SAFETY ANALYSIS REPORT ON THE D_2O COLD NEUTRON SOURCE FOR THE NATIONAL BUREAU OF STANDARDS REACTOR

NBSR 13

NBS Reactor Radiation Division
Center for Materials Science

August 1984

NBS

U.S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

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SECTION 1. INTRODUCTION

1.1 PURPOSE

The purpose of the National Bureau of Standards (NBS) cold neutron source is to enhance the intensity of cold neutrons available for materials research using neutron methods. Many experiments require the use of low-energy (cold) neutrons. The intensity of these neutrons can be greatly increased by putting a cold moderating material adjacent to the reactor core that can be viewed by one or more beam holes. Cold sources are being used extensively in Europe, but only one is currently operating at a U. S. reactor. Those in Europe and the current one in the U. S. use liquid hydrogen or liquid deuterium, whereas NBS plans to use cold D_2O ice.

1.2 CONCEPT

The neutron energy distribution in a reactor is approximately Maxwellian with a temperature near the temperature of the moderator. In most research reactors, the neutrons in the peak of the distribution have a wavelength of about 1.8 Å. A neutron wavelength greater than 4 Å is required for many experiments and for the efficient use of neutron guides. The normal energy distribution, peaking at 1.8 Å, includes only 2 percent of the neutrons with a wavelength equal to or greater than 4 Å. If the temperature of the distribution can be lowered significantly, the intensity of these long wavelength neutrons can be increased by a large factor (5 to 20 or more). This can be done in a local region by the installation of a cold source which contains moderating material at as low a temperature as is reasonably achieveable--usually in the 20 K range.

The NBSR is the only reactor in the U.S. designed to accommodate a large cold source. Figure 1 is a plan view of a segment of the reactor showing the configuration of the cold source and the arrangement of the two beam tubes that view it. D_2O ice was chosen as the moderator because earlier tests (1) indicated that it would provide fluxes in the 4-8 A range comparable to those from a liquid hydrogen source and would perform somewhat better at longer wavelengths. The large size of the beam tube allows the use of D_2O rather than H_2O. Although D_2O does not moderate as well as H_2O, it has a much lower thermal neutron absorbtion cross section. Therefore, D_2O is better when a large volume is available, particularly for the longer wavelength neutrons. As can be seen in figure 1 and in more detail in figure 2, the ice chamber is provided with a reentrant hole which allows more of the cold neutrons to be extracted from the cold source. The ice is cooled by helium gas from a refrigerator and is designed to operate at approximately 25 K. The ice chamber is vacuum insulated within an outer jacket and the whole assembly (the cryostat) is mounted on a shielding plug.

In order to reduce the D_2O ice heating rate, the cryostat is surrounded by a gamma radiation shield, which is mounted on a separate shielding plug. The cryostat and its mounting plug are inserted inside the shielding plug. The shielding plug is a straightforward design consisting of water cooled lead and bismuth shielding which has already been reviewed and approved by the NBSR Safety Evaluation Committee, so it will not be discussed in more detail in this report. To further reduce the ice heating, the cryostat is constructed of a magnesium alloy whose neutron absorbtion is about one-third that of aluminum thus significantly reducing the capture γ-ray heating in the ice chamber. During 20 MW reactor operation, the heat load on the ice filled chamber is expected to be 1100 W.

1.3 PREVIOUS EXPERIENCE

There is extensive experience in Europe on the use of liquid deuterium and hydrogen for cold sources and experience in the U. S. with liquid hydrogen at the Brookhaven National Laboratory. The major experience in the use of ice has been at the Argonne National Laboratory (ANL) and the Massachusetts Institute of Technology (MIT). At ANL, a D_2O ice cold source similar to the one proposed here was operated in the CP-5 reactor. They had no safety related difficulties with the ice and demonstrated that it is a sound, safe moderator. At MIT, several D_2O ice cold sources were installed and tested in the reactor thermal column. These tests and measurements took place over several years and demonstrated the practicality of using D_2O ice as a cold neutron source.

1.4 SAFETY CONSIDERATIONS

1.4.1 INTRODUCTION.

The major safety consideration in most of the existing cold sources is the energy release that could take place from the hydrogen-oxygen or deuterium-oxygen reaction. This has been successfully addressed at many reactors here and abroad, but this concern is eliminated by the use of D_2O ice. The concerns for the D_2O moderator are those associated with the cooling and structural integrity of components installed within the confines of the reactor; the prevention of ozone buildup on the cold surfaces of the vacuum chamber; and the radiolysis of the ice in the radiation field.

1.4.2 CRYOSTAT COOLING. The ice chamber is cooled by cold helium gas from a helium refrigerator. If that system should fail, a back-up compressor will circulate helium gas through a liquid nitrogen cooler and then into the cryostat to keep the ice well below freezing. Should all cooling fail at 20 MW reactor operation, the ice temperature would rise rapidly at first then more slowly at higher temperature. More than an hour would be required to reach the melting point of ice providing ample time to take corrective action or shut down the reactor. The heating rate is reduced to 85 W immediately after reactor shutdown, falling to 17 W one hour after shutdown. This is less than the heat leak through the cryostat insulation at low temperature (~ 50 W).

At the full reactor power of 20 MW, the heat generation in the vacuum jacket is approximately 400 W. This heat can be removed by air convection to the Bismuth Tip and conduction to the base plate. Although this cooling is adequate to keep the temperature of the vacuum jacket well below the melting temperature of magnesium, the jacket temperature might reach a value at which creep becomes a factor. This could result in some deformation. Therefore, water cooling coils, external to the vacuum jacket, are provided.

1.4.3 OZONE GENERATION IN VACCUM CHAMBER. If air should leak into the insulating vacuum it would condense on the cold surfaces of the ice chamber. Some of the condensed oxygen in the air would be converted into ozone by radiation. Subsequently, it could revert to oxygen exothermally. To assure that air cannot inadvertently enter the vacuum chamber, all components of the vacuum system are enclosed by helium. The free volume in the ice chamber is also filled with helium. Thus, any leak into the vacuum will be helium instead of air, and, since the helium would not condense on the cold surfaces, a leak would cause an increase in the vacuum pressure indicating the presence of the leak.

1.4.4 RADIOLYSIS OF ICE. The radiation field in which the cold source is located will cause radiolysis of the ice. In water moderated reactors, the volatile products of the radiolysis, O_2 and H_2/D_2 escape into a cover gas which sweeps the liquid surface and is either vented or put through a recombiner to maintain a low H_2/D_2 concentration. In the case of ice at the low temperature (25 K) of the cold source, some radiolysis products will be retained in the ice until the ice is warmed up. Thus, their concentration could build up and create the possibility of a sudden recombination when the ice is warmed up and the oxygen and hydrogen become mobile.

Based on experience at Argonne National Lab where a similar ice cold source was installed and on measurements of the radiolysis of ice, the release of gaseous radiolysis products should present little difficulty. Measurements(2, 3, 4) show that extensive recombination to form D_2O takes place in the ice even at low temperatures. Calculations based on these measurements show that an equilibrium condition is approached between production and recombination resulting in small steady state concentrations of radiolysis products. Extrapolation from data at lower radiation doses indicates that the amount of deuterium produced by radiation in the proposed cold source would be less than 1 g in the total volume. The experience at ANL showed no problems with the radiolysis products. Measurements were made on the release of oxygen and deuterium from the cold source as it was warmed up after irradiation. These measurements showed that the deuterium came out at relatively low temperatures and that the oxygen was not released until the ice was close to the melting point. These releases were easily handled by pumping on the system during warm-up. Measurements of the gaseous releases were consistent with the quantities anticipated from the calculations. A series of measurements of the gaseous releases from the ice during warm-up will be made as part of the cold source startup procedures to confirm release patterns and equilibrium concentrations.

SECTION 2. DESIGN

2.1 INTRODUCTION

The cold source system is designed to maintain 20 L of D_2O ice at about 25 K in a high-flux region of the NBSR. The ice chamber is vacuum insulated and cooled by helium gas from a helium refrigerator capable of removing 1100 W at 25 K. The cooling gas is passed through coils embedded in the ice. To prevent any air leaking into the vacuum and condensing on cold surfaces, the vacuum insulation is enclosed in a helium containment system. To prevent air condensing in the ice chamber, a separate helium cover gas system is provided which is also enclosed within the same helium containment system used to protect the vacuum. Ice is formed in place by freezing water, using liquid nitrogen (LN_2) coils in the bottom of the ice chamber. Once the ice has been frozen, the LN_2 lines are evacuated and backfilled with helium to become part of the helium cover gas system.

The main design features are the ice chamber and vacuum jacket which constitute the cryostat proper; the helium containment system; the helium cover gas system; the vacuum system; the helium cooling system; and the ice making system.

2.2 CRYOSTAT

2.2.1 INTRODUCTION. The cryostat is shown in figure 2. It consists of an ice chamber, a vacuum jacket/helium containment jacket combination, a base plate, and a variety of connecting lines. The helium cooling lines are vacuum jacketed and the vacuum chamber is pumped through these vacuum lines. The cryostat consists of the ice chamber with its associated tubing and the water cooled double-walled vacuum jacket that also serves as part of the helium containment.

2.2.2 ICE CHAMBER. The ice chamber (figures 2 and 3) is a 14" diameter cylinder with elliptic ends and is 13" long. A reentrant hole 8" in diameter and 6" deep is provided to extract cold neutrons from near the center of the cryostat. The chamber is fabricated from 1/16" magnesium alloy AZ31B and is of all welded construction. Certified materials and welders will be used and the welds will be radiographed.

Several lines enter the ice chamber. The ice is cooled by helium cooling coils. D_2O to form the ice enters through a tube which does not make direct contact with the ice chamber. Since it is anticipated that the ice will be frozen one layer at a time, it is necessary to add water to the ice chamber while it is being cooled to freeze the ice. Therefore, to avoid freezing the D_2O inlet line during ice making, the line is not welded directly to the ice chamber but runs inside another tube that is welded to the ice chamber to make the vacuum seal. A vent line is provided to vent the helium or nitrogen displaced in the ice chamber by the water. It is similarly insulated from direct contact with the ice chamber. The remaining lines are the LN_2 inlet and outlet lines used to make the ice and the D_2O drain line.

The two sets of concentric lines are straight and surrounded by a vacuum for about two feet from the cryostat to minimize heat conduction. All the other lines are increased in length to reduce heat conduction and to provide flexibility to allow for differential thermal expansion by coiling them in the vacuum space provided in the back of the cryostat.

The ice chamber is designed to be evacuated, when desired, resulting in a possible external pressure of one atmosphere, and to operate with up to two atmospheres internal pressure.

During reactor operation at 20 MW, the ice chamber heating rate is calculated to be 1100 W. This is removed by the coils embedded in the ice through which cold helium gas from a helium refrigerator is circulated. The refrigerator is equipped with a small backup compresser that will continue to circulate helium, cooled by a LN_2 bath, through the cooling coils to maintain the ice below freezing. Should that fail, LN_2 could be circulated through the LN_2 coils in the ice chamber as a short term backup. Should all cooling fail, the ice will warm up slowly, even at full reactor power. Figure 4 shows the calculated temperature of the ice as a function of time after loss of cooling at full reactor power. One hundred minutes is required for the ice to approach its melting point, providing ample time to investigate the cause and shut down the reactor if necessary. If the reactor is shut down, the heating rate drops by more than a factor of ten and, of course, the temperature rises much more slowly.

The volume of D_2O in the ice chamber is less than 24 L. Based on reactivity worth measurements in that region of the reactor reflector, the reactivity worth of the D_2O is estimated to be less than 45 cents, which is well below the Technical Specifications' limit for insertion and removal during operation.

2.2.3 VACUUM JACKET. The vacuum jacket is composed of an inner shell sealing the ice chamber in a vacuum and an outer shell which contains a helium atmosphere around the inner vacuum shell. These shells are arranged as shown in figure 2, welded to a two-piece base plate, and cooled by external cooling coils. The various lines from the ice chamber pass through the base plate into a helium filled box that extends through the reactor shield (figure 5). The LN_2 and cold helium lines are vacuum jacketed all the way through the box. The other lines are vacuum jacketed one foot into the box. All the vacuum jackets are welded to the inner portion of the base plate.

The space between the inner and outer shells of the vacuum jacket and between the two sections of the base plate are filled with helium as part of the helium containment system. Thus, the insulating vacuum is completely enclosed within helium. The inner shell of the vacuum jacket supports the ice chamber and is designed to operate with an internal vacuum and to support a differential pressure of 30 psi from either direction.

The base plate of the vacuum jacket is secured to a spacer which in turn is attached to the shielding plug. The spacer is water cooled and the outer shell of the vacuum jacket is cooled by closely fitting cooling tubes which are connected to the spacer cooling system. The inner shell of the vacuum jacket is cooled by conduction through the helium to the outer shell. The total heating rate in the vacuum jacket is less than 400 W, so only minimal cooling is required. If the water cooling failed, the jacket would still be cooled by convection through the CO_2 between the radiation shield and the jacket to maintain the jacket's maximum temperature below 200°C. This is not an immediate threat to the structural integrity of the system, but might result in long-term creep that could cause some deformation of the jacket.

The base plate is constructed of two plates with a helium filled gap between them. Each plate has a thin window for the neutron beam. The windows will withstand an overpressure of 200 psi.

2.3 HELIUM CONTAINMENT SYSTEM

2.3.1 INTRODUCTION. A concern common to all vacuum low temperature cryostats located in a radiation field is the leakage of air into the vacuum space. The cold surfaces act as a fast vacuum pump by condensing out (cryopumping) any leaking air. Consequently, if air leaks in, there is no pressure build-up to indicate a leak, which therefore could go undetected for a long period of time. This could result in a large buildup of frozen air on the cold surfaces. The oxygen in the air could then be converted to ozone by the radiation. Ozone is unstable and can revert back to oxygen exothermally. This situation is avoided by enclosing the vacuum jacket with helium. If a leak develops, helium, which cannot be cryopumped at 25 K, will enter the vacuum causing the vacuum pressure to rise. Even if the helium should contain some air, very little will enter and be condensed before the helium pressure would rise sufficiently to be easily detected and thus provide a warning.

The helium containment system includes the helium around the inner shell of the cryostat vacuum jacket and within a helium filled box. The box contains all the lines from the ice chamber, the cover gas system and junctions, valves, etc.

2.3.2 CRYOSTAT HELIUM CONTAINMENT. Section 2.2 described the helium containment around the cryostat. The cryostat containment is interconnected to the containment box to form the overall helium containment system.

2.3.3 HELIUM CONTAINMENT BOX. A helium containment box which encloses all the lines from the ice chamber is welded to the cryostat base plate. It is filled with helium to provide the helium containment. Figure 6 is a flow diagram of the helium and vacuum system. The containment box will be evacuated to remove any air in it before filling with helium. The helium is maintained at a pressure of approximately 2 psig. This assures that air cannot leak into the tube box through any but the smallest leaks, where diffusion processes are predominant.

The helium containment box is also filled with shielding material to prevent radiation streaming. The pressure of the helium containment will be monitored regularly. If the pressure falls by more than 1 psi, the containment gas will be sampled for the presence of air before readjusting the pressure. A pressure rise to more than 7 psig will activate a pressure release valve.

2.3.4 HELIUM CONTAINMENT BOX PENETRATIONS. The helium cooling lines are vacuum insulated all the way from the refrigerator to the cryostat. It is not necessary to have helium containment for the external transfer lines (which are not in a radiation field) so a special connection is required where they enter the tube box. This connection is shown schematically in figure 7. The vacuum around the external transfer line is terminated some distance into the containment box and the vacuum jacket sealed to the box. It is anticipated that the vacuum will be pumped down to the order of 10^{-5} torr while the cryostat is warm. Then the vacuum valve will be closed and the external line either back filled with helium or maintained evacuated. Thus, any leaks into the vacuum system or through the valve will not introduce air into the vacuum. If continuous pumping is necessary to maintain a satisfactory vacuum, the pumping system will be enclosed within the helium containment system and exhausted to the containment system.

All other lines are valved before they leave the helium containment with the external portions being evacuated or back filled with helium.

2.4 COVER GAS SYSTEM

To enhance thermal conduction within the ice (which will develop cracks as it freezes), the ice chamber is provided with a helium cover gas. To avoid ozone formation, air must not be allowed to leak into the system. Therefore, the entire cover gas system, including the cover gas ballast tank, is completely enclosed within the helium containment box (see figure 5). It is also maintained at a higher pressure than the containment gas so that any small amount of air in the containment gas will not leak into the cover gas even if a small leak would occur, except by the very slow diffusion process.

All of the lines opening into the ice chamber are part of the cover gas system. The LN_2 lines and the drain line are also part of the system. Each of these lines is valved into the ballast tank as shown in figure 5. During operation these valves are normally open so that all lines are interconnected through the ballast tank.

The purpose of the ballast tank is to accommodate changes in cover gas pressure resulting from temperature changes in the ice chamber. Since helium is almost an ideal gas even at 25 K, its pressure is proportional to the absolute temperature. Thus, if the cover gas were confined to the free volume in the ice chamber and the temperature were to rise from 25 K to an ambient temperature of 300 K, the pressure would increase by a factor of twelve. In order to maintain the pressure of the cover gas above that of the containment gas during operation at 25 K and still maintain acceptable pressures during periods of warmup, a ballast tank is used. This tank is sized so that the pressure rise resulting from a temperature increase from 25 K to 300 K is approximately a factor of one and one half.

Although most of the lines are interconnected at the ice chamber, each line is connected separately to the ballast tank. If only one line from the cryostat were connected, which would be adequate under normal conditions, it could possibly become plugged by vapor condensing and freezing. In that case, the pressure in the ice chamber could rise by a factor of twelve if the ice should warm up, resulting in a severe overpressure of the chamber. Therefore, each line is connected independently to the ballast tank so that four lines would have to plug simultaneously to over pressurize the ice chamber.

Since the pressure of the cover gas is a function of the temperature of the ice chamber, it can be used to monitor the temperature. A pressure gauge in the cover gas will be used to monitor the ice chamber temperature and provide an alarm if the temperature should rise significantly.

2.5 VACUUM SYSTEM

The evacuated regions within the helium containment include the cryostat vacuum insulation, the vacuum jacket around the LN_2 transfer lines, and the vacuum jacket around the helium cooling lines. The LN_2 vacuum jacket is terminated within the helium containment box and solid insulation is used for the remainder of the line. The vacuum jacket around the helium cooling lines are used as the vacuum pumping lines as indicated in figure 5. A vacuum separator, as discussed in Section 2.3.4, isolates the vacuum within the helium containment from the vacuum of the external helium transfer lines. The two vacuum jackets are joined near the helium transfer line penetrations, and a single vacuum lines goes to a pumping station.

A valve and pressure gauge are located inside the helium containment. The pumping station is used to evacuate the system before the ice chamber is cooled. Since the ice chamber acts as a large cryopump, it may not be necessary to use the pumping station continuously. When it is not needed, the vacuum valve will be kept closed during operation. Whenever the valve is shut, the downstream line is evacuated or backfilled with helium.

Since the vacuum is enclosed in helium, any leak will cause an increase in the pressure. This will be sensed by the vacuum gauge and generate an alarm.

2.6 HELIUM REFRIGERATION SYSTEM

The ice is cooled by cold helium gas flowing through cooling coils embedded in the ice. The helium transfer lines within the helium containment are vacuum jacketed as discussed in previous sections. The external lines are super-insulated helium transfer lines. A flow diagram of the helium refrigerator is shown in figure 8. The system is designed to provide 1100 W of refrigeration when the helium gas returning from the heat load is at a temperature of 30 K. The system is composed of four basic units: the compressor, cold box (containing the heat exchangers and associated low temperature equipment) an expansion turbine, and an emergency refrigeration system.

2.6.1 COMPRESSOR. The compressor used in this system is an Allis-Chalmers, oil-lubricated, three stage, rotary vane machine. An intercooler and an aftercooler are provided to reduce the temperature of the helium gas leaving the compressor. An oil separator and activated charcoal adsorbers are used to purify the gas stream before it enters the cold box.

2.6.2 COLD BOX. The cold box contains the heat exchangers, including a liquid nitrogen precooling exchanger, expansion turbine, and associated valves and piping. A high vacuum (10^{-5} torr or better) is maintained inside the cold box to provide insulation for the low temperature components. In addition, the coldest components are wrapped with multilayer insulation in order to minimize heat transfer by radiation.

2.6.3 TURBINE. The turbine expander is a small, high-speed machine supported on externally pressurized gas bearings. The bearing supply gas is taken from the compressor discharge. The work absorbing part of the turbine assembly is a small blower machined on one end of the end turbine shaft. This circulates helium gas through a water cooled exchanger to absorb the work done by the turbine. The helium side of the exchanger is vented to the compressor suction, allowing the turbine assembly to be sealed into the helium filled system.

2.6.4 EMERGENCY REFRIGERATION SYSTEM. A small refrigeration system using liquid nitrogen as the refrigeration source can be switched to maintain the load temperature below the freezing point of water in the event of failure in the main refrigeration system. This system has a helium make-up manifold, compressor, and cold box separate from the main system. The auxiliary heat load can also be manually changed from the main refrigeration system to the emergency refrigeration system.

2.6.5 HELIUM MAKE-UP AND PURIFICATION. A cylinder manifold is provided to supply helium gas to replace any that may be lost from the system. Charcoal adsorbers are provided in the compressor discharge line to remove oil. A small, activated charcoal purifier is in the high pressure line following the liquid nitrogen heat exchanger to remove trace impurities.

2.7 VACUUM JACKET COOLING SYSTEM

The outer shell of the vacuum jacket is cooled by close fitting cooling coils and the inner shell by conduction to the outer shell through the narrow, helium-filled space between the shells. The coolant will be D_2O from the D_2O Experimental Cooling System. The D_2O comes from the reactor primary cooling system. A booster pump is used to assure adequate pressure for the experimental facilities cooled by D_2O. A backup booster pump is also provided and both pumps are served by the reactor emergency power system if there is a loss of commercial power. Therefore the D_2O Experimental Cooling System is as reliable as the reactor cooling system.

2.8 ICE MAKING SYSTEM

Ice will be formed in the ice chamber with the reactor shut down. The ice will be frozen in layers to eliminate stress on the ice chamber. D_2O enters the ice chamber through the D_2O fill line. The D_2O fill and vent lines are shown in figures 2 and 3. Thermocouples are attached to the tips of the fill and vent lines to monitor their temperatures during the freezing process.

The freezing procedure puts a fixed quantity (approximately one liter) of D_2O into the cryostat through the D_2O fill line. The gas displaced by the D_2O is vented to the atmosphere through the vent line. Initially a small flow of nitrogen is established through the drain line to assure D_2O does not rise in it, freeze, and burst the line. Next, the LN_2 flow is started. When the gaseous nitrogen flow through the drain stops, the drain is sealed, preventing additional D_2O from entering. Another layer of D_2O is added after the first layer is completely frozen. After a predetermined length of time to permit the second layer of D_2O to completely freeze, a third layer is added. This process is repeated until all the ice chamber is filled with ice.

The temperature of the returning LN_2 which returns as vapor is a good indication of the temperature of the ice adjacent to the cooling tubes. This information combined with the temperature information from the thermocouples on the fill and vent lines is used to determine the appropriate rate of LN_2 flow.

Once the ice has been formed, it is cooled to near 90 K by the LN_2. Then the LN_2 is shut off and the ice chamber and all lines associated with the cover gas volume are evacuated. Finally, the ice chamber is back filled with helium to the appropriate pressure to provide the cover gas. The helium fill line is then valved off leaving a fixed mass of helium in the cover gas system. The helium cooling is now started and the ice chamber is cooled to its operating temperature as determined by the pressure of the cover gas and the return temperature of the helium refrigerant. Final adjustments are made in the cover gas pressure as needed once stable operating conditions are attained at full reactor power.

SECTION 3. CONTROL AND INSTRUMENTATION

3.1 INTRODUCTION

The control and instrumentation flow diagram is shown in figure 6. Once the ice has been formed and the cover gas volume evacuated and back filled with helium, the valves are aligned to open the cover gas system to the ballast tank and isolate it from the external lines. The external lines are back filled with helium or evacuated. Once these valves are aligned, they remain in that status throughout normal operation.

The complex array of lines and valves external to the helium containment simply provide for evacuation or helium back fill of external lines and for the ice freezing operation described in section 2.7. Only valves 13, 14, 15, and their associated lines have a direct role in normal operations and control.

3.2 HELIUM CONTAINMENT

The helium containment is initially evacuated to remove any air that might be present and then back filled with helium to a pressure of about 17 psia as determined by PG-1. This is about 2 psi greater than normal atmospheric pressure to assure that no air leaks into the helium containment. If PG-1 falls below 16 psia, an alarm will sound indicating a possible leak in the containment box. If a leak is suspected, a gas sample will be analyzed for air. If no significant amount of air is found, the helium containment is continuing to perform its function and the system will be repressurized to 17 psia. If the pressure continues to fall, more frequent samples will be taken and remedial action will be taken at the first opportunity. Note that if the leak were into the vacuum, it would be detected by the vacuum instrumentation long before any loss of pressure would be indicated by PG-1 in the helium containment system. The helium containment is protected against damage from overpressure by a pressure relief valve set to open at about 5 psi above normal operating pressure.

3.3 COVER GAS SYSTEM

After completing the ice making process in the ice chamber, the ice is cooled to about 100 K using the LN_2 coils. The cover gas region is evacuated during the initial cooldown. Once the ice chamber has cooled to about 100 K, the LN_2 flow is stopped. The system is then back filled with helium. The back fill pressure is chosen to give a pressure of about 19 psia when the ice chamber is cooled to 25 K. The 19 psia is 2 psi higher than the containment pressure, as discussed in section 2.4.

A differential pressure gauge measures the pressure differential between the cover gas and the containment gas. If it drops below 1 psi, an alarm is sounded indicating a possible leak from the cover gas to the containment gas. If a leak is suspected, the cover gas may be evacuated. Once a good vacuum is obtained, a gas analyzer can be used to look for helium leaking from the containment gas. This will determine if a leak exists and provide information on the leak rate on which to base future action. (The ice chamber may be evacuated during operation. The only detrimental effect would be less efficient cooling of the ice.)

The pressure of the cover gas is a reliable indication of the approximate temperature of the ice chamber. In the 25 K range an increase of 5 K would increase the pressure about 1 psi. Therefore, a high pressure alarm on PG-2 can be used to indicate a temperature rise.

A temperature rise to 80 K (LN_2 temperature) would release much of the deuterium formed by radiolysis. The deuterium released in this way would immediately be absorbed by the getter in the cover gas system shown in figure 6. The getter will be open to the cover gas system at all times during operation except when measurements of deuterium production are being made. Thus, the getter will play the role of a "helium sweep" system to assure that no deuterium builds up in the system.

If the helium cooling line in the ice chamber should develop a leak, the cover gas system could be overpressurized. To prevent damage, a pressure relief valve is set to open and alarm at about 5 psi above the warm cryostat operating pressure of the cover gas. The pressure relief valve is located in, and vents to, the helium containment which in turn is protected by its own pressure relief valve.

3.4 VACUUM SYSTEM

The vacuum region provides the thermal insulation for the ice chamber, and it will normally be evacuated at all times. However, if there is occasion to leave the ice chamber empty with no cooling, the vacuum will be back filled with helium or nitrogen in order to provide cooling to the ice chamber by thermal conduction and convection to the vacuum jacket and the water cooled plate to which the cryostat's base plate is attached.

The vacuum jacket is completely contained within the helium containment gas. If there is any leak in the system, helium will enter the vacuum and the pressure will rise. This will activate an alarm initiating action to investigate the cause. If the pressure should rise enough to spoil the vacuum insulation, the helium refrigerator would be shut down.

If a leak should develop in the helium cooling lines, it would be possible to overpressurize the vacuum region. To prevent damage, a pressure release valve in the vacuum system is set to open and alarm at about 5 psig. The valve is within the helium containment and vents to that region. The helium containment is also protected by a pressure relief valve set to open at about 7 psig. Thus, overpressurization of the vacuum system will vent to the helium containment which in turn will vent to the atmosphere.

3.5 HELIUM REFRIGERATOR

3.5.1 INTRODUCTION. The flow diagram for the helium refrigerator is shown in figure 8. The main components are the compressor, cold box, turbine, and an emergency refrigeration system. If the refrigerator should shut down, the cryostat temperature would rise and the cryostat temperature and pressure monitors would indicate the situation without any signal from the refrigerator. On the other hand, gross failure of the vacuum insulation or cold helium leakage into the ice chamber would initiate refrigerator shutdown.

The controls and instruments for the refrigerator are given below.

3.5.2 COMPRESSOR. The compressor is equipped with safety valves after each stage. The valves are vented, through a manifold, to the compressor suction. The intake line valve (SV-2) is vented to the atmosphere. An automatic by-pass valve is provided between the compressor intake and discharge lines. This valve is sized such that 100 percent of the compressor output can be automatically by-passed.

Pressure gauges, mounted on the graphic panel, are provided to monitor the compressor operation. Duplicate gauges are also located on a small panel in the compressor room.

Thermocouples are provided at the compressor to monitor cooling water temperatures and compressor intake and discharge temperatures.

Safety cut offs are provided to shut the compressor down in case of excessive cooling water temperatures, excessive helium discharge temperatures from each stage, and low intake pressure.

3.5.3 COLD BOX. Safety valves are provided at appropriate points in the system to prevent damage in case of excessive pressure. These safety valves are vented through a manifold to the compressor intake.

Manual valves (V-6, V-7, V-10, V-38) are provided to isolate the cold box from the compressor.

A solenoid operated shutoff valve is provided in the compressor discharge line (V-8) for emergency shut off of the turbine supply gas. This valve is operated by (a) turbine overspeed; (b) low bearing gas pressure; (c) low emergency bearing gas supply; and (d) manually. It must be reset manually after it is operated.

Pressure gauges are provided to monitor pressures throughout the system.

Vapor pressure thermometers are provided at the inlet and outlet of both the high pressure and low pressure streams of HX-3. The thermometers at the high temperature end are filled with pure nitrogen. The thermometers at the low temperature end are filled with pure hydrogen. The hydrogen vapor-pressure thermometers are provided with ortho-para catalyst, assuring an equilibrium concentration of para hydrogen over the operating range of the thermometer. The thermometer gauges are read in pressure units which must be converted to temperature using a vapor pressure-temperature table.

3.5.4 TURBINE. Safety controls. The turbine safety control system is designed to close valve V-8 in the high pressure helium line when: (a) the turbine speed exceeds a preset level; (b) the bearing supply pressure drops below 90 psig; and (c) the bearing emergency supply drops below 500 psig. In addition a manually operated momentary contact switch can be used to close the solenoid valve.

Pressure gauges are provided to monitor the bearing supply pressure, emergency bearing supply pressure, brake circuit pressure, and labyrinth differential pressure.

Hydrogen vapor pressure thermometers are provided in the turbine inlet and outlet streams.

3.5.5 EMERGENCY REFRIGERATION SYSTEM. Safety valves are provided at appropriate points in the system to prevent damage in case of excessive pressure. These safety valves are vented through a manifold to the main system gas holder.

Automatic air actuated valves are provided to change the heat load from the main refrigeration system to the emergency refrigeration system.

Pressure gauges are provided to monitor pressure throughout the system.

Thermocouples are provided to monitor temperature throughout the system.

An automatic heater is provided to maintain the compressor inlet temperature.

3.6 WATER COOLING SYSTEM

Water cooling is provided to the vacuum jacket of the cryostat by external cooling tubes and to the spacer between the cryostat and the shielding plug. The water cooled front plate of the spacer makes good thermal contact with the cryostat base plate to provide additional cooling to the vacuum jacket. Although no immediate damage would be done to the cryostat if the water cooling should fail, the cryostat temperature could rise as high as 200°C which might result in long term creep and possible deformation of the vacuum jacket. Therefore, it is important to maintain the water flow. The coolant is provided by the reactor experimental D_2O cooling system which is highly reliable. It is equipped with redundant pumps which are provided with back-up electric power from the reactor emergency power system.

The cooling flow is monitored and alarmed. If it cannot be restored within a few hours, the reactor will be shut down and appropriate action taken.

SECTION 4. OPERATIONS

4.1 INTRODUCTION

It is anticipated that the ice will be kept frozen for long periods of time, subject to the availability of primary or backup cooling. Once the ice has started to melt, it will be necessary to melt it completely and drain the ice chamber before new ice can be made. As the ice warms up, the products of radiolysis (deuterium and oxygen) will be released with the deuterium coming out at much lower temperature than the oxygen. Measurements reported in the literature (2, 3, 4) and calculations indicate that close to a steady state condition is reached at large radiation doses with only small concentrations of deuterium and oxygen. Therefore, it is anticipated that the duration of a continuous freeze will be determined by operating and programmatic needs rather than by the build up of radiolysis products. Whenever it appears desirable, the radiolysis products can always be annealed out by raising the ice temperature to just below the freezing point without melting the ice.

The operating procedures and controls make use of the fact that the mass of ice warms up slowly if cooling is lost providing ample time to take appropriate action.

4.2 INITIAL CONDITIONS

Initially, when the ice chamber is empty and no cryogenic cooling is provided, the ice chamber is filled with helium or nitrogen and cooled by back-filling the insulating vacuum with helium or nitrogen. This provides ample cooling by convection to the water cooled vacuum jacket and base plate. The helium pressure would be set at about 1 psig in both the ice chamber and the insulating vacuum region.

4.3 STARTUP

The reactor is down during cryostat startup so that heating of the ice chamber is not significant. The first step is to evacuate the insulating vacuum space. When an adequate vacuum is obtained, the ice making procedure is initiated. This procedure has already been described in section 2.8. Nitrogen is used as the cover gas during this operation in order to conserve helium. When the ice has been formed and cooled to near 90 K by the LN_2, the LN_2 cooling is stopped and the cover gas system including the LN_2 lines are evacuated. After all residual gas has been removed, the cover gas system is backfilled with helium. Finally, the helium cooling is started and the ice cooled to its operating temperature of 25 K. The reactor may be started up any time after the helium cooling of the ice has been started.

4.4 NORMAL OPERATION

The following items are monitored during normal operation:

Helium refrigerator parameters
Vacuum pressure
D_2O coolant flow to vacuum jacket
Cover gas pressure
Containment gas pressure

In the case of the last four items, variations outside of established parameters initiate alarms. An alarm may indicate that certain adjustments are needed or may indicate an abnormal event. Abnormal events are discussed in section 4.6. Routine adjustments are discussed here.

If an adequate insulating vacuum can be maintained with the vacuum valve closed, the system will be operated in this mode with periodic pump downs. Because of the size and complexity of the system, however, it may be necessary to pump continuously. The vacuum pressure will be monitored for indications of pressure changes that could indicate the presence of leaks. The amount of air that could be introduced through such leaks is discussed in section 4.6.

The D_2O coolant flow to the vacuum jacket cooling coils is monitored and alarmed. If the coolant should fail, the peak temperature at the vacuum jacket hot spot would not exceed 200°C. This is well below the melting point of the magnesium alloy, but high enough so that long term creep could occur. This would not result in immediate damage to the jacket but might result in damage over a protracted period of time. Thus, if the D_2O low flow alarms, there is ample time to investigate the cause. If flow cannot be restored within a few hours, the reactor will be shut down until the situation is remedied.

A decrease in the pressure of the cover gas would be most clearly indicated by the gauge which measures the differential pressure between the cover gas and the containment gas. If the differential pressure drops below 1 psi, an alarm is triggered, indicating a drop in the cover gas pressure. This could be caused by loss of cover gas or a decrease in the temperature of the cryostat. If a check of the helium refrigerator parameters indicate no change in cryostat cooling and the reactor power has not changed, a leak in the cover gas system must be suspected. This can be confirmed by evacuating the cover gas system which can be done during operation and checking for helium leaking in from the containment gas region. If the leak rate is small so that a negligible amount of air can leak in during the time to the next reactor shutdown, the cover gas will be refilled and operation continued until a scheduled shutdown. The containment gas would be checked for air content as part of this procedure to ensure that not enough air is present to cause a problem. If the leak is large, immediate steps would be taken to repair it.

The case of a leak in the containment gas system leading to a slow drop in pressure is discussed in section 3.2. If the air content of the cover gas remains small (less than 10%), the gas can be replenished to maintain the operating pressure. This is permissible since a leak large enough to cause a measurable pressure change in the psi range must be to the outside since a much smaller leak into the vacuum region would be readily detectable. The permissible level of air in the containment gas is discussed in section 4.6.

The temperature of the helium cooling leaving the refrigerator to enter the cryostat and returning from the cryostat is indicated on the refrigerator panel along with the temperature and pressure at various additional points in the refrigerator cycle. The inlet and outlet temperatures will vary depending on the heat load. Normal heat load variations (0 to 1500 W) can be accommodated by the refrigerator system. A temperature controlled heater may be used to maintain the temperature of the return gas if desired. Should any operating parameters deviate from the norm in such a way as to damage the refrigerator, the refrigerator will shut down automatically. If the main refrigerator should fail, the load can be switched automatically to the auxiliary refrigerator. The situation where all refrigeration fails is treated in section 4.6

4.5 SHUTDOWN

The cold source may be shut down with the reactor operating or shut down. The helium cooling is shut off and the cryostat allowed to warm up. When the ice has warmed up to about 100 K, as indicated by the pressure of the cover gas, the cover gas is vented and a nitrogen sweep over the surface of the ice is initiated. This will prevent any of the products of radiolysis from accumulating in the cryostat as the ice warms.

When the ice has melted, the vent is closed and the drain opened allowing the nitrogen to force the water out through the drain. The insulating vacuum is backfilled at this time to provide cooling for the ice chamber. The cryostat is now back to its initial condition.

4.6 ABNORMAL EVENTS

4.6.1 INTRODUCTION. The previous sections described normal operation and the procedures used to deal with anticipated normal deviations from routine operating conditions. This section addresses those abnormal occurrences that could result from major failure of various components of the system.

4.6.2 REFRIGERATION FAILURE. If the main helium refrigerator should fail, the heat load of the cryostat would automatically be transferred to the backup cooling system. This system circulates helium through a LN_2 bath to maintain the ice well below the freezing point. Under these conditions, the ice would warm up releasing most of the deuterium that was formed by radiolysis of the ice. This would be removed by the getter installed in the cover gas system. The system could continue to operate this way for a prolonged period of time, but the effectiveness of the moderator would be severly curtailed. Immediate steps would be taken to reactivate the main refrigerator. If this failed and a long refrigerator shutdown was required, the cryostat system would be shutdown.

If all refrigeration should fail, the system would be shut down as described in section 4.5.

4.6.3 HELIUM COOLANT LEAK. A helium coolant leak could occur either into the ice chamber or into the insulating vacuum. If the leak were into the ice chamber, the pressure would rise causing the differential pressure gauge to alarm. If a check of the thermocouple readings, insulating vacuum pressure, and reactor power indicated that there was no reason to expect a temperature rise, a helium coolant leak into the ice chamber would be suspected. This would be checked by trying to evacuate the cover gas. If the cover gas region could not be effectively evacuated, a leak from the helium coolant would be confirmed and the system shut down. This would involve bypassing the coolant flow at the refrigerator before final shutdown procedures were initiated. If the leak were large, the pressure could rise above 30 psig causing a high pressure alarm and the pressure relief valve to open.

If the leak were into the insulating vacuum, it would probably spoil the vacuum and require the system to be shut down for repairs. If the leak were so small that the vacuum pump could keep up with it, there would be no problem since the helium cooling gas cannot contain any air (it would be frozen out in the helium refrigerator). A large leak would pressurize the vacuum region resulting in a high pressure alarm and the opening of the relief valve (set and ~ 5 psig).

If either the cover gas system or the insulating vacuum system were pressurized by a leak of helium cooling gas, the refrigerator and cold source would be shut down.

4.6.4 VACUUM INSULATION LEAK. If a leak should develop in the vacuum insulation, the response would depend on the magnitude of the leak. If it were so small that the pump could continue to maintain an adequate insulating vacuum, operation would continue. If the leak were too large, the system would have to be shut down to repair the leak. The amount of oxygen that could leak in under two different modes of operation has been analyzed. One mode is the continuous pumping mode and the other is the mode in which the insulating vacuum is isolated by closing the vacuum valve. The latter mode of operation can be used only if the system is very leak tight and outgassing is minimal so that an adequate vacuum is maintained. The following assumptions are made for both modes of operation:

1. The containment gas contains 10% air by volume (2% O_2).
2. The helium and oxygen leak rates are inversely proportional to the square roots of their molecular masses. Thus, the oxygen to helium leak rate ratio for the same partial pressure differential is:

$$(4/32)^{1/2} = 0.354$$

3. Air is condensed on the ice chamber so only the helium remains as a gas in the vacuum region.

The continuous pumping mode will be considered first. In this mode the leak rate must equal the exhaust rate and the exhaust rate can be calculated based on the conductance of the vacuum lines and the pressure differential across the vacuum lines going to the pump. The basic formula is:

$$Q = F\Delta P$$

where:

F is the conductance of the vacuum lines

ΔP is the pressure differential across the vacuum lines $\cong$ P. Where P is the pressure in the insulating vacuum.

Q is the flow in liters per second of gas at pressure P.

The conductance, F, can be calculated from kenetic theory and found to be for cryostats vacuum lines:

$$F = 0.40\left(\frac{T}{M}\right)^{1/2}$$

where:

T = gas temperature in Kelvin

M = gram molecular mass = 4 for helium

In calculating F, the impedance of bends, the vacuum valve, and the lines from the vacuum valve to the pump were omitted so F is conservatively high and gives a correspondingly conservative value for the leak rate, Q.

Since the conductance is a function of temperature, the gas temperature must be estimated. The average temperature of the helium between the cold ice chamber and the warm vacuum jacket will be the average of those two temperatures, and, similarly, the gas in the vacuum lines will be the average of the warm outer pipe and the cold inner pipe. Since a vacuum of 5×10^{-4} torr (0.5 micron) is probably as high a vacuum pressure as would provide adequate insulation, that pressure is assumed in the analysis. Thus:

$$\Delta P \cong P = 0.5 \text{ micron}$$

$$T = \frac{320 + 30}{2} = 175 \text{ K}$$

Then the oxygen leak rate is:

$$Q = 1.3 \text{ micron-liters per second}$$

$$= 2.7 \times 10^{-8} \text{g/s} = 71 \text{ mg/month}$$

If this leak rate were to continue a whole year with no warmup above 100 K which would release the oxygen, less than one gram of oxygen would accumulate.

For the closed system mode, a pressure rise of 5×10^{-4} torr per day is assumed. Thus, pumping once a day would maintain an acceptable vacuum. The volume of the vacuum region around the ice chamber is less than 40 L, and the average gas temperature is 175 K as shown above. Under these conditions, the leak rate would be only .01 g/yr.

These analyses show that any leak that could be tolerated and not spoil the vacuum insulation would introduce no more than 1 g of oxygen in a year of continuous operation. The reaction $2O_3 \rightarrow 3O_2$ releases 34 kilocalories per mole of ozone. Thus, if all the oxygen were converted to ozone, the maximum potential energy released by 1 g of ozone reverting back to oxygen would be 0.71 kcal or less than 3000 J. This is less than three times the heat being deposited in the ice every second and so would be only a minor perturbation of normal operating conditions if the energy went into heating the system.

The result of all the energy going into heating the helium and condensed air in the vacuum region is discussed in section 5.

If the leak were significantly larger, it would be difficult to maintain an adequate vacuum to satisfactorily insulate the ice chamber. In this case, the system would be shut down and steps taken to identify the source of the leak.

If a major leak should develop between the insulating vacuum and the helium cooling lines, the vacuum chamber could be pressurized. To protect the system a pressure release valve, set at approximately 5 psig, will vent to the containment system which in turn will vent to the atmosphere if the pressure should continue to rise. The increased pressure will also initiate alarms. The system would be shut down and appropriate action taken to investigate the cause and make repairs.

4.6.5 <u>COVER GAS LEAK</u>. The cover gas pressure is monitored by PG-2 and the differential between it and the containment gas by DPG-1.

The problem of a leak from the helium coolant line to the cover gas which could cause a pressure increase was addressed in section 4.6.3. The problem of a leak out of the cover gas system will be considered here.

A leak out of the cover gas system is of concern only because it indicates the possibility of a reverse leak of air into the cover gas. Since the cover gas pressure is greater than the containment gas pressure, normally any leakage will be out and present no problem. But, if the leak is the slow, diffusive type, the leak rate would depend on the partial pressures of each gas present. Thus if the partial pressure of oxygen in the containment system were greater than that in the cover gas, the oxygen would leak in even if the helium gas pressure were higher in the cover gas.

A leak between the cover gas and the containment gas would decrease the pressure differential between the two and would most easily be detected by the differential pressure gauge. This gauge would normally indicate 2 psi under operating conditions. If it should decrease with no change in temperature of the ice chamber, a leak would be indicated. If it should drop to 1 psi (a change of 1 psi) an alarm would be triggered. Such a change would indicate a leak. If the leak is assumed to be the diffusive type, then oxygen could leak into the cover gas from the containment gas. If the following, very conservative assumptions are made, an estimate of the amount of oxygen that can leak into the cover gas can be made. The assumptions are:

1. The leakage rates are proportional to the partial pressure of the individual gases and inversely proportional to the square root of their molecular masses.
2. Helium containment gas contains 10 percent air (2 percent oxygen).

Under these conditions, when enough helium has leaked out of the cover gas to decrease the differential pressure by 1 psi, 0.16 g of oxygen could have leaked into the cover gas and condensed on the cold surfaces. The radiation field could convert some of the oxygen to ozone. The ozone could convert back to oxygen with the release of energy. Normally less than 50% of the oxygen would be converted to ozone in an equilibrium state, but, conservatively, it is assumed that all the oxygen that leaks into the cover gas is condensed on the cold surfaces and converted into ozone. Under these conditions, 0.16 g of ozone would be formed in the ice chamber before the differential pressure alarm sounded. The energy released in the reaction $2O_3 \rightarrow 3O_2$ is 34 kilocalories per mole of ozone. So 0.16 g of ozone converting back to oxygen would generate only .11 kcal or 470 J of energy. This is less than the amount of energy that is deposited in the ice every second during normal operation. Therefore, the release of this amount of energy would be only a minor perturbation of normal operating conditions if the released energy went into heating the system. Heating of the cover gas over the ice is discussed in section 5.

If a leak of this magnitude is indicated, the cover gas would be evacuated and any leak would be indentified using helium leak detection methods.

4.6.6 HELIUM CONTAINMENT LEAK. The helium containment system is a large, complex system. Although it is designed to be evacuated and back filled with helium, it must be assumed that some leaks will inevitably develop. The two objectives that must be met are: one; the air content of the containment gas must not exceed 10% by volume, and two; periodic pressurization must not require too large quantities of helium. Since the helium containment pressure is greater than atmospheric by about 2 psi, normally there will be no in-leakage of air and the air content will be far lower than 10%. However, a diffusive type leak would permit air in-leakage, although at a very slow rate. Therefore, if the containment pressure should drop by 1 psi or more, the gas will be measured for air content. If the content is low, the normal pressure of 2 psi will be reestablished by adding more pure helium. If the content is high (~ 10%) the containment gas will be evacuated and refilled with pure helium.

4.6.7 D_2O COOLANT FAILURE. The D_2O coolant is designed to keep the temperature of the cryostat vacuum jacket well below temperatures at which the structural integrity of the material would be jeapordized (260°C). If the cooling should fail, the maximum temperature reached would remain well below the melting point, but could be high enough to permit creep of the material. This would not threaten the structural integrity of the cryostat immediately, but corrective action should be taken within a few hours. This would allow ample time to determine if the loss of coolant were real and, if real, whether the coolant could be restored readily. If not, the reactor would be shut down, removing all possibility of structural failure due to overheating.

SECTION 5. SAFETY ANALYSIS

5.1 INTRODUCTION

Abnormal events that could be handled through operating procedures and activation of built-in pressure release valves were treated in the last section. In some cases, these events might require shutting down the cold source cryostat, but they did not present major safety questions. In this section, more severe accidents will be discussed which, although very unlikely, cannot be ruled out completely.

5.2 RUPTURE OF VACUUM JACKET

If the vacuum jacket should rupture, the insulating vacuum region would fill up with helium from the large containment gas system. This would have two major effects. It would increase the heat flowing into the ice and also heat the helium cooling lines.

The effect on the helium cooling lines can be estimated by calculating the heat flowing into the lines through the helium. Since the clearance between the lines and the warm vacuum jacket is only 0.8 cm, direct conduction is the main heat transfer mechanism. Under these conditions, the heat flow through the helium in the vacuum region is about 2000 W. This would almost triple the heat load on the refrigerator to well beyond its normal capacity and would probably cause the refrigerator to shut itself off. The auxiliary cooling system would come on automatically and continue to provide cooling to the ice chamber. However, to be conservative, all cooling is assumed to have ceased immediately following the vacuum jacket rupture.

With the vacuum region filled with helium, the initial heat flow into the ice is approximately 3000 W in addition to the 1100 W from reactor gamma-ray heating. This is based on the thermal conductivity of helium at 320 K (the temperature of the water cooled jacket). In fact, the average temperature of the helium would be cooler resulting in a lower thermal conductivity. The heat flow would, of course, be reduced as the ice warmed up and the temperature differential decreased. The temperature of the ice as a function of time after the rupture of the vacuum shell is shown in figure 9 assuming that the reactor continues to operate at 20 MW. As can be seen from the figure, about 40 minutes would be required to reach the melting point of ice. If the reactor were shut down immediately, this time would be only slightly more than doubled so there is no need for immediate reactor shutdown. This event leads to results that are not very different from normal warmup and shutdown procedures since the reactor heating alone warms the ice to melting within less than two hours. Thus, there is time to follow normal shutdown procedures.

The occurrence of this event would be signaled by the alarm on the vacuum pressure gauge, by the rise in cover gas pressure as the ice warmed up, and by the effect on the refrigeration system. These signals would provide adequate information to identify the problem and initiate normal cryostat shutdown procedures.

This event would not lead to additional cryostat damage nor present any hazard to the reactor or personnel.

5.3 RUPTURE OF HELIUM COOLING LINES

Normally the helium cooling lines are operating at only a few psi so the probability of a sudden rupture is unlikely. Nevertheless, the results of a sudden rupture will be addressed here.

The rupture of the cooling lines into the insulating vacuum would quickly spoil the vacuum and lead to the results discussed in the previous section. The loss of the helium, and the temperature and pressure imbalance introduced at the refrigerator would result in its automatic shutdown. The volume of cold helium (30 K) in the lines immediately adjacent to the cryostat (those coming through the shielding plug) would be about 6 liters at 320 K. Since the vacuum region is significantly larger than this, the vacuum region would not be immediately pressurized to more than about one-third of an atmosphere. However, as residual cold gas in the transfer lines flows into the vacuum region, pressure would probably rise enough to cause the pressure relief valve to open.

Thus the major results would be those discussed in the previous section and possibly the activation of the vacuum region relief valve. Neither result presents any danger to the reactor nor to personnel.

If the rupture were into the ice chamber, no enhancement of the ice heating would occur, but the cover gas would be over pressurized causing the relief valve to open. Again, there is no danger to reactor safety nor personnel.

5.4 AIR LEAK

Section 4.6 analyzed the possibility of air leaking into the vacuum system. It was shown that the maximum leak that would still permit regular operation would introduce 1 g of oxygen in a year of continuous operation. If all the oxygen were converted to ozone and the ozone were to decompose spontaneously heating the air and helium present, the pressure would rise to 8 psia which would cause no damage. The possibility of air leaking into the cover gas was also addressed in section 4.6. There it was shown that a conservative upper limit on the amount of oxygen that could condense and be converted into ozone was 0.16 g. If all this reverted to oxygen, 470 J would be released. In section 4.6, it was shown that, if all this energy went into heating the ice, it would only have a minor effect on the temperature of the cryostat. If all the energy were to go into heating the helium and condensed air in the cover gas, the pressure would rise significantly.

The pressure rise has been calculated assuming that all the energy is released in the small volume (1.1 L) over the ice since it is released too quickly to permit the pressure to be relieved by expansion into the rest of the cover gas system. Under these conditions, the peak pressure would be 60 psig. This is well below the calculated burst pressure of the ice chamber so the ice chamber would not rupture.

5.5 RADIOLYSIS OF ICE---RELEASE OF STORED ENERGY

5.5.1 INTRODUCTION. The use of vacuum insulated cryostats in high radiation fields in reactors is not new. Many such facilities have been used over the years and are currently in use around the world. Maintaining a large block of ice at cryogenic temperatures for long times in a radiation field, however, is less common. Therefore, it will be addressed in more detail here.

The primary products from the radiolysis of deuterated water are D_2O itself, along with deuterium, deuterium peroxide, and oxygen. Atomic and molecule mobilities are greatly reduced in ice at low temperatures compared to water, and these products are only released on warming. If the radiolysis were to proceed for a long period of time without recombination, the question must be asked whether the stored energy in the radiolysis products could be released in a short period of time upon warm-up of the ice. As will be shown below, the molecular kinetics of the system are such that any sudden release of sufficient energy to damage the reactor is not credible.

5.5.2 PREVIOUS EXPERIENCE. Heavy water (D_2O) ice moderators similar to the one proposed here have been installed in the MITR at MIT and in the CP-5 reactor at Argonne National Laboratory (ANL). The MIT cold source was primarily a development project and was only operated cold for a few days at a time and no examination of radiolysis products was carried out.

The source at CP-5, however, was operated for months, and extensive tests were conducted to measure the release of D_2, D_2O, and O_2. These measurements showed that most of the D_2 was released at relatively low temperatures (~ 190 K), whereas the bulk of the O_2 was not released until near the melting temperature (270 K) of the ice. No problem with the products of radiolysis was experienced.

5.5.3 RADIOLYSIS OF ICE. The direct products of radiolysis of D_2O ice are deuterium (D) and deuterium oxide (OD) free radicals, although there is also strong evidence for a role for "hydrated" electrons and other short lived intermediates in the radiolysis process. These chemical species recombine to form the primary radiolysis products (other than D_2O itself) D_2 and D_2O_2, although some O_2 is also observed. Detailed studies of radiolysis in H_2O or D_2O ice (primarily using Co^{60} γ rays and 1-5 cc quantities of ice) (2, 3, 4) show that the production of free radicals in ice is somewhat smaller than in the liquid. More importantly, these measurements show that the yield of the radiolysis products upon warming the ice after a prolonged irradiation at low temperatures is much smaller than the total yield from water exposed to a similar dose. These results indicate that the yields of such products (D_2, D_2O_2, O_2) reach close to steady state (or maximum) concentrations which are small, due to preferential regeneration of water by recombination reactions. For example, based on extrapolation of results for radiation doses below the steady state, the yields of D_2 after long irradiation at 30 K (> 10^{22} ev/g total dose) would be expected to be less than 1 g of D_2 for 25 liters of D_2O ice. These very small yields represent a distinct advantage of an ice moderator over hydrocarbons and other hydrogeneous materials, most of which are much more susceptible to decomposition by irradiation.

The irradiation times for the cold source at CP-5 were not sufficient to reach equilibrium condition, but the small releases that could be measured were qualitatively in agreement with predictions from earlier results mentioned above. The actual radiolysis product yields for the proposed moderator will be determined in the course of testing the cold D_2O source, as described below.

5.5.4 ACCIDENTAL RECOMBINATION OF RADIATION PRODUCTS. Care has been taken to assure that the deuterium concentration will never be great enough to react with any available oxygen or hydrogen peroxide. A hydrogen getter is always open, during operation, to the ice chamber. Thus, any deuterium that might be released is absorbed in the getter. Even without the getter, the normal warm-up procedure that sweeps the ice surface with nitrogen or helium will assure that most of the deuterium is removed before the oxygen escapes the ice. Nevertheless, the result of such an accident has been analyzed based on the following assumptions:

1. Neither the ballast tank getter nor the sweep system is operational during warm-up, and a vacuum is initially present above the ice. (Worst initial pressure condition.)
2. Deuterium is released, and a stoichiometric amount of oxygen is also released.
3. Deuterium and oxygen are uniformly distributed throughout the cover gas volume.
4. The equilibrium pressure in the ice chamber is 45 psia based on the pressure release valves failing to operate until the pressure has reached one and one half times its normal setting.
5. The temperature in the ice chamber is 270°K.
6. An ignition source is present and the reaction consumes all the deuterium present in the volume above the ice.

These conditions would result in a total gas pressure (deuterium plus oxygen) of 45 psia in the total cover gas volume of about twenty-two liters. Thus, approximately 3 moles of gas, 2 of deuterium and 1 of oxygen, would be present. Note that this would correspond to 8 g of deuterium compared to only 1 g estimated to be present in the ice after a long irradiation. If more than 8 g of deuterium and the corresponding amount of oxygen were released, the excess would escape through the pressure release valve into the containment gas and be absorbed by the getter in that system.

The deuterium-oxygen reaction releases 57.5 kcal per mole of D_2. If complete combustion of the stoichiometric mixture of deuterium and oxygen took place, the pressure in the ice chamber would rise to a maximum of 670 psia. Since the ice chamber has not been designed to withstand such high pressures, the chamber would rupture and the expanding D_2O vapor would fill the void in the vacuum chamber. The resultant pressure rise in the vacuum chamber would be only 21 psia, which the structure can easily take without any serious deformation.

If helium were present in the volume above the ice, the temperature and pressure resulting from an explosion would be reduced in proportion to the displacement of deuterium by the helium present in the system.

Although such an event would rupture the ice chamber, it would cause no damage to the vacuum jacket, which would easily contain a pressure well above 21 psia, and pose no threat to the safety or integrity of the reactor.

5.5.5 START-UP TESTS. In addition to the usual start-up tests relating to coolant flow, vacuum checks, temperatures, heat production rates, etc., a careful series of measurements will be performed to determine the rate of release of radiolysis products from the ice as a function of irradiation time, ice temperature, and warm-up rate. The following outline of the measurements is given to indicate the general start-up procedure. Specific reactor powers, temperatures, and irradiation times may differ depending on information obtained as the tests progress.

Initially, after the ice has been frozen and cooled to operating temperatures, the reactor will be started up and operated at reduced power (10 MW) for 100 hrs. This should generate about the same total amount of radiolysis products as were obtained in the CP-5 tests. During warm-up, with the reactor still at 10 MW, the release of the products (quantity and rate) will be measured by evacuating the cover gas system, sealing it, and recording the pressure rise as a function of time for a short interval. At the end of the interval, a fixed volume of the gas will be collected and analyzed. The time intervals will be chosen so that the amount of D_2 that is allowed to accumulate at any one time will be small. This procedure will be followed until the ice approaches its melting temperature. By this time, all the deuterium will have been released. To determine the amount of oxygen that has been released, the ice chamber will be backfilled with helium and samples taken at appropriate intervals as the ice melts and the water warms up. This procedure, rather than the evacuation method, will be used to prevent excessive sublimation of ice or evaporation of the water at temperatures greater than -20°C. Water samples will also be analyzed as soon as they are available to look for D_2O_2. When the ice is fully melted, the water will be drained and new ice made for the next test.

Once the first test has established that the release rates at low power are consistent with those expected, the above test will be repeated at 20 MW. Succeeding tests will be made at longer and longer irradiation times. It is planned to continue the tests until the expected equilibrium condition is reached or the total deuterium release begins to approach 5 g, which is well below the 8 g release analyzed in the previous section.

These tests will determine the appropriate procedures for normal operation. If the equilibrium condition is reached before the potential deuterium release reaches 5 g, the operating schedule will not be controlled by the potential release. If prolonged irradiation could generate potential deuterium releases in excess of 5 g, the operating schedule would be adjusted such that the ice would be warmed up to anneal out the deuterium before 5 g of deuterium could build up.

SECTION 6. SUMMARY

The proposed cold neutron source differs from the more conventional experimental proposals only in the question of the stored energy that might accumulate in very low temperature ice (30 K) irradiated to large doses. The more conventional safety considerations addressed in this analysis have arisen in a variety of research reactor experimental proposals. The only question in this proposal not previously addressed is the effect of the irradiation of ice at low temperatures resulting in the potential for the later release of stored energy. This has been specifically addressed in this report, and it is concluded that no credible accident involving the cold source could cause damage to the reactor or cause releases of radioactivity in excess of the limits in 10 CFR 20.

References

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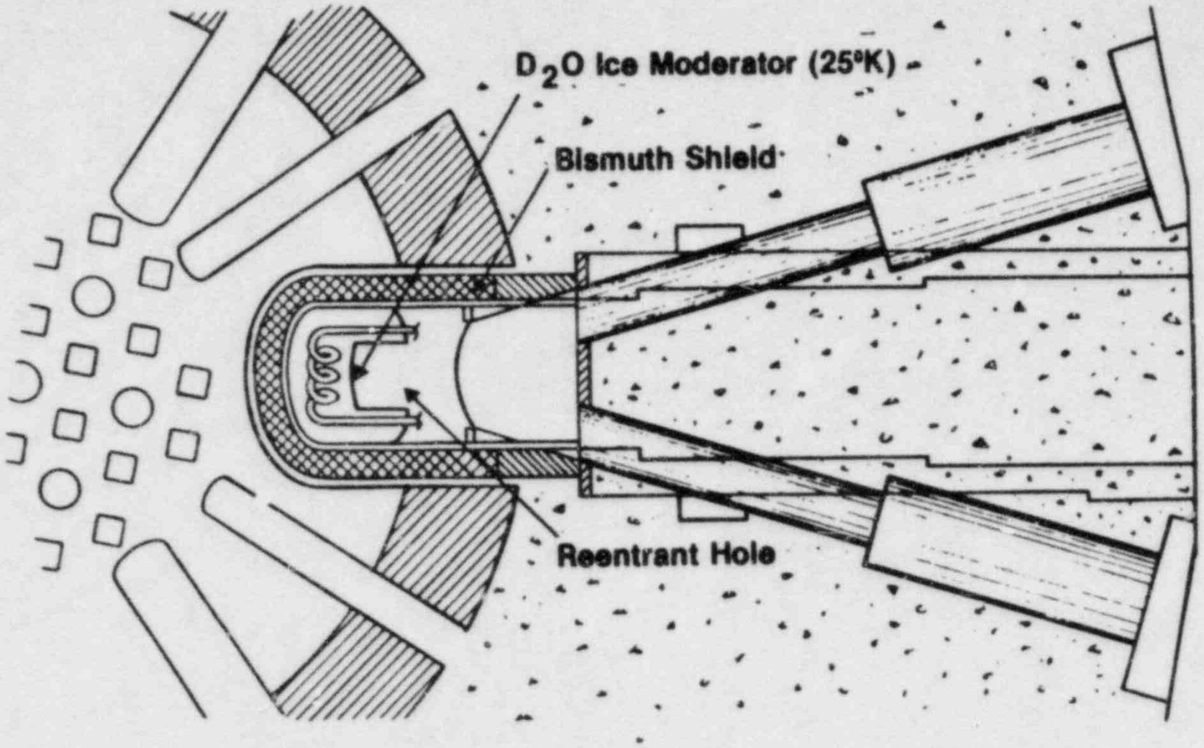

Figure 1. Plan view of cold neutron source installation

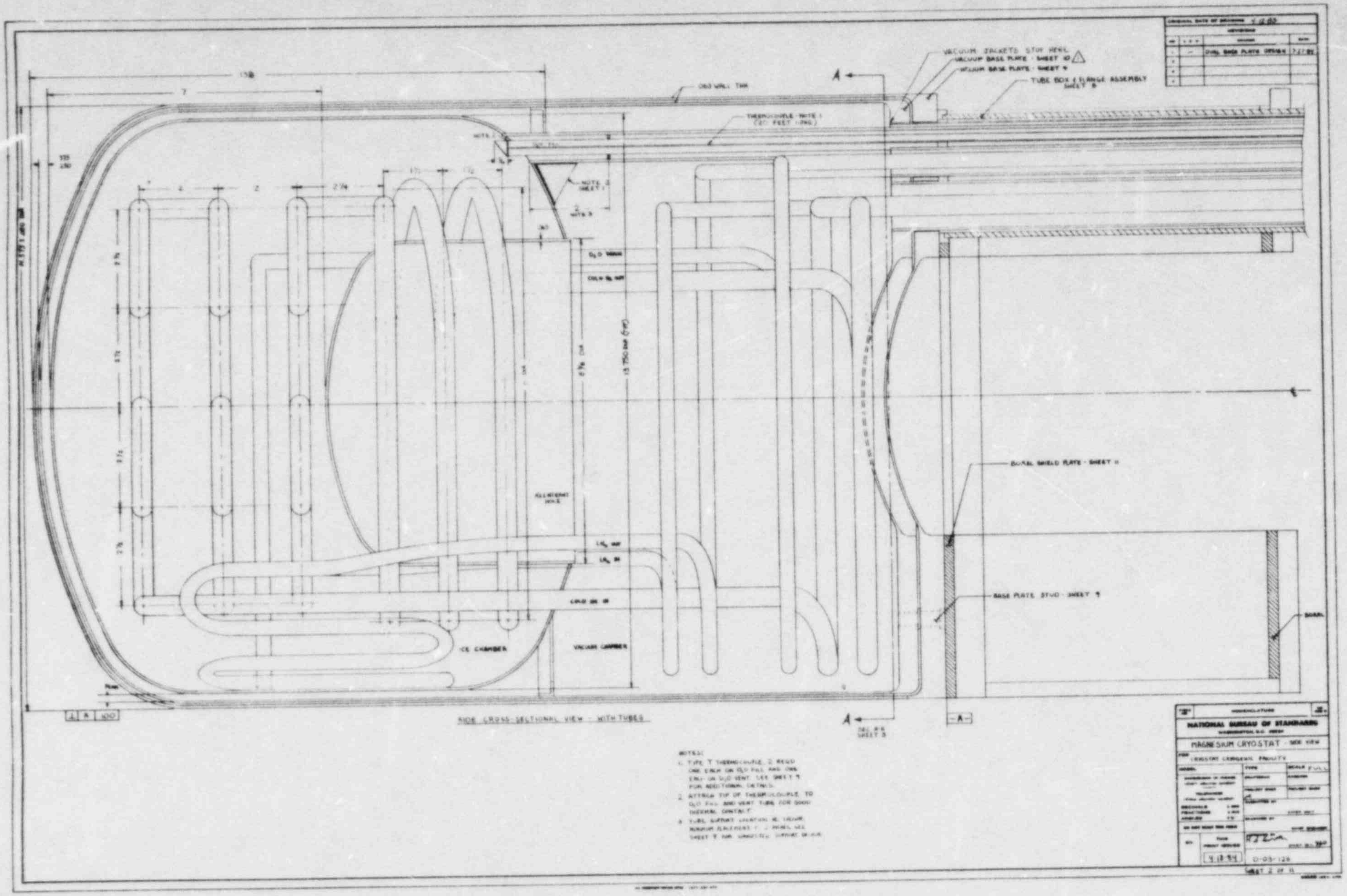

Figure 2. Elevation view of cryostat

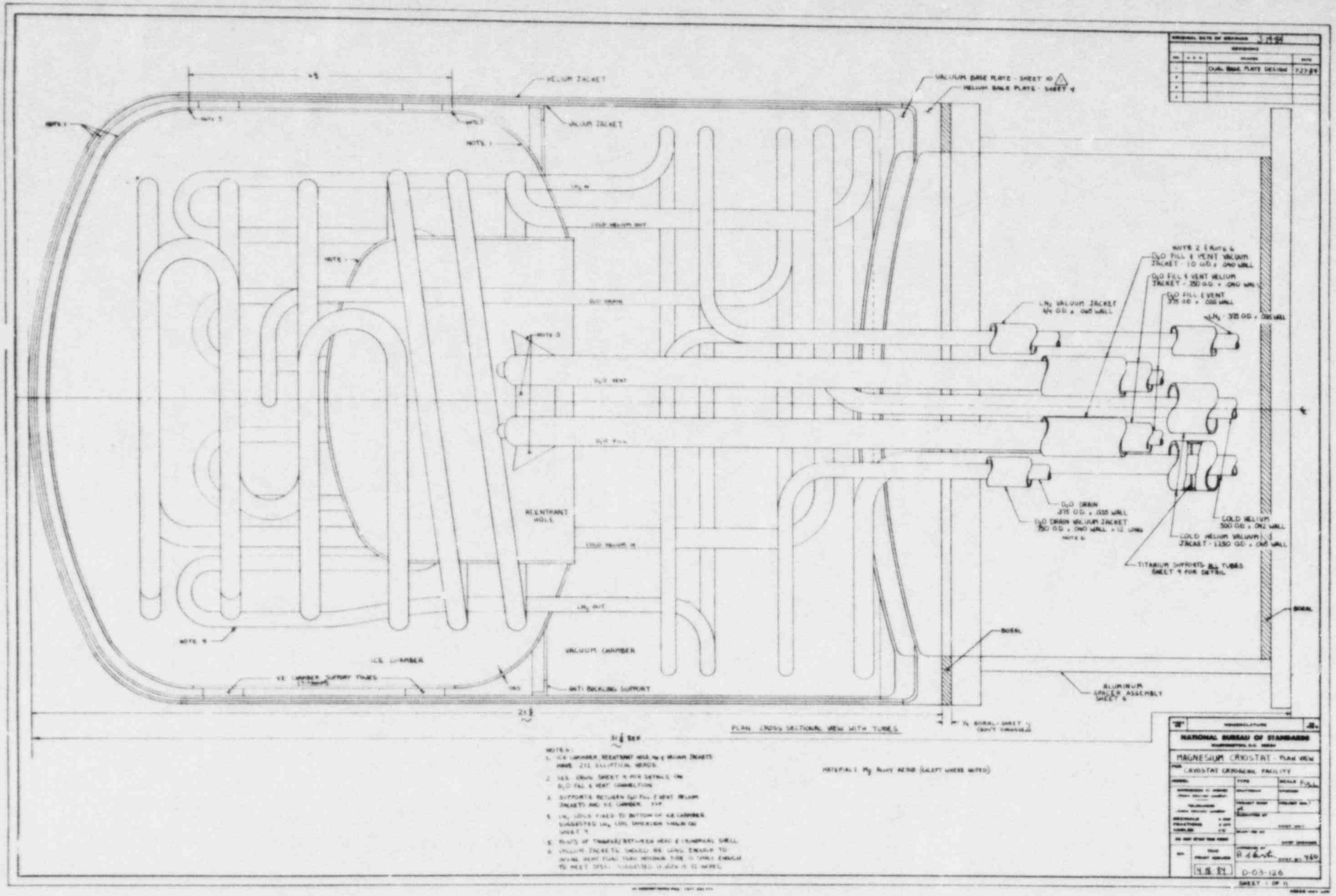

Figure 3. Plan view of cryostat

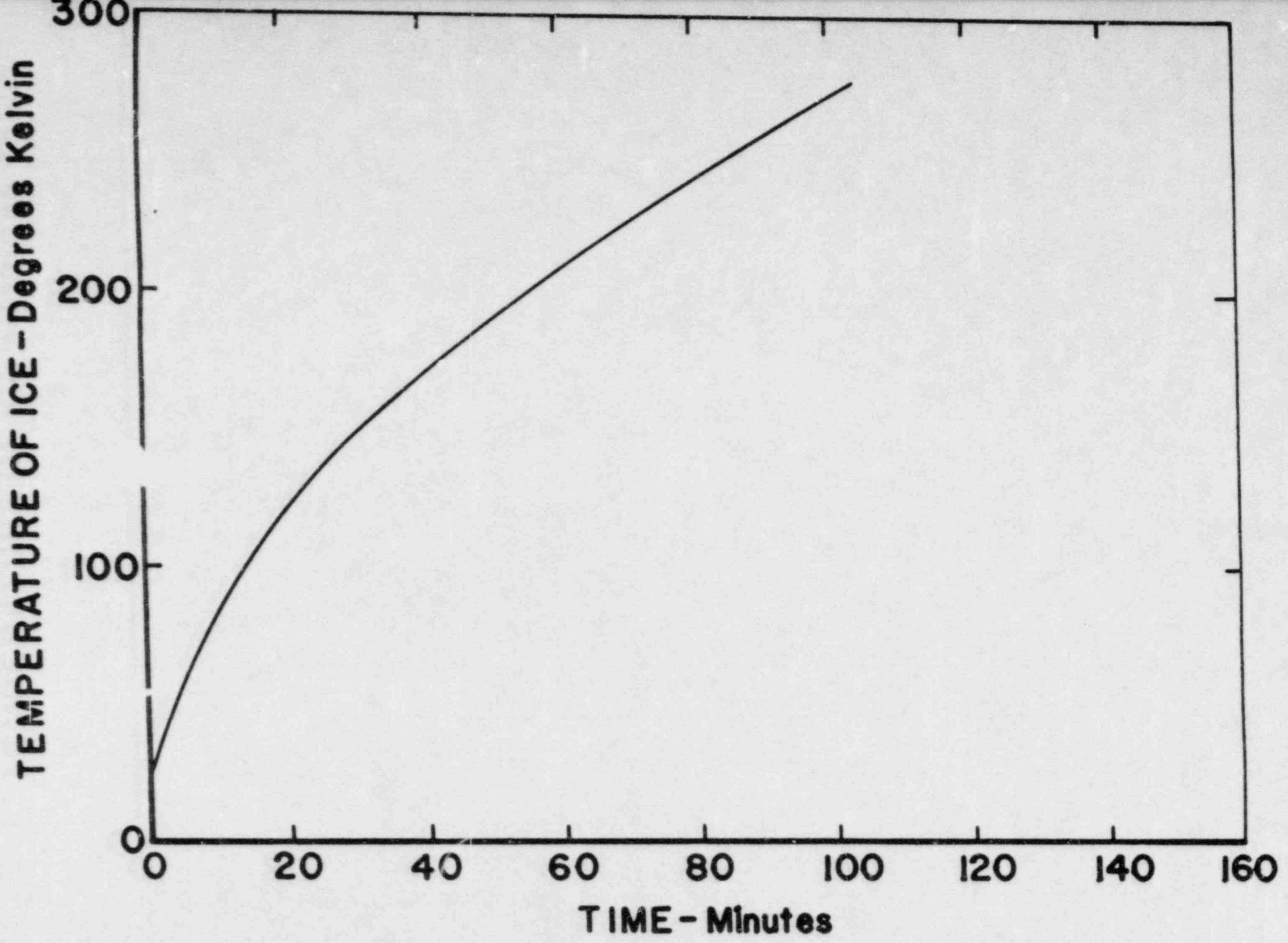

Figure 4. Ice temperature as a function of time after loss of cooling at full reactor power (20 MW)

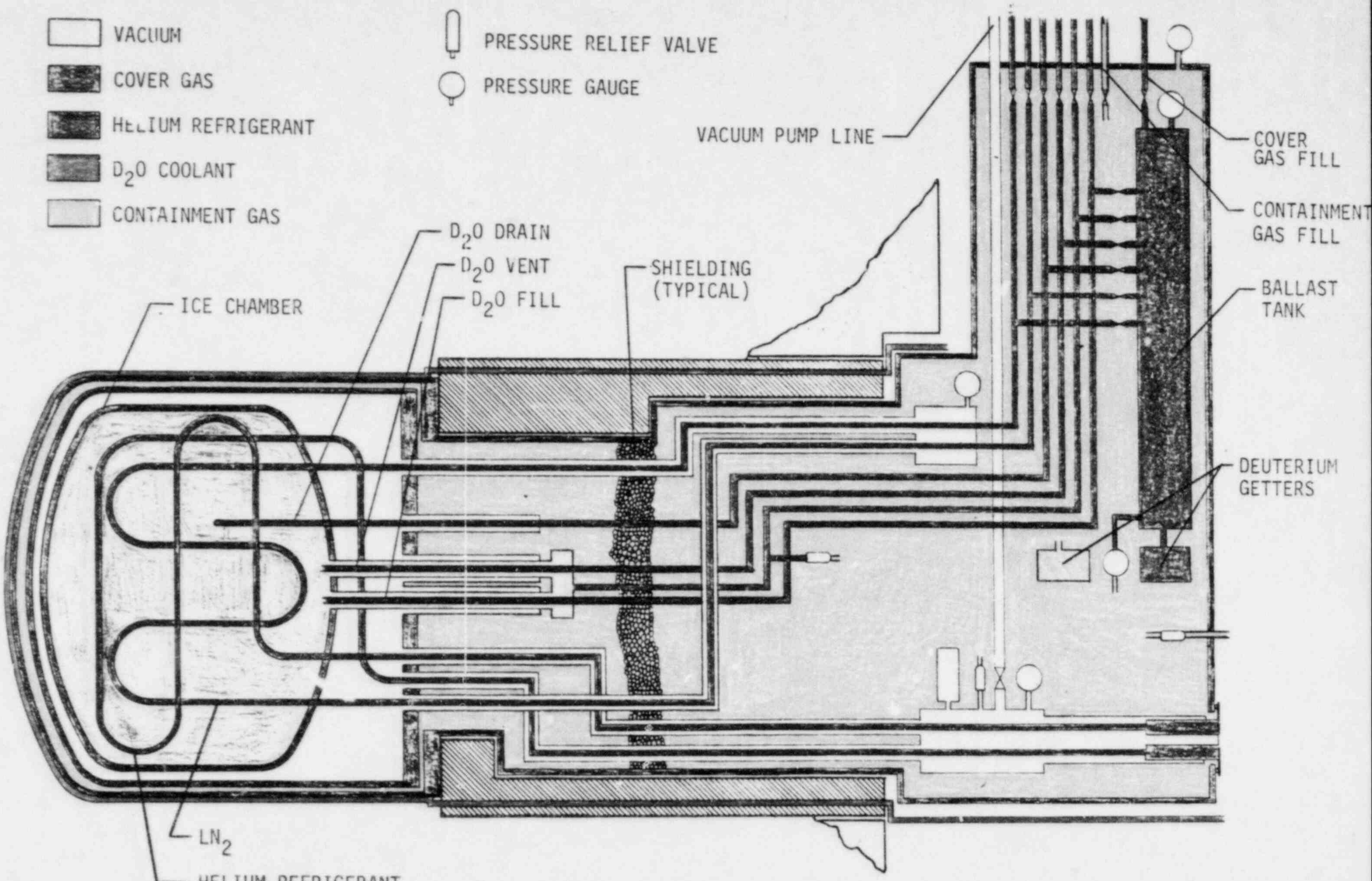

Figure 5. Schematic illustration of cold source facility

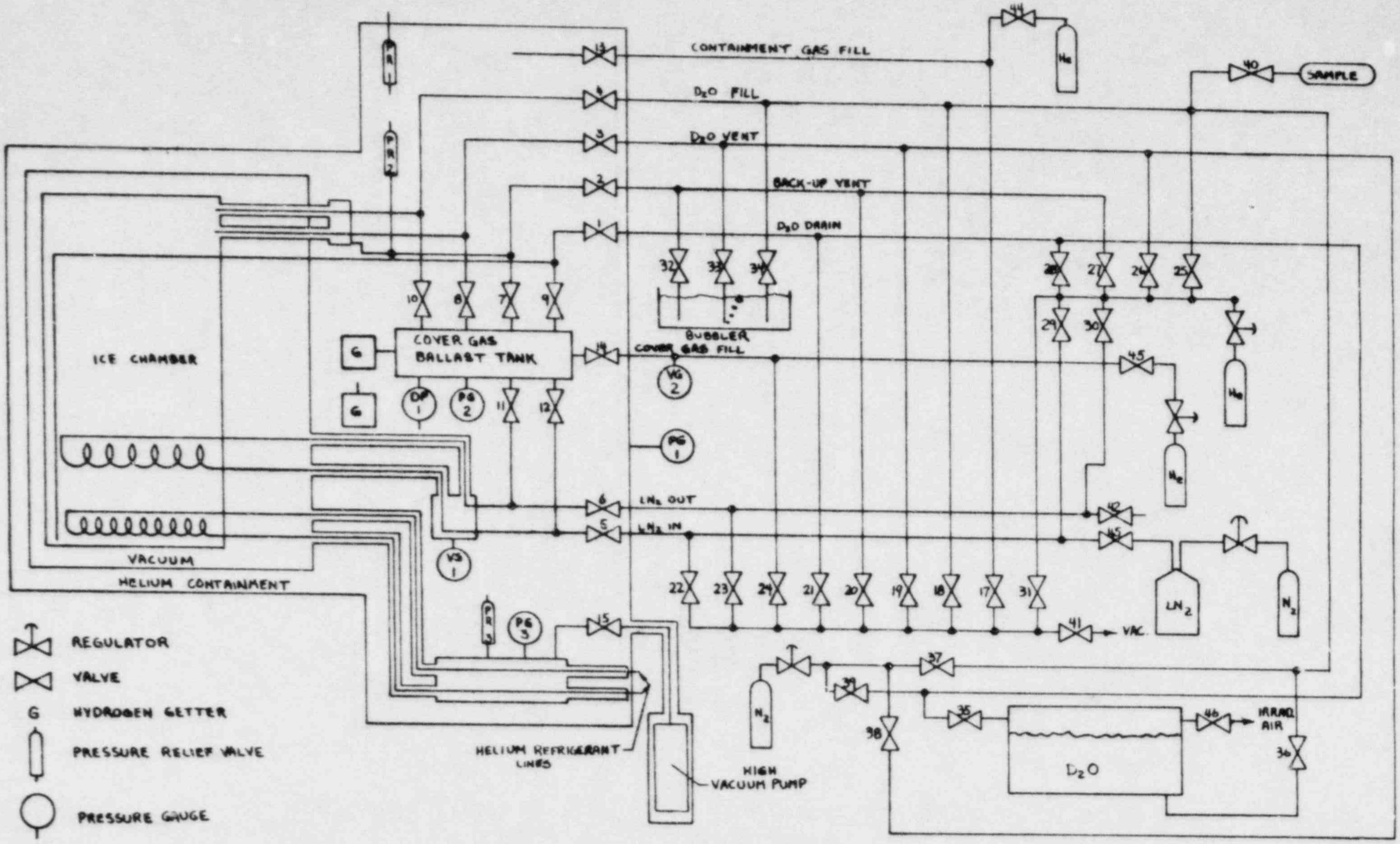

Figure 6. Flow diagram of cryogenic system

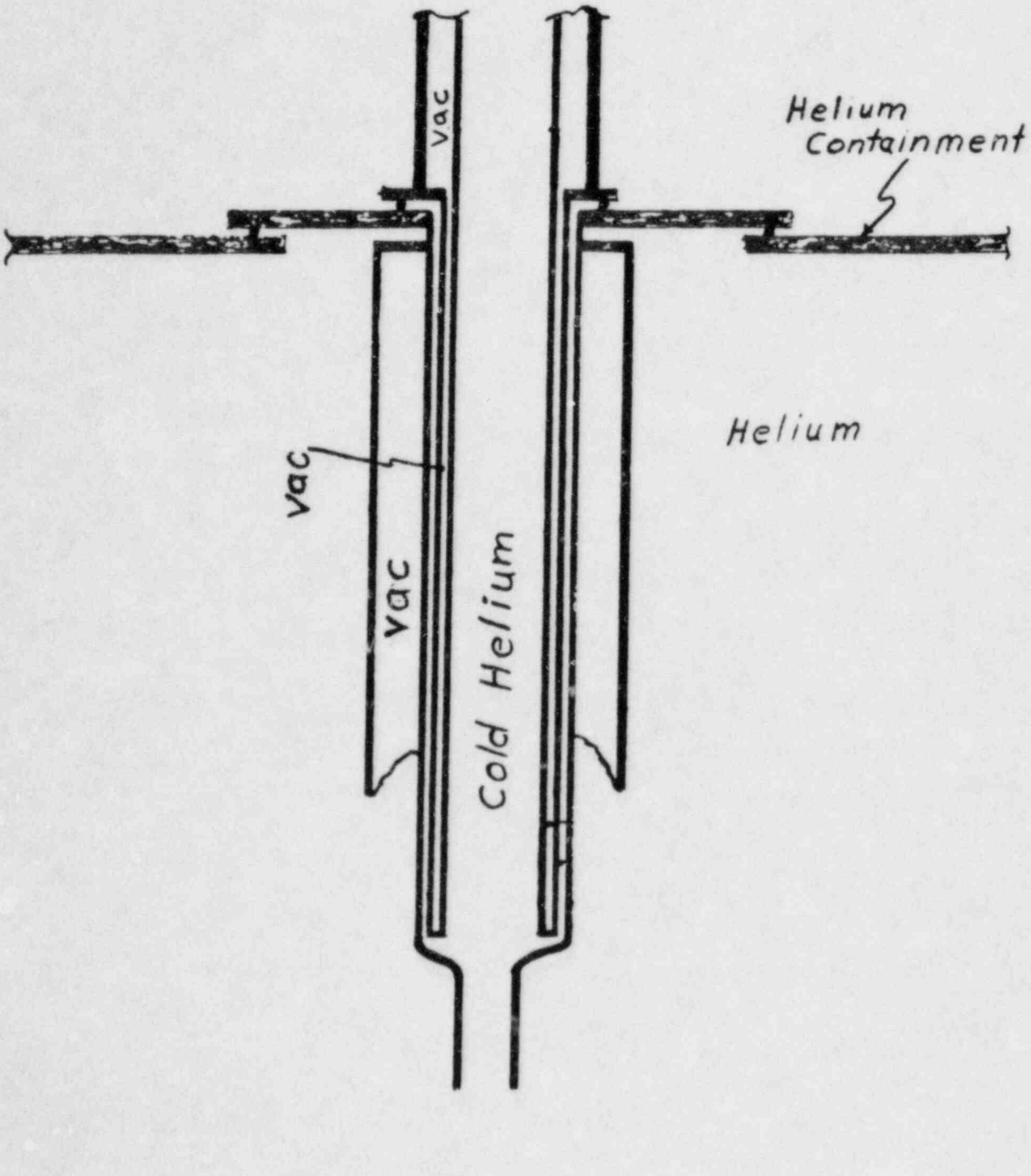

Figure 7. Helium cooling line penetrations/vacuum isolator

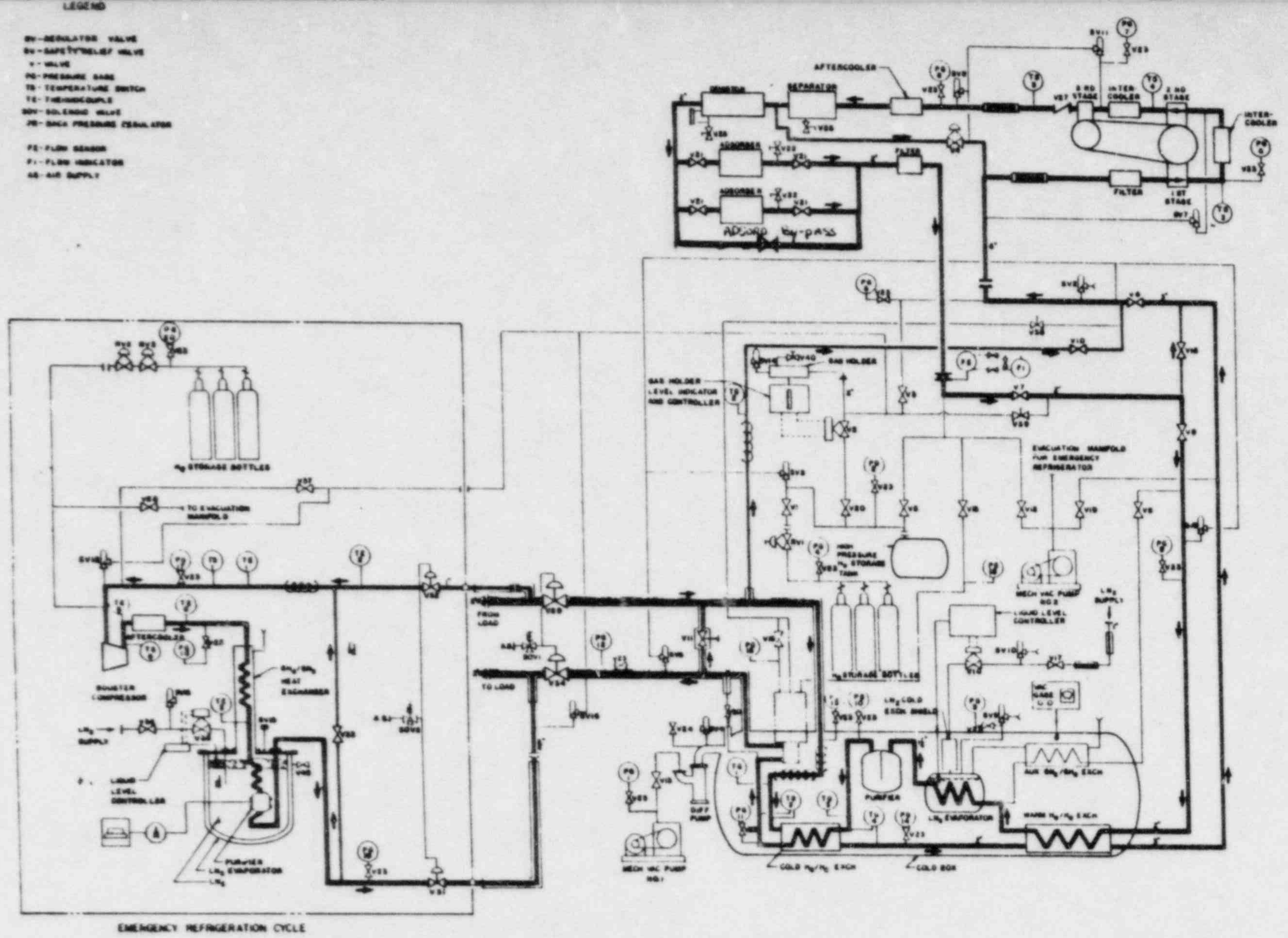

Figure 8. Flow diagram of helium refrigerator

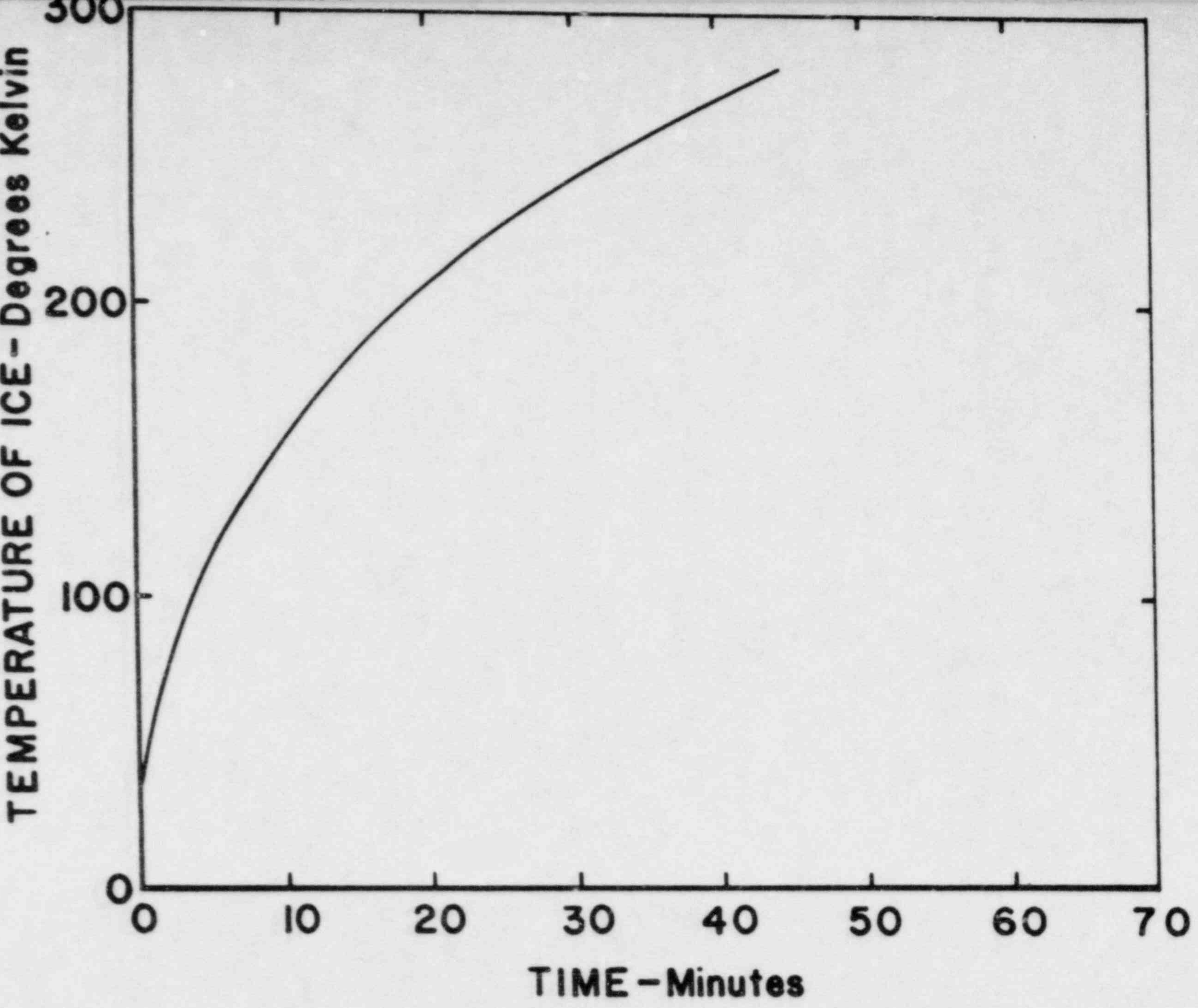

Figure 9. Ice temperature as a function of time after loss of insulating vacuum and coolant at full reactor power (20 MW)