Studies of S-CO_2 Power Plant Pipe Design for Small Modular Sodium-cooled Fast Reactor

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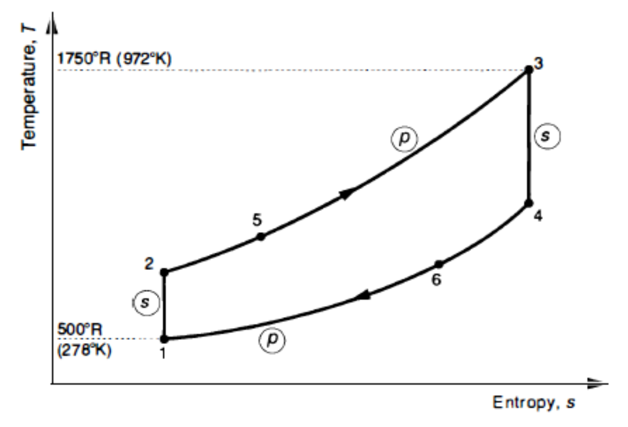
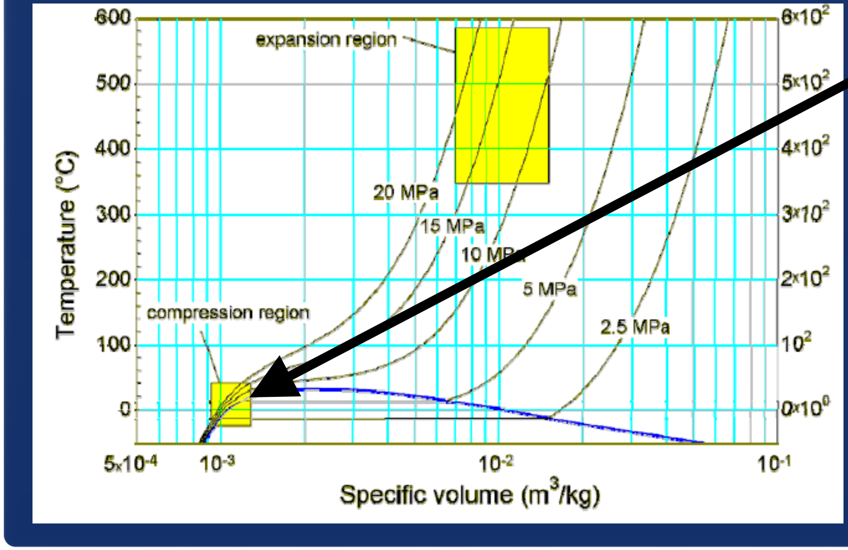
Ⅰ. Introduction

(1) S-CO_2 Cycle Background

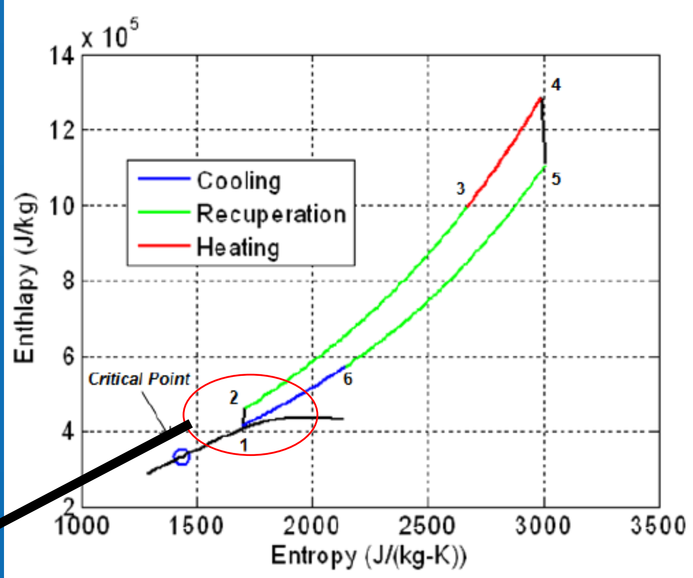
Ideal Gas Brayton Cycle



Specific Volume



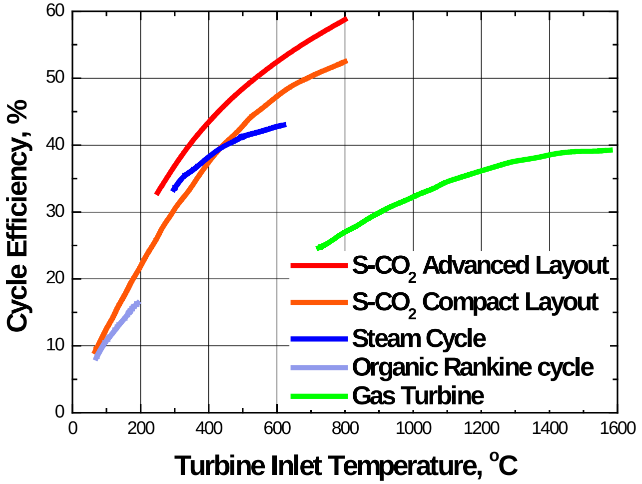
S-CO_2 Brayton Cycle



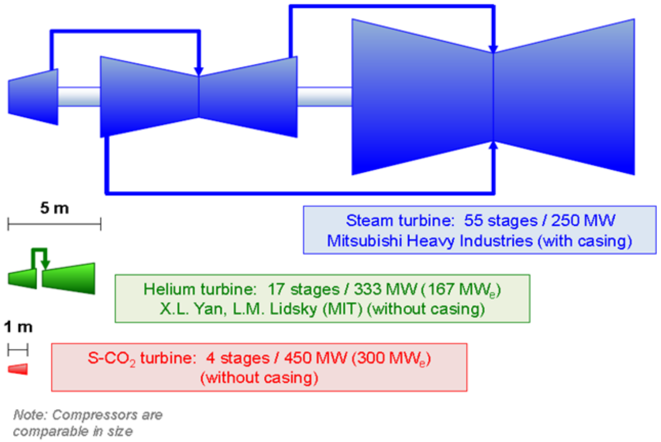
- S-CO_2 Cycle is a hybrid of Rankine and Brayton cycles to maximize advantages from both cycles

Ⅰ. Introduction

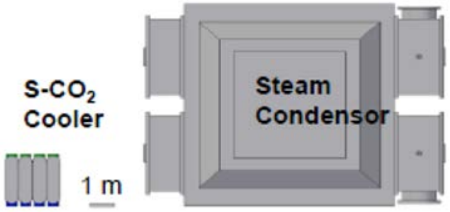
(2) Advantages of S-CO_2 Cycle



- High efficiency
  - Moderate turbine inlet temperature (450 ~ 750°C)
  - Small compressing work near the critical point
  - Better operational range and efficiency

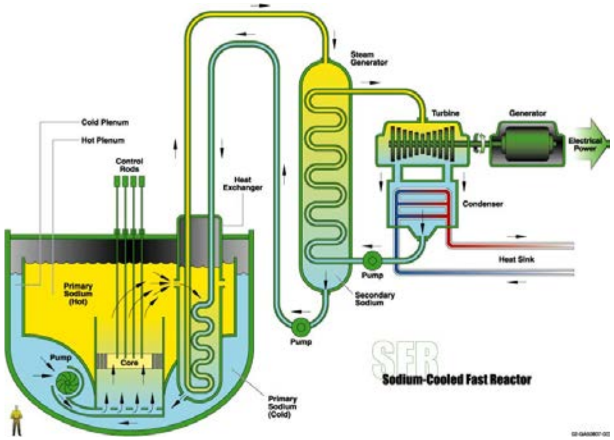


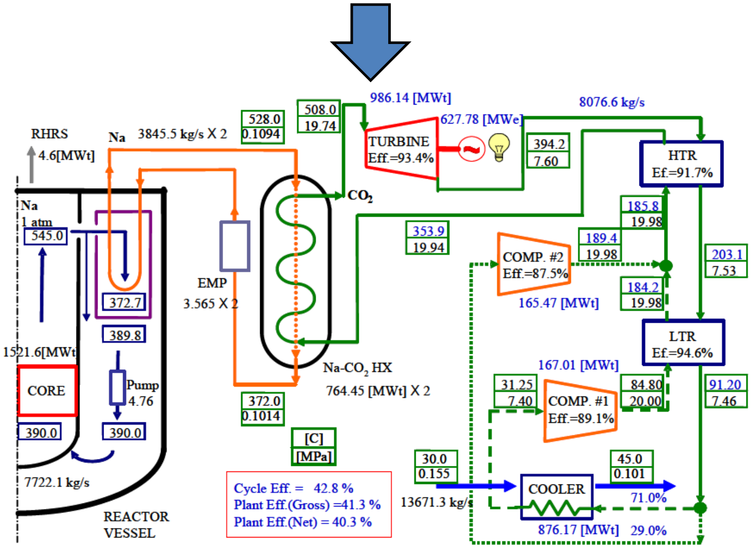
- Compact Turbomachinery & Heat exchanger
  - Compact Turbomachinery
    - Operating minimum pressure and density is higher than the steam Rankine cycle
  - High pressure operating Compact Heat exchanger
    - Wide operational range with high surface to volume ratio



Ⅰ. Introduction

(3) Sodium Fast Reactor (SFR)





SFR+S-CO_2 Cycle

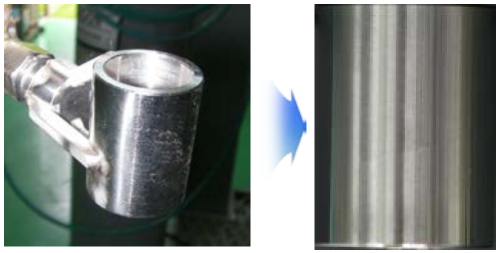
- SFR coupled to S-CO_2 cycle can substitute violent sodium-water reaction with milder sodium-CO_2 reaction which enhances safety.
- S-CO_2 cycle can achieve higher efficiency than water Rankine cycle.
- Due to its compactness and modularization, operation and maintenance are more flexible and easy.
- US, France, Japan and Korea are doing research over this application.

Ⅰ. Introduction

(4) SFR Applicability

- Improved Safety

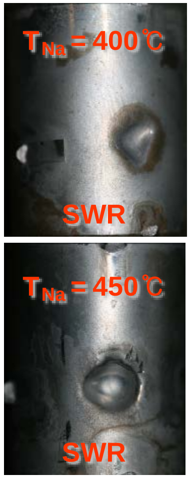
❑ Sodium-Water Reaction (SWR)



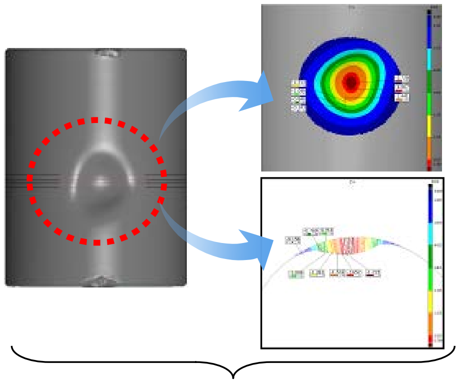
Before interaction

No solid particles

After interaction



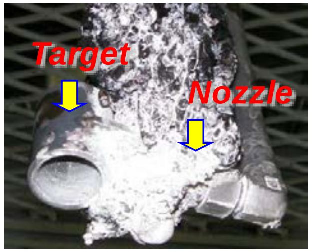
Surface degradation : 1.7~2.4 mm
(Nominal thkness : 3.5 mm)



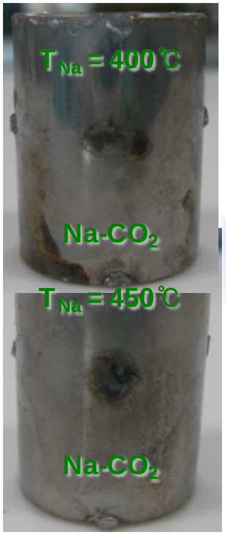
3D surface examination

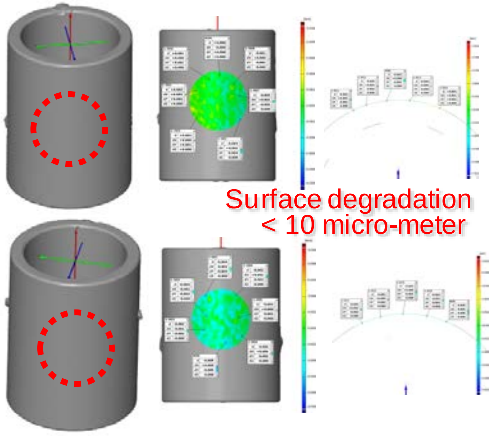
❑ Sodium-CO_2 interaction

Before interaction



After interaction



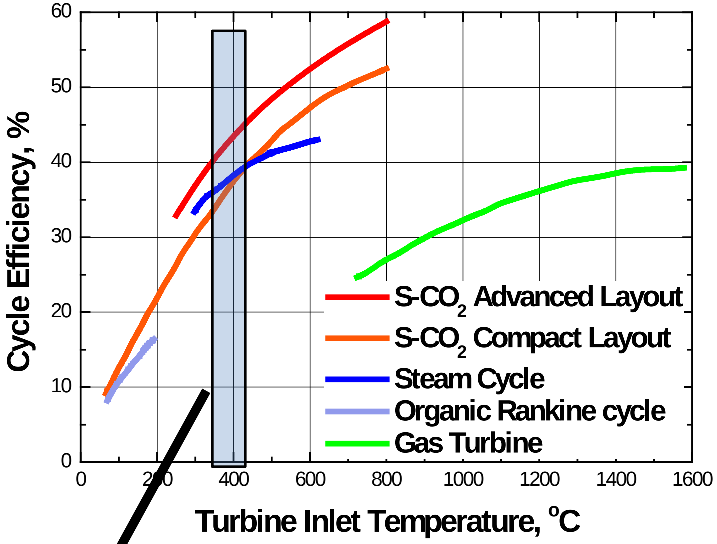


Surface degradation
< 10 micro-meter

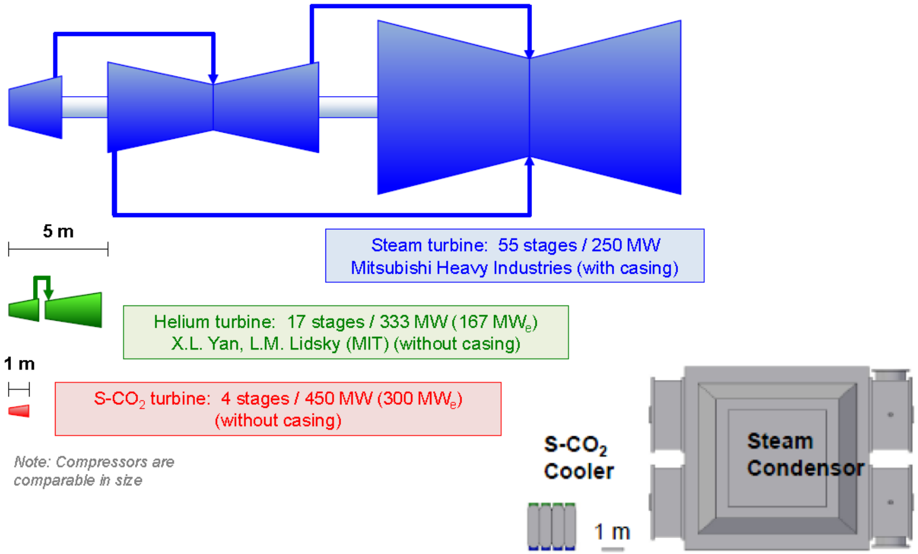
Ⅰ. Introduction

(4) SFR Applicability

- Improved Economy



Operating Condition of SFR

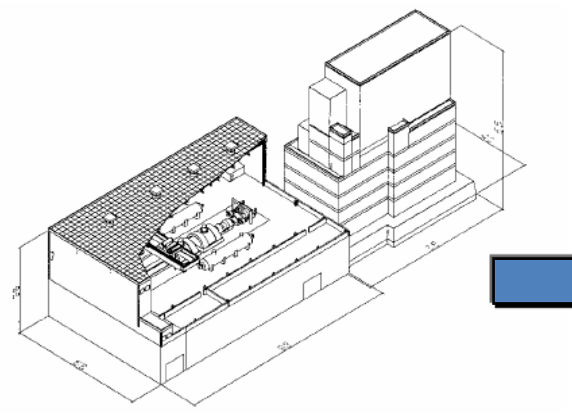


Steam turbine: 55 stages / 250 MW
Mitsubishi Heavy Industries (with casing)

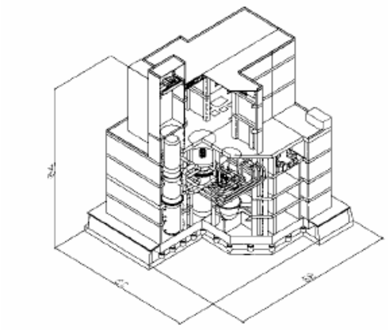
Helium turbine: 17 stages / 333 MW (167 MW$_e$)
X.L. Yan, L.M. Lidsky (MIT) (without casing)

S-CO$_2$ turbine: 4 stages / 450 MW (300 MW$_e$)
(without casing)

Note: Compressors are comparable in size



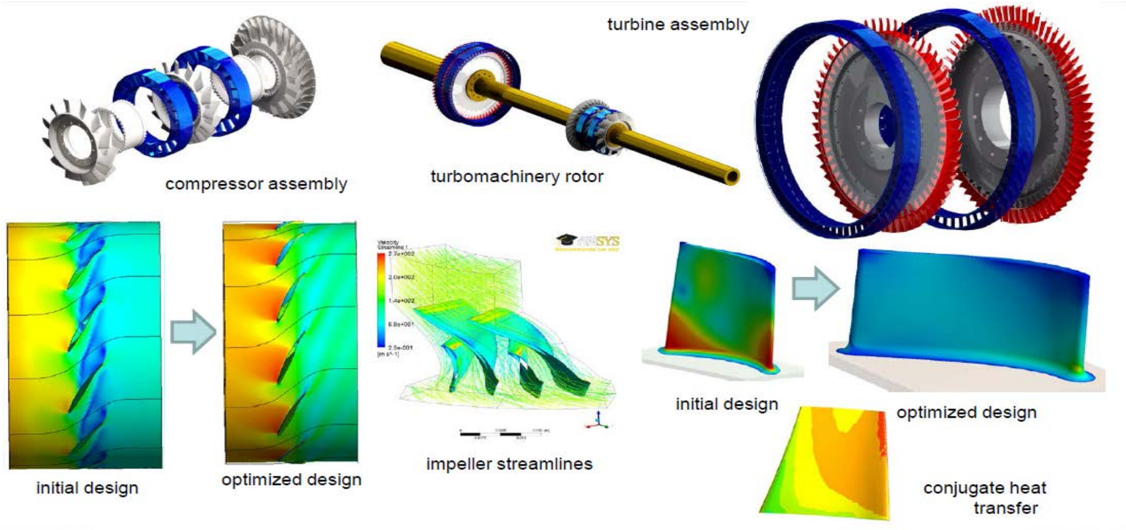
(a) Conventional Na-core-cooled steam-turbine plant
Volume: 160,000–170,000 m^3



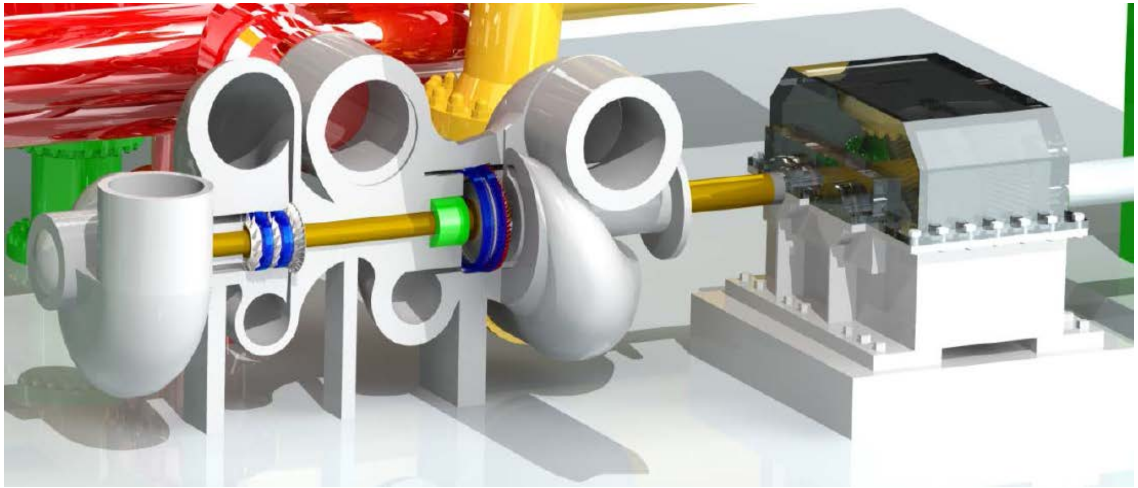
(b) Na-core-cooled S-CO$_2$ gas-turbine indirect cycle plant
Volume: 135,000 m^3

Ⅱ. S-CO_2 Power Plant Pipe Design

(1) Importance of Pipe Design



- ❖ Many studies focused on main system components.
- ❖ Compressor, turbine, and heat exchanger



- ❖ The cost of piping and piping related equipment approximately accounted for 7-8% of the total construction cost.
- ❖ Most of the leakage occurred in a pipe.
- ❖ Footprint is determined by pipe arrangement.

*Reference: Supercritical CO_2 Advanced Brayton Cycle Design, Mechanical and Aerospace Engineering, Carleton University

Ⅱ. S-CO_2 Power Plant Pipe Design

(2) Characteristic of S-CO_2 about pipe design

Section Condition	T (℃)	P (MPa)	ρ (kg/m3)			μ(Pa-s)[$\times 10^{-5}$]		
			Water	S-CO_2	Air	Water	S-CO_2	Air
① Turbine Inlet	505.00	19.78	49.1	106.9	68.6	4	4	4
② HT Recuperator HS Inlet	396.68	7.88	22.5	51.5	33.3	3	4	4
③ LT Recuperator HS Inlet	164.00	7.73	908.8	105.2	60.9	17	2	3
④ LT Recuperator HS Outlet	65.19	7.58	981.7	166.7	78.0	41	2	2
⑤ Precooler Inlet	65.19	7.58	982.2	166.9	78.0	41	2	2
⑥ MC Inlet	31.25	7.50	998.4	598.8	88.4	76	4	2
⑦ LT Recuperator CS Inlet	61.28	20.00	991.7	722.6	198.2	47	6	2
⑧ LT Recuperator CS Outlet	151.24	19.93	920.4	312.5	149.2	18	3	3
⑨ RC Inlet	65.19	7.58	981.7	166.9	78.0	41	2	2
⑩ RC Outlet	153.42	19.93	925.9	322.3	151.3	18	3	3
⑪ HT Recuperator CS Inlet	152.03	19.93	920.4	312.6	149.2	18	3	3
⑫ IHX Inlet	351.21	19.85	69.6	134.9	84.5	3	4	4

Ⅱ. S-CO_2 Power Plant Pipe Design

(3) Layout and Properties of S-CO_2 Brayton Cycle

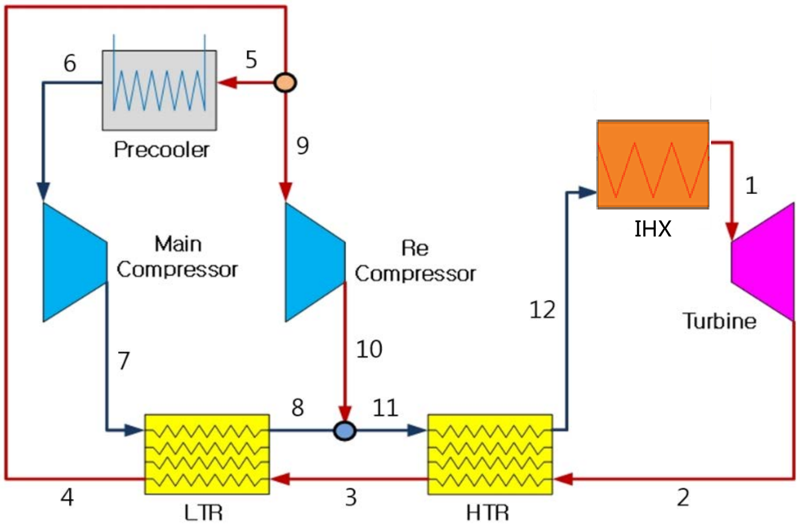


Fig. 1 S-CO_2 recompressing cycle layout

- Primary system specification:

IHX hotside outlet Pressure	0.110MPa
IHX hotside outlet Temp.	525℃
IHX hotside mass flow rate	1017.03kg/s

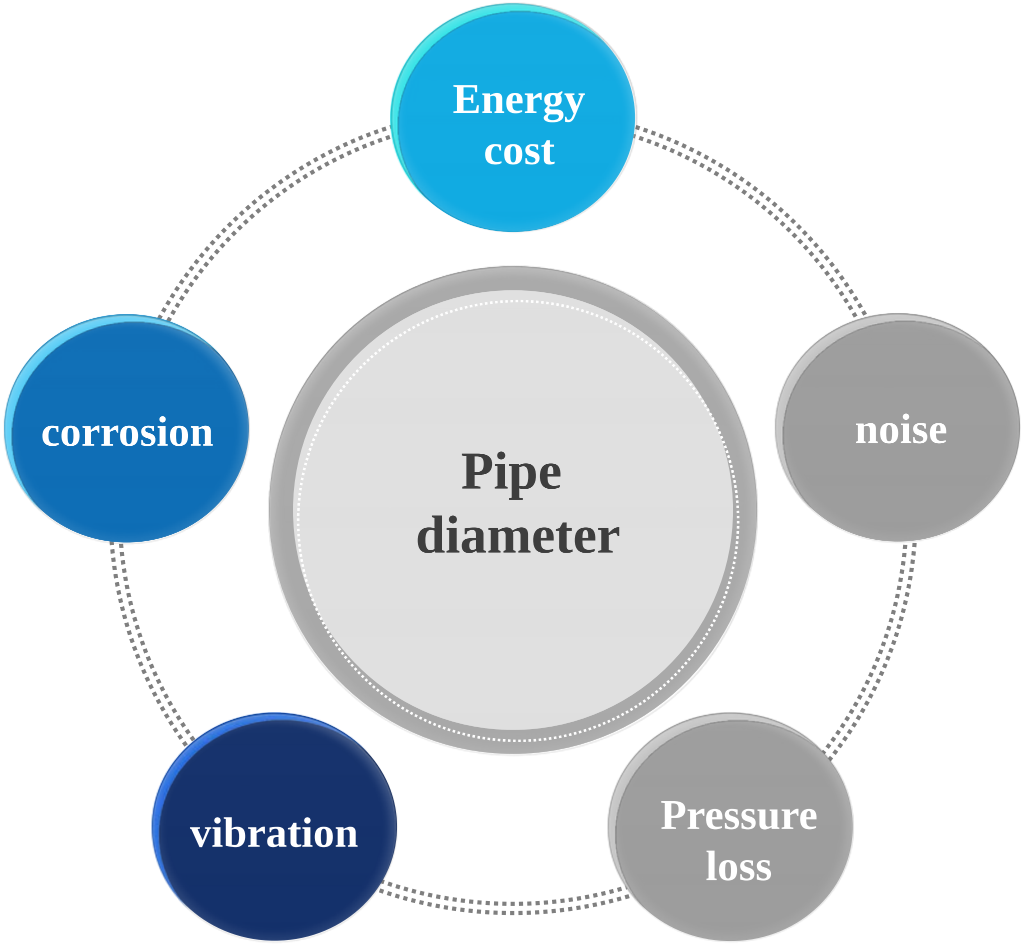
- Cycle design variables and specification:

Recompressing cycle		Net output	75.0MW
Maximum pressure	20MPa	HTR hot side pressure drop	150kPa
Turbine inlet temp.	505℃	HTR cold side pressure drop	75kPa
Turbine efficiency	92%	LTR hot side pressure drop	150kPa
Main and Re-compressor efficiency	88/90%	LTR cold side pressure drop	75kPa
Recompressing fraction	36%	Precooler CO_2 pressure drop	75kPa
Recuperator effectiveness	95%	IHX CO_2 pressure drop	75kPa
CO2 mass flow rate	912.75kg/s	Cycle thermal efficiency	43.55%

❖ Reducing the waste heat and increasing the recuperated heat to increase the η_{th}.

Ⅱ. S-CO_2 Power Plant Pipe Design

(4) Determination of Pipe Diameter and Thickness for S-CO_2 Cycle



Pipe diameter

Energy cost

noise

Pressure loss

vibration

corrosion

Flow Velocity

$$V = f_{pv}/\rho^{0.3}$$

by Ronald W. Capps(Chem. Eng. 1995.6)

V : optimal flow velocity $[m/s]$

f_{pv} : pipe velocity factor $[m(\frac{kg}{m^3})^{0.3}/s]$

ρ : density of flow $[\frac{kg}{m^3}]$

PIPE VELOCITY FACTORS	
Motive Energy Source	m $(kg/m^3)^{0.3}$ /s
Centrifugal Pump, Blower	14
Compressor Pipe dia<6in. Pipe dia>6in.	24 29
Steam Boiler	63 ~ 68

Ⅱ. S-CO_2 Power Plant Pipe Design

(4) Determination of Pipe Diameter and Thickness for S-CO_2 Cycle

The procedure to comply with the ASME standard is as follows:

① After obtaining the average diameter by optimal velocity, calculate the minimum required thickness.

② Set the outside diameter and thickness in accordance with the ASME standard by selecting the proper material.

③ In the case that the flow velocity is more than the optimal velocity, select larger outside diameter pipe and check whether it is on the ASME standard.

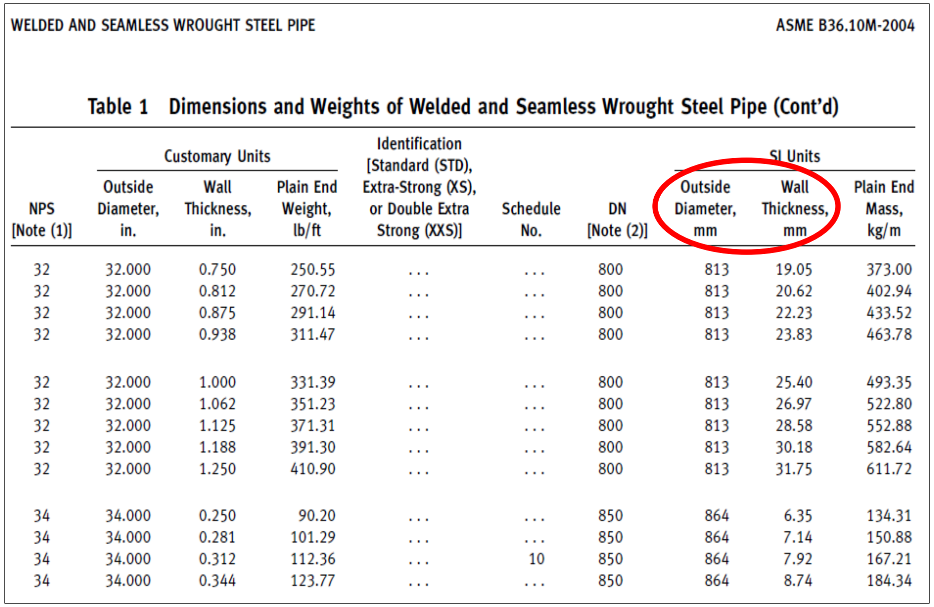
④ If there isn't standard thickness which is suitable for designed diameter or diameter is too large compared to the system, find the proper minimum required thickness by reducing the diameter lying down under pressure drop.

⑤ after 1-4 process, re-examine whether the thickness is longer than the revised minimum required thickness.

Minimum thickness

$$t_m = \frac{PD_0}{2(SE+Py)} + A$$

t_m: minimum required wall thickness [m],
Do: outside diameter of pipe [m],
E: weld joint efficiency,
A: additional thickness [m]
P: internal design pressure [Pa]
S: maximum allowable stress [Pa]
Y: coefficient



WELDED AND SEAMLESS WROUGHT STEEL PIPE

ASME B36.10M-2004

Table 1 Dimensions and Weights of Welded and Seamless Wrought Steel Pipe (Cont'd)

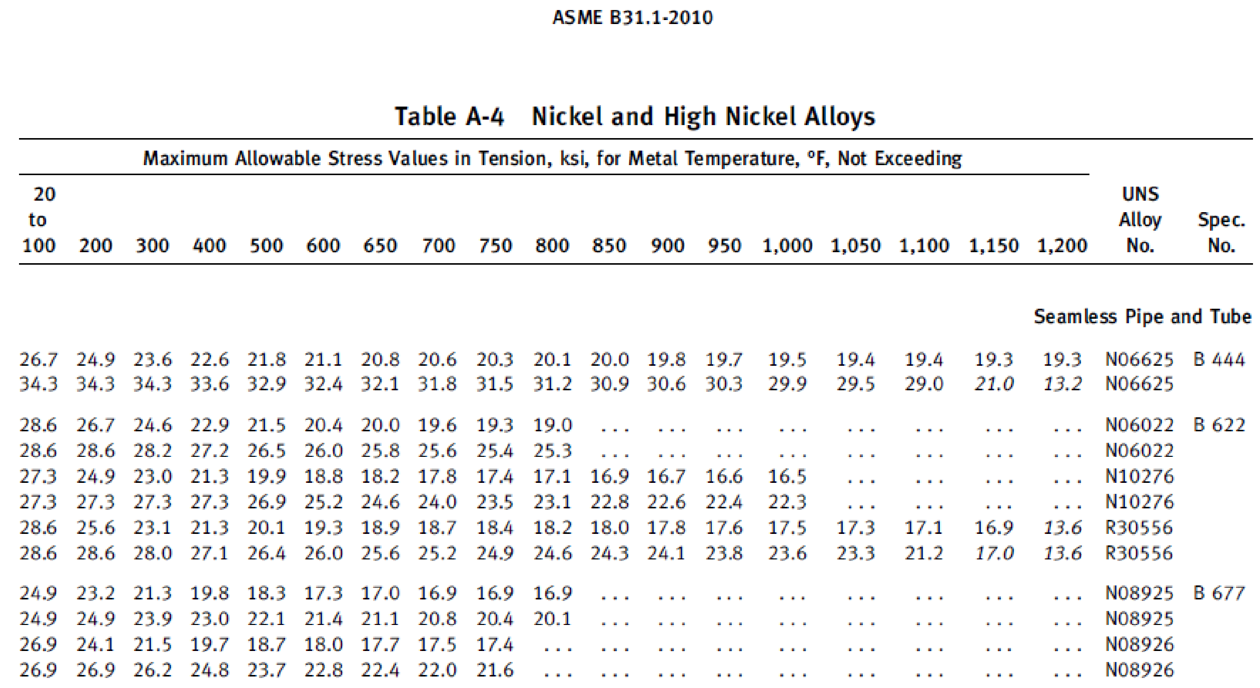
	Customary Units						SI Units		
NPS [Note (1)]	Outside Diameter, in.	Wall Thickness, in.	Plain End Weight, lb/ft	Identification [Standard (STD), Extra-Strong (XS), or Double Extra Strong (XXS)]	Schedule No.	DN [Note (2)]	Outside Diameter, mm	Wall Thickness, mm	Plain End Mass, kg/m
32	32.000	0.750	250.55	...	...	800	813	19.05	373.00
32	32.000	0.812	270.72	...	...	800	813	20.62	402.94
32	32.000	0.875	291.14	...	...	800	813	22.23	433.52
32	32.000	0.938	311.47	...	...	800	813	23.83	463.78
32	32.000	1.000	331.39	...	...	800	813	25.40	493.35
32	32.000	1.062	351.23	...	...	800	813	26.97	522.80
32	32.000	1.125	371.31	...	...	800	813	28.58	552.88
32	32.000	1.188	391.30	...	...	800	813	30.18	582.64
32	32.000	1.250	410.90	...	...	800	813	31.75	611.72
34	34.000	0.250	90.20	...	...	850	864	6.35	134.31
34	34.000	0.281	101.29	...	...	850	864	7.14	150.88
34	34.000	0.312	112.36	...	10	850	864	7.92	167.21
34	34.000	0.344	123.77	...	...	850	864	8.74	184.34

Ⅱ. S-CO₂ Power Plant Pipe Design

(4) Determination of Pipe Diameter and Thickness for S-CO₂ Cycle

- The optimal figures in accordance with the ASME standard

S.C.	Nominal Pipe Size	External Diameter(m)	Internal Diameter(m)	Schedule No.	Thickness(m)	Material type
①	24	0.610	0.553	60	0.02858	Nickel and High Nickel Alloys, N06625, B 444
②	28	0.711	0.679	30	0.01588	
③	28	0.711	0.682	20	0.01427	
④	28	0.711	0.676	30	0.01748	
⑤	28	0.711	0.676			
⑥	24	0.610	0.578			
⑦	22	0.559	0.502			
⑧	24	0.610	0.556			
⑨	28	0.711	0.676			
⑩	24	0.610	0.556			
⑪	24	0.610	0.556			
⑫	28	0.610	0.556			



ASME B31.1-2010

Table A-4 Nickel and High Nickel Alloys

Maximum Allowable Stress Values in Tension, ksi, for Metal Temperature, °F, Not Exceeding																			
20 to 100	200	300	400	500	600	650	700	750	800	850	900	950	1,000	1,050	1,100	1,150	1,200	UNS Alloy No.	Spec. No.
																		Seamless Pipe and Tube	
26.7	24.9	23.6	22.6	21.8	21.1	20.8	20.6	20.3	20.1	20.0	19.8	19.7	19.5	19.4	19.4	19.3	19.3	N06625	B 444
34.3	34.3	34.3	33.6	32.9	32.4	32.1	31.8	31.5	31.2	30.9	30.6	30.3	29.9	29.5	29.0	*21.0*	*13.2*	N06625	
28.6	26.7	24.6	22.9	21.5	20.4	20.0	19.6	19.3	19.0	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	N06022	B 622
28.6	28.6	28.2	27.2	26.5	26.0	25.8	25.6	25.4	25.3	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	N06022	
27.3	24.9	23.0	21.3	19.9	18.8	18.2	17.8	17.4	17.1	16.9	16.7	16.6	16.5	. . .	. . .	. . .	. . .	N10276	
27.3	27.3	27.3	27.3	26.9	25.2	24.6	24.0	23.5	23.1	22.8	22.6	22.4	22.3	. . .	. . .	. . .	. . .	N10276	
28.6	25.6	23.1	21.3	20.1	19.3	18.9	18.7	18.4	18.2	18.0	17.8	17.6	17.5	17.3	17.1	16.9	*13.6*	R30556	
28.6	28.6	28.0	27.1	26.4	26.0	25.6	25.2	24.9	24.6	24.3	24.1	23.8	23.6	23.3	21.2	*17.0*	*13.6*	R30556	
24.9	23.2	21.3	19.8	18.3	17.3	17.0	16.9	16.9	16.9	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	N08925	B 677
24.9	24.9	23.9	23.0	22.1	21.4	21.1	20.8	20.4	20.1	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	N08925	
26.9	24.1	21.5	19.7	18.7	18.0	17.7	17.5	17.4	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	N08926	
26.9	26.9	26.2	24.8	23.7	22.8	22.4	22.0	21.6	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	N08926	

Ⅱ. S-CO$_2$ Power Plant Pipe Design

(4) Determination of Pipe Diameter and Thickness for S-CO$_2$ Cycle

Pressure drop

$$\Delta p = f \cdot \frac{L}{D} \cdot \frac{\rho V^2}{2}$$

Δp: $pressure\ drop[Pa]$
L: length of pipe[m]
ρ: density of flow[kg/m^3]

f: friction factor
D: internal diameter of pipe[m]
V: optimal flow velocity[m/s]

Friction Factor

$$\frac{1}{\sqrt{f}} = -1.8 log[(\frac{\epsilon/D}{3.7})^{1.11} + \frac{6.9}{Re}]$$

ϵ: roughness

Re: Reynolds number of flow

Minor losses

$$\Delta p = K_L \cdot \frac{L}{D} \cdot \frac{\rho V^2}{2}$$

K_L: loss coefficient

[0.3(90°C), 0.2(45°C)]

Ⅱ. S-CO_2 Power Plant Pipe Design

(4) Determination of Pipe Diameter and Thickness for S-CO_2 Cycle

- The optimal figures and pressure drop

S.C.	Nominal Pipe Size	External Diameter(m)	Internal Diameter(m)	Schedule No.	Thickness(m)	Length (m)	Pressure drop (kPa)	HX Pressure drop (kPa)
①	24	0.610	0.553	60	0.02858	0.7	**39.27**	**75**
②	28	0.711	0.679	30	0.01588	1	**25.67**	-
③	28	0.711	0.682	20	0.01427	4	**48.47**	**150**
④	28	0.711	0.676	30	0.01748	0.7	11.91	**150**
⑤	28	0.711	0.676	30	0.01748	1	5.61	-
⑥	24	0.610	0.578	30	0.01588	0.5	0.85	**75**
⑦	22	0.559	0.502	80	0.02858	1	3.25	-
⑧	24	0.610	0.556	60	0.02697	4	17.52	**75**
⑨	28	0.711	0.676	30	0.01748	2	2.70	-
⑩	24	0.610	0.556	60	0.02697	1.5	2.46	-
⑪	24	0.610	0.556	60	0.02697	0.5	4.82	-
⑫	28	0.610	0.556	60	0.02697	2.7	**82.44**	**75**
Total pressure drop (kPa)							244.97	600

- Thermal efficiency

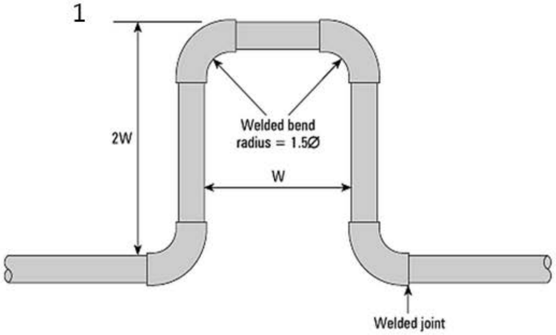
43.55% (75.0MWe) ⟶ 43.07% (74.2MWe)

Ⅱ. S-CO_2 Power Plant Pipe Design

(5) Design to compensate for thermal expansion

- The types of expansion joint

1



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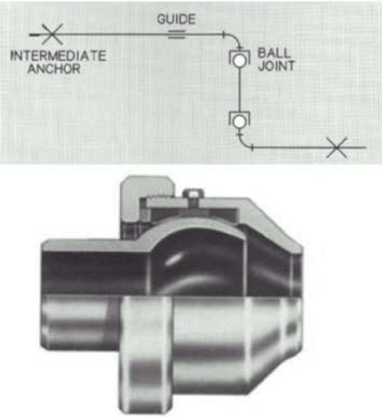
3



4

5

1. Hard U-shape loop, 2. flexible loop, 3. bend, 4. bellows and 5. sliding

Ⅱ. S-CO_2 Power Plant Pipe Design

(5) Design to compensate for thermal expansion

- Sizing the Recompressing Cycle
  - Turbo-machinery design

Main Compressor	
Rotating Speed	7200rpm
Diameter	0.722m
Length	1.082m
Efficiency	88%

Turbine	
Rotating Speed	7200rpm
Diameter	1.287m
Length	1.931m
Efficiency	92%

Re compressor			
1st stage		2nd stage	
Rotating Speed	7200rpm	Rotating Speed	7200rpm
Diameter	0.908m	Diameter	0.789m
Length	1.361m	Length	1.184m
Efficiency		90%	

Ⅱ. S-CO_2 Power Plant Pipe Design

(5) Design to compensate for thermal expansion

- Sizing the Recompressing Cycle
  - Heat Exchanger design
    - Channel D = 1.8mm, 1:1 Laminated structure

IHX	
Length	3.00m
Volume	0.881m^3
Hot side dP	110kPa
Cold side dP	75kPa
Pumping power	225.9kW

High Temperature Recuperator	
Length	4.79m
Volume	8.165m^3
Hot side dP	149kPa
Cold side dP	52kPa
Effectiveness	95.0%

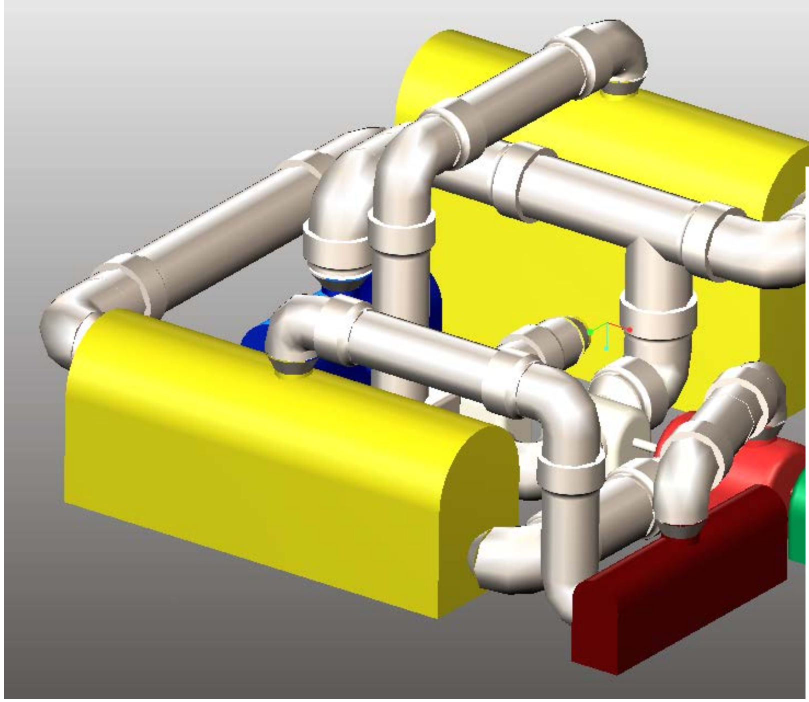
Low Temperature Recuperator	
Length	4.69m
Volume	15.31m^3
Hot side dP	148kPa
Cold side dP	18kPa
Effectiveness	95.0%

Precooler	
Length	2.271m
Volume	1.542m^3
Hot side dP	75kPa
Cold side dP	222kPa
Pumping power	441.9kW

Ⅱ. S-CO₂ Power Plant Pipe Design

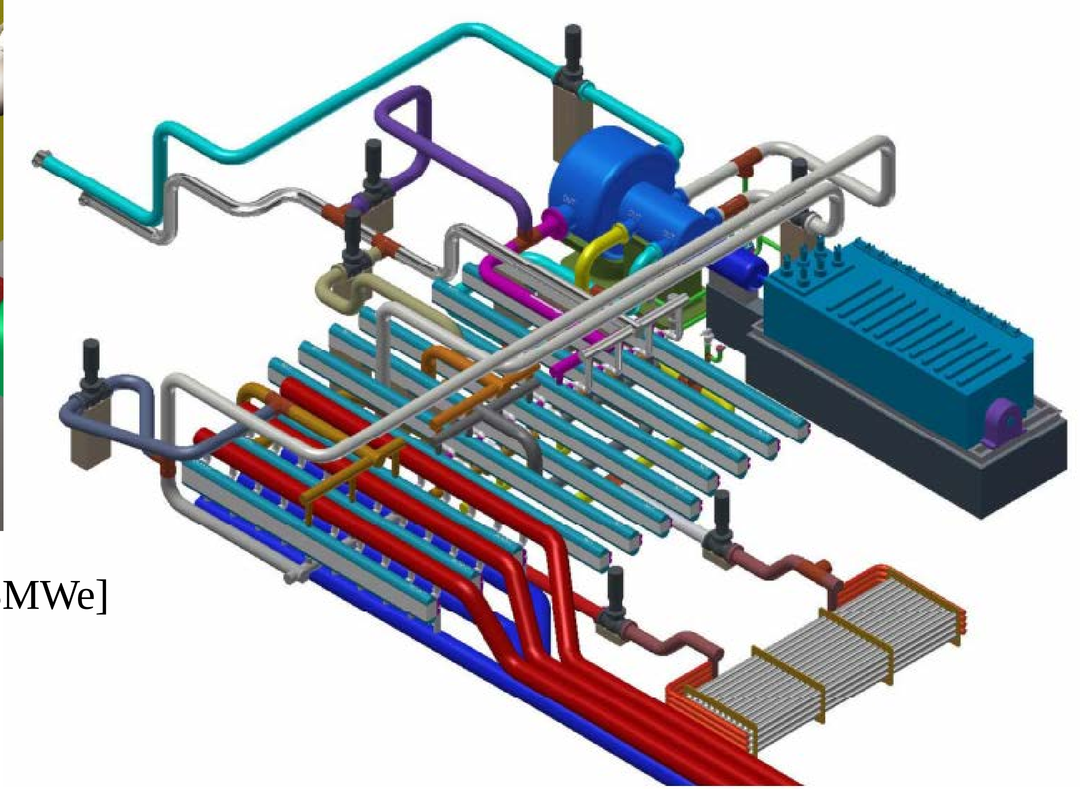
(5) Design to compensate for thermal expansion

- Sizing the Recompressing Cycle
  - Whole layout



- Total volume: 9.76m * 7.16m * 3.95m [75MWe]

- Total volume: (About) 21m * 15.5m * 6.5m [100MWe]

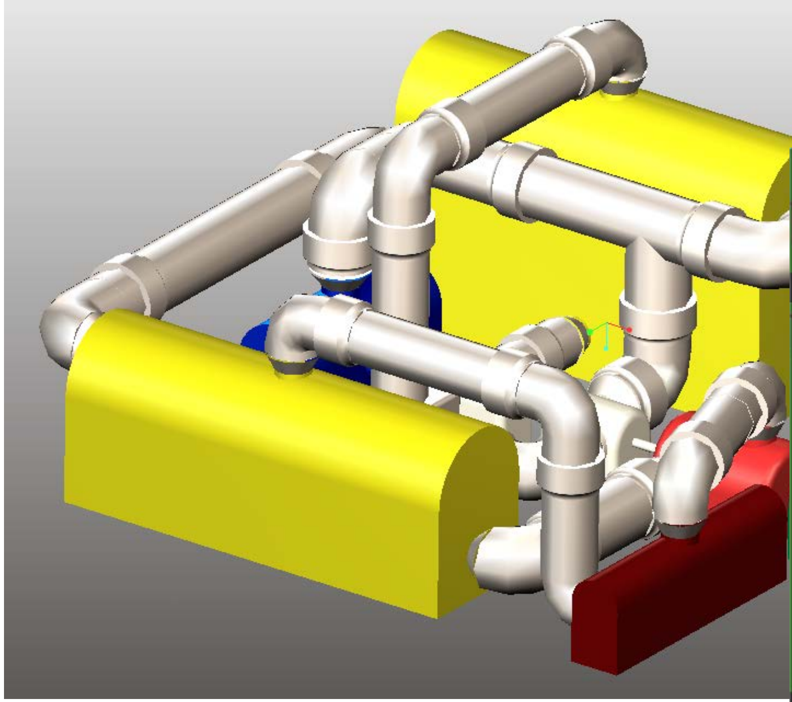


(100MWe) S-CO2 Brayton Cycle Power Converter, Argonne National Laboratory Argonne, Illinois USA

Ⅱ. S-CO$_2$ Power Plant Pipe Design

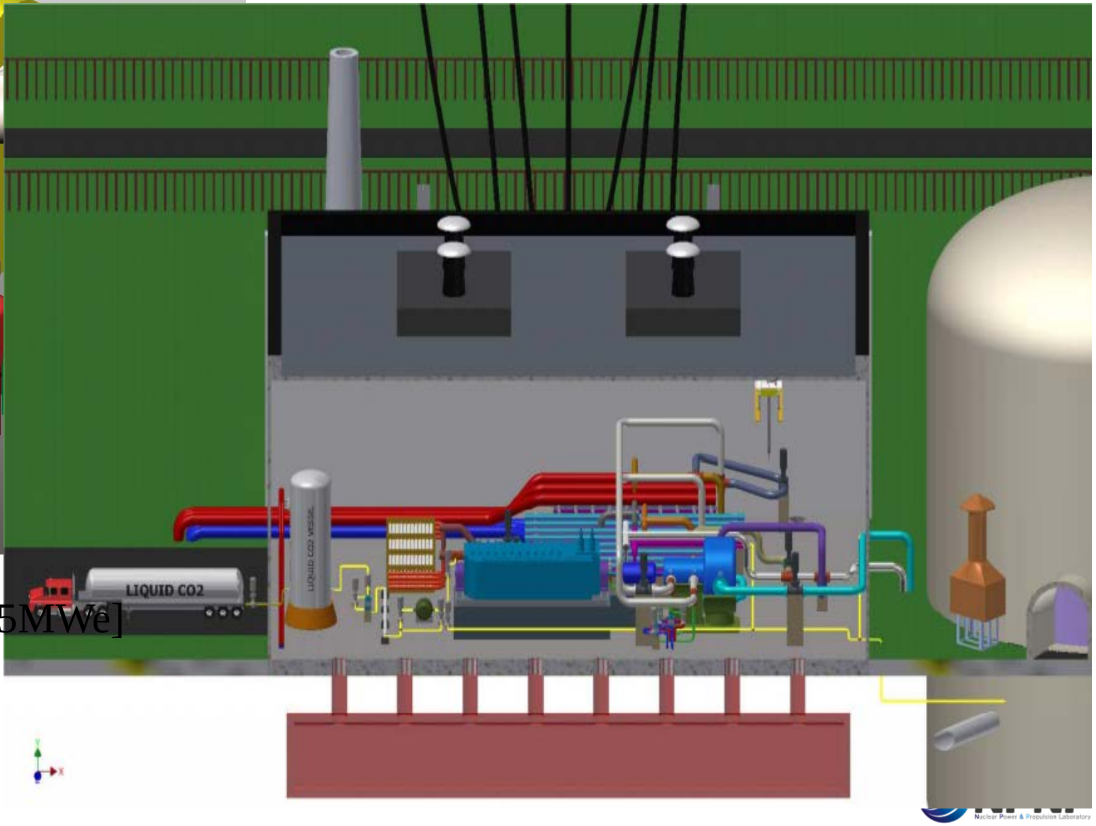
(5) Design to compensate for thermal expansion

- Sizing the Recompressing Cycle
  - Whole layout



- Total volume: 9.76m * 7.16m * 3.95m [75MWe]

- Total volume: (About) 21m * 15.5m * 6.5m [100MWe]



(100MWe) S-CO2 Brayton Cycle Power Converter, Argonne National Laboratory Argonne, Illinois USA

Ⅲ. Conclusion

(1) Summary

- Advantages of S-CO_2 cycle
  - Prevention of SWR
  - Relatively high efficiency (450 ~ 750°C)
  - Physically compact size

- Importance of pipe design
  - S-CO_2 power plant pipe design is more complex than existing power plant
    - high temperature, pressure condition and high mass flow rate
  - Re-confirm the compactness and simplicity of the S-CO_2 cycle
  - Conduct realistic and safe pipe design by considering thermal expansion

- Cycle efficiency applying pipe pressure drop
  - Still higher than existing steam Rankine cycle

Ⅲ. Conclusion

(2) Further works

- Additional study for a larger system such as 300MW class system in MIT report
  - When the S-CO_2 system becomes large, the pipe diameter may exceed the current ASME standard.
  - More innovative approach will be needed for the S-CO_2 pipe design.

- Conduct the process engineering considering capital cost, operating cost and life-cycle cost
  - To economically design the pipe of S-CO_2 cycle, optimal flow velocity is needed.
  - To support process engineering, theoretical calculation and empirical experiment are needed.

THANK YOU