The First COE-INES International Symposium
at Keio Plaza Hotel, November 3, 2004

Super Critical CO_2 Gas Turbine Cycle FBRs

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Program Title：

Innovative Nuclear Energy Systems for Sustainable Development of the World

1. **Advanced nuclear energy systems**
   - a) **Advanced reactors**
     - **CO_2 gas turbine reactors**
     - **Pb-Bi cooling fast reactors**
   - b) **Advanced partition and transmutation**
   - c) **Advanced energy utilization**
     - **Waste heat recovery system**
     - **Hydrogen production**
     - **Electricity and heat storage**
2. **Development of human resources**

Use of Na as Coolant in FBRs

Advantage:

- Efficient heat removal of tight fuel pin lattice.

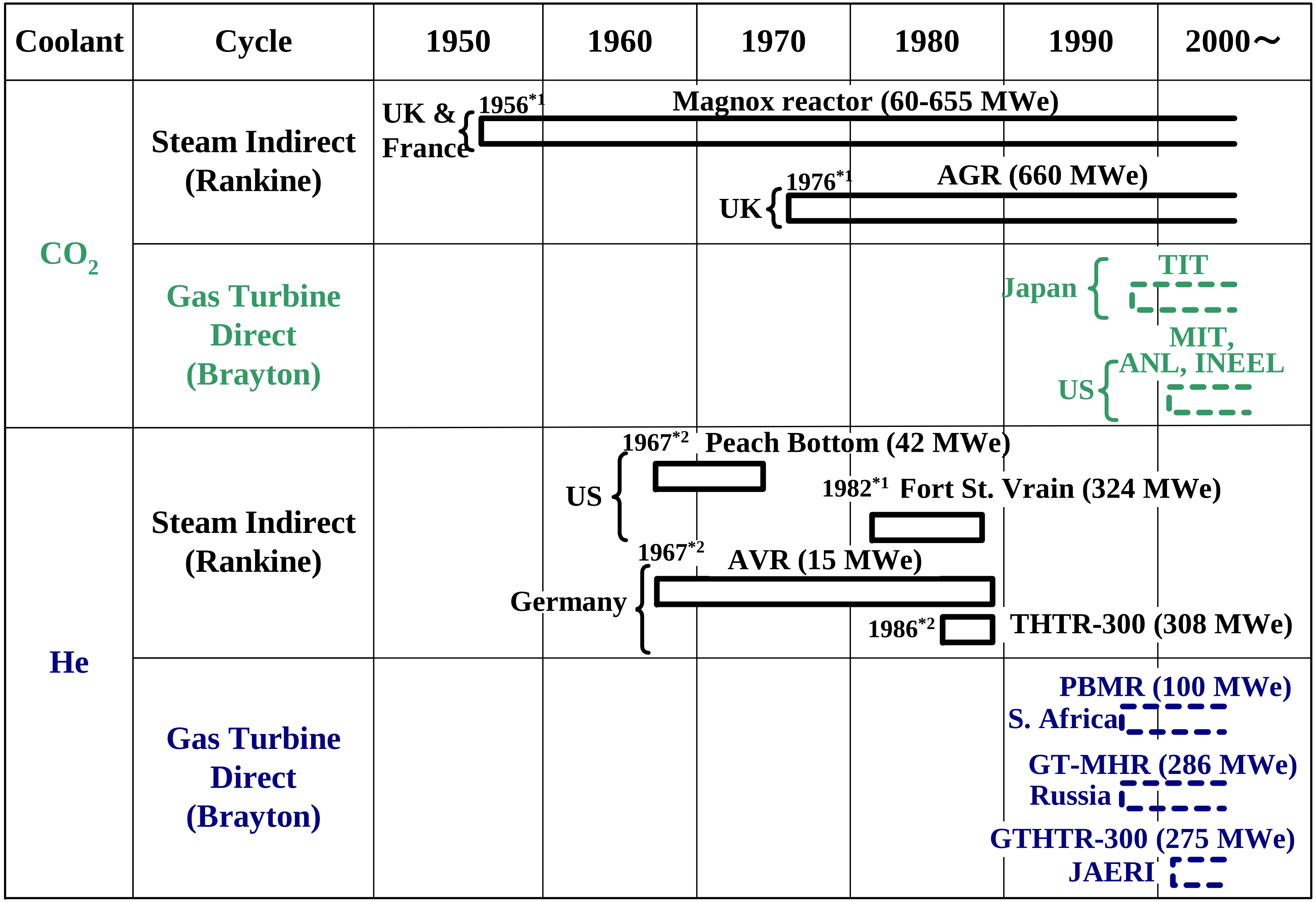
Disadvantages:

1) Positive sodium void reactivity.

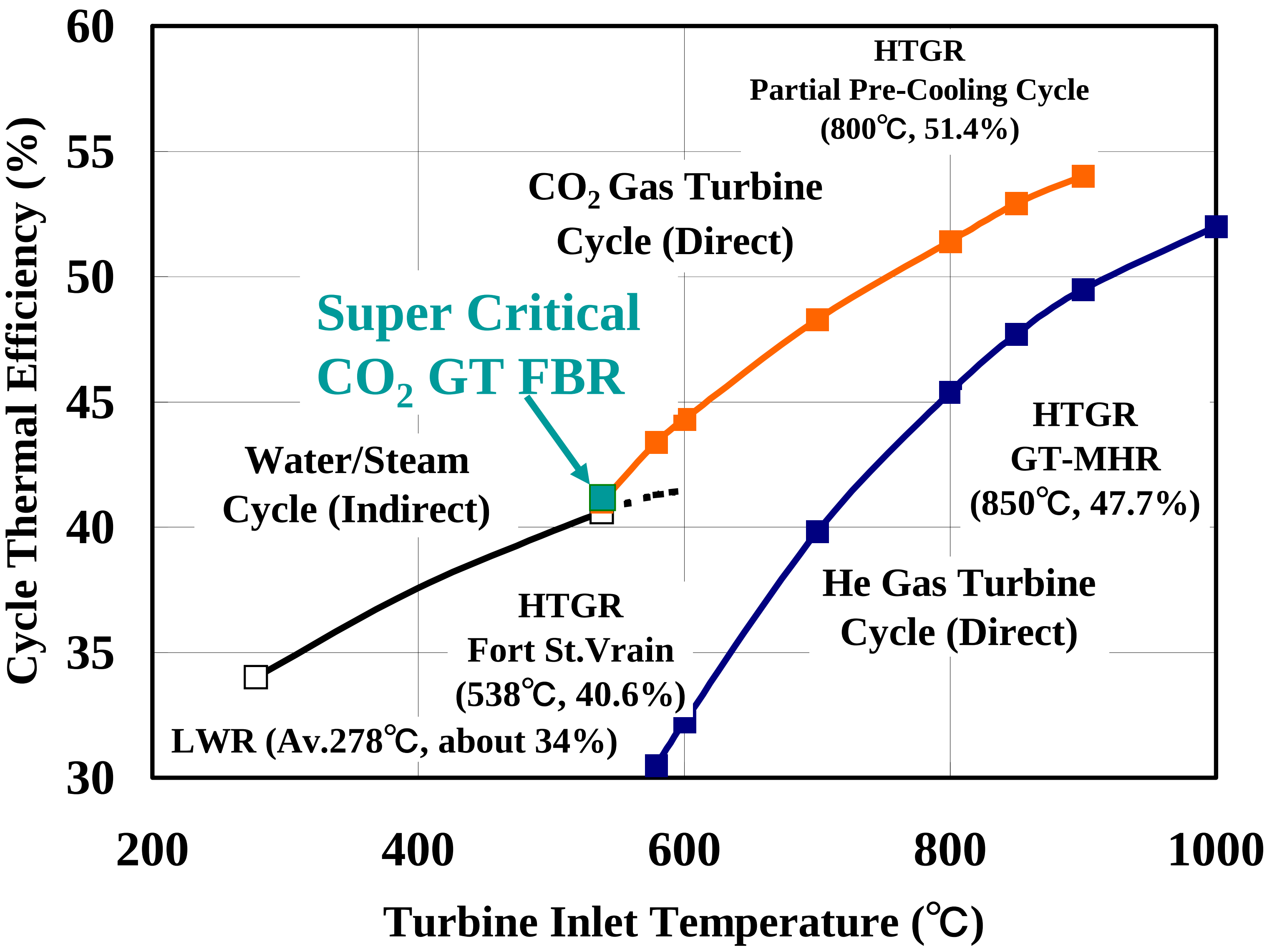
2) Hazardous (chemical) reaction with water or air in the event of sodium leakage.

3) Higher capital cost mainly ascribed to the need of extra intermediate cooling loops relative to light water reactors.

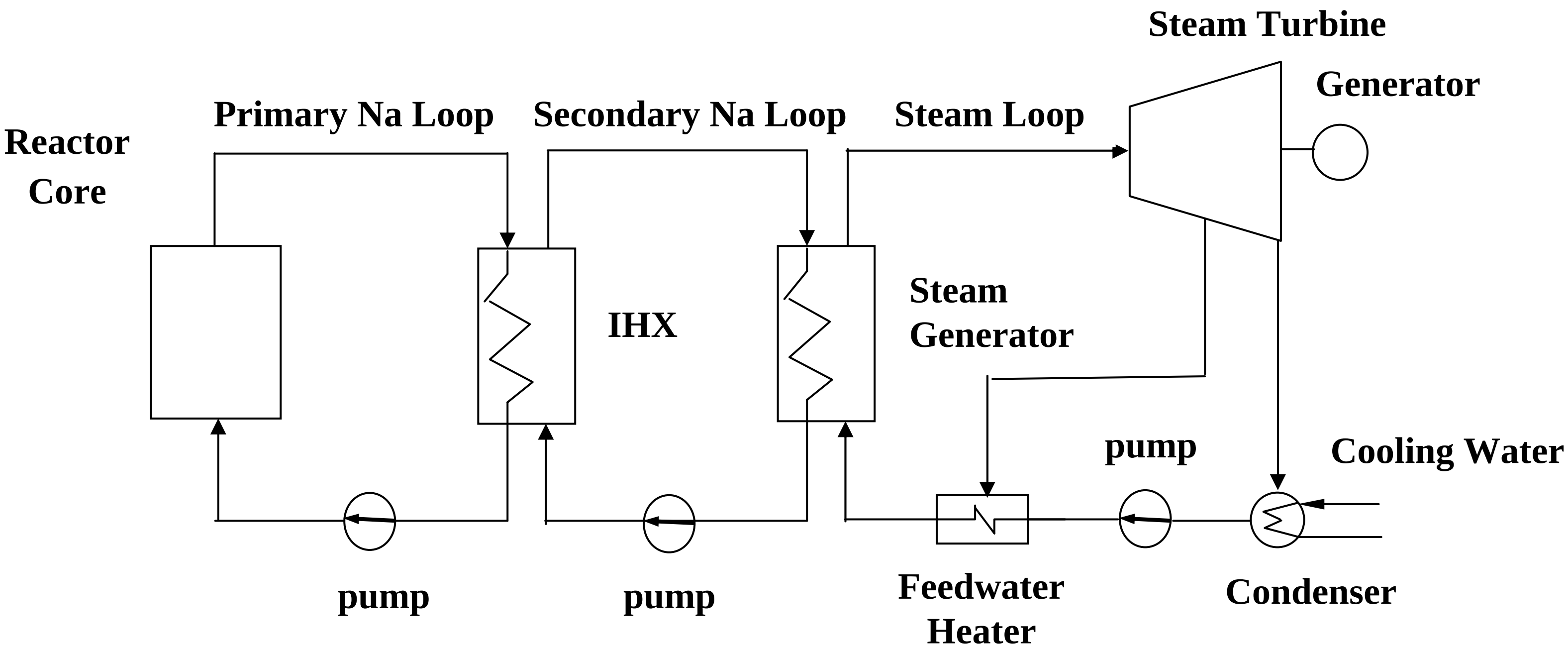
History of Gas Cooled-Reactors



*1: Start of operation, *2: Rated full power operation

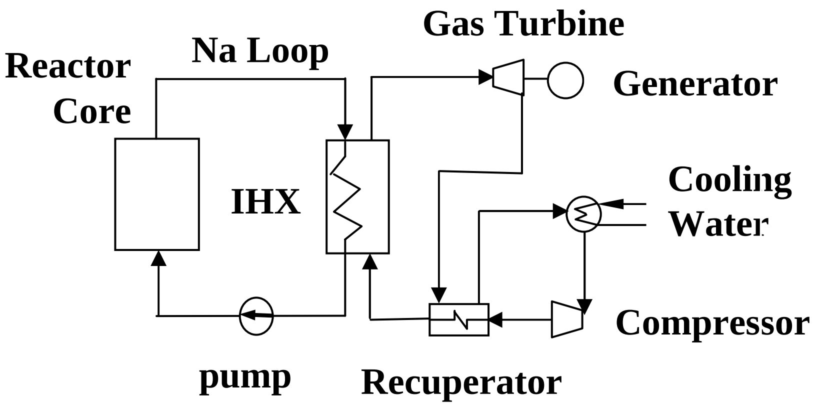


Comparison of Cycle Efficiency with Other Cycles



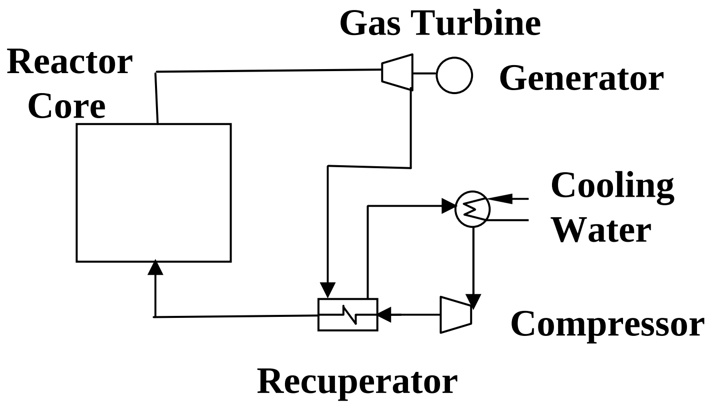
Na-Cooled Steam-Turbine Cycle System

(Monju, CRBRP)



a) Indirect Cycle System

Advantages
- No secondary Na loop
- Smaller & simpler turbine system
- Utilization of Monju Na R&D
- Smaller core size reference to direct cycle systems

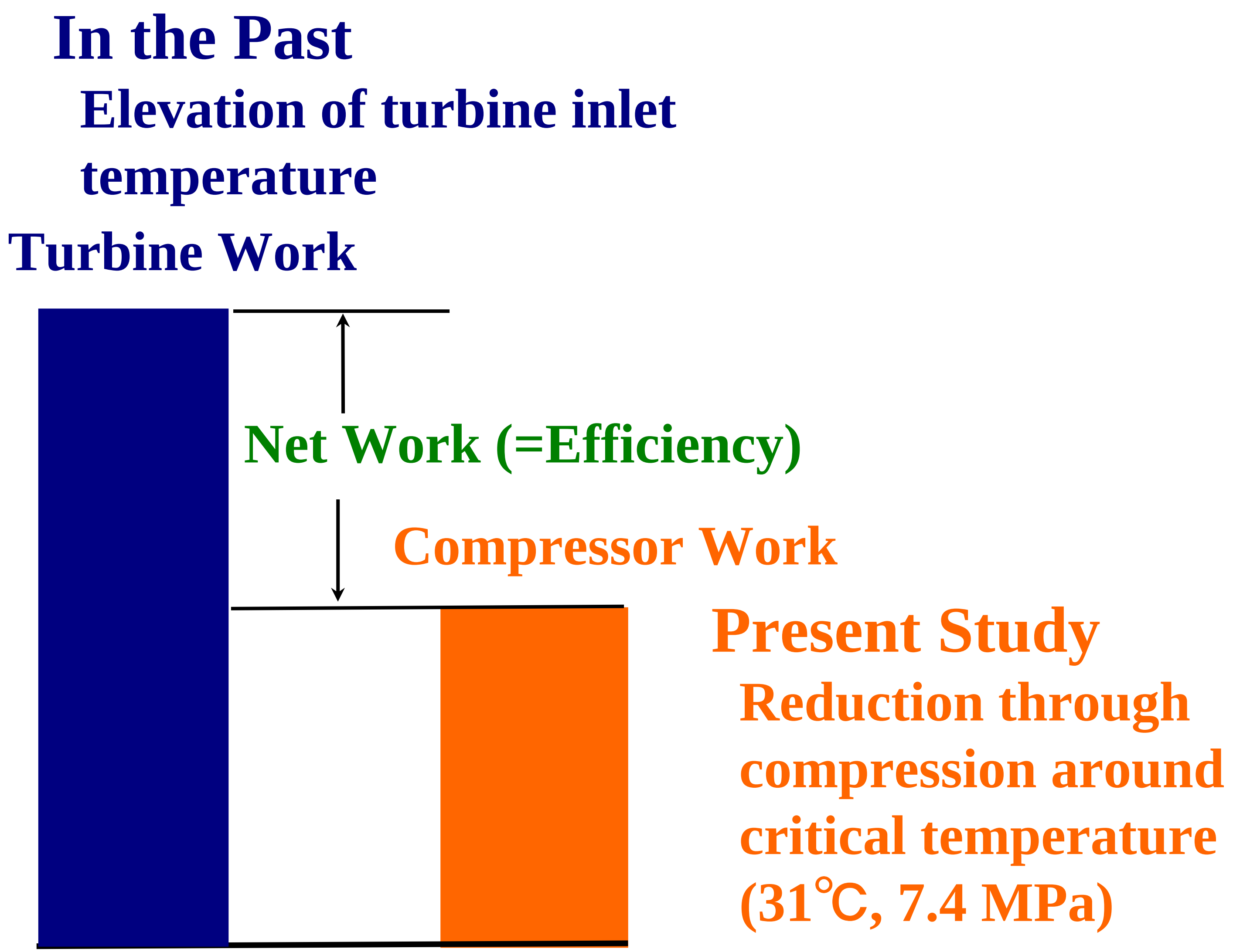


b) Direct Cycle System

Advantages
- No primary & secondary Na loops
- Smaller & simpler turbine system
- Lower void reactivity

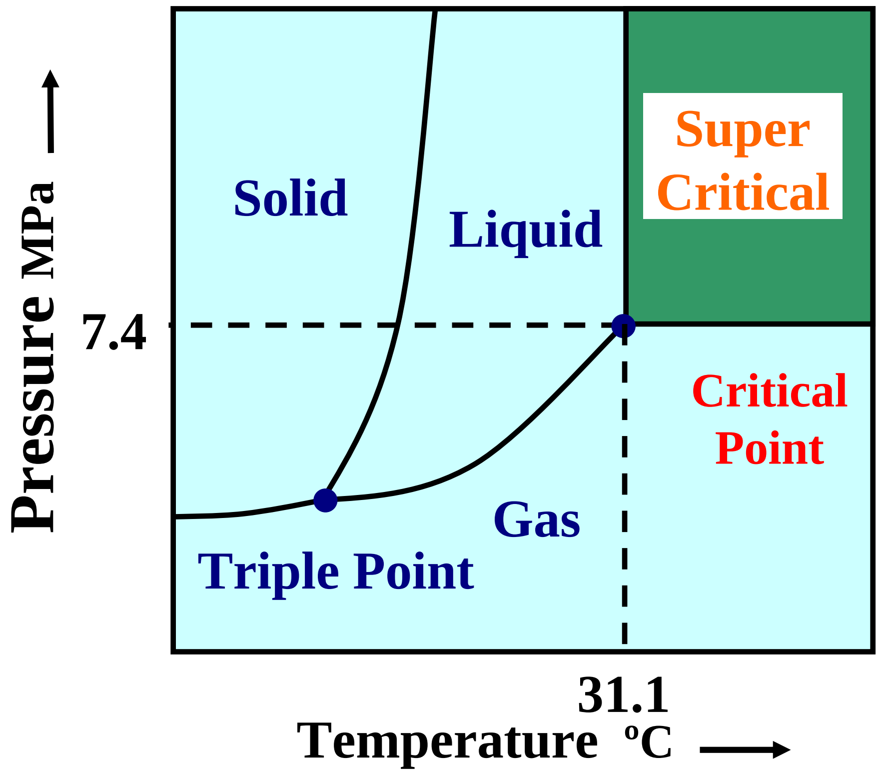
Disadvantages
- Larger core size reference to indirect cycle systems
- R&D on core cooling and T&H in a reactor vessel

CO_2 Gas Turbine FBRs

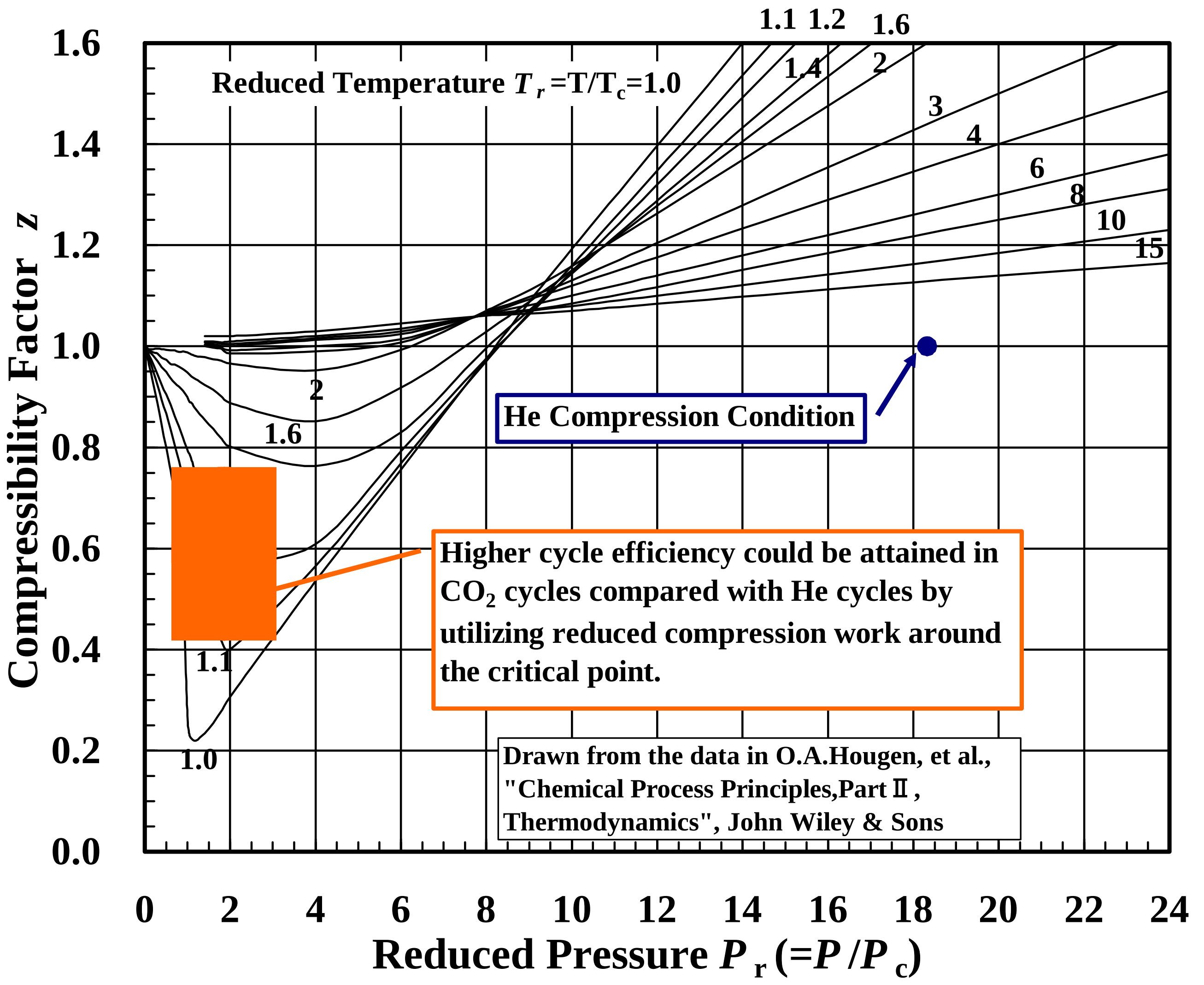


Enhancement of Cycle Efficiency

Materials	Critical Data	
	Temperature T_c (ºC)	Pressure P_c (MPa)
CO_2	31	7.4
H_e	-268	0.28
H_2O	374	22.1



Critical State of CO_2



Compressibility factor with P_r and T_r

Compression Work of Real Gas

Isentropic compression work W:

$$W = -\int V\,dP = -\int zRT\,dP/P,$$

where V=volume, P=pressure,

R=gas constant,

z=compressibility factor=$f\,(T_r, P_r)$,

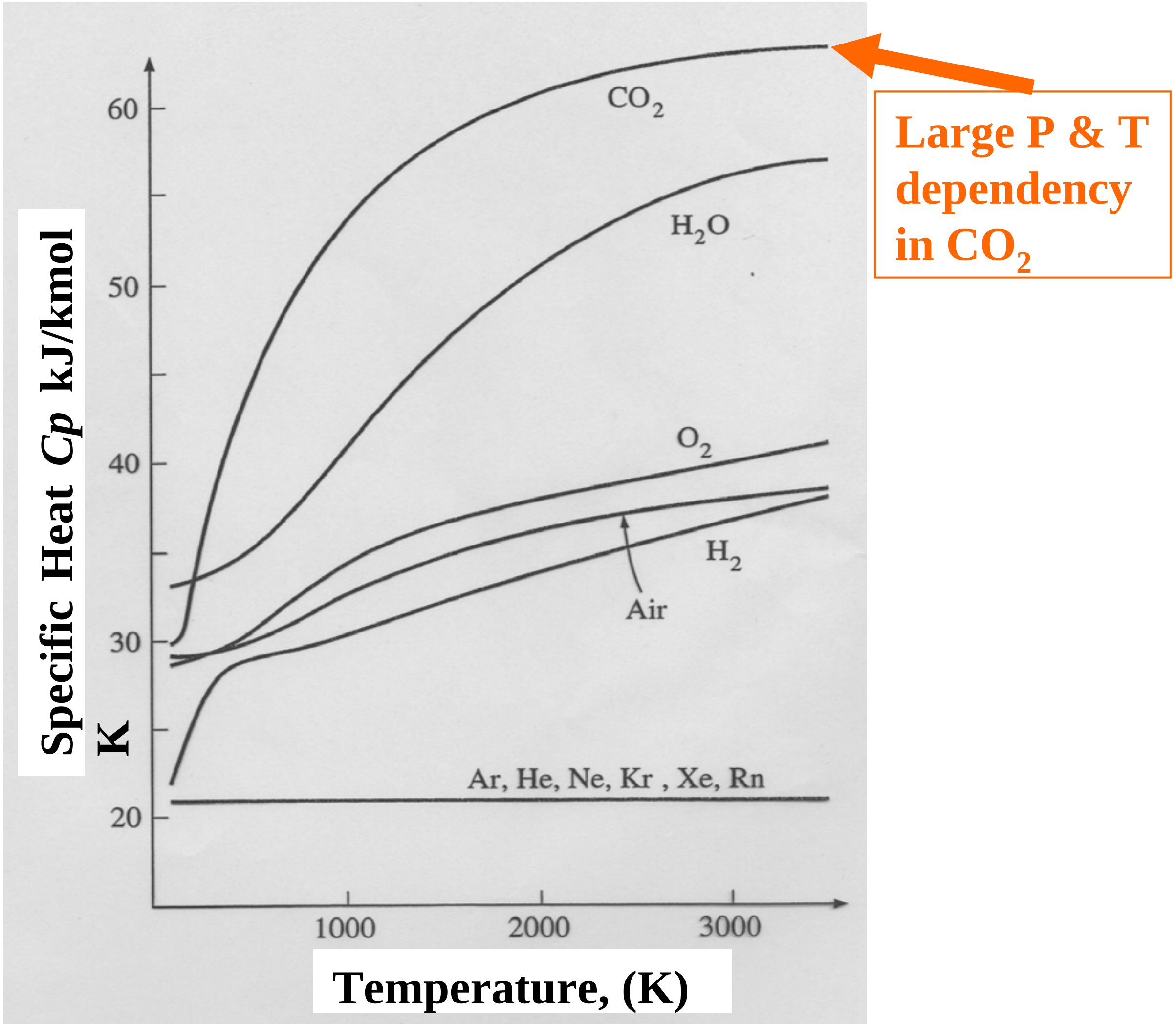
T_r=reduced temperature=T/T_c,

T_c=critical temperature,

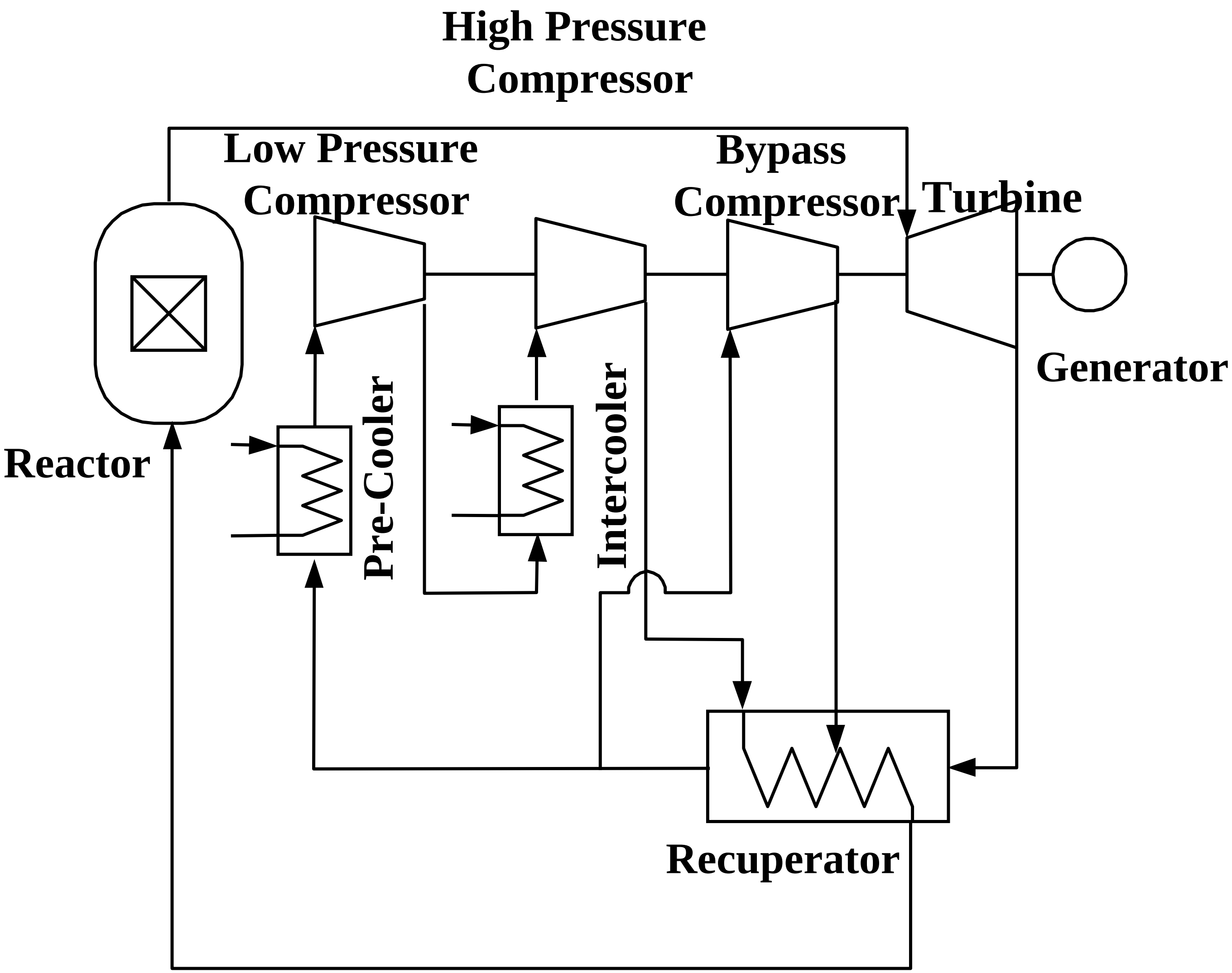
P_r=reduced pressure=P/P_c,

P_c=critical pressure.

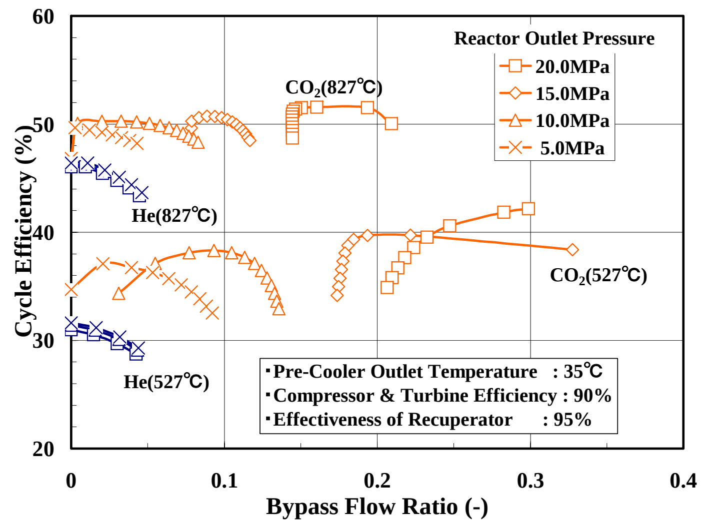
At the critical point, the z value takes an extremely low value as low as about 0.2 or a real gas is five times more compressible than an ideal gas.



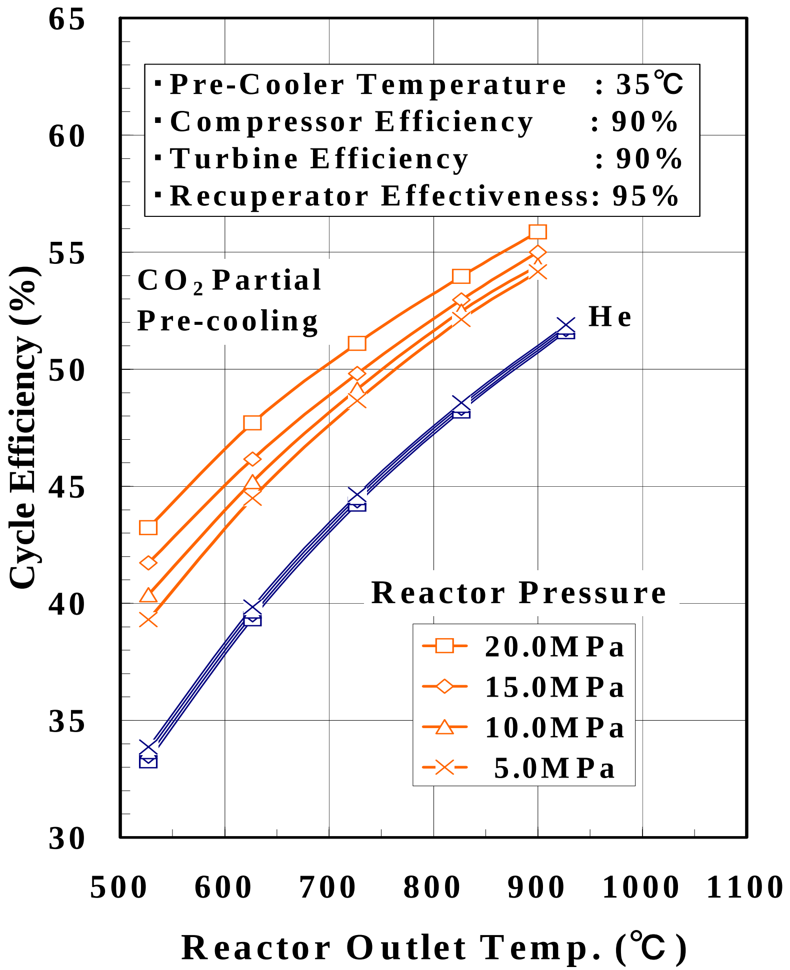
Cp Pressure & Temperature Dependency



Partial Pre-Cooling Cycle



Bypass Flow Fraction Dependency



Temperature & Pressure Dependency

Cycle Efficiency in Partial Pre-Cooling Cycle

Direct Cycle Core Parameters

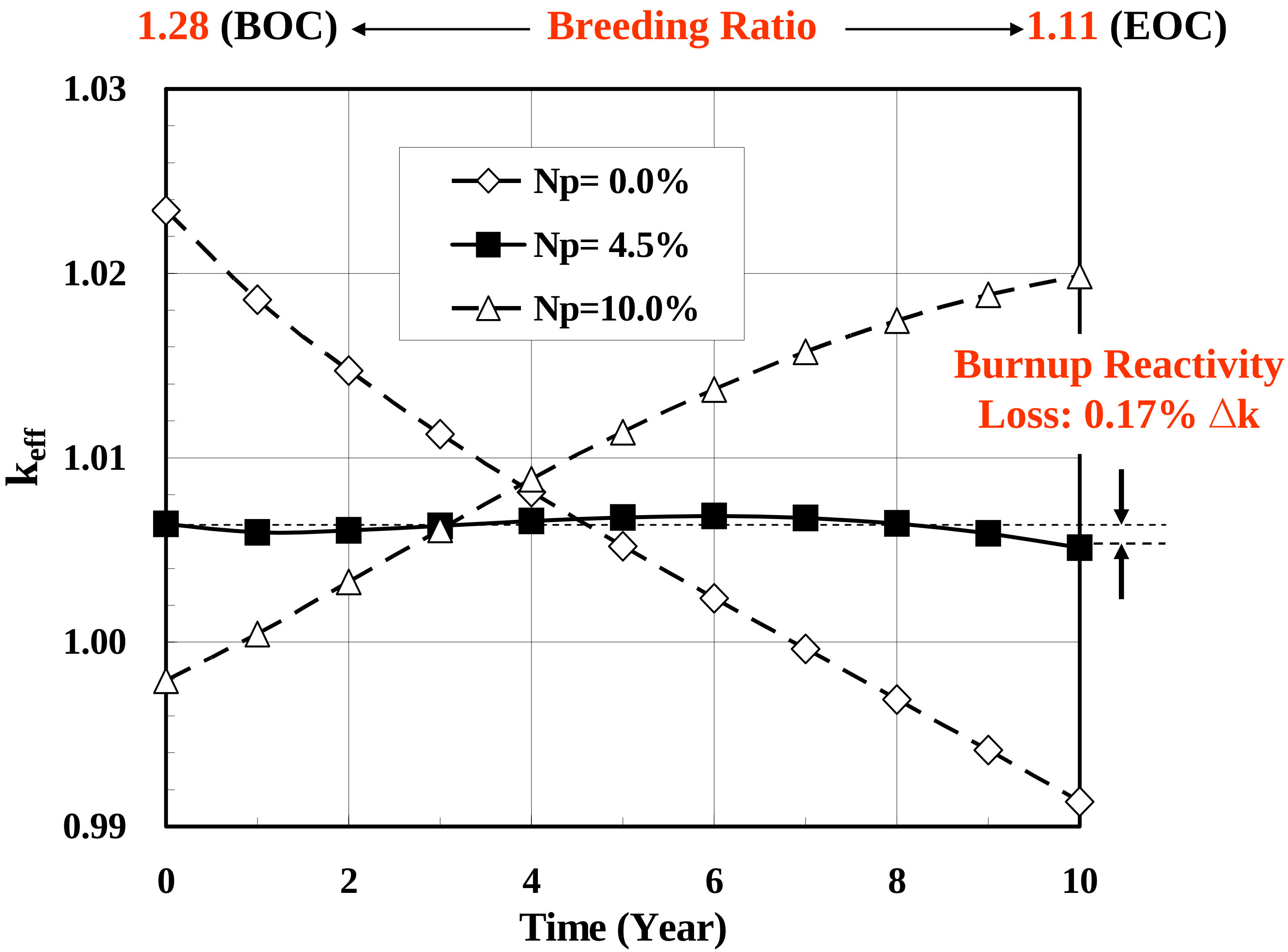
Materials	
Coolant	CO_2
Fuel	UO_2-PuO_2-NpO_2
Absorber (^{10}B = 90%)	B_4C
Structural	316 SS
Pu Enrichment (atomic %)	
Inner Core/Outer Core	14.0 / 19.0
Core Geometry (mm)	
Effective Core Height	150
Equivalent Diameter	2776
Blanket Thickness (mm)	
Axial/Radial	200 / 334.6
Subassembly Geometry (mm)	
Pitch/Duct Thickness	182/3.5
Core Fuel Pin	
Number per Subassembly	391
Outer Diameter (mm)	6.5
Cladding Thickness (mm)	0.35
Spacing	Grid Spacer
Pitch (mm)	8.45
Core Fuel Volume Ratio (%)	
Fuel	34.05
Structural Material	17.25
Coolant	46.74
Gap	1.96

$$^{237}\mathrm{Np} \xrightarrow{(n,\ \gamma)} {}^{238}\mathrm{Pu} \xrightarrow{(n,\ \gamma)} {}^{239}\mathrm{Pu}$$

$$^{238}\mathrm{Pu} \xrightarrow{\alpha\ \ \mathbf{87\ y}} {}^{234}\mathrm{U} \xrightarrow{(n,\ \gamma)} {}^{235}\mathrm{U}$$

Absorber	**Fertile**	**Fissile**

^{237}Np-^{239}Pu, ^{235}U Conversion Chain



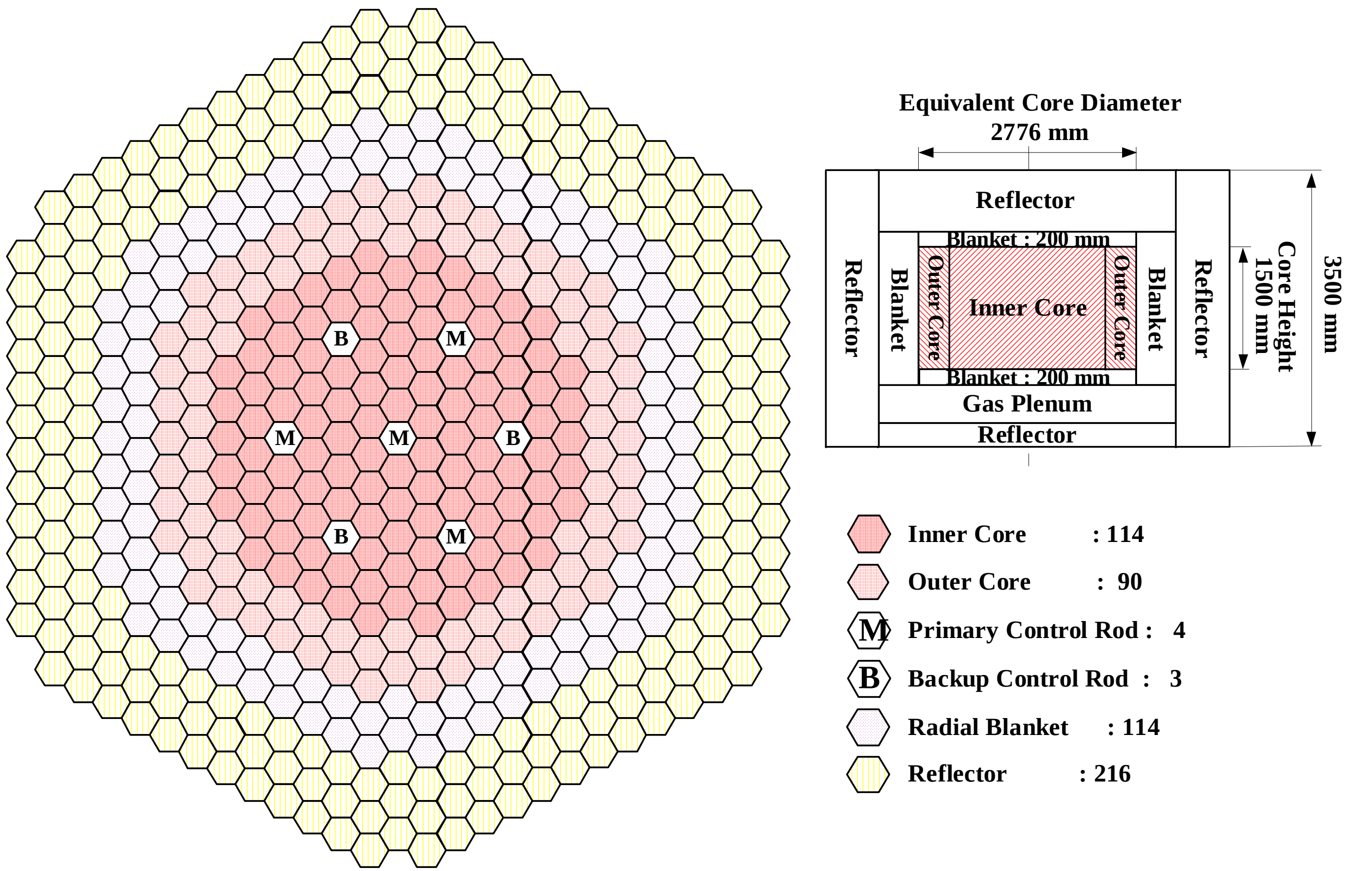
Burnup Performance with ^{237}Np Content

Control Requirement and Reactivity Worth

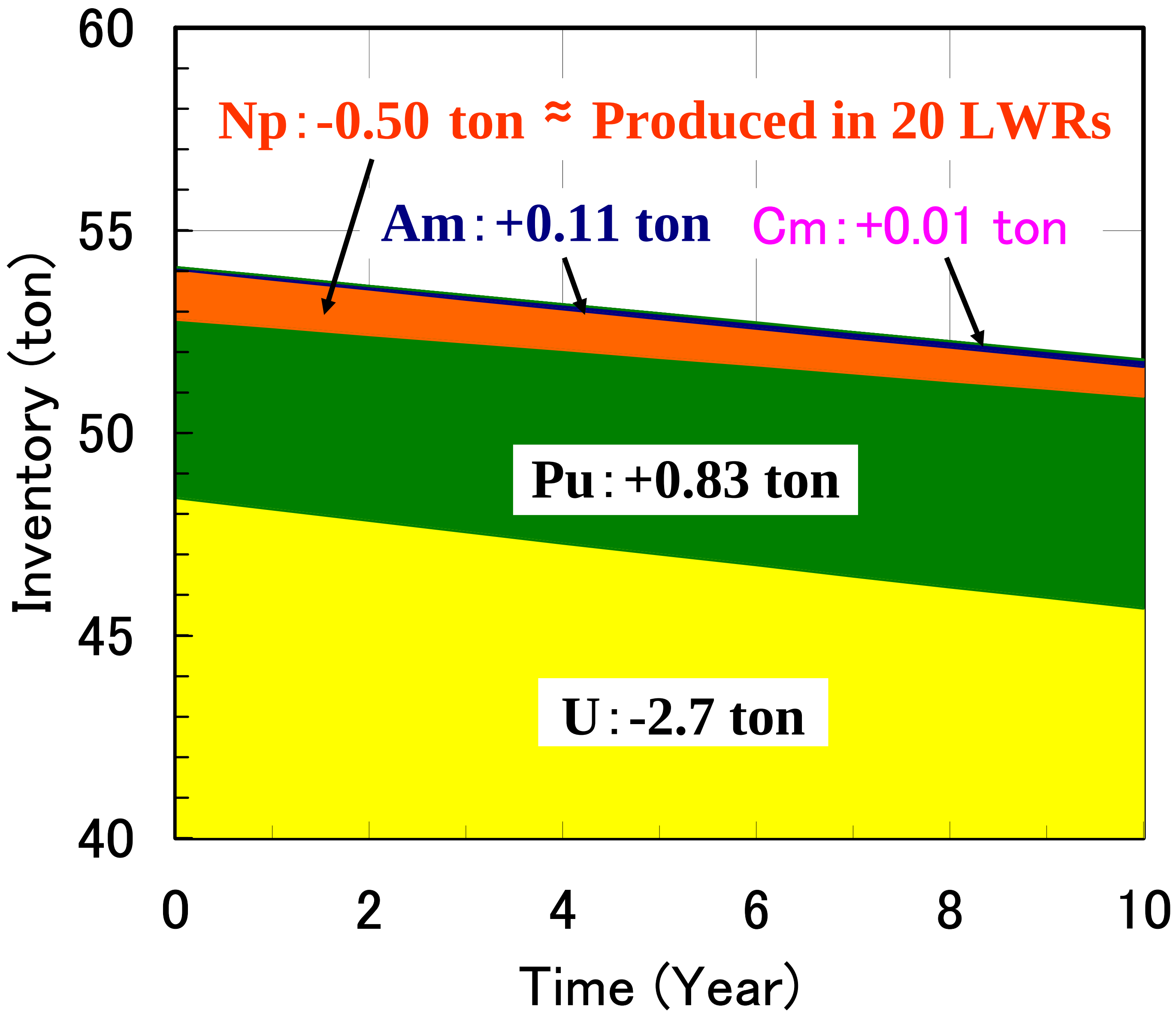
Items	Present GCFR (243.8 MWe)		Demonstration FBR (660 MWe)	
	Primary	Backup	Primary	Backup
Number of Control Rods	4	3	18	6
Control Requirement (%Δk/kk')				
Cold to Full Power Reactivity	0.6	0.6	1.3	1.3
Burnup Reactivity	0.3	-	3.1	-
Uncertainty	1.0	-	1.4	0.4
Allowance for Operation	0.3	-	0.2	-
Total	2.2	0.6	6.0	1.7
Reactivity Worth Available (%Δk/kk')	2.7*	3.2	8.0	2.4
Shutdown Margin (%Δk/kk')	0.5	2.6	2.0	0.7

* Worth of one stuck rod.

Direct Cycle Core Design



Core Configuration



HM Inventory Change with Burnup Time

Void Reactivity

- 0.61% $\Delta k/kk'$
- Reactivity in the case of depressurization from 12.5 MPa to atmospheric pressure.

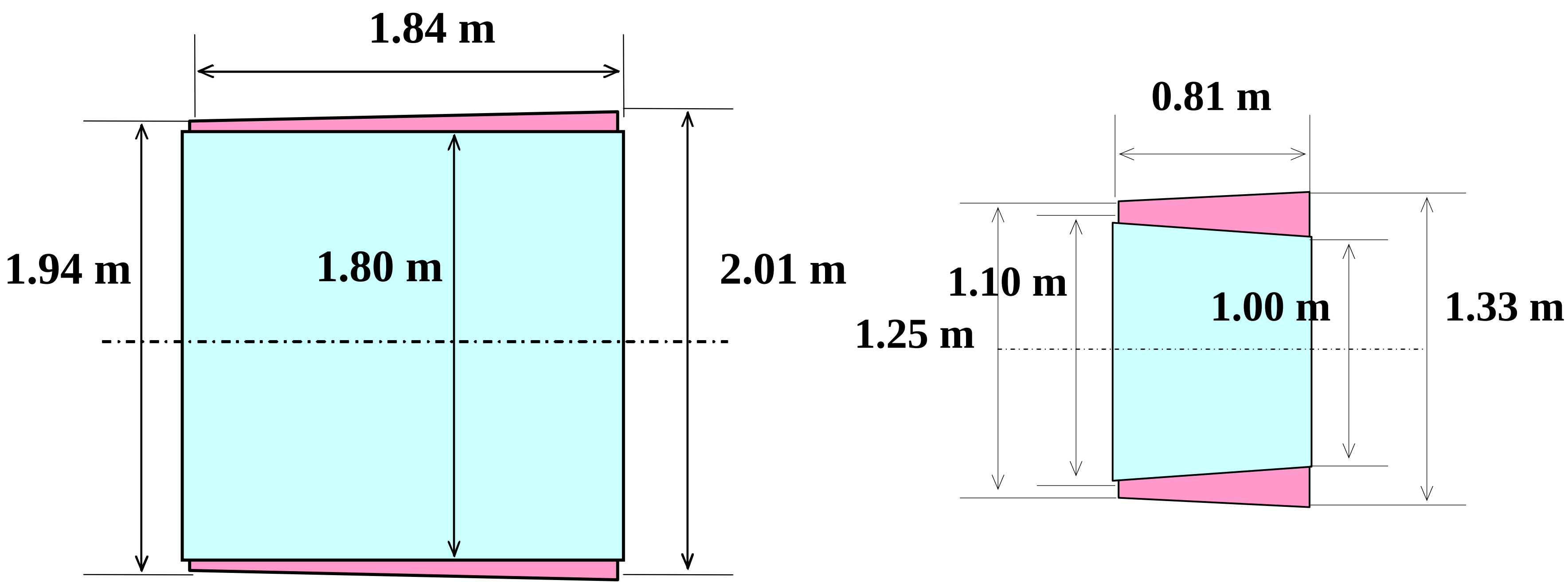
Hot Spot Temperature of Cladding

> 700°C (Maximum permissible temperature of 316SS)

Items	Hot Spot Factors		
	Coolant	Film	Cladding
Direct			
Power measurement	-	1.03	1.03
Power distribution	1.08	1.08	1.08
Inlet temperature	1.02	-	-
Subchannel flow	1.02	-	-
Total	1.12	1.11	1.11
Statistical			
Flow distribution	1.02	-	-
Coolant property	1.02	1.30	1.03
Manufacturing	1.03	1.04	1.06
Pellet eccentricity	-	1.16	1.20
Total	1.04	1.34	1.21
Grand Total	1.16	1.49	1.34

Gas Turbine Volume （≈ Weight or Cost）

5 : 1



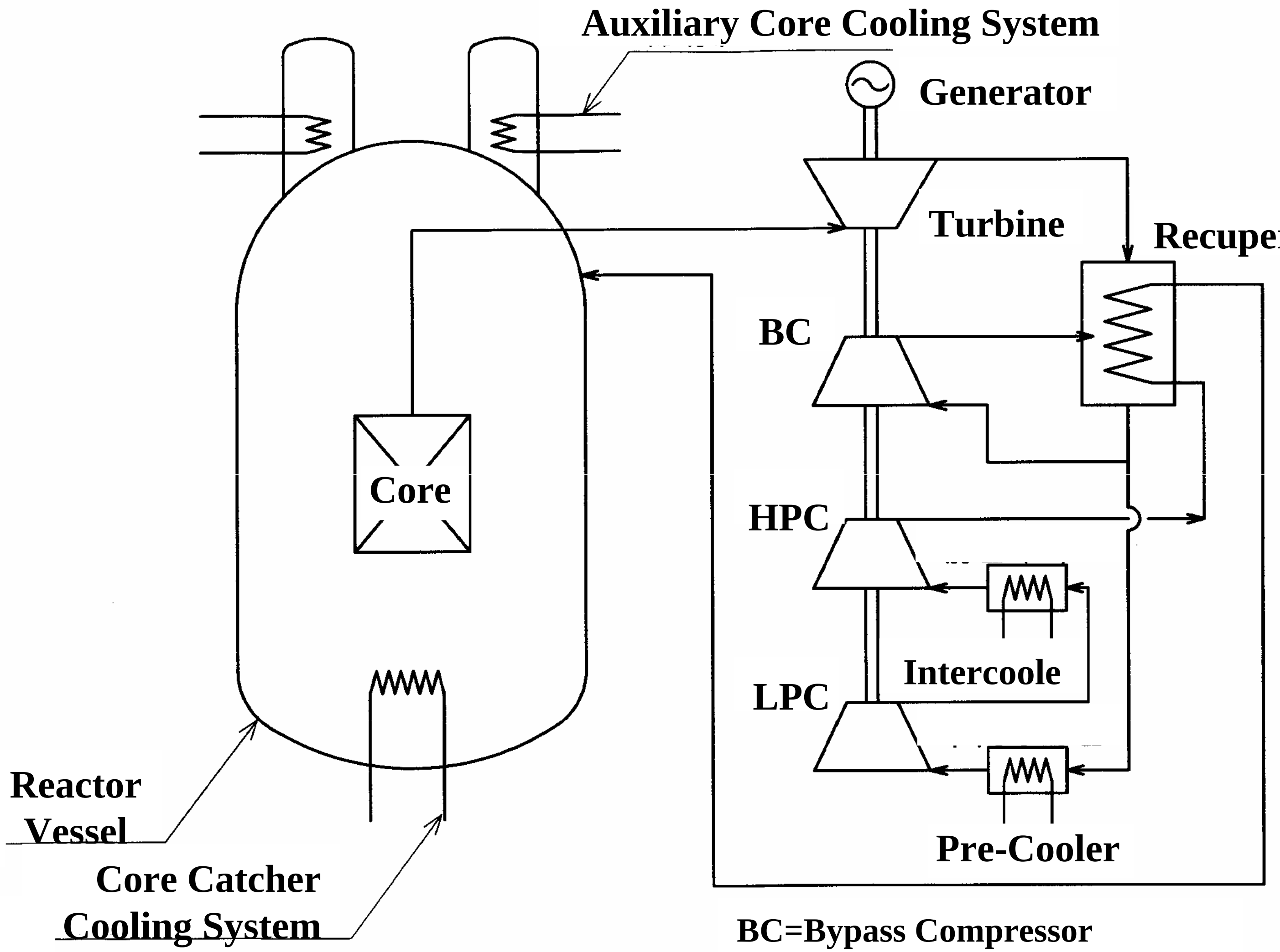
He Gas Turbine **CO_2 Gas Turbine**

Comparison of Gas Turbine Size

Basic Plant Design Conditions

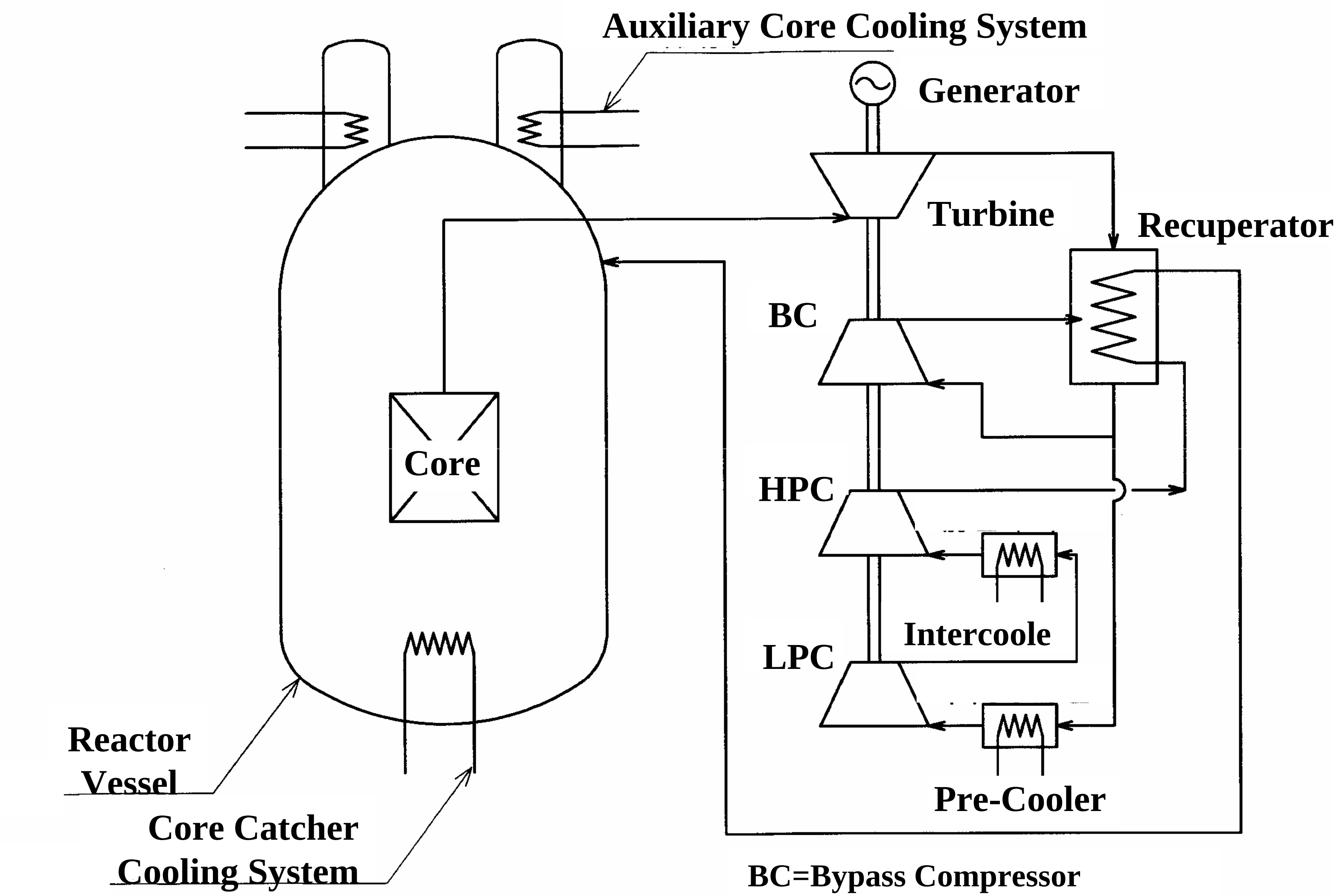
Design parameters		Direct Cycle	Indirect Cycle
Power Output	Thermal (MW)	600	
	Efficiency (%)	40	40/42
Core Cooling System	Coolant	CO_2	Na
	Core Inlet/Outlet Temperature (^oC)	388/527	425/550
	Pressure (MPa)	12.5	-
CO_2 Gas Turbine Inlet	Turbine Inlet Temperature (^oC)	527	
	Pressure (MPa)	12.5	12.5/20

Direct Cycle Plant Design - designed by Fuji Electric for TIT



BC=Bypass Compressor
HPC=High Pressure Compressor
LPC= Low Pressure Compressor

Direct Cycle Plant Design - designed by Fuji Electric for TIT



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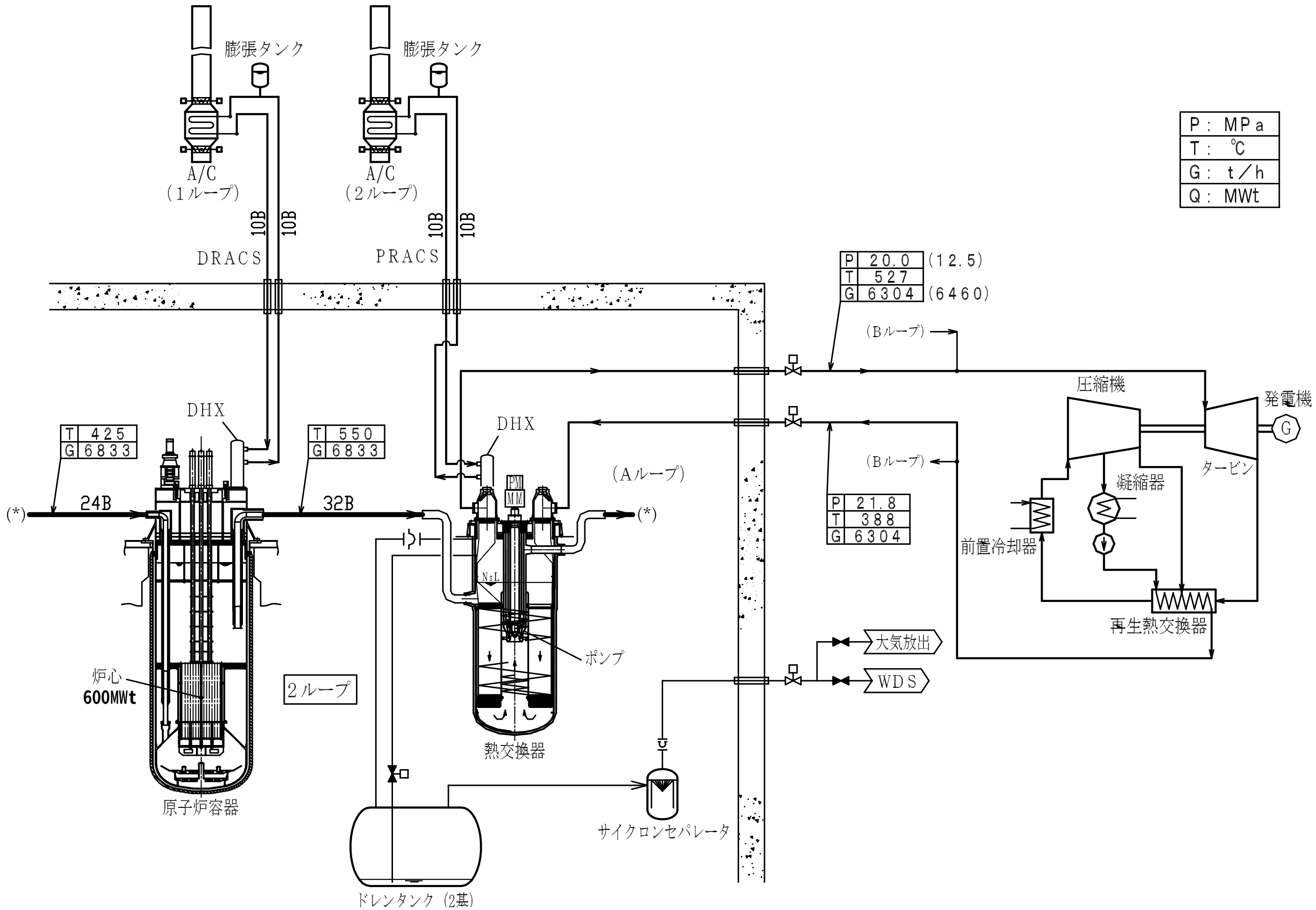
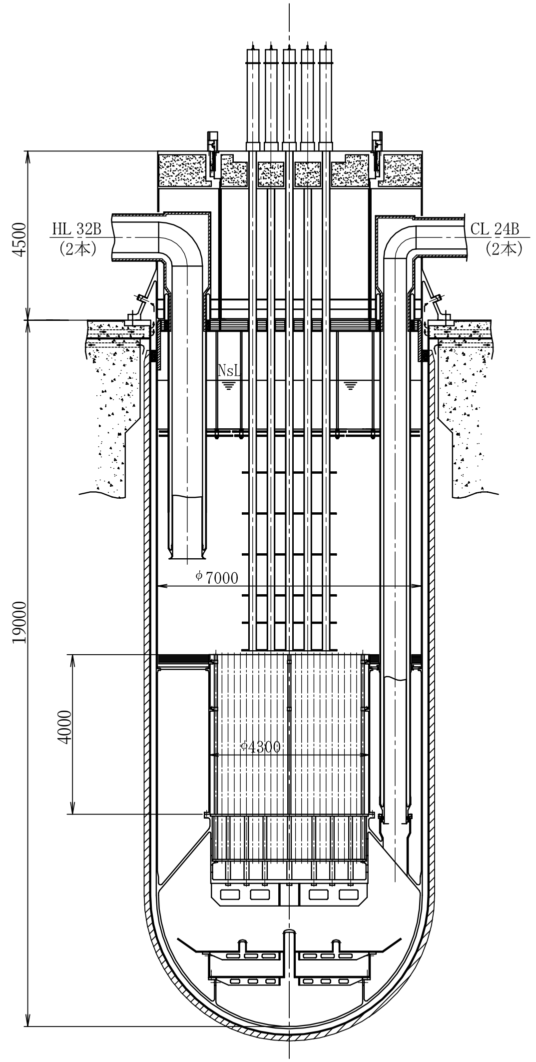


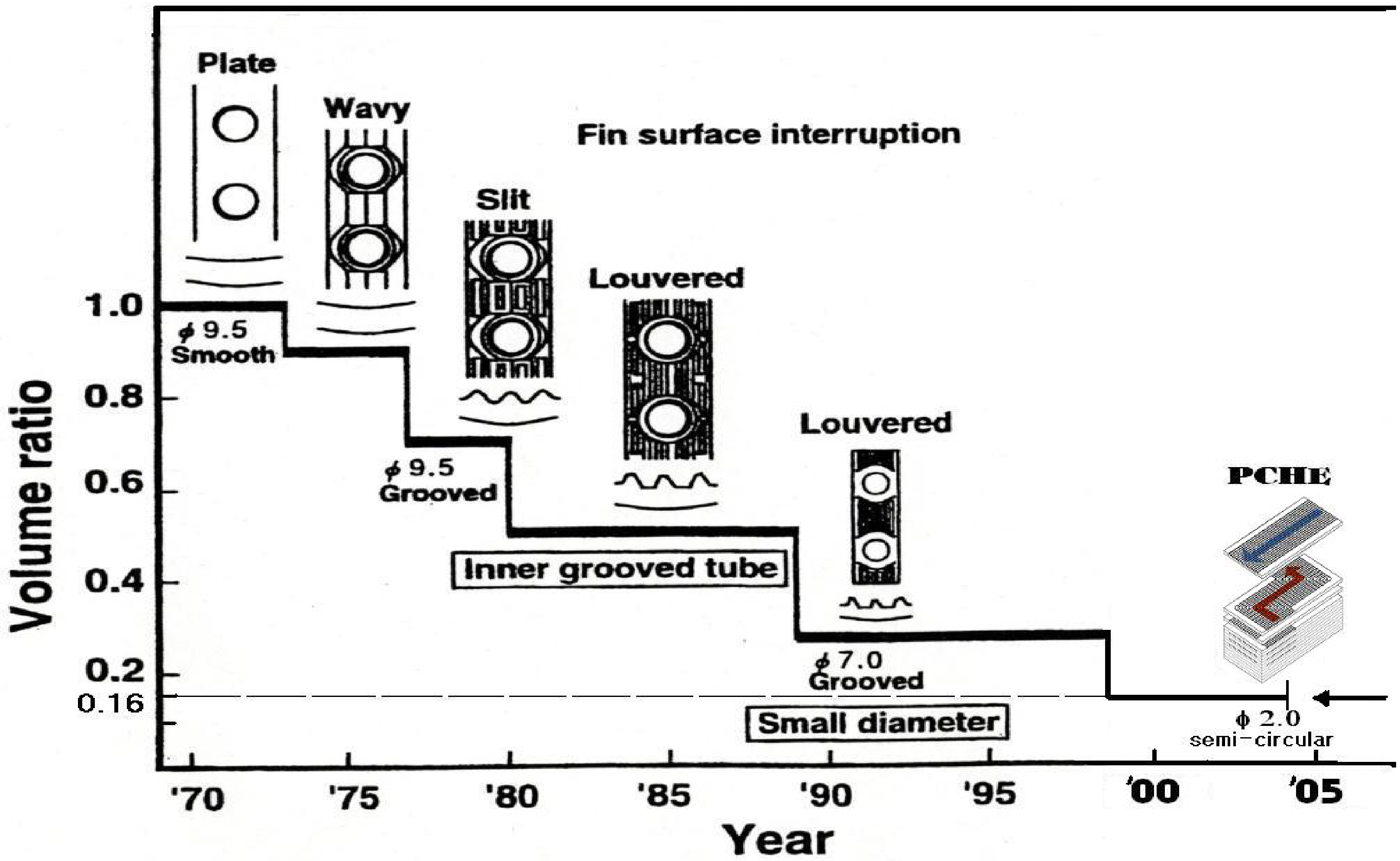
Indirect Cycle Plant Design- Loop Type (IHX-Pump Combined)

- designed by ARTECH for TIT



Indirect Cycle Reactor Structure Design
- designed by ARTECH for TIT

Compact Heat Exchangers Development History



What is the PCHE?

- ✓ **Fluid flow channels are etched chemically on metal plates.**
  - **- Typical plate: thickness = 1.6mm,**

    width = 600mm, length = 1200mm,
  - **- Channels have semi-circular profile with 1-2 mm diameter.**
- ✓ **Etched plates are stacked and diffusion bonded together to fabricate a block**
- ✓ **The blocks are then welded together to form the complete heat exchanger core**

Construction of PCHEs

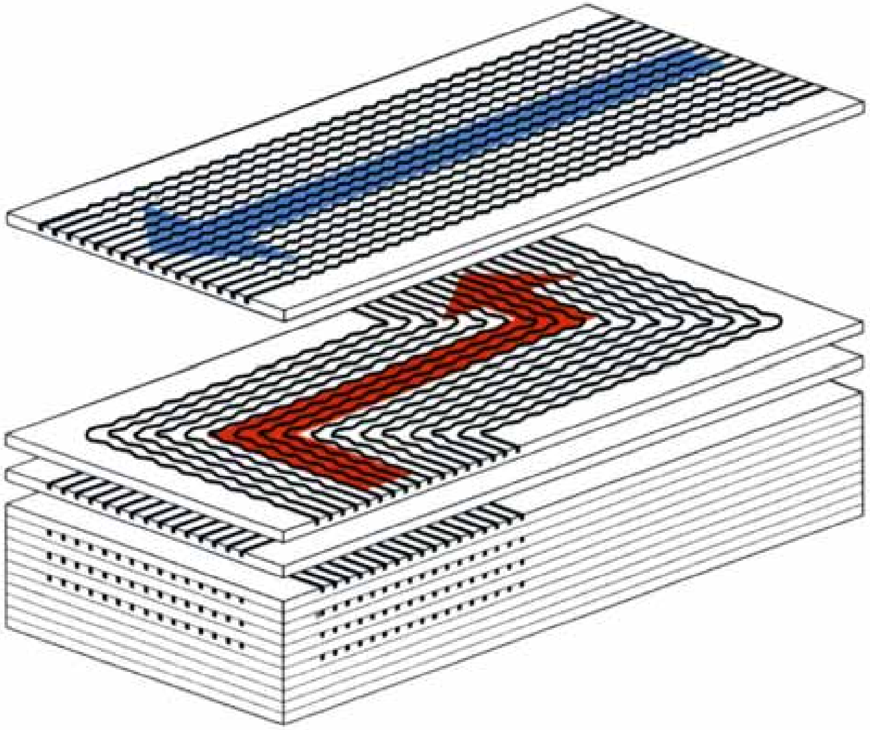
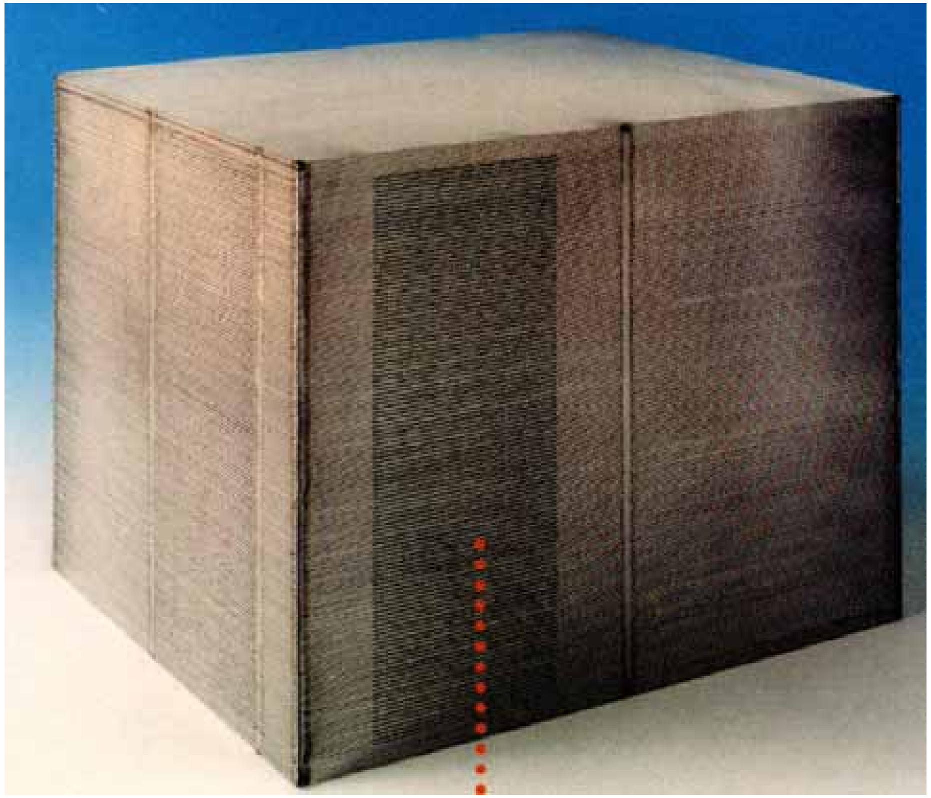


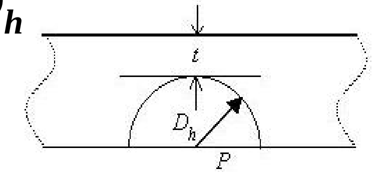
Plate stacking



Diffusion bonding

Advantages of PCHE

- **Photo-etching technology:**
  - ➔ **Micro channels with smaller hydraulic diameter D_h**

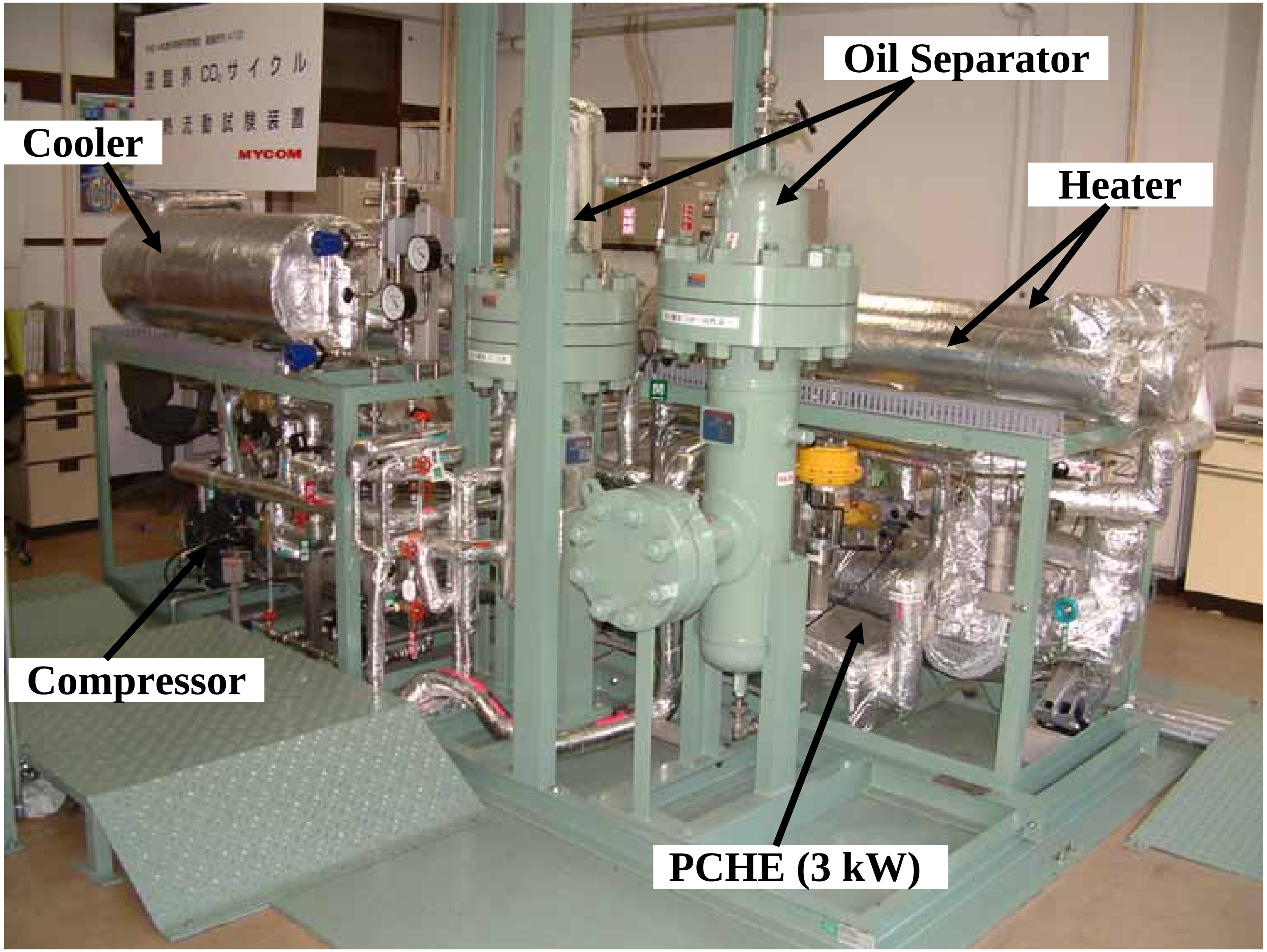


    - ⇨ **Pressure capability > 50 MPa.**
    - ⇨ **Compact size (L) or higher efficiency (98%).**

      $j=(D_h/4L)\ \mathrm{Pr}^{2/3} N$,

      where $N=NTU$ (Number of Thermal Units)$=(T_{out}-T_{in})/\Delta T_{LMTD}$.
  - ➔ **No plate-fin brazing:**
    - ⇨ **Manufacturing cost reduction.**

- **Diffusion bonding technology:**
  - ➔ **Maintain parent material strength:**
    - ⇨ **Temperature capability up to 700°C.**
  - ➔ **No braze, flux or filler:**
    - ⇨ **Corrosion resistant.**



PCHE T-H Test Loop for CO_2 Cycle GCRs

New PCHE Model in TIT

Parameters		HEATRIC Model	TIT Model
Flow Channel		Zigzag	**
Fluid		CO_2	
PCHE Size (mm)	Width/Length	10.3/121	
Metal Plate	Material/ Thickness (mm)	316 SS/1.6	
Fin Geometry	Angle (degree)/ Width (mm)	38/0.8	
Channel Geometry (mm)	Width/Depth	1.9/0.94	
Flow Rate (kg/s)	Hot/Cold Side	$6.9 \times 10^{-4}/1.3 \times 10^{-3}$	
Coolant Inlet Temp. (℃)	Hot/Cold Side	553/382	
Coolant Outlet Temp. (℃)	Hot/Cold Side	439/494	438/496
Overall Heat Transfer Coefficient* (w/m^2K)		1134 (0.96)	1187 (1)
Pressure Drop* (kP/m)	Hot/Cold Side	336/312 (5.8/6.5)	58/48(1/1)

* Values in brackets are normalized to unity in the case of the TIT model.

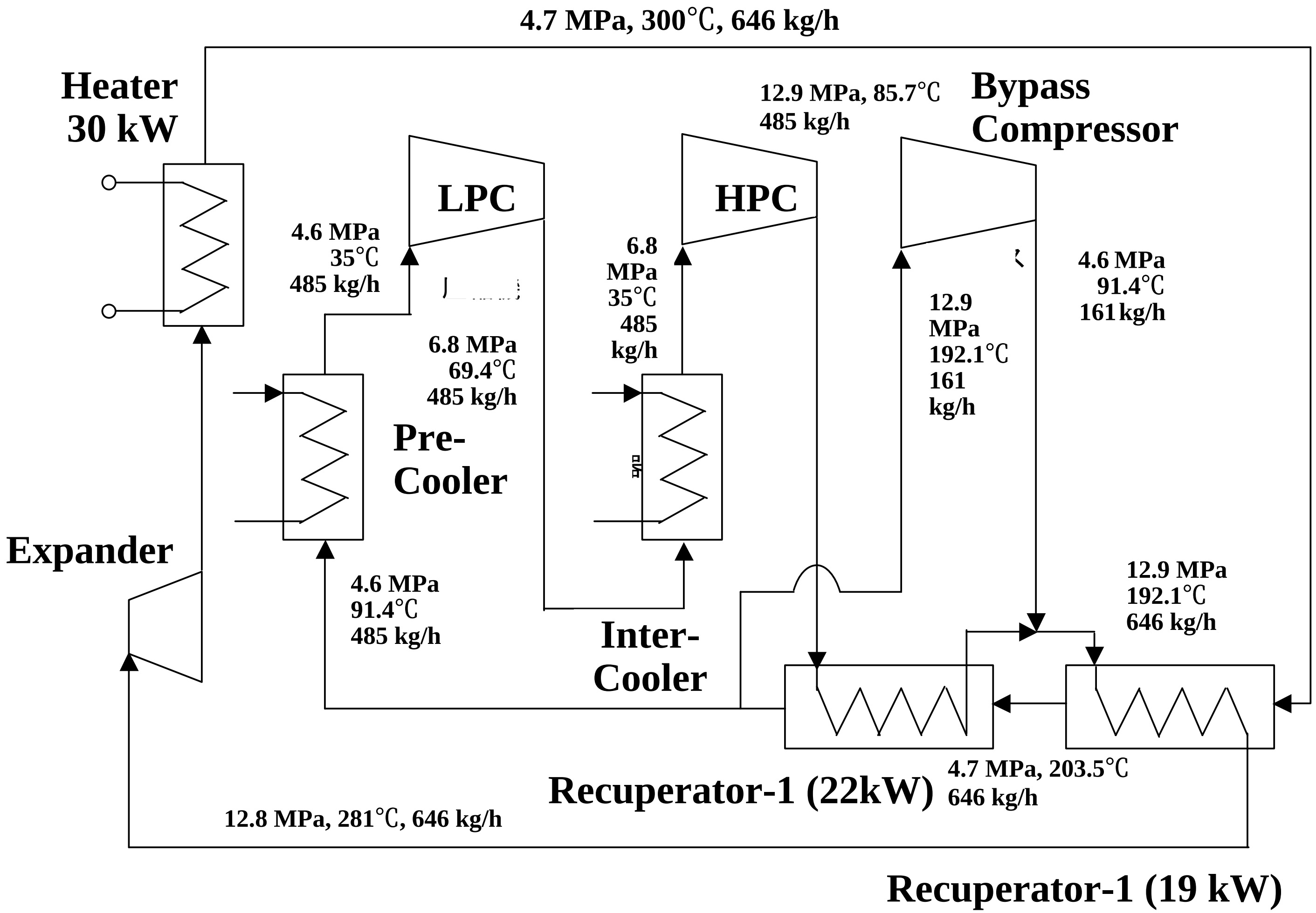
** Now applying for a patent.

To be presented at HEAT-SET 2005, April 5-7, 2005, Grenoble, France.

CO_2 Gas Turbine Cycle Mockup Test

Verification of

- **Compression work reduction around critical point**
- **PCHE T&H performance**
- **Operability of bypass flow configuration**

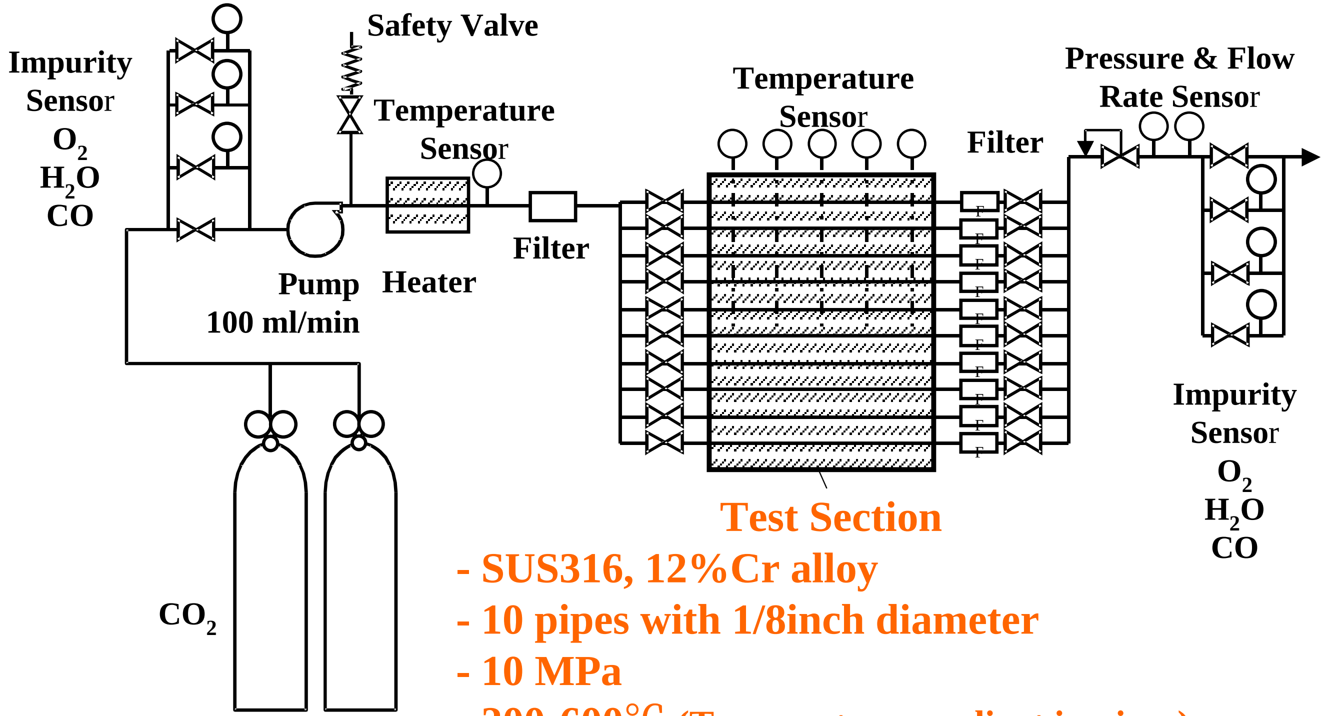


Flow Diagram of Mockup Test Facility

LPC= Low Pressure Compressor, HPC= High Pressure Compressor

Material Corrosion Test

- Corrosion rate & mechanism (break away corrosion?)
- Material selection & corrosion control

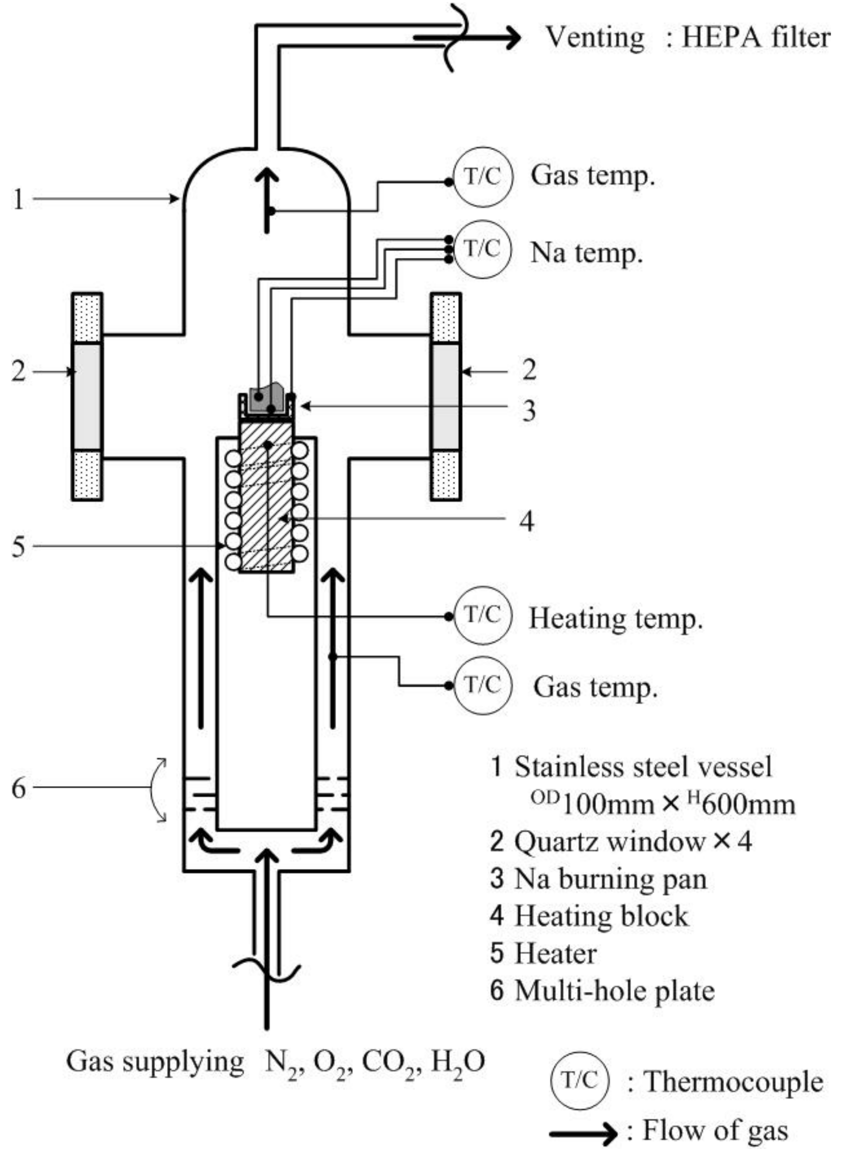


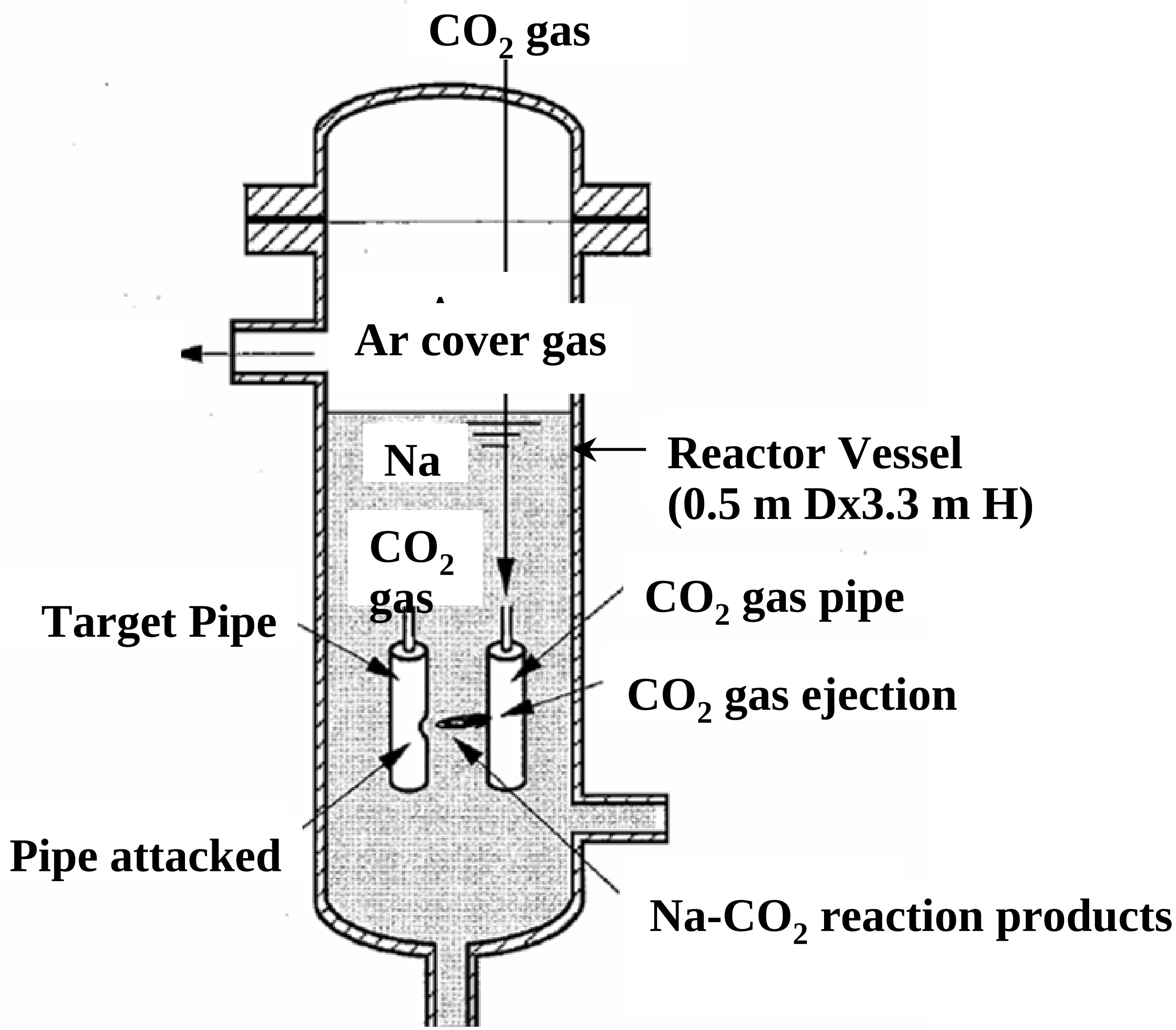
- SUS316, 12%Cr alloy
- 10 pipes with 1/8inch diameter
- 10 MPa
- 200-600℃ (Temperature gradient in pipes)

Flow Diagram of Material Corrosion Test Facility

Na–CO_2 Reaction Test

- Heat of reaction
- Chemical kinetics
- Rupture propagation





Pipe Rupture Propagation Test

using SWAT for MONJU

Mile stone for Super Critical CO_2 FBR Construction

Phase	First Step (MEXT Program) （2003-2006）	Second Step （2007-2010）	Third Step （2011-2015）
	Verification of Fundamental Performance, System Design & Evaluation	Turbomachinery & IHX Mockup Tests	Engineering Mockup Tests
R&D	**1. Cycle Mockup Test** - Compressor work reduction around critical point - PCHE T&H performance - Operability **2. Material Corrosion Test** - Corrosion Mechanism - Corrosion control **3. Na-CO_2 Reaction Test** - Reaction mechanism - Rupture propagation **4. Design Study** - Direct/indirect system design - Comparison with conventional systems - Selection of next generation FBR system	**1. Turbomachinery Test** - Turbine - Compressor **2. Na-CO_2 IHX Test** - T&H performance - CO_2 leak protection	**1. Engineering Test** - Core - Components - Materials - Safety et al **2. Prototype Plant Construction**
	Information Exchange as I-NERI *	International Collaboration	International Project

* Japan, US, France, England, Korea

Super Critical CO_2 Gas Turbine Cycle FBRs

1. Carbon dioxide gas turbine cycles are achievable 4 to 11% higher cycle efficiency than He cycles due to compressor work reduction around the critical points.
2. Cycle efficiency of the CO_2 cycles are about 41% at 527 ºC and 12.5MPa,which is comparable with those of LMFRs at the same core outlet temperature.
3. The CO_2 cycles might exclude the problems related to safety, cost and maintenance.
4. Fast reactors with the CO_2 cycles are expected to be a potential alternative option to LMFRs.