

Power Conversion Options and Solutions for LFTR & MSR's

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Outline

- What is a Heat Engine?
- Market Demands/Cal ISO Duck
- Options
- Desirable attributes of a heat engine
- Comparisons
- Recommendations
- Questions

What is a heat engine

- An assembly of equipment designed to convert thermal energy into mechanical work

A few words on philosophy

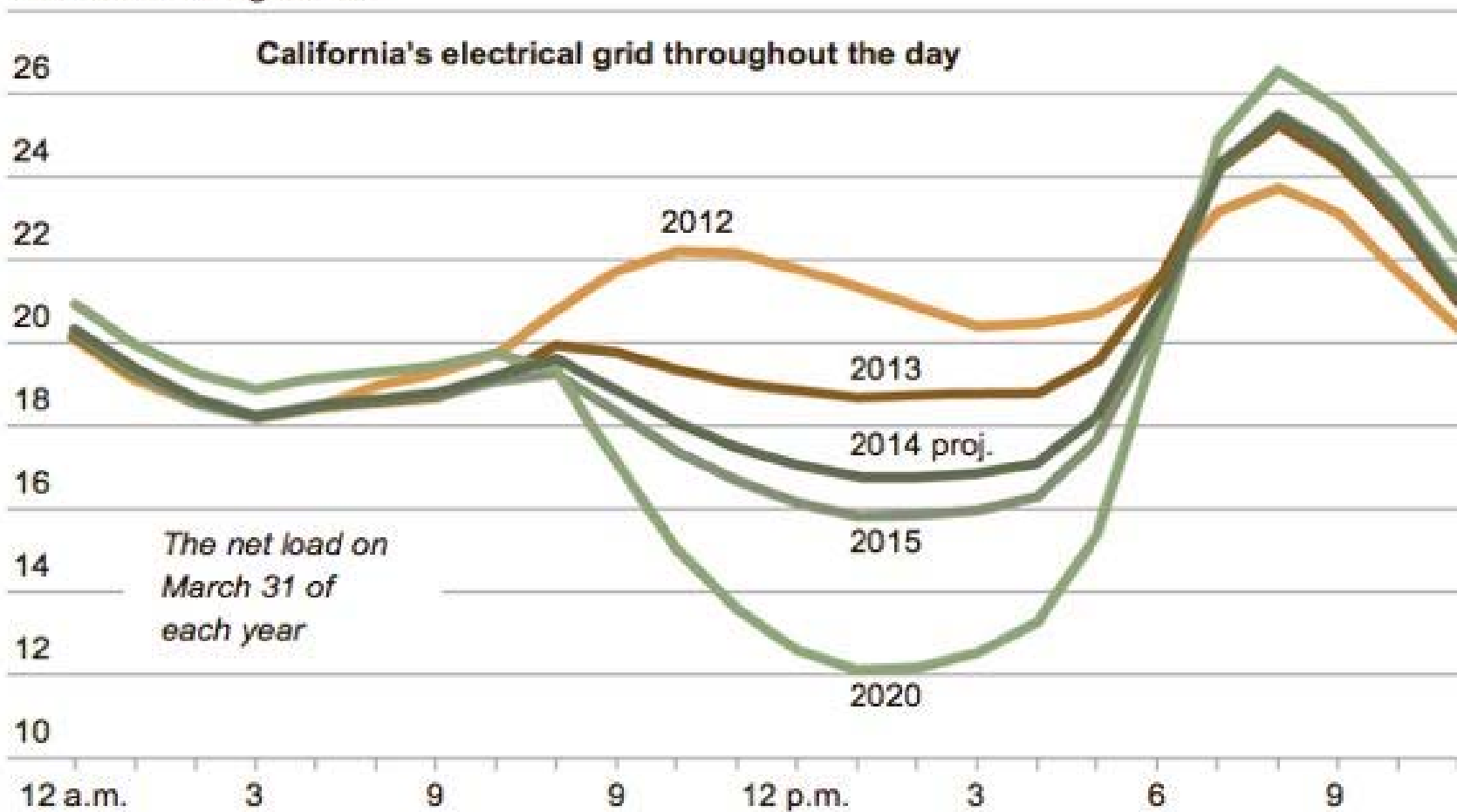
- The power conversion system must serve the nuclear system
- Generation Solutions has targeted some power conversion system solutions that exceed today's requirements, why?
- To make it hard to say no to LFTR/MSR based on quasitechnical reasons

Market Demands

- Accommodation of renewables
- Fast ramp rates up and down
- Peaking by storage or gas firing has value
- Introducing the Cal ISO Duck
- This is what you get with large scale solar

Cal ISO Duck

28 thousand megawatts



Source: CalISO

Living with the Cal ISO Duck

- Fast ramp rates
- A lot more spinning and regulating reserve
- More fast response peaking power needed
- LFTR/MSR can play a part
 - MS thermal storage a 50% LF can follow the Cal ISO Duck in 2020
 - Cofiring natural gas - UCB NACC FHR proposal is a good example providing spinning reserve and peaking service on demand while being very efficient with the use of fuel

Living with the Cal ISO Duck – GSL Work

- 10%-20%/min ramp rates
- 10 minute notice gas cofiring up to +30% of nuclear MCR
- 30% peaking is not enough to satisfy the Duck in 2020, but it is very helpful and can run continuously
- Options
 - Black start and support of grid restoration
 - Trip to house load with indefinite idle
 - Cofired option has segregation between GTG and STG providing high levels of fault tolerance

Heat Engine Options

- Steam turbine (Rankine Cycle)
- Open cycle gas turbine (Brayton Cycle)
- Closed cycle Brayton
 - SC-CO₂
 - Simple helium
 - Multi reheat, recuperated and intercooled
- Combined Cycle, Brayton and Rankine together
- Exotic creatures
 - Binary mercury/steam
 - Boiling aluminium chloride
 - Air-breathing hybrid CCGT
 - Air-breathing open cycle Brayton

Desirable Heat Engine Characteristics

- Safe
- Efficient – thermodynamically, financially and in the use of all resources
- Reliable
- High availability
- Robust – fault tolerant
- Low maintenance and easy to maintain
- Cheap – low first cost
- Diversity of supply – multiple vendors

Heat Engine Characteristics continued

- Flexible – load following, ramping, peaking
- Scalable – works well in a range of sizes
- Adaptable – can be upgraded/updated
- Must be sympathetic to the nuclear island
- Environmentally benign during all stages of its life cycle

Helium Brayton Cycles

- Can use high temperature heat sources efficiently
- Higher temperatures enables higher efficiencies
- Up to 54% at 900C for triple pressure recuperated and intercooled helium Brayton as a closed loop cycle
- Not used commercially
- Largest example Oberhausen II 50 MW
- More stages (blade rows) than normal GT's
- Multiple configurations, (1c/1t, 2c/1t) x 1, 2 or 3 expansion steps

Helium Brayton – A Benchmark

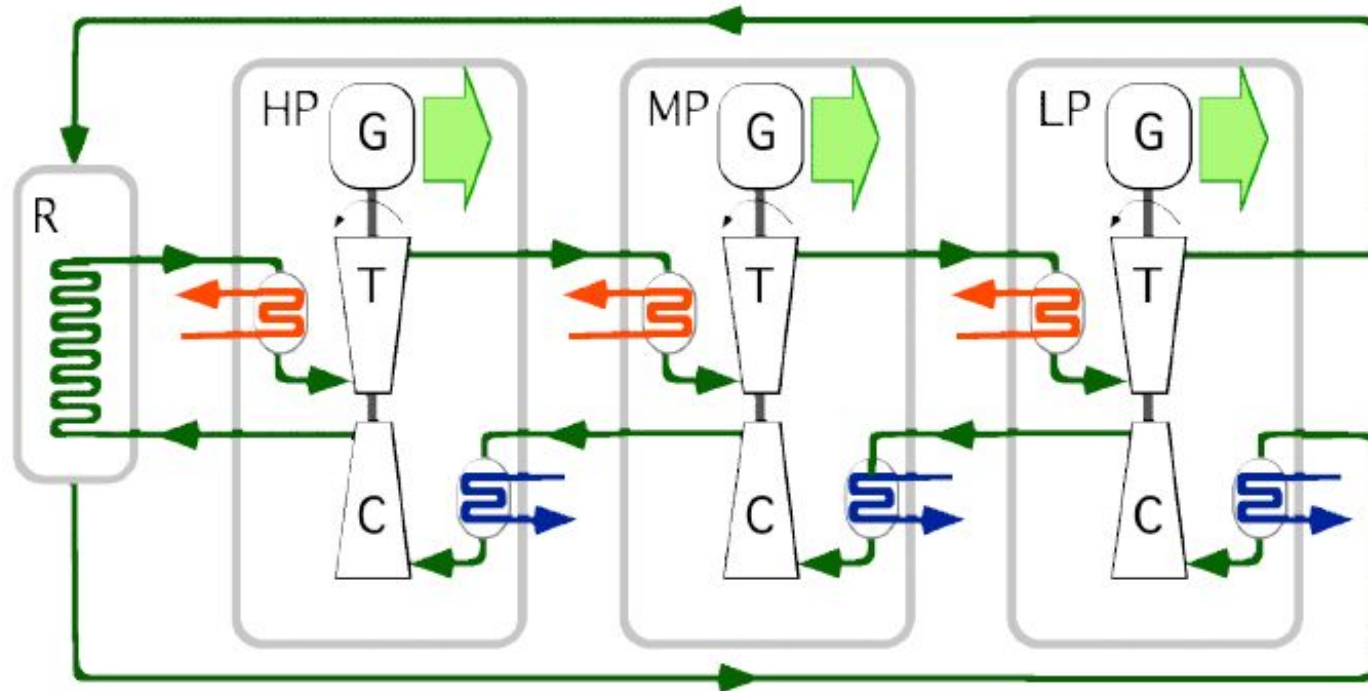


Fig. 2 Schematic flow diagram for the reference three-expansion-stage MCGC, using three PCU modules (HP, MP, and LP) each containing a generator (G), turbine (T), compressor (C), and heater and cooler heat exchangers, with a recuperator (R) located in a fourth vessel.

Reference: Zhao and Peterson 2004,
A Reference 2400 MW(t) Power Conversion System Point Design for Molten-Salt-Cooled Fission and Fusion Energy Systems

Helium Brayton – A Real Machine (286 MW)

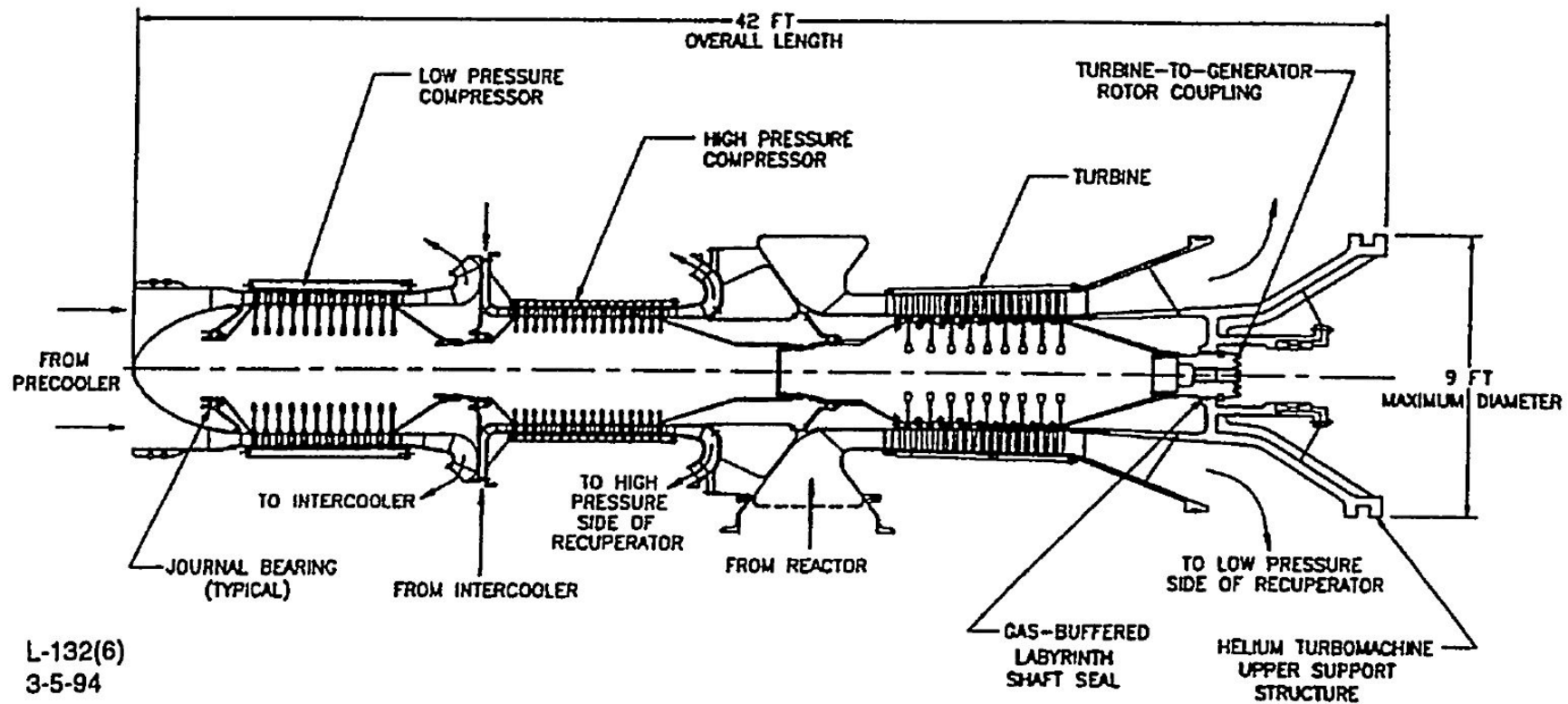


FIG. 7. HELIUM TURBOCOMPRESSOR LAYOUT

Reference: McDonald 1994,
Helium Turbomachine Design for GT-MHR Power Plant

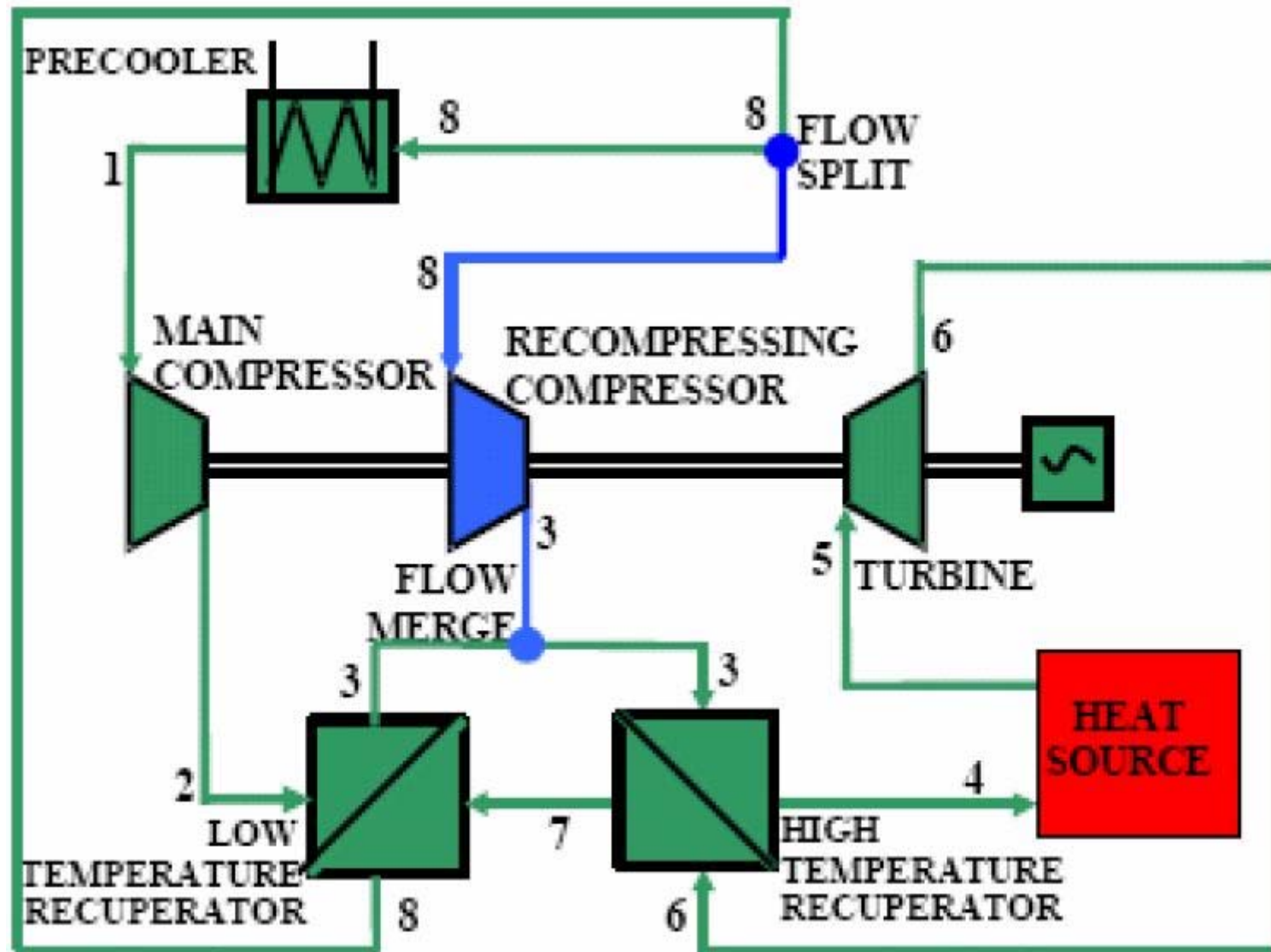
Helium Brayton Cycles

- Advantages
 - Relatively compact
 - Efficient
 - Adaptable to dry cooling and desalination duty with little if any efficiency penalty
- Disadvantages
 - Reasonably high peak pressure (~ 70 bar) coincident with peak temperature
 - Helium prone to leaking especially at hi temp & press
 - High rotational speed, often greater than 3600 rpm
 - General lack of experience with helium turbomachinery, nothing 'off the shelf'
 - Conflict between optimal PR and return temperature

Supercritical CO₂ Brayton Cycles

- Taking advantage of lower compression work when working close to the critical temperature of CO₂
- High peak pressure (120-200 bar) coincident with peak temperature
- Extremely compact turbomachinery
- High speed turbomachinery
- Efficiency advantage at moderate temperature
- Efficiency not as good as helium Brayton at high temperatures
- Requires a good recuperator, low temp heat sink

Supercritical CO₂ Brayton Cycles



Supercritical CO₂ Brayton Cycles

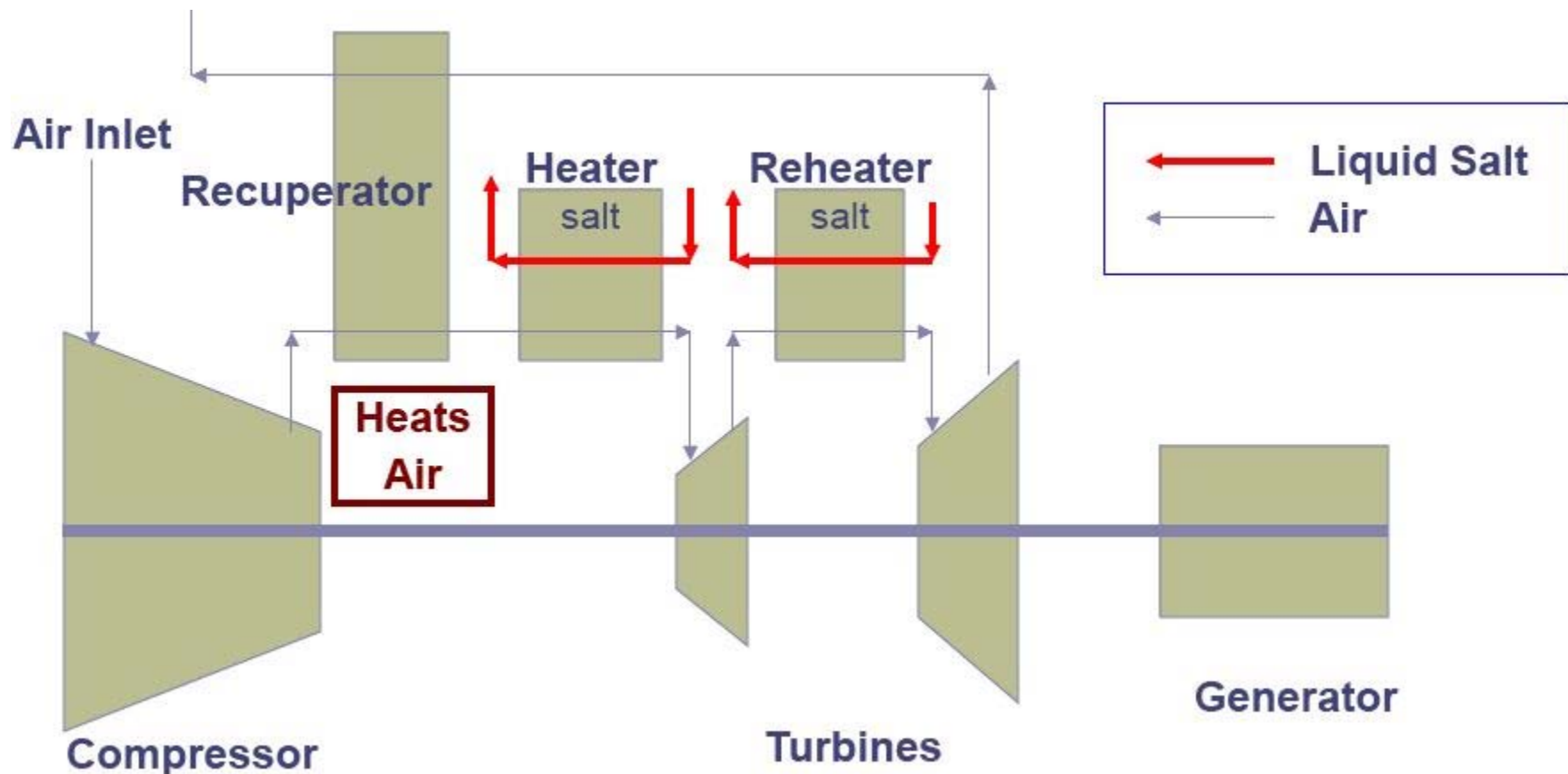
- Challenges
 - High pressure – HX material strength (creep)
 - Compact size – Tip clearances an issue
 - Compact size – Strength of turbine
 - High speed – High speed reduction gearboxes
 - Does not seem to work so well above 850C

Exotic Creatures

- Boiling Aluminium Chloride
 - No serious work done on this
- Mercury/Water Binary
 - Experimental prototype built
 - Mercury leaks a challenge
 - Mercury highly toxic, no longer acceptable
- Combined Cycle with Nuclear Cofiring
 - Low cost, high efficiency (50-60%)
 - Potential Hybrid with nuclear heat
 - Tension between high eff and nuclear heat use

Exotic Creatures

- Air-breathing Brayton ($\sim 40\%$ Eff at 700°C)
- A good option for water free applications



Air-breathing Brayton

- High integrity heating loop must be completely free from radioactive materials
- Not off the shelf exactly but it may be possible to build Frankenstein's baby by scavenging bits from other GT's and adapting
 - Power turbine from an existing model
 - An industrial GT with a modified turbine section as the gas generator
 - Alstom GT24/GT26 (a commercial reheat GT) but wrong pressure ratio

Old Faithful – The Steam Turbine

- Any size you like from 5 kW to 1600 MW
- Efficiencies of large STG's are greater than many people realise, up to ~50% net for power conversion system
- Biggest challenge is salt freeze in HX
- Not expensive – Flammannville €200/kW

Steam Turbine

- Very reliable
- Long service intervals (~4 years)
- Very familiar for Utility Executives
- Multiple vendors
- Competitive procurement process
- Nothing new or fancy
- Performs best with low temperature heat sink

Steam Turbine

- Disadvantages

- Temperature limited to 600C/620C at the moment
- Requires 8 stages of feedwater heating for best efficiency
- Can consume a lot of cooling water
- Reliant on a safe durable salt driven steam generator that is freeze resistant and can recover from salt freeze

Comparative Evaluation

- SC-CO₂
 - Efficient at intermediate temperatures
 - Compact
 - Still in development
 - Extreme compactness will be punishing on tip clearances and possibly mechanical strength

Comparative Evaluation

- Triple Pressure Helium Brayton
 - Efficient
 - Compact
 - No large units built yet
 - Keeping the system gas tight is challenging
 - Very heat sink friendly and ideal partner for desalination, district heating and similar apps

Comparative Evaluation

- Combined Cycle with Nuclear Cofiring
 - Cheap turbo machinery
 - Still burning fossil fuels (36 – 47%)
 - More complex
 - More failure modes
 - May have operational limitations

Comparative Evaluation

- Air-breathing Brayton
 - Definitely has potential
 - May be a very good partner for SmAHTR
 - Simple and Robust
 - Acceptable efficiency
 - Nothing directly off the shelf

Comparative Evaluation

- Steam Turbine
 - Ubiquitous – they are everywhere
 - More efficient than most people think
 - Moderate operating temperatures 500-620C
 - 100% off the shelf
 - Does need a robust HX solutions

Recommendations

- The overall solution must be Duck friendly
- Look through risk corrected spectacles
- Consider the needs of your application from the top down
- Draw up some risk informed performance criteria and use them
- Evaluate the impact overall
- Remember the most economic solution is unlikely to be the most efficient

Questions