6.9 Heat Transport and Thermal Energy Conversion

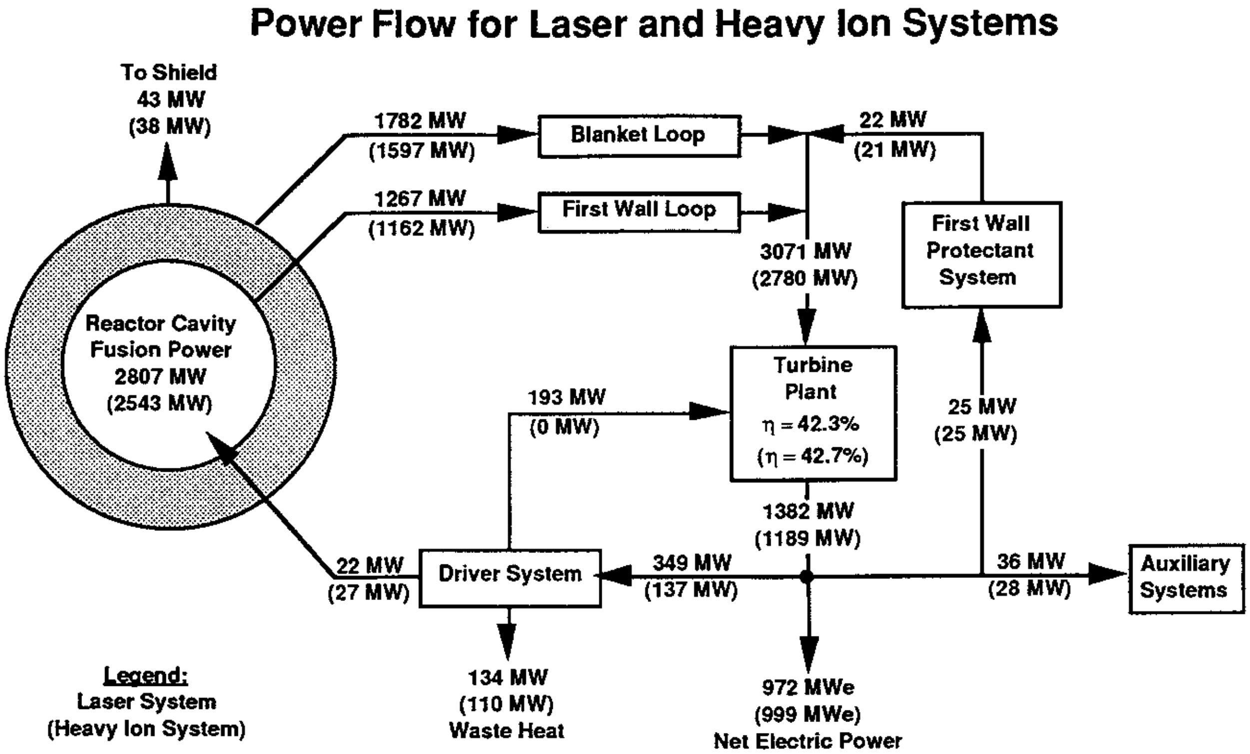
Various heat transport and thermal energy conversion concepts were considered and evaluated during development of the Prometheus designs. This section addresses thermal energy sources, heat transport, and distribution systems.

High grade thermal energy sources available in the Prometheus reactor are: (a) first wall energy, (b) blanket energy, and (c) KrF laser waste heat. First wall heat is extracted by liquid lead, while helium coolants provide the transport for blanket energy and laser driver waste heat. These coolants transfer thermal energy to Rankine cycle steam generators, steam reheaters, and feedwater heaters.

6.9.1 Energy Sources - The Prometheus reactors develop energy from the fusion of deuterium-tritium fuel in the reactor cavity. Deuterium-tritium (DT) targets injected into the cavity are imploded using either laser or heavy ion beams, resulting in an energy gain of approximately 100. Each DT fusion reaction produces a 14.1 MeV neutron plus a 3.5 MeV alpha particle. Alpha particles are stopped by the first wall, while neutrons and secondary gammas are absorbed or thermalized in either wall or blanket components. Resultant heat is transferred, by lead or helium, to the energy conversion system.

Prometheus-L (laser) total energy is 3,264 MW which is derived from four sources as shown in Figure 6.9-1. Proceeding outward from the reactor chamber center, a flowing first wall protection film absorbs 22 MW of energy. This first wall protection consists of a liquid lead film to absorb a portion of the x-ray, neutron, and debris energy. Next, a first wall lead coolant loop extracts 1,267 MW of power deposited in this region. A helium-cooled loop is used to extract 1,782 MW from the blanket. Finally, the high temperature laser driver waste heat, 193 MW, is recovered via a helium transfer medium into the energy conversion process. Representative operating temperatures are: liquid lead = 977°F, blanket helium = 1,202°F and KrF laser waste heat = 900°F. Energy conversion is accomplished through six parallel steam generator circuits from the main reactor core. A representative Prometheus-L energy conversion system is shown schematically in Figure 6.9-2.

Prometheus-H (heavy ion) total energy is 2,780 MW which is derived from three sources as shown in Figure 6.9-1. Proceeding outward from the reactor chamber center, a flowing first wall protection film supplies 21 MW of energy. This first wall protection consists of a liquid lead film to absorb a portion of the x-ray, neutron, and debris energy. Next, a first wall lead coolant loop extracts 1,162 MW of power deposited in this region. Finally, a helium-coolant loop is used to extract 1,597 MW from the blanket. Power conversion, like the Prometheus-L, is accomplished through six parallel steam generator circuits from the main reactor core. A representative Prometheus-H energy conversion system

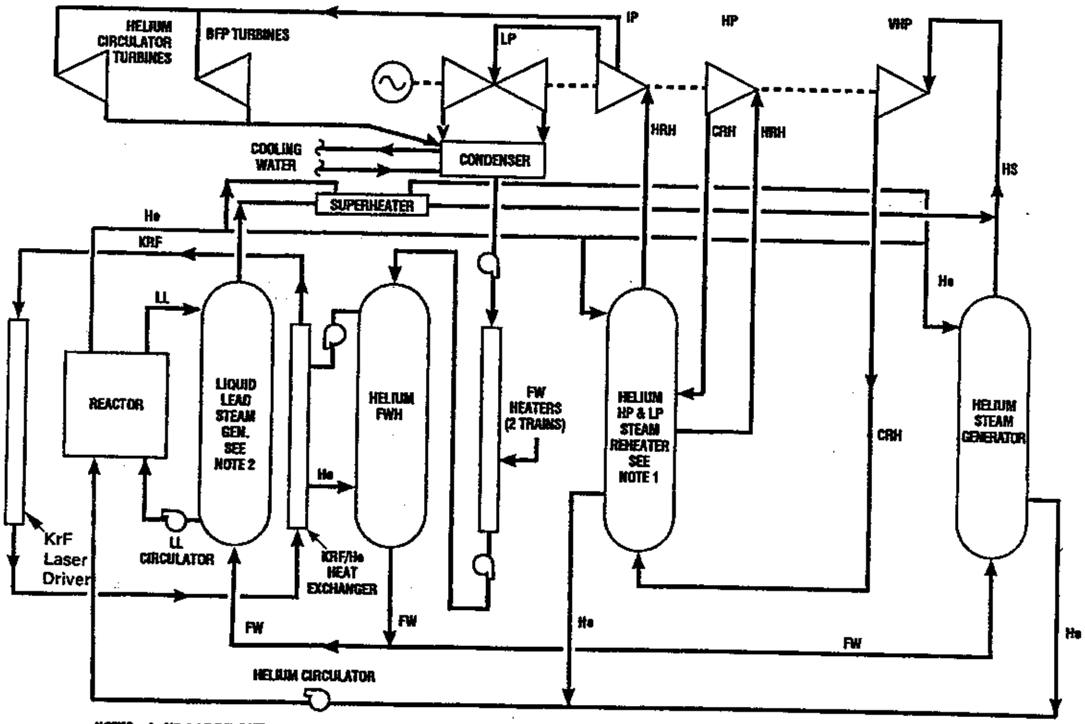


Thermal Source	-L	-H
Blanket Loop	1,782	1,597
First Wall Loop	1,267	1,162
First Wall Protection	22	21
Driver Loop	193	0
Total Energy	3,264	2,780

Figure 6.9-1. Prometheus Baseline Power Flow

is shown schematically in Figure 6.9-3. To achieve the same net electrical power, total Prometheus-H thermal power is 10% lower than Prometheus-L. This Prometheus-H advantage is due to higher driver efficiency.

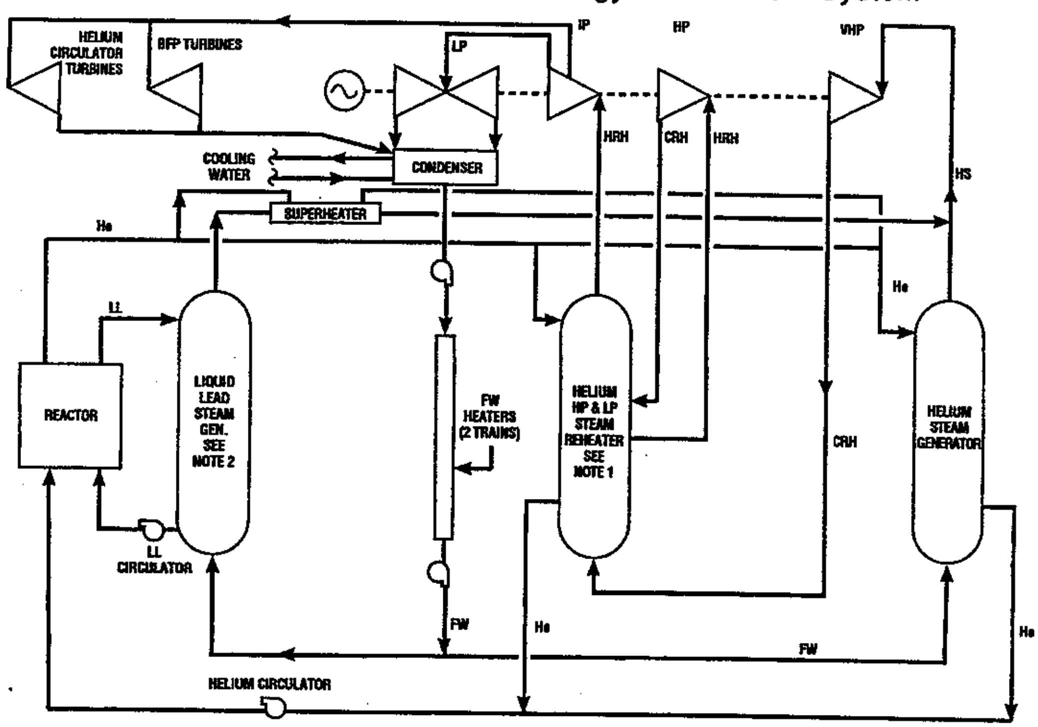
6.9.2 Design Rationale – Study team members selected liquid lead and helium heat transfer coolants after examining safety aspects, heat transfer properties, and nuclear characteristics of alternate materials (see Reference 1 and Section 4.4). Liquid lead provides good heat transfer properties, first wall protection, and 40% energy absorption plus some neutron energy multiplication. In addition, liquid lead and water do not present a fire hazard. However, the maximum operating temperature of lead is limited (977°F) to minimize intergranular attack on the ferritic pipe and tubing materials.



NOTES: 1. HP & LP REHEATER SECTIONS ARE WITHIN EACH OF SIX VESSELS

2. USING DOUBLE-WALL TUBES, AN INTERPOSED LIQUID SODIUM CIRCUIT IS INCLUDED IN EACH OF SIX LIQUID LEAD STEAM GENERATORS

Figure 6.9-2. Prometheus-L Energy Conversion System



NOTES: 1. HP & LP REHEATER SECTIONS ARE WITHIN EACH OF SIX VESSELS

2. USING DOUBLE-WALL TUBES, AN INTERPOSED LIQUID SODIUM CIRCUIT IS INCLUDED IN EACH OF SIX LIQUID LEAD STEAM GENERATORS

Figure 6.9-3. Prometheus-H Energy Conversion System

A helium-cooled blanket concept provides a high degree of safety, acceptable thermal properties chemically compatible with structural materials, and reduced radioactive material circulation. Prometheus-L laser system waste heat is transferred to the feedwater heating system through an intermediate helium coolant loop. An intermediate helium loop is incorporated to isolate a possible hot fluorine leak into the steam cycle.

6.9.3 Thermal Cycle - Two thermal cycles were considered for this nominal 1000 MW power station—a closed Brayton cycle and an advanced Rankine cycle. An advanced Rankine cycle (using supercritical steam and a double reheat turbine) was chosen. An advanced Rankine cycle features high thermal conversion efficiencies compatible at coolant temperatures and reasonable extrapolation of the existing database.

The selected advanced Rankine cycle uses a tandem compound double reheat turbine (see Figures 6.9-4 and 6.9-5). This turbine consists of a very high pressure (VHP) turbine, a high pressure (HP) turbine, and a double flow intermediate pressure (IP) turbine. The IP turbine exhaust steam then flows into three double flow low pressure (LP) turbine sections and to a surface condenser. Turbine input conditions are presented in Table 6.9-1.

Table 6.9-1. Turbine Input Conditions

Turbine Type	Parameter	Prometheus-L	Prometheus-H
VHP	Temperature (°F)	950	950
	Pressure, psia	3,715	1,184
HP	Temperature (°F)	950	950
	Pressure, psia	977	977
IP	Temperature (°F)	950	950
	Pressure, psia	334	334

Currently, large power stations use single reheat turbines, typically a 2,400 psia or 3,500 psia turbine with steam conditions of 1000°F/1000°F (throttle/reheat). Introducing a second reheat turbine raises cycle efficiency approximately 1.1% for 2400 psia throttle steam, 2.0% for 3500 psia steam, and 2.3% for 4500 psia steam. A double reheat turbine cycle, throttle/reheat1/reheat2 steam (1000°F/ 1000°F/1000°F), and raising throttle pressure from 2400 psia to 4500 psia increases thermal efficiency approximately 4%.[2] Therefore, in the interest of attaining a high thermal conversion efficiency, a double reheat turbine cycle was selected with steam conditions, ultimately limited by temperatures and flows of the reactor coolants, but finally set by the requirement for temperature differentials that permit reasonably sized steam generators and reheaters.

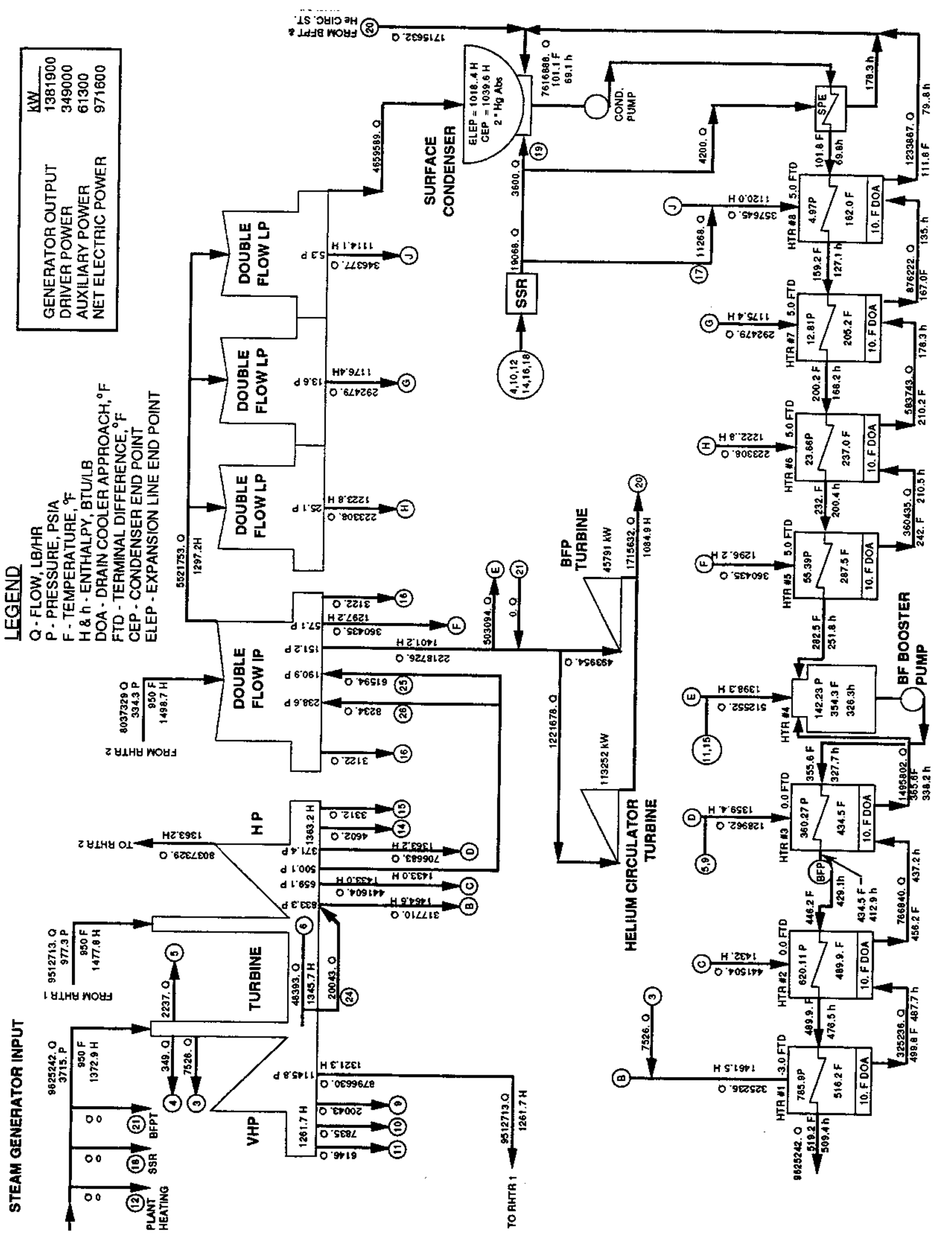


Figure 6.9-4. Prometheus-L Turbine Thermal Cycle

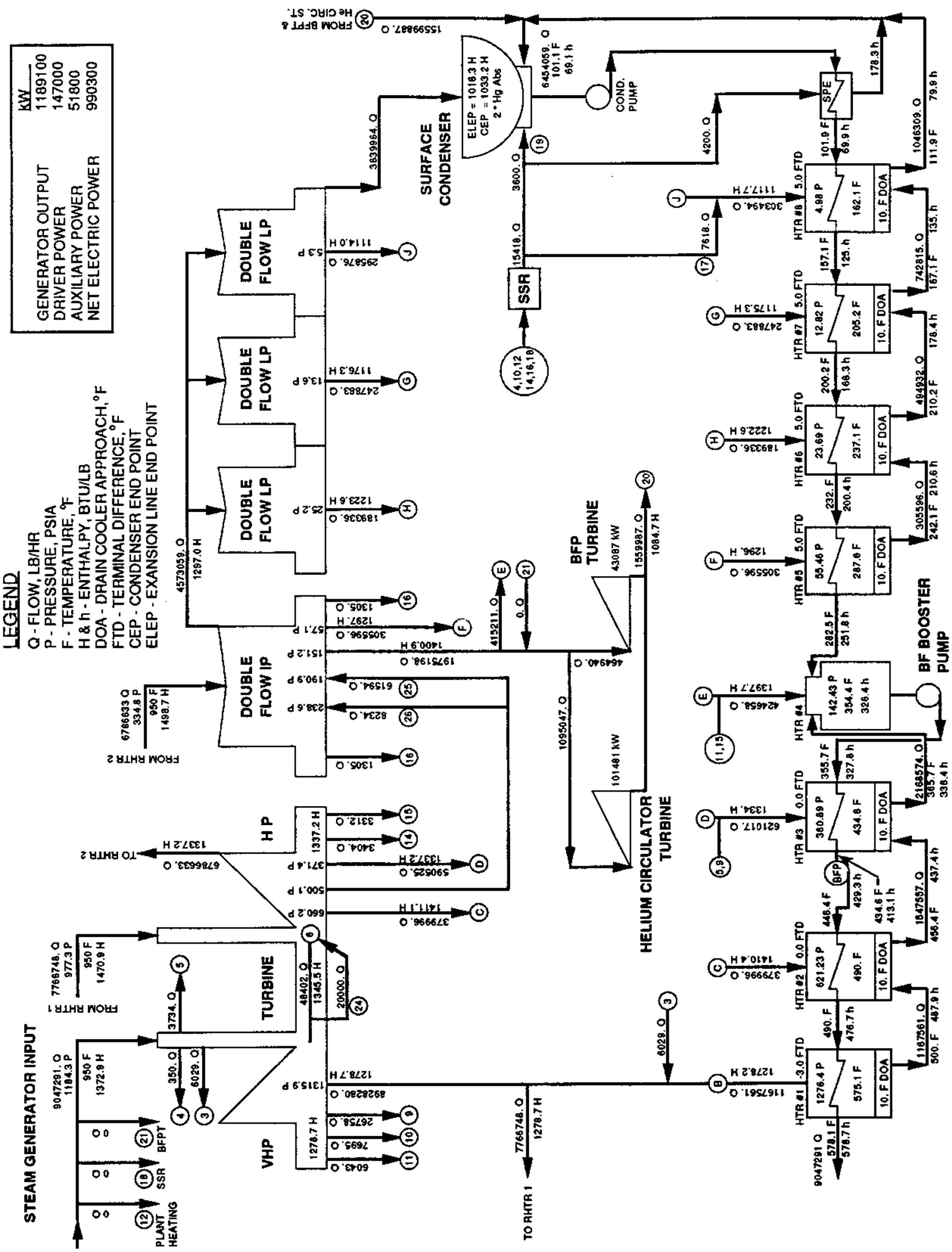


Figure 6.9-5. Prometheus-H Turbine Thermal Cycle

The Prometheus-L generator gross output is 1382 MWe and a 1550 MVA rating at 0.9 power factor. The Prometheus-H generator has a gross output of 1189 MWe and a 1321 MVA rating. The tandem compound turbine-generator performance is predicated on the future availability of a single 3600 RPM generator of this size. Design and performance of the steam turbine-generator is based on information received from Brown Boveri Corporation.

Steam is generated in six identical helium-to-steam vessels and in six liquid lead-to-steam vessels. Steam exiting the generator is held at 800°F to maintain a reasonable terminal temperature difference between the lower temperature liquid lead and the steam. Steam is superheated to 955°F by helium, then joined with steam from the helium steam generator. (Refer to Section 6.9.5 for additional details.)

The Prometheus feedwater system consists of two parallel 50% capacity strings of eight regenerative feedwater heaters. The temperature of feedwater leaving each string is raised from 519°F to 578°F in its respective helium-to-water heat. Helium serving the last feedwater heater obtains its heat from the KrF-to-helium heat exchanger.

A recirculating water system transfers condenser heat to the atmosphere through a natural draft cooling tower. Alternative systems include "once through" condenser cooling that utilizes natural bodies of water and air cooled condensers where the site cannot make available the large water requirement to make up tower evaporation, drift, and blowdown losses (approximately 19 x 10^6 gallons/day). This "once through" system eliminates the circulating water pumps, piping, and surface condenser but requires more site area (50% to 100% greater) plus auxiliary power and installation costs.

6.9.4 Auxiliary Power - The steam turbine-generator supplies auxiliary power through transformers that step the 26 kV down to motor levels; i.e., 13200, 4150, and 480 volts. After auxiliary allocations, net power is transformed up to grid voltage of 345 or 500 kV.

Auxiliary power requirements of both Prometheus-L and H are summarized in Table 6.9-2. The total auxiliary power for Prometheus-L exceeds Prometheus-H by 10.5 MW. Prometheus-L requires 5.7 MW to circulate helium from the KrF heat exchanger to the feedwater heaters. The remaining 3.8 MW is derived from 10.5% greater heat input and corresponding larger, condensate, feedwater, cooling water, and liquid lead pumps.

Auxiliary power transformer losses amount to 0.4% plus driver power requirements, 1600 kW for Prometheus-L and 800 kW for Prometheus-H. Most of this auxiliary power increase is attributable to the large laser driver power requirement.

Table 6.9-2 Auxiliary Power Requirements (kW)

		Prometheus-L	Prometheus-H
Condensate Pumps		2700	2300
Feedwater Booster Pumps		5600	5400
Circulating Water Pumps		8300	7000
Auxiliary Cooling Water Pumps		700	600
Steam Turbine Auxiliaries		3004	300
Water Treatment		300	300
HVAC		300	300
Lighting		200	200
Miscellaneous		600	600
Auxiliary Transformer Loss		1600	800
	Subtotal	20600	17800
Liquid Lead Pumps		25000	24000
Helium Circulator for KrF		5700	0
Reactor Auxiliaries		10000	10000
	Total	61300	51800

Diesel generators provide emergency auxiliary power for safe shutdown upon a trip of the steam turbine generator.

Diesel generators provide emergency power to these essential systems:

- Helium Circulator Drives
- Liquid Lead Pump
- Circulating Water Pump
- Auxiliary Cooling Water Pumps
- Liquid Lead Heat Tracing and Safety Air Conditioning
- Condenser Vacuum Pump
- Closed Cooling Water Pump
- Detritiation Systems
- Station Lighting, Controls, and Instrumentation

Helium and liquid lead circulation size determine the emergency diesel-generator system. Material design limits during an emergency shutdown and transient thermal analyses are the design drivers.

6.9.5 Plant Performance - Plant performance of both Prometheus-L and -H designs are summarized and compared in Table 6.9-3.

Table 6.9-3 Performance

	Prometheus-L	Prometheus-H
Heat Input, MWe	3091.0	2797.0
Gross Power Input, MWe	1381.9	1189.1
Driver Power, MWe	349.0	147.0
Auxiliary Power, MWe	61.3	51.8
Net Power Output, MWe	971.6	990.3
Gross Efficiency, %	44.7	42.5
Net Efficiency, %	31.4	35.4

Efficiency is based on total heat input which is the sum of the thermal power in the blanket, wall protection, and shield power losses.

Net power output is to the primary side of the main transformers. Main transformers have an estimated loss of 3000 kW.

Gross efficiency at the generator terminals is 2.2% lower for a heavy ion-based plant. This is because the heavy ion plant supplies a smaller proportion of cycle heat (57.8% as compared to 58.4%) with helium (the hotter fluid) for the laser-based cycle. This lower efficiency heavy ion plant thermal conversion system is more than offset by the more efficient driver.

Disadvantages of this heavy ion, low gross cycle efficiency is offset by a 202 MW decrement in driver power requirement.

For the above reasons, as well as the auxiliary power differentials shown in Table 6.9-2, plant net efficiency for the heavy ion cycle is 35.4%, or four points above that for the laser cycle.

By extracting large quantities of steam from the IP turbine, the mechanical helium circulators reduce output at the generator terminals. Electric motors drive one or more helium circulators at startup and during shutdown. Future cycle optimization should consider higher pressure steam for the helium circulator drive turbines. Drive turbines would exhaust steam to either the HP reheater cold line or to the main condenser. Smaller steam turbines and lower cost could be weighed against a plant efficiency decrement.

6.9.6 Steam Generators, Reheaters, and Superheaters - Helium and liquid lead serve as reactor coolants, transferring reactor heat for steam generation, superheating, and reheating. Six parallel flow paths transfer thermal energy from the reactor to the turbine (see Figure 6.9-6). Both Prometheus-L and -H designs generate 75% of the total high pressure steam through a liquid lead-heated system loop. Remaining high pressure steam flow is produced in the helium system loop (see Figure 6.9-7). The helium loop also acts as a steam superheater for the liquid lead heater and for the high and low pressure steam returning from the turbine steam reheater.

(a) Helium Steam Generators - Six modules arranged in parallel helium flow paths make up the helium-heated steam generation system. Each module consists of three heat exchangers supplied with helium (1202°F) from the fusion reactor (Figure 6.9-7). Each heat exchanger has the same basic concept—horizontal tube banks suspended in a water-cooled, gas tight square enclosure. Water and steam flow through the inside of the tubing. Helium flows around the

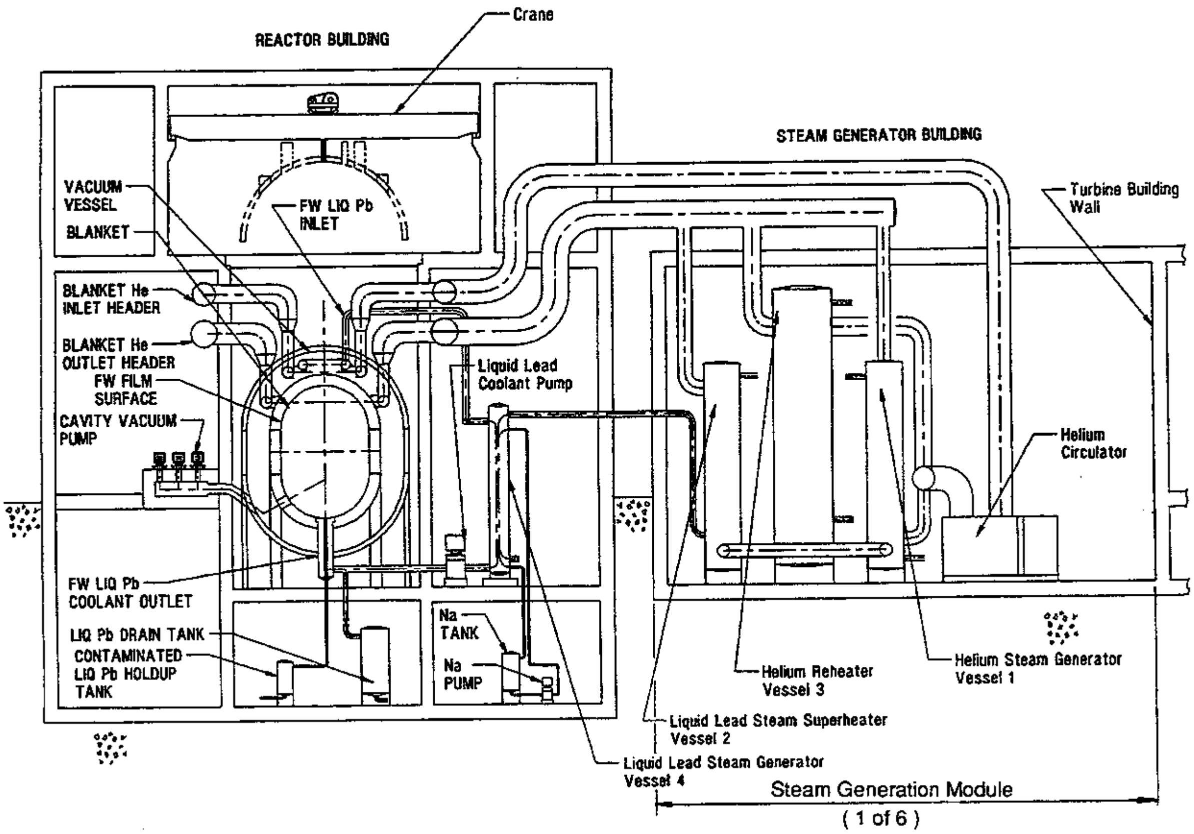


Figure 6.9-6. Coolant Distribution and Steam Generation

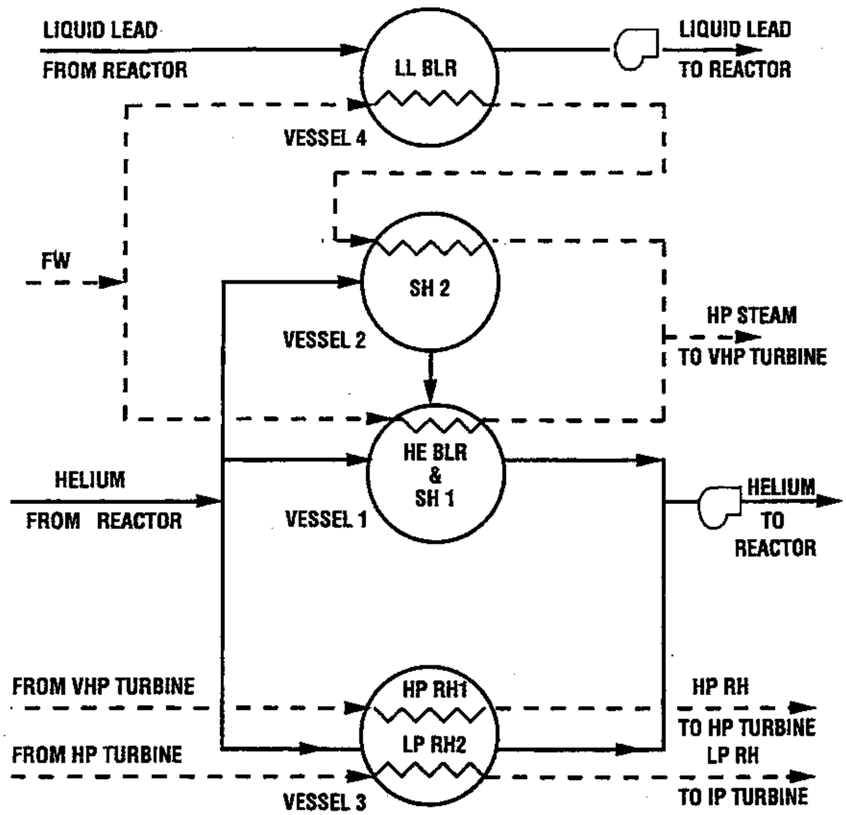


Figure 6.9-7. Steam Generation Flow Schematic

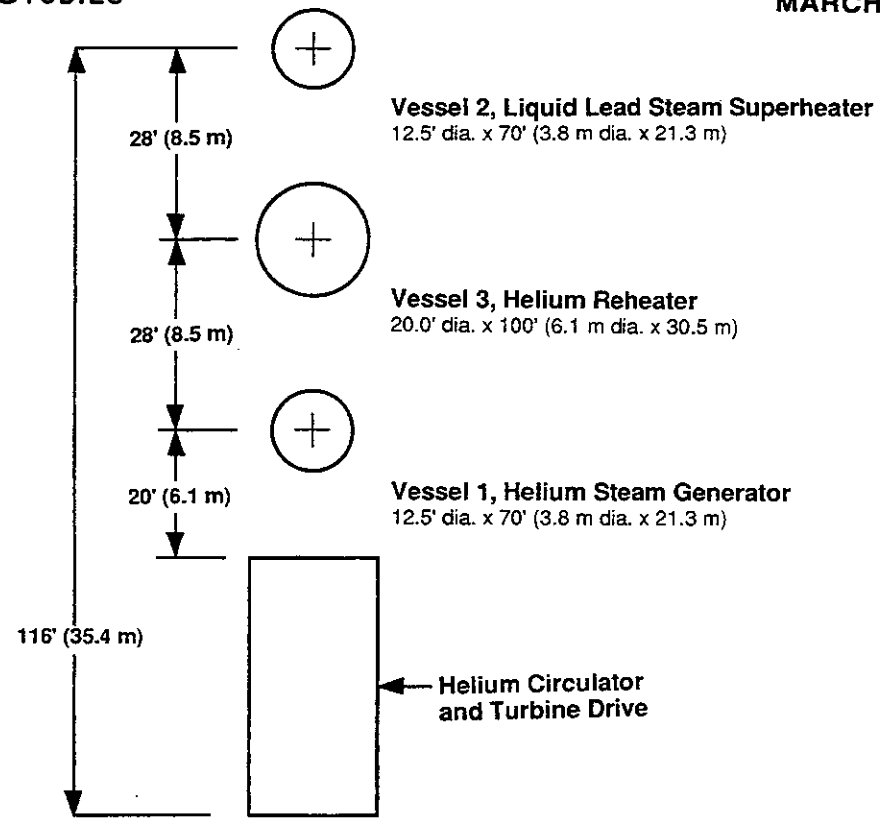


Figure 6.9-8. Helium Heat Exchanger Module

outside of the tube banks. Each tube bank and water-cooled enclosure is arranged vertically within a cylindrical pressure vessel. Hot helium circulates in such a way as to protect this pressure vessel from high temperature helium.

Only cooled helium contacts the pressure vessel after exposure to heat transfer surfaces. Hot helium enters the water-cooled enclosure through the inner pipe of a concentric gas inlet/outlet nozzle and passes over the tube banks. The cooled helium then flows through the annular space between the water-cooled tube bank enclosure and the pressure vessel wall and leaves the pressure vessel through the outer annulus of the gas inlet/outlet nozzle.

Vessel 1 (High Pressure Boiler/Superheater 1) - Vessel 1 contains a high pressure boiler and superheater (Figure 6.9-9). High temperature reactor helium enters the top of the pressure vessel and flows through the superheater. It then joins the liquid lead stream discharge (850°F), flowing downward through the high pressure boiler. Cooled helium leaves the boiler and flows upward along the pressure vessel walls. Helium exits through a side or top gas inlet/outlet nozzle for later circulation.

On the steam/water side, feedwater flows upward through the boiler and then the superheater. During startup conditions, Vessel 1 requires an external supply of saturated steam to the superheater to stabilize cooling flow.

Vessel 1 Physical Data:

Pressure vessel	
Internal diameter	12.5 ft. (3.8 m)
Overall height	70 ft. (21.3 m)
Material	SA 299 (carbon steel)
Tubing	
Outside diameter	1.000 in.
Minimum wall thickness	0.165 in.
Materials	Ferritic steel
Heating surface, boiler (lower)	8264 sq.ft.
Heating surface, superheater (upper)	8264 sq.ft.

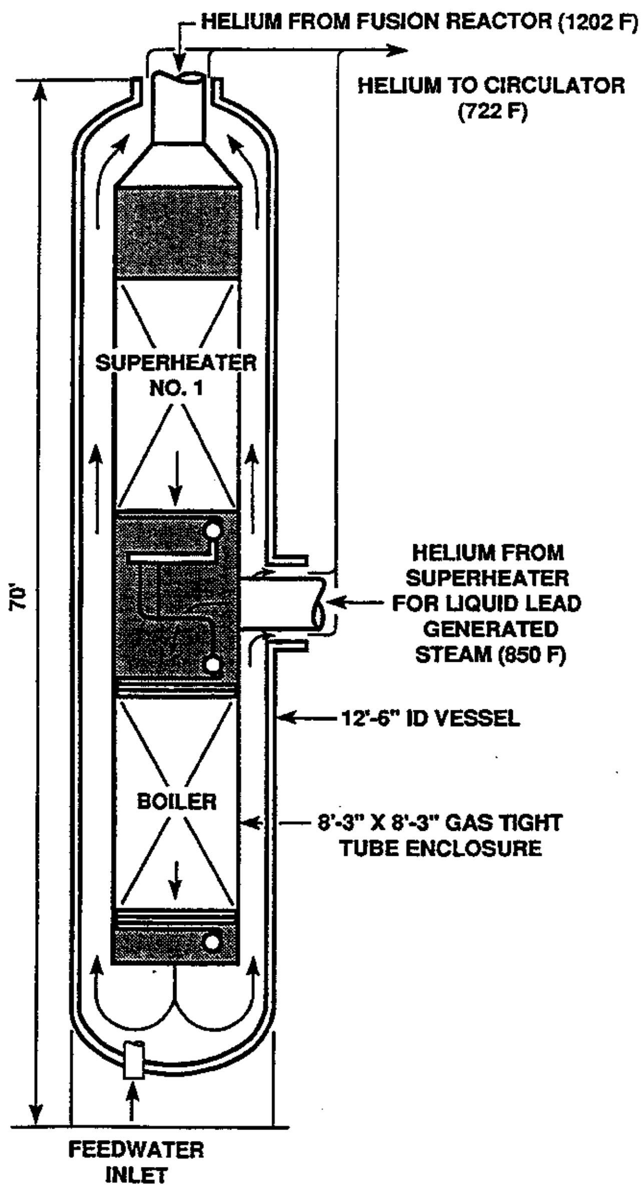


Figure 6.9-7. Vessel #1, Helium Steam Generator

Vessel 2 (Superheater 2) - Vessel 2 contains the heat exchanger transferring heat from the high temperature helium to the steam generated in the liquid lead heated steam generator to raise steam temperature to the final level. Reactor heater helium enters the pressure vessel through an inlet nozzle located at mid-height. Helium flow splits inside the superheater enclosure, flowing upward and downward through upper and lower superheater elements. Cooled helium, exiting each superheater, flows outward between pressure vessel walls and the superheater enclosure. The two cooled helium flows recombine before exiting the pressure vessel. On the steam side, the two superheater sections are arranged in parallel.

Steam enters the vessel from both the top and bottom and flows counter to local helium flow. Superheated steam is extracted from the middle of the pressure vessel.

Vessel 2 Physical Data:

Pressure vessel	
Internal diameter	12.5 ft. (3.8 m)
Overall height	70 ft. (21.3 m)
Material	SA 387 Grade 11
Tubing	
Outside diameter	1.250 in.
Minimum wall thickness	0.200 in.
Materials	Ferritic steel
Heating surface, boiler	21,785 sq.ft.

Vessel 3 (Reheater 1, Reheater 2) - Vessel 3 contains high pressure reheater RH-1 and low pressure reheater RH-2. High temperature reactor helium enters through side nozzles in the upper portion of the pressure vessel. Helium flow splits—half flows upward through RH-1 and half flows downward through RH-2. A second high temperature reactor helium flow, entering at the bottom of the pressure vessel, flows upward over RH-1. Helium cooled through the upper RH-2 reheater flows downward along the pressure vessel walls toward a bottom gas outlet. Helium flow streams of RH-1 and the bottom portion of RH-2 join at the top of RH-1 and flow from there downward along the pressure vessel wall to the gas outlet nozzle.

Vessel 3 Physical Data:

Pressure vessel	
Internal diameter	20.0 ft. (6.1 m)
Overall height	100 ft. (30.5 m)
Material	SA 299 (carbon steel)

Tubing	
Outside diameter	2.000 in.
Minimum wall thickness	0.120 in.
Materials	Ferritic steel
Heating surface, RH-1	9,450 sq.ft.
Heating surface, RH-2	16,580 sq.ft.

Vessel 3 diameter requires on-site erection. A scheme utilizing two 12.5-ft. diameter RH-1/RH-2 vessels versus a single 20-ft. diameter vessel might offer a cost advantage.

Vessel 4 (Liquid Lead Steam Generators) - Vessel 4 liquid lead is a steam generator system consisting of six identical heat exchangers (Figure 6.9-10). Each heat exchanger utilizes vertical, concentric double wall tubes (Figures 6.9-11 and 6.9-12). High pressure water/steam flows upward through the inner tubes while liquid lead flows downward around the outer tubes. Liquid sodium slowly circulates through the annulus between inner and outer tubes to remove tritium and prevent contamination of the steam.

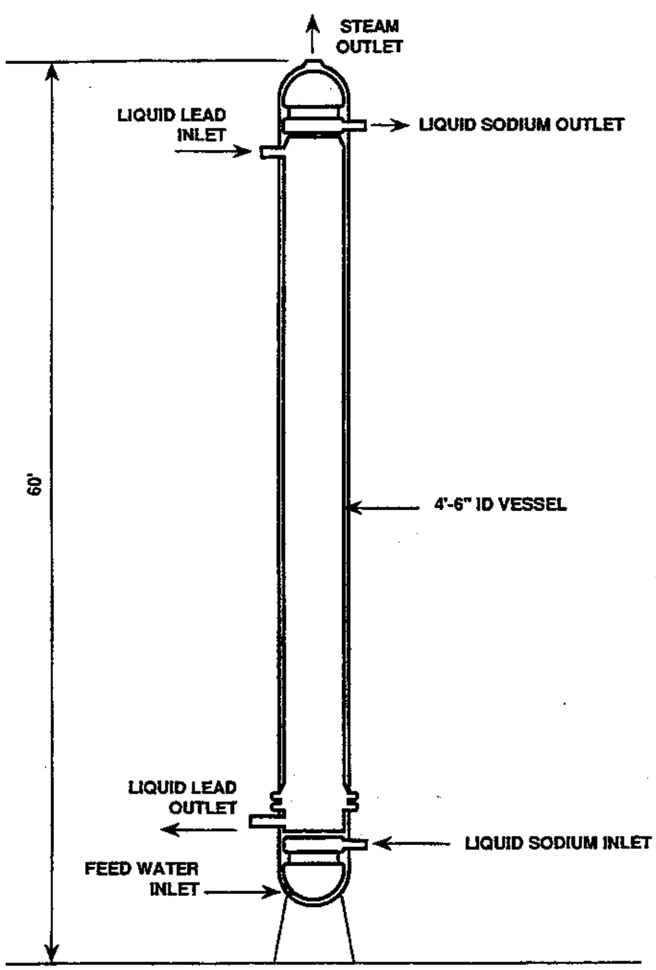


Figure 6.9-10. Vessel 4, Liquid Lead Steam Generator

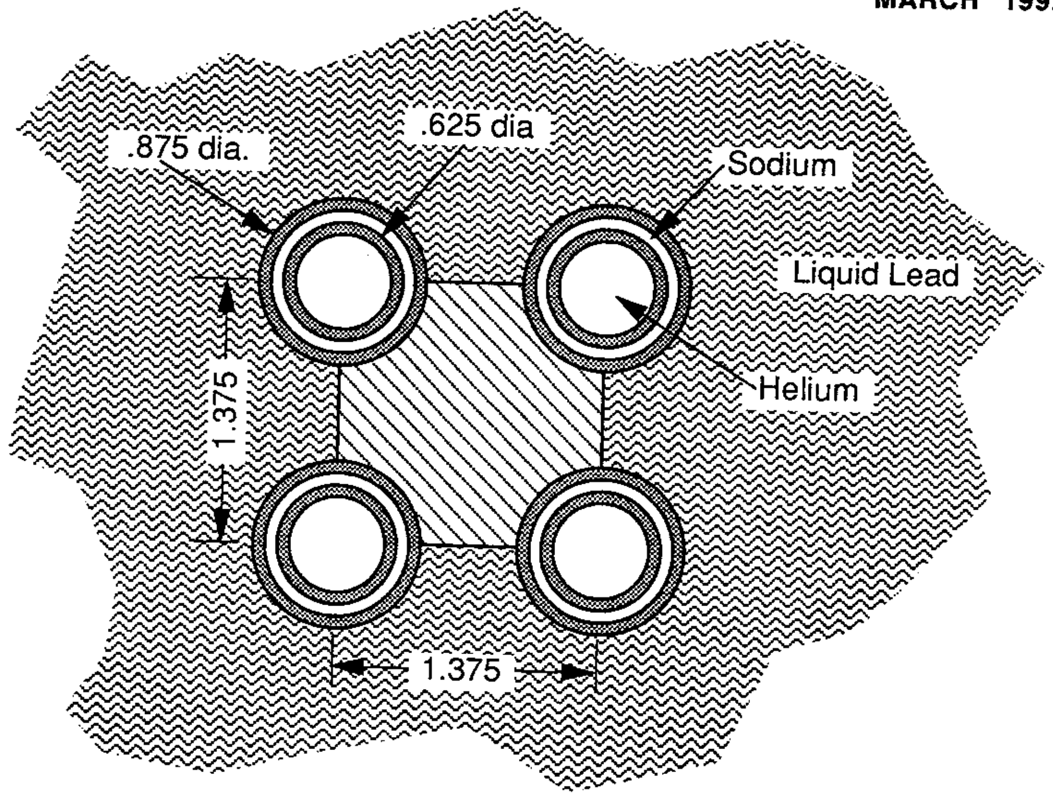


Figure 6.9-11. Liquid Lead Heat Exchanger - Cross Section

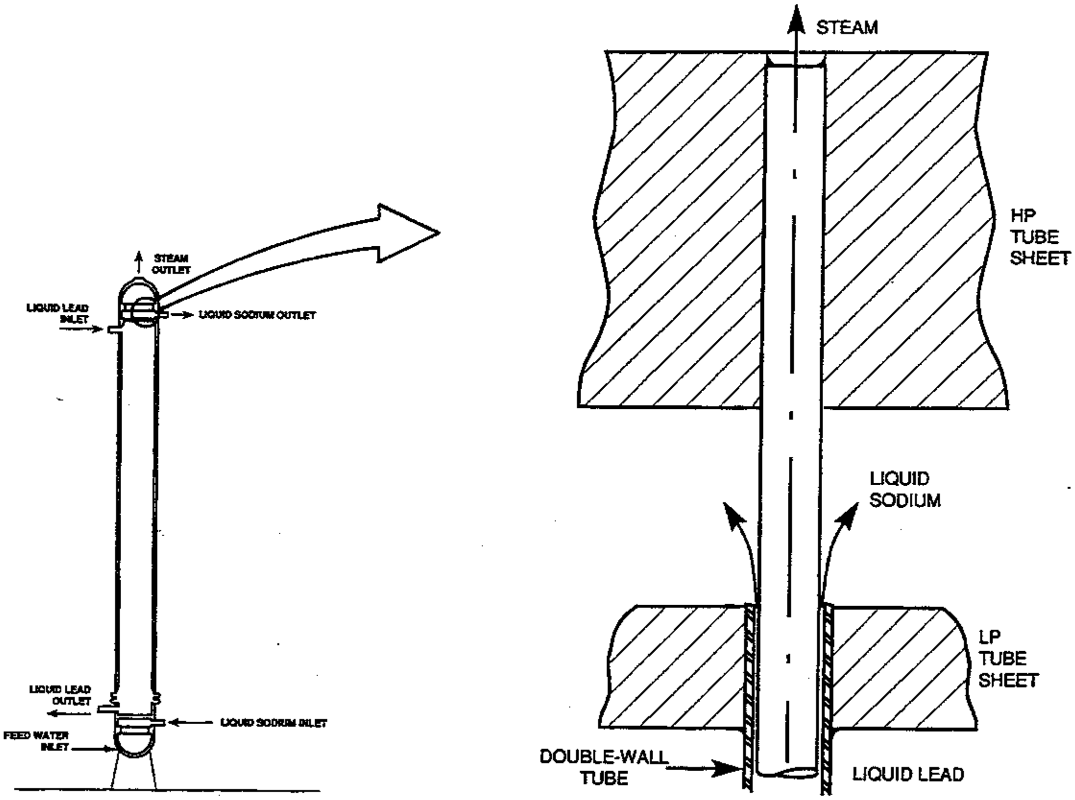


Figure 6.9-12. Liquid Lead Steam Generator - Top Tube Sheet Connections

High pressure feedwater enters the inner tubes, extending between the high pressure tube sheets, through the lower head of the pressure vessel. High pressure steam at 800°F leaves the upper vessel head and flows from there to the helium heated superheater. Liquid lead from the reactor, 977°F, enters the top of the pressure vessel, flows downward, and exits the lower portion of the heat exchanger.

Liquid sodium circulates between high and low pressure heat exchanger tubes. Flow is upward from the vessel bottom to an upper exit (Figure 6.9-12). Tritium is removed at a rate of about 1000 lb/hr and a temperature of 920°F. Detritiated sodium returns to the heat exchanger at a temperature of about 665°F.

A pressure vessel bellows-type expansion section accommodates differential expansion between tubing and shell.

Vessel 4 Physical Data	
Pressure vessel	
Internal diameter	4.5 ft. 1.4 m)
Overall height	60 ft. (18.3 m)
Material	SA 299 (carbon steel)
Inner Tubing	
Outside diameter	0.625 in.
Minimum wall thickness	0.105 in.
Outer Tubing	
Outside diameter	0.875 in.
Minimum wall thickness	0.050 in.
Heating surface	16,800 sq.ft.

(b) Design Options - A number of design options influence the relative size and cost of the steam generation system components. Design options considered were:

(1) Helium reheater vessel and steam generator supply routing in parallel versus in series.

When routed in parallel, the steam generator has approximately 34% less surface while the reheater has respectively 18% and 43% more surface for the high and low pressure sections. Because of the higher pressure requirements of the steam generator which influenced the 9% higher cost per unit heat transfer surface, parallel flow was selected.

(2) Raise liquid lead heat exchanger stream temperature from 800°F to 900°F.

This reduces the liquid lead system load on the helium heater Superheater 2, releasing additional high temperature helium to the helium steam generator. The result is an increase of 50% in liquid lead steam generator surface and a decrease of 22.5% in helium steam generator surface. This option was rejected due to: (a) the 170% greater surface unit cost of the liquid lead steam generator which results from the double walled tubing, and (b) the difficulty of fitting larger liquid lead steam generators in the more congested area near the reactor vessel.

(3) Raise Turbine Inlet Steam Temperature

Increasing turbine inlet temperature and pressure will tend to improve cycle performance, but as the heat source temperatures are approached by the steam temperature, heat transfer equipment enlarges until crossovers between the hot and cold fluids occur. Holding the throttle pressure at 3715 psia and with parallel flow of helium, it was not possible to raise the throttle temperature to 1000°F without causing LP cold reheat steam temperature to rise above the temperature of helium leaving the reheater. Raising throttle pressure above 3715 psia aggravates this loss of temperature differential. It was, therefore, concluded that, for the available design flows and temperatures of the helium and liquid lead, inlet steam conditions of 3715 psia and 950°F would provide reasonable sizing criteria for the steam generators and reheaters. These reduced steam conditions also result in cost savings for the steam turbine, boiler feed pumps, and piping.

(4) Reduce the cold reheat pressure and temperature to eliminate crossovers of temperature of helium entering the reheater.

Although this permitted a 100°F rise in throttle temperature for the series connection of helium to the reheaters and steam generator, it re-established the low pressure turbine expansion line end point too close to the saturation line (2% moisture). At this new end point location, part load operation can cause the turbine last stage blades to pass higher temperature superheated steam with resulting loss in blade material strength properties and blade overstress. This option was, therefore, rejected.

6.9.7 Helium System Piping

(a) General - All helium piping and manifolds within the bulk shield are generally constructed of SiC. The transition joint from SiC to steel piping is planned to be in the region between the vacuum vessel and the shield or directly at the shield wall. Only the aspects of the external steel piping will be discussed in this section. Helium system pipes are pressurized to approximately 200 psig and operate at temperatures between 1202°F and 752°F. Helium entering the circulator and leaving the steam generators is 722°F due to pumping energy. Reactor helium flows through six branch pipes, each 9 ft. (2.7 m) diameter with 1.25 in. (32 mm) walls, at velocities of 170 ft/sec.

Current thick wall pressure vessel design experience in the chemical industry forms a serviceable basis for the helium piping.[3] However, special attention is required in the following areas and those sections of helium pipe at 1202°F.

- Pipe supports and connections need robustness to withstand seismic forces and thermal expansion. Pipe bearing and bending stresses can be controlled by a reduction in pipe support spans. However, pipe supports, anchors, and restraints are major structural assemblies that affect building space requirements. Special pipe connections are required to transmit the large reaction forces between anchors and restraints to the high temperature pipe.

- Vibration caused fatigue failure must be addressed. Flow induced vibrations are possible at fittings, internal bracing, and the helium circulator. Pipe reinforcement must be considered to stiffen local wall sections.

- Helium Pipe Isolation Valves - No industrial experience base addresses the combination of high temperature, large size (9' diameter) and leak-tight containment of 200 psig helium.

  Current technology industrial butterfly valves[4,5] can be adapted to meet the above criteria; e.g., for control of leakage from the system envelope, valve package can be modified by encasement of the valve stem in a bonnet that is pressurized with an external source of helium. For control of gas leakage past a closed isolation valve, metallic stressed seals have been used by one manufacture for temperatures to 650°F and to sizes of 216 in. (5.5 m) at a gas pressure of 18.8 psia. This arrangement consists of a thin annular metal band in the valve body which is inflated against the closed disk by a pressurized inert gas.[6]

  Upgrading the capability of such features to operate under the combined helium temperature and pressure conditions of a fusion power plant would require further engineering and testing.

(b) Pipe Sizing - The velocity and pressure loss rate criteria for sizing the helium piping was reviewed in terms of annualized capital costs for the helium circulators, value of energy use by the circulators, and the annualized cost of the helium piping system.

Pipe weight and installed cost are based on system wall thickness, hot and cold sections, plus a $21 per lb. unit cost. Piping materials assigned to the hot and cold sections were SA 407 Alloy 800H and SA 213T91, respectively. Seven supply pipe sizing velocities, from 100 ft/sec to 300 ft/sec, were investigated. Return pipe sizing velocities were reduced, 10 to 20 ft/sec, in order to maintain about the same pressure drop gradient.

Annual circulator energy cost was approximated using a plant capacity factor of 0.8 and energy cost of $.07/kWh. The steam turbine-driven axial helium compressors were assigned a polytropic efficiency of 88% and unit price of $400 per shaft kilowatt.

Indirect cost factors were 52% of Total Direct Cost (TDC), contingency 10% of TDC and Annual Fixed Charge Rate 10% of TDC.[8]

Minimum total annual cost occurs with supply pipe sizing velocities of 160 to 170 ft/sec. (reference Table 6.9-3 and Figure 6.9-13) when circulator power is 116 to 119 MW.

Pressure drops in Table 6.9-3 refer to external system piping which varies according to pipe size. However, total circulator duty is after addition of the following values:

	psi
Steam generator	3.50
Reactor headers	1.45
Reactor	3.63
Subtotal	8.58

Table 6.9-3 Helium Pipe Costs

Helium Velocity (Ft/Sec)		Piping Pressure Drop	Total Pressure Drop	Pipe Weight	Circulator Power	Annualized Cost (10^6 Dollars)			
Supply	Return	(Psi)	(Psi)	(1000 lb)	(MW)	Energy	Circ	Pipe	Total
300	280	6.96	15.54	3642	176.3	86.5	11.4	14.9	112.8
240	220	4.19	12.77	4585	144.4	70.8	9.4	18.7	98.9
200	180	2.81	11.39	5584	128.6	63.1	8.3	22.8	94.2
170	150	1.96	10.54	6571	118.8	58.3	7.7	26.8	92.8
160	140	1.71	10.29	6947	116.0	56.9	7.5	28.4	92.8
140	125	1.37	9.89	7897	111.4	54.6	7.2	32.2	94.1
100	90	0.67	9.25	10925	104.1	51.1	6.7	44.6	102.4

(c) Valving - Valves are positioned at key locations in the helium distribution system to support both operation and safety procedures. Valves permit maintenance and repair isolation of components while the system continues operation. Valves are essential to either startup or shutdown during normal or emergency conditions. Butterfly valves are assigned key locations in the Prometheus system (see Table 6.9-4).

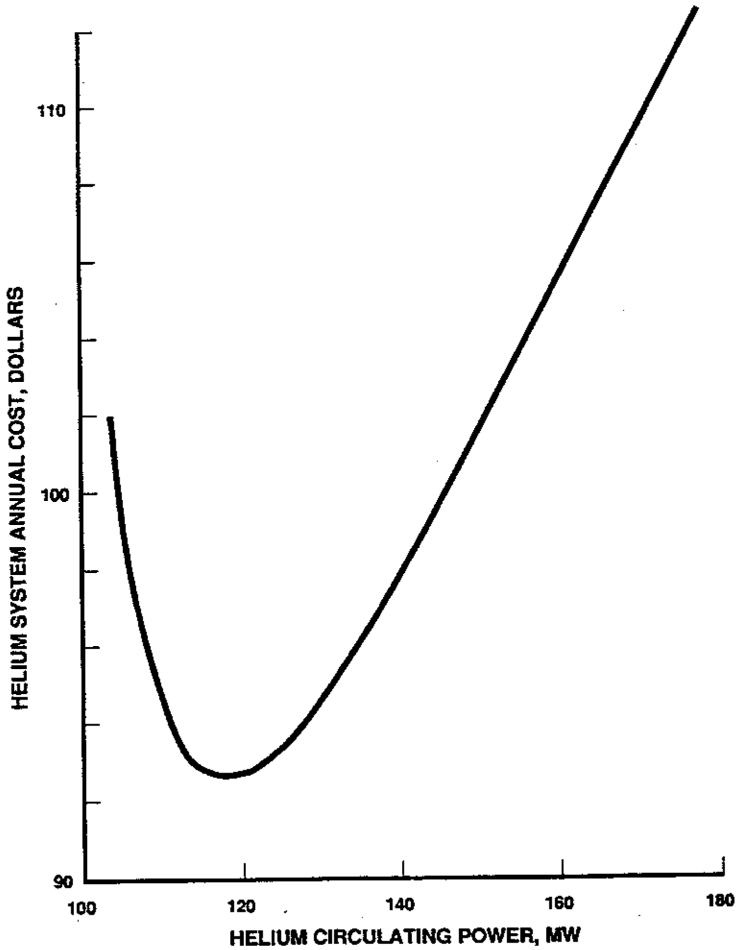


Figure 6.9-13. Helium System Cost vs. Circulating Power

Table 6.9-4. Key Helium System Valves

Location	Diameter (Inches)	Operating Temperature (°F)	Total Number Required
Supply Branches From Reactor	110	1202	6
Helium Steam Generators, In	78	1202	6
Helium Steam Generators, Out	68	722	6
Helium Reheaters, In	78	1202	6
Helium Reheater, Out	68	722	6
Helium Superheater 2-In	60	1202	6
Helium Feedwater Heaters, In	74	890	2
Helium Feedwater Heaters, Out	72	630	2
Helium Circulators, In	96	722	6
Helium Circulators, Out	96	752	6

6.9.8 Liquid Lead System Piping - The lead piping and manifolds within the bulk shield are generally constructed of SiC. The transition joint from SiC to steel piping is planned to be in the region between the vacuum vessel and the shield or directly at the shield wall. Only the aspects of the external steel piping will be discussed in this section. The external liquid lead piping system uses martensitic alloy HT-9, 12 Cr-1 Mo steel and 0.48% nickel, with high resistance to liquid metal embrittlement.

Liquid lead operational limits (temperature) are predicated on corrosion rates of 5 micron/year. However, the corrosion rate varies by a factor of 10 from 3 ft/sec (low) to 23 ft/sec (high) flow velocities.[7]

A high liquid lead temperature, 977°F (525°C), is acceptable when considering liquid lead and ferritic or martensitic steel interactions. Further investigation will confirm and quantify these interactions as a function of temperature, flow velocity, and pipe metallurgy.

Prometheus liquid lead distribution piping was sized at 9.8 to 11 ft/sec. Individual 24-in. (61 cm) pipes supply each of six steam generators with pressure gradients of approximately 4 psi/100 ft. and a 180 psi friction loss.

References 6.9

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