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NETPOWER

The NET Power Cycle and the Combustor and Turbine Development

March 2013

Toshiba Corporation
Power Systems Company

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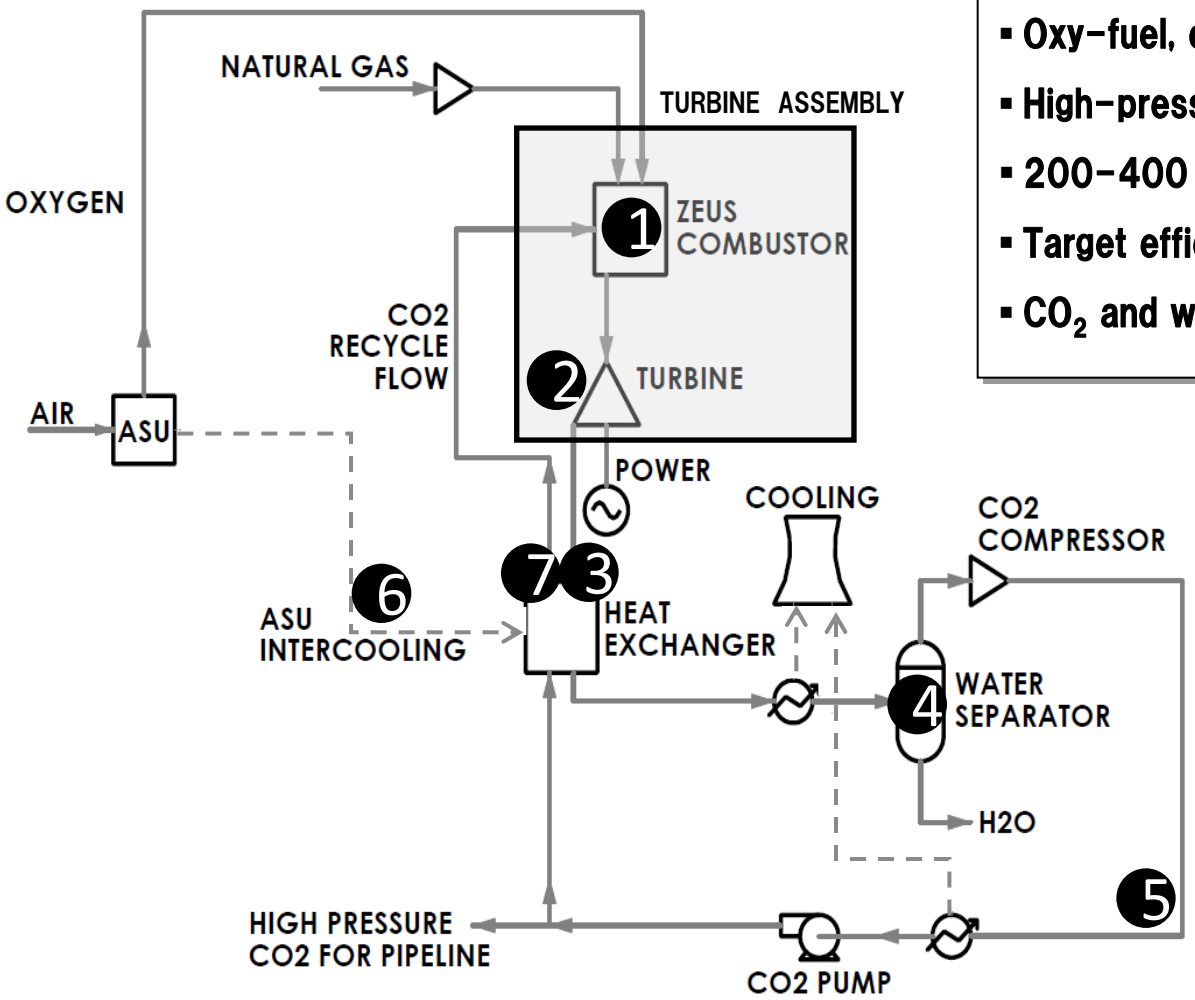
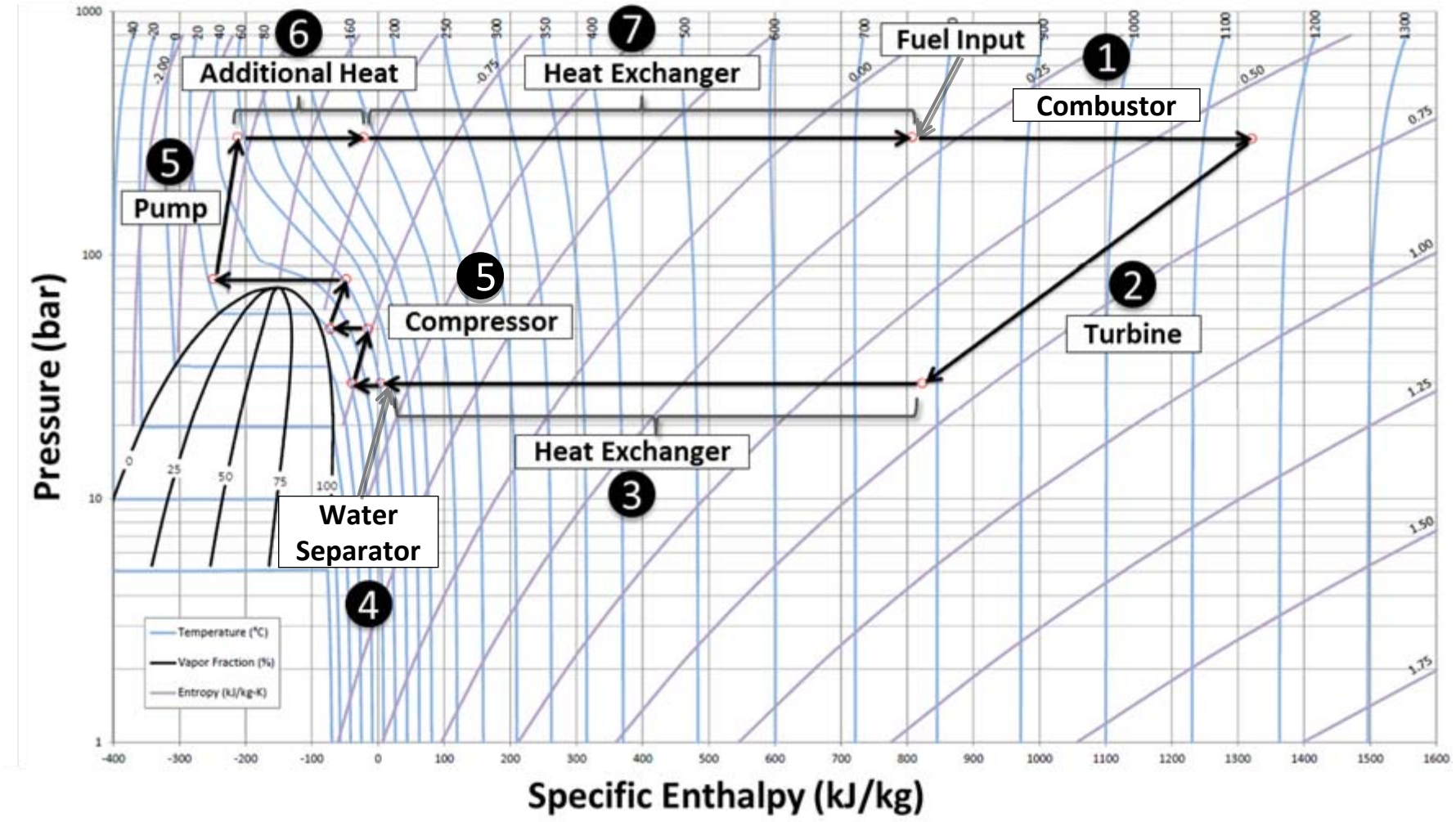
Natural Gas Cycle: The Platform



- Oxy-fuel, closed-loop, CO_2 working fluid
- High-pressure-low-pressure ratio
- 200-400 bar; 6-12 pressure ratio
- Target efficiency 59% (LHV with 100% CC)
- CO_2 and water are the only by-products

1. Fuel Combustion
2. CO_2 Turbine
3. Heat Rejection
4. Water Separation
5. Compression and Pumping
6. Additional Heat Input
7. Heat Recuperation

Pressure and Enthalpy Diagram



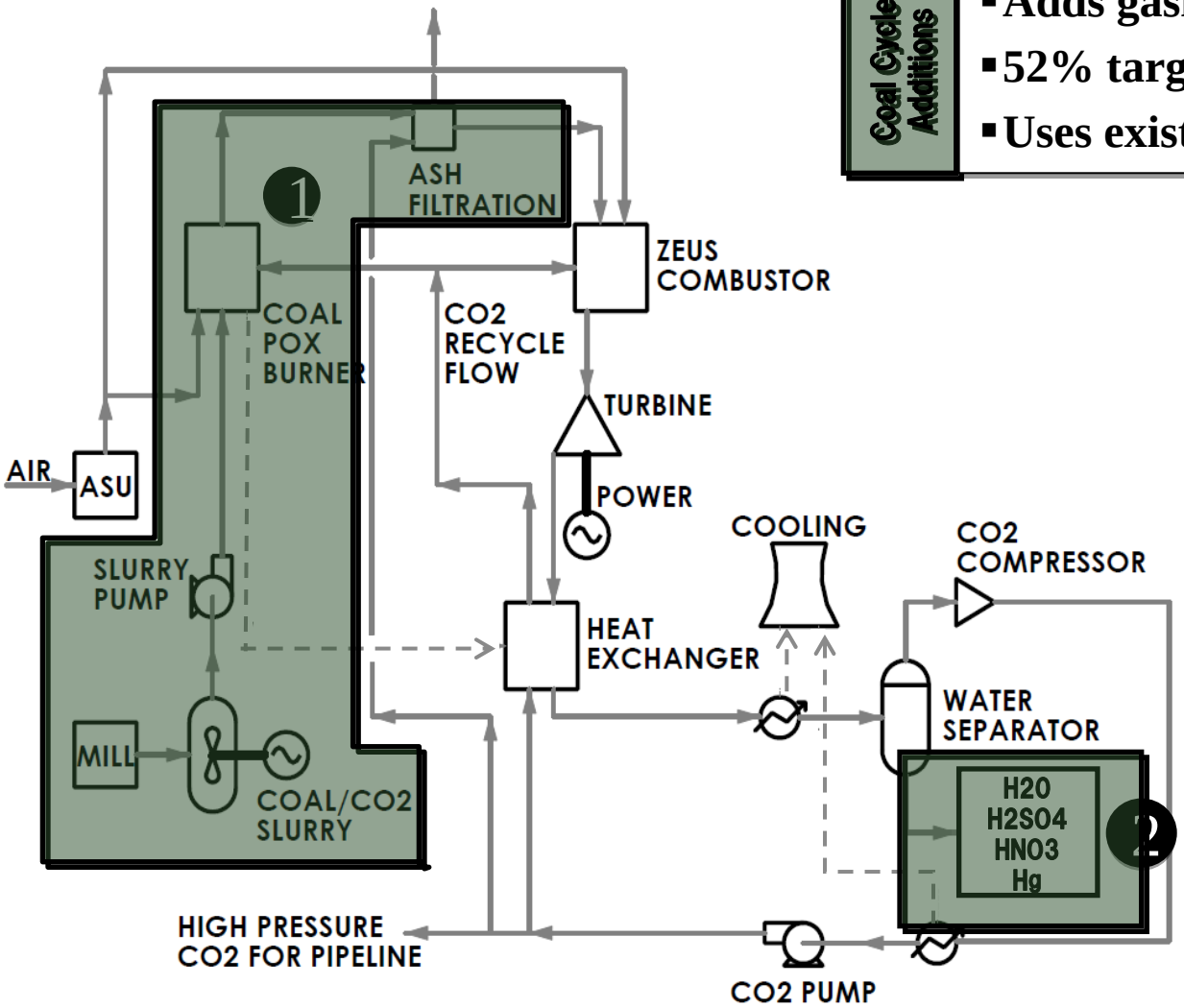
NET Power Platform Target Efficiency

Natural Gas Platform Target Efficiencies (100% CO_2 Capture at 300 bar)		
Energy Components	**HHV**	**LHV**
Gross Turbine Output	75%	83%
CO_2 Compressor Power	-11%	-12%
Plant Parasitic Power (primarily ASU)	-11%	-12%
Net Efficiency	53%	59%

Coal Application

Coal Cycle Additions

- **Adds gasification & cleanup**
- **52% target eff. (LHV with 100% CC)**
- **Uses existing gasification technology**

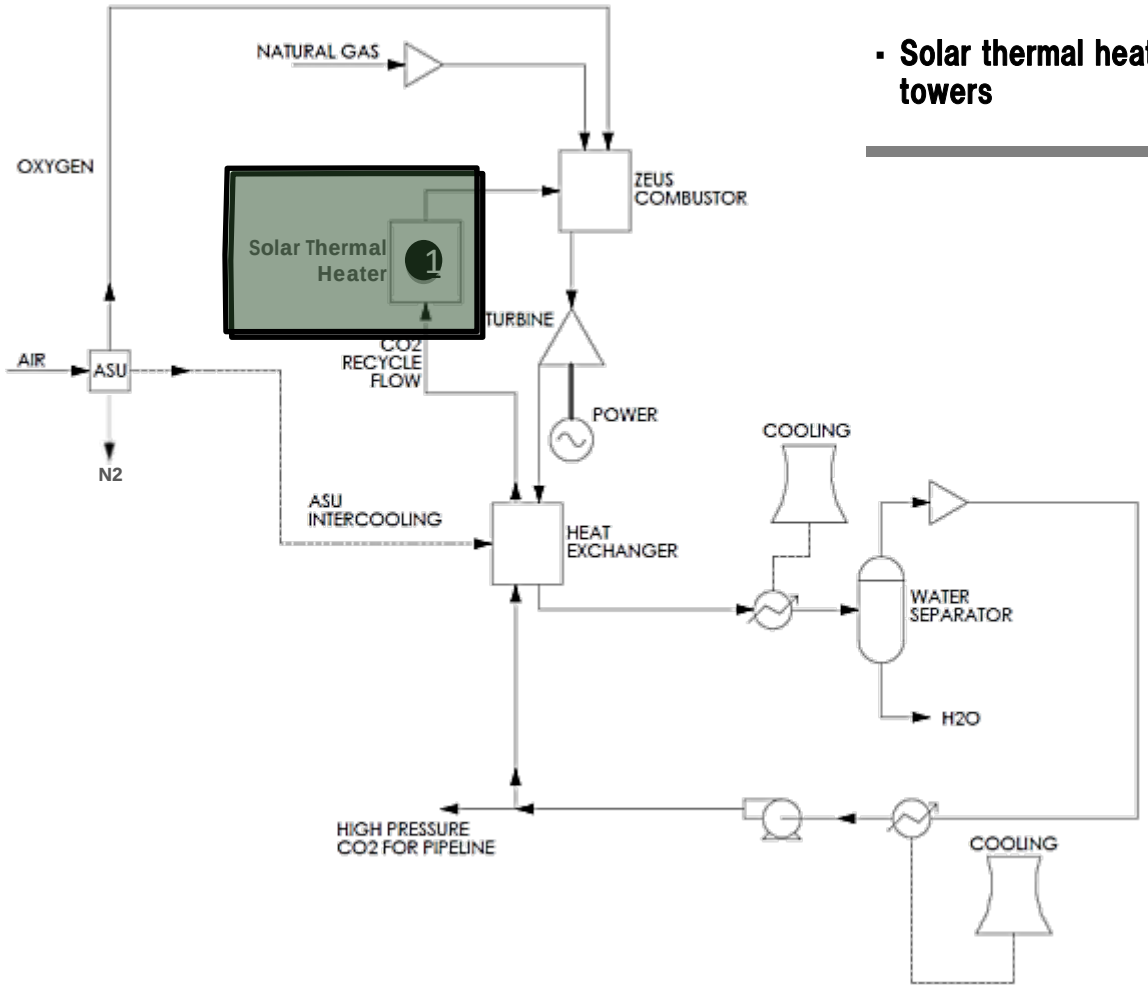


1 **Coal Gasification**

2 **Impurity Cleanup**

Direct Solar Integration

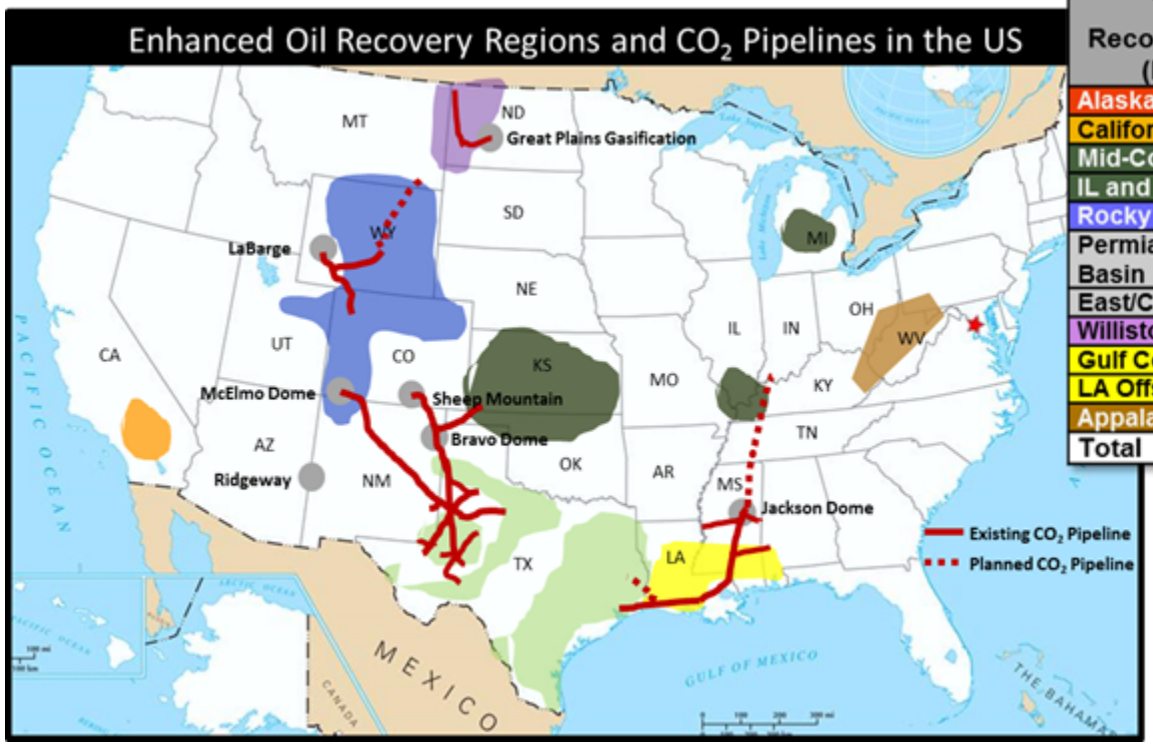
- **Year-long efficiency at 74% in US Southwest**
- **Solar thermal heat most likely in the form of solar power towers**



1 Solar-thermal heat source

EOR Market: A Large Financial and CO_2 Storage Opportunity

85 billion barrels technically recoverable in the US; industry is tethered to current pipeline and geologic CO_2 infrastructure



Technically Recoverable Oil in US (Billion BBls)	
Alaska	12.4
California	6.3
Mid-Cont.	10.6
IL and MI	1.2
Rocky Mts.	3.6
Permian Basin	15.9
East/Cent. TX	17.6
Williston	2.5
Gulf Coast	7.0
LA Offshore	5.8
Appalachia	1.6
Total	84.8

Source: DOE NETL

470-1,000 billion barrels of oil technically recoverable globally

GLOBAL CO_2 EOR POTENTIAL	
Region	Billion Bbls
Middle East	230
Russia	78
United States	85
S. America	32
Asia Pacific	18
Europe	16
Africa	15

Assuming a plant size of 550 MW, this need would support the CO_2 production from 1382 NET Power gas plants (691 coal).

Four Way Agreement and Commercial Relationships

NET Power*

Inventor and developer of the technology. Responsible for overall project development, systems engineering and commercial development

Toshiba*

Developing the turbine and combustor

Goodwin Steel*

CB&I (Shaw*)

Provided substantial investment in this project and performing EPC services.

Exelon

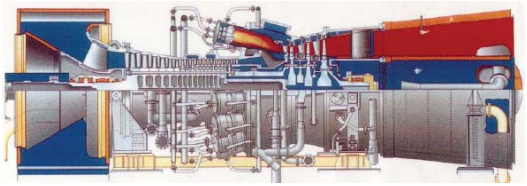
Assisting with the siting, permitting, and commissioning of the natural gas demo facility; providing operations and maintenance support.

*Note; UK grant was awarded for the development.

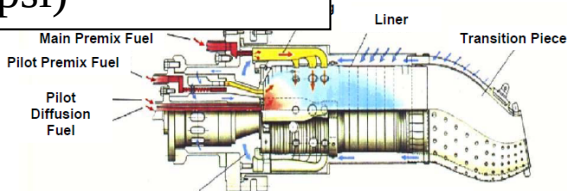
Necessary Technology for NET-Power Turbine

Gas Turbine Technology

1100-1500C (2012-2730F)



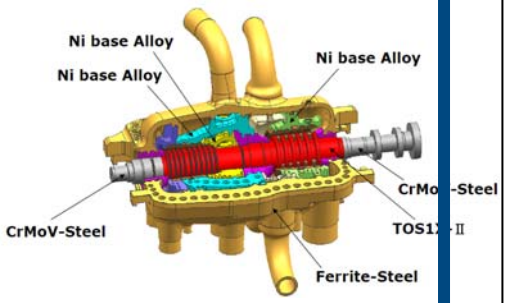
Working fluid; CO2
Pressure;2MPa⇒30MPa
(290psi→4350psi)



Combustor Technology
1100-1500C

Working fluid; CO2
Pressure;2MPa⇒30MPa

Steam Turbine Technology
USC& A-USC
Pressure; 24-31MPa (3500-4500psi)
Temperature; 600-750C (1112-1382F)



Temperature ⇒1150C (2110F)

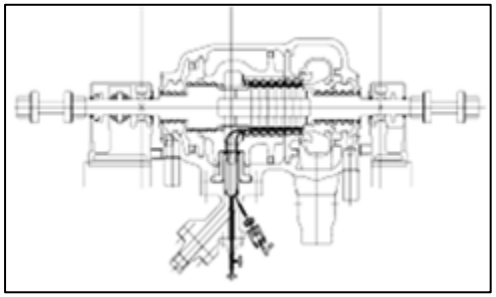
Temperature; E-Class
Pressure; USC & A-USC

Turbine & Combustor for
Net Power
Temp. 1150C (2110F)
Press. 30MPa (4350psi)

Toshiba is the only company that manufactured commercial turbine of 31Mpa main steam pressure.
Toshiba has been keen on A-USC development.

Turbine for 25MWe Demo Plant

A) Intended to be a scale model of commercial turbine (250MWe) as much as possible
B) Rotational speed is 6000rpm and connected to compressor and reduction gear
C) Double shell configuration
D) Rotors are welded together
E) Single can type combustor for 25MWe turbine



Materials

Rotor; Ni base forging and CrMoV forging are welded together
Casings; Ni base casting for high temperature part
CrMoV casting for lower temperature part
Blades; Ni base casting

All the necessary materials have been already developed.
Purchase orders for long-lead materials will be placed soon.

R&D results of Ni base Forging and Ni base Casting
- Make the best use of R&D results for A-USC -

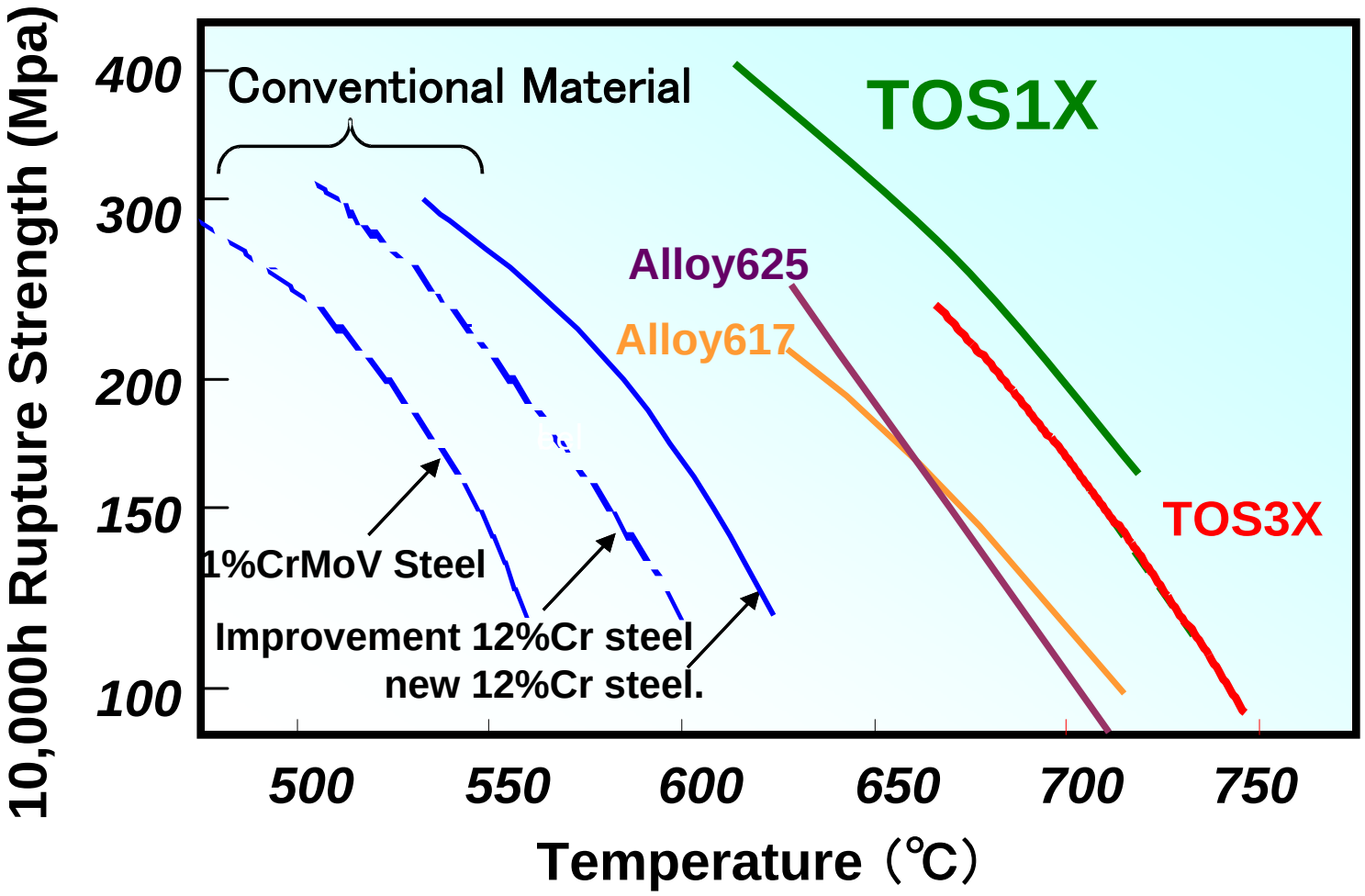
First trial forging for TOS1X was completed (above photograph)
Second trial forging for rotational test will be manufactured soon.

Alloy625
Trial Inner casing for A-USC

TOS3X Test Piece

Two candidates, Alloy 625 and TOS3X, are available for S-CO2 Turbine

Comparison of Creep Rupture Strength



Necessary materials are already applicable

Cooling Design

High Temperature

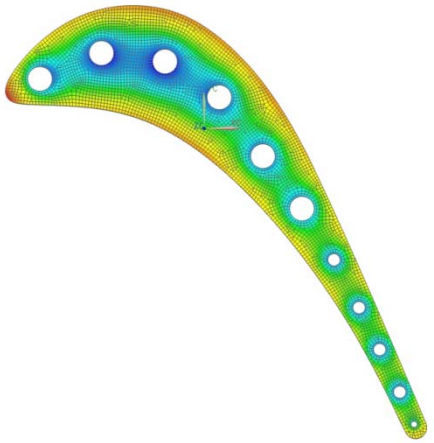
⇩

- Needs cooling both for nozzles and moving blades
- However, very complicated cooling technology is not necessary because the temperature is not extremely high compared with cutting-edge gas turbines.

⇩

Both mean temperature and local temperature satisfy design criteria thanks to two contributor

- Convection cooling by cold CO2
- Thermal barrier coating



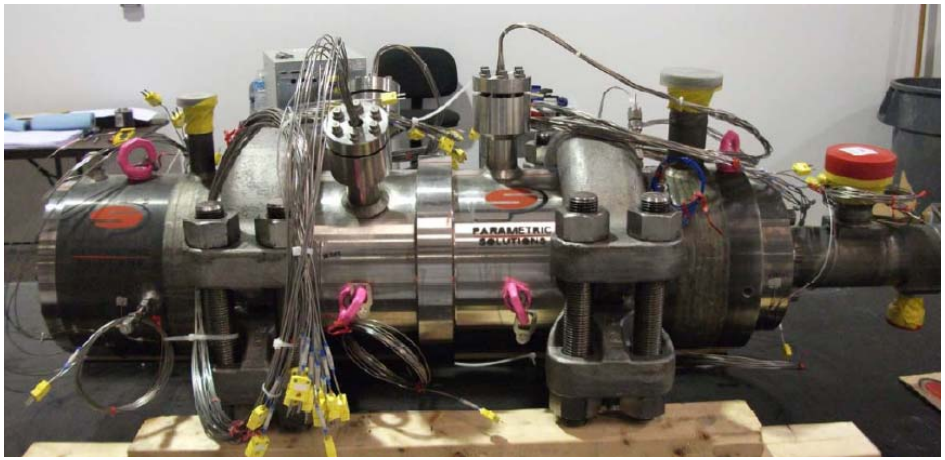
Temp. Contour

Concept of Combustor Design

No NOx Emission → No need of complex pre-mix technology
Simple Diffusion Flame can be used

High Pressure → Thick Wall Casing against high Pressure

Rather moderate temperature compared with gas turbines → Experienced Cooling Scheme

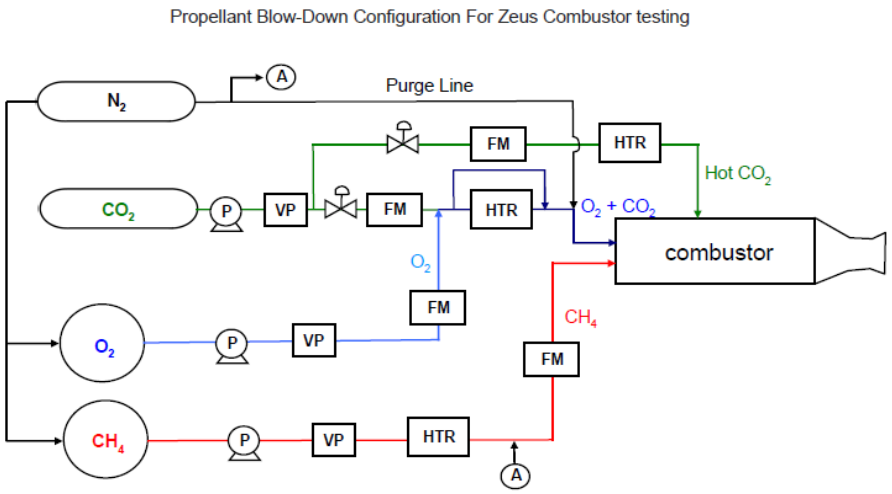


5MWt Rig Test Combustor

Rather simple combustion and cooling are expected , yet verification under high pressure using a rig test combustor is necessary.

Present Status of Combustor Development

- ✓ First Ignition was successfully done at the middle of January using test facility in U.S.A.
- ✓ Phase 1 Test up to 5Mpa has been completed.
- ✓ All the test data was carefully checked and evaluated.
- ✓ Stable flame was confirmed enabling us to proceed to higher pressure test (Phase 2).
- ✓ Modification of facility is being done for Phase 2 test.
- ✓ Design of the combustor for 25MW Demo plant will be synchronized with Turbine Development.



Rig Test Combustor at the Test Stand

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