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National Institute of Standards and Technology
Gaithersburg, Maryland 20899

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Mr. Theodore S. Michaels
Project Manager
PDNP
Office of Nuclear Reactor Regulation
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

Dear Mr. Michaels:

NIST respectfully requests review of the enclosed proposal for a new liquid hydrogen cold source to replace the existing heavy water (D_2O) source. Both the NIST staff and the Safety Evaluation Committee have determined that the proposal meets every criterion of 10CFR50.59 and accordingly does not involve an unreviewed safety question. Because this is a major undertaking of vital national importance that involves extensive effort and high cost, NRC confirmation is requested. The development of the new source represents a major breakthrough for U.S. Science and Technology. When completed, the NIST Cold Neutron Research Facility will not only be the premier and only such facility in the U.S. but will also be among the best in the world.

Please accept our sincere appreciation. I am enclosing copies of relevant parts of the references to facilitate the review.

Sincerely,

JMRowe

J. Michael Rowe
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Enclosures

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ANALYSIS OF SAFETY ISSUES INVOLVED IN A LIQUID HYDROGEN SOURCE IN THE NBSR

J. M. Rowe, P. Kopetka, and R. E. Williams

1. INTRODUCTION

The normal spectrum of neutrons emerging from the beam tubes at the NBSR can be well represented by a Maxwellian distribution of energies with a characteristic temperature of 350 K. For such a spectrum, less than 1.5 % of the total neutron flux is comprised of neutrons with energies less than 5 meV (.005 eV), or, equivalently, with wavelengths greater than 0.4 nm, which are commonly referred to as cold neutrons. The present cold neutron moderator source at the NBSR is a block of heavy water (D_2O) ice. This has provided a cold neutron intensity gain of more than five compared to normal beam tubes. For several years, use of this source was restricted to two instruments located inside the confinement building. In recent years, primarily as a result of the work done at the Institut Laue Langevin in Grenoble, France, the great utility of such neutrons has been realized. In fact, the National Academy of Sciences appointed a Committee in 1984 to set priorities for Major Facilities for Materials Research and Related Disciplines, which assigned the highest priority to provision of facilities for cold neutron research. In response, NIST and the Department of Commerce approved the construction of the Cold Neutron Research Facility which is now being brought into operation. This major facility, the only one of its kind in the United States, includes a large guide hall outside the confinement building with seven neutron guide tubes which can accomodate up to 20 experiments simultaneously. The state-of-the-art instrumentation being installed is fully competitive with any world-wide, and provides an entirely new measurement capability for U.S. researchers.

The initial operation of this facility has been a great success, attracting the best researchers from industry, universities, and other government laboratories. They have utilized the unique capabilities to perform key measurements on a broad range of materials, with applications extending from biology to polymer chemistry to advanced ceramic processing to fundamental neutron physics. This success has given impetus to exploring new technologies that could make the cold source even more competitive.

Preliminary preconceptual design indicated that a considerable improvement in performance could be attained by the use of liquid hydrogen or deuterium as a moderating material, primarily as a result of the moderator remaining liquid down to temperatures below 20 K. Several hydrogen or deuterium based sources have been operating for the past decade or more (at the Institut Laue Langevin in France, at the Saclay reactor near Paris, at the reactor at Julich, Germany, and at the HFBR in Brookhaven), and data from these sources were the basis for the preconceptual work done here. In addition, a hydrogen based source offers significant simplification in design, construction and operation relative to the current source. As a result, more extensive design work was undertaken, including Monte Carlo simulations based on the MCNP code maintained and distributed by Los Alamos National Laboratory. From these studies, a design that can provide intensity gains in excess of two when compared to the present source over the entire cold neutron energy range has emerged.

In this report, the safety implications arising from the use of hydrogen as a moderator are analysed, and shown to be allowable under 10CFR part 50, section 59, "Changes, tests, and experiments", since it does does not involve changes in the technical specifications or an unreviewed safety question.

2. SUMMARY DESCRIPTION OF HYDROGEN SOURCE

A block diagram of the proposed liquid hydrogen cold source system for the NBSR is shown in Fig. 1. The moderator chamber contains the liquid hydrogen used to moderate the neutrons to a lower effective temperature. (All components will be discussed individually below in more detail.) The heat generated by neutrons and γ-rays in the liquid hydrogen and its aluminum container is removed by boiling of the liquid. The vapor generated exits from the moderator and cryostat and returns to the hydrogen condenser by the vapor return line, where it is re-liquified and returned to the moderator chamber by the liquid supply line. The overall vapor and liquid are maintained at approximately 21 K, and the cooling necessary to remove the heat is supplied by the closed cycle helium gas refrigerator, which can deliver up to 3.5 kW of cooling with a final gas temperature of 18 K. Under normal operating conditions, the entire hydrogen system is maintained at a constant pressure of approximately 22 psi (150 kPa), so that the boiling temperature is approximately 21 K. A large ballast volume, maintained at room temperature, has sufficient volume to contain the entire hydrogen inventory with the refrigerator stopped, and the system at 300 K, at a system pressure of less than 75 psi (500 kPa). The driving force necessary to establish flow of liquid down to the moderator and vapor back to the condenser is supplied by the density difference between liquid and vapor, acting over the height difference between the condenser and the moderator. This is known as a natural circulation loop (sometimes referred to as a "thermosiphon"), which requires no moving parts to ensure flow of liquid to the moderator for cooling purposes. The calculated flow for the NBSR installation, based upon both the original calculations of γ-ray and neutron fluxes, as well as independent Monte Carlo calculations using MCNP, is 3-4 g/s, corresponding to a heat load of 1.2-1.6 kW. Calculations of the loop stability, as well as independent friction calculations, indicate that about 20 cm of head is adequate for this circulation, while the actual separation is in excess of 200 cm, leaving ample margin.

With this system, the hydrogen loop and ballast volume, once leak-tight and charged with hydrogen, is entirely closed. This eliminates further gas handling, and thus minimizes the possibility of inadvertent oxygen contamination. In addition, all hydrogen lines are either within the biological shield, encased within heavy steel shields, or run in an existing floor trench, so as to absolutely prevent accidental rupture during operation. All hydrogen containing components are completely surrounded by an atmosphere of helium gas, maintained at a pressure above atmospheric, so that there can be no in-leakage of air into the system, and thus no oxygen available to combine chemically with the hydrogen. The only controlled and monitored system parameter is the absolute pressure of hydrogen in the vapor phase, which, in equilibrium, is a measure of the temperature of the hydrogen in the source (in direct analogy to a vapor bulb thermometer). This system has the advantage that no active measuring device need be installed in a high radiation area. The entire design philosophy is to rely on simple, passive safety features that minimize the possibility of a system failure or a procedural problem. With the closed system, gas handling is minimized (the only charging is done at installation, and after the system is opened for corrective maintenance).

There is no provision for hydrogen venting in this system, as this would again create more possible failure modes with no safety gain. Rather, as described below, the capacity of the ballast tank is relied upon to hold the entire charge safely. If the system must be emptied of hydrogen to allow maintenance on a component, this is done by absorbing the entire inventory into a storage metal hydride, which then can be removed from the confinement building. This reliance on simple passive systems is, in our view, the best safety philosophy to guarantee reliable and safe operation.

The components of the system are described in more detail below. It should be noted that all vessels and piping are designed to the ASME code for pressure vessels, using the maximum design stress specified for 6061-T6 aluminum with welded joints (6000 psi). The rupture strength for such vessels will be many times the design working pressure. In each case, the design working pressure will be specified in the descriptions below.

2.1 MODERATOR CHAMBER

The reactor vessel, beam port, moderator chamber, cryostat, and neutron guides are shown in the plan view of cryogenic port F in Fig. 2, and the moderator chamber is shown in more detail in Fig. 3. The liquid hydrogen cold moderator is arranged in the form of an annulus formed by two concentric spherical shells. The outer shell consists of a sphere made from 6061-T6 aluminum which is 32 cm. in diameter, and 1 mm thick. The liquid hydrogen supply line and vapor return line enter from the top into a dome known as a "bubble cap" (which acts as a liquid-vapor phase separator). It should be noted that the liquid enters via a 0.5 in. OD (1 cm^2 area) inner tube, while the vapor leaves through the annulus formed by the 1.25 in. OD outer tube, (with 4 cm^2 flow area), an arrangement which ensures that the system is isothermal. The inner shell consists of a sphere made from 0.25 mm thick 6061-T6 aluminum, 28 cm in diameter, with a tube penetrating from the bottom. This inner sphere is held in the center of the larger sphere by centering and supporting devices, and has a protrusion on the side facing away from the reactor which matches the outer sphere diameter. This prevents liquid from entering the area of the source which is viewed by the cold neutron beams (see Fig. 2). Thus, the beams view the inner surface of the spherical shell, in "black-body" geometry, a design feature which substantially increases cold neutron flux. With the reactor operating, the liquid in the shell will be cooling the outer and inner spheres. The bubbles rise to the top, where they feed the vapor return line, leaving a calculated liquid fraction of greater than 80%, as required for moderation. The total volume of the annular space is approximately 5 liters, which implies 4 liters of liquid during operation. The outer sphere with bubble cap is designed to the ASME pressure vessel code, for an internal working pressure of 75 psi (500kPa) and an external working pressure of 23 psi (150 kPa).

During normal operation, the inner sphere will be filled with only hydrogen vapor, as any liquid will boil off, and the resultant pressure will not allow liquid to enter from the bottom. This arrangement allows a large viewing area for the beams, while reducing the total hydrogen inventory, and allowing the use of the spherical shape, the best for stress reduction. The tube which connects the two parts of the moderator chamber reduces normal liquid vapor interchange to a diffusion limited process, and allows the vapor to have a different ortho/para hydrogen ratio than the liquid. (Normal hydrogen is 75% ortho, while the equilibrium ratio at 20 K is virtually 100 % para.) For cold neutron efficiency, the vapor should approach equilibrium at nearly 100% para, while the liquid should be maintained at nearly 75% ortho, since the ortho form with spin 1 is a strong neutron scatterer while the para form with spin 0 is a weak scatterer. While the spherical shape and other details are new to this source, the concept of a vapor filled dome is not, and has been shown to work satisfactorily in a hydrogen source at Saclay.

2.2 MODERATOR CRYOSTAT

For heat transfer reasons, the moderator chamber and all other low temperature regions of the system will be enclosed in a high vacuum insulation region (< 10^{-4} mm Hg). In line with the overall design philosophy, this vacuum must be surrounded by a blanket of helium to prevent the possibility of air entering the hydrogen system. The vacuum and helium vessels will be cooled, since they will be in a region of radiation heating. All of these requirements are met by the cryostat assembly shown in Fig. 4, which includes the moderator chamber and hydrogen lines. Since this assembly is also the barrier between the moderator and the reactor beam tube, the helium and heavy water cooling jackets have been designed with internal working pressures of 139 and 141 psi respectively (945 and 960 kPa), and external working pressures of 235 and 19 psi respectively (1626 and 130 kPa). These pressures are for each pressure vessel working independently, so that the two together will be correspondingly stronger. The calculated rupture strength of the helium jacket is greater than 1800 psi internal pressure. The water cooling for the aluminum cryostat assembly is supplied by the auxiliary D_2O cooling system, just as for the existing ice cryostat. The calculated heating rate will require 25 gpm of cooling water flow for a temperature rise of 18 °F. In order to ensure adequate cooling of the vacuum shell (which is separated from the cooling water by helium gas), the space between the two shells will be filled with aluminum "wool", which will not affect the helium, but will increase the thermal conductivity by at least one order of magnitude over that of helium alone.

The entire cryostat, moderator chamber, and associated lines (helium, vacuum, liquid and vapor hydrogen) will be attached to a plug similar to the one used for the existing ice cryostat, with openings for the neutron guides. This plug and cryostat assembly will be rolled into the beam port from a shielded cask following the same general procedures as were used for insertion of the present source assembly.

2.3 HYDROGEN CONDENSER AND CONNECTING HYDROGEN LINES

The hydrogen condenser is shown schematically in Fig. 5, along with the liquid-vapor phase separator at the bottom, the connections to the hydrogen liquid supply and vapor return lines, the connection to the helium refrigerator, the connection to the ballast tank, and an auxiliary system for ensuring that the ortho concentration in the liquid remains near 75% for good neutron moderation performance. The separator itself is a plate-fin type heat exchanger obtained commercially, with working pressures for the helium and hydrogen sides of 300 and 150 psi respectively (2040 and 1020 kPa), and a 3.5 kW heat transfer capability. Cold helium gas enters the heat exchanger at approximately 14K and a pressure greater than the hydrogen pressure of 74 psia (warm). As it passes through it is warmed by condensation of hydrogen and returned to the refrigerator at approximately 18 K. The liquid drains to the bottom of the heat exchanger into the phase separator region, which allows the incoming vapor stream to expand and any liquid carried over to be separated and returned to the cryostat through the liquid supply line. This feature ensures against accidental voiding of the chamber as a result of transient conditions. The operating point for the condenser is controlled by the incoming helium temperature and mass flow, which are controlled by the absolute hydrogen pressure, which is a good measure of the moderator temperature, since the supply and return lines are isothermal by construction.

The auxiliary system shown removes approximately 0.1 g/s of hydrogen vapor from the condenser system, warms it up to 300 K, converts it to the normal 300 K ortho/para ratio (3/1), and returns it to the condenser. This system imposes an additional heat load of less than 100 W, and is very effective in maintaining good neutronic performance for the moderator system. As was discussed for the moderator, the condenser is surrounded by an insulating vacuum, which is in turn surrounded by a helium blanket. The auxiliary system is entirely enclosed by a helium blanket.

2.4 HELIUM REFRIGERATOR

The helium refrigerator is of standard design, obtained commercially with a cooling capacity of 3.5 kW. The gas is circulated in a closed loop from the refrigerator to the heat exchanger/condenser to remove the heat generated in the cold source.

2.5 BALLAST TANK

The ballast tank and pipe which connects it to the rest of the system are shown in Fig. 6, which also shows the relative location of all system components. The purpose of the ballast tank is to provide an adequate hydrogen gas reservoir to hold the entire hydrogen inventory at a pressure of less than 74 psi (500 kPa) when the entire system is at 300 K. In view of the large ratio of volumes between liquid at 21 K and gas at 300 K (approximately 800 at one atmosphere pressure), this tank must have a large volume. It is entirely surrounded by a helium blanket in order to prevent air from entering the hydrogen system. The line which connects the ballast volume to the condenser has a check valve installed to ensure that hydrogen can always return to the tank, but that gas can only leave the tank when the solenoid valve (AV-1 in the figure) is activated. This feature ensures that hydrogen cannot be trapped in the cold system with no expansion volume, while also ensuring that if AV-1 is closed, gas which enters the tank cannot leave again. The design limits the volume of gas in the external system when the system is not operating (i.e. during maintenance), when the system could be vulnerable to accidental rupture, since shields may be removed.

The tank will be located on the first floor of the confinement building wall (C-100, see Fig. 6). The tank will be surrounded by a steel frame to protect it against any accidental damage that might occur as a result of any operation in C-100. The piping from the tank to the reactor biological shield, where the condenser will be located, will be inside the existing floor trench, where it is protected from any possibility of accidental rupture. At the reactor biological shield face, the pipe will pass up through the massive radiation shielding to the condenser, which will also be surrounded by steel shielding to prevent accidental rupture from any external cause. Since the system will not be operated unless the shielding is in place, the entire hydrogen system will be enclosed by protective shielding which will prevent the possibility of damage as a result of any external occurence while the system is cold, and the inventory of hydrogen available for release is large. When the system is warm, most of the hydrogen will be in the ballast tank, and protected from release by the valve system described above. This design protects against a massive spill of the inventory to the confinement building, with the possibility of delayed ignition and detonation.

It should be noted that there is <u>no</u> provision for either automatic or manual venting of the hydrogen inventory, either inside or outside of the confinement building. This is a conscious decision, based upon analysis of various scenarios that might occur, such as loss of cryogenic cooling, leaks in the system, loss of insulating vacuum, fire and others. In each case, it was concluded that the ballast tank is the safest possible location for the hydrogen. In any venting system, great care must be taken to maintain high discharge velocities (to prevent back-mixing of air), to maintain an inert gas atmosphere in the vent lines, to ensure that venting does not result in an explosive cloud, to ensure that all of the hydrogen is pushed out of the system, and to ensure that the gas used to vent is inert. All of these requirements require complexity in apparatus and procedures, thus introducing new failure modes. The ballast tank is designed to safely withstand any pressures that might be generated by an external fire . If the system must be emptied, it will be absorbed into a commercial metal hydride storage device, which can then be safely removed from the building. With the system warm, and the ballast tank filled to 75 psi, the remainder of the system will contain less than 10 g of hydrogen (approximately 110 STP liters) out of a total inventory of more than 500 g. As will be shown below, this amount of hydrogen, even if released and ignited, will not cause structural damage to the confinement building.

3. GENERAL SAFETY ISSUES

For reference, the definition of an unreviewed safety question, as defined in 10CFR50.59 is reproduced in whole.

"A proposed change, test, or experiment shall be deemed to involve an unreviewed safety question (i) if the probability of occurrence or the consequences of an accident or malfunction of equipment important to safety previously evaluated in the safety analysis report may be increased; or (ii) if a possibility for an accident or malfunction of a different type than evaluated previously in the safety analysis report may be created; or (iii) if the margin of safety as defined in the basis for any technical specification is reduced."

The issues raised by the use of hydrogen in the beam port of the NBSR are limited to damage to the reactor vessel or to the confinement building as a result of a chemical reaction between hydrogen and oxygen with a large energy release. Because the density of hydrogen atoms in the liquid is much less than in water or ice, any reactivity effect will be less than that of existing systems.

The primary safety philosophy in the source design consists of preventing oxygen from interaction with the hydrogen by passive design features, such as surrounding all hydrogen containing volumes with a blanket of helium gas as a barrier to air in-leakage, minimizing external connections which penetrate this helium barrier, and minimizing hydrogen gas handling which could lead to inadvertent contamination of the hydrogen by air. In addition to these design elements, all components are fabricated to withstand the reaction which could take place if air were introduced. Finally, all hydrogen containing pipes are protected by shields designed to prevent accidental rupture of any line. Calculations based upon both theory and experiment are presented which show that no incident could damage either the reactor vessel or the confinement building.

4. CHEMICAL REACTIONS

When hydrogen reacts with the oxygen in air to form water, it releases a large amount of energy, equal to 1.2 x 10^8 joules per kilogram (or 24 kg TNT per kg). Further, hydrogen has a wide range of flammable concentrations in air - from 4 to 75 % by volume - and of detonability limits - from 18 to 59 % by volume (the stoichiometric volume fraction is 30 % hydrogen by volume). This wide range of flammable and detonable limits is partially compensated by the rapid dispersal of hydrogen in air, as compared to other flammable gases. In this regard, the following definitions are used. A deflagration (or fire) is a reaction in which the flame front moves through the flammable mixture with a velocity less than the speed of sound. In such a reaction, one can use the usual adiabatic form of the gas law to show that the maximum pressure ratic (gas after combustion/gas before combustion) in a closed vessel filled with a combustible mixture is approximately 7. A detonation is a chemical reaction in which the flame front is propagated at velocities exceeding the velocity of sound, generating a shock wave. For such a reaction, the ratio previously defined is less than 16. In an unconfined reaction, a deflagration is of little consequence beyond the damage done by the fire itself, while a detonation can cause damage by the blast loading resulting from the shock wave generated.

As discussed earlier, the primary design goal for the proposed NBSR liquid hydrogen source is to prevent mixing of air or oxygen and hydrogen, by passive design features, and by minimizing hydrogen gas handling. Thus, it is difficult to create a credible scenario that will involve either a deflagration or a detonation of any significant volume of hydrogen. However, in order to show that the system will not involve any unreviewed safety questions, a series of possible occurrences are analyzed, and will be shown not to cause any damage to the cryogenic port, to the reactor, to any safety system, or to the confinement building itself.

4.1 RELEASE OF HYDROGEN TO CONFINEMENT BUILDING

As discussed in Section 2 above, all of the hydrogen system external to the biological shield is either surrounded by steel shields, or located in existing floor trenches during cold source operation. The ballast tank is well protected from damage both by location and by the steel frame which surrounds it. These features make any massive rupture of the hydrogen lines (which might result from an accidental contact with any load being moved on the C-100 level) when the hydrogen inventory is primarily located in the moderator not credible. However, during reactor and source shutdown, when maintenance on the guide system might be performed, the shielding at the reactor face (which forms a large part of the protection of the piping) might have to be removed. Although most of the hydrogen will then be in the ballast tank, and held there by the check valve and AV-1, which will be closed, as much as 10 g of hydrogen gas at 74 psi (500 kPa) could be in the moderator chamber, condenser and connecting lines. The consequences of the release of that amount of hydrogen to room C-100 have therefore been analysed.

When hydrogen gas is released three possibilities exist - first, the gas can diffuse rapidly until its concentration is below the flammable limit with no other consequences; second, the gas could ignite as it is released, leading to a continuous deflagration in open air (this is highly likely, as any accident that is of sufficient intensity to rupture pipes will generate sparks as an instantanous ignition source); and third, the gas could mix with air, followed by delayed ignition and detonation. Of these possibilities, the third is clearly the most severe (although least likely), and so has been analysed. The theoretical maximum energy release from this is equivalent to 240 g of TNT, if the mixing is 100 % effective at exactly the stoichiometric composition of 30 % hydrogen in air. However, this yield cannot be achieved in practice, due to the nature of diffusive mixing, and so the yield will be substantially smaller - 10 % is generally considered conservative. Nevertheless, if we do assume the maximum possible yield, then the blast effects can be estimated from standard distance curves for TNT (see Fig. 7, which was obtained from Ref 1). As is discussed in detail in Ref. 1, it is essential to consider both peak pressure and peak impulse (pressure x time) in assessing the hazards associated with explosions. This reference also shows, on the basis of extensive analysis of bomb damage in London during the Second World War, that threshold values of peak pressure and impulse can be defined *independently* for which no structural damage will occur. In particular, if the impulse generated is less than 120 Pa·s, then no structural damage will occur even for residential construction. Using Fig. 7, the peak impulse for detonation of 240 g of TNT (10 g hydrogen) will be less than 48 Pa·s for all detonation distances of more than 1.5 m. This impulse can be doubled by reflection from the wall, but even this reflected impulse will be less than 100 Pa·s, well below the limit for structural damage. Any actual hydrogen release would have to occur much further from the confinement building walls than 1.5 m, since the only exposed systems which might be damaged, leading to a release, are near the biological shield 10 m from the wall, and air flow is away from the wall. Thus, such a release could not damage the confinement building integrity, although it could have consequences for equipment and personnel in the immediate vicinity. The secondary effects, such as wind driven missiles, present a less hazard to the building.

Since all of the assumptions in this analysis are conservative (100 % yield, release of all 10g of hydrogen even though the rate of release would slow very rapidly when the hydrogen pressure reaches one atmosphere, damage criterion based on residential construction standards), it is concluded that such an accident will not lead to damage to the confinement building, and therefore cannot increase the consequences of any accident previously analysed. Every precaution has been taken to minimize the possibility of a gas release, and procedures will minimize this probability even further, since this provides the only possibility of personnel injury associated with the hydrogen source operation. In addition to all passive features described, hydrogen monitors, set to alarm and shut down the refrigerator if the concentration of hydrogen exceeds 50 % of the lower flammable limit, will be installed in the area and will give audible and visual warning to any personnel present

4.2 OXYGEN CONTAMINATION OF THE HYDROGEN

The entire design philosophy of this source (and every other hydrogen source in operation) is to prevent the possibility of oxygen entering the hydrogen system *e.g* . all systems are surrounded by helium blankets, gas handling is minimized by use of a closed system with no moving parts. Nevertheless, two possible accident scenarios have been analysed, one of which is considered possible, arising from residual oxygen in the supply gas, and one of which is not considered credible, arising from an unknown cause and leading to a stoichiometric hydrogen-air mixture in the moderator.

All hydrogen gas contains residual oxygen at levels measured in ppm by volume. Since this is far outside the limits of flammability, it is normally of no concern. However, in a system containing liquid hydrogen, solid oxygen might concentrate in the liquid. Again, this is normally of no concern, since there is no ignition source, but in a radiation environment, the creation of ozone, followed by conversion back to oxygen can provide such an ignition source. The NBSR source will be filled with high grade hydrogen of less than 10 ppm oxygen, and will be tested before being brought into the confinement building. For conservatism, we assumed that in fact the oxygen contamination is 100 ppm by volume, and that all of this will end up in the moderator as solid (this is so unlikely as to be incredible - most of the oxygen will remain in the condenser). Since the maximum hydrogen inventory will be less than 1 kg, this implies 1.6 g oxygen in the moderator chamber. Assuming maximum yield, this corresponds to the reaction of 0.2 g hydrogen, with an energy release of 2.4×10^4 joules. This energy will show up as a temperature (and therefore pressure) rise of the hydrogen and/or as steam. In either case, the resultant pressure will be less than the elastic limit for the moderator chamber, and will therefore result in no damage to any component of the source. Therefore, this accident scenario presents no hazard to any part of the reactor, its safety systems, or to the confinement building.

Although no credible scenario that will produce the appropriate conditions has been identified, a case in which the moderator vessel is filled with a stoichiometric mixture of hydrogen and air at a pressure of 14.7 psi and 300 K (clearly, the pressure cannot exceed one atmosphere, or else there would be no air present) has also been analyzed. In this case, the resultant pressure from a deflagration would not exceed 7 times the initial pressure, or 103 psi. This is below the rupture strength of the moderator vessel, and so would present no problem for the reactor or any component of the source. A detonation, on the other hand, could lead to pressures of 16 times the initial pressure, or 235 psi, which should not rupture the moderator vessel for which the calculated rupture strength is greater than 500 psi. However, the *working* pressure of the helium containment chamber is 139 psi, and the volume of this vessel is six times that of the moderator. Therefore, even if the moderator vessel did rupture, the outer vacuum and helium vessels would contain the resultant pressures easily, and the effect of such an event would be entirely contained in the cryostat assembly. It is therefore concluded that neither scenario could result in damage to the reactor, its safety systems, or to the confinement building.

4.3 INTRODUCTION OF AIR INTO THE INSULATING VACUUM SPACE

Although all insulating vacuum spaces surrounding the cryogenic portions of the system are surrounded by helium, the consequences of air entering these regions, and being cryopumped onto the cold surfaces, has been analyzed. This would require both that a leak to the vacuum space exists and that the helium gas is contaminated by air (the helium containment systems will be continuously monitored for oxygen during operation, and maintained above atmospheric pressure). The possibility of cryopumping air into the existing cryostat has been previously analysed in NBSR-13 (Ref. 3), and shown not to be a problem in and of itself. We therefore go beyond this scenario, and further postulate that after prolonged, undetected cryopumping, the moderator vessel ruptures, and a strong detonation source is present (all of these postulates are necessary - otherwise, the reactor would be shut down, the source would be warmed up, and the problem repaired). In order to estimate the magnitude of such an event, some level of air contamination in the helium containment system must be assumed. A level of 100 % was used in spite of the fact that it is not credible. A leak rate that would go undetected, for example as a degradation of the insulating vacuum, was also assumed. This has been analysed in detail in NBSR-13 (Ref. 3) for the present D_2O ice source, where it was concluded that no more than 1 g/year could result from a leak with 10 % contamination of air. Therefore, for the postulated scenario of 100 % air, 10 g of oxygen would be the absolute maximum. In a series of tests with a strong detonation source (Ref. 2), the peak pressure ever recorded for a deliberate detonation of hydrogen with 80 g of solid oxygen was 1120 psi, well below the rupture pressure of the cryostat helium and vacuum jackets. Thus, the entire effect would be contained in the cryostat system, and would have no effect on the reactor or any of its systems. This scenario, which goes well beyond the maximum credible accident, in that it assumes failure of many independent systems simultaneously, and violation of many operating procedures, serves as the design basis accident for the NBSR hydrogen source. The results of this postulated accident are entirely contained within the cryostat, and do not affect the reactor or any safety system.

5.0 STARTUP TESTING AND PROCEDURES

Prior to insertion of the new source into the beam port, a set of startup testing and operation procedures will be developed and reviewed by the Safety Evaluation Committee. The startup tests will be designed to verify the design calculations of heating rates, thermal stability, shutdown mechanisms and other critical parameters. The initial tests will be performed at low reactor power, with limits on observed parameters which must be met before proceeding to higher power tests. During these tests, the neutron performance will also be measured, using the already installed instruments in the guide hall.

All existing reactor operation procedures relating to operation of the existing source will be reviewed for applicability to the new source, modified as required, reviewed by the Safety Evaluation Committee, and updated prior to operation of the new source.

6. CONCLUSION

Since none of the accidents analysed here, or identified in the overall safety analysis, have any effect on the reactor or its safety systems, nor on the confinement building, it is concluded that the liquid hydrogen source for the NBSR does *not* involve any unreviewed safety questions.

7. REFERENCES

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2. D. L. Ward, D. G. Pearce, and D. J. Merret, Advances Cryo. Eng. 9, 390 (1964)

3. NBSR-13, Safety Analysis Report on the D_2O Cold Neutron Source for the National Bureau of Standards Reactor, August 1984 (Revised May, 1987).

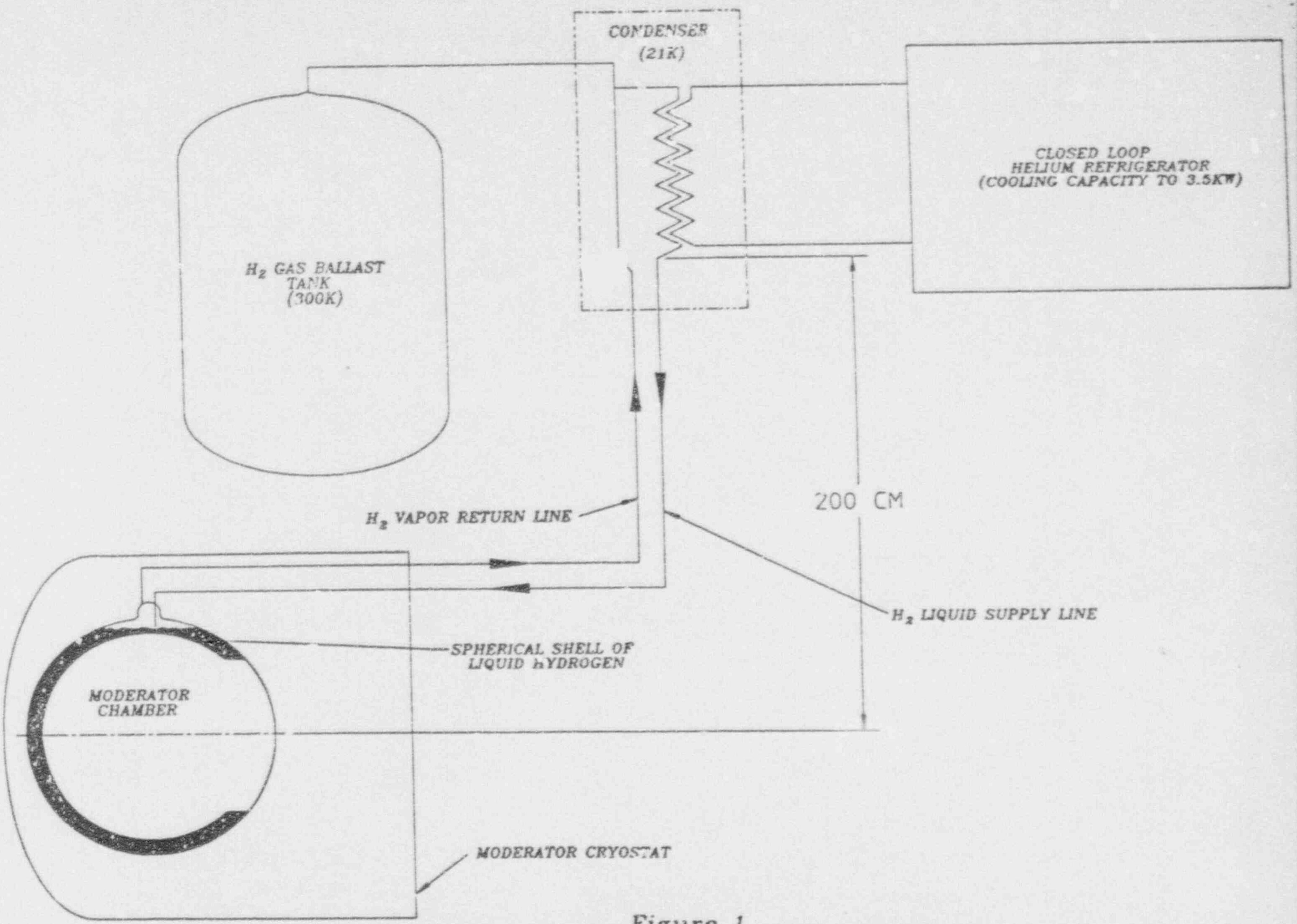
CONDENSER
(21K)
CLOSED LOOP
HELIUM REFRIGERATOR
(COOLING CAPACITY TO 3.5KW)
H_2 GAS BALLAST
TANK
(300K)
200 CM
H_2 VAPOR RETURN LINE
H_2 LIQUID SUPPLY LINE
SPHERICAL SHELL OF
LIQUID HYDROGEN
MODERATOR
CHAMBER
MODERATOR CRYOSTAT

Figure 1

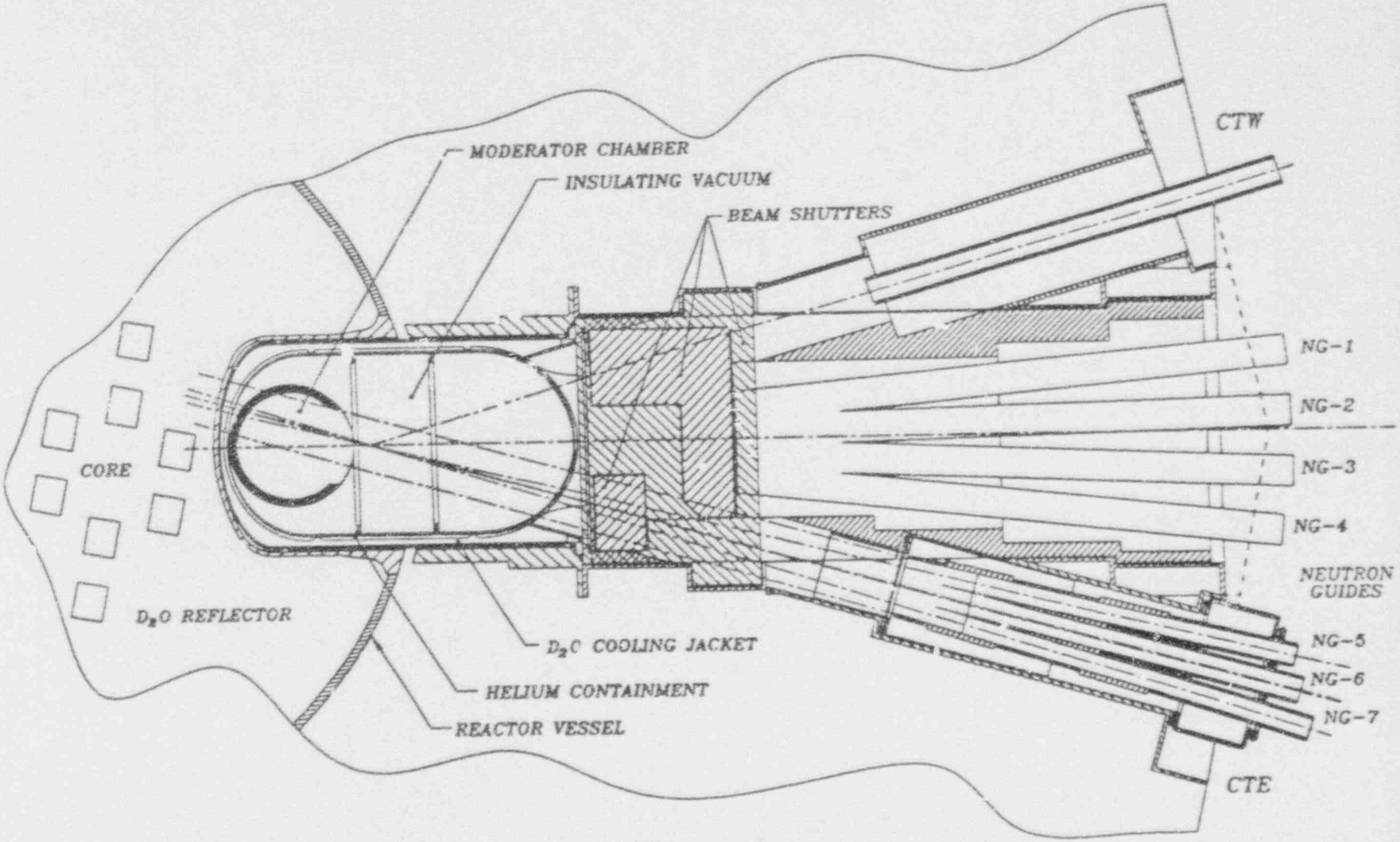
MODERATOR CHAMBER
INSULATING VACUUM
BEAM SHUTTERS
CTW
NG-1
NG-2
NG-3
NG-4
NEUTRON GUIDES
NG-5
NG-6
NG-7
CTE
CORE
D_2O REFLECTOR
D_2O COOLING JACKET
HELIUM CONTAINMENT
REACTOR VESSEL

Figure 2

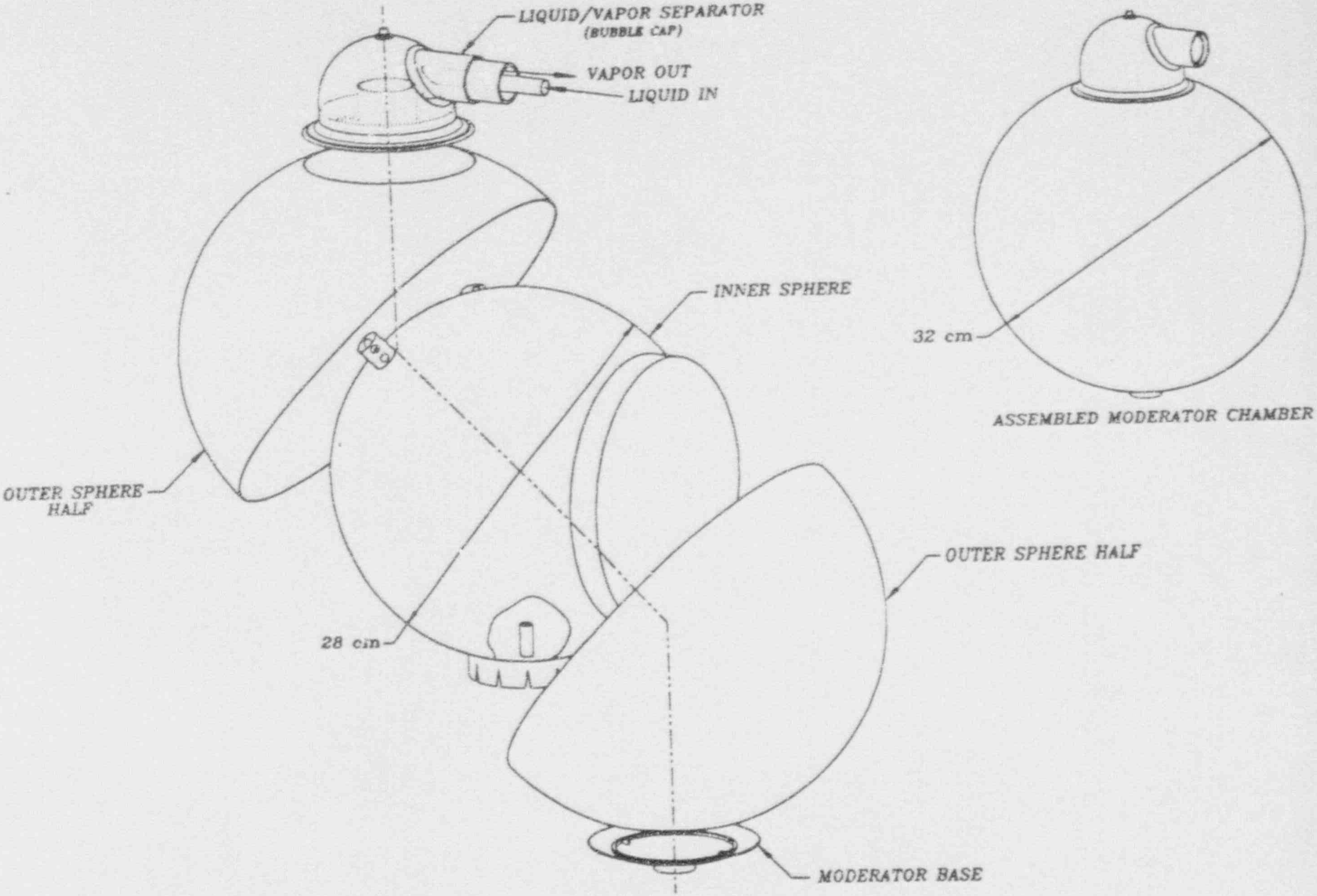
LIQUID/VAPOR SEPARATOR
(BUBBLE CAP)
VAPOR OUT
LIQUID IN
INNER SPHERE
OUTER SPHERE HALF
28 cm
OUTER SPHERE HALF
MODERATOR BASE
32 cm
ASSEMBLED MODERATOR CHAMBER

Figure 3

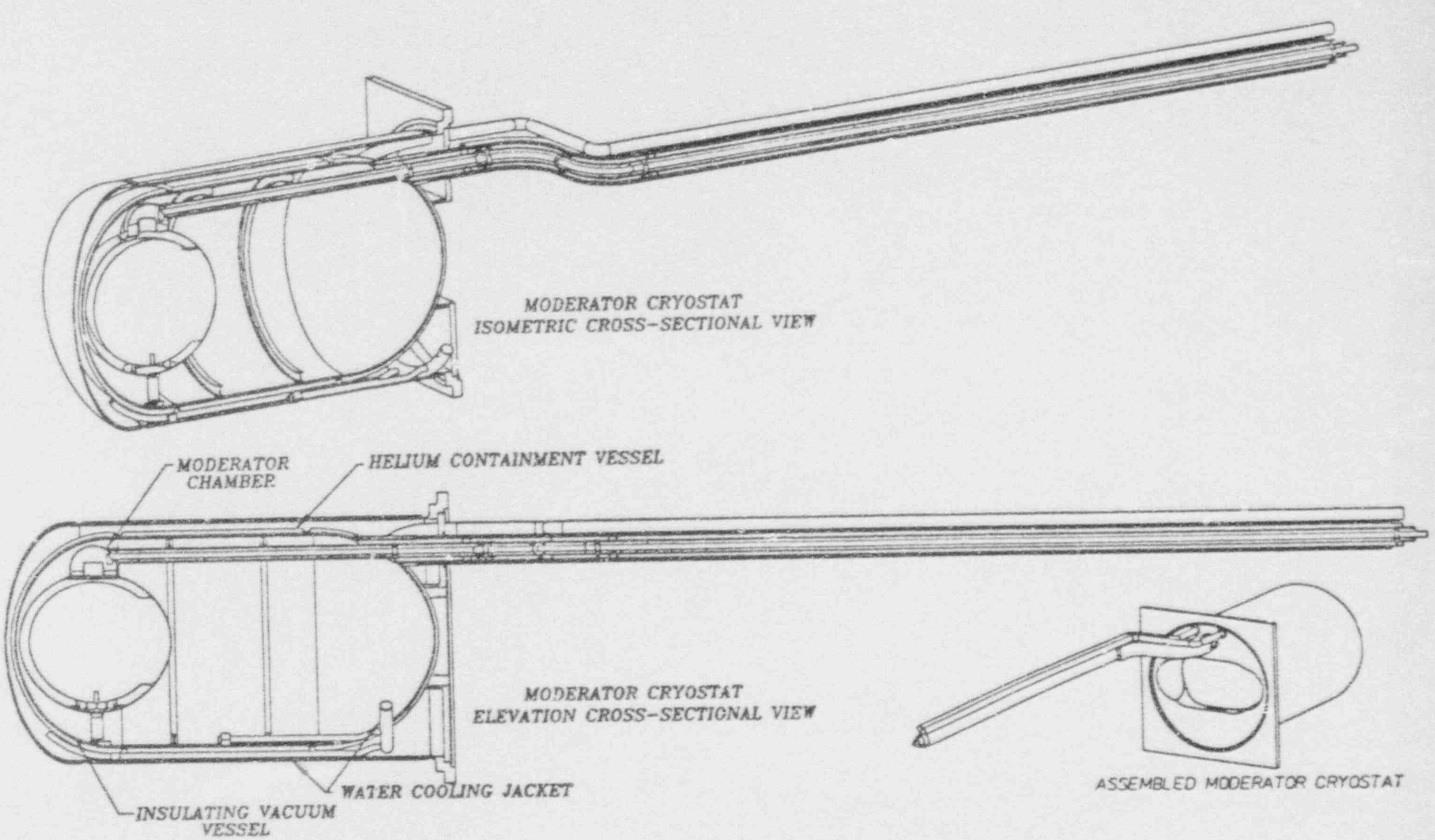
MODERATOR CRYOSTAT
ISOMETRIC CROSS-SECTIONAL VIEW
MODERATOR CHAMBER
HELIUM CONTAINMENT VESSEL
MODERATOR CRYOSTAT
ELEVATION CROSS-SECTIONAL VIEW
WATER COOLING JACKET
INSULATING VACUUM VESSEL
ASSEMBLED MODERATOR CRYOSTAT

Figure 4

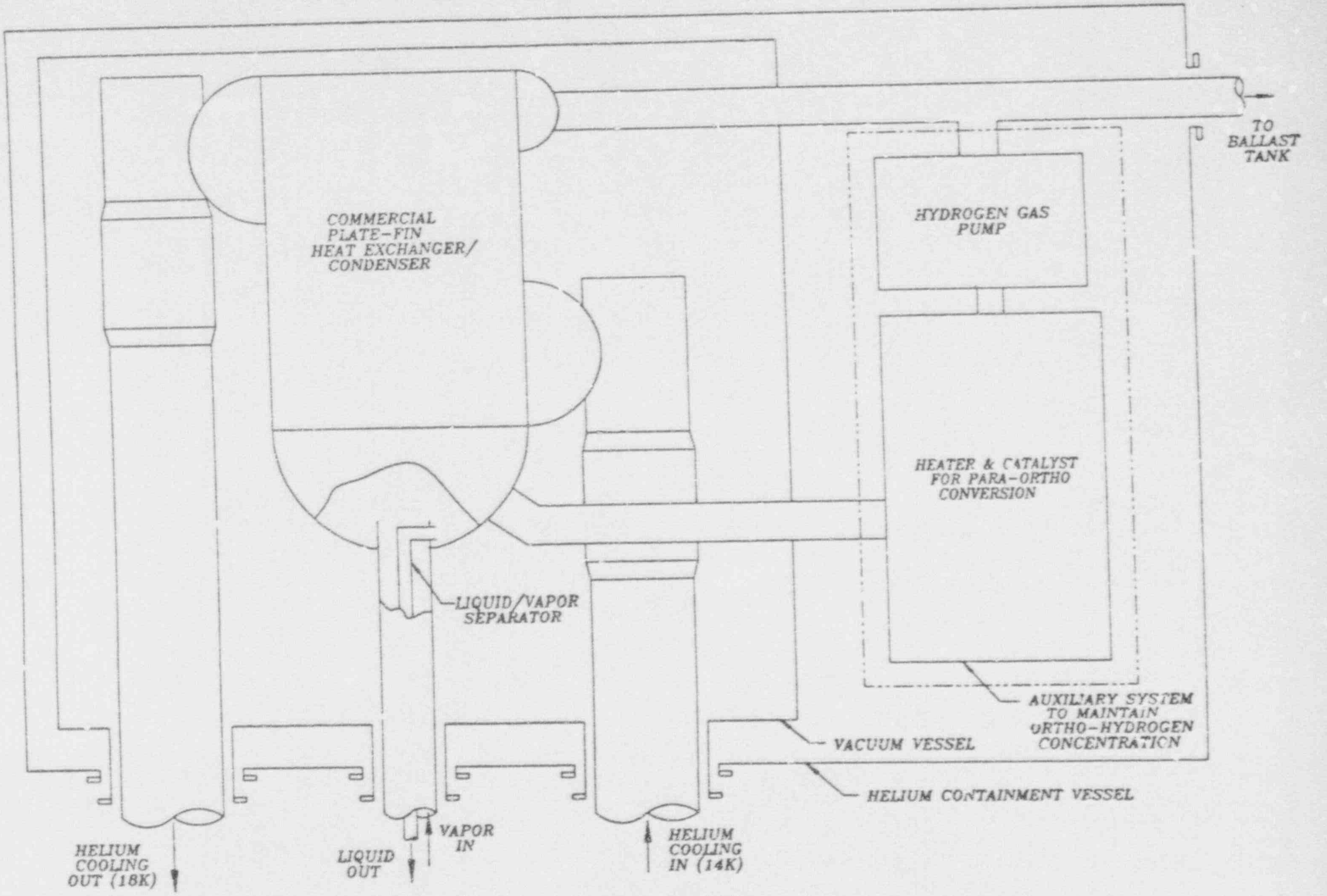
TO BALLAST TANK
COMMERCIAL PLATE-FIN HEAT EXCHANGER/ CONDENSER
HYDROGEN GAS PUMP
HEATER & CATALYST FOR PARA-ORTHO CONVERSION
LIQUID/VAPOR SEPARATOR
AUXILIARY SYSTEM TO MAINTAIN ORTHO-HYDROGEN CONCENTRATION
VACUUM VESSEL
HELIUM CONTAINMENT VESSEL
HELIUM COOLING OUT (18K)
LIQUID OUT
VAPOR IN
HELIUM COOLING IN (14K)

Figure 5

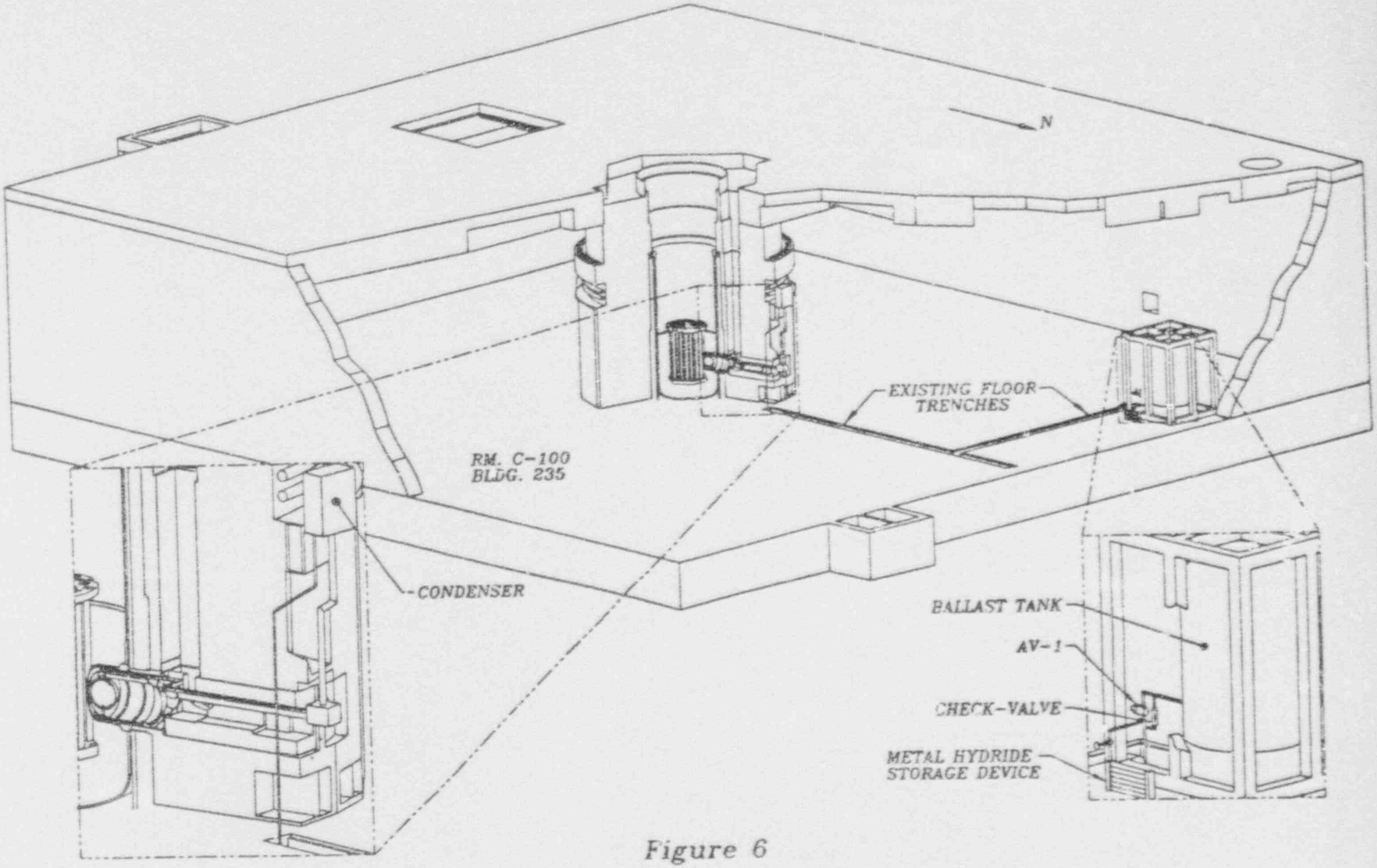
N
EXISTING FLOOR TRENCHES
RM. C-100
BLDG. 235
CONDENSER
BALLAST TANK
AV-1
CHECK-VALVE
METAL HYDRIDE STORAGE DEVICE

Figure 6

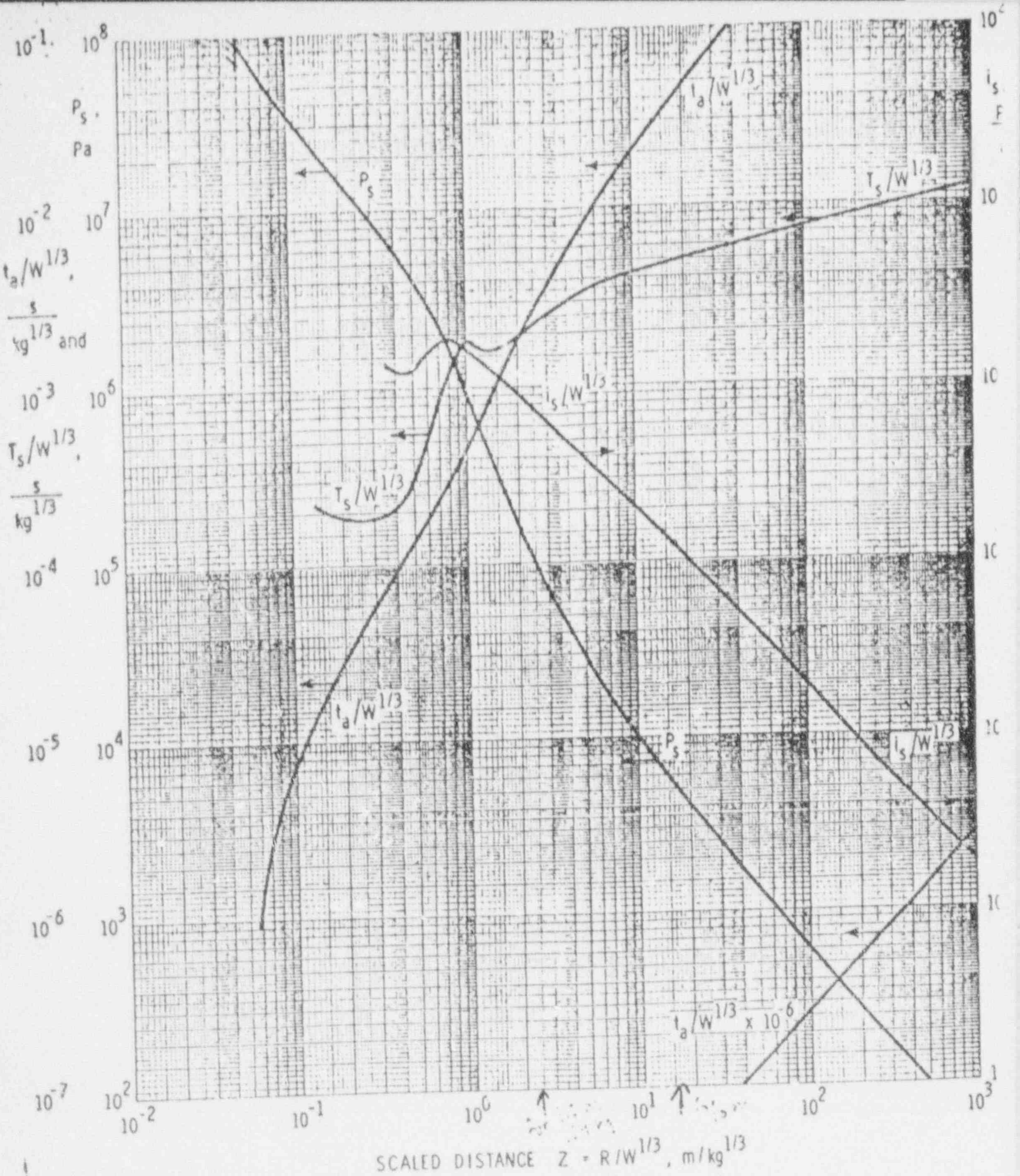

Figure 2-45. Side-On Blast Parameters for TNT

Fig 7