NPDGamma Liquid Hydrogen Target Engineering Document

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## NPDGamma Liquid Hydrogen Target Engineering Document Update/Revision Log

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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.

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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.

Figure 5 shows an original line diagram for the overall LH2 target and figure 11 gives the legend. Figure 12 shows a floor plans on the flight path 12 cave top where the gas handling system, compressors of the refrigerators, and instrumentation racks are located.

1.1 Plans for Target System Testing

The target system will be first tested in building, MPF-35 (shed) outside the ER2. For these tests the relief and vent systems will be different compared to the relief system shown in figure 5. 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 the bldg MPF-35 (shed). A plan is first to do full testing of the system in shed including tests with hydrogen. After passing the shed 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. Shown are cryostat and relief system.
Fig. 6. The LH$_2$ target vacuum system.
Fig. 7. The LH\textsubscript{2} target hydrogen gas handling system.
Fig. 8. The LH$_2$ target hydrogen supply manifold.
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 - 11.
Fig. 12. A floor plan of the cave roof for the gas handling system (GHS), refrigerator compressors, and SLC system on top of the FP12 experimental cave. The neutron source is on right. The vent line will go from (GHS) along the beam line to right, climb up along ER2/ER1 wall, and then penetrate the ER2 wall so that it can be terminated safely outside ER2.

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 x 10 cm size of the beam 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 30 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 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 17 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 found 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 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.

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. 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. The gas supply pressure is regulated to about 200 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 experimental cave. At pressure of 200 psig the hydrogen gas will pass in GHS through a gas purifier, PRFR (a Pd membrane) to reduce the concentration of gases other than hydrogen to ppb levels (PRFR). Then the gas go through a liquid nitrogen trap (TRAP) to remove water and other contaminants, and an ortho-para conversion chamber (OPC) based on ferric oxide powder and operated at 77K for partial
conversion of the gas before entering the refrigerator. All of the modules associated with cleaning and converting the gas can be isolated with manual valves for necessary activation (which typically involving some combination of baking and a pump/purge cycle) and cleaning. The gas flow rate, liquefying rate, which is determined by the cooling power of the refrigerators and the properties of hydrogen (see below), will be 10 standard cm$^3$/minute regulated by V130.

In addition to the hydrogen line, the gas handling system will also possess another line connected to the target system; 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 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 valve RV104 and the rupture disks RD101, RD201, RD202. A residual gas analyzer (RGA) on the gas handling system 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 gas composition for helium and other gases during operation. Pressure gauges on the gas handling system will monitor pressures in the target and in the main vacuum chamber. An electrical feed-through 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. Two turbo pumps on the gas handling system will be used to evacuate the target chambers. The pumps will be isolated from the target vacuum with an automatic valve 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 manifold will be introduced into the main vacuum chamber of the cryostat when fast warm up of the target is required for emergency response (fire etc.). Plumbing lines entering the target possess section of flexible line for connection to the target fill-vent stack which extends through the top of the experimental cave. At ER2 GHS will be closed inside a metal enclosure with its own ventilation line to outside ER2. In shed GHS, target cryostat, and part of the relief system are covered by a tent ventilated to outside shed.

The pre-converted hydrogen gas enters the cryostat in the experimental cave in ER2 through a reentrant hole in the cave roof shielding. It passes 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 liquefy the hydrogen and perform the ortho-para conversion for the given flow rate as calculated below. 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 concave 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 narrow 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 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 and outlet lines of the target are bent to avoid excessive radiative heat loads from a line-of-sight view of a room temperature surface.

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. Given the cooling powers stated above and the known thermodynamic properties of hydrogen, we estimate a filling time for the target of about 2 days. Because of the physics reasons the Al target vessel will be used in the NPDGamma experiment.

The exhaust line from the liquid hydrogen vessel possesses a large inner diameter (1.5”). This exhaust line passes through a flange on the main vacuum chamber and through the cave ceiling to the outside of the cave, where it is connected to a relief system that is part of a main relief pipe that vents hydrogen to a safe location outside the ER2 building. The diameter of this pipe has been determined by a series of calculations outlined below to insure that there is no release of hydrogen 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” diameter) which ensures that there is no release of hydrogen 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 with a section of stainless steel tubing. This section of the exhaust line contains a heater, which is used to locally heat the liquid, wrapped around the tubing. Due to the low thermal conductivity of the liquid para-hydrogen (1.2x10$^{-3}$ W/cm K at 19 K) and the SST tubing (2x10$^{-2}$ 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 during 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 automatic 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 convenient 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 21 liters) coupled with its location in a confined space, the experimental cave, during the experiment (the cave is 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 much 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. Details of the calculations are included.

Hydrogen-air mixtures in concentrations ranging from 4% to 75% of H₂ 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 (LH₂) 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.
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 report is available in the web page www.iucf.indiana.edu/U/lh2target/export-files/).

(a) A loss of either refrigeration or vacuum 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 line that exhausts safely outside the ER2 building. This vent 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 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 is valved off from the vacuum vessel.

(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 very quickly. This will be done by filling the vacuum vessel with argon thus letting the LH$_2$ boil off at a controlled rate. This scenario is similar to the one described under (1) 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 47 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 43 psia for an inner diameter of the pressure relief piping is 2.5 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 boiloff 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.

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 and nitrogen with a 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 Experiment Construction project has nine work packages, the Hydrogen Target is one of them. 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.


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 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 LH2 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 Pentilla 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-23 Group Safety Officer) will review the 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 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. 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 LH₂ 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.

<table>
<thead>
<tr>
<th>Object</th>
<th>Mechanical Properties</th>
<th>Connections</th>
</tr>
</thead>
<tbody>
<tr>
<td>LH₂ target vessel</td>
<td>Dimensions: 30 cm diameter, 30 cm length, wall thicknesses: cylindrical shell 0.25 cm, entrance window 0.32 cm, exit window 0.38 cm</td>
<td>Cylindrical Al or Ti body welded from cold-rolled sheet. Rear dome machined from monolithic material. Bi-metalic friction welded Al-SST joints between LH₂ target vessel and piping. Fill/vent line 1.5” dia.</td>
</tr>
<tr>
<td>80K radiation shield</td>
<td>Dimensions: 36 cm diameter, 80 cm length, 0.1 cm thickness</td>
<td>Soldered from cold-rolled and annealed sheet. 22 cm diameter mechanical connection to refrigerator #1 and 8 cm diameter connection to refrigerator #2.</td>
</tr>
<tr>
<td>Main vacuum chamber</td>
<td>Dimensions: 40 cm diameter, 98 cm length, 0.30 cm thickness</td>
<td>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. 2.5 cm diameter flange to external pump and GHS.</td>
</tr>
<tr>
<td>Helium channels</td>
<td>Internal channels machined into Al body of the main vacuum system and appropriate weld joint areas before welding</td>
<td>Pipe-threaded external access holes connected to all internal channels, filled with small connectors and fed by small ID tubing for helium gas connection.</td>
</tr>
</tbody>
</table>
Fig. 13. 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. 14. 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. 15. 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.
4.2 Strength Calculations for the Vessels (H. Nann, 08-10-01)

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 LH₂ 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)
- \( \mu \) = Poisson’s ratio
- \( E \) = weld joint efficiency factor

(a) Cylindrical shell under internal pressure.

\[
t = \frac{pD}{2(SE - 0.6p)}
\]  \hspace{1cm} (1)

(b) Elliptical head under pressure on concave side

\[
t = \frac{pDK}{2(SE - 0.1p)} = \frac{pD_0K}{2(SE + pK - 0.1p)},
\]  \hspace{1cm} (2)

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

\[
t = \left[ \frac{2p_c\left[3(1-\mu^2)\right]^{1/2}}{YE} \right]^{1/2} R_o^*,
\]  \hspace{1cm} (3)
with $R_0^* = K_1 D_0$.

$K_1$ is given in table UG–33.1 of the ASME Code as a function of $\frac{D_0}{2h_0}$.

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

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

The ASME Code specifies that the critical pressure $p_c$ is four times the maximum allowable external working pressure.

4.2.2 Values for Material Parameters

The following material constants at room temperature, taken from AMS Handbook, Vol. 2 (Ref. 5), are used. The materials have (about $30\% - 40\%$) higher allowable stresses at low temperature.

(a) Aluminum 6061-T66061-T6 (ASME Code approved!)

Ultimate tensile strength: $S_u = 42000$ psi

$\Rightarrow$ allowable stress $S = \frac{1}{4} S_u = 10500$ 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 approved)

Ultimate tensile strength: $S_u = 50000$ psi

$\Rightarrow$ allowable stress $S = \frac{1}{4} S_u = 12500$ psi (see ASME Code)

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

Poisson’s ratio: $\mu = 0.34$

(c) Magnesium AZ31B-H24 or AZ31C-H24 alloy, Hard rolled sheet (not ASME Code approved)

Ultimate tensile strength: $S_u = 38000$ psi
allowable stress $S = \frac{1}{4} S_u = 9500$ psi (see ASME Code)

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

Poisson’s ratio: $\mu = 0.35$

### 4.2.3 LH₂ Target Vessel (cylinder with elliptical heads)

First we calculate the minimum wall thickness for an internal design pressure of $p = 75$ psia. $E = 1.0$ (butt joints with complete penetration, fully radiographed)

1. **Cylindrical shell:**

   Material: 6061-T66061-T6 Aluminum

   $R = 6.0$ inch, $D = 12.0$ inch, $L = 12.0$ inch

   $$t = \frac{(75)(12.0)}{2(10500)(1.0) - (0.6)(75)} = 0.043 \text{ inch}$$

2. **Entrance window, elliptical head, machined from one piece, pressure on concave side:**

   Material: Magnesium alloy AZ31B-H24

   $D = 10.5$ inch
   $h = 2.3$ inch
   $$\frac{D}{2h} = 2.3 \quad \Rightarrow \quad K = 1.21$$

   $$t = \frac{(75)(9.5)(1.21)}{2(9500)(1.0) - 0.1(75)} = 0.045 \text{ inch}$$

3. **Exit window, elliptical head, pressure on convex side:**

   Material: 6061-T66061-T6 Aluminum

   $D_o = 8.75$ inch
   $h_o = 1.90$ inch
   $$\frac{D_o}{2h_o} = 2.3 \quad \Rightarrow \quad K_1 = 1.03 \quad \Rightarrow \quad R_o \star = 9.01 \text{ inch}$$

   assume $p_c = 4\times45$ psi = 180 psi
\[ t = \left[ \frac{(2)(180)\left\{1 - (0.35)^2\right\}}{1.0 \times 10^7} \right]^{0.5} (9.01) = 0.069 \text{ inch} \]

Conclusions:

To provide a safety factor, we will use \( t = 0.1 \) inch for the thickness of the cylindrical part, \( t = 0.125 \) inch for the entrance window, and \( t = 0.15 \) inch for the exit window. These thicknesses can then be used in the above formulae. Assuming a welding efficiency of 0.9 (except for the entrance window, which contains no welds), we obtain for the maximum allowable internal working pressures:

<table>
<thead>
<tr>
<th></th>
<th>Cylindrical shell: ( p_{int} )</th>
<th>Entrance window: ( p_{int} )</th>
<th>Exit window: ( p_{int} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>( p_{int} = 159 \text{ psia} )</td>
<td>( p_{int} = 168 \text{ psia} )</td>
<td>( p_{int} = \frac{1}{4} p_c = 190 \text{ psia} )</td>
</tr>
</tbody>
</table>

and for the maximum allowable external working pressures:

<table>
<thead>
<tr>
<th></th>
<th>Cylindrical shell: ( p_{ext} )</th>
<th>Entrance window: ( p_{ext} )</th>
<th>Exit window: ( p_{ext} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>( p_{ext} = \frac{1}{4} p_c = 44 \text{ psia} )</td>
<td>( p_{ext} = \frac{1}{4} p_c = 67 \text{ psia} )</td>
<td>( p_{ext} = 267 \text{ psia} )</td>
</tr>
</tbody>
</table>

4.2.4 Cylindrical Part of the Main Vacuum Chamber (cylinder with elliptical heads)

First, we calculate the minimum wall thickness for an internal design pressure of \( p = 75 \text{ psia} \) 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. \( E = 1.0 \) (butt joints with complete penetration, fully radiographed)

(1) Cylindrical shell:

Material: 6061-T6 Aluminum

\[ R = 8.0 \text{ inch}, \quad D = 16.0 \text{ inch}, \quad L = 37.0 \text{ inch} \]

\[ t = \frac{(75)(16.0)}{2[10500)(1.0) - 0.6(75)]} = 0.057 \text{ inch} \]

(2) Entrance window, elliptical head, pressure on convex side:

Material: Titanium Grade 2, Annealed

\( D_o = 13.5 \text{ inch} \)
\[ h_o = 2.9 \text{ inch} \]
\[
\frac{D_o}{2h_o} = 2.3 \quad \Rightarrow \quad K_1 = 1.03 \quad \Rightarrow \quad R_o^* = 13.9 \text{ inch}
\]
assume that \( p_c = 4 \times 45 \text{ psi} = 180 \text{ psi} \), then
\[
t = \left[ \frac{(2)(180)\left[3\left(1-0.34^2\right)\right]^{0.5}}{1.45 \times 10^7} \right]^{0.5} \left(13.9\right) = 0.088 \text{ inch}
\]

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

Material: 6061-T6 Aluminum
\[ D = 8.75 \text{ inch} \]
\[ h = 1.90 \text{ inch} \]
\[
\frac{D}{2h} = 2.3 \quad \Rightarrow \quad K = 1.21
\]
\[
t = \frac{(75)(16.0)(1.21)}{2\left[(10500)(1.0)-(0.1)(75)\right]} = 0.069 \text{ inch}
\]

To provide a safety factor, we use a wall thickness \( t = 0.12 \text{ inch} \) for the cylindrical shell and the elliptical heads.

Next we calculate whether the target vessel can withstand an external pressure of 18 psia .
\[
\Rightarrow \quad p_c = 4 \times 18 \text{ psia} = 72 \text{ psia}
\]

(1) Cylindrical shell under external pressure

Assume no stiffening ring except the two flanges at the ends, which act as stiffening rings.
\[ L = 37 \text{ inch}, \quad D_o = 16.0 \text{ inch}, \quad t = 0.12 \text{ inch} \]
\[
\frac{L}{D_o} = 2.31 \quad \frac{t}{D_o} = 0.0075
\]
The RHS of eq. (4) is
\[
RHS = \left[ \frac{(72)(1-0.33^2)^{0.75}\left\{2.31-0.45(0.0075)^{0.5}\right\}}{2.42\left[1.0 \times 10^7\right]\left(1.0\right)} \right]^{0.4} (16.0) = 0.13 \text{ inch}
\]
This value is larger than the assumed thickness of 0.12 inch. Thus a stiffening ring at the middle of the cylinder is required.
Now \( L \) becomes the distance between the stiffening rings. \( \Rightarrow \quad L = 18.5 \text{ inch} \)
\[ \frac{L}{D_0} = 1.156 \]

The RHS of eq. (4) is now

\[ \text{RHS} = \left( \frac{72(1-0.33^2)^{0.75}\left[ 1.156 - 0.45(0.0075)^{0.5} \right]}{2.42(1.0 \times 10^{-7})(1.0)} \right)_{(16.0)} = 0.10 \text{ inch} \]

This value is smaller than the assumed thickness. Thus a cylindrical vacuum vessel with a wall thickness of 0.12 inch and stiffening rings at the middle and two ends will be sufficient to keep it from collapsing due to pressure of 18 psi on the outside.

(2) Entrance head, pressure on concave side:

\[ \frac{D}{2h} = 2.3 \quad \Rightarrow \quad K = 1.21 \]

\[ t = \frac{(18)(16)(1.21)}{2(12500)(1.0) - 2(18)(1.21 - 1)} = 0.014 \text{ inch} \]

This value is smaller than the design thickness of 0.12 inch.

(3) Exit head, pressure on convex side:

\[ \frac{D_0}{2h_0} = 2.3 \quad K_1 = 1.03 \quad R_0^s = 16.5 \text{ inch} \]

\[ t = \left[ \frac{2(72)(3(1-0.33^2))^{0.5}}{1.0 \times 10^{-7}} \right]_{(15.5)} = 0.080 \text{ inch} \]

This value is smaller than the design thickness of 0.12 inch.

Conclusion:

The vacuum chamber can withstand an external pressure of 18 psig without collapsing.

Using a wall thickness of \( t = 0.25 \text{ inch} \) for the cylindrical shell and \( t = 0.12 \text{ inch} \) for the entrance and exit windows, we obtain for the maximum allowable internal working pressures:

(1) Cylindrical shell: \( p_{int} = 292 \text{ psia} \)
(2) Entrance window: \( p_{int} = \frac{1}{4} p_c = 83 \text{ psia} \)
(3) Exit window: \( p_{int} = 155 \text{ psia} \)

and for the maximum allowable external working pressures:
(1) Cylindrical shell: $p_{ext} = \frac{1}{4} p_c = 289$ psia
(2) Entrance window: $p_{ext} = 163$ psia
(3) Exit window: $p_{ext} = \frac{1}{4} p_c = 40$ psia

4.2.5 Rectangular Part of the Main Isolation Vacuum Chamber (H. Nann, 09-06-02)

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

$$ t = d \sqrt{\frac{Z C p}{SE} + \frac{6 W h_G}{SE L d^2}} $$

with

- $C = \text{factor depending upon method off attachment of head: } C = 0.3$
- $p = \text{internal design pressure: } p = 75$ psi
- $S = \text{maximum allowable stress: } S = 12000$ (for aluminum)
- $E = \text{joint efficiency: } E = 1.0$
- $W = \text{total bold load: } W = 9000$ lb
- $h_G = \text{gasket moment arm: } h_G = 1.66$ inch
- $L = \text{perimeter of bolted head measured along the centers of bolt holes: } L = 115.5$ inch
- $d = \text{short span of rectangular head: } d = 19.25$ inch
- $D = \text{long span of rectangular head: } D = 38.50$ inch

$$ Z = 3.4 - \frac{2.4d}{D} = 3.4 - \frac{(2.4)(19.25)}{38.50} = 2.20 $$

$$ t = (19.25) \sqrt{\frac{(2.20)(0.3)(75)}{(12000)(1.0)} + \frac{(6)(9000)(1.66)}{(12000)(1.0)(115.5)(19.25)^2}} = 1.26 \text{ inch} $$

Conclusion:

To provide a safety factor, we will use $t = 2.0$ inch for the thickness. Using a wall thickness of $t = 2.0$ inch ($t = 1.5$ inch), we obtain for the maximum allowable working pressure: $p_{MAWP} = 193$ psi ($p_{MAWP} = 107$ psi).

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/](http://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 LH2 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 LH2 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 7, 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](http://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: Sept. 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](http://www.iucf.indiana.edu/U/lh2target/export-files/Vendor Tests under excelco_test_results.pdf).

Inspector: Michael J. Bent, Excelco, Eric Niedbalski, Excelco
Quality Assurance manager: Eric Niedbalski, Excelco
Approved by: 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](http://www.iucf.indiana.edu/U/lh2target/export-files/Vendor Tests under excelco_test_results.pdf).

Inspector: Robert A. Balow, AccuTemp Heat, Eric Niedbalski, Excelco
Quality Assurance manager: 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 LH2 vessel was connected to a helium leak detector with a sensitivity of $1.2 \times 10^{-10}$ atm cc/sec. The background level on the leak detector was $1.0 \times 10^{-9}$ 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: David Barber, Ability  
Approved by: 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 LH2 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: David Barber, Ability  
Approved by: 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 $1.5 \times 10^{-9}$ 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 $3.0 \times 10^{-9}$ atm cc/sec. This background did not increase with time while the leak detector was connected to the Al chamber.

Test was performed by: Satyaranjan Santra, IUCF

Approved by: 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](http://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:** Sturat Gillespie, Calumet  
**Interpreter:** Stuart Gillespie, Calumet  
**Approved by:** Mike Morgan, Ability, Bill Lozowski, IUCF

### 5.3 Tests of the Vacuum Chamber and Components

#### 5.3.1 Pressure Testing of the Vacuum Chamber

**Date:** Feb. 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](http://www.iucf.indiana.edu/U/lh2target/export-files/Vendor Tests under aft_reports_mam_vac_vessel.pdf).

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

#### 5.3.2 Leak Testing of the Vacuum Chamber
Date: Feb. 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 $1.0 \times 10^{-10}$ atm cc/sec. The leak detector background at the start of the test was $8.0 \times 10^{-9}$ 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 $4.0 \times 10^{-9}$ 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_vae_vessel.pdf.

Test was performed by: Bob Peterson, Ability  
Approved by: 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: M. Barrajas, Calumet Testing  
Interpreter: Stuart Gillespie, Calumet  
Approved by: Mike Morgan, Ability, Bill Lozowski, IUCF

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

Date: Feb. 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 $1.0 \times 10^{-10}$ atm cc/sec. The leak detector background at the start of the test was $6.0 \times 10^{-9}$ 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 $5.0 \times 10^{-10}$ atm cc/sec. No evidence for a leak above this level. The certificate describing this test can be found at the website
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 < 5.0x10^-9 atm cc/sec.

Test Performed by:  
Bob Peterson, Ability  
Satyaranjan Santra, IUCF

Approved by:  
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:  
Bob Peterson, Ability

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

5.3.8 Leak Testing of the Aluminum Vacuum Chamber Windows

Date: Feb. 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: Bob Peterson, Ability
Approved by: Mike Morgan, Ability, Bill Lozowski, IUCF

5.3.9 Leak Testing of the Mg Vacuum Chamber Windows

Date: Feb. 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: Bob Peterson, Ability
Approved by: Mike Morgan, Ability, Bill Lozowski, IUCF
5.4 Design and Operating Pressures and Maximum Allowable Working Pressures
(H. Nann, 8-22-01)

Table 2 defines design, operating, maximum allowable working pressures, maximum internal pressures, and proposed settings for rupture disks and pressure relief valves for the LH₂ vessel and the main vacuum chamber. The components are tested to 90 psid. Official atmospheric pressure at LANL is 11.2 psia.

Table 2. Pressures associated with LH₂ vessel and vacuum chamber and pressure setpoints.

<table>
<thead>
<tr>
<th>Vessel</th>
<th>Normal operating pressure</th>
<th>Calculated maximum pressures (from ASME CODE)</th>
<th>Internal Maximum Allowable Working Pressure (from ASME CODE)</th>
<th>Pressure relief valve set points</th>
<th>Rupture disk set points</th>
</tr>
</thead>
<tbody>
<tr>
<td>LH₂ target vessel</td>
<td>15 psia</td>
<td>Internal: 159 psia</td>
<td>60 psid</td>
<td>15 psid</td>
<td>60 psid</td>
</tr>
<tr>
<td>Main vacuum chamber</td>
<td>vacuum</td>
<td>Internal: 83 psia</td>
<td>60 psid</td>
<td></td>
<td>30 and 35 psid</td>
</tr>
</tbody>
</table>

Summary of pressures and relief pressure set points for the LH₂ vessels and vacuum chamber:

1. LH₂ target vessel:
   Material: 6061-T6 aluminum; wall thickness of cylindrical shell 0.10 inch, wall thickness of entrance window 0.12 inch, and wall thickness of exit window 0.15 inch.
   (a) Design pressure (calculated according to CODE formulae): internal: 159 psia (10.8 atm) - external: 44 psia (3.0 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 ID piping from the LH₂ 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: 15 psid
   (g) Rupture disk set point: 60 psid.

2. Main isolation vacuum chamber (cylinder with elliptical heads):
   Material: 6061-T6 aluminum except for grade-2 titanium entrance window; wall
thicknesses: entrance and exit windows 0.12 inch; cylindrical body 0.25 inch; rectangular box 2.0 inch.
(a) Design pressure (calculated according to CODE formulae): internal 83 psia (5.6 atm) - external: 40 psia (2.7 atm)
(b) Normal operating pressure: vacuum
(c) Maximum allowable working pressure (internal): 70 psig (4.8 atm)
(d) Relief paths: single 2.5-inch id piping from the cryostat to the relief system that contains of a relief valve and two parallel rupture disks.
(e) Relief valve flow capacity: 0.50 lb/s at pressure relief valve set point
(f) Pressure relief valve set point: 20 psid
(g) Set points of the two rupture disks: 30 psid and 35 psid.

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

There are two stainless steel Conflat (CF) 2-3/4” flanged seals with copper gaskets inside the cryostat at low temperatures and one ¼” VCR joint, see drawings SNEUT-Y-111-007, SNEUT-Y-111-008, and SNEUT-Y-212-016 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 DESIGN AND DIMENSIONAL CALCULATIONS FOR RELIEF SYSTEMS AND VENT LINES (H. Nann, 8-22-01)
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 remains subsonic at all times and that the maximum pressure in each component remains well below its bursting point. Based on the formulae and algorithms in these 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 used in the model. The information that was used as input to the calculations as well as results are given in tables 4 and 5. The calculation of the maximum pressure in the LH$_2$ target vessel and the vacuum chamber during the catastrophic discharge takes into consideration all the pipes and bends up to the main exhaust line, including the pressure relief valve. Note, that these calculations do not include the long relief pipe in ER2 with the check valve. They are included in results in section 7.4. Furthermore, it is assumed that all the mass flows passes out through the relief valve RV104 and rupture disk RD101, into the main relief pipe that exhausts safely outside of the ER2 building. The friction factor for each relief system was taken from the Crane Technical Paper No. 410. They were $f = 0.021$ for a 1.5 inch inner diameter smooth pipe and $f = 0.019$ for a 2.5 inch inner diameter smooth pipe. The resistance coefficients $K$ for the two relief systems were calculated for each component of the relief line and then added up. (It should be noted that $K$ is constant for any given obstruction under all conditions of flow.) The results were between $K = 8$ and $K = 10$. Thus a value of $K = 10$ was used for calculating the maximum pressure.

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

The following are results of calculations 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 vent line contains all pipes, bends, and pressure relief valves up to the relief chamber. The rate of mass flow through pipes, valves and fittings is given by the Darcy formula

$$w = 0.1192Yd^2 \sqrt{\frac{p_1(p_1 - p_2)}{p_1 M \frac{K}{T}}}$$

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
- $K =$ 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 $Y$ vs $(p_1 - p_2)/p_1$ is given in the charts on page A-22 of the Crane Technical Report No. 410 [11])
6.1.1 Maximum Pressure in the LH$_2$ Vessel Due to Catastrophic Failure of Vacuum Chamber

Assumptions: 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: $p_2 = 15$ psia, venting to air at standard atmospheric pressure.
Resistance coefficient (specified for a reference id of 1.5 inch of smooth pipe; friction factor $f = 0.021$):

<table>
<thead>
<tr>
<th>Component</th>
<th>$L/d$</th>
<th>Resistance coefficient $K$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pipe, 10 feet long, 1.5 inch id</td>
<td>80.0</td>
<td>1.68</td>
</tr>
<tr>
<td>5 - 90$^\circ$ elbows</td>
<td></td>
<td>3.15</td>
</tr>
<tr>
<td>Sudden enlargement, $d/D = \frac{1}{4}$</td>
<td></td>
<td>0.56</td>
</tr>
<tr>
<td>Relief valve</td>
<td></td>
<td>4.20</td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td>9.59</td>
</tr>
</tbody>
</table>

Use $K = 10$

Results:

<table>
<thead>
<tr>
<th>Mass flow rate [lb/s] $w$</th>
<th>0.05</th>
<th>0.10</th>
<th>0.10</th>
<th>0.10</th>
<th>0.15</th>
<th>0.20</th>
<th>0.30</th>
<th>0.30</th>
</tr>
</thead>
<tbody>
<tr>
<td>ID of pipe [inch] $d$</td>
<td>1.0</td>
<td>1.0</td>
<td>1.125</td>
<td>1.5</td>
<td>1.125</td>
<td>1.5</td>
<td>1.5</td>
<td>1.75</td>
</tr>
</tbody>
</table>

| Sonic flow rate [lb/s] $w_{sonic}$ | 0.13  | 0.13 | 0.16 | 0.29 | 0.16 | 0.29 | 0.29 | 0.40 |
| Inlet pressure [psia] $p_1$        | 28.4  | 52.5 | 42.1 | 26.0 | 61.9 | 47.0 | 69.5 | 51.4 |

6.1.2 Maximum Pressure in the Vacuum Chamber Due to Rupture of the LH$_2$ Vessel

Assume: Flow temperature: $T = 293$ K
Outlet pressure: $p_2 = 15$ psia
Resistance coefficient: $K = 10$
Here the LH$_2$ is in contact with larger warm surface area causing a larger boil-off rate and thus larger mass flow rate.

Results:

<table>
<thead>
<tr>
<th>Mass flow rate [lb/s] $w$</th>
<th>0.5</th>
<th>0.5</th>
<th>0.75</th>
</tr>
</thead>
<tbody>
<tr>
<td>ID of pipe [inch] $d$</td>
<td>2.0</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Sonic flow rate [lb/s] $w_{sonic}$</td>
<td>0.52</td>
<td>0.82</td>
<td>0.82</td>
</tr>
<tr>
<td>Inlet pressure [psia] $p_1$</td>
<td>65.2</td>
<td>42.6</td>
<td>62.7</td>
</tr>
</tbody>
</table>

Table 3. Boil-off rates of the 21 liter LH$_2$ target.

<table>
<thead>
<tr>
<th>Heat flux into target [W/m$^2$]</th>
<th>LH2 target vessel</th>
<th>Vacuum chamber</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>13,000*</td>
<td>40,000**</td>
</tr>
<tr>
<td></td>
<td>100,000</td>
<td>100,000</td>
</tr>
<tr>
<td>Surface area [m$^2$]</td>
<td>0.50</td>
<td>0.25</td>
</tr>
<tr>
<td>---------------------</td>
<td>------</td>
<td>------</td>
</tr>
<tr>
<td>Boil-off time [s]</td>
<td>102</td>
<td>66</td>
</tr>
<tr>
<td>Mass boil-off rate [lb/s]</td>
<td>0.032</td>
<td>0.049</td>
</tr>
</tbody>
</table>

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

The results show that, in the case of a catastrophic vacuum failure to air, the LH$_2$ target vessel is subjected to pressure of no more than 47 psia if the inner diameter of the fill/vent piping is 1.5 inch, if a boil-off rate of 0.20 lb/s is assumed. The maximum pressure in the vacuum vessel for the case of a rupture of the target flask is 43 psia for an inner diameter of the relief piping is 2.5 inch, if a boil off rate of 0.50 lb/s is assumed. Both pressures are well below the 70 psid pressures that the LH2 target vessel and vacuum chamber have been tested at.

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

<table>
<thead>
<tr>
<th>Mass flow rate [lb/s]</th>
<th>LH2 target vessel</th>
<th>Vacuum chamber</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.05</td>
<td>0.10</td>
</tr>
<tr>
<td>ID of relief pipe [in]</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Sonic mass flow rate [lb/s]</td>
<td>0.13</td>
<td>0.13</td>
</tr>
<tr>
<td>Maximum pressure [psia]</td>
<td>28.4</td>
<td>52.5</td>
</tr>
</tbody>
</table>

* 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.

In summary, the fill/vent pipe of a 1.5-inch inner diameter for the LH$_2$ target vessel and a 2.5-inch inner diameter discharge pipe for the vacuum chamber, will respond safely to catastrophic failures when the maximum mass flow rate is less than 0.5 lb/s.

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

The 1.5 inch id pipe from the LH$_2$ target vessel is connected to the relief chamber and the main isolation vacuum chamber is connected to the same relief chamber using the 2.5 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 outside of the ER2 building 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 or vacuum chamber. A check valve, CKV101, is provided in the relief pipe to limit backflow of air. The pipe section up to the check valve is filled with helium gas to 2 psid. The relief pipe outside the ER2 building 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.

Calculations based on the Bates Internal Report #90-02 [21] and the Crane Technical Paper No.
410 [11] show that the 6-inch inner diameter relief pipe can safely handle a mass flow rate of 2.0 lb/s (four times the assumed boil-off rate of 0.5 lb/s from a catastrophic rupture of the target vessel spilling 21 liters of LH$_2$ into the vacuum vessel) with a pressure build-up of no more than 29 psia. For the total resistance coefficient a value of $K = 8$ was used. Calculations based on the “$K$” Factor Tables on p. A-26 to A-229 of Ref. 11, assuming a pipe length of 100 feet, two 90-degree bends and a check valve, give $K = 6.9$.

The hydrogen pressure relief system consists of:

1. The 1.5” id hydrogen fill/vent line from the cryostat to the relief valve RV104 which is parallel with a rupture disk RD101 in the relief chamber, see figures 5.
2. The isolation vacuum is connected with a 4” id pipe to the relief valve RV105, which is parallel with two rupture disks RD201 and RD202 in the relief chamber, see figures 5 and 16.
3. All these relief devices are connected to the same volume, the relief chamber, shown in figure 16. The relief chamber and 6” pipe up to the check valve CKV10, is filled with helium gas to 2 psid to prevent air to become contact with hydrogen gas in case of a leak in the relief devices.

Table 5 contains a list of the various parts of the relief system along with their performance specifications. Each component from the individual enclosures possesses a primary relief system consisting of a spring-loaded pressure relief valve and a secondary relief system consisting of rupture disks in parallel with the relief valve. All pressure relief systems are connected to a large (6” diameter) relief line which is filled with helium gas to 2 psid pressure and conducts the hydrogen gas outside of the experimental room, ER2. Figure 16 shows the assembly of the relief chamber.

<table>
<thead>
<tr>
<th>Relief lines</th>
<th>Mechanical and conductance properties of relief lines/blow-offs</th>
<th>Max. pressure in worst-case failure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dimensions</td>
<td>Material</td>
</tr>
<tr>
<td>LH$_2$ target fill/vent line</td>
<td>1.5 “diameter resistance coefficient $K = 10$</td>
<td>304 stainless steel</td>
</tr>
<tr>
<td>Main vacuum vent line</td>
<td>2.5” diameter resistance coefficient $K = 10$</td>
<td>304 stainless steel</td>
</tr>
<tr>
<td>Main relief pipe in ER2</td>
<td>6” diameter</td>
<td>304 stainless steel</td>
</tr>
</tbody>
</table>
Fig. 16. Relief chamber. 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. 17. Design for the seals for the rupture disks. For details see drawing SNEUT-Y-212-011 available at web site 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))

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 relief line up to the check valve CKV101 is filled with helium at 2 psid. The output of the check valve is connected to a 6 inch diameter 304L stainless steel pipe which ends outside ER2.
### 6.3.1 LH2 Vessel Relief Valve - RV104

Let’s assume the mass flow is caused by loss of the isolation vacuum.
Maximum H\textsubscript{2} mass flow rate = 0.2 lb/s (per Nann).
Pressure difference through 1.5” id fill/vent line up to the relief valve is 32.5 psid (per Novak, 8/8/01)

Specifications for the LH\textsubscript{2} vessel relief valve:
- Must be vacuum tight to the level of 10\textsuperscript{9} bar cc/s, allowing the LH\textsubscript{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.
- Pressure rise of 10% above set pressure at full flow rate is fine, 15% is acceptable.
- Pressures:
  - Normal operation = 0 to ~20 psia
  - System design pressure = 160 psia (per Nann)
  - Maximum allowed working pressure = 70 psig (per Nann)

Considerations regarding Anderson Greenwood (AG) valves:
- We can pick from direct-acting spring types since pilot-operated types like AG model 91 will open when flask is evacuated.
- We pick the AG model 83.

Considerations regarding physical size of valve:
Using AG’s “Safety Size” valve selection program, we can select the valve body sizes, orifice sizes, and minimum set pressures that will pass 0.2 lb/s of H\textsubscript{2} gas at room temperature.

<table>
<thead>
<tr>
<th>Candidate Valves:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Set pressure (psig)</td>
</tr>
<tr>
<td>---------------------</td>
</tr>
<tr>
<td>20</td>
</tr>
<tr>
<td>34</td>
</tr>
<tr>
<td>62</td>
</tr>
</tbody>
</table>

Set pressures up to 62 psig have the same physical size of the valve body. A valve with 62 psig set pressure is smaller, but 62 psig seems a bit high, considering the normal operating pressure range of the system. Better to have a larger margin of safety over the design pressure.

Is it better to have the H or the J orifices?
For a given set pressure, spring force increases proportional to nozzle area. But seal load, unless there is a mechanical stop, increases with nozzle radius. Thus larger orifice helps sealing (to first order). Thus, pick the J orifice (1.287 in\textsuperscript{2} flow area).

What is a good set pressure?
Let’s pick 30 psig.
It is far from the operating pressure 30 psig / 6 psig = 5:1
It is far from the design pressure 160 psia / (30 + 14.7) psia = 3.6:1
The weep point is far from the operating pressure;
Weep point = 85% of set point = 22.5 psig
Ratio to operating pressure = 22.5 / 6 psig = 4:1
Flow rate at set pressure: AG Safety Size gives ASME Rated mass flow capacity of 0.306 lb/s with J orifice.

6.3.2 LH2 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 does not give flow resistance, $K$, for a ruptured SR-H disk, but gives $K$ for the similar HOV disk/flange set $K=2.02$ and $K$ for the CPV-C disk $K=3.5$. These numbers indicate a rather free opening after the disk ruptures. The SR-H is listed as suitable for full vacuum load.
Are these rupture disks vacuum-tight? Dallas Clayton (Scientific Sales, 505-266-7861) says they are. 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 50 psig which is adequately far from the relief valve set point of 30 psig. The pressure tolerance +0 – 10% gives 50-5= 45 psid. Maximum pressure ahead of relief valve at full flow = 1.1 x set pressure = 33 psid.
Ratio is 33 / 45 = 73%, which is an enough large margin. The burst disk should not break accidentally.
It is adequately far from the design pressure. (50 + 14.7) / 160 psia = 0.40.

6.3.3 Main Vacuum Chamber: Relief Valve – RV105 - and Rupture Disks – RD201 and RD202

We have two different situations that we 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 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, 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 (per Nann). A relief valve alone cannot handle the flow and therefore we have two 4” diameter rupture disks parallel.

Pressure difference through 2.5” id pipe to rupture disks is 28.2 psid (per Novak, 8/24/01).

Specifications for the relief valve:
- 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 = 140 psia (per Nann)
  - Maximum allowable working pressure = 70 psig (per Nann)
  - Pressure set point = 5 psid

Vacuum Chamber rupture disks RD201 and RD202:

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

Specifications:
- Must be vacuum tight to the level of $10^{-9}$ bar cc/s.
- Pressures:
  - Normal operation = vacuum
  - Vacuum chamber design pressure = 140 psia (per Nann)
  - Maximum allowable working pressure = 70 psig (per Nann)
  - Pressure set points = 20 psig and 30 psig.

Rupture disks are Fike model 4” SRL/Ni/30#/72f/std with pressure tolerance of =0-10% and with burst pressures of 20 psig and 30 psig. The holder is 4” SRX-GI/150#/CS/CS.

### 6.3.4 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:

<table>
<thead>
<tr>
<th>Type</th>
<th>Pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal</td>
<td>159 psia</td>
</tr>
<tr>
<td>External</td>
<td>44 psia</td>
</tr>
</tbody>
</table>

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 15 psid
* pick set pressure for rupture disk at 60 psid
(2) Vacuum Vessel:
Calculated maximum pressure according to ASME code:
- internal: 83 psia
- external: 40 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 30 psid, the other with 35 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)

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 high-pressure H$_2$ supply line downstream of the flow-restrictive orifice and upstream of the mass flow meter.
- Setpoint: 220 psid cracking pressure
- Reasoning: The maximum rated flow through the H$_2$ purifier (PRFR) is obtained with a supply pressure of 200 psid. Short-term exposure to pressures as high as 220 psid is sufficiently low to avoid damage to the purifier and sufficiently high to avoid unnecessary venting of H$_2$.

RV102
- Function: relieve an over-pressure condition in the H$_2$ line downstream from the purifier and between V117 and V120 (normally locked open).
- Location: between V117 on the output of the purifier and the LN cold trap. Effectively it is on the inlet of the cold trap.
- Setpoint: 50 psid cracking pressure
Reasoning: If V125 must be throttled down during filling (e.g., to accommodate pressure fluctuations due to flash evaporation of LH₂ in the internal OP catalyst chamber), this setting is sufficiently high to avoid venting H₂ 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 RV103 are vents for the inlet and outlet of the LN-immersed cold trap and OPC chamber.
Location: between V120 (on the inlet of the external OP catalyst chamber) and V125 (the last H₂-supply valve in the line to the LH₂ vessel)
Setpoint: 50 psid cracking pressure
Reasoning: as for RV102

RV104

Function: relieve an over-pressure condition in the LH₂ vessel
Location: inside the pressure vent box with RD101, RD201 and RD202,
Setpoint: 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 LH₂ vessel. Because RV101 opens fully when the H₂ pressure exceeds the set point, 20 psid is sufficiently low with respect to the 60 psid burst pressure of rupture disc RD101.

RV201

Function: relieve an over-pressure condition in the vacuum vessel
Location: in the external plumbing of the vacuum system
Setpoint: 15 psid cracking pressure
Reasoning: This setpoint is one-half the burst pressure of RD201.

RV401

Function: relieve an over-pressure condition in the helium system
Location: in the He line to V405 (which allows He to enter the vent line system)
Setpoint: 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 He channel system)
Setpoint: 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 (which allows argon to enter the vacuum system)
Setpoint: 3 psid cracking pressure
Reasoning: This setpoint 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 setpoint 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 isolation box containing RV104, RD101, RD201 and RD202
Setpoint: 2 psig opening pressure
Reasoning: This setpoint is adequate to contain a blanket of He in the vent line. The 2 psig backpressure will be an insignificant offset for the setpoints 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 isolation box containing RV104, RD101, RD201 and RD202
Setpoint: 3 psig opening pressure
Reasoning: This setpoint is adequate to contain a blanket of He in the vent line. The 3 psig backpressure will be an insignificant offset for the setpoints of the other pressure-relief devices.

RD101
Function: passive rupture device for the H₂ vessel in the event RV104 should fail to open adequately
Location: in the vent isolation box of the main vent line
Setpoint: 60 psid
Reasoning: This setpoint is designed to remove the possibility of over-pressuring the H₂ vessel.

RD201
Function: passive rupture device for the vacuum isolation chamber
Location: in the vent isolation box of the main vent line
Setpoint: 35 psid
Reasoning: This setpoint 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 PT202 and PT203.

RD202
Function: backup for RD201
Location: in the vent isolation box of the main vent line
Setpoint: 40 psid
Reasoning: backup to RD201, with a pressure sufficiently higher to avoid unnecessary rupture.

6.4 Vent and Relief System in Shed and in ER2

6.4.1 Calculations of Inlet Pressures of the Relief Pipes

Values of resistance coefficients for clean 4 inch id commercial steel pipes:

1. 1 ft long pipe: \( K = 0.05 \)
2. standard 90° elbow \( K = 0.51 \)
3. standard 45° elbow \( K = 0.27 \)
4. standard tee: flow thru run \( K = 0.34 \)
    flow thru branch \( K = 1.02 \)
5. pressure relief valve \( K = 3.40 \)

Values of resistance coefficients for clean 6 inch inner diameter commercial steel pipes:

1. 1 ft long pipe: \( K = 0.03 \)
2. standard 90° elbow \( K = 0.45 \)
3. standard 45° elbow \( K = 0.24 \)
4. standard tee: flow thru run \( K = 0.30 \)
    flow thru branch \( K = 0.60 \)
5. pressure relief valve \( K = 3.00 \)

Table 6. Maximum pressure rise at the entrance to the relief/vent line for various tubing sizes and values of the resistance coefficient \( K \), assuming a mass flow rate of 0.5 lb/s. The exit pressure is 14.7 psia at LANL.

<table>
<thead>
<tr>
<th>( p_{\text{max}} ) ( (K = 6) )</th>
<th>Pipe id =2.5” inlet pressure (psia)</th>
<th>Pipe id=4.0” inlet pressure (psia)</th>
<th>Pipe id=6.0” inlet pressure (psia)</th>
</tr>
</thead>
<tbody>
<tr>
<td>35.1</td>
<td>18.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( p_{\text{max}} ) ( (K = 8) )</td>
<td>39.0</td>
<td>19.8</td>
<td></td>
</tr>
<tr>
<td>( p_{\text{max}} ) ( (K = 10) )</td>
<td>42.4</td>
<td>20.8</td>
<td>17.0</td>
</tr>
<tr>
<td>( p_{\text{max}} ) ( (K = 15) )</td>
<td>50.1</td>
<td>23.3</td>
<td>23.8</td>
</tr>
</tbody>
</table>

### 6.4.2 Hydrogen Vent Stack in Shed

Figure 16 shows the relief system and vent stack for the target in MPF-35, shed. After the cryostat there is a relief chamber followed by a check valve and then a 4” id and 20 ft long stainless steel pipe which conducts hydrogen gas outside shed. The design criteria and drawings for this vent stack can be found at web site [www.iucf.indiana.edu/U/lh2target/export-files/](http://www.iucf.indiana.edu/U/lh2target/export-files/). The total resistance coefficient \( K \) for the 4” shed relief system is about \( K = 7 \); 30 ft long 4” id pipe \( K = 1.53 \), four 90-degree bends \( K = 2.04 \), one check valve \( K = 1.7 \), one pipe entrance \( K = 0.50 \), and one pipe exit \( K = 1.00 \).
6.4.3 Hydrogen Vent Stack in ER2

Figure 17 shows the relief system in ER2 where the length of the pipe is large and several 90-degree bends are required. The total length of the pipe in ER2 is about 100ft and the inner diameter is 6”. The design criteria and drawings for this relief line can be found at web site www.iucf.indiana.edu/U/lh2target/export-files/. The total resistance coefficient $K$ of the ER2
relief vent system is $K=7.8$ consisting of 100 ft long 6” id pipe $K=3.00$, four 90-degree bends $K=1.80$, one check valve $K=1.50$, one pipe entrance $K=0.50$, and one pipe exit $K=1.00$.

Fig. 19 Hydrogen relief and vent stack system in ER2.
6.4.4 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 H₂ gas (GH2) 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: \( d = 6.065 \text{ in} \)
Transverse internal area: \( A = 28.89 \text{ in}^2 = 0.2006 \text{ ft}^2 = 0.01864 \text{ m}^2 \)
Weight/Mass \( 18.97 \text{ lb/ft} = 8.62 \text{ kg/ft} \)
External surface: \( 1.734 \text{ ft}^2/\text{ft} = 0.161 \text{ m}^2/\text{ft} \)

Properties of LH₂ and H₂ gas at normal boiling point (NBP):
Density: vapor \( 1.338 \text{ kg/m}^3 = 0.0835 \text{ lb/ft}^3 \)
liquid \( 70.78 \text{ kg/m}^3 = 4.42 \text{ lb/ft}^3 \)
Specific heat at constant pressure:
\( c_p = 12.15 \text{ kJ/kg·K} \)

Properties of GH2 at normal temperature and pressure (NTP):
Density: \( 83.764 \text{ g/m}^3 = 0.00523 \text{ lb/ft}^3 \)
Specific heat at constant pressure: \( c_p = 14.89 \text{ kJ/kg·K} \)

Heat from heat capacity of vent pipe:
Specific heat of steel: \( c = 0.449 \text{ J/g·K} \)
Initial temperature of GH2: \( T_{\text{initial}} = 23 \text{ K} \)
Temperature difference: \( \Delta T = 293 \text{ K} – 23 \text{ K} = 270 \text{ K} \)
Heat content of pipe: \( Q = m c_p \Delta T = (8.62 \times 10^3 \text{ g/ft})(0.449 \text{ J/g·K})(270 \text{ K}) \)
\( = 1.045 \times 10^6 \text{ J/ft} \)

Mean velocity of compressible fluid in pipe:
\[ v = \frac{188.3w}{d^2 \rho} \text{ ft/sec}, \]

where \( w = \text{rate of flow in lb/sec} \)
\( d = \text{diameter of pipe in inches} \)
\( \rho = \text{density of fluid in lb/ft}^3 \)

Density of GH2 at \( T_{\text{initial}} = 23 \text{ K}: \)
\( \rho = 0.0736 \text{ lb/ft}^3 \)

For \( w = 0.5 \text{ lb/sec}: \)
\[ v = \frac{(188.3)(0.5)}{(6.065)^2(0.0736)} = 34.8 \text{ ft/sec} = 10.6 \text{ m/s} \]
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: \(V/t = (\text{mean velocity}) \times (\text{transverse internal area})\)

Time:

$$t = \frac{\text{(volume of transferred GH2)}}{\text{(volumetric flow)}}$$

For $w = 0.5$ lb/sec: 

$$t = \frac{(21 \times 10^{-3} m^3)(850)}{(10.6 m/s)(0.01864m^2)} = 90.3 \text{ sec}$$

Temperature increase per foot:

$$\Delta T = \frac{Q/t}{w \cdot c_p} = \frac{(1.045 \times 10^6 J/ft)/(90.3s)}{(0.23 \text{ kg/s})(12.15 \times 10^3 J/kg \cdot K)} = 4.1 \text{ K/ft}$$

For $w = 0.2$ lb/sec:

$$t = \frac{(21 \times 10^{-3} m^3)(850)}{(4.2 m/s)(0.01864m^2)} = 228 \text{ sec}$$

Temperature increase per foot:

$$\Delta T = \frac{Q/t}{w \cdot c_p} = \frac{(1.045 \times 10^6 J/ft)/(228s)}{(0.091 \text{ kg/s})(12.15 \times 10^3 J/kg \cdot K)} = 4.1 \text{ K/ft}$$

Summary ($\Delta T$ is calculated approximately after every 2 ft.):

<table>
<thead>
<tr>
<th>Initial temperature: $T_{\text{initial}}$ (K)</th>
<th>Temperature increase per ft: $\Delta T$ (K/ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>23</td>
<td>4.1</td>
</tr>
<tr>
<td>31</td>
<td>5.5</td>
</tr>
<tr>
<td>42</td>
<td>7.1</td>
</tr>
<tr>
<td>56</td>
<td>9.0</td>
</tr>
<tr>
<td>74</td>
<td>10.9</td>
</tr>
<tr>
<td>96</td>
<td>12.8</td>
</tr>
<tr>
<td>122</td>
<td>14.0</td>
</tr>
<tr>
<td>150</td>
<td>14.4</td>
</tr>
<tr>
<td>179</td>
<td>13.8</td>
</tr>
<tr>
<td>207</td>
<td>12.0</td>
</tr>
<tr>
<td>231</td>
<td>9.7</td>
</tr>
<tr>
<td>250</td>
<td>7.2</td>
</tr>
<tr>
<td>264</td>
<td>5.2</td>
</tr>
</tbody>
</table>

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 than the density of solids.

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

Temperature increase per foot:

For \( w = 0.2 \text{ lb/sec} \):

\[
\Delta T = \frac{Q}{\Delta t} = \frac{2093W/ft}{0.091kg/s)(12.15\times10^3J/kg\cdot K)} = 1.9 \text{ K/ft}
\]

For \( w = 0.5 \text{ lb/ft} \):

\[
\Delta T = \frac{Q}{\Delta t} = \frac{2093W/ft}{0.23kg/s)(12.15\times10^3J/kg\cdot K)} = 0.7 \text{ K/ft}
\]

6.5 Testing of the Model (H. Nann, 8-22-01, modified 5-1-03 WMS)

6.5.1 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 estimates given by calculations. Also three liters of LN\(_2\) was emptied into the vacuum chamber to simulate a rupture of the LH\(_2\) vessel and the boil-off was measured.

6.5.1.1 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 insolation 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 value 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 $\Delta t = 55 \text{ min} = 3300 \text{ s}$. 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.

$$w_H = \frac{h_v(N_2)}{h_v(H_2)} w_N = \frac{198.8 \text{ J/g}}{445 \text{ J/g}} \cdot 0.01 \text{ lb/s} = 0.0045 \text{ lb/s},$$

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

Conclusion:
The mass flow rate of 0.0045 lb/s can safely be handled by the designed pressure relief system, which is able to discharge 0.2 lb/s with a maximum pressure build-up of no more than 47 psia in the LH2 vessel.

### 6.5.1.2 Simulation of Rupture of the LH2 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 $\Delta t = 62 \text{ s}$. 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 $w_H = 0.04 \text{ lb/s}$. 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 $w_H = 0.28 \text{ lb/s}$.

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 43 psia in the vacuum chamber.
6.6 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 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, and RV103 were tested. There is a 10-15% pressure range around the cracking pressure where the valve will open and seal back.

6.7 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. The bellows 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 helium leak test confirmed (to a leak rate of $1 \times 10^{-9}$ atm cc/s) that the bellows did not crack.

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

6.8 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 psig. While pressurized, it was repeatedly opened and closed, thereby expanding and contracting its bellows. After repeated exposures to 80 psig, a helium leak test in the leak rate level of $2 \times 10^{-9}$ atm-cc/s indicated that the bellows did not crack.
7 SUMMARY OF 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 LH2 target organized by item and vendor. All welding for all parts was performed by certified welders. Certifications for materials and welders are available from 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 in 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 $1 \times 10^{-9}$ 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.

Titanium Target Vessel:
The titanium liquid hydrogen target vessel was 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 with no leaks visible.

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/cm².

**Aluminum Target Vessel:**

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 with no leaks visible.

**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.

8 H₂ GAS HANDLING SYSTEM

The H₂ gas handling system is shown in figure 7, see also figures 5 – 11.

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

Table 6 lists the main components of the H₂ gas handling system and their relevant properties. The plumbing will be constructed of stainless steel components with VCR connections of welded tubing.
Table 7. Properties of major gas handling system components.

<table>
<thead>
<tr>
<th>Components</th>
<th>Relevant properties</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Inlet and outlet</td>
<td>Material/type, Operating/cleaning temperature</td>
</tr>
<tr>
<td></td>
<td>pressures</td>
<td></td>
</tr>
<tr>
<td>Flow rate meter (FM101)</td>
<td>150 psia inlet and</td>
<td>304 stainless steel, 300 K</td>
</tr>
<tr>
<td></td>
<td>outlet</td>
<td>Measure H2 gas flow rate</td>
</tr>
<tr>
<td>Hydrogen gas purifier (PRFR)</td>
<td>150 psia inlet and</td>
<td>304 stainless steel body, palladium leak</td>
</tr>
<tr>
<td></td>
<td>15 psia outlet</td>
<td>470 K</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Removes all non-hydrogen components to sub ppm concentration</td>
</tr>
<tr>
<td>Liquid N$_2$ cold trap/Ortho-para</td>
<td>15 psia inlet and</td>
<td>FeO powder, OFHC copper/304 SS container, porous copper inlet and</td>
</tr>
<tr>
<td>converter (OPC)</td>
<td>15 psia outlet</td>
<td>outlet 77 K/150 °C</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Trap water vapor and other freezable at 77K contaminants. Partial</td>
</tr>
<tr>
<td></td>
<td></td>
<td>conversion of gas to para-hydrogen state</td>
</tr>
<tr>
<td>Residual gas analyzer (RGA)</td>
<td>10$^{-3}$ Torr inlet</td>
<td>Quadrupole RGA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>300 K</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hydrogen gas purity, helium leak detection, gas monitoring in the main</td>
</tr>
<tr>
<td></td>
<td></td>
<td>vacuum</td>
</tr>
<tr>
<td>Turbo pumps TP201 and TP301</td>
<td>N/A</td>
<td>300 K</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Evacuate target, main vacuum, and gas handling system</td>
</tr>
</tbody>
</table>

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 looks for hydrogen and helium in the residual gas of the main vacuum system. A diagram of the gas handling system is shown in figures 5 - 11. The pressure ratings of all the components of the system are shown in Table 7. 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 for the palladium leak purifier and is fed with a line that possesses a 10 SLM restrictive orifice and is fed by lines with 20 micron filters to eliminate particulate contamination from the bottles.
2) Palladium leak (PRFR). The palladium purifier will be used to extract impurities such as N$_2$, Ne, CH$_4$, CO, CO$_2$ and others. Palladium has the property that hydrogen can diffuse (leak) through it, but other elements cannot. The palladium leak is a commercial device consisting of a palladium membrane that can be heated to increase the transmission rate of hydrogen. The temperature of the palladium membrane is raised to ~200°C to achieve a flow rate of 10 SLM. The operation of the membrane produces an outflow of hydrogen gas into a side port of 2.5 cc/sec which must be fed
into the vent stack. The entrance to the purifier is guarded by an automatic valve (V114) which only opens under certain interlock conditions.

3) Cold Trap and Ortho/para converter (OPC): The cold trap consists of a cold trap and an ortho-para converter both held at liquid nitrogen temperature. The cold trap catches any non-hydrogen impurities emanating from the palladium purifier (occasionally the operation of this device can release small amounts of water vapor). The ortho-para converter consists of a 77K cell in which the hydrogen is exposed to a catalyst consisting of a fine powder. The purpose of the converter is to partially convert ortho-hydrogen into para-hydrogen, which is the ground spin state of the hydrogen molecule.

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

1) The turbo pump system which evacuates the main vacuum of the target. It can be isolated from the main vacuum with an automatic valve (V204) which is interlocked.

2) The turbo-pump system that evacuates the hydrogen target flask

3) The residual gas analyzer (RGA1) which can be used to monitor the main vacuum system for hydrogen and helium through an interlocked automatic valve (V207).

4) The relief system consisting of check valves in the GHS itself (RV104, RV201, RV103, RV101, RV401) and in the vent line (CKV101) along with rupture disks (RD202, RD201, RD101)

5) The non-hydrogen gas supply systems: a helium supply system to deliver helium gas to the helium chambers on the main vacuum system and an argon supply system to fill the main vacuum system for emergency venting of the liquid hydrogen in the event of a fire.

Operating Procedures for the gas handling system can be found at 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/expulsion of the liquid hydrogen. Preparation consists of the following steps:

1) The GHS/target should be grounded with a grounding strap and checked with an ohmmeter to ensure that there is no electric charge building up on the system which could produce a spark.

2) The target chamber and main vacuum system must be pumped down to a pressure of \(10^{-4}\) Torr or lower.

3) The target chamber, main vacuum system, and GHS must be leak checked when under vacuum with a helium leak checker which has been verified to be in proper working order before and after the leak checks. Any detectable leaks must be corrected and verified to be leak tight before operation.

4) The hydrogen lines must be pumped and purged with helium gas before introducing hydrogen into the system.

5) Helium gas must be introduced into the helium channels.

6) Argon gas must be loaded and ready for introduction in the event that a fast warm up
of the target is required.
7) A low oxygen monitor with warning signs and flashing warning lights at the edge of the oxygen depletion hazard area should be set up.
8) The enclosure of the GHS must be posted with appropriate warning signs:
   a) Cryogens in use
   b) Flammable Gas (Hydrogen) in use; Smoking and Open Flames Prohibited
   c) Oxygen Depletion Possible

For a manual vent of the hydrogen, the refrigerators are turned off and the valve V128 is opened. In cases where rapid boil off is required the main vacuum is filled with argon gas. The boiling hydrogen then passes through the valve V128 and/or the relief valve RV104 to the vent line.

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° bend, a bellows, and a ¼-inch VCR side connection;
2) a short tube with a 90° 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 in the H2 vent line

Components 1-4 were first verified to be He leak tight at rate of \( \leq 1 \times 10^{-9} \) atm cc/s. All pieces were then cleaned by submersion (2.5 minutes) in a solution of 25% HNO3 + 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 LN2. 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) H2 gas handling system
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 $0.3 \times 10^{-9}$ 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 $0.5 \times 10^{-9}$ atm cc/sec.
   (iii) V113 was opened. A leak was found near V116 was fixed and the background rate decreased to $0.3 \times 10^{-9}$ atm cc/sec.
   (iv) V122 was opened, no leak, background ~ $0.3 \times 10^{-9}$ atm cc/sec.
   (v) V125 was opened, no leak, background ~ $0.3 \times 10^{-9}$ atm cc/sec.
   (vi) V111 and V107 were opened, no leak, background ~ $0.3 \times 10^{-9}$ atm cc/sec.
   (vii) V117, V119A and V120 were opened, exposing the leak detector to the LN2 trap, pumped on overnight. No leak, background ~ $0.75 \times 10^{-9}$ atm cc/sec.
Therefore, the whole GHS was leak tight with base level helium leak below $0.75 \times 10^{-9}$ atm cc/sec.

b) H2 supply manifold
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 ~ $1.0 \times 10^{-9}$ atm.cc/sec.
   ii) V131 was opened. No leak, background ~ $1.0 \times 10^{-9}$ atm.cc/sec.
   iii) V130 was opened. No leak, background ~ $1.0 \times 10^{-9}$ atm.cc/sec.

c) Helium and Argon supply manifold
Helium and Argon gas supply manifolds (without the pressure regulators and cylinders) were leak checked and found to be leak tight, background ~ $5.0 \times 10^{-8}$ atm.cc/sec. The base level leak rate was little higher which is understandable because some of the helium and argon lines are made of poly tubes.

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

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 (V114, V129, V201, V204, V205, V207 and V303) 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: Satyaranjan Santra, IUCF
Approved by: 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: Bill Lozowski, IUCF, Satyaranjan Santra, IUCF
Approved by: Bill Lozowski, IUCF

**8.3.5 Verification of Operation of Palladium Membrane Filter**

Date: April 11, 2002
DUT: palladium membrane
Object: verification of proper operation of palladium membrane filter

The inlet of the palladium membrane filter was fed by UHP zero-grade H2 gas at 200 psid. The outlet was connected to a graduated cylinder and the time to displace 1000 ml of water was measured in 4 trials. The average flow rate measured was 7.2 liters/minute with an accuracy of about 5%.

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

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

Date: Oct. 15, 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 150°C 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: Vivek Jeevan, IUCF
Approved by: Bill Lozowski, IUCF

8.4 Gas Handling System Enclosure

Design criteria for the gas handling system

8.5 Ventilation Line for the GHS Enclosure

8.5.1 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 outside shed through a 8” diameter ventilation channel.

8.5.2 Ventilation of GHS in ER2

The GHS in ER2 is located on the top of the FP12 neutron guide tunnel. The GHS is closed inside an aluminum enclosure that has a 8” ventilation line to outside 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 on the gas handling system and operates at 77 K. The other is on the cold stage of the cryo-refrigerator and doubles as the liquefaction region. We plan to use iron oxide in the GHS converter and chromic oxide (CrO₃) as the active converter material at 20K. Our choice of CrO₃ is based on the data of N. S. Sullivan et al. [22], which showed that CrO₃ is a more effective catalyst than the more commonly-used iron oxide.

In addition, CrO₃ is anti ferromagnetic at low temperatures and therefore should not disturb the magnetic environment of the experiment.

We do not intend to insulate the lines from the gas handling system o-p converter except perhaps with styrofoam to prevent condensation of water vapor on the lines. Given the dryness of LANL, we expect that this may not be necessary either.

The idea is to use the o-p converter in the gas handling system to reduce the heat load on the refrigerator and speed up the fill time. If it does not work the only consequence is a somewhat longer LH2 fill. For that reason we do not see it as a safety issue.
9.1 Specifications (M. Snow, 6-16-01, B. Lozowski)

Both converters will be enclosed in OFHC copper chambers with fine mesh to prevent converter material from moving to other volumes. Both converters will be bakeable for reactivation. Table 7 lists the important properties of the two ortho-para converters.

Table 8. Ortho-para converter data.

<table>
<thead>
<tr>
<th>Ortho-para converter</th>
<th>Geometric and thermodynamic data</th>
<th>Geometry and cooling</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Volume</td>
<td>Rate of heat removal</td>
</tr>
<tr>
<td>Gas handling system</td>
<td>500 cc</td>
<td></td>
</tr>
<tr>
<td>LH2 fill/vent line</td>
<td>280 cc</td>
<td></td>
</tr>
</tbody>
</table>

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 doubles as the liquid condensation chamber. The gas is liquefied at the top of the chamber by thermal contact with a grooved OFHC copper surface. The liquid drips down into the ortho-para converter in a separate chamber. The body of the converter is made of copper to allow the converter material to be heated for regeneration if necessary. The CrO$_3$ is prevented from leaving the annular region with fine wire mesh on the inlet and outlet tubes. The body of the converter is designed as a two-piece device to allow for the replacement of the converter if required.

9.3 Test results

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 8 lists the relevant properties of the two cooling stages.

Table 9. Properties of the two-stage cryo-refrigerators

<table>
<thead>
<tr>
<th>Cooling stage</th>
<th>Thermodynamic data</th>
<th>Mechanical data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cooling power @ Temperature stability, no load</td>
<td>Operating range</td>
</tr>
<tr>
<td>Stage 1</td>
<td>60 W at 77 K</td>
<td>0.5 K</td>
</tr>
<tr>
<td>Stage 2</td>
<td>12 W at 20 K</td>
<td>0.5 K</td>
</tr>
</tbody>
</table>

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

Basic properties of liquid hydrogen and its thermodynamics:

- Density: 0.071 g/cm³
- Latent heat of vaporization of normal-LH₂: 444 J/g at 18 K
- Heat of ortho-para conversion: 709 J/g
- Specific heat of normal-H₂ gas depends on temperature:
  - 10.5 J/(g·K) at 20 K,
  - 10.6 J/(g·K) at 70 K, and
  - 14.5 J/(g·K) at 300 K

The LH₂ volume of the target is 21 liters. This gives a target mass of 1.5 kg and corresponds to a total gas volume at room temperature and 1 bar pressure of 18 cubic meters. 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, with about a third of the heat of conversion released by 80 K. If we neglect the effect of the ortho-para conversion in the gas handling system and assume that all ortho-para conversion occurs in the condenser, 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 liquefication 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 a temperature two degrees lower (15 K) than the target temperature (17 K). (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 H₂: 1.2 mW/(cm·K), gaseous H₂: 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

\[
\frac{\text{area}}{\text{length}} = \frac{0.5}{(20 \times 2)} = 0.0125 \text{ cm}
\]

For a length of 20 cm for the thermal connection between the refrigerator and target, this gives a cross sectional area of 0.25 cm². 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](http://www.iucf.indiana.edu/U/lh2target/export-files) includes a plot of the cooling power of the two stages of the CV1 CGR511 refrigerator and the Cryomech refrigerator which will be used to liquefy and convert the hydrogen.

10.4 Test Results

The following is the report of the cryogenic tests done at Indiana before shipment to Los Alamos.

First a guided tour of some pictures of various parts of the apparatus which can be accessed at [http://www.iucf.indiana.edu/~snow/NPDGamma](http://www.iucf.indiana.edu/~snow/NPDGamma).

Image 004 is an (almost) successful attempt to include all elements of the system in one picture. Visible are, from left to right, (1) the front edge of the LH2 main vacuum system, (2) the two helium compressors for the 2 mechanical refrigerators, (3) the pumping/gas handling system, and (4) a rack with the PLC control system and pressure/temperature measurement.
Images 002 and 010 are different views of the target main vacuum on the Manitoba stand. In image 002 at the bottom you can see a part of the aluminum LH2 target chamber. This chamber finally arrived this week. It successfully passed an pressure test at 90 psia and helium leak check and will be cooled down at LANL. Image 010 shows a rear view of the chamber with the Cryomech pulse tube refrigerator on top.

Images 001 and 007 are front and side views of the gas handling/pumping system. The residual gas analyzer is the gray box mounted vertically near the center of the picture. Two turbopumps lie on the other side of the panel. In image 007 the palladium membrane hydrogen purifier at upper left is resting on top of the turbopump control: on the right one can see the liquid nitrogen-cooled cold trap and ortho-para converter to partially pre-convert the hydrogen gas and reduce the heat load on the cryogenic system which rests on a separate stand that allows us to drop the dewar.

Image 005 shows the control system rack. The PLC display is at the top with a schematic display of the gas/target system with its status. Lower are the pressure and temperature gauges and controls.

Image 009 shows the helium compressors for the two refrigerators mounted on a common rack and the flexible metal hoses that connect to the refrigerators.

To test the thermal performance of the cryogenic system under an almost "worst-case" situation we assembled and conducted a test cooldown under the following conditions, which I relate in detail for those who may be interested and will supplement with more images later (others can skip to the punchlines below). First we installed the titanium target chamber into the vessel. Titanium has a much worse thermal conductivity than the aluminum vessel we plan to use for the experiment. Then we separated the titanium vessel from the surrounding copper radiation shield by plastic with poor thermal conductivity similar to that for the lithium-loaded plastic that will surround the target vessel. The thermal connection between the refrigerator and the target consisted only of a copper clamp at the rear of the target which did not directly touch the target vessel at all: only the copper radiation shield outside of it. This radial clamp is soldered onto a soft copper bar which was bent by 90 degrees at the downstream end of the vacuum chamber for thermal connection to the cold stage of the Cryomech pulse tube cryorefrigerator. Therefore the thermal connection to the target itself was relatively poor but preserved the possibility of hermetically surrounding the entire target vessel with neutron shielding everywhere except the entrance and exit of the neutron beam. The outside of the copper shield was covered with low-emissivity aluminum tape. The chamber was centered inside the polished cylindrical ~80K copper shield with a G-10 plastic centering ring. The 80K copper shield was in thermal contact with both the cryorefrigerators. The outside of the 80K shield was wrapped in about 30 layers of superinsulation consisting of Mylar coated on both sides with aluminum and with layers separated with thin plastic netting and periodic small holes for easier evacuation of gas between layers. The 80K shield was thermally isolated from the inside surface of the main vacuum with two G-10 spacers. The neutron beam entrance windows consisted of thin aluminum taped to the copper with copper tape. The target fill line was connected to an ortho-para converter chamber in thermal contact with the lower CVI mechanical refrigerator and from there to the H2.
liquefaction chamber in thermal contact with the Cryomech pulse tube refrigerator. The vent line was not installed for this test since it is being welded together now: this is the reason for the "almost" in the first sentence above. However it is nonmag stainless steel and we estimate that the additional heat load that it delivers to the target is small compared to the other sources present in the system. Finally the entire inner surface of the aluminum vacuum chamber was polished to an almost mirror finish to reduce emissivity using alumina powder and one of those buffer wheels that people use to polish cars.

Under these conditions and with both refrigerators operating, the temperature of the titanium target vessel as measured by a thermometer at the farthest point from the refrigerator reached 9.4K. The temperature of the cold stage of the Cryomech refrigerator as measured at the farthest point away from the titanium vessel reached 8.25K. Implications are that (1) we will have no problem reaching the operating temperature of 17K with heaters, (2) the overall heat load on the Cryomech cold stage based on its final temperature is a few watts, consistent with expectations, and can be decreased further with more superinsulation, (3) there is an upper bound on the thermal gradient across the target of 1.15K, the real gradient is probably smaller than this by at least an order of magnitude and will be smaller still in the aluminum vessel, which means that we expect that the aluminum vessel would have reached in the same test a temperature between 8.25 and 9.4K (4) we will not require a direct thermal contact between the liquid hydrogen target vessel and the copper cold finger, the plastic neutron shielding will be able to surround the sides of the vessel in a hermetic fashion. There will be some more thermal contact between the target vessel and the refrigerator through clamps on the exit line and so again we would expect the target temperature to be lowered with this addition. These effects will compensate for the increase in thermal load when the target vent line is connected and full of hydrogen gas.

We then turned off the CVI mechanical refrigerator and determined whether or not the Cryomech pulse tube refrigerator was capable of maintaining the target temperature at a low enough value by itself after the initial cooldown. The asymptotic values of the target temperature and the Cryomech cold stage in this case were 13K and 11K, respectively. This would be good because the operation of the CVI refrigerator introduces mechanical vibrations into the system which we would like to avoid. The Cryomech refrigerator introduces no detectable vibrations to the vacuum system. We would then use the CVI mechanical refrigerator only for the initial liquefication and ortho-para conversion of the hydrogen (the o-p conversion heat is comparable to the liquefication heat and is significant). To do this we may need to introduce an additional thermal link between the Cryomech and the ortho-para converter to keep it cold enough. This can be done easily with copper braid and will be the subject of further cryogenic tests at LANL.

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. Outside the system, the instrumentation consists of gas sensors inside the cave to detect
hydrogen.

Table 10. Instrumentation associated with target operation.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Transducer requirements</th>
<th>Mechanical data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Locations</td>
<td>Operating range</td>
</tr>
<tr>
<td>Thermometers</td>
<td>LH$_2$ target, o-p converter, cryorefrigerator stages, radiation shields, target outlet. No thermometers inside LH$_2$ chamber</td>
<td>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</td>
</tr>
<tr>
<td>Pressure gauges</td>
<td>LH$_2$ target, main vacuum, He jacket. All located on GHS external to cave</td>
<td>2-&gt;10$^{-7}$ bar on main vacuum and LH$_2$ target. 2-&gt;10$^{-3}$ bar on He jacket</td>
</tr>
<tr>
<td>Heaters</td>
<td>LH$_2$ target, o-p converter, cryorefrigerator stage 2, target outlet at liquid-vapor phase boundary.</td>
<td>0 to 25 W</td>
</tr>
</tbody>
</table>

11.1 Specifications

11.2 Design (M. Snow, 4-22-01)

The pressure gauges and thermometers are commercially available components.

Table 11. Range and type of the pressure transducers.

<table>
<thead>
<tr>
<th>Name of the trans.</th>
<th>Type / Model</th>
<th>Output range (Volt)</th>
<th>Pressure range (Psia)</th>
<th>Pressure range (bar)</th>
<th>Input address in PLC</th>
<th>ADC input range (Volt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PT101</td>
<td>OMEGA PX203-030A5V</td>
<td>0.5 – 5.5</td>
<td>0-30</td>
<td>0-2.068</td>
<td>1:2.0</td>
<td>0-10</td>
</tr>
<tr>
<td>PT102</td>
<td>Millipore NTT205</td>
<td>0.05-5.05</td>
<td>0-500</td>
<td>0-34.48</td>
<td>1:2.1</td>
<td>0-10</td>
</tr>
<tr>
<td>PT103</td>
<td>OMEGA</td>
<td>0.5-5.5</td>
<td>0-30</td>
<td>0-2.068</td>
<td>1:2.2</td>
<td>0-10</td>
</tr>
</tbody>
</table>
Table 12. Voltage & flow range and type of the flow meters.

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

11.3 Test Results

11.3.1 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. 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: Satyaranjan Santra, IUCF
Approved by: Bill Lozowski, IUCF

11.3.2 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: Satyaranjan Santra, IUCF
Approved by: Bill Lozowski, IUCF

12 HYDROGEN DETECTORS

12.1 Specifications
The cave will be equipped with two H₂ monitors and two low-oxygen monitors. The low-oxygen
monitor will be connected to the local alarm. The H₂ sensors will be interlocked to the power of
the cave.

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 and to the LANSCE CCR.
We furthermore propose 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 such as fans associated with hydrogen safety. It would be interlocked in an appropriate manner with the LANSCE safety systems.

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 setpoints and other valve positions), and override controls.

Closed/Not-Closed indication of 22-25 manual round-knob valves will be implemented via one microswitch when it changes state may be used by the SLC. This arrangement allows 2-conductor hookup for each valve.

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 XXX. 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 whole point of the safety design is to allow for the possibility to use ordinary equipment in
the experimental cave by preventing hydrogen from entering the cave in the first place. We
argue that therefore we do not need explosion-proof electronics. This argument was agreed to in
the second safety meeting by 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

14.2.1 Design and specifications (H. Nann, 6-10-01)

We intend to design the ventilation as needed for personnel comfort and the needs of the
experiment. This air flow 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: 6,000 l/min (200 cfm) (this means that we change air in the
cave every 10 min.)

Fan motor either explosion-proof or mounted outside air stream. Rotor to be non-sparking
construction. Exhaust ducted to outside of building.

15 MATERIAL DATA SHEETS AND WELDING AND OTHER CERTIFICATES

Copies of the relevant material data sheets are at web site
www.iucf.indiana.edu/U/lh2target/export-files/. All of the materials listed above 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 certificates

The weldings have been done by certified welders. Certifications at web site
www.iucf.indiana.edu/U/lh2target/export-files/.
16 RADILOGICAL 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) $^3$He(n,p)$^3$H

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

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

Natural abundance of $^3$He: $1.37 \times 10^{-6}$

At STP: 22.4 L of helium contain $6.02 \times 10^{23}$ atoms

1 cm$^3$ at 1.2 atm contains $3.22 \times 10^{19}$ atoms

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

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

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

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

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

Activity: $A = \lambda \cdot N$

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

$$\lambda = \frac{\ln 2}{t_{1/2}} = 1.78 \times 10^{-9} \text{ s}^{-1}$$

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

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

(n,$\gamma$) cross section at 25 meV: $\sigma(25$ 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 $^2\text{H}$: $1.48 \times 10^{-4}$

$20 \text{ L of LH}_2$: 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$_2$: $M = 2.016 \text{ g/mol}$

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

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

$20 \text{ L of LH}_2$ contain $5.83 \times 10^{22}$ deuterium nuclei. They are distributed over a circular area of 30 cm diameter.

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

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

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

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

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 propose 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. 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 (horns, lights, signs). All personnel should leave the area. Neutron beam in experiment flight path shut off. CCR automatically notified. Phone dialer initiated.
Table 13. Warning, alarm, and interlocks.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Location</th>
<th>Trip point</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂ concentration #1</td>
<td>Cave, in stagnant air near ceiling</td>
<td>10% of LEL</td>
<td>Warning</td>
</tr>
<tr>
<td>H₂ concentration #2</td>
<td>Cave, in stagnant air near ceiling</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air flow</td>
<td>Cave exhaust</td>
<td>70% of normal flow</td>
<td>Warning</td>
</tr>
<tr>
<td>Vacuum (pressure) sensor</td>
<td>Vacuum vessel</td>
<td>Bad</td>
<td>Warning</td>
</tr>
<tr>
<td>H₂ concentration</td>
<td>Vacuum vessel</td>
<td>Low</td>
<td>Warning</td>
</tr>
<tr>
<td>H₂ concentration</td>
<td>Vacuum vessel</td>
<td>High</td>
<td>Alarm. H₂ System shutdown and rapid H₂ dump.</td>
</tr>
<tr>
<td>RGA</td>
<td>Vacuum vessel</td>
<td>He peak &gt; Low</td>
<td>Warning</td>
</tr>
<tr>
<td>RGA</td>
<td>Vacuum vessel</td>
<td>He peak &gt; High</td>
<td>Alarm. H₂ System shutdown and rapid H₂ dump.</td>
</tr>
<tr>
<td>RGA</td>
<td>Vacuum vessel</td>
<td>N₂ peak &gt; Low</td>
<td>Warning</td>
</tr>
<tr>
<td>RGA</td>
<td>Vacuum vessel</td>
<td>H₂O peak &gt; Low</td>
<td>Warning</td>
</tr>
<tr>
<td>He pressure</td>
<td>Helium jacket</td>
<td>p &lt; 3 psig</td>
<td>Warning</td>
</tr>
<tr>
<td>H₂ pressure</td>
<td>Target gas in condenser unit</td>
<td>p &gt; 11 psig, p &lt; 9 psig</td>
<td>Warning</td>
</tr>
<tr>
<td>O₂ concentration #1</td>
<td>Cave, at normal breathing space elevation</td>
<td>Low</td>
<td>Warning</td>
</tr>
<tr>
<td>O₂ concentration #2</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- signals connected to facility
- local status signals
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 can be found in web page
www.iucf.indiana.edu/U/lh2target/export-files/.

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

Defination 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- >10⁰/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- <10⁰/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 10⁻¹-10⁴ 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 10⁻⁴-10⁶ tries -or- <10⁻²/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 10⁶-10⁸ tries -or- <10⁶/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 -- Experiment Worker (EW) and Experiment (E)
An Experiment Worker is a person inside the general NPDGamma experiment area.

<table>
<thead>
<tr>
<th></th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>B</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>C</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>4</td>
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<tr>
<td>D</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>E</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>
TABLE 3 –SUMMARY OF CONTROLS REQUIRED

All vessels and associated piping (H2, vacuum, helium):
   Design to approved Functional and Operational Requirements and Design Plan that includes:
      Design to ASME Codes
      Consideration of high reliability and leak-tightness under both pressure and vacuum.
      Capability to contain full rupture of LH2 vessel and withstand rupture(s) of adjacent vessels.
      Capability of vessels to withstand external pressures as appropriate.
      Vent lines and relief valve capacity capable of handling maximum credible gas load from insulating system failures.
      Using highest pressure and thickest materials consistent with physics goals
      Using ASME code relief valves or devices with equal reliability.
      Using ductile materials for all vessels at all temperatures.
      Using mechanical gauges as appropriate.
      Using Power-To-Close valves where appropriate.
      Using Power-To-Open valves where appropriate.

Weld all joints wherever possible.
Using high reliability components

For piping outside cave that is difficult to enclose in helium jacketing, build from very strong, reliable components. Provide mechanical guards to protect from damage.
Verify design with independent FEA analysis.
Build and test to approved QA Plan (e.g., use certified materials, use certified welders, radiograph welds, pressure test final assembly, etc.).

H2 gas handling system:
   Design to approved Design Plan that includes consideration of high reliability and leak-tightness under both pressure and vacuum. Design relief system appropriately for gas supply system failure. Build and test to approved QA Plan. For piping outside cave that is difficult to enclose in helium jacketing, build from very strong, reliable components. Provide mechanical guards to protect from damage.

Helium gas handling system:
   Design pressure control and relief system appropriately to avoid high external pressures on vacuum jacket.
   Design helium jacketing relief system appropriately for He supply system failure.
Enclose weld joints and o-ring seal areas inside cave in helium jacketing so that vacuum space will be filled with helium, not air. Thus, vacuum leaks will draw in helium instead of air, hydrogen leaks will leak into helium instead of air, and there will be one more level of containment for hydrogen components inside the cave.
Control of contamination in H2 gas:
   Have cleanup components in H2 gas handling system.
   Use certified clean feed gases.
Use approved procedures to remove contaminants from H₂ input gas before cool-down. Have helium purge on discharge side of all relief devices.

Control of contamination in vacuum and helium spaces:
    Have helium purge on discharge side of all relief devices.

Provide LH₂ “fast empty” system to quickly remove hydrogen in case of emergencies.

Interlocks:
    LH₂ “fast empty” system interlocked to fire alarm.
    Target pressure and temperature sensors interlocked to alarm and possibly to refrigerator shutoff.
    Target temperature controller interlocked to refrigerator operation and/or flask temperature.
    Vacuum valve(s) interlocked to vacuum or pump operation. Mechanically lock valves as appropriate.

Vent stack:
    Locate vent stack in safe area.
    Put vent line check valve close to exit to minimize length/volume of air/H₂ mixture.
    Purge line between relief valves and check valve with helium.

Operate entire H₂ target system per approved procedures, including QA aspects (e.g., use thorough leak check procedures before each run).

Good housekeeping.
All personnel out of cave during power outage.

Local fire extinguishers

19 DRAWINGS

The drawings for the LH₂ target are saved on a website at IUCF

20 HYDROGEN SAFETY COMMITTEE REPORTS
REFERENCES (H. Nann, M. Snow, 6-25-01)


[9] ASME Boiler and Pressure Vessel Code, Section VIII, Division 1 and 2.


