6.6 Vacuum System

Vacuum system requirements vary significantly between the two Prometheus reactor systems. Pressure requirements are significantly lower for the laser driven reactor which, when coupled with the higher mass flow, results in a significantly higher volumetric flow rate. The differences in the vacuum system requirements results in two different designs. These designs are presented separately in the following sections.

6.6.1 Laser Driven Reactor Vacuum System

6.6.1.1 **<u>General Description</u>** - The reactor requires both roughing and high vacuum systems. The high vacuum system maintains the reactor cavity pressure at the prescribed levels by pumping non-condensable gases, resulting from the fusion reaction, from unburned fuel and from target debris. The roughing vacuum system provides initial pumping from ambient pressure and serves as a backing system for the high vacuum pumps.

Many previous fusion reactor design studies have selected compound cryogenic pumps for the high vacuum system. Cryogenic pumps were also selected for this design. These pumps are a robust design which can provide adequate reliability in the power plant. Ten cryogenic pumps are located on each vacuum manifold. One vacuum manifold is attached to each of the three vacuum ports, providing a total of 30 cryogenic pumps for the high vacuum system. Each cryogenic pump has an isolation valve between it and the pump manifold to allow regeneration without affecting reactor operation.

The rough vacuum system consists of single stage roots blowers with single stage rotary vane backing pumps. A rough vacuum module is dedicated to each of the three ports. Each module consist of a roots blower backed by two rotary vane pumps. Inclusion of the roots blower in the rough vacuum system modules provides additional pumping speed and reductes oil migration at pressures near high vacuum cross-over. All rough vacuum system components are currently commercially available products with proven reliability.

Three vacuum system ports are used to evacuate the cavity and maintain high vacuum during reactor operation. Penetrations are provided in the lead shield wall for vacuum pumping and the ports are attached to the vessel walls behind these openings. The entrance to the vacuum ports are covered with high efficiency, H-type cold traps which preclude transmission of lead vapor into the pumping system during reactor operation.

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6.6.1.2 **System Design** - Reactor exhaust mass flow rates are stated in Table 6.6-1. Vacuum system volume flow rate at 800 K, the required reactor pressure, and vacuum system design parameters are also provided in Table 6.6-1.

Table 6.6-1
Laser Driven Reactor Vacuum System Design Requirements

Reactor Pressure Requirement: 3×10^{-3} torr
Mean Exhaust Gas Temperature: 800 Kelvin

REACTOR NON-CONDENSABLE GAS EXHAUST

	Mass Flow Rate	Volume Flow Rate
Hydrogen (total–all forms)	28.0 mg/sec	262,000 liters/sec
Tritium	12.24	67,800 liters/sec
Deuterium	8.16	67,800 liters/sec
Hydrogen	7.6	126,400 liters/sec
Helium	6.70 mg/sec	27,900 liters/sec
TOTAL	34.7 mg/sec	289,900 liter/sec

The lead vapor trap at the entrance to the vacuum system ports insures that exhaust gas temperatures do not exceed 800 K. The vacuum design does not take advantage of reduction in mean gas temperature between the lead vapor traps and the pumps. Temperature reduction will be required in the vacuum ducts to optimize cryogenic pump efficiency. Since thermal analyses were not performed for this portion of the study, a “conservative case” vacuum system design is presented. The perfect gas constant is utilized to convert from mass flow rate to volume flow, making the volume flow rate a direct function of the absolute temperature of the pumped gas. Conductance of the vacuum ducts is proportional to the square root of the absolute temperature of the pumped gas. Thus, the reader can appreciate the dependence of the vacuum system design on pumped gas temperature.

The arrangement of the vacuum system components and the design of the ducts provides two large volumes in each port. The first volume is located between the lead shield and the vacuum vessel wall. The second volume is the vacuum pump manifold. Both volumes were considered large enough to randomize the gas flow and were analyzed by the methods presented by D. J. Santeler.[1]

Several parametric studies were performed during the design process. These studies included pumping speed as a function of pump diameter, the number of vacuum ports required as a function of port diameter, the number of pumps required as a function of number and size of ports, and pump hydrogen capacity as a function of diameter. Several iterations of the parametric studies were performed during the course of the vacuum system design. Multiple iterations insured that, as the design progressed, all previous decisions were included in the analyses. The last iteration of each parametric study is presented in this report. The parametric analyses presented in the following paragraphs were used to design the vacuum system.

Currently available cryogenic pump vendor data for hydrogen pumping speed was used to determine the effect of pump size on pumping speed. A plot of this data with a least squares curve fit is presented in Figure 6.6-1. The data, although not smooth due to step changes in pump design, was deemed adequate to conclude the relationship between pump size and pumping speed. The data curve demonstrates that significant increases in pumping speed may be obtained by increases in pump diameter. The least squares fit was considered acceptable to extend hydrogen pumping speed data to pumps of two meters diameter. Two-meter cryogenic pumps were selected for the high vacuum system. The curve fit projects a hydrogen pumping speed of 158,500 liters per second for two-meter diameter cryogenic pumps. A hydrogen pumping speed of 150,000 liters per second was used for the analyses. Additional increases in hydrogen and helium pumping speed may be obtained by optimizing the design for these gas species but this was not included in this study.

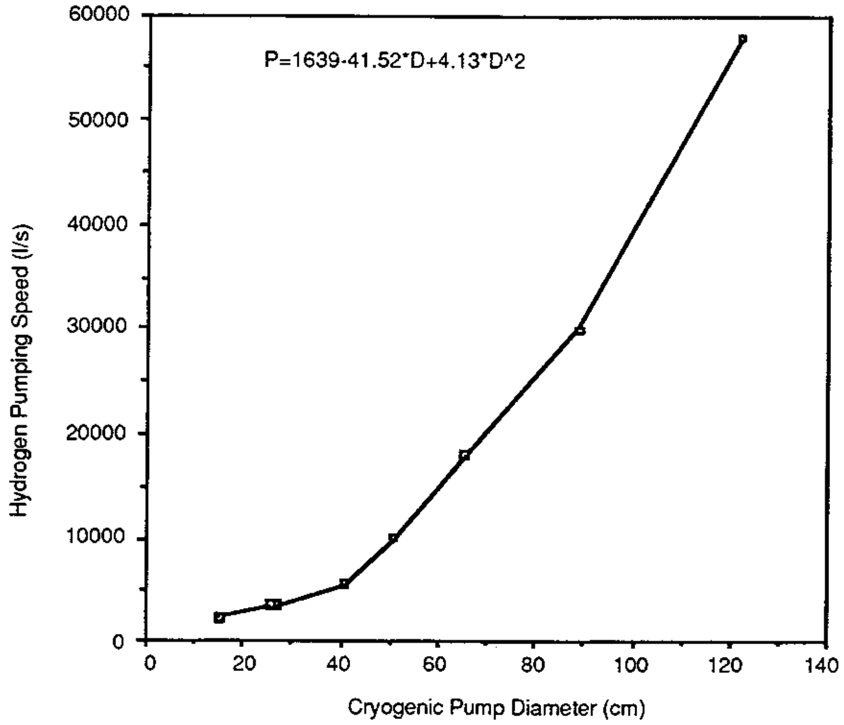

Figure 6.6-1. Hydrogen Pumping Speed Vs. Pump Diameter

The minimum number of ports required to provide adequate conductance for the specified reactor exhaust gas flow is a function of port diameter. This is shown by the equations utilized to calculate conductance as well as by the curve presented in Figure 6.6-2. Previous reactor design studies have utilized small ports or have coupled the vacuum system to the laser beam ports. The parametric analysis performed for this study indicated that maximizing port diameter will decrease the number of vacuum ports required. Port sizes larger than two meters in diameter were deemed impractical due to spatial constraints. Three 2-meter diameter vacuum ports were selected for the design.

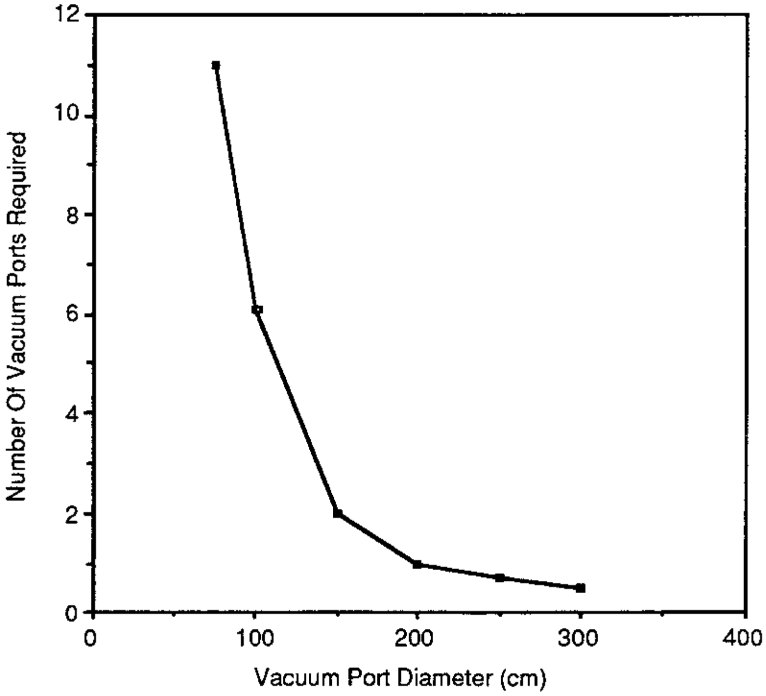

Figure 6.6-2. Vacuum Ports Required

The number of active cryogenic pumps required to obtain sufficient pumping speed for the specified reactor pressure, gas temperature, and gas flow rate is a function of the number and size of the high vacuum ports. Several previous studies have utilized one pump per vacuum port. The parametric study performed for this design indicated that manifolding several pumps on a large diameter pump port results in a reduction of the number of pumps required for the system. The results are shown in Figure 6.6-3. The shape of the curves produced in this parametric study confirmed the decision to choose three 2-meter diameter vacuum ports. The calculations and curves also

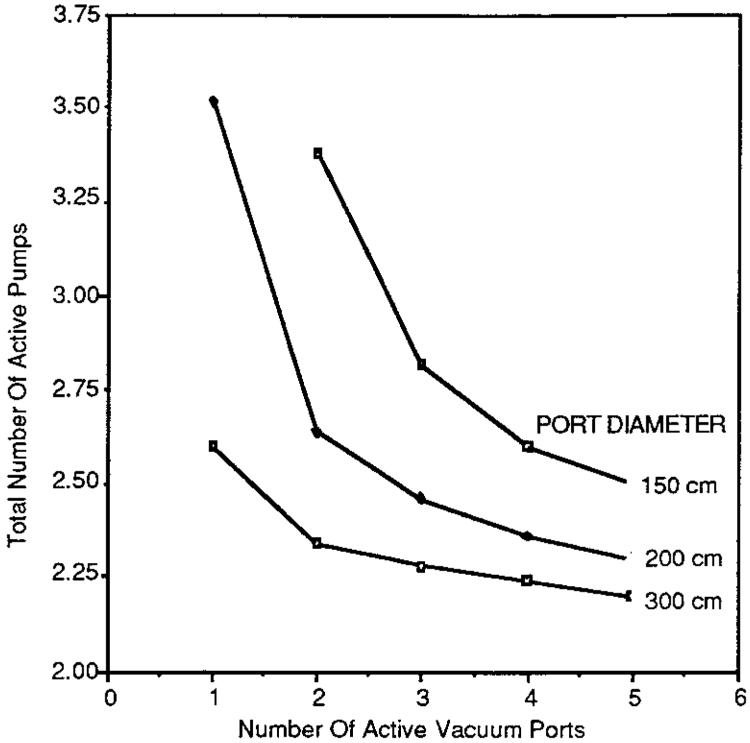

Figure 6.6-3. Total Active Cryogenic Pump Required Vs. Number of Vacuum Ports

demonstrate the requirement for a minimum of three active pumps during reactor operation. Hydrogen pumping speed and hydrogen pump capacity are the driving requirements. The total number of cryogenic pumps is, however, based on the hydrogen capacity of the cryogenic pumps.

Hydrogen, in various isotopes, is the primary gas species pumped during the reactor operation. A parametric study of cryogenic pump hydrogen capacity was performed. Vendor hydrogen capacity for commercially available cryogenic pumps was used to determine the effect of pump size on hydrogen capacity. A plot of this data with a least squares curve fit is presented in Figure 6.6-4. Extending the curve to pumps which are two meters in diameter indicates a hydrogen pump capacity of approximately 285 standard liters (24 grams). The following linear equation was utilized to determine the number of active cryogenic pumps and the time period before pump regeneration is required:

$T = C * N / m$ where:

T = time period between regenerations
m = hydrogen mass flow rate (total)
N = number of active cryogenic pumps

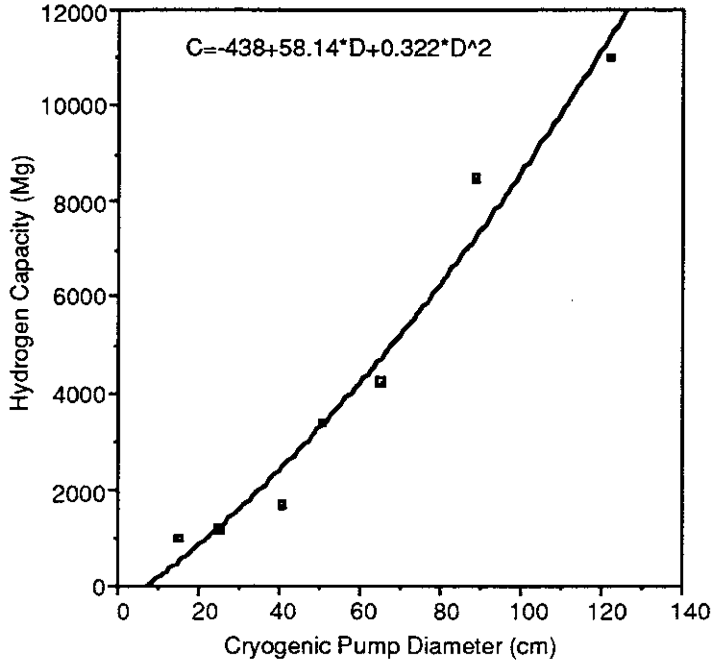

Figure 6.6-4. Cryopump Hydrogen Capacity Vs. Pump Diameter

This equation and the information presented in Table 6.6-1 was utilized to determine that a total of 12 active cryogenic pumps should be utilized. This will provide an active pumping time of approximately three hours and result in a total of approximately 132 grams of tritium and 88 grams of deuterium in the pumps at the beginning of regeneration. A total of 30 cryogenic pumps are specified for this design. This number will allow one active set, one set in regeneration, and an additional six pumps which may be valved into the system to compensate for the reduction in pumping speed of the active pumps as they approach capacity. The additional pumps also provide some margin for pump failures. The laser-driven reactor vacuum manifold arrangement is shown in Figure 6.6-5.

Significant increases in hydrogen pump capacity are probable for the tenth-in-kind reactor. Increases in hydrogen capacity could be achieved by optimizing the design for pumping of hydrogen at the expense of other species. This would extend active pumping periods for the pumps and result in pump regenerations on a once-per-eight-hour basis. This may be advantageous for the vacuum system operation but has consequences for the fuel processing system and tritium/deuterium inventory.

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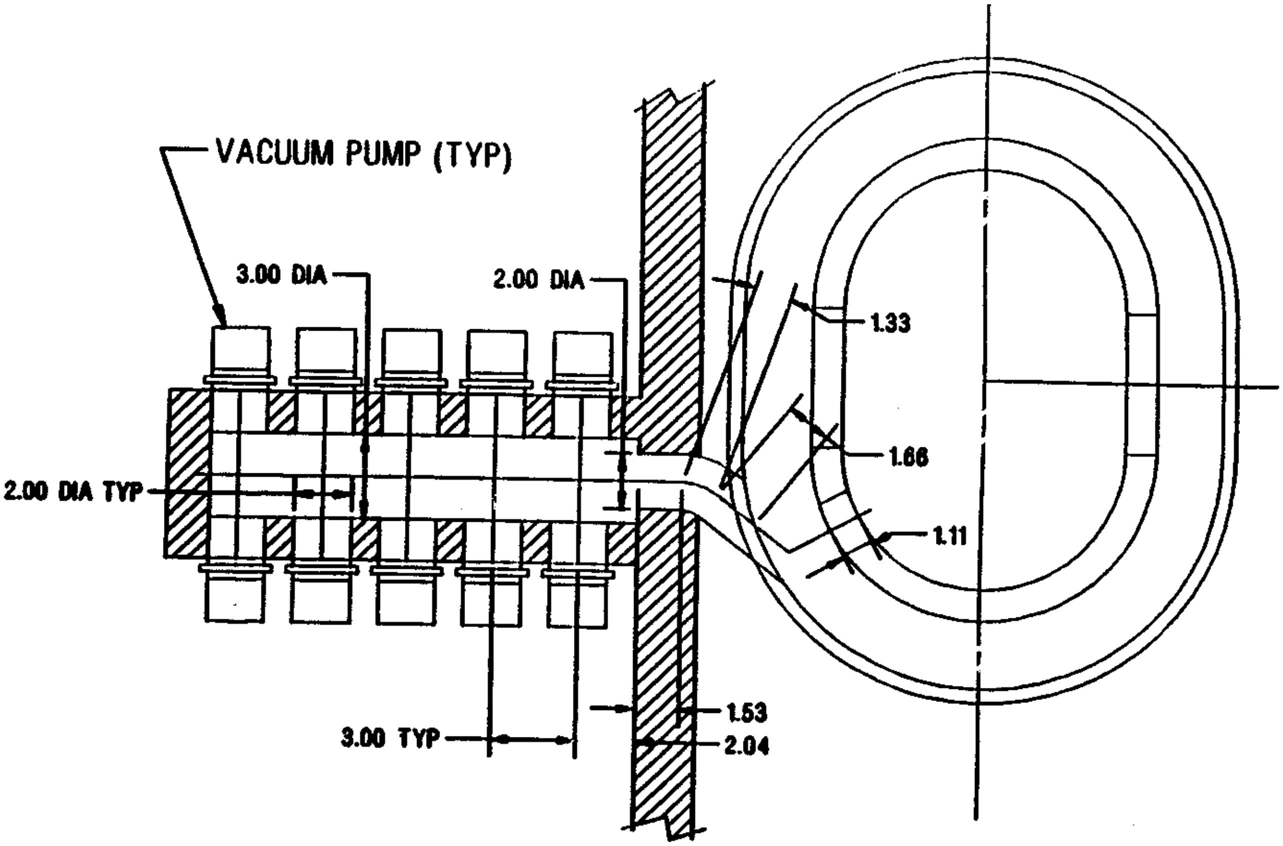

Figure 6.6-5. Laser-Driven Reactor Vacuum Manifold System Arrangement

6.6.2 Heavy Ion-Driven Reactor Vacuum System

6.6.2.1 General Description - This reactor requires a vacuum system capable of maintaining the reactor cavity pressure at the prescribed levels by pumping non-condensable gases, resulting from the fusion reaction, from unburned fuel and from target debris. The vacuum system consists of a set of single stage roots blowers with single stage rotary vane backing pumps. Three vacuum modules is dedicated to each of the four ports. Each module consists of a roots blower backed by two rotary vane pumps. The roots blower provides additional pumping speed and reductions in oil migration during the roughing operation. In addition, the roots blower is capable of maintaining the vacuum required during reactor operation. All vacuum system components are currently commercially available products with proven reliability.

Three vacuum system ports will be used to evacuate the cavity and maintain high vacuum during reactor operation. Penetrations are provided in the lead shield wall for vacuum pumping and the ports are attached to the vessel walls behind these openings. The entrance to the vacuum ports are covered with high efficiency, H-type cold traps which preclude transmission of lead vapor into the pumping system during reactor operation.

6.6.2.2 System Design - Reactor exhaust mass flow rates are stated in Table 6.6-2. Vacuum system volume flow rate at 800 K, the required reactor pressure, and vacuum system design parameters are also provided in Table 6.6-2. The increased hydrogen exhaust flow is due to the mass of the indirect drive target radiation case and energy convertor plugs.

The lead vapor trap at the entrance to the vacuum system ports insures that exhaust gas temperatures do not exceed 800 K. Like the Laser-Driven Vacuum System design, this design does not take advantage of reduction in mean gas temperature between the lead vapor traps and the pumps. Temperature reduction will be required in the vacuum ducts to preclude over temperature conditions in the roots pumps. However, since thermal analyses were not performed for this study, a "conservative case" vacuum system design is presented. The perfect gas constant is utilized to convert from mass flow rate to volume flow, making the volume flow rate a direct function of the absolute temperature of the pumped gas. Conductance of the vacuum ducts is proportional to the square root of the absolute temperature of the pumped gas.

Table 6.6-2
Heavy Ion Driven Reactor Vacuum System Requirements

Reactor Pressure Requirement: 1×10^{-1} torr
Mean Exhaust Gas Temperature: 800 Kelvin

REACTOR NON-CONDENSABLE GAS EXHAUST

	Mass Flow Rate	Volume Flow Rate
Hydrogen (total–all forms)	104.6 mg/sec	47,308 liters/sec
Helium	6.0 mg/sec	748 liters/sec
TOTAL	110.6 mg/sec	48,056 liter/sec

The arrangement of the vacuum system components and the design of the system ducting provides two large volumes in each port, similar to the Laser-Fired Reactor Vacuum System. Again, the first volume is located between the lead shield and the vacuum vessel wall while the second volume is the vacuum pump manifold. The methods presented by D. J. Santeler[1] were again utilized for the analyses.

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Parametric studies, similar to those performed for the Laser-Fired Reactor Vacuum System, were performed during the design process. The studies were more limited in scope due to the higher reactor chamber pressure and only included the number of vacuum ports required as a function of port diameter and the number of pumps required as a function of number and size of ports. Iterations in the studies were minimized by the limited effect of these parameters due to the higher reactor pressure. The final design is a result of the parametrics; however, the parametric curves are not presented.

Vendor data for currently available roots pumps were used for the basis of system design. System roots pumps with three times the currently available roots pump speed were deemed an achievable advance for support of the reactor. Advances in pump size were required only in response to a desire for space savings and for probable maintenance advantages. The system could be reconfigured for currently available roots pumps with minimal alterations to the design presented herein.

Analyses were performed to determine an optimum number and size for the vacuum ports required to provide adequate conductance for the specified reactor exhaust gas flow rates. The higher operating pressure for this reactor design allows a significant reduction in the size of the vacuum ducts. Port sizes larger than one meter in diameter are not warranted since increases in effective pumping speed are marginal for significant increases in the port diameter. Four 1-meter diameter vacuum ports were selected for the design. The general manifold arrangements for the heavy ion-driven reactor is shown in Figure 6.6-6.

The number of roots pumps required to obtain sufficient pumping speed for the specified reactor pressure, gas temperature, and gas flow rate is a function of the number and size of the vacuum ports. The parametric study performed for this design confirmed the conclusion of the Laser-Fired Reactor Vacuum System and indicated that manifolding several pumps on a large diameter pump port results in a reduction of the number of pumps required for the system. The calculations showed that a minimum of eight active roots pumps are required during reactor operation. Hydrogen is the main component of the reactor exhaust and effective hydrogen pumping speed is the driving requirement. A total of twelve 9,500 liter/sec roots pumps, three per reactor vacuum port, are specified for the design.

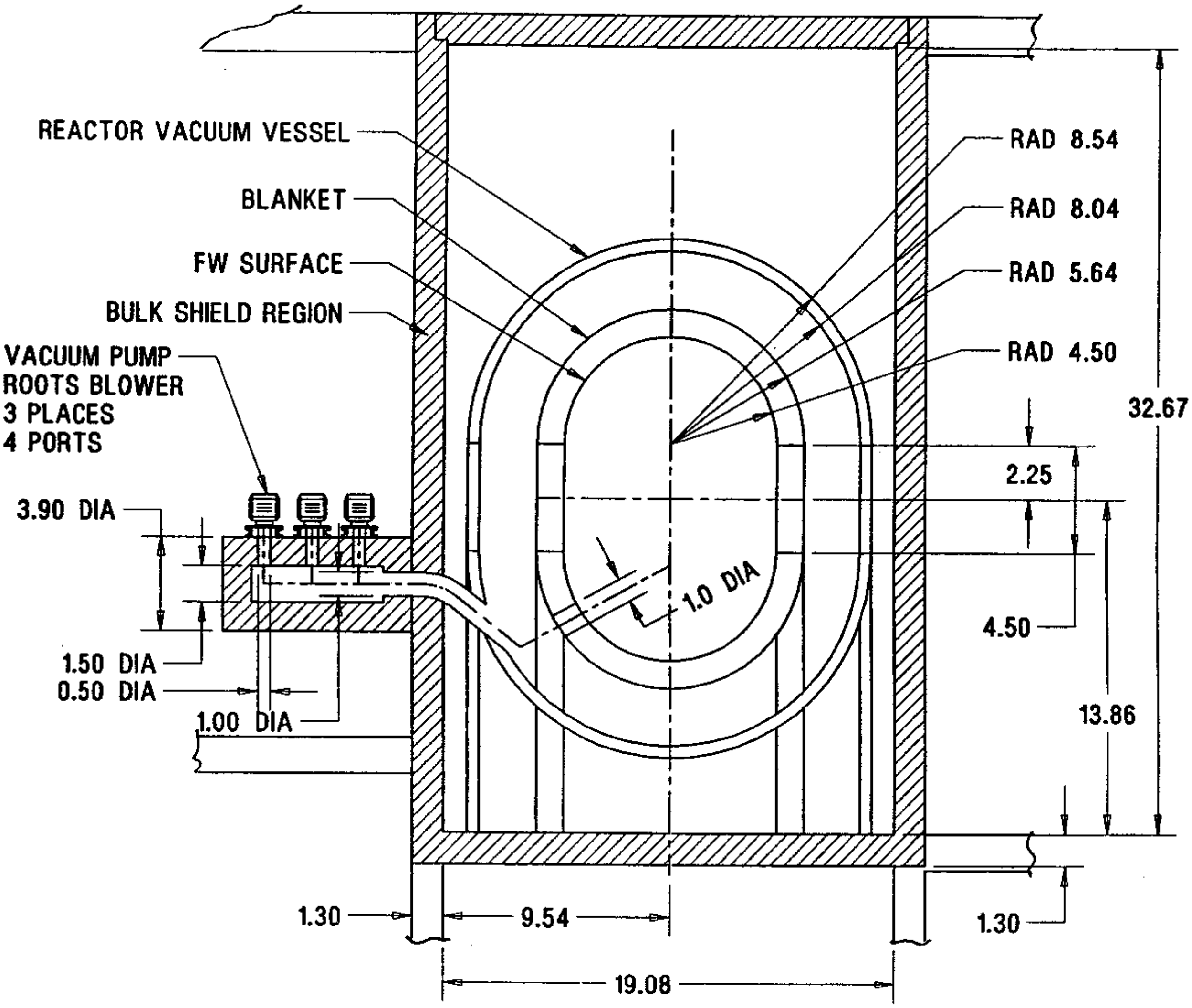

Figure 6.6-6. Heavy Ion Reactor Vacuum Manifold Systems Arrangement

Reference 6.6

1. D. J. Santeler, Journal of Vacuum Science and Technology, Vol. 4, No. 3, May/June 1986

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