HTGR Technology Course for the Nuclear Regulatory Commission

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Module 10f

Gas Turbine Power Conversion Systems

Scott Penfield

Technology Insights

Idaho National Laboratory

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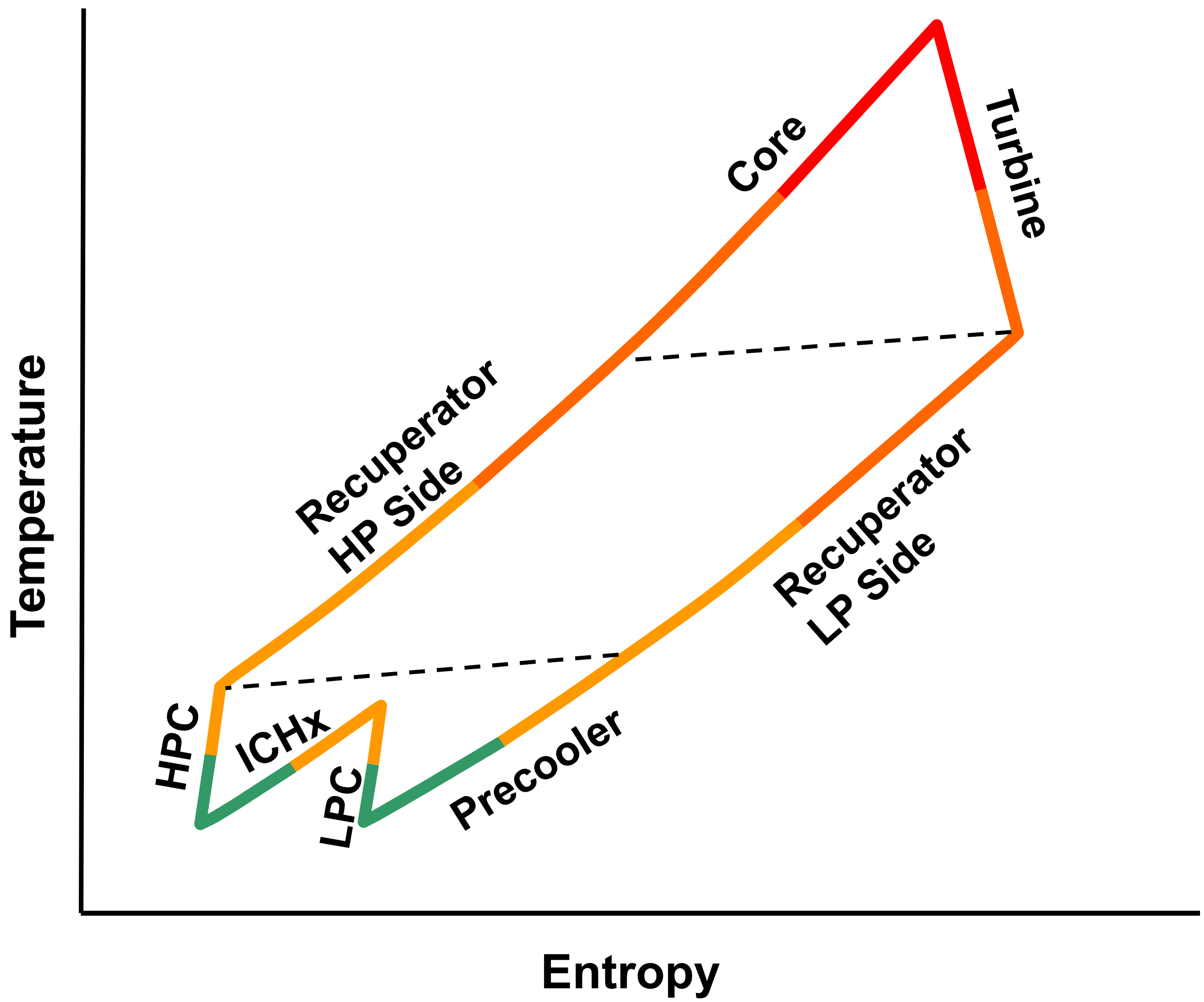
Objectives

- Review basic principles of the gas-turbine (Brayton) cycle and their implications for HTGRs
- Introduce major power conversion system components
- Provide insights regarding tradeoffs leading to design selections in current concepts
- Identify important technical issues in ongoing development

Outline

- **Influence and selection of key parameters in gas-turbine cycles**
- **Characteristics of major Power Conversion System (PCS) components**
  - Turbomachinery
  - Major heat exchangers
- **PCS design tradeoffs**
- **PCS development issues**

Gas Turbine (Brayton) Cycle TS Diagram



Key Cycle Parameters

- **Input Requirements**
  - Physical properties of Helium
  - Heat Rejection Temperature
  - Thermal/Electrical Power Output
- **Design Selections**
  - Reactor Outlet/Turbine Inlet Temperature
  - Recuperator Effectiveness
  - Cycle Pressure Losses
  - Primary System Pressure
  - Intercooling
  - Pressure Ratio

Helium and Air Fluid Properties Comparison

Fluid	Helium		Air	
Cycle State Point	Compressor Inlet	Turbine Inlet	Compressor Inlet	Turbine Inlet
Pressure, atm.	25	70	1	15
Temperature, °C (°F)	25 (78)	850 (1562)	25 (78)	1290 (2350)
Molecular weight	4.003		28.97	
Gas constant, ft lb/lb°R	386		53.3	
Specific heat, Btu/lb	1.244	1.242	0.24	0.278
Viscosity, lb/hr.ft	0.048	0.118	0.045	0.106
Thermal conductivity, Btu/hr.ft°F	0.089	0.218	0.015	0.042
Adiabatic coefficient, γ	1.666	1.665	1.4	1.33
Sonic velocity, ft/sec	3337	6469	1137	2533
Prandtl number	0.671	0.672	0.72	0.70
Density, lb/ft^3	0.255	0.190	0.074	0.212
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	

(Source: General Atomics)

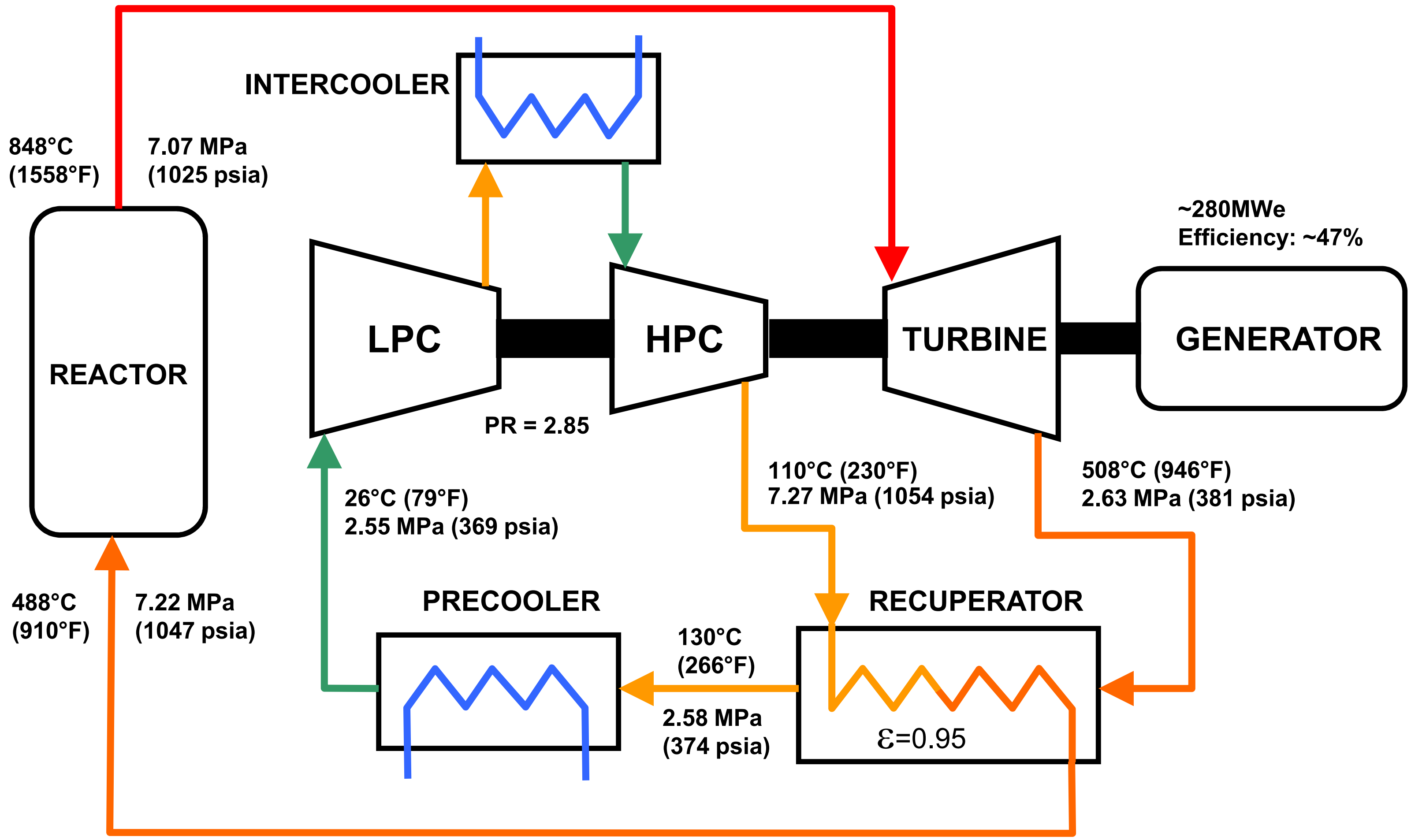
Significance of Helium Properties

- **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 turbomachine designs
  - Higher flow rates, loads during blowdown
- **Lower dielectric strength**
  - Increased difficulty for electrical insulation design
- **Chemically Inert**
  - Minimizes corrosion problems
  - Tendency for self-welding of metallic components

Significance of Cycle Parameters

- **Heat Rejection Temperature**
  - Brayton Cycle is more sensitive to ambient temperature than Rankine Cycle
  - ~17F/~9C = 1%
- **Reactor Outlet Temperature**
  - ~27C = 1%
- **Recuperator Effectiveness**
  - ~1.3% eff = 1%
- **Cycle Pressure Losses/Bypass Flows**
  - Large penalties for inefficient use of compressor work
  - 1.2%dP/P = 1%
- **Intercooling**
  - One stage provides optimum benefits (3-4% added efficiency), but adds complexity, somewhat offset by pressure losses and bypasses
- **Pressure Ratio**
  - Typically optimizes in the range of 2 - 3

GT-MHR Cycle



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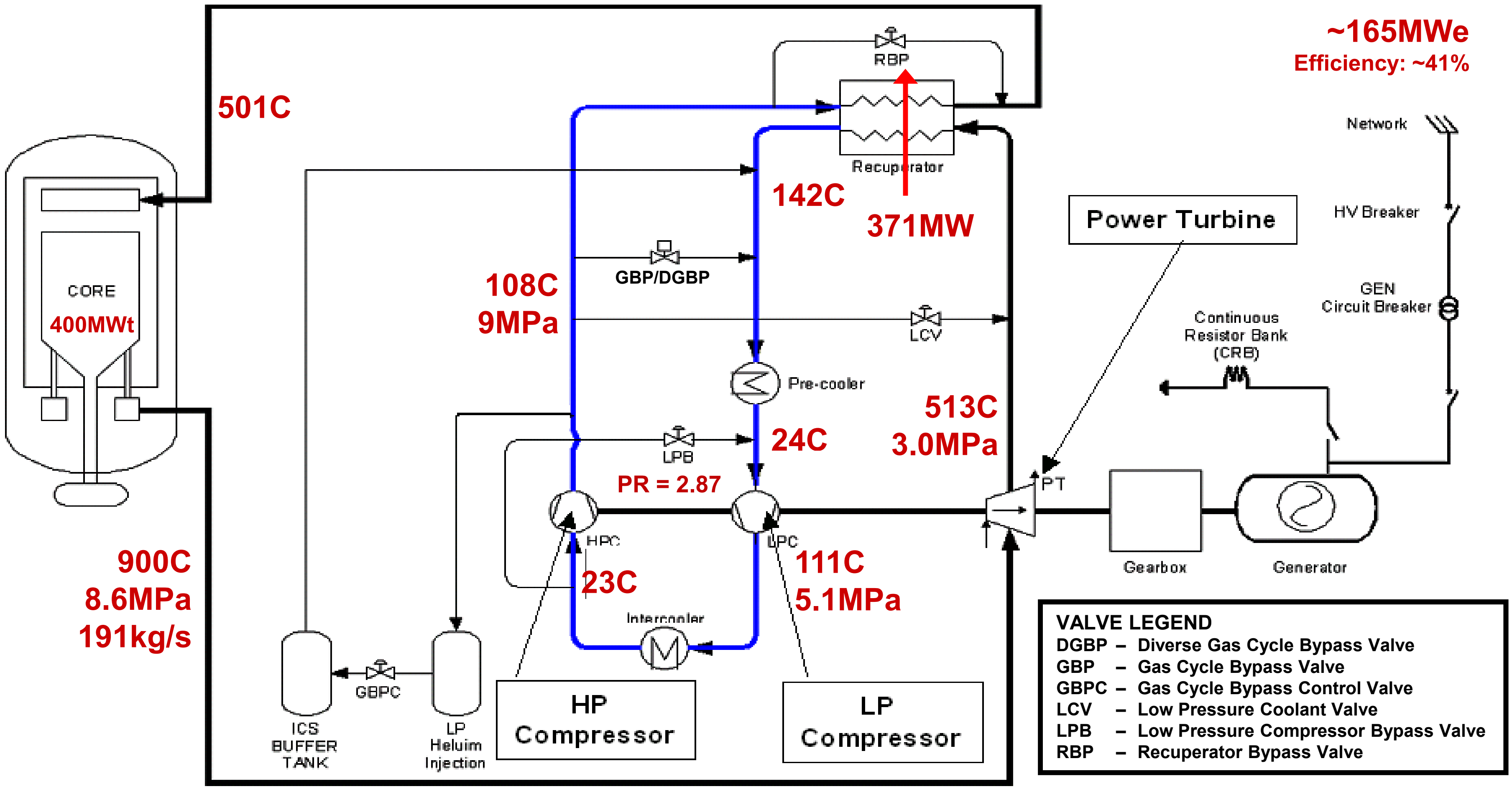
PBMR

PBMR-DPP400 Cycle



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

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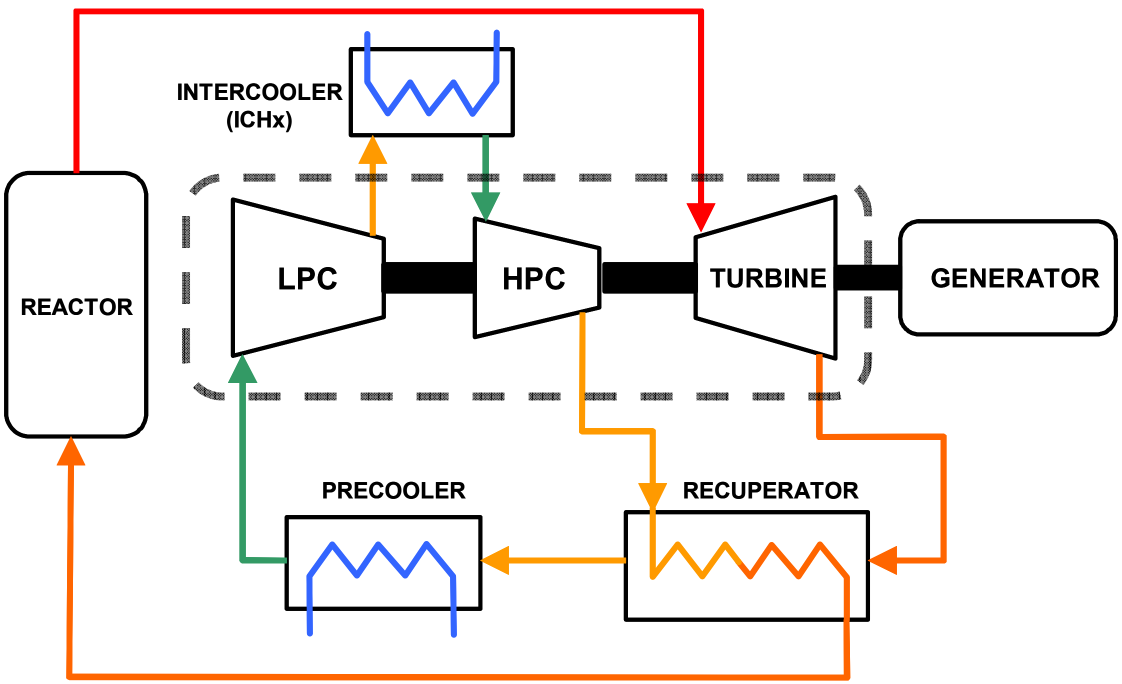
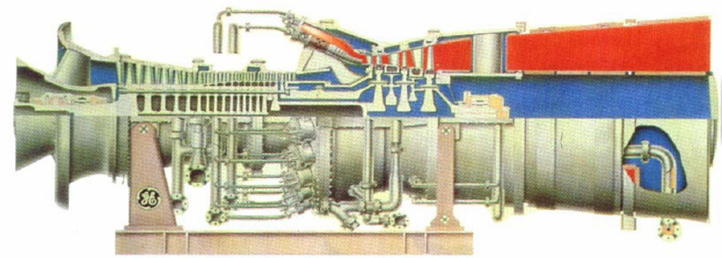
- **PCS design tradeoffs**
- **PCS development issues**

Turbocompressor Functions



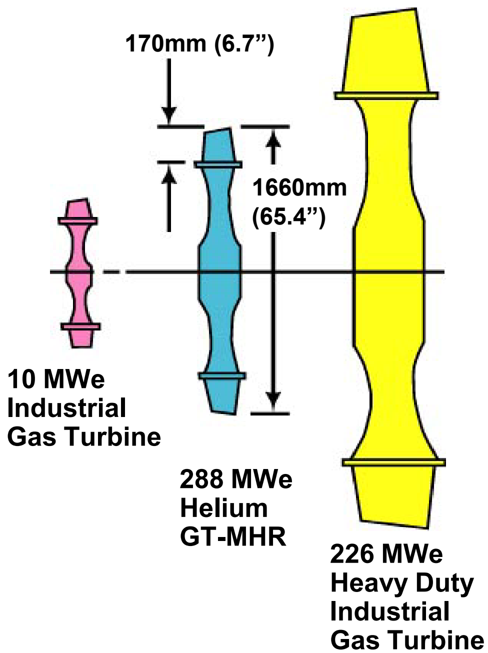
- **Convert thermal energy into mechanical energy**
- **Compress and circulate helium during normal operation for power production**
- **Circulate helium during certain transients and shutdown modes for decay heat removal**
  - Generator used as motor

GT-MHR Turbocompressor



226 MWe Open-Cycle Industrial Gas Turbine (GE MS 9001F)

Turbine Last Stage
Relative Size



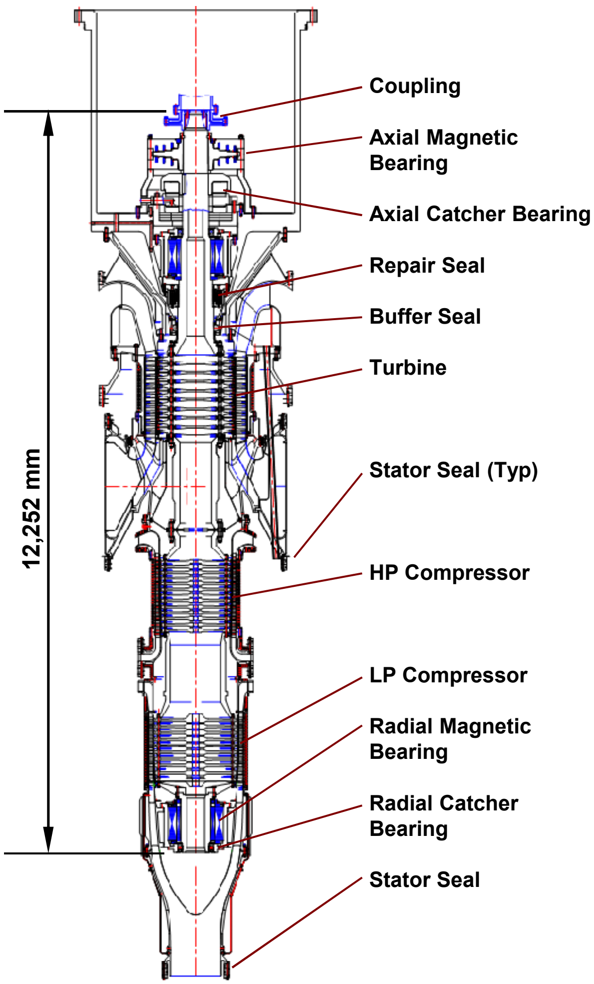
TURBINE

- Power
  560MWt/288MWe
- Rotation Speed
  4400rpm
- He Flow
  322 kg/s
- Inlet/Outlet Temp
  849/508C
- Inlet/Outlet Press
  7.0/2.7MPa

LP/HP COMPRESSOR

- Capacity
  323 kg/s
- Inlet Temp
  24/26C
- Inlet Press
  2.6/4.4MPa
- Outlet Temp
  103/107C
- Outlet Press
  4.4/7.2MPa

GT-MHR Turbocompressor



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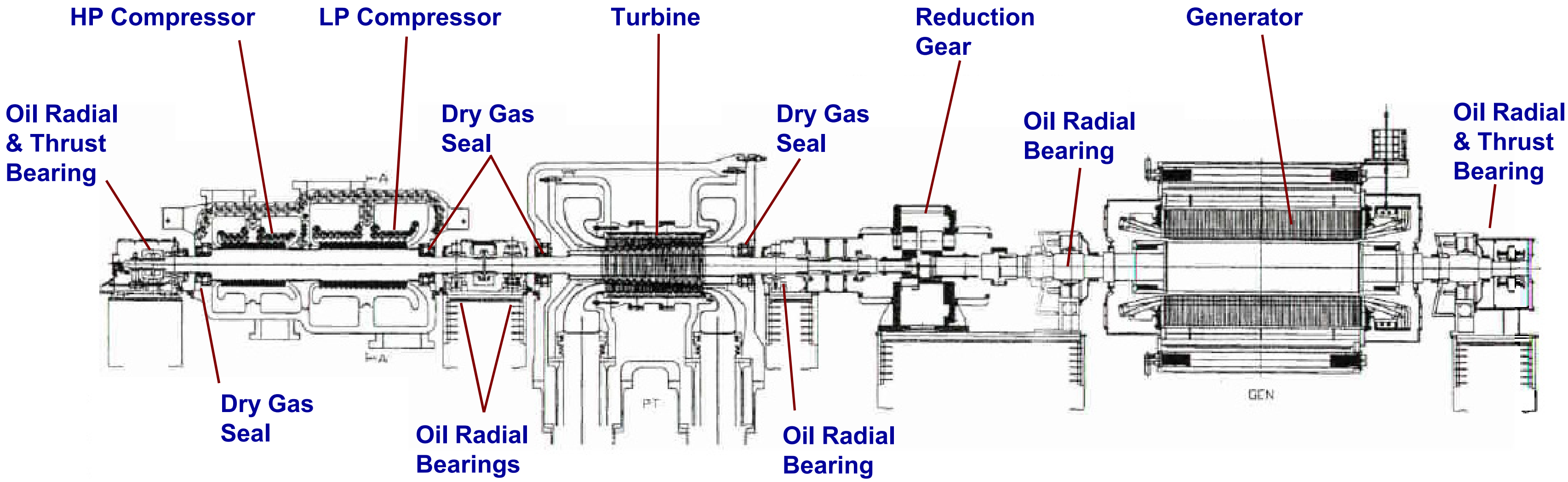
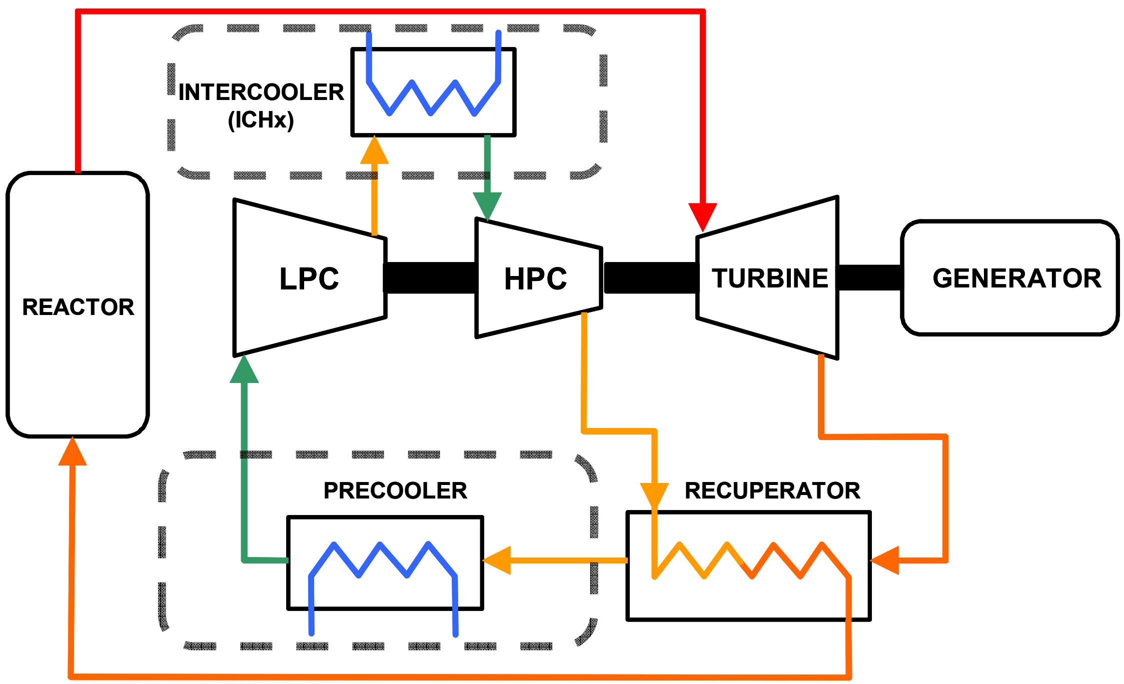
PBMR Turbomachine



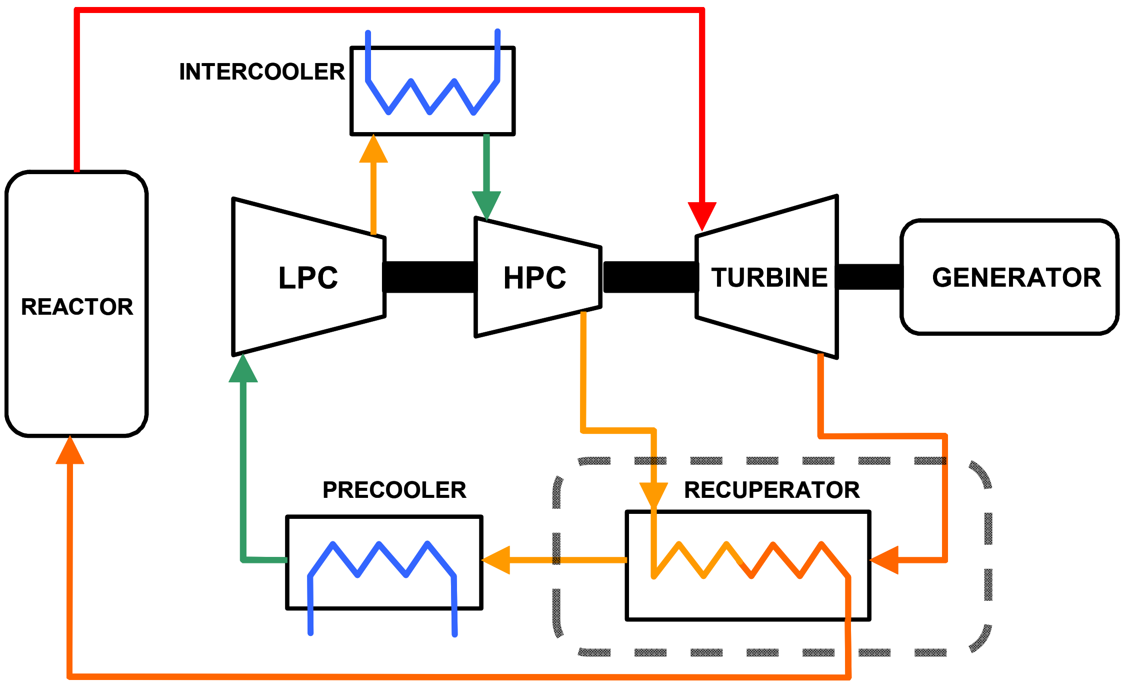
Speed (rpm):		Flow (kg/s):	193
Compressor & Turbine	6000	Turbine Inlet Temp (C):	900
Generator	3000	Turbine Inlet Press (MPa):	~9
Shaft Power (MW):	177	Cycle Efficiency:	≥41

Precooler/Intercooler Functions



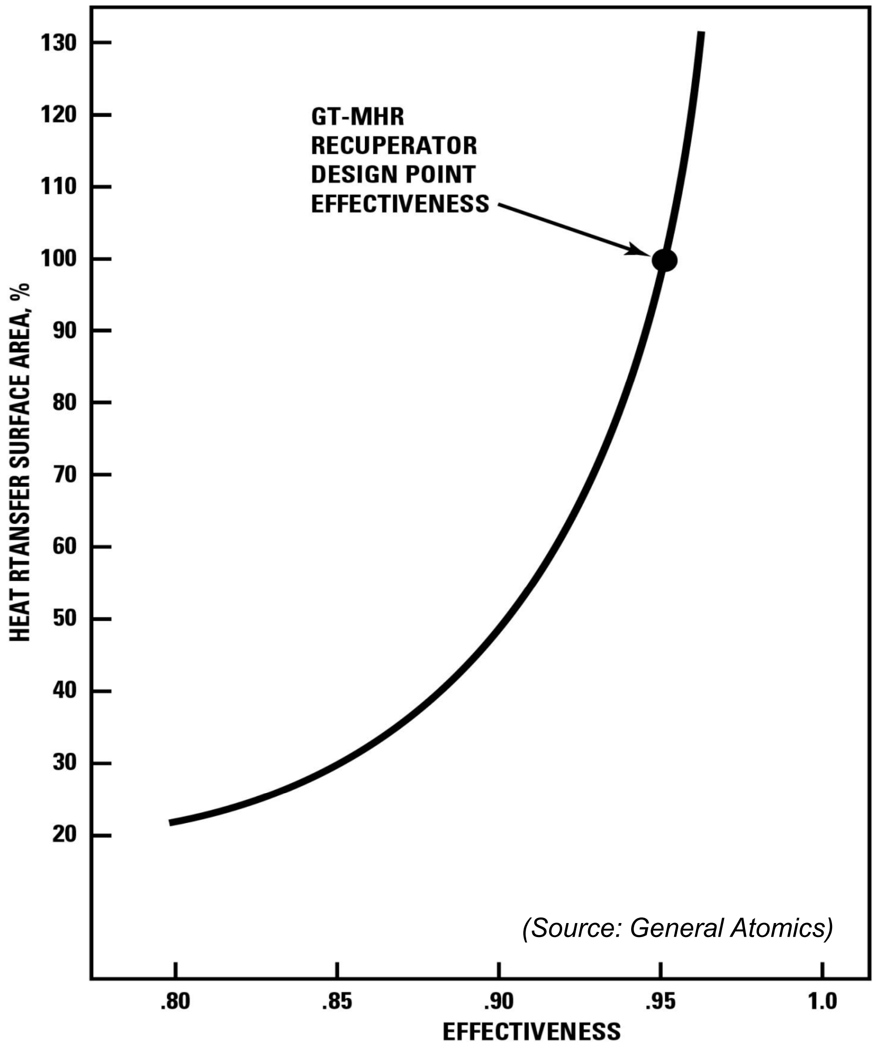
- Reject waste heat from the power conversion cycle
- Remove decay heat during shutdown
- Enhance compression efficiency (ICHx)
- Maintain pressure boundary integrity

Recuperator Functions



- **Recover heat from the turbine exhaust stream and transfer it to the reactor helium inlet stream**
  - Major factor in achieving high cycle efficiency
- **Provide separation between the high and low pressure sides of the cycle**
  - Not a helium pressure boundary component

Recuperator Surface-Effectiveness Relationship

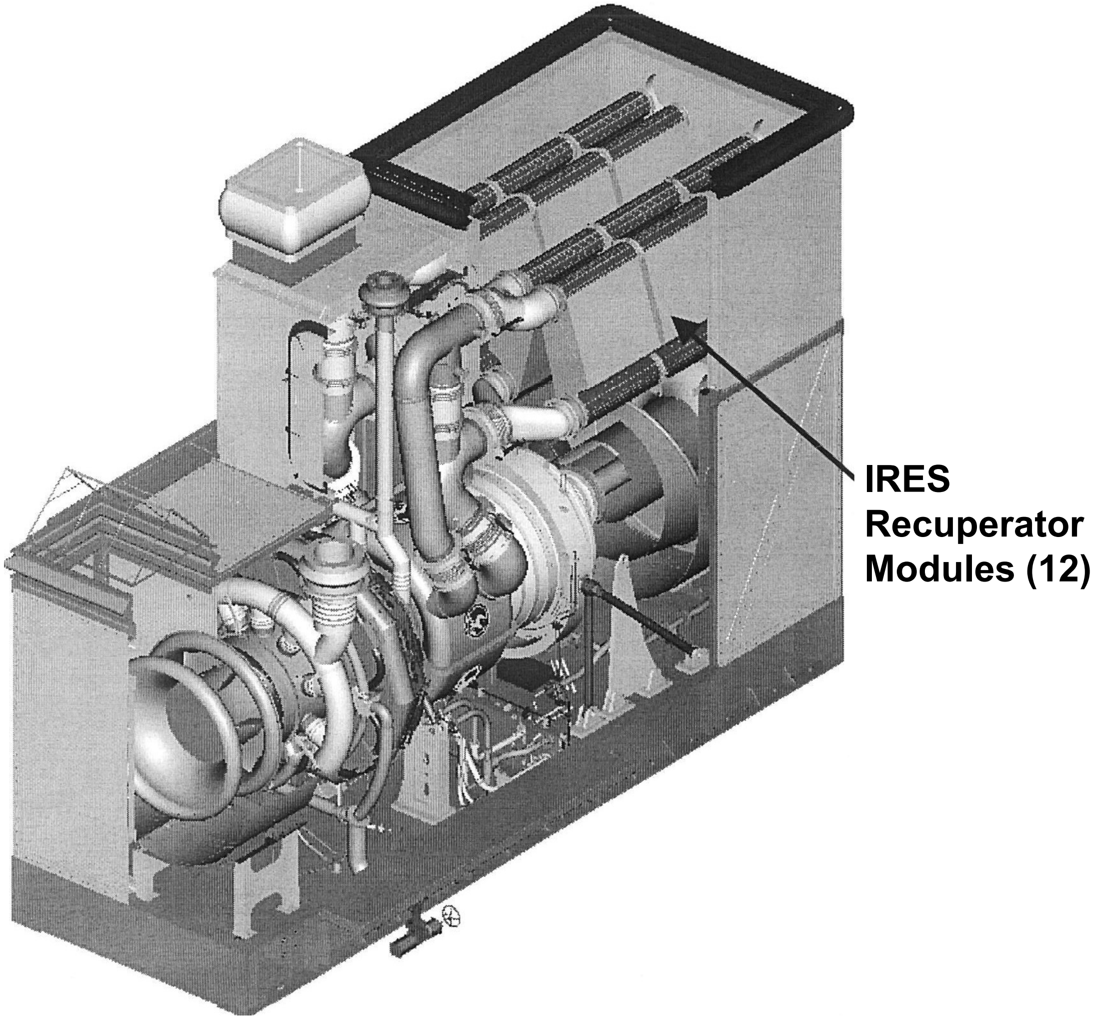


- Recuperator surface area strongly impacted by effectiveness requirement
- Compact plate-fin surface geometries needed to minimize recuperator size for installation in power conversion vessel

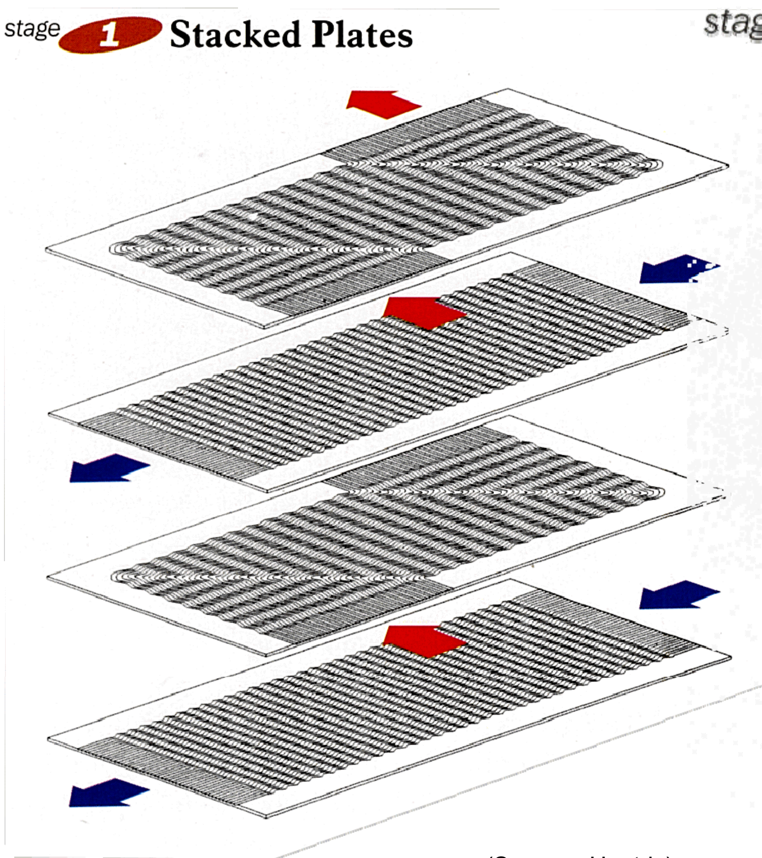
IRES Plate-Fin Heat Exchanger

(Source: Ingersoll-Rand Energy Systems)

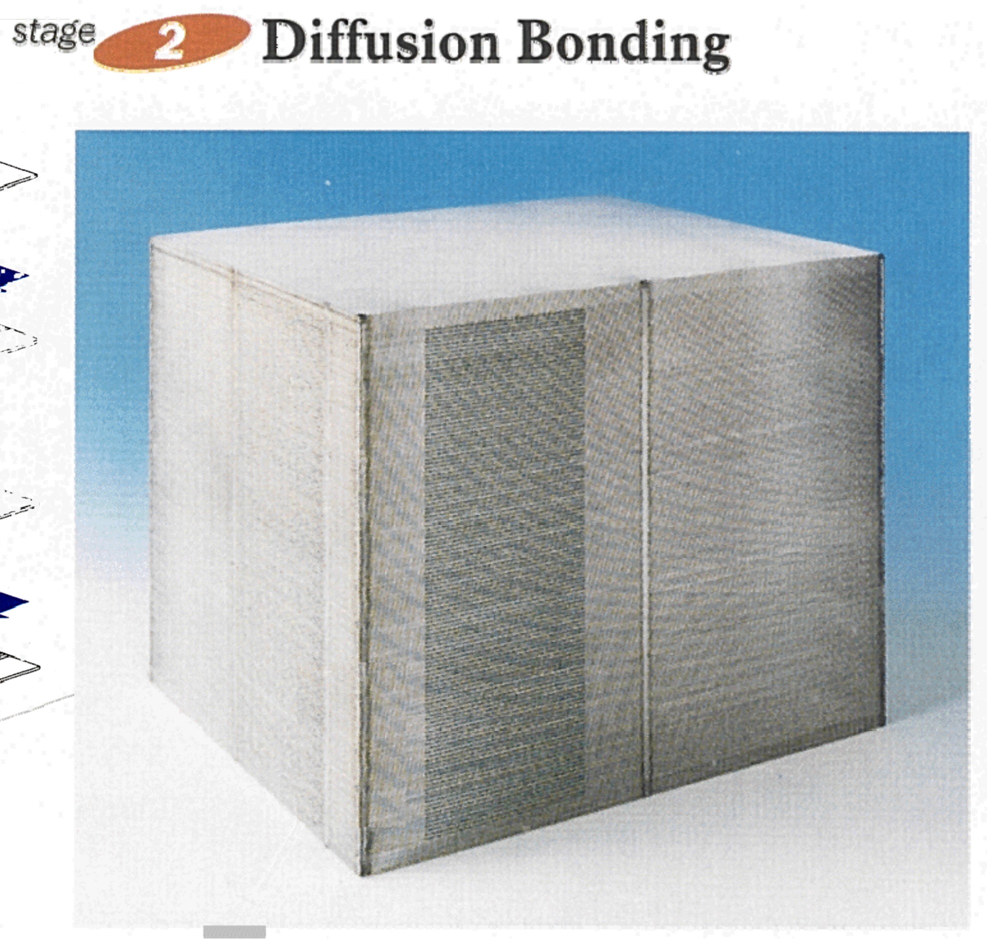
WR21 Recuperated Gas Turbine (U.S. Navy)



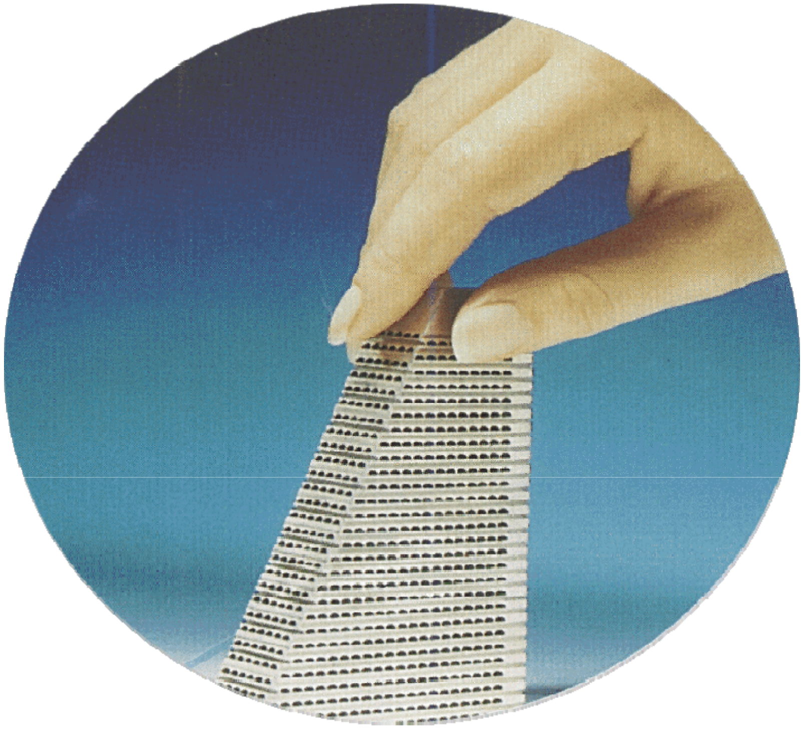
Heatric Plate-Type Heat Exchanger

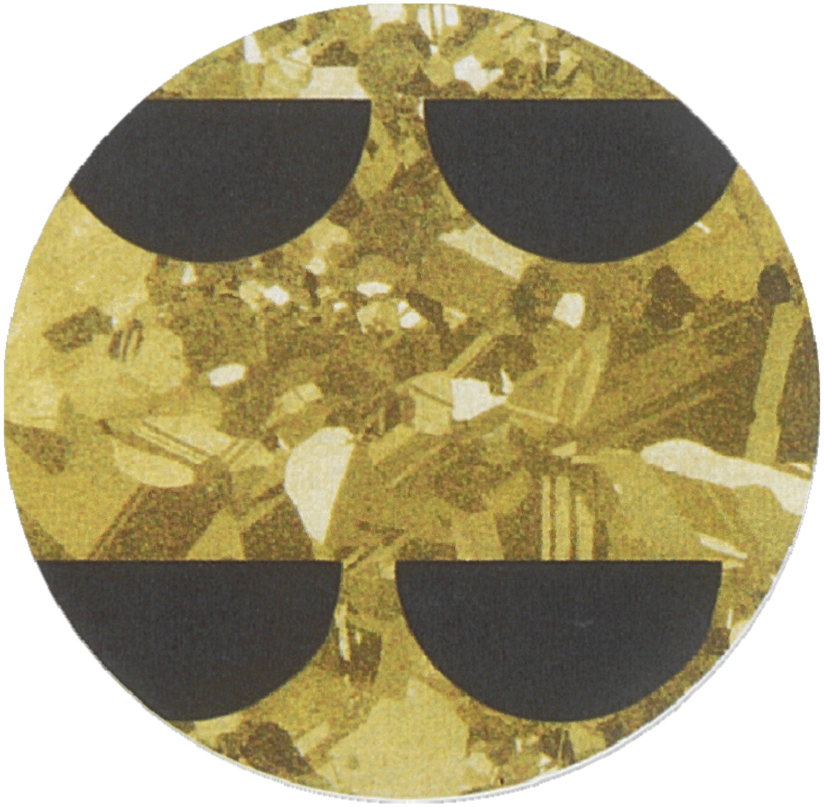


(Source: Heatric)



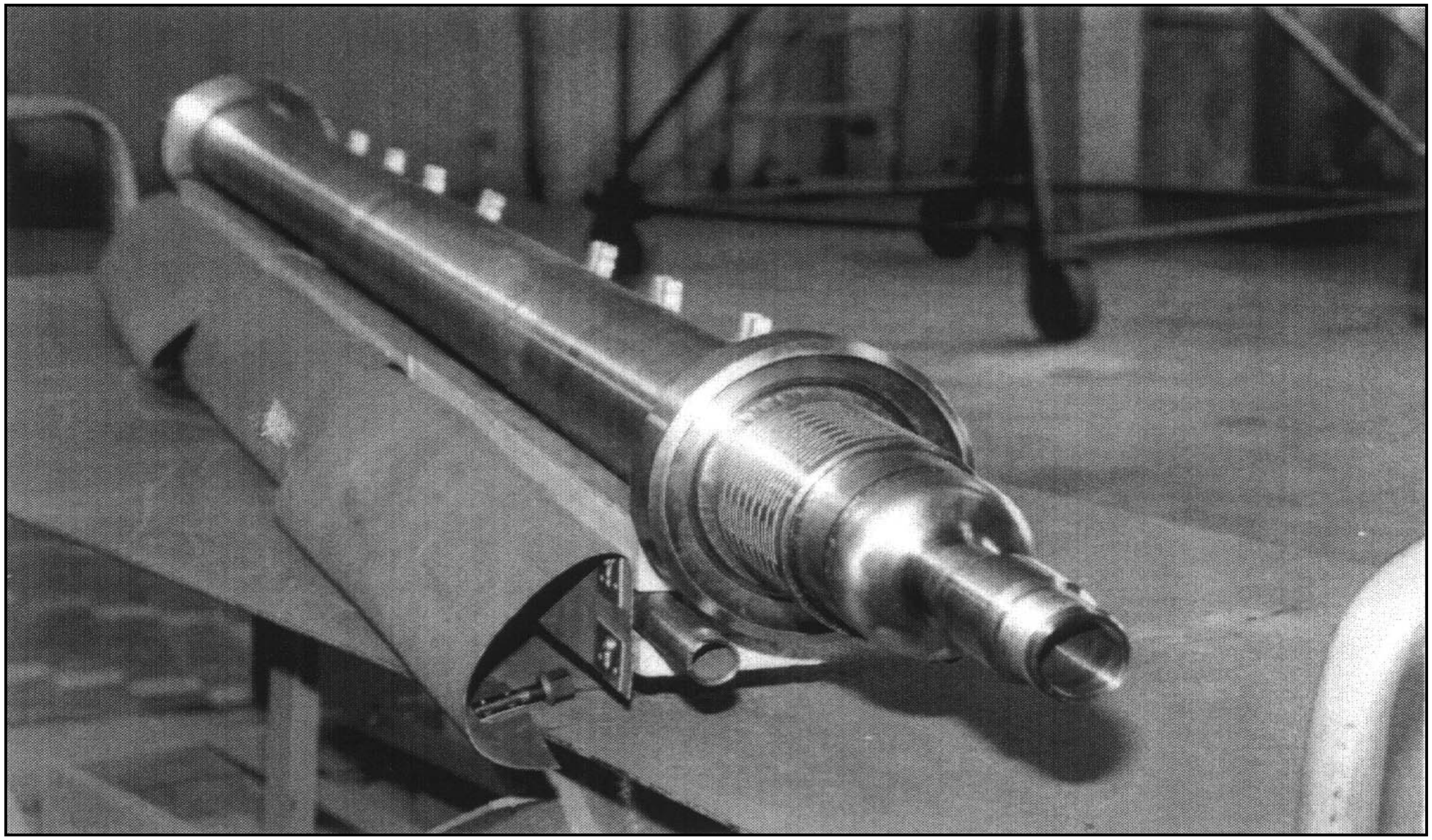
Heatric Plate-Type Heat Exchanger





(Source: Heatric)

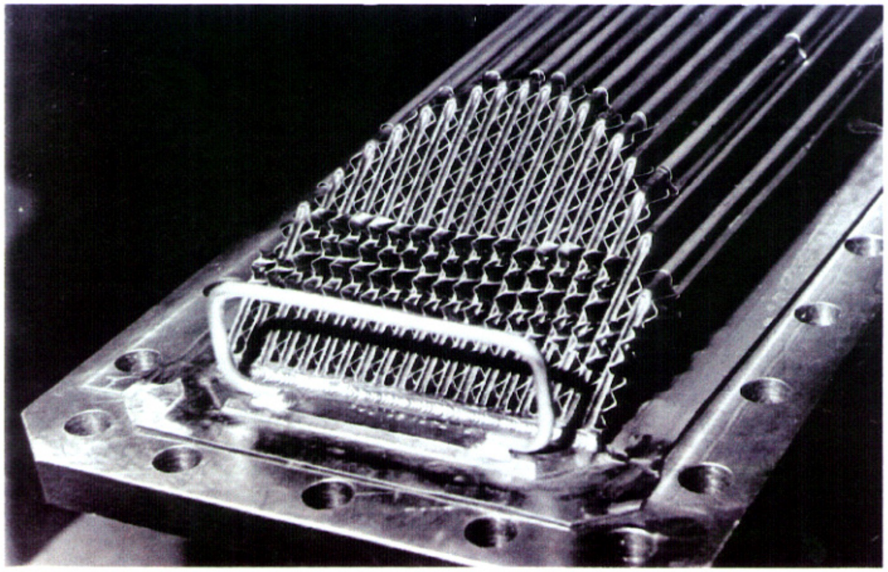
OKBM GT-MHR Recuperator Element



(Source: General Atomics)

OKBM GT-MHR Recuperator Element

Inlet section of GT-MHR recuperator heat exchange element



Fabrication of plate-type heat exchanger section

(Source: General Atomics)

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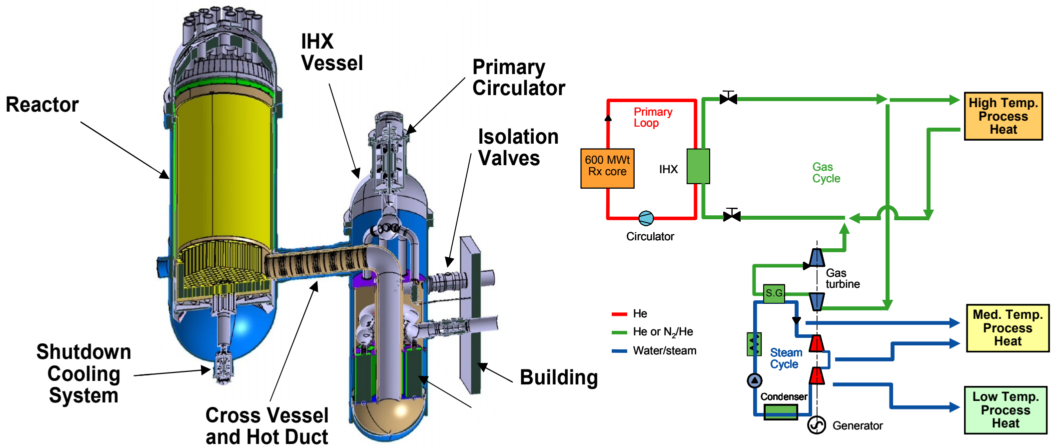
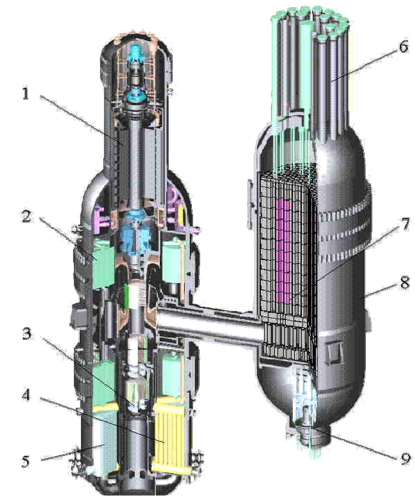
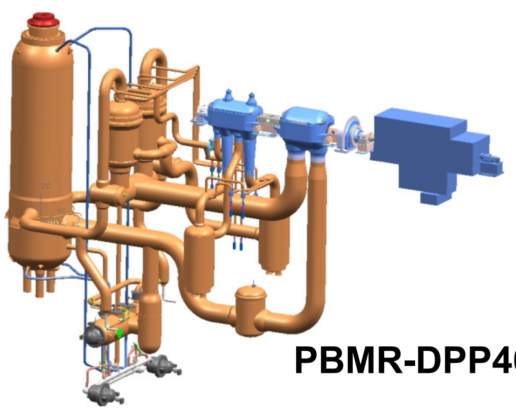
Why Do These Look so Different?



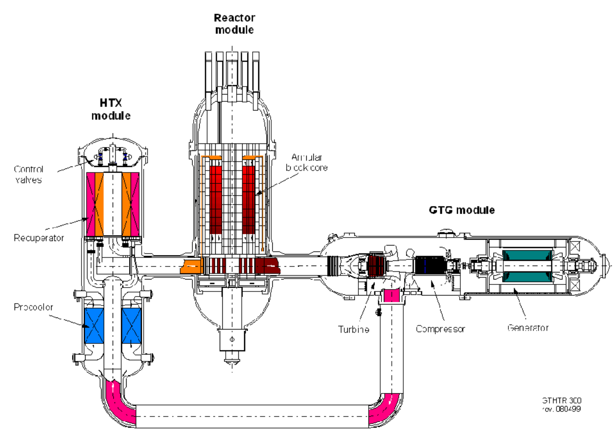
ANTARES



GT-MHR600



PBMR-DPP400



GTHTR300

Direct Cycle Power Conversion Options

Feature	Principal Tradeoffs
Direct vs. Indirect Cycle	Increased efficiency, reduced capital cost vs. cycle flexibility, PCS maintainability, IHX development
Integrated vs. Distributed PCS	Increased efficiency, reduced capital cost vs. integration challenges, maintainability
Recuperated vs. Simple Cycle	Increased efficiency vs. increased capital cost
Intercooling vs. Non-Intercooling	Increased efficiency vs. increased capital cost
Synchronous vs. Asynchronous Turbogenerators	Simplicity vs. increased efficiency, complexity, increased capital cost (?)
Submerged vs. External Generator	Static helium pressure boundary, high-voltage penetrations vs. rotating shaft seal, improved generator access, reduced windage losses
Vertical vs. Horizontal Turbomachines	Smaller PCS building, vertical lifts for maintenance vs. independent maintainability access to TC/generator (w/split casing or separate pressure boundary), radial support of weight

Summary of Design Selections

Feature	PBMR-DPP400	GT-MHR	ANTARES	GTHTR300
Direct vs. Indirect Cycle	Direct	Direct	Indirect	Direct
Cycle Type	Brayton	Brayton	Closed GTCC	Brayton
Recuperated vs. Simple Cycle	Recuperated	Recuperated		Recuperated
Intercooled vs. Non-Intercooled	Intercooled	Intercooled		Non-Intercooled
Integrated vs. Distributed PCS	Distributed	Integrated		Distributed
Single vs. Multiple TM Shafts	Single	Single		Single
Synchronous vs. Asynchronous	Asynchronous	Asynchronous		Synchronous
Vertical vs. Horizontal TM	Horizontal	Vertical		Horizontal
Submerged vs. External Generator	External	Submerged		Submerged
Magnetic vs. Oil Lubricated Bearings	Oil	Magnetic		Magnetic

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Gas Turbine PCS Development Issues

- **Turbocompressor/Generator Support & Coupling**
- **Submerged vs. External Generator Tradeoffs (Direct Cycle)**
  - Rotating Dry Gas Seals or High Voltage/High Power Electrical Penetrations in Primary Helium Pressure Boundary
- **Bearing Tradeoffs**
  - Active magnetic bearings
  - Oil Bearings
- **Internal Seals**
  - Bypass/efficiency losses
- **Recuperator Reliability**
- **Fast Acting Control and Bypass Valves**
- **Maintainability**
  - Provisions for component removal/replacement
  - Implications of radionuclide contamination
- **IHX Development (Indirect Cycle)**

Summary

- Developments in enabling technologies (particularly compact HXs) make gas turbine cycles a feasible option
- With the exception of compact intermediate heat exchangers, component feasibility has been established through R&D and/or contemporary applications
- Technical issues primarily relate to system integration

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Suggested Reading

1. *", Evaluation of the Gas Turbine Modular Helium Reactor*, DOE-GT-MHR-100002, Gas-Cooled Reactor Associates, San Diego, CA, February 1994.
2. Yan, X., et. al., "Design and Development of GTHTR3000", *HTR2002, the 1st International Topical Meeting on HTR Technology*, Petten, Netherlands, April 22-24, 2002.
3. PBMR Design and Safety Familiarization Sessions, Power Conversion Unit, Presentation to NRC, March 1, 2006.
4. Breuil*, E., et.al.,* "Development of the IHX for ANTARES Paper *6457*, *ICAPP '06*, June 4-8, 2006.