Energy Conversion

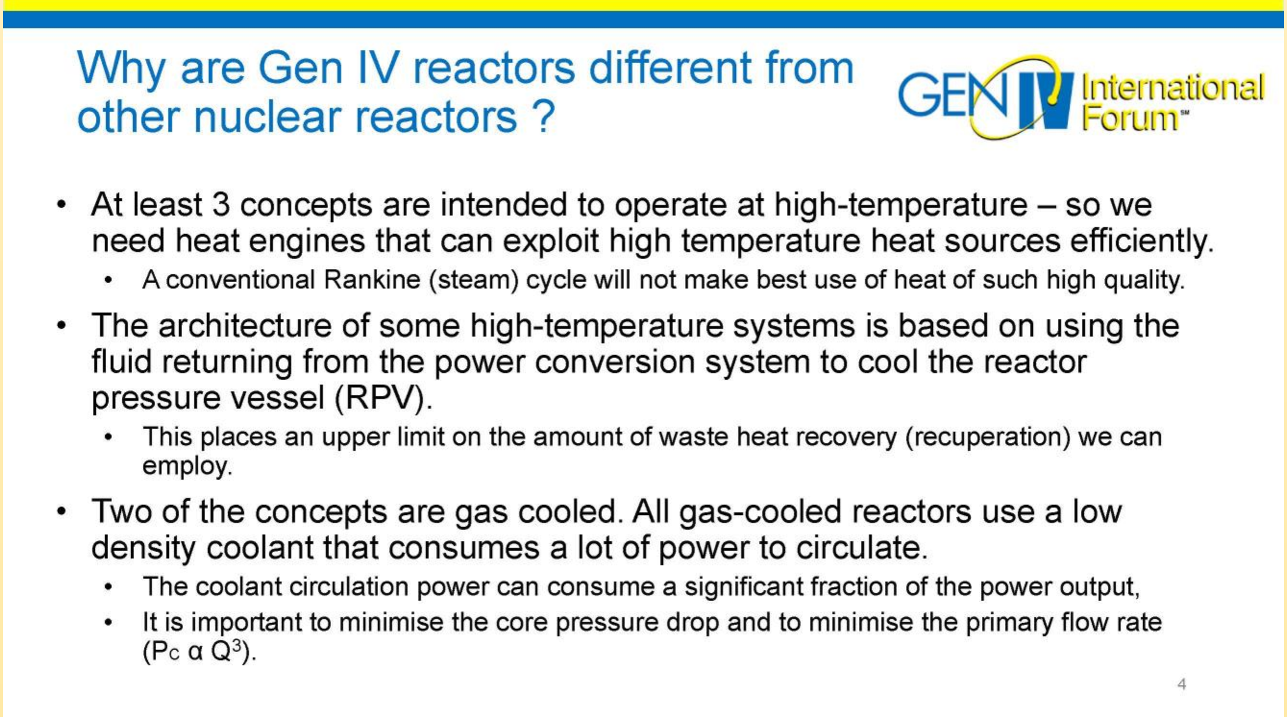
Summary / Objectives:

The rotary motion, high pressure steam engine was patented by James Watt in 1781. The evolution of steam engines and high pressure boiler technology led directly to the development of the steam turbine coupled to an electrical generator by Charles Parsons in 1884. Since then, over the last 133 years, the world has been using steam turbines to convert heat into electricity in almost all of the world's thermal power stations and in all of the world's nuclear power stations. Specifically for the latter, steam turbines and the Rankine thermodynamic cycle in which they operate offer high efficiency for moderate steam temperatures, temperatures typical of first, second and third generation nuclear reactors. Generation IV reactors offer the potential to move away from the steam Rankine cycle to systems such as helium (or nitrogen) Brayton or supercritical CO2 gas turbine cycles to exploit the higher temperatures that some of the systems generate, to offer plant simplification and potentially higher conversion efficiencies. Non-steam cycles offer other advantages, particularly in connection with the sodium cooled fast reactor, such that the risk of sodium water reactions is massively reduced. Within this webcast, the basic thermodynamics and performance limits of energy conversion systems will be explained and each of the technological options proposed for the energy conversion systems of Generation IV reactors will be presented..

Meet the Presenter:

Dr. Richard Stainsby is a mechanical engineer with a PhD in computational fluid dynamics and heat transfer. He is Chief Technologist for Advanced Reactors and Fuel Cycles at the UK's National Nuclear Laboratory, having worked both in research facilities and industry before joining NNL. He has spent the last 32 years working on light water, high temperature gas (HTGR) and liquid metal and gas fast reactors. He has worked on contracts for PBMR in South Africa on core design and whole plant simulation, for the National Nuclear Regulator, also in South Africa, and for the USNTRC on the development of licensing tools for HTGRs. He is a past Chair of the GIF GFR System Steering Committee and a current Euratom member of the GIF SFR System Steering Committee. He has led two European projects (GCFR-STREP and GoFastR) on gas cooled fast reactors (GFR) and was a leader of the innovative architecture and balance of plant sub-project within the Euratom CP-ESFR project between 2009-2013.

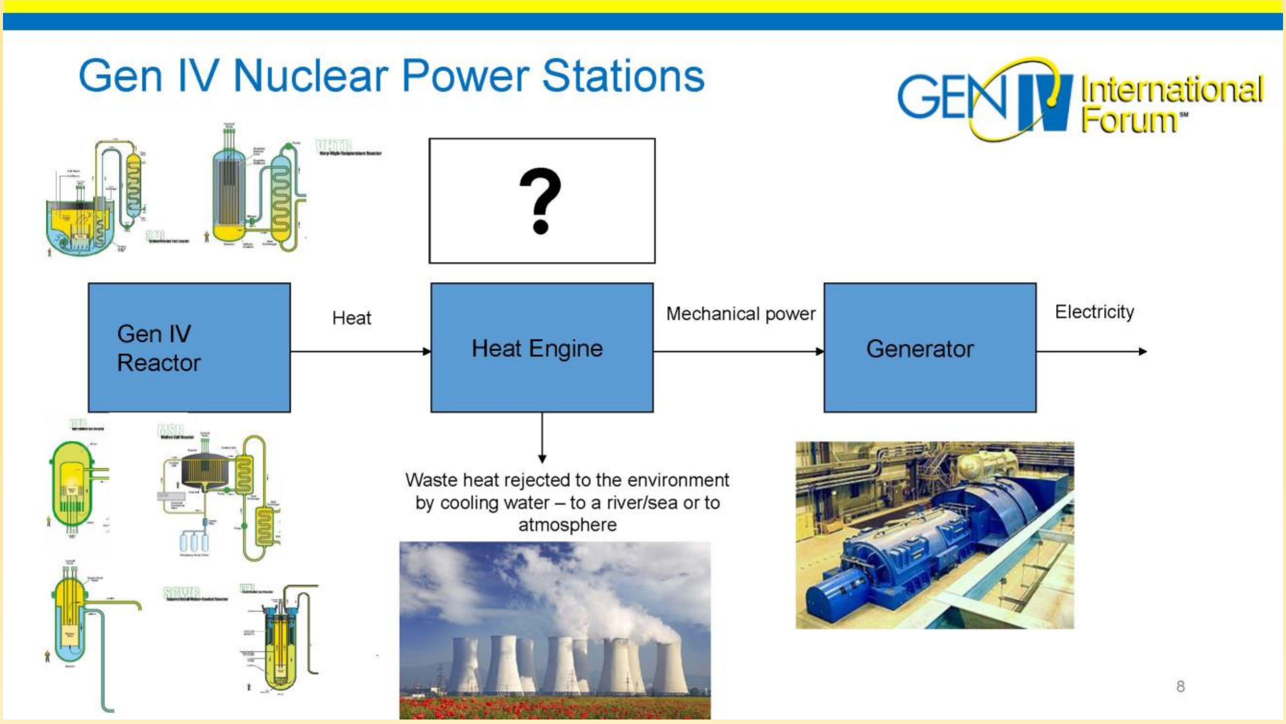
The linkage between a nuclear reactor and its power conversion system : The reactor must supply a flow of heat that is controllable and of sufficient quality to match the requirements of the power conversion system (or engine). The engine must supply a stable flow of coolant to the reactor inlet that respects its material limits and neutronic requirements. A reactor is a temperature dependent heat source not fuel flow dependent as in a fossil fueled plant.



Why are Gen IV reactors different from other nuclear reactors ?

- At least 3 concepts are intended to operate at high-temperature – so we need heat engines that can exploit high temperature heat sources efficiently.
  - A conventional Rankine (steam) cycle will not make best use of heat of such high quality.
- The architecture of some high-temperature systems is based on using the fluid returning from the power conversion system to cool the reactor pressure vessel (RPV).
  - This places an upper limit on the amount of waste heat recovery (recuperation) we can employ.
- Two of the concepts are gas cooled. All gas-cooled reactors use a low density coolant that consumes a lot of power to circulate.
  - The coolant circulation power can consume a significant fraction of the power output,
  - It is important to minimise the core pressure drop and to minimise the primary flow rate ($P_C \, \alpha \, Q^3$).

Heat engine for Gen IV reactors: There is no single optimal heat engine for all six types of Gen IV reactors. We need to consider how much mechanical power do we get for a given amount of thermal power, rejecting heat to the environment, and maximize the efficiency of the whole system.



Gen IV Nuclear Power Stations

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Gen IV Reactor

Heat

Heat Engine

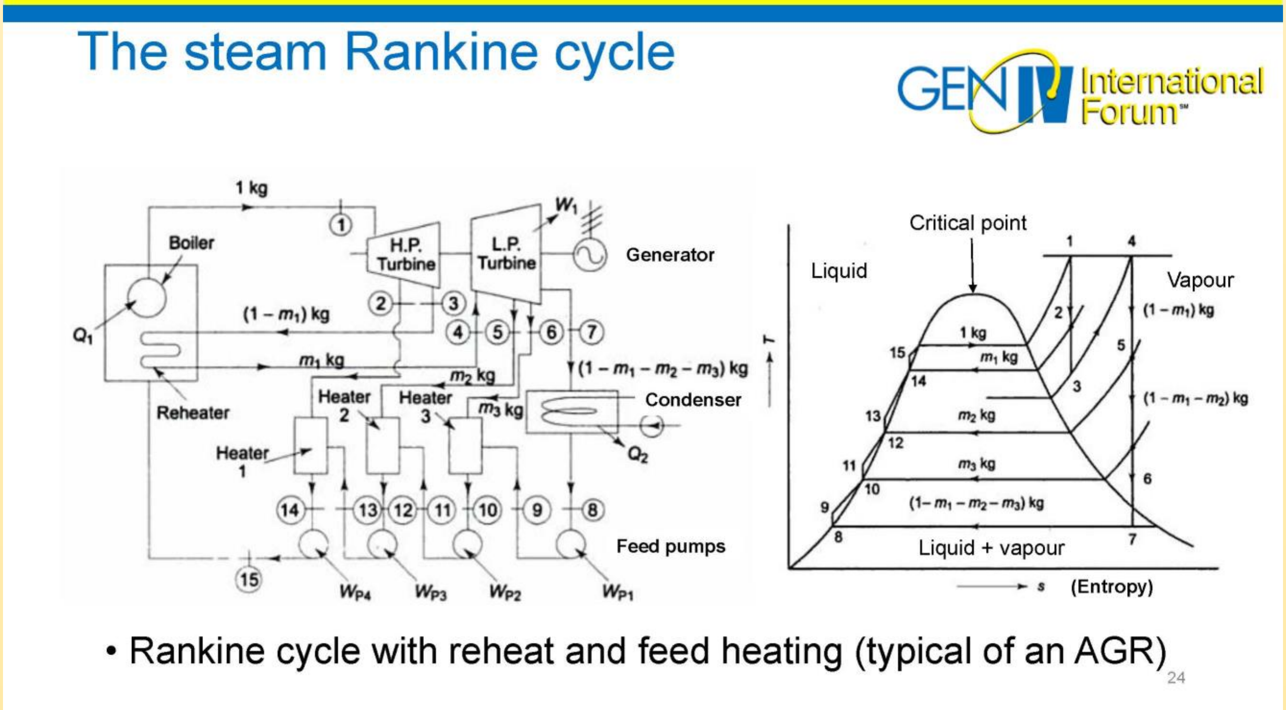
Mechanical power

Generator

Electricity

Waste heat rejected to the environment by cooling water – to a river/sea or to atmosphere

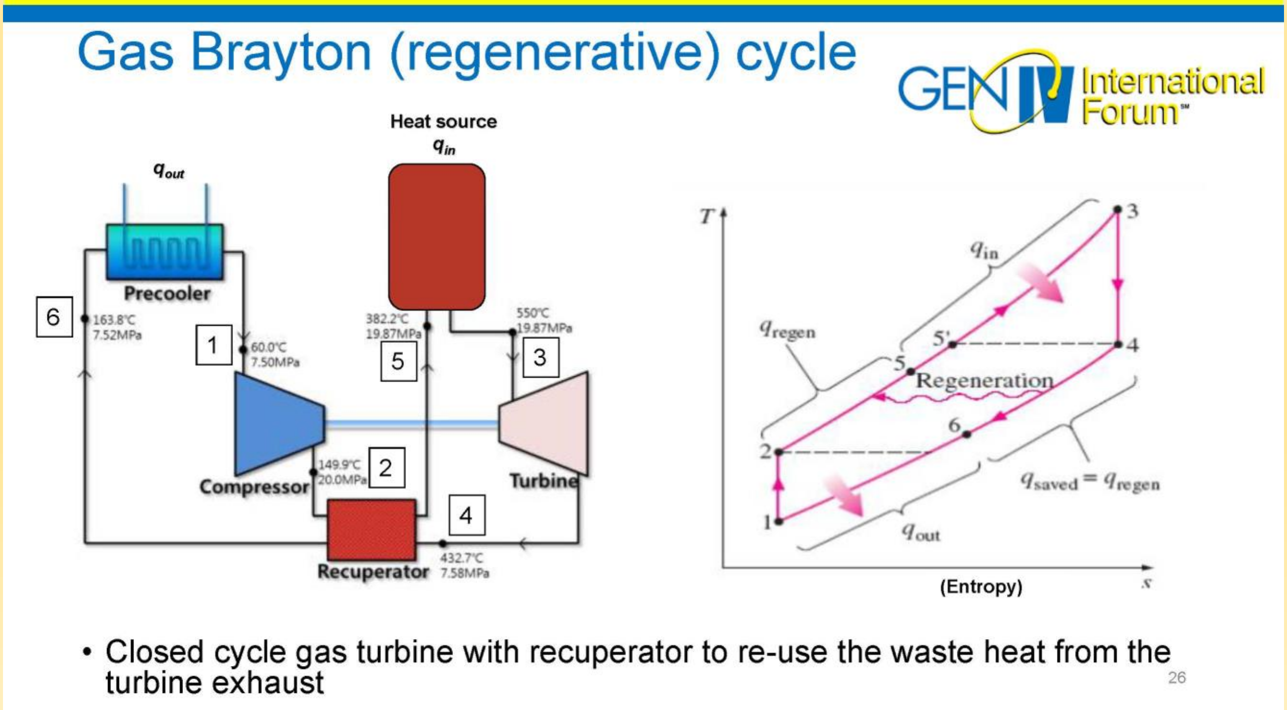
Rankine cycle: Rankine cycle is well known for over 120 years now and it is used as the way of generating electricity in the world power plant. High efficiency is achieved because of excellent work ratio and bulk of heat addition and heat rejection both occur as constant temperature processes.



The steam Rankine cycle

- Rankine cycle with reheat and feed heating (typical of an AGR)

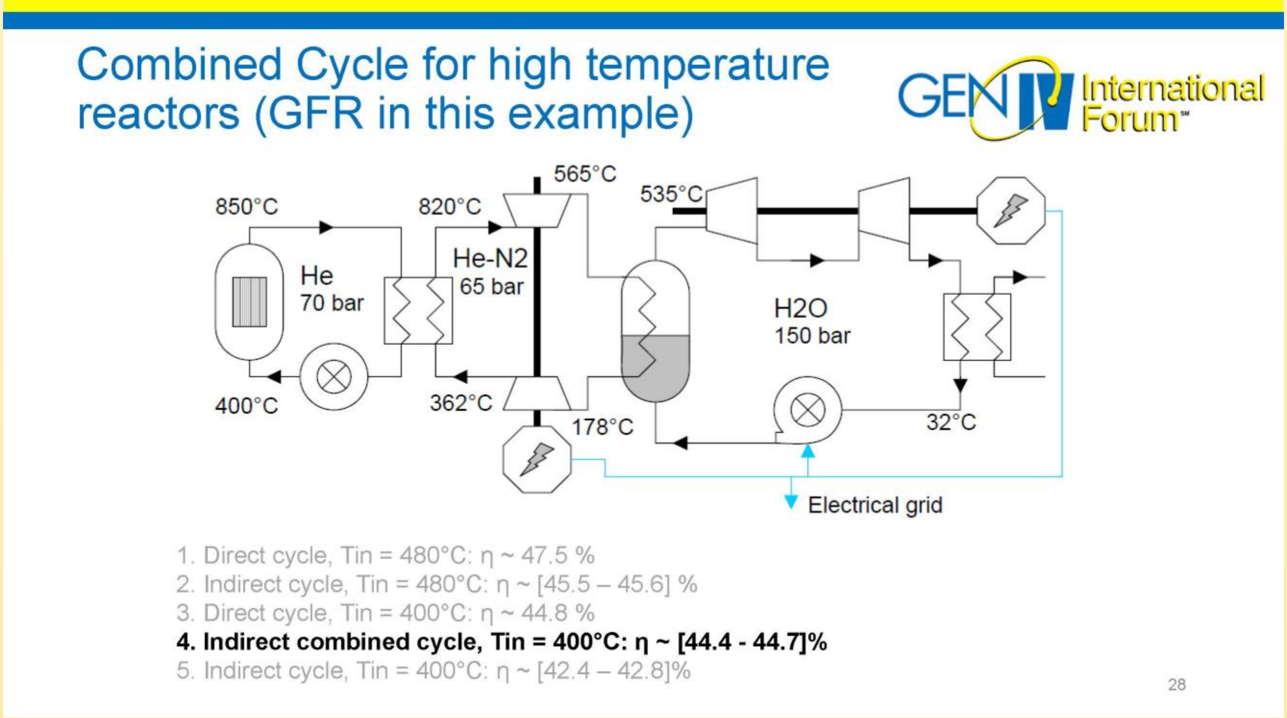
Brayton cycle: In the case of high temperature power generation, turbine technology can be applied to power generation. For a good gas turbine cycle, the difference in height between 4 and 3 should be as large as possible between 1 and 2.



Gas Brayton (regenerative) cycle

- Closed cycle gas turbine with recuperator to re-use the waste heat from the turbine exhaust

Combined cycles : Combined cycles have a good track record of use in many fossil fired CCGT power plants. Gas turbines and high-efficiency gas-to-gas recuperators are expensive. On the other hand, steam turbines are cheap and heat recovery steam generators are a low-risk technology.



Combined Cycle for high temperature reactors (GFR in this example)

1. Direct cycle, Tin = 480°C: η ~ 47.5 %
2. Indirect cycle, Tin = 480°C: η ~ [45.5 – 45.6] %
3. Direct cycle, Tin = 400°C: η ~ 44.8 %
4. **Indirect combined cycle, Tin = 400°C: η ~ [44.4 - 44.7]%**
5. Indirect cycle, Tin = 400°C: η ~ [42.4 – 42.8]%

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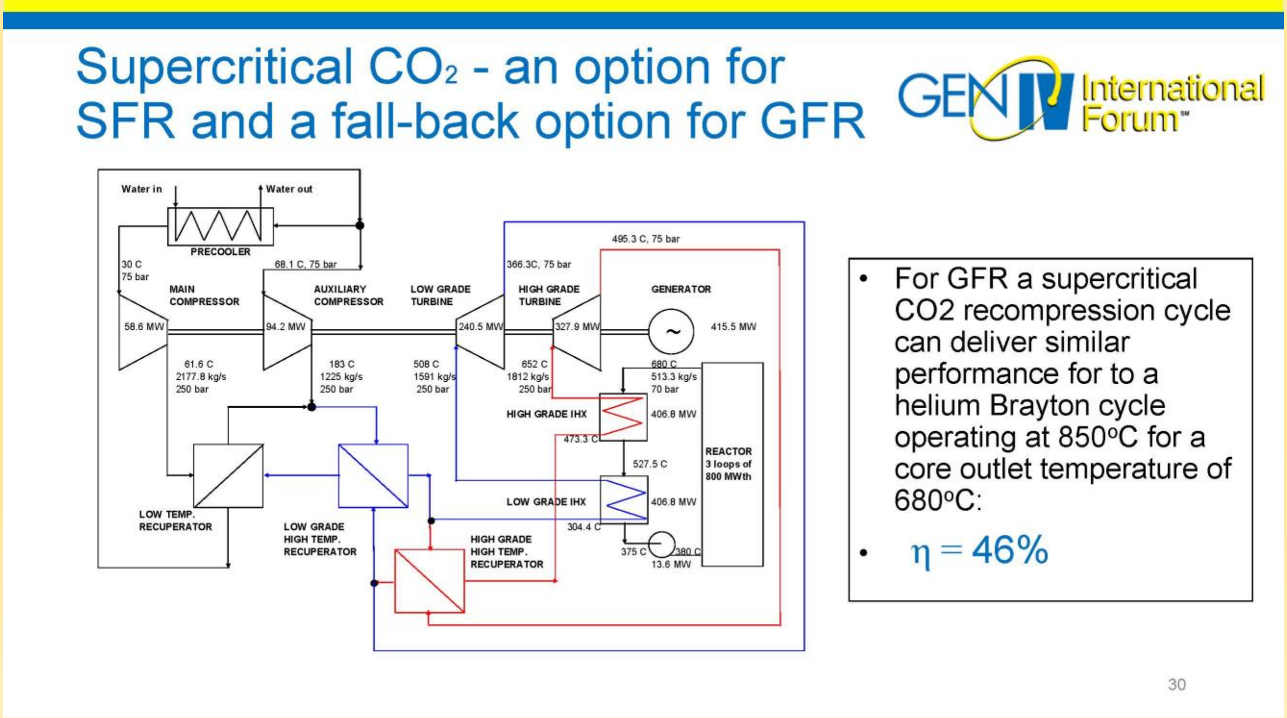
Supercritical CO2 : This cycle is a gas turbine cycle using a supercritical fluid. This cycling technology is very well understood thermochemically but needs to be checked for practicality in engineering. One of the biggest problems we face is that we must operate under very high pressure.



Supercritical CO_2 - an option for SFR and a fall-back option for GFR

- For GFR a supercritical CO2 recompression cycle can deliver similar performance for to a helium Brayton cycle operating at 850ºC for a core outlet temperature of 680ºC:
- η = 46%

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