ORNL/TM-13058

The Advanced Neutron Source Liquid Deuterium Cold Source

A. T. Lucas

August 1995

Advanced Neutron Source

OAK RIDGE
NATIONAL
LABORATORY

MARTIN MARIETTA

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FOR THE UNITED STATES
DEPARTMENT OF ENERGY

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THE ADVANCED NEUTRON SOURCE LIQUID DEUTERIUM COLD SOURCE

A. T. Lucas

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ACKNOWLEDGMENTS

The cold source task was a team effort, and the following names are those people most directly involved. Without their help, the design described would not have advanced to the level it had at the termination of the Advanced Neutron Source project:

David Vandergriff—Principal Engineer (Engineering Division)
Steve McGrath—Finite Element Analysis (Engineering Division)
Paul Williams—Thermal-Hydraulic Analysis (Computational Physics and Engineering Division)
Bob Nelson—Engineer Designer (Engineering Division)
Ronnie Taylor—Designer Draftsman (Engineering Division)

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ABSTRACT

The Advanced Neutron Source will employ two cold sources to moderate neutrons to low energy (<10 meV). The cold neutrons produced are then passed through beam guides to various experiment stations. Each cold source moderator is a sphere of 410-mm internal diameter. The moderator material is liquid deuterium flowing at a rate of 1 kg/s and maintained at subcooled temperatures at all points of the circuit, to prevent boiling. Nuclear heat deposited within the liquid deuterium and its containment structure totals more than 30 kW. All of this heat is removed by the liquid deuterium, which raises its temperature by 5 K. The liquid prime mover is a cryogenic circulator that is situated in the return leg of the flow loop. This arrangement minimizes the heat added to the liquid between the heat exchanger and the moderator vessel, allowing the moderator to be operated at the minimum practical temperature.

This report describes the latest thinking at the time of project termination. It also includes the status of various systems at that time and outlines anticipated directions in which the design would have progressed. In this regard, some detail differences between this report and official design documents reflect ideas that were not approved at the time of closure but are considered noteworthy.

1. INTRODUCTION

1.1 PHYSICS REQUIREMENTS AND OBJECTIVES

Both moderators are positioned close to the core of the reactor within the heavy water moderator. Isolation from the heavy water moderator is achieved by a vessel called the outer thimble, which is attached to the reflector vessel wall projecting inward. Each thimble is orientated so that no straight guide has a direct view of the reactor core assembly. The moderator vessels are within a thermal flux of greater than 2×10^{19} $m^{-2} \cdot s^{-1}$ and are required to provide an optimized flux within an energy spectrum corresponding to an effective temperature below 40 K. Each moderator illuminates seven horizontal cold guides 50 mm wide and 200 mm high. The guides have a critical acceptance angle of 1.0° at a wavelength of 1 nm.

1.2 GENERAL ENGINEERING PARAMETERS

Each cold source system is fully independent and is required to be operationally stable at all reactor power levels (see Fig. 1). At 0.1 MPa, deuterium freezes at 18.69 K and boils at 24 K. To create a workable operating envelope, therefore, the liquid is controlled at predetermined pressures. Pressure at the circulator output is 0.4 MPa, and the anticipated overall pressure drop is 0.25 MPa. The operating envelope illustrated in Fig. 2 shows that the liquid is always subcooled by at least 2 K. At the design flowrate of 1 kg/s, the power level would have to rise by 6 kW to raise the liquid temperature by one degree, so an unlikely surge of at least 12 kW would be required to cause boiling. Normally, the cold source would be full and under temperature control before the reactor is started. The reliability of the circulator is therefore extremely important, and both cold source systems include a redundant unit. Also, the design allows an unserviceable circulator to be remotely isolated and filled with inert gas, ready for on-line replacement (see Fig. 3). Rupture discs protect the deuterium loops, the vacuum jackets, and the inert gas blankets from excessive positive pressure in the event of a system failure.

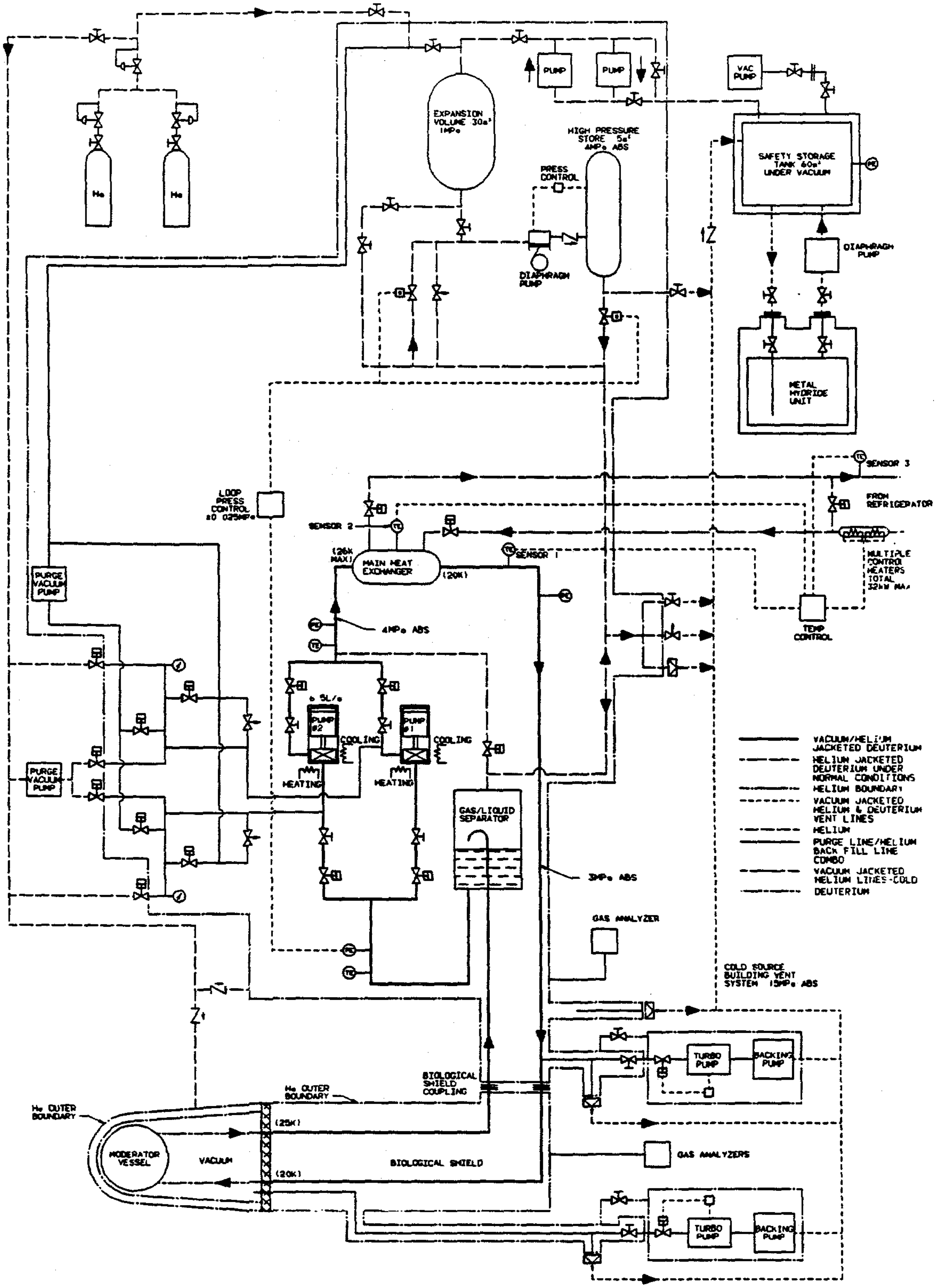


Fig. 1. General flow diagram for the complete cold source.

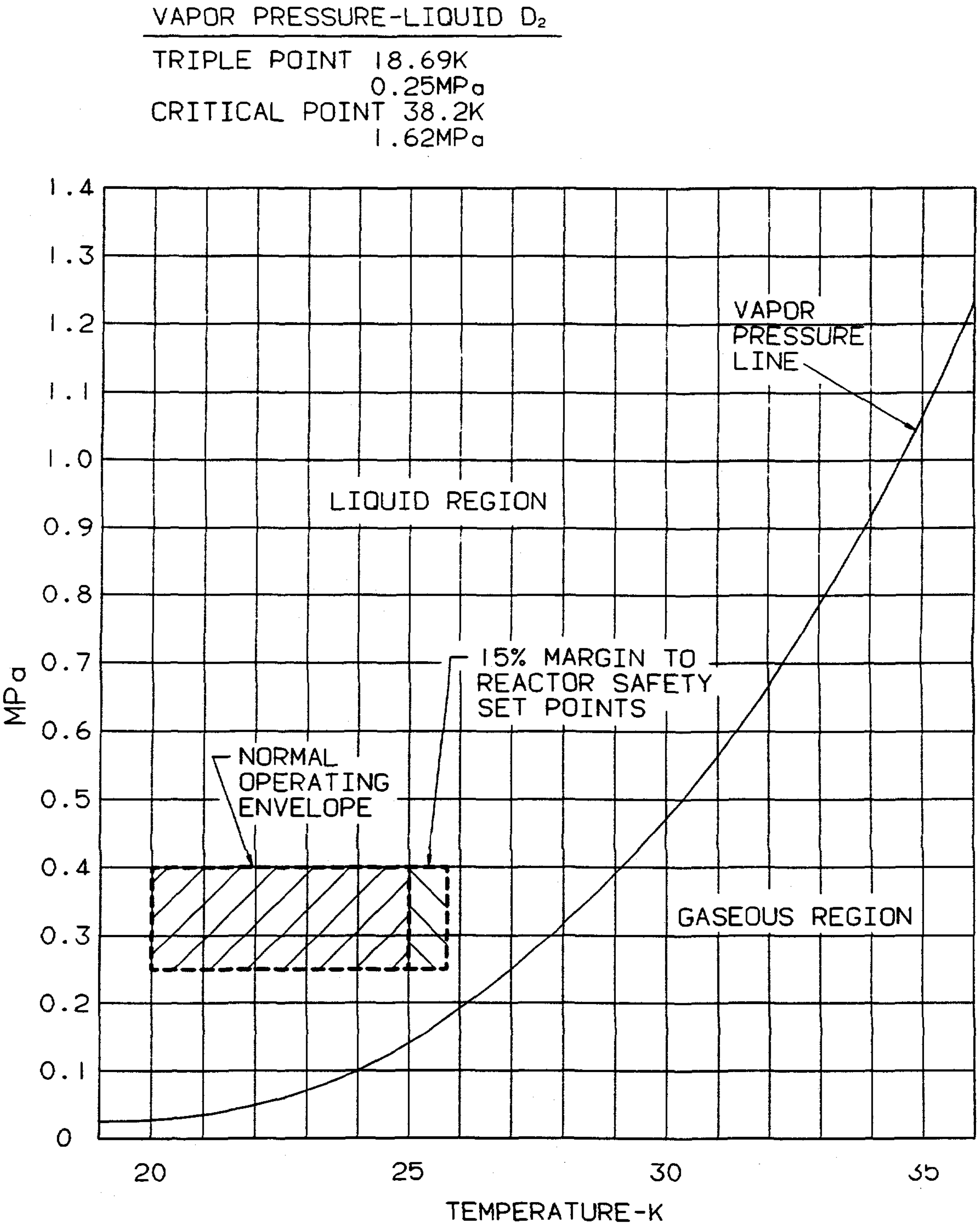
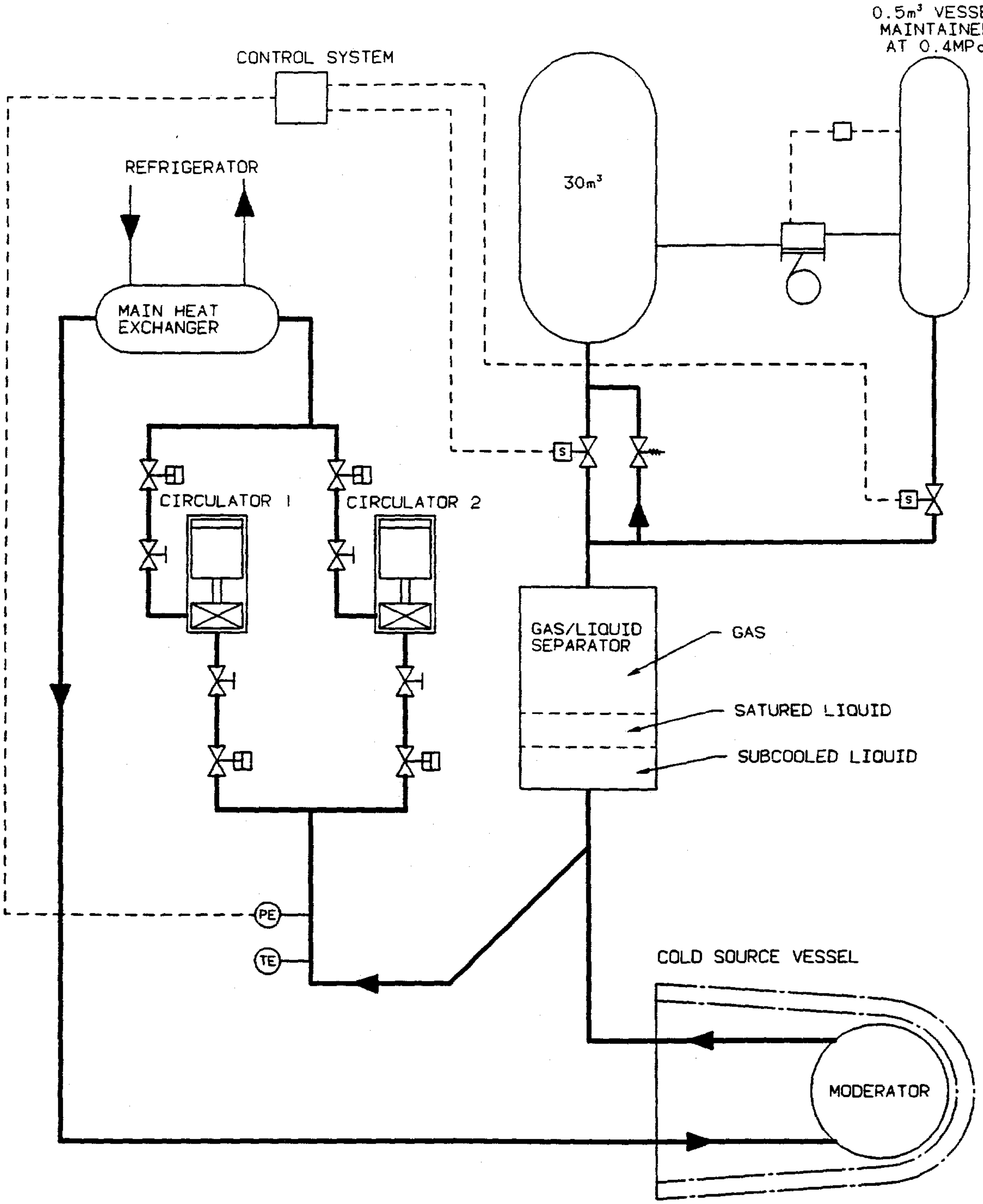


Fig. 2. Operating envelope of the deuterium loop in terms of temperature and pressure.



STATE	NORMAL OPERATION	SYSTEM OFF AT AMBIENT TEMP
LOOP PRESSURE MPa	0.25-0.4	0.4
$30m^3$ TANK PRESSURE MPa	0.1	0.4

Fig. 3. Flow diagram of liquid deuterium loop and gas handling system.

2. GENERAL DESIGN PRINCIPLES

Each deuterium system operates as a closed loop. An expansion vessel of 30-m^3 capacity limits the overall system pressure to 0.4 MPa at ambient temperature. A pressure control system maintains the loop pressure within fixed setpoints. During cooldown, gas is added to the loop, as its density increases, by a transfer pump. This pump removes gas from the expansion vessel until its pressure is reduced to 0.02 MPa. Under operational conditions the loop pressure is 0.4 MPa at the outlet of the circulator and about 0.25 MPa at the inlet. During warmup, the liquid in the loop evaporates, and the increased pressure causes gas to reenter the expansion tank until the whole system is at ambient temperature. This configuration allows the overall gas inventory to be substantially reduced and also helps the design of all loop components since pressure in the loop is similar under all conditions. The expansion vessel is double walled to meet the double containment requirements, and the interspace between the walls is evacuated by a pump that exhausts into the building unless deuterium gas is detected.

3. THIMBLE ASSEMBLY

The moderator vessel is a sphere of 410-mm internal diameter with an internal cavity to allow the guide tubes to view the highest density of cold neutrons, which is at the center of the sphere. A cavity in the form of an indent in the vessel wall would have produced unacceptably high stresses, so a thin-walled internal cavity was designed to avoid disturbing the stress symmetry of the sphere. The cavity was open at the bottom to trap a quantity of the flowing liquid, which would subsequently be boiled off to gas by neutronic heating. The cavity would remain of sufficiently low density to be almost transparent to the cold neutrons as long as the reactor was operating. Heat generated in the vessel walls and internal components accounts for half of the total heat load, and to achieve the required heat transfer coefficients to remove this heat, incoming liquid was forced through an annular gap formed by an internal spherical baffle. It was then returned through the baffle to the top service point of the vessel. The inner sphere also supported the cavity assembly. The moderator vacuum chamber (called the inner thimble; see Fig. 4) fitted into an outer thimble, which formed an integral part of the reflector vessel wall. The thimble assembly that was developed is shown in Fig. 5 in which the inner thimble was to be made from straight tubes of two different diameters, joined end to end by a transition flange. These tubes would possibly be extruded with flow ways through the walls for helium monitor gas that would provide an early warning of leakage. The outer thimble is a single straight tube with a hemispherical end. Cooling of both thimbles is effected by heavy water coolant flowing between the two thimbles. The coolant flow requires flow baffling to control heat transfer.

The thimble assembly was large enough to accommodate the cold neutron exit windows in addition to the cryogenic service pipe and an ultracold neutron guide. The inner thimble design was evaluated using finite element analysis. The complete thimble assembly, including its rigid transfer line, was designed to be assembled and exhaustively tested in a support jig to assist in reliability and dimensional repeatability. The thimble assembly in respect to other major components is shown in Fig. 6.

3.1 MATERIALS OF CONSTRUCTION

After careful evaluation of a number of candidate materials, the baseline material selected for the moderator vessel was 6061 aluminum alloy. This is by far the best documented material for high-radiation use, with the possible exception of high-purity aluminum. However, the higher working stresses of 6061 were required for the design pressures involved. Although primarily a vacuum vessel, the inner thimble was designed also as a pressure vessel, which it would become in the event of a failure of the deuterium containment, and 6061 was chosen for this also. Carbon/carbon composites remained an innovative candidate material for both vessels, but extensive testing and development would have been required.

Anticipated radiation damage required that the moderator vessel would have to be annealed at about 100°C on a regular basis. This was to allow a redistribution of silicon clusters, created by transmutation in the vessel material, to control its internal stresses. The procedure postulated to carry out this process is described in Sect. 11 of this report.

The cold neutron exit windows would ideally be made from a low-cross-section material such as beryllium, but manufacturing difficulties would probably have led to the use of 6061 for these also.

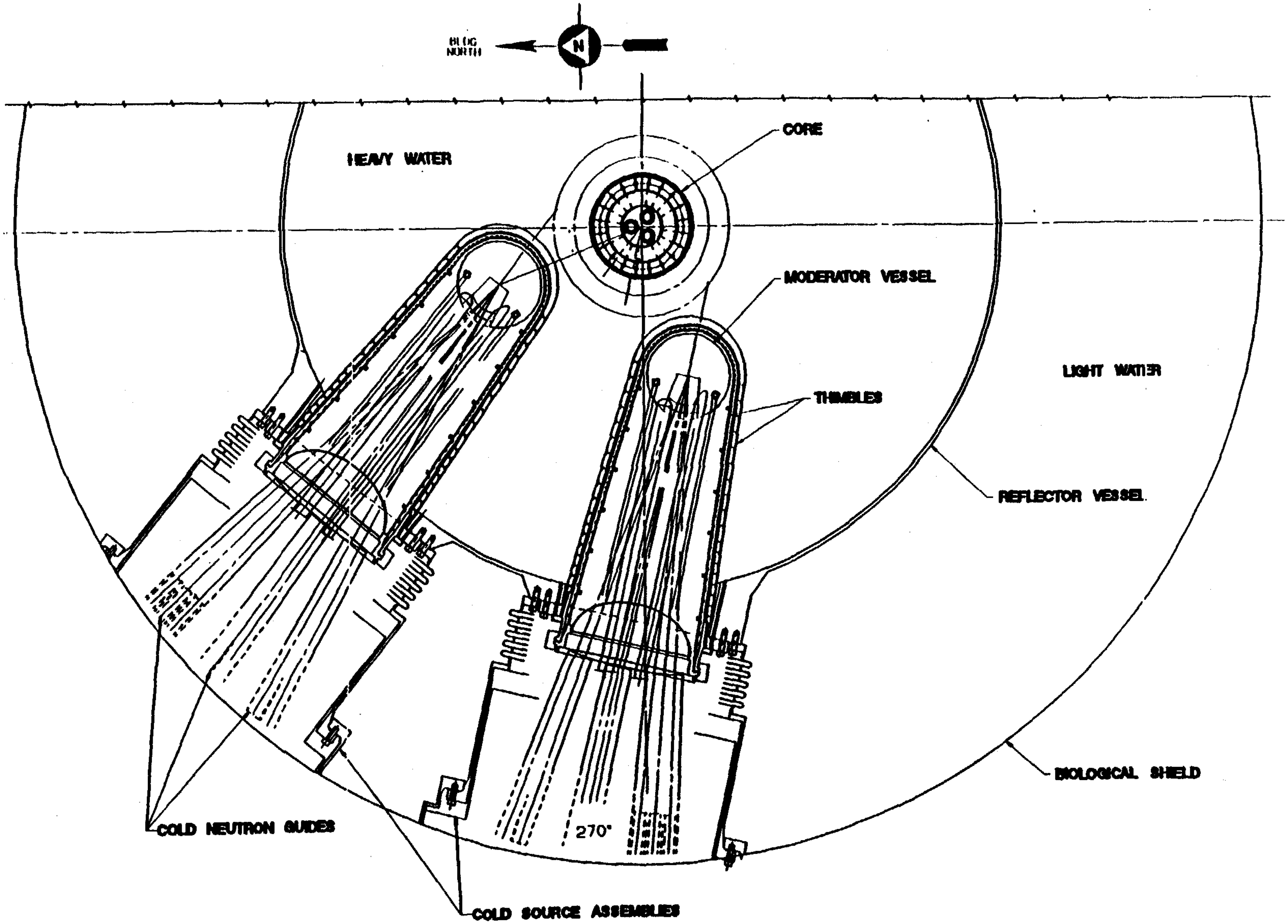


Fig. 4. Cold source thimbles relative to reactor core.

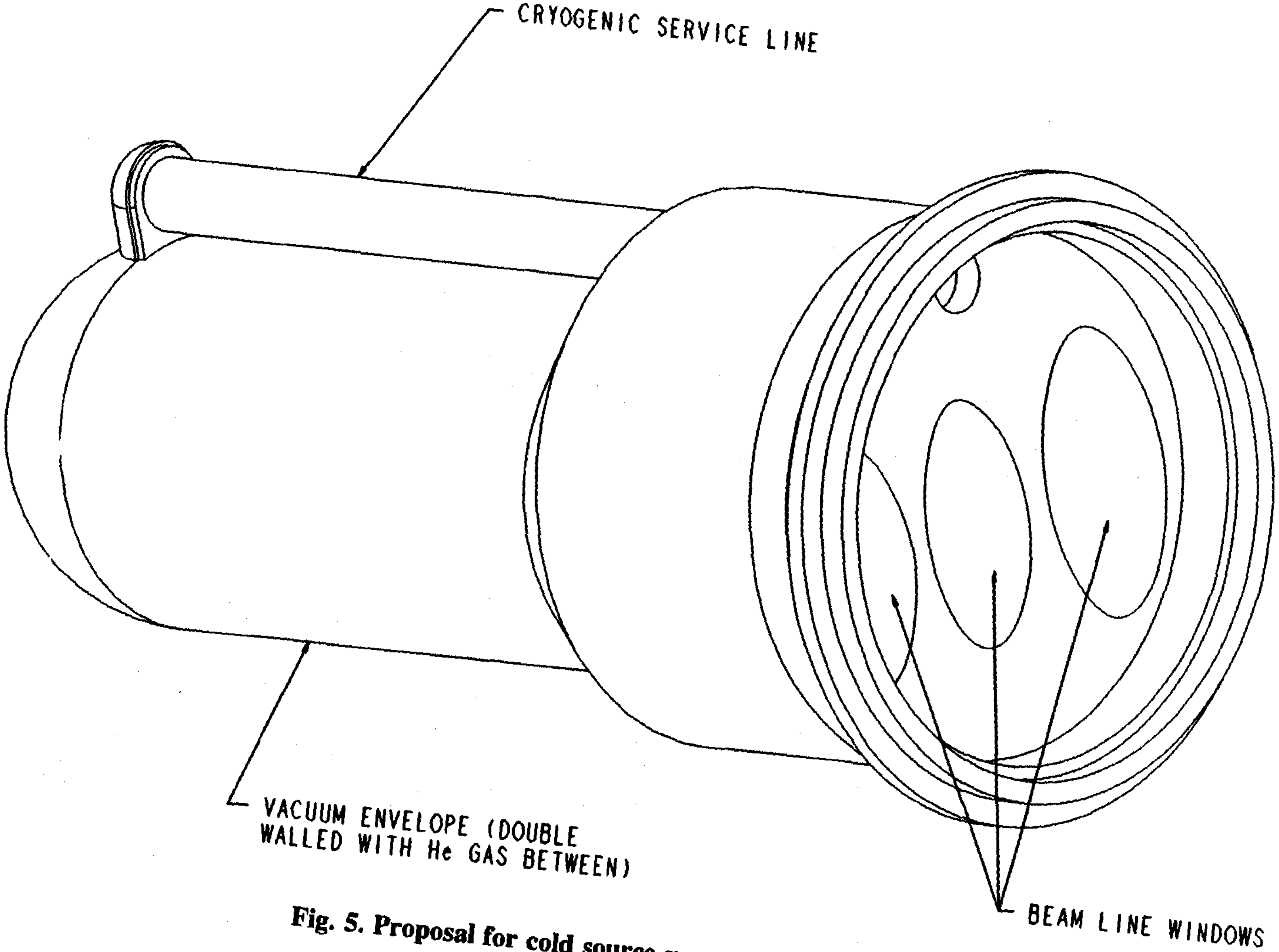


Fig. 5. Proposal for cold source vacuum thimble.

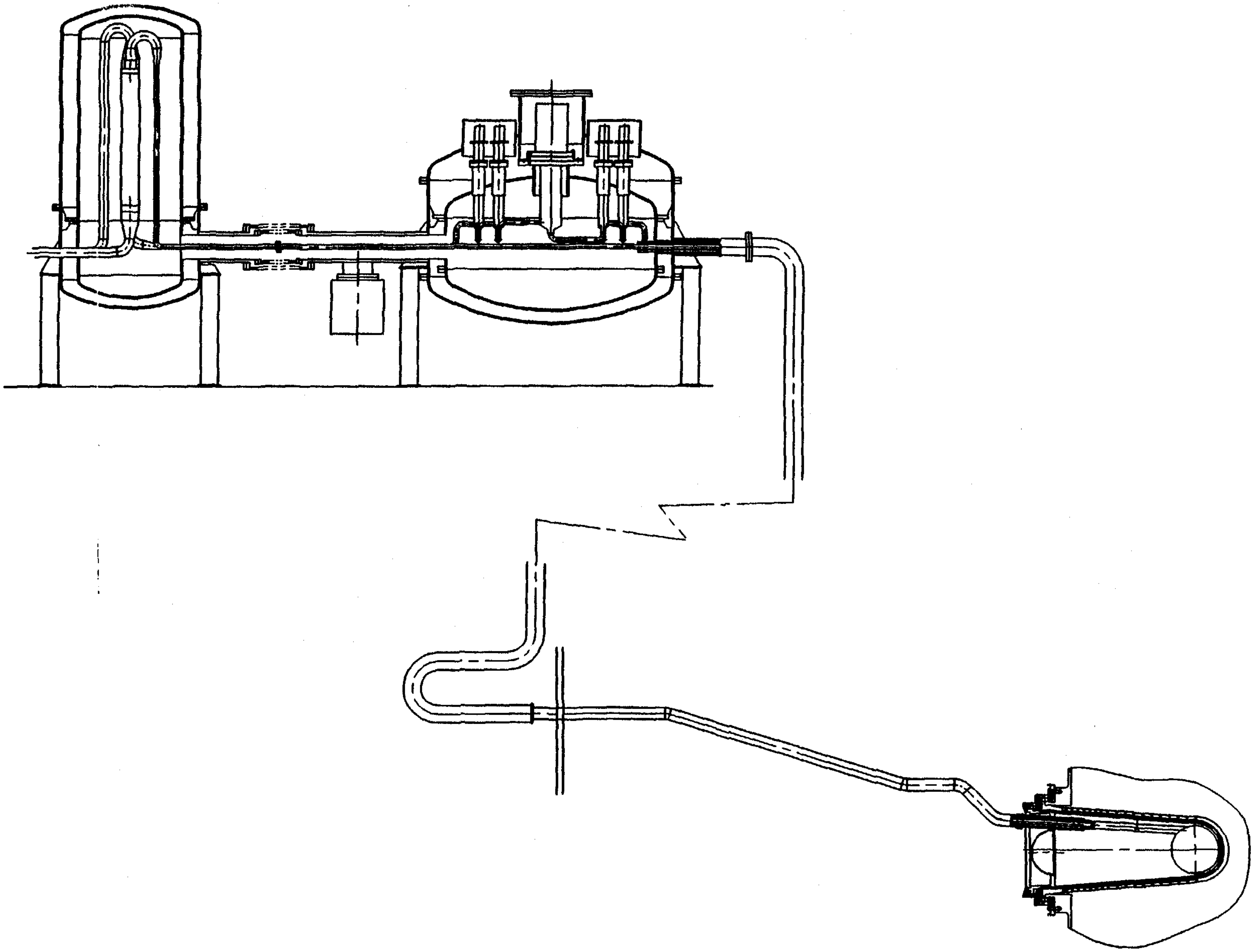


Fig. 6. Condensed view of heat exchanger, pumping module, thimble assembly, and transfer lines (~12 m long).

3.1.1 Stress Analysis

Preliminary stress analysis was carried out using the NISA finite element code.[1] A report[2] covering the moderator vessel, the windows, and the inner thimble is included in the ANS closeout package.

3.1.2 Thermophysical Analysis[3]

The initial stage of a modeling exercise was carried out using the FLOW3-D code.[4] Various configurations were modelled in an attempt to provide a design that minimized boiling. The effects of relative movement between the vessel and its internal baffle in operation were also examined. Plans were made to produce otherwise unavailable thermophysical data for liquid deuterium. Physical modeling was also planned, using a surrogate fluid, to examine visually flow patterns as an aid to providing first-order baffle designs.

3.2 WORKING PRESSURES AND SAFETY CONSIDERATIONS

Since pressure in the loop when the system is at ambient temperature is the same as the maximum pressure when the system is operating, the relief systems are set at 1.5 × normal working pressure (0.6 MPa). The outer thimble is the primary boundary for the reactor heavy water and was designed to meet the requirements of the ASME III code. The cooling water pressure between the thimbles is nominally equal to that of the reflector vessel so that normally the thimble is not under stress. Nevertheless, the thimble is designed to withstand external pressure of 0.6 MPa to allow for abnormal conditions. Total failure of the outer thimble would destroy the inner thimble, making the cold neutron windows the final barrier to prevent heavy water from entering the beam guides. These windows would therefore be designed to withstand a maximum pressure of at least 0.6 MPa, which is the rupture disc setting.

3.3 VERY COLD GUIDE

A beam guide designed to transport very cold neutrons with energy levels between 10^{-6} and 10^{-4} eV has a forward section that is integral with the thimble assembly. This comprises a tube of 70-mm internal diameter, formed from aluminum, and internally coated with nickel. It passes through the end flange above the neutron windows and extends into the thimble to a point that allows it to fully view the inner wall of the cavity. The section of the tube outside of the flange is closed by a thin window that comprises part of the thimble. This is designed to withstand the same internal pressure as the rest of the thimble assembly. Heat generated within the tube material is removed either by heat shunts connected to the thimble body or helium gas cooling channels incorporated in the tube walls. A beam guide attaches to the outer stub pipe after installation (see Fig. 7).

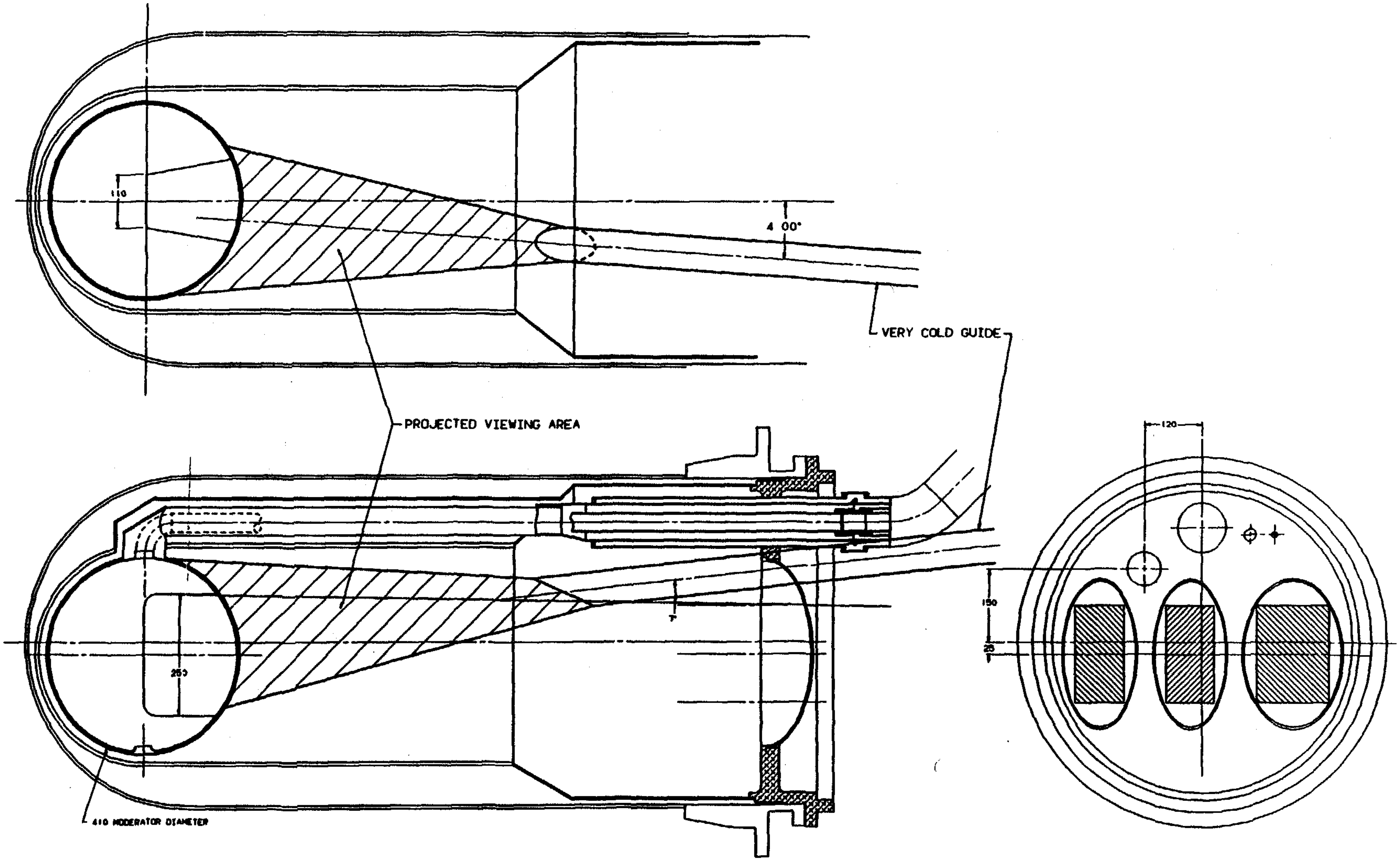


Fig. 7. Thimble assembly showing beam transport lines.

3.4 REPLACEMENT PROCEDURES

The inner thimble assembly is designed to be replaced as a complete assembly. A cask system transports the unit to the charging area, which has been formerly cleared of all beam line equipment. A remote handling module then feeds and clamps the thimble assembly into position before releasing itself from the thimble and transfer line. After draining the thimble heavy water circuit, the inner thimble is removed using a module equipped with a cutter to sever the transfer line. Both vessel and line are then loaded into the cask. If the outer thimble were required to be removed at the same time, it would be necessary to drain the reflector vessel also. Both thimbles could then be removed as a single unit (see Fig. 8).

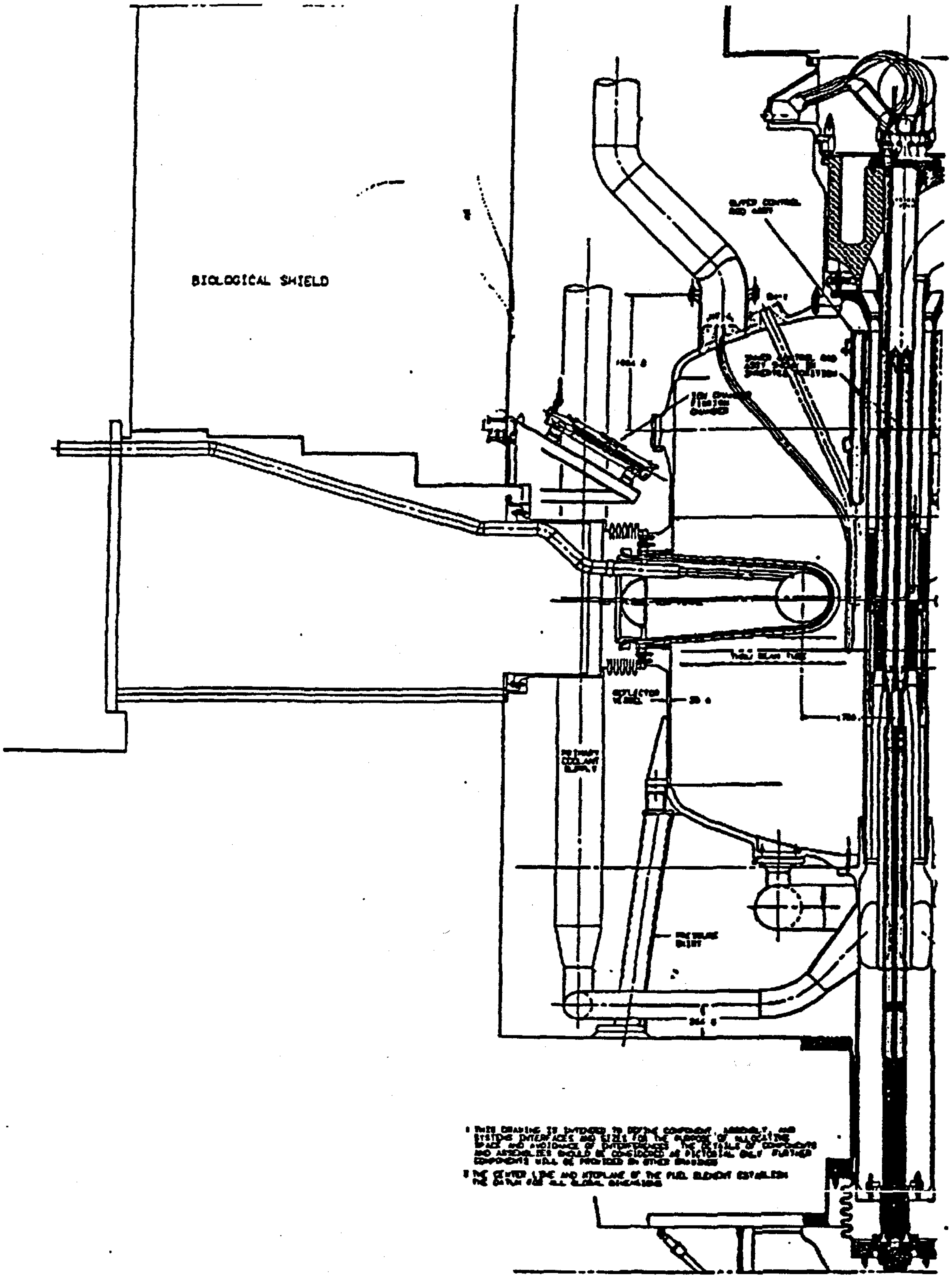


Fig. 8. Cold source thimble relative to reactor system.

4. PUMPING MODULE

4.1 GENERAL DESCRIPTION

Each cold source pumping module (see Fig. 6) houses two cryogenic circulators and their isolation valves. Internal pipework is designed to thermally isolate the spare circulator from the main circuit to allow it to be warmed to ambient temperature without affecting normal operation of the loop. The module also contains deuterium loop temperature and pressure sensors, which are designed to be replaceable without letting up the insulation vacuum. The complete loop was designed with a natural fall to promote good natural convection without the circulator, during cooldown and liquefaction. The containment vessel comprises part of one of the two vacuum zones that are described in Sect. 7. A further containment encloses the vacuum chamber, and this forms a part of the inert gas containment described in Sect. 8.

4.2 CRYOGENIC CIRCULATORS

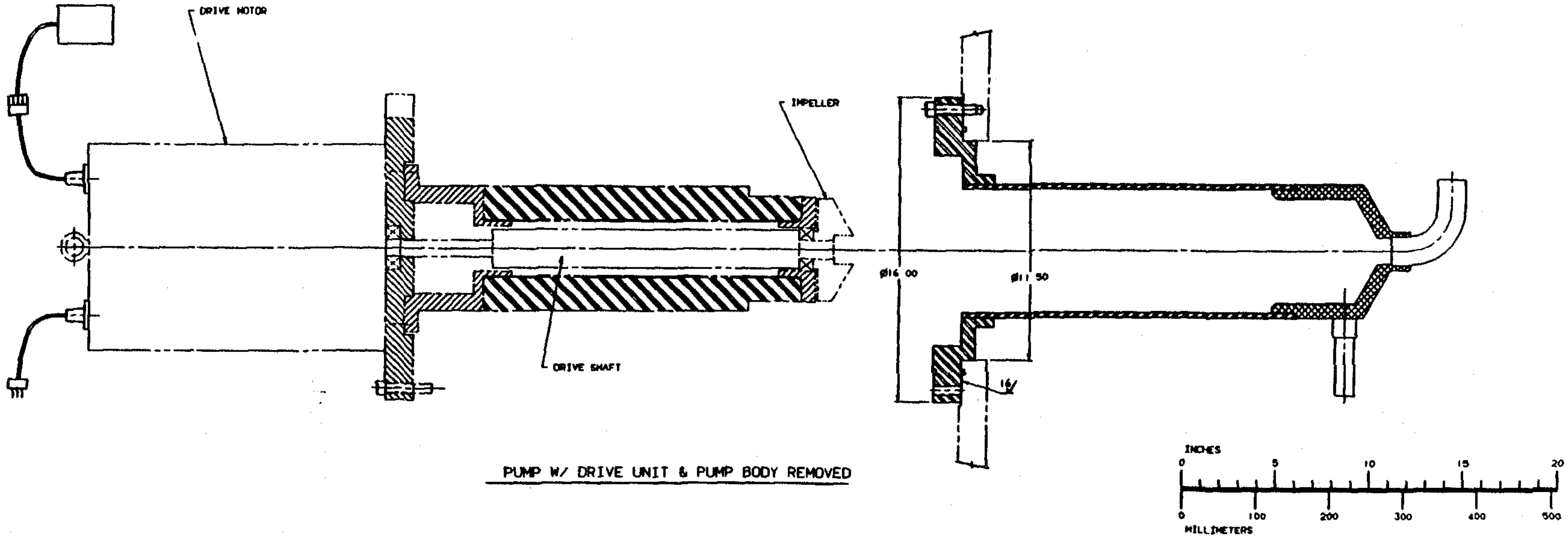
Each circulator provides a flowrate of 1 kg/s against a developed pressure head of about 0.15 MPa. The circulators are designed in two parts so that the drive and impeller assembly can be replaced without breaking into the vacuum system. A circulator can be warmed to ambient temperature and replaced using the procedures described in Sect. 3.4 without affecting normal operation of the cold source. Frequency invertors allow the circulator speed to be optimized in operation. Parameters such as speed, vibration, bearing temperatures, and winding temperatures are monitored to provide early warning of failure. Rapid and extreme changes of temperature are required, and both heating and cooling of impeller housings are provided to allow rapid changeover and replacement. The drive motor operates in a pocket of gas connected to the loop, to eliminate rotating seals (see Fig. 9).

4.3 CRYOGENIC ISOLATION VALVES

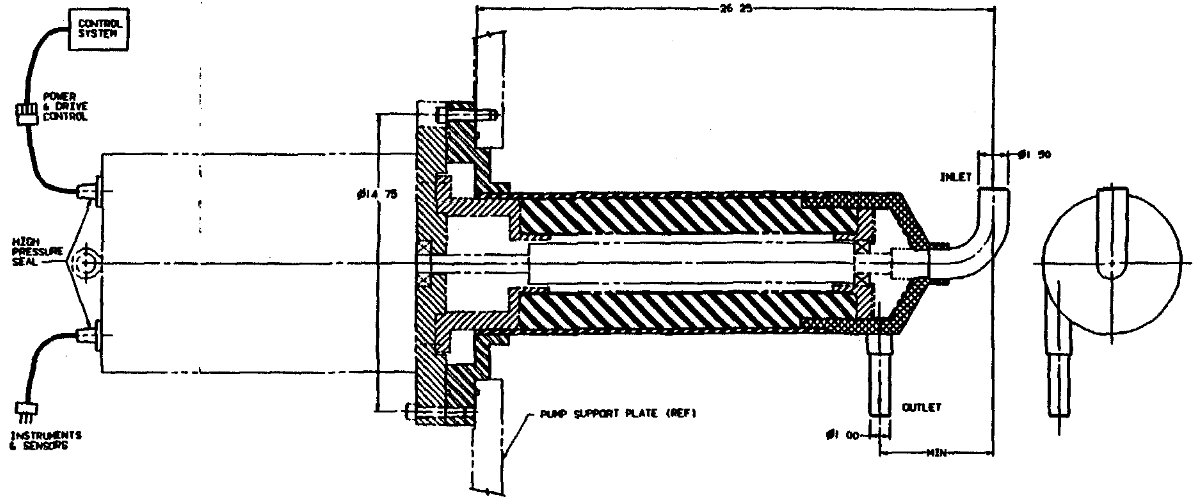
Circulators are required to be completely isolated and filled with inert gas prior to replacement. Double valving in both feed and return lines is necessary to meet the double containment requirements during the replacement operation. Outer valves are remotely operated but are provided with a manually operated "lock-closed facility" for safety. The inner valves are totally manually operated, and they remain open except for circulator replacement procedures. All valves must seal against a pressure differential of 0.6 MPa, and the seals must be replaceable without opening the vacuum system.

4.4 CIRCULATOR REPLACEMENT PROCEDURES

Redundant circulators are provided with precooling to bring them to service temperature quickly. Usually a circulator would exhibit early warning signs of failure. At this point the spare would be brought on-line, allowing a failing circulator to be isolated in good time. It can then be purged remotely and warmed to ambient temperature for removal. Before removal, however, the outer valves are locked and the inner valves closed. The circulator is now doubly



PUMP W/ DRIVE UNIT & PUMP BODY REMOVED



ASSEMBLED COMPONENTS

Fig. 9. Schematic liquid deuterium circulator.

isolated from the deuterium circuit, allowing a local section of the inert gas blanket to be opened to atmosphere. The circulator is then replaced and the outer inert gas blanket reestablished. The manual valves can then be opened and the outer valves unlocked. After purging with helium gas (using a separate vacuum pump that exhausts into the inert gas blanket), the circulator can be filled with D_2 gas and cooled, ready for operation (see Fig. 10).

4.5 TEMPERATURE AND PRESSURE SENSORS

The pressure sensors are of the strain gauge type in which strain in a diaphragm is monitored as a measure of pressure. Current through the strain gauges is applied by certified barrier systems that are required to meet the conditions of intrinsic safety. All sensors are mounted to a common flange and connected to their measurement points by small bore capillary pipes. The temperature sensors are solid state devices in the liquid stream. They are passed through thin-walled tubes and through the vacuum vessel wall and are sealed by compression fittings. Replacement of all temperature and pressure sensors is possible without the need to open up the vacuum system (see Fig. 11).

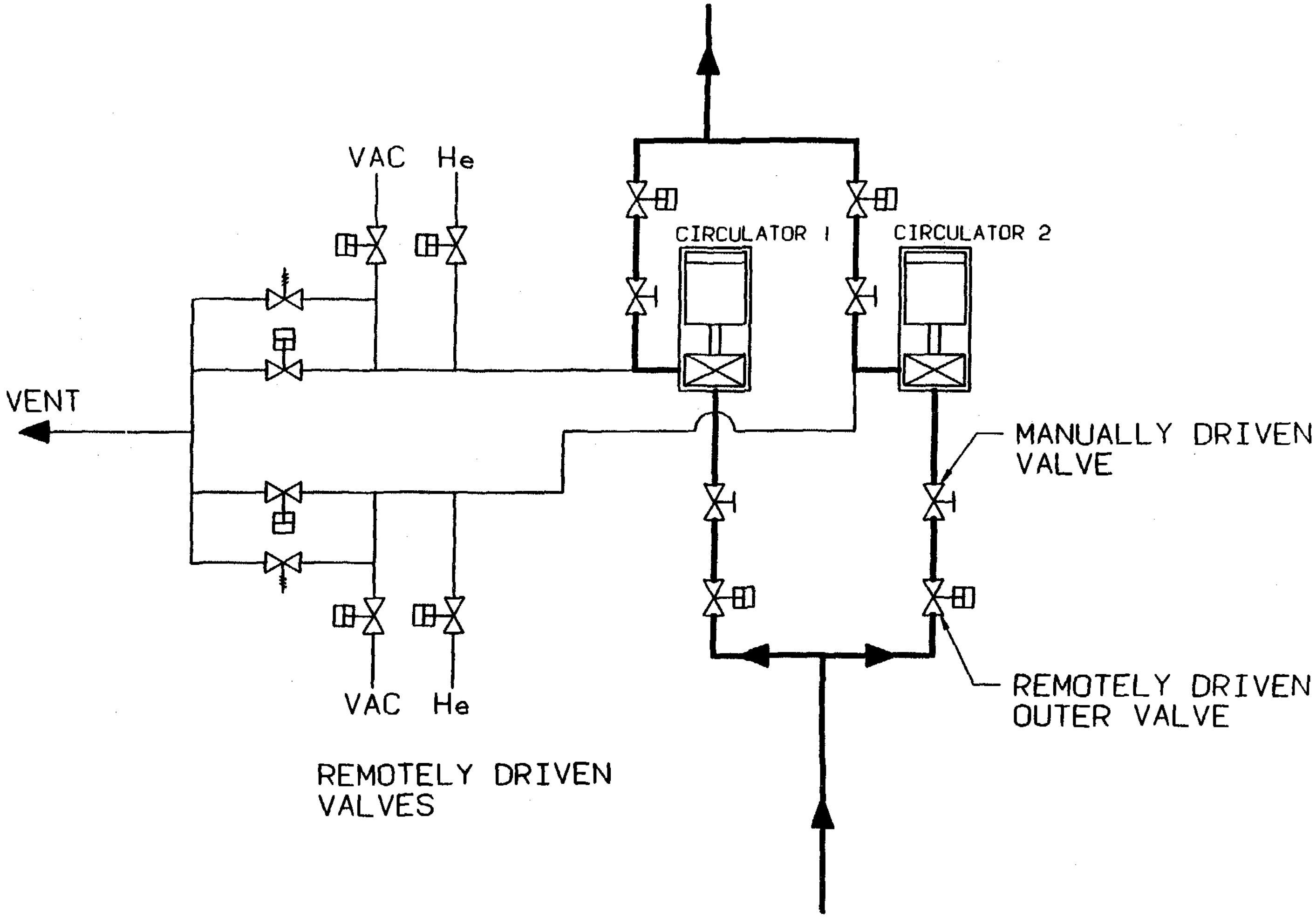


Fig. 10. Circular purging and replacement system.

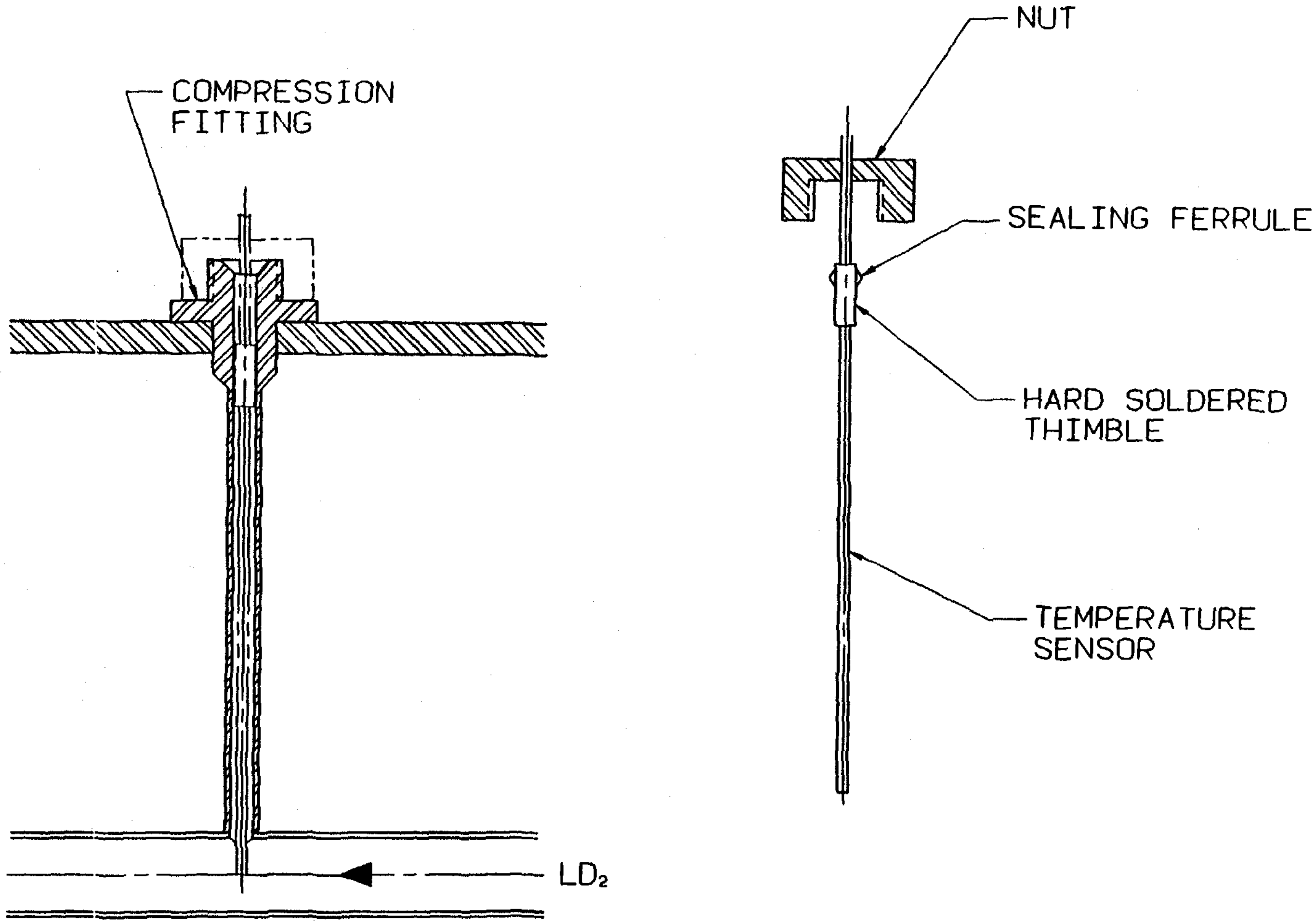


Fig. 11. Temperature sensor mounting arrangement.

5. CRYOGENIC TRANSFER LINES

5.1 DESIGN CONCEPT

Two design configurations of transfer line were evaluated, and each has two variants.

1. Discrete two-pipe designs have the advantage of simplicity of construction and elimination of heat transfer between flowing and returning fluid. However, connections must be made using cryogenic fittings or separate "Johnston" (long-nosed) couplings. This raises the risk of leaks that cannot be rectified without warming up the system or doubles the number of couplings required.

2. Concentrically configured transfer lines provide a smaller overall cross-sectional area that is advantageous when lines pass through biological shielding, etc. Heat transfer between the flow and return ways can be controlled by providing a vacuum space between them. A single long-nosed coupling can be designed to seal both flow and return ways with the aid of an internal cold activated coupling between the two. The actual metal seal normally operates at ambient temperature.

Either of the above designs is possible in a rigid section or semiflexible configuration. The latter uses spirally convoluted stainless steel tubing that combines axial and diametral stiffness with an ability to bend. Convoluted piping is produced by Kabel Metal Electro, Inc. (Germany), but is also under license in the United States. Flexible lines require fewer joints and are easier to install, eliminating shorter, carefully dimensioned sections. The overall mass of material in a flexible line is also reduced because of the inherent stiffness of the tubes. If the innermost tube is used as the feed line, the return gas surrounding it acts as a very effective radiation shield, allowing very little transit temperature rise between the heat exchanger and the moderator. This allows the moderator temperature to be as low as possible. A vacuum between the flow and return lines minimizes heat conduction between the two. The latter design was selected for the ANS, the inner and outer vacuum spaces being internally connected (see Fig. 12).

5.2 COUPLING DESIGN

Transfer line interconnections are made using long-nosed couplings with a single metal seal and one-bolt manacle clamp. The seal normally remains at ambient temperature. An internal dissimilar metal sleeve joint isolates the flow and return ways as the line cools to operating temperature. An outer tube provides continuity of the inert gas blanket, and this also uses a manacle clamp, which is sealed when the main clamp seal has been made.

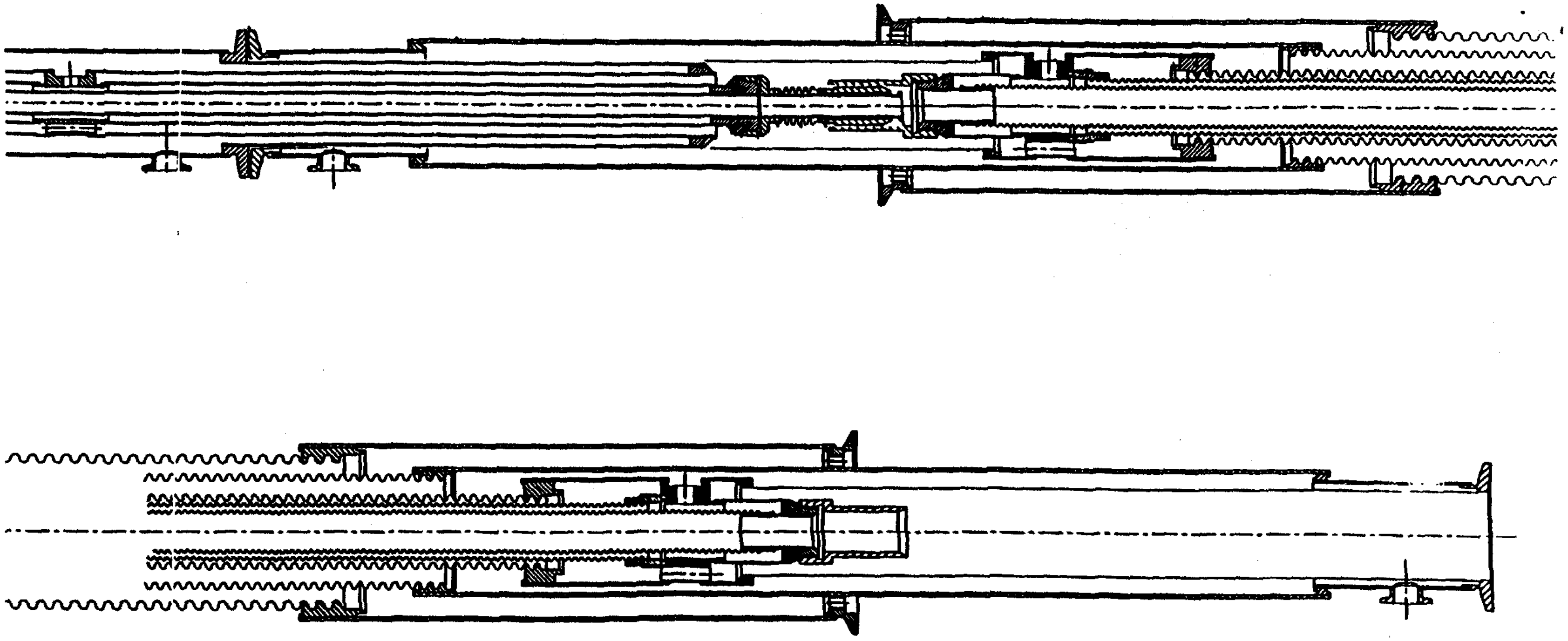


Fig. 12. Cross section of liquid deuterium transfer line.

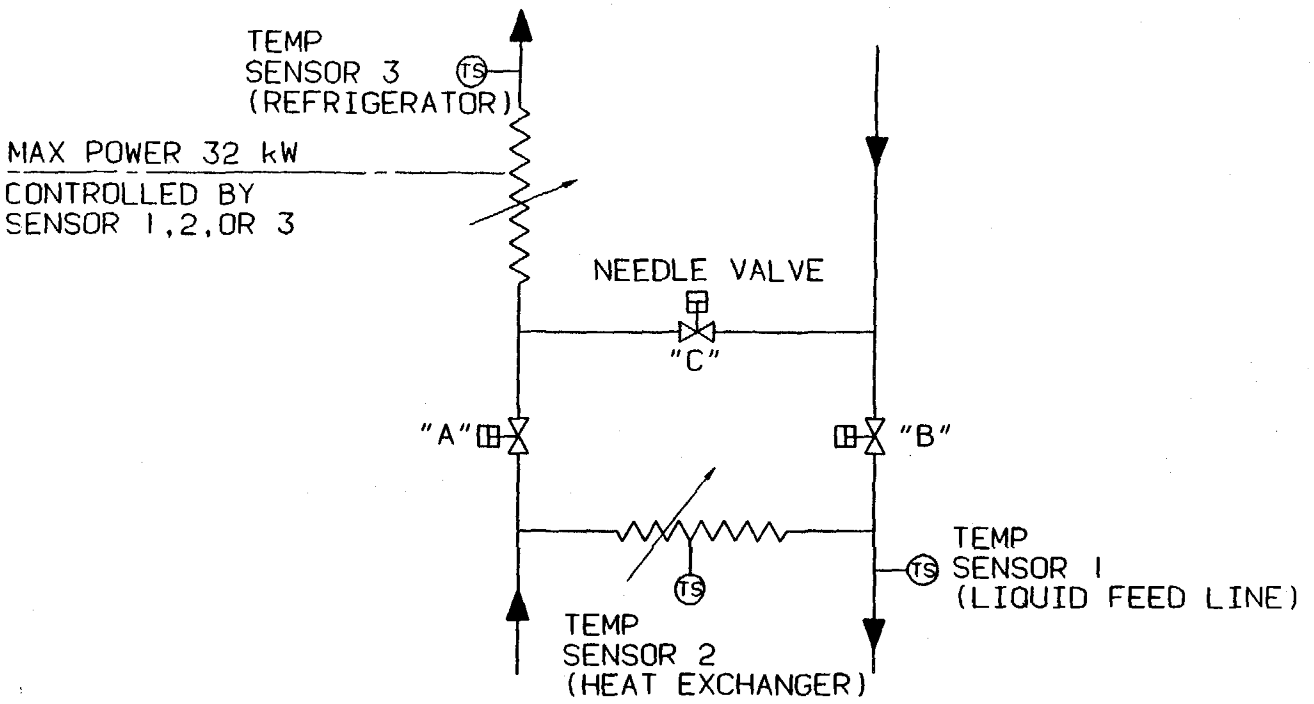
6. REFRIGERATION

6.1 OVERALL REQUIREMENTS

Independent refrigerators for each cold source were stipulated, specified to remove 32 kW of heat at 20 K from the secondary side of the main heat exchanger. The helium refrigerant operates within a temperature range of 15–20 K. Screw-type compressors, with redundant capacity, were to be located outside of the containment building, and isolation valves on each side of the containment building walls were required to meet the isolation requirements. The cold boxes, containing expansion turbines, interstage heat exchangers, and control heaters, were situated on the top floor of the containment building. Possible power outages of up to 1/2 s in duration, without endangering the high-speed turbines, was specified.

6.2 CONTROL CONCEPT

In consideration of thermal shock, 20 h is considered a reasonable time for one cold source system to be cooled and filled with liquid, starting from ambient temperature. The cold sources would always be cooled and filled before the reactor is started. An estimate of the total enthalpy removal from the loop and fluid indicates that the cooling power required to achieve this is about 1 kW. However, the refrigerator normally operates at full power with control heaters to tailor its output to suit the prevailing requirements. During the cooldown and liquefaction stages, the heater power responds to a temperature sensor on the heat exchanger secondary cooling surface, which is set just above the freezing point of deuterium. This limits the applied refrigeration power to the thermal capacity of the heat exchanger during the cooling and liquefaction stages. The cooling rate increases with gas density as the temperature of the gas falls. A dramatic density increase occurs with liquifaction until the system is ultimately filled with saturated liquid. The objective is to complete the liquefaction phase using natural convection to avoid cavitation problems during the two-phase fluid period. A fall in temperature indicates the start of the subcooling phase, and the circulators can be started. At this point, control will then be switched to a sensor located in the liquid feed line where the temperature is representative of that in the moderator vessel. During short down periods, the loop would be warmed without the refrigerator. In this case, isolation valves and a bypass valve would allow refrigerant to flow around a small loop controlled by a third sensor close to the refrigerator. As an economy, the refrigerator cycle could be changed to reduce its output during these periods (Fig. 13).



REQUIREMENT	REFRIGERATOR ON IN STANDBY MODE. LOOP AT AMBIENT TEMP.	REFRIGERATOR IN STANDBY MODE. LOOP TO BE COOLED TO OPERATIONAL TEMP.	REFRIGERATOR AND LOOP TO BE COOLED FROM AMBIENT TEMP TOGETHER.	NORMAL COLD OPERATION.
VALVE STATE	A & B-CLOSED C-OPEN	A & B-OPENED C-"TIMED" CLOSE	A & B-OPEN C-CLOSED	A & B-OPEN C-CLOSED
TEMP SENSOR CONTROLLING	3	2	2	1

Fig. 13. Temperature control schematic outline.

7. MAIN HEAT EXCHANGER

7.1 DESIGN PARAMETERS

The heat exchanger in relation to other major components is shown in Fig. 6. During normal operation, the heat exchanger is required to transfer a total of 32 kW of heat from liquid deuterium flowing at 1 kg/s. However, the initial cooling and liquefaction phases are restricted by the thermal capacity of the fluid and the thermal capacity of the heat exchanger. Too small a heat exchanger would limit the refrigeration power that could be used without local freezing of deuterium. Too large a heat exchanger would have a higher internal liquid inventory and could subject the cold loop to excessive thermal shock. The heat exchanger would therefore be designed to effect cooling and liquefaction within about 20 h and fulfill the liquid cooling requirements.

7.2 LOCATION

The heat exchanger would be vacuum insulated and further contained by an inert gas blanket. It would be mounted upright and adjacent to the pumping module though slightly higher to promote good natural convection during cooling and filling. The refrigerator and cold loop would usually be cooled down at the same time, but sometimes the refrigerator could be running already at operating temperature. In such cases the isolation valves would be required to be opened and the bypass valve closed progressively to reduce thermal shock to the heat exchanger. Once a full refrigerant flow through the heat exchanger is achieved, the cooldown procedure would be identical to that of a normal cooldown.

8. VACUUM SYSTEMS

8.1 GENERAL

All cryogenic components of the deuterium loop are required to be vacuum insulated. The vacuum enclosure is divided into two zones, each of which has two pumping stations, one in standby. The standby station can be brought on-line and the spare replaced without any interruption in operation (see Fig. 14).

8.2 PUMPING STATIONS

A vacuum station comprises a turbo/backing pump combination and instrumentation together with isolation valves. The whole station is built into a containment vessel that effectively becomes a part of the inert gas vessel. A pumping station is replaceable without breaking the double containment.

8.3 EXHAUST ARRANGEMENTS

The exhaust from all pumping stations is piped to the vent vessel, which is initially evacuated. Initial pumpdown of the system would be made using portable vacuum equipment that vents into the building. Thereafter, the entire deuterium inventory resides in either the main loop system or the vent vessel.

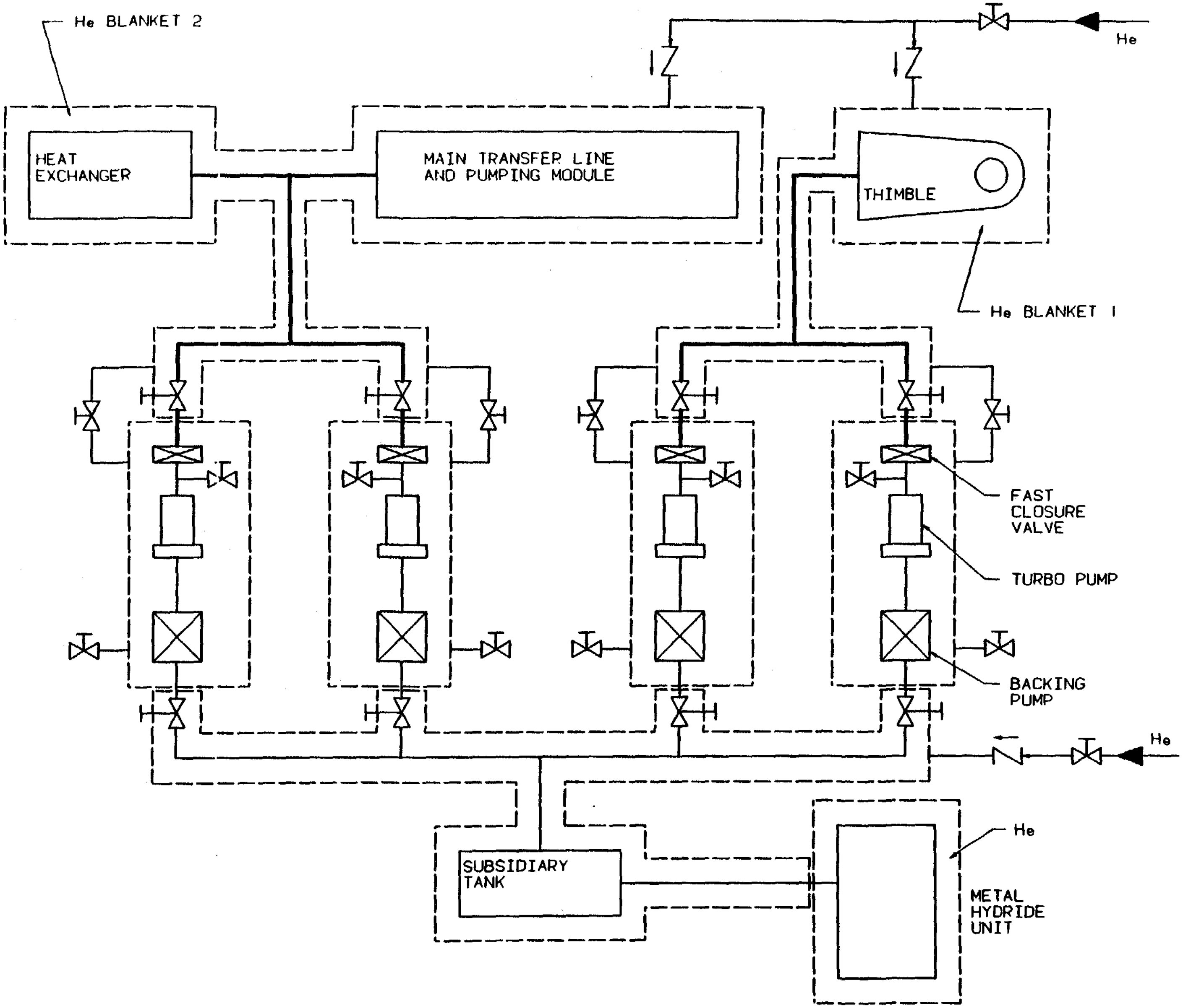


Fig. 14. Vacuum systems flow diagram.

9. INERT GAS CONTAINMENT

The entire deuterium-containing system (including all vacuum-insulated components) must be enclosed by an inert gas blanket or a vacuum vessel. The thimble assembly has its own inert gas blanket to limit the spread of contamination in the event of failure. The remainder of the cold components of the loop is contained by a separate inert gas blanket. Other items that remain at ambient temperature but are deuterium bearing are surrounded by a vacuum vessel. The inert gas or vacuum, respectively, is constantly monitored for leaks, and the vessels are designed as pressure vessels in case of major leaks. Rupture discs protect the outer containment from pressure in excess of 0.2 MPa.

10. PRESSURE RELIEF SYSTEMS

The system pressure relief system is divided into three sections:

1. Primary deuterium containment, which includes all deuterium-containing components, are protected against pressures in excess of 0.6 MPa by a rupture disc.
2. Rupture discs also protect both vacuum systems against pressures above 0.2 MPa.
3. Rupture discs also protect both inert gas blanket systems against pressures above 0.2 MPa.

All rupture discs and vent valves are connected to the main vent vessel.

11. MAIN VENT VESSEL

The main vent vessel has a volume of 60 m^3, which is sufficient to limit the pressure of the gas inventory, at ambient temperature, to 0.12 MPa. This is without the additional volume of the vacuum space that would be added in the event of an internal system failure. The vent vessel is double walled, and the central inner chamber is under vacuum. The intermediate chamber is effectively a part of the double containment system and is held under vacuum by an independent rotary vacuum pump that vents into the building. This vacuum, in addition to forming a monitored safety barrier, also prevents loss of vacuum in the vessel center.

12. ANNEALING OF MODERATOR VESSEL

Annealing of the moderator vessel would be required during each fuel change. After shutting down the reactor, the circulator would be stopped, causing the liquid trapped in the moderator vessel to be vaporized by the residual heat in 1–2 min. The resulting volumetric increase expels all remaining liquid in the loop to the expansion vessel through the control valve. Since the secondary containment of this vessel is under vacuum, the liquid boils off within it at a controlled rate. A high volumetric flow gas circulator is now started, which drives the gas around the loop to prevent overheating. It has been shown that a flow of 10 L/s of gas at 100 K is capable of achieving the required heat transfer coefficients in the vessel to remove 15 kW of heat for a temperature rise of 170 K. For the purpose of this calculation, full operational reactor power was assumed. When the annealing temperature of 370–400 K has been reached, the recooling cycle to operational temperature can be started.

13. TRITIUM CONTROL

13.1 TRITIUM HANDLING

It has been decided (ORNL/ANS/INT-40) that the heavy water tritium concentration goal is 2 Ci/L, which is considered acceptable to the workers and meets health and safety requirements. On a deuterium basis, this is equivalent to about 9 Ci/kg. Tritium is considerably more hazardous in its oxide form with a hazard ratio of about 10,000 for T_2O over T_2. To have a hazard equal to that of heavy water at a level of 2 Ci/L, the deuterium gas would have a tritium concentration of about 90,000 Ci/kg.

Because of radiation damage, the cold source moderator vessel would be changed every 2 years. Calculations, based on 0.75 g/year (97,200 Ci/year), indicate a tritium production of 6600–6800 Ci/kg in the 19-kg deuterium inventory. As long as the deuterium remains in its elemental form, the hazard is lower than that from the heavy water coolant. If, however, the tritium is oxidized to heavy water, its tritium concentration of 1500 Ci/L would present a considerably greater hazard.

Accidental leakage to the containment is a serious concern since the tritium could readily become oxidized. However, since the postulated accident scenarios are remote and the gas would always be handled as discussed in Sect. 12.2, it is believed that complete inventory changes every 2 years is reasonable.

13.2 GAS HANDLING

All gas loading and unloading are carried out through the vent vessel, using portable metal hydride beds. In normal operation, the vent vessel is under vacuum, and the entire inventory is contained within the main loop system. In the event of a rupture disc operation, the gas occupies both at a uniform pressure of 0.12 MPa. Gas can then be fully returned to the loop system by a pump after replacement of the rupture disc, or the entire inventory can be pumped into the vent vessel, raising its pressure to 0.2 MPa. This allows the loop to be filled with inert gas for servicing and the vent vessel emptied to vacuum by portable metal hydride beds. The vent vessel is then charged to 0.2 MPa with fresh gas, and the loop system is evacuated by portable vacuum pumps, which are allowed to exhaust into the building. The complete inventory is then returned to the loop leaving the vent vessel under vacuum. A report prepared by Hofer[5] indicates that an optimum-sized hydride unit would be large enough to contain about one-third of the gas inventory. The coupling design allows for a unit to be changed without breaking the double containment philosophy at any time. A similar arrangement operates in the detritiation plant to remove tritiated deuterium from the portable beds and recharge them with detritiated gas (see Fig. 15).

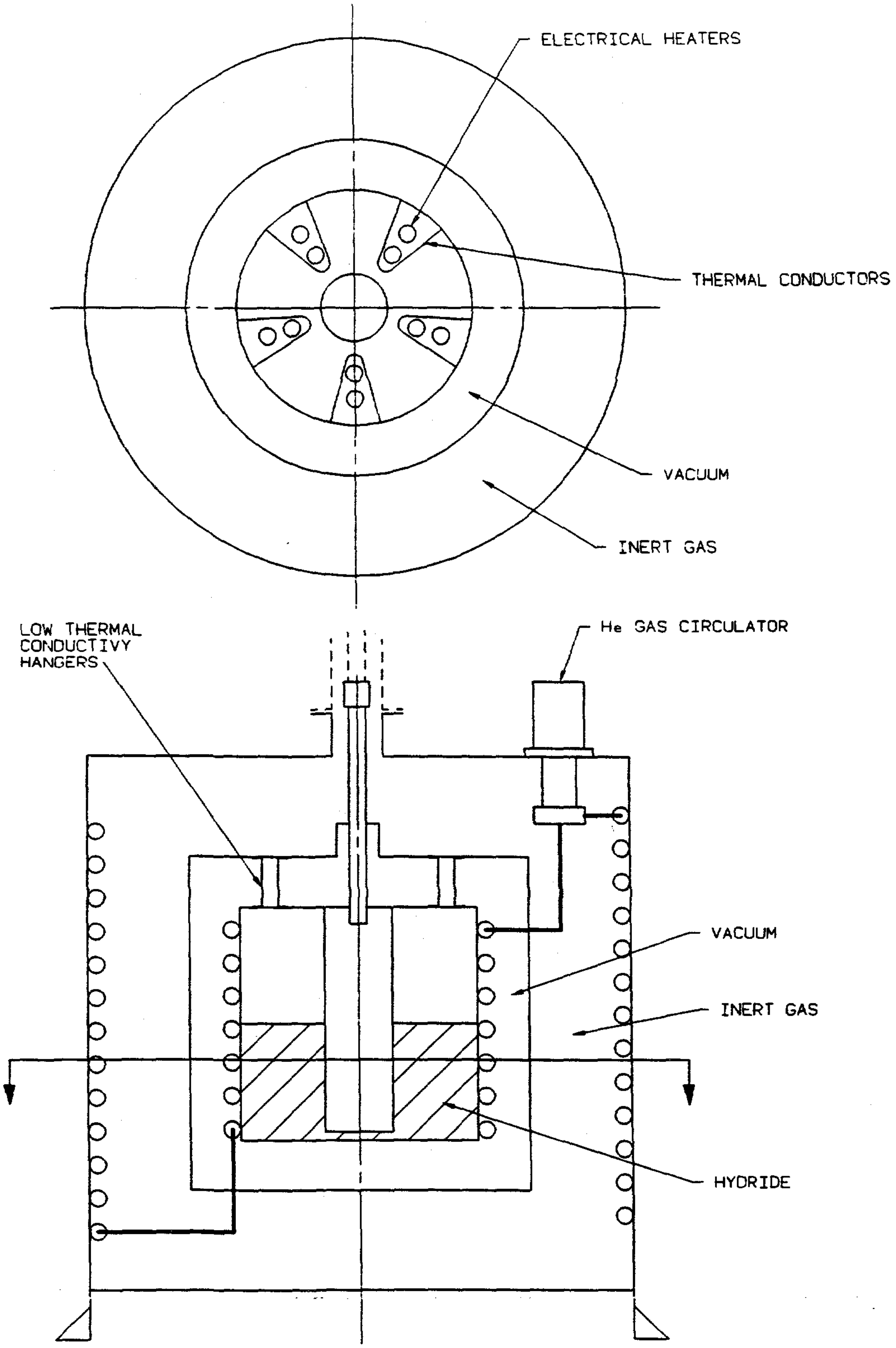


Fig. 15. Conceptual outline of metal hydride bed.

14. SAFETY

14.1 DOUBLE/TRIPLE CONTAINMENT

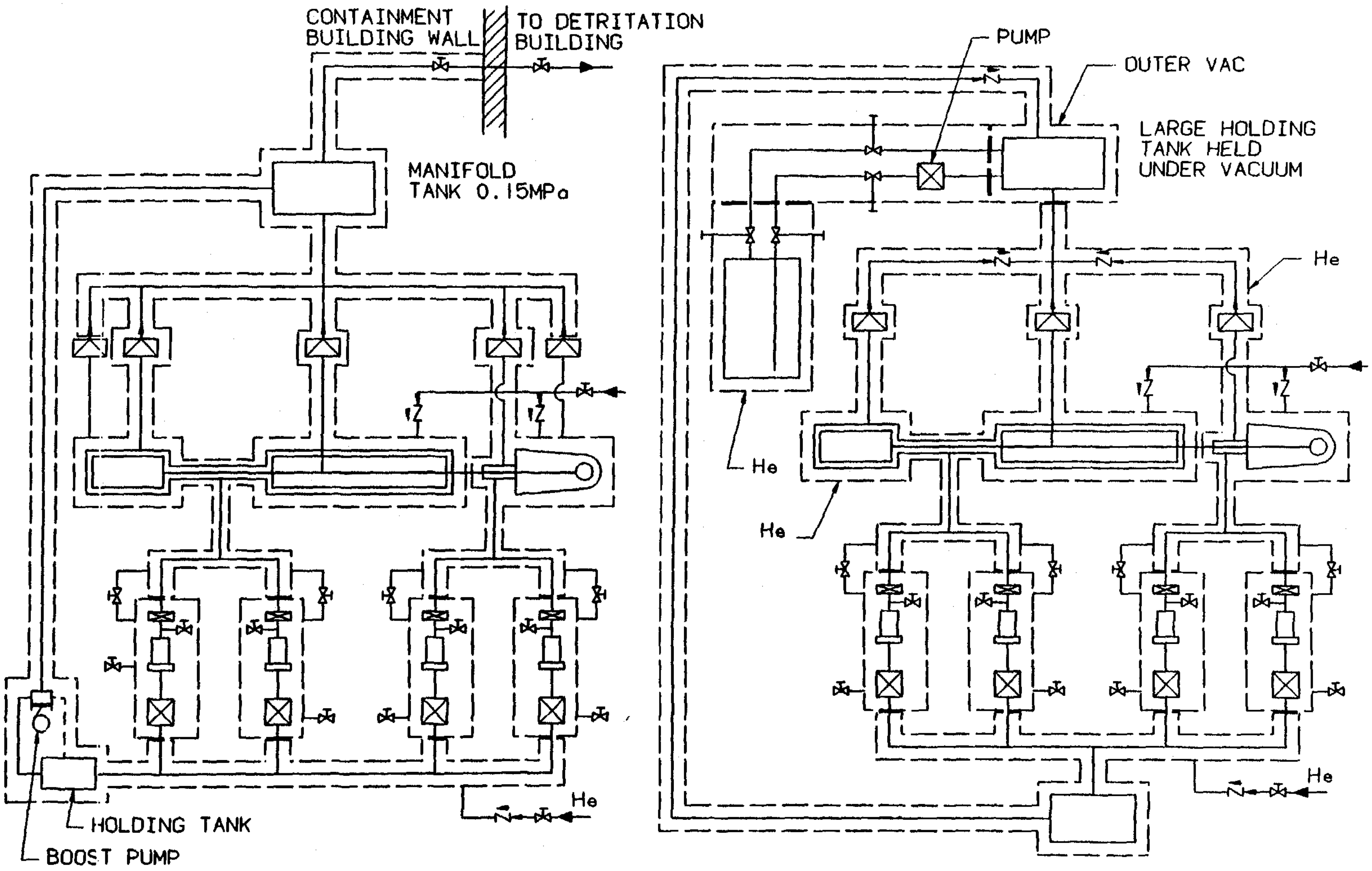
The safety case of the ANS cold sources leans heavily on the efforts devoted to isolating deuterium from air. To this end, the entire system, including cold items that are vacuum insulated, is doubly enclosed. The interspace around components that are vacuum insulated is filled with inert gas. Components that comprise part of the loop system, but remain at ambient temperature, are contained by an evacuated vessel. In both cases, the inert gas or vacuum is monitored to give an early warning of contamination, which could indicate leakage. The blankets are protected against overpressure by rupture discs that are connected to the vent vessel. Gas handling operations carried out as part of the operation have been carefully designed to preserve the double containment philosophy at all times.

14.2 CONTAINMENT AND EMERGENCY MEASURES

The objective of a closed-loop system is to restrict gas handling to carefully controlled conditions. The frequency of complete deuterium inventory replacement is governed by its percentage tritium contamination. The most recent calculations indicate that a change will be required every 2 years to keep levels acceptable. Consideration has also been given to the possibility of liquid deuterium mixing with the heavy water reflector. Double containment and the identification of primary and secondary barriers have allowed reasonable and acceptable levels of risk to be established for operation of the cold sources (see Fig. 16).

14.3 SAFE ROOM

A safe room is an enclosure that is provided with a blowoff panel in the roof or a wall. Air in the enclosure is constantly changed and monitored for hazardous gas, and all electrical equipment is rendered spark free, either by using intrinsic safety electrical barriers or by inert gas blanketing of potential spark-producing components. Personnel within the room must wear antistatic outer garments and personal grounding protection. An ANS safe room on the second floor of the containment building will serve both cold sources. It will be connected to the building ventilation system during normal operation, but a deuterium gas signal would cause the normal vent route to be closed and a closed circuit cleanup loop to be started. The loop contains a catalytic converter to reduce any deuterium to heavy water to be collected in a replaceable molecular sieve for transport to the detritiation plant. The safe room contains all of the most vulnerable items in the system, including those that require servicing with the system operating. The safe room is situated on the second floor and is shown in Fig. 17.



EXHAUST PIPELINE

METAL HYDRIDE OPTION

Fig. 16. Alternative venting arrangements and secondary containment.

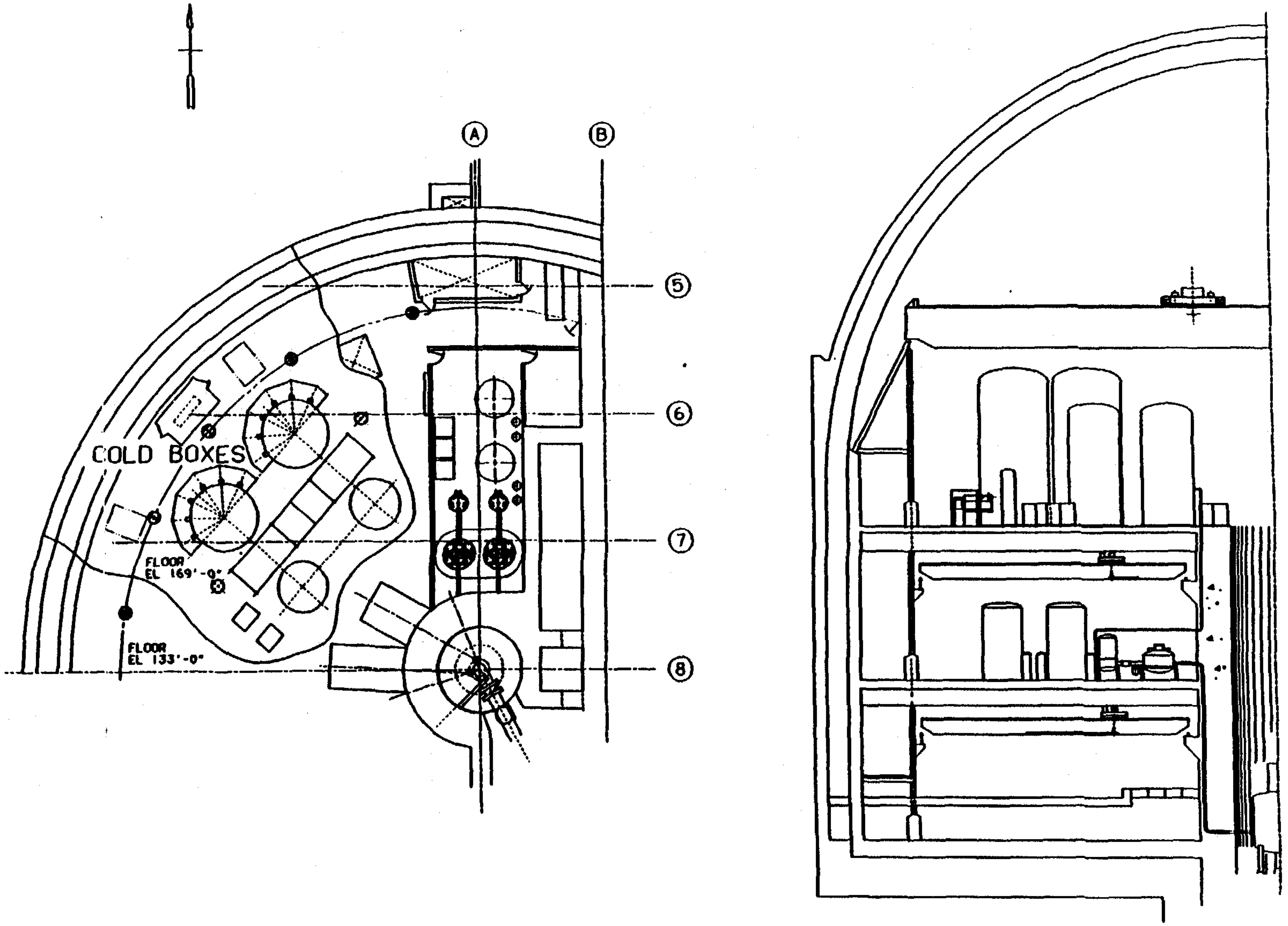


Fig. 17. System conceptual design in reactor containment.

15. TESTING

Testing of the cold source systems will be done in three separate but overlapping areas since realistic operational conditions cannot be artificially replicated at one time outside of the true reactor environment:

1. Simulated high flux testing using inductive heating. The heating method is the subject of a report by Yousef.[6] A realistically pumped deuterium loop, including a full-sized moderator vessel and cooled by liquid hydrogen, would be set up in a vacuum containment. Heat loads up to the equivalent of full reactor power would be possible, and the outside surface of the vessel would be scanned for indications of hot spots, which would indicate inadequate heat transfer. Simulations of fault conditions such as circulator or refrigerator failure could also be readily reproduced (see Fig. 18).

2. Cooldown and filling tests. A full-sized realistic loop system will replicate the difficult two-phase liquefaction operation. Since the use of deuterium for this test would be impractical, hydrogen will be used with appropriate correction factors applied to the results. This facility will also identify any unstable behavior of the loop under certain faulted conditions.

3. Testing of the refrigerator system against a realistic dummy load. This will be carried out after actual installation of the refrigerator system into the ANS facility because it is too large and complex to make double installation practical. This allows maximum refrigeration and low-power operation to be simulated and a full cooldown to be demonstrated. Cooldown can be carried out with the refrigerator already operating in standby or by cooling the refrigerator and loop together.

These tests will provide valuable information regarding the anticipated behavior of the final cold source system, allowing any necessary modifications to be carried out in good time before final installation.

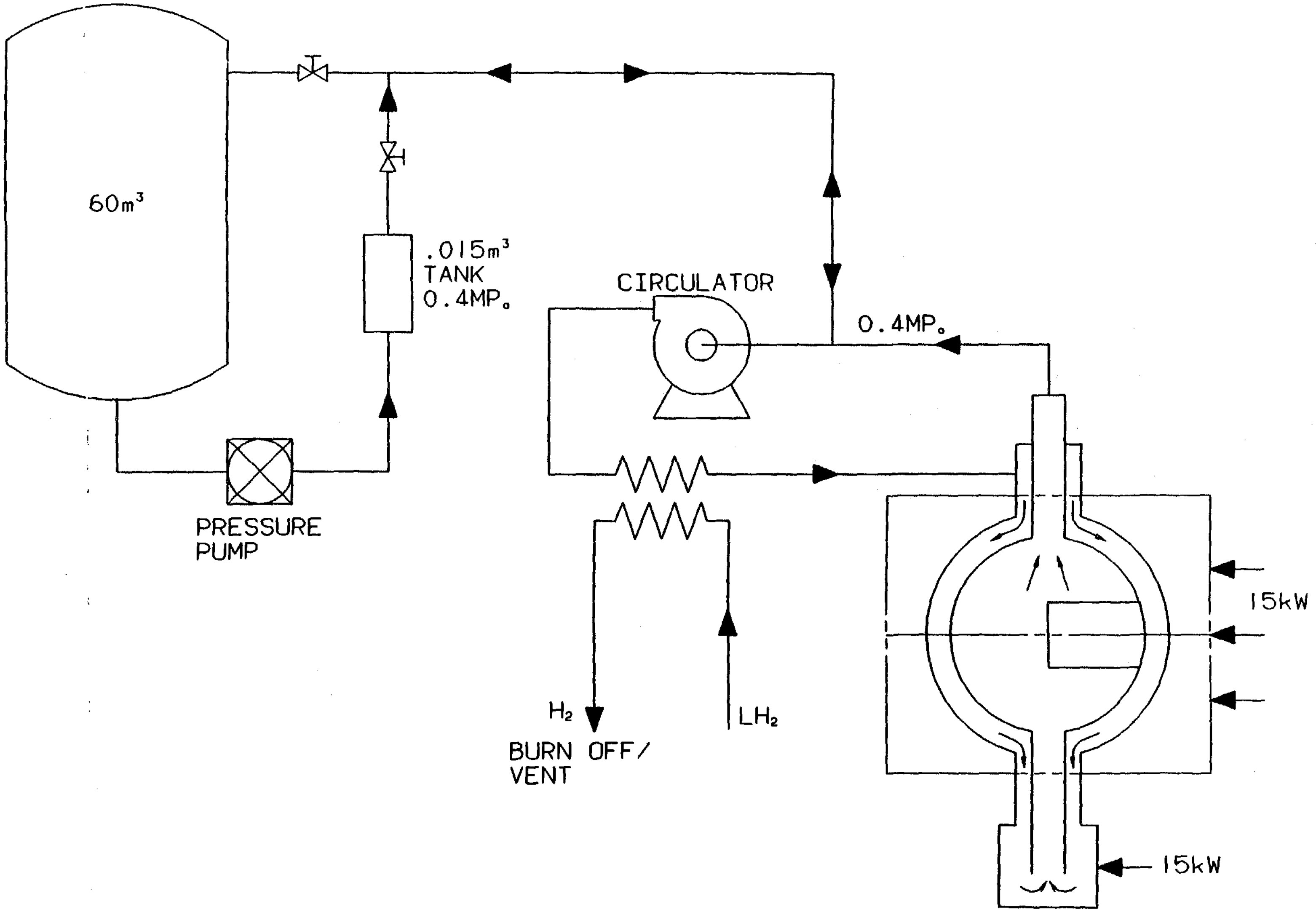


Fig. 18. Test loop for full-power testing.

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