Brayton Power Cycles with Peaking Capability and Storage

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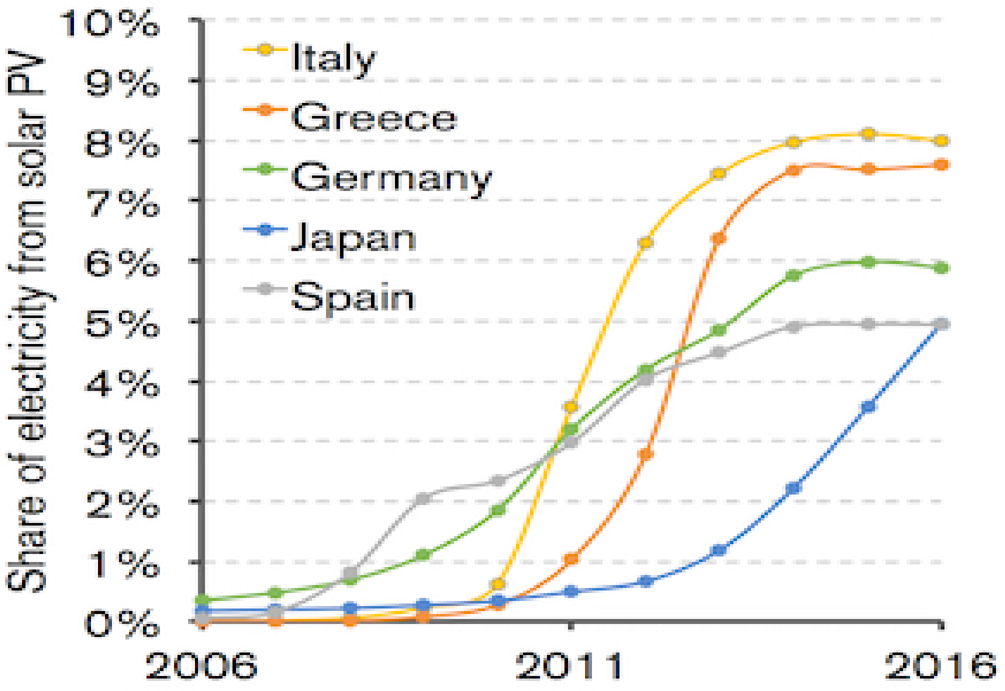
Outline

- The Problem
- A Proposed Solution
- Implementing the Solution

The Duck Curve and Saturation



As more Renewables come on line, the price of Electricity drops when they are available, but remains High when they are not available.

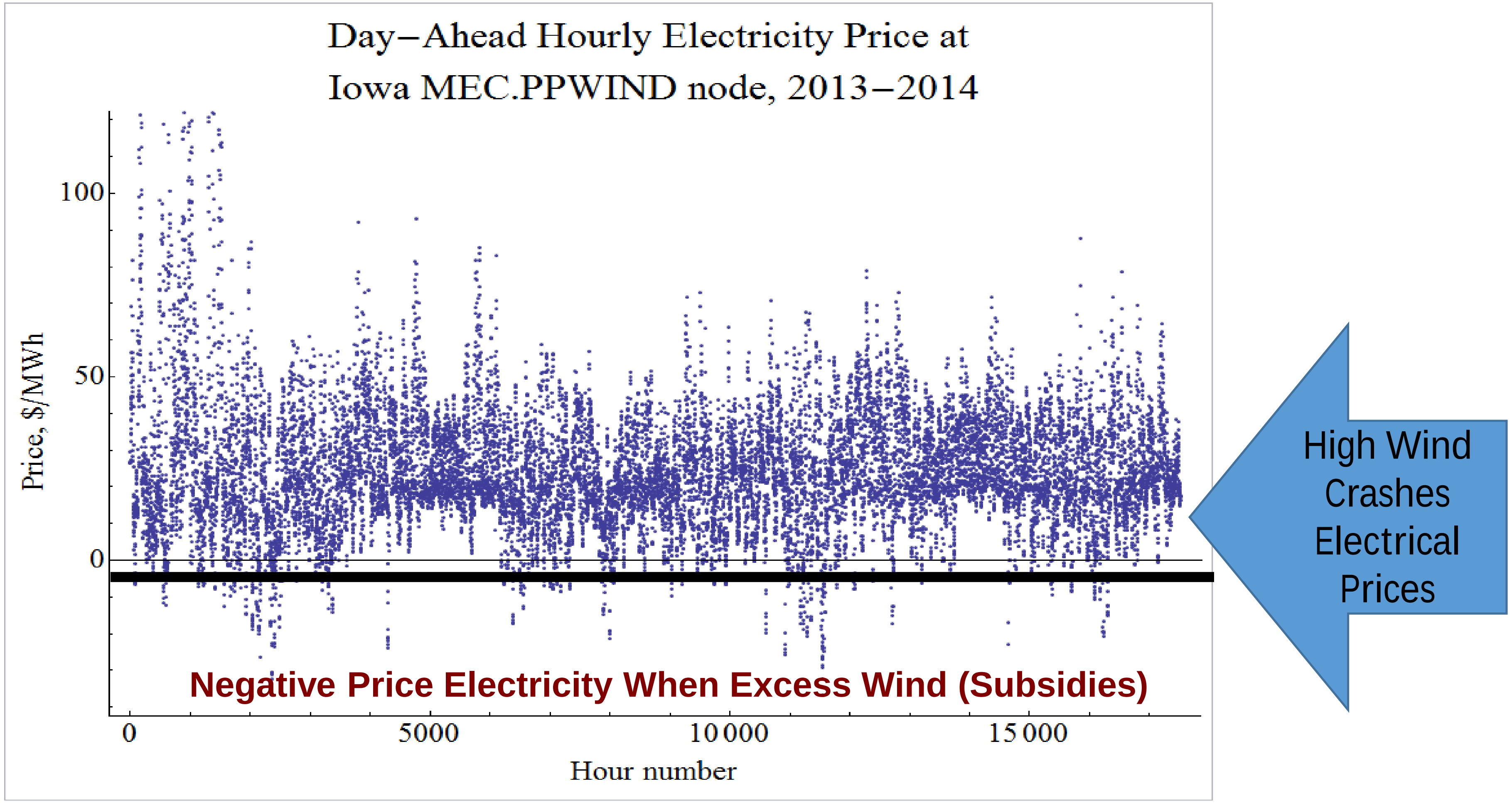
Due to the drop in price with high penetration, the market becomes saturated,

(n.b. Both figures stolen from Charles Forsberg presentation May 2018)

The Problem

Iowa Wholesale Electricity Prices: Two Years

Large Incentive to Sell Peak Electricity and Avoid Sales at Other Times



Energy Storage is the Obvious Solution

- There are two types of storage available at an arbitrary site.

- Electrical Storage (Obvious choice, typically batteries)
  - Currently approximately $280-$400 /kWh(e) at Terrawatt Scale
  - Essentially doubles the price of electricity
  - DOE is pursuing electrical storage research – Goal is $150/kWh(e)

- Heat Storage (Phase Change Material, Firebrick, Hydrogen Electrolysis)
  - DOE Heat Storage – Goal $15/kWh(t)
  - Can be used by Solar Thermal Plants but not PV
  - Even with conversion losses heat storage can be recovered at less cost

Increased Renewables Parallel increased Cost

- Introduction of increased renewables in Europe (primarily Germany) have driven the cost of electricity in Europe over 20% since 2008.
- In the US during this same period the cost of electricity has dropped by 50% due to the expansion of natural gas systems
- The heavy introduction of renewables into the California energy market has paralleled the European experience while the rest of US has experienced the 50% drop in cost of electricity.

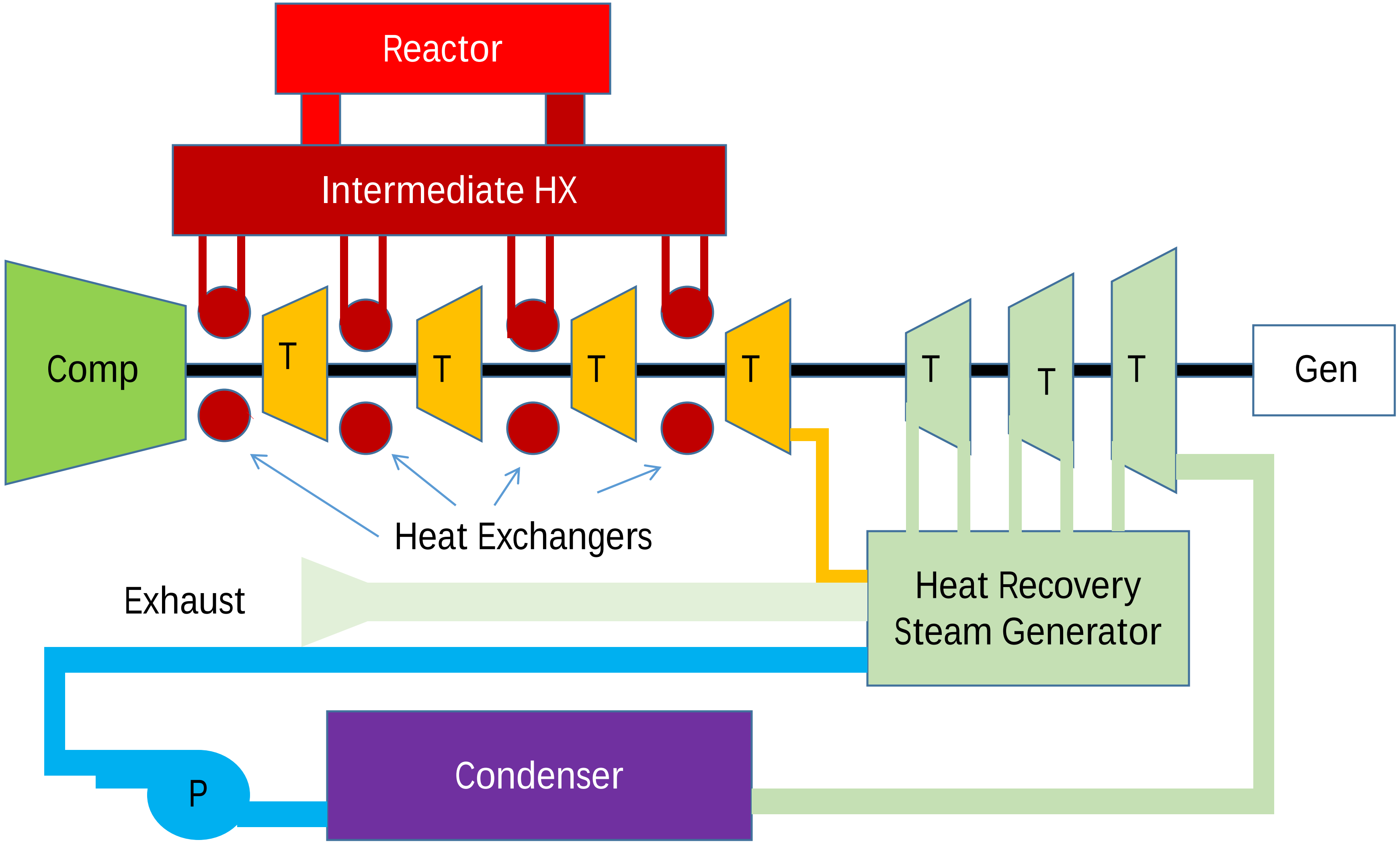
Heat In A Bottle, An Innovative Storage System

The variability of solar and wind power is causing headaches for utilities. Adding heat storage to light-water reactors could help promote a reliable low-carbon power industry as Implementing the Solution

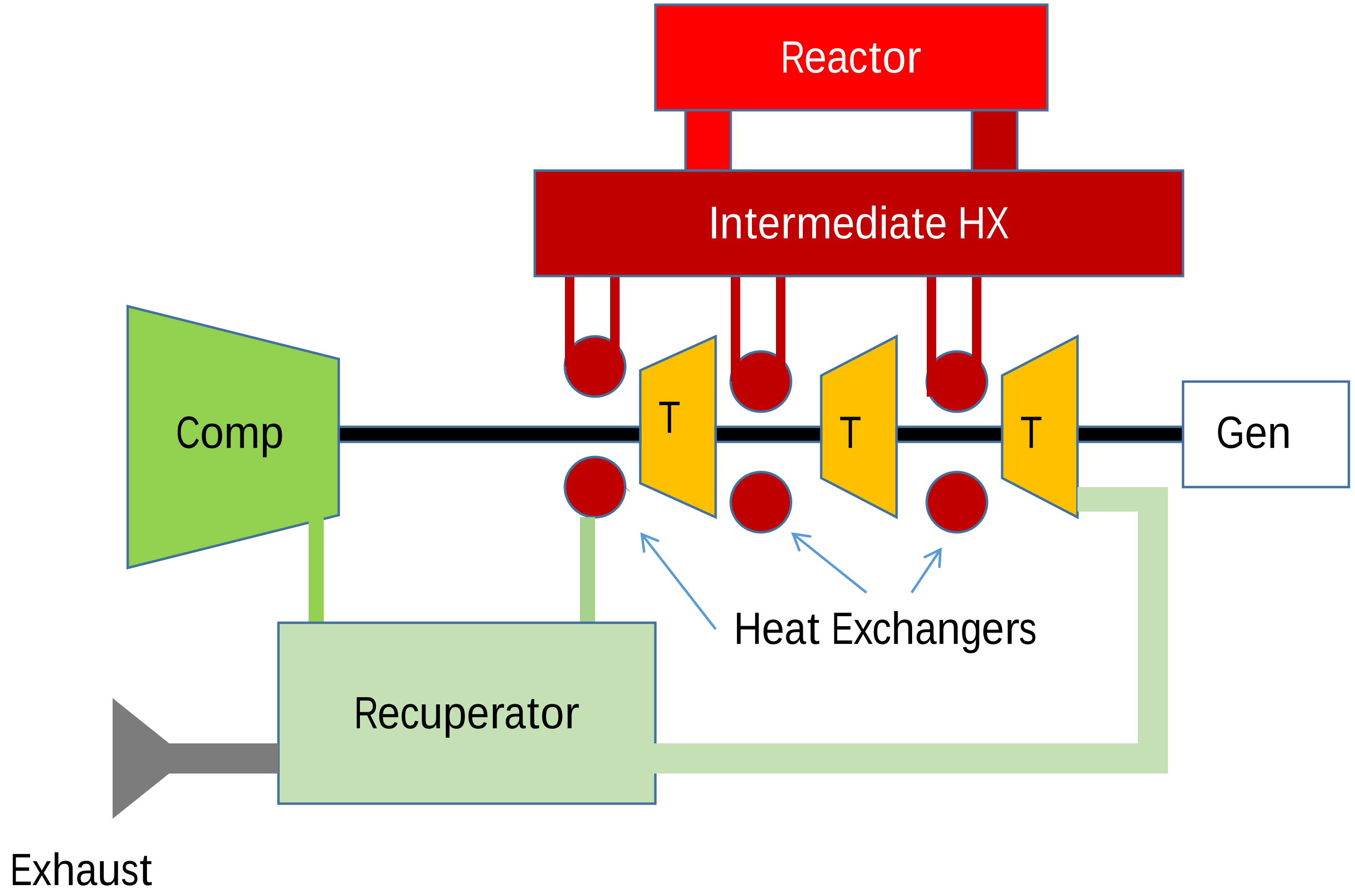
Nuclear Air Brayton Systems

- It is difficult, but not impossible, for LWR systems to take advantage of lower cost heat storage
- For advanced reactors, particularly Small Modular Reactors, Nuclear Air-Brayton systems may be effective.
- Nuclear Air-Brayton Combined Cycle (NACC) Systems can be built that operate similar to Gas Turbine Combined Cycle Systems
- Nuclear Air-Brayton Recuperated Cycle (NARC) Systems can be built based on the Same Technology
- The only innovation will be a liquid metal/molten salt-to-air heat exchanger. These have been demonstrated in the past on the 1960s ANP program and as heat dumps for the FFTF and are currently proposed for the VTR.

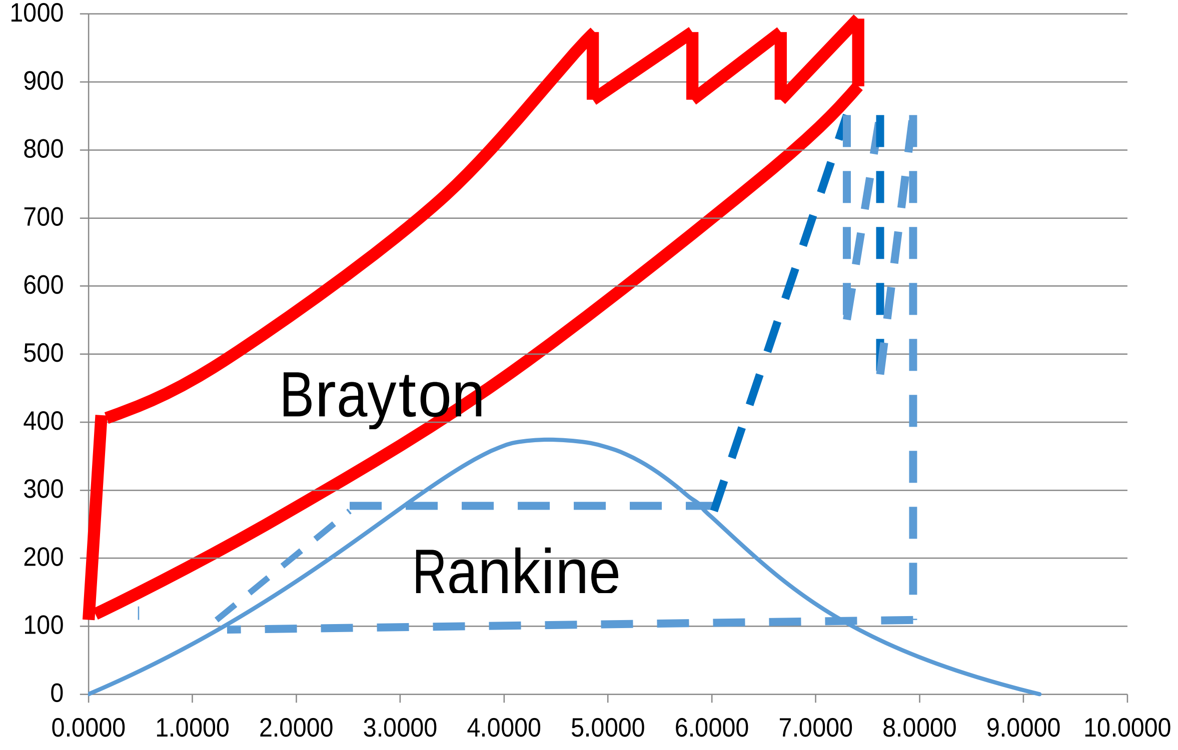
Typical NACC System Layout (4T)



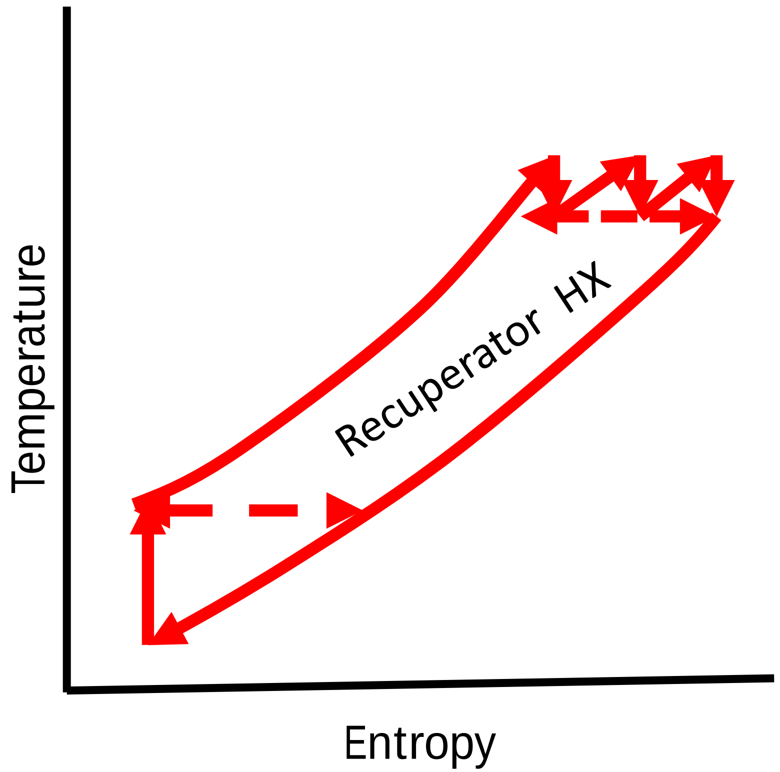
Typical NARC System Layout(3T)



Thermodynamic Cycle Diagrams



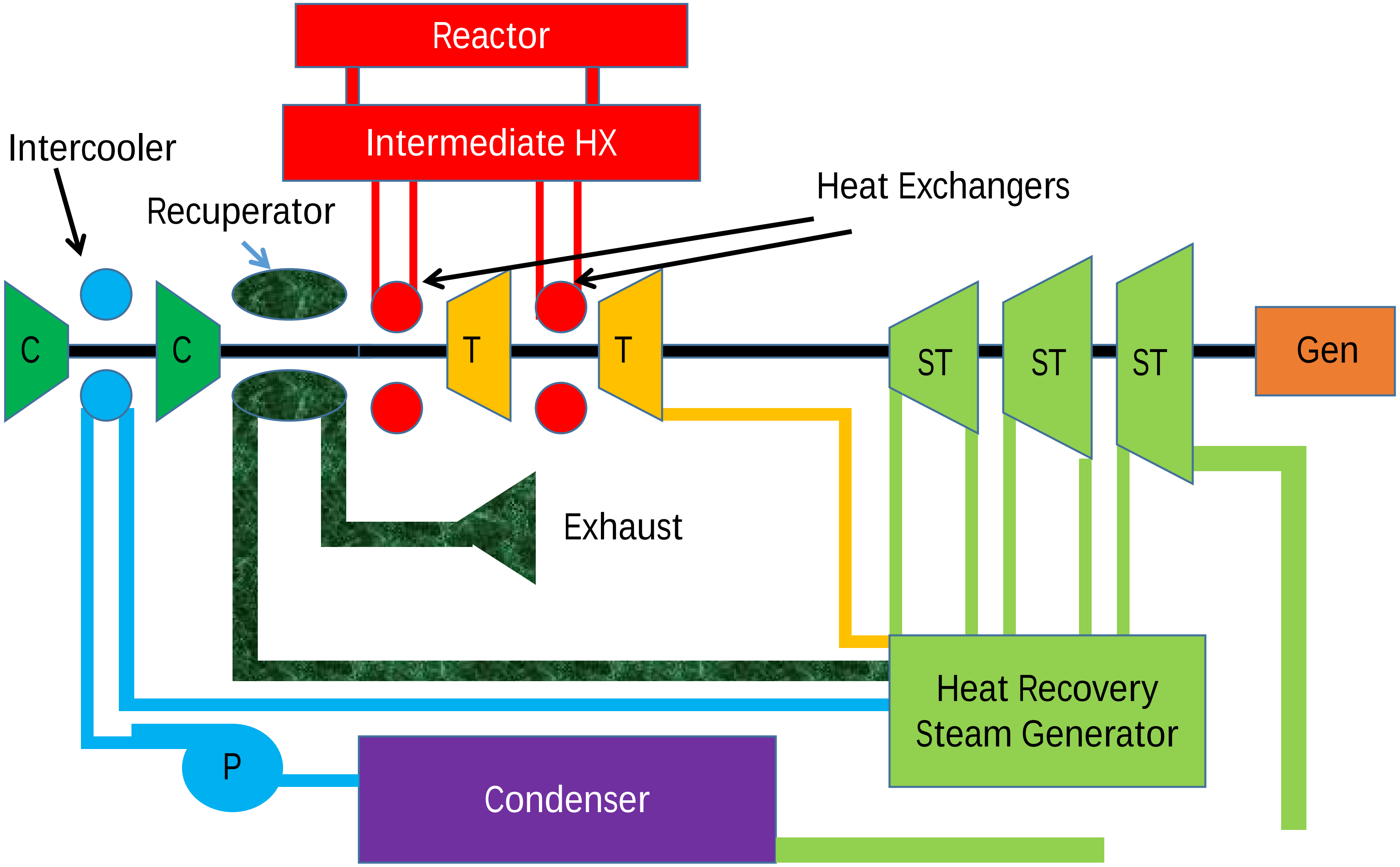
NACC System



NARC System

A Possible Solution

NACC w/Recuperator and Intercooler



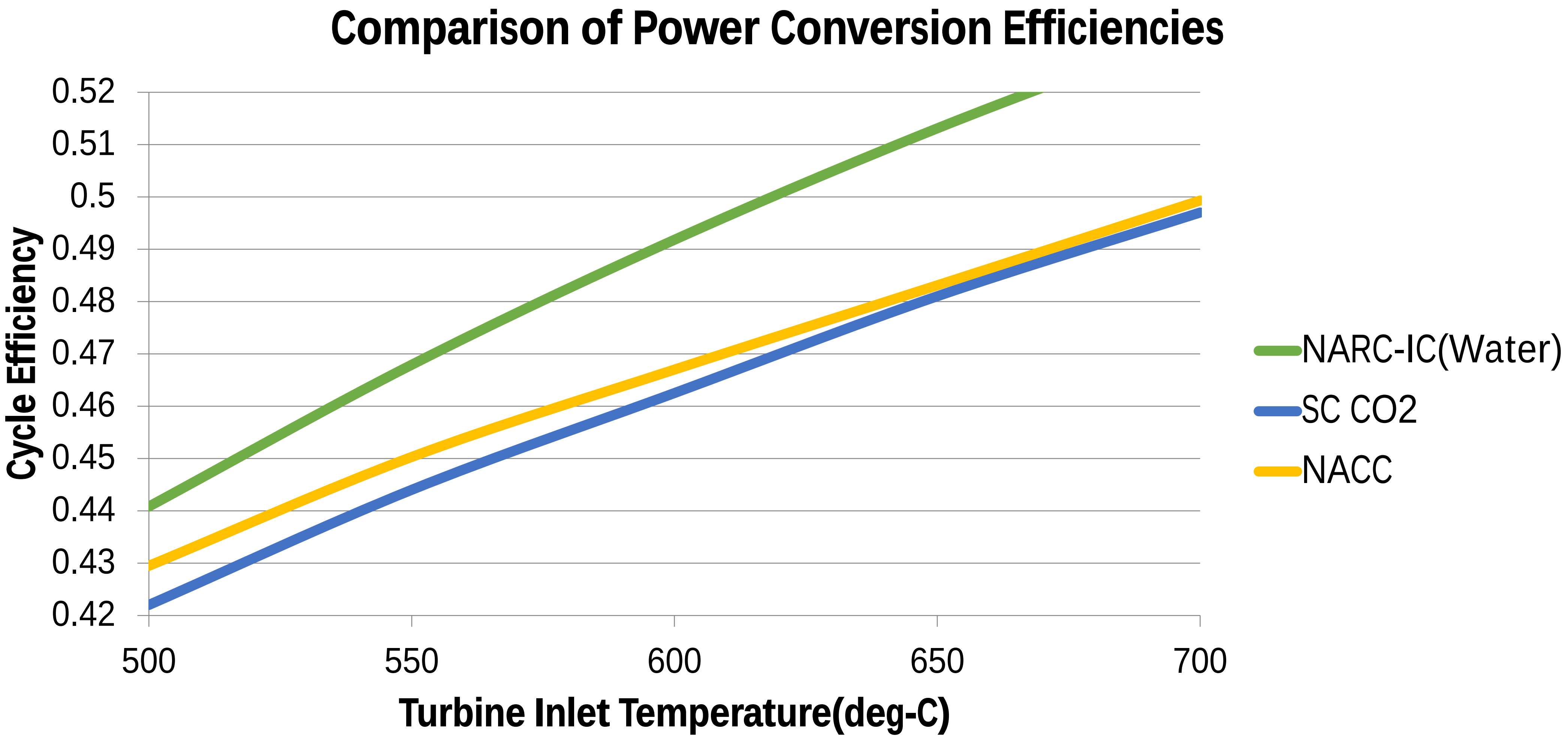
Possible Reactor Heat Sources

Generation IV Systems

- Sodium Cooled Fast Reactor
- Lead Cooled Fast Reactor
- Molten Salt Cooled Reactor
- Gas Cooled Fast Reactor
- Very High Temperature Reactor
- Super-Critical Water-Cooled Reactor

All But the Super-Critical Water-Cooled Reactor should be easily adaptable to an Air-Brayton System.

Baseline Efficiencies vs. Turbine Inlet Temperature



Advantages of NACC and NARC Systems

- NACC Systems Require Significantly Less Cooling Water

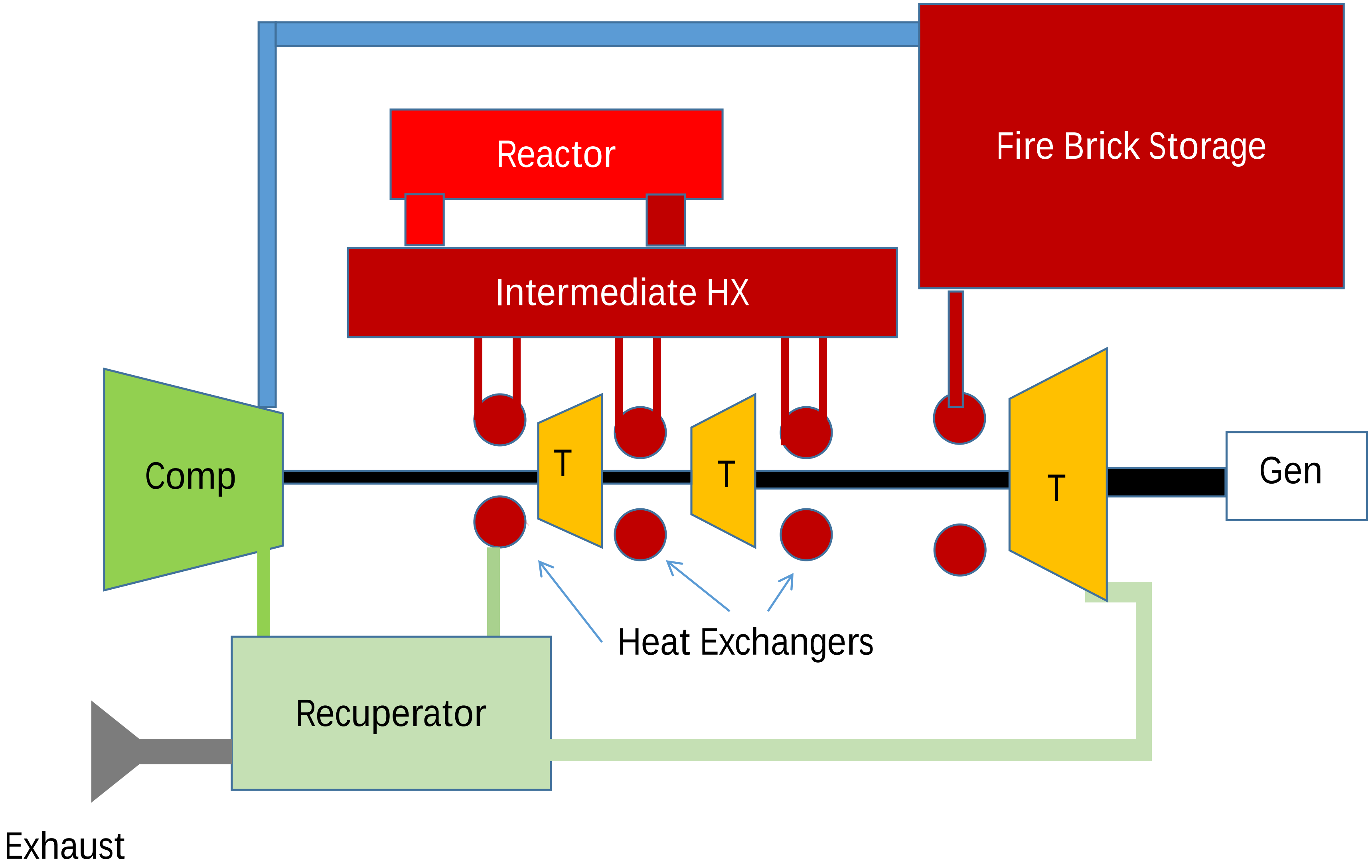
LWR at 35% Efficiency	92.9 MW(t)
NuScale at 31% Efficiency	111.3 MW(t)
Near Term LM NACC at 40.0% Efficiency	40.3 MW(t)
Advanced MS NACC at 44.5% Efficiency	25.5 MW(t)
Near Term LM IC NACC at 42.0% Efficiency	39.8 MW(t)
Advanced MS IC NACC at 45.6% Efficiency	38.4 MW(t)
Near Term LM IC NARC at 46.1% Efficiency	23.6 MW(t)
Advanced MS IC NARC at 51.1% Efficiency	18.6 MW(t)
Near Term/Advanced NARC	0.0 MW(t)

- Gas Turbine Industrial Base is Huge, Dwarfing Steam Turbine Industrial Base
- Liquid Metal/Molten Salt Heat Exchangers Operate at a few atmospheres, vs ~10 Megapascals
- Gas Turbine Maintenance Appears More Cost Competitive

Coupling to Storage Systems - Firebrick

- The most efficient system is probably the Firebrick system
- Firebrick is heated electrically to ~ 2000 K
- This can be accomplished with nuclear system electricity or excess solar electricity
- The stored heat is then recovered by passing compressed air over the Firebrick
- The heated air is mixed with the nuclear heated air and exhausted over the last air turbine
- A variable throat nozzle is required before the last turbine
- The exhaust passes to either the Heat Recovery Steam Generator or Recuperator

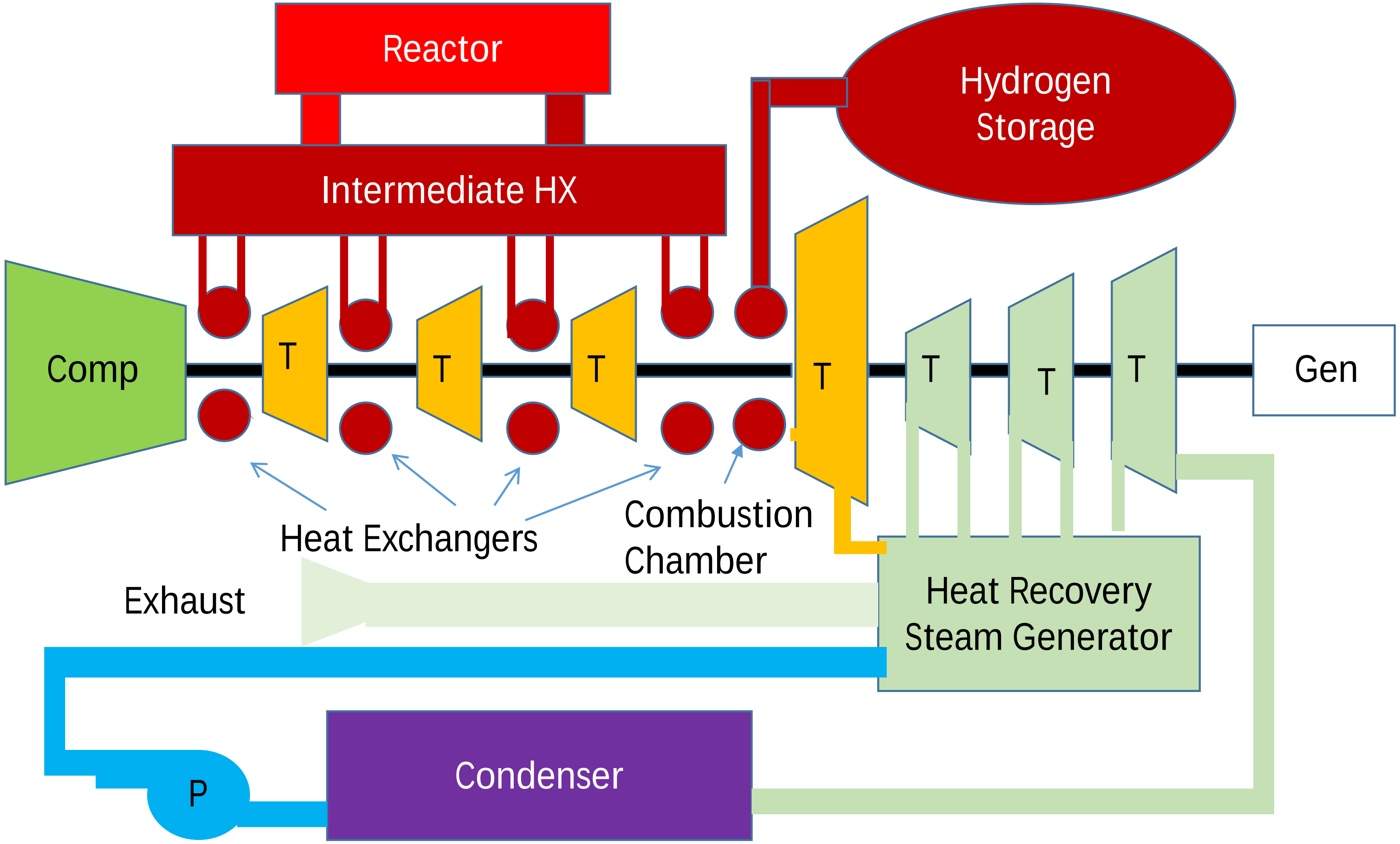
NARC System W/Firebrick Storage



Coupling to Storage Systems - Hydrogen

- Produce hydrogen by high temperature electrolysis – 60-80% efficient
- Use nuclear, excess solar, or excess wind electrical power
- Hydrogen Storage is a developed technology
  - Store hydrogen under pressure ~3000-5000 psi
  - Store at ambient temperature
- For power peaking burn hydrogen in a combustion chamber after last sodium/molten salt heat exchanger, prior to last turbine
- If we run out of hydrogen, natural gas or other suitable fuel can be substituted.

NACC System with Hydrogen Combustion



Storage Systems Pro/Con

- Firebrick Storage Systems are More Efficient, ~95-98% vs 60%-80% for Hydrogen Electrolysis.
- Producing the heat from electricity on a Multi-Megawatt Hour scale for Firebrick Systems is probably a simpler process than Hydrogen Electrolysis on that scale.
- Storage Systems are sized for the maximum time they will be needed.
  - Firebrick Storage represents a fixed installation.
  - Hydrogen storage can be added to or subtracted from fairly easily (tanks).
- Firebrick Heat Storage must be maintained at high pressure and temperature.
- Hydrogen Storage must be maintained at higher pressure but ambient temperature is okay.
- The State of the Art for Hydrogen Combustion is probably better understood than manipulating a Firebrick Store for this application.
- Production of Hydrogen has many other applications.

NACC Performance w/Storage

- Consider two levels of final turbine inlet temperature with hot gas injection or hydrogen burn - 1100 K (uncooled), 1700 K (cooled)
- Evaluate a Three Gas Turbine system

Turb 1&2 Nom Exit Temp	Turb 3 Nom Exit Temp	Turb 3 Aug Inlet Temp	Base Efficiency	Burn Efficiency	Combined Efficiency	Brayton Gain	Overall Gain
Sodium Near Term System (Normal Inlet Temperatures - 773 K)							
680.5 K	640.5 K	1100 K	32.8%	71.1%	48.4%	1.464	2.522
680.5 K	640.5 K	1700 K	32.8%	74.2%	60.4%	2.347	5.744
Molten Salt Advanced System (Normal inlet Temperature – 973 K)							
792.5 K	722.5 K	1100 K	45.5%	74.5%	51.1%	1.168	1.403
792.5 K	722.5 K	1700 K	45.5%	75.0%	61.6%	1.834	3.070

NARC Performance w/Storage

- For NARC Systems the peak augmented last turbine temperatures are driven by the output temperatureof the Recuperator to the first heat exchanger. When the Recuperator delivers air at the outlet temperature of the first heat exchanger the burn temperature can go no higher. The reactor must also be throttled back as it is no longer providing heat to the first heat exchanger.
- Evaluate a Three Gas Turbine system

Turb 1&2 Nom Exit Temp	Turb 3 Nom Exit Temp	Turb 3 Aug Inlet Temp	Base Efficiency	Burn Efficiency	Combined Efficiency	Brayton Gain	Fractional RX Power
Sodium Near Term System (Normal Inlet Temperatures - 783 K)							
765.5 K	655.5 K	958.7 K	40.9%	78.8%	47.2%	1.390	0.220
Sodium Near Term System (Normal Inlet Temperatures - 783 K, intercooled)							
748.0 k	618.0 K	1011.6 K	43.7%	83.4%	51.1%	1.447	0.285
Molten Salt Advanced System (Normal inlet Temperature – 973 K)							
922.5 K	762.5 K	1204.2 K	48.5%	81.1%	54.8%	1.409	0.203
Molten Salt Advanced System (Normal inlet Temperature – 973 K, Intercooled)							
902.5 K	722.5 K	1268.7 K	51.5%	84.7%	58.4%	1.448	0.276

Summary Conclusions

- Air-Brayton Power Conversion Systems appear feasible for Advanced Nuclear Systems.
- Air-Brayton Power Conversion Systems will require significantly less water as a heat dump, allowing more flexibility in siting.
- Air-Brayton Power Conversion Systems will allow Advanced Nuclear Systems to achieve economic performance on a grid with a high penetration of Renewable Power Sources.
- In fact Nuclear Air-Brayton Systems will be the future plants of choice for burning combustible fuels to satisfy increased demand.