PBMR

Power Conversion Unit

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Outline

- **Basics of Gas Turbine Cycles in Helium**
  - Brayton cycle overview
  - Helium properties and implications
  - Key influences in cycle performance
  - Bases for key design selections
- **PBMR Power Conversion Unit (PCU) Overview**
  - Top-level PCU functions
  - Process Flow Diagram
  - Overall physical layout, key components
  - Power level control concepts
- **PCU Subsystems, Components**
  - Turbomachinery
  - Heat exchangers
  - Gas cycle valves
  - Gas cycle pipes

Related Systems

- **Helium Inventory Control System**
- **Helium Pressure Boundary**

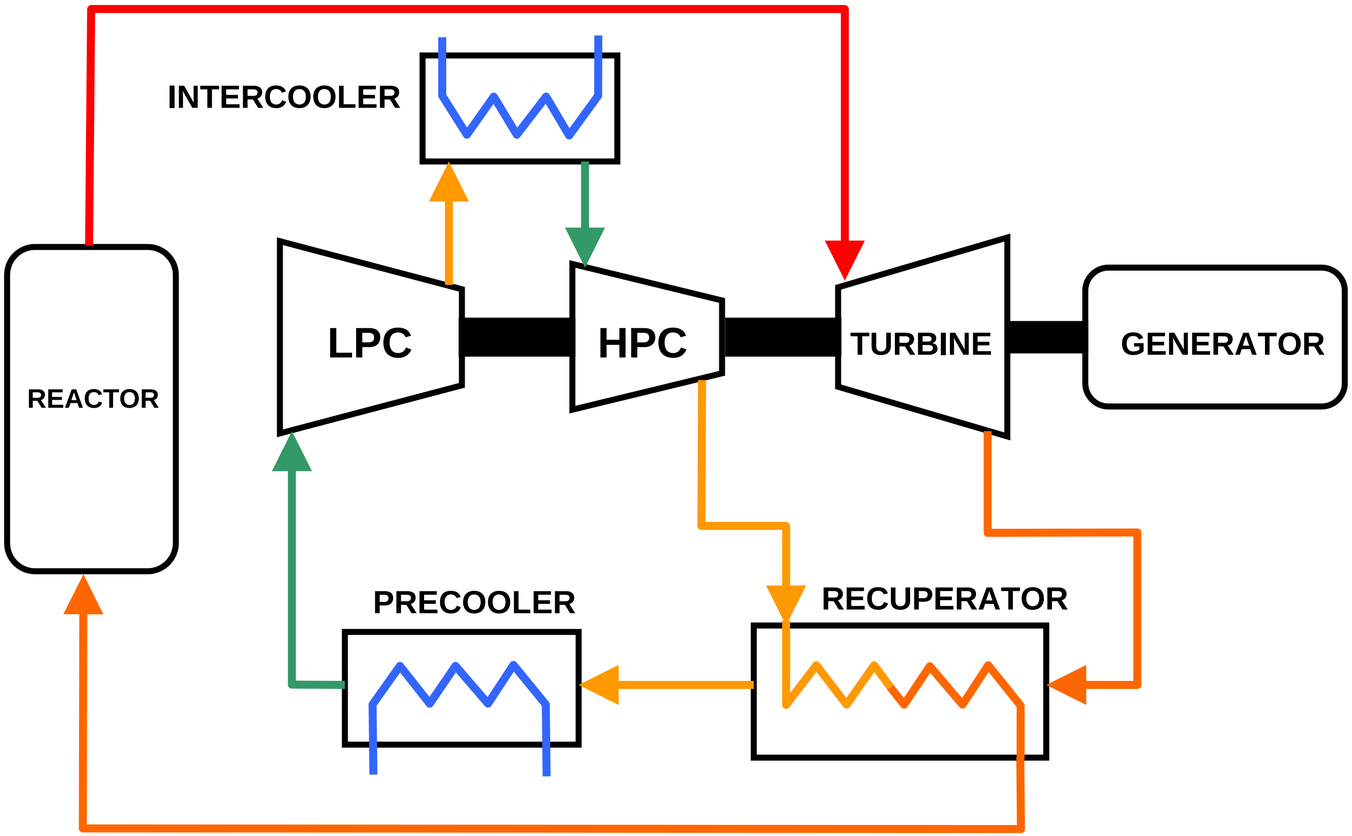
Power Conversion Unit

Basics of Gas Turbine Cycles in Helium

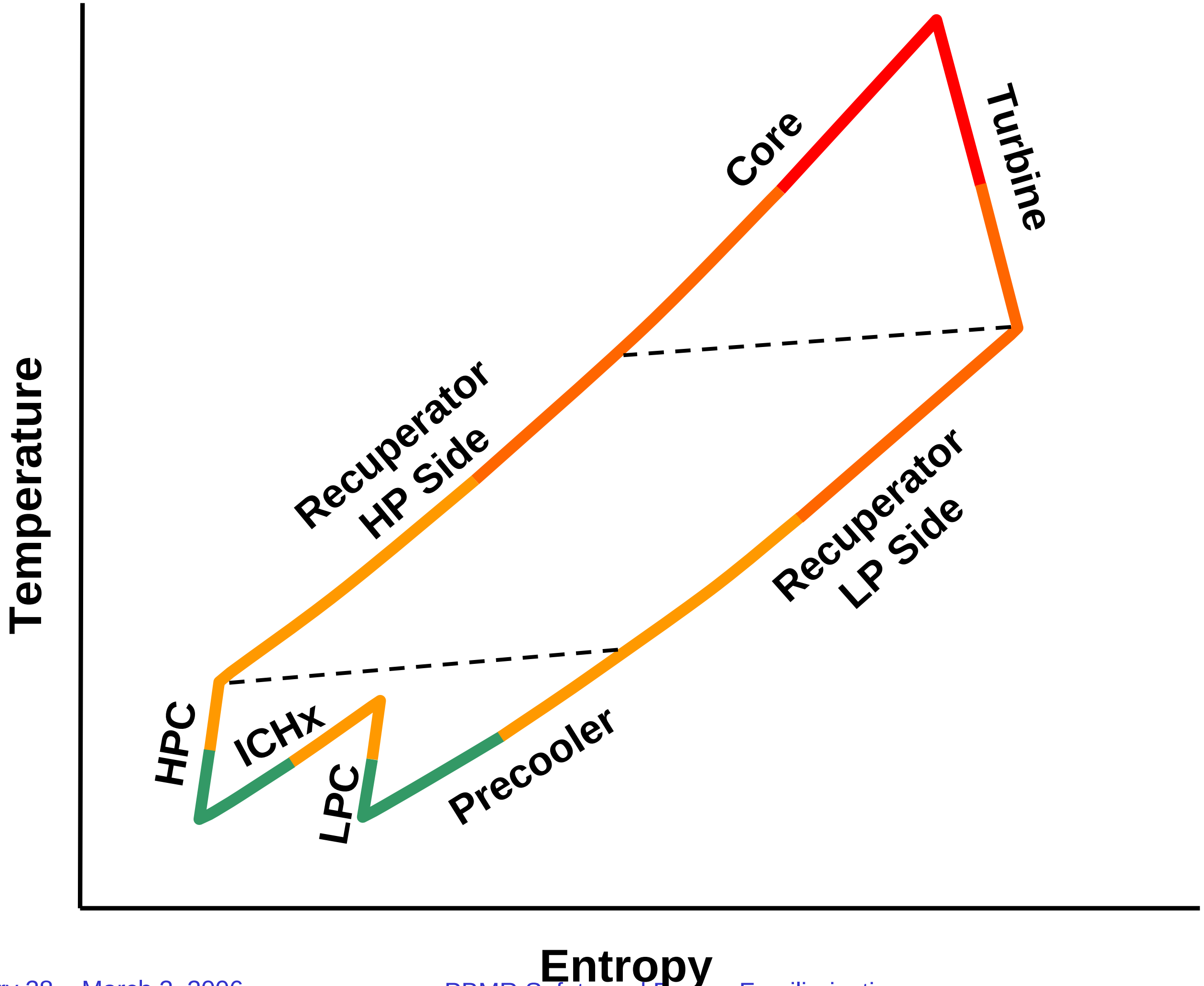
Note

The illustrative data shown in this section of the presentation are not necessarily specific to the PBMR.

Typical Closed GT Cycle



GT Cycle TS Diagram



Key Cycle Parameters

- Physical Properties of Helium
- Heat Rejection Temperature (Input Requirement)
- Thermal/Electrical Power Output
- Reactor Outlet/Turbine Inlet Temperature
- Primary System Pressure
- Cycle Pressure Losses
- Recuperator Effectiveness
- Intercooling
- Pressure Ratio

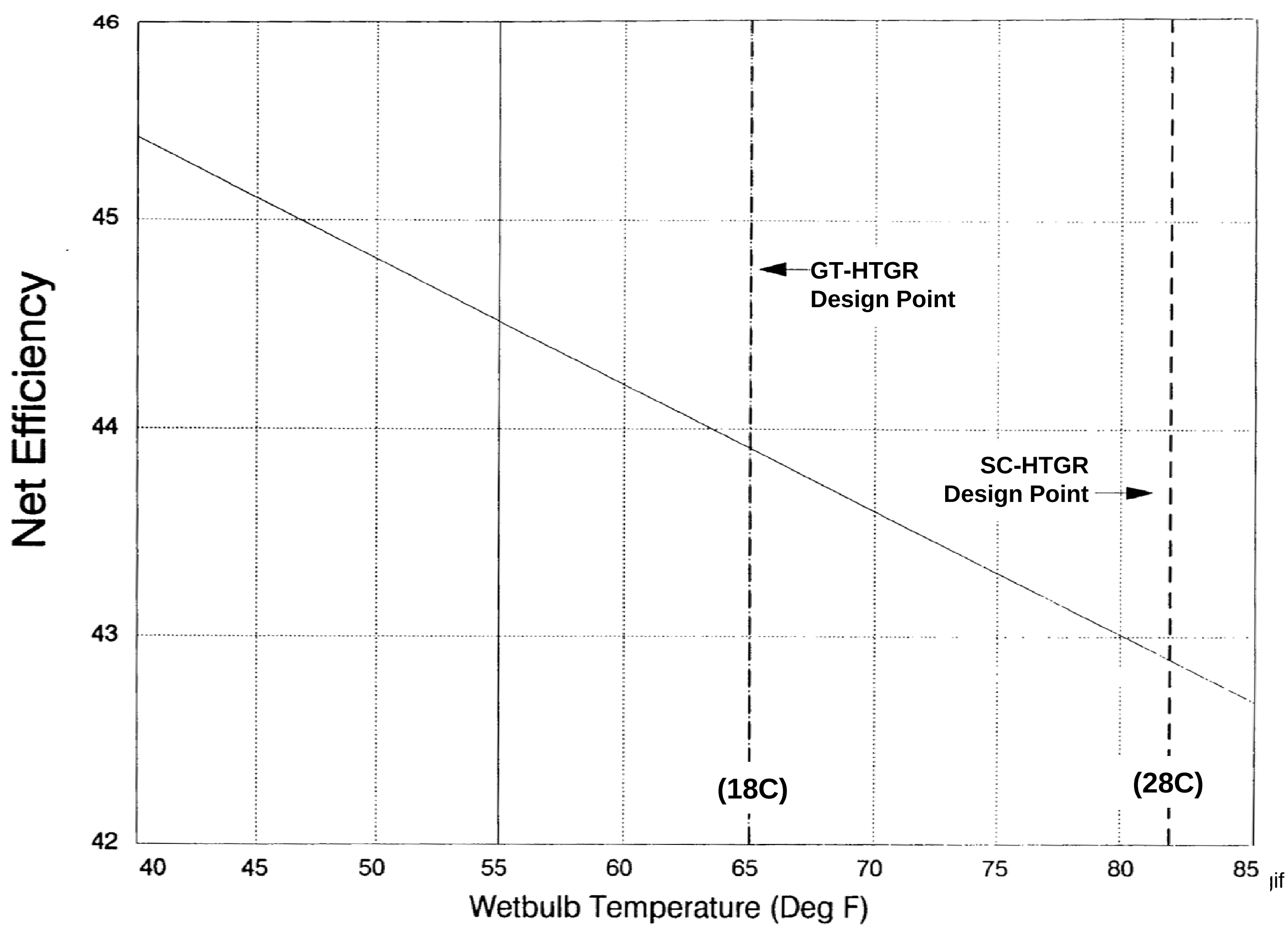
Helium and Air Fluid Properties Comparison

Fluid	Helium		Air	
Cycle State Point	Compressor Inlet	Turbine Inlet	Compressor Inlet	Turbine Inlet
Pressure, bar	25	90	1	15
Temperature, °C	25	900	25	1290
Molecular weight	4.003		28.97	
Gas constant, J/kg·°K	2077		287	
Specific heat, kJ/kg	5.193	5.190	1.00	1.16
Viscosity, μPa·s	19.9	51.8	18.6	43.8
Thermal conductivity, W/m·K	0.157	0.407	0.026	0.073
Adiabatic coefficient, γ	1.666	1.665	1.4	1.33
Sonic velocity, m/sec	1027	2031	347	772
Prandtl number	0.671	0.672	0.72	0.70
Density, kg/m^3	3.99	3.66	1.19	3.40
Dielectric strength (at ambient temperature)	Approximately linear from 200 volts/cm @ 5 torr to 1000 volts/cm @ 600 torr		350 volts/cm @ 0.6 torr 5,000 volts/cm @ 2 torr	

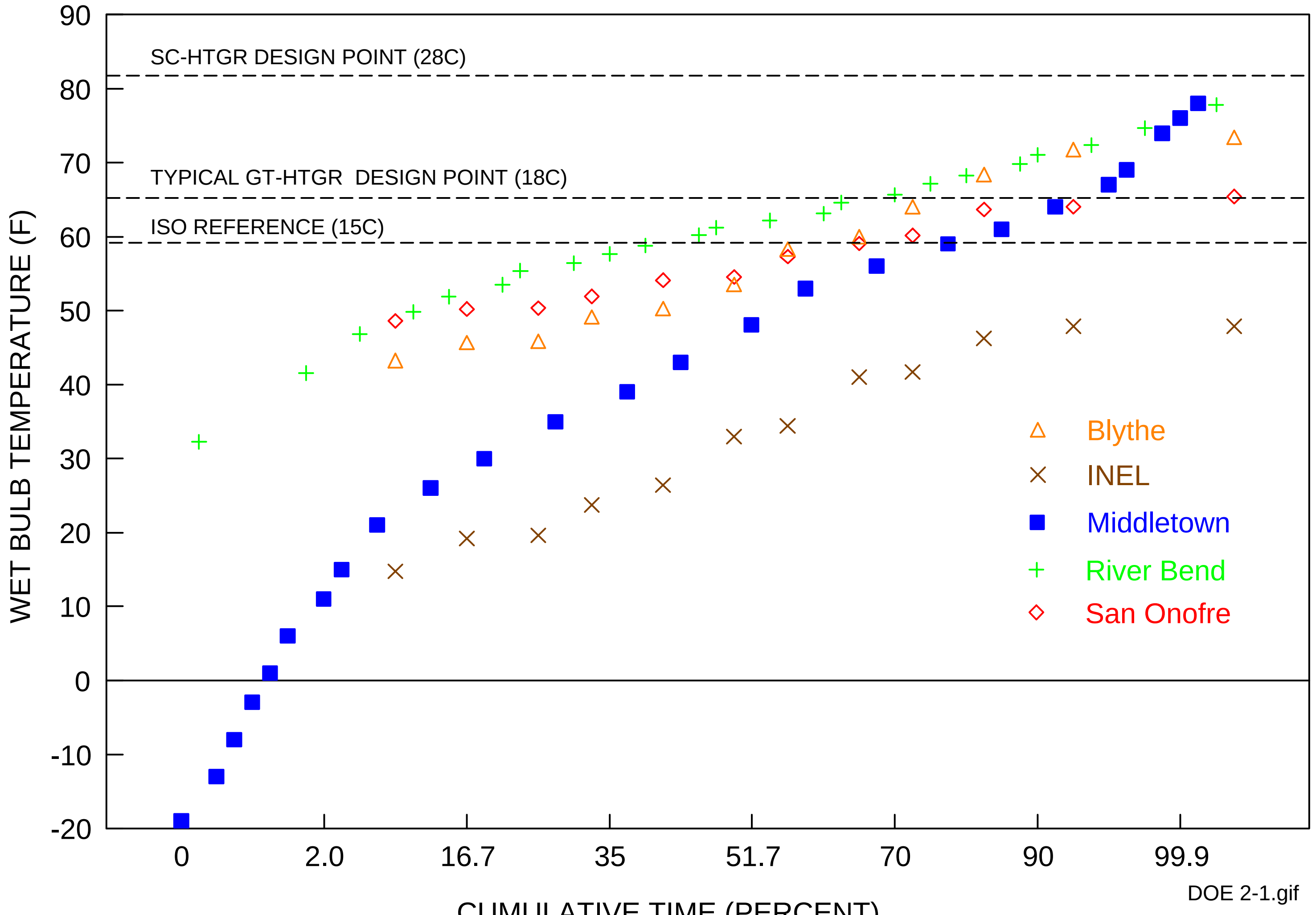
Significance of Helium Properties

- **Low Molecular Weight**
  - Requires larger volumes of gas to carry equivalent energy
- **High Specific Heat**
  - Can carry larger amounts of energy per unit of mass
  - Partially offsets low molecular weight effects
- **High Thermal Conductivity**
  - Improves film coefficients for heat transfer
- **High Sonic Velocity**
  - Avoids sonic effects in T/M designs
  - Higher flow rates, loads during blowdown
- **Lower dielectric strength**
  - Increased difficulty for electrical insulation design
- **Chemically Inert**
  - Tendency for self-welding of metallic components

Efficiency vs. Ambient Temperature



Representative Site Temperature Profiles



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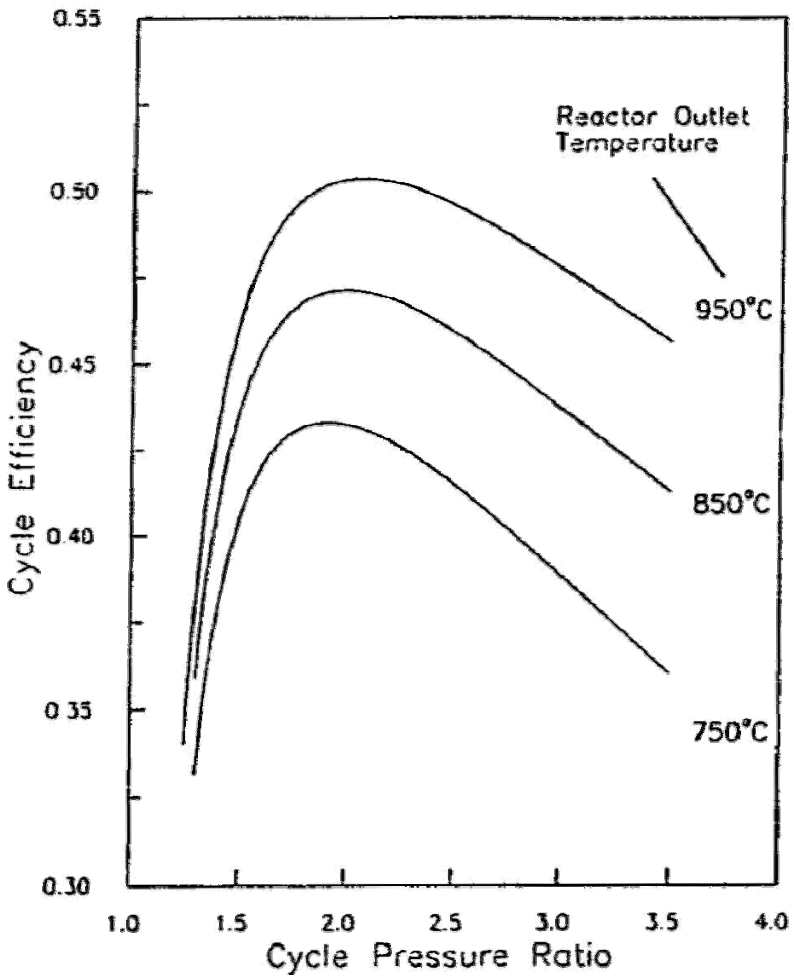
Power Output

- **Thermal Power Limited by:**
  - Characteristics of fuel
  - Core design considerations (e.g., neutron control)
  - Passive safety objectives of modular designs
- **Electrical Power Determined by**
  - Thermal power produced in reactor
  - Efficiency of power conversion cycle
  - Ambient temperature
  - Overhead loads

Reactor Outlet Temperature



***BASIS*:**

- **Recuperator Effectiveness** **95%**
- **Cycle Pressure Drop** **6%**
- **Compressor Inlet Temperature** **30ºC**
- **Efficiency of Turbines and Compressors** **90%**
- **Non-intercooled Cycle**

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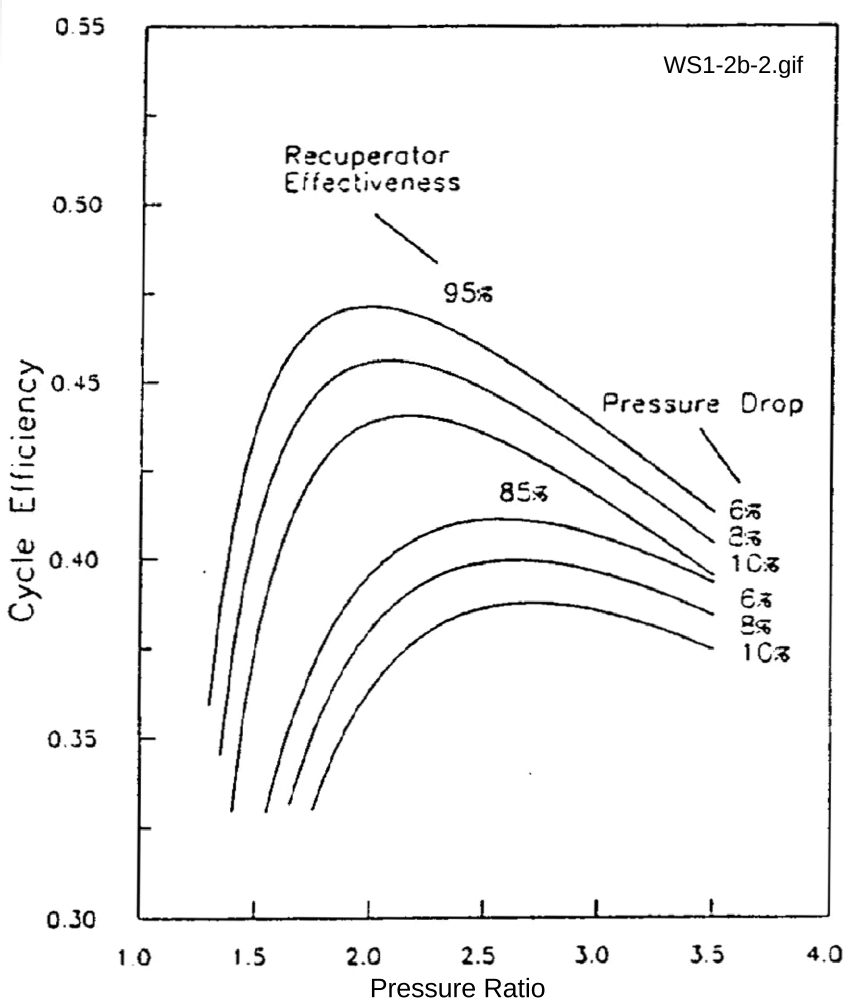
Cycle Pressure

- **High pressure reduces velocity for given mass flow, reduces cycle pressure losses**
- **Recuperator size decreases with higher pressure for given losses**
- **Turbomachine size decreases, optimum speed increases with higher pressure, due to aerodynamic considerations**
  - Optimum speeds (5000-10,000+ rpm) are substantially higher than synchronous speeds (3000-3600 rpm)
- **Limited by:**
  - Pressure vessel design
  - Maintenance considerations (helium leakage)

Cycle Pressure Losses

- One of the major determinants of cycle efficiency
- Primarily a function of the individual component designs and layout of the power conversion cycle
- Ducts and pathways for routing helium from component to component are key factors

Cycle Pressure Losses



***BASIS*:**

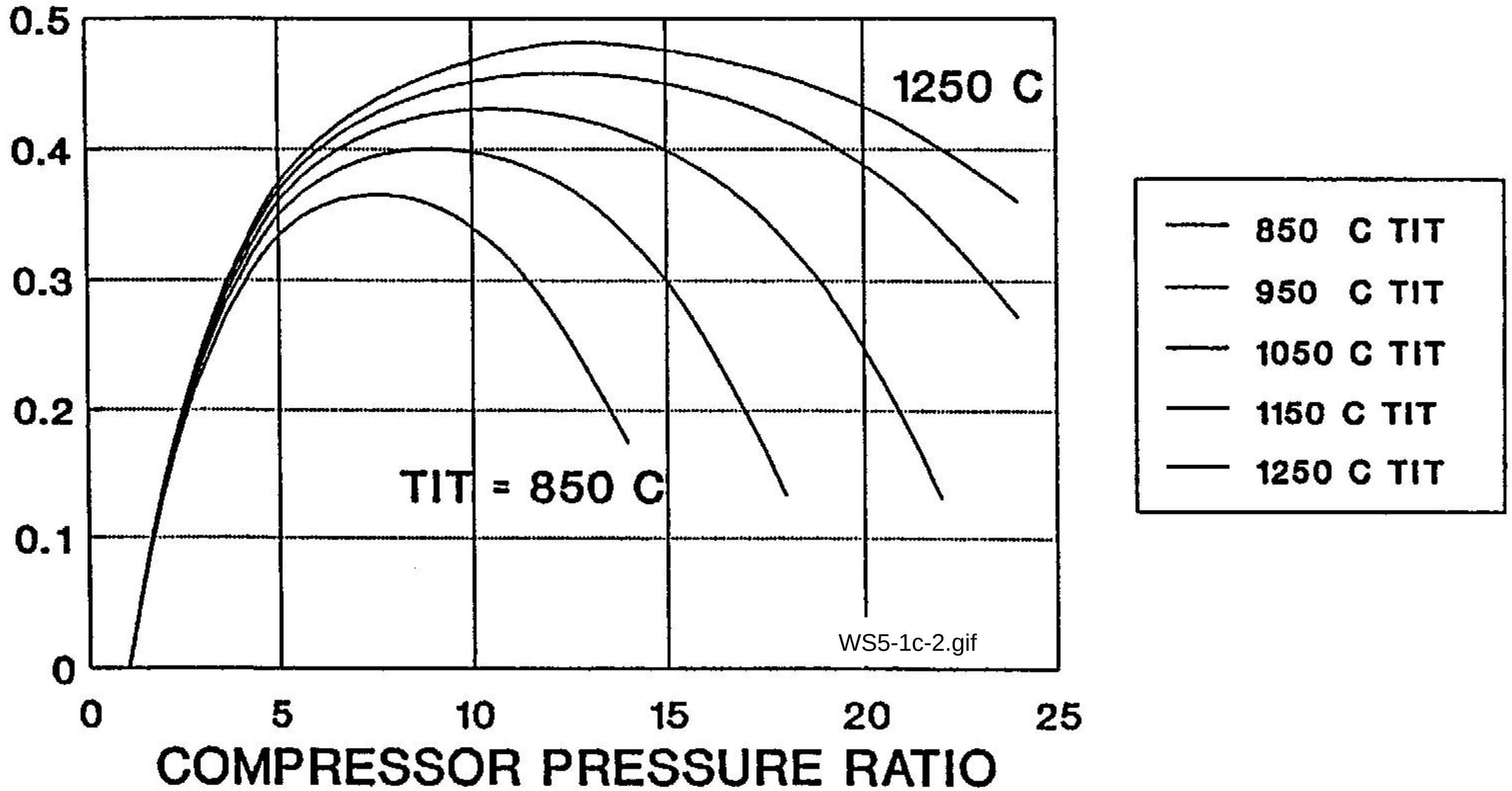
- **Reactor Outlet Temperature** **850ºC**
- **Compressor Inlet Temperature** **30ºC**
- **Efficiency of Turbines and Compressors** **90%**
- **Non-intercooled Cycle**

Bypass Flows

- **Bypass flows can have a substantial adverse effect on cycle efficiency**
- **Bypass flows are used to cool parts of the turbine hot section and various static structures in the reactor and PCS**
  - Cooling flow derived from the LP or HP compressor outlets
  - Minimized by careful design and appropriate selection of materials
- **Pressure balancing utilizes bypass flows to offset unbalanced axial pressure loads on turbomachinery**
- **Leakage flows are unintentional bypass flows, primarily through various static seals**
  - Leakage is more difficult to control in helium environment

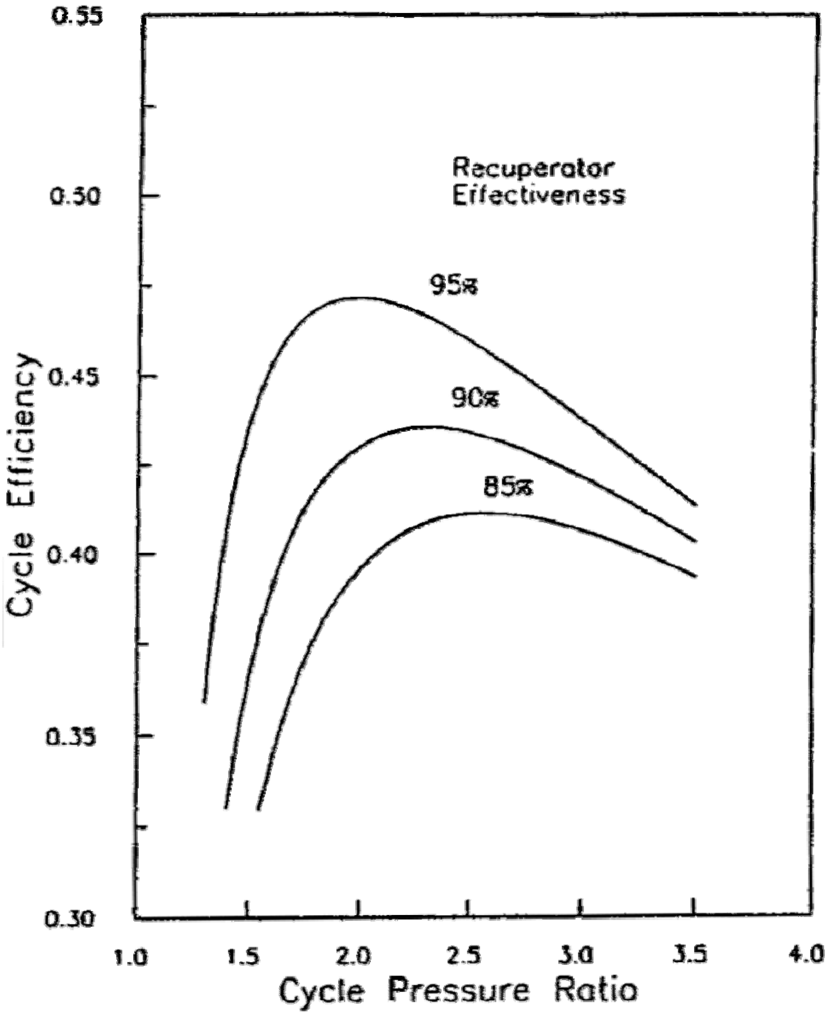
Recuperator Effectiveness

Simple Cycle Efficiency (No Recuperator)



Comp & turb polytropic eff = 0.92
DP/P = 0.05; Gen/mech eff = 0.965
Comp inlet temp = 30 C

Recuperator Effectiveness



***BASIS*:**

• **Reactor Outlet Temperature**	**850ºC**
• **Cycle Pressure Drop**	**6%**
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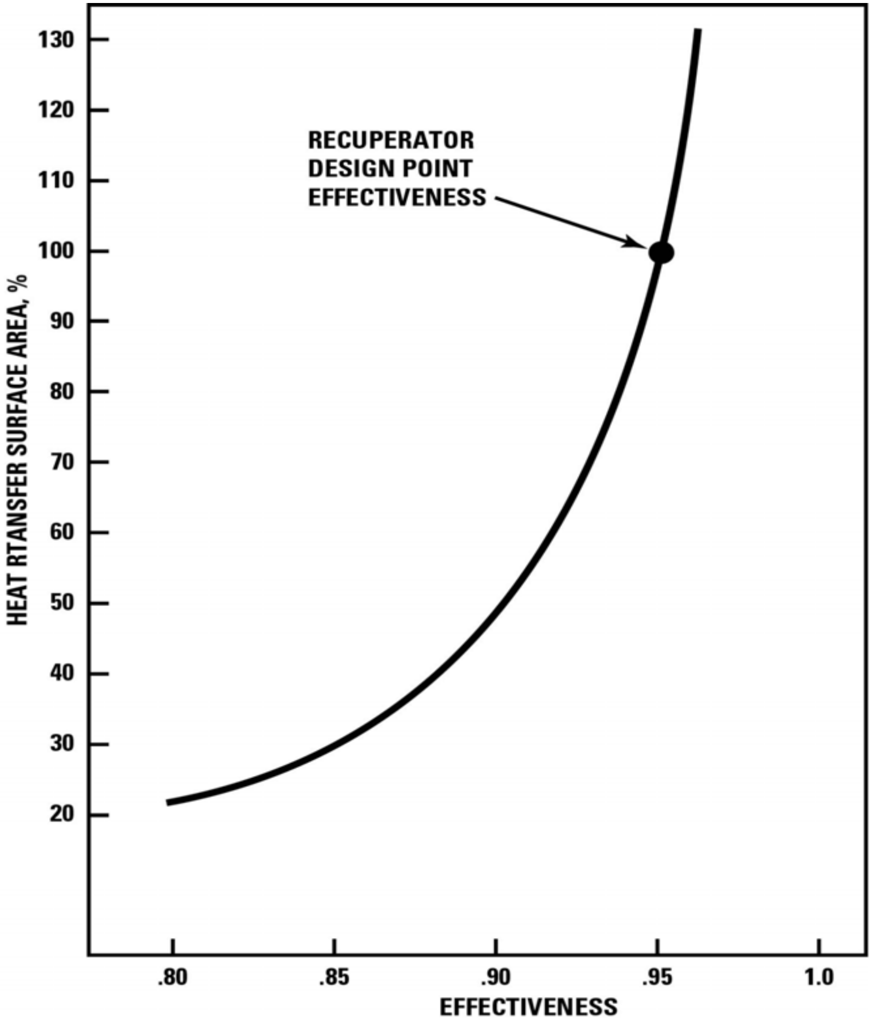
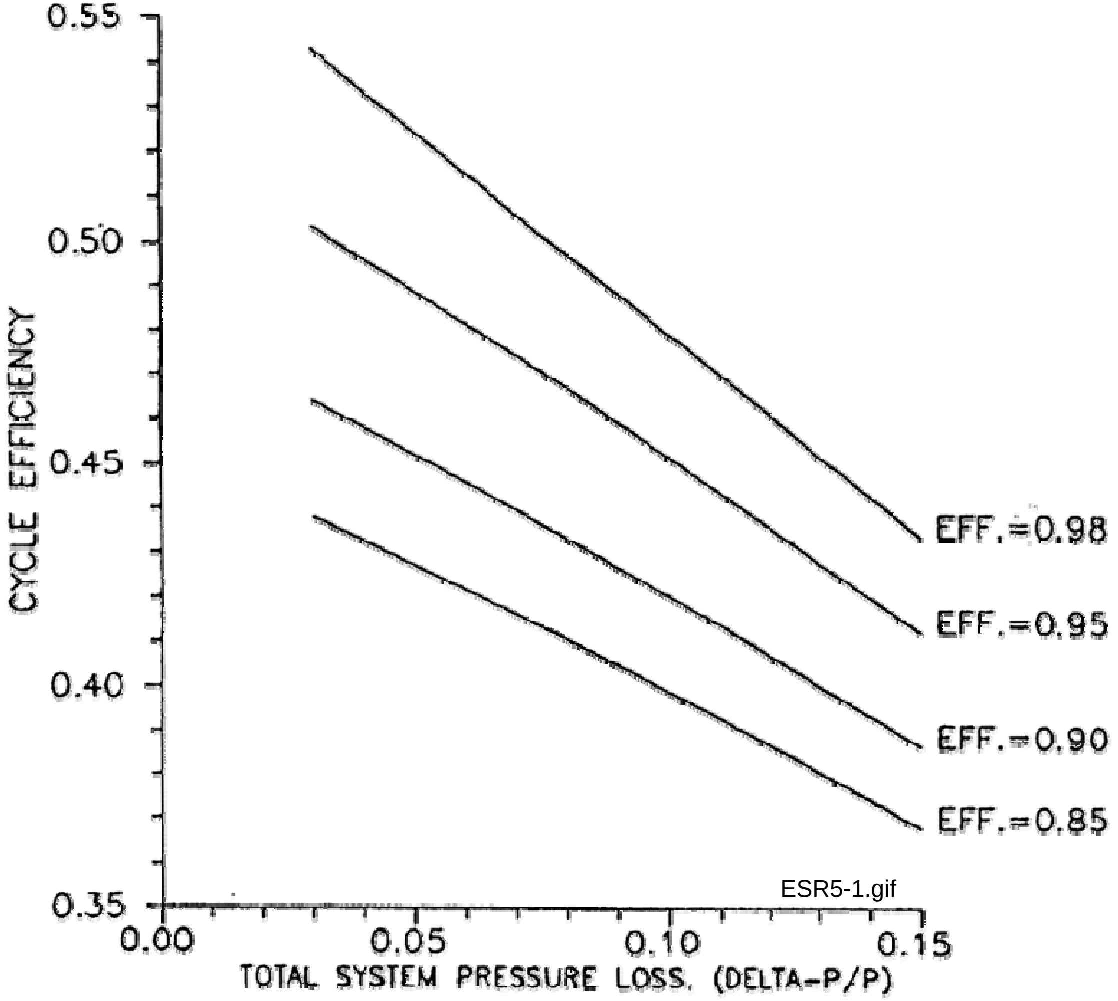
• **Non-Intercooled Cycle**	

Recuperator Area vs. Effectiveness

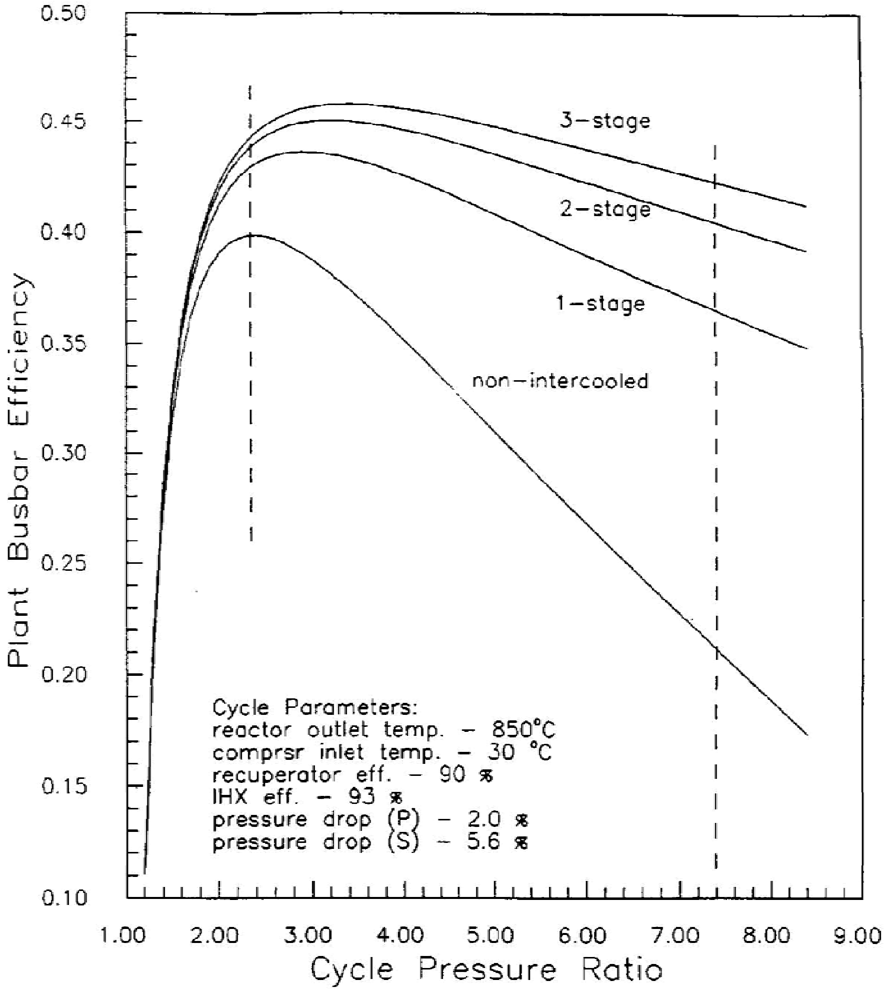


- Recuperator surface area strongly impacted by effectiveness requirement
- Compact plate-fin surface geometries needed to minimize recuperator size for installation in power conversion vessel

Effect of System Pressure Losses and Recuperator Effectiveness on Cycle Efficiency



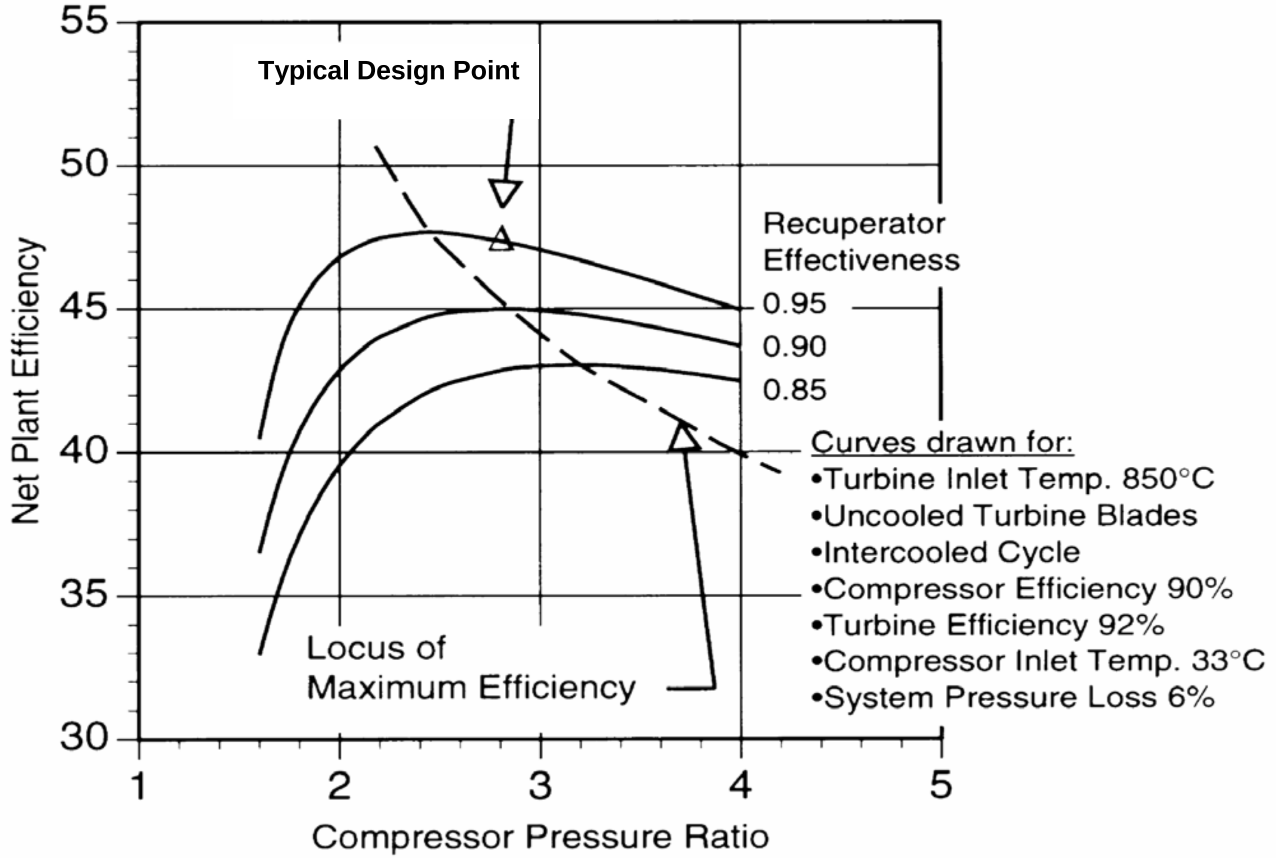
Effect of Intercooling



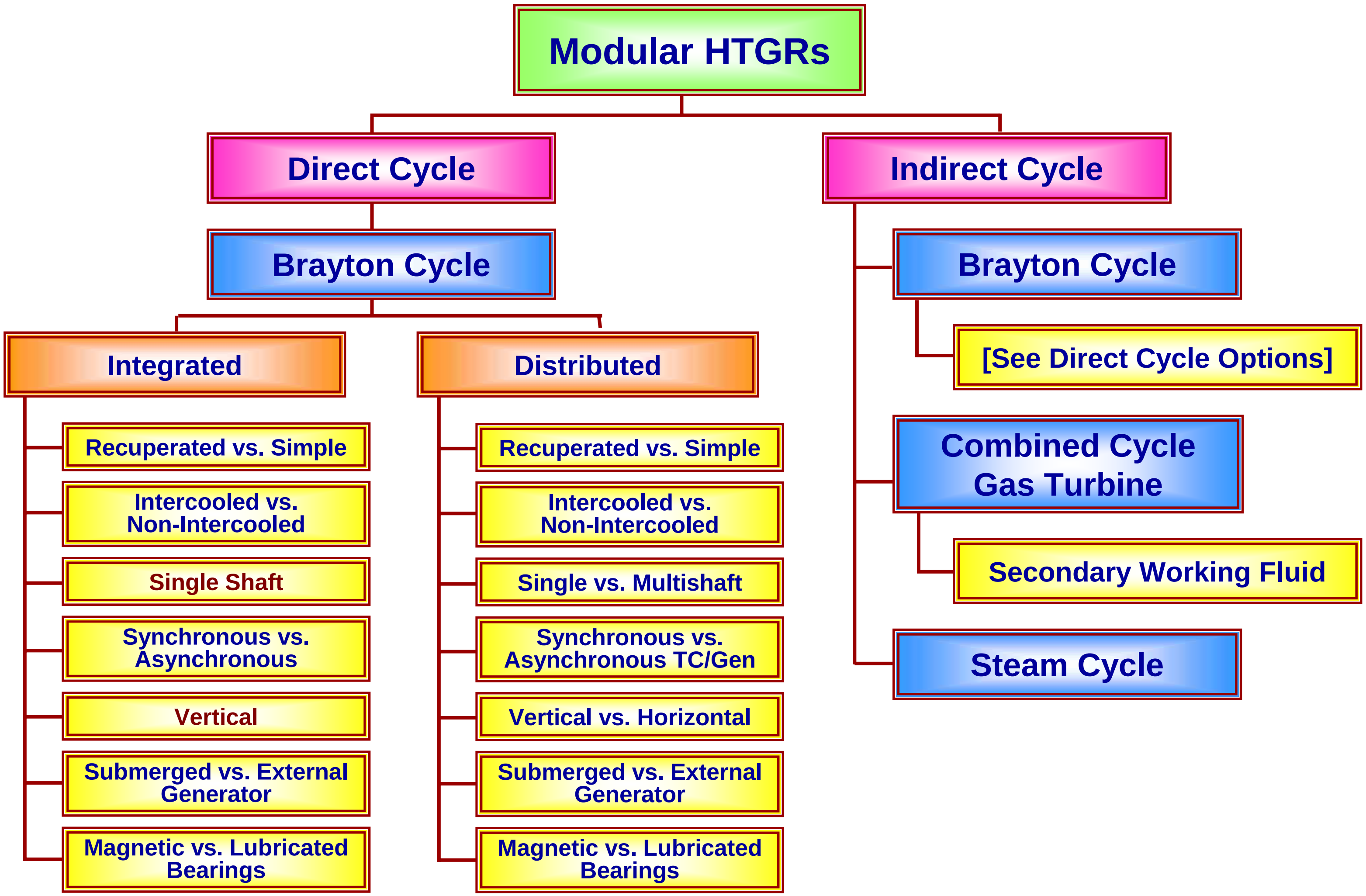
***BASIS*:**

- **Curves shown are for indirect cycle case with TIT = 810ºC**
- **One stage of intercooling provides greatest benefit at optimum pressure ratio of ~2**

Typical Design Map



PCU Configuration Hierarchy



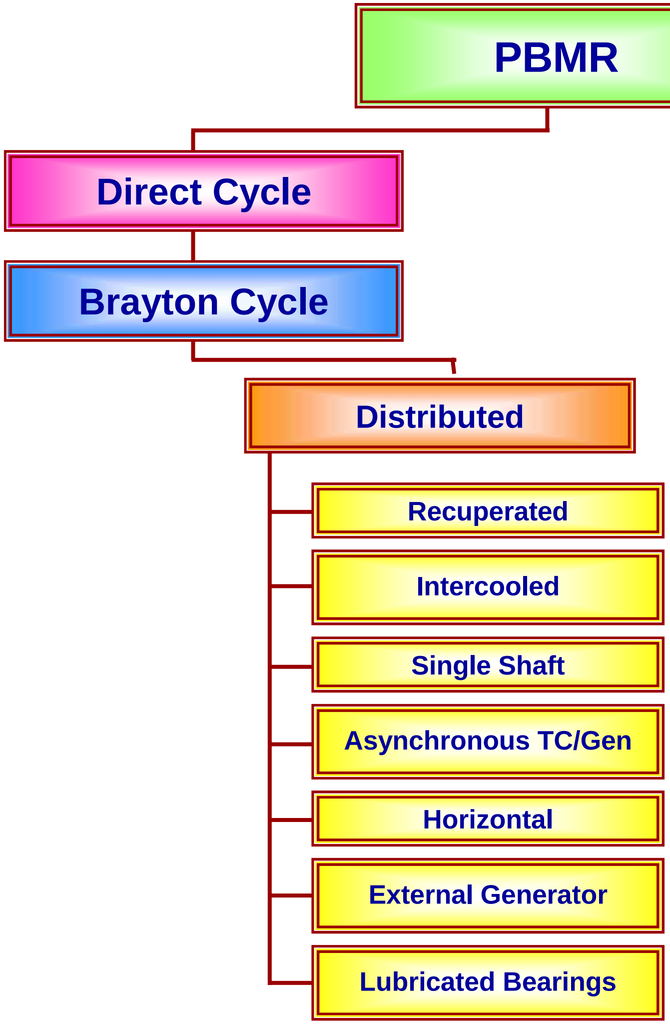
Bases for Key PBMR Design Selections

- **Direct Cycle**
  - Reduced capital cost
  - Increased cycle efficiency
  - Allows adaptation of proven materials and technologies (turbomachinery and heat exchangers) with modest R&D needs
- **Distributed Power Conversion Unit**
  - Conservative design, requiring less development
  - Maintenance access
- **Recuperated and Intercooled**
  - Cycle efficiency
- **Single Shaft Turbocompressor (TC)/Generator**
  - Improved controllability, transient response (loss of load)

Bases for Key PBMR Design Selections

- **Asynchronous Turbocompressor (TC)/Generator with Gearbox for Speed Reduction**
  - TC optimization for helium (higher speed)
  - Flexibility for 50/60Hz
- **Horizontal TC/Generator**
  - Conventional design
  - Maintenance access
- **External Generator**
  - Conventional design
  - Low windage losses
  - Maintenance access
  - Avoids contamination potential
- **Oil Lubricated Bearings**
  - Conventional design

PBMR Configuration Selections



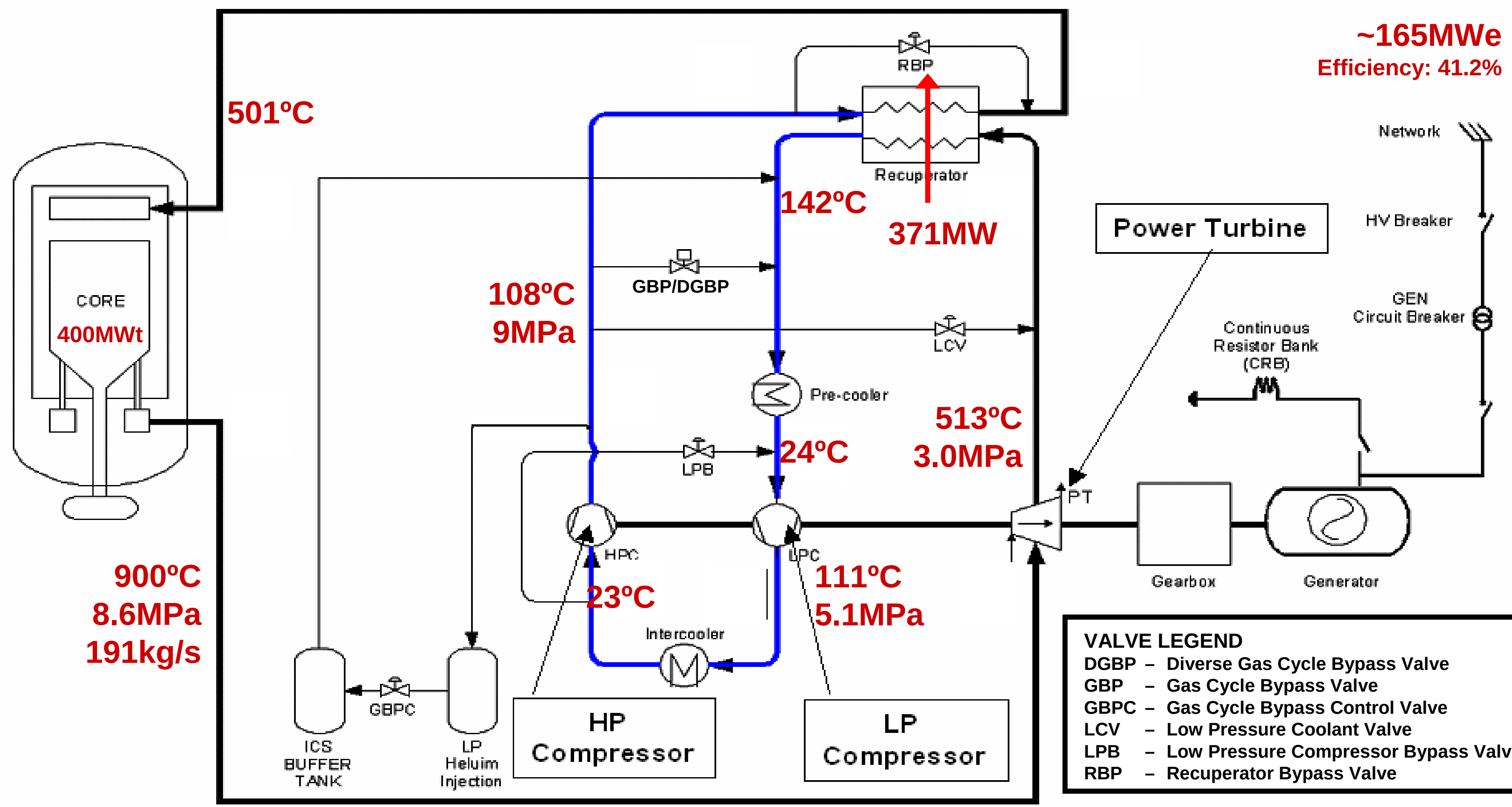
Power Conversion Unit

System Overview

Key PCU Functions

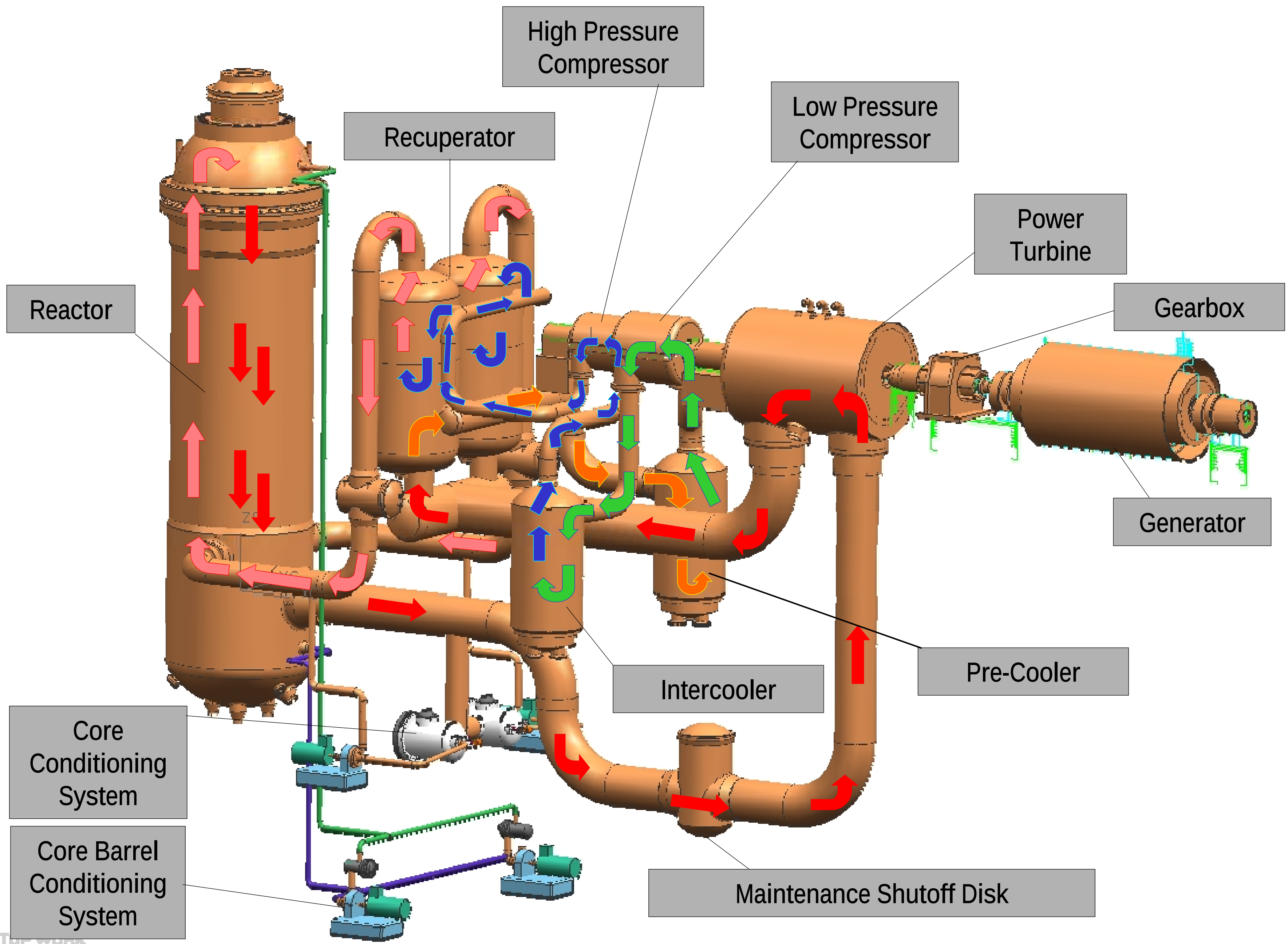
- Convert thermal energy produced in the reactor to mechanical and thence electrical energy
- Circulate helium within the primary circuit
- Provide a path for removal of reactor heat during startup, shutdown and other specified events

Simplified Power Conversion PFD

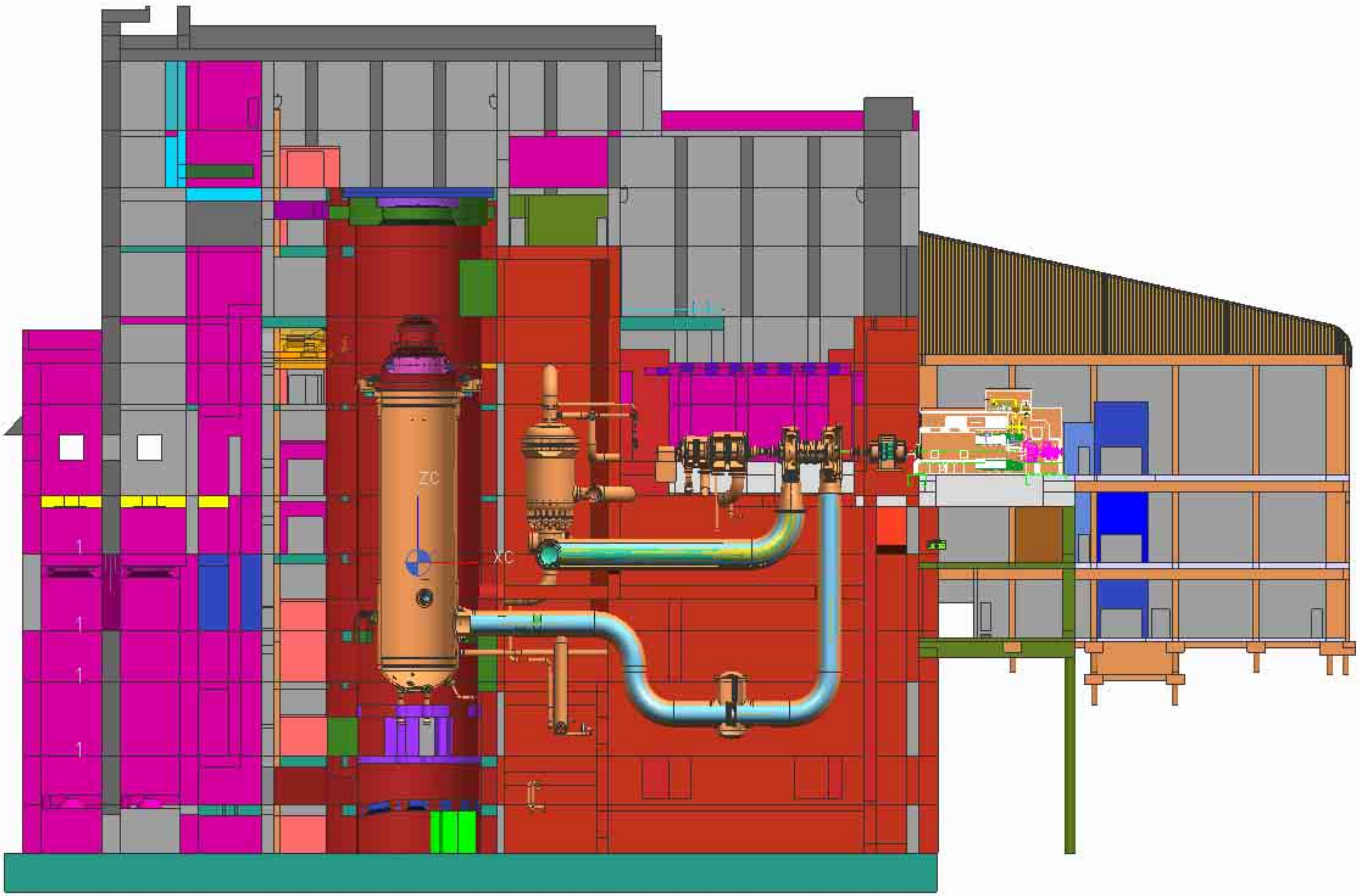


VALVE LEGEND

DGBP	–	Diverse Gas Cycle Bypass Valve
GBP	–	Gas Cycle Bypass Valve
GBPC	–	Gas Cycle Bypass Control Valve
LCV	–	Low Pressure Coolant Valve
LPB	–	Low Pressure Compressor Bypass Valve
RBP	–	Recuperator Bypass Valve


High Pressure Compressor
Low Pressure Compressor
Recuperator
Power Turbine
Gearbox
Reactor
Generator
Intercooler
Pre-Cooler
Core Conditioning System
Core Barrel Conditioning System
Maintenance Shutoff Disk

PCU Location



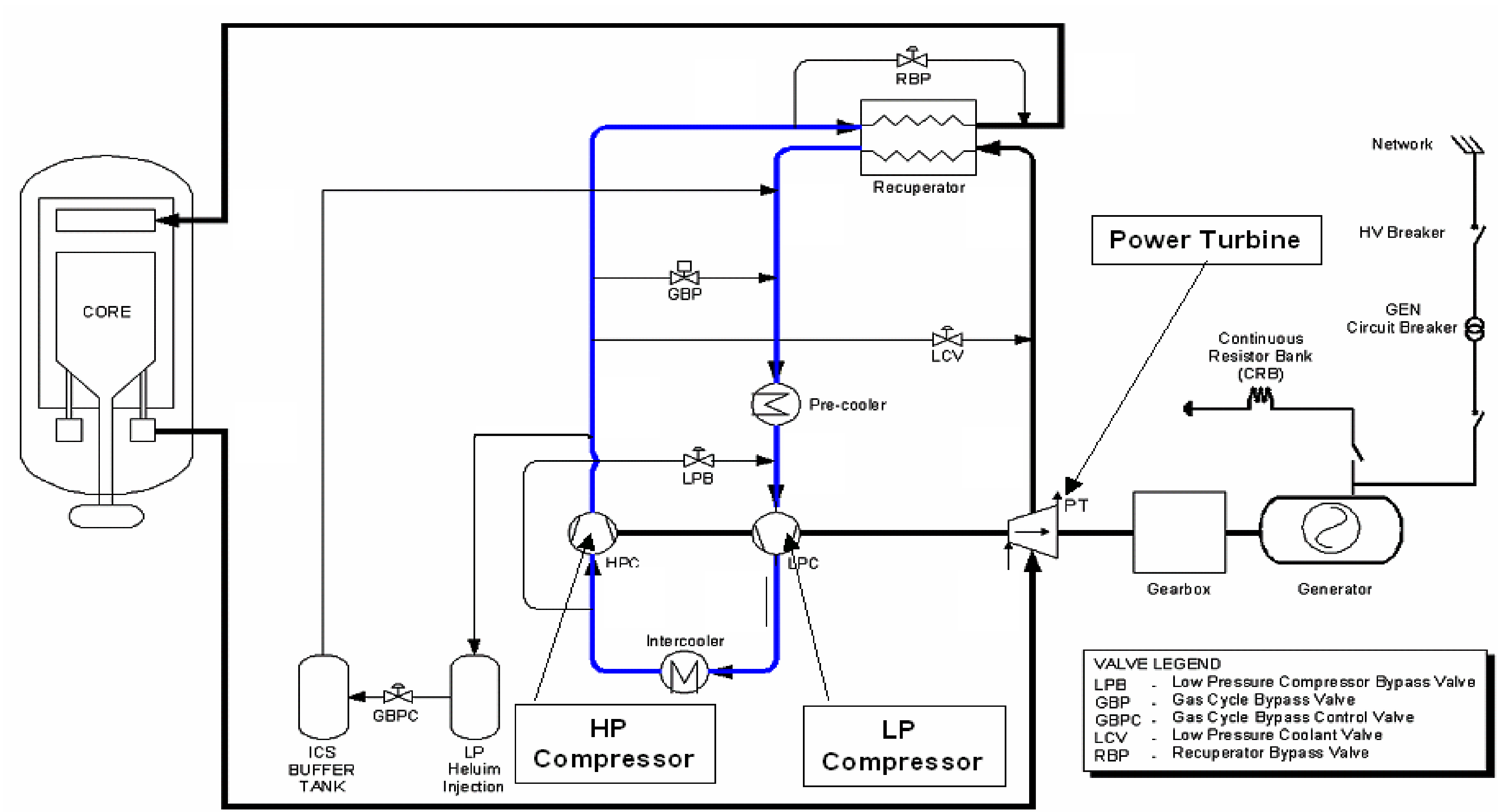
Basic Brayton Cycle Control Concepts

- **Cycle power output is controlled by two complementary means**
  - Bypass control for rapid changes
  - Inventory control for slow changes
- **Bypass control**
  - Bypass valves opened/closed to reduce/increase flow through reactor for rapid power changes
  - Significant efficiency penalty (only want to use for short term)
  - At higher bypass levels, collapses cycle pressure ratio for rapid shutdown (e.g., loss of generator load)

Basic Brayton Cycle Control Concepts

- **Inventory control**
  - Add/withdraw helium from cycle to increase/decrease power
  - Reduces mass flow while maintaining volumetric flow, cycle temperatures close to optimum levels
  - Rate of 10%/min over range of 40-100% power
  - High efficiency at variable power levels
- **Bypass and inventory control are used together to meet maneuvering requirements, while maintaining high efficiency overall**
- **Reactor power normally follows demand via negative temperature coefficient**
  - Reactivity control used to reduce outlet temperature for certain transients (e.g., loss of load)

PCU Control Elements



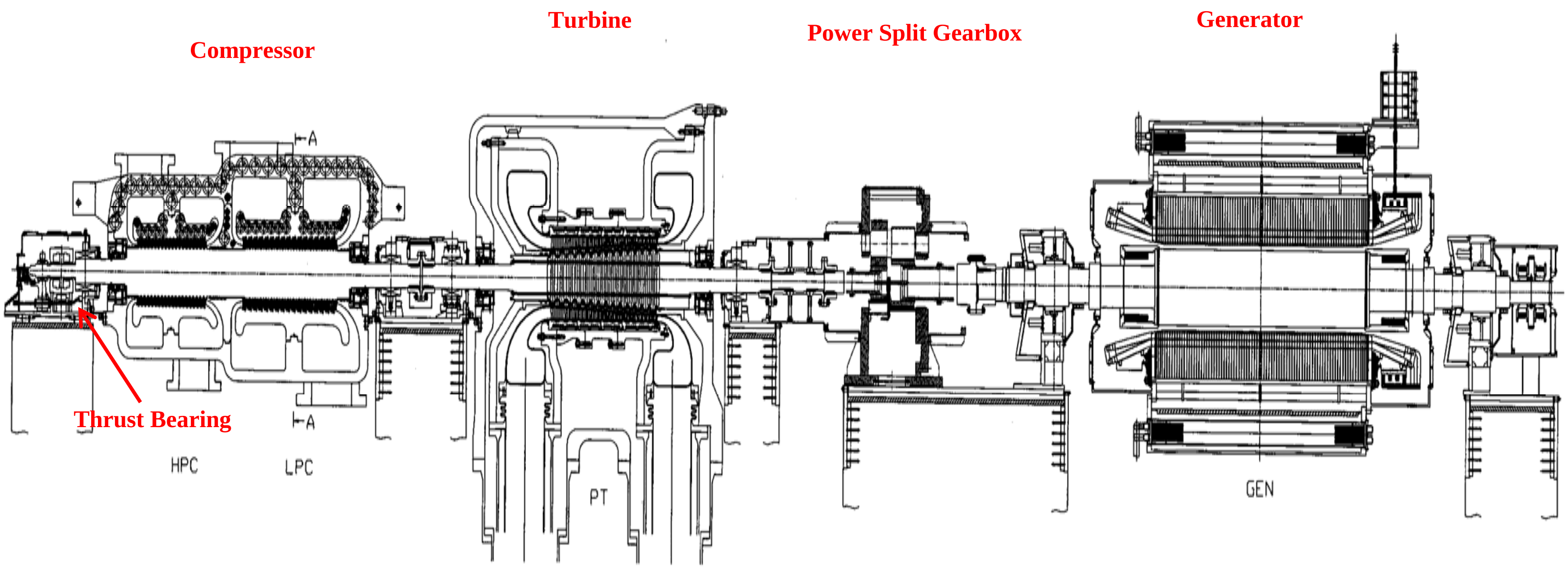
Power Conversion Unit

Turbomachinery

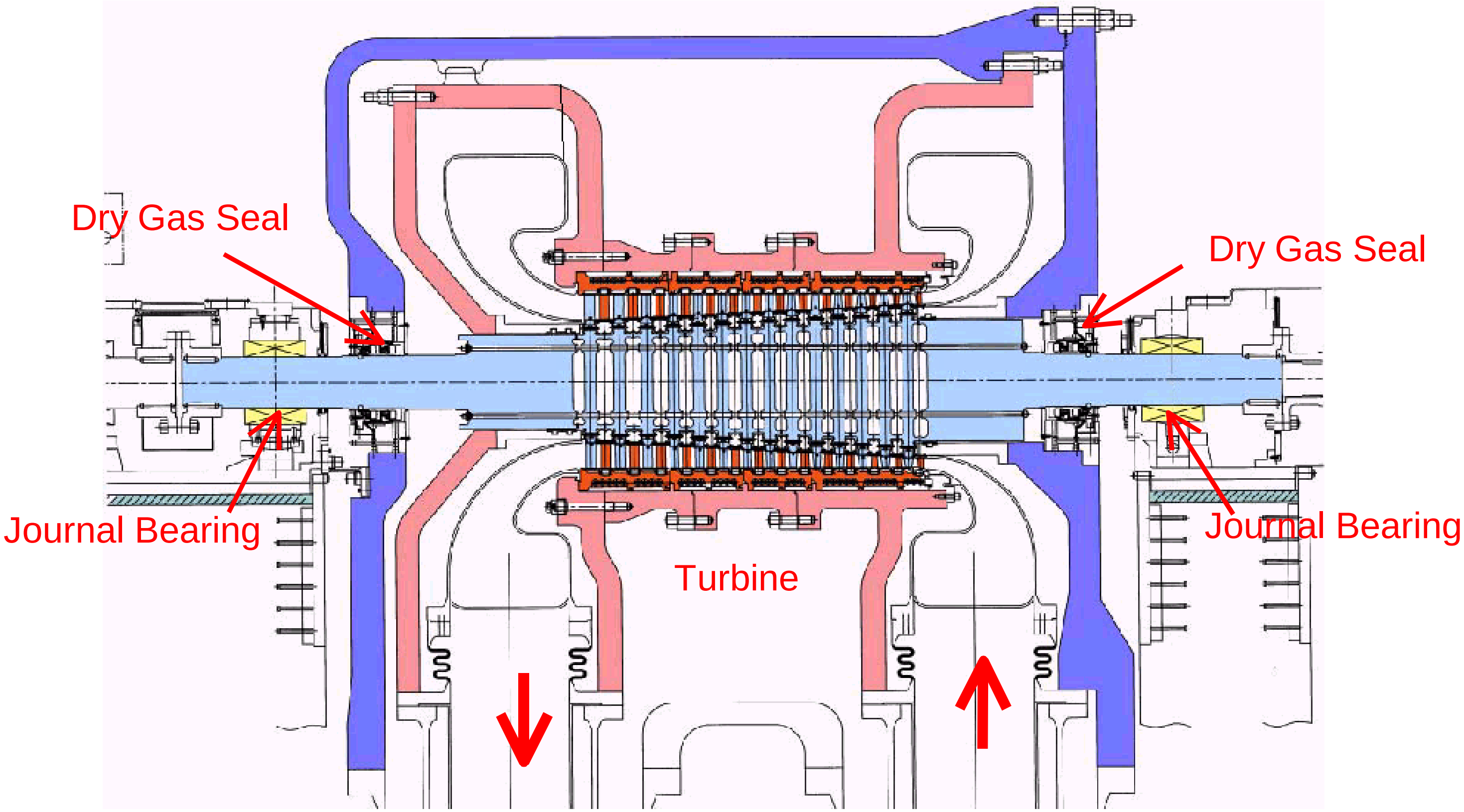
Turbomachinery Functions

- **The functions of the Turbo-Generator Set (TGS) are as follows:**
  - To convert thermal energy from the reactor to mechanical and, thence, to electrical energy during normal power production
  - To provide flow during Brayton cycle start-up
  - To provide flow for conditioning of MPS Components
  - To provide flow for the removal of core decay heat (Brayton cycle not operational)
  - To provide flow to maintain the MPS at operating temperature after a PCU trip

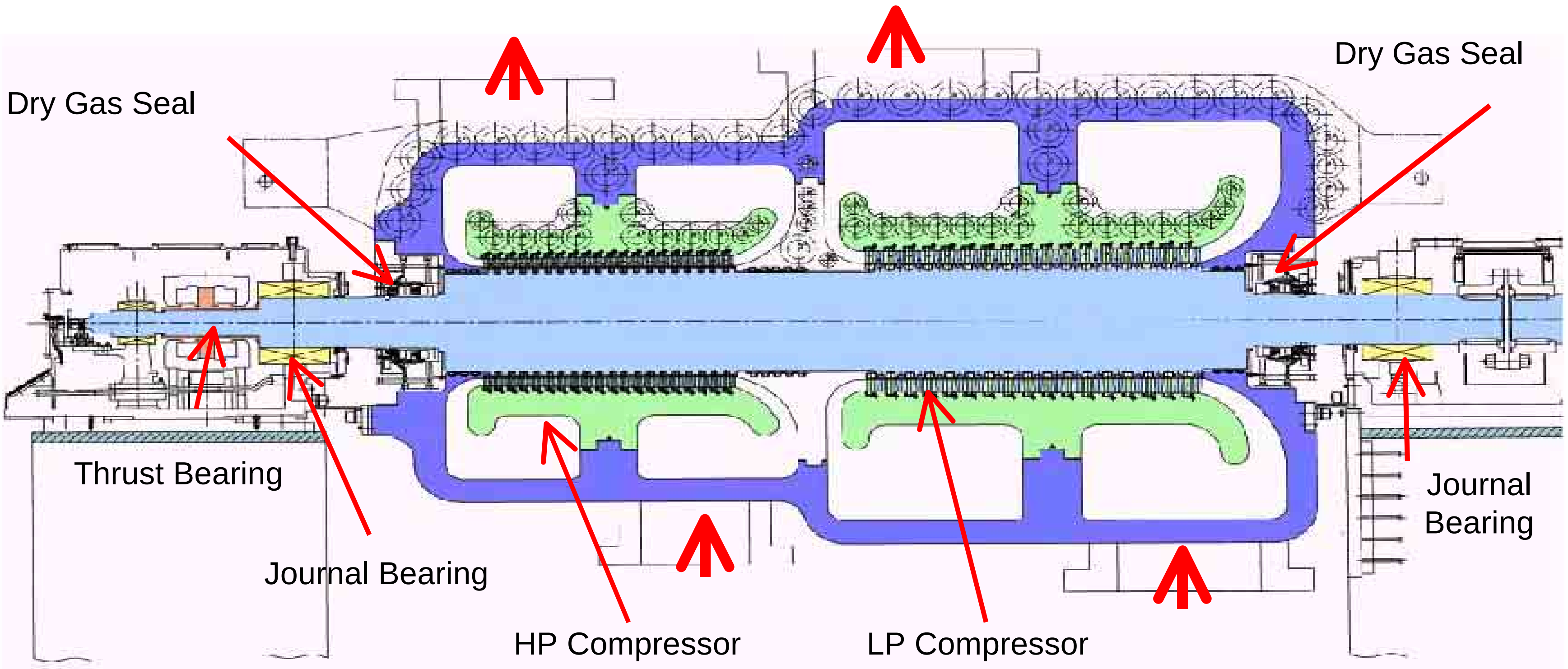
PCU Turbomachinery



Power Turbine



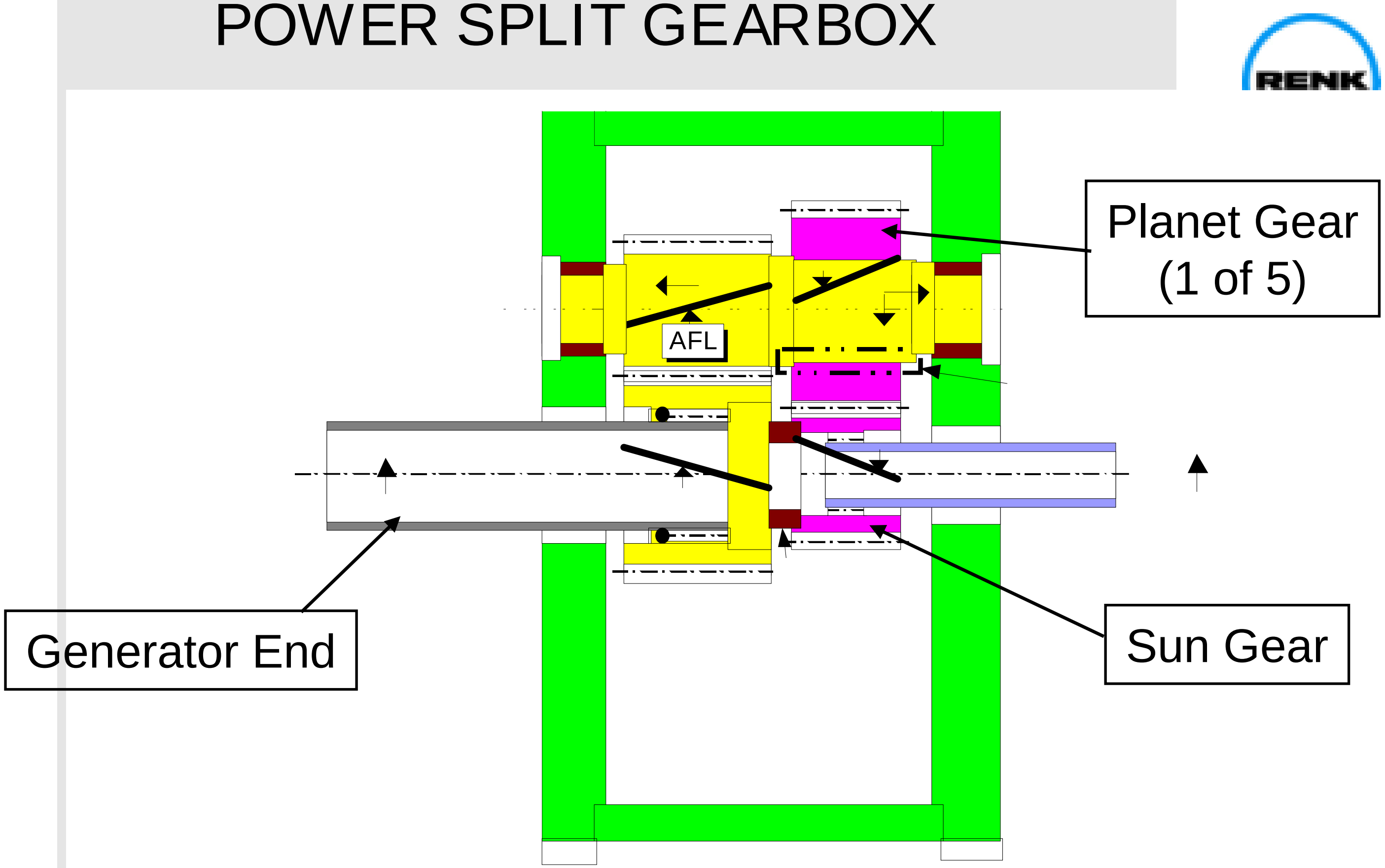
LP/HP Compressors



Reduction Gearbox

- **Reduction gearbox provides 2:1 speed reduction for 50Hz application**
  - Enables turbocompressor to operate at optimum speed of 6000rpm
- **Based on sun/planet gear design**
  - 5 planet gears surround sun gears of input and output shafts

POWER SPLIT GEARBOX



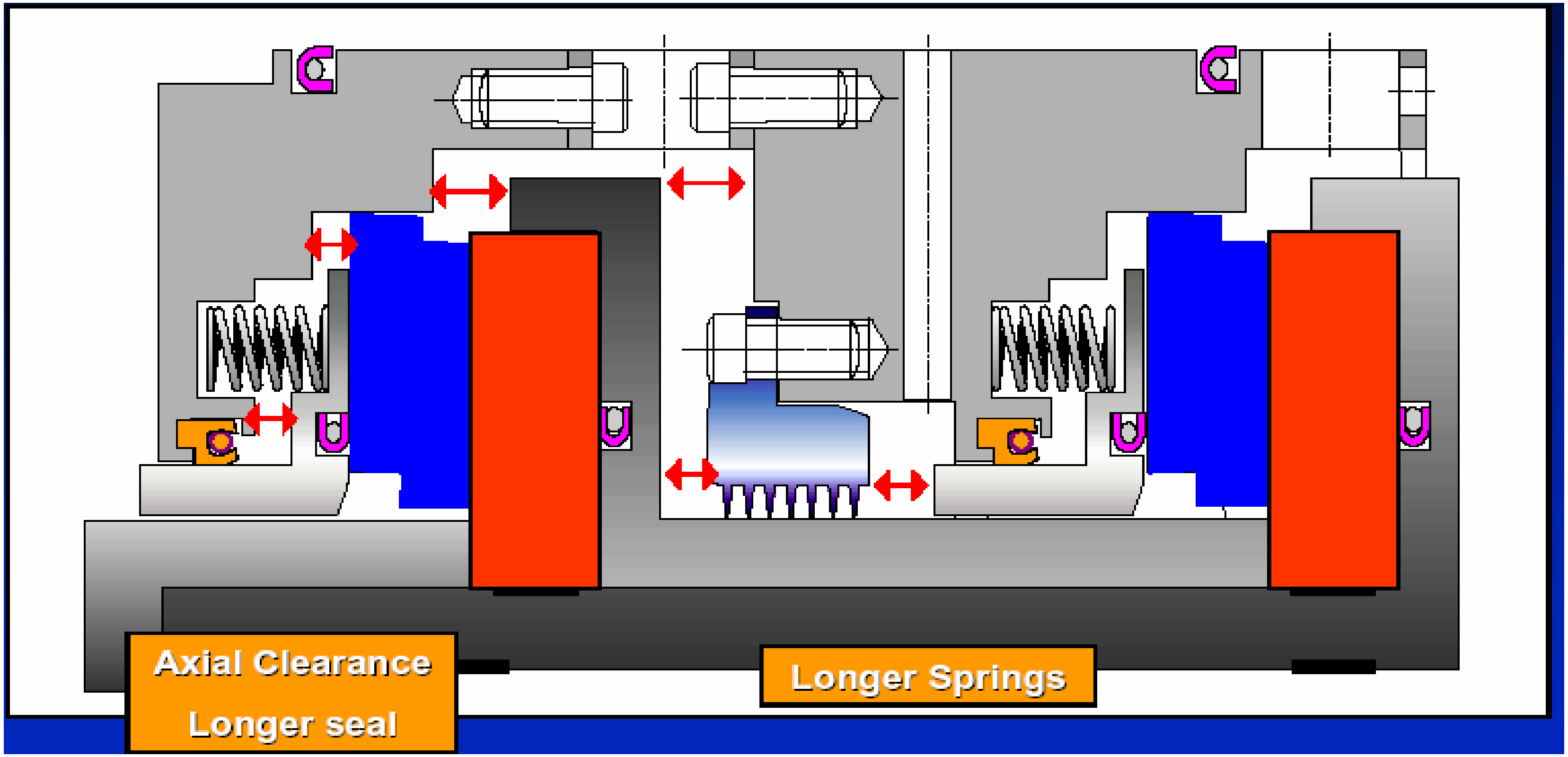
Powering the Future

Dry Gas Seals

- **Dry Gas Seals (DGS) enable the use of conventional bearing technology, while avoiding potential for oil contamination of primary helium.**
  - Significant experience base in conventional applications (e.g., gas pipeline compressors)
  - PBMR application requires modest extension of current experience base.
  - Initial tests confirm feasibility of PBMR design.
- **PBMR design employs 4 DGS at ends of turbine and compressors.**

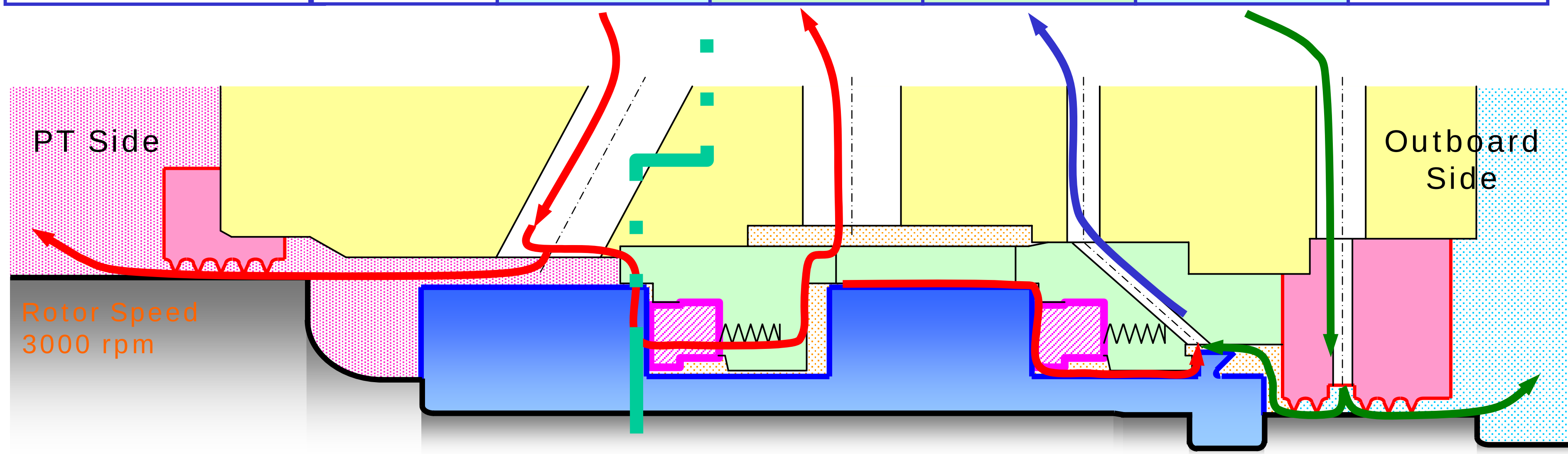
Dry Gas Seal

DGS Concept

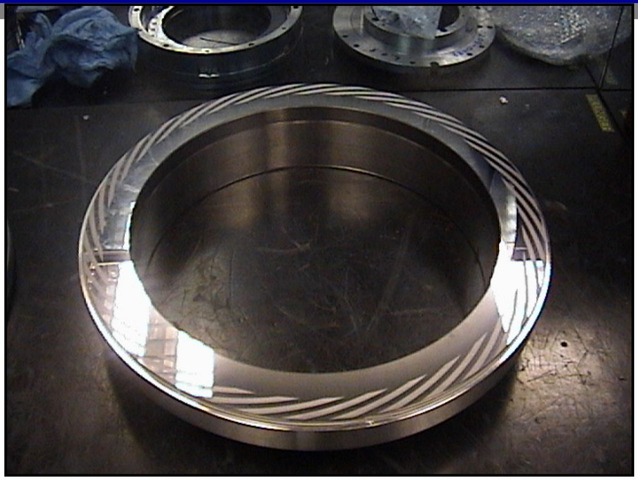


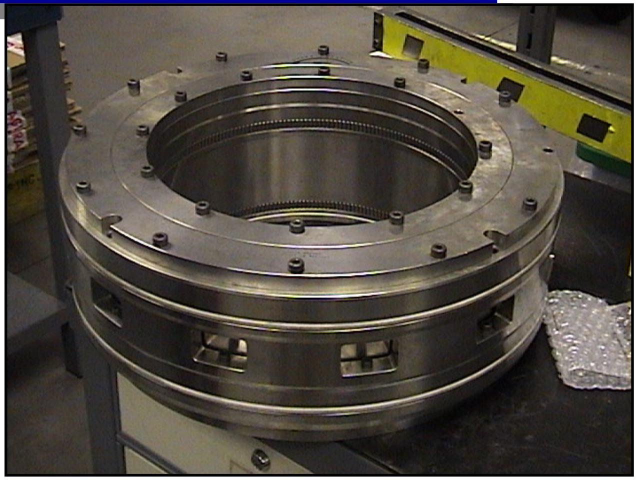
Dry Gas Seal System

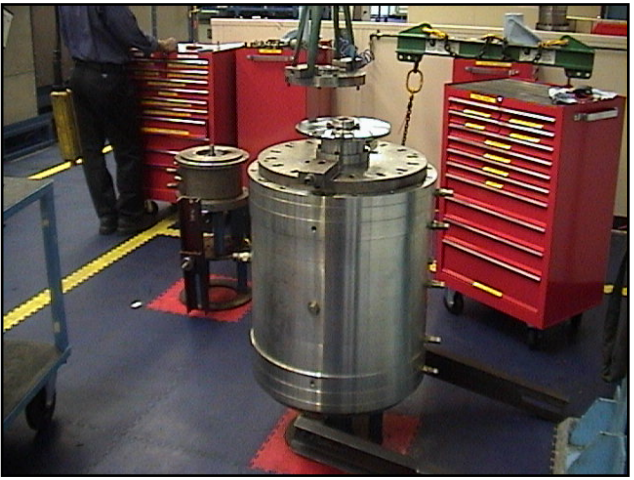
Rated Condition (MCR 100%)						
Labyrinth Seal	PT Side Condition	[1] Pure Helium Gas Supply Source	[2] Dischg. Helium Recovery System	[3] Mixed Fluid Discharge System	[4] Clean Air Supply Source	Generator Side Condition
Fluid	Helium	Pure Clean Helium	Helium	Helium + Air	Clean Dry Air	Atmos. (Air)

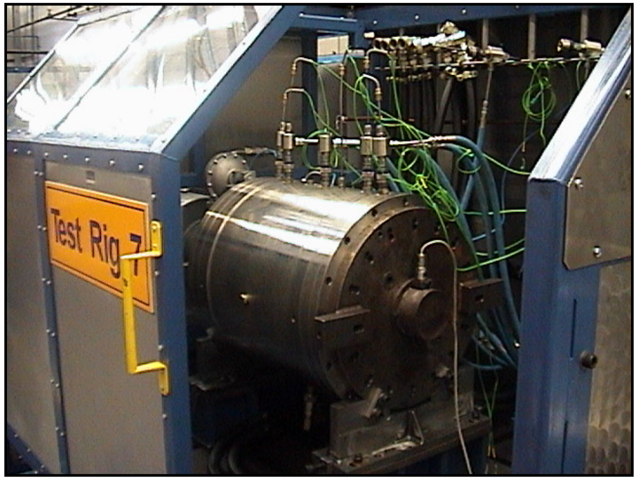


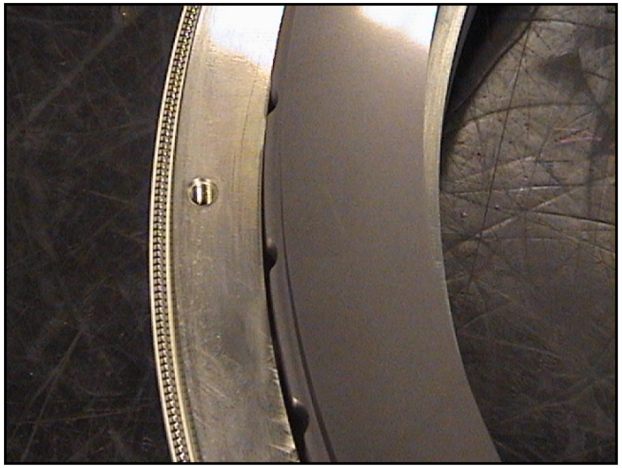
PBMR Dry Gas Seal Testing





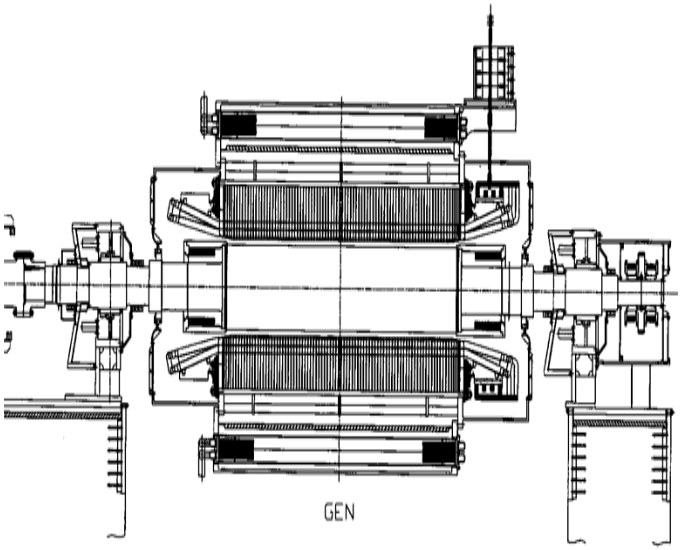






- **Air-cooled generator applies conventional technology**

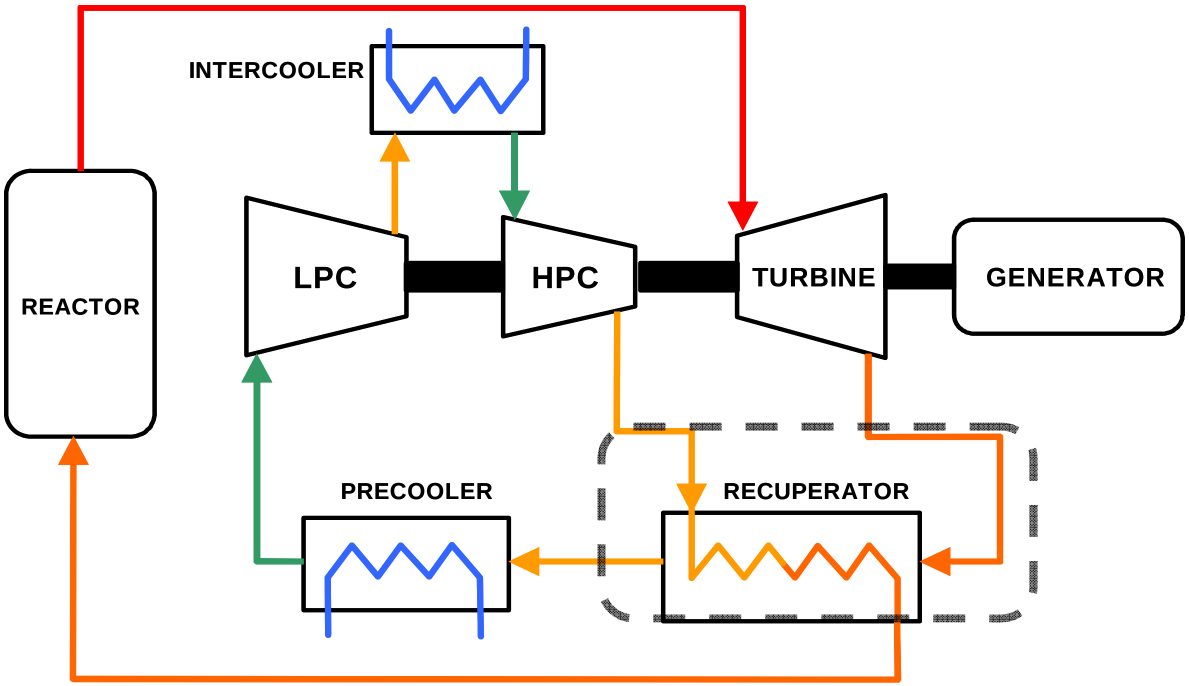
Parameter	Value
Rated active power	180 MW
Rated power factor	0.85 lagging
Rated voltage	13.2 kV
Rated frequency	50 Hz ±2%
Rated speed	3 000 rpm ±2%
Excitation	Static (brushes)
Design standard	International Electrotechnical Commission (IEC)



Power Conversion Unit

Heat Exchangers

Recuperator Functions

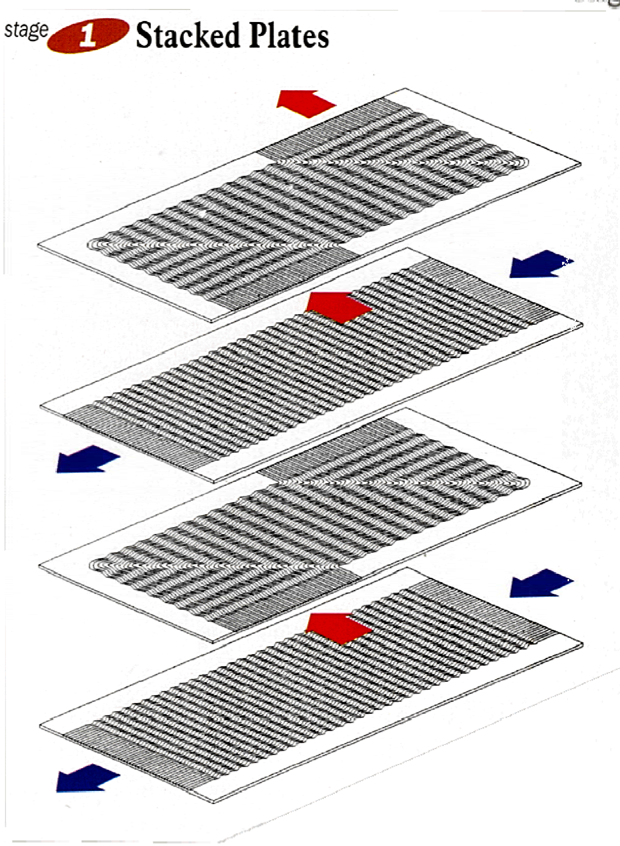


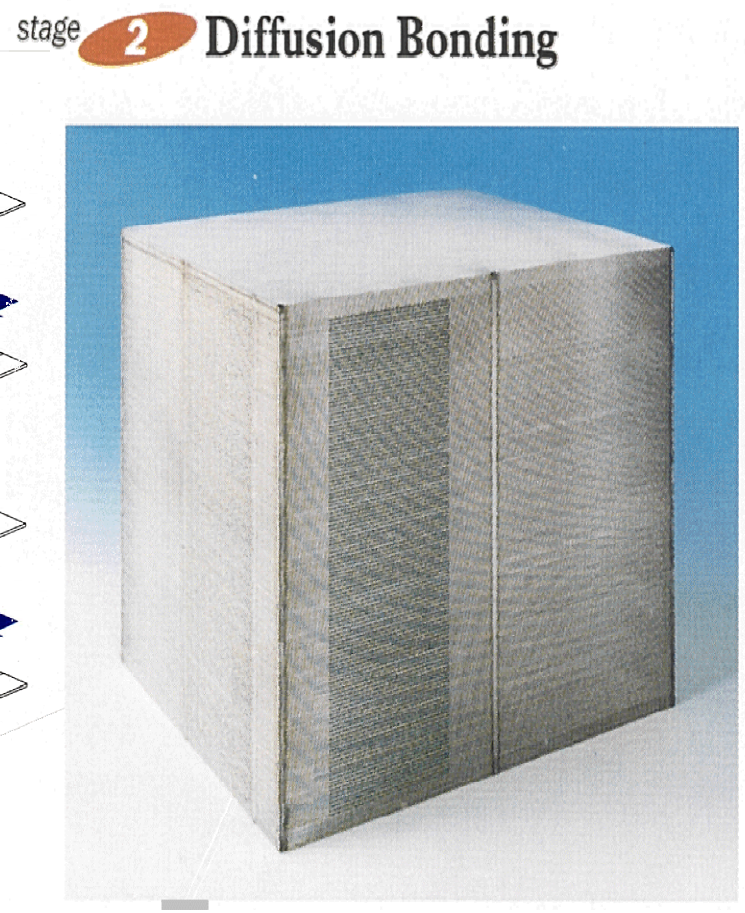
- **Recover heat from the turbine exhaust stream and transfer it to the reactor helium inlet stream**
  - Major factor in achieving high plant efficiency
- **Provide separation between the high and low pressure sides of the cycle**

Typical Recuperator Requirements

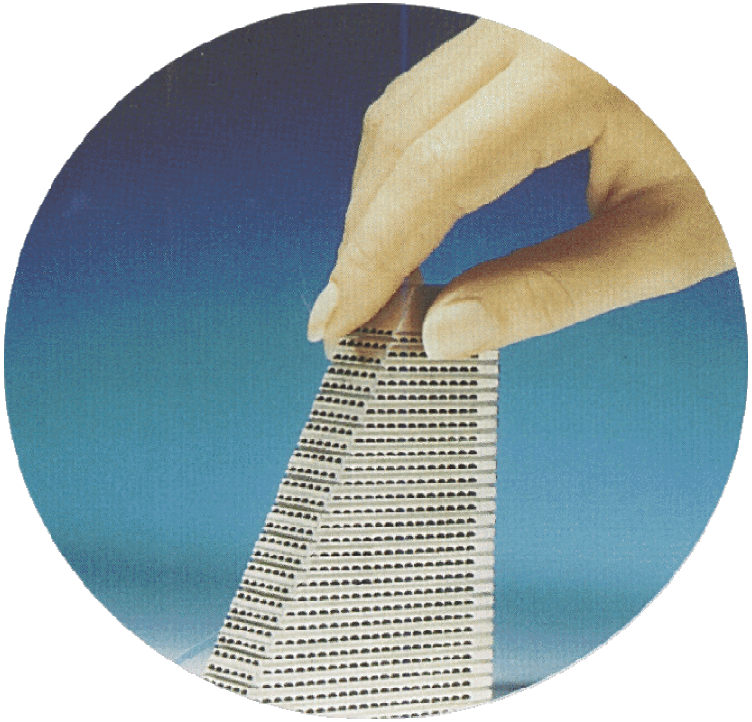
- **Accommodate heat transfer requirements**
  - Heat transferred via recuperator typically exceeds thermal rating of reactor
- **Provide separation between high and low pressure sides of cycle**
  - Leakage results in degraded cycle efficiency
- **Accommodate design duty cycle events**
  - Steady state and transient pressures and temperatures
- **Integration within Power Conversion System**
  - Compact surface geometry implicitly required
  - Interfaces with other components and/or ducts
- **Provisions for maintenance inspection, removal, replacement**
  - Modular assembly implied
- **Design for service life of plant**

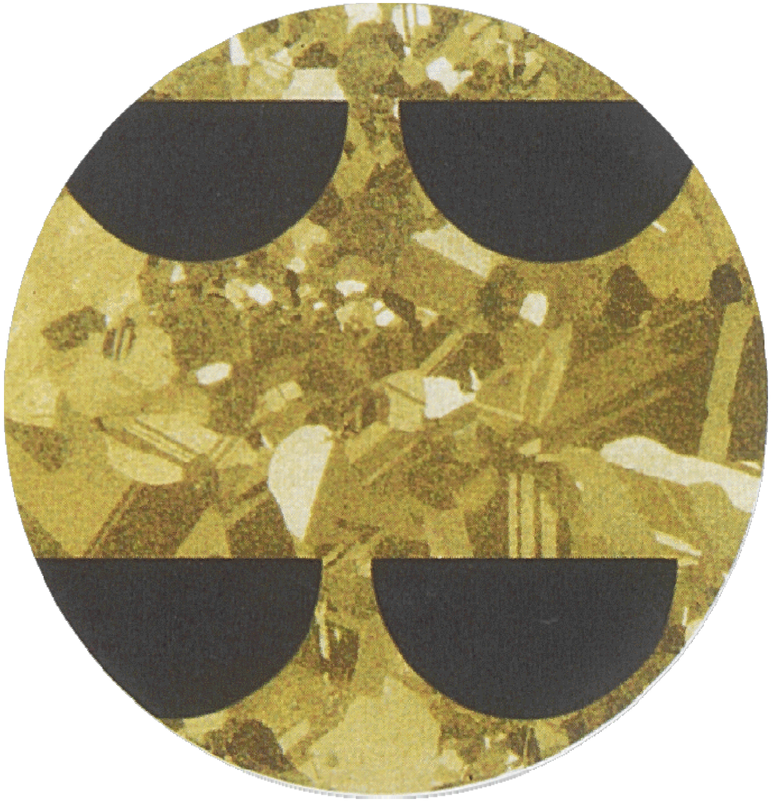
Heatric Printed Circuit HX





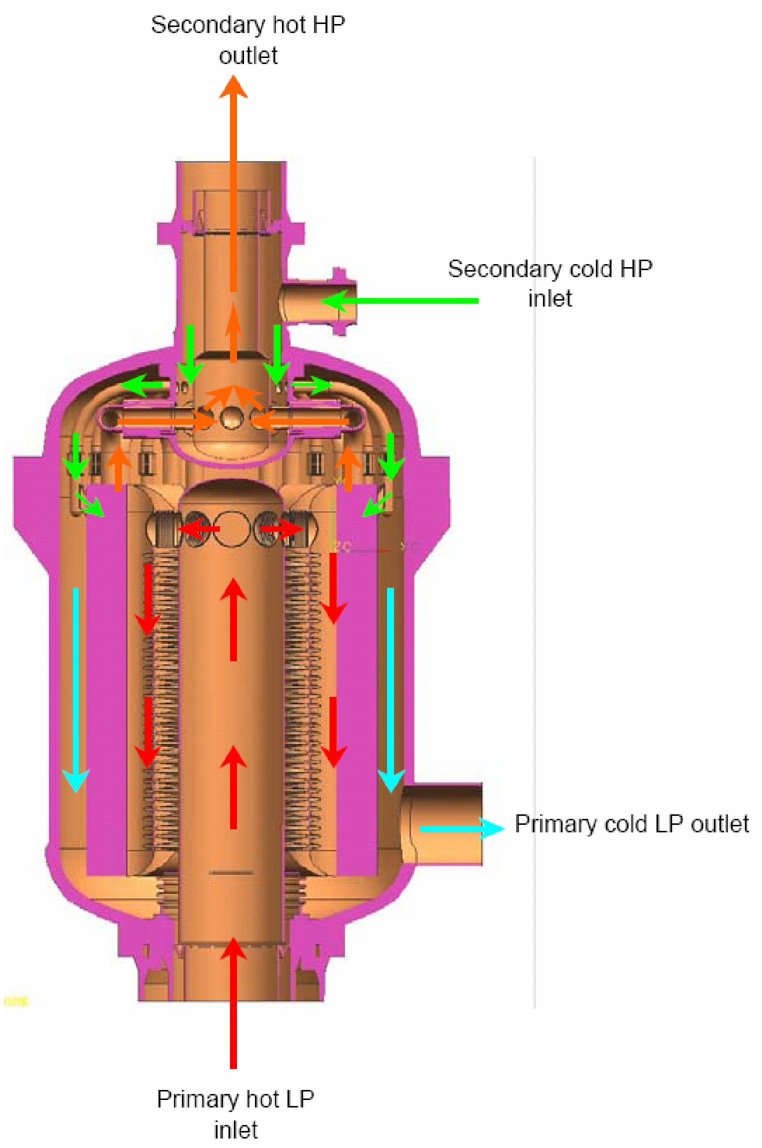
Heatric Printed Circuit HX



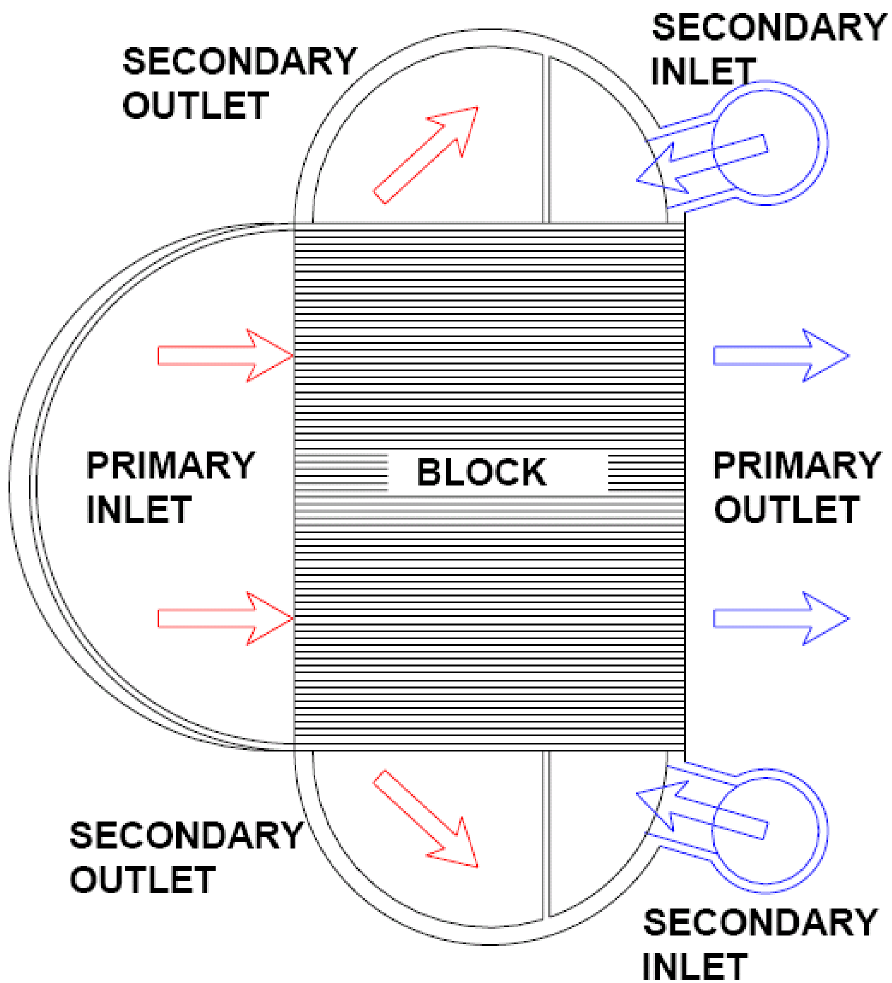


Heatric Printed Circuit HX

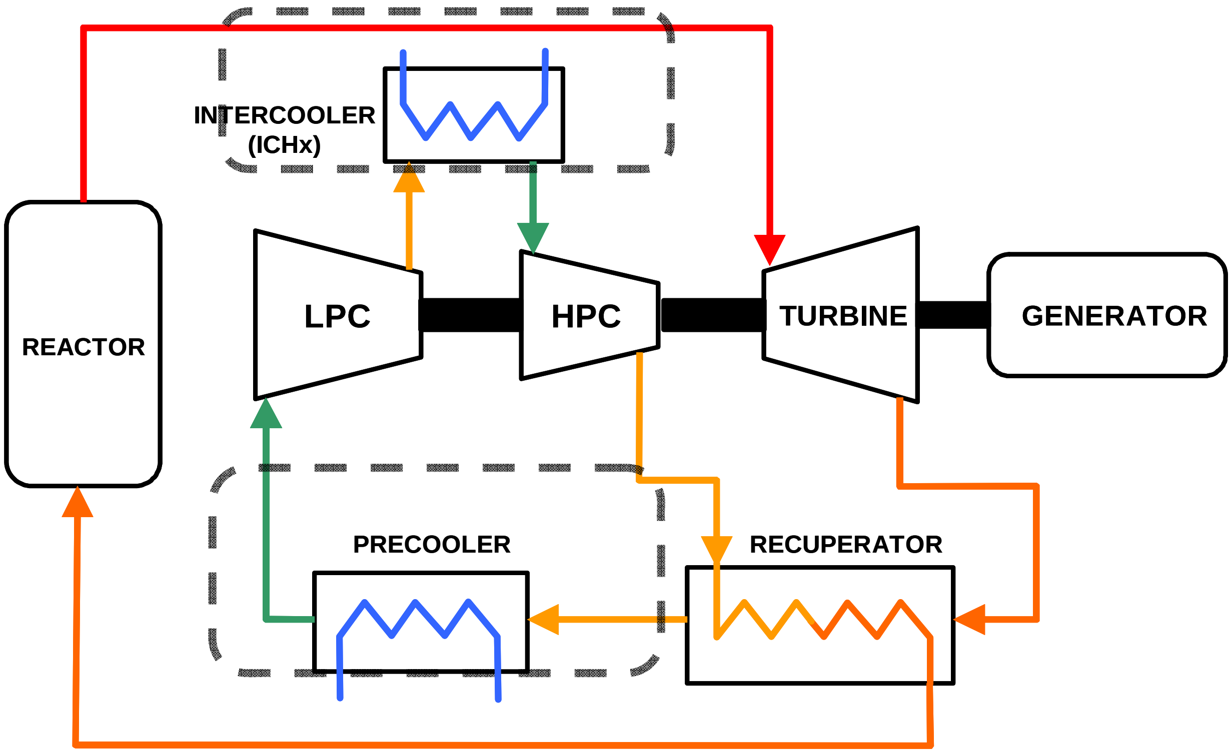
PBMR Recuperator



PBMR Recuperator Module



Precooler/Intercooler Functions

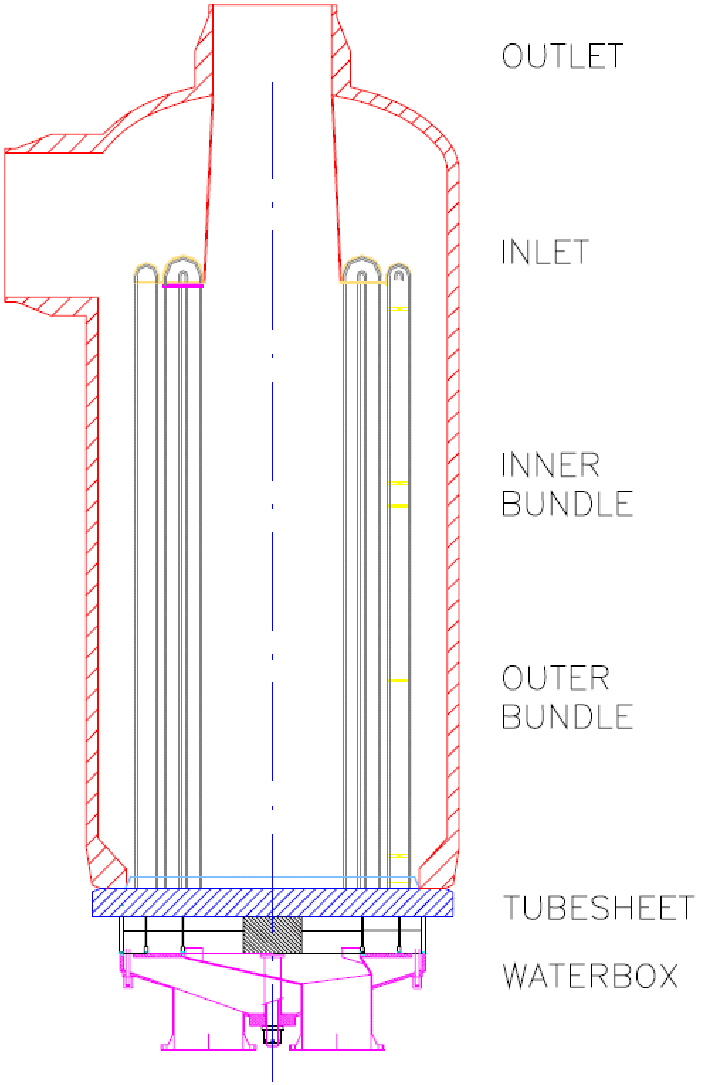


- Reject waste heat from the power conversion cycle
- Remove decay heat during other defined events
- Enhance compression efficiency
- Maintain pressure boundary integrity

Precooler and Intercooler Typical Requirements

- **Accommodate heat rejection requirements for all operating conditions and events within the design basis**
  - Part load operations under bypass valve control demand higher precooler and intercooler heat duty than full load operation
- **Modest temperatures (typically < 200ºC)**
- **Design for service life of plant**
  - High reliability
- **Pressure boundary integrity assured at HX surface or via isolation valves**
  - Avoid helium leaks from primary loop
  - Avoid water ingress into primary loop (primary loop depressurized)
- **Accommodate mechanical, thermal-structural and seismic loads**
- **Heat exchangers must be drainable and inspection and maintenance access must be provided.**

PBMR U-Tube Cooler Concept



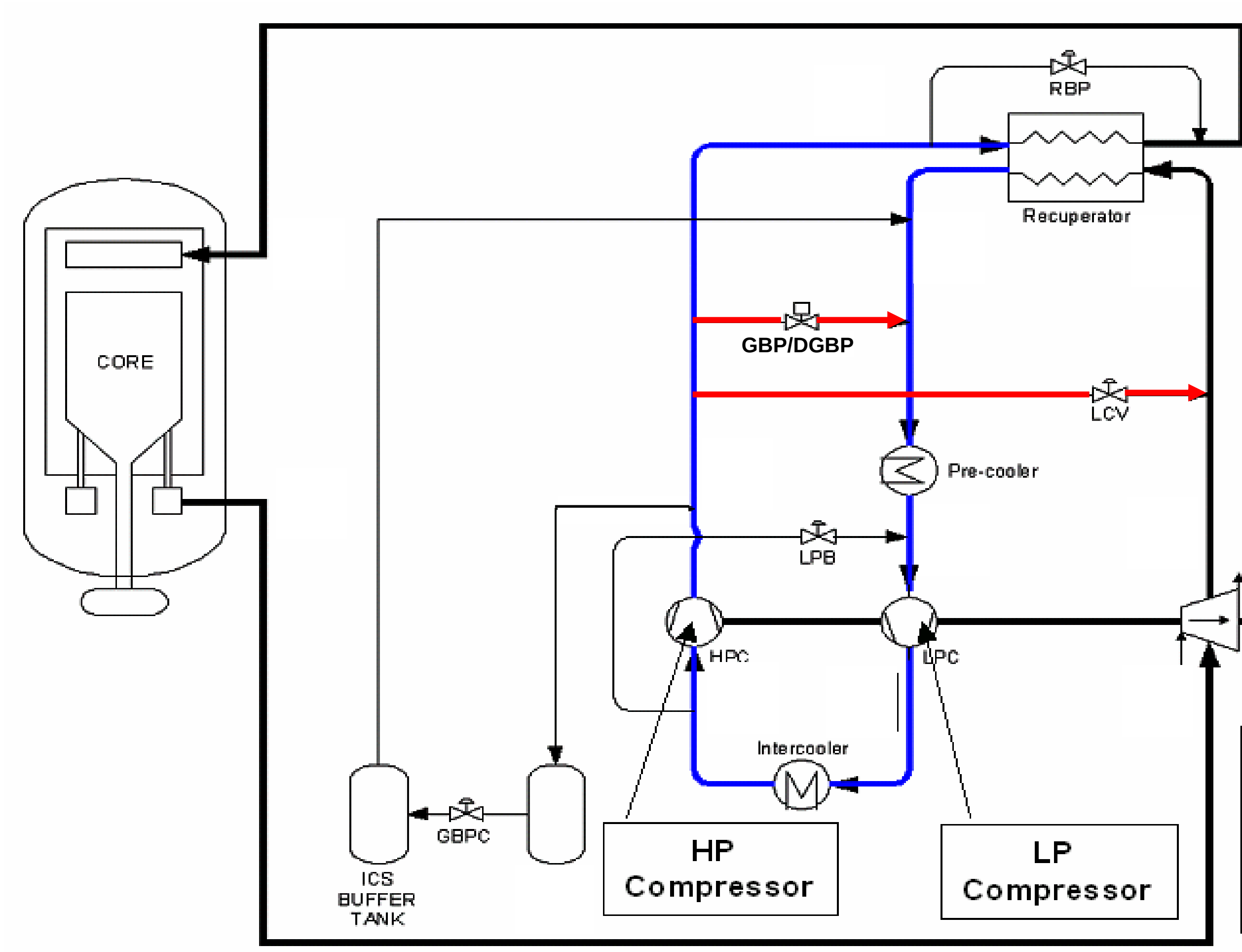
Power Conversion Unit

Gas Cycle Valves

Gas Cycle Valves

- **The main purposes of the Gas Cycle Valves (GCV) are control and equipment protection**
- **The GCV consist of:**
  - Gas Cycle Bypass Valves (GBP)
  - Diverse Gas Bypass Control Valve (DGBP)
  - Low-pressure Coolant Valves (LCV)
  - Low-pressure Compressor Bypass Valves (LPB)
  - Recuperator Bypass Valves (RBP)
  - Gas Cycle Bypass Control Valve (GBPC)

Gas Cycle Valves



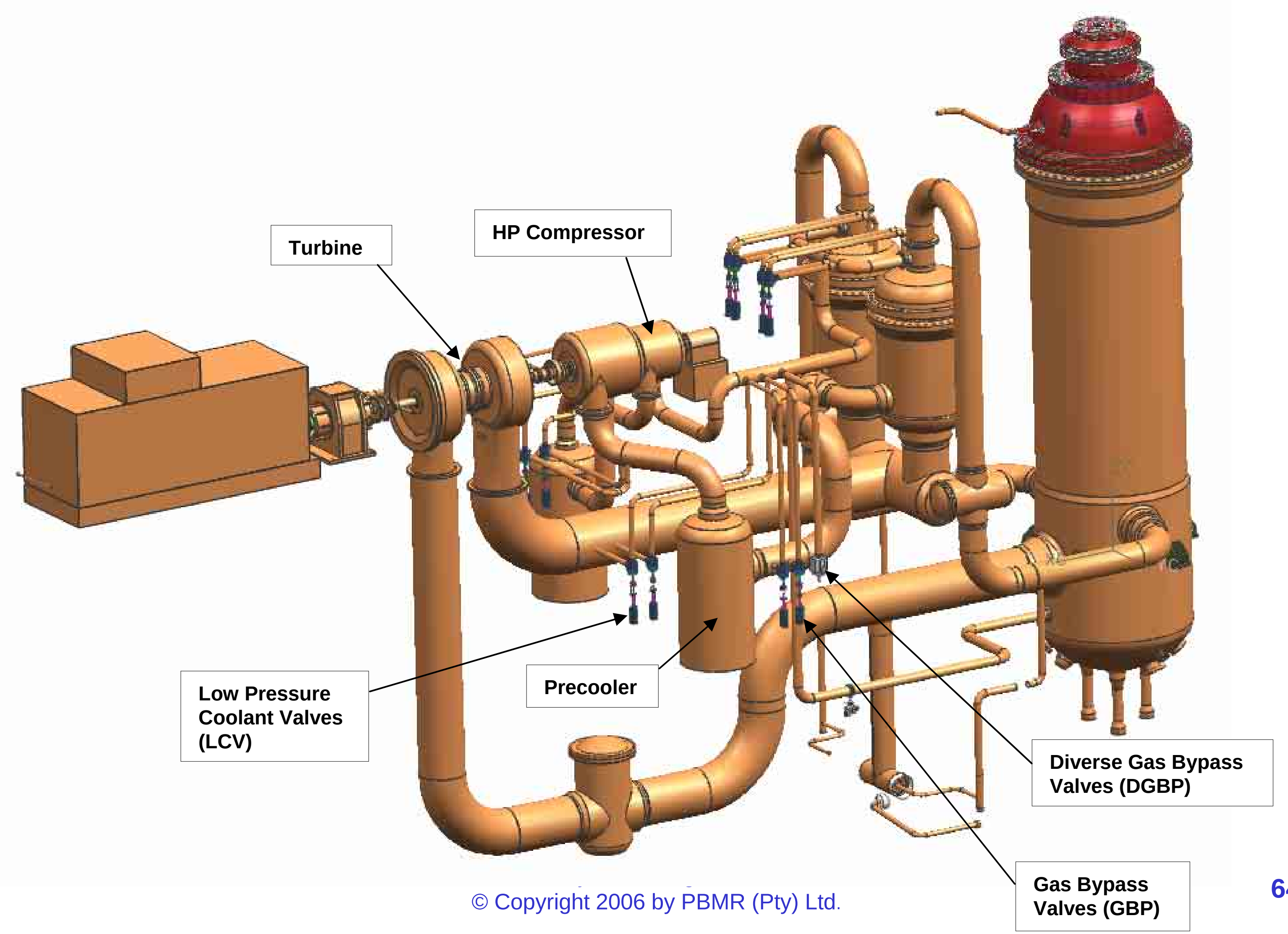
VALVE LEGEND

DGBP	–	Diverse Gas Cycle Bypass Valve
GBP	–	Gas Cycle Bypass Valve
GBPC	–	Gas Cycle Bypass Control Valve
LCV	–	Low Pressure Coolant Valve
LPB	–	Low Pressure Compressor Bypass Valve
RBP	–	Recuperator Bypass Valve

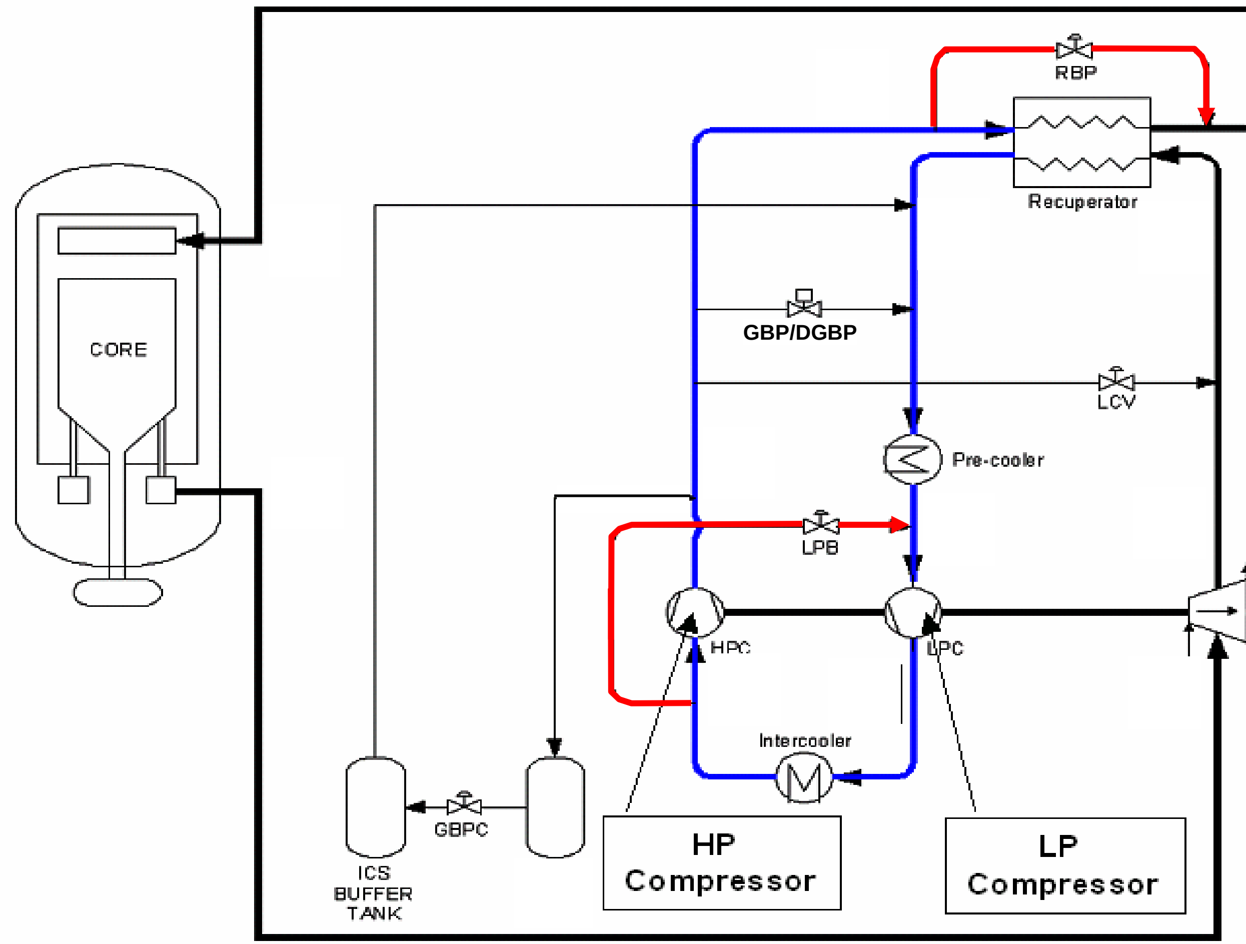
Gas Cycle Valve Functions

- **Gas Cycle Bypass/Diverse GCB Valves (GBP/DGBP)**
  - Prevent turbine overspeed during PCU trip and loss of load transients
- **Low Pressure Coolant Valves (LCV)**
  - Prevent excessive temperatures at recuperator inlet during transients
- **Low Pressure Compressor Bypass Valves (LPB)**
  - Enable low power operation at high inventory levels
- **Recuperator Bypass Valves (RBP)**
  - Maximize removal of heat from reactor by preventing recuperative heat transfer
- **Gas Cycle Bypass Control Valve (GBPC)**
  - Use in load following/frequency regulation

Gas Cycle Valves



Gas Cycle Valves

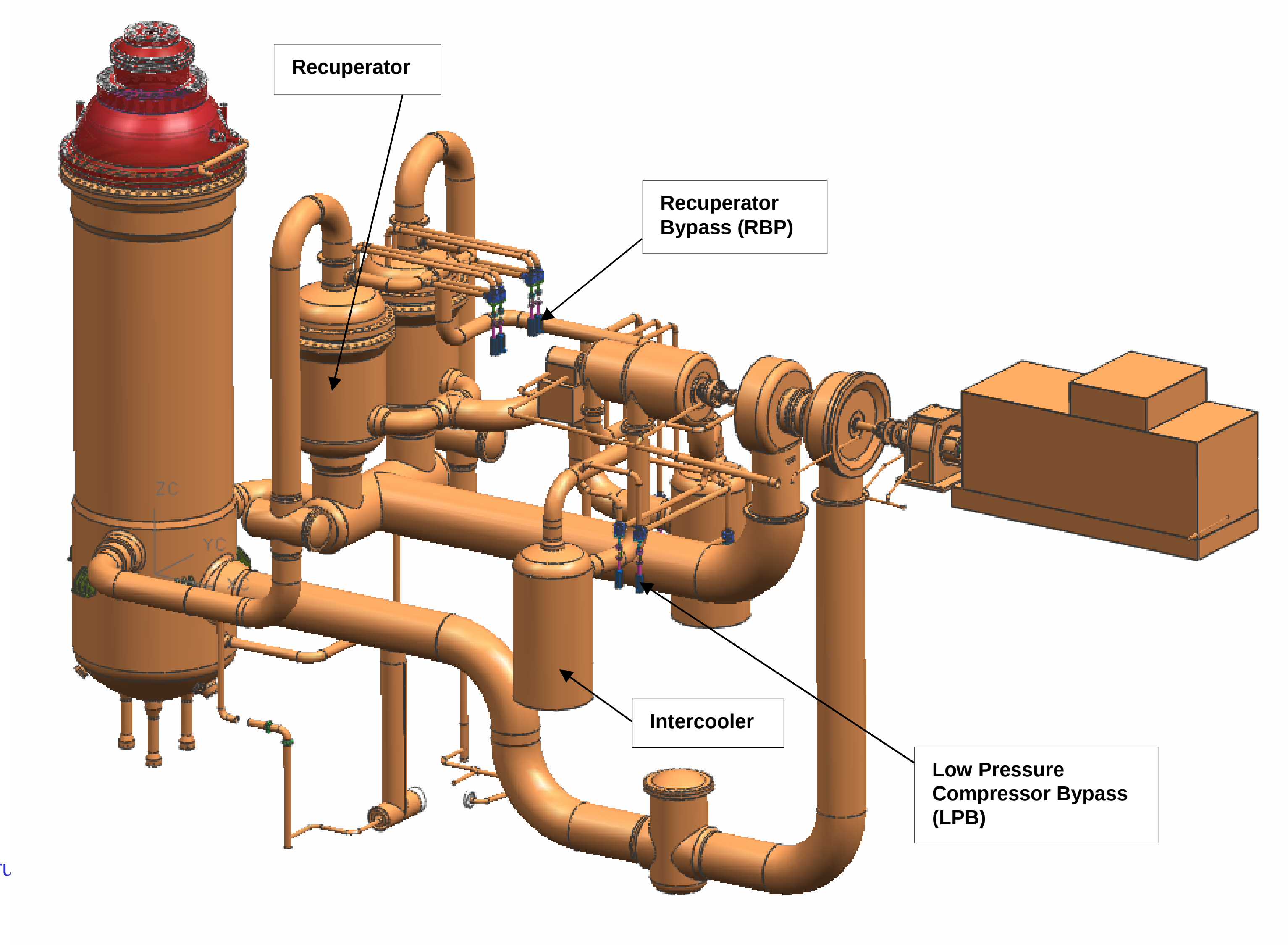


VALVE LEGEND		
DGBP	–	Diverse Gas Cycle Bypass Valve
GBP	–	Gas Cycle Bypass Valve
GBPC	–	Gas Cycle Bypass Control Valve
LCV	–	Low Pressure Coolant Valve
LPB	–	Low Pressure Compressor Bypass Valve
RBP	–	Recuperator Bypass Valve

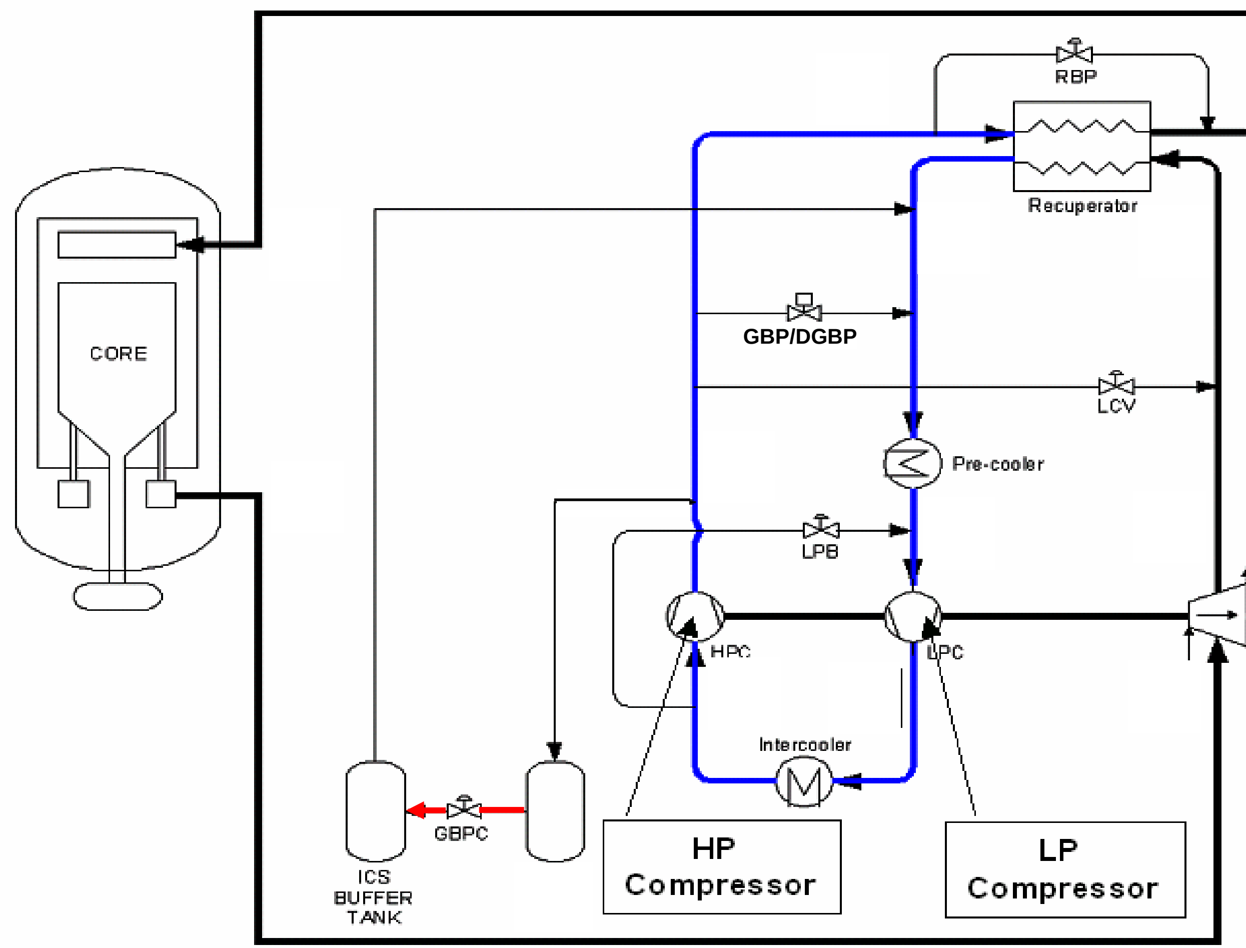
Gas Cycle Valve Functions

- **Gas Cycle Bypass/Diverse GCB Valves (GBP/DGBP)**
  - Prevent turbine overspeed during PCU trip and loss of load transients
- **Low Pressure Coolant Valves (LCV)**
  - Prevent excessive temperatures at recuperator inlet during transients
- **Low Pressure Compressor Bypass Valves (LPB)**
  - Enable low power operation at high inventory levels
- **Recuperator Bypass Valves (RBP)**
  - Maximize removal of heat from reactor by preventing recuperative heat transfer
- **Gas Cycle Bypass Control Valve (GBPC)**
  - Use in load following/frequency regulation

Gas Cycle Valves



Gas Cycle Valves



VALVE LEGEND

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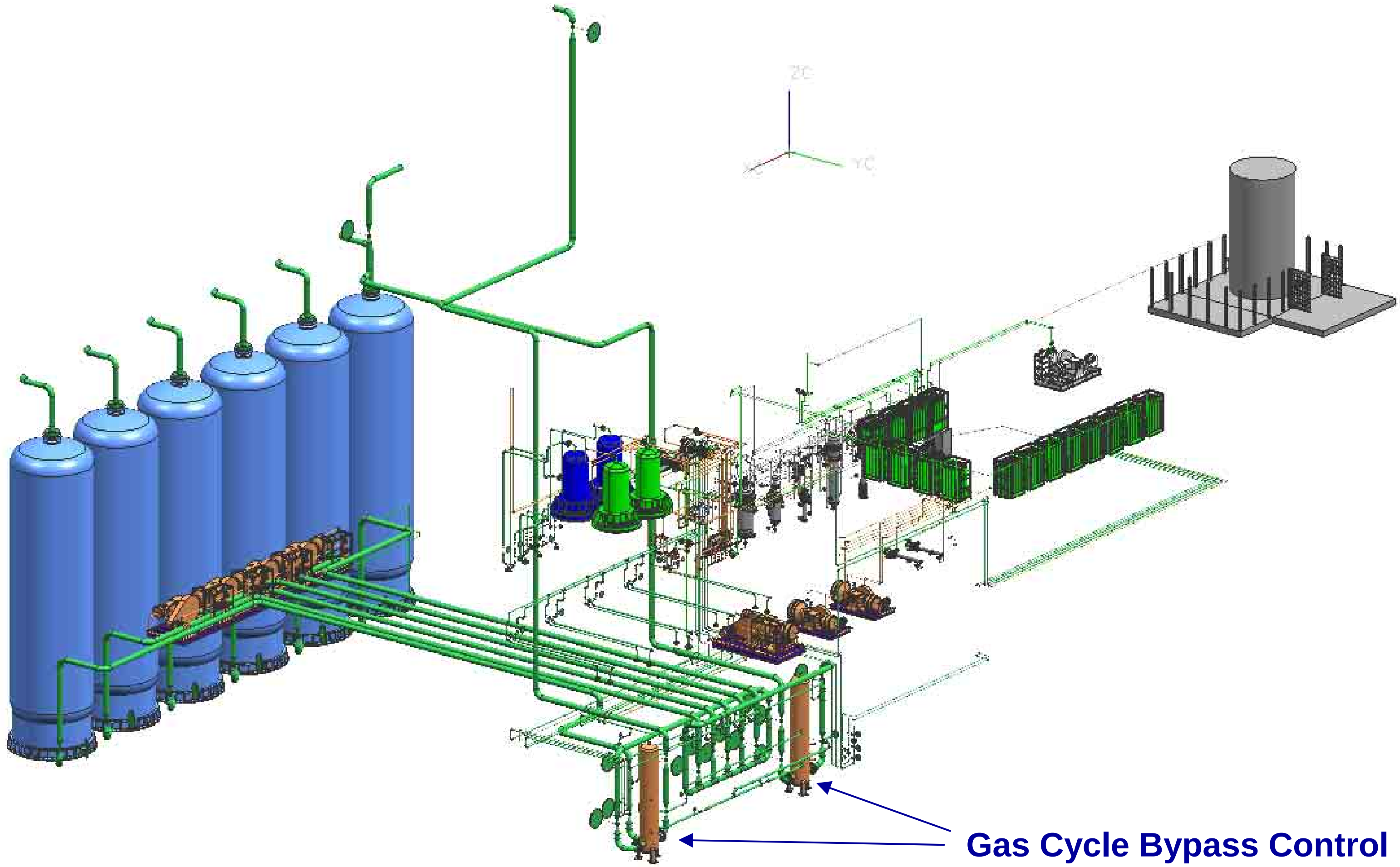
Helium Inventory Control System



Gas Cycle Bypass Control Valve (GBPC) located in a line connecting the HP/LP Buffer Tanks

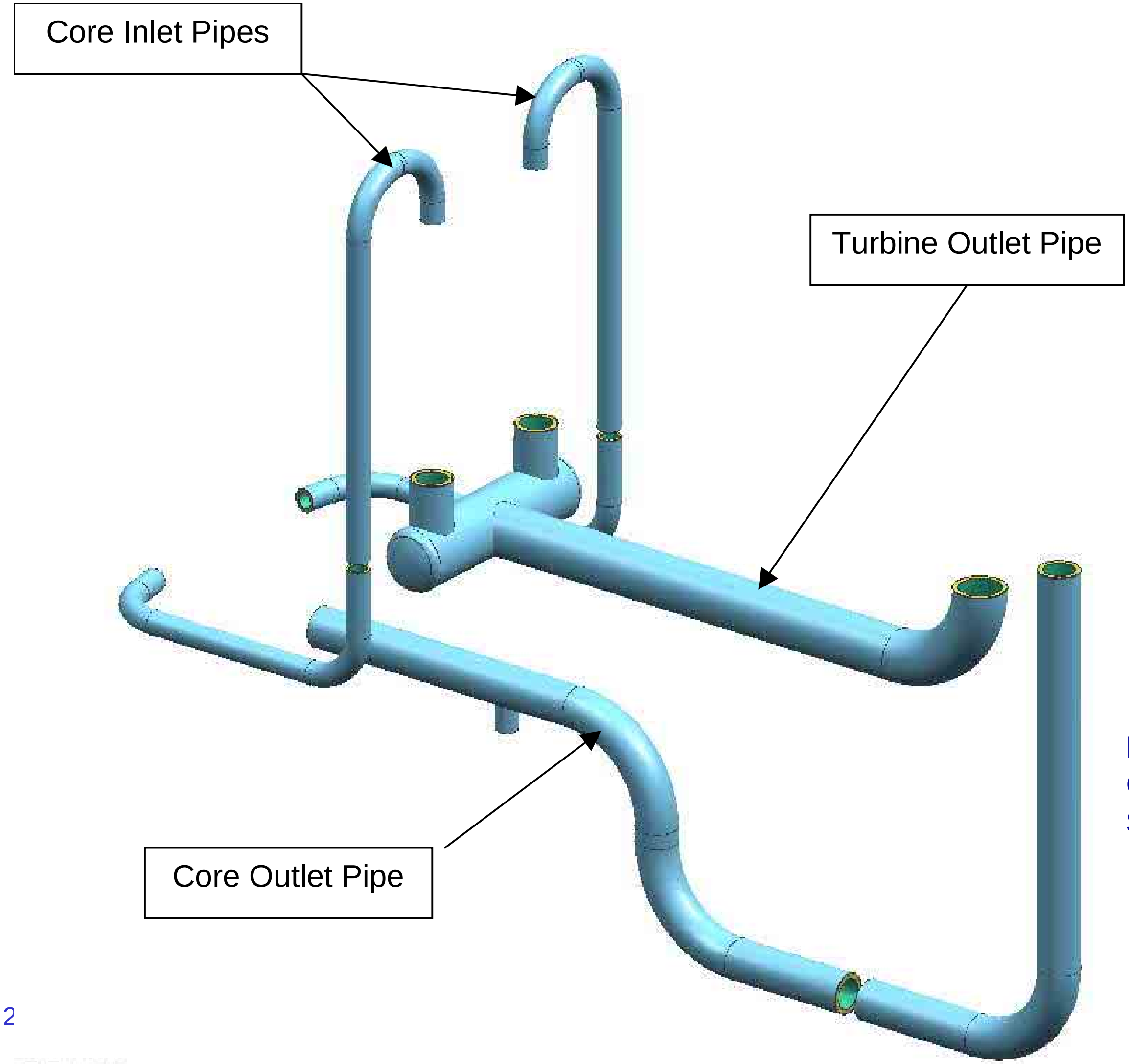
Power Conversion Unit

Gas Cycle Pipe System

Gas Cycle Pipe System

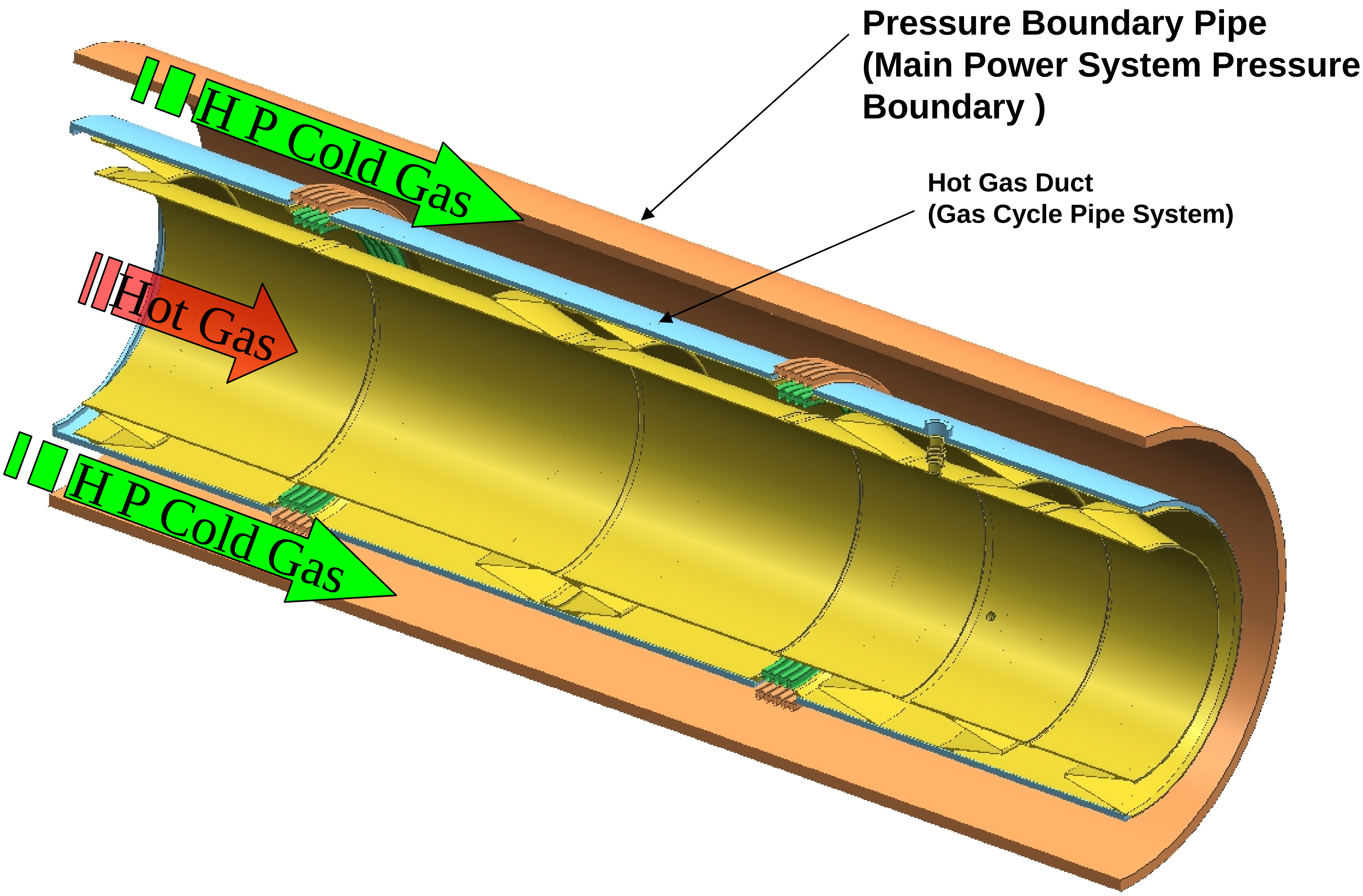
- **The Gas Cycle Pipe System (GCPS) is a passive structure within the PCU.**
- **The GCPS consists of insulated pipes for the transport of hot (>300°C) gas**
  - From the Core Structures outlet to the turbine inlet
  - From the turbine outlet to the LP recuperator inlet
  - From the HP recuperator outlet to the Core Structures inlet (2 pipes)
  - Core Conditioning System pipes (one inlet and one outlet)
- **The GCPS is within, not a part of, the helium pressure boundary.**
- **The GCPS is externally cooled by gas diverted from the HP compressor outlet.**

Gas Cycle Pipes



Note:
Core Conditioning System pipes not shown

System Reference

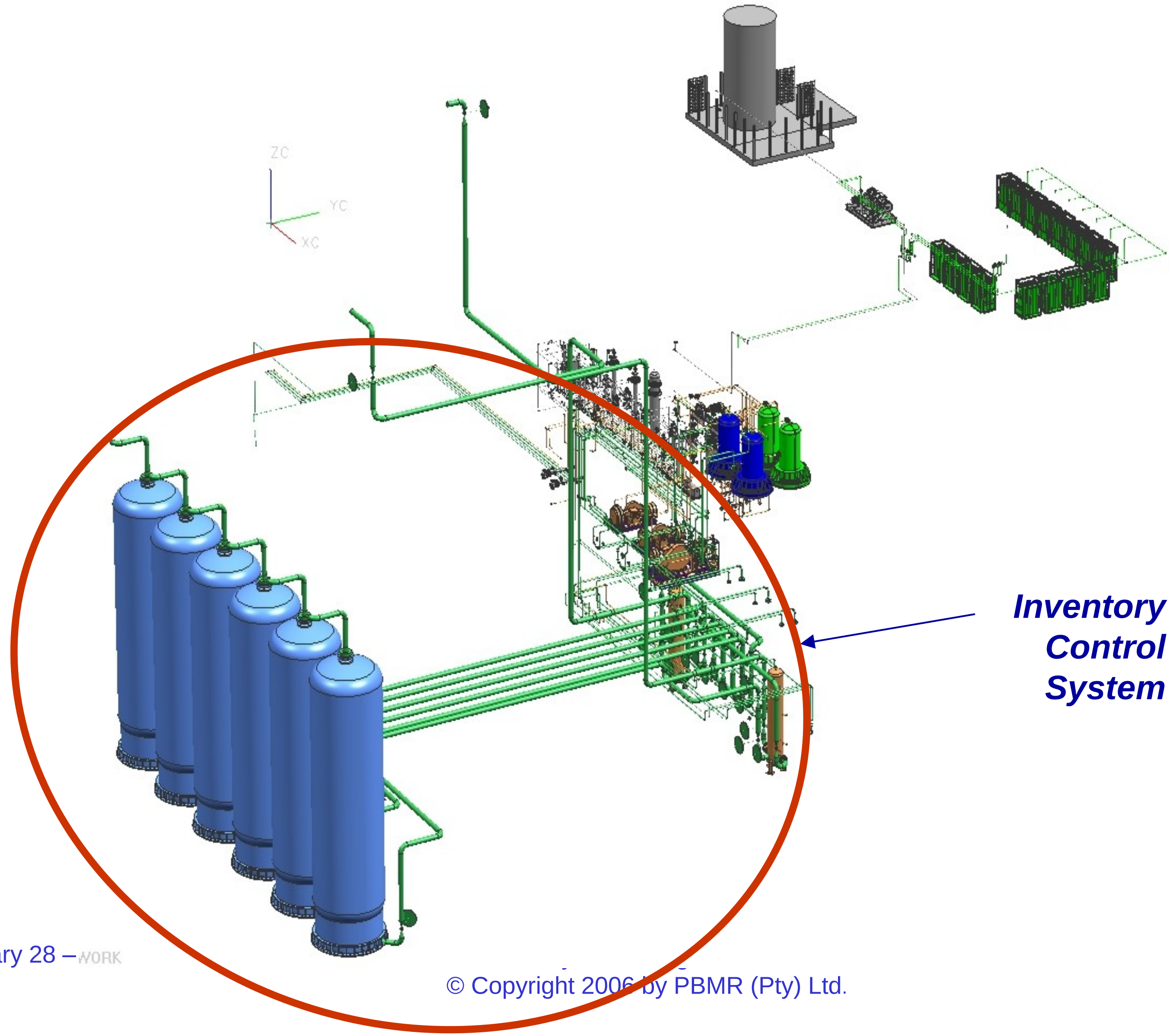


Helium Inventory Control System

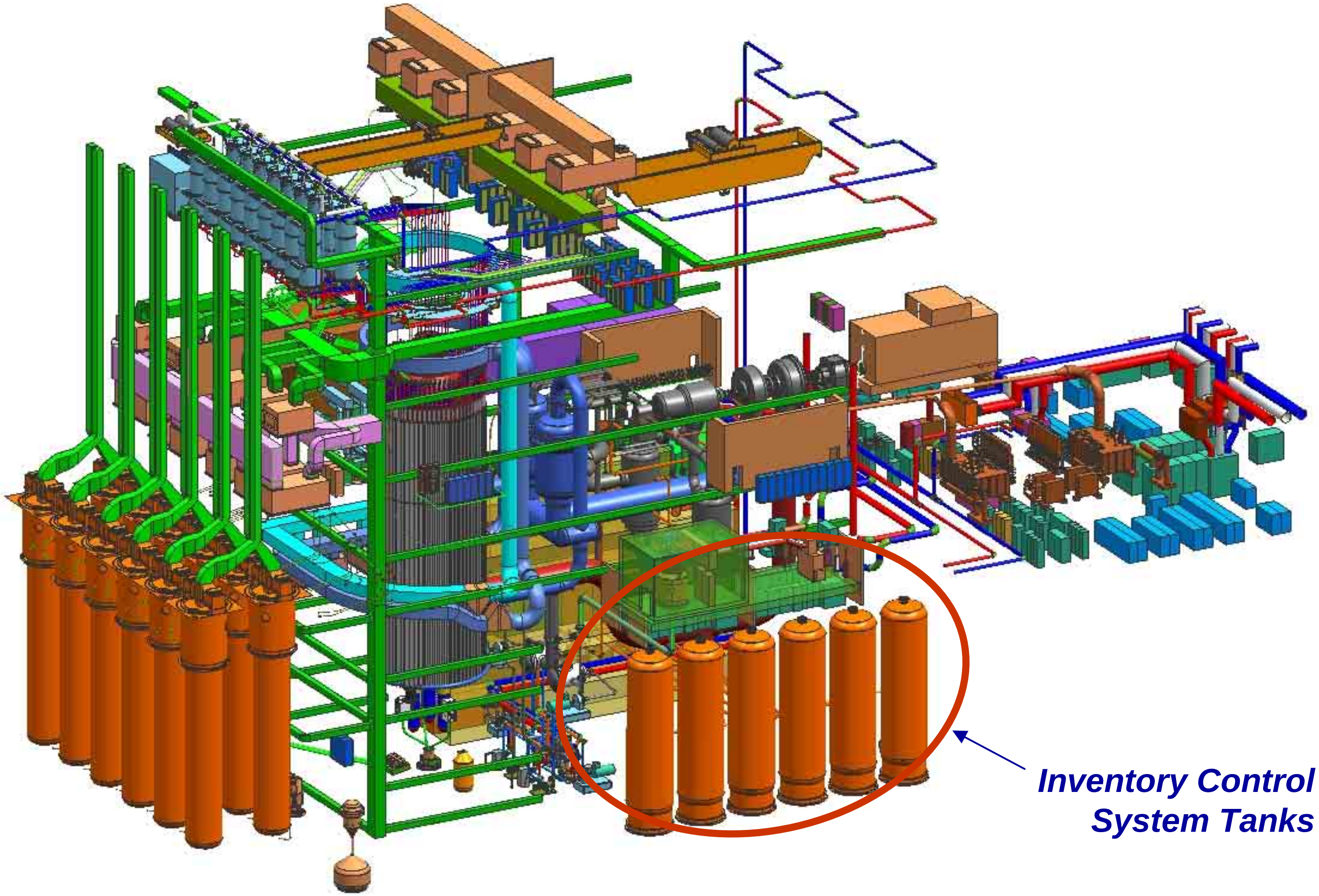
HICS Systems & Functions

Inventory Control System (ICS)	• Control of the helium mass within the MPS • Storage of the helium of the MPS and FHSS during a maintenance outage
Helium Purification System (HPS)	• To remove the gaseous contaminants • To purify the primary system after inspections and maintenance
Helium Make-up System (HMS)	• To replenish the MPS daily helium leakages • To initially fill the MPS with the required amount of helium
Dry Gas Seal Supply and Recovery System (DSRS)	• To supply dust-free helium to the DGS of the Turbo Machines • To recover helium from the DGS of the Turbo Machines • To supply dust-free helium to the blowers of the CCS, the FHSS and the DSRS

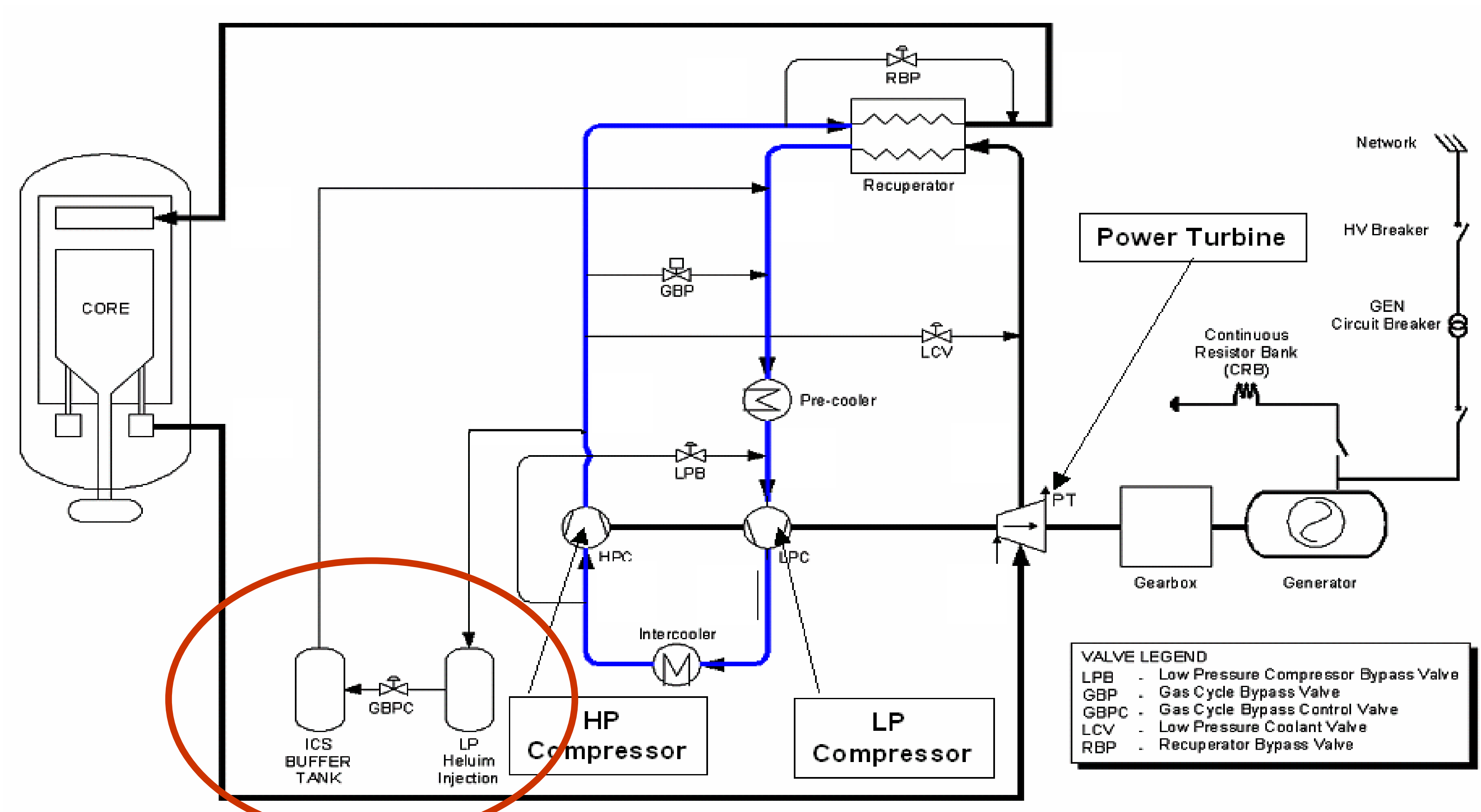
Helium Inventory Control System



Inventory Control System Orientation



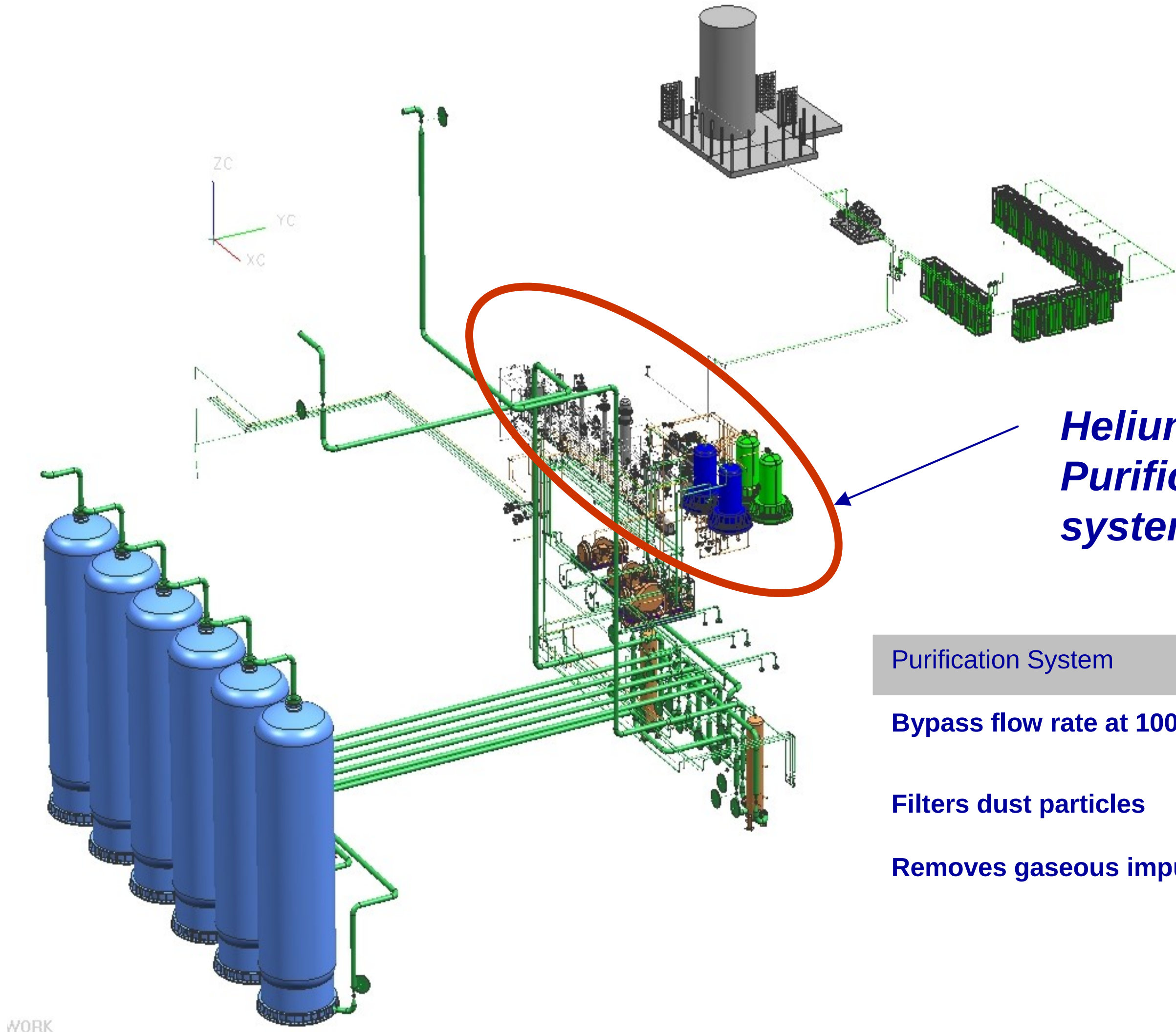
PCU Control Elements



Inventory Control System

- **The primary functions of the ICS are:**
  - Control of the helium mass within the MPS
  - Storage of the helium of the MPS and FHSS during a maintenance outage
- **MPS power maneuvering via inventory control**
  - Range: 40% to 100%
  - Rate: 10%/min
- **Method of operation**
  - Power Reduction - Helium is extracted from the high pressure section of the MPS and transferred into storage vessels (transferring into the highest pressure vessel first, and then the second highest vessel, and so on)
  - Power Increase – Helium is injected into the low pressure section of the MPS (starting with the lowest pressure vessel, and then the second lowest pressure vessel, and so on)
  - The MPS compressors do most of the work required to increase the pressure of the helium in order to store it in the storage vessels
- **Extraction from MPS to storage vessels for maintenance**
  - From 40% Max Capability Rating Inventory (MCRI) to 1 bar - 41 h

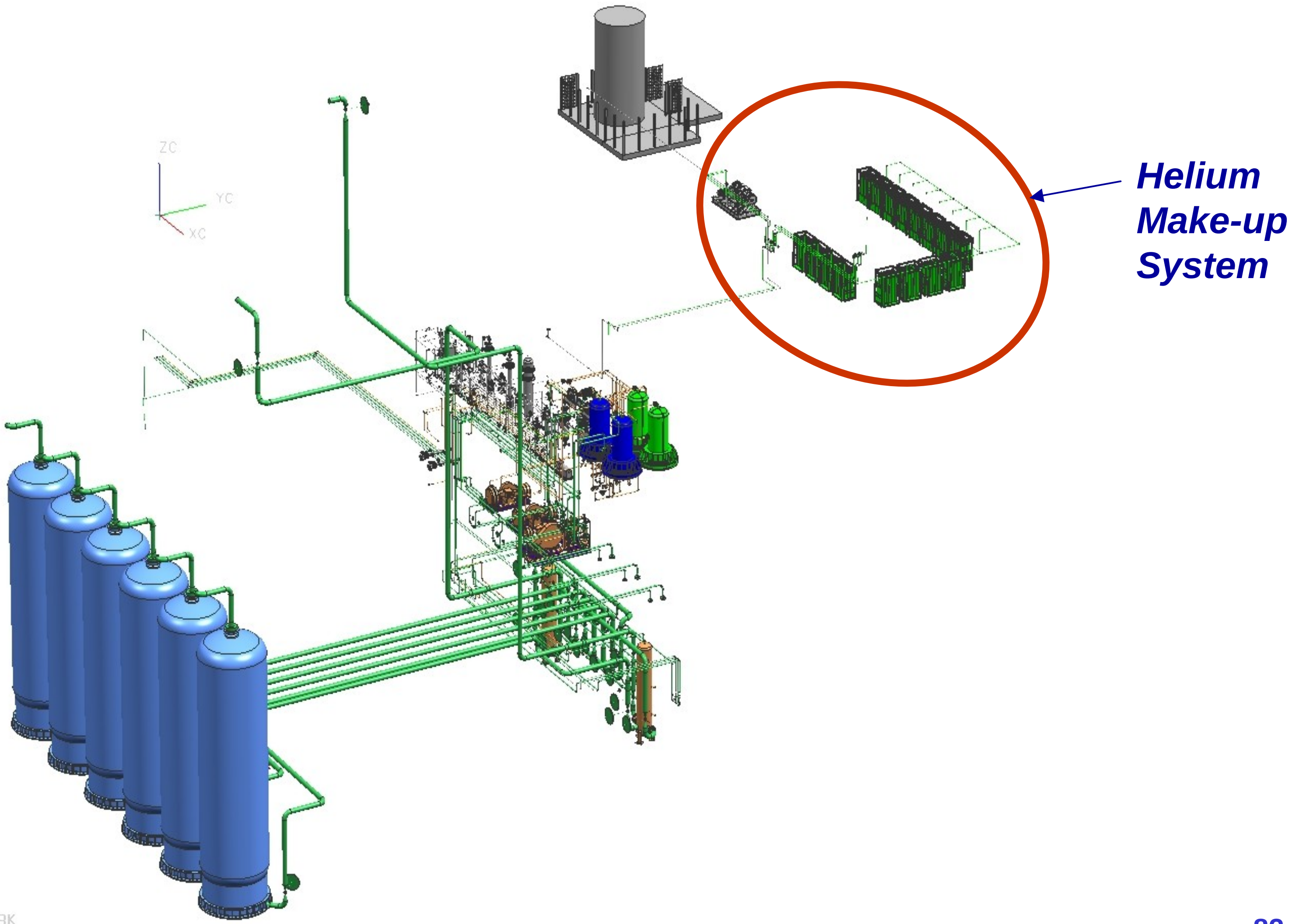
Helium Purification System



Helium Purification system

Purification System	
Bypass flow rate at 100%	**100 kg/h**
Filters dust particles	**> 0.5 µm**
Removes gaseous impurities:	**H_2 : < 1.0 ppmv**
	C0 :< 1.0 ppmv
	$C0_2$:< 0.1 ppmv
	H_20:< 0.1 ppmv
	CH_4:< 1.0 ppmv
	N_2: < 1.0 ppmv

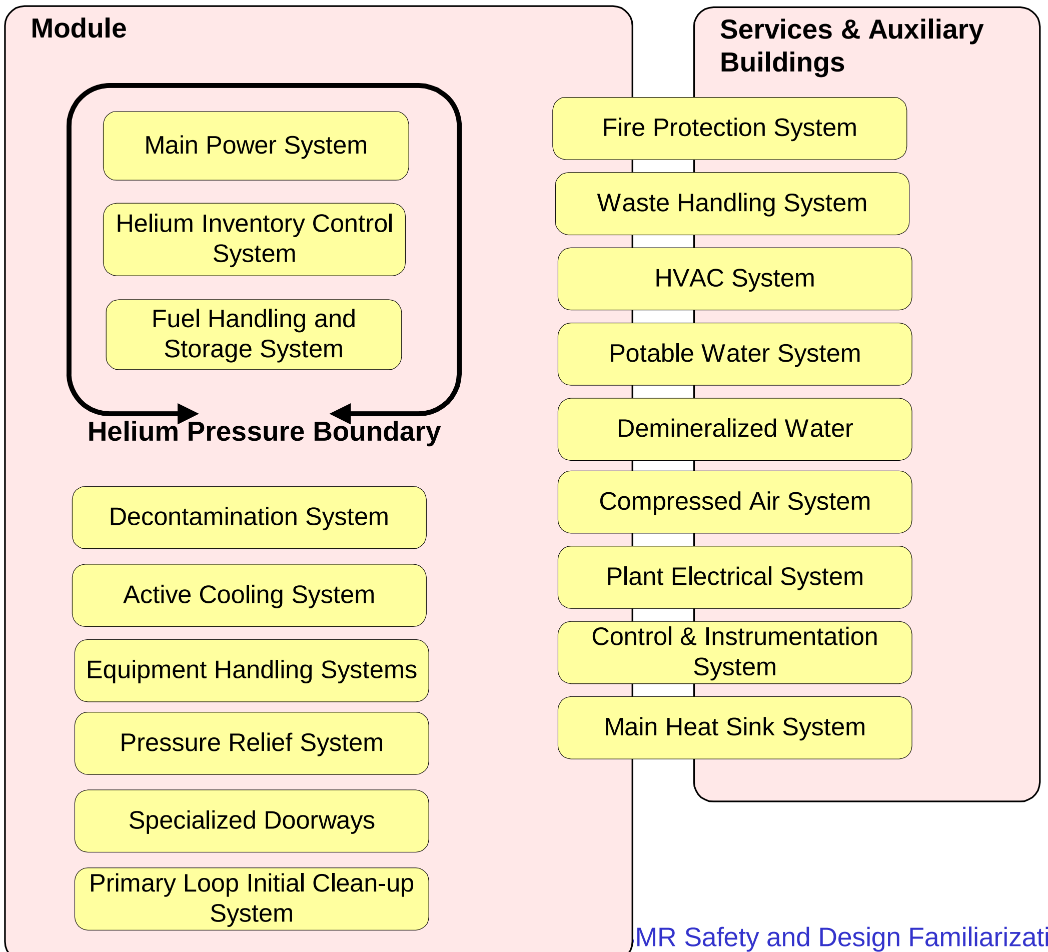
Helium Inventory Control System



Helium Pressure Boundary

Pressure Boundary Systems

PBMR Power Plant System Diagram



This discussion will focus on key features of the MPS Pressure Boundary (MPS-PB).

Key Functions

The key functions of the MPS Pressure Boundary are:

- Retain helium coolant inventory
- Barrier to the release of circulating fission products
- Limitation of air and water ingress
- Provision of structural support and alignment for the Reactor Unit and PCU components
- Transfer of the decay heat from the reactor core via the RPV to the Reactor Cavity Cooling System (RCCS) during loss of forced cooling events (ensure adequate core heat removal)
- Ensuring that the geometry of the core stays within acceptable geometrical limits under all normal and abnormal events

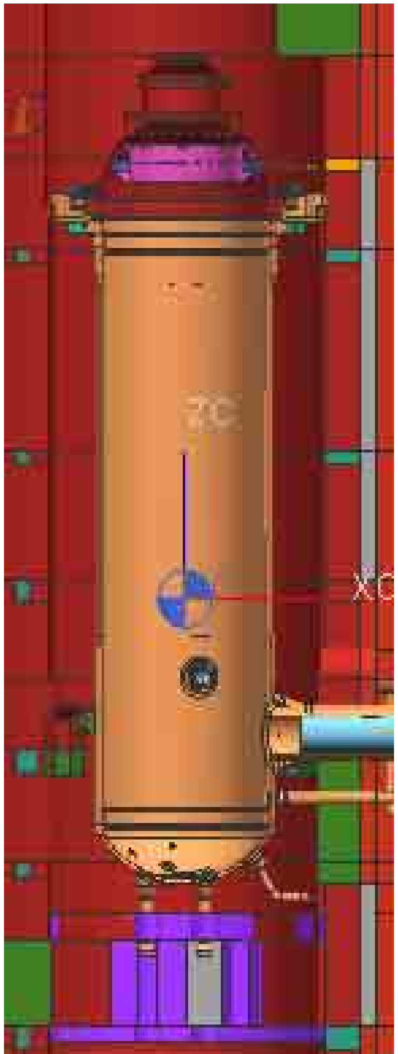
The MPS Pressure Boundary consists of:

- Reactor Pressure Vessel
- Power Conversion Unit vessels
- Gas Cycle Valves
- Maintenance Shut-off Disk Vessels
- Core Conditioning System
- Core Barrel Conditioning System
- Pipes connecting all of the above
- Vessel Support System
- MPS Pressure Relief System
- External Insulation System

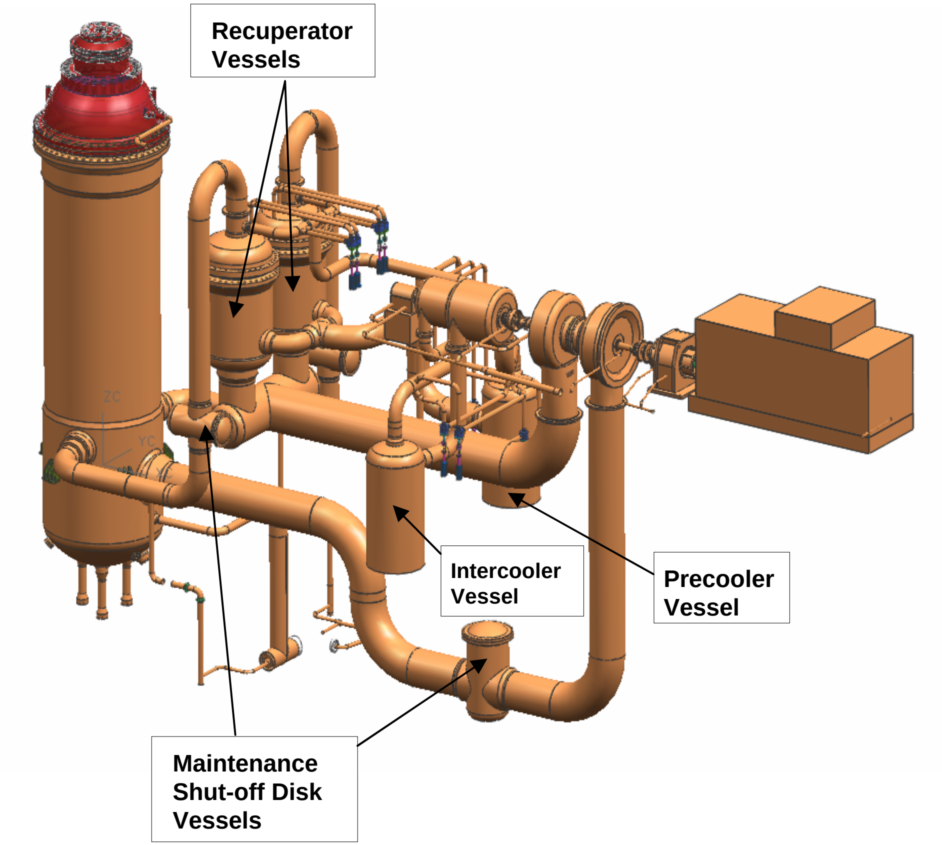
Bases for MPS-PB Operating Conditions

- **Pressure**
  - Maximum (9MPa) established by capability of PCU compressors at full inventory and rated power
  - Upon PCU trip at full inventory, MPS pressure rapidly equalizes at ~6.8MPa
- **Temperature – Reactor Pressure Vessel**
  - Established by heat transport path from core to Reactor Cavity Cooling system
- **Temperature – Other MPS-PB components**
  - Temperature limited by insulation and/or active flow

Reactor Pressure Vessel

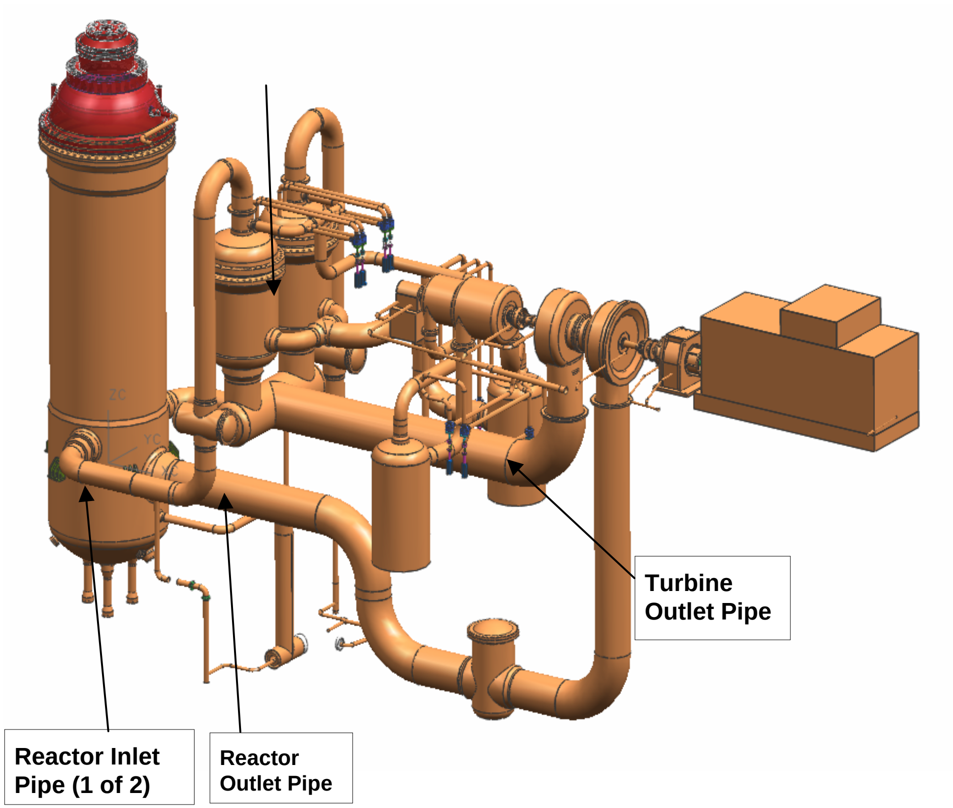


- **Dimensions:**
  - Internal Diameter: 6.2m
  - Nominal thickness: 180mm
  - Height: 30m
- **Operating Conditions**
  - Pressure:
    - *Operating: 9MPa (max)*
    - *Design: 9.7MPa*
  - Temperature
    - *Normal: 280-300ºC*
    - *LOFC: 527ºC*



- **Dimensions (ID x thickness)**
  - Recuperator: 3.8m x 110mm
  - Precooler: 3.1m x 100mm
  - Intercooler: 3.1m x 100mm
- **Operating Conditions**
  - Maximum pressure
    - *All PCU Vessels* *6.8MPa*
  - Nominal temperature
    - *Recuperator* *150ºC*
    - *Precooler* *150ºC*
    - *Intercooler* *130ºC*
  - Design temperature
    - *All* *250ºC*

Major PCU Pipes



Dimensions

- Recuperator to RPV: 1.12m x 50mm
- RPV to turbine: 1.95m x 50mm
- Turbine to recuperator: 2.3m x 65mm

Maximum Pressure

- Recuperator to RPV: 9MPa
- RPV to turbine: 9MPa
- Turbine to recuperator: 6.8MPa

Temperature

- Nominal: 150ºC
- Design 250ºC

Vessel Support System

- **Function**
  - Transfers the weight of the MPS-Pressure Boundary System to the building and maintains its orientation under all postulated abnormal conditions
- **Reactor Pressure Vessel Support System**
  - Provides the vertical and horizontal support for the RPV
  - Constrains the RPV in a seismic event
  - Fixed at intersection of RPV vertical axis and outlet pipe
- **Power Conversion Vessel Support System**
  - Provides the vertical and horizontal support for the Power Conversion Unit vessels