- ***Symposium on Supercritical CO2 Power Cycle for Next Generation Systems***
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Overview of Supercritical CO2 Power Cycle and Comparison with Other Cycles

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Outline

- What is the SCO2 cycle?
- Why the supercritical CO2 cycle for new reactors?
- Supercritical CO2 recompression cycle and its parameters
- What issues need to be resolved?

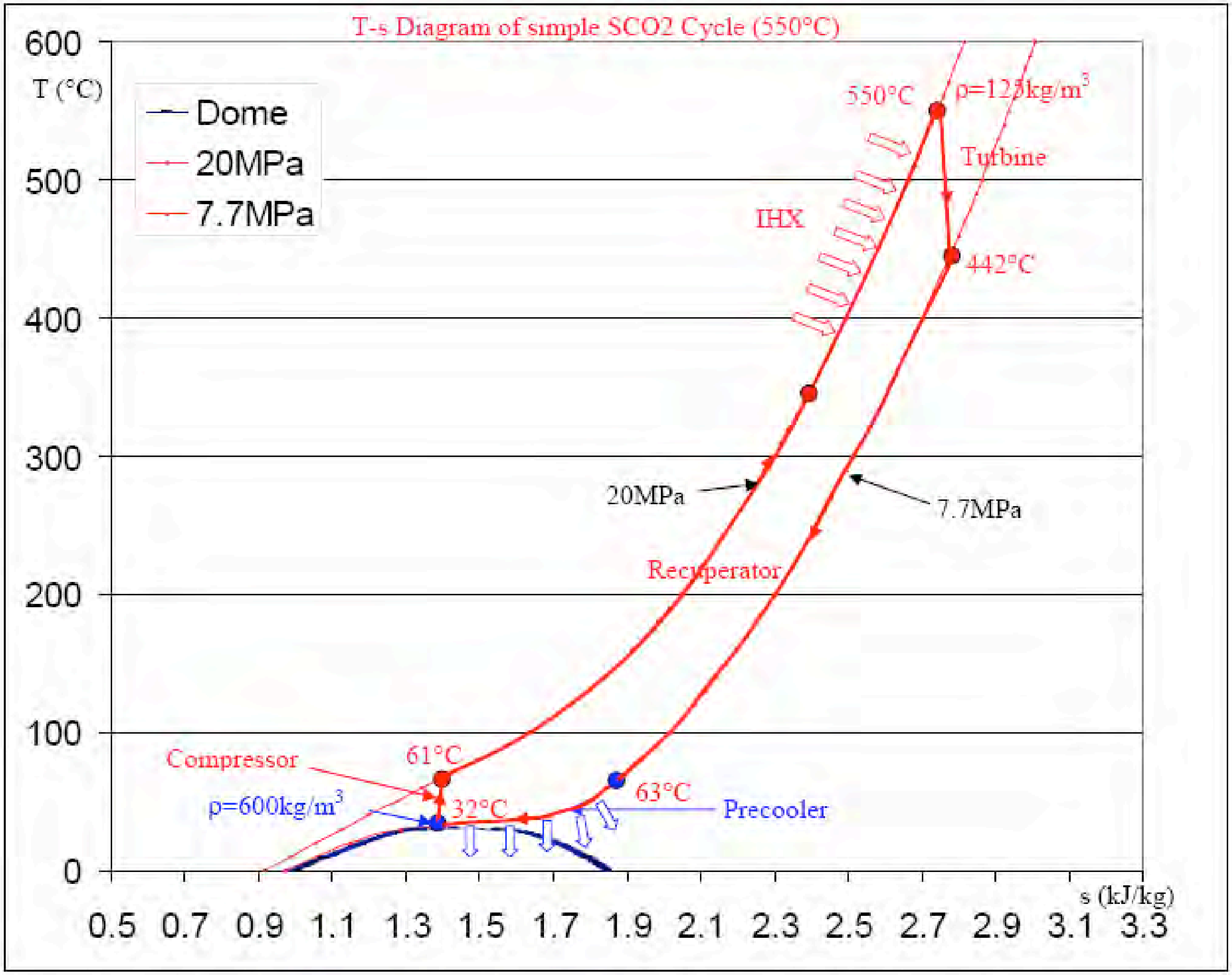
This is an overall review of the SCO2 cycle

More details can be found in 2 papers on MIT work on the SCO2 cycle in:

Nuclear Technology June 2006 issue

What is supercritical CO2 cycle?

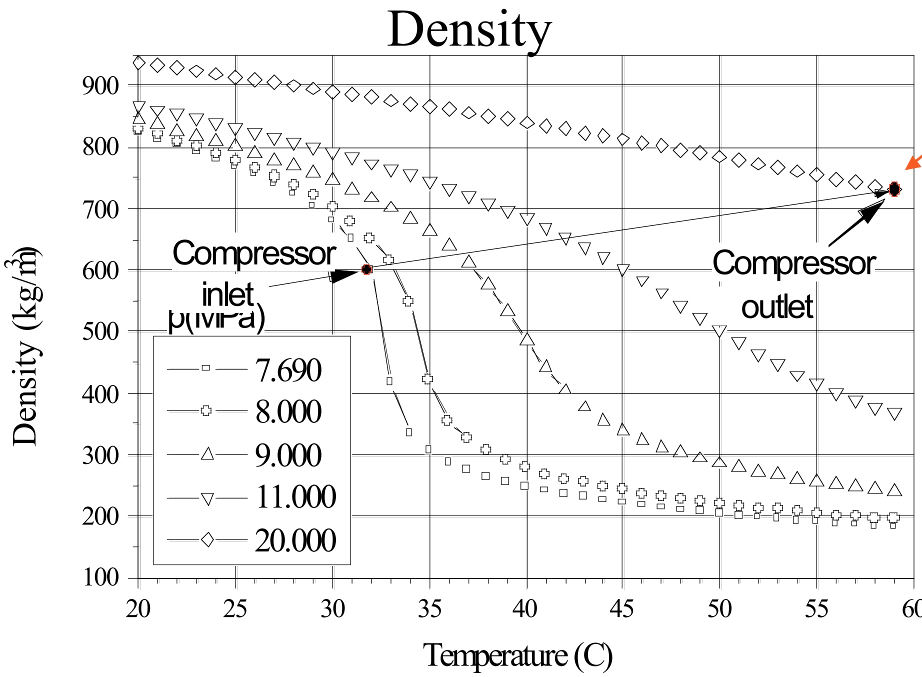
Entire cycle is above the dome, no condensation



- Sometimes term transcritical used
- High efficiency at medium temperatures
    - High density near crit. Point (CP) small compressor work
    - Flat isobar above CP, hence low heat rejection Tave
- Small pressure ratio (2.6 versus 1300 for Rankine)
- High mass flow rate, small vol. flow rate

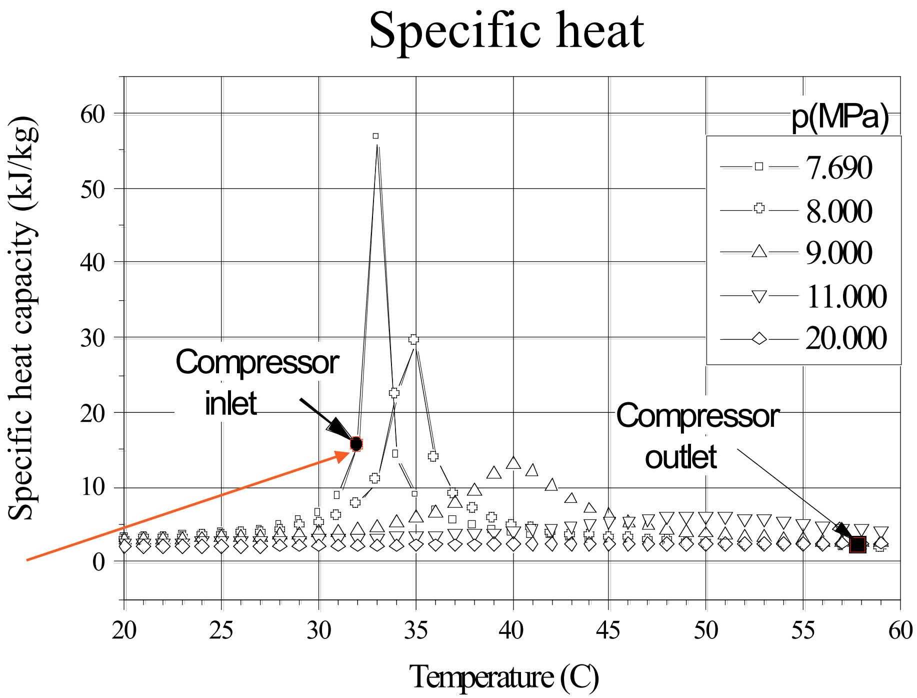
Property changes near critical point

- Large property changes near critical point



Benefit of high density

(low compression work, small machine)

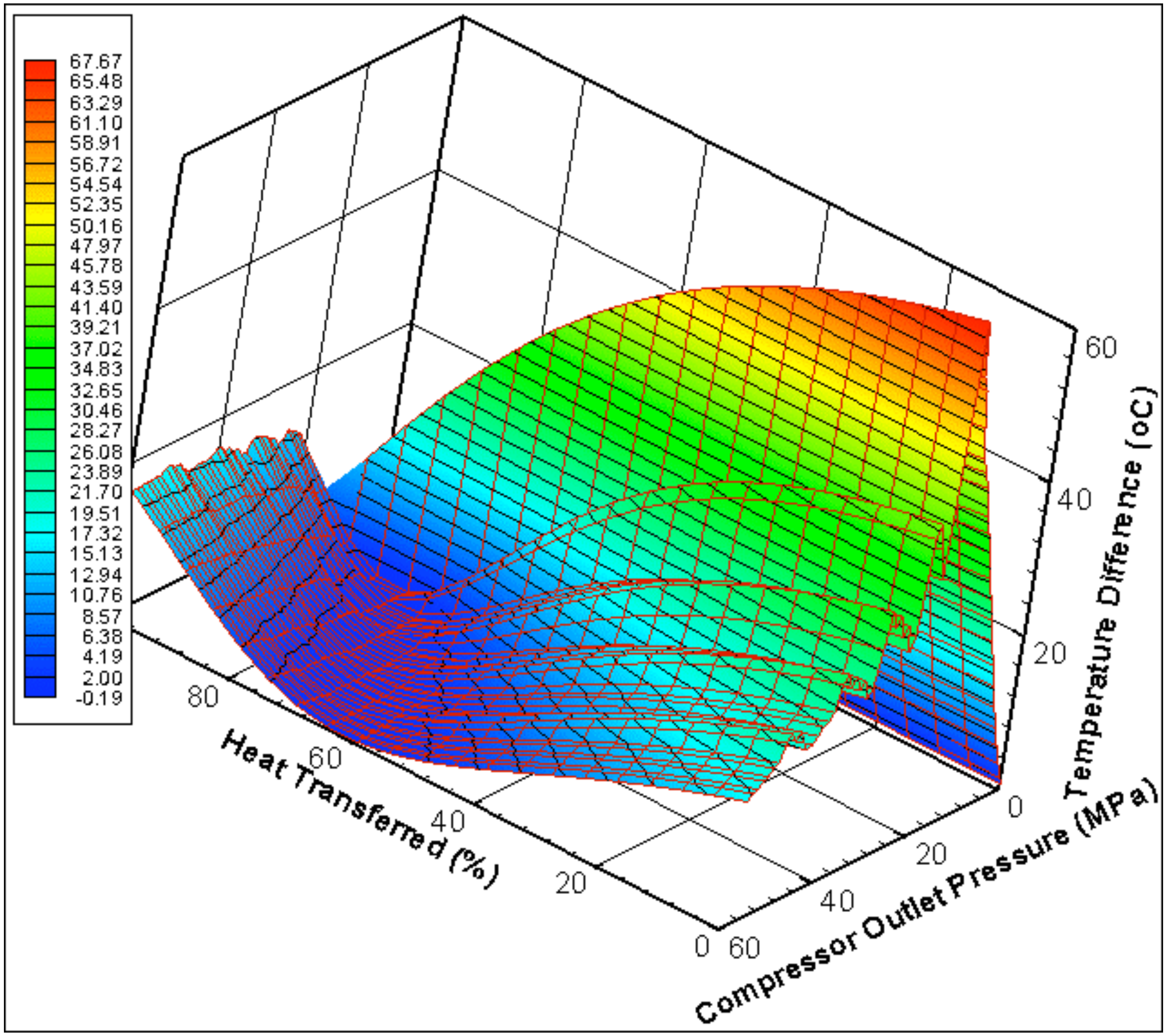


Drawbacks of c_p variation

(pinch point in recuperator)

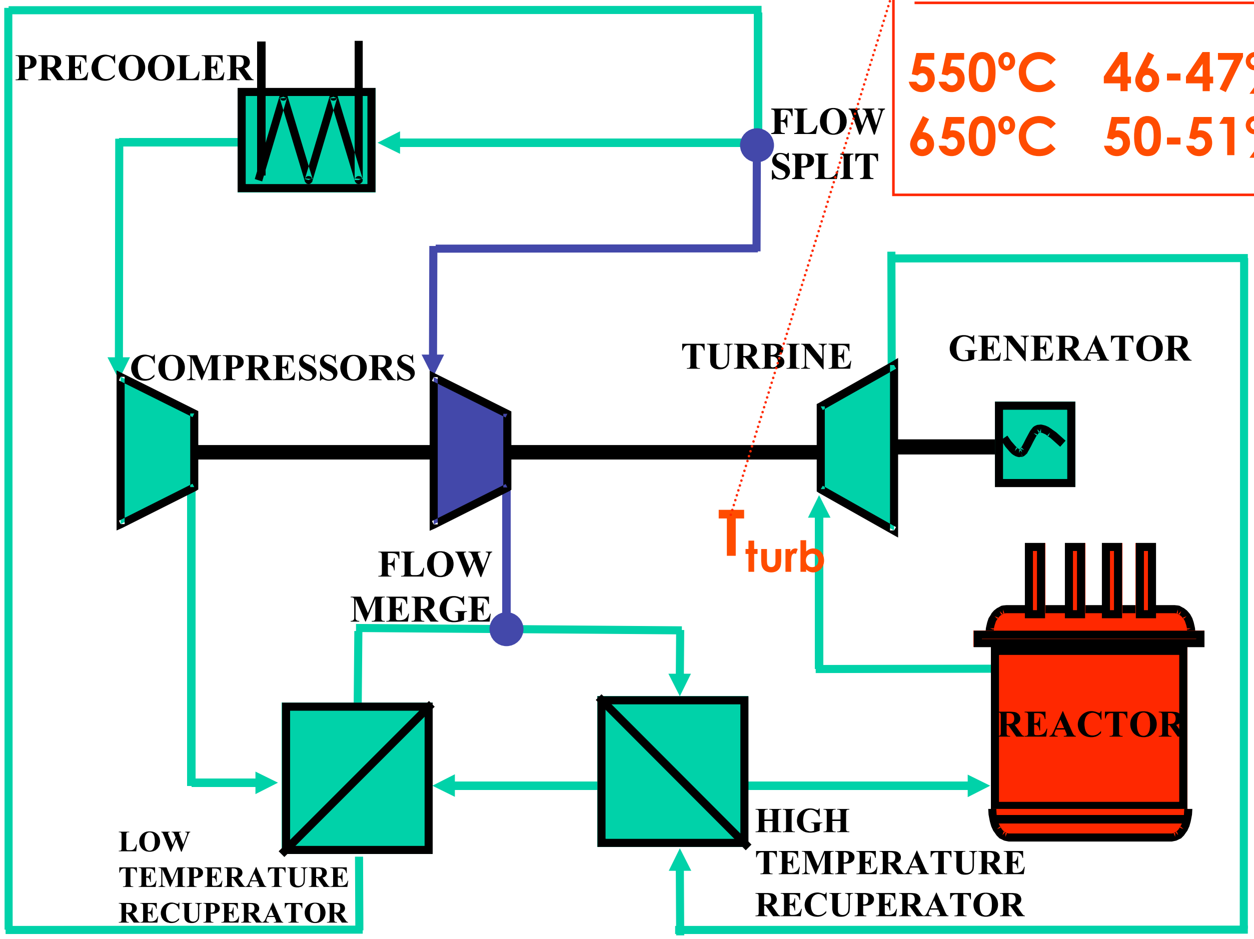
But drawback of pinch point inside recuperator

- Large cp variation above the CP
- Difficulties to maintain positive temperature difference between cold and hot streams in recuperator
- **Minimum temperature difference can be reached inside the recuperator and <u>NOT</u> at the inlet or outlet**



Recompression SCO2 Brayton cycle needed for high efficiency

Supercritical CO_2 Recompression Cycle



T_{turb}	$\eta_{thermal}$	η_{net}	
550°C	46-47%	43-44%	Basic
650°C	50-51%	47-48%	Advanced

Net efficiency:
- Cooling water pumping power (1.6MW)
- 2% generator loss
- 1% mechanical losses
- 0.5% switchyard loss
- 2% other losses (cooling, leakage bypass)-assumed

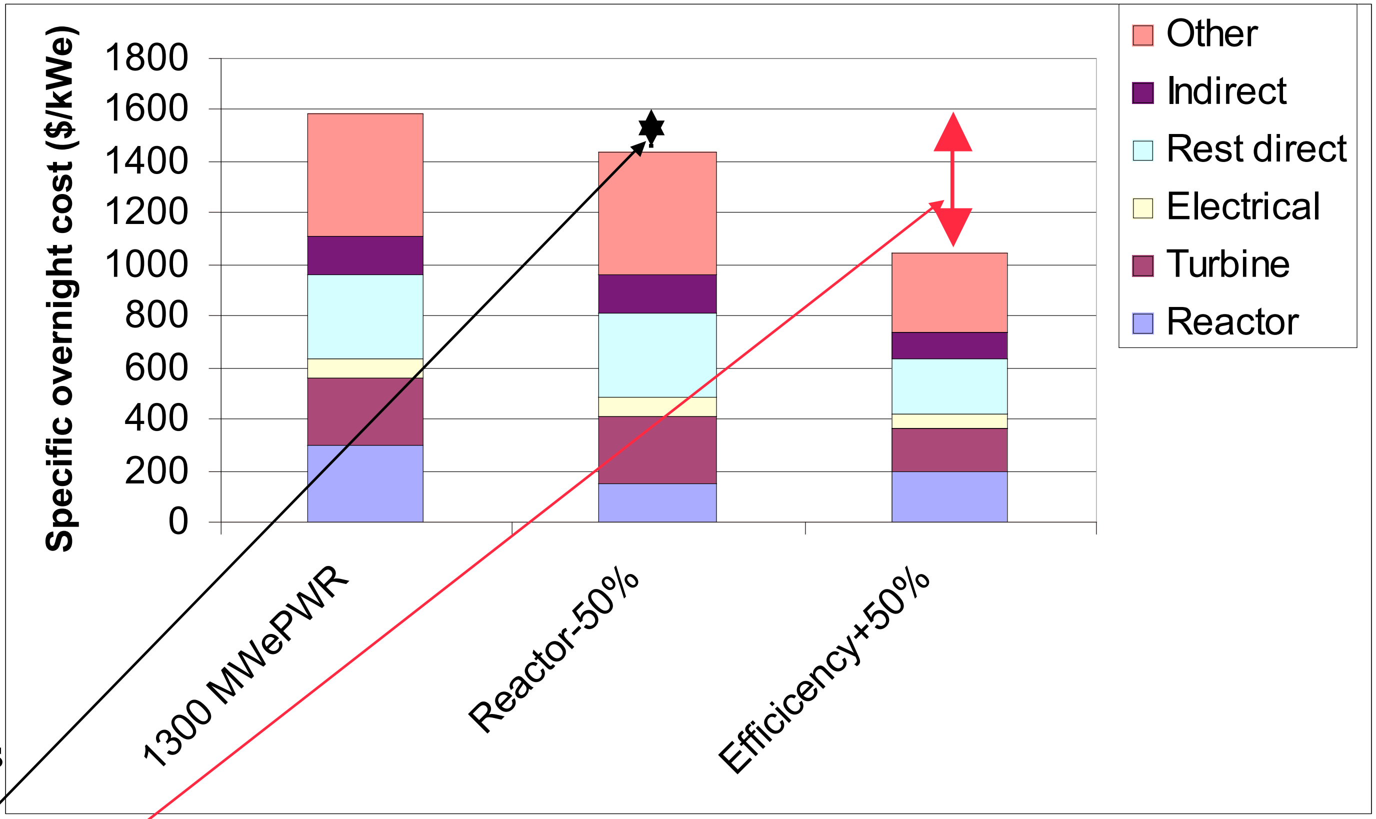
Why do we need a new cycle?

- New Gen IV reactors
  - Some reactor concepts have core outlet temperature range where Rankine cycle potential to benefit from higher temperatures is limited
  - Combined fossil cycles achieve much higher efficiencies (60%) than current LWRs; increase of thermal efficiencies for nuclear needed to improve competitiveness
  - Economics is key goal for new nuclear to make an impact, high cost also main reason for slowdown of nuclear power plant deployment)
- So far, most effort focused on Gen IV reactor designs, but limited potential in addressing the economy goal
- Selection of BOP can significantly improve economy and also improve sustainability

SCO2 cycle and Gen IV goals (Cont’)

- Other
  - Owners cost
  - spare parts
  - contingencies
  - initial fuel cost
- Indirect
  - design
  - project management
- Rest direct
  - Land
  - heat rejection
  - miscellaneous
  - construction services

Capital investment decomposition – typical ALWR

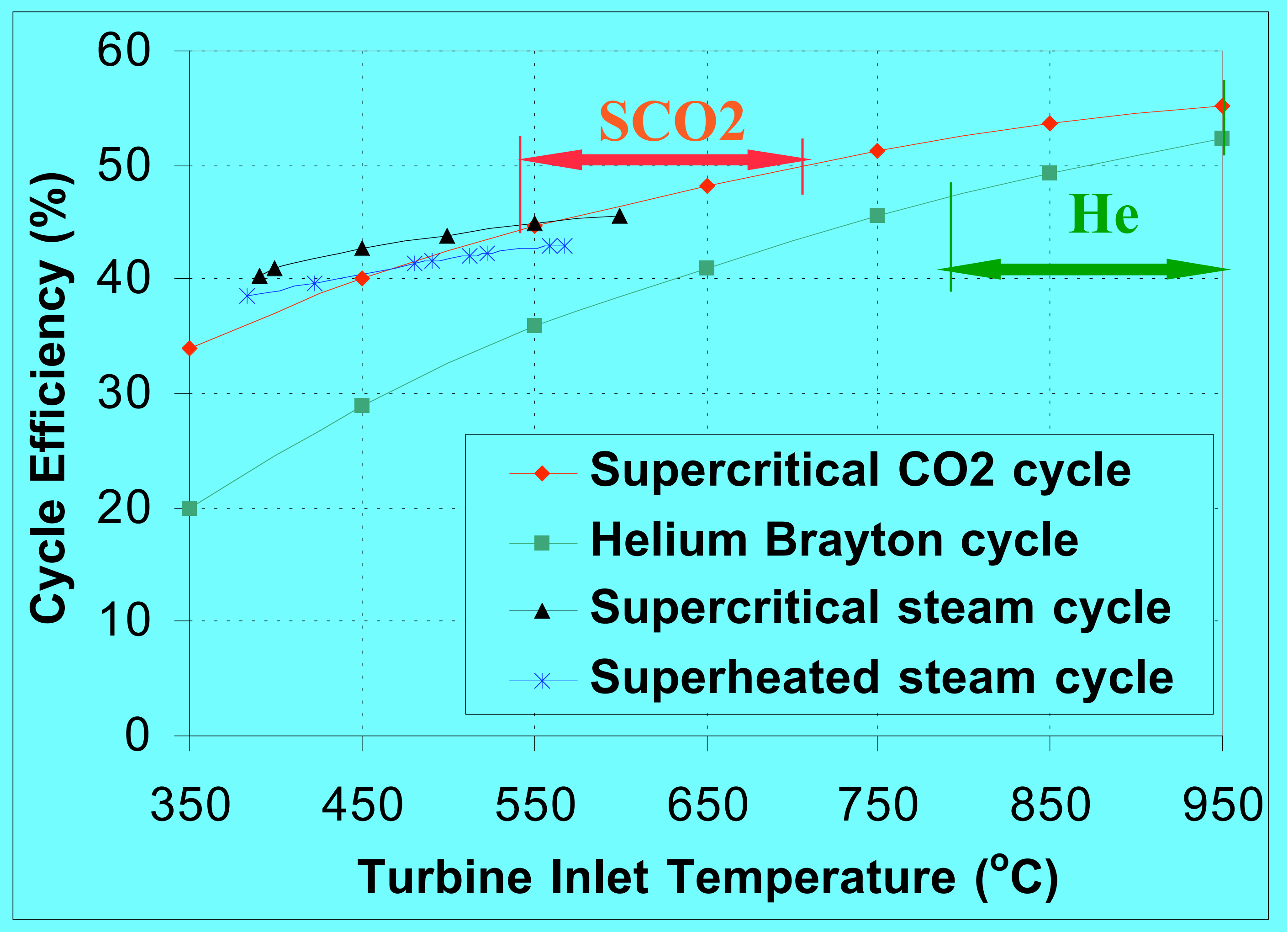


Reducing reactor plant equipment cost by 50% has a small impact on spec. cost

Increasing efficiency from 34% to 50% has a large effect on $/kWe!

Conclusion #1: Competitive economy will require high cycle efficiencies

Efficiency of potential cycle candidates

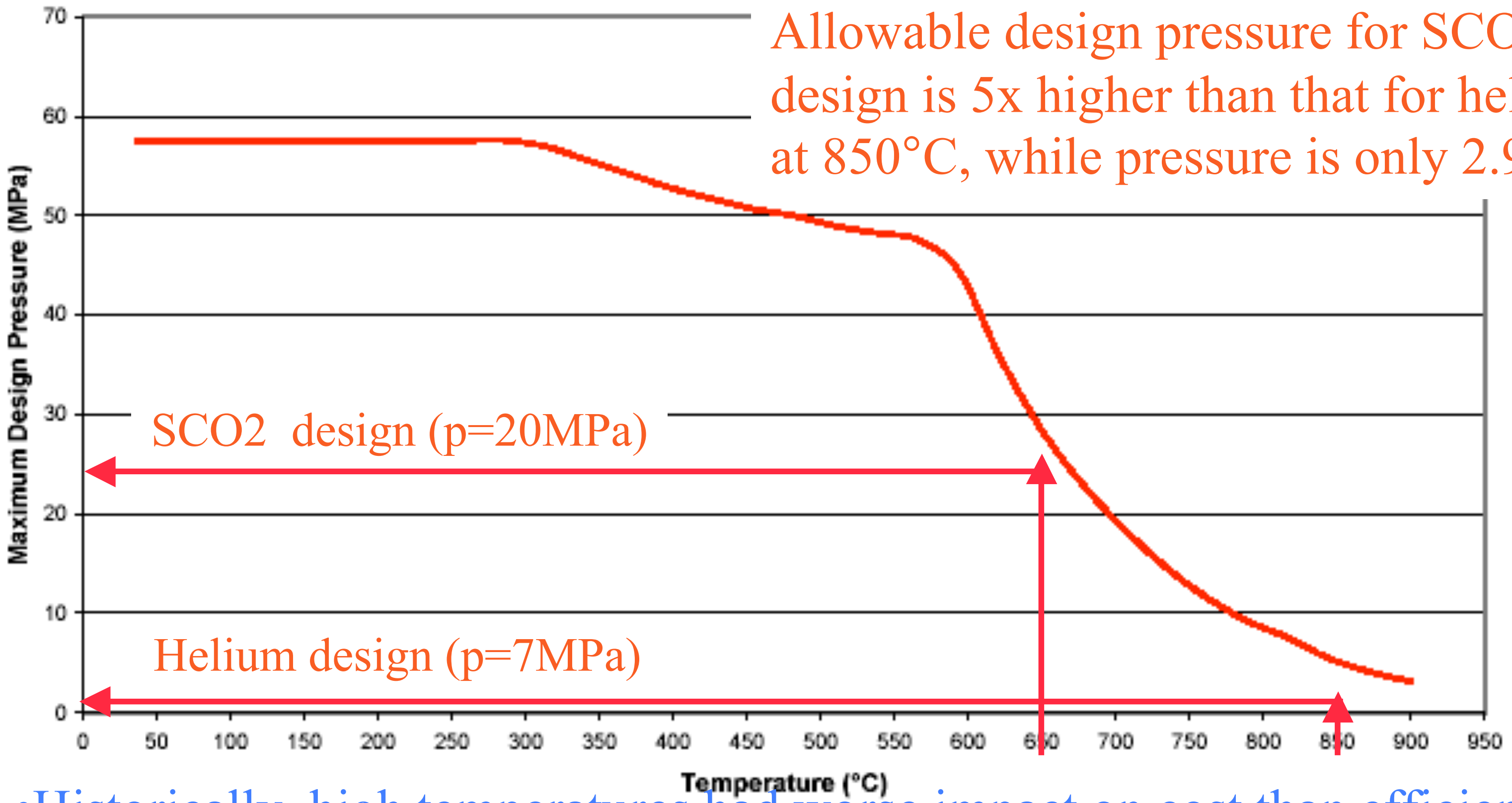


- Steam cycles have lower efficiency above 550°C, hence employ Brayton cycles
- SCO2 achieves same efficiency at 650°C as helium at 850°C, but needs higher pressure

Cost benefits from lower temperature

Maximum design pressure for HEATRIC HX

Alloy 800 HT (from Dewson&Thonon, at ICAPP03, paper3213)



Allowable design pressure for SCO2 advanced design is 5x higher than that for helium design at 850°C, while pressure is only 2.9 higher

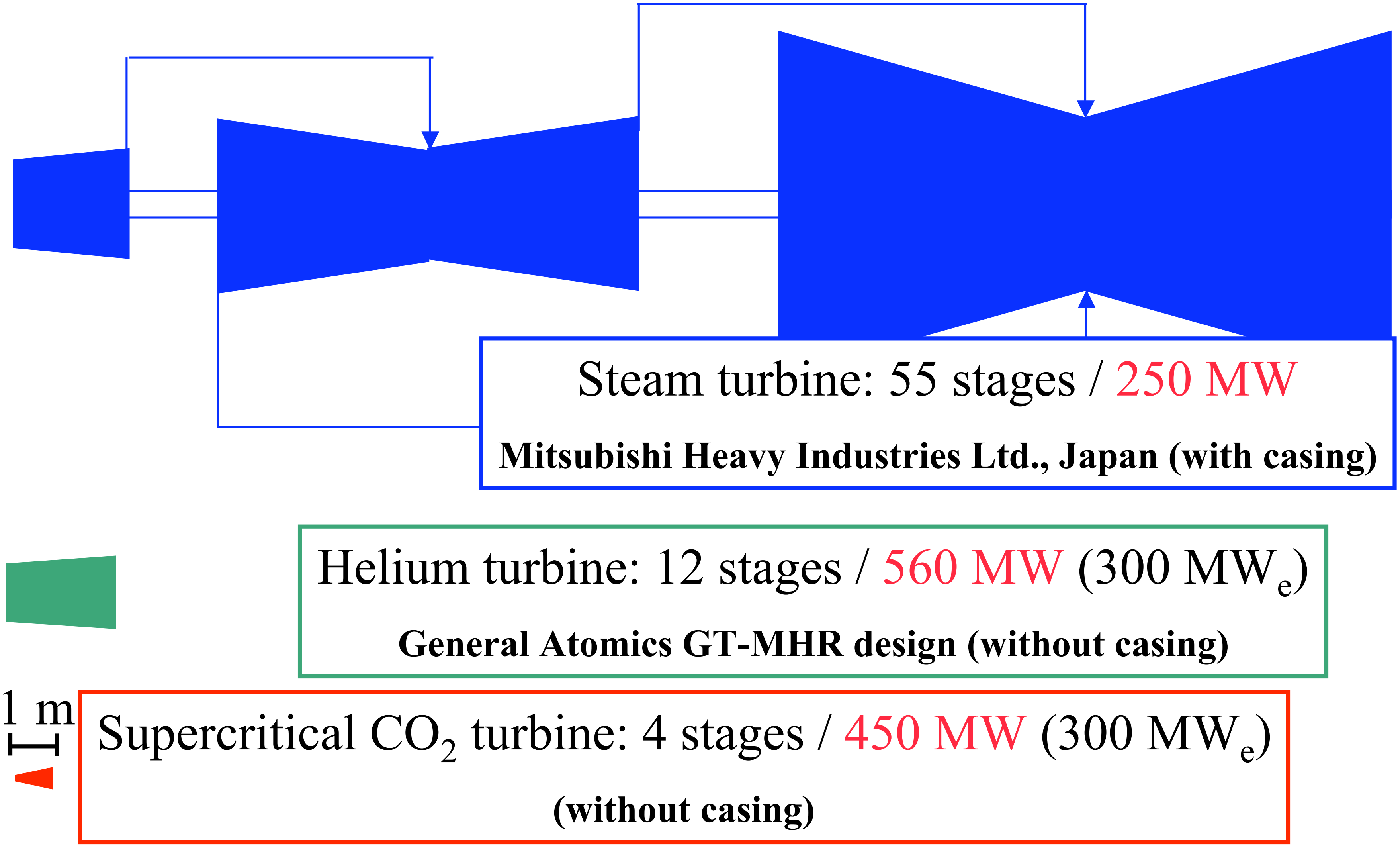
SCO2 design (p=20MPa)

Helium design (p=7MPa)

- Historically, high temperatures had worse impact on cost than efficiency benefit
- Easier to design HX for **high p and medium T** than for **high T and medium p**
- Less mass, hence lower costs of components

Cost benefit from compact turbomachinery

High pressure → small volumetric flow rate



Steam turbine: 55 stages / 250 MW

Mitsubishi Heavy Industries Ltd., Japan (with casing)

Helium turbine: 12 stages / 560 MW (300 MW$_e$)

General Atomics GT-MHR design (without casing)

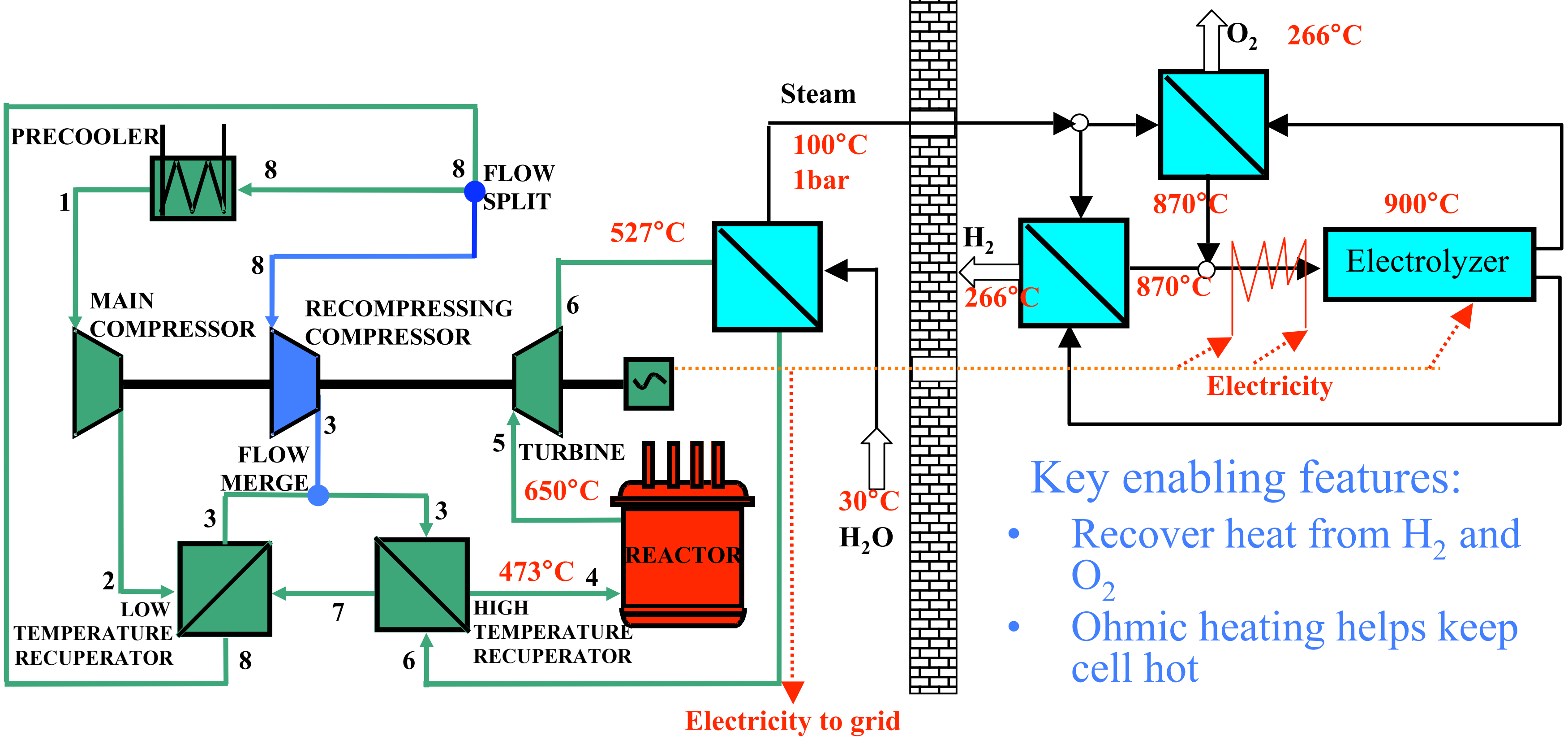
Supercritical CO$_2$ turbine: 4 stages / 450 MW (300 MW$_e$)

(without casing)

H2 mission – can H2 be made at medium T?

Nuclear plant (SCO2-GFR)

Electrochemical plant



Key enabling features:

- Recover heat from H_2 and O_2
- Ohmic heating helps keep cell hot

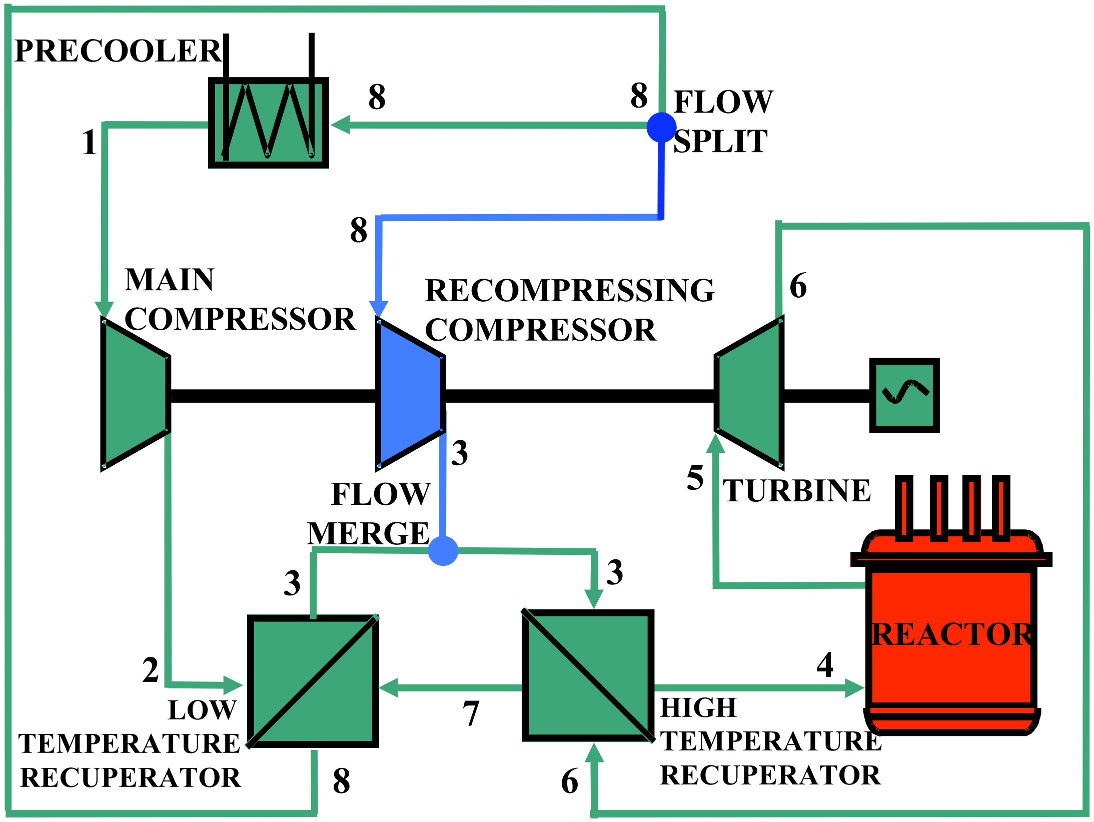
- Yes and at very attractive efficiencies – 51% at 650°C compared to 47% at 950°C using SI
- IHX material problem eliminated (T=527°C)
- Materials problem for heat transport eliminated (steam line at 100 °C)
- Reactor operates between 473 and 650 °C and only electrochemical plant runs at 900 °C

Why SCO2 cycle for Gen IV reactors - summary

- It offers potentially substantially improved economy
  - high efficiency at medium temperatures
  - lower capital cost – simplicity, compactness
- It makes possible H2 production at high efficiencies
- There is experience with materials and operation of CO_2 cooled reactors at medium temperatures (14 British AGRs have operated more than 15 years using CO_2 at 650°C), hence less challenging material development
- It can achieve high efficiency when applied to **all (except water cooled) Gen IV reactor concepts** (sodium, lead-alloy, liquid salt, molten salt-cooled, and direct SCO2 cooled GFR) while Brayton helium cycle is usable (at high efficiency) only with helium and liquid salt cooled reactors
- SCO2 cycle is very attractive candidate for Gen IV reactors

Optimized design statepoints - advanced design T=650° C

	Advanced design	
Point	P	T
	MPa	°C
1	7.692	32
2	20	60.91
3	19.989	159.11
4	19.948	481.83
5	19.818	650
6	7.919	527.15
7	7.804	168.31
8	7.702	70.89



Depending on realizable compressor and turbine efficiencies

Thermal/net efficiency = 50%-51%/ 47-48%

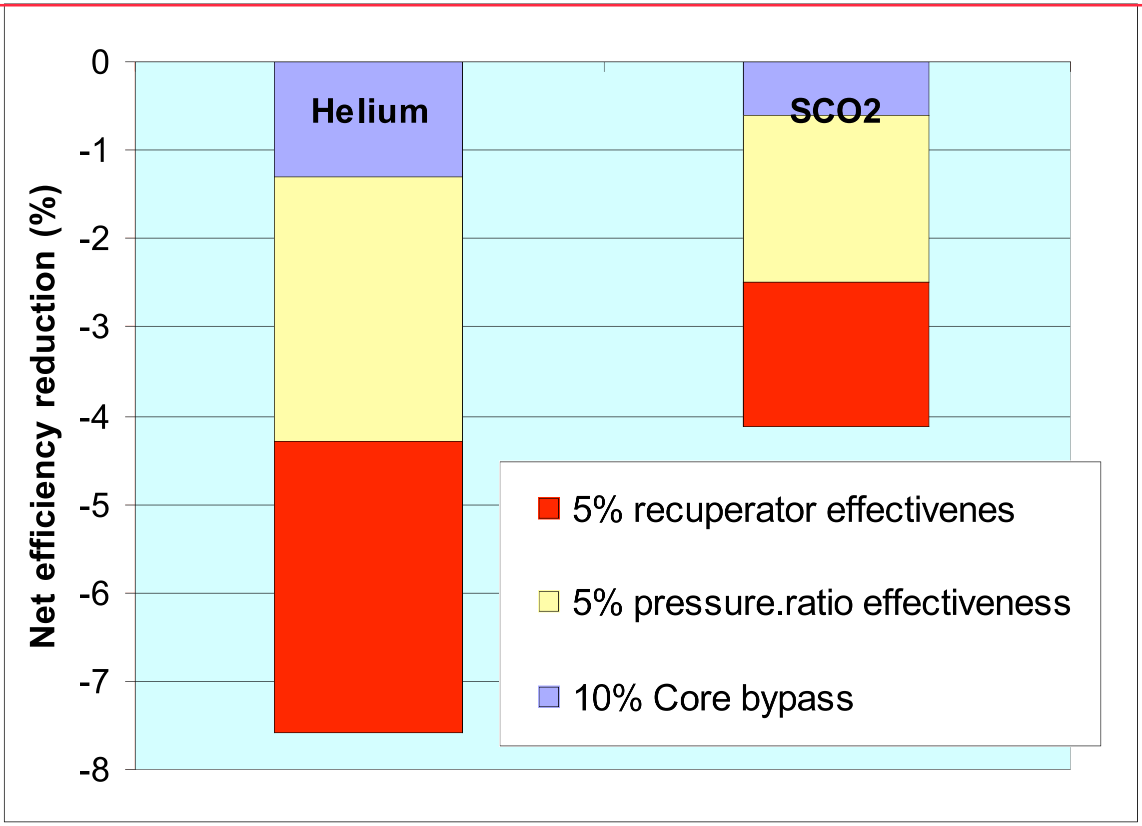
Note on predicted efficiencies

Predicted efficiencies may not be easy to achieve in practice

Predicted net efficiency:generator, mechanical losses 2%,1%
at 850°C = 48% at 650°C = 48%

But
efficiency is sensitive to:

- Core bypass flow
- Pressure drops
- Recuperator effectiveness (flow maldistribution)
- Plus leakage and cooling penalty
- Predicted efficiencies will be difficult to achieve!



SCO2 cycle much less sensitive to these penalties!!!

Turbomachinery Design - 600 MW_{th}^{*}

	Main Compressor (radial)	**Recompressing Compressor (radial)**	**Turbine (axial)**
Number of stages	**2**	**3**	**4**
Impeller diameter (m)	**0.6**	**0.9**	**1.2**
Total-to-static efficiency (%)	**89**	**89**	**92**

* *By MIT Gas Turbine Laboratory engineers*

- **Turbomachinery is extremely compact and has high efficiency**
- **Good diffusers needed to maximize pressure recovery**
- **Cycle efficiency is sensitive primarily to turbine efficiency**

More details on turbomachinery in a separate session

Recuperators and precooler

- SCO2 cycle is highly recuperative
  - for 600MWth plant 1400MWt is recuperated
  - hence very compact HXs required
- Large pressure difference (20MPa against 8MPa)
- But moderate temperatures (440°C for high temperature recuperator)
- Cycle is sensitive to HX effectiveness – high effectiveness required
- Heatric’s printed circuit heat exchangers are excellent candidates – used for all heat exchangers
- Separate session dedicated to heat exchangers

What will the cycle layout look like?

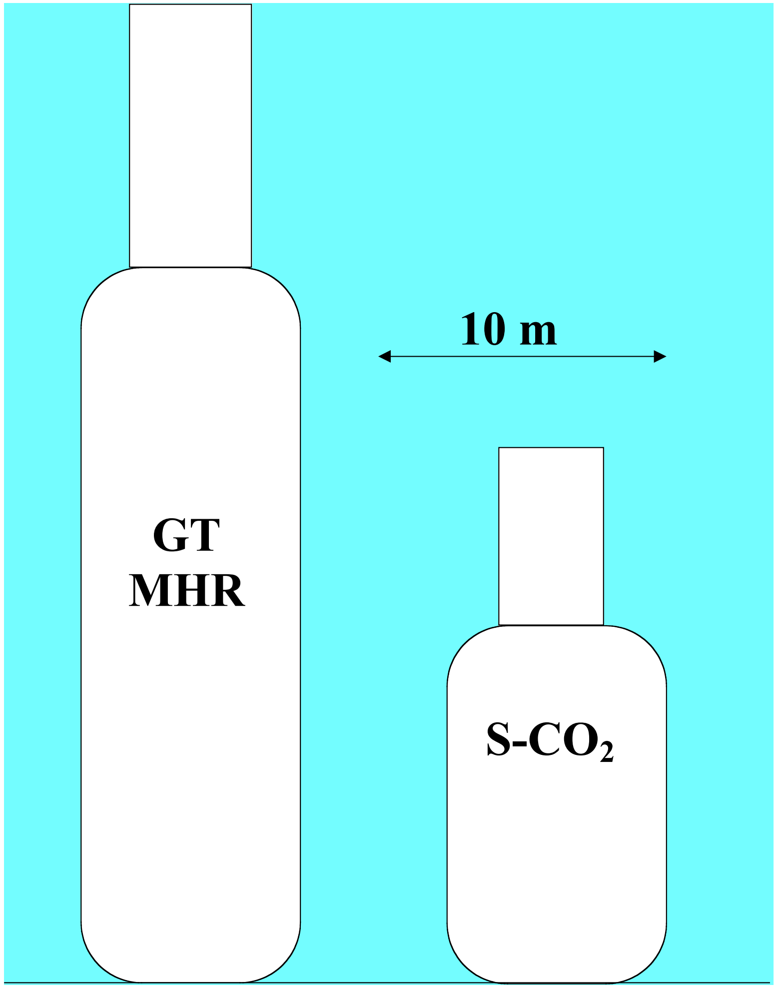
- Challenge of large power rating units
  - Economy of scale favors large ratings of nuclear units
  - Brayton cycle efficiency is sensitive to pressure drops
  - Large mass flow rates result in large ducts, pushing the design envelope of power plant experience
  - Connecting pipes should be short and large diameter
  - Largest high pressure pipes ~30" - unit power rating of Brayton cycles is limited to ~300MWe
  - This is an issue for all Brayton cycles – helium cycle performance even more sensitive to ducting because of lower pressure (2.6MPa versus 7.7MPa on low pressure side)
  - So how to design large SCO2 PCS unit at high efficiency?

Modules with integral layout (as GT-MHR)

Comparison of SCO2 and GT-MHR PCU-integral layout

Volume	S-CO_2/GT-MHR	550/1000m3
Power	S-CO_2/GT-MHR	288/288MWe
Power density	S-CO_2/GT-MHR	0.5/0.3MW/m3

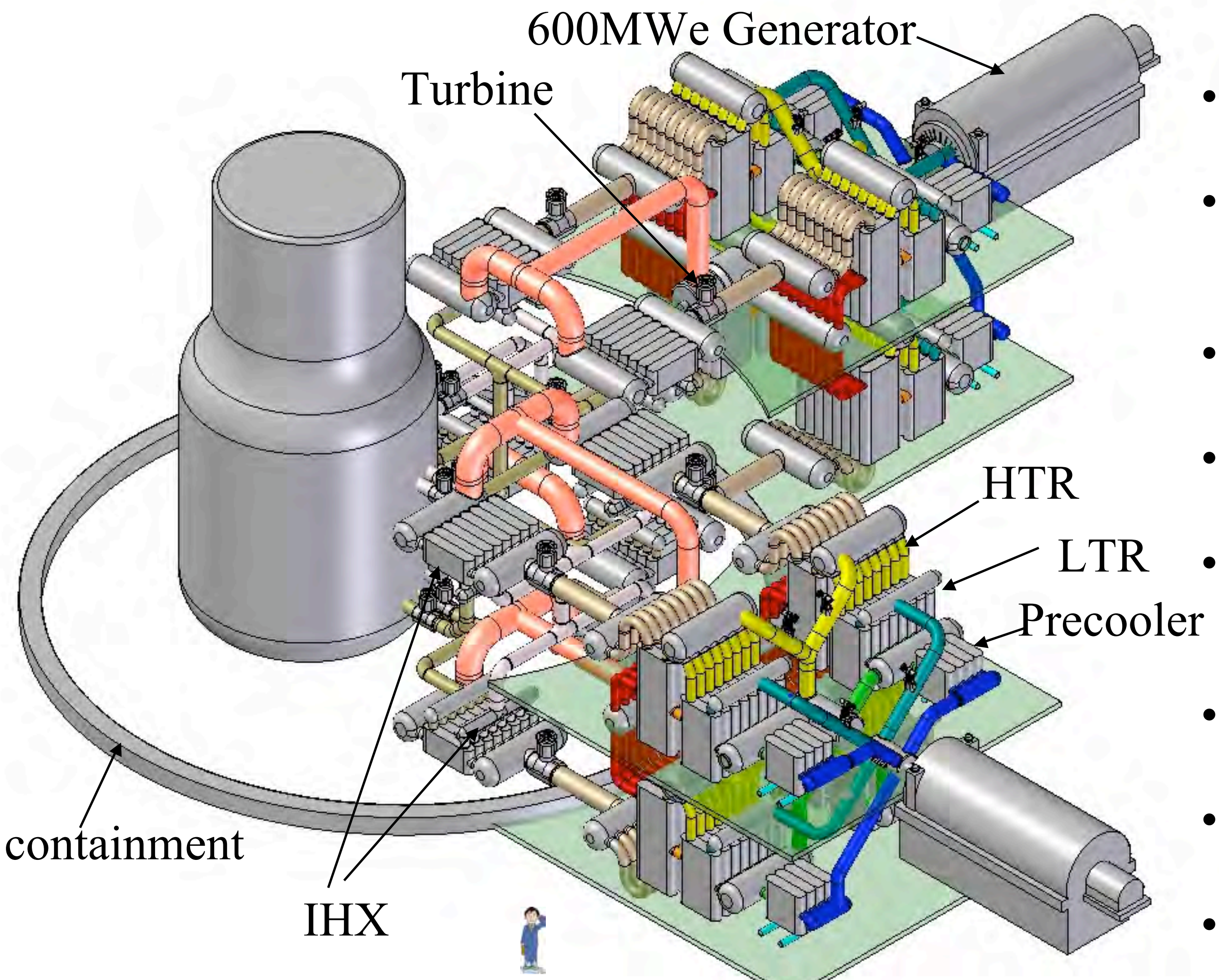
SCO2 more compact than GT-MHR



Integral layout

- Very compact
- low Δp (no pipes)
- difficult maintenance
- How to place valves?
- Vertical shaft – problem
- Limit 300MWe – need modules

Distributed layout – 1200MWe 2-loop plant

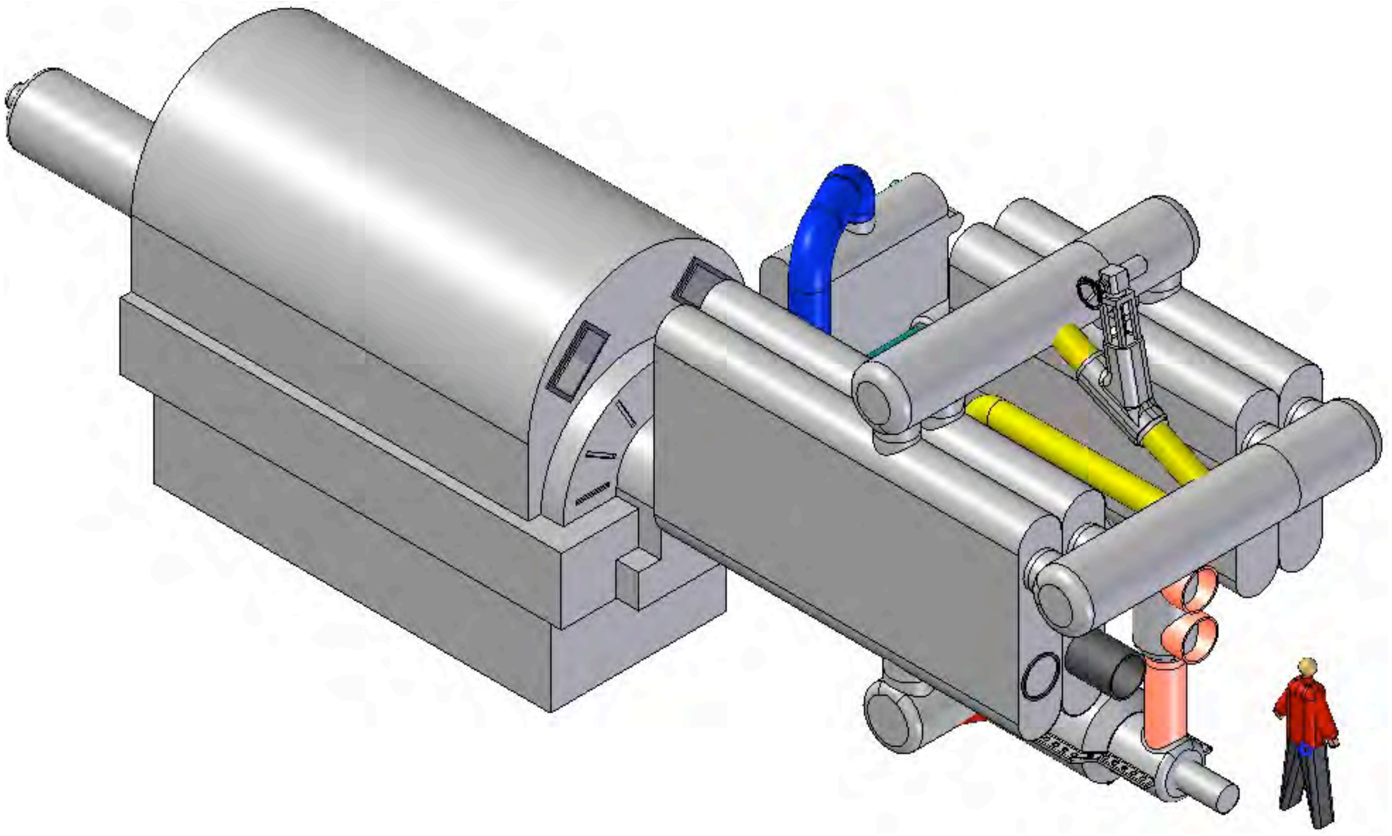


- Two 600MWe, 1800rpm shafts
- Each served by 4 HX trains, straddling the shaft, two floors
- Indirect cycle, IHX inside containment
- HEATRIC PCHE modules
- Turbine blade stress limits power to 600MWe per shaft
- Double flow turbine 1200MWe possible
- HP ducts limited to 1m
- Efficiency loss due to ducting Δp - 1%

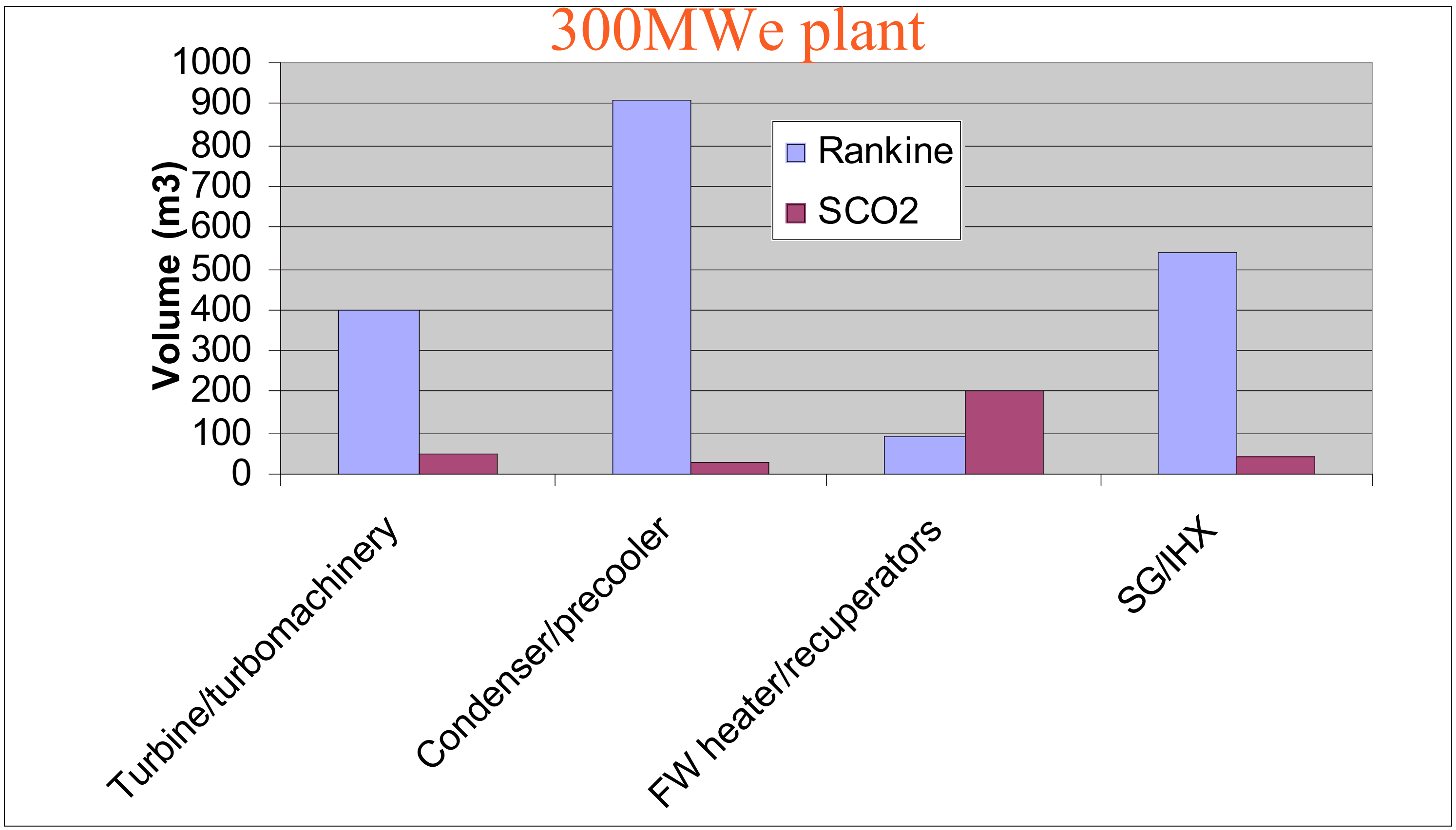
Modularity, inspectability, maintainability

50MWe Power Conversion Unit

- Small units - much simpler layout



Size comparison with Rankine PCS



- SCO2 cycle very compact
  - high expansion pressure (7.7MPa versus near vacuum)
  - small volumetric flow rate (high max. pressure of 20 MPa and high density near the critical point)
  - compact PCHEs (HTR – 27MW/m^3, LTR – 12MW/m^3, Precooler 22MW/m^3)
  - SCO2 needs 200m^3 of storage tanks for inventory control (compared with 1500m^3 for helium Brayton)
- Expectation – lower capital cost than Rankine cycle

Issues to be resolved

- Operation at partial load and cycle control; transient/accident response
- Radial compressor design and test of main compressor operation in the vicinity of critical point, operation in two-phase region during transients
- How to prevent dry ice formation in depressurization accidents
- Material compatibility with the supercritical CO2 (hot high density SCO2 may attack protective oxide layers)
- Detailed HX design including stresses, development of non-proprietary h & f correlations in zigzag channels
- Turbomachinery detailed design (housing, seals, inlet/outlet ducting and bearing components)
- R&D needs will be discussed in the last session