DESIGN AND SAFETY DOCUMENT OF THE NPDGAMMA LIQUID HYDROGEN TARGET

11 November 2011
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1.0 INTRODUCTION

1.1 Scope of the document

This Design and Safety Document of the NPDGamma Liquid Hydrogen Target gives an overview of the hydrogen target and summarizes design, operation, and safety of the target system. The target will be operated on beamline 13 (BL13) (known also as FNPB) at SNS by the NPDGamma experiment. The Design and Safety Document attempts to coherently summarize most of the detailed documents, calculations, and drawings associated with the target design. In addition, this document lists procedures for safe operation of the target, and defines qualifications and training for target specialists who will be responsible for everyday target operation.

1.2 Overview of the NPDGamma experiment and the hydrogen target

The NPDGamma experiment searches for parity violation in the angular distribution of 2.2-MeV gamma rays produced by polarized cold neutron captures in unpolarized liquid para-hydrogen target. The only way that the experiment can reach the physics goal is to use a 16-liter liquid para-hydrogen target. The 2.2-MeV gamma rays from the neutron capture on hydrogen are detected by CsI detectors surrounding the hydrogen target cryostat. A full discussion of the experiment can be found in [1]. For the purposes of this document we will define the “target” broadly to include (1) the target cryostat and its isolation vacuum system inside the BL13 shielding enclosure (cave), where the neutron captures take place, (2) the gas supply, handling, and target control system external to the cave, and (3) the safety system, including the relief devices and vent lines. Figure 1 shows a conceptual view of the experiment and the beamline. Figure 2 shows an overview of the BL13 setup as shown by the model. The assembly drawing of the experiment is FUND13NPDG00M8U8713-A001. Figure 3 and 4 show views of the apparatus and the components outside the cave as given by the design model.
Fig. 1. A conceptual view of the BL13 with the NPDGamma experiment. The cold neutron beamline BL13 has a curved neutron guide with two choppers. Neutrons from the guide are polarized for the experiment by a supermirror polarizer. Most of the radiological shielding around the beamline and experiment is not shown in figure. The details of the shielding can be found from the radiological shielding report [2]. In addition to the radiological shielding, the experiment has a number of shielding components for gamma rays and neutrons to reduce detector backgrounds. Distance from the moderator to the end of the guide is about 16m and from the guide exit window to the center of the gamma detector array is about 2.5m.
1.3 History of the target: Reviews and the run at LANSCE

In 2006 the NPDGamma experiment with the liquid parahydrogen target was operated for 3 months on FP12 at LANSCE. Before running, the hydrogen target had to pass an extensive review process: in particular, the hydrogen safety was thoroughly reviewed. Prior to the target operation in FP12, several target tests were performed to verify that the target meets specification and operates according to design. For example, these tests included a measurement of the target boil-off rate by opening the isolation vacuum to air when the target was full of liquid hydrogen. During the production run on FP12 the target was filled three times. An overall conclusion from the LANSCE run was that the target performed as designed. The target used at LANSCE is described in detail in the literature [3]. The LANSCE target safety, review reports, and design documentation can be found at the web site http://battlestar.phys.utk.edu mediawiki/index.php/Hydrogen_Target_Documents under Documents of Target Operation at Los Alamos. Results and operating experience at LANSCE have been used to further improve the target safety and performance for the SNS run, where the target has to
meet more stringent safety and physics requirements. The plans for the target improvements are listed in document LH2TargetModificationsb1d.pdf, which is available at web site http://battlestar.phys.utk.edu/mediawiki/index.php/Hydrogen_Target_Documents under Liquid Hydrogen Dewar/ Target Vessel Modifications for SNS.

Fig. 3. Closer view of the NPDGamma apparatus from the design model.
Fig. 4. Outside the cave on a platform is the relief/isolation cabinet. The cabinet contains a relief/isolation chamber that includes all the hydrogen relief systems. A vent stack connected to the chamber conducts the H2 gas safely outside the Target Building. The cabinet is ventilated through a pipe to outside the building. The gas handling cabinet (red) stands on the floor under the platform and contains the hydrogen gas manifold. This cabinet is also ventilated.

Fig. 5. A view of the relief cabinet from mezzanine with cover removed.

1.4 Code compliance plan: codes and standards

A goal in the design of the target was to meet the national codes and SNS requirements. If a component could not be designed to be in strict compliance with the code without compromising the physics goals, equivalent measures were taken, including (for example) FEA analyses or special tests. The target also has some legacy issues; some of the components were designed and used in the target that was operated at LANSCE. These components were reanalyzed and the associated documentation filed as required for the new design. Table 1 lists some of the main codes and standards used in the design.
Table 1. Codes and Standards

- Section VIII of ASME - Boiler and Pressure Vessel
- ASME B 31.3 - Process Piping
- ASME B 31.12-2008 - Hydrogen Piping and Pipelines
- CGA S-1.3 - Pressure Relief Device Standards-Part 3 – Compressed Gas Stationary Storage Containers
- CGA G-5.5 – 2004 - Hydrogen Vent Systems
- Expansion Joint Manufacture Association (EJMA) - division 1, of the ASME Boiler and Pressure Vessel Code, and standards
- DOE-STD-1020, PC-2
- SNSBL13WELDING.pdf describes ORNL welding requirements.
- SNS Cryogenic Manual
- SNS Quality Manual, SNS-QA-P01 Revision 5, SNS 102040000-QA0001-R05

1.5 Target reviews at SNS

The volume of the liquid hydrogen target (16 liters of liquid) coupled with its location inside the BL13 radiological shielding structure (cave) and the presence of several electrical systems inside the cave and in parts of the apparatus dictates stringent safety requirements. A preliminary assessment of the safety goals for the target was performed in 2007 at ORNL by the Liquid Hydrogen Safety Committee. The assessment and recommendations of this Committee, which evaluated a preliminary conceptual design of the target, is summarized in Reportof1stSafetyReview.pdf on the website under Supporting Documents. Due partly to the physics goals at SNS, partly to changes in DOE requirements after the 2006 run at LANSCE, and partly to different levels of safety at ORNL, some major changes in the target were required. These changes are listed in LH2TargetModifications.pdf. The most significant changes relative to the LANSCE system are as follows:

(a) The aluminum target vessel is manufactured in accordance with Section VIII of the ASME Boiler and Pressure Vessel Code and is U stamped. The goal here is to have a pressure stamped LH2 vessel
with a thinner neutron entry window. The use of a stamped hydrogen vessel is a significant improvement of the safety of the target.

(b) To reduce the background contributions in the detector signals, the thickness of the neutron entrance windows on the isolation vacuum chamber has been reduced. This improves the physics performance of the experiment without reducing the overall safety envelope of the target.

(c) A new ~8 m long horizontal section of the coaxial fill/vent/vacuum line is needed to connect the cryostat to the relief/isolation chamber, to the vacuum system, and to the gas handling system located outside the cave downstream from the cave entry. The goal with the new coaxial structure of the fill/vent line is to minimize the number of non-welded demountable joints in the hydrogen system inside the cave. In the coaxial fill/vent line the hydrogen line is inside the vacuum line, which serves as a buffer against air. The hydrogen line itself possesses only one demountable joint between the entrance to the cave and the entrance to the target cryostat. In the cave all demountable joints on the isolation vacuum chamber and on the fill/vent line must be surrounded by helium. Outside the cave all the demountable joints are inside the two ventilated cabinets; the gas handling cabinet and relief/isolation cabinet.

(d) Liquid helium cooling and partial ortho-para conversion of the incoming gas has been replaced with cooling by a mechanical refrigerator coupled to the fill/vent line in order to reduce the target filling time.

(e) The target structure has to meet DOE-STD-1020, PC-2 seismic requirements.

(f) In their role as a part of the “one-time event boundary” of the volume defined as the venting volume, major subsystems (the isolation vacuum volume of the target cryostat, the vacuum volume of the fill/vent line, and relief/isolation chamber) are designed to withstand an internal pressure event of 150 psi as required by CGA G-5.5-2004 to confine a possible detonation/deflagration of the hydrogen in the volume. These design goals mean that various vacuum components such as vacuum gauges, cryocooler couplings, penetrations etc. also must tolerate a one-time 150 psi pressure event without failure. The vent stack also has to be designed to the 150 psi standard as required by CGA G-5.5 – 2004 - Hydrogen Vent Systems.

1.6 Unreviewed safety issue determination (USID)

As the first step in the hydrogen safety assessment of the target, a USID for the target system had to be performed to see whether the installation and operation of the NPDGamma liquid hydrogen target in the
Target Building constitutes an unreviewed safety issue. The emphasis in this assessment was on whether the hydrogen target could significantly affect the previously reviewed analyses of the safety of the mercury spallation target. The negative result of the analysis showed that the hydrogen target doesn’t constitute a USI. The results of the analysis are documented in SNS 102030102-ES0029-R01 located on the website under Supporting Documents.

1.7 The 2nd hydrogen safety review

The 2nd Hydrogen Safety review was held at SNS on September 2008. One of the main conclusions of this review was that “There is enough concern (lack of expertise) from the committee that we (committee) would like the Hydrogen System design to be peer reviewed and further presented to the SNS Cryogenic Safety Committee”. A summary of these comments can be found in 2ndSafetyReview.pdf. Following the advice of the Committee the sizing and safety calculations of the target were verified and findings recorded in the report “Study of Sizing of Components of the NPDGamma Liquid Hydrogen Target with Respect to Hydrogen Safety” by Michael MacDonald in 2009, located at http://www.indiana.edu/~lh2targ/NPDG/SupportingDocuments/LH2TgtEngStudy.pdf.

In addition Phil Buchanan, an expert from National Research Management, was charged to perform a thorough peer review of the overall target system design. His results are summarized in the Design Analysis and Calculations FUND13NPDG-20-DA0001-R00, NPDGamma – Beam Line 13 Liquid Hydrogen Target System, Structural Analysis Calculation. In addition, Peter Ladd from SNS was charged by ISSC to perform a thorough review of the design calculations for the piping and relief systems. This evaluation process has been interactive and has increased the credibility of the design and the calculations.

1.8 Target design review

In April 2010 the Hydrogen Supply to Cryogenic Target, Relief and Vent System Design Review was held at SNS to obtain additional feedback from the SNS experts for the proposed target design. File FUND13NPDG-24-DE0001-R00.pdf contains the presentations and comments from this review.
1.9 Completion of the target construction and installation

The 3rd hydrogen target safety review organized by ISSC was held on October 22, 2010 at SNS. Memo 3rdH2SafetyReview.pdf is from the committee, which lists the review comments. Our responses to the Committee can be found in The3rdReviewMemoResponses.pdf. The 1st IRR of the FNPB instrument was held in November 2010. This IRR dealt with radiological shielding issues of the experiment excluding the hydrogen target, as described in Preliminary Operations Plan for SNS Beamline 13B; Beam Characterization and Test Samples, FUND13NPDG-00-OP0002-R00. The next IRR is planned to be hold in November 2011 to deal mainly with the LH2 target since no modifications to the beam line as approved by the 1st IRR are required. Prior to the 2nd IRR we need to complete the installation, documentation and have executed our testing plan of the target system, see TestPlan.pdf. One item in the test plan is a cooldown with neon gas and operation of the target system with neon as it is assumed to be operated with hydrogen filled target. A part of the IRR committee walked through the target system on October 10, 2011. A walk-down by NRM with respect to the DAC has taken place.

1.10 Responsibilities

The Physics Division and SNS jointly operate the BL13 user program according to the draft MOU “The Operation of the Fundamental Neutron Beam Physics Beamline”, http://www.indiana.edu/~lh2targ/NPDG/SupportingDocuments/MOUDraft.pdf. This MOU proposes the roles and responsibilities of the both parties. The NPDGamma experiment uses the MOU as its guidance for the operations and interaction with SNS.

The NPDGamma experiment works with the BL13 Lead Instrument Scientist Geoff Greene to install and operate the experiment and the LH2 target in BL13B with SNS support to meet safety and other SNS requirements. Internal roles and responsibilities in the experiment are carried by the spokesman (David Bowman/ORNL), project manager (Seppo Penttila/ORNL during the installation and commissioning), project engineer (Rick Allen/ORNL and Jack Thomison/NRM), project ES&H officer (Paul Mueller/ORNL) and nine work package leaders, who in many cases are outside users. The experiment is governed by the NPDGamma Collaboration, which consists some 14 national and international institutes. The charge of the Executive Committee is to follow the operations and make sure that the collaboration decisions are followed. The funding of most of the construction, installation, and operation comes from the DOE Low Energy Nuclear Physics Office through the nuclear physics program manager at ORNL, who presently is the Physics Division Director (David Dean). The responsibility for Safety is shared between the P-division and
SNS. The Physics Division is responsible for the training of the NPDGamma personnel.

The responsibilities of the target construction, installation and safety issues are shared between the Indiana University group led by Mike Snow and the ORNL NPDGamma LH2 target team. The LH2 target effort at Indiana is funded by NSF.

2.0 DESCRIPTION OF THE NPDGAMMA LH2 TARGET SYSTEM

2.1 Introduction of target components and their functions

The NPDGamma liquid hydrogen target and the components of the hydrogen gas handling system (LH2 vessel-fill/vent line-relief system) are shown schematically in figure 5. The 16-liter liquid hydrogen target is contained in an isolation vacuum chamber (IVC). The hydrogen gas is conducted into the LH2 vessel through a single combined fill/vent line, see figures 9 and 10, and condensed into the target vessel using three mechanical refrigerators. The fill/vent line connects the LH2 vessel to a relief system in the relief/isolation chamber (RIC) outside the experimental cave and to a hydrogen gas handling system (GHS). The three hydrogen gas supply cylinders and supply manifold are housed in a cylinder shed (Gas Cylinder Bldg. 107100800M8U8711A098) located on the northeastern end of the slab outside of the Target Building. After passing through two flow restricting devices, FR101 (FR102, FR103) and FR104 and a pneumatically operated valve (PV100, see figure 6), the gas is conducted to the gas handling manifold (GHM) which is located outside the experimental cave, by a ¼"-diameter 100 ft long stainless steel supply line, see figure 4. The gas lines on the gas handling system consist of welded components and Conflat flanged and VCR-based joints constructed for better than $10^{-9}$ atm cm$^3$/s helium leak specifications. All the demountable joints that are exposed to hydrogen are either in ventilated cabinets (gas cylinder building, gas manifold cabinet, #1, and relief/isolation cabinet, #2) or they are separated from atmosphere by helium gas (this method is used inside the cave). In addition to the hydrogen fill/vent line, the gas handling system also possesses a vacuum system for evacuation of the cryostat isolation vacuum, for leak testing of components, and for monitoring the residual gas composition in the main vacuum with a residual gas analyzer (RGA). Two turbo pumps on the gas handling system will be used to evacuate the target vessel, the lines, and the IVC. Pressure gauges on the gas handling system monitor pressures in the target and in the IVC. The GHS manifold is contained inside a metal enclosure (cabinet #1) with a ventilation line to the outside of the SNS experimental hall. Helium manifolds are used to provide helium gas to all vacuum seals and weld joints inside the cave, to fill the vent stack, and to flush and backfill the hydrogen lines. When the target is operated in steady-state mode, most of
the GHS will be isolated using valve MV126, evacuated, and filled with helium gas except for the portions which contain the relief valves, rupture disks, and the residual gas analyzer (RGA). Also the vent stack has also a helium-filled buffer volume (see vent stack section 3.13).

The hydrogen gas from the GHS enters the hydrogen vessel in the cryostat through a flow-restricting device (FR100) and then through a combined fill/vent line (1.5” OD hydrogen line centered inside a 6” OD vacuum line). This fill/vent line possesses a slightly tilted ~8 m horizontal section whose exit is connected to vent isolation chamber that holds the relief valves and rupture disks and a vent stack that vents hydrogen safely outside of the Target Building. The fill/vent line bends 90 degrees to meet the cryostat. At the bend there is a section of the hydrogen line, which is cooled by a mechanical refrigerator to precool the incoming hydrogen gas during target filling in order to reduce the filling time. Inside the cryostat the gas travels vertically into the liquefaction chamber, which is thermally connected to the cooling stages of a pulse-tube cryo-refrigerator, see figure 5. The gas then enters the hydrogen target vessel through the internal ortho-to-para converter, an iron oxide-filled chamber which is thermally connected to a second mechanical refrigerator, see figure 5. The experiment requires more than 99% of the hydrogen to be in the para-hydrogen molecular state [3,4]. The refrigerator cold heads are mounted on the cryostat, and their associated compressors are located outside the BL13 cave boundary on the top of the concrete roof shielding. The cooling powers of the refrigerators suffice to keep the liquefied hydrogen at 17 K and completely perform the ortho-para conversion for the given H2 flow rate. Gas produced by the heat from the ortho-para conversion and by boiloff in the LH2 vessel is re-condensed by the liquefying chamber, and the gas re-circulates in a closed loop until essentially all (99.8% at 20 K) of the liquid in the target vessel is converted to the parahydrogen state. The thermodynamic state of the target is determined using pressure sensors and temperature measurements on the target cryo-refrigerators, ortho-to-para converter, and exhaust line. There are no sensors located inside the liquid hydrogen volume. Pressures, temperatures, flows, temperature stabilizing heater power to the refrigerators, and the information from the RGA is monitored by the target DAQ system (see section 4.1 target monitoring system) which records and displays the history and present status of the target parameters. A target signal processing system (SPS) based on the EPICS system used at SNS (see section 4.2 target signal processing) monitors hydrogen levels inside the cave and inside both cabinets, operates the four pneumatic valves, and guards some of pressures and flows. If a set point of a variable is exceeded the SPS alerts or alarms the target shift specialist. In the case of a hydrogen alarm, the SPS gives an alarm and closes the valves, see section 4.2 and Table 4. The Signal Processing System is designed, built, and maintained by the SNS RAD Protection Systems group. This group is also responsible for the periodic calibration of the four hydrogen sensors.
Fig. 6. A schematic view of the LH2 target showing cryostat, vacuum, fill/vent line, and relief/isolation chamber with relief devices. The three cryo-coolers, locations of temperature sensors and two heaters, and the flow path of the hydrogen gas from gas handling system into the LH2 vessel are also indicated.
2.2 Overall safety aspects of the target

The safety goal in the target design has been to prevent the hydrogen gas from coming into contact with air in the course of any type of target failure. Several aspects of the design contribute to this goal. First of all, the target vessel itself is a pressure vessel built according to the ASME code. The pressure vessel consists of the shell, the entrance and exit heads, and the inlet and outlet nozzles. The target possesses three layers of safety containment. The LH$_2$ target vessel (first containment layer) is connected to the external world by a single fill/vent line. This line is in turn protected from atmosphere inside an isolation vacuum chamber (IVC) and vacuum line (second containment layer), which also provides thermal insulation together with a 80 K radiation shield. Helium channels (third containment) surround the demountable joints and o-ring seals of the IVC and the hydrogen piping system inside the experimental cave. During normal operation the hydrogen is isolated from air by helium-filled buffer volumes wherever and whenever possible. A buffer volume for the vent stack, for example, is formed by RD102 and backside of the relief devices in the relief chamber.
The target safety is first designed to protect the personnel in the experiment and in the Target Building and secondly to prevent property damage. The target safety is designed to handle the worst possible target failures, which are either a loss of isolation vacuum (IVC) or the rupture of the hydrogen vessel into the IVC. The target relief system is designed to handle the hydrogen boil off rates in either accident scenario. This requirement along with the BL13 shielding structure sets constraints on the length and diameter of the fill/vent line piping and the nature and properties of the gas conduction devices (relief valves and rupture disks) described below. Each of the components of the LH\textsubscript{2} target system – hydrogen volume and isolation vacuum – has separate pressure relief systems, which are sufficiently robust to respond safely to any maximum credible accident. The conductance of each safety relief system has been designed to be large enough that a pressure rise will not lead to a rupture of the weakest component in the system. The sizing of the lines and relief systems are discussed in http://www.indiana.edu/~lh2targ/NPDG/312644-001_Vent-Fill_Line/DesignDocs/DesignreliefventRev5.6.pdf. The target system is also designed to withstand forces from earthquakes and tornados as defined by DOE-STD-1020, PC-2, for analysis results see FUND13NPDG-20-DA0001-R0.

3.0 DESIGN OF THE LH\textsubscript{2} TARGET SYSTEM

The physics goals of the experiment coupled with the known properties of cold neutron and MeV-range gamma ray 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 physics 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 > 99.9% parahydrogen at temperatures no higher than 17 K. Given the 10 cm x 12 cm beam size on the polarizer exit window, the phase space of the beam from the cold neutron guide ($m=3$ supermirror neutron guide) and the scattering cross section of cold neutrons in parahydrogen, the target size of 27 cm diameter and 30 cm length has been chosen on the basis of Monte Carlo simulations using MCNP and the LANL hydrogen neutron scattering kernel. This target will absorb 60% of the incident cold neutron flux. The target system therefore requires a cryostat to liquefy gaseous hydrogen and an ortho-to-para converter to catalyze the formation of parahydrogen. The details of the target sizing calculations can be found in [3].
(2) The target must possess negligible attenuation for the incident neutrons and for the 2.2 MeV gammas from neutron capture. This requires the use of low Z materials in the target vessel and associated neutron 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 liquid parahydrogen, we require a liquid target in which bubbles are suppressed to acceptable levels and in which fluctuations in the pressure and temperature of the liquid are held to acceptable levels. The suppression of bubbles will be insured by the following design features: (a) using two cryorefrigerators which will be capable of cooling the radiation shield surrounding the target vessel to a temperature below 80 K, thereby reducing the heat load on the 17 K target LH2 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 in the 17K target.

(4) To ensure that no false effects are introduced by gamma rays produced by polarized slow neutron capture on target materials other than parahydrogen, we must select the target vessel material carefully. The window materials seen by the incoming neutron beam consist of Al alloy (type 6061). The remainder of the components around the target vessel, although made of Al and Cu, are protected from polarized neutron capture by a $^6$Li-rich plastic neutron absorber wrapped around the target vessel and other internal components. This shield possesses a small exit hole at the downstream end of the vessel large enough to permit efficient monitoring of the neutron beam exiting the target. A careful measurement of the transmitted neutrons gives the parahydrogen concentration in the liquid [4]. Materials like Al, Cu, Li, and In are used in the structures of the cryostat and in some seals (In) and they have to be studied in auxiliary measurements as needed to make sure that they do not produce a false gamma ray asymmetry in the experiment.

(5) To ensure that the interaction of circularly polarized gamma rays from neutron capture on parahydrogen produces negligible systematic effects and that the magnetic field in the target can be maintained with sufficient uniformity, the target materials close to the neutron beam must be nonmagnetic (relative magnetic permeability $\mu_r<1.02$). Any magnetic components in the target system must result in negligible magnetic field gradients [5].
In addition to the physics goals, the target system design has to meet the requirement of hydrogen safety, cryogenic safety, pressure safety, radiological safety, and meet the PC-2 requirements for earthquakes.

3.1 Hydrogen gas handling

3.1.1 H2 supply manifold

Figure 6 shows the flow and piping diagram for the target system. Figure 7 shows a snapshot view of the hydrogen supply manifold part of the diagram. The H2 supply manifold drawing is located in document FUND13NPDG24P8U8713-A005-R00. Three size A compressed gas cylinders with 2200 psi initial hydrogen pressure (required for one fill of the target) are connected to the supply manifold. The chemical purity of the hydrogen gas is 99.99% or better, and the equilibrium ortho-to-para ratio in hydrogen gas is 3:1 at room temperature. After the regulators PR101, PR102, PR 103 in the line is a particle sieve followed by flow restrictors (FR101, FR102, FR103) and then a flexible metal hose rated to 1500 psi connecting the cylinders to the supply manifold. The components on the manifold are protected against overpressures by the flow restrictors (FR) and relief valve RV101. The FRs are sized so that, if the regulator fails at the cylinder pressure of 2200 psi, the relief valve RV101 with the cracking pressure of 100 psid and the vent line can handle the flow rate while keeping the pressure in the manifold near the normal operating pressure. Any hydrogen gas flowing from the manifold through RV101 is conducted outside the storage building by a ¼” OD pipe. For details of the flow and pressure calculations in the supply manifold see Flow-Pressures.pdf. The role of FR104 is to limit to flow rate into the Target Building to about 20 SLPM at 100 psia in case the line between the supply manifold and the gas-handling manifold is broken. Normally closed pneumatic valve PV100 is controlled by the Signal Processing System (SPS). If hydrogen gas is detected in the cave or in the two cabinets, PV100 will be closed to stop any additional H2 flow into Target Building. MV131 is used to isolate the supply manifold from the rest of the target system. From the supply manifold a 100-ft long stainless steel ¼" line conducts the H2 gas to the gas handling manifold (GHM) located in the cabinet #1 under the platform. This ¼” line is a long welded line with VCR connections on both ends. The target filling process takes about 1-2 days and the target filling frequency is expected to be about once every two months. When the target filling process is over, the lines and manifolds will be evacuated by hydrogen pump MP101 and filled with helium. A He cylinder connected to the hydrogen supply manifold is used to flush the lines before hydrogen filling and to fill the lines after the target is filled and liquefied. All these operations are performed according to a corresponding procedure. The manifold complies with both ASME B31.3 and ASME B31.12 codes.
Fig. 8. Diagram of the hydrogen supply manifold located outside of the Target Building in the Gas Cylinder Bldg. 107100800M8U8711A098.
3.1.2 Hydrogen supply storage building

Three H2 cylinders, one He cylinder, and the hydrogen supply manifold are located in the prefabricated chemical storage building Gas Cylinder Bldg. 107100800M8U8711A098 which has an approved fire barrier. The hydrogen gas cylinders are held in one of the two independent rooms in this building, which is located on the northeastern part of the slab. Both rooms have their own forced ventilation to remove and leaked gas safely to the outside of the building. The relief valve RV101 has a vent tube that conducts relieved gas outside of the building if the gas pressure exceeds its set pressure of 100 psid. The cylinder securing system is a typical system used in industry. By contrast, the mounting of the manifold and the piping are designed for an earthquake. Operation of the supply manifold and the replacement of empty cylinders are covered by procedure “Operating Procedures for the NPDGamma Liquid Hydrogen Target at the BL13B ; Replacing of an empty hydrogen gas cylinder”.

Fig. 9. Picture of the hydrogen supply manifold in the Gas Cylinder Building. Only the helium cylinder is shown attached to manifold.
3.2 Gas handling manifold

The gas from the supply manifold is conducted to the gas handling manifold by a long stainless steel \( \frac{1}{4}'' \) OD line with welded joints, see drawing FUND13NPDG24P8U8713-A002-R00. The gas handling manifold (GHM) is located in the gas handling cabinet #1 along with a hydrogen proof mechanical pump MP101, which exhausts through a check valve CV102 to the vent stack. Figure 10 shows the diagram of the GHM and figure 11 a picture of the gas handling manifold in place. Components in the GHM are welded where possible. A few demountable (VCR) connections must be used for operational reasons (to allow set point verification of the relief valves, for example).

The maximum gas flow rate into the target vessel is determined by the cooling power of the mechanical refrigerators and the thermodynamic properties of hydrogen, and is approximately 20 SLPM. The flow-control valve FCV100 in the GHM regulates the flow rate of the hydrogen gas into the target. The hydrogen proof mechanical pump MP101, Alcatel model Adixen 2010 C2, is connected to the GHM allowing pumping of the small volume of hydrogen out from the target vessel and the associated piping as needed to complete the warm up or cool down process. The exhaust of the pump is connected through a check valve CV102 to the vent stack. A liquid nitrogen cold trap makes the last cleaning of the gas. The liquid nitrogen cold trap is equipped with two 100-psid relief valves RV102 and RV103. The design drawings for the cold trap are at http://www.indiana.edu/~lh2targ/NPDG/MiscParts/DesignDocs/4010218_6-20-11b1d.pdf. The cold trap (see figure 12) is operated under the GHM operating procedure, which is part of the target operating procedures. The He and N2 gas supply panels are connected to GHM through MV119, He and N2 gases are used to flush and fill the manifold and lines. Figure 10 shows the He and N2 manifolds, see drawing FUND13NPDG24P8U8713-A001-R01. FR100 passively limits the flow rate to about 20 SLPM at 100 psia, the maximum possible pressure in the GHM, see flow restrictor discussion in Flow-Pressures.pdf. The manifold is controlled by both ASME B31.3 and ASME B31.12 codes. From the GHM the gas is conducted into the vent/isolation cabinet and then through MV126 into the fill/vent line and to the target vessel.
Fig. 10. Piping and flow diagram of the gas-handling manifold.

Fig. 11. Picture of the gas-handling manifold in the gas handling cabinet.
3.3 LH2 vessel

Aluminum is the only practical material for the LH$_2$ vessel, which can meet the experimental goals (nonmagnetic, low Z, no LH$_2$ embrittlement, http://www.indiana.edu/~lh2targ/NPDG/312644-001_Vent-Fill_Line/DesignDocs/HembrittlementFINAL.pdf. The question then becomes the shape and wall thickness of the vessel. The target vessel has gone through several design phases, a summary of these designs prior to the ORNL design can be found in the NPDGamma Liquid Hydrogen Target Engineering Document, http://www.indiana.edu/~lh2targ/NPDG/SupportingDocuments/LH2EngDocV3.4.pdf. For the SNS experiment, the neutron entry window on the vessel had to be thinner than that used at LANSCE to reduce the gamma background. The mechanical strength of the thin-window vessel was originally studied by Luttrell, http://www.indiana.edu/~lh2targ/NPDG/315279-000_LH2_Vessel/DesignDocs/LH2vesselORNLEAresuits.pdf. Her FEA analysis indicated that the LH2 vessel can become a stamped pressure vessel and still meet all the safety and physics requirements with thinner Al windows. The vessel has to meet both ASME B31.3 and ASME B31.12 codes. The LH$_2$ vessel is a code-stamped pressure vessel with two weld seams, one at the convex entrance dome and the other at the concave exit dome fabricated by an ASME authorized vendor (Ability Engineering). The
concept of the vessel design was arrived at through FEA calculations also performed at ORNL in [http://www.indiana.edu/~lh2targ/NPDG/315279-000_LH2_Vessel/DesignDocs/LH2vesselORNLFEAresults.pdf](http://www.indiana.edu/~lh2targ/NPDG/315279-000_LH2_Vessel/DesignDocs/LH2vesselORNLFEAresults.pdf). The thickness for the beam entrance and exit windows of the target vessel are 0.0625". The target vessel has a Finite Element Analysis (FEA) calculated MAWP of 71 psia and was successfully tested at 72 psia by the vendor. The document [http://www.indiana.edu/~lh2targ/NPDG/315279-000_LH2_Vessel/Fabrication&TestsRecords/TestsandReports/AbilityVesselReportcopy.pdf](http://www.indiana.edu/~lh2targ/NPDG/315279-000_LH2_Vessel/Fabrication&TestsRecords/TestsandReports/AbilityVesselReportcopy.pdf) contains vendor’s FEA analyses as required by ASME. The document [http://www.indiana.edu/~lh2targ/NPDG/315279-000_LH2_Vessel/Fabrication&TestsRecords/TestsandReports/ThermalCyclingBimetalJointFINAL.pdf](http://www.indiana.edu/~lh2targ/NPDG/315279-000_LH2_Vessel/Fabrication&TestsRecords/TestsandReports/ThermalCyclingBimetalJointFINAL.pdf) describe our thermal cycling and helium leak checking performed at Indiana University to confirm the performance of the aluminum to stainless steel bimetallic joints in the hydrogen target vessel. An overall vendor report on the design, QA, and testing/certification of the target vessel is stored in [http://www.indiana.edu/~lh2targ/NPDG/315279-000_LH2_Vessel/Fabrication&TestsRecords/TestsandReports/](http://www.indiana.edu/~lh2targ/NPDG/315279-000_LH2_Vessel/Fabrication&TestsRecords/). Document [http://www.indiana.edu/~lh2targ/NPDG/311220-000_VacuumVessel/Fabrication&TestRecords/QAvesselwindowsFINAL.pdf](http://www.indiana.edu/~lh2targ/NPDG/311220-000_VacuumVessel/Fabrication&TestRecords/QAvesselwindowsFINAL.pdf) provides the documentation of the procedures and instruments used in the tests of the vessel and vacuum windows.

### 3.3.1 Bi-metallic joints

Low thermal conductivity stainless steel connection lines are required to minimize cryogenic heat loads into the target and must be connected to the aluminum vessel. Commercial friction welded bimetallic joints are used to join the aluminum target vessel to the stainless steel fill and vent lines. The bimetallic joints were designed and procured by Indiana and welded to the target vessel by certified welders at Ability Engineering. The document [http://www.indiana.edu/~lh2targ/NPDG/311220-000_VacuumVessel/Fabrication&TestRecords/QAvesselwindowsFINAL.pdf](http://www.indiana.edu/~lh2targ/NPDG/311220-000_VacuumVessel/Fabrication&TestRecords/QAvesselwindowsFINAL.pdf) also provides information on the pressure and helium leak testing of these components since this was performed after the bimetallic joints has been welded to the vessel. Testing was performed on these joints to confirm that they can withstand the required internal pressure during accident scenarios and thermal cycling. The results of these tests are contained at [http://www.indiana.edu/~lh2targ/NPDG/315279-000_LH2_Vessel/Fabrication&TestsRecords/TestsandReports/ThermalCyclingBimetalJointFINAL.pdf](http://www.indiana.edu/~lh2targ/NPDG/315279-000_LH2_Vessel/Fabrication&TestsRecords/TestsandReports/ThermalCyclingBimetalJointFINAL.pdf). Figure 13 shows the assembly of the target vessel, OPC, condensing chamber, a section of fill/vent line, and 6Li loaded plastic neutron shielding that is wrapped around the assembly.
3.4 Fill/vent line

The fill/vent line is shown in figures 14, 15, 16, and 17. The function of this coaxial line is to connect the target vessel and the target IVC to the relief/isolation chamber where the relief devices are located and where the gas line from the gas handling manifold is connected to the fill/vent line. Design and fabrication of the fill/vent line is one of the largest modifications to the previous target system operated at LANSCE. In addition to the ability to respond to the most serious accident scenarios mentioned above, the required functions of this fill/vent line system also include:

(1) safe filling of the hydrogen gas into the target vessel,
(2) precooling of the incoming hydrogen gas to help minimize the overall time of target filling,
(3) evacuation of the target and cryostat isolation vacuum,
(4) consistency with the vacuum monitoring requirements for hydrogen
safety involving the use of a RGA on the IVC to monitor for leaks into the IVC,
(5) proper design to withstand an earthquake according to SNS PC-2 requirement, see FUND13NPDG-20-DA0001-R0,
(6) proper design to handle the thermal contraction and expansion of the hydrogen line experienced during the target venting, ThermalDistribution.pdf and FUND13NPDG-20-DA0001-R00,
(7) proper design of the support structure to handle the ~5000-lb truss load in the 6” line caused by use of bellows when the 6” line is under vacuum, see FUND13NPDG-20-DA0001-R00,
(8) safe conduct of the hydrogen gas from the target vessel to the relief/isolation chamber during the target warm up process, see http://www.indiana.edu/~lh2targ/NPDG/312644-001_Vent-Fill_Line/DesignDocs/DesignreliefventRev5.6.pdf
(9) safe conduct of the hydrogen gas from the IVC to the relief/isolation chamber in case of a rupture of the target vessel http://www.indiana.edu/~lh2targ/NPDG/312644-001_Vent-Fill_Line/DesignDocs/DesignreliefventRev5.6.pdf,

The fill/vent line has to meet both ASME B31.3 and ASME B31.12 codes. Design documents of the fill/vent line can be found at http://www.indiana.edu/~lh2targ/NPDG/312644-001_Vent-Fill_Line/DesignDocs/. Figures 14 and 15 show assembly of the fill/vent line. The fill/vent line consists of a welded hydrogen fill/vent tube inside of a vacuum tube with a long horizontal section and a short vertical section with a portion of the hydrogen line cooled by a mechanical refrigerator. On the target/cryostat end, the fill/vent line connects to the target vacuum system and the target vessel. On the downstream end past the cave boundary the fill/vent line connects to the relief/isolation chamber and the hydrogen target gas handling system, see flow and piping diagram. The distance from the target to the relief chamber is about 9 m.
Fig. 14. Assembly drawing of the coaxial fill/vent line. During filling the incoming hydrogen gas is cooled and then conducted into the target vessel. The line also serves as the relief path for the hydrogen from the vessel to the relief system. The 6" vacuum line connects the IVC to the vacuum pumps and relief system outside the cave and also serves as a boundary between hydrogen volume and air. The purpose of the bellows is to accommodate inevitable small alignment errors with respect to the relief chamber and the cryostat. It must also handle the truss load from vacuum and thermal contraction.
Fig. 15. Model view of the assembly of the cryo-cooler end of the fill/vent line. Incoming gas is pre-cooled by a cryo-refrigerator. The 70 K radiation shields at the 90 degree bend are indicated by brown color. Not visible in this model view are two electrical feedthroughs on the right side 6” CF flange.

The hydrogen fill/vent line is a 1.5” outer diameter stainless steel tube (inner diameter: 1.37”) interspersed with bellows. All joints in the hydrogen line are welded by certified welders except for a demountable 2.75” Conflat flange connected to the liquid hydrogen vessel at the lower end of the vertical section. 10% of the welds are radiographed for QA. The 280” long horizontal section has an upward tilt angle of 0.5 degree from the bellows to the relief/isolation chamber for venting hydrogen gas. Several support structures inside the 6” pipe mechanically support the hydrogen
line in the center of the pipe, thermally isolate the line, and stabilize the line against any possible uncontrolled radial motion relative to the vacuum line. The outside surface of the hydrogen fill line vertical section is wrapped in cryogenic superinsulation to reduce the heat load from thermal radiation. The hydrogen fill line is surrounded by a 6" outer diameter (inner diameter: 5.75") stainless steel vacuum tube. One end will be mounted to the top of the cryostat isolation vacuum chamber and the other end will extend through the hole in the cave wall to the relief/isolation chamber. The assembly procedure for the hydrogen fill line inside the vacuum line, both of which consist primarily of welded components, was nontrivial and requires a coordinated sequence of welds, weld inspections, flux dye penetrants and radiography tests, and subsequent helium leak checking/testing with weld joints strategically located to ensure that all of the assembly and testing described above is possible. The use of vacuum-compatible components inside the vacuum with minimal outgassing is required to allow the use of sensitive partial pressure monitoring by the RGA to verify the absence of leaks and therefore the maintenance of the triple containment condition for the hydrogen.

All the Conflat flanged joints in the vacuum line inside the experimental cave but outside the target vessel are concentrated in the 90 degree bend area. This area is surrounded by a helium gas atmosphere contained in an aluminum box, which seal on the outside of the vacuum tubing. An example of such a cover in the horizontal/vertical transition region is shown in figures 16 and 17. The vacuum line connects to the isolation vacuum chamber with a flange possessing a double o-ring joint (indium on the inside and viton elastomer on the outside) with helium gas between the sealing rings.
Fig. 16. Model view of an aluminum box assembly around the 6-way cross of the fill/vent line. The box is sealed gas tight around the pipes and is continuously flushed inside with helium gas to maintain the triple containment requirement in the CF flange joints in the cave.
3.4.1 Bellows

Stainless steel bellows in both the 1.5" hydrogen line and the 6" vacuum line are used for reducing stresses from thermal contraction during the filling and operation of the target system and the venting of the cold hydrogen gas and also to help meet mechanical tolerances in alignment/assembly. The specifications for the bellows are included in http://www.indiana.edu/~lh2targ/NPDG/312644-001_Vent-Fill_Line/DesignDocs/HlineBellowsCertificationinfoFINAL.pdf

In the horizontal section the central 1.5" tube is radially constrained in the 6" line by centering spiders. At each end there is a 1.5" bellows with the outer ends fully constrained by welded brackets. This allows for thermal contraction due to cooling of the central line. Since the bellows are axially constrained at each end, deformations short of full squirm (at 178psi for these bellows) should not occur. Since this section is axially aligned and there are fixed points just outside the bellows, loads due to pressure differential are not taken up on the bellows (other than on the convolutions themselves).

The 1.5" bellows between the cold head and the 6" bellow are also fully axially constrained between the welded bracket and an axial spider. Here the loads due to thermal and pressure differentials are necessarily taken up axially by the cold head and differential contraction is taken up by the bellows, estimated to be on the order of 0.06" at 20 K, see
For the bellows just before the connection to the LH$_2$ vessel, a bellows frame is required to prevent large 5000 lb cantilever loads on the cold head due to thermal contraction and pressure differentials. We will pre-position the LH$_2$ vessel so that after cooling it will end up centered in the beam. Results for the load analysis on the fill/vent are presented in FUND13NPDG-20-DA0001-R00.

In certain hydrogen accident scenarios the relieved gas from the target vessel will cool the fill/vent line, which will decrease the length of the long line. In ThermalDistribution.pdf we estimate the size of the contraction and in FUND13NPDG-20-DA0001-R00 the load from the contraction is analyzed when the 6" bellow length is locked with the three rods, see figures 14, 15, 17. When there is no vacuum in the line, the 6" bellow is in its nominal length. When the line is under vacuum, there is an 850-lb axial force on the bellow trying to shorten its length, which is prevented by the nuts on the rods inside the bellow flanges. In an incident where the 6" line cools down and its total length shortens about 1", there is a strong axial force to make the bellow longer to accommodate the length change. The rods have nuts outside the bellow flanges positioned so that a 1-inch increase in the bellow length is possible.

Other possible hazard specific to the fill/vent line and their mitigations are discussed in LH2HazardAnalysisFINAL.pdf. All the Conflat flanges and VCR joints of the fill/vent line in the relief/isolation chamber end are inside the ventilated relief/isolation cabinet.

### 3.5 Cryocooler and electrical feedthroughs

Three electrical feedthroughs on the cryostat will provide signal paths for all thermometers in the target and control of heaters. All target signal wiring is located in the main vacuum chamber; there is no penetration through the hydrogen boundary. The 6-way 6" CF cross in the fill/vent line is used to allow the connection of the horizontal and vertical parts of the line and coupling of the precooling cryo-cooler. One of the 6" access flanges will possess three helium leak-tight ceramic electrical feedthroughs for instrumentation connections (electrical heaters and thermometers) from the target cryostat. The MAWP for these electrical feedthroughs is 165 psig. Shear stress of the feedthrough welds under 150 psig internal pressure have been analyzed in [http://www.indiana.edu/~lh2targ/NPDG/312644-001_Vent-Fill_Line/DesignDocs/3X50SubD_8inCF.pdf](http://www.indiana.edu/~lh2targ/NPDG/312644-001_Vent-Fill_Line/DesignDocs/3X50SubD_8inCF.pdf). Another access flange will connect to the mechanical refrigerator to the 1.5" tube.

3.6 Precooling of H2

In order to reduce time to liquefy the hydrogen gas and fill the target vessel, and thereby increase the target safety by reducing the time when the hydrogen gas is in the gas handling system, a mechanical refrigerator is used to accelerate the filling by pre-cooling the incoming gas. The pre-cooler consists of a mechanical refrigerator with compressor located outside the cave. This refrigerator is mounted to the 6-way 6" cross which connects the main vacuum line vertical and horizontal sections, see figures 9, 10, and 11. A copper sleeve with direct thermal contact to the second stage of the refrigerator is soft soldered onto the outside of the hydrogen line to cool down the stainless steel tubing and the incoming gas flow. A radiation shield is connected to the first stage of the refrigerator and surrounds a portion of the cooled fill/vent tube. The available cooling power is 35 W at 77 K and 12 W at 20 K. The temperature of the refrigerator will be monitored using diode thermometry. None of these elements change the integrity/safety of the hydrogen line as there are no new joints introduced. The refrigerator will cool the hydrogen gas with the maximum flow rate of 10 SLPM to approximately 100 K temperature. The estimated target filling time with the pre-cooler is about 24 hours, significantly shorter than the three day filling time at LANSC. The measured cooling rates are shown in the document http://www.indiana.edu/~lh2targ/NPDG/312644-001_Vent-Fill_Line/DesignDocs/FilltimeestimateFINAL.pdf. Results of the cooling test of the 3rd refrigerator are reported in http://www.indiana.edu/~lh2targ/NPDG/312644-001_Vent-Fill_Line/Fabrication&TestRecords/refrigerator3coolingtestFINAL.pdf.

3.7 Cooling of the LH2 vessel

The two cryo-refrigerators on the cryostat will both be two-stage closed-cycle refrigerators. The liquid hydrogen flows down the fill line into a liquefaction chamber, and ortho-to-para converter, and the bottom of the 16-liter cylindrical hydrogen target vessel. The vessel is wrapped with 6Li-loaded flexible plastic neutron shielding (~2mm thick) and superinsulation (Mylar coated with aluminum on both sides with adjacent layers separated by polyethylene netting) and is supported and separated from the 80 K copper radiation shield by a thermally-insulating support structure made of a G-10 ring. Thermal connections of both refrigerators to the target chamber, ortho-to-para converter, and radiation shield are made by mechanical connections to the cold stage flanges, see figure 13. A similar G-10 support structure separates the 80-K radiation shield from the inside of the main vacuum chamber. This support structure allows the liquid target vessel to slide horizontally upon thermal contraction. Stresses on the target vessel from differential thermal contraction in the vertical direction are accommodated with the use of a stainless bellows on the target line. Stress
on the 80-K 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 refrigerator. The inlet/outlet line of the target has bends to avoid excessive radiating thermal heat loads from a line-of-sight view of room temperature surfaces. Thermometry, heaters, and associated electrical wiring and target monitoring are discussed in section 4.1.

3.8 Hydrogen-liquefying chamber and ortho-para converter

The gas from the fill/vent line enters a copper liquefaction chamber thermally connected to the upper cryo-refrigerator with internal grooves to increase the surface/volume ratio for hydrogen condensation. Hydrogen gas is liquefied in this chamber and then drips down into an ortho-para converter. Stainless steel lines guiding the hydrogen gas into and out of the liquefaction chamber are either welded (to stainless parts) or silver soldered (to copper parts). A 1.33” Conflat flange with strengthening clamping flanges for larger axial sealing forces to withstand accident scenarios is present between the fill/vent line and the liquefaction chamber, see figure 13.

An ortho-para converter (OPC) in the hydrogen loop on the cold stage of the lower cryorefrigerator at 17 K is required to convert fully the liquid to the parahydrogen state required by the experiment in a short time period. The convertor body must possess high thermal conductivity to be capable of removing the heat from ortho-to-para conversion process in the convertor material. The convertor volume must also be capable of being heated for reactivation of the convertor material. This operation requires opening of the isolation vacuum and pumping of the hydrogen line while introducing heat to OPC. The body of the convertor is made of copper to have a good thermal contact with the cryocooler head to remove the conversion heat, and to allow the converter material to be heated for regeneration if necessary. We use hydrous ferric oxide Fe$_2$O$_3$ as the convertor material. The Fe$_2$O$_3$ is prevented from leaving the OPC with two layers of fine wire mesh on the inlet and outlet tubes.

The inlet to the converter has a 2.75” Conflat flange to allow for filling of the convertor powder. This inlet is located below the hydrogen-liquefying chamber. The outlet is connected to a small diameter stainless steel tube welded to the target vessel. Joints on the OPC are vacuum brazed. Details of the design and testing are described in http://www.indiana.edu/~lh2targ/NPDG/SupportingDocuments/TargetplumbingOPCsepeb1dWMS.pdf
3.9 Target cryostat

The target cryostat consists of an isolation vacuum chamber (IVC) with neutron beam entrance and exit windows, many layers of superinsulation, a 100 K shield made from Cu sheet for thermal radiation, the target vessel itself, and interconnected plumbing. The target has to meet also the earthquake code DOE-STD-1020, PC-2, see report EarthquakeAnalysisvessel.pdf.

Fig. 18. The target cryostat. The beam is coming from the left, the cylindrical section of the cryostat is inside the gamma detector array and holds the LH2 vessel. The rings on the left are beam collimators made from 6Li loaded plastic.
Fig. 19. The target cryostat installed on the beam line. The neutron beam is coming from the left. The back cover of the cryostat is removed for access inside the cryostat. A 10-gauss magnetic field for the experiment is produced by four current coils, and three of them (the red colored coils) can be seen in the picture. In front of the cryostat is the gamma detector array covered by a black neutron absorbing shield.
3.9.1 Isolation vacuum chamber (IVC)

The vacuum thermally isolates the target vessel from the warm walls of the isolation vacuum chamber (IVC). In addition it provides one of the “triple containment” boundaries between the liquid hydrogen and air, and it is designed to form the last level of the hydrogen boundary in the accident scenarios. The outer jacket of the IVC is constructed entirely of 6061-T6 aluminum by a contractor (Ability Engineering), see figures 18 and 19. The outer jacket of the IVC, except for the new neutron entrance windows, was used in the LANSCE experiment in 2006. The IVC possesses a horizontal cylindrical region with 0.25” wall thickness, which inserts into the gamma detector array and a downstream rectangular cross-section box with 1.25” thick walls with a removable 1.25” thick back plate sealed with an outer viton o-ring seal and an inner indium seal. Nonmagnetic Helicoil inserts are used 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 number of weld joints. The inside surface of the chamber and the inside surfaces of the windows are polished to a mirror finish and also covered with aluminum tape to reduce emissivity of heat radiation. All the demountable joints and weldments in the IVC are surrounded by internal channels filled with slowly flowing helium.

The design information for the IVC can be found from http://www.indiana.edu/~lh2targ/NPDG/311220-000_VacuumVessel/, BeamWindowDesignSafetyFINAL.pdf and also from the document http://www.indiana.edu/~lh2targ/NPDG/SupportingDocuments/LH2EngDocV3.4.pdf, which was the design and safety document for the target system operated at LANSCE. Report http://www.indiana.edu/~lh2targ/NPDG/311220-000_VacuumVessel/Fabrication&TestRecords/AETVacuumvesselreportsco.py.pdf contains the design/QA/testing reports for the IVC.

3.9.2 Neutron beam windows

The beam entrance and exit windows in the IVC define the MAWP of the IVC to 31 psid. The double neutron entrance and exit windows on each end of the IVC are formed from 6061-T6 aluminum alloy into a trapezoidal shape for increased strength, see figure 20. Report http://www.indiana.edu/~lh2targ/NPDG/311220000_VacuumVessel/Design Docs/BeamWindowDesignSafety-FINAL.pdf contains a detailed description of the design calculations, FEA analyses, and safety mitigation involved in the design of the vacuum windows. Document http://www.indiana.edu/~lh2targ/NPDG/311220
contains the vendor’s test report on the windows. The entrance and exit windows are 0.062" thick per window to minimize the gamma backgrounds in the detector. The MAWP of the entrance and exit window is 31 psid. SNSBL13LH2MVVWINDOW.pdf contains a comparison of the vacuum window properties with Code requirements.

3.9.3 Cu shielding against thermal radiation

Copper shielding against thermal radiation surrounds the LH2 vessel and the interconnected piping and is connected to a cryorefrigerator to reduce thermal radiative heat loads on the LH2 vessel. In the IVC we have – from outside to inside – a 0.5 cm thick multilayer of superinsulation to reduce radiative heating, radiation shielding made from 0.04” thick copper foil connected to the second stages of the cryorefrigerators and operated at about 100K, a G-10 ring to support the target vessel, more superinsulation, a copper cylinder around the target vessel, and the 6Li plastic neutron shielding. None of these layers are vacuum tight. Superinsulation is used in areas outside the neutron beam and Al foils in the beam areas. The function of the superinsulation, Al foil, or Cu is to minimize thermal radiative heating on the LH2. In addition they also serve to reduce convective heat transfer to the LH2 vessel in case of a failure of the vacuum. An additional shield against the radiative heating is the 6Li-loaded neutron absorber, a 3-4 mm thick 6Li loaded plastic, see figures 13 and 20. This shield will absorb neutrons that have scattered out from the liquid hydrogen and would otherwise create a gamma background.
Fig. 20. A side cut view of the target IVC. The neutron beam enters from the left. The locations of the 6Li plastic neutron absorber sheets inside the cryostat are shown in blue. The purpose of the neutron shield is to absorb neutrons that scatter out from the liquid hydrogen before being captured to minimize gamma ray backgrounds.

3.9.4 He channels

Inside the cave every demountable seal or welded joint in the IVC or in the fill/vent line has a He channel. Helium gas is introduced into the space between the double-layer neutron entrance and exit windows, into gas channels machined into the IVC between the inner indium 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 isolation vacuum. To
prevent helium diffusion through the inner seals they are made with indium. If a leak occurs in a welded joint, demountable joint, or seal in the vacuum chamber, the leak is detected immediately by a residual gas analyzer (RGA), which monitors the helium partial pressure in the IVC. If the partial pressure passes a predetermined set point level, the Signal Processing System will close PV100 and give an alert, see table 4 in section 4.2. The helium channels also prevent air or other gases from penetrating into the vacuum through such leaks if they appear. If gases other than helium (and hydrogen) get in contact with the cold LH$_2$ vessel or the cold sections of the hydrogen piping, they will immediately freeze. The presence of solidified gases are difficult to detect, as they will not produce a pressure increase.

### 3.10 Vacuum system

The target vacuum system consists of two turbo pumps TURBO 1 and TURBO 2 with dry backing pumps. The main function of the vacuum system is to keep the pressure in the IVC low enough for cryogenic operation. Since the operating temperature of the LH2 target is 20 K or less, the cold surfaces in the target will efficiently pump any gases: the pumping speed of the cold surfaces is significantly larger than the pumping speed of 70 l/m by turbo 2, whose speed is in any case limited by the long vacuum/vent line. The degassing comes from the many layers of superinsulation in the IVC. Because of the potential for condensation of gases onto cold surfaces (except for He and H2), a warm up of the target after a long run must be done slowly so that the turbo pumps can pump vaporizing gases out without any overpressure in the IVC. CV201 is used to protect against over pressures in the IVC during warm ups.

#### 3.10.1 Vacuum system and pumps

Figure 21 shows the relief/isolation cabinet (cabinet #2), which contains the relief/isolation chamber as well as the vacuum system. The vacuum system has two turbo pumps; TURBO 1 and TURBO 2, which are backed by roughing pumps DMP201 and DMP301. The pumps are located outside the cabinet and are connected to the target isolation vacuum by two pneumatic in-line valves PV204 (normally closed) and PV207 (normally closed). These valves are interlocked to the target Signal Processing System (SPS) and their function is to isolate the pumps from the main vacuum if changes in the target parameters monitored by the SPS require a change in the status of the valves, see Signal Processing System section 4.2, table 4. The pneumatic valves PV204, PV207, and PV303 are operated through the SPS. After a power failure the valves will close and the vacuum is protected, and in a failure of the isolation vacuum the valves will be closed by the SPS. The pump system (mainly TURBO 1) is used also to pump the GHM through MV124. The vacuum system flow and piping diagram is shown in drawing 13. TURBO 1 keeps the local gas...
pressure low enough for RGA operation. Components of the vacuum system that requires electricity such as pumps and pressure transducers are located outside of the relief cabinet.

Fig. 21. A snapshot view of the vacuum parts in the flow and piping diagram.

### 3.10.2 RGA

A residual gas analyzer (RGA) in the gas handling system is used to monitor with high sensitivity the partial pressures of water, $O_2$, $N_2$, and He both in the hydrogen lines and in the IVC during target testing prior to cooling, and to sample the main vacuum residual gas composition for helium and other gases during hydrogen operation. The helium partial pressure level in the IVC is monitored by the Signal Processing System, see section 4.2.

### 3.11 Relief/isolation chamber

The function of the relief/isolation chamber is to house the relief devices, relief valve RV104 and parallel rupture disk RD101, and the two parallel rupture disks of the IVC, RD201 and RD202. The relief/isolation chamber has to meet both ASME B31.3 and ASME B31.12 codes. The relief/isolation chamber (RIC) design documents and drawings can be found at [http://www.indiana.edu/~lh2targ/NPDG/315337-000_ReliefChamberMods/](http://www.indiana.edu/~lh2targ/NPDG/315337-000_ReliefChamberMods/).

The installed relief/isolation chamber is show in figure 22. A vertical cut view of the RIC is shown in figure 23. The RIC allows all the four main relief devices to vent to a single volume and relieved gas conducted by a single vent stack to outside the Target Building. The hydrogen fill/vent line is
terminated by relief valve RV104 and a parallel rupture disk RD101. The 6"
vacuum/vent line is terminated by parallel rupture disks RD201 and RD202. After the relief devices the volume up to RD102 during the hydrogen operation is filled with helium to 2 psid to form a buffer volume between air and hydrogen. This volume is used also for a sensitive He leak checking of the relief devices. The RIC is designed for a 150 psi one-time pressure event, see FUND13NPDG-20-DA0001-R0. The RIC is installed to the ventilated relief cabinet on the support platform, which is designed for seismic forces, see FUND13NPDG-20-DA0001-R0.

3.11.1 Relief of overpressures from the LH2 vessel and from the isolation vacuum chamber

The hydrogen fill/vent line and relief system have been designed with the two most serious incident scenarios in mind. The function of RV104 and a parallel rupture disc RD101 is to protect the LH2 vessel for overpressures. In a boiloff of the liquid hydrogen in the target vessel the following relief events can take place;

1) For an extremely fast boiloff of the liquid hydrogen from a loss of isolation vacuum (LOV) an overpressure is generated in the vessel and in the 30 ft long fill/vent line. RD101 ruptures, RD102 ruptures and the relieved gas flows into the vent stack, which conducts the gas outside of the Target Building. During this event, the pressure in the LH2 vessel before the ruptures of RD101 and RD102 can reach up to 56 psia, which is less than MAWP of the vessel, 87 psia. After the ruptures the pressure in vessel 15-20 psia.

2) For a very fast boiloff from a partial LOV with an overpressure generated in the vessel and fill/vent line, RV104 opens and the relieved gas flows into the buffer volume. If the flow rate is high enough, the pressure in the buffer volume increases over the rupture pressure of RD102, 7psid, and the gas flow into the vent stack. During this event, the pressure in the LH2 vessel before the rupture of RD102 can reach up to 42 psia, significantly less than MAWP of the vessel, 87 psia. After the rupture pressure in vessel settles to about 35-40 psia.

3) For a reasonably fast boiloff, RV104 opens but CV105 can handle the flow without a pressure difference of 7 psid across RD102. Pressure in the vessel reaches 38 psia. After opening of RV104, pressure in vessel settles to about 35 psia.

4) For a slow boiloff from the target emptying process, MV128 will open and the gas slowly flows through CV104 and CV105. The pressure in the vessel settles to 20 psia.
In case of a rupture of the target vessel or piping inside the IVC and a LH$_2$ release into the vacuum, a pressure relief system with two parallel rupture disks RD201 and RD202 with the rupture pressure of 7 psid, is designed to safely release the hydrogen gas through the 30 ft long and 6” diameter fill/vent vacuum line into the RIC and to the vent stack while maintaining the pressure within the isolation vacuum chamber at a safe level, less than 30 psia, which is significantly less than MAWP of 46 psia of the IVC vacuum windows. Figure 22 shows the RIC installed on the ventilated relief cabinet on the platform, figure 23 shows a horizontal cut view of the RIC, see also figure 5.

![Vent isolation chamber and Fill/vent line](image)

Fig. 22. A model view of the relief/isolation chamber inside the ventilated relief/isolation cabinet with the cabinet cover removed. See also the photo in figure 5 from the relief cabinet.

The pressure relief valve RV104 has an ASME rated mass flow capacity of 140 g/s and a 20 psid calibrated set pressure. This defines a minimum requirement for the items in the hydrogen line; they have to withstand an internal pressure of 38 psia. In addition, a rupture disk RD101 with a set point of 30 psid is used in parallel with RV104 in case RV104 does not function properly. The LH$_2$ target pressure in the steady state operating mode will not exceed ¼ above the atmospheric pressure: $1.25 \times 14.7 \text{ psia} = 18.4 \text{ psia}$. See table 2.
Fig. 23. Horizontal cut view of the relief/isolation chamber with assembled relief valve, RV104, and rupture disks RD101, RD201, and RD202. Gas enters from the fill/vent line port on the left side and exits on the right side to vent stack. See detailed drawings in drawing series 315337.

Transient pressures in the hydrogen line must stay below the MAWP during the relief process, and the hydrogen flow must remain subsonic. For a given rate of vaporization of the liquid hydrogen in the target, this requirement sets a minimum gas conductance for the path between the target vessel and the vent stack. We have experimental data on the rate of vaporization of the liquid hydrogen in our system under these conditions from operation at LANSCE, and we have calculated the gas conductance for our SNS design. We estimate that the pressure in the target vessel will rise to no more than 35 psia with the pressure relief device RV104 open, see table 2 and http://www.indiana.edu/~lh2targ/NPDG/312644-001_Vent-Fill_Line/DesignDocs/DesignreliefventRev5.6.pdf. Similar considerations apply to the second accident scenario. We estimate that the pressure in the IVC will rise no more than 19 psia. Again, this is far below the MAWP, see table 3. Detailed calculations for both of these scenarios are presented in the document http://www.indiana.edu/~lh2targ/NPDG/SupportingDocuments/AnalysisConflatsUnderPressure.pdf. Accidentscenariotesting.pdf describes testing performed in support of these calculations. Ventisolationchamberreport.pdf contains the calculations and specifications for the relief/isolation chamber. ThermalDistribution.pdf calculates the temperature distribution during
venting. Bellows performance can be found from HlineBellowsCertificationInfoFINAL.pdf, and the strength analysis of the Conflat flange can be found from AnalysisConflatsUnderPressure.pdf

Table 2. Internal pressures for components in the hydrogen line and relief pressure for relief through RV104 and RD102 or relief through RD101 and RD102.

<table>
<thead>
<tr>
<th>Component</th>
<th>Operating internal pressure (psia)</th>
<th>Calculated maximum internal pressure (psig)</th>
<th>Tested internal maximum pressure (psig)</th>
<th>Vessel pressure (psia) during relief through - RV104 (20psid) - RD102 (6psid)</th>
<th>Vessel pressure (psia) during relief through - RD101 (30psid) - RD102 (6psid)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LH2 vessel</td>
<td>18.4</td>
<td>72</td>
<td>72</td>
<td>41</td>
<td>51</td>
</tr>
<tr>
<td>Bellows</td>
<td>18.4</td>
<td>186</td>
<td>75</td>
<td>41</td>
<td>51</td>
</tr>
<tr>
<td>1.3&quot; Conflat joint</td>
<td>18.4</td>
<td>-</td>
<td>100</td>
<td>41</td>
<td>51</td>
</tr>
<tr>
<td>PT106</td>
<td>18.4</td>
<td>?</td>
<td>?</td>
<td>41</td>
<td>51</td>
</tr>
</tbody>
</table>

Table 3. Internal pressures for devices connected to the isolation vacuum volume and relief pressure in the isolation vacuum.

<table>
<thead>
<tr>
<th>Component</th>
<th>Operating internal pressure</th>
<th>Calculated maximum internal pressure (psia)</th>
<th>Tested internal maximum pressure (psig)</th>
<th>Pressure (psia) in isolation vacuum during relief through RD201/RD202 (7psid) and RD102 (6psidf)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isolation vacuum chamber with windows</td>
<td>vacuum</td>
<td>46</td>
<td>46</td>
<td>28</td>
</tr>
<tr>
<td>1.5&quot; bellows</td>
<td>vacuum</td>
<td>50</td>
<td>193</td>
<td>28</td>
</tr>
<tr>
<td>8&quot; Conflat joints</td>
<td>vacuum</td>
<td>?</td>
<td>200</td>
<td>28</td>
</tr>
<tr>
<td>Ceramic electrical feedthroughs</td>
<td>vacuum</td>
<td>na</td>
<td>165</td>
<td>28</td>
</tr>
</tbody>
</table>

3.11.2 A possible deflagration and explosion in fill/vent line: 150-psig one-time-event boundary

The triple containment of the liquid hydrogen, the helium backfilling of unused piping, the helium gas surrounding all welds and demountable joints, the RGA monitoring of partial pressures in the isolation vacuum, the thorough helium leak checks prior to target fillings, the ventilated gas
cabinets surrounding gas handling system components, the checklists and procedures which will be implemented for target filling and operation, and the absence of electrical feedthroughs into the hydrogen volume all greatly reduce the probability that hydrogen will come contact with air with more 4% concentration in the presence of an ignition source. Nevertheless one can ask whether or not the hydrogen remains contained in such an event: namely, a deflagration or explosion in the fill/vent line.

According to CGA G5.5 – 2004- Hydrogen Vent Systems, if the appropriate “one-time event boundary” of the volume defined as the venting volume (in this case the vacuum volume formed by the cryostat isolation vacuum, vacuum of the fill/vent line up to the relief devices) is capable of withstanding an internal pressure of 150 psi, then even in this extreme event the hydrogen can be contained. We have, therefore, conducted a series of tests and analyses to evaluate whether or not our system meets this requirement. The answer is yes. The analysis consists of a combination of test measurements on components, FEA analyses, and use of standard Code estimation procedures. These measurements and calculations are summarized in the document deflagration.pdf. Report AnalysisConflatsUnderPressure.pdf contains relevant FEA calculations. In report Ventlinestress.pdf shows results from stress calculations in the tubing. SNSBL13CROSSEVALUATION.pdf contains a FEA analysis of the 6-way cross on the fill/vent line. ExemptioncomponentlistV1.2.pdf lists the relevant properties of components in the fill/vent line. See also http://www.indiana.edu/~lh2targ/NPDG/312644-001_Vent-Fill_Line/DesignDocs/VentLineStress150PSIFINAL.pdf http://www.indiana.edu/~lh2targ/NPDG/SupportingDocuments/AnalysisConflatsUnderPressure.pdf

3.12 Vent stack

The vent stack has to meet CGA G5.5 – 2004- Hydrogen Vent Systems and the seismic PC-2 requirements, see FUND13NPDG-20-DA0001-R00 and SNS welding requirement SSNSBL13WELDING.pdf. A 6” OD pipe made from stainless steel conducts relieved gas from the RIC to outside the Target Building, see drawing FUND13NPDG-24-P8U8713-A001-R~1. Because of the short length of the line and its large diameter, the vent stack makes a negligible change to the overall flow impedance for the hydrogen gas as indicated in document http://www.indiana.edu/~lh2targ/NPDG/312644-001_Vent-Fill_Line/DesignDocs/DesignreliefventRev5.6.pdf. During a hydrogen operation the volume in the vent stack defined by relief devices and RD102 is filled with He gas to 2 psid to isolate the air and hydrogen. Figure 12 shows the RIC cabinet and vent stack and ventilation line.
3.13 Cabinet ventilation line

Outside the cave the demountable VCR and Conflat joints are located inside the two cabinets, #1 and #2, so that the gas from any leak from a loose joint is contained and conducted outside the building. The cabinets are connected to each other with 6” OD pipe section and then from the cabinet #2 a 6” OD pipe conducts the gas outside the Target Building. This pipe has also to meet CGA G5.5 – 2004- Hydrogen Vent Systems and the seismic PC-2 requirements, see FUND13NPDG-20-DA0001-R00. The 6” OD pipe is made from stainless steel, see drawing FUND13NPDG24P8U8713-A001-R~1. The buoyancy of the hydrogen gas in air and “chimney effect” drives any hydrogen leaking from a joint outside the Target Building. The designed maximum ventilation rate is estimated to be 20 SLPM which is also the maximum flow rate of hydrogen in the gas handling system. Each cabinet is equipped with one hydrogen sensor. Vent isolation/relief cabinet drawings are shown in FUND13NPDG24M8U8713-A003-R00.

4.0 INSTRUMENTATION

The target instrumentation is required for the operation of the hydrogen target. The instrumentation can be divided into two subsystems: one internal to and another external to the isolation vacuum. Inside the isolation vacuum the instrumentation consists of thermometry in the target vacuum and pressure gauges in the GHS and RGA. See figure 5 for the locations of the diode temperature sensors. Outside the isolation vacuum, the instrumentation consists of flow meters, pressure transducers, hydrogen sensors, readouts, and a computer to display the parameters and file records for offline data analysis.

4.1 Monitoring of target performance

The main target operating parameters are the target vessel temperatures, the vapor pressure of the LH2, the isolation vacuum pressure, the pressure of and flow rate in the Helium channels, and the helium pressure in the vent stack buffer volume. During target filling the H2 flow rate and hydrogen supply pressures are monitored. Document target-instrumentation.doc gives the wiring diagram for the target thermometers and their locations in the cryostat. ComputerDAQFINAL.pdf describes the computer, software, and features of the PC, which reads data from the LH2 target but doesn’t have any feedback tasks. The only feedback loops in the target are the three heaters H1, H2, and H4 on the cryo-refrigerators, which have set points with temperature sensors T1, T2, and T12, respectively. The heaters keep the target temperature constant and are also used to help vaporize the hydrogen liquid during the target emptying process. The
target data are filed for data analysis, and some of the information is also sent to the main DAQ system of the NPDGamma experiment. target-instrumentation.doc, http://www.indiana.edu/~lh2targ/NPDG/Controls/ComputerDAQFINAL.pdf.

4.2 Target signal processing system

The primary function of the Target Signal Processing system is to monitor hydrogen levels in the cave and in the two cabinets, the secondary task is to monitor the pressure in the isolation vacuum, helium partial pressure in the isolation vacuum, hydrogen pressure in the target vessel, and flows and source pressures in the He channel manifold and in the vent stack buffer volume. The target Signal Processing System has three modes of operation;

a. Bypass Mode, no hydrogen in system
b. Normal Mode, hydrogen in system, this is the LH2 target run mode
c. Emergency Stop Mode, this manual stop overrides the other two modes.

In the Bypass Mode with no hydrogen in system, all controls are available to the Target Shift Specialist and the Signal Processing System is used to operate the pneumatic valves and read the pressures and flows.

In the Emergency Stop Mode, when the emergency button has been pushed, the pneumatic valves, PV100, PV204, PV207 will be closed and the power to PT204 will be turned off.

The switch from the Bypass Mode to the Normal Mode is performed by a Hall Coordinator who has the system key. The Signal Processing System will be turned to the Normal Mode when the target filling with hydrogen starts.

When the Signal Processing System is in the Normal Mode and there is an alarm other than hydrogen, the alarm can be acknowledged on the monitor by shift specialist. The Lead Experiment Scientist has the staff login authority, and can remove the alarm and open the closed valves and turn power on.

If one of the four hydrogen level sensors measures 10% of LEL value, which is 0.4% hydrogen in air, there will be an alert and PV100 will be closed and stays closed until the H2 alert is cleared. If the hydrogen level reaches 25% LEL, there will be an alarm including an audio signal from a horn: PV100 will be closed and both the alarm and PV100 will stay closed until the H2 alarm is cleared. During the hydrogen alarm, there is no staff login authority. If a H2 sensor fails, the SNS RAD Protection Systems group will have access and can put the failed sensor into maintenance mode during the replacement of the sensor. Detailed description of Target Signal Processing System is given in Instrument Controls BL13 LH2 Target Signal Processing, SNS-109090200-PN00XX-R00. Table 4 shows the SPS responses to different signal set points.
Table 4. Signal Processing System responses to sensor signals.

**ACTION MATRIX FOR THE BL13 LH2 TARGET SIGNAL PROCESSING WHEN HYDROGEN IN SYSTEM**

<table>
<thead>
<tr>
<th>Event</th>
<th>Alert</th>
<th>Alarm</th>
<th>PV 100</th>
<th>PV 303</th>
<th>PV 207</th>
<th>PV 204</th>
<th>PT 204</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial state of valves before H2 operation</td>
<td>off</td>
<td>off</td>
<td>c</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>ped</td>
<td></td>
</tr>
<tr>
<td>H2 filling starts</td>
<td>on</td>
<td>on</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>ped</td>
<td></td>
</tr>
<tr>
<td>If following event then:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydrogen sensors lower level 10% LEL</td>
<td>x</td>
<td>c</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Visual alarm</td>
</tr>
<tr>
<td>Hydrogen sensors upper level 25% LEL</td>
<td></td>
<td>x</td>
<td>c</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Visual and audio alarm</td>
</tr>
<tr>
<td>Hydrogen sensor failure</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Loss of power</td>
<td>x</td>
<td>c</td>
<td>c</td>
<td>c</td>
<td>c</td>
<td>po</td>
<td></td>
<td>Visual alarm</td>
</tr>
<tr>
<td>RGA; relay activated</td>
<td>x</td>
<td>c</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>po Visual alarm</td>
</tr>
<tr>
<td>RGA failure</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PT204; relay activated</td>
<td>x</td>
<td>c</td>
<td>c</td>
<td>c</td>
<td>c</td>
<td>c</td>
<td>po</td>
<td>Visual alarm</td>
</tr>
<tr>
<td>PT204 failure</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Visual</td>
</tr>
<tr>
<td>PT106 lower limit passed</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Visual</td>
</tr>
<tr>
<td>PT106 upper limit passed</td>
<td></td>
<td></td>
<td>x</td>
<td>c</td>
<td></td>
<td></td>
<td></td>
<td>Visual</td>
</tr>
<tr>
<td>PT106 failure</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FM501 limit passed</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Visual</td>
</tr>
<tr>
<td>FM501 failure</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FM701 limit passed</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Visual</td>
</tr>
<tr>
<td>FM701 failure</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PT501 limit passed</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Visual</td>
</tr>
<tr>
<td>PT501 failure</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>I</td>
</tr>
<tr>
<td>PT701 limit passed</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Visual</td>
</tr>
<tr>
<td>PT701 failure</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manual emergency shut off</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

c=closed, o=open, po=power off, ped=powered
LFL=lower flammable limit in air = 4.1%, deflagration
LEL=lower explosive limit for hydrogen
Lower detonation limit is 18.3% hydrogen in air.
When the Target Signal Processing system is in the Normal Mode and the hydrogen alarm is on, the target shift specialist cannot stop the alarm; it stops only when the alarm is cleared.

The target signal processing system is designed, built, and maintained by the SNS RAD Protection Systems group. They are also responsible for the periodic calibration of the four hydrogen sensors. The target signal processing system is described in documents Integration Test Document, SNS-RAD-ICS-PN-0001-R00, ACL, SNS-RAD-ICS-PN-0002 - R00, and Requirements Document, SNS-RAD--SR-ADICSSR0001-R00.

Set point values other than hydrogen sensor set points are defined by the experiment. If the set point of the sensor monitored by the Target Signal Processing System needs to be changed, the Lead Experiment Scientist and Lead Instrument Scientist will discuss the proposed change, the change will be recorded and confirmed with their signatures.

5.0 TARGET OPERATION

5.1. Target operation

The experiment including the target system is operated under RSS 8305.0 "Installation, Commissioning, and Operation of the NPDGamma Experiment at the FNBP. Detailed tasks in the target operation are performed under the Operating Procedures for the NPDGamma Liquid Hydrogen Target System at the BL13. The procedures cover leak checking, cooldown, steady-state running, the normal target emptying process, emergency target emptying, replacement procedures for empty H2 cylinders, how to perform a bubble leak test after a H2 cylinder has been replaced, how to perform a helium leak check of the GHS, how to pump and flush the GHS with He, how to calibrate relief and check valves, how to operate vacuum system, and other operations. The procedures are authorized by the Lead Experimental Scientist and Lead Instrument Scientist.

5.2 Training of target personnel

Everyday target operation is the responsibility of a Target System Shift Specialist or a Target System Expert. These are two different seniority levels with different knowledge/skill requirements and responsibilities. Roughly, the difference is that a Specialist knows how to monitor the performance of the target system and what the different components are but is not allowed to change running conditions of the target without permission of the Target Expert in charge.

5.3. The NPDGamma LH2 target system shift specialist training
The NPDGamma LH2 Target System Shift Specialist (TSSS) Training consists of On-the-Job-Training (OJT) as directed by the ORNL Physics Division NPDGAMMA LH2 Target System Shift Specialist training module FUND13NPDG-31-OP0002-R00 and specified by the ORNL Physics Division Fundamental Neutron Physics Beam Line (SNS BL13) NPDGAMMA LH2 Target System Shift Specialist Qualification Standard FUND13NPDG-31-ST0001-R00. The LH2 Target System Shift Specialist Qualification Standard is based on the OJT that was used at Los Alamos National Laboratory (LANL) when the NPDGamma experiment was run at LANSCE in 2006. The LH2 Target System Shift Specialist Qualification Standard follows the guidance given in the Guide to Good Practices for On-the-Job Training (DOE-HDBK-1206-98) and ORNL On-The-Job Instructor Training (Module 14017). The LH2 Target System Shift Specialist Qualification Standard incorporates as much as possible the content and organization of the Target Operations Shift Technician Initial Qualification Standard (SNS-OPM 4.T-7) (SNS mercury target technician’s training), that is relevant for On-the-Job-Training (OJT). After the TSSS has based OJT and his/her performance positively evaluated, the Lead Experiment Scientist will proposed to the Lead Instrument Scientist to authorize the person to be TSSS.

During the LH2 target operation, hydrogen in the target system, a Target System Shift Specialist has to be present in the experiment 24/7.

5.4. The NPDGamma LH2 target system shift expert selection

The NPDGamma LH2 Target System Shift Expert (TSSE) will be selected from the qualified TSSSs. A TSSE candidate is assumed to have solutions for abnormal target conditions and they are expected to show a significantly higher level of knowledge and skills than a TSSS.

Target System Shift Expert selection is performed by the Target Scientist from among the certified NPDGamma LH2 Target System Shift Specialists. Certified Shift Specialists are eligible for selection for TSSE if they can demonstrate to the satisfaction of the Target Scientist the following:
- Sufficient operational experience as a Shift Specialist
- Thorough knowledge of general cryogenic and vacuum operations
- Thorough knowledge of hydrogen safety
- Detailed knowledge of the NPDGamma LH2 target system through design, testing or assembly
- Familiarity with Experimental Hall services that interface with LH2 target system
- Detailed knowledge of LH2 target system documents and procedures
- Good working relations with Instrument Hall Coordinators and other SNS staff
- Clear understanding of all possible LH2 target system accident conditions
and responses
- Mature safety judgment
- Ability to communicate clearly during rapidly changing situations

The Target Scientist and Lead Instrument Scientist will discuss the possibility to nominate a TSSS to a TSSE and the decision will be confirmed with signatures of both Scientists.

During the target filling or emptying processes, a TSSE who is in charge has to be present on the experiment with a TSSS. During normal operation – meaning that the target is smoothly running and the experiment is taking data - there has to be at least a TSSS on the experiment and an Expert on call.

5.5 Operation of the LH2 target

Target operation includes four different phases:
1. Preparations
   a. vacuum checking,
   b. flushing and cleaning lines,
   c. instrumentation check
2. Filling of the target
3. Operation of the target
4. Emptying the target

All these operations will be performed by a Target System Shift Specialist and/or a Target System Shift Expert according to Operating Procedures for the NPDGamma Liquid Hydrogen Target System at the BL13. Prior to the target system operation, the system has to go through testing according to the TestPlan.pdf and have the required approvals for hydrogen operation.

The target is designed so that after the filling process has been completed (when the Target Experts and Specialists are both actively involved) and the target is running in its normal mode, the target does not need active manual control: only its performance will be monitored. In case of a failure, the relief system will allow the hydrogen to be conducted passively and safely outside the Target Building.

During normal operation the only automatically controlled target parameter is the target temperature. The temperature sensor readings of T2, T3, and T12 are stabilized by heaters, H1, H2, and H4, respectively. A stable target temperature is required for the physics measurement. Currents in the two heaters are set and the feedback loop keeps the temperature at the set point by regulating the current in the heaters. The Target System Shift Specialist can change the temperature set points but this has to be agreed by the experiment since the change of the target temperature will change the ortho-para ratio in the target. For the other set points (pressure in the hydrogen line, vacuum pressure, and He content in the IVC), a change of the set points must go through the target parameter change process; the
experiment has to agree to the new set point value and it needs to be documented and signed by the Lead Experiment Scientist and the Lead Instrument Scientist.

As described above the target Signal Processing System has feedback tasks. When certain set points are passed the signal processing system will alert or warn the Target System Shift Specialist and close PV100 to stop H2 flow to GHS or isolate vacuum pumps from the IVC by closing PV204 and PV207. The alerts and warnings from the Signal Processing System inform the Target System Shift Specialist that the target system is in an abnormal condition, see section 4.2. This allows the Target System Shift Specialist to perform additional monitoring and contact the Target System Shift Expert for advice to fix the problem.

6. QUALITY PROGRAM

The quality program of the project is based on the laboratory Quality Program and the use of the SNS Quality Manual, SNS 102040000-QA0001-R05.

The goal of the quality program is to provide advice for the safe, efficient, reliable, and compliant performance of the experiment and especially for the LH2 target to achieve the scientific result. The quality program includes;

1) A proper management structure for the project with well-defined responsibilities. An example of an imperfect situation here is that the MOU between the beamline, P-division, and SNS has not been yet signed.
2) Use of proper engineering approaches, incorporating design, reviews, inspection visits to vendors, configuration management, operating procedures, etc.
3) Personnel and environment safety.
4) Use of the highest competence available and training procedures such as OJT.

6.1 Configuration management

The design documents of the target system are filed in Project Wise, the training documents are kept by Physics Division, and at a website maintained for the experiment by the Indiana University group. The existing signed documentation defines the baseline for the design of the target system and should describe accurately the as-built target system. Any change to the target system baseline has to go through the document change revision process, defined by the QA program. If the proposed change significantly affects the approved safety envelope of the experiment, the proposed change has to get approval from the IRR committee.
6.2 Calibration of the instruments

6.2.1 Calibration of relief and check valves

The LH2 target system consists of a number of relief and check valves. All the relief valves and the check valves used in the target system are manufactured by Swagelok. The overall safety of the target system depends on the functionality of the safety devices that have to work as designed. Therefore, the calibration of the relief valves and check valves is necessary and has to be performed prior to the installation and operation of the target. The calibration has to be performed following the Operating Procedures for the NPDGamma Liquid Hydrogen Target System at the BL13; Setting and measuring opening pressures of relief and check valves in the NPDGamma hydrogen target system.

This calibration requirement covers all the relief valves and check valves except for RV104 which has to have a valid manufacturer’s calibration with a certificate, see http://www.indiana.edu/~lh2targ/NPDG/315337-000_ReliefChamberMods/Fabrication&TestRecords/RD101.pdf and http://www.indiana.edu/~lh2targ/NPDG/315337-000_ReliefChamberMods/Fabrication&TestRecords/RV104.pdf.

6.2.2 Calibration of the other instrumentation

Pressure transducer PT204 monitors pressures in the isolation vacuum within a pressure range of $10^{-4} – 10^{-6}$ bar. PT204 is a new pressure gauge with a factory calibration. Its performance has been compared with other vacuum gauges. PT106 have been calibrated against a Mensor 15000 precision digital pressure indicator with an accuracy of 0.25%. The Mensor gauge has also been used to calibrate other pressure transducers which do not play any direct safety role in the experiment but are required for operations.

6.2.3 Calibration of the hydrogen sensors

The calibration and maintenance of the four hydrogen level sensors, two in the cave and two in the gas cabinets, is the responsibility of the SNS RAD Protection Systems group. Calibration procedure is described in the Integration Test Document SNS-RAD-ICS-PN-0001-R00.

6.3 Testing of the target system at Indiana
The components of the target system and assembled parts of the target system have been tested at Indiana and the testing reports can be found on the website. Prior to shipping the target system to ORNL, the target was cooled down and 2 liters of liquid neon was condensed and the full target system cryogenically tested, test results are reported in Heatloadtovesselrev5b15d.pdf. During the test a test was performed where the vacuum was spoilt and then boil off rate of neon was measured to establish the heat load to the target in this failure scenario, see report HeatLoadtoVesselbyspoilingVacuum.pdf. In these test the fill/vent line was not in place but was tested separately with the precooling system, see report TestofPrecooling.pdf.

7.0 FAILURE AND HAZARD ANALYSIS

The RSS 8305.0 Installation, Commissioning, and Operation of the NPDGamma Experiment at the FNPB includes a general hazard analysis of the NPDGamma experiment at BL13 including the LH2 target system. The document FailureHazardAnalysis.pdf specifically discusses hazards related the LH2 target. Tritium production in the target is considered in TritiumProduction.pdf.
REFERENCES


