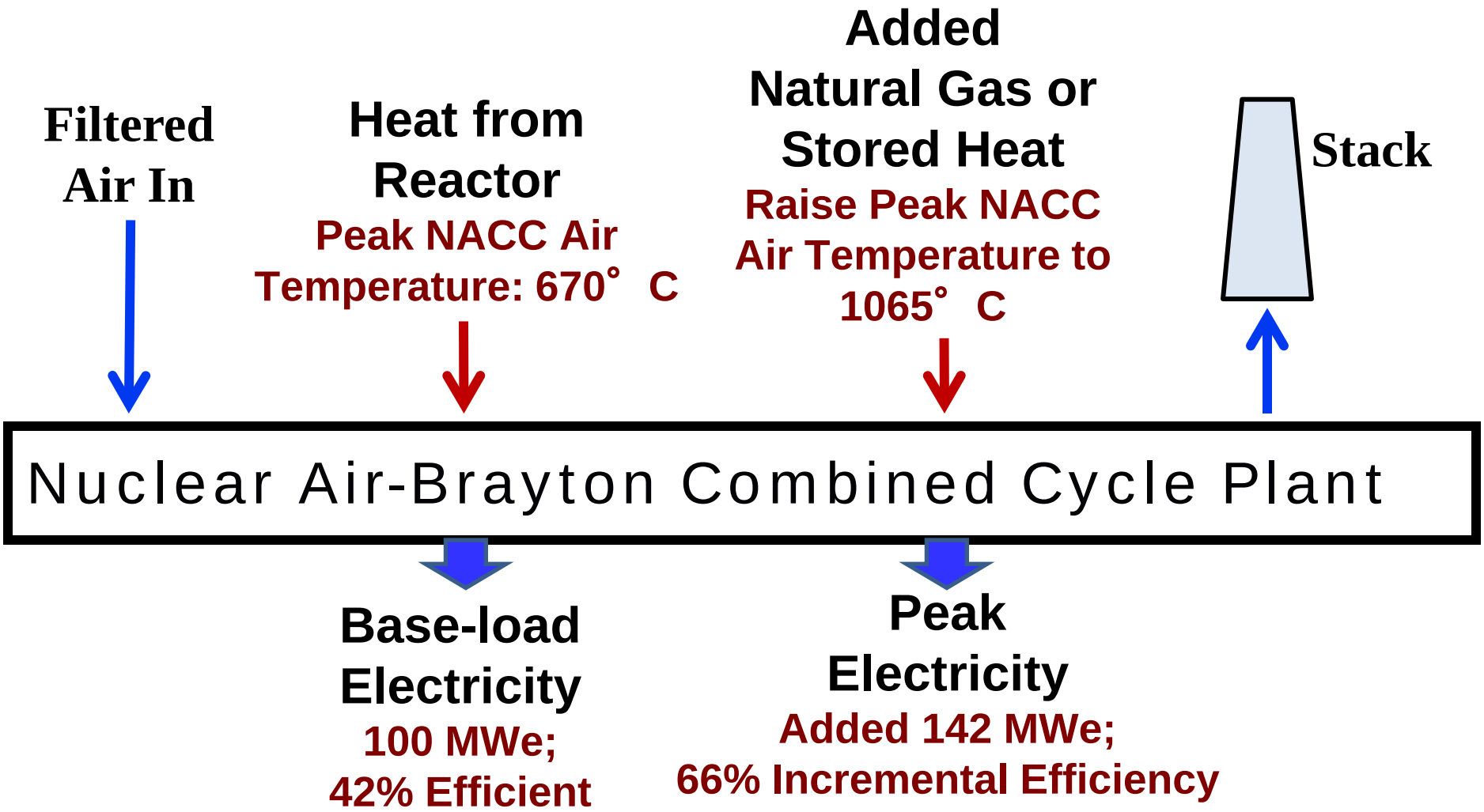
Coupling Reactors to Gas-Turbines is Transformational

Advances In Natural Gas Combined Cycles Enable Coupling Reactors to Gas Turbines



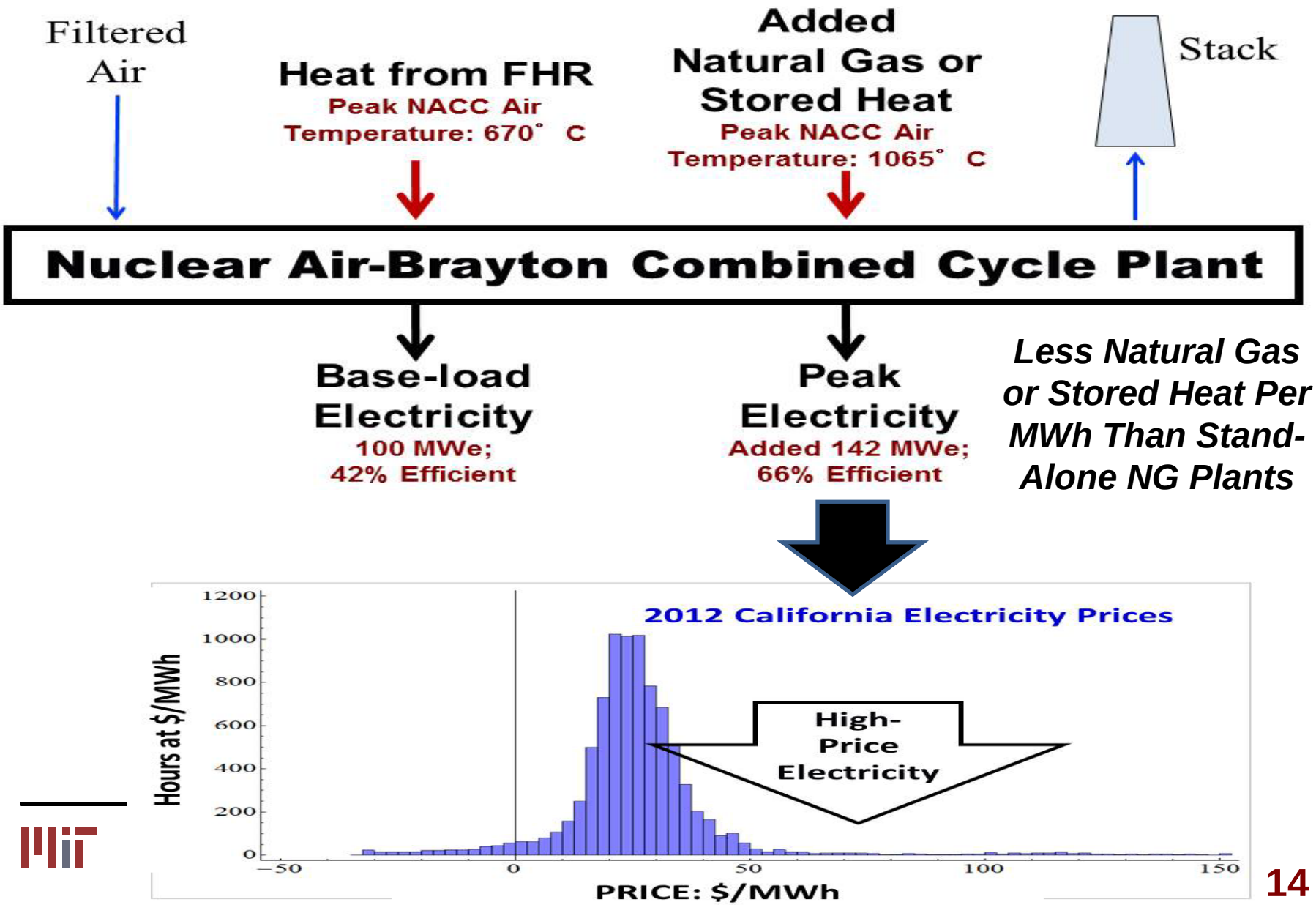
Gas-Turbine Technology Not Viable 15 Years Ago

NACC for Variable Electricity Output



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

NACC Produces More Electricity When Prices Are High and a Need for More Electricity



NACC Revenue Using 2012 Texas and California Hourly Electricity Prices

After Subtracting Cost of Natural Gas, No FIRES

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

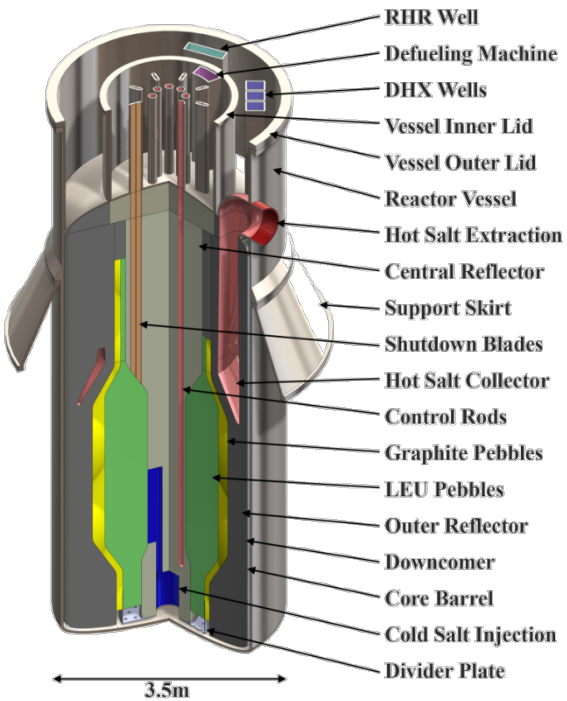
If Triple Price of Natural Gas (Europe and Asia Prices), Revenue is Twice a Base-Load Nuclear Plant

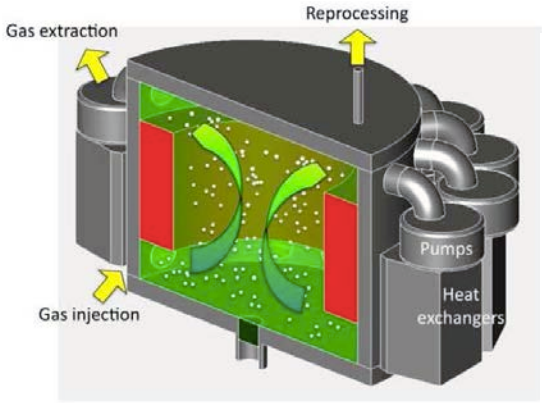
Reactors Coupling to NACC

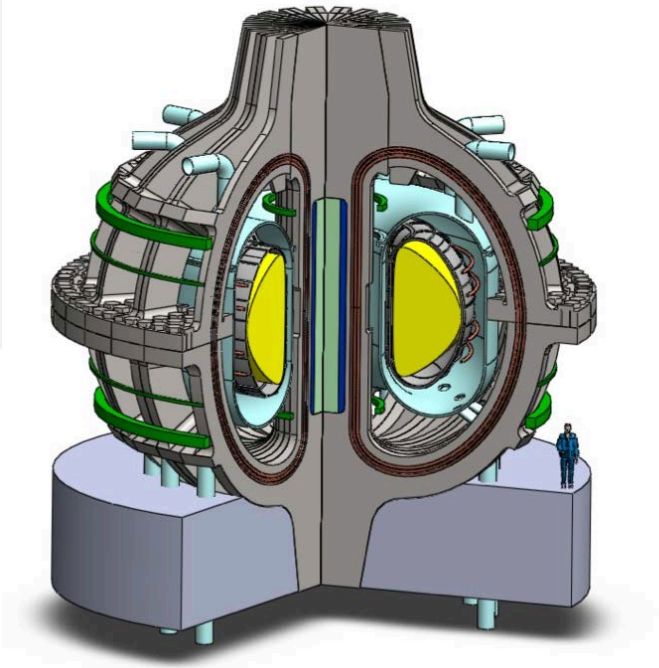
Only Salt-Cooled Reactors Couple Efficiently to NACC

Commercial gas-turbine exit air compressor temperatures are between 400 and 500°C; thus, must deliver all heat above these temperatures

Salt-Cooled Reactors Capable of Coupling to NACC







FHR/AHTR (Solid Fuel) **MSR (Fuel in Salt)** **Fusion**

NACC Does Add Requirements Such as to the Tritium Control Strategies

Can't Trap Tritium in the Power cycle

October 27-28, 2015

http://tcw15.mit.edu/

Workshop on Tritium Control and Capture in Salt-Cooled Fission and Fusion Reactors

Experiments, Models, and Benchmarking

October 27-28, 2015 at the DoubleTree by Hilton Hotel Salt Lake City Airport

Hosted by the Massachusetts Institute of Technology Nuclear Science and Engineering Department, Nuclear Reactor Laboratory, and Plasma Science and Fusion Center, the University of Wisconsin–Madison, and the Chinese Academy of Sciences.

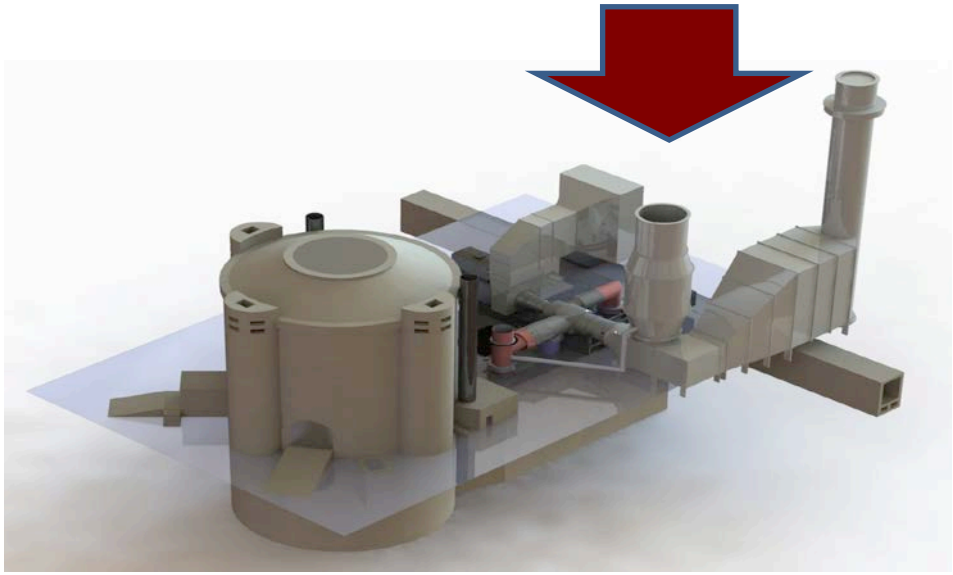
This workshop on tritium control and capture in high-temperature salt-cooled fission and fusion reactors brings together researchers involved in experiments, modeling, and benchmarking to:

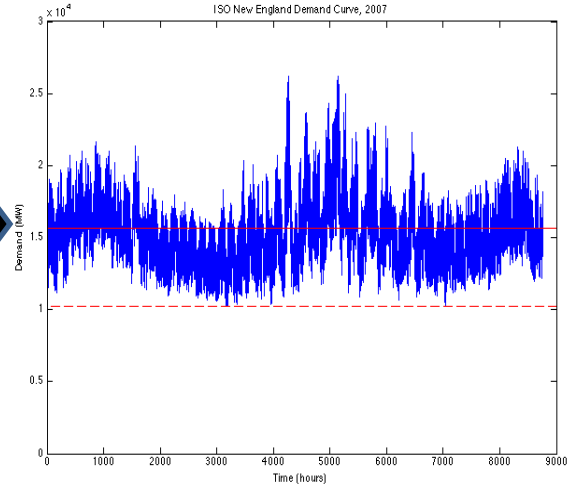
1. Exchange information and enable future exchange of information,
2. Initiate an effort for benchmarking of experiments and models, and
3. Encourage cooperation between different groups working on the same challenges.

See the full Workshop flier

Questions

Stored Heat and/or Natural Gas



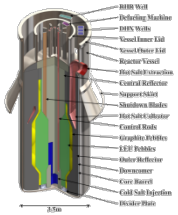


Base-Load Reactor

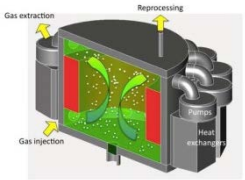
Gas Turbine

Variable Electricity

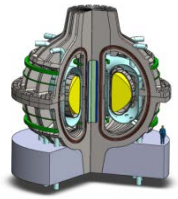
FHR/AHTR



MSR



Fusion



Added Information

NACC with Energy Storage

Possible Fusion Breakthrough and Implications for Salt-Cooled Reactors

Biography: Charles Forsberg

Dr. Charles Forsberg is the Director and principle investigator of the High-Temperature Salt-Cooled Reactor Project at the Massachusetts Institute of Technology. He teaches the fuel cycle and waste management classes in the Department of Nuclear Science and Technology. 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. He received the American Nuclear Society special award for innovative nuclear reactor design on salt-cooled reactors and the 2014 Seaborg Award.

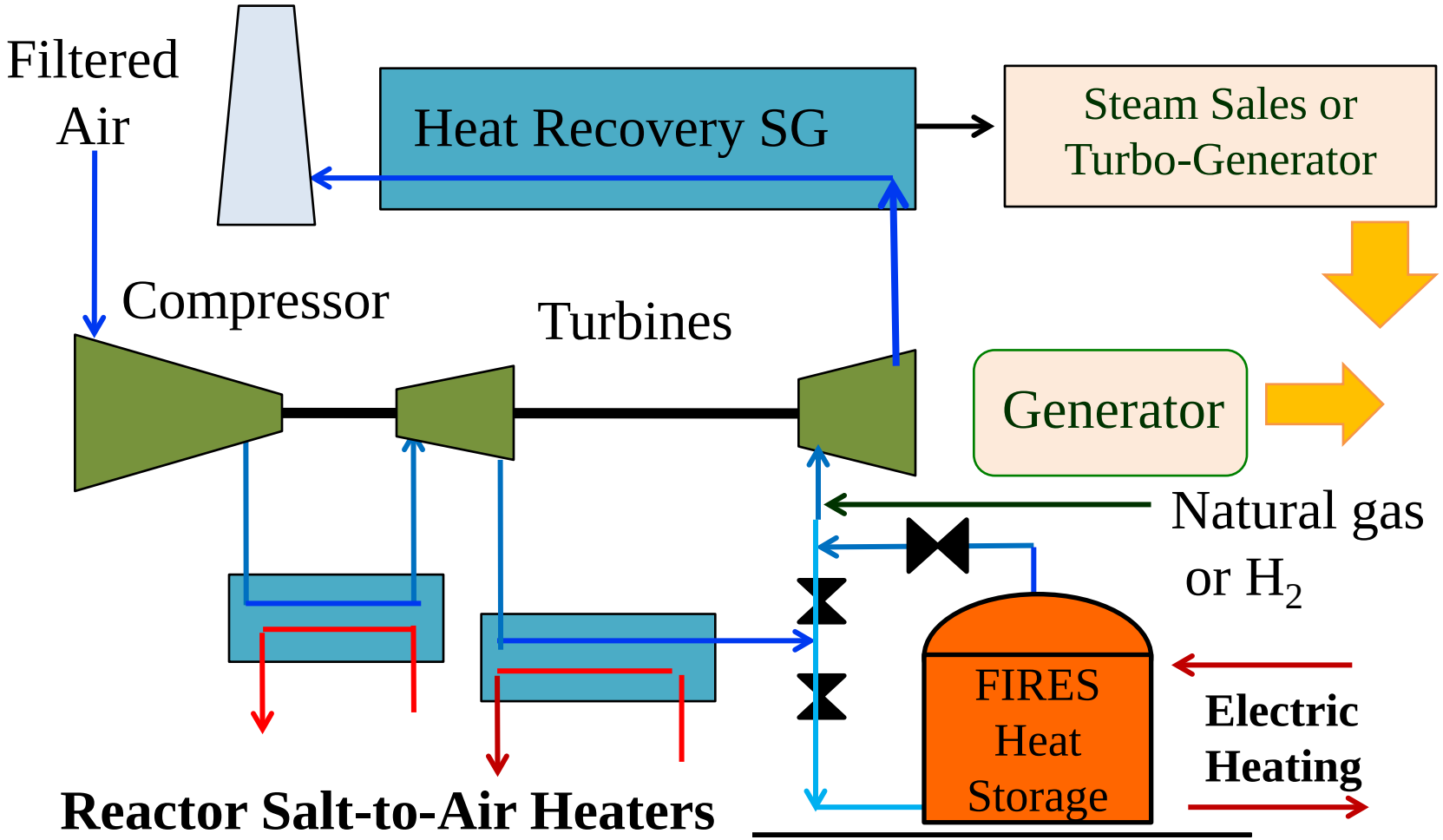
http://web.mit.edu/nse/people/research/forsberg.html

Nuclear Air-Brayton Combined Cycle (NACC)

Heat Storage: Enabling NACC to Replace Batteries, Pumped Storage and Similar Technologies

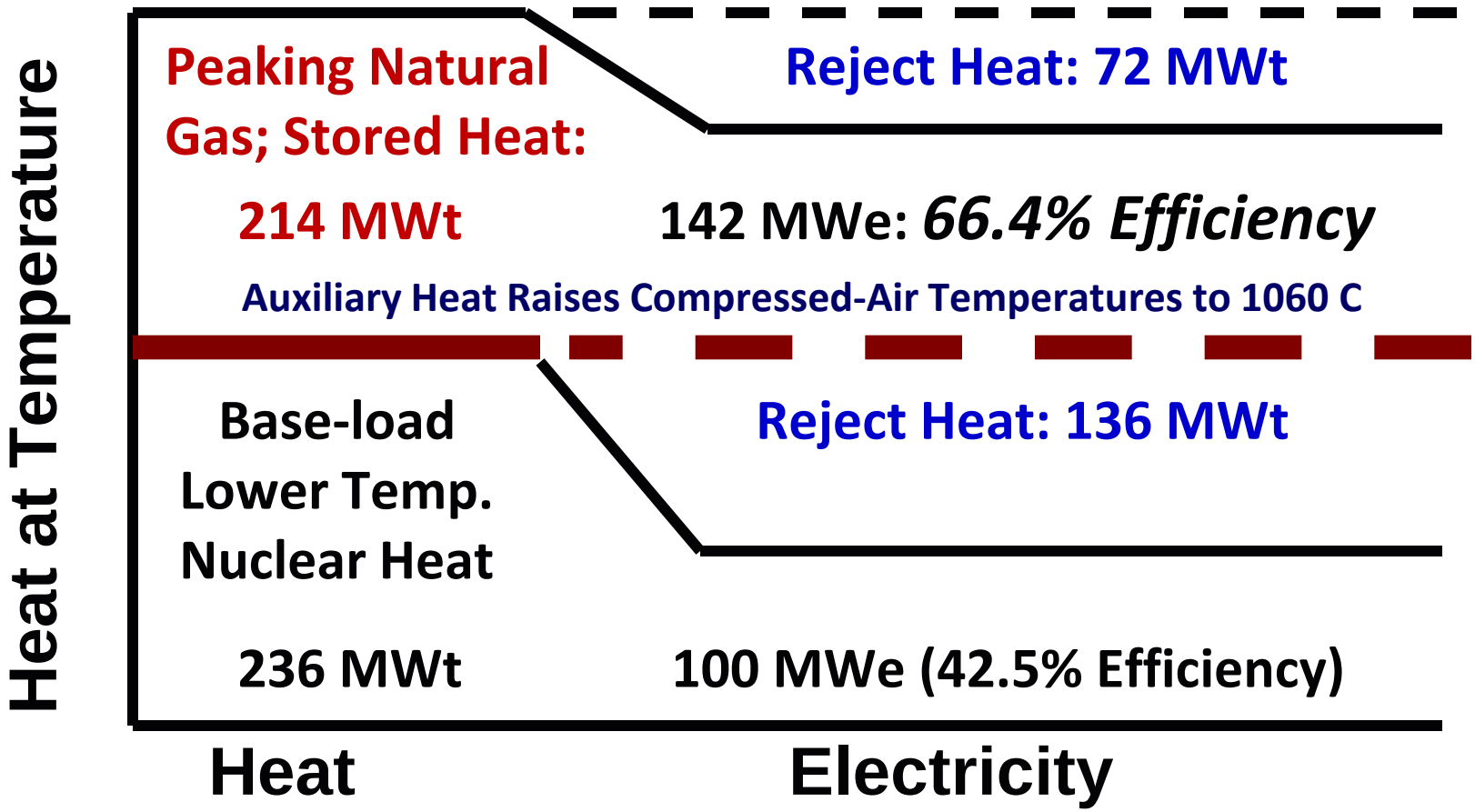
NACC Power System

Modified Natural-Gas-Fired Power Cycle



66% Peak Heat-To-Electricity Efficiency Better Alternatives

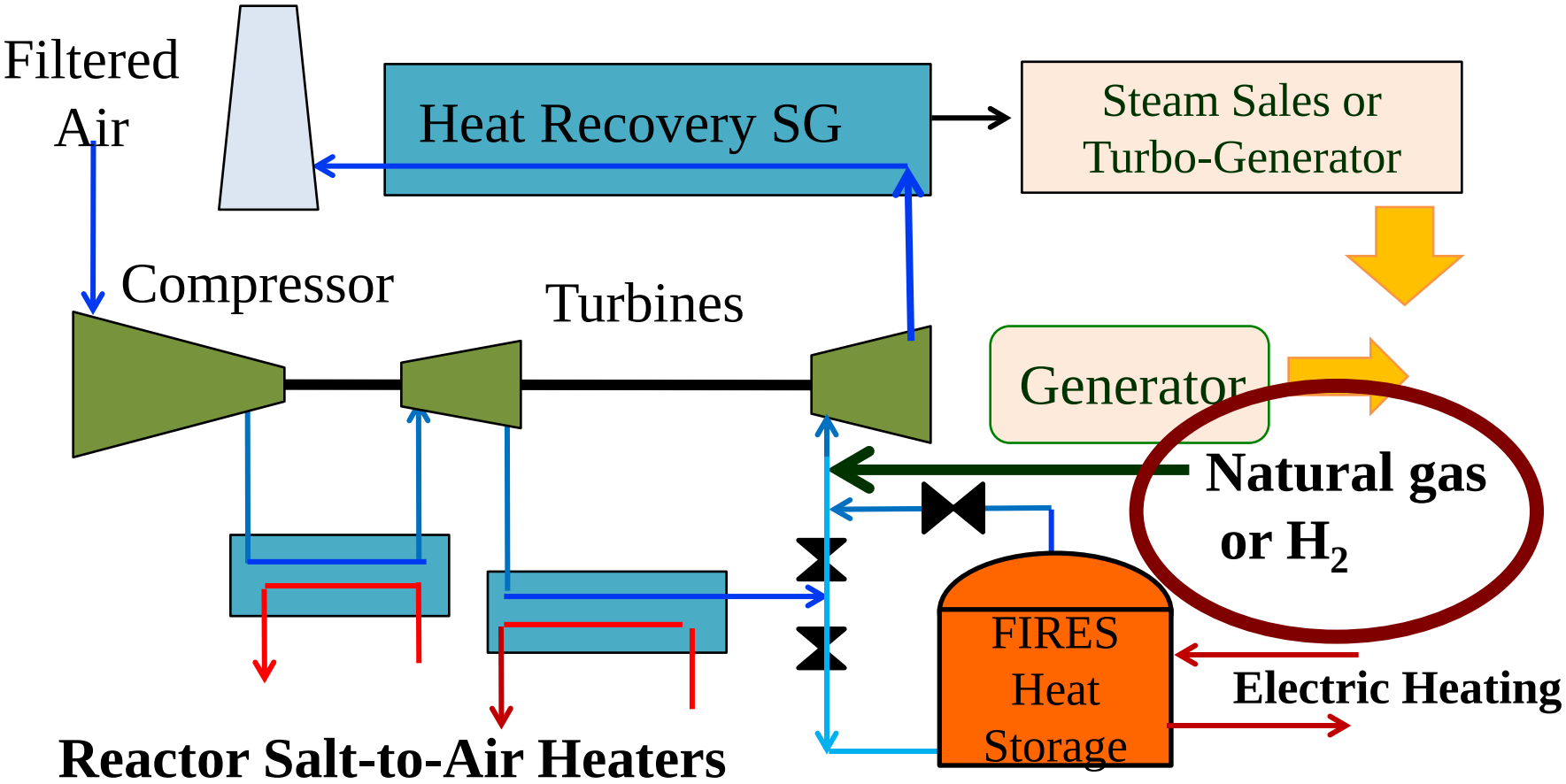
Natural-Gas Combined Cycle Gas Turbine: 60%



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

Power Response: Tens of Milliseconds

Time from Gas Injection to First Turbine Blade



Fast Response Because Peak Electricity Above Base Load And Temperatures Above Auto-ignition of Fuel

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

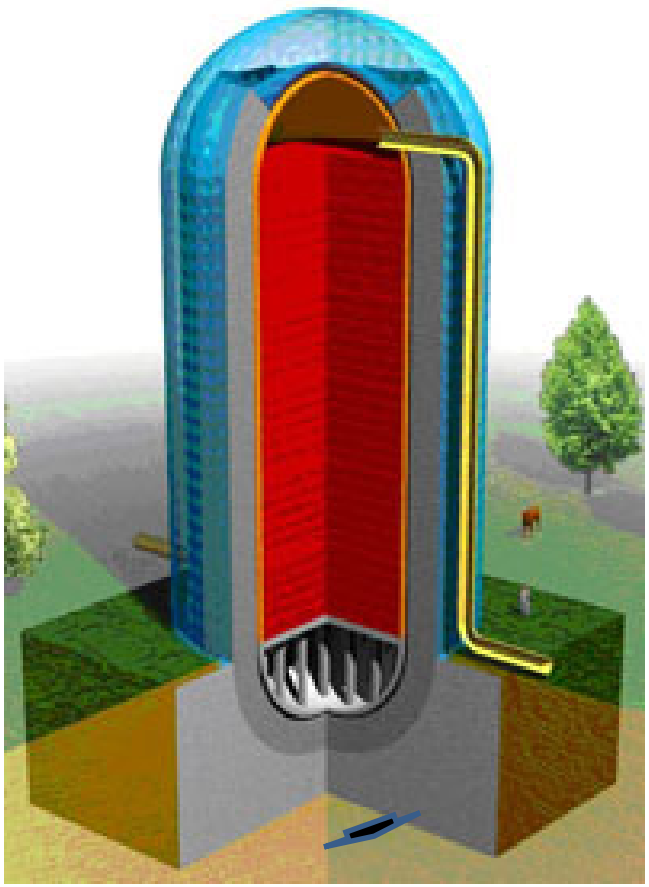
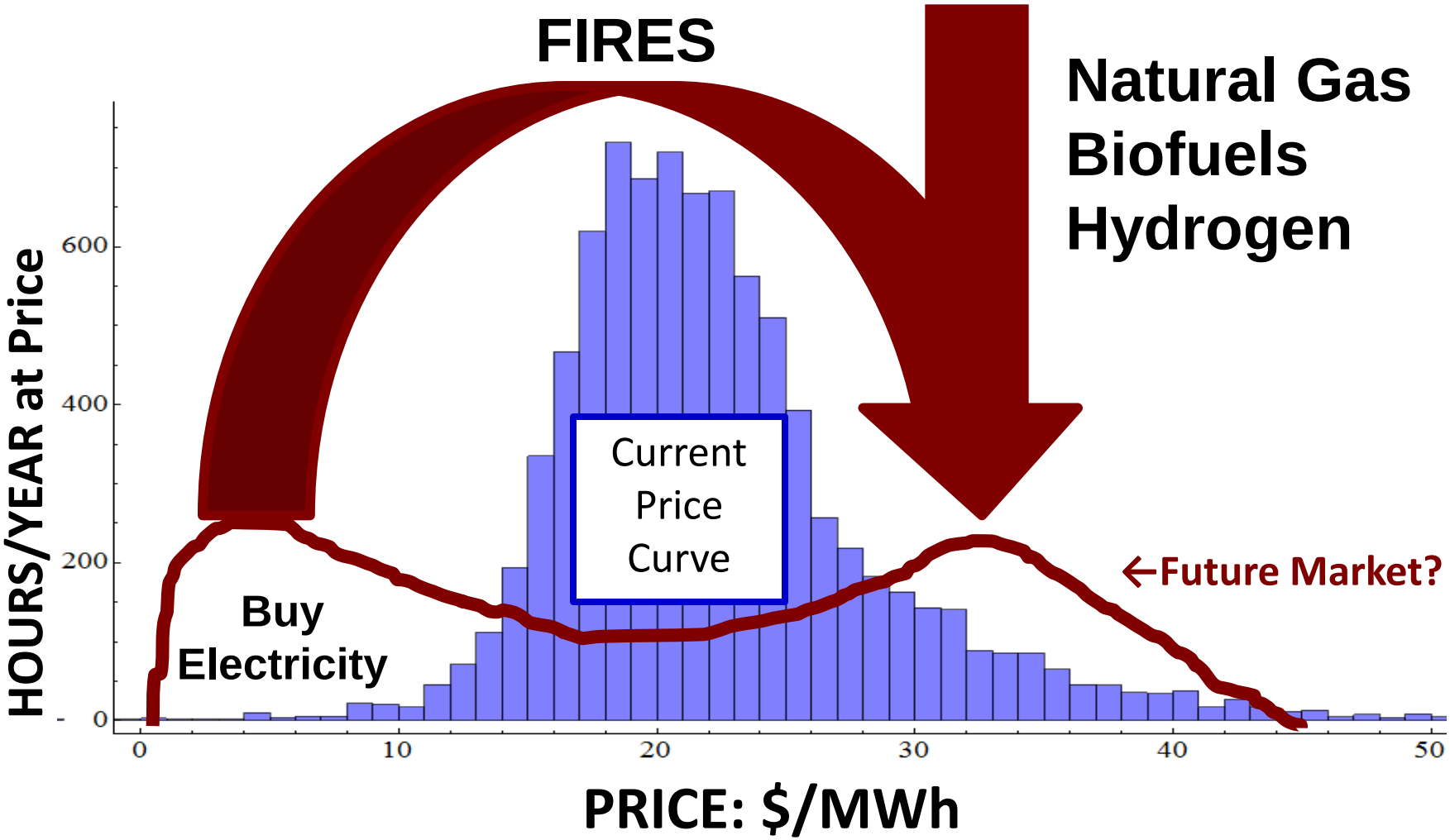


Figure courtesy of General Electric Adele Adiabatic Compressed Air Storage Project that is Integrating Firebrick Heat Storage with Gas Turbine

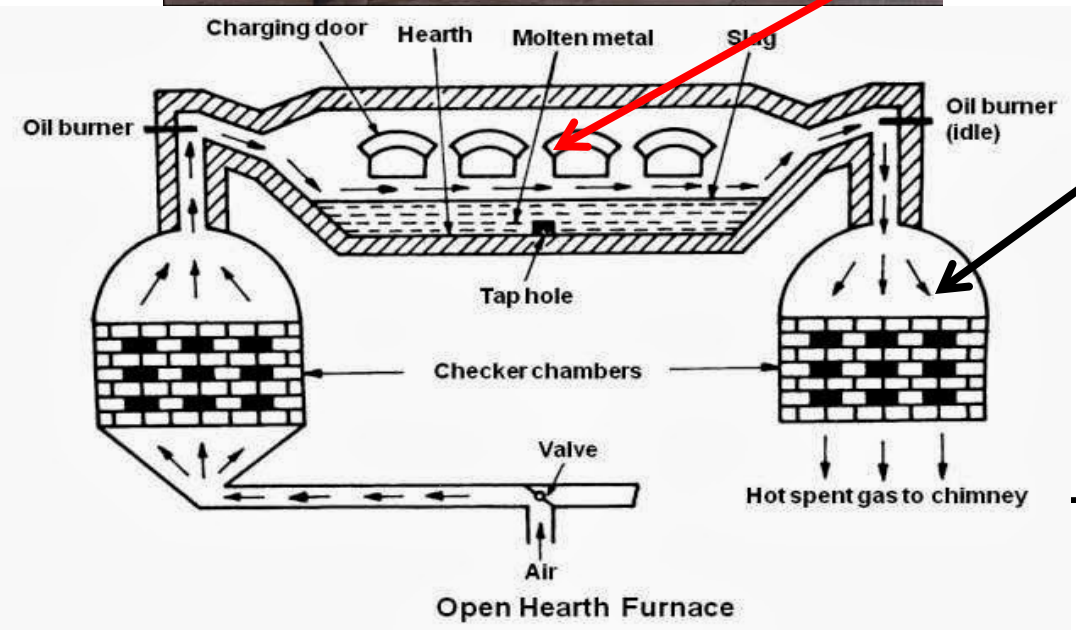
- Firebrick electrically heated when low electricity prices; less than price of natural gas or excess wind/solar electricity generation
  - Electricity from FHR
  - Electricity from grid
- **Use hot firebrick as substitute for natural gas peak electricity**
- Reasonable round-trip efficiency
  - 100% electricity to heat
  - 66+% heat-to-electricity efficiency (peak power)
- **Lower cost storage than hydro pump-storage, batteries, etc.**

NACC with FIRES Economics Improves As Add Solar that Collapses Electricity Prices



FIRES Helps Solar/Wind By Slowing Price Collapse

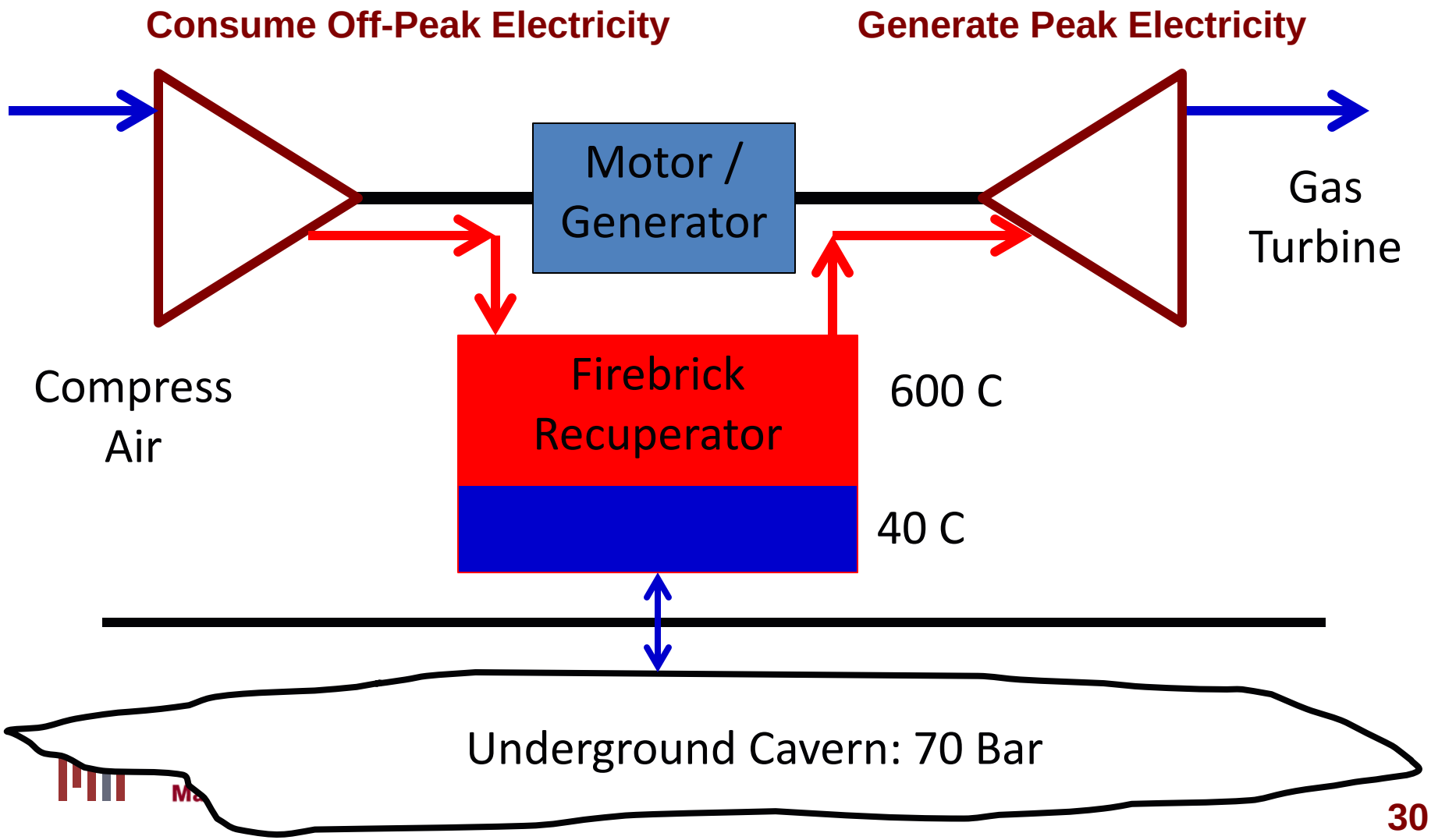
Firebrick Air Recuperators Developed for Open-Hearth Steel Production (1920s)



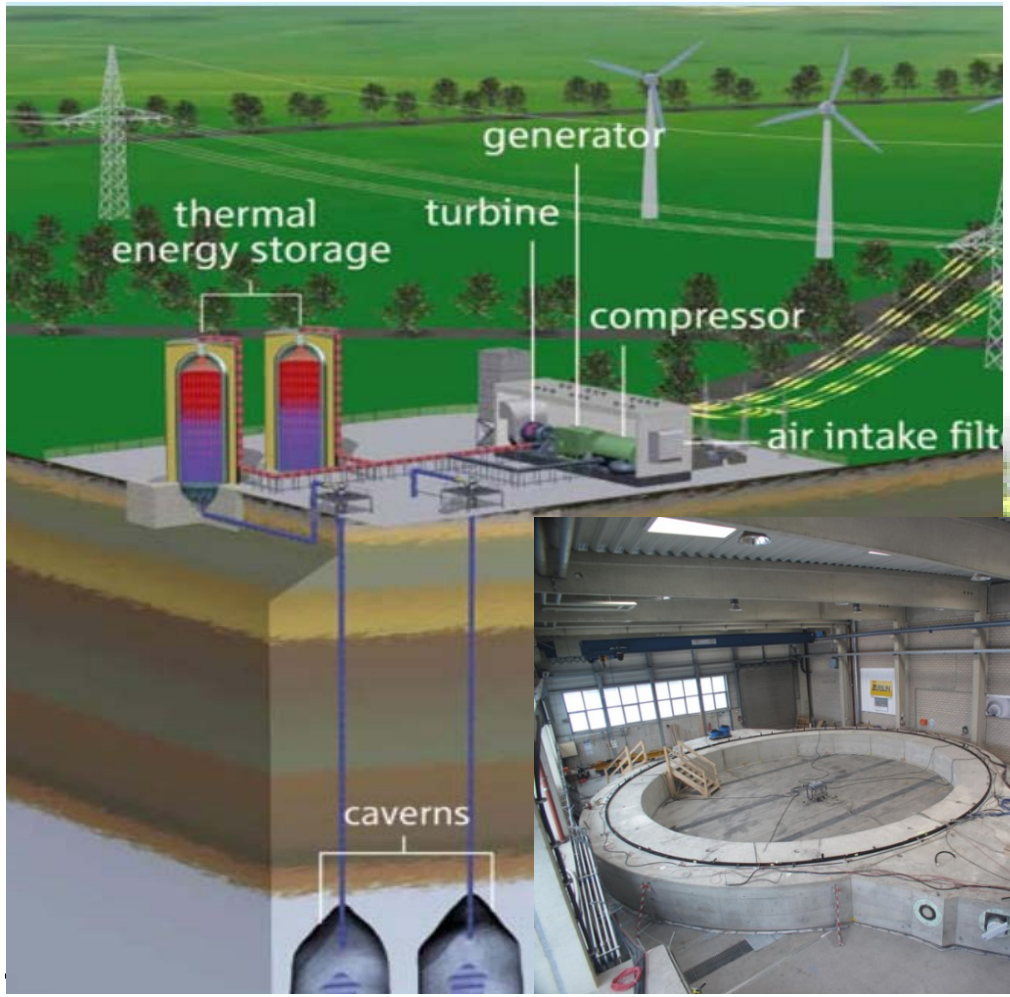
- Open-Hearth Steel production
- Firebrick Recuperators

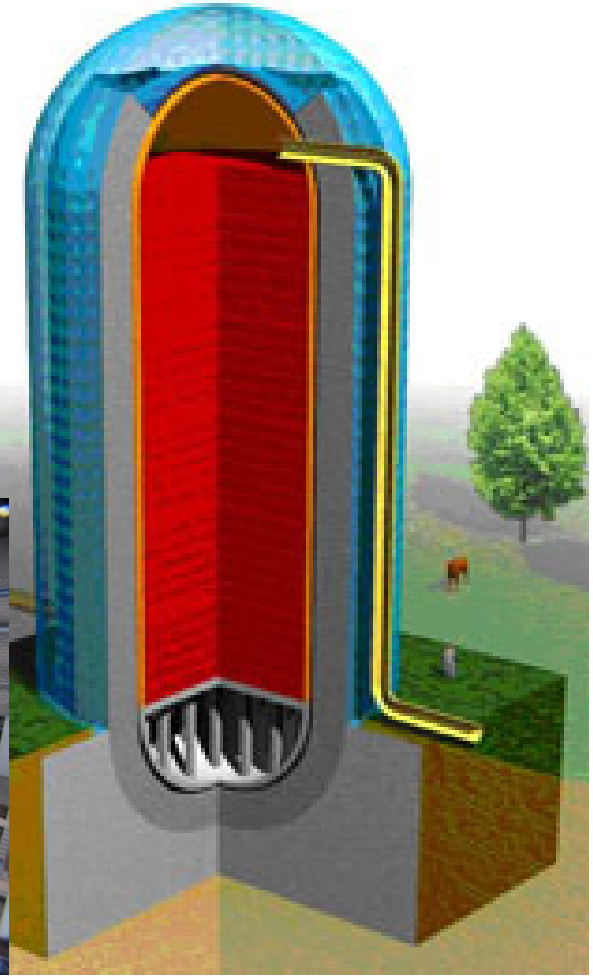
FIRES Technology Partly Being Developed by GE

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



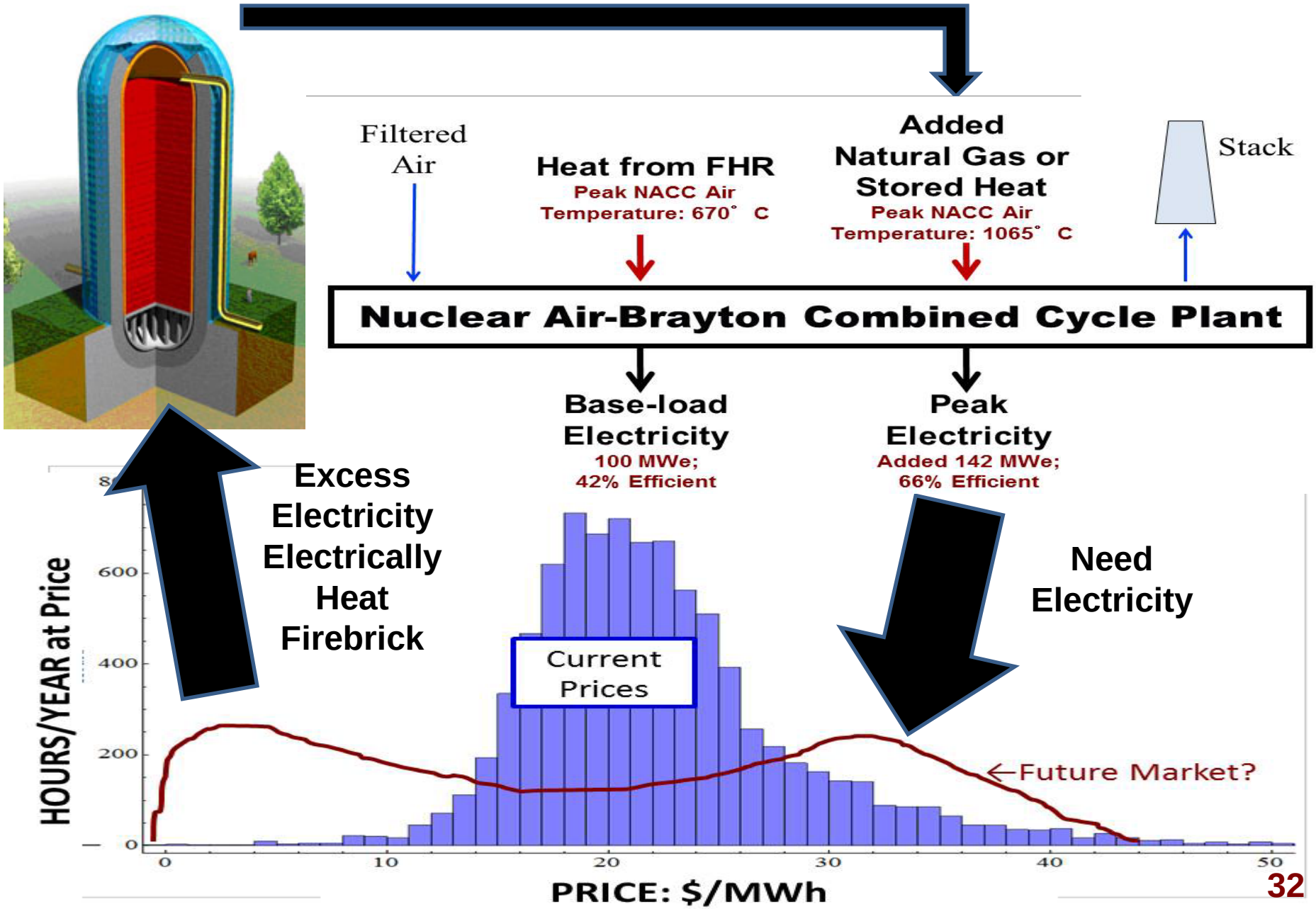
FIRES Builds Upon GE/RWE Adiabatic Compressed Air Storage Integration of Firebrick Heat Storage with Gas Turbines





Differences between Adele and FIRES. FIRES lower pressure, higher temperature and electric heating

FHR With FIRES May Replace Grid Storage



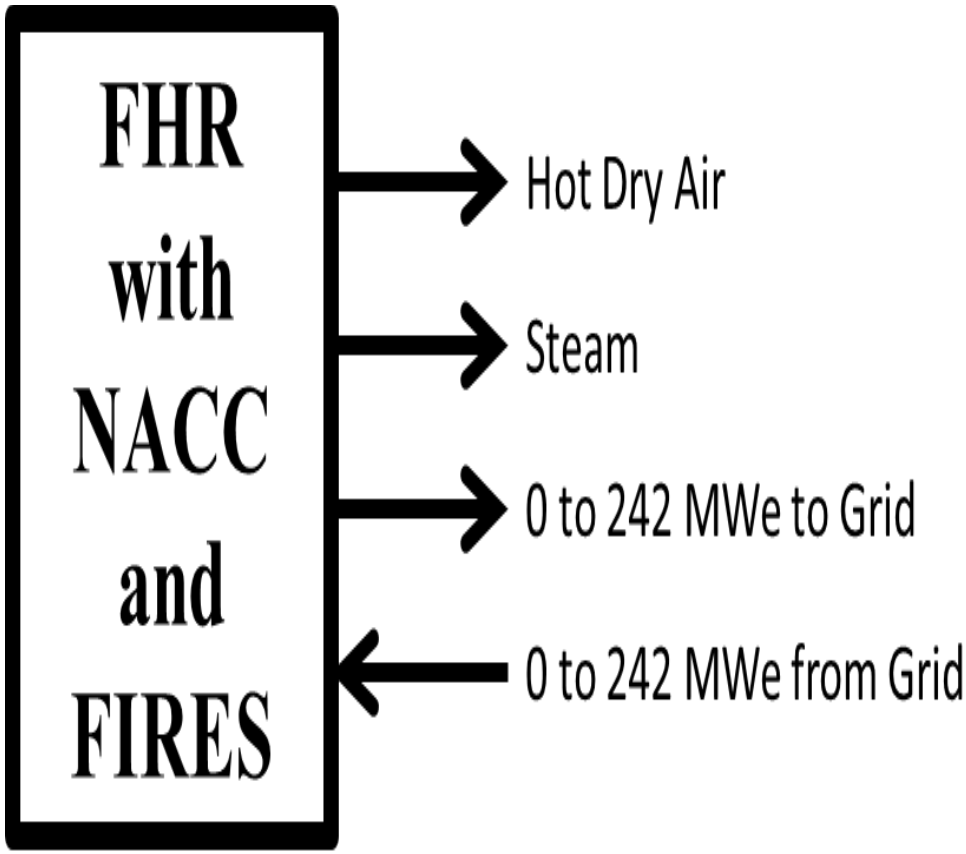
In a Zero-Carbon World, NACC Would Use FIRES and Hydrogen for Peak Power

Replace Pump Storage, Batteries, Natural Gas

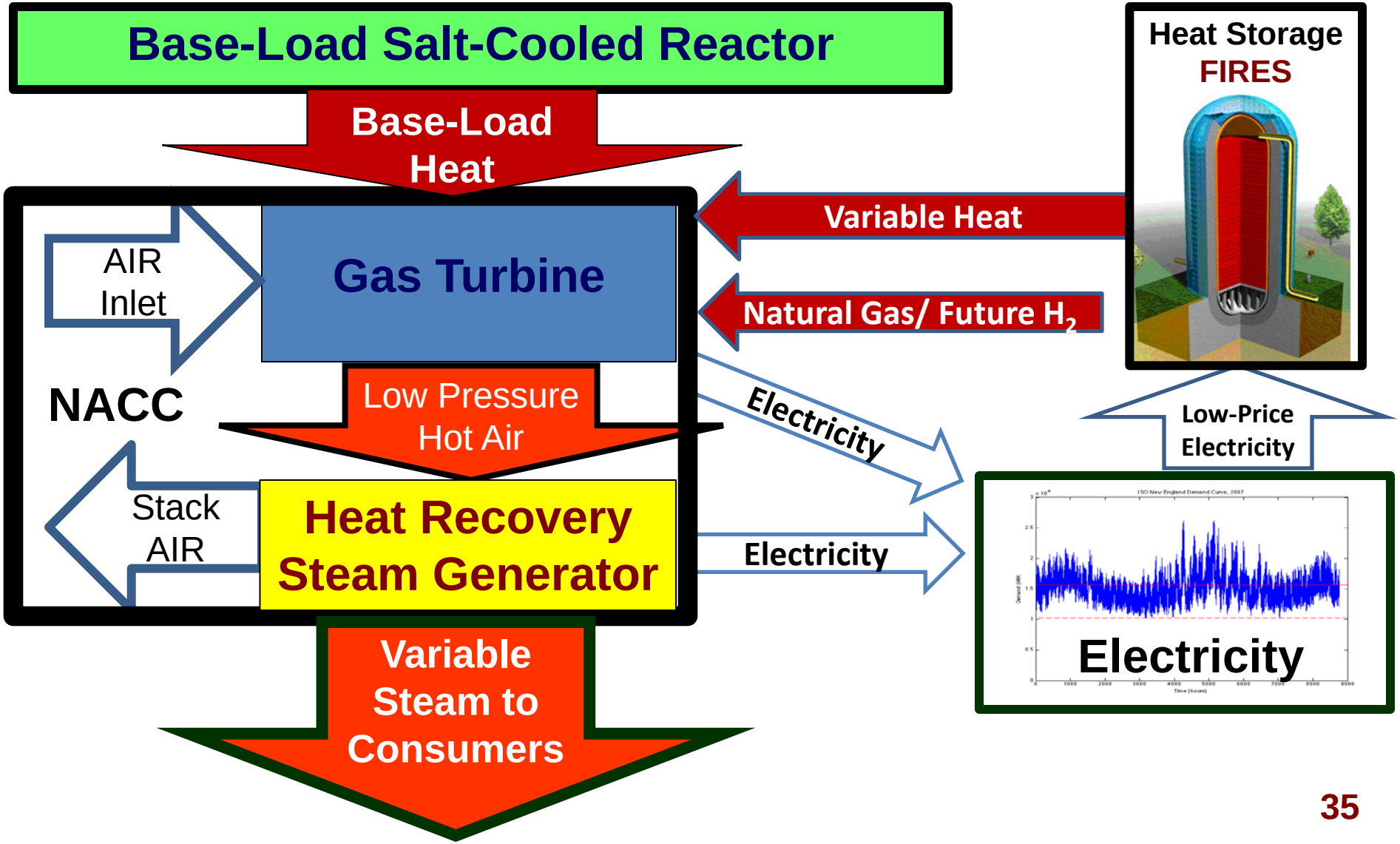
- FIRES Energy Storage
  - With 66% (future 70%) electricity-to-heat-to-electricity, it is potentially competitive with other storage options
  - FIRES is cheap storage for a day but expensive long-term energy storage because cost of FIRES prestress concrete vessel holding the firebrick
- Hydrogen Energy Storage
  - Energy storage efficiency with any system (electricity-to hydrogen-to-electricity) is less than 50%--inefficient
  - Underground hydrogen storage (a commercial technology) is cheap—same as natural gas storage
  - Hydrogen preferred for seasonal storage
  - **FHR with NACC is the most efficient hydrogen-to-electricity generating system**

FHR With FIRES May Replace Pumped Storage & Other Storage Systems

- Per 100 MWe base
  - Added 142 MWe peaking capability
  - Assume electricity buy capability match sell capability
- Economics
  - Firebrick inexpensive but have vessel cost
  - Round-trip efficiency similar to pump storage

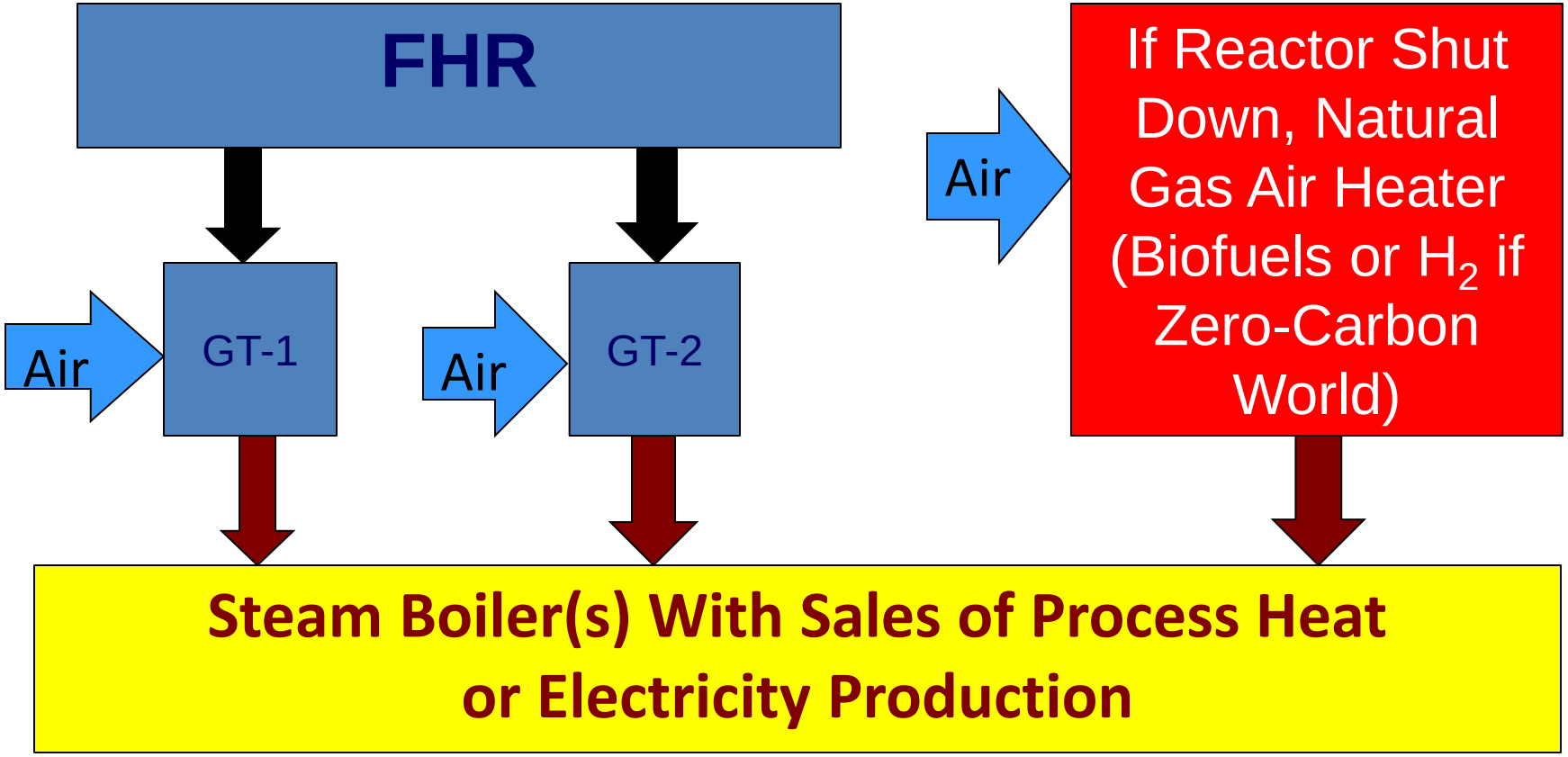


NACC With FIRES Enables Base-Load Nuclear with Variable Electricity and Steam to Industry



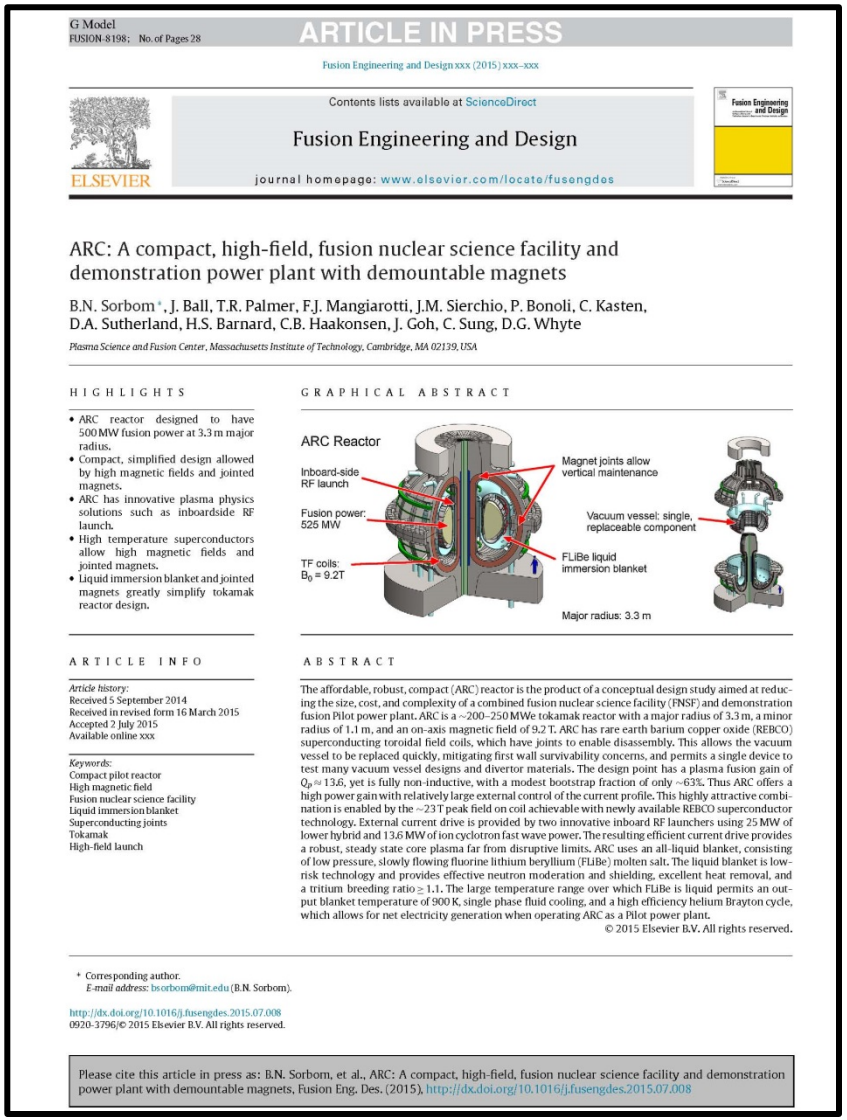
Air Brayton Power Cycle Enables Reliable Steam Supply for Industry

Similar to Power Systems in Chemical Plants



Eliminates Historic Nuclear Process Heat Problem: What if the Nuclear Reactor Shuts Down?

Fusion Breakthrough May Drive Fusion to Liquid-Salt Blankets (Flibe)



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ARC: A compact, high-field, fusion nuclear science facility and demonstration power plant with demountable magnets

B.N. Sorbom *, J. Ball, T.R. Palmer, F.J. Mangiarotti, J.M. Sierchio, P. Bonoli, C. Kasten, D.A. Sutherland, H.S. Barnard, C.B. Haakonsen, J. Goh, C. Sung, D.G. Whyte

Plasma Science and Fusion Center, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

HIGHLIGHTS

- ARC reactor designed to have 500 MW fusion power at 3.3 m major radius.
- Compact, simplified design allowed by high magnetic fields and jointed magnets.
- ARC has innovative plasma physics solutions such as inboardside RF launch.
- High temperature superconductors allow high magnetic fields and jointed magnets.
- Liquid immersion blanket and jointed magnets greatly simplify tokamak reactor design.

GRAPHICAL ABSTRACT

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Superconducting joints
Tokamak
High-field launch

ABSTRACT

The affordable, robust, compact (ARC) reactor is the product of a conceptual design study aimed at reducing the size, cost, and complexity of a combined fusion nuclear science facility (FNSF) and demonstration fusion Pilot power plant. ARC is a ~200–250 MWe tokamak reactor with a major radius of 3.3 m, a minor radius of 1.1 m, and an on-axis magnetic field of 9.2 T. ARC has rare earth barium copper oxide (REBCO) superconducting toroidal field coils, which have joints to enable disassembly. This allows the vacuum vessel to be replaced quickly, mitigating first wall survivability concerns, and permits a single device to test many vacuum vessel designs and divertor materials. The design point has a plasma fusion gain of $Q_p \approx 13.6$, yet is fully non-inductive, with a modest bootstrap fraction of only ~63%. Thus ARC offers a high power gain with relatively large external control of the current profile. This highly attractive combination is enabled by the ~23 T peak field on coil achievable with newly available REBCO superconductor technology. External current drive is provided by two innovative inboard RF launchers using 25 MW of lower hybrid and 13.6 MW of ion cyclotron fast wave power. The resulting efficient current drive provides a robust, steady state core plasma far from disruptive limits. ARC uses an all-liquid blanket, consisting of low pressure, slowly flowing fluorine lithium beryllium (FLiBe) molten salt. The liquid blanket is low-risk technology and provides effective neutron moderation and shielding, excellent heat removal, and a tritium breeding ratio ≥ 1.1. The large temperature range over which FLiBe is liquid permits an output blanket temperature of 900 K, single phase fluid cooling, and a high efficiency helium Brayton cycle, which allows for net electricity generation when operating ARC as a Pilot power plant.

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Fusion Confinement Physics Strongly Favors High Magnetic Fields (B)

$$\frac{P_{fusion}}{S_{wall}} \sim \frac{\beta_N^{\,2}\epsilon^2}{q_*^2} R B^4$$

Power Density

But

- Require superconducting magnets to confine plasma to minimize electricity consumption
- High magnetic fields destroy superconductivity so magnetic field strength limited by superconductor

A Revolution in Super-Conductors in Last 5 Years May Double Magnetic Fields

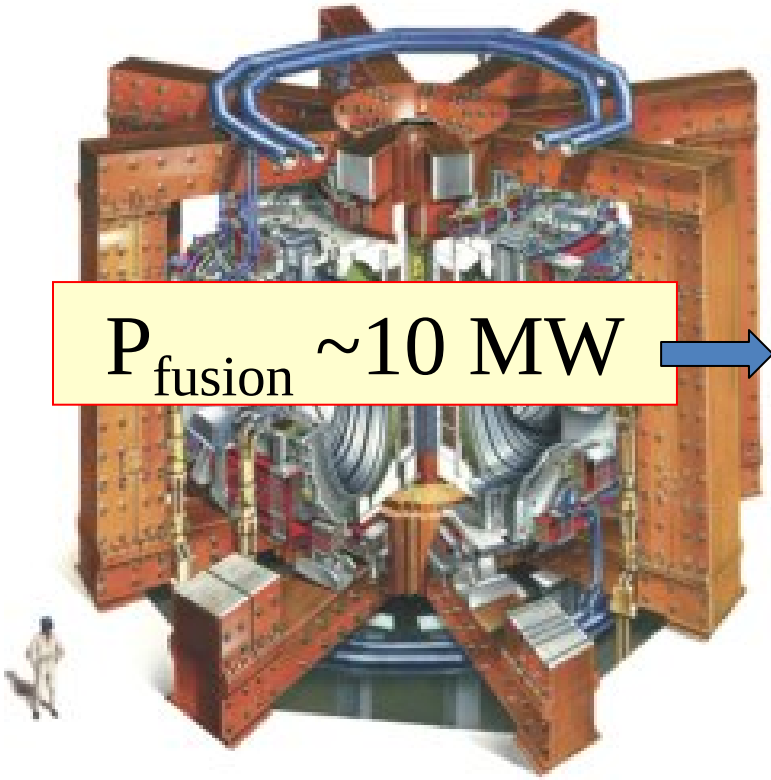
REBCO (Rare-Earth Barium Cu Oxide) remain superconducting at VERY high B-field and above liquid He temperatures

for compact fusion devices

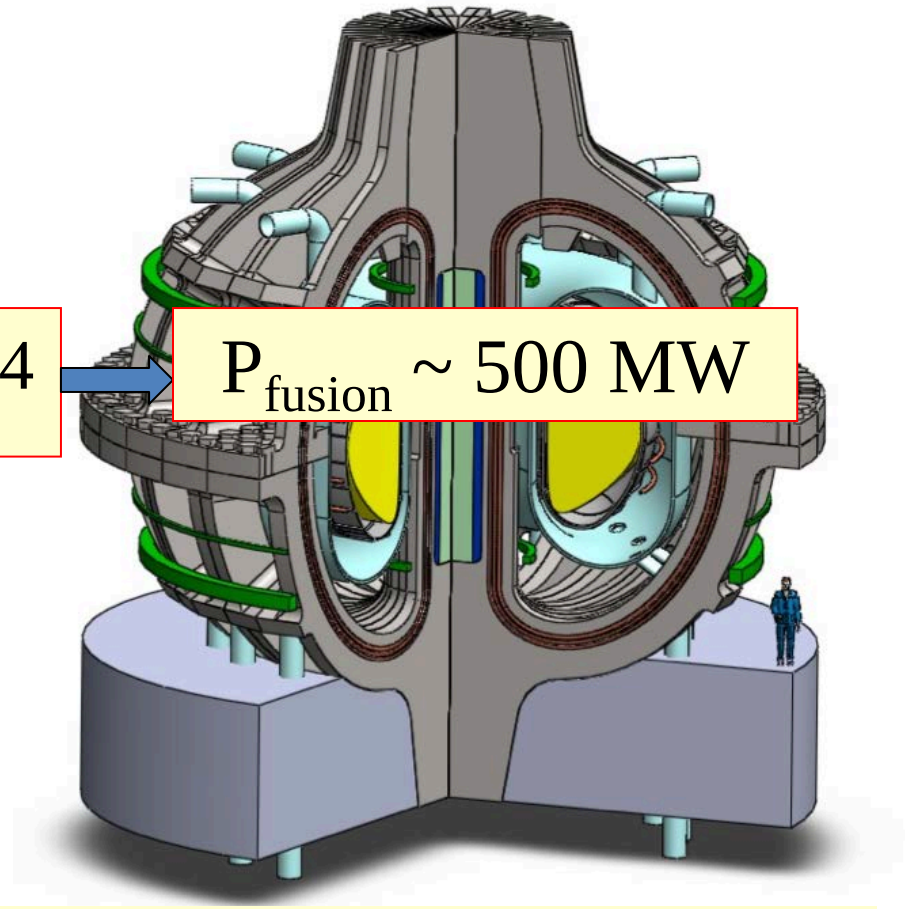
Higher Magnetic Field Reduces Fusion Machine Size—Path To Fusion

Copper, B = 3.5 T

REBCO superconductor B = 9.2 T



P_{fusion} ~10 MW → x B^4 → P_{fusion} ~ 500 MW



JET: R ~ 3 m
~4 years construction
Operated in U.K

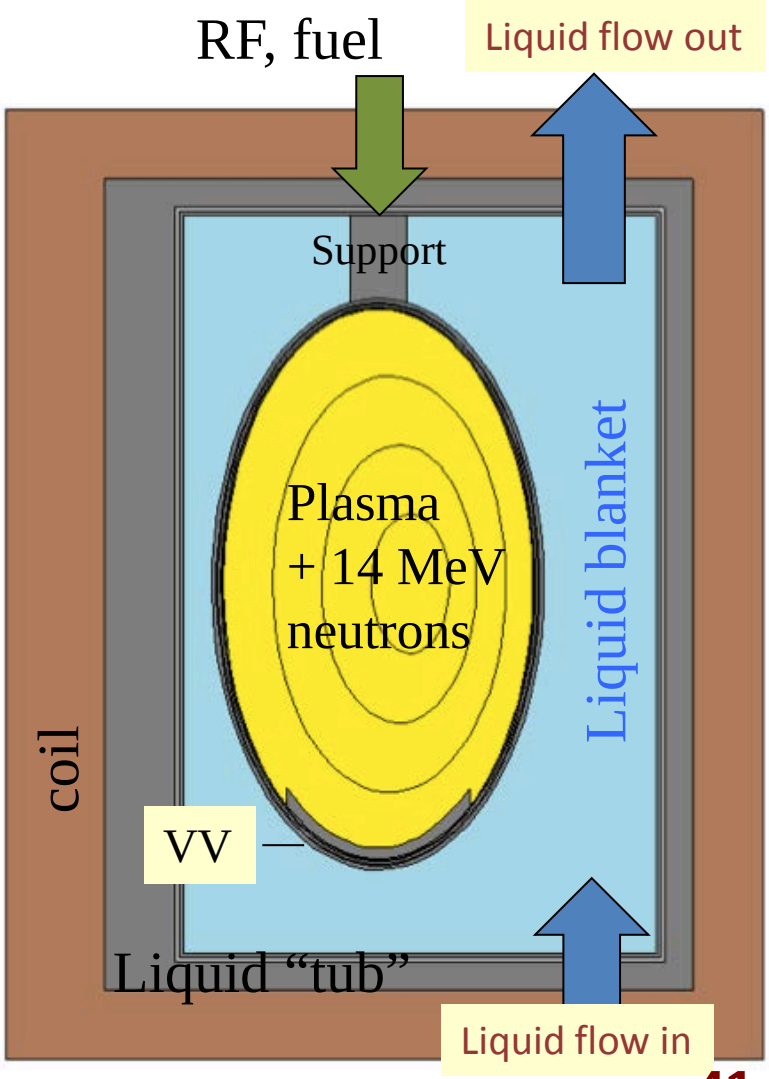
Proposed: ARC: R ~ 3.2 m

Higher Power Density Drives Design Toward Flibe Salt Immersion Blanket

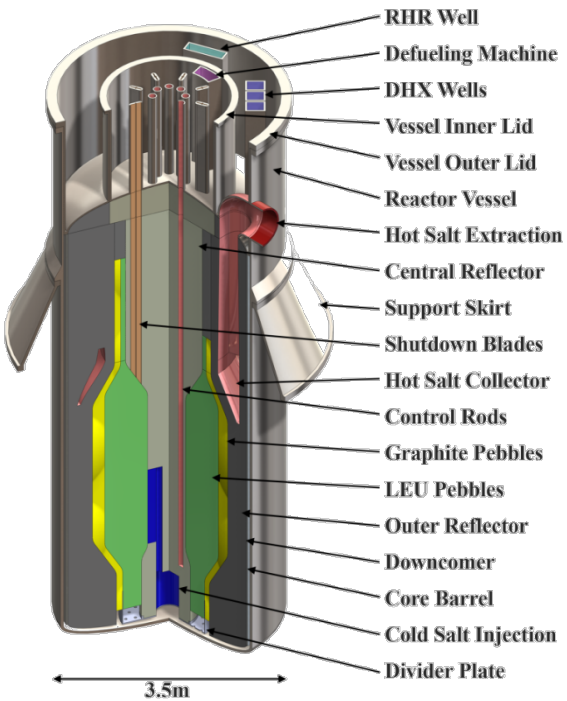
- **Vacuum Vessel (VV) is right beside plasma**
- **VV is immersed in liquid blanket**

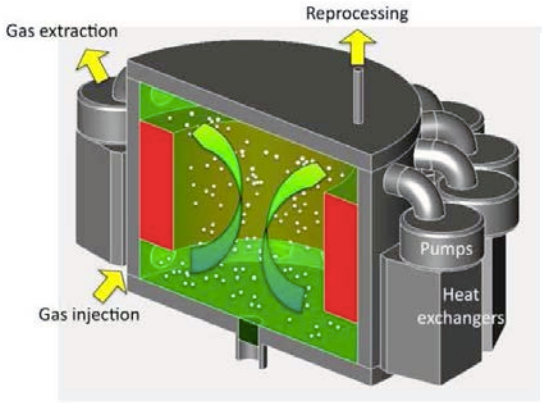
<u>Advantages</u>

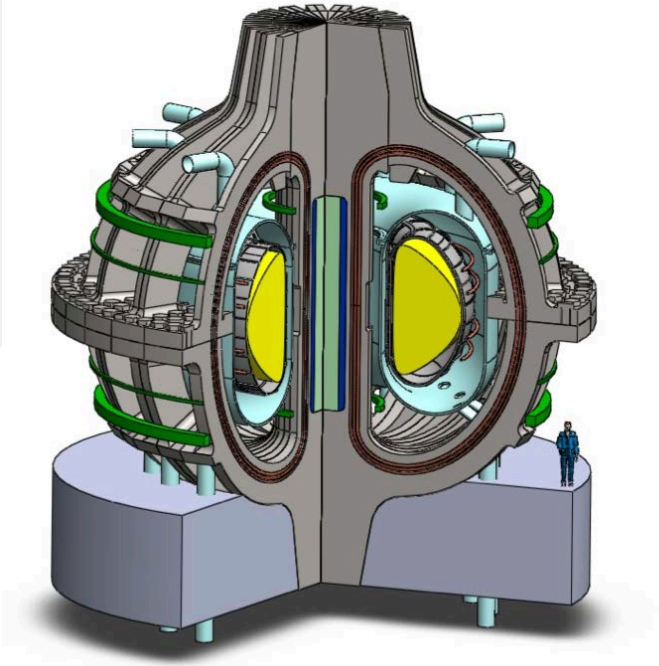
- **Simple**
- **Neutronics/nuclear engineering at atmospheric pressure.**
- **No gaps for effective radiation shielding**
- **Energy & tritium extraction with single-phase low-velocity flow**
- **No DPA limits in blanket**
- **Minimized solid waste**
- **Tub is robust safety boundary**
- **Salt has reduced interactions with high magnetic field relative to liquid metal coolants**



The FHR, MSR, and Fusion May Require Common Liquid-salt-coolant Technologies







FHR/AHTR **MSR** **Fusion**

Potential for Cooperative Synergetic Programs

Implications for FHR, MSR, and Fusion

- Liquid salts may become the common technology base for three technologies: FHR, MSR, and Fusion
- All couple to Nuclear Air-Brayton Combined Cycle (or helium cycle) for base-load nuclear and variable electricity to the grid
- Large incentives for cooperative programs between FHR, MSR, and Fusion on liquid salt technologies
  - Mechanical (pumps, seals, etc.)
  - Corrosion and tritium control
  - Instrumentation
  - Materials