NPDGAMMA LIQUID HYDROGEN TARGET ENGINEERING DOCUMENT

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NPDGamma Liquid Hydrogen Target Engineering Document

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NPDGamma Liquid Hydrogen Target Engineering Document Update/Revision Log

Revision Number	Date	Description of Changes	Pages Changed
0.0	12-02-2004	Base line for the document	n/a
0.01	11-19-2005	Updated baseline	n/a
1.00	03-07-2006	Approved document / SePe	several

1 INTRODUCTION (M. Snow, 6-20-01)

This document consists of a general description of the design, operation, and safety criteria of the liquid para-hydrogen target for the NPDGamma experiment that is under commissioning on flight path 12 at LANSCE. The purpose of the experiment is to search for parity violation in the angular distribution of 2.2 MeV gamma-rays produced by polarized cold neutron capture in hydrogen. The experiment therefore requires a hydrogen target. For the purposes of this document we will define the "target" broadly to include (1) the target cryostat and vacuum system inside the experimental cave, where the neutron captures take place, (2) the gas handling and target control system external to the cave, and (3) the safety system, including the relief valves and relief and ventilation piping. A conceptual diagram of the overall experiment is shown in figure 1. The components of the experiment and beam line are shown in figure 2. Figure 3 shows a view in flight path 12 and figure 4 shows the NPDGamma apparatus without the LH_2 target in the cave during the 2004-commissioning run.

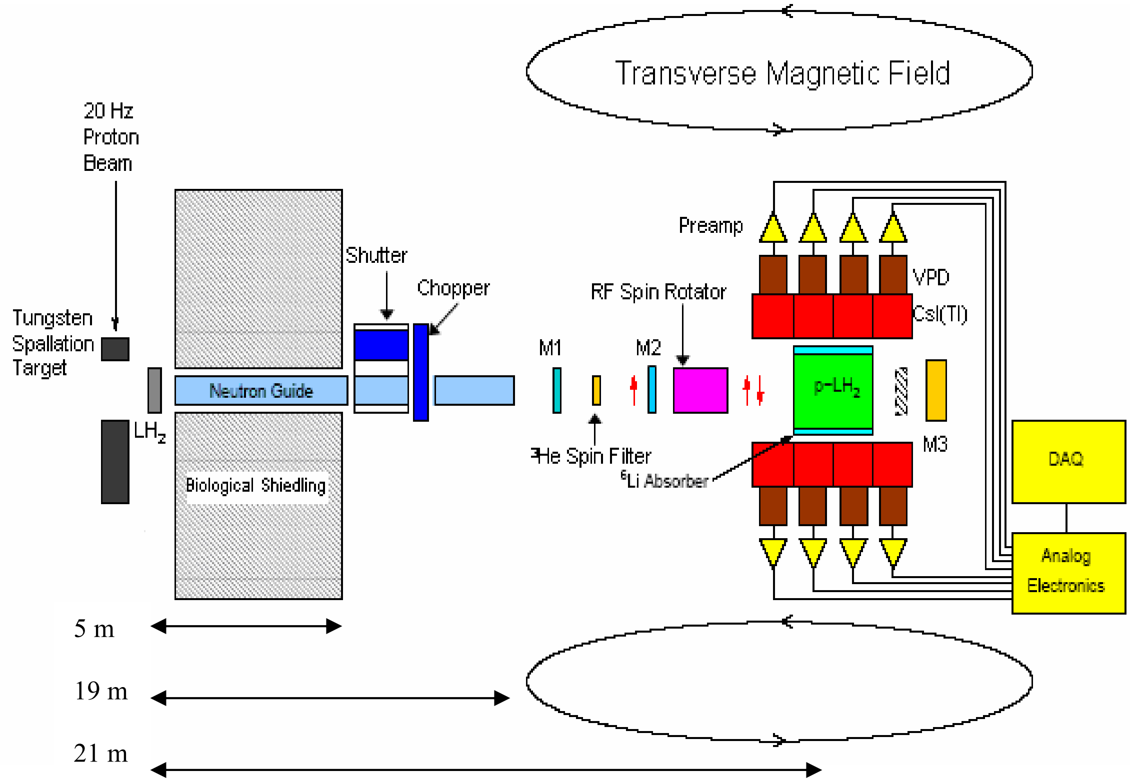

Fig. 1. Conceptual diagram of the NPDGamma experiment. This document concerns the liquid para-hydrogen target (p-LH_2).

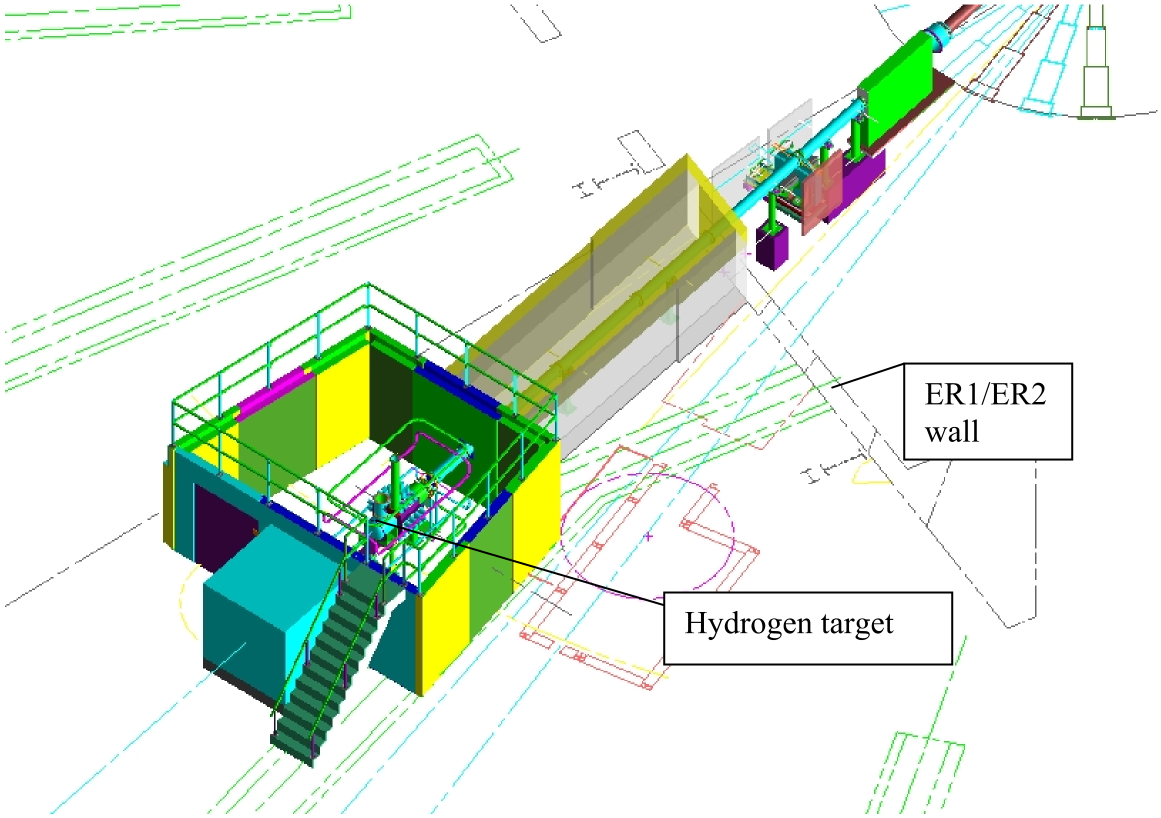

Fig. 2. The NPDGamma experiment on flight path 12 at LANSCE.

Fig. 3. A view on flight path 12.

Fig. 4. The NPDGamma apparatus in flight path 12 cave during the 2004 commissioning run.

The target system is tested first in building MPF-35 (shed) which is a different building from ER2 building where the flight path 12 locates. In this document we try to separate these two locations when we are discussing design, safety, testing, and operation of the target system. In general, the cryostat and relief systems are same in the both cases but, for instance, the gas handling systems will be different.

Figure 5 shows a schematic of the LH_2 target system in shed, figure 6 shows the target vacuum system, figure 7 the gas handling system, figures 8, 9, and 10 the gas panels for hydrogen, helium, and argon, respectively, and figure 11 gives the legend. Two photos in figure 12 show the cryostat and the valve panel of the gas handling system in shed. Figure 13 shows a footprint on the flight path 12 cave top where vent stack, new gas handling system, compressors of the refrigerators, and target instrumentation racks are located.

1.1 Plans for Target System Testing

The target system will be first thoroughly tested in shed. After the successful testing and proper approvals the target will be moved to the flight path 12 at ER2. For the ER2 operations the target system will undergo some modifications, for instance, there will be a new gas panel which is closed into an enclosure which is vented to the outside of ER2. The design of the ER2 gas panel and its operating procedures are given in a separate document "Design Criteria for the NPDGamma Liquid Hydrogen Target's Hydrogen Gas Handling System at ER2". This document can be found in the web page www.iucf.indiana.edu/U/lh2target/export-files/.

The components and the assembled target system went through a preliminary testing at the Indiana University and was then disassembled and moved to LANL. At LANL the target system was reassembled in shed. A plan was first to do a full testing of the system including tests with hydrogen. After passing these tests the target system will be installed to the flight path 12 cave for the production runs with neutron beam.

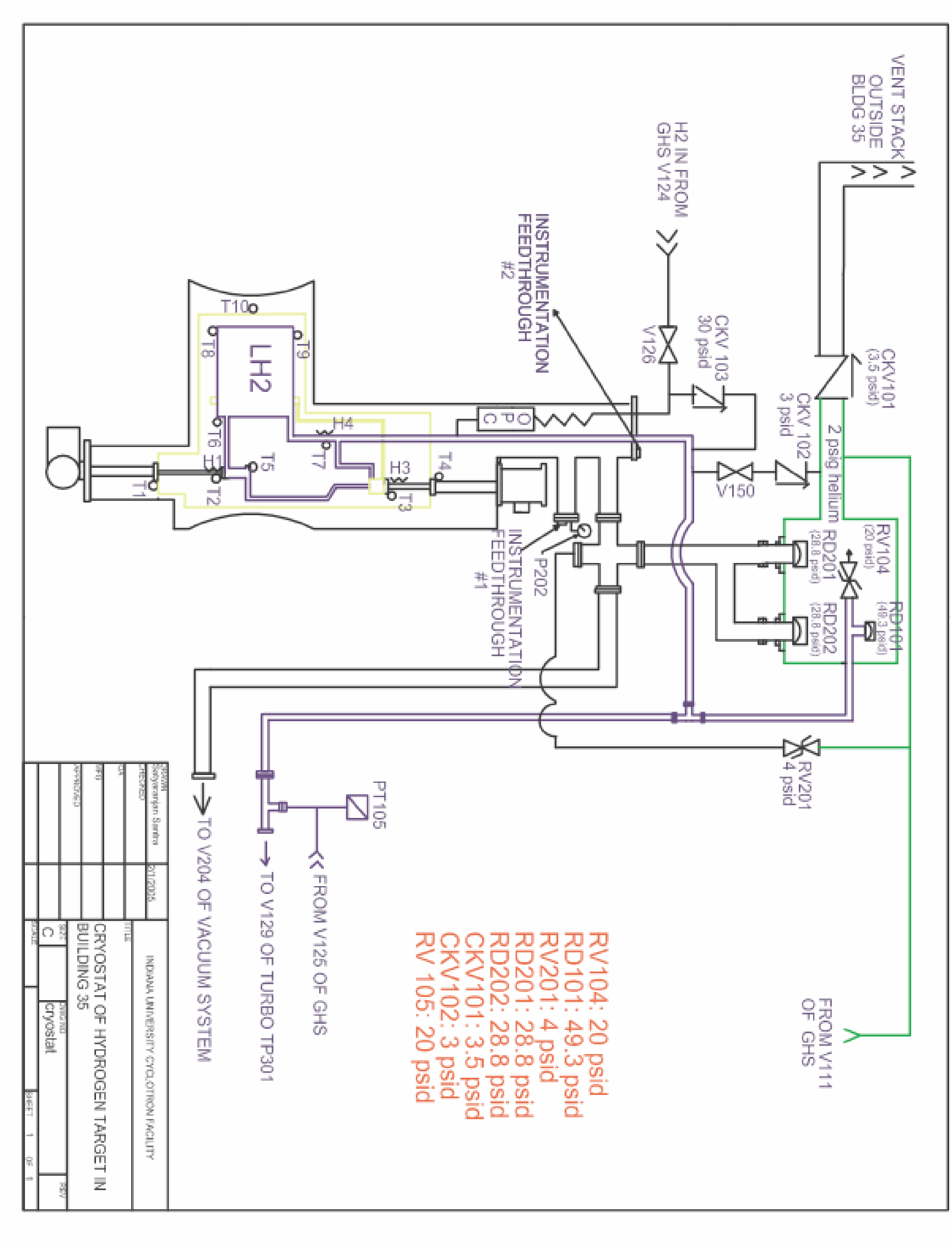

Fig. 5. The LH_2 target diagram for the shed operation. Shown are cryostat and relief system.

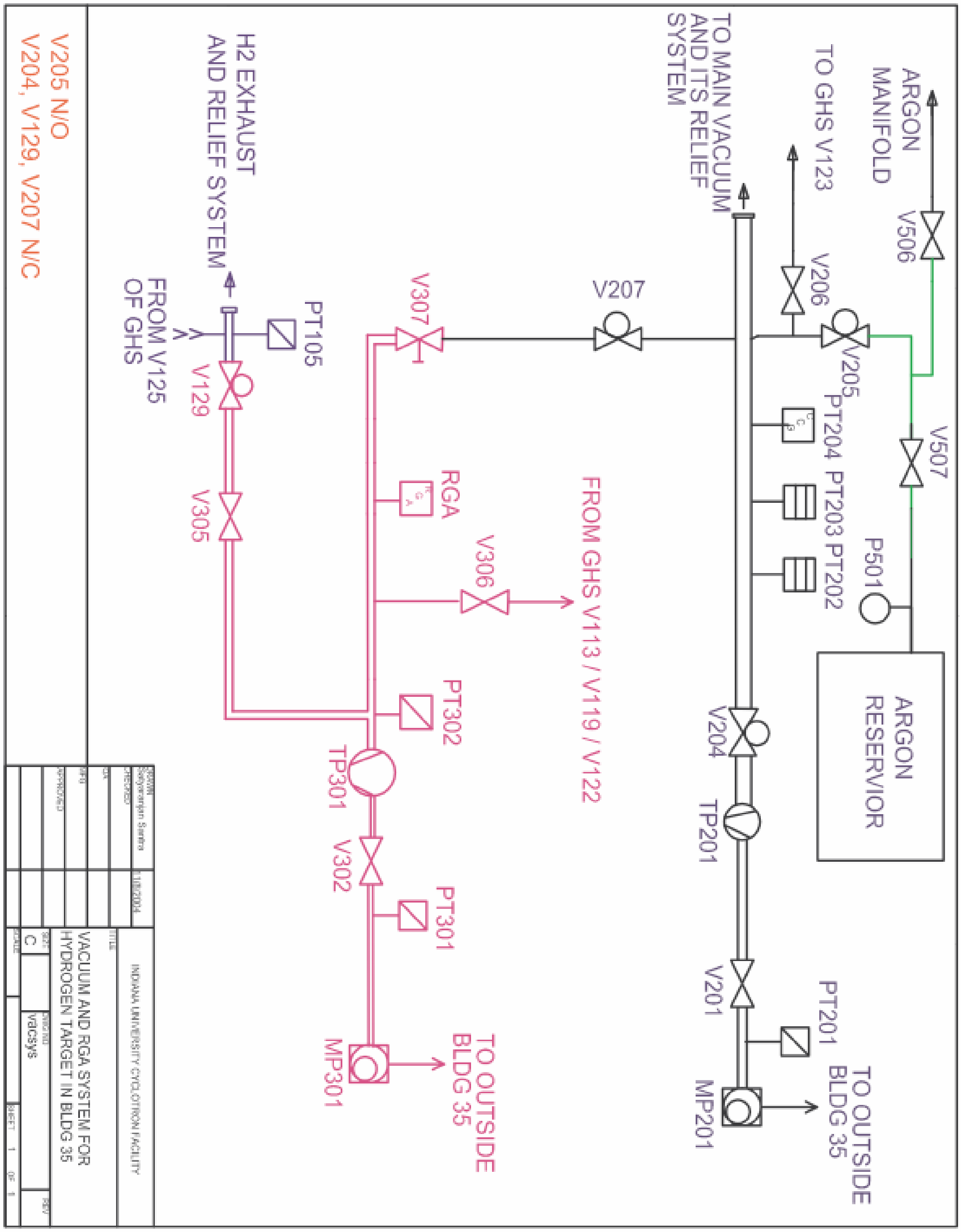

Fig. 6. The LH_2 target vacuum system in shed.

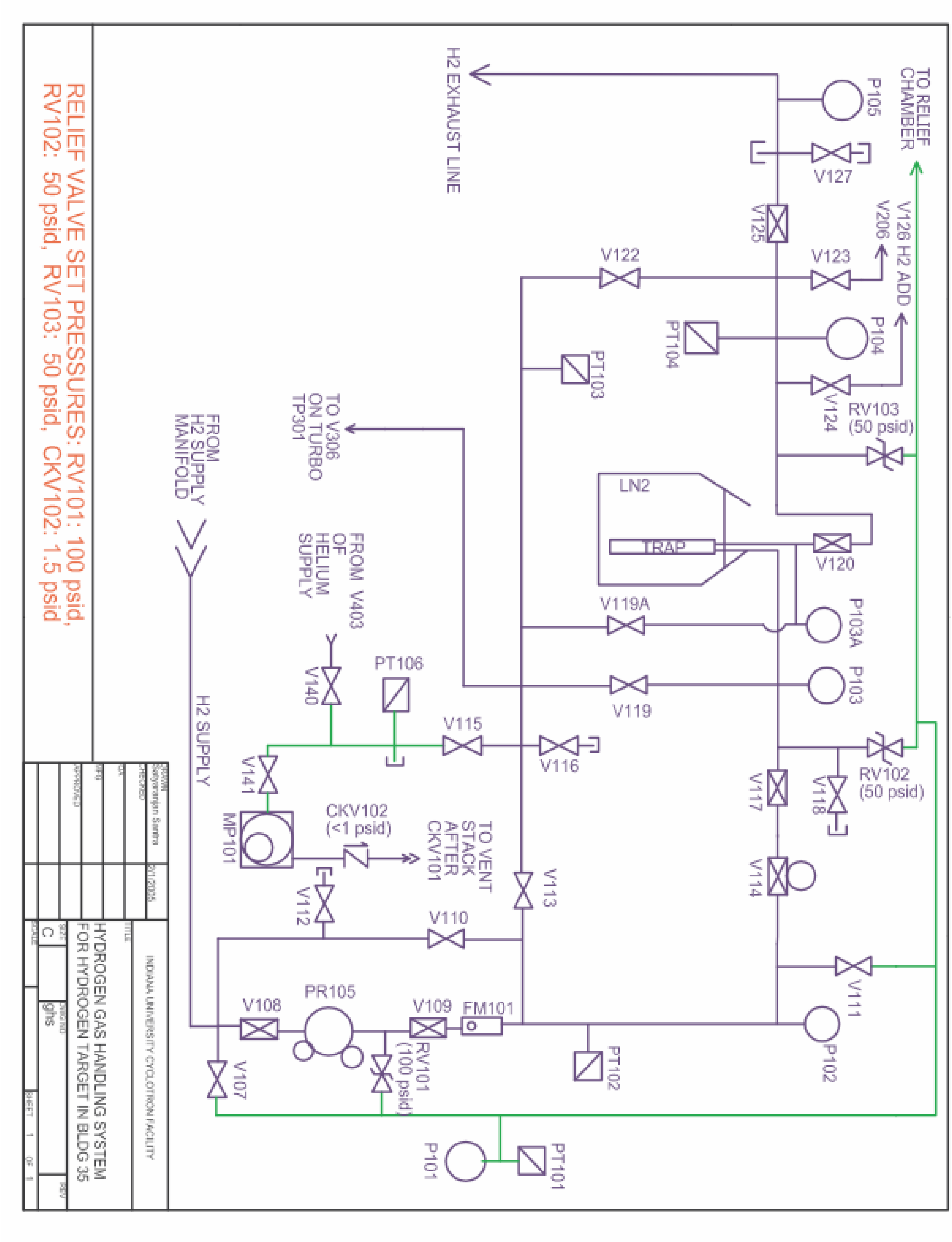

Fig. 7. The LH_2 target hydrogen gas handling system for the shed operation.

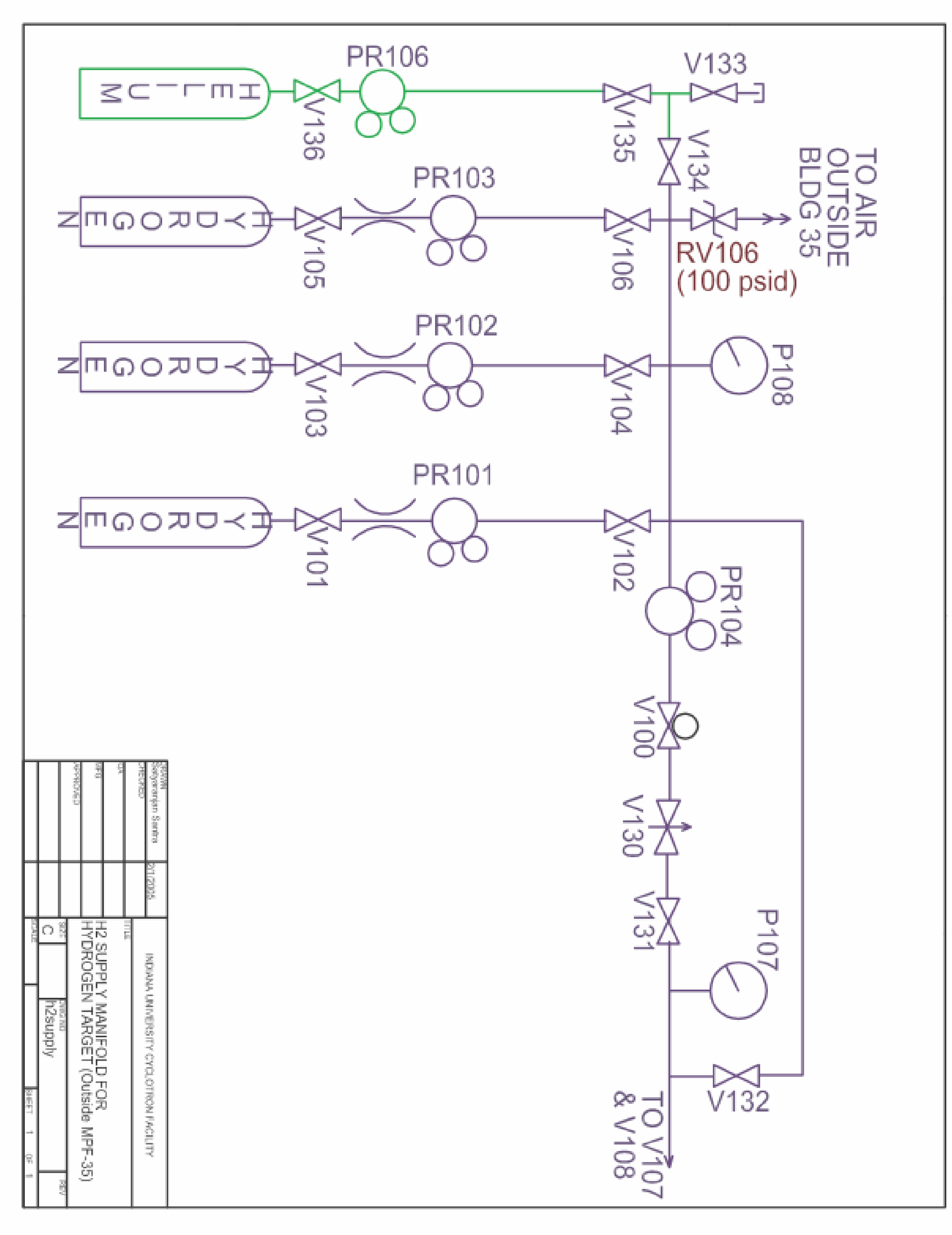

Fig. 8. The LH_2 target hydrogen supply manifold outside of MPF-35.

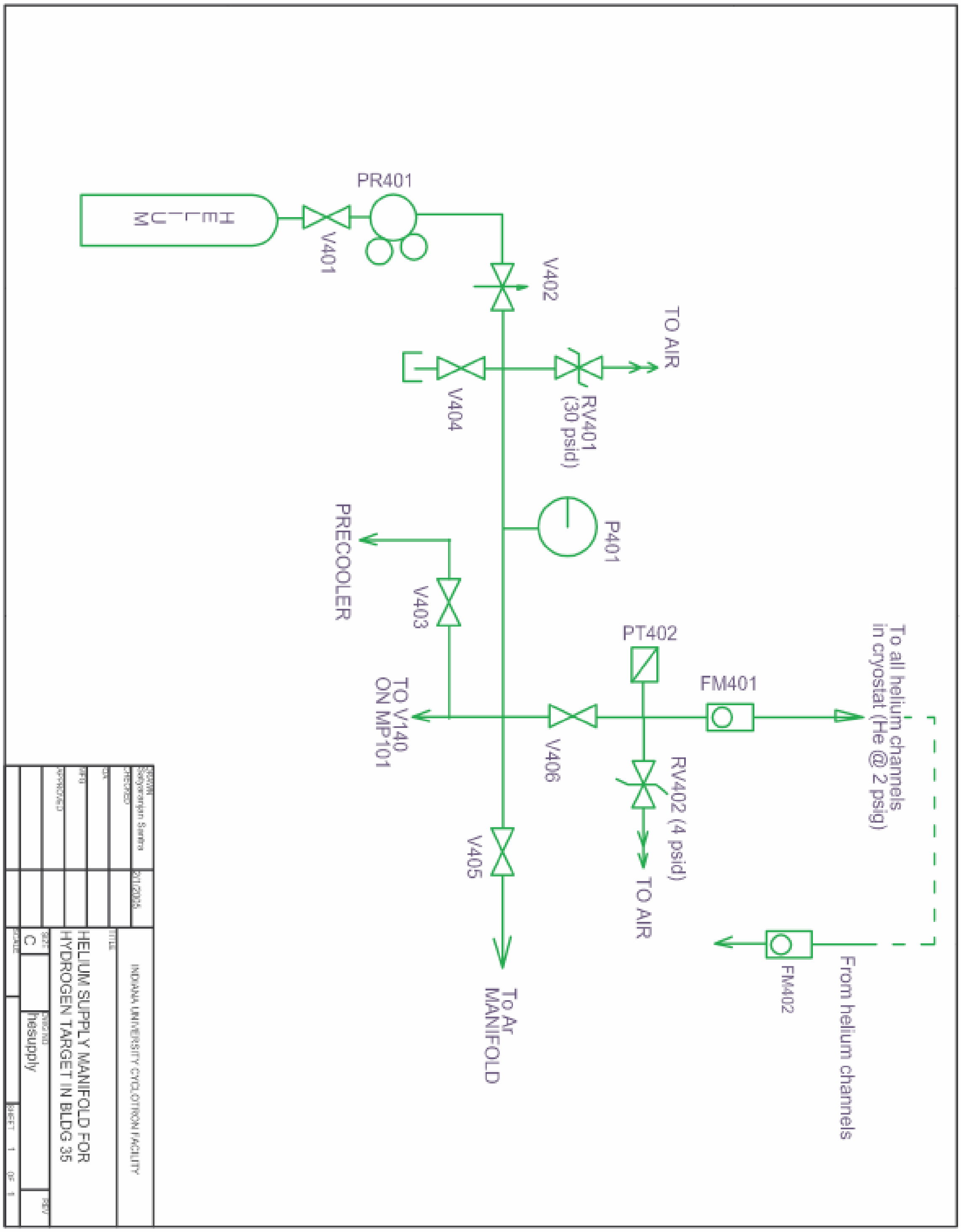

Fig. 9. The LH_2 target helium gas manifold.

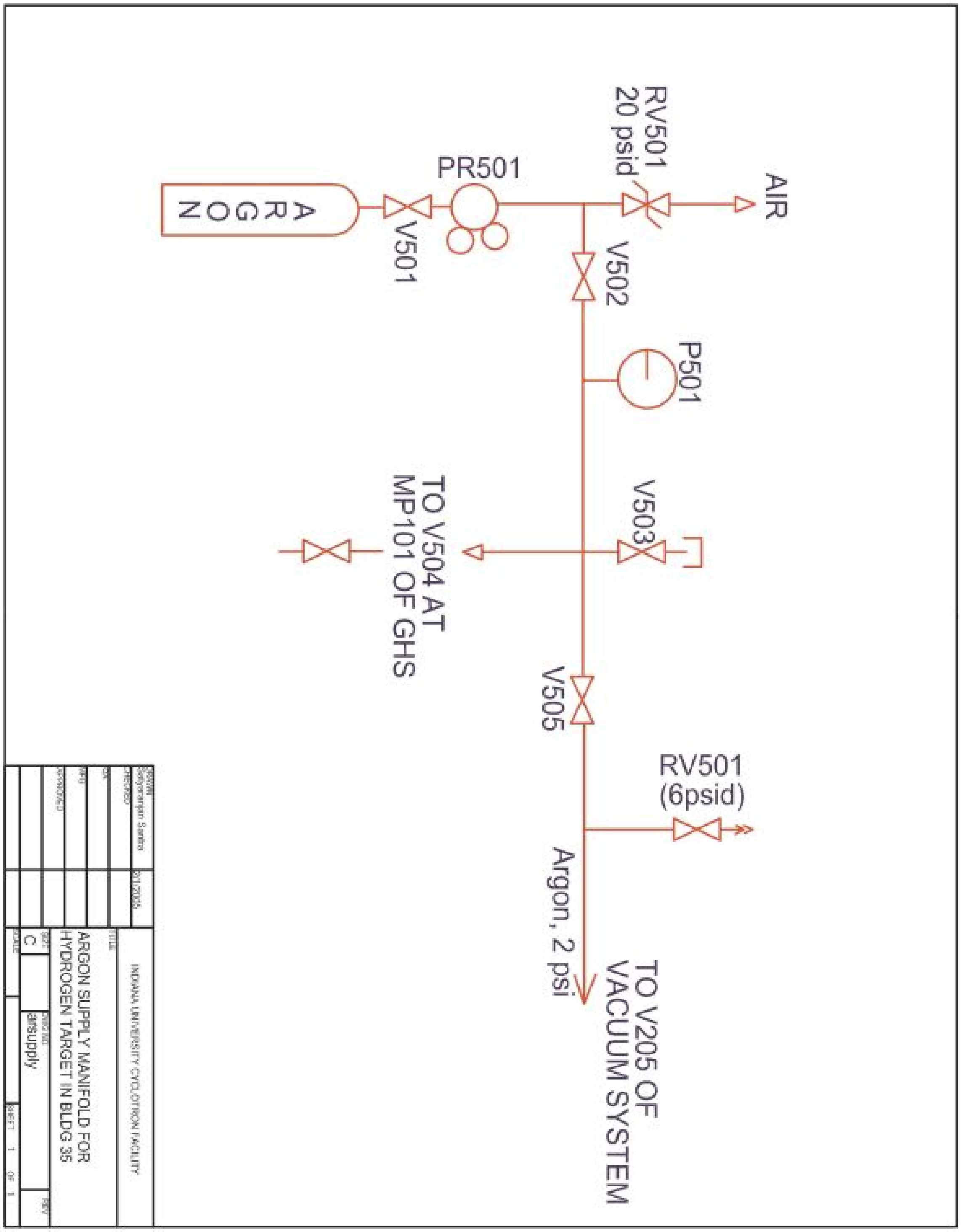

Fig. 10. The LH_2 argon gas manifold.

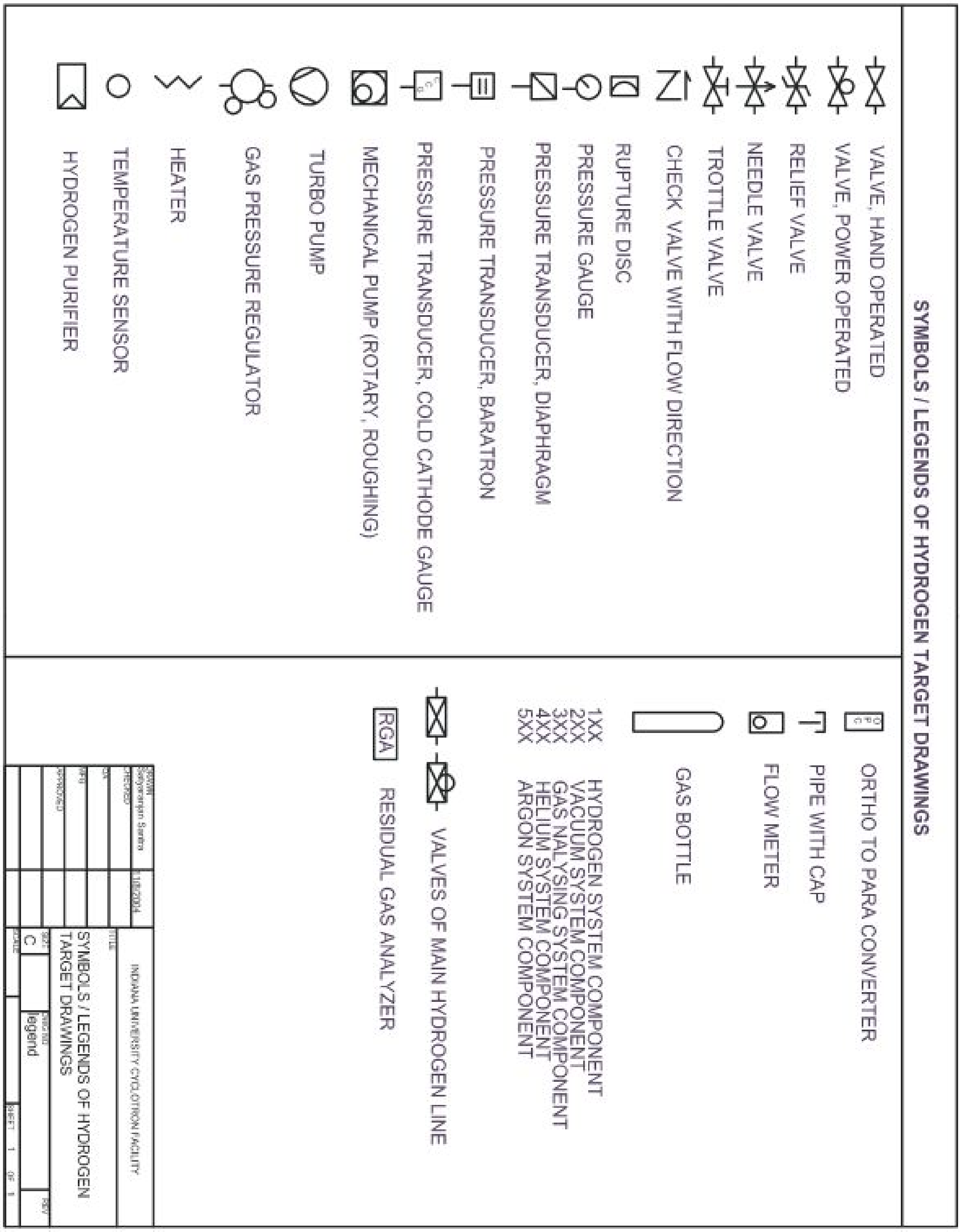

Fig. 11. Legend for the LH_2 target system shown in figures 5 - 10.

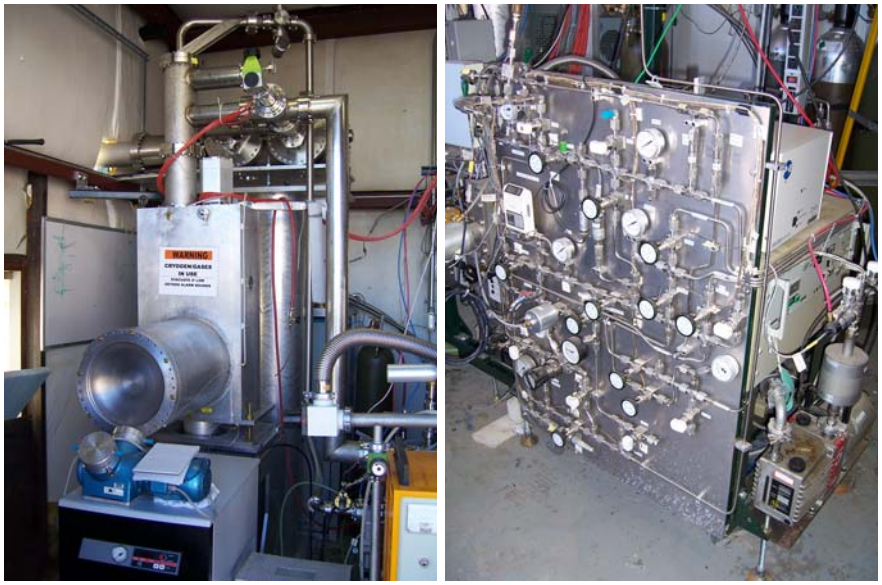

Fig. 12. Target cryostat and the valve panel of the gas handling system in shed.

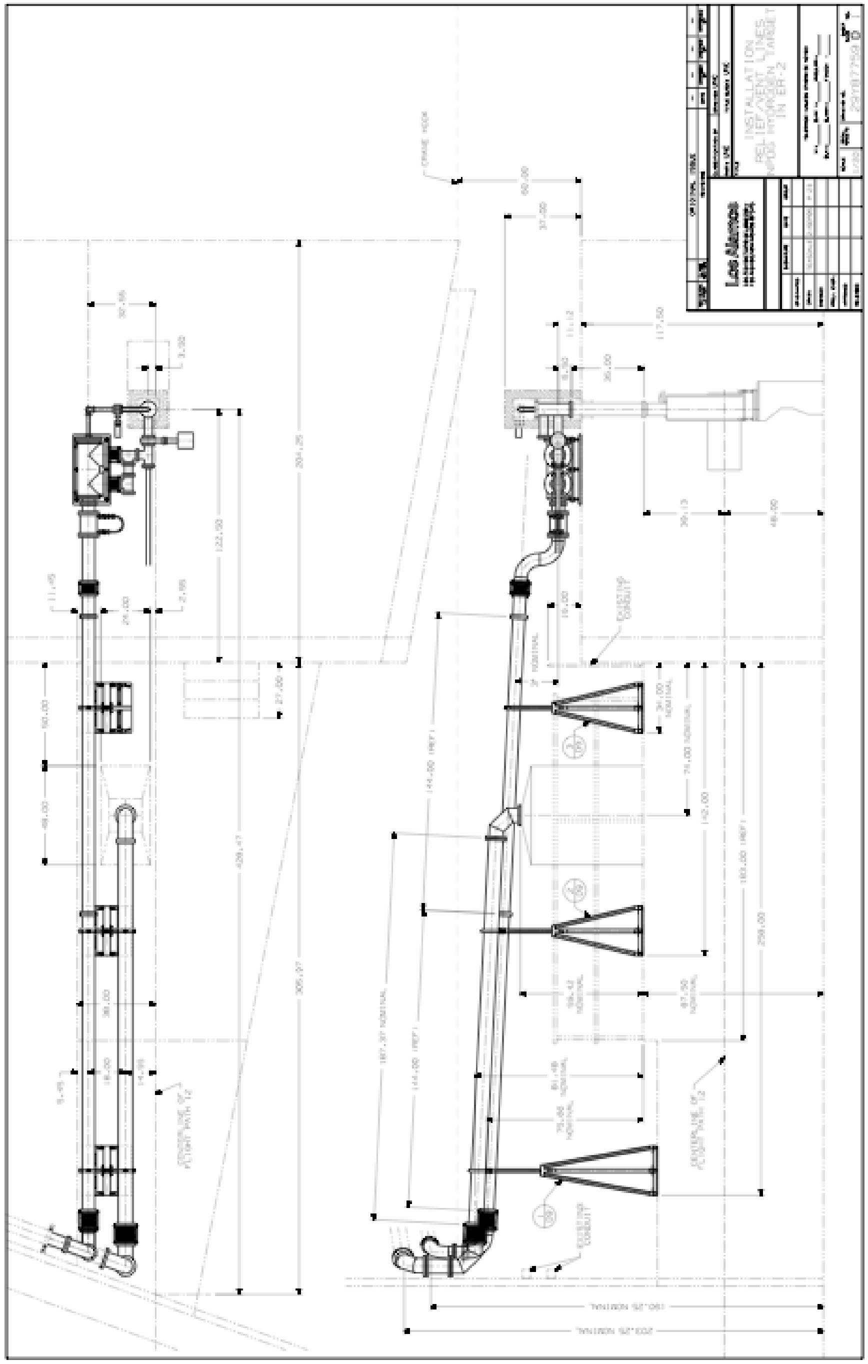

Fig. 13. Vent stack and GHS ventilation piping on top of FP12 drawing # 29Y87759 D1.

2 THE NPDGamma LH_2 TARGET (M. Snow, 6-20-01)

Next we give a brief description of the physics goals of the experiment. The goal of this experiment is to search for a parity-violating asymmetry in the angular distribution from polarized cold neutron capture on protons with a sensitivity of 5 ppb. To reach this level of statistical accuracy will require operation of the experiment at the LANSCE neutron source for a live time of approximately one year. In addition, we must insure that there exists no other effect in the experiment which introduces an asymmetry in the apparatus which does not come from the reaction of interest. Our goal is to limit the size of all such possible "false" effects to a size of 0.1 ppb. A detailed description of the means by which the overall experiment plans to achieve these goals is included in the DOE NPDGamma proposal. This and other documents relevant to the physics goals of the experiment and the current status of progress toward those goals can be found on the website http://p23.lanl.gov/len/npdg/.

2.1 Design Criteria for the Target (M. Snow, 6-20-01, 8-20-02 by WMS)

The physics goals of the experiment coupled with the known properties of cold neutron and MeV gamma interactions with materials, the properties of hydrogen, and the need for the target system to be consistent with the other subsystems of the experiment implicitly define the following design criteria for the target:

(1) The target must absorb as much of the polarized cold neutron beam flux as possible without depolarizing the neutron beam before capture. The need to prevent neutron depolarization requires the target to consist of para-hydrogen at a temperature no higher than 17 K. Given the 10 cm diameter of the beam size on flight path 12, the phase space of the beam from the cold neutron guide using m=3 supermirror neutron guides, and the scattering cross section of cold neutrons in para-hydrogen, the target size of 27 cm diameter and 30 cm length has been chosen on the basis of Monte Carlo simulations using MCNP and the LANL hydrogen neutron scattering kernel. This target will absorb 60% of the incident cold neutron flux. The target system therefore requires a cryostat to liquefy gaseous hydrogen and an ortho-para converter to catalyze the formation of para-hydrogen.

(2) The target must possess negligible attenuation for the incident neutrons and for the 2.2-MeV gammas from neutron capture. This requires the use of low Z materials in the target vessel and associated radiation shields as well as the vacuum vessel.

(3) To ensure that the statistical accuracy of the measurement is not compromised by extra noise due to density fluctuations in the target, we require a liquid target in which bubbles are suppressed to acceptable levels and in which fluctuations in the pressure and temperature of the target are held to acceptable levels. The suppression of bubbles will be insured by the following design features: (a) using two cryo refrigerators which will be capable of cooling the radiation shield surrounding the target vessel to a temperature below 80 K, thereby reducing the heat load on the 17 K target vessel, and (b) the use of a heater on the exhaust line of the target which can maintain the pressure in the (re-circulating) target chamber at a value above that of the equilibrium vapor pressure of 246 Torr (4.8 psia) at 17 K, in other words, the target is superheated (see figure 8).

(4) To ensure that no false effects are introduced by gammas produced by polarized slow neutron capture on target materials other than para-hydrogen, we must select the target vessel material carefully. The window materials seen by the incoming neutron beam will consist of Al alloy as also on the target vessel itself. The remainder of the target chamber, although made of Al and Cu, is protected from polarized neutron capture by a ^{6}Li-rich plastic neutron shield outside of the target flask. This shield will possess an exit hole which will be small enough for polarized neutron capture in the Al exit window to produce a negligible systematic effect but large enough to permit efficient monitoring of the neutron beam exiting the target. Materials like Al, Cu, B, and In were studied during the 2004-commissioning run and fund not to be a source of a false gamma-ray asymmetry in the NPDGamma experiment.

(5) To ensure that the interaction of circularly polarized gammas produces negligible systematic effects and that the magnetic field in the target can be maintained with sufficient uniformity, the target materials in the vicinity of the neutron beam must be nonmagnetic (relative magnetic permeability less than $\mu_r<1.02$). Any magnetic components in the target system must result in negligible magnetic field gradients.

2.2 Responsibilities (M. Snow, 6-20-01)

The Hydrogen Target is responsibility of the Hydrogen Target Work Package (WBS 1.7) in the NPDGamma Experiment construction project. The project manager is Seppo Penttila and the work package leader is Mike Snow. The target is designed and constructed, and will be operated jointly by the NPDG collaboration. Inside the Hydrogen Target Work Package responsibilities have been organized so that the design is done jointly by Indiana University and Los Alamos. Roughly speaking, Indiana University has the major responsibility for target design, construction, and non-LH_2 testing at Indiana and LANL has the main responsibility for the testing of the target system, interfacing the target to the facility, target safety, and keep the project in compliance with the Laboratory safety policies and regulations which mainly are based on the National Codes.

2.3 Basics of the Target System (M. Snow, M. Gericke, H. Nann, 6-20-01, 9-13-02 by WMS,)

Here we describe the basics of the overall design of the target system, including important parameters when required but not including detailed design calculations that are outlined later in the document. We will organize the discussion by following the hydrogen path during the filling process in the shed operation. We will restrict here our description to the filling procedure and steady-state operation of the target with some general comments on the main safety features.

The hydrogen gas starts from the supply manifold located outside of the experimental building ER2 or shed. In the supply manifold three 2000 psi compressed gas cylinders with an ortho-para ratio appropriate to room temperature in thermodynamic equilibrium (3:1) are connected to pressure regulators PR101, PR102, and PR103. Between the cylinders and regulators are flow restrictors which allow maximum flow of about 20 slpm. The gas supply pressure is regulated to about 100 psig by PR104. After the regulator the gas flows through a remotely controlled valve, V100 which will close in the event of an appropriate warning signal or loss of electrical power, then the flow is restricted by V130 (see figure 8). The supply line from the supply manifold is connected to a gas handling system (GHS) located close to the target. Next the gas goes through a liquid nitrogen trap (TRAP) in the GHS panel to remove water and reduce other contaminants. The maximum gas flow rate, liquefying rate, which is determined by the cooling power of the precooler, the refrigerators, and the properties of hydrogen (see below), will be 20 standard liter/minute regulated by the flow restrictors on the regulators and V130.

In addition to the hydrogen fill line, there is a main vacuum line for evacuation of the cryostat isolation vacuum and, for leak testing of components. A helium manifold is used to provide a small flow of helium gas to all vacuum seals and weld joints and fill with helium gas the buffer volume between the check valve CKV101 and the relief chamber containing the valve RV104 and the rupture disks RD101, RD201, RD202. A residual gas analyzer (RGA) will be used to monitor water, N_2, and He content in the vacuum during target testing prior to cooling, and to sample the main vacuum residual gas composition for helium and other gases during operation. The helium signal level is interlocked to the target safety system. Pressure gauges will monitor pressures in the target and in the main vacuum chamber. Two electrical feed-throughs on the cryostat will provide signals from all thermometers in the target and control of heaters. All transducer signals from the target possess wiring that is located in the main vacuum chamber. A turbo pump will be used to evacuate the target chamber. The pump will be isolated from the target vacuum with an automatic valve V207 during filling and manually during steady-state operation to prevent loss of vacuum to the target during a power failure. The plumbing on the gas handling system will consist of welded components and CF flanged and VCR-based joints constructed to typical (better than 10^{-9} atm cc/sec) helium leak tight specifications. Relief valves and rupture disks are mounted at all required locations to protect personnel and apparatus. Argon gas from the argon reservoir will be introduced into the main vacuum chamber of the cryostat when fast warm up of the target is required for emergency response. Plumbing lines entering the target cryostat possess sections of flexible lines and bellows for connections and mechanical isolation. At ER2 the new valve panel of the GHS will be closed inside a metal enclosure with its own ventilation line to outside of ER2. In shed GHS, target cryostat, and part of the relief system are covered by a tent ventilated to outside of shed.

In ER2 the hydrogen gas enters the extended cryostat top head which reaches outside the cave top through a reentrant hole in the cave roof shielding. Inside the cryostat the gas first passes through the combined precooler and ortho-para conveter operated at about 30 K. Then the gas travels vertically into the main vacuum chamber and is thermally connected to the cooling stages of a pulse-tube cryorefrigerator (Cryomech) where the hydrogen is liquefied. It then enters the hydrogen target vessel and will be filling also the ortho-para converter chamber which is thermally connected to a mechanical refrigerator (CVI). The refrigerators are mounted on the cryostat and their associated compressors are located on the top of the cave. The cooling powers of the refrigerators suffice to keep the hydrogen at 17 K and complete the ortho-para conversion. Gas produced by the heat of conversion during filling is recondensed in the ortho-para and liquefying chamber and gas produced by boil-off in the chamber re-circulates until essentially all (99.8% at 20 K) of the liquid in the target is converted to the para-state.

The outer jacket of the main vacuum system is constructed entirely of 6061-T6 aluminum by an IU contractor (Ability Engineering). It possesses a horizontal cylindrical region which inserts into the CsI gamma detector array and a downstream rectangular cross-section box whose downstream wall is removable with a viton o-ring seal and In seal and nonmagnetic Helicoil inserts to avoid galling of the aluminum threads. The rectangular portion is machined out of a solid block of aluminum and the cylindrical portion is cut from extruded pipe to minimize the required amount of weld joints. The two-layer neutron entrance and exit windows, on each side, are formed into a trapezoidal shape for increased strength. Two sets of windows exist: one made of 6061-T6 aluminum alloy and the other made of magnesium alloy (Ability Engineering). Helium gas is introduced into the space between the windows, into gas channels machined into the chamber and introduced using pipe threaded holes, and in the space between the inner In seal and outer viton o-ring seals in such a way that every seal and weld joint is exposed to helium gas to catch any leaks into the vacuum system. To prevent helium diffusion through the viton o-ring seals the inner seals are made with indium wire. The top of the chamber possesses threaded holes for lifting eye-bolts. The inside surface of the chamber and the inside surfaces of the windows are polished to a mirror finish to reduce emissivity of heat radiation.

The liquid para-hydrogen flows down a fill line into the bottom of a 20-liter cylindrical target chamber. The chamber is wrapped with Li-loaded flexible plastic neutron shielding (~2mm thick), a thin (0.025”) copper shield, and superinsulation (Mylar coated with aluminum on both sides with adjacent layers separated by polyethylene netting) and is supported and separated from the 80K copper radiation shield by a thermally-insulating support structure made of a G-10 ring. Thermal connection of both refrigerators to the target chamber, ortho-para converter, and radiation shields is effected by both mechanical connection to the cold stage flanges, a thick copper bar and clamps on the rear of the vessel and along the exhaust line, and, where necessary, by flexible copper braid. A similar G-10 support structure separates the 80K radiation shield from the inside of the main vacuum chamber. This support structure allows the liquid target chamber to slide horizontally upon thermal contraction. Stresses on the target from differential thermal contraction in the vertical direction are accommodated with the use of a stainless bellow on the target line. Stress on the 80K radiation shield due to differential thermal contraction in the vertical direction is accommodated by the flexibility of the thin walls of the radiation shields introduced by cutting radial slots into the soft copper sheet near the thermal contact to the lower (CVI) refrigerator. The inlet/outlet line of the target has bends to avoid excessive radiative heat loads from a line-of-sight view of room temperature surfaces.

Two target LH_2 vessels were fabricated. The titanium (Excelco) and aluminum (Ability Engineering) target vessels are identical in design. They are both welded pressure vessels with two weld seams, one at the convex entrance dome and the other at the concave exit dome, that have been pressure tested, helium leak tested, and thermally shocked by dunking into liquid nitrogen. The test and results are given below. The vessel design was arrived at through finite element calculations performed by the ARES Corporation (report available in the web page www.iucf.indiana.edu/U/lh2target/export-files/).
The inner surface of the titanium vessel was treated to ensure that a sufficiently-thick oxide layer exists to reduce any possible hydrogen embrittlement of the titanium to negligible levels and tests were conducted on separate titanium test pieces treated in the same manner to ensure that the treatment did not reduce the yield strength of the titanium alloy used. Outside the target chamber is a cylindrical neutron shield loaded with Li to prevent polarized neutron capture on materials around the target vessel with about a 18 cm in diameter entrance hole for the neutron beam and a much smaller, about 2 cm, exit hole for monitoring purposes downstream of the

target. Because of the physics reasons the Al target vessel and Al windows will be used in the NPDGamma experiment.

The exhaust line from the liquid hydrogen vessel possesses a large inner diameter (1.5” OD with 0.032” wall). This exhaust line passes through a top flange of the main vacuum chamber extension that penetrates the cave roof ceiling to the outside of the cave, where it is connected to a relief system that is part of a main relief path that vents hydrogen safely outside of the ER2 building. The diameters of the pipes have been determined by a series of calculations outlined below to insure that there is no release of hydrogen to ER2 or shed in the event of a loss of vacuum. These calculations were verified in a series of test measurements described below. In addition, the main vacuum chamber also possesses a similar vent line (4” outer diameter) which ensures that there is no release of hydrogen to ER2 or shed in the event of a rupture of the target vessel.

The H_2 liquid fills the target vessel and also a portion of the exhaust line. The exhaust line is thermally isolated from the target vessel by stainless steel tubing which has a low thermal conductivity. A section of the exhaust line which is above the hydrogen level, contains a heater wrapped around the tubing. The heater is used to locally heat the liquid. Due to the low thermal conductivity of the liquid para-hydrogen (1.2×10^{-3} W/cm K at 19 K) and the SST tubing (2×10^{-2} W/cm K at 20 K), it is possible to maintain a small temperature gradient of 3 K in the liquid in the exhaust line. The heater performs two functions: (1) it maintains the gas pressure in the target chamber at a value little higher than the equilibrium vapor pressure of the liquid seen by the neutron beam, thereby superheating the target and suppressing bubble formation, and (2) it induces the circulation of hydrogen through the target through a small-diameter connection which reintroduces the evaporated gas back into the target fill line and back through the liquefier and the ortho-para converter. In this way when the target is full and in steady-state operation, it is bubble-free and is continuously reconverted to liquid para-hydrogen.

During the filling of the LH_2 system and steady-state operation the hydrogen pressure will be maintained above 15 psia (776 Torr), which is comfortably above the local atmospheric pressure of 11.2 psia at Los Alamos, as required by the Hydrogen safety. When the target is operating in the steady-state mode most of the GHS will be valved off except for the relief valve and ruptured disks and the residual gas analyzer. The thermodynamic state of the target is determined using pressure and temperature measurements on the target, cryo refrigerators, ortho-para converter, and exhaust line.

The voltage signals from the thermometers are read by commercial temperature monitors (Lakeshore and Scientific Instruments) which also produce the feedback power to the refrigerators to control the temperatures. This information, along with pressures, the status of remotely controlled valves on the GHS, and the information from the RGA, is fed into a SLC-based monitoring system (Allen-Bradley) whose function is to monitor the status of the target, to take appropriate action if any measured parameters are out-of-range, to record and display the history of these parameters, to communicate the status of the target to the facility, and to present the status of the target visually to operators using a front-panel display.

2.4 Safety Features of the Target (M. Snow, H. Nann, 6-20-01, 3-6-03 by WMS)

The size of the liquid hydrogen target (approximately 16 liters) coupled with its location in a confined space, the experimental cave at ER2, during the experiment (the cave is required for neutron and gamma shielding), the need for access in the cave while the target is full, and the presence of several electrical systems inside the cave in other parts of the apparatus, dictate safety requirements. A preliminary assessment of the safety requirements for this target was performed in 1999 at LANL by Liquid Hydrogen Safety Committee. The report of this safety assessment and recommendations of the Hydrogen Safety Committee, which evaluated a preliminary conceptual design of the target is available in the web page www.iucf.indiana.edu/U/lh2target/export-files/. Because of the preliminary phase of the design at that time, certain details of the recommendations of the committee are no longer relevant to the current design. The second safety review, which was held at Indiana University in the fall of 2001, evaluated a more mature version of the design. The report and recommendations of this Hydrogen Safety Committee Review is also available in the web page www.iucf.indiana.edu/U/lh2target/export-files/). The main recommendations of the 1999 safety review were as follows:

(1) The target must be designed so that no release of hydrogen into the experimental cave occurs in the event of either a failure of the main vacuum system or a failure of the target vessel.

(2) All parts of the target vacuum system inside the cave must be surrounded by a helium jacket.

The second condition was later clarified in a request to the safety committee to apply to only the weld joints and the o-ring seals in the parts of the target system inside the cave. The point is that parts of the solid walls of the main vacuum unmodified from the state as supplied by the manufacturers will not spontaneously develop leaks in the absence of gross chemical or physical assaults on the material. Therefore, it is not necessary to surround the outside surfaces of the unwelded portions of the main vacuum system with helium gas. The main vacuum system was therefore designed with internal channels and double-walled windows in such a way that the outside surfaces of all o-ring seals and weld joints are surrounded with helium. The exchange with the safety committee detailing these arguments is available in the web page www.iucf.indiana.edu/U/lh2target/export-files/).

Recommendation (1) and the modified form of (2) have been incorporated into the target system. Here we summarize the results of our analysis of the most serious safety issue: response of the system to a catastrophic vacuum or target failure assuming the target volume of 21 liters (note that real target volume is 16 liters). Details of the calculations are included.

Hydrogen-air mixtures in concentrations ranging from 4% to 75% of H_2 by volume are highly explosive. Normally a spark of some kind is needed for ignition, but hydrogen vapor escaping from leaks has been known to spontaneously combust. It is, therefore, of paramount importance to eliminate the possibility of explosive hydrogen-air mixtures occurring and to prevent ignition. The mechanical aspects of the liquid hydrogen (LH_2) target system are designed to remove the possibility of a hydrogen release into the experimental cave and ER2 in case of a leak or rupture due to overpressure. A control system is developed to allow the careful monitoring of the target system behavior. The target system is designed so that in a case of any failure, hydrogen gas will vent safely outside ER2 or shed.

The liquid hydrogen target system consists of three components ("triple containment"). The LH_2 target flask (first containment) connected to the condenser unit by a filling and a gas vent line is contained inside a vacuum chamber, (second containment) which provides thermal insulation together with the 80K radiation shield. Helium channels (third containment) surrounds the weld joints and o-ring seals in the vacuum chamber and the hydrogen piping system inside the experimental cave. This helium channels have a dual purpose. First, if a leak occurs in a weld joint or seal in the vacuum chamber, the leak can be detected immediately by a RGA monitoring helium content in the vacuum. Second, the helium channels prevent air or other gases from penetrating into the vacuum through such leaks. If gases other than helium (and hydrogen) get in contact with the LH_2 flask or the hydrogen piping from the refrigerators to the target, they will immediately freeze. Solidified gases are difficult to detect, as they will not produce a pressure increase.

Several maximum credible accidents are possible. The full hazard analysis is documented in The NPDGamma LH_2 Target –Failure Analysis. The document is available in the web page www.iucf.indiana.edu/U/lh2target/export-files/).

(a) A loss of either refrigeration or vacuum or purposely spoiling the vacuum with Ar gas will lead to a rapid boiling in the target flask and cause pressure in the target vessel and target lines to rise. In the case of overpressure buildup, a pressure relief system, consisting of a relief valve RV104 and a rupture disc RD101 in parallel, will release the hydrogen gas into a relief chamber connected through CKV101 to vent stack line that exhausts gas safely outside of the ER2 building. This vent stack line is a 6-inch diameter, 304 stainless steel pipe closed toward the outside atmosphere by a leak tight check valve CKV101 and filled with helium at 2 psid.

(b) A rupture of the target flask or piping inside the vacuum chamber will release the LH_2 into the vacuum and hydrogen will boil off quickly. Again when overpressure through the rapid boil off occurs, a pressure relief system, a relief valve RV105 and two parallel rupture disks RD201 and RD202, will safely release the hydrogen gas into the relief chamber and thus to the vent line and then outside of the building while maintaining the pressure within the target vessel at a safe level. It should be mentioned that during normal operation the vacuum pump TP201/MP201 is valved off by V204 from the vacuum vessel but RGA is measuring gas levels in the vacuum through metering valve V307. In case of indication of helium in vacuum or raising pressure in vacuum the valve V207 will isolate RGA and TP301/MP301 from the vacuum.

(c) In case of fire in the experimental area or for some other reasons, the LH_2 in the target flask has to be disposed off quickly. This will be performed by filling the vacuum vessel with argon from the Ar reservoir connected to the vacuum through V205 thus letting the LH_2 boil off at a controlled rate. This scenario is similar to the one described under (a) above.

Each of the components of the LH_2 target system has a separate pressure relief system, which is sufficiently robust to respond safely to any maximum credible accident. The conductance of each safety relief system has to be large enough that a pressure rise will not lead to a rupture of the weakest component in the system. Calculations based on the Bates Internal Report # 90-02 [21] and the Crane Technical Paper No. 410 [11] were performed to determine the size of the relief plumbing such that the mass flow remains subsonic at all times and that the maximum pressure in each component remains well below its bursting point. The final results show that, in the case of a catastrophic vacuum failure to air, the target flask is subjected to a maximum pressure of no more than 43 psia if the inner diameter of the pressure relief piping is 1.5 inch in the cryostat, assuming a boil-off rate of 0.20 lb/s. The maximum pressure in the vacuum vessel for the case of a rupture of the target flask is 25.5 psia for an inner diameter of the pressure relief piping is 4.0 inch and a boil-off rate of 0.50 lb/s. Both pressures are well below the 70 psid pressures that the target flask and vacuum vessel are tested at. These upper bounds for the maximum pressures and boil-off rates were confirmed by measurements which used nitrogen as the working fluid in the target vessel along with the appropriate scaling of the results for the thermodynamic differences between liquid nitrogen and liquid hydrogen.

In summary, pressure relief systems with a 1.5-inch inner diameter discharge pipe for the target vessel and a 4-inch inner diameter discharge pipe for the vacuum chamber will respond safely to catastrophic failures assuming that outside piping and relief system has large enough conductance.

The sizing of the external relief piping was reviewed by an internal Laboratory committee which met on December 3, 2004 to review the 10% designs for the vent and ventilation lines of the liquid hydrogen target. The review report is available in the web page www.iucf.indiana.edu/U/lh2target/export-files/.

In the experimental cave and in the GHS enclosure hydrogen gas monitoring systems are used to ensure that an explosive mixture does not occur in the first place. We are going to monitor the vacuum space for helium, nitrogen, and water with RGA. We believe (and the Hydrogen Safety Committee in its second report concurs) that there is no need to monitor the helium channels for hydrogen, since hydrogen will be detected in the main vacuum long before it is seen in the helium.

3 QUALITY MANAGEMENT PLAN

3.1 Quality Assurance Plan

The NPDGamma Project Management Plan (PMP) ensures that the formal management, management control, and appropriate reporting are in place. It defines responsibilities inside the project and in the work packages. The Hydrogen Target is one of nine work package of the Experiment Construction project. The technical content, specifications, and schedule content of the Hydrogen Target have been defined in MOU. Through the signed PMP the Hydrogen Target Work Package has to meet Laboratory ES&H requirements and policies, relevant Laboratory Quality Assurance requirements, and to be in compliance with other Laboratory regulations and policies.

The NPDGamma Project Management Plan is available in the web page http://p23.lanl.gov/len/npdg/ under construction bullet.

3.2 Configuration Management

The Configuration Management consists of the control of the NPDGamma Liquid Hydrogen Target Engineering Document, the technical drawings, and other technical documents related to the target system such as review reports, test reports, and operating procedures.

The NPDGamma Project Manager, Seppo Penttila, LANL, has the lead responsibility for initiating and coordinating updates of the NPDGamma Liquid Hydrogen Target Engineering Document. Updates are recorded to the Update/Revision Log table of this document and the latest version of the Document is always available in the web page www.iucf.indiana.edu/U/lh2target/export-files/.

The target system will have drawings made at Indiana University and at LANL. The following configuration management covers the drawings made in the both places.
A component of the target has to have its technical drawing with identifying drawing number. The drawing has to correspond the fabricated component, to be an as-built drawing. The drawings have to be properly approved and signed and they have to be recorded in the LH_2 Target Drawing Logbook kept in the Indiana University by Walter Fox. The signed drawings are available in the web www.iucf.indiana.edu/U/lh2target/export-files/.
If modifications are required, they have to be properly approved and signed, and recorded in the drawing and in the Logbook.
Mike Snow is responsible to file the signed hard copies of the drawings made in the Indiana University.
Seppo Penttila is responsible to file the signed hard copies of the drawings made at LANL.

3.2.1 Change Control of Design (3-9-03 WMS)

The second hydrogen safety review defined a change control process by which formal requests for changes in the baseline design presented to the Hydrogen Safety Committee could be forwarded to the committee for response.

Change control is part of the larger issue of quality assurance (QA). The basis for all QA will be the Engineering Document and the assembly drawings. Any deviations from this basis, for whatever reasons, will be subject to the change control process. The Hydrogen Safety Committee recommended the following broad details be included in the change control process:

- When a change is identified, the Hydrogen Target Work Package Leader sends a written change request to the Project Leader. The change request will include sufficient detail to describe the change and full justification for the request.

- A Target Change Control Board (TCCB) consisting of J.D. Bowman (Experiment Spokesman), J. Knudson (Review Committee Chair), S. Penttilä (Project Manager), and J. Schinkel (P-Division Deputy Leader/ was P-23 Group Safety Officer) will review the proposed change.

- The TCCB will either approve the change or recommend that it be forwarded to an appropriate level for further review and approval. The hierarchy of levels might be: TCCB, LANSCE Facility, LANL LH_2 Safety Committee, LANL management, DOE.

The TCCB will function mostly as a screening committee. The Hydrogen Work Package has adapted this change control process.

The changes to the base design of the target approved through the change control process were (1) the approval of the potential use of titanium as a target vessel material, (2) the redefinition of the areas requiring external helium atmosphere to the weld joints and o-ring seals and the subsequent redesign of the vacuum system to incorporate internal channels for the introduction of the helium in the needed locations, (3) approval of the use of the Cryomech pulse tube cryo-refrigerator for one of the mechanical refrigerators, (4) clarification of the nature of the radiography requirements associated with the change in design to incorporate the internal channels for helium conduction, approval of adding the precooler/OPC to the upper part of the cryostat to increase the condensation rate of the hydrogen gas. Reports and correspondence with the TCCB is available in the web page www.iucf.indiana.edu/U/lh2target/export-files/.

4 TECHNICAL DESIGN OF TARGET VESSELS (M. Snow, 8-19-03)

This section consists of a detailed description of the summary of the specifications of the NPDGamma liquid hydrogen target system.

4.1 Cryostat and LH_2 Vessels

4.1.1 Specifications (M. Snow, 6-15-01, 2-21-03 by WMS)

Table 1 lists the main mechanical specifications of the target vessel, main vacuum, helium channels and radiation shields.

Table 1: Specifications of LH2 target, radiation shields, main vacuum, and He channels.

Object	Mechanical Properties			Connections
	Dimensions	Material	Fabrication	
LH_2 target vessel	27 cm diameter 30 cm length wall thicknesses: cylindrical shell 0.30 cm, entrance window 0.33 cm, exit window 0.33 cm	6061 Al or Ti (grade 2)	Cylindrical Al or Ti body welded from cold-rolled sheet. Rear dome machined from monolithic material	Bi-metalic friction welded Al-SST joints between LH_2 target vessel and piping Fill/vent line 1.5" od
80K radiation shield	36 cm diameter 80 cm length 0.1 cm thickness	OFHC Cu	Soldered from cold-rolled and annealed sheet	22 cm diameter mechanical connection to refrigerator #1 and 8 cm diameter connection to refrigerator #2
Main vacuum chamber	40 cm diameter 98 cm length 0.30 cm thickness	6061 Al body 6061 Al or Mg (AZ313-H24) windows	Cylindrical Al body welded from cold-rolled sheet. Rectangular Al box machined from single Al piece. Inlet and outlet flanges welded. Al/Mg windows formed from plate	4" diameter line for external pump and GHS
Helium channels			Internal channels machined into Al body of the main vacuum system and appropriate weld joint areas before welding	Pipe-threaded external access holes connected to all internal channels, filled with small connectors and fed by small ID tubing for helium gas connection

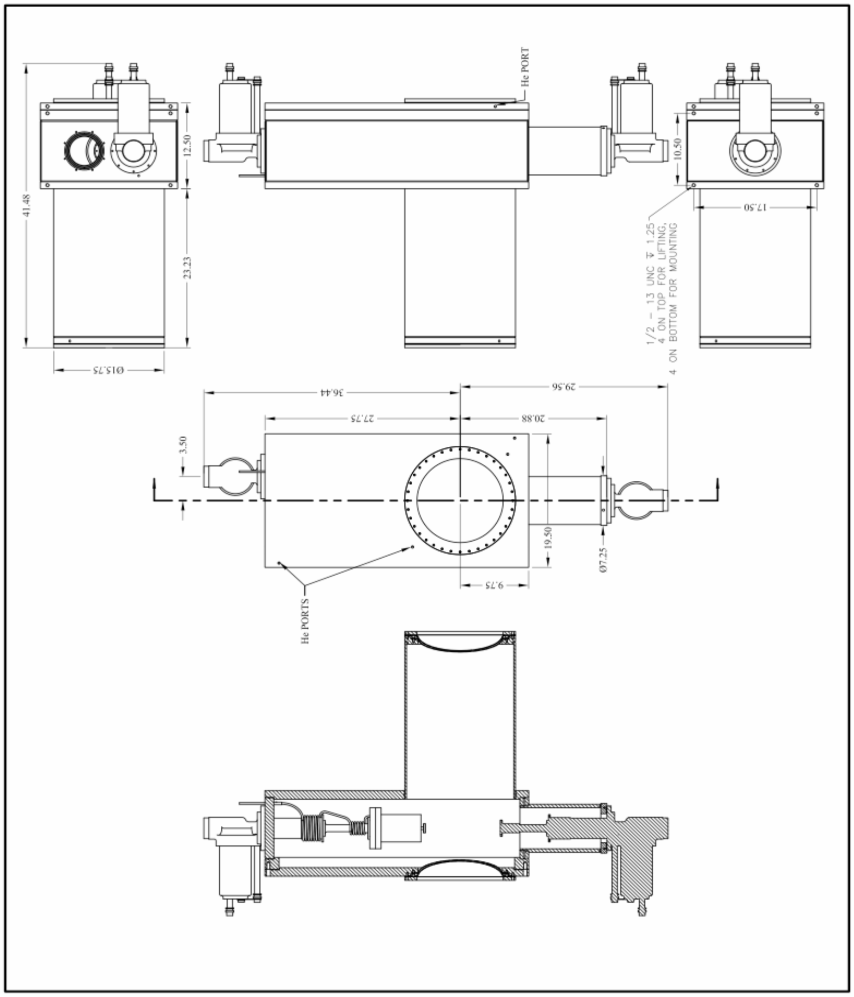

Fig. 14. Main target isolation vacuum chamber. The target vacuum chamber includes two cryo-refrigerators, the concave double windows for the neutron beam entrance and exit, and the two-part main vacuum chamber with a horizontal cylindrical section that houses the hydrogen target vessel and the box section which contains the refrigerator and feed line penetrations along with a removable rear flange for access to the rear (downstream of the neutron beam) end of the chamber. The neutron beam enters at the front of the cylindrical section. The vacuum chamber drawings are available in www.iucf.indiana.edu/U/lh2target/export-files/.

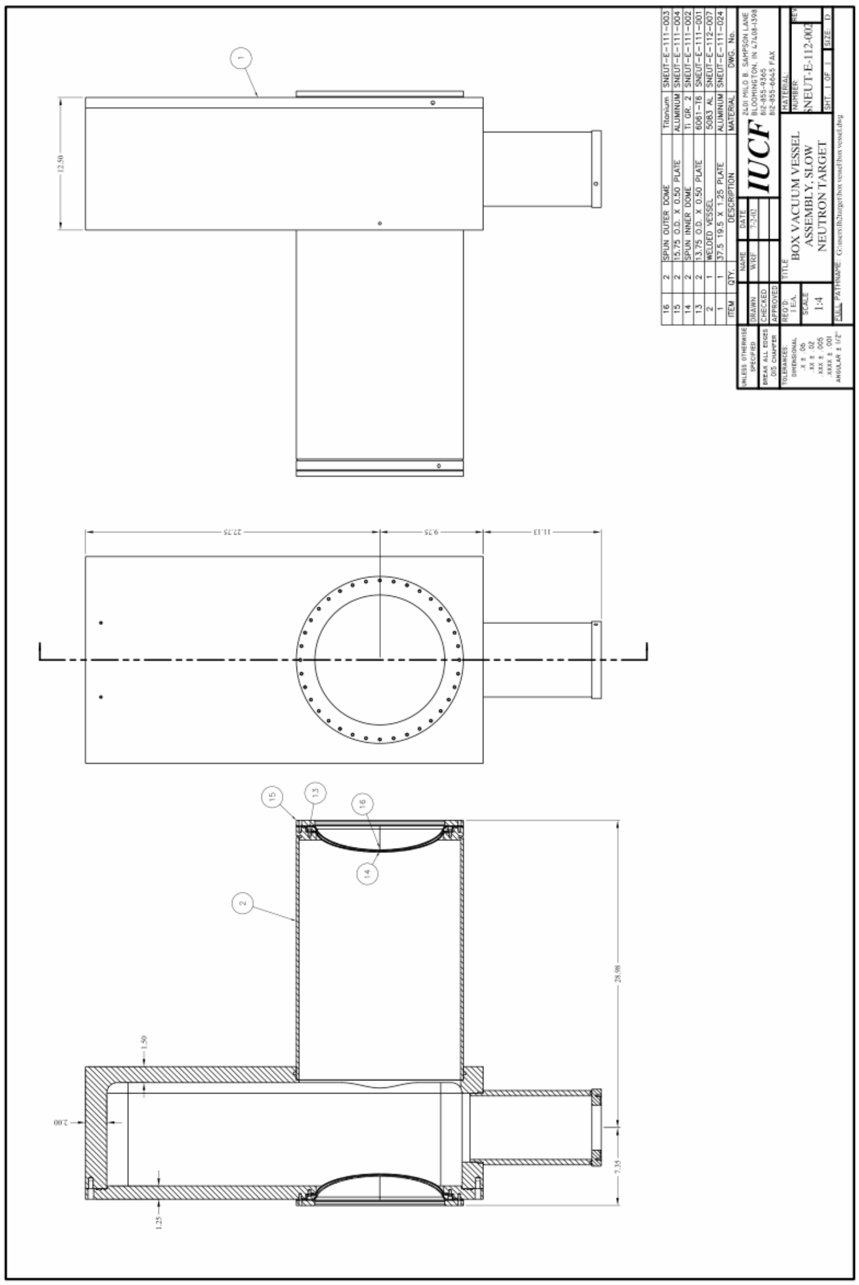

Fig. 15. Assembly of the LH_2 target main isolation vacuum chamber. In the drawing is shown the thickness of the Al box section of the vacuum chamber, with the removable rear panel. The main body of the box section of the vacuum chamber was machined from a single ingot of aluminum to minimize weld joints. This drawing # SNEUT-E-112-002 is available in www.iucf.indiana.edu/U/lh2target/export-files/.

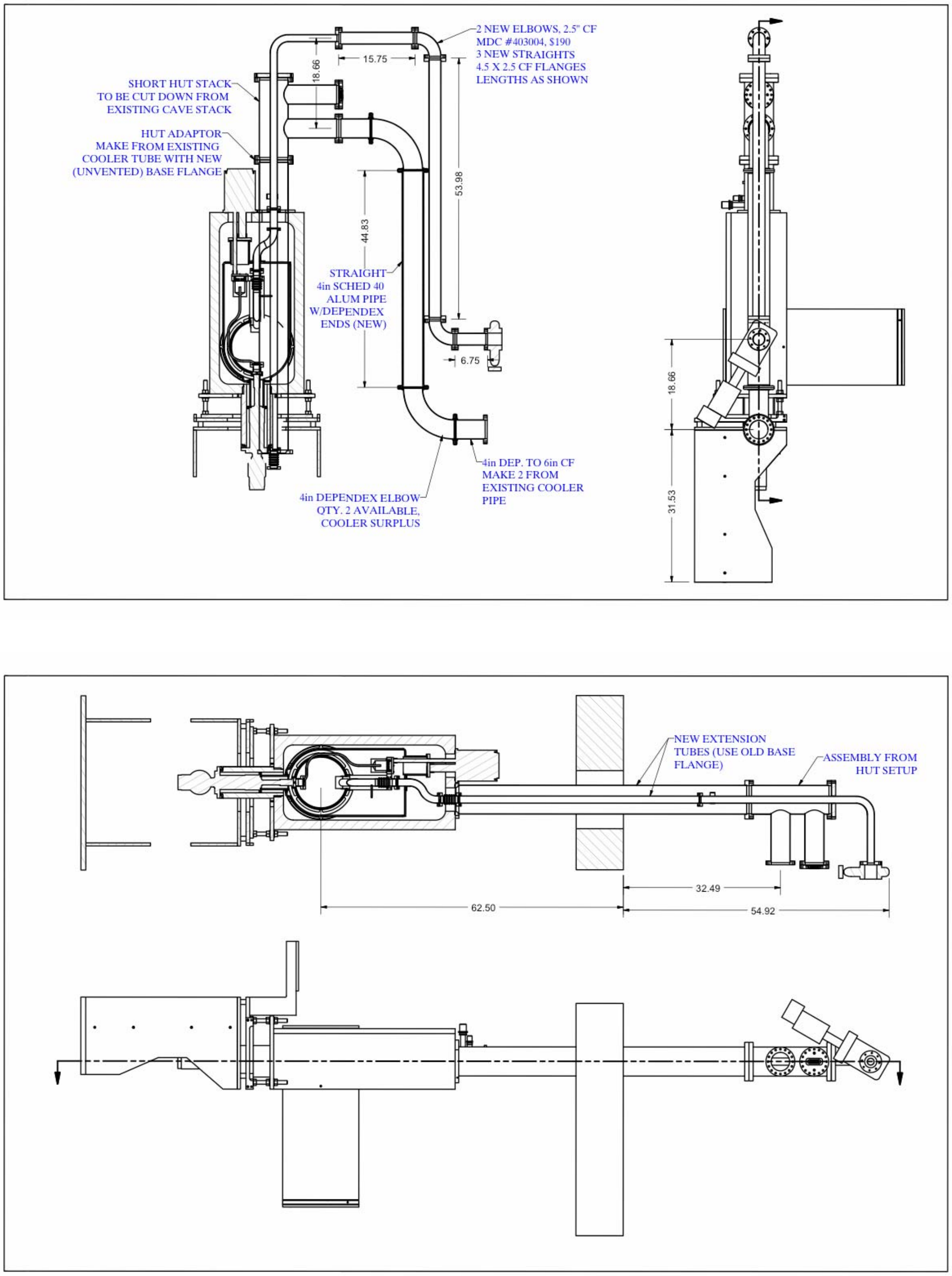

Fig. 16. Assembly drawings of the internal piping system extending from the hydrogen target vessel to the gas handling system. The upper figure shows how the pipes are connected to the GHS that is on floor in shed. The lower figure shows how the pipes penetrate the flight path 12 cave roof where GHS is located.

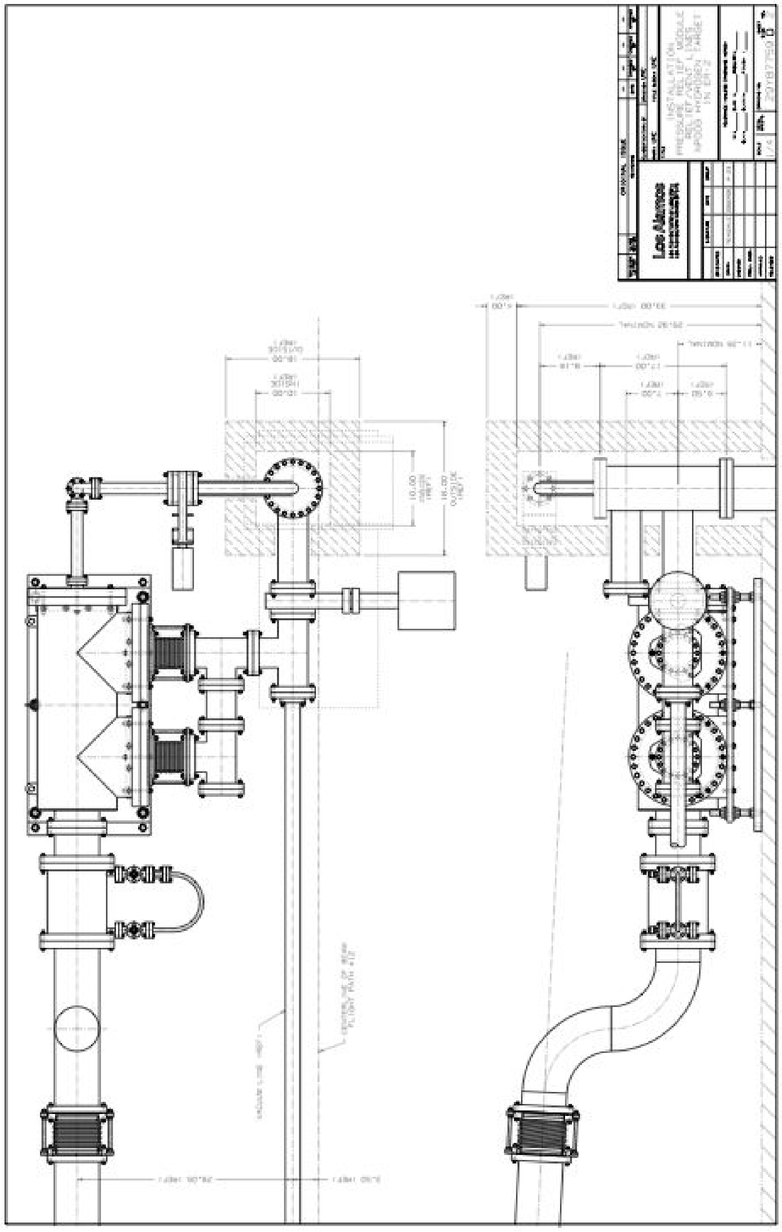

Fig. 17. The connection of the relief chamber to the cryostat at ER2 drawing # 29Y87759 D2.

4.2 Strength Calculations for the Vessels (H. Nann, 08-10-01, revised 12-09-04)

4.2.1 Symbols and Formulae

The ASME Code, Section VIII, [9] and Cryogenic Process Engineering [13] provide the design equations, which were used to calculate the minimum shell thickness for the LH_2 vessel and the main vacuum chamber.

List of symbols used in the formulae below:

- t = minimum thickness [inch]
- p = internal design pressure [psi]
- p_c = critical pressure [psi]
- R = inside radius [inch]
- R_o = outside radius [inch]
- D = inside diameter [inch]
- D_o = outside diameter [inch]
- L = length of cylinder or distance between two stiffening rings, respectively [inch]
- S = allowable stress [psi]
- Y = modulus of elasticity (Young's modulus)
- μ = Poisson's ratio
- E = weld joint efficiency factor

(a) Cylindrical shell under internal pressure.

$$t = \frac{pD}{2(SE - 0.6p)} \tag{1}$$

$$p = \frac{2SEt}{D + 1.2t} \tag{1a}$$

(b) Elliptical head under pressure on concave side

$$t = \frac{pDK}{2(SE - 0.1p)} \tag{2}$$

$$p = \frac{2SEt}{DK + 0.2t} \tag{2a}$$

where the constant K is given by $K = \frac{1}{6}\left[2 + \left(\frac{D}{2h}\right)^2\right]$ with

$\frac{D}{2h}$ = ratio of the major to the minor axis of elliptical heads.

(c) Elliptical head under pressure on convex side

$$t = \left[\frac{2p_c\left[3\left(1-\mu^2\right)\right]^{1/2}}{YE}\right]^{1/2} R_0^*, \tag{3}$$

$$p_c = \left(\frac{t}{R_0^*}\right)^2 \frac{YE}{2[3(1-\mu^2)]^{1/2}} \tag{3a}$$

with $R_0^* = K_1 D$.

K_1 is given in table UG–33.1 of the ASME Code as a function of $\frac{D}{2h}$.

The ASME Code specifies that the critical pressure p_c be four times the maximum allowable (external) working pressure (MAWP) on a vessel.

(d) Cylindrical shell under external pressure

The minimum thickness can be obtained by solving iteratively the relation

$$t = \left[\frac{p_c\left(1-\mu^2\right)^{3/4}\left[\left(L/D_0\right)-0.45\left(t/D_0\right)^{1/2}\right]}{2.42YE}\right]^{2/5} D_0 \tag{4}$$

$$p_c = \left(\frac{t}{D_0}\right)^{5/2} \frac{2.42YE}{\left(1-\mu^2\right)^{3/4}\left[\left(L/D_0\right)-0.45\left(t/D_0\right)^{1/2}\right]} \tag{4a}$$

The ASME Code specifies that the critical pressure p_c is four times the maximum allowable external working pressure ($p_c = 4p$)

(e) The required thickness for unstayed flat heads is calculated by the following formula:

$$t = d\sqrt{\frac{ZCp}{SE} + \frac{6Wh_G}{SELd^2}} \tag{5}$$

$$p = \left[\left(\frac{t}{d}\right)^2 - \frac{6Wh_G}{SELd^2}\right]\left(\frac{SE}{ZC}\right) \tag{5a}$$

With C = factor depending upon method off attachment of head
p = internal design pressure
S = maximum allowable stress
E = joint efficiency
W = total bold load
h_G = gasket moment arm
L = perimeter of bolted head measured along the centers of bolt holes
d = short span of rectangular head
D = long span of rectangular head

$$Z = 3.4 - \frac{2.4d}{D}$$

4.2.2 Values for Material Parameters

The following material constants at room temperature, taken from AMS Handbook, Vol. 2 (Ref. 5) and manufacturer's spec sheets, are used. (The materials have (about 30% – 40%) higher allowable stresses at low temperature. These higher values are not used here.)

(a) Aluminum 6061-T6 (ASME Code approved!)

Ultimate tensile strength: S_u = 49600 psi
$\Rightarrow$ allowable stress $S = ¼\ S_u$ = 12400 psi (see ASME Code)

Modulus of elasticity: $Y = 1.0 \times 10^7$ psi

Poisson's ratio: $\mu = 0.33$

(b) Titanium Grade 2, Annealed (ASME Code)

Ultimate tensile strength: S_u = 50000 psi
$\Rightarrow$ allowable stress $S = ¼\ S_u$ = 12500 psi (see ASME Code)

Modulus of elasticity: $Y = 1.45 \times 10^7$ psi

Poisson's ratio: $\mu = 0.34$

(c) Magnesium AZ31B-H24, hard rolled sheet (NOT ASME Code approved)

Ultimate tensile strength: S_u = 42800 psi
$\Rightarrow$ allowable stress $S = ¼\ S_u$ = 10700 psi (see ASME Code)

Modulus of elasticity: $Y = 6.5 \times 10^6$ psi

Poisson's ratio: $\mu = 0.35$

4.2.3 LH_2 Target Vessel (cylinder with elliptical heads)

4.2.3.1 Calculation of the minimum wall thickness

First we calculate the minimum wall thickness for an internal design pressure of p = 75 psia. Use E = 1.0 (butt joints with complete penetration, fully radiographed, see ASME Code, section VIII, table UW-12)

(1) Cylindrical shell, pressure on inside:

Material: 6061-T6 Aluminum

R = 5.25 inch, D = 10.5 inch, L = 12.0 inch

Eq. (1) gives t = 0.032 inch.

(2) Entrance window, elliptical head, machined from one piece, pressure on concave side:

Material: 6061-T6 Aluminum

D = 10.5 inch
h = 2.5 inch

$$\frac{D}{2h} = 2.1 \quad \Rightarrow \quad K = 1.07$$

Eq. (2) gives t = 0.034 inch.

(3) Exit window, elliptical head, pressure on convex side:

Material: 6061-T6 Aluminum

D_o = 10.75 inch
h_o = 2.0 inch

$$\frac{D_0}{2h_0} = 2.7 \quad \Rightarrow \quad K_1 = 1.23 \quad \Rightarrow \quad R_0^* = 13.22 \text{ inch}$$

assume p_c = 4x75 psi = 300 psi

Eq. (3) gives t = 0.010 inch.

4.2.3.2 Design pressures from actual thicknesses

To provide additional safety, we will use t = 0.12 inch for the thickness of the cylindrical part and t = 0.13 inch for the entrance and exit windows.
These thicknesses are used in the above formulae 1a, 2a, 3a, and 4a to calculate the maximum design pressure the target vessel can withstand. Again a welding efficiency of 1.0 was used. We obtain the following internal pressures:

(1) Cylindrical shell: p_{int} = 279 psi
(2) Entrance window: p_{int} = 286 psi
(3) Exit window: p_{int} = ¼ p_c = 207 psi

and the following external pressures:

(1) Cylindrical shell: $p_{ext} = ¼\, p_c = 81$ psi
(2) Entrance window: $p_{ext} = ¼\, p_c = 74$ psi
(3) Exit window: $p_{ext} = 296$ psi

4.2.4 Main Vacuum Chamber

4.2.4.1 Calculation of the minimum wall thickness

4.2.4.1.1 Cylindrical part of the main vacuum chamber (cylinder with elliptical heads)

First, we calculate the minimum wall thickness for an internal design pressure of p = 60 psi since the main concern for the vacuum chamber is that it has to withstand the pressure buildup in the case of a rupture of the target vessel.
Use E = 1.0 (butt joints with complete penetration, fully radiographed)

(1) Cylindrical shell:

Material: 6061-T6 Aluminum

R = 7.625 inch, D = 15.25 inch, L = 24.5 inch

Eq. (1) gives t = 0.055 inch.

(2) Entrance and exit windows, elliptical head, pressure on convex side:

D_o = 11.5 inch
h_o= 2.4 inch
$\frac{D}{2h} = 2.4 \quad \Rightarrow \quad K_1 = 1.08 \quad \Rightarrow \quad R_0^* = 12.4$ inch
assume that p_c = 4x60 psia = 240 psia, then for

Material: 6061 – T6 Aluminum:

eq. (3) gives t = 0.11 inch.

Material: Magnesium AZ31B-H24:

eq. (3) gives t = 0.13 inch.

4.2.4.1.2 Rectangular part of the main isolation vacuum chamber (H. Nann, 09-06-02)

In calculating the wall thickness of the rectangular part of the vacuum vessel we use
C = 0.25 (from Fig UG-34 of the ASME code)

p = 60 psi
W = 9000 lb
h_G = 1.66 inch
L =110.0 inch
d = 18.5 inch
D = 36.5 inch
Z = 2.18

Eq. (5) then gives t = 0.98 inch.

4.2.4.2 Design pressures for cylindrical and rectangular part from actual thicknesses

To provide additional safety, we will use t = 0.25 inch for the thickness of the cylindrical part, t = 0.125 inch for the elliptical entrance and exit windows, and t = 1.25 inch for the thinnest wall of the rectangular box.
These thicknesses are used in the above formulae 1a, 3a, 4a, and 5a to calculate the maximum design pressure the target vessel can withstand. Again a welding efficiency of 1.0 was used. We obtain the following internal pressures:

(1)	Cylindrical shell:	p_{int} = 399 psia
(2)	Entrance/exit window:	p_{int} = ¼ p_c = 90 psia for Aluminum
		p_{int} = ¼ p_c = 59 psia for Magnesium
(3)	Rectangular box:	p_{int} = 99 psia

and the following external pressures:

(4)	Cylindrical shell:	p_{ext} = ¼ p_c = 134 psia
(5)	Entrance/exit window:	p_{ext} = 208 psia for Aluminum
		p_{ext} = 180 psia for Magnesium
(6)	Rectangular box:	p_{ext} = 99 psia

4.3 Finite Element Analysis of the LH_2 Vessel

A finite element analysis on the LH_2 vessel was performed by the ARES Corporation. The report is available on web page www.iucf.indiana.edu/U/lh2target/export-files/ as LH2 Vessel FEA Report. The recommendations from the FEA analysis for the shape of the vessel were incorporated directly into the final design of the Al and Ti vessels.

5 TESTING OF TARGET CRYOSTAT COMPONENTS

5.1 Testing of the Ti LH2 Vessel

5.1.1 Helium Leak and Thermal Shock Testing of the Ti LH2 Vessel

Date: March 21, 2003
DUT: Titanium Liquid Hydrogen Vessel
Object: To determine if the vessel develops leaks when under stresses from large temperature changes.

The Titanium LH_2 vessel was evacuated to $6x10^{-6}$ Torr and dunked into liquid nitrogen. Within the liquid nitrogen, vacuum level shifted to $5.4x10^{-6}$ Torr. Upon reaching thermal equilibrium with nitrogen, the vessel was quickly lifted out of the nitrogen, helium leak-checked, and then dunked back in. After four such cycles, the vessel was allowed to warm to room temperature, and helium leak-checked again. Throughout testing, helium leak rates never rose above the base leak rate of $1.0x10^{-9}$ Torr-liter/s.

Test was performed by:
Vivek Jeevan , IUCF
Bill Lozowski, IUCF
John Vanderwerp, IUCF

Approved by:
Bill Lozowski, IUCF

5.1.2 Pressure Testing of the Ti LH2 Vessel

Date: March 04, 2003
DUT: Titanium Liquid Hydrogen Vessel
Object: Pressure test of Ti LH2 target vessel

The Titanium LH_2 vessel was pressurized to 90 psid with an inert gas by Excelco Developments Inc. of Silver Creek, NY. The chamber neither failed nor deformed as a result of the test. The certificate describing this test can be found at the website www.iucf.indiana.edu/U/lh2target/export-files/Vendor Tests under excelco_test_results.pdf.

Test was performed by:
Eric Kredbahk, Excelco

Approved by:
Michael J. Bicet, Excelco, Bill Lozowski, IUCF

5.1.3 Radiography of the Ti LH2 Vessel

Date: March 07, 2003
DUT: Ti Liquid Hydrogen Vessel
Object: Radiography of the Ti Liquid Hydrogen Vessel

The Ti liquid hydrogen vessel welds were radiographed per MIL-STD-271F with acceptance per NAVSHIPS 0900-003-9000 Class 1. All welds were found to be satisfactory. The certificate describing this test can be found at the website www.iucf.indiana.edu/U/lh2target/export-files/Vendor Tests under excelco_test_results.pdf. Documentation of the radiographs is on file at Excelco.

Quality Assurance manager:
Eric Niedbalski, Excelco

Approved by:
Gregory Lis, Excelco, Bill Lozowski, IUCF

5.1.4 Fluorescent Dye Penetrant Test of the Ti LH2 Vessel

Date: September 23, 2003
DUT: Ti Liquid Hydrogen Vessel
Object: Fluorescent Dye Penetrant test of the Ti Liquid Hydrogen Vessel

The Ti liquid hydrogen vessel welds were inspected using liquid penetrant per MIL-STD-271F with acceptance per NAVSHIPS 0900-003-8000 Class 2. No defects were reported. The certificate describing this test can be found at the website www.iucf.indiana.edu/U/lh2target/export-files/Vendor Tests under excelco_test_results.pdf.

Inspector: Quality Assurance manager: Approved by:
Michael J. Bent, Excelco, Eric Niedbalski, Excelco, Gregory Lis, Excelco, Bill Lozowski, IUCF

5.1.5 Annealing/Oxidation of the Ti LH2 Vessel

Date: March 3, 2003
DUT: Ti Liquid Hydrogen Vessel
Object: Annealing/Oxidation of the Ti Liquid Hydrogen Vessel

The Ti liquid hydrogen vessel was annealed in an Argon atmosphere for 1 hour at 1292 F and oxidized for 5 minutes at 1400 F, then cooled in air. The purpose of this treatment was to deposit a sufficiently thick oxide layer on all of the internal surfaces of the Ti target so that there is no risk of hydrogen embrittlement through diffusion into the Titanium. This treatment was performed by AccuTemp Heat Treating, contact Bob Balow, Racine, WI, contact is Bob Balow (262)634-9102, under subcontract from Excelco The certificate describing this test can be found at the website www.iucf.indiana.edu/U/lh2target/export-files/Vendor Tests under excelco_test_results.pdf.

Inspector: Quality Assurance manager:
Robert A. Balow, AccuTemp Heat, Eric Niedbalski, Excelco,
Approved by: Gregory Lis, Excelco, Bill Lozowski, IUCF

5.2 Testing of the Aluminum LH2 Vessel

5.2.1 Helium Leak Testing of the Aluminum LH2 Vessel

Date: August 6, 2003
DUT: Aluminum Liquid Hydrogen Vessel
Object: To determine if the vessel is helium leak tight

The Aluminum LH_2 vessel was connected to a helium leak detector with a sensitivity of 1.2×10^{-10} atm cc/sec. The background level on the leak detector was 1.0×10^{-9} atm cc/sec. No leak was detected. The certificate describing this test can be found at the website www.iucf.indiana.edu/U/lh2target/export-files/Vendor Tests under aft_reports_mam_vac_vessel.pdf.

Test was performed by: Approved by:
David Barber, Ability Mike Morgan, Ability, Bill Lozowski,
IUCF

5.2.2 Pressure Testing of the Aluminum LH2 Vessel

Date: August 6, 2003
DUT: Aluminum Liquid Hydrogen Vessel
Object: Pressure test of the AL LH2 target vessel

The Aluminum LH_2 vessel was pressurized to an internal pressure of 90 psid.
No deformation of the vessel was observed. The certificate describing this test can be found at the website www.iucf.indiana.edu/U/lh2target/export-files/Vendor Tests under aft_reports_mam_vac_vessel.pdf.

Test was performed by: Approved by:
David Barber, Ability, Mike Morgan, Ability, Bill Lozowski,
IUCF

5.2.3 Helium Leak and Thermal Shock Testing of the Aluminum LH2 Vessel

Date: September, 2004
DUT: Aluminum Liquid Hydrogen Vessel
Object: To determine if the aluminum LH2 vessel develops leaks after thermal cycling.
The Al target vessel was connected to a leak detector and covered by plastic bag filled with helium. The background helium leak rate into the vessel was $1.5\text{x}10^{-9}$ atm cc/sec before and after insertion of the vessel into the He bag. The vessel was dunked into liquid nitrogen until the boiling of the LN2 stopped and removed and kept in the air for 10 minutes. This procedure was repeated 4 times. In the final step the vessel was kept inside the LN2 container until all the LN2 boiled off and there was no freezing on the outside surface of the vessel. The helium leak check was repeated in the same way with the target vessel inside a plastic bag filled with helium gas. The background helium leak rate had by now changed to $3.0\text{x}10^{-9}$ atm cc/sec. This background did not increase with time while the leak detector was connected to the Al chamber.

Test was performed by: Approved by:
Satyaranjan Santra, IUCF Bill Lozowski, IUCF

5.2.4 Radiography of the Aluminum LH2 Vessel

Date: August 11, 2003
DUT: Al LH2 Vessel

Object: Radiography of the Al LH2 Vessel

The Al LH2 vessel welds were radiographed by Calumet Testing Services under subcontract to Ability Engineering. All welds were found to be satisfactory. The certificate describing this test can be found at the website www.iucf.indiana.edu/U/lh2target/export-files/Vendor Tests under aft_reports_mam_vacuum_vessel.pdf. Documentation of the radiographs is on file at IUCF, where we have the radiography film exposures.

Examiner: Interpreter: Approved by:
Sturat Gillespie, Calumet Stuart Gillespie, Calumet Mike Morgan, Ability, Bill Lozowski, IUCF

5.2.5 Radiography of the Welds of the Bimetalic Joints

Date: April 15, 2005 and May 11, 2005
DUT: Al LH2 Vessel
Object: Radiography of the two Al welds of the bimetallic joints

The two Al CF flanges on the Al LH2 vessel we cut off and replaced with the SST-Al bimetallic joints. See LANL drawings 29Y87755 D 1 – D 8 in the web site website www.iucf.indiana.edu/U/lh2target/export-files/. The Al welds were specified and after welding job was performed, they were inspected by Atomic Inspection Labs. The welding specifications and acceptance criteria, inspection reports, and vacuum testing results can be found in the web site www.iucf.indiana.edu/U/lh2target/export-files/.

5.2.6 Vacuum Testinging of the Precooler Heat Exchanger/OPC System

To increase the cooling power and thus a hydrogen gas condensation rate, a cold helium gas heat exchange loop with an ortho-para converter was added to the upper part of the cryostat, see LANL drawings 29Y87755 D 1, 29Y87755 D 11 – D 24. The precooler/OPC was vacuum tested and then thermally shocked by immersing it to LN2 and letting it to reach equilibrium temperature and then warming the system back to room temperature. This procedure was repeated three times. The hydrogen loop of the system was also pressurized at room temperature to 90 psig with helium and helium signal was monitored in the helium loop. Then the helium loop was pressurized to 30 psig and helium signal monitored in the hydrogen volume. No signals in the level of less than 1×10^{-9} atm cm^3/s were observed. See LH2 Target Logbook #2 p. 21.

5.3 Tests of the Vacuum Chamber and Components

5.3.1 Pressure Testing of the Vacuum Chamber

Date: February 21, 2003
DUT: Al vacuum chamber
Object: Pressure test of Al vacuum chamber

The Al vacuum chamber was internally pressurized to 70 psid with the Al windows in place. Pressure was maintained for 10 minutes with no measurable decrease. Soap bubble application on all o-ring seals and weld joints showed no visible leaks. The certificate describing this test can be found at the website www.iucf.indiana.edu/U/lh2target/export-files/Vendor Tests under aft_reports_mam_vac_vessel.pdf.

Test was performed by: Approved by:
Bob Peterson, Ability Mike Morgan, Ability Bill Lozowski, IUCF

5.3.2 Leak Testing of the Vacuum Chamber

Date: February 21, 2003
DUT: Al vacuum chamber
Object: Leak test of Al vacuum chamber

The Al vacuum chamber was connected to a helium leak detector of sensitivity 1.0 x 10^{-10} atm cc/sec. The leak detector background at the start of the test was 8.0 x 10^{-9} atm cc/sec. Helium was sprayed all around the outside of the vessel, especially around welds and o-ring joints. Vessel was surrounded by a bag filled with helium for 5 minutes. Final background reading on leak detector was 4.0 x 10^{-9} atm cc/sec. No evidence for a leak above this level. The certificate describing this test can be found at the website www.iucf.indiana.edu/U/lh2target/export-files/Vendor Tests under aft_reports_mam_vac_vessel.pdf.

Test was performed by: Approved by:
Bob Peterson, Ability Mike Morgan, Ability, Bill Lozowski, IUCF

5.3.3 Radiography of the Vacuum Chamber

Date: March 11, 2003
DUT: AL LH2 Vacuum Chamber
Object: Radiography of the Al Vacuum Chamber

The vacuum chamber welds were radiographed by Calumet Testing Services under subcontract to Ability Engineering. All welds were found to be satisfactory. The certificate describing this test can be found at the website www.iucf.indiana.edu/U/lh2target/export-files/Vendor Tests under excelco_test_results.pdf. Documentation of the radiographs is on file at IUCF, where we have the radiography film exposures.

Examiner: Interpreter: Approved by:
M. Barrajas, Calumet Testing Stuart Gillespie, Calumet Mike Morgan, Ability, Bill Lozowski, IUCF

5.3.4 Leak Testing of the Main Weldment of the Box Portion of the Vacuum Chamber

Date: February 12, 2003
DUT: AL LH2 vacuum chamber
Object: Leak test of the main weldment of the Box Vacuum chamber

The main weldment of the Box vacuum chamber portion of the AL LH2 vacuum chamber was separately leak tested before final welding of the vessel. It was connected to a helium leak detector of sensitivity 1.0 x 10^{-10} atm cc/sec. The leak detector background at the start of the test was 6.0 x 10^{-10} atm cc/sec. Helium was sprayed all around the outside of the vessel, especially around id and od weld joints. Vessel was surrounded by a bag filled with helium for 5 minutes. Final background reading on leak detector was 5.0 x 10^{-10} atm cc/sec. No evidence for a leak above this level. The certificate describing this test can be found at the website www.iucf.indiana.edu/U/lh2target/export-files/Vendor Tests under aft_reports_mam_vac_vessel.pdf.

Test was performed by: Approved by:
Bob Peterson, Ability Mike Morgan, Ability, Bill Lozowski, IUCF

5.3.5 Leak Testing of the He Channels in the Vacuum Chamber

Date: May, 2004
DUT: He channels, cryostat vacuum chamber
Object: Leak testing of the He channels in the cryostat main vacuum

There are seven helium channels around the joints of the vacuum enclosure (the vacuum chamber) which are meant to block outside air from reaching the inside of vacuum enclosure through o-ring seals or weld joints. They are connected in series with one inlet and one outlet connected to the helium supply manifold. Each of these channels has two seals: Indium (inner seal) and Viton O-ring (outer seal). Helium gas flows in between these two seals. Each helium channel has been leak tested separately and is leak tight with helium leak rate < 5.0×10^{-9} atm cc/sec.
Test Performed by: Approved by:
Bob Peterson, Ability, Satyaranjan Santra, IUCF Mike Morgan, Ability, Bill Lozowski, IUCF

5.3.6 Pressure Testing of the Mg Vacuum Chamber Windows

Date: Feb. 10, 2003
DUT: Mg vacuum chamber windows
Object: Pressure test of Mg vacuum chamber windows

The Mg vacuum chamber windows were internally pressurized to 80 psid (inner domes) and 117 psid (outer domes) with nitrogen gas on the concave side of the windows, which is the side that faces into the vacuum vessel. Pressure was maintained for 5 minutes with no measurable decrease on pressure gauge and no deformation of the domes. The certificate describing this test can be found at the website www.iucf.indiana.edu/U/lh2target/export-files/Vendor Tests under aft_reports_mam_vac_vessel.pdf.

Test was performed by: Approved by:
Bob Peterson, Ability Mike Morgan, Ability, Bill Lozowski, IUCF

5.3.7 Pressure Testing of the Aluminum Vacuum Chamber Windows

Date: June 18, 2003
DUT: Al vacuum chamber windows
Object: Pressure test of Al vacuum chamber windows

Both the inner and outer Al vacuum chamber windows were internally pressurized to 60 psid with nitrogen gas on the concave side of the windows, which is the side that faces into the vacuum chamber. Pressure was maintained for 5 minutes with no measurable decrease on pressure gauge and no deformation of the domes. The certificate describing this test can be found at the website www.iucf.indiana.edu/U/lh2target/export-files/Vendor Tests under aft_reports_mam_vac_vessel.pdf. NOTE: later the Al windows were tested to 70 psid as part of the complete pressure tests of the main vacuum system.

Test was performed by: Approved by:
Bob Peterson, Ability Mike Morgan, Ability, Bill Lozowski, IUCF

5.3.8 Leak Testing of the Aluminum Vacuum Chamber Windows

Date: February 10, 2003
DUT: AL vacuum chamber windows
Object: Leak test of Al vacuum chamber windows

The inner and outer Al windows of the main vacuum system were separately connected to a helium leak detector of sensitivity 1.0 x 10^{-10} atm cc/sec. The leak detector background at the start of the test varied between 3.0-3.5 x 10^{-10} atm cc/sec for the different windows. The windows were bagged and helium was sprayed all around the outside of the windows. Final background reading on leak detector varied between 3.0-3.5 x 10^{-10} atm cc/sec. In all cases there was no increase in the background leak detector reading. The certificate describing this test can be found at the website www.iucf.indiana.edu/U/lh2target/export-files/Vendor Tests under aft_reports_mam_vac_vessel.pdf.

Test was performed by: Approved by:
Bob Peterson, Ability Mike Morgan, Ability, Bill Lozowski, IUCF

5.3.9 Leak Testing of the Mg Vacuum Chamber Windows

Date: February 10, 2003
DUT: Mg vacuum chamber windows
Object: Leak test of the Mg vacuum chamber windows

The inner and outer Mg windows of the main vacuum system were separately connected to a helium leak detector of sensitivity 1.0 x 10^{-10} atm cc/sec. The leak detector background at the start of the test varied between 2.8-3.0 x 10^{-10} atm cc/sec for the different windows. The windows were bagged and helium was sprayed all around the outside of the windows for 5 minutes. Final background reading on leak detector varied between 2.8-3.0 x 10^{-10} atm cc/sec. In all cases there was no increase in the background leak detector reading. The certificate describing this test can be found at the website www.iucf.indiana.edu/U/lh2target/export-files/Vendor Tests under aft_reports_mam_vac_vessel.pdf.

Test was performed by: Approved by:
Bob Peterson, Ability Mike Morgan, Ability, Bill Lozowski, IUCF

5.4 Design and Maximum Allowable Working Pressures

(H. Nann, 8-22-01; revised 12-16-04**)**

Table 2 defines design, operating, maximum allowable working pressures, maximum internal pressures, and proposed settings for rupture disks and pressure relief valves for the LH_2 vessel and the main vacuum chamber. The components are tested to 60 and 80 psid. Official atmospheric pressure at LANL is 11.2 psia.

Table 2. Pressures associated with LH_2 vessel and vacuum chamber and pressure set points.

Vessel	Normal operating pressure	Calculated maximum pressures (from ASME CODE)	Internal Maximum Allowable Working Pressure (from ASME CODE)	Pressure relief valve set points	Rupture disks set points
LH2 target vessel	15 psia	Internal: 207 psia External: 74 psia	60 psid	20 psid	49.3 psid
Main vacuum chamber	vacuum	Internal: 90 psia External: 99 psia	60 psid	Small relief valve: 3 psid	28.8 and 28.8 psid

Summary of pressures and relief pressure set points for the LH_2 vessels and vacuum chamber:

1. LH_2 target vessel:
   Material: 6061-T6 aluminum; wall thickness of cylindrical shell 0.12 inch, wall thickness of entrance and exit windows 0.13 inch.
   (a) Design pressure (see chapter 4.2): internal: 207 psia (14.1 atm) - external: 74 psia (5.0 atm).
   (b) Normal operating pressure: 14 psia (1.2 atm at Los Alamos); the official atmospheric pressure at Los Alamos is 11.2 psia.

(c) Maximum allowable working pressure (internal): 60 psid (4.1 atm).
(d) Relief paths: single 1.5-inch OD piping from the LH_2 vessel up to the relief chamber that contains of a relief valve and rupture disk.
(e) Relief valve flow capacity: 0.20 lb/s at relief valve set point.
(f) Pressure relief valve set point: 20 psid
(g) Rupture disk set point: 49.3 psid.

2. Main isolation vacuum chamber (cylinder with elliptical heads):
Material: 6061-T6 aluminum; wall thicknesses: entrance and exit windows 0.125 inch; cylindrical body 0.25 inch; rectangular box 1.25 inch for thinnest wall.
(a) Design pressure (see chapter 4.2): internal 90 psia (6.1 atm) - external: 99 psia (6.7 atm)
(b) Normal operating pressure: vacuum
(c) Maximum allowable working pressure (internal): 60 psid (4.1 atm)
(d) Relief paths: single 4.0-inch OD piping from the cryostat to the relief chamber box that contains of a small relief valve and two parallel rupture disks.
(e) Rupture disk flow capacity: 0.50 lb/s
(f) Set points of the two rupture disks: 28.8 psid and 28.8 psid
(g) Small direct-acting spring loaded relief valve with set point of 3 psid

5.4.1 Set Pressures for Relief Valves and Rupture Disks (H. Nann, 09-06-02, updated 11-24-04)

(1) Target Flask:

Calculated maximum pressure according to ASME code:

internal:	207 psia
external:	74 psia

Normal operating pressure:	0 to 18 psia	or	-15 to 3 psid
at Los Alamos:	0 to 15 psia	or	-12 to 3 psid

Maximum allowable working pressure set at: 60 psid
(Note: the MAWP is 2/3 of the pressure at which the target flask was tested.)

* pick set pressure for relief valve at 20 psid

* pick set pressure for rupture disk at 49.3 psid

(2) Vacuum Vessel:
Calculated maximum pressure according to ASME code:

internal:	90 psia
external:	99 psia

Normal operating pressure: vacuum

Maximum allowable working pressure conservatively set at: 60 psid

Suitable set of relief devices:

* Two rupture disks (one with burst pressure 28.8 psid, the other with 28.8 psid)
* Small direct-acting spring valve to protect rupture disks from unnecessary rupture (set point 3 psid), needed as safety relief when vacuum vessel is flooded with Argon to empty the LH_2 target.

These set pressures satisfy the following scenarios:

(A) Emptying the target and catastrophic failure of the vacuum:

In both cases the pressure in the vacuum vessel is no higher than 15 psia (1.25 times atmospheric pressure at Los Alamos). The back-pressure on the rupture disk can go up to 30 psid before the rupture disk blows open. This is very unlikely.

(B) Failure of the refrigeration units:

This causes a slow warm up of the target vessel with only small amounts of LH_2 evaporating. However, the pressure relief valve opens at 15 psid spilling cold hydrogen gas into the vent isolation box increasing the pressure in it. It is very unlikely that the pressure rises up to 30 psia where the rupture disk, which separates the box from the vacuum, will blow open. Note that the operating pressure in the vent isolation box is 14 psia (1.2 times atmospheric pressure at Los Alamos)

5.5 Low-temperature CF Seals (M. Snow, 2-22-01, modified 8-18-02 by WMS)

There are three stainless steel Conflat (CF) two 2-3/4" and one reinforced 1-1/3" flanged seals with copper gaskets inside the cryostat at low temperatures, see LANL drawings 29Y87755 D 1- D9 on web side www.iucf.indiana.edu/U/lh2target/export-files/. The demountable joints are for assembly/disassembly of the target vessel. The CF seals are used in other operating LH_2 targets (at Thomas Jefferson Lab, for example) and are known to be reliable at cryogenic temperatures if properly used. We have done an exhaustive investigation of their reliability at low-temperatures and under internal pressures. The test results are available on web side www.iucf.indiana.edu/U/lh2target/export-files/ and are summarized in the next section.

5.5.1 Testing of Conflat and VCR Seals by Thermal Cycling and under Pressure

Problem: Confirm the reliability of the CF flanged joints at low temperatures (LN_2 temperatures) and under internal pressure (up to 100-200 psig).
Confirm the reliability of the VCR joint at low temperatures and under internal pressure.
Method:

- Carefully make a joint by using a torque wrench and torques defined by the manufacturer
- Carefully leak check the joint when thermal cycled or when the joint still cold.
- Pressurize with helium gas the joint to 100-200 psig inside and leak test the joint.

The detailed description of the procedures and results are available in web page www.iucf.indiana.edu/U/lh2target/export-files/.

As a summary we can say that in the level of 10^{-10} Torr liter/s no leaks were found. Using sniffer no leaks were seen in the sensitivity of 10^{-7} Torr liter/s.

6.0 DESIGN AND DIMENSIONAL CALCULATIONS FOR RELIEF SYSTEMS AND VENT LINES (H. Nann, 8-22-01, updated 1-15-05 and 5-20-05)

Calculations based on the Bates Internal Report # 90-02 [21] and the Crane Technical Paper No. 410 [11] were performed to determine the size of the relief piping such that the mass flow (mass boil-off rate) due to catastrophic vaporization of the liquid hydrogen in the target vessel or isolation vacuum chamber remains subsonic at all times – Sonic flow represents the maximum possible flow in a piping system. – and that the maximum pressure in each component remains well below its bursting point. Based on the formulae and algorithms in these two reports, two computer programs were written. The first program calculates the mass evolution rate and boil-off time from geometric information and the properties of both the target material and vacuum spoiling gas, whereas the second program yields the maximum pressure occurring during the discharge through the relief system. The information that was used as input to the calculations as well as results is given in tables 3 and 4.

Table 3. Boil-off rates of the 21 liter LH_2 target.

	LH2 target vessel		Vacuum chamber	
Heat flux into target [W/m^2]	13,000*	40,000**	100,000	100,000
Surface area [m^2]	0.50	0.25	0.5	1.0
Boil-off time [s]	102	66	13.2	6.6
Mass boil-off rate [lb/s]	0.032	0.049	0.25	0.49

* Calculated under the assumption that the target vessel is surrounded by air.
** With an imaginary 10kW of heating power transferred to lateral surface of the target vessel.

Table 4. Response of the pressure relief system for various mass flow rates and pipe sizes. A value of $K = 10$ for the resistance coefficient was assumed.

	LH_2 target vessel					Vacuum chamber	
Mass flow rate [lb/s]	0.05	0.10	0.05	0.10	0.20	0.50*	0.50*
ID of relief pipe [in]	1.0	1.0	1.5	1.5	1.5	2.5	4.0
Sonic mass flow rate [lb/s]	0.13	0.13	0.29	0.29	0.29	0.81	2.10
Maximum pressure [psia]	28.4	52.5	18.0	26.0	46.8	42.6	20.8

* Mass flow rate when all of the 21 liters of LH_2 is at once in contact with the vacuum chamber wall at 293 K.

The hydrogen pressure relief system consists of:

1. The 1.5” ID hydrogen vent line from the target vessel to the relief valve RV104 which is parallel with a rupture disk RD101 in the vent isolation box, see figures 5 and 18.
2. The isolation vacuum chamber is connected with a 4.0” ID pipe to the relief valve RV201, which is parallel with two rupture disks RD201 and RD202 in the relief chamber, see figures 5 and 18.
3. All these relief devices are connected to the same volume, the relief chamber shown in figure 18. The relief chamber and the 6” ID pipe up to the check valve CKV101 are filled with helium gas of 2 psid to prevent air to come in contact with the hydrogen gas in the vent line of the target vessel and the isolation vacuum in case of a leak in the relief devices.

The calculation of the maximum pressure in the LH_2 target vessel and the isolation vacuum chamber during the catastrophic discharge takes into consideration all the pipes and bends up to the relief chamber (see figure 18), including the pressure relief valves in the relief chamber. Note, that these calculations do not include the long relief pipe with the check valve from the relief chamber to the outside of ER2 and in shed where the LH_2 target will be tested (main relief pipe). The latter calculations are presented in section 6.4. The final results are given in section 6.5. The friction factors for each component in the relief system were taken from the Crane Technical Paper No. 410 [11].
Hydrogen gas is lighter than NTP air and will rise at temperatures above 23 K (normal boiling point temperature is 20.3 K). Buoyant velocities are related to the difference in air and gaseous H_2 densities. The buoyant velocity of hydrogen in NTP air is 3.9 to 29.5 ft/s.

6.1 Calculated Flow Rates and Pressure Drop in the Relief Line in the Event of a Catastrophic Vacuum or Target Failure (H. Nann, 6-6-01)

The following describes calculations and results based on the formulae and procedures of the Bates Internal Report # 90–02 [21] and the Crane Technical Report No. 410 [11] for various mass flow rates and inner diameters (ID) of the vent pipe. The rate of mass flow through pipes, valves and fittings is given by the Darcy formula

$$w = 0.1192 Y d^2 \sqrt{p_1 (p_1 - p_2) \left(\frac{M}{KT} \right)}$$

where w = mass flow rate [lb/s]
p_1 = inlet (upstream) pressure [psia]
p_2 = outlet (downstream) pressure [psia]
d = inner diameter of vent pipe [inch]

Y = net expansion factor for compressible flow through orifices, nozzles, or pipe (The functional dependence of Y vs $(p_1 - p_2)/p_1$ is given in the charts on page A-22 of the Crane Technical Report No. 410 [11])
K = total resistance coefficient for the vent system
T = absolute temperature of the flowing gas [K]
M = molecular mass of the gas [g/mol]
L = length of the pipe [inch]

The functional dependence of Y versus $(p_1 - p_2)/p_1$ is linear and can be written in the form

$$Y = 1 - mx$$

where m = absolute value of slope
$x = (p_1 - p_2)/p_1$
$0 \le x \le x_{max}$ (The value x_{max} corresponds to sonic flow)

Substituting the linear form for Y into the Darcy equation yields

$$w = 0.1192 d^2 (1 - mx)\left(\frac{p_2}{1-x}\right)\sqrt{\frac{Mx}{KT}}$$

Squaring both sides of this equation leads to a cubic equation of the form

$$x^3 + ax^2 + bx + c = 0$$

where

$$a = -\frac{(w^2 + 2Fm)}{Fm^2}$$

$$b = \frac{(F + 2w^2)}{Fm^2}$$

$$c = -\frac{w^2}{Fm^2}$$

$$F = 0.01423 \cdot \left(\frac{Md^4 p_2^2}{KT}\right)$$

This cubic equation was numerically solved for x. For subsonic flow, at least one root must lie in the range $0 < x < x_{max}$. If not, then the flow is sonic. The steady-state pressure is then given by

$$p_1 = \frac{p_2}{1-x}$$

6.1.1 Maximum Pressure in the LH_2 Vessel Due to Catastrophic Failure of Vacuum Chamber

The vent line contains all pipes, bends, and pressure relief valves from the target vessel up to the vent isolation box. Individual resistance coefficients for the various components in the relief line, including the relief valve are given in table 5. A friction factor of $f = 0.021$ for clean commercial steel pipe of 1.5 inch ID is used.

Table 5: Calculation of total resistance coefficient for the relief line from the target vessel to the relief chamber; reference diameter 1.5 inch.

Component	Resistance Coefficient K
8 feet pipe	1.34
3 - 90° elbows	1.89
2 - 45° elbows	0.68
1 – standard tee (flow through branch)	1.26
1 – relief valve*	0.82
1 – pipe exit	1.00
TOTAL	6.99

* according to manufacturer (Anderson Greenwood) for type 83 safety valve with J orifice at 90% flow capacity

The steady-state pressure in the vacuum vessel was calculated as a function of the total resistance coefficient K with the following assumptions:

Mass flow rate: $w = 0.2$ lb/s

Flow temperature: $T = 293$ K, taken at the warmest point in the relief system. This will overestimate the inlet pressure p_1, but this will be an error on the side of safety.

Outlet pressure: $p_2 = 14.7$ psia, venting to air at standard atmospheric pressure.

Results:

Total resistance coefficient:	$K =$	8.0	10.0	15.0
Sonic flow rate [lb/s]	$w_{sonic} =$	0.29	0.29	0.29
Inlet pressure [psia]	$p_1 =$	43.0	46.8	55.4

Note: For an outlet pressure of $p_2 = 11.2$ psia (the normal atmospheric pressure at Los Alamos), the calculated inlet pressures p_1 are slightly lower.

6.1.2 Maximum Pressure in the Vacuum Chamber Due to Rupture of the LH_2 Vessel

The vent line contains all pipes, bends, and pressure relief valves from the vacuum chamber up to the vent isolation box. Individual resistance coefficients for the various components in the relief line, including the relief valve are given in table 6. A friction factor of $f = 0.017$ for clean commercial steel pipe of 4.0 inch ID was used.

Table 6: Calculation of total resistance coefficient for the relief line from the vacuum chamber to the relief chamber; reference diameter 4.0 inch.

Component	Resistance Coefficient *K*
8 feet pipe	0.72
3 - 90° elbows	1.62
1 – standard tee (flow through branch)	1.08
1 – standard tee (flow through run)	0.36
1 – rupture disk*	1.88
1 – pipe exit	1.00
TOTAL	6.66

* according to manufacturer (Fike) for SR-H rupture disks

The steady-state pressure in the vacuum chamber was calculated as a function of the total resistance coefficient K with the following assumptions:

Mass flow rate: w = 0.5 lb/s (Here the LH_2 is in contact with larger warm surface area causing a larger boil-off rate and thus larger mass flow rate.)

Flow temperature: T = 293 K

Outlet pressure: p_2 = 14.7 psia

Results:

Total resistance coefficient:	K =	8.0	10.0	15.0	20.0
Sonic flow rate [lb/s]	w_{sonic} =	2.10	2.10	2.10	2.10
Inlet pressure [psia]	p_1 =	19.8	20.8	23.3	25.5

Note: For an outlet pressure of p_2 = 11.2 psia (the normal atmospheric pressure at Los Alamos), the calculated inlet pressures p_1 are slightly lower.

6.2 Main Relief Pipe (H. Nann, 06-04-03 and 05-20-05)

6.2.1 Buoyancy of Hydrogen Gas in the Vent Lines

Hydrogen gas is lighter than air at normal temperature and pressure and tends to rise at temperatures above 23 K. However at temperatures lower than 23 K, the saturated vapor is heavier than air and will not rise until the temperature increases above 23 K.

In the case of a catastrophic vacuum failure to air or of intentionally introducing dry nitrogen gas into the main vacuum chamber to cause a rapid venting of the LH_2 target, the pressure in the target vessel will rise till the emergency relief valve opens at its set point of 30 psi. During that time the liquid hydrogen will warm up to 23 K, but will not evaporate. After the relief valve has opened, the LH_2 will boil and the cold hydrogen gas will rise slowly. The buoyant velocity is related to the difference in density of the hydrogen gas and the nitrogen in the exhaust line. As the temperature of the hydrogen gas increases due to the heat absorbed from the walls of the vent line it quickly becomes lighter than nitrogen and will rapidly flow out through the main exhaust line. However, this will leave the uninsulated vent line sufficiently cold (less than 77 K) to condense air onto the outside of the pipe.

Calculations were performed to find out how long it will take to warm up the hydrogen gas from 23 K to 77 K, the temperature region where the cold hydrogen gas will condense air, to see if heating of the vent line is necessary. It was assumed that the surface area of the target vessel and the exhaust pipe within the vacuum vessel and the heat flux into it were 0.5 m^2 and 13,000 W/m^2, respectively. For the specific heat of hydrogen gas the value at normal temperature and pressure of 14.89 kJ/(kg·K) was taken (The value at the boiling point is smaller.). The resulting time of t = 3.65 min is considered too long for warming up the hydrogen gas from 23 K to 77 K.

6.2.2 Vent Lines and Main Relief Pipes

A 1.5-inch ID pipe connects the LH_2 target vessel to the relief chamber. In addition, the main isolation vacuum chamber is also connected to the same relief chamber by a 4.0-inch ID pipe. The relief chamber, in turn, is connected to a 6-inch inner diameter main relief pipe which conducts the hydrogen gas through a check valve to the outside of the ER2 building or shed in normal operation or in case of an accident or emergency. This main relief line has to handle the flow from all discharges and thus has to have a capacity which is sufficient to avoid over-pressurizing the LH_2 vessel and/or the isolation vacuum chamber. A check valve, CKV101, is provided in the relief pipe to limit backflow of air. The relief chamber up to the check valve is filled with helium gas to 2 pisg. The relief pipe from the check valve, CKV101, to the outside the ER2 building or the shed at MPF-35 is constructed and located so that it meets all the safety requirements and codes. The portion of the relief line from the top of the FP12 experimental cave to the ER2/ER1 wall has a slight upward grade so that the buoyancy of the hydrogen gas drives it to flow naturally in the pipe. Table 7 contains a list of the various parts of the relief system along with their performance specifications.

Table 7. Summary of the individual vent lines and main relief pipes.

Relief lines	Mechanical and conductance properties of relief lines/blow-offs			Max. pressure in worst-case failure
	Dimensions	Material	Mass flow capacity	
LH_2 target vent line	1.5 “diameter Total resistance coefficient K = 7.0	304 stainless steel	0.20 lb/sec	46.8 psia (for total resistance coefficient K = 10)
Main vacuum vent line	4.0” diameter Total resistance coefficient K =6.7	304 stainless steel	0.50 lb/sec	23.3 psia (for total resistance coefficient K = 15)
Main relief pipe in ER2	6” diameter Total resistance coefficient K=15.3	304 stainless steel	0.50 lb/sec	
Main relief pipe in shed	4” diameter Total resistance coefficient K=14.1	304 stainless steel	0.50 lb/sec	

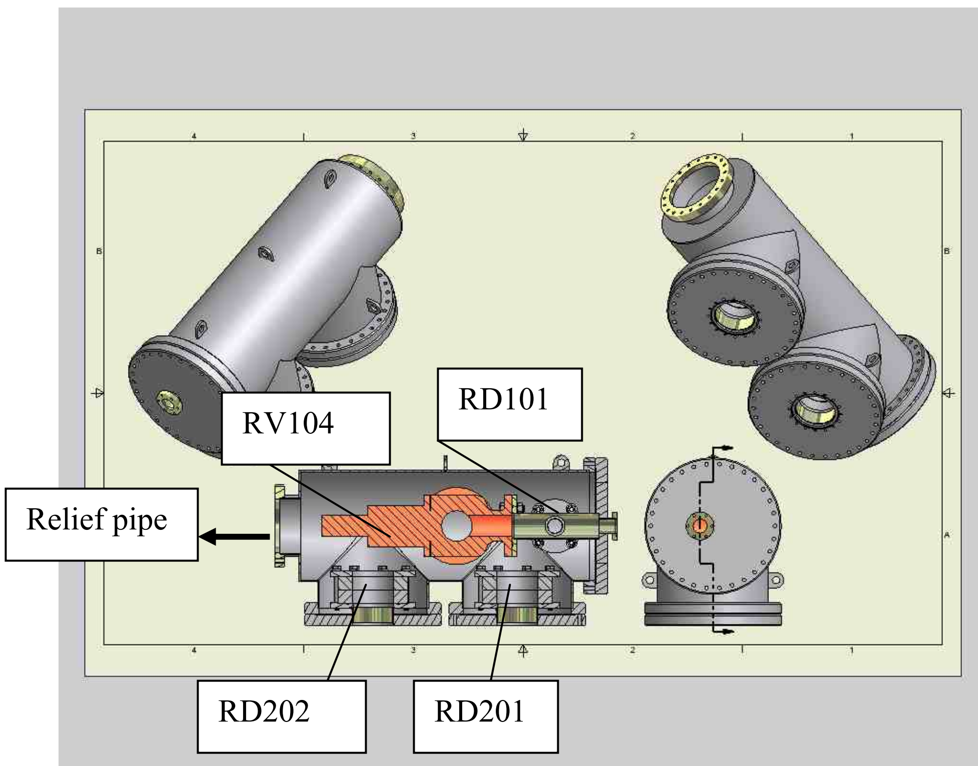

Fig. 18. Relief chamber with assembly of the relief valve, RV104 and rupture disks, RD101, RD201, and RD202. The three rupture disks and relief valve are opening to the same helium atmosphere present in the first part of the relief pipe.

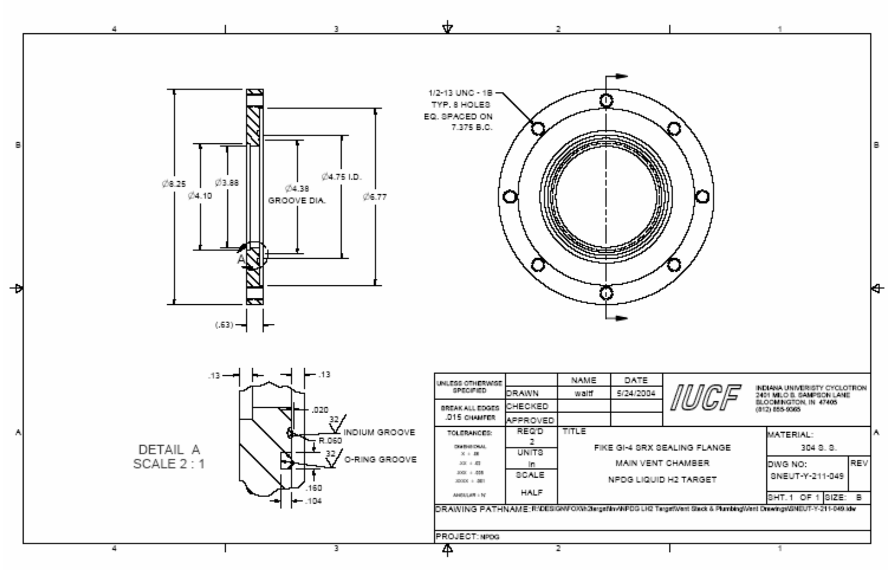

Fig. 19. Design of the seals for the rupture disks. For details see drawing SNEUT-Y-212-015 Main Vent Assy.pdf, available on web page www.iucf.indiana.edu/U/lh2target/export-files/. The design incorporates an indium groove inside of the viton o-ring groove so that there is no diffusion of helium gas from the relief pipe into the main vacuum system or the LH_2 target vessel. This design produces no mechanical modification to the burst disks themselves which are certified by the manufacturer.

6.3 Specifications for Relief Devices and Pipes (H. Nann, 6-20-01, J. Novak, 11-10-01, and H. Nann, 9-10-02)

As described before, the LH_2 target system consists of two main components: a target vessel containing the liquid hydrogen and an insulation vacuum chamber. These components were designed according to the ASME Boiler and Pressure Vessel Code, Section VIII, Division 1 and 2 [9]; ASME B31.3 Code for Pressure Piping – Process Piping [10]; CGA S-1.3 Pressure Relief Device Standards – Part 3 – Stationary Storage Containers for Compressed Gases [6] (referred to as CODE). Each volume is equipped with a primary relief system of a spring-loaded pressure relief valve and a parallel, secondary relief system consisting of a rupture disk(s). All pressure relief systems are connected to a large relief chamber which is then connected to a 6 inch diameter 304L stainless steel relief pipe. The vent isolation box up to the check valve CKV101 is filled with helium at 2 psig. The output of the check valve is connected either to a 6 inch diameter 304L stainless steel pipe which ends outside ER2 or to a 4 inch diameter 304L stainless steel pipe which ends outside shed.

6.3.1 LH_2 Vessel Relief Valve - RV104

In choosing the LH_2 target vessel relief valve RV104, we assume that the mass flow (maximum H_2 mass flow rate = 0.2 lb/s) is caused by loss of the isolation vacuum. The pressure difference through 1.5" ID fill/vent line up to the relief valve is 43.0 psid (see section 6.1.1).

Specifications for the LH_2 vessel relief valve are:

- Must be vacuum tight to the level of 10^{-9} bar cc/s, allowing the LH_2 vessel to be evacuated for leak checking and held evacuated without leakage.
- Essentially no leakage under pressure up to 85% of the set pressure.
- Pressures:
  - Normal operation = -15 to ~3 psig (0 to ~18 psia)
  - System design pressure = 207 psia
  - Maximum allowed working pressure = 60 psid

We chose the Anderson Greenwood (AG) direct-acting spring valve model 83 with a "J" orifice (1.287 in^2 flow area) and a 20 psig set pressure. Pilot-operated relief valve types like the AG model 91 are not suitable since they will open when the target flask is evacuated. The J orifice (flow rate at set pressure: AG Safety Size gives ASME rated mass flow capacity of 0.306 lb/s which is larger than the assumed maximum H_2 flow rate of 0.2 lb/s.) has a larger nozzle area than the H orifice and, therefore, seals better (to first order).

6.3.2 LH_2 Vessel Rupture Disk – RD101

Fike Corporation sells model SR-H rupture disks that have a molded-on gasket and fit Tri-Clover flanges. The Fike catalog gives a flow resistance coefficient K =1.88 for a ruptured SR-H disk. This number indicates a rather free opening after the disk ruptures. The SR-H is listed as suitable for full vacuum load. According to Dallas Clayton (Scientific Sales, 505-266-7861) these rupture disks are vacuum-tight. But we need to carefully leak check them.

A 2" diameter rupture disk model 2"SRL/Ni/50#/72F/STD with SRL-GI/150#/CS/CS holder was picked with range of +0 – 10%.
The pressure set point is 60 psid which is adequately far from the RV104 relief valve set point of 20 psid. The pressure tolerance +0 – 10% gives 60 – 6 = 54 psid. Maximum pressure ahead of relief valve at full flow = 1.1 times set pressure = 22 psid.
Ratio is 22 / 54 = 41%, which is a large enough margin. The burst disk should not break accidentally.
It is adequately far from the design pressure. (60 + 14.7) / 207 psia = 0.36

6.3.3 Main Vacuum Chamber: Relief Valve – RV201 – and Rupture Disks – RD201 and RD202

We have here two different situations that need pressure relief valve protection. When the cryostat is cold, air can be condensed on the cold surfaces. This is not possible in the normal operational mode because of the helium filled gas channels but in an operational mode where hydrogen is not used like cryogenic testing and, therefore, the helium channels are not filled with helium. If there is a leak to vacuum, air can be condensed on the cold surfaces. When the cryostat is warmed up, an over pressure is possible in the vacuum chamber. A relief valve with a

low set point is required, and mass flows are small. This incident should not cause a burst of the rupture disks.
The other incident type is when we have a total rupture of the LH_2 vessel causing a high mass flow (maximum H_2 mass flow rate = 0.5 lb/s). A direct acting spring loaded relief valve alone cannot handle this flow and, therefore, we have two 4” diameter rupture disks in parallel.

Rupture disks should open only when there is a catastrophic failure of some component inside the isolation vacuum chamber. The spring-loaded relief valve would not be counted on for Code compliance since no ASME-rated valve is available with a reasonably small pressure set point. Therefore, a spring-loaded relief valve is used only to vent small amounts of gas that may enter the vacuum chamber, thus protecting the rupture disks from unnecessary rupture. The rupture disk is the primary device used to achieve Code compliance for the high mass flow situation. A second disk is used to gain additional redundancy.

Pressure difference through 4.0” ID pipe to the relief valve and rupture disks is 19.8 psid.

Specifications for the small relief valve RV201:

- Must be vacuum tight to the level of 10^{-9} bar cc/s, which is a low enough leakage rates that vacuum chamber can be isolated from pump system for weeks.
- Essentially no leakage under pressure up to 85% of set pressure
- Pressures:
    - Normal operation = vacuum
    - Vacuum chamber design pressure = 90 psia
    - Maximum allowable working pressure = 60 psid
    - Pressure set point = 3 psid

Swagelok relief valve SS-4CA-VCR-50 was chosen.

Specifications for rupture disks RD201 and RD202:

- Must be vacuum tight to the level of 10^{-9} bar cc/s.
- Pressures:
    - Normal operation = vacuum
    - Vacuum chamber design pressure = 90 psia
    - Maximum allowable working pressure = 60 psig
    - Pressure set points = 20 psid and 30 psid.

We chose the Fike model 4” SRL/Ni/30#/72f/std rupture disks with pressure tolerance of 0 – 10% and burst pressures of 28.8 psid. The holder is 4” SRX-GI/150#/CS/CS.

6.3.4 Backpressure on Rupture Disks RD201 and RD202 (H. Nann, 01-15-05)

In the case of a failure of the two refrigerators (e.g. power failure) with no vacuum failure the LH_2 target vessel will slowly warm up causing the liquid hydrogen to boil off. This will cause a slow pressure increase in the 1.5-inch ID relief line up the pressure relief valve RV104, situated in the relief chamber, till RV104 opens at its set pressure of 20 psid. Then hydrogen gas will flow into the relief chamber causing a pressure increase in the box. The two pressure relief valves, check valves CKV101.1 and CKV101, from the relief chamber to the outside atmosphere have a set pressure of 2.6 psid and 3.5 psid, respectively. Assuming a normal atmospheric pressure of 11.2 psi at Los Alamos, then the maximum pressure in the relief chamber is 11.2 psi + 2 psid + 2.6 psid = 15.8 psi with respect to vacuum, provided that the gas flow into the relief chamber is not larger than the gas flow out of the chamber into the atmosphere. Considering the nozzle area of the relief valves RV104 and CKV101 this will not happen.

Calculation of the pressure increase in the relief chamber due to failure of the two refrigerators:

Assume a heat flux of 15.5 W into the LH_2 target vessel (this is the sum of the measured cooling power of the two refrigerators at 17 K. The actual heat flux is less than 15.5 W). This gives a boil off rate of w = 0.00348 g/s = 0.0173 mol/s.
Using the ideal gas equation, this yields a pressure increase in the 1.5-inch ID relief line (volume $V_{pipe} = 3.475 \times 10^{-3}$ m^3) of $\Delta p = 8.25 \times 10^4$ Pa/s = 12.0 psi/s.
When the pressure relief valve RV104 opens at its set point of p = 20 psid, the hydrogen gas in the 1.5-inch ID relief line expands into the relief chamber which has a volume $V_{box} = 3.934 \times 10^{-2}$ m^3. This will increase the pressure in the relief chamber by Δp = 1.8 psid. Once valve RV104 is open, the pressure increase in the 1.5-inch ID relief line and the relief chamber is Δp = 0.97 psid/s. This is a slow pressure increase. Once the set pressure of CKV101.1 (2.6 psid) is reached, it opens up and relieves the built up pressure through the main vent line into the outside atmosphere.

6.3.5 Justification for the Relief Valve and Rupture Disk Pressures (B. Lozowski, 11-24-04)

RV101

Function: relieve an over-pressure condition in the supply line from the H_2 gas cylinders
Location: in the H_2 supply line downstream of the flow-restrictive orifice and upstream of the mass flow meter.
Set point: 220 psid cracking pressure
Reasoning: Short-term exposure to pressures as high as 220 psid is sufficiently high to avoid unnecessary venting of H_2.

RV102

Function: relieve an over-pressure condition in the H_2 line between V117 and V120 (normally locked open).
Location**:** between V117 on the output of the LN cold trap. Effectively it is on the inlet of the cold trap.
Set point: 50 psid cracking pressure
Reasoning: If V125 must be throttled down during filling (e.g., to accommodate pressure fluctuations due to flash evaporation of LH_2 in the internal O-P catalyst chamber), this setting is sufficiently high to avoid venting H_2 unnecessarily and adequately below the yield strength of the cold trap and the external OPC chamber.

RV103

Function: relieve an over-pressure condition upstream of V125, as for RV102. Because

V120 is normally locked open, RV102 and RV102 are vents for the inlet and outlet of the LN2-immersed cold trap.
Location: between V120 and V125 (the last H_2-supply valve in the line to the LH_2 vessel)
Set point: 50 psid cracking pressure
Reasoning: as for RV102

RV104
Function: relieve an over-pressure condition in the LH_2 vessel
Location: inside the relief chamber with RD101, RD201 and RD202,
Set point: 20 psid, at which it opens fully
Reasoning: As per Section 7.3.1 of the engineering document, this set point is less than half the 60 psid maximum working pressure of the LH_2 vessel. Because RV101 opens fully when the H_2 pressure exceeds the set point, 20 psid is sufficiently low with respect to the 60 psid burst pressure of rupture disc RD101.

RV106
Function: relieve an over-pressure condition in the H_2 supply system
Location: H_2 supply manifold outside building
Set point: 100 psid cracking pressure
Reasoning**:** This set point avoids the possibility of over-pressuring the H_2 supply line.

RV201
Function: relieve an over-pressure condition in the vacuum vessel
Location: in the external plumbing of the vacuum system
Set point: 3 psid cracking pressure
Reasoning: A 3 psid overpressure is acceptable in the vacuum isolation chamber.

RV401
Function: relieve an over-pressure condition in the helium panel
Location: in the He line to V405 (which allows He to enter the vent line system)
Set point: 30 psig cracking pressure
Reasoning: A 30 psig overpressure of the He blanket in the main vent line (normally 2 psig) would occur only if CKV101 and CKV101.1 both failed to open when the He regulator malfunctioned or was set excessively high.

RV402
Function: relieve an over-pressure condition in the helium-channel system of the vacuum isolation chamber
Location: in the He line to V405 (which allows He to enter the vent line system)
Set point: 6 psig cracking pressure
Reasoning: A 6 psig overpressure of the helium channels (normally 2 psig) would be acceptable.

RV501
Function: relieve an over-pressure condition in the argon system
Location: in the argon line to V205

Set point: 3 psid cracking pressure
Reasoning: This set point avoids the possibility of over-pressuring the vacuum vessel with argon, due to a malfunction in pressure regulator PR501. When V205 is open, it also functions as the high-pressure set point for the vacuum vessel.

CKV101

Function: relieve an over-pressure condition in the main vent line for the target.
Location: in the 6" diameter, stainless steel vent line beyond the relief chamber containing RV104, RD101, RD201 and RD202
Set point: 3.5 psid opening pressure
Reasoning: This set point is adequate to contain a blanket of He in the vent line. The 2 psig backpressure will be an insignificant offset for the set points of the other pressure-relief devices.

CKV101.1

Function: backup in the event CKV101 fails to open at 2 psig
Location: in the 6" diameter, stainless steel vent line beyond the relief chamber containing RV104, RD101, RD201 and RD202
Set point: 2.6 psid opening pressure
Reasoning: This set point is adequate to contain a blanket of He in the vent line. The 3 psig backpressure will be an insignificant offset for the set points of the other pressure-relief devices.

RD101

Function: passive rupture device for the H_2 vessel in the event RV104 should fail to open adequately
Location: in the vent isolation box of the main vent line
Set point: 49.3 psid
Reasoning: This set point is designed to remove the possibility of over-pressuring the H_2 vessel.

RD201

Function: passive rupture device for the vacuum isolation chamber
Location: in the vent isolation box of the main vent line
Set point: 28.8 psid
Reasoning: This set point is 5 psid higher than the maximum rated pressure of the turbopump in the RGA system, but is necessary to accommodate the worst-case scenario of backpressure in the main vent system. To protect the turbo, we will rely on V207 to close via the interlocks with PT204 and PT302.

RD202

Function: backup for RD201
Location: in the vent isolation box of the main vent line
Set point: 28.8 psid
Reasoning: backup to RD201, with a pressure sufficiently higher to avoid unnecessary rupture.

6.4 Vent and Relief System in MPF-35 and at ER2 (H. Nann 11-24-04, updated 5-20-05)

6.4.1 Hydrogen Vent Stack in MPF-35

The total resistance coefficient for the relief vent line in the shed, shown in figure 20, was calculated assuming the components given in table 8 together with their individual *K*-values. The reference diameter was 4.0 inch ID. The design criteria and detailed design for the relief line can be found in the web site www.iucf.indiana.edu/U/lh2target/export-files/.

Table 8. Resistance coefficients for the shed vent stack.

Component	Resistance Coefficient *K*
30 feet pipe	1.53
4 – 90° elbows	2.04
1 – lift check valve	9.00
1 – pipe entrance	0.50
1 – pipe exit	1.00
TOTAL	14.07

Conversion to 1.5 inch reference diameter pipe:

$$K_a = K_b\left(\frac{d_a}{d_b}\right)^4 = 14.07\left(\frac{1.5}{4.0}\right)^4 = 0.28$$

Figure 18 shows the relief system in the shed at MPF-35. After the cryostat there is a vent isolation box followed by check valve CKV101 and then a 4.0-inch ID, 30 ft long stainless steel pipe which conducts hydrogen gas to the outside of the shed. The design criteria for this relief line can be found in the web side www.iucf.indiana.edu/U/lh2target/export-files/.

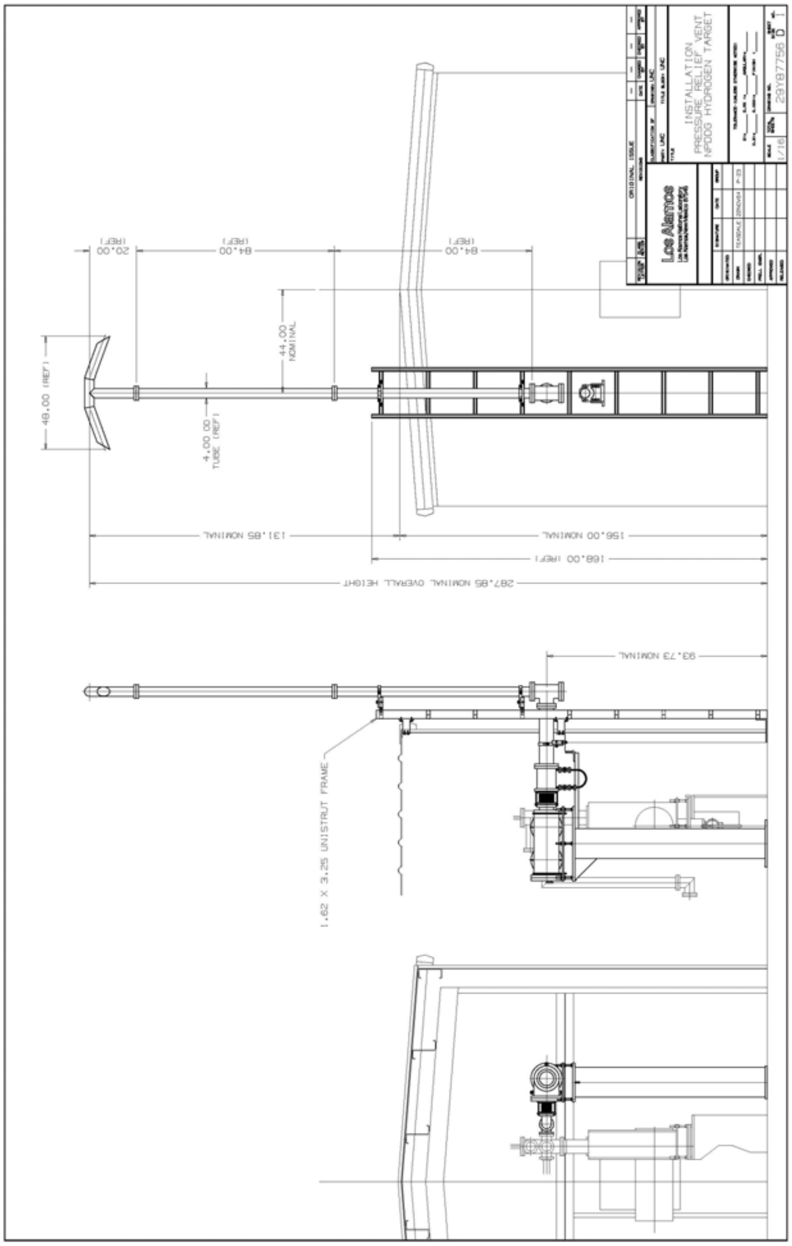

Fig. 20. Hydrogen vent stack in shed drawing # 29Y87756 D M3.

6.4.2 Hydrogen Vent Stack at ER2

Figure 21 shows the relief system at ER2 where a 6-inch ID, 100 ft long pipe and 4 - 90° bends are required. The design criteria and detailed design for this relief line can be found in the web site www.iucf.indiana.edu/U/lh2target/export-files/. The total resistance coefficient for the relief vent line in ER2 was calculated assuming the components given in table 8 together with their individual *K*-values.

Table 8. Resistance coefficients for the ER2 vent stack.

Component	Resistance Coefficient *K*
100 feet pipe	3.00
4 – 90° elbows	1.80
1 – lift check valve	9.00
1 – pipe entrance	0.50
1 – pipe exit	1.00
TOTAL	15.30

Conversion to 1.5 inch reference diameter pipe:

$$K_a = K_b\left(\frac{d_a}{d_b}\right)^4 = 15.30\left(\frac{1.5}{6.0}\right)^4 = 0.06$$

Conversion to 4.0 inch reference diameter pipe:

$$K_a = K_b\left(\frac{d_a}{d_b}\right)^4 = 15.30\left(\frac{4.0}{6.0}\right)^4 = 3.02$$

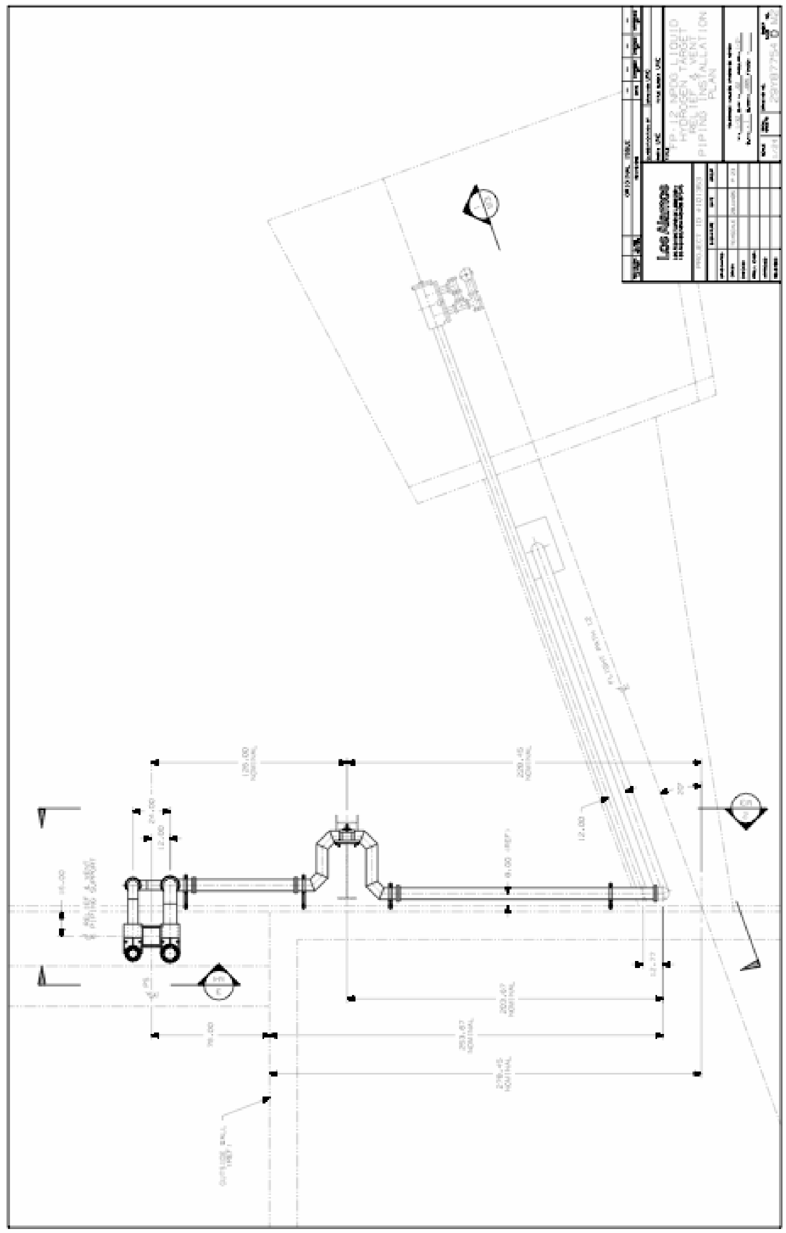

Fig. 21. Hydrogen relief and vent stack piping at ER2 drawing # 29Y87754 DM2.

6.5 Calculations of Inlet Pressures of the Relief Pipes up to the Outside Atmosphere

6.5.1 Resistance Coefficients for the Entire Vent System in Shed and at ER2

A) Target vessel relief line: reference diameter 1.5 inch

From target vessel to the relief chamber: K = 6.99

From the relief chamber to outside:		
	In shed	K = 0.28
	In ER2	K = 0.06
TOTAL	In shed	K = 7.27
	In ER2	K = 7.05

B) Vacuum vessel relief line: reference diameter 4.0 inch

From vacuum vessel to the relief chamber:		K = 6.66
From the relief chamber to outside:		
	In shed	K = 14.07
	In ER2	K = 3.02
TOTAL	In shed	K = 20.73
	In ER2	K = 9.68

Table 10. Maximum pressure rise at the entrance to the relief/vent line for various tubing sizes and values of the resistance coefficient *K*. The exit pressure is 14.7 psia.

	Target Vessel	Vacuum Vessel
Resistance Coefficient	Reference Pipe ID 1.5 inch w = 0.2 lb/sec	Reference Pipe ID 4.0 inch w = 0.5 lb/sec
	p_{max} (psia)	p_{max} (psia)
$K = 6$	38.6	
$K = 8$	43.0	19.8
$K = 10$	46.8	20.8
$K = 15$	55.4	23.3
$K = 20$		25.5

Conclusion:

The results show that, in the case of a catastrophic vacuum failure to air, the LH_2 target vessel is subjected to a pressure of no more than 43.0 psia if the inner diameter of the fill/vent piping is 1.5-inch for an assumed boil-off rate of 0.20 lb/s. The maximum pressure in the vacuum vessel for the case of a rupture of the target flask is 25.5 psia for a 4.0-inch ID relief piping if a boil off rate of 0.50 lb/s is assumed. Both pressures are well below the 90 and 60 psid pressures that the LH_2 target vessel and vacuum chamber, respectively, were tested at.

In summary, the results of the above calculations show that the relief piping is properly sized to prevent excessive pressures in the LH_2 target and isolation vacuum after catastrophic failures.

6.6 Temperature Distribution in the Relief /Vent Pipe

To eliminate in design stresses caused by the thermal contraction of the relief/vent pipe, we have estimated temperature distribution in the pipe during the maximum cold hydrogen mass flow.

The heat which will warm up the cold H_2 gas (GH_2) in the vent pipe comes from two sources: the heat capacity of the stainless steel pipe and the heat from the surrounding air.
Let's assume schedule 40 stainless steel pipe, nominal pipe size 6 inches.

Inside diameter:	d = 6.065 in
Transverse internal area:	A = 28.89 in^2 = 0.2006 ft^2 = 0.01864 m^2
Weight/Mass	18.97 lb/ft = 8.62 kg/ft
External surface:	1.734 ft^2/ft = 0.161 m^2/ft

Properties of LH_2 and H_2 gas at normal boiling point (NBP):

Density:	vapor	1.338 kg/m^3 = 0.0835 lb/ft^3
	liquid	70.78 kg/m^3 = 4.42 lb/ft^3
Specific heat at constant pressure:		
	vapor	c_p = 12.15 kJ/kg·K

Properties of gas H2 at normal temperature and pressure (NTP):
Density: 83.764 g/m^3 = 0.00523 lb/ft^3
Specific heat at constant pressure: c_p = 14.89 kJ/kg·K

<u>Heat from heat capacity of vent pipe:</u>

Specific heat of steel: c = 0.449 J/g·K
Initial temperature of GH_2: $T_{initial}$ = 23 K
Temperature difference: ΔT = 293 K – 23 K = 270 K
Heat content of pipe: $Q = m{\cdot}c{\cdot}\Delta T = (8.62 \times 10^3 \text{ g/ft})(0.449 \text{ J/g·K})(270 \text{ K})$
$= 1.045 \times 10^6$ J/ft
Mean velocity of compressible fluid in pipe:

$$v = \frac{188.3w}{d^2 \rho} \text{ ft/sec,}$$

where w = rate of flow in lb/sec
d = diameter of pipe in inches
ρ = density of fluid in lb/ft^3

Density of gas H_2 at $T_{initial}$ = 23 K: ρ = 0.0736 lb/ft^3

For w = 0.5 lb/sec: $$v = \frac{(188.3)(0.5)}{(6.065)^2(0.0736)} = 34.8 \text{ ft/sec} = 10.6 \text{ m/s}$$

For w = 0.2 lb/sec: $$v = \frac{(188.3)(0.2)}{(6.065)^2(0.0736)} = 13.9 \text{ ft/sec} = 4.2 \text{ m/s}$$

Volumetric flow: V/t = (mean velocity) × (transverse internal area)

Time: t = (volume of transferred GH2) / (volumetric flow)

For w = 0.5 lb/sec: $$t = \frac{(21\times10^{-3} m^3)(850)}{(10.6 m/s)(0.01864 m^2)} = 90.3 \text{ sec}$$

Temperature increase per foot:

$$\Delta T = \frac{Q/t}{w\cdot c_p} = \frac{(1.045\times10^6 J/ft)/(90.3 s)}{(0.23 kg/s)(12.15\times10^3 J/kg\cdot K)} = 4.1 \text{ K/ft}$$

For w = 0.2 lb/sec: $$t = \frac{(21\times10^{-3} m^3)(850)}{(4.2 m/s)(0.01864 m^2)} = 228 \text{ sec}$$

Temperature increase per foot:

$$\Delta T = \frac{Q/t}{w\cdot c_p} = \frac{(1.045\times10^6 J/ft)/(228 s)}{(0.091 kg/s)(12.15\times10^3 J/kg\cdot K)} = 4.1 \text{ K/ft}$$

Summary (ΔT is calculated approximately after every 2 ft.):

Initial temperature: $T_{initial}$ (K)=	Temperature increase per ft: ΔT (K/ft) =
23	4.1
31	5.5
42	7.1
56	9.0
74	10.9
96	12.8
122	14.0
150	14.4
179	13.8
207	12.0
231	9.7
250	7.2
264	5.2

Heat transfer from air:

Assume heat flux into pipe: $\frac{Q}{A \cdot \Delta t} = 13000 \text{ W/m}^2$

This heat comes predominantly from the latent heat of vaporization when the air condensates on the outside of the vent pipe. This condensation stops when the temperature of the vent pipe is higher than 78.7 K. The heat capacity of the air surrounding the pipe is very small since the density of air is at least three orders of magnitude smaller that the density of solids.

$$\frac{Q}{\Delta t} = (13000W / m^2)(0.161m^2 / ft) = 2093 \text{ W/ft}$$

Temperature increase per foot:

For w = 0.2 lb/sec:

$$\Delta T = \frac{Q / \Delta t}{w \cdot c_p} = \frac{2093W / ft}{(0.091kg / s)(12.15 \times 10^3 J / kg \cdot K)} = 1.9 \text{ K/ft}$$

For w = 0.5 lb/ft:

$$\Delta T = \frac{Q / \Delta t}{w \cdot c_p} = \frac{2093W / ft}{(0.23kg / s)(12.15 \times 10^3 J / kg \cdot K)} = 0.7 \text{ K/ft}$$

6.7 Testing of the Model (H. Nann, 8-22-01, modified 5-1-03 W.M. Snow)

6.7.1 Accident Scenario Testing (May 2003)

Tests were performed to study the target vessel boil off rate when the isolation vacuum was spoiled and results were compared to estimates given by calculations. Also three liters of LN_2 were emptied into the vacuum chamber to simulate a rupture of the LH_2 vessel and the boil-off was measured.

6.7.1.1 Spoil of the isolation vacuum

Similar tests have been performed at JLAB with their cryo modules [16].

The LH_2 target vessel, surrounded by one layer of copper heat shielding, was mounted inside the insulation vacuum chamber. Both the target vessel and the heat shield were thermally connected to the top (Cryomech) refrigerator. The exhaust line from the target vessel to the pressure relief valve had an inner diameter of 0.5 inch, was about 50 inches long, and contained three 90-degree elbows. The pressure relief valve was set at 2.4 bar (= 35 psi) absolute. Pressure and temperature sensors were placed throughout the target and isolation vacuum system.

The target vessel was filled with 18 liter of LN_2. Dry argon was then bled into the vacuum chamber and a constant pressure of 1 atmosphere was held till all of the LN_2 in the target vessel was evaporated. Both the top and bottom refrigerators were operating during the test.

When the pressure in the target vessel exhaust line reached the preset 2.4 bar (=35 psi) absolute, the pressure relief valve opened, and the pressure dropped to 2.2 (=32 psi) bar, stayed there for 28 minutes, and then dropped slowly to 1 bar (=15 psi). The target was empty after 55 minutes.

The mass of 18 liters of LN_2 is 14.53 kg; it evaporated in Δt = 55 min = 3300 s. Thus the mass flow rate is

$$w_N = \frac{m}{\Delta t} = \frac{14.53\text{kg}}{3300\text{s}} = 0.0044\,\text{kg/s} = 0.01\text{lb/s}.$$

Next convert this nitrogen mass flow rate to the mass flow rate of hydrogen by assuming that the heat flux into the target is the same.

$$w_H = \frac{h_V(\text{N}_2)}{h_V(\text{H}_2)} w_N = \frac{198.8\text{J/g}}{445\text{J/g}} \cdot 0.01\text{lb/s} = 0.0045\text{lb/s},$$

where $h_V(N_2)$ and $h_V(H_2)$ are the enthalpies of vaporization per unit mass for nitrogen and hydrogen, respectively.

Conclusion:
This mass flow rate is 40 times less than w = 0.2 lb/s which was assumed for calculating the maximum pressure in case of a catastrophic failure of the insulating vacuum. Therefore, the designed pressure relief system can safely handle such a catastrophic event.

6.7.1.2 Simulation of rupture of the LH_2 vessel

Three (3) liters of LN_2 was emptied using a remote control into the vacuum vessel at room temperature and atmospheric pressure. The LH_2 target vessel and Cu heat shield were inside the vacuum vessel. Thus the volume, into which the LN_2 vaporized, closely resembled that of the operating LH_2 target. In the test the relief line from the vacuum vessel to the rupture disk, RD201 or RD202, had an inner diameter of 0.75 inch. The rupture disk was burst at 2.3-bar (33 psi) absolute pressure. It took 62 seconds for these 3 liters of LN_2 to evaporate.

The mass of three liters of LN_2 is 2.43 kg, it evaporated in Δt = 62 s. Thus the mass flow rate through the pressure relief system was

$$w_N = \frac{m}{\Delta t} = \frac{2.43\text{kg}}{62\text{s}} = 0.04\,\text{kg/s} = 0.09\text{lb/s}.$$

This corresponds to a mass flow rate for hydrogen of w_H = 0.04 lb/s. Assuming that 21 liter of LH_2 evaporate in the same time – this assumption can be justified since all of the 21 liters of LH_2

are in contact with the vacuum vessel wall at the same time – the mass flow rate is w_H = 0.28 lb/s.

Conclusion:
Again the mass flow rate of 0.28 lb/s can safely be handled by the designed pressure relief system, which is able to discharge 0.5 lb/s with a maximum pressure build-up of no more than 25.5 psia in the vacuum chamber.

6.8 Tests of Various Components

6.8.1 Testing of Relief Valves

Object:
It has been observed that the relief valves in GHS are not entirely gas tight close to the cracking pressure. Instead, there may be a pressure range in which the valves will leak. It was therefore important to characterize the leakage of the valves.

These measurements are described in a document Testing of Relief Valves that is available in web page www.iucf.indiana.edu/U/lh2target/export-files/.

Summary of Results:
Valves RV101, RV102, RV103, and RV104 were tested. There is a 10-15% pressure range around the cracking pressure where the valve will open and seal back.
See LH2 Target Logbook #1 p. 130 where primary testing and tuning was performed and then Logbook #2 p. 13, where RV104 was tested during the 1st neon cool down. RV104 functioned as designed.

6.8.2 Pressure Testing of the 24" Bellows

Date: February 18, 2003
Purpose: To test if the bellows can be safely pressurized to 30 psig.
Bellow under test: 24" long position in gas handling system: foreline of TP201.

The braided bellows are from Kurt Lesker, model MH-CF-G06 with 0.015" walls. Each bellow was pressurized to 30 psig. At maximum pressure, it expanded to 28" long (flange-to-flange), but recovered its initial length after reduction to ambient pressure. After repeated exposures to 30 psig, a hydrogen leak test confirmed (to a leak rate of $1x10^{-9}$ cc/s) that the bellows did not crack.

Test Performed By:	Approved By:
Vivek Jeevan	Bill Lozowski

6.8.3 Pressure Testing of Target Isolation Valve – V128

Date: February 17, 2003
Purpose: To test if the bellow of the valve V128 can be safely pressurized to 80 psig, which is 1.14 times the maximum allowable working pressure of the LH_2 target vessel.

Valve tested: MDC Vacuum Products Corporation model #: AV—150M
serial #: 94-47248
note: contains copper gasket seat under the bonnet to seal the bellows

The valve was pressurized to 80 pisg. While pressurized, it was repeatedly opened and closed, thereby expanding and contracting its bellows. After repeated exposures to 80 psig, a hydrogen leak test to the leak rate level of $2x10^{-9}$ cc/s indicated that the bellows did not crack.

Test performed by: Approved by:
Vivek Jeevan Bill Lozowski

6.8.4 Testing of Check Valve CKV101

Date : January 27, 2005
Purpose: Tuning of the cracking pressure, testing opening and closing of CKV101, and then leak checking the valve.

See LANL drawings 29Y87753 D 1 - D 9. The testing is described in LH2 Target Logbook #1 p.135.
Test performed by: Approved by:
Satyaranjan Santra Seppo Penttila

7 SUMMARY OF TESTING DOCUMENTATION FOR THE LH2 TARGET (M. Snow, 5-1-03)

This is a brief summary of the tests performed by vendors who have fabricated parts of the NPDG LH_2 target organized by item and vendor. All welding for all parts was performed by certified welders. Certifications for materials and welders are available upon request.

Main vacuum chamber and windows:

The main vacuum chamber, fabricated by Ability Engineering Technology, is an aluminum vessel with internal channels which expose all weld joints and o-ring seals to helium gas from the outside. In addition there are two sets of double windows at the entrance and exit for the neutron beam. The tests discussed here were performed with magnesium and aluminum windows.

For materials certificates see Certificates on web page www.iucf.indiana.edu/U/lh2target/export-files/. All pieces meet appropriate AMS/ASME/ASTM specifications.

Pressure tests:
The assembled vacuum chamber with aluminum windows was pressurized to 70 psid successfully. The inner magnesium windows were pressure tested to 80 psid and the outer magnesium windows to 117 psid.

Helium leak tests:
Leak testing of the assembled vacuum chamber, the main weldment, and the aluminum and magnesium windows were performed with a helium leak detector on scales in the range of $1\text{-}10^{-9}$ atm cc/sec with no leaks found.

Radiography:
Note that due to the nature of the welds for this vessel, radiography is not required according to the ASME code and as approved in a Change Control Request to the LANL safety committee. Nevertheless, radiography was performed anyway. The vendor was Calumet Testing Services, 1945 N. Griffith Blvd., Griffith, IN 46319, (219)-923-9800, (708)-474-5860. X-ray radiographs were performed with x-ray source internal and external to the vessel in specified geometries referenced to stamped letters on the outside of the vessel. As expected the radiographs show the inclusions which are due to the helium gas channels required by the safety committee.

Subsequent history:
Later work at Indiana uncovered a leak in one of the internal welds. This weld was redone by a certified welder from Ability Engineering and the weld is now helium leak-tight.

<u>Titanium Target Vessel:</u>

The titanium liquid hydrogen target vessel, fabricated by Excelco Development Inc., is an all-titanium cylindrical welded chamber with one inlet and one outlet port. The shape of the vessel was chosen to reduce potential stress concentrations during various accident scenarios based on the results of finite-element analysis calculations performed by ARES Corporation.

For materials certificates see Certificates in web page www.iucf.indiana.edu/U/lh2target/export-files/.

Helium leak test:
Leak test of the chamber was performed at Excelco using a helium leak detector and no leaks were found.

Pressure test:
Pressure test of the chamber was performed at Excelco to 90 psid with no deformation of the vessel.

Fluorescent liquid inspection:
A fluorescent liquid penetrant test was performed by Excelco to look for gross welding faults/cracks. None were found.

Radiography:
The titanium vessel was radiographed by Excelco. No faults were found.

Heat Treatment:
Heat treatment on the target vessel after fabrication was performed by Accu-Temp Heat Treating, INC, 2400 Racine St. , Racine, WI 53403, (262)-634-1905, fax (262)-634-9102. The vessel was heated in an Argon atmosphere for 1 hour at 1292F and oxidized for 5 minutes at 1400F, then air cooled. This annealing procedure appears in table 3 of "TIMETAL 50A CP Ti" literature from TIMET corp. The oxidation procedure (5 minutes in air) appears in "Corrosion Resistance of Titanium," a technical manual of TIMET at http://www.timet.com/productsframe.html. Stacey Nyakana, a researcher at TIMET (708-566-4403) was consulted in the choice of this procedure. The object of this treatment was to ensure the development of an oxide layer on the inside surface of the chamber to suppress the possibility of hydrogen entering into the titanium.

Post-treatment tests:
Grade-2 Ti tensile-test samples were loaded to failure after they received the annealing and oxidation procedure designed to ensure the existence of a thick oxide layer on the inner Ti surface. The test results, both from the dry run and the run with the Ti vessel, confirmed that the oxide layer formed was tough and adherent and that the mechanical properties of the Ti were not altered from those of annealed grade-2 Ti.

Subsequent history:
Vessel was helium leak tested at IUCF and thermally shocked via repeated immersion in liquid nitrogen without detectable leak on the 10^{-9} atm cc/sec scale. Vessel was then pressure tested to a pressure of 90 psid successfully. As a double-check on the annealing-oxidation procedure, the annealing-oxidation procedure was performed at IUCF on seven Ti foil samples that ranged from 0.2 mil to 12.8 mil in thickness. The samples 1.5 mil and thicker remained ductile and had an adherent oxide layer. The oxide layers formed were 200-330 microgram/cm^2.

<u>Aluminum Target Vessel:</u>

The aluminum liquid hydrogen target vessel, fabricated by Ability Engineering, is a 6061-T6 aluminum cylindrical welded chamber with one inlet and one outlet port. The shape of the vessel was chosen to reduce potential stress concentrations during various accident scenarios based on the results of finite-element analysis calculations performed by ARES Corporation. The designs of the aluminum and titanium vessels are identical.

For materials certificates see Certificates in web page www.iucf.indiana.edu/U/lh2target/export-files/.

Helium leak test:
Leak tests of the chamber were performed at Ability using a helium leak detector and no leaks were found.

Pressure tests:

Pressure tests of the chamber were performed at Ability to a pressure of 90 psid with no deformation of the chamber.

Radiography:
The aluminum target vessel was radiographed by Calumet Testing Service under subcontract to Ability Engineering. No faults were found.

Subsequent history:
Vessel was helium leak tested and thermally shocked via repeated immersion in liquid nitrogen without detectable leak on the 10^{-9} atm cc/sec scale. The aluminum vessel has been used in a number of system cool down tests. The vessel has been pressurized up to 95 psia at room temperature and at cold down to 20K. No leaks or other failures have been observed.

8 H_2 GAS HANDLING SYSTEM

The target gas handling system for the shed operation is shown in figure 7, see also figures 5 – 11. The gas handling system for the ER2 operation is available in the web site www.iucf.indiana.edu/U/lh2target/export-files/ under “Design Criteria for the NPDGamma Liquid Hydrogen Target’s Hydrogen Gas Handling System at ER2”.

8.1 Specifications (M. Snow, M. Gericke, 7-1-01, B. Lozowski)

Table 11 lists the main components of the H_2 gas handling system and their relevant properties. The plumbing will be constructed of stainless steel components with VCR connections of welded tubing.

Table 11. Properties of major gas handling system components.

Components	Relevant properties			Function
	Inlet and outlet pressures	Material/type	Operating/ cleaning temperature	
Flow rate meter (FM101)	150 psia inlet and outlet	304 stainless steel	300 K	Measure H2 gas flow rate
Liquid N_2 cold trap	15 psia inlet 15 psia outlet	304 SS container	77 K/ 150 ºC	Trap water vapor and other contaminants at 77K.
Residual gas analyzer (RGA)	10^{-3} Torr inlet	Quadrupole RGA	300 K	Helium leak detection, monitoring the main vacuum
Turbo pumps TP201 and TP301	N/A		300 K	Evacuate target, main vacuum, and gas handling system
Mechanical pump MP101: Hydrogen explosion proof pump Motor is rated for Class I, Division I, Group D and Glass II Division I, Groups E, F and G				Pumping of target volume, GHS, and vacuum if hydrogen present

8.2 Design and Operation (M. Gericke, 7-1-01, modified by M. Snow, 8-15-03)

The gas handling system has two primary purposes: to transport the hydrogen from gas cylinders to the cryostat while conditioning the gas and regulating and metering the flow. The gas system also has a monitoring function: the residual gas analyzer (RGA) on the system monitors helium and other residual gases in the main vacuum system. Diagrams of the gas handling system are shown in figures 5 - 11. The pressure ratings of some of the components of the system are shown in Table 11. The set points of the relief and check valves are listed in section 6.3.5 and also indicated in figures 5-6.

The gas handling system connects the hydrogen bottles with the cryostat. The subsystem which conducts hydrogen gas into the target consists of three key components, which each play a part in conditioning the hydrogen or regulating or metering it as it flows into the cryostat. The major components and their functions are:

1) Pressure regulator PR105. This regulator sets the fill pressure and is fed with a line that possesses an about 20 SLPM restrictive orifice and is fed by lines with 20 micron filters to eliminate particulate contamination from the bottles.
2) Cold Trap. The cold trap consists of a cold trap held at liquid nitrogen temperature.

The cold trap catches any non-hydrogen impurities in the gas flow.

3) In addition to the hydrogen filling portion of the GHS, there are five other major components to the system as follows:

   a) The turbo pump system TP201/MP201 evacuates the main vacuum of the target. It can be isolated from the main vacuum with a remote controlled valve V204 which is interlocked.
   b) The turbo-pump system TP301/MP301 evacuates the hydrogen target vessel.
   c) The residual gas analyzer RGA is used to monitor the main vacuum system for helium and other residual gases through an interlocked remote controlled valve V207 and metering valve V307.
   d) The relief system consisting of relief valves in the GHS; RV101, RV102, and RV103.
   e) The non-hydrogen gas supply systems. A helium supply system provides helium gas to GHS through V140 and also through GHS to the relief chamber through valves V140, V115, V113, and V111. An argon supply system is used to fill the Argon reservoir that is used to spoil the main isolation vacuum if required by opening the remotely controlled valve V205.

Operating procedures for the gas handling system "Operating Procedures for the NPDGamma Liquid Hydrogen Target in TA-53, Building MPF-35" are available in the web site www.iucf.indiana.edu/U/lh2target/export-files/.

The gas handling system has four primary modes of operation: preparation and liquefaction of the hydrogen, steady-state monitoring, and warm up/fast boil off of the liquid hydrogen.

Preparation of the gas handling system for an operation:

1) The GHS/target system has to be carefully grounded with grounding straps and checked with an ohmmeter to ensure that there cannot be any electric charge building up on the system which could produce a spark.
2) The target vessel and main vacuum system must be pumped down to a pressure of 10^{-4} Torr or lower. See for details "The Operating Procedures for the NPDGamma Liquid Hydrogen Target in TA-53, Building MPF-35".
3) The target vessel, main vacuum system, and GHS must be properly leak checked with a helium leak detector and results written down to the Target Logbook. Any detectable leaks must be corrected and verified to be leak tight before operation.
4) The hydrogen lines must be pumped and purged several times with helium gas before introducing hydrogen into the system. See for details "The Operating Procedures for the NPDGamma Liquid Hydrogen Target in TA-53, Building MPF-35".
5) Helium gas must be introduced into the helium channels.
6) Check that the Argon reservoir is full and valve V505 open.
7) Check that the low oxygen monitor is functioning
8) Check that the two hydrogen monitors; one in tent and another one in shed, are functioning. Check that the hydrogen warning light outside shed is functioning

For a controlled vent of the hydrogen, the refrigerators are turned off and the valve V130 is opened. In cases where rapid boil off is required the main vacuum is filled with argon gas from the argon reservoir by opening V205. See for details "The Operating Procedures for the NPDGamma Liquid Hydrogen Target in TA-53, Building MPF-35".

8.3 Test Results

8.3.1 Thermal Cycling and Leak Testing of the GHS Components

Date: October, 2003
DUT: LH2 plumbing
Object: thermal cycling and leak check of LH2 plumbing

Components tested were:

1) A tube with a 90^o bend, a bellows, and a ¼-inch VCR side connection;
2) a short tube with a 90^o bend (to be used in the external plumbing between a side connection of the 2.75"- CF cross in the vent line and a rupture disk);
3) a welded, S-shaped tube;
4) a transition piece between 0.75"-CF flanged and 4.5"-CF flanged components n the H_2 vent line

Components 1-4 were first verified to be He leak tight at rate of $\leq 1x10^{-9}$ atm cc/s. All pieces were then cleaned by submersion (2.5 minutes) in a solution of 25 % HNO_3 + 2 % HF + 73 % water, by volume, followed a through rinse in hot tap water, a final rinse in de-ionized water, a wipe down to remove the passivating layer, and drying. Parts 1-3 were then joined with copper CF gaskets and continuously connected to the leak checker during two cycles between room temperature and equilibrium in LN_2. At each end of the temperature range, liberal spraying with He failed to find a leak anywhere. At the end of the tests, a final check determined that the sensitivity of the leak checker had remained in calibration.

Test Performed by:
Alan Eads, Bill Lozowski, IUCF

Approved by:
Bill Lozowski, IUCF

8.3.2 Leak Testing of the Gas Handling System

Date: September, 2004
DUT: GHS
Object: leak tests of GHS components

a) <u>H2 gas handling system</u>
Leak detector was connected to inlet (near V107 & V108) of GHS.

(i) First all valves of the GHS were closed. There was no leak in the connection line (flexible hose) between the leak detector and the H2 inlet port. Base level helium background was $0.3x10^{-9}$ atm cc/sec.

(ii) V108, V109 and V110 were opened. Leaks found at the joints around V113, P102, V111 and PT102 were found to be caused by untightened flanges and were fixed by tightening. The helium leak rate did not increase above $0.5x10^{-9}$ atm cc/sec.

(iii) V113 was opened. A leak was found near V116 was fixed and the background rate decreased to $0.3x10^{-9}$ atm cc/sec.

(iv) V122 was opened, no leak, background ~ $0.3x10^{-9}$ atm cc/sec.

(v) V125 was opened, no leak, background ~ $0.3x10^{-9}$ atm cc/sec.

(vi) V111 and V107 were opened, no leak, background ~ $0.3x10^{-9}$ atm cc/sec.

(vii) V117, V119A and V120 were opened, exposing the leak detector to the LN2 trap, pumped on overnight. No leak, background ~ $0.75x10^{-9}$ atm cc/sec.

Therefore, the whole GHS was leak tight with base level helium leak below $0.75x10^{-9}$ atm cc/sec.

b) <u>H2 supply manifold</u>

The hydrogen supply manifold (without H2 gas cylinders and pressure regulators) was leak tested independently. Leak detector was connected to V106.

i) The points at the H2 outlet and near V104 and V102 were blanked off, and all other valves were closed. V106 was opened. No leak, background ~$1.0x10^{-9}$ atm.cc/sec.

ii) V131 was opened. No leak, background ~ $1.0x10^{-9}$ atm.cc/sec.

iii) V130 was opened. No leak, background ~ $1.0x10^{-9}$ atm.cc/sec.

c) <u>Helium and Argon supply manifold</u>

Helium and Argon gas supply manifolds (without the pressure regulators and cylinders) were leak checked and found to be leak tight, background ~$5.0x10^{-8}$ atm.cc/sec. The base level leak rate was little higher <u>which</u> is understandable because some of the helium and argon lines are made of poly tubes.

Test Performed by:	Approved by:
Satyaranjan Santra, IUCF	Bill Lozowski, IUCF

Since these tests the GHS has gone through several modifications. See for instance Change Control Board Reports available in the web site www.iucf.indiana.edu/U/lh2target/export-files/. Several times the GHS has been leak checked, see LH2 Target Logbooks #1 and #2. A few occasions, leaking VCR connections have been found. Reason for the leak is that the connections has loosened. Otherwise the GHS has been leak tight under vacuum and pressure.

8.3.3 Verification of Operations of Solenoid Valves and Interlock Conditions

Date: February, 2004
DUT: solenoid valves
Object: verification of proper operation and interlock states

There are seven solenoid-operated valves (V100, V114, V129, V204, V205, and V207) in the GHS. These valves are operated by pressing their corresponding buttons on the SLC Panel-

View (as programmed through the SLC). Their operation was tested by running the SLC in test mode. All valves operate properly with 60 psid gas pressure except V114, which requires 110 psid. After the valve operations were tested successfully with SLC in test mode, the SLC was switched into interlock mode. It was verified that each of the above valves opens/closes only when all the interlock conditions are satisfied.

Test Performed by: Approved by:
Satyaranjan Santra, IUCF Bill Lozowski, IUCF

8.3.4 Verification of Operation of the Residual Gas Analyzer

Date: October, 2004
DUT: RGA
Object: verification of proper operation of RGA

The total pressure and partial pressure of helium read by the RGA was compared with the pressure readings shown by the vacuum gauges PT302 & PT303 and the leak detector and were in agreement. The operation of the ALARM voltage signal from the RGA was verified.

Test Performed by: Approved by:
Bill Lozowski, IUCF, Satyaranjan Santra, IUCF Bill Lozowski, IUCF

8.3.6 Testing of Chemical Compatibility of O-P Catalyst with Aluminum

Date: October, 2002
DUT: O-P catalyst
Object: verification of chemical compatibility of O/P catalyst with Al

The $Fe(OH)_3$ catalyst material was exposed to air, placed in an aluminum flange, and was left in room air for one day. No change in the surface appearance in a 10x microscope was visible. Then the Al flange and catalyst were heated in an air oven at 150C for one day. Again no change in the surface appearance in a 10x microscope was visible. This test in air should greatly exaggerate any possible chemical incompatibility due to oxidation. We conclude that in the operating temperature range of the O/P converter needed for catalyst regeneration there is no severe degradation of the aluminum surface.

Test Performed by: Approved by:
Vivek Jeevan, IUCF Bill Lozowski, IUCF

8.4 Ventilation of the GHS Enclosure

8.4.1 Ventilation of GHS in Shed

In shed the cryostat, GHS, and part of the relief and vent stack system are inside a tent that is ventilated to the outside of the shed through a 8” diameter ventilation channel.

8.4.2 Ventilation of GHS at ER2

The GHS at ER2 is located on the top of the FP12 neutron guide tunnel. The GHS is closed inside a metal enclosure that has 8” ventilation line to the outside of ER2.
Design Criteria for the GHS enclosure and for the ventilation line can be found at web site www.iucf.indiana.edu/U/lh2target/export-files/.

9 ORTHO/PARA CONVERTERS (M. Snow, 6-16-01, B. Lozowski)

There are two ortho-para converters (OPC) in the target system. One is in the precooler/OPC system which will be operated at about 30 K. The other is on the cold stage of the cryo-refrigerator at 17 K. We plan to use hydrous ferric $Fe(OH)_3$ converter with the mesh size of 30x50 in the both OPCs.

9.1 Specifications (M. Snow, 6-16-01, B. Lozowski)

The converting powder will be enclosed in OFHC copper chambers with fine mesh to prevent converter material from moving to other volumes. The converters will be heated for reactivation. Table 12 lists the important properties of the ortho-para converter.

Table 12. Ortho-para converter data.

Ortho-para converter	Geometric and thermodynamic data			Location and cooling
	Volume	Max rate of heat removal with 20 slm flow	Operating temperature and end o-p ratio	
Precooler heat exchanger	20 cc	21 W	30 K->97% para	Gas inlet of the cryostat. Cold helium gas.
LH2 fill/vent line	36 cc		17 K->99.95% para	On the cold head at 17 K. Cryo-refrigerator.

9.2 Design (M. Snow, 4-11-01, modified by WMS 2-2-03)

The ortho-para converter chamber which is operated on the 17 K cold head of the cryo-refrigerator. The body of the converter is made of copper to allow the converter material to be heated for regeneration if necessary and also to have a good thermal contact with the cryocooler head to remove the conversion heat. The $Fe(HO)_3$ is prevented from leaving the annular region with fine wire mesh on the inlet and outlet tubes.

9.3 Test Results

The flow impedance of the $Fe(OH)_3$ powder was measured at room temperature with helium gas. Details of the measurement are available in the LH2 Target Logbook #2 p. 22-25. The thickness of the convert was 14 mm. The flow impedance of Z=4x10^6 cm^{-3} was obtained. The two converters in the cryostat will have only a small flow restriction.

10 CRYOCOOLERS

10.1 Specifications (M. Snow, 5-26-01, modified 12-16-02 by WMS)

The cryorefrigerators will both be two stage closed-cycle refrigerators. One, made by CVI, is based on the Gifford McMahon cycle and possesses mechanical moving parts. The other, made by Cryomech and called a pulse-tube refrigerator, involves only the motion of helium gas. The operation of the CVI refrigerator is independent of their spatial orientation, whereas the Pulse-tube refrigerator orientation must be vertical. The CVI refrigerator contains moving parts which were specially made of sufficiently nonmagnetic materials (nonmagnetic stainless is sufficient) so that the magnetic field in the experiment can be made with sufficient uniformity. Table 13 lists the relevant properties of the two cooling stages.

Table 13. Properties of the two-stage cryo-refrigerators

Cooling stage	Thermodynamic data			Mechanical data
	Cooling power @	Temperature stability, no load	Operating range	Frequency
Stage 1	60 W at 77K	0.5 K	77 K->300 K	1.2 Hz
Stage 2	12 W at 20K	0.5 K	11 K->300 K	1.2 Hz

10.2 Cryostat Cooling Calculations (M. Snow, 4-10-01)

Basic properties of liquid hydrogen and its thermodynamics:

Density: 0.071 g/cm^3
Latent heat of vaporization of normal-LH_2: 444 J/g at 18K
Heat of ortho-para conversion: 709 J/g
Specific heat of normal-H_2 gas depends on temperature:
10.5 J/(g K) at 20 K,
10.6 J/(g K) at 70K, and
14.5 J/(g K) at 300 K

The LH_2 volume of the target is 21 liters. This gives a target mass of 1.5 kg and corresponds to a total gas volume of 18 cubic meters at STP. For this volume, 4300 kJ is required to cool the gas from 300 K to 80 K, 950 kJ is required to cool the gas from 80 K to 20 K, 665 kJ is required to liquefy the gas at 20 K, 40 kJ is required to cool the liquid from 20 K to 17 K, and 1070 kJ is required to convert the gas to parahydrogen. If we assume that all ortho-para conversion occurs in the 17 K OPC, then the 80K stage of the cryorefrigerator must remove 4835 kJ and the 17 K stage must remove 2190 J. Given the cooling power of one cryorefrigerator (60 watts at 80 K, 12 watts at 20K) and the radiative heat load on the 80 K and 17 K radiation shields (15 watts and 0.1 watts, respectively), then the liquification of the target takes 2 days, with the rate set by the cooling power of the 17 K cooling stage. This corresponds to a gas flow rate in the gas handling system of about 10 standard liters/minute.

The radiative heat loads on the radiation shields quoted above are calculated using the usual Stefan-Boltzmann law assuming a geometry of concentric cylinders, an emissivity of 0.02, and temperatures for the radiating surfaces of 300 K, 150 K, and 17 K. The second cryorefrigerator will easily be able to remove the 0.1 W heat load on the inner radiation shield.

The radiation shields and the thermal connection to the target chamber will be made of OFHC copper. Given the thermal conductivity of copper (20 W/(cm·K) at 20 K), one can estimate the required cross sectional area of the thermal connection to the target as follows. For the liquid target, assume that the refrigerator is operated at temperature two degrees lower (15 K) than the target temperature (17K). (This is safely above the solidification temperature of liquid hydrogen at a pressure of 1/3 bar of 14 K). Furthermore, assume that one requires a cooling power 5 times the expected radiative heat load on the target without the operation of the second refrigerator, or 0.5 W. In fact, with the operation of the second cryorefrigerator cooling the radiation shield to a temperature below 17 K, the dominant heat load on the target is due to the thermal conductance of the liquid hydrogen itself in contact with the warmer vapor in the exhaust line and the thermal conductance of the exhaust line tubing. Given the small conductivities involved [liquid H_2: 1.2 mW/(cm·K), gaseous H_2: 0.15 mW/(cm·K), stainless steel in the exhaust line: 10 mW/(cm·K)], the expected heat load from this source is on the order of tens of mW. Heat due the neutron beam capture and gamma loss in the target is at the few microwatt level. Then the required ratio of area to length for the thermal connection in this extreme case is

(area/length)=0.5W/([20W/cm*K]*2K)=0.0125 cm

For a length of 20 cm for the thermal connection between the refrigerator and target, this gives a cross sectional area of 0.25 cm^2. This cross sectional area can easily be supplied using copper braid.

10.3 Cooling Power

The website http://www.iucf.indiana.edu/U/lh2target/export-files includes a plot of the cooling power of the two stages of the CVI CGR511 refrigerator and the Cryomech refrigerator which will be used to liquefy and convert the hydrogen.

11 TARGET INSTRUMENTATION (M. Snow, 4-22-01)

The instrumentation required for the operation of the liquid hydrogen target can be divided into systems internal to and external to the main vacuum system. Inside the vacuum system, the instrumentation consists of thermometry in the target vacuum and pressure gauges in the GHS. See figure 5 for the locations of the diode temperature sensors. Outside the system, the instrumentation consists of gas sensors inside the cave to detect hydrogen.

Table 14. Instrumentation associated with target operation.

Instrument	Transducer requirements			Mechanical data
	Locations	Operating range	Accuracy	Reproducibility
Thermometers	LH_2 target, o-p converter, cryorefrigerator stages, radiation shields, target outlet. No thermometers inside LH_2 chamber	10-300 K on target, second stage of refrigerators, o-p converter, cold radiation shield. 70-300 K on warm radiation shield, first stage of refrigerators	0.2 K accuracy in 10-30 K range, 2 K accuracy in 70-300K range	0.1 K in 10-30 K range, 2 K in 70-300 K range
Pressure gauges	LH_2 target, main vacuum, He jacket. All located on GHS external to cave	2->10^{-7} bar on main vacuum and LH_2 target. 2->10^{-3} bar on He jacket	11 K->300 K	3% near atmospheric pressure
Heaters	LH_2 target, o-p converter, cryorefrigerator stage 2, target outlet at liquid-vapor phase boundary.	0 to 25 W		

11.1 **Design** (M. Snow, 4-22-01)

Table 15 gives information for the pressure gauges and transducers used in the target system.

Table15. Range and type of the pressure transducers.

Name of the trans.	***Type / Model***	***Output range (Volt)***	***Pressure range (Psia)***	***Pressure range (bar)***	***Input address in PLC***	***ADC input range (Volt)***
PT101	OMEGA PX203-030A5V	0.5 – 5.5	0-30	0-2.068	I:2.0	0-10
PT102	Millipore NTT205	0.05-5.05	0-500	0-34.48	I:2.1	0-10
PT103	OMEGA PX203-030A5V	0.5-5.5	0-30	0-2.068	I:2.2	0-10

Name of the trans.	Type / Model	Output range (Volt)	Pressure range (Psia)	Pressure range (bar)	Input address in PLC	ADC input range (Volt)
PT104	MKS 722A14TCE2FJ	0.0-10.0	0-193.4	0-13.335	I:2.3	0-10
PT105	OMEGA PX303-100A5V	0.5-5.5	0-100	0-6.895	I:2.4	0-10
PT106	OMEGA PX303-050A5V	0.5-5.5	0-50	0-3.448	I:2.5	0-10
PT201	OMEGA PX303-050A5V	0.5-5.5	0-50	0-3.448	I:2.6	0-10
PT202	MKS 122AA-10000BB	0.0-10.0	0-193.4	0-13.335	I:2.7	0-10
PT203	OMEGA PX303-050A5V	0.5-5.5	0-50	0-3.448	I:3.0	0-10
PT301	Balzers compact Pirani Gauge TPR250				I:3.1	0-10
PT302	Balzers compact full range gauge PKR250	0.0-10.0		$5x10^{-12}$ – 1.0	I:3.2	0-10
PT303	MKS sensavac Series 941	0.0-8.0 1V offset		$1.3x10^{-13}$ – $1.3x10^{-5}$	I:3.3	0-10

Table16. Voltage & flow range and type of the flow meters.

Name of flowmeter	Model Number	Output range (Volt)	Flow range (SLPM)	Input address in PLC	ADC input range (Volt)
FM101	822S-L-8-OV1-PV1-V1-HP	0.0-5.0	0-15	I:3.4	0-10
FM401	822S-L-8-OV1-PV1-V1-HP	0.0-5.0	0-15	I:3.5	0-10

11.2 Test Results

11.2.1 Test of Thermometers, Heaters, and Temperature Controllers

Date: October, 2004
DUT: thermometry, heaters, and temperature control
Object: test of the operation of the temperature control system

There are 10 temperature sensors (T1, T2, ……,T10) at different locations of the target and H2 fill/vent lines inside the cryostat to monitor the temperature distribution, see figure 5. In addition there are 3 heaters (H1, H3 and H4), out of which two (H1 & H3) are on the colder heads (stage II) of both the refrigerators and H4 is on the fill/vent line to supply heat to increase temperature if/when required. All the sensors and the heaters are connected through an instrumentation feedthrough to 4 commercial temperature controllers kept in the control panel. During a cooldown of the target all thermometers were tested and found to be working satisfactorily.

Operation of the temperature controllers was verified by varying the set point temperature externally and verifying that the heaters drove the temperature to the setpoint. The set temperature was maintained for as long as the temperature controller was in control mode.

Test Performed by: Approved by:
Satyaranjan Santra, IUCF Bill Lozowski, IUCF
During the cool down tests the temperature sensors and heaters have performed as designed. We have had a loose wire problem and a grounding problem which is typical for the new system. See for instance, the first neon test results in web site "1st Neon Test of the LH_2 Target".

11.2.2 Calibration of Pressure Gauges on the Gas Handling System

Date: April, 2004
DUT: pressure gauges
Object: calibration and test of the pressure gauges

The transducer type pressure gauges of the gas handling system (i.e., PT101, PT102, PT103, PT104, PT105, PT106, PT201, PT202, PT203) have been calibrated by measuring the voltages produced at atmospheric pressure at Los Alamos (777 mbar) and at high vacuum (~0 mbar). The remainder of the pressure gauges are cross-calibrated relative to these gauges by applying pressure in the GHS. Their readings are consistent with the values read by already calibrated pressure gauges.

Test Performed by: Approved by:
Satyaranjan Santra, IUCF Bill Lozowski, IUCF

12 HYDROGEN DETECTORS

12.1 Specifications

The FP12 cave will be equipped with a H_2 monitor and a low-oxygen monitor. The other H_2 monitor is inside the gas handling enclosure. The gave H_2 sensor will be interlocked to the power of the cave. The both sensors will be interlocked to the target.

12.2 Test Results

13 SYSTEM OPERATION AND SAFETY CONTROLS (M. Snow, 5-6-01)

13.1 Design

We propose to provide an Allen-Bradley Logic Controller (SLC) for operation of the target. The SLC performs the monitoring and communications with all of the transducers for the target. The control software provides an operator with a computer interface with real-time control and data acquisition in both text and graphical format. All parts of the system will be depicted with animation that can display graphically all signals, both in real-time mode and in a historical mode. An information page of the status of the system will be created for network communications to be sent both to the NPDG DAQ.

We furthermore will have a separate safety control system. This system would be concerned with the monitoring of only those transducer signals, which are associated with target safety. It would monitor safety-sensitive signals and operate devices. Signals are available for the facility use.

The SLC system implements 30-ft wire runs between the I/O of the SLCs and the components of the gas handling system (GHS) to maintain flexibility in location of the SLC. The Panel View display pages allow control of the 6 normally closed solenoid valves located in the GHS and display the following components:

a) H2 system (1xx),
b) Main Vacuum System (2xx),
c) RGA System (3xx), and
d) He System (4xx),
e) Temperature sensor values and graphic display of the sensor locations (10, to be supplied),
f) Pressure values indicated by the 9 Omega PTs (0.5-5.5V output signals),
g) Readout of the 2 mass-flow meters (FM401 and FM101),
h) Valve-control interlocks (activated by PT set points and other valve positions), and override controls.

The SLC interfaces with the temperature output signals of 8 silicon diodes (standard curve 10) activated and monitored by the Lakeshore 215 8-channel sensor monitor and the Scientific Instruments. It also interfaces with the Lakeshore DRC-91C Temperature Controller to: obtain the temperatures indicated by 2 silicon-diode sensors and adjust the control setpoint of the unit.

During power outages of less than 20 minutes, the control system must continue to monitor and display (View Panel) the target pressures and temperatures. Beyond 20 minutes, the SLC must shut down gracefully. This is ensured through the use of 4 UPSs.

13.2 Test results

14 CAVE HYDROGEN SAFETY

14.1 Electricity (H. Nann, 5-1-01)

The main goal of the safety design of the target system is to allow a use of ordinary experimental equipment in the cave without being strictly compliance with the National Electrical Code, NFPA-70. The helium channels around the cryostat joints and welds should bring us to achieve equivalent compliance. This argument was presented in the second review meeting of the safety committee. The robust design of the flask and vacuum jacket plus the addition of the helium jacket makes release of hydrogen into the cave extremely unlikely.

14.2 Ventilation (H. Nann, 6-10-01)

The FP12 cave is ventilated to ER2 by a 200 cfm fan. This ventilation is not a primary part of the hydrogen safety system since the hydrogen is considered to be adequately contained by the robust hydrogen flask, vacuum vessel, and helium jacket.

The exhaust port will be located near ceiling of cave in a location, which allows for the best neutron shielding. Ventilation rate: about 6,000 l/min (200 cfm) means that we change air in the cave every 10 min.

15 MATERIAL DATA SHEETS AND WELDING AND OTHER CERTIFICATES

Copies of the relevant material data sheets are available in the web site www.iucf.indiana.edu/U/lh2target/export-files/. All of the materials used for the target vessel and its piping construction are ASME Code approved materials for use with liquid hydrogen as specified in the NASA safety references [1,2]. The NASA safety standards are in accordance with the ASME Code [9,10].

Welding specifications and certificates are available in the web site.

The welds have been done by certified welders. Their certifications are in the web site.

16 RADIOLOGICAL SAFETY (H. Nann, 5-20-01)

The exposure of various items of the experiment to the neutron beam for a time of approximately one year will cause activation of certain components. Almost all of this activation will be prompt gammas from cold neutron capture. However, there are a couple of sources of tritium generation in the experiment. Here we make estimates of the amount of tritium generated in the hydrogen target due to (A) interactions with ^{3}He impurities in the ^{4}He jacket, (B) interactions with deuterium in the LH_2 target.

(A) $^3He(n,p)^3H$

(n,p) cross section at $E_n = 1$ keV: $\sigma(1\text{ keV}) = 27$ b

Assume $\sigma \propto 1/v$ dependence $\Rightarrow$ $\sigma(4\text{ meV}) = 1.35 \times 10^4\text{ b} = 1.35 \times 10^{-20}\text{ cm}^2$

Natural abundance of ^{3}He: 1.37×10^{-6}

At STP: 22.4 L of helium contain 6.02×10^{23} atoms

1 cm^3 at 1.2 atm contains 3.22×10^{19} atoms

1 cm^3 of natural He at 1.2 atm contain 4.41×10^{13} atoms of ^{3}He.

Assume a target thickness of 1 cm $\Rightarrow$ $d(3He) = 4.41 \times 10^{13}\text{ atoms/cm}^2$

Neutron flux: $\Phi = 1 \times 10^{10}$ neutrons/sec

Luminosity: $L = \Phi \cdot d = 4.41 \times 10^{23}\text{ s}^{-1}\text{ cm}^{-2}$

Tritium yield: $Y = L \cdot \sigma = 5954\text{ s}^{-1} = 1.88 \times 10^{11}$ per year

Activity: $A = \lambda \cdot N$

Half-life of tritium: $t_{1/2} = 12.33\text{ yr} = 3.89 \times 10^8\text{ s}$

$$\lambda = \frac{\ln 2}{t_{1/2}} = 1.78\times10^{-9}\ \text{s}^{-1}$$

$$A = (1.78 \times 10^{-9}\ \text{s}^{-1})(1.88 \times 10^{11}) = 335\ \text{s}^{-1}$$

(B) $^2H(n,\gamma)^3H$

(n,γ) cross section at 25 meV: $\sigma(25\ \text{meV}) = 5.2$ mb

Assume $\sigma \propto 1/v$ dependence $\Rightarrow$ $\sigma(4\ \text{meV}) = 13\ \text{mb} = 1.3 \times 10^{-26}\ \text{cm}^2$

Natural abundance of ^2H: 1.48×10^{-4}

20 L of LH_2 density of LH_2: $\rho = 66\ \text{kg/m}^3$

mass of LH_2: $m = \rho V = (66\ \text{kg/m}^3)(20 \times 10^{-3}\ \text{m}^3) = 1.320\ \text{kg} = 1320\ \text{g}$

molecular mass of H_2: $M = 2.016$ g/mol

number of moles: $n = m/M = (1320\ \text{g})/(2.016\ \text{g/mol}) = 655$ mol

number of atoms: $N = n N_A = (655\ \text{mol})(6.02 \times 10^{23}\ \text{mol}^{-1}) = 3.94 \times 10^{26}$

20 L of LH_2 contain 5.83×10^{22} deuterium nuclei. They are distributed over a circular area of 30 cm diameter.

$d(^2H) = 8.25 \times 10^{19}$ nuclei/cm^2

Neutron flux: $\Phi = 1 \times 10^{10}$ neutrons/sec

Luminosity: $L = \Phi \cdot d = 8.25 \times 10^{29}\ \text{s}^{-1}\ \text{cm}^{-2}$

Tritium yield: $Y = L \cdot \sigma = 1.07 \times 10^4\ \text{s}^{-1} = 2.78 \times 10^{10}$ per month

Activity: $A = \lambda \cdot N$

$A = (1.78 \times 10^{-9}\ \text{s}^{-1})(2.78 \times 10^{10}) = 50\ \text{s}^{-1}$.

17 WARNINGS, ALARMS, AND INTERLOCKS (J. Novak, H. Nann, 6-22-01)

We have a three-tiered hierarchy of status indicators for the system as follows:

Normal: The system operating as designed with all interlocks and sensors active and within set ranges.
Warning: Some sensor(s) are at values between low and high trip points. Local indication (horn, lights, signs) and possibly phone dialer initiated. Target operator attention is required but automatic shutdown action is not needed. Necessary personnel may be near the equipment with caution; others should stay away.
Alarm: Some sensor(s) have exceeded their high trip levels. Automatic safety and/or shutdown systems take over. Local indications (horn and light). All personnel should leave the area. Neutron beam in experiment flight path shut off. CCR automatically notified. Phone dialer initiated.

Table 17. Warning, alarm, and interlocks in shed and at ER2.

Sensor	Location	Trip point	Action
H_2 concentration #1	Shed or FP12 cave, in stagnant air near ceiling	10% of LEL	Warning

Sensor	Location	Trip point	Action
H_2 concentration #2	GHS tent or enclosure		
H_2 concentration #1 H_2 concentration #2	Shed or FP12 cave, in stagnant air near ceiling GHS tent or enclosure	25% of LEL	Alarm. H_2 system shutdown and rapid H_2 dump. Electrical power in cave shut off.
Vacuum pressure sensor	Vacuum vessel	Bad, higher than set point	Warning
RGA	Vacuum vessel	He peak > Low set point	Warning
RGA	Vacuum vessel	He peak > High set point	Alarm. H_2 System shutdown and rapid H_2 dump.
RGA	Vacuum vessel	N_2 peak > Low set point	Warning
RGA	Vacuum vessel	H_2O peak > Low set point	Warning
He source pressure for channels	Helium channels	p < 3 psig	Warning
He flow out from channels	Helium channels	Flow < set point	Warning
H_2 pressure	Target H_2 gas in exhaust line	p > 16 psig, p < 9 psig	Warning
O_2 concentration	Shed or at FP12 cave, at normal breathing space elevation	Low	Warning

18 RISK MANAGEMENT

Hazard Analysis (J. Novak, 11-10-01, updated by M. Snow, 8-15-03)
Details of the NPDGamma LH2 target failure analysis is available in the web site www.iucf.indiana.edu/U/lh2target/export-files/.

Note that,
The Failure Analysis describes the hazards to Experimenters at LANSCE from failures of experimental components. The hazards to personnel (workers in adjacent experiments and other people inside ER2) will be substantially less than hazards to Experimenters. There is no hazard to the general public outside the TA-53 boundary.

Definition of likelihood levels:

I Frequent/Expected Likely to occur often during the life of the experiment. "Happened to you many times." Expected once in 1-10 tries -or- >10^0 /yr.

II Probable/Likely Likely to occur several times during the life of the experiment. "Happened to you once." Expected once in 10-100 tries -or- <10^0 /yr. to >10^{-2} /yr.

III Occasional/Unlikely Should not occur during the life of the experiment. "Was a near-miss to you." Expected once in 10^2-10^4 tries -or- <10^{-2} /yr. to >10^{-4} /yr.

IV Improbable/Extremely unlikely Unlikely but possible to occur during the life of the experiment. "Happened once to someone you know." Expected once in 10^4-10^6 tries -or- <10-4 /yr. to >10^{-6} /yr.

V Remote/Beyond extremely unlikely Should not occur during the life of the experiment. "Happened once, long ago, at another facility." Expected once in 10^6-10^8 tries -or- <10^{-6} /yr.

Consequence severity levels:

A Catastrophic
Health: Immediate health effects. Death, coma, loss of limb, loss of sight – "H-A"
Experiment: Experiment cancelled. – "E-A"

B Critical
Health: Long-term health effects, disability, or severe injury -- non-life threatening. Broken bones, bad cuts, 3rd degree burns, unconsciousness, out of work 1 week to 1 month. – "H-B"
Experiment: Experiment loses 1 run cycle. – "E-B"

C Moderate
Health: Lost-time injury, work restrictions but no disability. 2nd degree burns, out of work 1 day to 1 week, work restrictions up to 1 week. – "H-C"
Experiment: Experiment loses 1 week. – "E-C"

D Minor
Health: Lost-time injury but no disability or work restrictions. – "H-D"
Experiment: Experiment loses 1 day. – "E-D"

E No measurable consequences – "H-E, E-E"

Risk Matrix -- Experimenter (EW) and Experiment (E)
An Experimenter is a person inside the general NPDGamma experiment area.

	I	II	III	IV	V
A	1	1	2	2	3
B	1	1	2	3	4
C	1	2	3	4	4
D	2	3	4	4	4
E	4	4	4	4	4

19 DRAWINGS

The drawings for the LH_2 target system and related components are available in the web site.

20 HYDROGEN SAFETY COMMITTEE REPORTS

The reports of the two Hydrogen safety Reviews are available in the web site. As also the report of the vent stack review.

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