Why Fast Reactors with Air-Brayton Power Cycles

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Outline

- The Problem
- Solution Components
- Implementing the Solution

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We Need a Nuclear Restart

- Nuclear generated electricity is not competitive with Gas Turbine Combined Cycle Power plants or heavily subsidized renewable systems when the sun is shining and the wind blowing.
- A zero carbon economy is not likely to save nuclear power.
- New nuclear systems need to address three major changes
  - Smaller more modular systems
  - Move from thermal spectrum reactors to fast spectrum reactors
  - Transition power conversion systems from high pressure water systems to low pressure Air-Brayton systems

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Smaller More Modular Systems

- LWR systems have focused on ~1 Gigawatt systems based on a supposed “Economy of Scale”.
- “Economy of Scale” is based on the simple notion that as we make something bigger the ratio of included volume to surface area increases. However if the most expensive part of the system is the volume component (nuclear reactor and fuel), this becomes a weak argument.
- The only economy of scale that the current LWR fleet has exhibited has been the location of multiple units on one site.
- Building reactor power plants at the 1 Gigawatt level requires a very large utility and an intermittent construction sequence. The team is assembled to build the power plant and when it is finished, everyone goes home for 10+ years. This greatly inhibits any learning curve economies. Almost every nuclear plant starts over from scratch. Licensing has been unique for each plant.
- Power station islands can only handle a few 1 Gigawatt plants based on required local load and available cooling resources.
- Loss of 1 Gigawatt for refueling outages or maintenance events can have a big impact.
- Small Modular plants can overcome most of these liabilities by locating multiple plants on one site, maintaining a production facility that matches the growth in demand for electricity, forcing most of the plant to look similar, and phasing the refueling intervals.

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Transition to Fast Spectrum Reactors

- The impact of high penetration of renewables into the electricity production market demands that reactor power stations will need to change power levels on a diurnal cycle.
- Fast spectrum reactors are more capable of changing power levels if for no other reason than the xenon poisoning problem in LWRs.
- Fast spectrum reactors can achieve significantly higher conversion ratios than thermal reactors and thus will use the uranium resource better, and produce less high level waste per gigawatt-hour of electricity.
- Fast reactor spent fuel will contain a much smaller spontaneous neutron source easing the handling/storage problem and possible recycle.
- Fast reactors tend to be smaller and probably more “shippable” than LWR-like small modular reactors.

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High Penetration of Renewables Dramatically Changes the Demand Curve

- The intermittency of renewable electrical energy generators cries out for coupling all power plants to an energy storage system.
- 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

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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.

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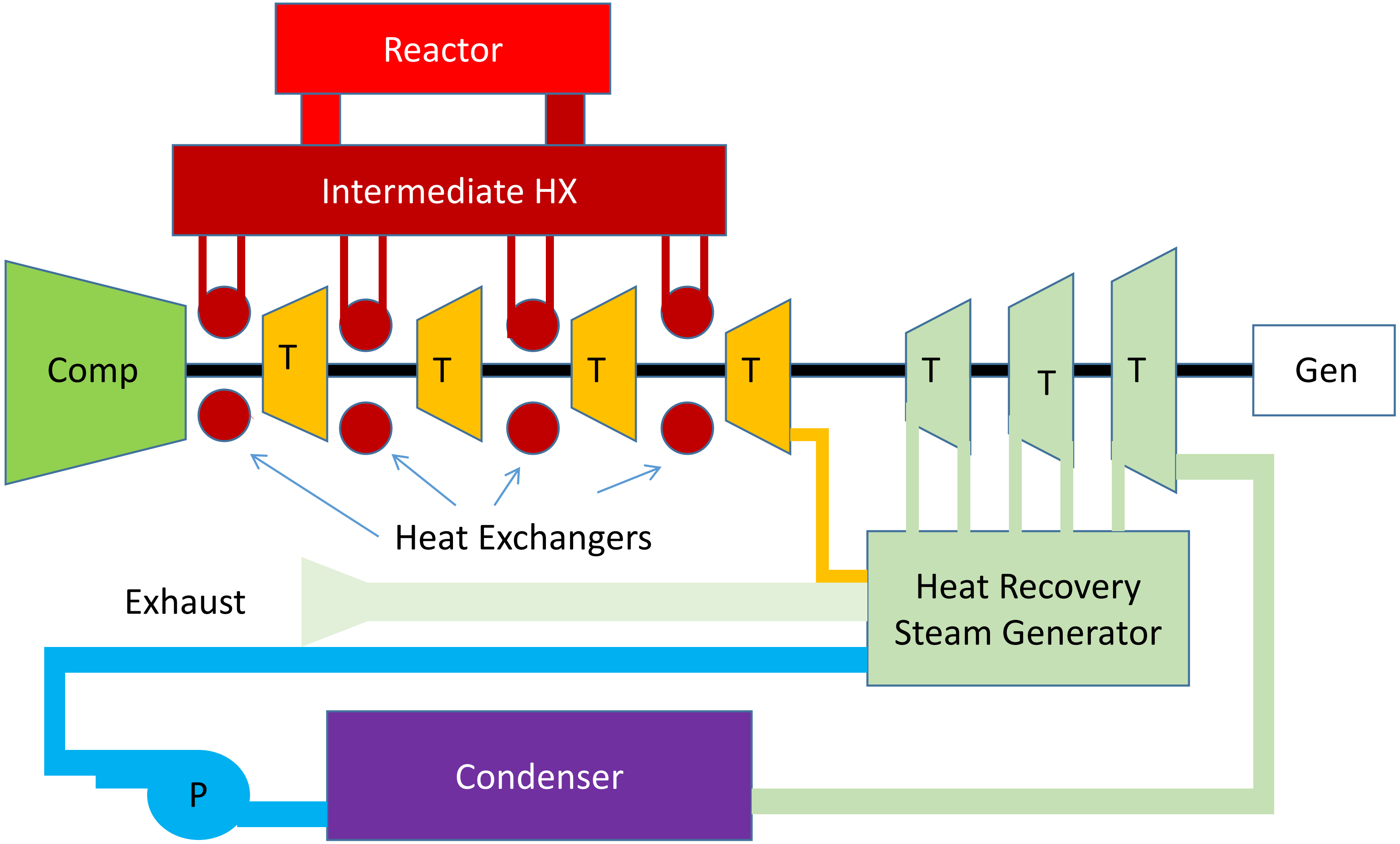
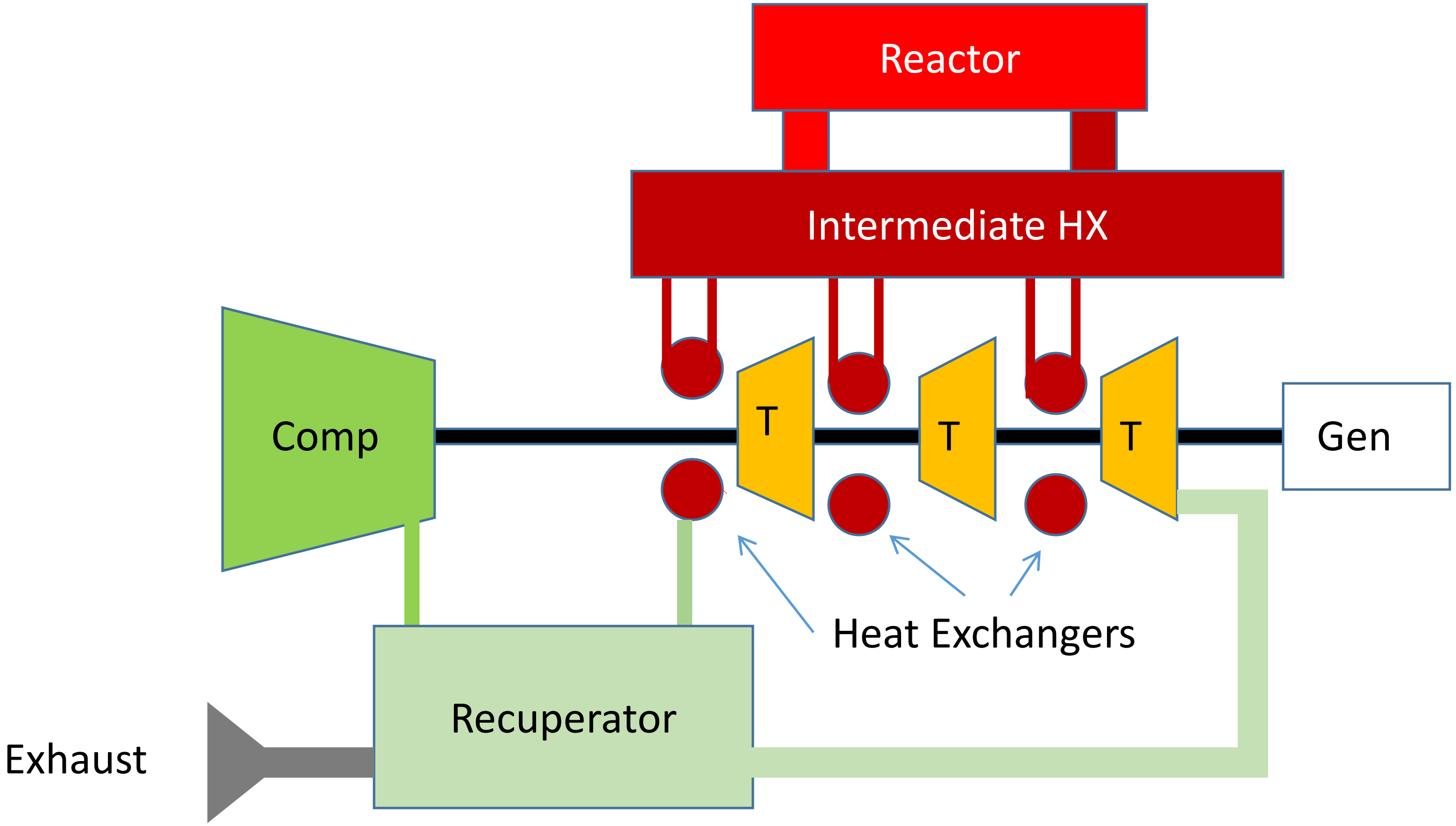
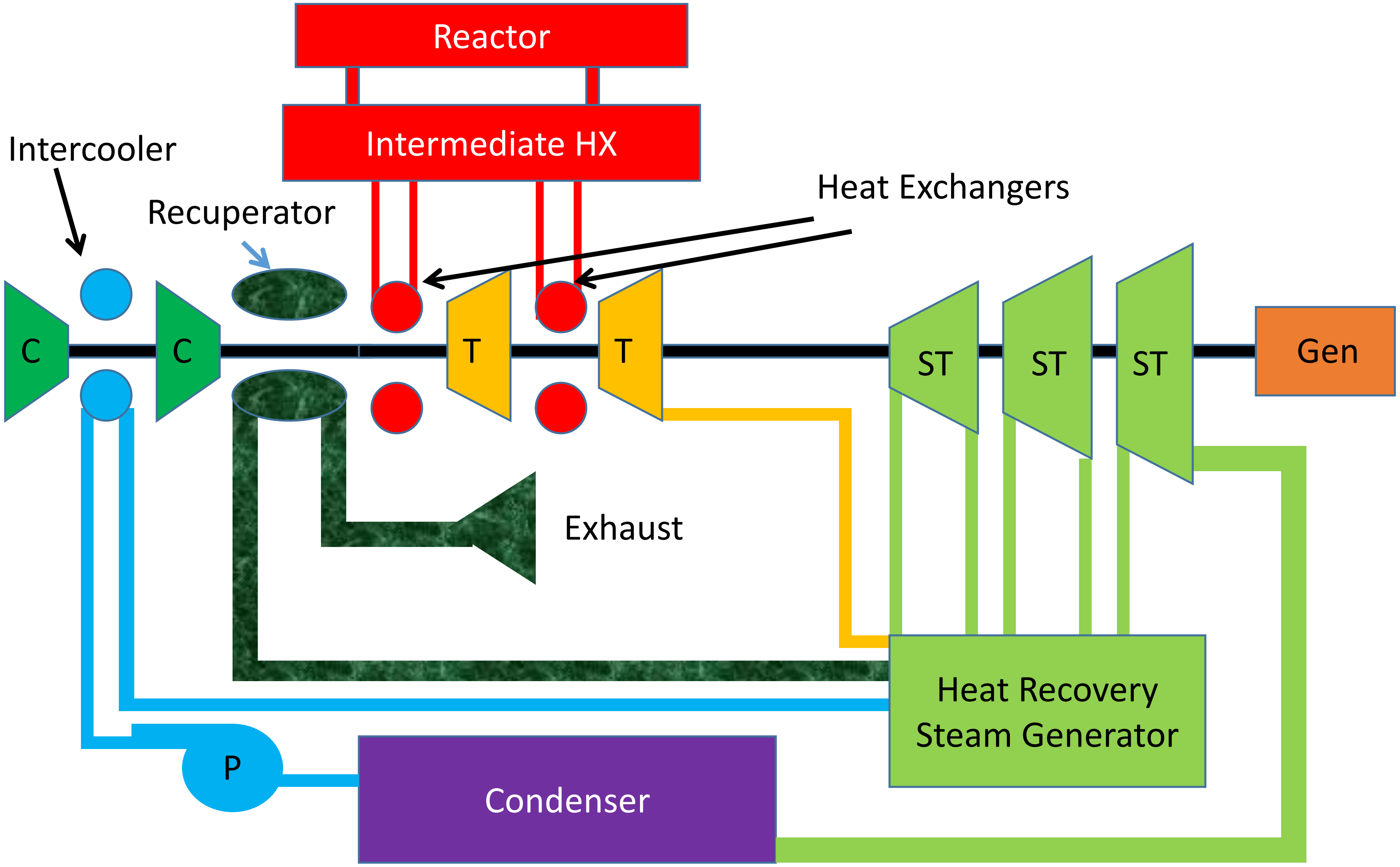
Typical NACC System Layout (4T)



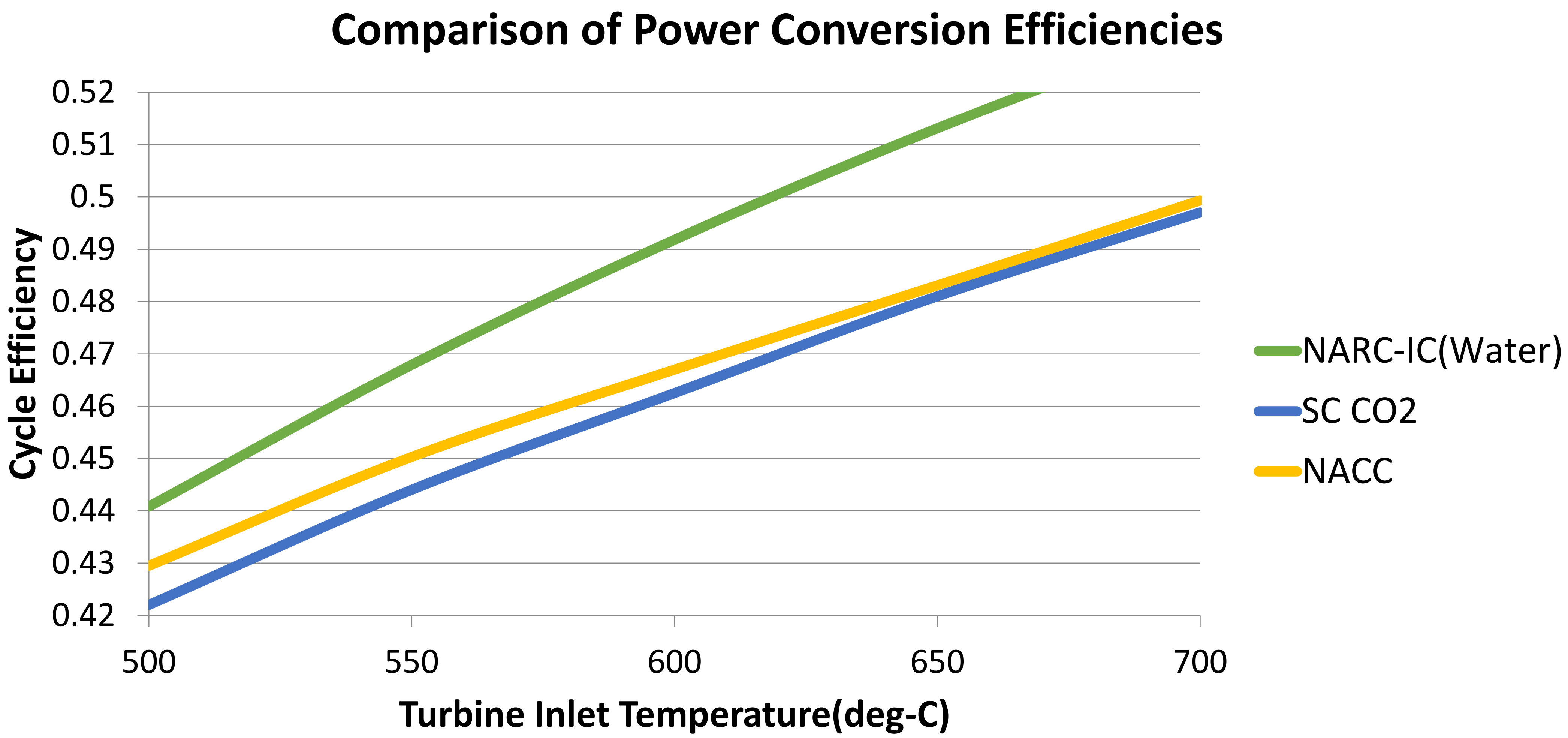
Typical NARC System Layout(3T)



NACC w/Recuperator and Intercooler



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

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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

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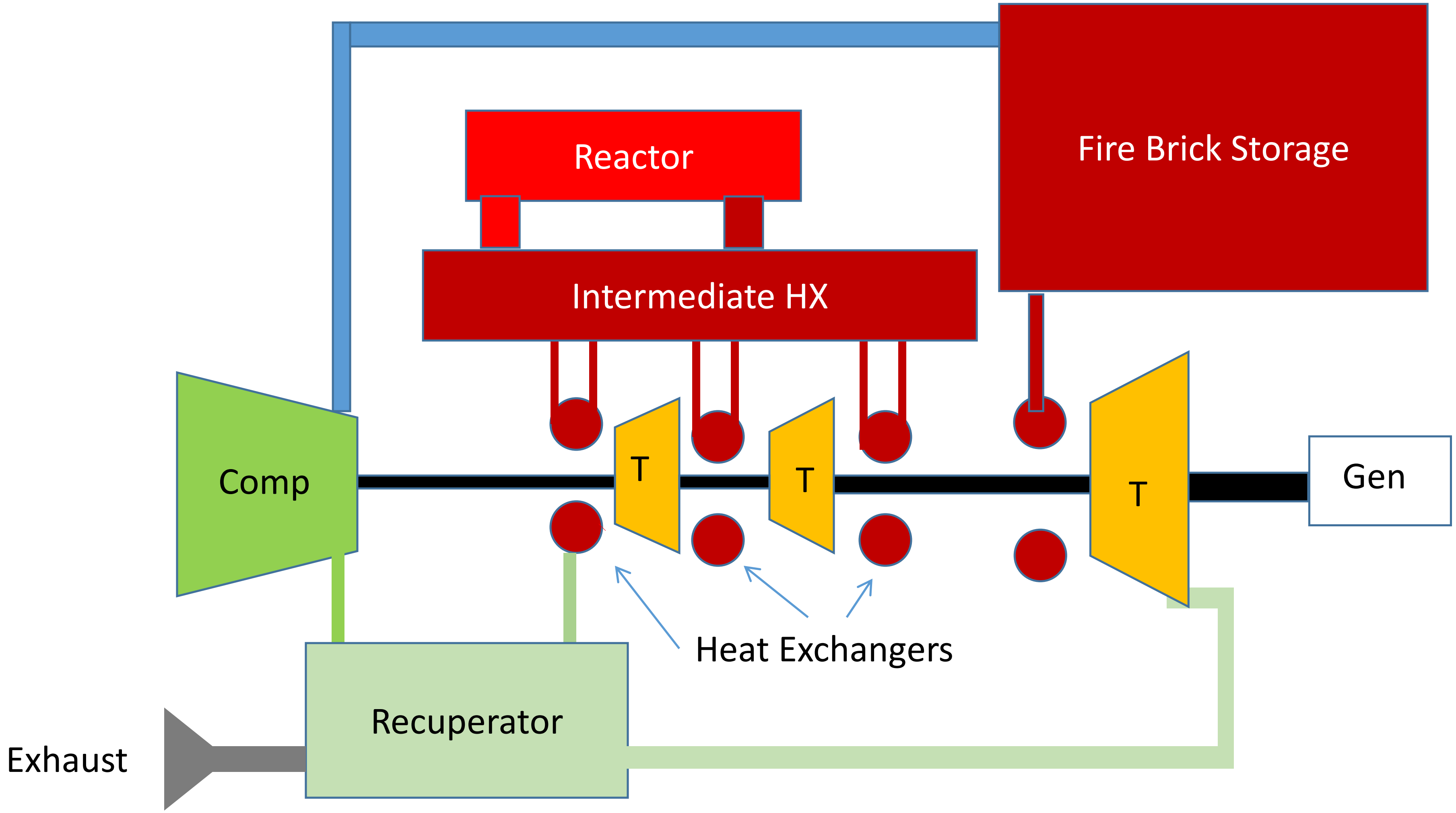
NARC System W/Firebrick Storage



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.
- Excess hydrogen production can be marketed to other industries and possible fuel cell transportation systems.

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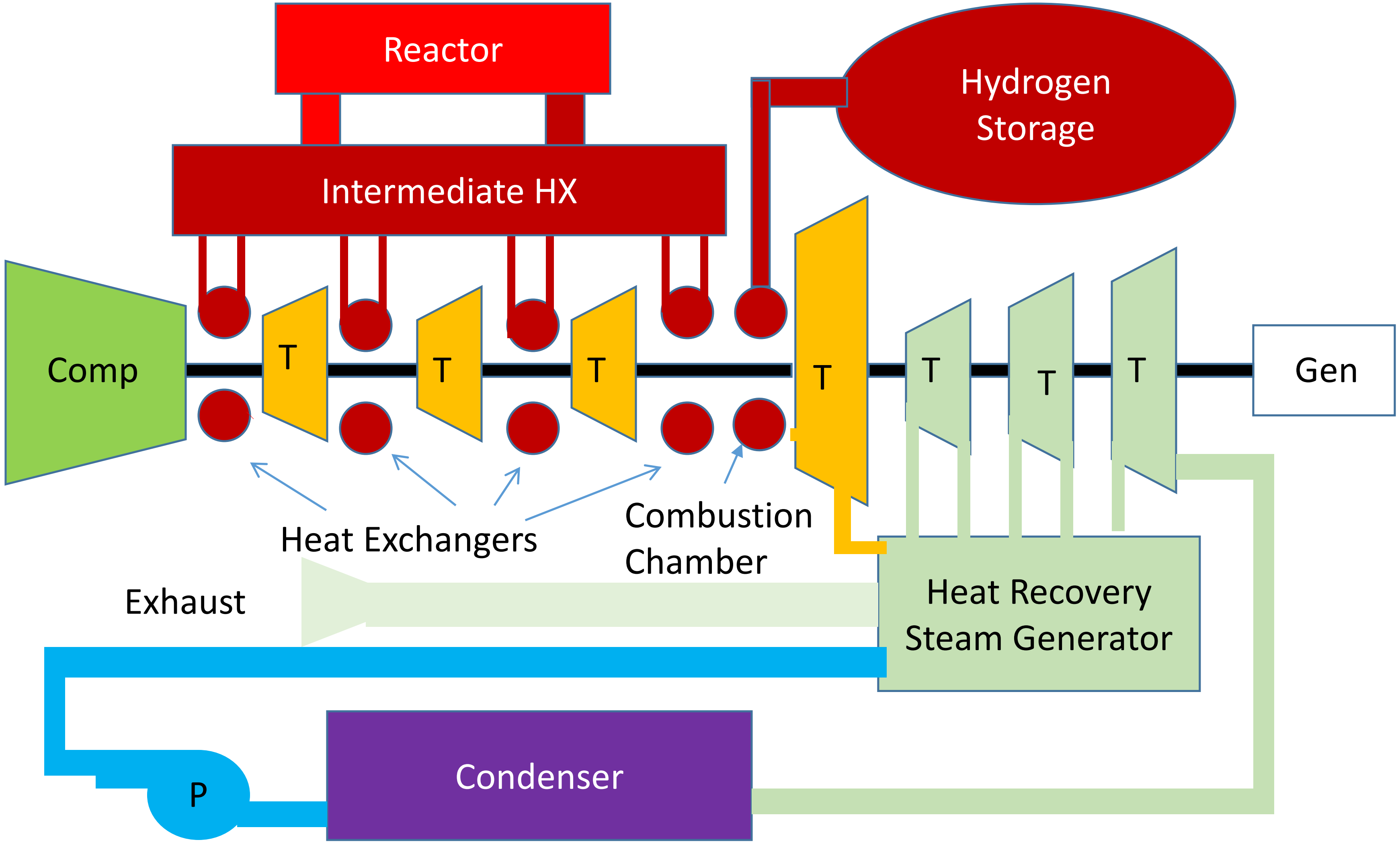
NACC System with Hydrogen Combustion



Storage Systems Pro/Con

- Firebrick systems are probably cheaper, more efficient, and safer.
- Recent experience with firebrick recuperators is not extensive but the concept and technology is not new.
- Turn on and turn off will need some simulation to achieve an optimal approach.
- Firebrick systems tend to be designed for a fixed size.
- Hydrogen systems have strong knowledge base. Utilities have experience with hydrogen cooled generators.
- Initiating and terminating combustion is a well understood process.
- Hydrogen systems are easily expandable and there are other markets for hydrogen.
- Initial calculations at 3000 psi for hydrogen storage indicate a 2 to 1 volume ratio for hydrogen to firebrick systems.

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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

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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

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Summary Conclusions

- Small modular reactors have number of advantages over current LWRs that should make nuclear systems more cost competitive.
- Fast reactor systems have a number of significant advantages in future energy markets.
- Nuclear Air-Brayton power conversion systems can adapt to the highly penetrated renewable energy market and present some significant advantages over pure steam systems.
- NACC and NARC systems may compete well with gas turbine systems with regard to incremental efficiency to burn hydrogen or natural gas when augmented power is required.

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Extra Slides

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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.

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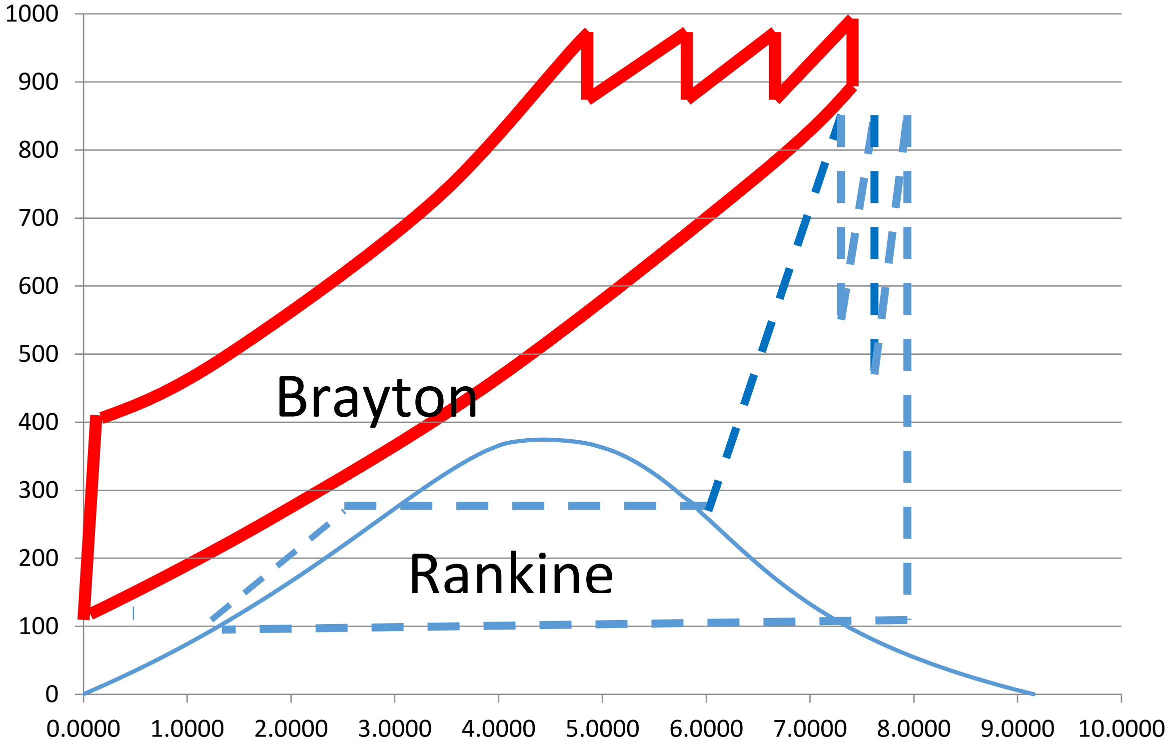
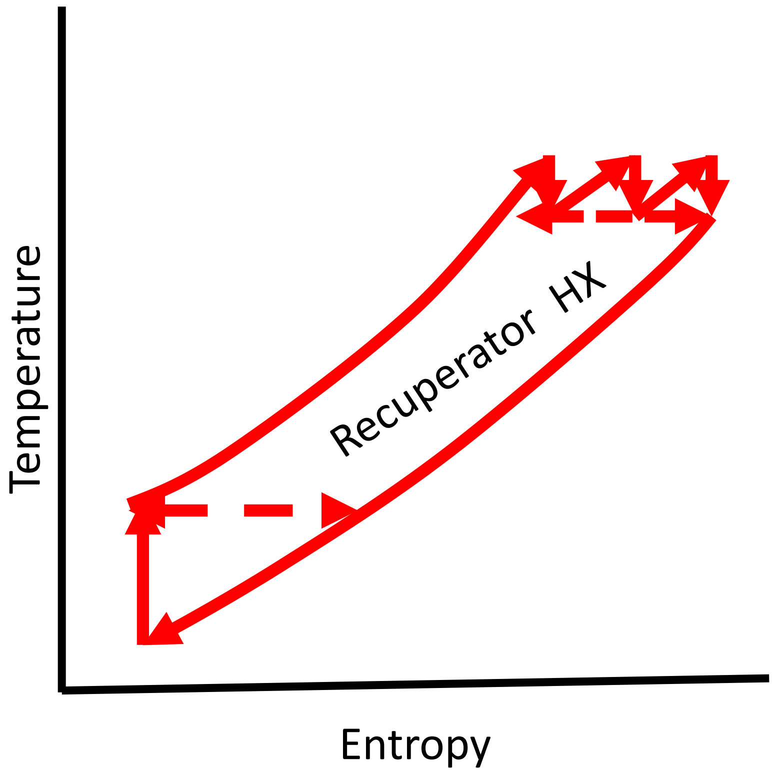
Thermodynamic Cycle Diagrams



NACC System



NARC System

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