1. Introduction

This document describes the hazards associated with the standard Hall A and Hall C liquid hydrogen targets at the Jefferson Laboratory.

2. Description of System

The cryogenic target installation consists of the hydrogen and deuterium storage tanks, located behind the counting house (outside the building), a gas panel, located in the hall, the actual target, and piping which connect the tanks with the gas panel and the target. The gas panel is used for pump/purge operations and filling the targets. Flow diagrams for the systems are included as an appendix. These systems are constructed entirely of metal. Metal gasketed fittings (Conflat, VCR, or equivalent) are used where demountable joints are required.

The actual target consists of a thin-walled aluminum cell mounted on an aluminum block with entrance and exit flanges for the target fluid. The fluid is circulated through the cell and a heat exchanger by a vaneaxial fan, which is located inside the heat exchanger. The fan motor is submerged in the target fluid. The fluid passes over a heater, which is used to regulate the temperature of the fluid. The complete assembly of target cells, the heat exchanger and the piping that connects them is referred to as a "target loop" (figure 1).

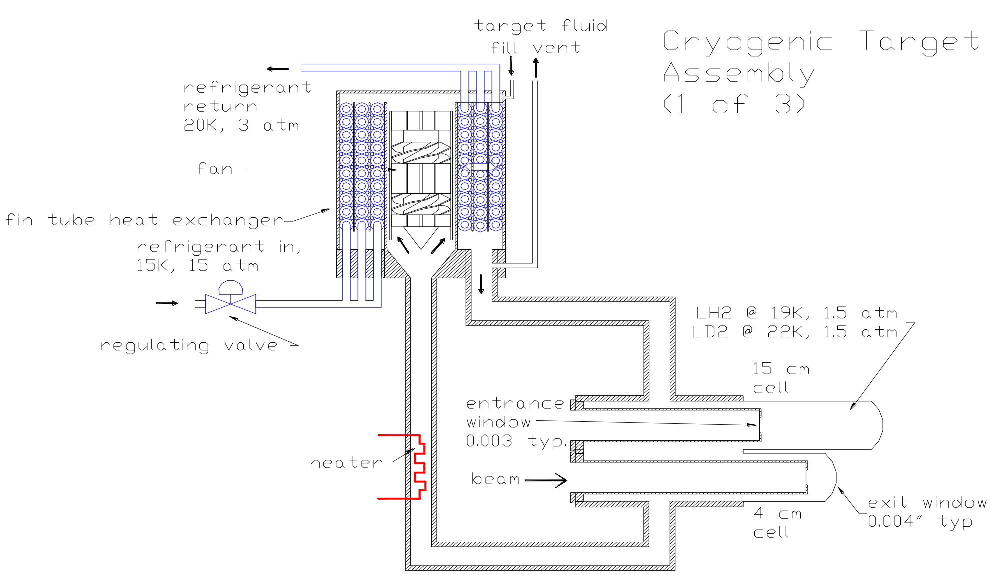

Figure 1. Schematic representation of a typical target loop.

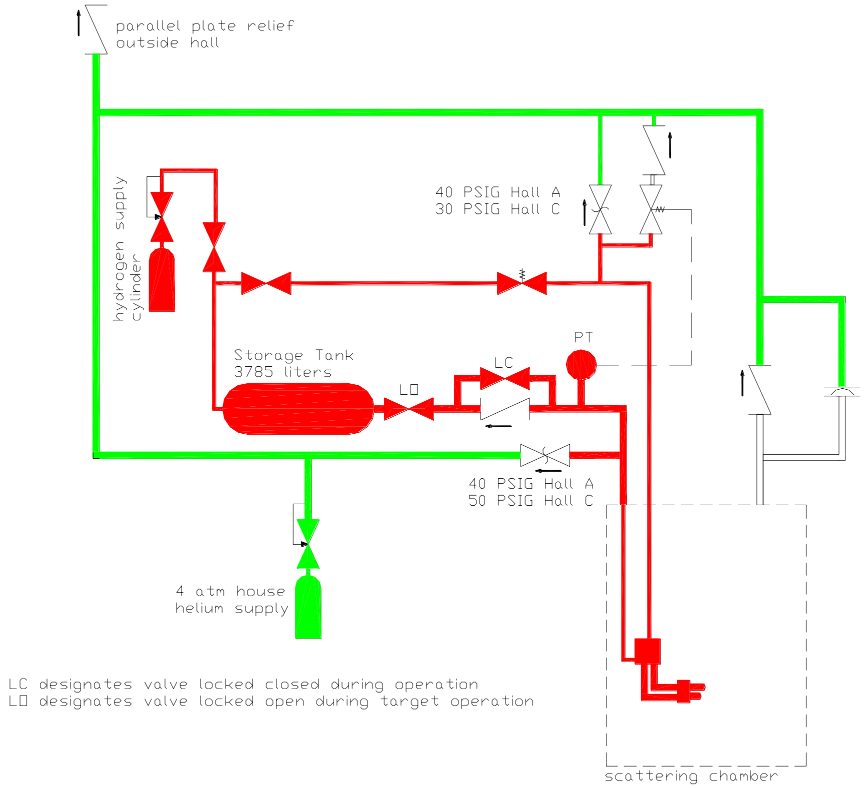

Figure 2. Simplified target flow diagram. Only one of three target loops is shown.

Our target systems contain three target loops. In normal operation, one target loop will contain hydrogen and one will contain deuterium. A third target loop, filled with low-pressure helium gas, serves as a spare. The heat exchangers are normally cooled by 15K helium gas from the End Station Refrigerator for hydrogen target operation. The target has also been operated with 4K helium liquid refrigerant. Each target loop is connected to an external gas handling system by a fill and a vent line. In the hydrogen and deuterium gas handling systems, the target return line is connected to a gas storage tank via a check valve to provide a simple, passive pressure relief. Relief valves which vent outside the hall provide a secondary relief path. A simplified flow diagram for a single hydrogen or deuterium loop is shown in Figure 2. The target loops are mounted inside the scattering chamber, with the target cells in a vertical array. The scattering chamber is fitted with large, thin aluminum windows for the spectrometers. The required target cell is positioned in the beam by an external lifting mechanism. In Hall C the cryogenic target is also able to rotate out of the beam to allow the introduction of a separate solid target assembly. The positioning devices are interlocked to prevent a foul between the two.

Several different types of target cells have been used. The most common has been a dual long (15 cm) and short (4cm) cell arrangement. These target cells are cylindrical with 0.007" thick walls and 0.003" thick entrance and 0.004" thick exit windows. The outer wall of the cell is 2.6" in diameter and is formed from an aluminum beverage can by etching the end of the can to the required thickness. The entrance window is formed by soldering an aluminum foil (annealed 5052) to the end of an aluminum tube. The entire assembly of cells, entrance windows and the cell block is soft-soldered together by first copper plating the surfaces to be soldered. This arrangement of entrance window and cell provides a target volume which is well forward of obstructions (such as piping for the target fluid), allowing the spectrometers to view the targets even when set at large angles. These thin-walled cells typically have burst pressures of approximately 80 psi, however, the observed burst pressures vary widely due to variations in the chemically etched exit windows.

Other cells which have been used include 1.6" diameter cylinders with spherical ends machined from 7075 aluminum and having 0.005" thick exit windows and walls (burst pressures over 400 psi). Upright cylinders (beam enters and exits through cylindrical wall) have also been used. These cells have 0.005" thick walls and typically burst at 270 psi when fabricated from 6061 alloy and 400 psi when fabricated from 7075 alloy.

2. Hazard Analysis

These are relatively small, simple systems and we have eight years of experience in their operation. A formal hazard and operability analysis has not been prepared. Possible failure modes are summarized in Table 1. The presence of a significant quantity of flammable gas is the major hazard associated with this system. The formation of a hydrogen/air mixture is to be avoided. When the target is in use, the bulk of the hydrogen/deuterium inventory is condensed in a thin-walled cell located inside a vacuum chamber that is fitted with thin windows. This clearly represents the greatest hazard for the uncontrolled release of hydrogen. The sudden loss of vacuum in the chamber, possibly caused by the failure of a window, would cause the hydrogen to boil rapidly and burst the cell if an adequate relief path for the target cells is not present. The failure of one cell, for any reason, would cause the sudden loss of isolation vacuum for the other cell. If one or more cells were to fail then expanding gas could cause the scattering chamber windows to rupture if an adequate relief path for the scattering chamber is not provided. If any gas other than helium were to contaminate the hydrogen or deuterium gas systems then these contaminants would freeze out in the target piping and could block the relief path. The possibility that frozen deuterium would block the relief path if temperature regulation of the loop fails has long been a concern. (The 15K refrigerant inlet temperature is normally above the freezing point of hydrogen). The target fluid temperature is set by a heater which is controlled by an IOC (single board VME computer). A second heater power supply, which can be controlled manually from the counting house, can be used to operate the heater if the IOC fails and must be rebooted. (The fluid temperatures can be observed on a TV monitor in the counting house if the IOC is unavailable). A target operator is required to be on shift at all times when the target contains liquid. With targets in operation in Hall C since 1996 and in Hall A since 1997, no events in which the target fluid froze have been observed.

Table 1 Cryogenic Target Failure Modes

Event	Possible Consequences	Mitigating Measures
Scattering chamber window failure due to excessive load or puncture.	cell rupture on loss of isolation vacuum	windows tested to failure windows tested for failure on puncture adequate relief path for target cells provided
Breach of scattering chamber window and cells by tool or object.	hydrogen/air mixture in the scattering chamber	window covers visual warning of target status limit access to pivot
Damage hose during a target move if hose becomes entangled with fixed object.	hydrogen/air mixture in hall solid air condensed in target target cell burst on warm-up	metal braid jackets on all flammable gas hoses check lifter operation after reinstallation
Cell failure due to excessive internal pressure.	chamber window rupture	adequate relief for chamber adequate pressure testing of cells
Cell failure if relief path blocked by frozen contamination or target fluid.	chamber window rupture	adequate relief for chamber maintain system above 1 atm at all times manual back-up heater controls
Breach of gas panel piping due to material handling accident or human error.	hydrogen/air mixture in hall solid air condensed in target target cell burst on warm-up	piping protected and labeled
Breach of tank or piping due to vehicle accident, material handling accident or human error.	hydrogen release	concrete barriers proper postings

Since these targets have been in use, three events have occurred in which significant quantities of hydrogen have been released from the targets. These are summarized in Table 2.

ODH hazards are mitigated by the enormous volume of the halls (40×10^6 liters for Hall A and 26×10^6 liters for hall C) in comparison with the volume of gas present in these systems.

In the past, the scattering chamber pressure relief was provided by a 4" parallel plate relief valve. Any event in which a cell ruptured caused hydrogen to be vented into the hall. When the targets are reinstalled in 2004, the scattering chamber relief valves will vent outside the hall through a 2" line maintained under a helium gas atmosphere. With this improvement, a flammable mixture of helium and air could only be formed in the hall if both a vacuum window and a cell fail simultaneously. The new relief line will include ports to purge all parts of the line with helium in the event that hydrogen is released into the line. The vent line will be fitted with a pressure switch which will alert the target operator if a positive pressure is not maintained in the vent line.

Table 2 Past Cryogenic Target Failures

Event	Cause	Corrective Measures
Destruction of cells	lifter malfunction	lifter converted to single axis drive, mechanical stops installed, electrical over-travel protection installed
Burst hydrogen cell	contamination blocked gas lines	low pressure alarm installed check valves changed to eliminate leaks automatic valves removed from computer control helium buffered vent line to be installed
Window and cell failure	Beam exit window failed. Cell burst due to crossed fill and vent hoses.	thin beam exit window eliminated hoses modified to prevent interchange additional relief valves installed

3. Flammable Gas

A. Flammable Gas Installation Classification

For the purpose of evaluating the flammable gas hazard in the hall the quantity of gas that would reduce the storage tank pressure to one atmosphere is considered. No additional gas will flow into the hall once the storage tank pressure reaches one atmosphere.

Hall A: The 1000 gallon storage tanks are initially pressurized to 48 psia at 25° C.
[(48psia-14.7psia)/14.7 psia/atm] x 3785 liters x (273K/300K) = 7800 STP liters
7800 STP liters/22.4 liters/mole x 2g/mole = 697 grams hydrogen

Hall C: The 1000 gallon storage tanks is pressurized to 40 psia at 25°C.
[(40psia-14.7psia)/14.7 psia/atm] x 3785 liters x (273K/300K) = 5928 STP liters
5928 STP liters/22.4 liters/mole x 2g/mole = 529 grams Hydrogen

If the hydrogen and deuterium loops are simultaneously in use then the total hydrogen equivalent is 15,600 STP liters in Hall A and 11,800 STP liters in Hall C.

One B size cylinder of hydrogen (2000 liters) and one B size cylinder of deuterium (3000 liters) are located behind the gas panel. These are only valved in to the panel during the initial pump/purge operation and briefly at the end of a cool-down if additional gas is needed. They are not valved in to the system during normal operation and they are therefore not included in the target system inventory.

NFPA article 45 *Fire Protection for Laboratories Using Chemicals* defines a Class D (Minimal Fire Hazard) Laboratory Unit as one having less than 4 liters of a liquefied flammable gas per $9.3m^2$ of laboratory area. This standard applies to laboratories using liquefied flammable gasses. Our systems contain less than 0.1 liter of liquefied flammable gas per 9.8 m^2 of floor area in the hall and thus fall well within this limit.

To evaluate the hazard posed by a flammable gas installation, it is useful to distinguish between an inventory that would burn in a local flash fire and an inventory which could cause an explosion if ignited. Burning in an unconfined space, a hydrogen combustion wave requires 10.4m to reach significant overpressure[1]. A spherical volume 10.4m in diameter with a 4% hydrogen concentration would contain 23,000 liters of hydrogen. Both of our systems contain less than 23,000 liters of hydrogen. The volume of the halls (40×10^6 liters for Hall A and 26×10^6 for Hall C) would make them an unconfined area. In view of these considerations, we will take the following approach to classifying the flammable gas installations:

- These systems are sufficiently small that the release of the entire inventory in an unconfined area would, at worst, result in a local flash fire. Measures used at large commercial or NASA installation, such as using only listed electrical devices within 15 feet of the system, are not justified here. Every reasonable effort will be made to avoid the formation of a hydrogen/air mixture in the system, to vent hydrogen gas in a safe manner when necessary and to minimize sources of ignition in and around the systemlogout.

- The scattering chamber will serve as a secondary containment volume for the hydrogen gas in the event of a target cell rupture. Only in the event that the scattering chamber vacuum windows and the cells rupture simultaneously would hydrogen be released into the hall.

While the quantity of hydrogen in our target systems would be expected to burn in a local flash fire in an unconfined space, it should be recognized that a hydrogen/air mixture in a confined space such as the scattering chamber is an explosion hazard. To place the flammable gas hazard associated with the cryogenic targets in perspective we consider liquid propane. Cylinders containing as much as 33 pounds of liquid propane are in use on this site to power fork trucks and lifts. With an equivalency factor[2] of 0.35 this corresponds to 5.25 kg of hydrogen; almost four times the total inventory of the Hall A target.

<u>B. Specific Hazard Mitigation Measures:</u>

1. All hydrogen storage tanks are ASME coded vessels, are equipped with appropriate safety relief valves, are protected from damage by vehicles, and are appropriately marked.
2. The hydrogen gas handling systems are fabricated from stainless steel tubing and fittings. Joints are made by welding or by flanges or fittings employing metal gaskets.

All valves, gauges and regulators are appropriate for hydrogen service. All pipes or tubes which may contain hydrogen (including vent lines) are clearly marked and the appropriate signage is positioned at gas storage and handling locations.

3. Detailed operating procedures are in place to insure that air is removed from the system before hydrogen is introduced and to insure that hydrogen is removed from the system before it is opened or disconnected.
4. Valves which could close the primary relief path between the target cell containing liquid hydrogen and the gas storage tank are equipped with locking handles and are locked open at the time the tank is valved into the system as per the operating instructions.
5. All piping is securely mounted and is protected from damage with the exception of the metal hoses which span the last 20 feet before the target to allow for target motion.
6. The outdoor portion of these installations are located at least 15 feet from the nearest building and 25 feet from the nearest inlet to ventilating or air-conditioning equipment. Points at which hydrogen is vented will be located at least twelve feet above the ground, 25 feet from the nearest building and 50 feet from the nearest inlet to ventilating or air-conditioning equipment.
7. Target cells are fabricated entirely from metal. Glued joints are not used. Target cells are pressure tested to at least 1.5 times the maximum pressure that they would be expected to experience in a catastrophic loss of isolation vacuum incident.
8. Thin windows on the scattering chamber are metal. Windows identical to those installed are punctured under vacuum to demonstrate that they do not fail catastrophically if punctured. Windows identical to those installed have been pressure tested to greater than 1.5 times their normal operating pressure differential.
9. When the target contains liquid hydrogen, window covers are installed over the scattering chamber windows before the hall is taken to restricted access or before any work is done on the pivot in controlled access.
10. Valves on both the upstream and downstream side of the scattering chamber close automatically if the vacuum in the chamber rises above the 10^{-5} Torr range.
11. Flammable materials and oxidizing gases are not stored within twenty feet of the system.
12. Electrical devices which communicate with the internal volume of the hydrogen gas system or the scattering chamber will be listed for use in Class 1, Group B, Division 2 locations whenever possible. The mechanical vacuum pumps on the gas handling systems and the scattering chambers are rated for Class 1, Group B, Division 2 service. The ion gauges and turbo pumps used on the scattering chambers are not listed, however, these devices shut down or are isolated by valves automatically if high pressure exists in the scattering chamber.
13. Visual warning at the pivot of the presence of liquid hydrogen will be provided whenever liquid hydrogen is present in the target.
14. The primary relief path of the hydrogen system will be through a check valve into a storage tank. It will be demonstrated that this relief path is adequately sized to prevent rupture of the cells in the event of the sudden loss of isolation vacuum in the scattering chamber.

15. All secondary relief devices or venting valves for the hydrogen systems will vent into a relief line in which a helium atmosphere is maintained. This relief line will vent outside of the hall.
16. The scattering chambers will be protected from overpressure by a check valve (1 psi) in parallel with a burst disk (3 psi) which vent outside of the hall. The relief line must be sized to accommodate the flow that would result if both target loops were to rupture. A scattering chamber fitted with vacuum-formed thin windows has been tested to an internal pressure 1.5 times the maximum pressure that would be expected in the scattering chamber if both target cells were to rupture simultaneously.
17. To prevent contamination, the operating procedures for the system specify that the hydrogen target loops and gas systems are to be maintained above atmospheric pressure at all times once the supply tanks have been valved into the system. Audible alarms in the hall and in the counting house warn of low pressure in the hydrogen systems.
18. The hydrogen gas system is helium leak tested after installation and after any repairs which involve cutting and welding piping for hydrogen gas. The operating procedures call for a rate of rise test to be performed on the hydrogen gas system and target loop as part of the system start-up.
19. Hydrogen gas detectors are installed above the gas panel and above the target. These detectors will give a low alarm if a hydrogen concentration greater than 20% of the LEL is detected and a high alarm if a hydrogen concentration greater than 40% of the LEL is detected. The emergency procedures will specify what actions are to be taken in the event of a hydrogen gas detector alarm.
20. The target control devices will be powered by a UPS. Hard wired switches in the counting house allow the target to be shut down (JT valves closed and high power heaters shut of) in the event of a controls or network outage.
21. A trained target operator is on shift, either in the counting house or in the hall, at all times when the target contains liquid.

4. Relief Path Evaluation - Loss of Isolation Vacuum

The calculation consists of two parts; determining the heat flux into the target fluid on loss of isolation vacuum and evaluating the pressure drops which result. A model developed at Bates[3] is frequently used to estimate the heat flux into the target fluid if the isolation vacuum were lost. This model combines the rate of convection through gas surrounding the target (which is assumed not to condense), the rate of conduction through the walls of the target and the rate of convection through film-boiling hydrogen to arrive at an overall heat transfer rate. This model, which is dependent on the characteristic dimensions of the loop, typically predicts heat fluxes of 8 kW/m^2 to 15kW/m^2.

If the vacuum surrounding the target is broken by nitrogen then the nitrogen would be expected to condense on the target. Cooling nitrogen gas at 1 atmosphere from 300K to 78K requires approximately 223J/g while condensing the nitrogen would require an additional 200 J/g. Condensation of the nitrogen will tend to hold the exterior surface of the target cell at approximately 77K. Heat transfer to liquid hydrogen in the film boiling regime is described by the Breen and Westwater correlation[4].

$$h\left(\frac{\sigma}{g\,\Delta\rho_f}\right)^{\frac{1}{8}}\left(\frac{\mu_f\,\Delta T}{k_f^3\,\rho_f\,\Delta\rho_f\,g\,\lambda'}\right)^{\frac{1}{4}}=0.37+0.28\left(\frac{\sigma}{g\,D^2\Delta\rho_f}\right)^{\frac{1}{2}}$$

where:

$\lambda' = [\lambda + 0.34C_{p,f}\,\Delta T]^2/\lambda$
λ = heat of evaporation
h = coefficient of heat transfer
g = acceleration of gravity
k = thermal conductivity
μ = viscosity
$\Delta T = T_w - T_\ell$
σ = surface tension of the liquid
$\Delta\rho_f = \rho_\ell - \rho_f$
ρ = density
D = diameter
C_p = specific heat

Quantities with subscript w are evaluated at the wall temperature, ℓ at the liquid temperature and f at the film temperature, which is taken to be the mean of the wall and liquid temperatures. We assume that the wall temperature is fixed at 77K by condensation of nitrogen and that the liquid is boiling at 21.7K at a pressure of 1.5 atmospheres. The characteristic dimension of the system is taken to be the diameter of a beverage can cell; D = 2.6" = 0.066m. The relevant quantities are[5]:

T_w = 77K
T_ℓ = 21.7K
$\mu_f = 2.414 \times 10^{-6}$ Pa s (49K, 1.5 atm)
ρ_ℓ = 69.08 kg/m^3 (21.7 K, 1.5 atm)
$\Delta\rho_f$ = 68.3 kg/m^3
$\sigma = 1.691 \times 10^{-3}$ N/m (21.7K, 1.5 atm)
ΔT = 77K - 21.7K = 55.3K
$T_f = ½ (T_w + T_\ell)$ = 49K
k_f = 0.03688 W/mK (49K, 1.5 atm)
ρ_f = 0.7622 kg/m^3 (49K, 1.5 atm)
$C_{p,f} = 1.909 \times 10^4$ J/kg K (49K, 1.5 atm)
$\lambda = 4.376 \times 10^5$ J/kg

$\lambda' = [4.376 \times 10^5$ J/kg + 0.34(1.909 x 104 J/kg K)(55.3 K)$]^2/4.376 \times 10^5$ J/kg
$= 1.45 \times 10^6$ J/kg

$$h\left(\frac{1.691x10^{-3}\,\frac{N}{m}}{(9.8\,\frac{m}{s^2})(68.3\,\frac{kg}{m^3})}\right)^{\frac{1}{8}}\left(\frac{(2.414\times10^{-6}\,\frac{Ns}{m^2})(55.3K)}{(0.03688\,\frac{W}{mK})^3\,(0.7622\,\frac{kg}{m^3})(68.3\,\frac{kg}{m^3})\,(9.8\,\frac{m}{s^2})(1.45\times10^6)\,\frac{J}{kg}\,\lambda'}\right)^{\frac{1}{4}}$$

$$=0.37+0.28\left(\frac{1.691x10^{-3}\,\frac{N}{m}}{(9.8\,\frac{m}{s^2})\,(0.066m)^2\,(68.3\,\frac{kg}{m^3})}\right)^{\frac{1}{2}}$$

h $(1.54 \times 10^{-3}$ m^{2}K/W) = 0.37 + 0.28(0.0241)

h = 244 W/m^{2}K

$h\Delta T$ = (244 W/m^{2}K)(55.3K) = 13500 W/m^2

This is comparable to the heat flux predicted by the Bates calculation. The thermal conductivity of the walls of the cell and loop will have a small effect on the heat flux. For example, the cylindrical wall of the heat exchanger is 0.125" thick stainless steel which has a thermal conductivity of 8W/mK at 80K[6]. This gives a conductance per unit area of

$$(8 \text{ W/mK})/(0.0032\text{m}) = 2500 \text{ W/m}^2\text{K}$$

This is much larger than the heat transfer coefficient for film boiling hydrogen. Most of the walls of the loop, cellblock and cells are thinner than 0.125" and aluminum has a higher thermal conductivity than stainless steel. The thermal resistance of the metal walls will be neglected. For uninsulated surfaces, a heat flux of 13500 W/m^2 will be assumed.

The loops and heat exchangers are insulated with 25 layers of superinsulation. The effective thermal conductivity of this blanket at 1 atmosphere pressure is expected to be[7] approximately 0.02 W/mK (similar to the thermal conductivity of air) for a 7mm thick blanket. It will be assumed that all surfaces of the heat exchanger and loop piping are covered with 0.007m thickness of insulation having k = 0.02W/mK and that the outer surface of the insulation is at 300K. This gives an effective heat transfer coefficient for insulated surfaces of:

$$h_{eff} = [1/(244 \text{ W/m}^2\text{K}) + 0.007\text{m}/(0.02\text{W/ mK})]^{-1} = 2.82 \text{ W/m}^2\text{K} \quad \text{heat exchanger/loop}$$

The heat flux for insulated surfaces is (280K)(2.82 W/m^{2}K) = 790 W/m^2 .
The internal areas of the various target cells which have been used in these targets are summarized below:

<u>Hall C: - original "beverage can" cell</u>

Long cell 6.47cm diameter x 16.9cm long	344 cm^2
Cell exit window 6.47cm diameter	33 cm^2
Short cell 6.47cm diameter x 11.3 cm long	230 cm^2
Cell exit window 6.47cm diameter	33 cm^2
Entrance tube 4.0cm diameter x 10.2cm long	128 cm^2
Entrance window 4.0cm diameter	13 cm^2
Entrance tube 4.0cm diameter x 15.5cm long	195 cm^2
Entrance window 4.0cm diameter	13 cm^2
Cell Block 6.43 cm diameter x 7.30 cm long	321 cm^2
3.46 cm diameter x 1.2cm long	
Loop 3.81cm diameter x 100cm long (insulated)	1197 cm^2
Heat exchanger 18.4cm diameter x 21.8 cm long (insulated)	1792 cm^2

Total 1310 cm^2 uninsulated
2989 cm^2 insulated loop/heat exchanger

Hall A: - original "beverage can" cell

Long cell 6.47cm diameter x 16.9cm long	344 cm^2
Cell exit window 6.47cm diameter	33 cm^2
Short cell 6.47cm diameter x 11.3 cm long	230 cm^2
Cell exit window 6.47cm diameter	33 cm^2
Entrance tube 4.0cm diameter x 22.9cm long	300 cm^2
Entrance window 4.0cm diameter	13 cm^2
Entrance tube 4.0cm diameter x 28.4cm long	369 cm^2
Entrance window 4.0cm diameter	13 cm^2
Cell Block 6.43 cm diameter x 20.3 cm long x 2 3.46 cm diameter x 5cm long x 2	930 cm^2
Loop 3.81cm diameter x 221cm long (insulated)	2645 cm^2
Heat exchanger 18.4cm diameter x 21.8 cm long (insulated)	1792 cm^2

Total 2265 cm^2 uninsulated
4437 cm^2 insulated loop/heat exchanger

Hall C short cylinder

cell 4.45 cm diameter x 3.28 cm tall	45.8 cm^2
block (internal) 27.0cm x 6.3 cm x 3.53 cm	521 cm^2
Loop 3.81cm diameter x 100cm long (insulated)	1197 cm^2
Heat exchanger 18.4cm diameter x 21.8 cm long (insulated)	1792 cm^2

Total 567 cm^2 uninsulated
2989 cm^2 insulated loop/heat exchanger

Hall C: - machined cell (helicoflex gasket)

Long cell 4.85cm diameter x 14.4cm long	220 cm^2
Cell exit window 2.43 cm hemisphere	30 cm^2
Short cell 4.85cm diameter x 8.95 cm long	136 cm^2
Cell exit window 2.43 cm hemisphere	30 cm^2
Entrance tube 2.54cm diameter x 9.26cm long	74 cm^2
Entrance window 2.54cm diameter	5 cm^2
Entrance tube 2.54cm diameter x 14.8cm long	118 cm^2
Entrance window 2.54cm diameter	5 cm^2
Cell Block 6.43 cm diameter x 20.3 cm long x 2 3.46 cm diameter x 5cm long x 2	147 cm^2
Loop 3.81cm diameter x 100cm long (insulated)	1197 cm^2
Heat exchanger 18.4cm diameter x 21.8 cm long (insulated)	1792 cm^2

Total 765 cm^2 uninsulated
2989 cm^2 insulated loop/heat exchanger

Hall A; - 20cm cell

Cell 18.31 between centers, 0.978cm radius, 3.58cm high	153 cm^2
Cell Block 3.49cm diameter x 68cm long	
exclude cell area 0.978 radius x 18.31 between centers	668 cm^2
Loop 3.81cm diameter x 221cm long (insulated)	2645 cm^2
Heat exchanger 18.4cm diameter x 21.8 cm long (insulated)	1792 cm^2

Total 821 cm^2 uninsulated
4437 cm^2 insulated

The predicted heat loads and mass evolution rates are:

Hall C original cell
$(13500 W/m^2)(0.131 m^2) + (790\ W/m^2)(0.2989\ m^2) = 2005W$;
$2005W/437.6\ J/g = 4.58\ g/s$

Hall A original cell
$(13500W/m^2)(0.2265m^2) + (790\ W/m^2)(0.4437m^2) = 3408W$;
$3408W/437.6J/g = 7.79\ g/s$

Hall C machined cell
$(13500W/m^2)(0.0765m^2) + (790\ W/m^2)(0.2989\ m^2) = 1269W$;
$1269W/437.6\ J/g = 2.90\ g/s$

Hall A 20cm cell
$(13500W/m^2)(0.0821m^2) + (790\ W/m^2)(0.4437m^2) = 1459W$;
$1459W/437.6J/g = 3.33\ g/s$

Hall C short cylinder
$(13500W/m^2)(0.0567m^2) + (790\ W/m^2)(0.2989\ m^2) = 1002W$;
$1002W/437.6\ J/g = 2.29\ g/s$

Relief Paths:

Hall A	Hall C
19" 3/8 od/0.035 wall tube, 1 elbow	8' 3/8"od/0.020 wall tube, 2 elbows
10' 1/2"od/0.035" wall tube, 4 elbows	
20' 1" id metal hose	20' 1" id hose
50' 1" tube, 3 elbows	45' 1" tube, 4 elbows
switch panel: 5x 90° bend, diaphragm valve	ball valve
check valve, Circle Seal 259B6PP	check valve, Circle Seal 269B6PP
9' 1" id metal hose	
90' 2" pipe, 7 elbows	150' 2" pipe, 13 elbows
5' 1"id hose	9' 1"id hose
ball valve	ball valve

To calculate the pressure drops along the relief path, it is necessary to make some assumptions about the temperature of the gas at each point in the path. The most conservative assumption would be to assume that the gas is at 300K over the entire path. However, this is clearly unrealistic. At the point where vapor exits the loop, for example, it will be at the boiling point of the liquid. In the cryogenic targets, the first section of the relief path is a stainless steel tube which connects to the target loop at the base of the heat exchanger and exits the vacuum chamber at the top of the service can. This tube has a relatively small mass and would be expected to cool rapidly as a mixture of gas and vapor is initially expelled from the target. The tube is uninsulated over most of its length. It will be assumed that condensation of nitrogen holds the tube at 77K. Hydrogen vapor entering the tube at 22K would exchange heat with the walls at a rate given by[8]:

$$h = 0.023 N_{RE}^{0.8} N_{PR}^{0.4} (k/D)$$

In Hall A, the tube is 0.5"OD/0.035 wall over most of its length while in Hall C it is 0.35" OD/0.035" wall over its entire length. For hydrogen vapor at 24.6K and 3.0 atm, $\rho = 3.715$ kg/m^3, $\mu = 1.366 \times 10^{-6}$ Pa-s, k = 0.02122 W/mK and $N_{PR} = 1.087$.

Hall A

$$v = \frac{0.0039\text{kg/s}}{(3.715\text{kg/m}^3)(9.37 x 10^{-5}\text{m}^2)}$$

$v = 11.2$m/s

$$N_{RE} = \frac{(3.715\text{ kg/m}^3)(11.2\text{ m/s})(1.09 \text{ x } 10^{-2}\text{ m})}{1.366 \text{ x } 10^{-6}\text{ Pa - s}}$$

$N_{RE} = 3.3 \text{ x } 10^5$

$$h = \frac{0.023(3.3 \text{ x } 10^5)^{0.8}(1.087)^{0.4}(0.02122\text{ W/mK})}{1.09 \text{ x } 10^{-2}\text{ m}}$$

$h = 1200$ W/m^{2}K

Hall C

$$v = \frac{0.0024\text{kg/s}}{(3.715\text{kg/m}^3)(4.714 x 10^{-5}\text{m}^2)}$$

$v = 13.7$ m/s

$$N_{RE} = \frac{(3.715\text{ kg/m}^3)(13.7\text{ m/s})(7.75 \text{ x } 10^{-3}\text{ m})}{1.366 \text{ x } 10^{-6}\text{ Pa - s}}$$

$N_{RE} = 2.9 \text{ x } 10^5$

$$h = \frac{0.023(2.9 \text{ x } 10^5)^{0.8}(1.087)^{0.4}(0.02122\text{ W/mK})}{7.75 \text{ x } 10^{-3}\text{ m}}$$

$h = 1530$ W/m^{2}K

For a volume element of length ℓ in a tube of length L and radius r, the heat transferred to the gas at temperature T from the walls at temperature T_w causes the temperature of the gas to increase:

$$C_p \pi r^2 \rho \ell \, dT = h(2\pi r \ell)(T_w - T)dt$$

If gas enters the tube at temperature T_0 flowing at velocity v then at length L the temperature will be given by:

$$\ln\left(\frac{T_w - T}{T_w - T_0}\right) = \frac{-2h}{C_p \rho r}\frac{L}{v}$$

The heat capacity of hydrogen vapor is approximately 16000J/kgK over a wide range of temperatures. Taking the wall temperature to be 77K and the initial temperature to be 24K we obtain:

$$\ln\left(\frac{77K - T}{77K - 24K}\right) = \frac{-2(1200 W/m^2 K)}{(1.6x10^4 J/kgK)(3.7\ 15kg/m^3)(6.35\ x\ 10^{-3} m)}\frac{3.0m}{9.77m/s} \qquad \text{Hall A}$$

T=70K

$$\ln\left(\frac{T - 24K}{77K - 24K}\right) = \frac{-2(1530 W/m^2 K)}{(1.6x10^4 J/kgK)(3.7\ 15kg/m^3)(3.87\ x\ 10^{-3} m)}\frac{2.4m}{11.4m/s} \qquad \text{Hall C}$$

T=74K

It will be assumed that the hydrogen vapor is at 77K over the entire length of metal tube inside the target chamber and at 300K in the external hoses and piping. The formulas used to calculate the pressure drops are:

$$v = \dot{m}/\rho A$$

$$N_{RE} = \rho v D/\mu$$

$$\Delta P = (4f)\,\tfrac{1}{2}\rho v^2\,(L/D) \text{ for hose, tube and pipe and}$$

$$\Delta P = \tfrac{1}{2}\rho v^2\,(K) \text{ for fittings}$$

The target systems normally operate at a pressure of 1.5 atmospheres. If the isolation vacuum is lost then the maximum pressure in the cells would occur when the pressure in the storage tank approaches the storage value of 50 psia (3.4 atm) for Hall A or 40 psia (2.72 atm) for Hall C. The pressure drops along the relief path will be estimated assuming that the system is at the storage tank pressure. The gas properties used to calculate the pressure drops are:

Hall A:
internal tubing/fittings T = 77K, P = 3.4 atm, ρ = 1.091 kg/m^3, μ = 3.453 x 10^{-6} Pa-s
external tubing/fittings T = 300K, P = 3.4 atm, ρ = 0.2779 kg/m^3, μ = 8.961 x 10^{-6} Pa-s

Hall C:
internal tubing/fittings T = 77K, P = 2.72 atm, ρ = 0.8719 kg/m^3, μ = 3.448 x 10^{-6} Pa-s
external tubing/fittings T = 300K, P = 2.72 atm, ρ = 0.2224 kg/m^3, μ = 8.960 x 10^{-6} Pa-s

Hall A Original Cell 7.79 g/s

Element	**v m/s**	**N_{RE}**	**4f or K**	**ΔP psi**
3/8" tube	75.73	1.9×10^5	0.016	1.80
3/8" elbow	75.73		0.9	1.63
½" tube	38.10	1.3×10^5	0.016	2.05
½" elbows	38.10		0.9	1.24
1" hose	27.66	2.2×10^4	0.072	2.07
1" tube	36.54	2.5×10^4	0.024	1.77
1" elbows	6.47		0.9	0.87
diaphragm valve	30 SCFM			0.07
check valve	30 SCFM			1.5
2" pipe	6.47	1.1×10^4	0.027	0.05
2" elbows	6.47		0.9	0.02
Total:				13.1

Hall C Original Cell 4.58 g/s

Element	**v m/s**	**N_{RE}**	**4f or K**	**ΔP psi**
3/8" tube	51.80	1.14×10^5	0.016	3.94
3/8" elbow	51.80		0.9	2.82
1" hose	18.91	1.34×10^4	0.072	0.67
1" tube	24.99	1.54×10^4	0.024	0.69
1" elbows	24.99		0.9	0.33
diaphragm valve	20 SCFM			0.05
check valve	20 SCFM			1.3
2" pipe	4.43	6.49×10^3	0.027	0.03
2" elbows	4.43		0.9	0.02
Total:				9.86

In Hall A, the relief valves at the target service can are set for 55psia, however, the pressure drop across the internal tubing and fittings would still exist and the pressure in the cells would reach 55psia+6.7 psia = 61.7 psia. In Hall C the 55 psig rupture disk will not break and the peak pressure will be the maximum storage tank pressure added to the pressure drops along the relief path.

The peak pressures in the cells are:

Hall A : 61.7 psia Hall C: 49.9 psia

The assembled cell blocks have been pressurized to at least 70 psig in a vacuum chamber (85 psid) before they are installed. The test pressure is more than 1.5 times the maximum anticipated absolute pressure that is expected in the cells for the Hall C target. For Hall A target cells of the original design this test pressure must be increased to 1.5(61.7) = 93psid. The original "beverage can" cells are a worst case in terms of mass flow due to their large area. The pressure drops for all of the cells are summarized below.

Flow and Pressure Drop on Loss of Vacuum - Uninsulated cells and cell blocks

Cell Type	Mass Flow	Pressure Drop	Peak Pressure
Hall A "beverage can"	7.79 g/s	13.1 psi	61.7 psia
Hall C "beverage can"	4.58 g/s	9.86 psi	49.9 psia
Hall C machined cell	2.90 g/s	4.72 psi	44.7 psia
Hall A 20cm cell	3.30 g/s	3.57 psi	53.6 psia
Hall C short 4 cm cylinder	2.29 g/s	3.43 psi	43.4 psia

The flow rates and pressure drops are modest for the newer cell designs due to their smaller areas. The situation for the conventional "beverage can" cells could be improved by insulating the cell block. The cell block can be covered with a 25 layer MLI blanket along with the loops and heat exchanger. Newer types of insulation based on aerogel[9] and composits[10] would offer similar performance with thinner layers and may be easier to apply to the complex shape of the cell block. A 3mm thick layer of "Cryocoat Ultralight" from Composite Technology Development was tested in a catastrophic loss of insulating vacuum experiments on a superfluid helium dewar[11] and was shown to reduce the heat flux by a factor of seven in comparison with an untreated surface. The manufacturer quotes a thermal conductivity of 0.02 W/mK for this material at 1 atmosphere pressure.

If the cell block only is covered with 0.002m thickness of insulation having k = 0.02W/mK and that the outer surface of the insulation is assumed to be at 300K then the effective heat transfer coefficient for insulated surfaces is:

$h_{eff} = [1/(244\ W/m^2K) + 0.002m/(0.02W\ mK)]^{-1} = 9.61\ W/m^2K$ cell/block

The heat flux heat is $(280K)(9.61\ W/m^2K) = 2690\ W/m^2$ for the surface of the cell block.

Hall A original cell with block insulated
$(13500W/m^2)(0.1335m^2) + ((2690\ W/m^2)(0.093m^2) + (790\ W/m^2)(0.4437m^2) = 2403W$;
$2403W/437.6J/g = 5.49\ g/s$

This would reduce the pressure drop to 7 psi and the peak pressure in the cell to 57psia in a loss of isolation vacuum incident. In this case, the present test pressure of 85 psid would be adequate.

5. Relief Path Evaluation - Scattering Chamber

We assume that the contents of both the hydrogen and deuterium cells are deposited on the base of the scattering chamber and undergo film boiling with a surface that remains at 300K. The liquid inventories are: (we calculate the volume of hydrogen and double the volume to account for the deuterium loop)

Hall A: The 1000 gallon storage tank is pressurized to 48 psia at 25°C. This pressure falls to approximately 22 psia when the target is condensed. The volume contained in one loop corresponds to:

[(48psia-22 psia)/14.7 psia/atm] x 3785 liters x (273K/300K) = 6092 STP liters
6092 STP liters/22.4 liters/mole x 2g/mole = 544 grams hydrogen
544 g/(0.0723g/cm^3) = 7.52 liquid liters condensed volume

Hall C: The 1000 gallon storage tans is pressurized to 40 psia at 25°C. This pressure falls to approximately 22 psia when the target is condensed. The volume contained in one loop corresponds to:

[(40psia-22 psia)/14.7 psia/atm] x 3785 liters x (273K/300K) = 4217 STP liters
4217 STP liters/22.4 liters/mole x 2g/mole = 376 grams Hydrogen
376 g/(0.0723g/cm^3) = 5.21 liquid liters

If the volume of the scattering chamber is more than 52 times the total liquid inventory then the liquid can boil to form cold vapor without the pressure in the scattering chamber exceeding 1 atmosphere. The venting process will then be relatively slow as the cold vapor warms up.

Hall A	Hall C
40" diameter x 93" tall	49" diameter x 52" tall
volume: 1900 liters	volume 1600 liters
target liquid volume: 15.0 liters	target liquid volume: 10.4 liters

In both cases we are well above the required volume ratio of 52. For the purposes of this calculation the hydrogen and deuterium combined will be treated as two hydrogen liquid inventories. The relief valve will open once the vapor has warmed sufficiently to bring the scattering chamber to 1 atmosphere:

Hall A	Hall C
1088g H^2/1900liters at 1 atm	752g H_2/1600liters at 1 atm
$\rho = 6.168 \times 10^{-4}$ g/cm^3; T = 40.45K	$\rho = 4.70 \times 10^{-4}$; T = 52.65K

It will be assumed that the walls of the chamber remain at 300K. the rate at which heat is delivered to the hydrogen vapor may be calculated using the correlations[8]:

$$N_{UL} = 0.68 + \frac{0.670 N_{RA}^{1/4}}{\left[1 + \left(\frac{0.492}{N_{PR}}\right)^{9/16}\right]^{4/9}} \qquad \text{vertical surface}$$

$$N_{UL} = 0.54 N_{RA}^{1/4} \qquad \text{base}$$

$$N_{UL} = 0.27 N_{RA}^{1/4} \qquad \text{lid}$$

$$\text{where}: N_{RA} = N_{GR} N_{PR}$$

$$N_{GR} = \frac{g\beta(T_S - T)D^3}{\mu^2} \text{ and } \beta = 1/T \text{ for an ideal gas.}$$

D is the characteristic dimension; the height for the vertical surface and the diameter for the base and lid.

For T = 40.45K and P=1 atm
μ =2.046 x 10^{-6} Pa-s, N_{PR} = 1.196
k = 0.03122 W/mK, C_P = 18.20 J/gK

D = 2.63m, β = 1/40K = 0.0247 K^{-1}

N_{GR} = 2.16 x 10^{14}

N_{RA} = 2.58 x 10^{14}

<u>vertical surface:</u>
N_{UL} = 2175
h = (k/D)N_{UL} = 28.77 W/m^{2}K
area a = π(1.016m)(2.36m) = 7.53 m^2
ha = 217 W/K

<u>base:</u>
1.016m diameter
N_{UL} = 2164
h = (k/D)N_{UL} = 66.4 W/m^{2}K
area a = π(1.016m/2)^2 = 0.81 m^2
ha = 53.8 W/K

<u>lid:</u>
1.016m diameter
N_{UL} = 1082
h = (k/D)N_{UL} = 33.3 W/m^{2}K
ha = 26.9 W/K

For T=52.62K and P=1 atm
μ =2.556 x 10^{-6} Pa-s, N_{PR} = 1.235
k = 0.0390 W/mK, C_P = 18.85 J/gK

D = 1.32m, β = 1/53K = 0.019 K^{-1}

N_{GR} = 1.62 x 10^{13}

N_{RA} = 2.00 x 10^{13}

vertical surface:
N_{UL} = 1152
h = (k/D)N_{UL} = 34.04 W/m^{2}K
a = π(1.24m)(1.32m) = 5.14 m^2
ha = 175 W/K

base:
1.244m diameter
N_{UL} = 642
h = (k/D)N_{UL} = 20.2 W/m^{2}K
a = π(1.24m/2)^2 = 1.21 m^2
ha = 24.4 W/K

lid:
1.244m diameter
N_{UL} = 19.0
h = (k/D)N_{UL} = 20.2 W/m^{2}K
ha = 21.7 W/K

The total power transfer to the gas is:

(217 W/K+53.8 W/K + 26.9 W/K)(260K)
=77,300W

(175 W/K + 24.4W/K +21.7 W/K)(248K)
= 54,800W

The gas warms at a rate:

$$\frac{77{,}300\text{W}}{(18.2\ \text{J/gK})(1088\ \text{g})} = 3.90\text{K/s}$$

$$\frac{54{,}800\text{W}}{(18.85\text{J/gK})(752\text{g})} = 3.87\ \text{K/s}$$

For an ideal gas $\frac{1}{V}\frac{dV}{dt} = \frac{1}{T}\frac{dT}{dt}$

$$\frac{dV}{dt} = \frac{1900\ell}{40\text{K}}(3.90\text{K/s}) = 185\ \ell/\text{s}$$

$$\frac{1600\ell}{52\text{K}}(3.87\text{K/s}) = 119\ \ell/\text{s}$$

Assuming that the gas is warm (300K) and at 1 atm over most of the 2" vent pipe (D = 5.08cm) we have:

ρ = 0.088184 kg/m3, μ = 8.958 x 10-6 Pa-s for hydrogen at 300K and 1atm

v = 91.3 m/s

v = 58.7 m/s

$$N_{RE} = \frac{(0.088184\ kg/m^3)(91.3\ m/s)(5.08\ x\ 10^{-2}\ m)}{8.958\ x\ 10^{-6}\ Pa-s}$$

$$N_{RE} = \frac{(0.08818 kg/m^3)(58.7\ m/s)(5.08\ x\ 10^{-2}\ m)}{8.958\ x\ 10^{-6}\ Pa-s}$$

N_{RE} = 4.5 x 10^4

N_{RE} =2.9 x 10^4

For smooth pipe a friction coefficient of 0.03 would be appropriate. The relief paths are:

Hall A
155' 2" pipe (L/D = 930)

7x 2" elbows
259B16PP check valve
parallel plate relief

Hall C
140' 2" pipe
9' 2" ID hose
7 x 90° elbows
259B16PP check valve
parallel plate relief

The nine feet of 2" hose is equivalent to three times that length of pipe, so the two relief paths will be practically identical.

$\Delta P = (0.03)\frac{1}{2}\ (0.08818 kg/m^3)(91.3/s)^2\ (930) = 10254$ Pa (1.5 PSI) 2" pipe
$\Delta P = 7\ x\ \frac{1}{2}\ (0.08818 kg/m^3)(91.3 m/s)^2\ (0.9) = 2315$ Pa (0.3 PSI) elbows

The 2" check valves are quoted as having a C_v of 51. The pressure drop across this valve will be:

$$\Delta P = \frac{T\,S}{63.5\,P}\left(\frac{\dot{V}}{C_v}\right)^2 = \frac{(300K)(0.0659)}{(15psi)(63.5)}\left(\frac{185\ell/s}{51}\right)^2 = 0.27 psi\ \ (Hall\ A)$$

In this formula, S is the specific gravity relative to air, P is in psi, T is the temperature in K and the flow is in liters/s. The parallel plate relief valve will be set for 2 psi or less. The total pressure in the scattering chamber will be approximately 4 psig, which should be contained by the windows. The three psi rupture disk would not be expected to break as it sees only the pressure drop across the check valve.

6. Scattering Chamber and Scattering Chamber Windows

The scattering chambers are located near the center of each hall. They are not surrounded by shielding or any other type of enclosure. The large volume of the halls makes the hall an unconfined space for the volume of hydrogen in our system. The beam entrance and exit flanges are attached to the scattering chamber using metal gaskets. Joints between sections of the chamber and between spectrometer windows and the chamber are sealed by rubber O-rings. The chambers are pumped by a single 1000 l/s turbomolecular pump (Hall C) or by a two parallel 900l/s pumps (Hall A). A valve immediately in front of the chamber isolates the beam line from the chamber if the vacuum in the chamber rises above 5×10^{-5} Torr.

Concerns have been raised that small air leaks into the scattering chamber could go unnoticed and lead to the build-up of significant quantities of solid nitrogen and oxygen over time. Our experience indicates that this is not the case. Even when the targets are cold, the scattering chamber vacuum (as indicated by a cold cathode ionization gauge) is sensitive to small air leaks from the outside. Most cold surfaces of the target are covered with superinsulation, which reduces their effectiveness as a cryopump. When the targets have been operated under conditions of poor vacuum (mid to high 10^{-6} Torr range) a thin (~0.1mm) layer of frost was observed on uninsulated surfaces of the cellblock. This layer did not appear to grow over a period of weeks. The quantity of air frozen out on cold surfaces under these conditions was not significant. Since the targets are not operated if the scattering chamber pressure is above 5×10^{-5} Torr, small air leaks from the outside are not expected to lead to significant accumulations of frozen air inside the chamber and are therefore not a significant hazard.

Solid oxygen at 27K to 30K has a vapor pressure in the 10^{-7} Torr to 10^{-6} Torr range[12]. On the 18K - 22K surfaces of the target, a layer of solid oxygen several millimeters thick would be required to bring the surface of the oxygen to this temperature under the heat load of thermal radiation. One might expect solid oxygen to deposit on a cold surface until the vapor pressure on the warmest surface of that deposit matches the partial pressure of oxygen in the vacuum chamber. No such deposits are observed in our system. The concept of vapor pressure is meaningful only when the vapor and the solid or liquid are in equilibrium at the same temperature. The mean free path of oxygen molecules at 300K and 5×10^{-6} Torr is 10 meters[13]. Molecules collide with the 300K inner walls of the scattering chamber much more frequently than with each other. The surface area of the chamber walls exceeds the area of exposed cold surfaces by a factor of 20 to 60. The cold surfaces of the target are surrounded by warm vapor and not by cold vapor. This would explain why significant deposits are not observed in our system.

The thin windows on the scattering chambers are a significant hazard. The windows are exposed when the target is in use. Procedures call for window covers to be installed as the first step when the hall is taken to restricted access or to controlled access when work around the scattering chamber is anticipated. In Hall A the two windows are identical, while in Hall C the HMS and SOS windows differ. The thin beam exit window formerly used in Hall C was removed when an evacuated downstream beam line was installed.

When the chambers are evacuated these windows take a concave shape and vertical ridges form. For the Hall C HMS window these ridges have a spacing of 2.3". The Hall A window is very similar. For the SOS window the ridge spacing is typically 2", however, the ridge pattern is less regular.

Window	Thickness/Material	Dimensions
Hall A	0.016" thick 5052 H34 Aluminum	7" high, 170° on 43" OD chamber
Hall C SOS	0.008" thick 5052 H39 Aluminum	4" high, 165° on 55" diameter
Hall C HMS	0.016" thick 5052 H34 Aluminum	8" high, 80° on 53.5" OD chamber

The stress in a membrane of dimensions a x b (a being the long dimension) clamped at the edges is[14,15]

$$\sigma = n[E(pa/t)^2]^{1/3}$$

where E is the modulus of elasticity, p is the pressure, t is the thickness and the coefficient n depends on a/b. The modulus of elasticity for this alloy is 1.02×10^7 psi. With the scattering chamber evacuated the stresses on the windows are:

Hall A: $\sigma = 0.272[1.02 \times 10^7\text{psi}(14.7\text{ psi } 7''/0.016'')^2]^{1/3} = 20{,}400$ psi

Hall C HMS $\sigma = 0.272[1.02 \times 10^7\text{psi}(14.7\text{ psi } 8''/0.016'')^2]^{1/3} = 22{,}300$ psi

Hall C SOS $\sigma = 0.336[1.02 \times 10^7\text{psi}(14.7\text{ psi } 4''/0.008'')^2]^{1/3} = 27{,}500$ psi

The ultimate tensile strength for 5052H34 aluminum is 38,000psi[16]. The ultimate tensile strength for the H39 alloy is not readily available but for the H38 temper it is 42,000 psi. According to this estimate the larger windows are operating at roughly 60% of the ultimate tensile strength of the material while the smaller window operates at roughly 66% of the tensile strength of the material. However, treating this complex shape as a simple rectangular membrane will only yield a rough estimate of the actual stress. A more accurate result may be obtained by treating each segment of the window as a cylinder having a radius of curvature corresponding to the measured deflection of the segment. The measured deflections give a radius of curvature of 10.0" for the Hall C SOS window and 26.2" for the Hall C SOS window. The predicted stresses are:

$\sigma = Pr/t$ = 24,000 psi Hall C HMS
= 18,000 psi Hall C SOS

Tests in which these windows were punctured with the scattering chamber under vacuum demonstrated that the windows would not fail catastrophically if punctured. Hydrostatic tests of the Hall C windows yielded burst pressures of 35 psid for the HMS window and 40 psid for the SOS window. Two windows were burst for each test. With the scattering chamber under vacuum these windows are subjected to 14.7 psid and therefore operate with a safety factor of greater than two. Treating the window sections as segments of a cylinder rather than a membrane more accurately predicts the burst pressures.

With vacuum-formed thin windows installed, the Hall C scattering chamber was pressurized to 6 psig. This is 1.5 times the maximum pressure that would be expected in the scattering chamber if both cells were to rupture.

7. Target Electrical Installation

Electrical devices in and around a hydrogen system are potential sources of ignition. However, few of the devices used in research laboratories are listed for use in a Class I, Division 2 locations (locations in which a flammable gas mixture could form as a result of equipment failure). Furthermore, "bag and purge" methods are clearly not practical for devices such as vacuum gauge heads. These difficulties are recognized in NFPA article 45 *Fire Protection for Laboratories Using Chemicals,* which states that "Laboratory work areas…shall be considered as unclassified electrically". Our approach has been to use hydrogen safe devices whenever they are available. Devices which could act as an ignition source are shut-off or isolated if high pressure is detected in the scattering chamber. The volumes that we consider potentially hazardous are the internal volume of the hydrogen system, the internal volume of the scattering chamber and the internal volume of the vent line. Two methods of detecting high pressure in the scattering chamber are used: a Granville-Phillips Convectron gauge with a set point of 5 Torr or a hydrogen-safe pressure switch set near its minimum actuation pressure (10 Torr).

Devices connected to the hydrogen system:

<u>Pressure Transducers:</u> The Sensotec type TJE and FMA pressure transducers as well as the NOSHOK type 625 pressure transducers are designated intrinsically safe by Factory Mutual. The Omega PX750 differential pressure transducers are Factory Mutual listed for Class I, Divisions 1 and 2, Group B (hydrogen).

<u>Temperature Sensors</u>: The diodes and resistors used as temperature sensors are energized by low-level voltage or current sources to prevent self-heating effects from interfering with the temperature measurement at low temperatures. They are not potential ignition sources.

<u>High Power Heaters</u>: The high power heaters are fabricated from 0.051" diameter Nichrome wire wound on a G-10 support (Hall C) or by heater wire sandwiched in Kapton film (Hall A). They are powered by 40V/25A (Hall C) or 150V/7A (Hall A) power supplies. These heaters are normally operated in a PID control loop by the target IOC. The PID loop would reduce the heater power to zero in an event such as loss of isolation vacuum. If the IOC is in a hung state or is rebooting, the PID control is inactive and the power level is constant. In some cases the heater may be powered by an auxiliary power supply manually controlled from the counting house. (This would occur when the IOC hangs while the beam is on and the power setting is low. If the beam goes off then higher power may be needed to prevent the loop temperature from dropping too far.) The high power heater is a potential source of ignition. This is particularly true if it is not under PID control. All high power heater power supplies (main and auxiliary) are shut off if high pressure is detected in the scattering chamber.

Fans: Presently, the fans which circulate target fluid are three phase induction motors powered by variable frequency power supplies (PDL Electronics Microdrive Elite ME-6.5). The fans themselves do not contain brushes and are not sources of ignition. While the voltages across the motor coils are tens of volts, the voltages from the coils to ground can be considerably higher. It is possible for an electrical discharge to occur around the motor terminals at low pressures. However, at pressures low enough for a discharge to develop, combustion is not possible. The fans and power supplies are not an ignition source.

Thermocouple vacuum gauge Thermocouple vacuum gauges operate with the thermocouple at 250°C (DV-4) to 300°C (DV-6) when the thermocouple is in high vacuum[17]. The autoiginition temperature for a hydrogen air mixture at one atmosphere is stated to be 500°C in NFPA 50A. NASA[18] reports that ignition of a hydrogen-air mixture at reduced pressure can occur due to prolonged contact with objects at temperatures as low as 317°C. The DV-6 gauge tube can only approach this temperature under conditions of high vacuum. The thermocouple gauge tubes should not be potential ignition sources.

Mechanical vacuum pump: Hydrogen safe pumps (Class I, Division 2, Group B) are used on the gas panels.

Devices connected to the scattering chamber:

Mechanical vacuum pump: Hydrogen safe pumps (Class I, Division 2, Group B) are used on the scattering chambers.

Turbomolecular pump: Turbomolecular pumps do not employ brushes and are not likely to be an ignition source. However, they are not rated for hydrogen service. Gate valves close to isolate the turbopumps if high pressure is detected in the scattering chamber.

Cold cathode vacuum gauge: The cold cathode vacuum gauge would normally cease to discharge at pressures above 10^{-2} Torr. It is possible that contamination would allow the gauge to arc or discharge at higher pressures. The cold cathode gauges will be powered off if high pressure is detected in the scattering chamber.

Thermocouple vacuum gauge (Hall C) As noted above, the thermocouple gauge tubes should not be potential ignition sources.

Convectron gauge: The Convectron gauge element operates at 105°C and is not a potential ignition source[19].

Barksdale vacuum switch: The Barksdale DX1-A3SS is UL listed for hazardous locations, Class I, Group B (hydrogen).

Devices connected to the vent line:

Pressure Switch: The Dwyer 1950 differential pressure switch is UL and Factory Mutual listed for Class I, group B hazardous locations.

8. Control System

The target control system is based on a single board VME computer located in the hall. VME carrier boards provide this computer with A/D, D/A, digital IO and serial communications capabilities. This VME computer monitors the target temperatures, the gas system pressures, the high power heater voltage and current, the fan speed, the JT valve positions, the target position and the scattering chamber pressure. It controls the high power heater power supplies, the JT valve positions, the fan controllers, target motion and the fill solenoid valves. The operator has access to these functions through a GUI, which may be run on a computer in the counting house or the hall and communicates with the VME computer over the network. An alarm handler, running alongside the GUI, provides an audible alert if any system pressures or temperatures deviate from preset boundaries. In normal operation, the JT valve position (refrigerant flow) is fixed and the high power heater operates under PID control from the VME computer to regulate the loop temperature. The VME computer and critical devices such as the pressure and temperature monitors and the JT valve controllers operate from a UPS. The VME computer status is monitored by the alarm handler. Occasionally this computer locks-up and must be rebooted. This may be done from the counting house.

We do not rely on the VME control system to perform critical safety functions. An auxiliary high power heater power supply, controlled manually from the counting house, may be used to maintain the loop temperature if the VME computer is not operating. Separate hard-wired alarms alert the operator of loss of scattering chamber vacuum or low pressure in the hydrogen or deuterium systems. The hydrogen sensors are hard-wired to a control/alarm unit located in the counting house. Switches in the counting house allow the operator to close the JT valves and shut off the high power heater supplies should the need arise.

9. Recommendations for Future Installations

In the present design the vent line is connected to the target loop at the base of the heat exchanger and is partially filled with liquid during normal operation. In a loss of vacuum event, liquid hydrogen would be expelled into warm sections of tubing. Flash boiling of the liquid could result in high and unpredictable back pressures in the target loop. Ideally this line would be connected at the top of the target loop piping. Also, ideally this line would be insulated and heat-sunk to the refrigerant return line in a carefully engineered and well documented way.

NASA prohibits the use of soft solder joints in their hydrogen systems and reports that soft solder joints are subject to hydrogen embrittlement[18]. NFPA article 50A *Gaseous*

Hydrogen Systems at Consumer Sites specifies that all brazing materials used in hydrogen gas systems shall have a melting point greater than 538° C. Our experience has been that soft solder joints are not reliable. In future installations, efforts should be made to avoid the use of soft solder joints on hydrogen cells

10. Modifications to Existing Installations

Any modifications to the target system that would contravene any of the measures listed in section 3B or which significantly alter any of the numbers used in any of the engineering calculations contained in this document must be approved by the Physics Division. This includes modifications such as introducing new thin windows, significantly altering the volume of the scattering chamber or the gas inventory, or altering the dimensions of the vacuum windows. Minor modifications (such as changing cell dimensions) must be evaluated by the target group.

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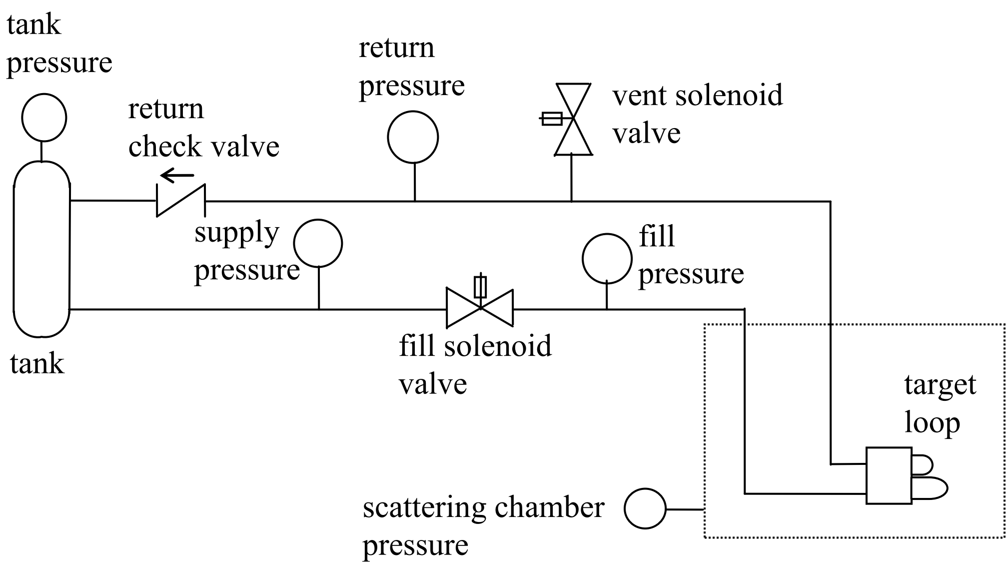
Appendix I - Procedures for Off-Normal Events

System Schematic and Component Designations

Target Gas System Schematic



Designations used in flow sheets and controls

	tank pressure	supply pressure	fill pressure	return pressure	fill solenoid valve	vent solenoid valve	scattering chamber pressure
Hall A Hydrogen	PT133	PT127	PT128	PT131	CSV33	CSV28	VPI149
Hall A Deuterium	PT142	PT136	PT137	PT140	CSV56	CSV57	
Hall C Hydrogen	PT9145	PT9009	PT9013	PT9023	SV9012	SV9014	PI9056
Hall C Deuterium	PT9145	PT9079	PT9083	PT9093	SV9082	SV9084	

The low pressure alarm operates from the return side pressure transducer and the vent solenoid operates from the fill side pressure transducer.

Procedures for Off Normal Events

If any of these events occur when an expert is not present (generally the case when the target is in operation) the first action should be to call the on-call expert.

I. Low Loop Pressure Alarm;

A. <u>During cool-down</u> - low loop pressure alarms are common and indicate that the gas is being condensed so rapidly as to produce a pressure drop between the storage tank and the loop. Close the appropriate JT valve to keep the loop pressure above one atmosphere at all times.

B. <u>During normal operation</u> - the low pressure alarm could be caused by:

- The loop temperature had gone above normal, expelling gas through the check valve and into the tank. The temperature has now fallen and the pressure has dropped.
- The loop temperature is now much too low.
- The cell has ruptured.
- The system is loosing gas, either due to a slow leak or a breach of the system.
- The pressure transducer is defective.

1. <u>Loop temperatures normal:</u> Check the pressures at the fill, return, supply and tank. If the tank and supply pressures are high while the fill and return pressures are low then the system has lost pressure either through an over temperature event, a slow leak or a sudden breech of the system. Open the fill solenoid valve to recharge the system. This should cause the loop temperature to rise as gas is condensed. While gas is condensing, check the pressure and temperature charts for evidence of recent temperature or pressure excursions. A significant pressure difference between the fill and return sides indicates possible blockage of the loop by frozen air. If opening the fill solenoid causes the tank pressure to drop while the system pressure fails to increase then a breach of the system is indicated.

2. <u>Loop temperature low:</u> Use the TV monitor to check the loop temperatures if the control system is down. If the temperature of the loop is low then close the appropriate JT valve and check the operation of the high power heater for that loop The high power heater should be in PID control with a reasonable (typically 400W to 600W) maximum power setting. If the controls are inoperative then it should be possible to use the auxiliary high-power heater supply to bring the loop temperature back up. If the control system is inoperative and it is not possible to bring the loop temperature back up using the auxiliary high power heater supply then it will be necessary to use the manual shut-down switch to close the JT valves. This will close the JT valves for all loops. Shut off all auxiliary and main high-power heater supplies immediately after closing the JT valves.
3. <u>Loop temperature high</u>; If gas is condensing (fill valve open) then a low pressure condition may be created if gas condenses too rapidly. If the temperatures of all operating loops have gone high, the scattering chamber vacuum reads high and valves to the beam line and beam dump have closed then it is possible that a cell has failed.

II. Low Vent Line Pressure Alarm

The hydrogen vent line is filled with helium gas and is maintained slightly above ambient pressure to prevent contamination. If a low vent line pressure alarm occurs during target operation, verify that the 4 atmosphere house helium supply is turned on (contact the cryogenics group). Inspect the vent line and the parallel-plate relief valve at the termination of the vent line. Check the reading of the pressure gauge on the vent line. If necessary, increase the helium regulator setting to increase helium flow into the vent line. If it is not possible to maintain a positive pressure in the vent line then initiate the target warm-up procedure.

III. Vent Solenoid Open Alarm

If the vent valve were to open and remain open it would reduce the system pressure to 1 atmosphere and make contamination of the system possible.

A. During start-up: Adding gas to the storage tank or overfilling the system during a pump/purge operation may cause the vent solenoid to open. It should close when the system pressure falls below the set point. It may be necessary to readjust the set point if gas is added to the system.

B. During normal operation: If all temperatures and pressures (other than the fill pressure) appear normal then a defective fill-side pressure sensor is likely. Unplug the transducer to close the vent solenoid. If the system temperatures and pressures are high then a loss of isolation vacuum may have occurred. See part IV.

IV. Hydrogen Sensor Alarm

All previous hydrogen sensor alarms have been caused by defective sensors, defective amplifier cards or gases other than hydrogen. The alarms failed to detect the release of large quantities of hydrogen following previous target cell failures, which is not unexpected because hydrogen disperses rapidly in air. The loss of any significant quantity of hydrogen from the gas system should be evident by the loss of pressure in the system.

A. Target not installed: If a hydrogen sensor alarm occurs when the target is not in use (gas tanks are valved off outside the hall) verify that the gas tanks are valved off. Visually inspect the area around the sensor. The sensor may then be disabled and must be replaced before the hydrogen system is returned to service.

B. Target installed: If a hydrogen sensor alarms while the target is in use (tank valves open), warn anyone present in the hall to stay clear of the area (pivot or gas panel). Check the system pressures. Unless a pump/purge operation is underway, they will be at the storage pressure (48 psia for Hall A, 40 psia for Hall C) if the target is warm, or approximately 22 psia if the target is condensed. If a pump/purge is underway, pump out any hydrogen in the system, backfill with helium perform a leak test.

1. If loss of inventory is not indicated (system pressures normal), inspect the system for damaged hoses or piping. Use a portable hydrogen sensor to approach and probe the area. Inspect the sensor wiring. Replace the sensor.
2. If a sudden and significant loss of inventory is indicated see V, Breach of Hydrogen System. It is unlikely that any event short of a sudden and significant loss of hydrogen inventory would trigger a real hydrogen sensor alarm.

V. Loss of Isolation Vacuum

Loss of isolation vacuum is indicated by a low alarm on the scattering chamber pressure (a readback of less than 10^{-10} Torr indicates that the gauge has tripped off), an alarm from the scattering chamber vacuum switch, closure of the scattering chamber entrance and exit valves and the generation of an FSD, and the sudden warm-up of the target. Loss of isolation vacuum may be caused by a leak from the refrigerant system, a leak from the hydrogen system or a leak from the exterior of the scattering chamber. If the loss of isolation vacuum is due to a hydrogen leak then the hydrogen must be pumped into the hydrogen vent using a hydrogen safe pump.

1. Close the fill solenoid valves if they are open. Immediately close the JT valves and initiate the target warm-up procedure. Shut off the fans. Check pressures in the gas systems to determine whether or not a cell has ruptured. The fill side and return side pressures will fall if there is a significant leak to the scattering chamber. The storage tank pressure will not increase as the target warms-up. Valve off the tanks once the targets have evaporated.

2. The gate valve which isolates the turbopumps will close if the pressure in the chamber exceeds 5 Torr. (The Hall A vacuum system has this provision and the Hall C system will be modified to make it identical). Shut off the turbopumps and the ion gauges. Open the bypass valve and attempt to evacuate the chamber using the mechanical pump.

3. If a poor vacuum exists in the scattering chamber then the gas panel may be used to evacuate each target cell and backfill it with helium gas. This will both remove hydrogen from the system and test for the source of the leak. If the scattering chamber is at high pressure then avoid evacuating and crushing the target cells. If the chamber can not be pumped down before the system is opened then a helium gas purge from the gas panel must be used to flush hydrogen from the target cells and piping..

4. If a significant quantity of hydrogen has been deposited in the hydrogen vent line then that branch of the line should be purged with helium. Close the helium supply valve to the vent line and set the regulator for 10 psig. Open the valve and allow the purge to run for 5 minutes. (This provides one gas change for the entire line). On completion reset the regulator for the vent line operating pressure.

VII. Breach of Hydrogen System

Damage to hydrogen piping or hoses may result in the release of hydrogen into the hall.

A. If targets are not condensed: Clear the area. Valve off the tanks to stop the flow of gas. Run the smoke removal fan to aid the dispersal of hydrogen.

B. If targets are condensed: Clear the area. Valve off the tank of the affected system only. Close the JT valves and shut off all fans and heaters. Do not attempt to speed up evaporation of the liquid by using fans or heaters. (The side of the system which has been breached may be blocked by frozen air or water, however, the secondary relief valves may allow the hydrogen to be vented through the remaining side.) Run the smoke removal fan to aid the dispersal of hydrogen.

VII. Simultaneous Vacuum Window and Target Cell Failure

If the breach of the vacuum windows is small and the chamber can be evacuated to 15 Torr or less then evacuating the chamber and backfilling with nitrogen will eliminate the flammable gas mixture.

If a large opening in one of the vacuum windows has been created:

1. Clear the area. Shut off the fans and high power heater power supplies. Do not operate the target lifter. Valve off the tanks. The D65B rotary vane pumps connected to the scattering chambers have a pumping speed of 90 m^3/hr. Allow the pump to pump on the chamber for a total of one hour. Shut the pump off and allow it to cool as needed. Increase the pumping time if the pressure at the pump inlet is reduced (two hours if the pressure is ½ atmosphere).

2. Approach the scattering chamber with a portable hydrogen sensor. Probe the area around the breach and inside the scattering chamber. Leave the area and continue to pump if readings of 2% or higher are encountered.