Alternative power conversion cycles for He-cooled fusion reactor concepts

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Aknowledgement

- This study has been done in the frame of the EFDA task TW5-TRP-006
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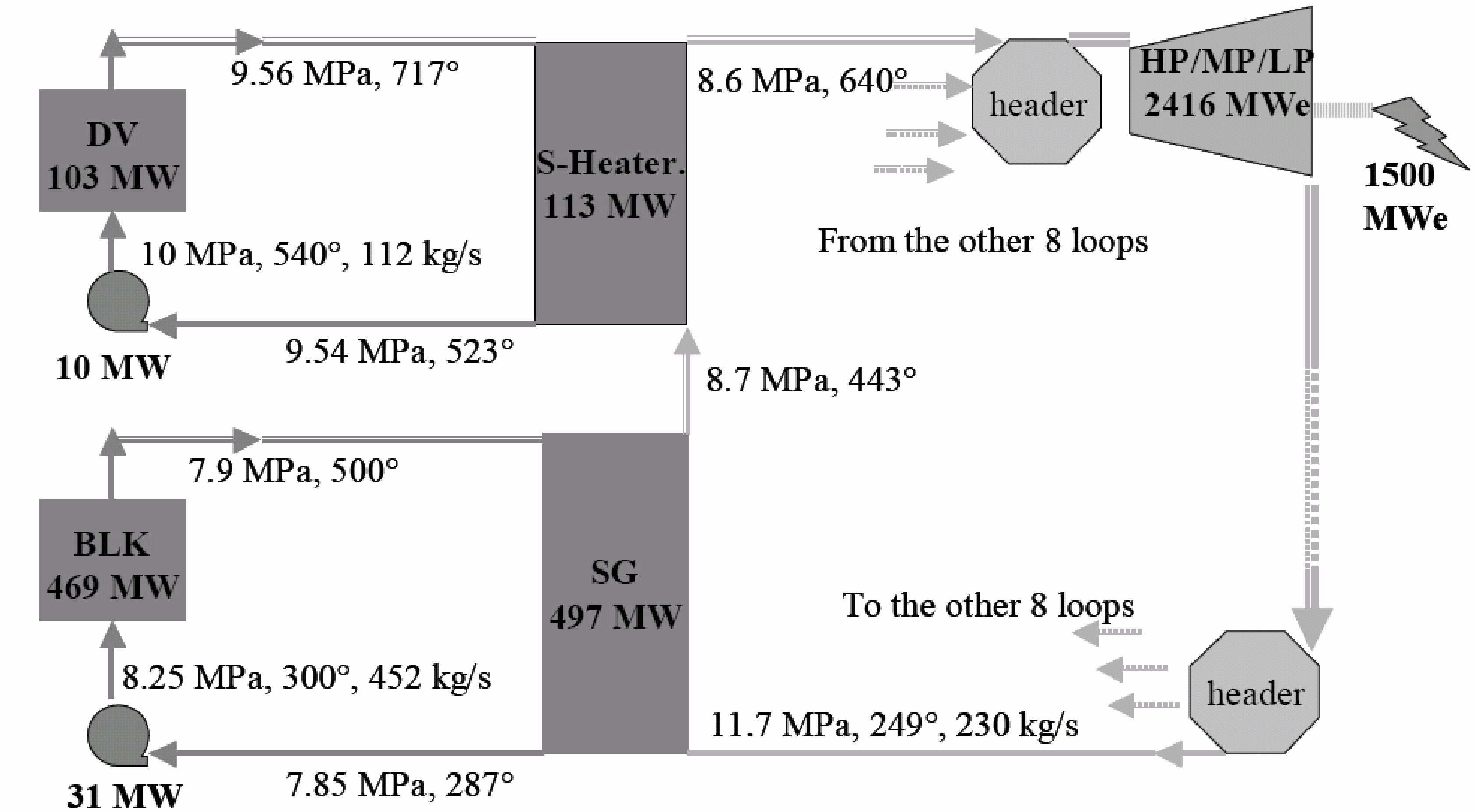
Objective of the study

- Investigate possible improvements of the gross efficiency by using other types of conversion cycles: the indirect Brayton cycle using supercritical CO_2 as working fluid and the supercritical steam Rankine cycle.
- Investigate possible improvements of the net efficiency by reducing the recirculating power, mainly through an optimization of the pressure drops allowing a reduction of the pumping power, without considering the internal layout of the blanket modules or segments.

PPCS HCLL: Power repartition and primary system

Blanket (+HTS) (MW)	4478
Divertor (MW)	983
Number of loops (blanket)	9
Number of loops (divertor)	9
Inlet/Outlet temperature (blanket) (°C)	300/500
Inlet/Outlet temperature (divertor) (°C)	540/720
Operating pressure (blanket) (MPa)	8
Operating Pressure (divertor) (MPa)	10
Heat Sink (blanket)	Steam Generator
Heat Sink (divertor)	Superheater

PPCS HCLL: BLK and DV cooling loops



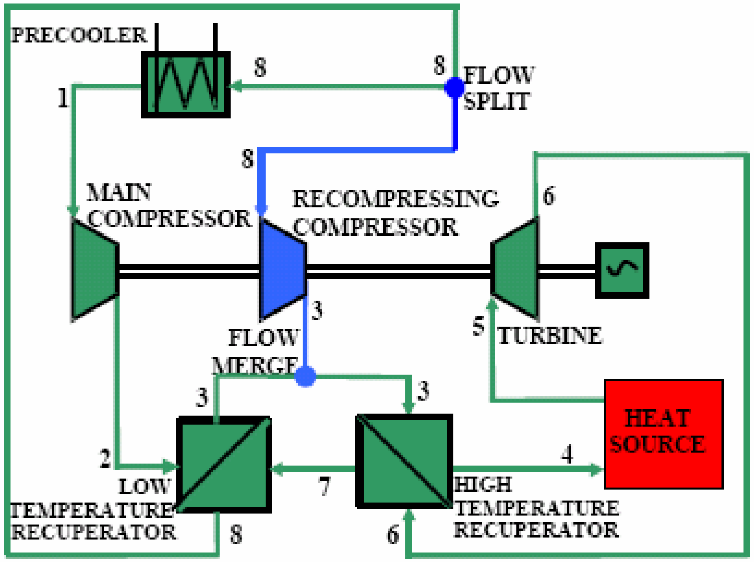
Previous results (PPCS)

	Model A (WCLL)	Model AB (HCLL)	Model AB (WCD)
Fusion power (MW)	5000	4290	4290
Blanket power (MW)	4845	4219	4219
DV power (MW)	894	926	926
Pumping power (MW)	110	418	355
Heating power (MW)	246	286	286
Gross electric power (MW)	2066	2353	2150
Net electric power (MW)	1546	1458	1318
Gross efficiency[1]	0.413	0.548	0.501
Plant efficiency[2]	0.31	0.34	0.307

1 Gross electric power / fusion power
2 Net electric power / Fusion power

Brayton cycle with supercritical CO2

- Interesting physical properties of the working fluid (critical temperature near room temperature, moderate value of critical pressure, stability under 1400 °C)
- Small turbines needed



Brayton cycle with supercritical CO2

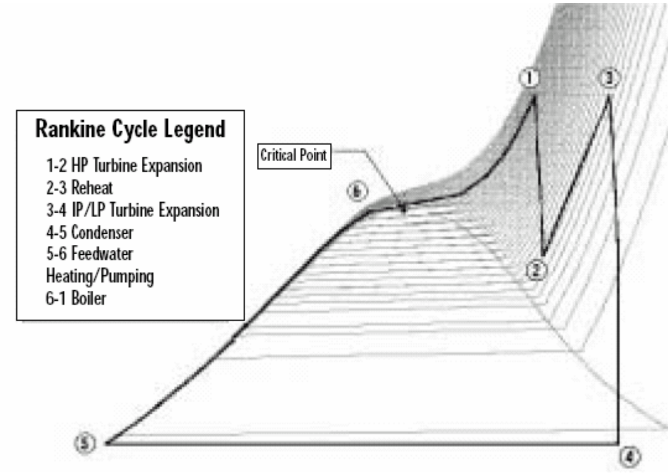
- General parameters
  - Compressor inlet and outlet pressure and temperature
  - Cooling water inlet temperature
  - Heat exchanger (precooler and recuperators) volume
  - Recompressed fraction
  - Main compressor efficiency
  - Recompressing compressor efficiency

Brayton cycle with supercritical CO2

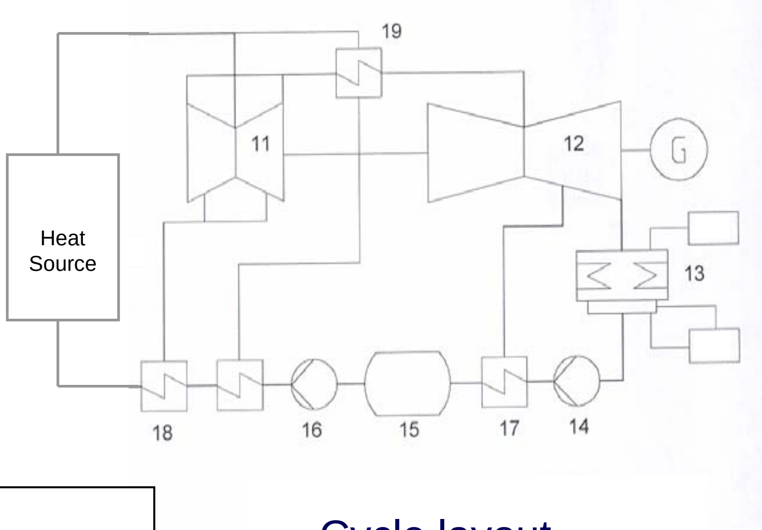
- Turbine parameters
  - Number of stages
  - Pressure ratio
  - Efficiency
  - Length
  - Hub diameter
  - Tip diameter
  - Flow rate
  - Inlet temperature
- Intermediate heat exchangers (IHX) parameters
  - Inlet and outlet pressure and temperature
  - Heat exchange surface
  - Volume

Supercritical Rankine cycle

- Already used in coal-fired power plants; the turbine technology can be assumed mature



Temperature Entropy Diagram



Cycle layout

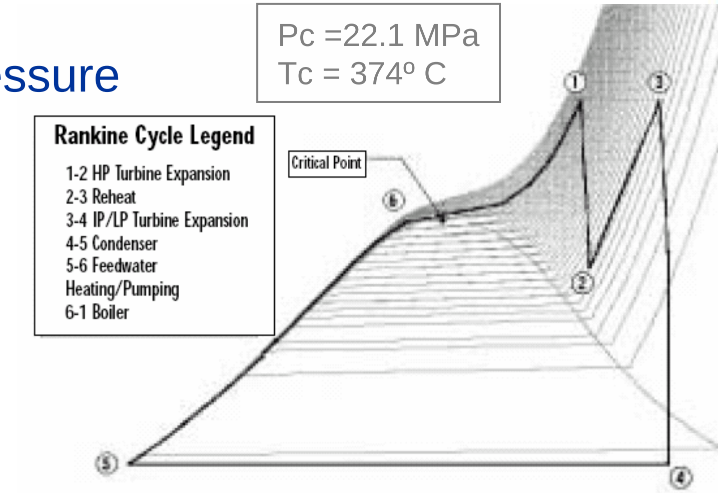
11. HP turbine
12. LP turbine
13. Condenser
14. Condensate water pump
15. Feedwater tank
16. Main feedwater pump
17. LP reheater
18. HP reheater
19. Water separator, reheater

SC Rankine cycles: general

Main Characteristics

- Rankine SC cycles work above the water critical pressure
- The effect of operating at high pressure

→ raise the average temperature at which heat is transfer to the steam → **increase of the efficiency**



TS diagram for a SC Rankine

Configurations analysed

1) Superheat cycle

blanket → *steam generation*
divertor → *superheating*

2) Reheat cycle

blanket → *steam generation + superheat*
divertor → *reheating*

3) Improved cycle: *investigation of the optimum cycle from heat exchange point of view*

Input parameters

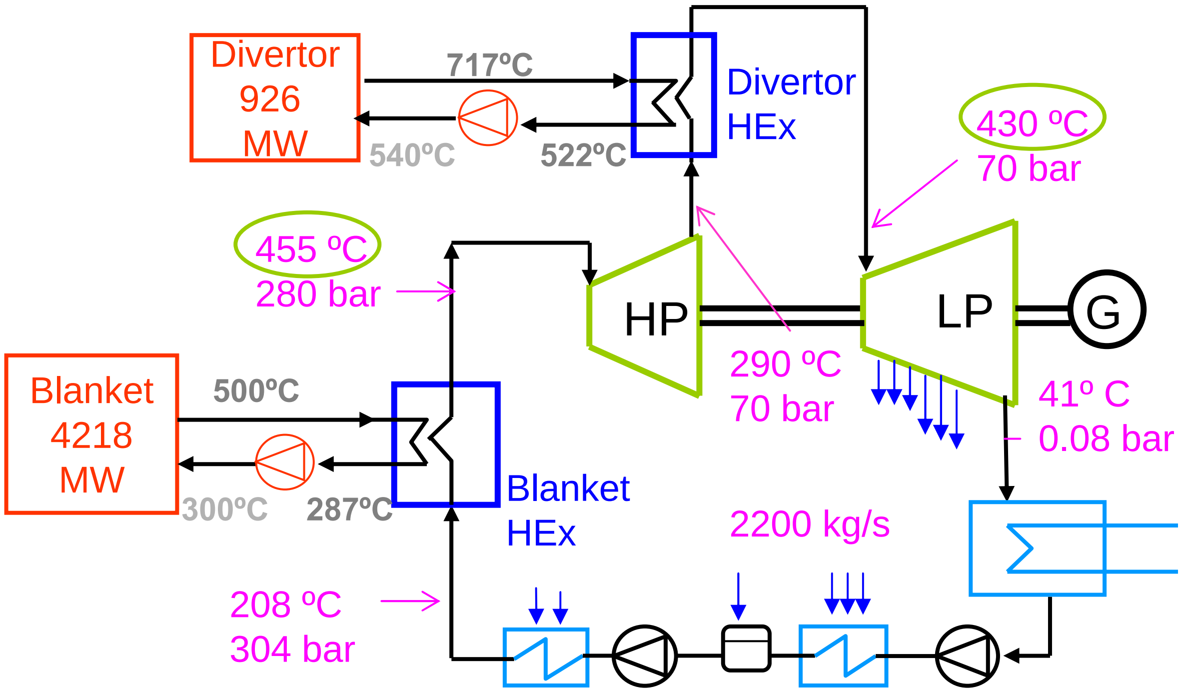
Maximum cycle pressure = 280 bar
Minimum cycle pressure = 0.08 bar
Turbine isentropic efficiency = 0.95
Electromechanical efficiency = 0.98
Pinch temperature HEx´s = 10/25 ºC

SC Rankine cycles: superheat and reheat cases

Maximum turbine inlet temperatures: 530 ºC / 455-430 ºC respectively

No important efficiency gain is obtained compared to the standard Rankine

- *The low temperatures of the Blanket limit the thermal efficiency*
- *The heat transfer effectiveness in the Divertor HEX is very poor.*
- *The heat exchange between primary & secondary can be optimised*



Reheat case

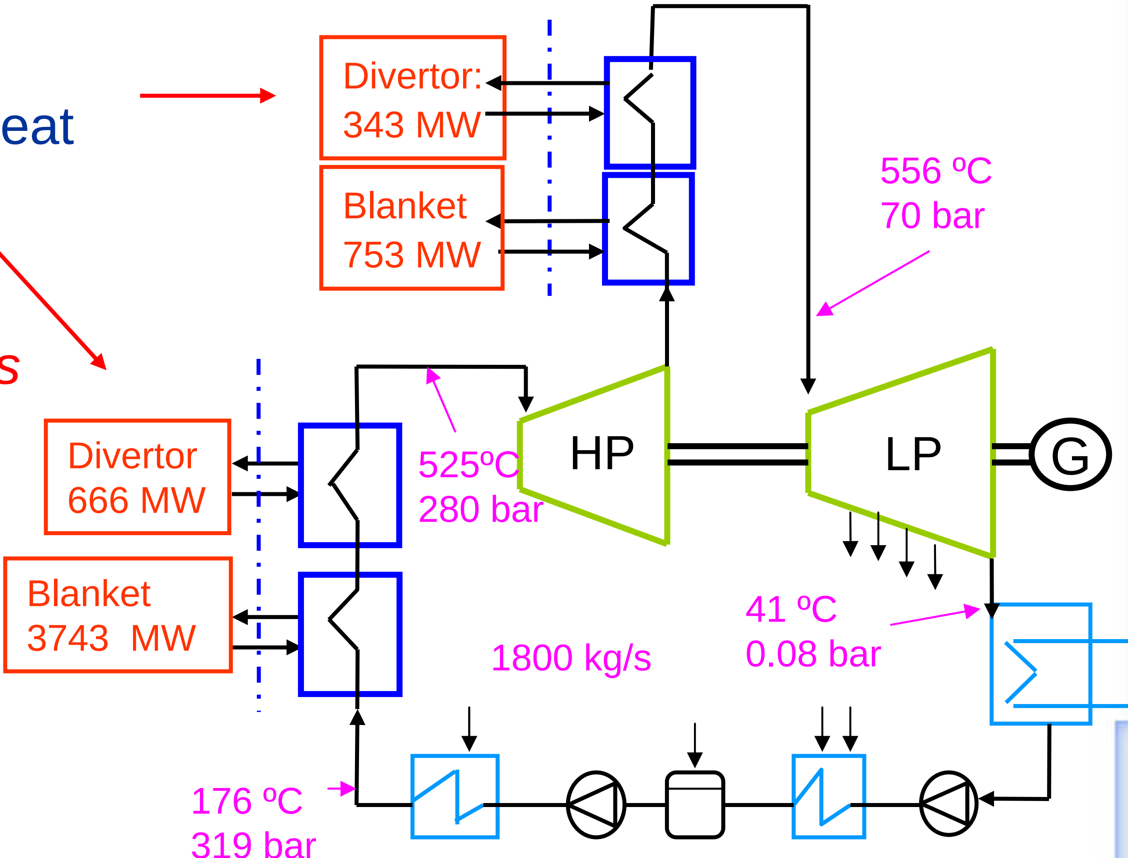
SC Rankine cycles: the improved cycle

The Improved cycle aims at optimising the thermal exchange between primary and secondary to achieve the maximum efficiency.
A new layout for the primary circuit was investigated

The optimum arrangement of the blanket and divertor heat is considered

- *Higher steam temperatures*
- *Lower mass flow*

Turbine HP/ LP inlet temperature = 525 / 556 ºC
Mass flow = 1800 kg/s
Gross efficiency = 49.88 %
Net efficiency = 31.68 %



SC Rankine cycles: results

	SC Superheat cycle	**SC Reheat** cycle	**SC Improved cycle**	**Subcritical Rankine** (PPCS)
Thermal power (MW)	5144.83	5144.83	5144.83	5144.83
HP inlet temperature (ºC)	530.8	456.7	525.4	642.5
LP inlet temperature (ºC)	--	433	556.4	346.2
HP inlet pressure (Bar)	280	280	280	86
LP inlet pressure (Bar)	--	70	70	12
Steam mass flow (kg/s)	2400	2200	1800	3737
Gross power (MW)	**2433.8**	**2400.96**	**2566.233**	**2353.3**
Feedwater pump power (MW)	113.032	102.959	86.147	42.84
Condensate pump power (MW)	3.778	3.468	2.176	4.907
Other auxiliaries (MW)	847.43	847.43	847.92	847.43
Net Power (MW)	**1469.56**	**1447.10**	**1629.99**	**1458.23**
Cycle Gross Efficiency (%)	47.31	46.67	**49.88**	45.74
Cycle Net Efficiency (%)	28.56	28.13	**31.68**	28.34

Cycle gross efficiency = gross electrical output /thermal power
Cycle net efficiency = net electrical output / thermal power

S-CO_2 Brayton cycle: general

Main characteristics

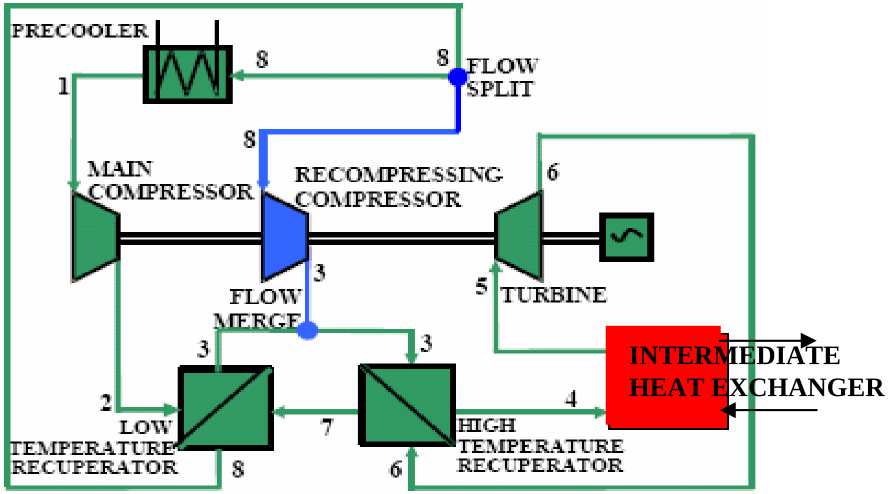
- SCO_2 has been considered as the secondary fluid: reduced compression work if the gas inlet is close to the critical point → **improvement of the thermal efficiency**
- Extensive studies carried out for the GCFR GIV (MIT/EU)

Configurations analysed

Pc =7.38 MPa
Tc = 31° C

1) Base case : simple recuperated, single stage compression cycle

2) Recompression cycle

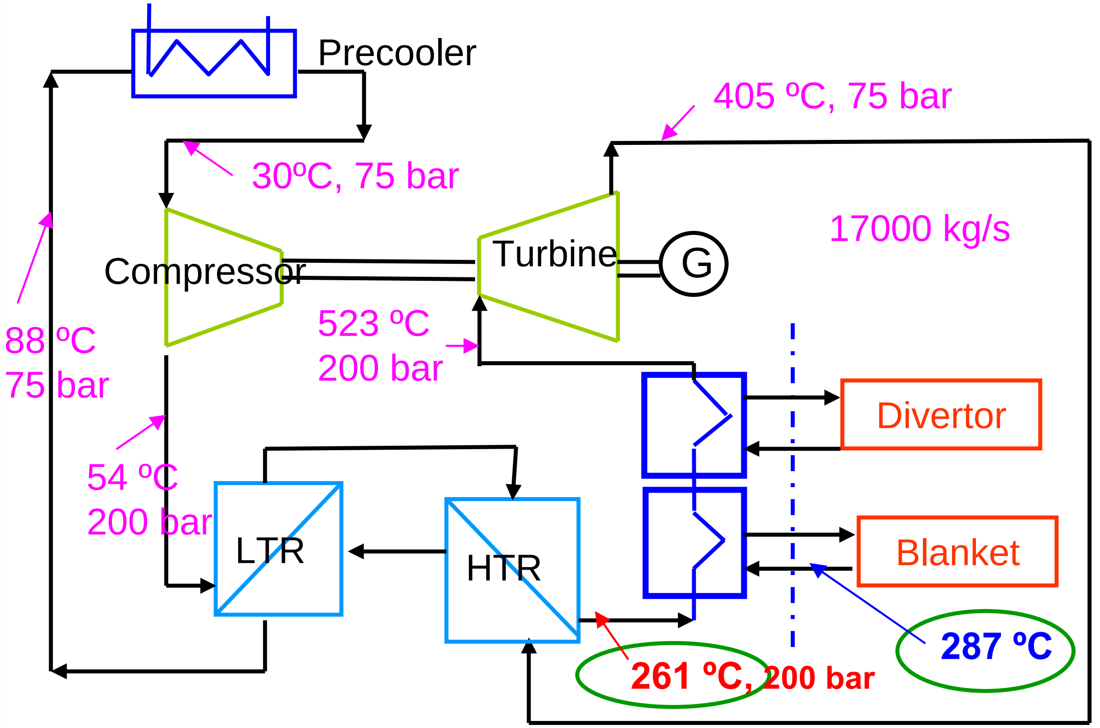


- Auxiliary compressor compresses a flow fraction without previous cooling
- The rest of the flow proceeds to the precooler to the main compressor → improve the *performance of the recuperators*
- Optimum recompression fraction → *maximized the cycle efficiency*

S-CO_2 Brayton cycle: Base case

Single compression cycle shows very low efficiency (net = 18.85 %)

- Maximum temperature at the turbine inlet : 523 ºC
- The turbine exhaust gas is at high temperature → preheating the return gas.
- Limit temperature for the CO_2 return→ all the energy available cannot be recovered
  - *Low effectiveness of the recuperators*
  - *No effective use of the divertor energy*

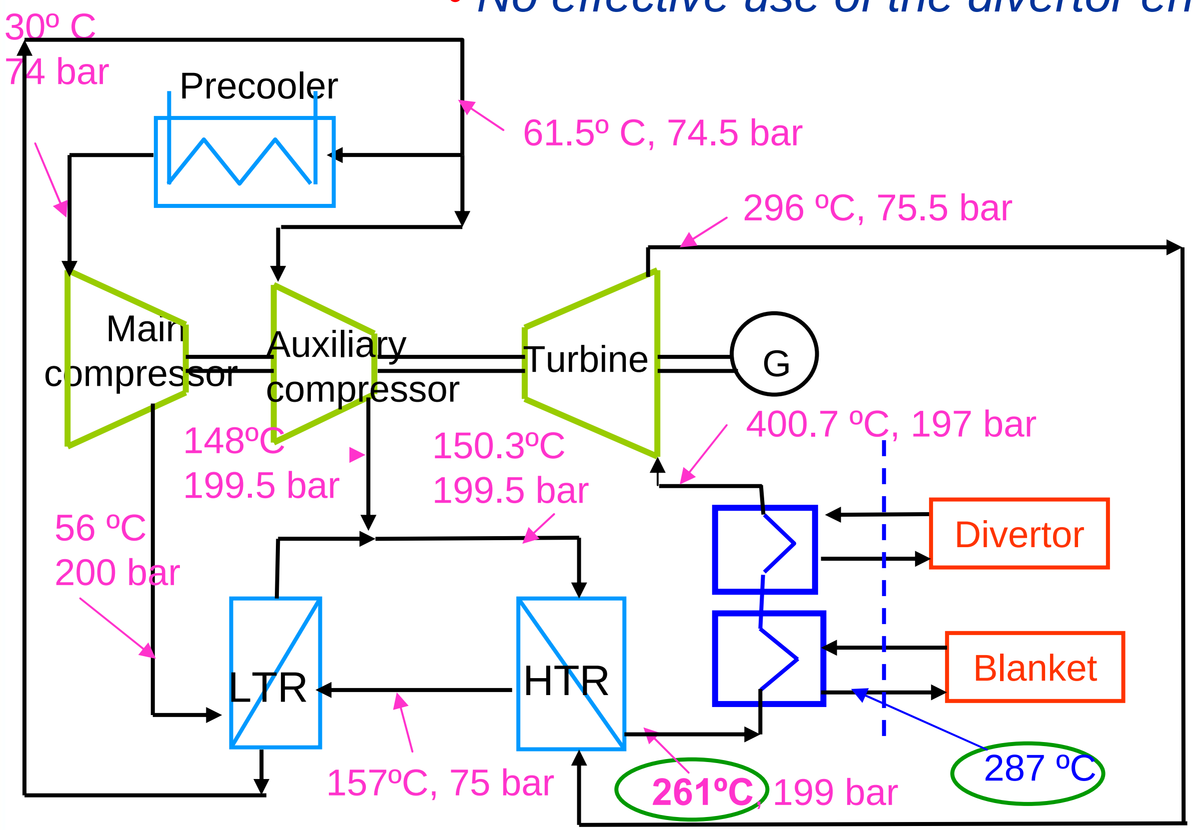


Maximum cycle pressure = 200 bar
Minimum cycle pressure = 75 bar
Minimum temperature = 31-32 ºC

S-CO_2 Brayton cycle: recompression case

The recompression cycle presents higher efficiency values

- Recuperators efficiency of 95 % (state of the art) is considered
- The inlet turbine temperature is reduced to 400.7 ºC (by increasing the mass flow)
- The limit for the CO_2 return temperature (261 ºC) is maintained
  - *The energy available is fully recovered → improvement of the thermal efficiency*
  - *No effective use of the divertor energy*



Turbine inlet temperature = 400.7 ºC
Recompression fraction = 0.41
Mass flow = 32000 kg/s
Gross efficiency = 42.48 %
Net efficiency = 26.01 %

S-CO_2 Brayton cycle: results

The recompression cycle coupled to model AB remains uncompetitive with respect to SC Rankine. The low efficiency obtained is due to the *limitation of the turbine inlet temperature*

- CO_2 return temperature limit → Blanket He inlet temperature limit
- The Divertor heat does not contribute to the cycle efficiency

⇩

The proposal was to consider **independent cycles** for the Blanket and the Divertor by taking advantage of the particular characteristics of each heat source.

⇩

S-CO_2 Dual recompression cycles yield the best results for the different cases analysed.

- Blanket cycle efficiency similar to that of the integrated cycle
- High efficiency obtained from the Divertor thermal fraction
  - *more efficient heat transfer at the Divertor Hex*
  - *high turbine inlet temperature*

S-CO2 Brayton cycle: dual cycles

S-CO_2 Dual recompression cycles for the Blanket and Divertor

Blanket

Cycle pressures = 250 / 75 bar
Turbine inlet temperature = 440º C
Mass flow = 21619 kg/s
Recompression fraction = 0.37
Gross efficiency = 45.70 %

Divertor

Cycle pressures = 200 / 75 bar
Turbine inlet temperature = 680º C
Mass flow = 4444 kg/s
Recompression fraction = 0.38
Gross efficiency = 56.94 %

Combined efficiency

Gross power = 2455 MW
Net power = 1608 MW
Gross efficiency = 47.73 %
Net efficiency = 31.26 %

2nd possible candidate

Results from UKAEA/AMEC-NNC

Conclusions

1. Different conversion cycles have been analysed for Model AB with the objective of *improving the thermodynamic efficiency* with respect to the subcritical Rankine studied in the PPCS.

2. SC steam Rankine and SCO_2 cycles have been investigated

3. The SC Rankine (improved case) leads to the highest gross and net efficiencies.

4. *S-CO_2 Dual* Brayton recompression cycles (Blanket & Divertor) yield *net efficiencies comparable* to those of the improved *SC-Rankine*.
   The improvement is more than 3 percentage points when compared to PPCS.

	Rankine Standard (PPCS)	SC-Rankine “improved”cycle	S-CO_2 Brayton Independent cycles
Gross Efficiency (%) Net Efficiency (%) Net electrical power(MW)	**45.74** **28.34** **1458**	**49.88** **31.68** **1630**	**47.73** **31.26** **1608**

5. Higher He temperatures in the Blanket would increase the efficiencies for all cycle configurations. Particularly the S-CO_2 recompression cycle (integrating Blanket & Divertor) would present noticeable efficiency gains if the inlet temperature at the Blanket – limited to 300 ºC – is increased.