Safety Assessment Document for the Hall A Cryogenic Targets

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The potential hazards associated with the operations of cryogenic targets in Hall A are reviewed and the efforts to mitigate these hazards are described.

1 Introduction

The Hall A cryogenic target system consists of two completely instrumented targets, H_2 and D_2. In addition a third target loop will be installed in the scattering chamber but these cells will not be connected to a full gas handling system. This third loop will later be used as a Helium target.

The hydrogen and deuterium targets present a number of potential hazards. The most notable of these are associated with the fire/explosion hazard of the flammable gas, the hazards connected with the vacuum vessel and those of handling cryogenic liquids (ODH and high pressure). In this document the hydrogen target will be referred to but the deuterium target is essentially identical and almost all comments apply to both targets.

2 Flammable Gas

Hydrogen and deuterium are colorless, odorless gases and hence not easily detected by human senses. Hydrogen air mixtures are flammable over a large range of relative concentrations: from 4 % to 75 % H_2 by volume. Detonation of explosions can occur with very low energy input, less than $\frac{1}{10}$ that required by mixtures of air and gasoline. At temperatures above -250 C hydrogen gas is lighter than (STP) air and hence will rise. At atmospheric pressure the ignition temperature is approximately 1000 degrees F but mixtures at pressures of 0.2 to 0.5 Atm can be ignited at temperatures as low as 650 degrees F. Hydrogen mixtures burn with a colorless flame [1].

The total volume of liquid hydrogen in the heat exchanger is about 2 liters. The target cells and their associated plumbing hold an additional 3.4 liters. Thus the total volume of hydrogen in the target is approximately 5.4 liquid liters. The volume changes between the liquid state and gas at STP by a factor of about 800. Thus filling the target would require about 4,300 STP liters of hydrogen. The hydrogen target is connected to a

1,000 Gallon (about 3,800 liters) recovery tank. Normal running condition for hydrogen is 26 PSIA. So the total amount needed to fill the target and the tank is about 10,900 STP liters. For deuterium, the target is about 4,300 STP liters. The normal running condition for deuterium is 22 PSIA. So the total volume needed to fill the tank is about 5,600. The total to fill both the target and the tank is about 9,900 STP liters.

The Hall A inventory of hydrogen and deuterium gas is stored outside the Hall A gas shed, adjacent to the counting house. The current inventory is two A size cylinders of hydrogen ($\approx$ 6,800 STP liters each) and four A size cylinders of deuterium ($\approx$ 5,000 STP liters each). One bottle of hydrogen and one deuterium bottle will be kept in the Hall in order to fill the targets. These bottles will be placed in a gas rack behind the gas panels.

The basic idea behind safe handling of any flammable or explosive gas is to eliminate oxygen (required for burning) and to prevent exposure to any energy source that could cause ignition. In the Hall A environment the most likely source of oxygen is of course the atmosphere and the most likely ignition sources are from electrical equipment.

2.1 Electrical Installation

The hall contains a lot of electrical equipment and almost all of it could serve as an ignition source in the presence of an explosive oxygen and hydrogen mixture. We have made an effort to minimize the dangers from the equipment that is most likely to come into contact with hydrogen gas.

There are a number of electrically powered devices associated with the target gas handling system. All the pressure transducers in the system are approved for use in a hydrogen atmosphere. The solenoid valves on the gas panels are explosion-proof. The AC power for the solenoids is carried by wires which are contained in either hard or flexible conduit. There are also LED's on the gas panels that provide an indication as to the status of the valve solenoids. These are powered by a 24 Volt DC supply. The readouts for the pressure transducers are mounted on the gas panels and the AC power for these readout units is in conduit. All the pressure transducers have 4-20 mA outputs.

In addition to the electrical devices in the gas handling system there are a number of devices inside of or mounted on the scattering chamber.

All the devices which are in the scattering chamber must have their power delivered to them by wires in vacuum. The insulation of these wires should be radiation resistant, so Kapton has been used where available.

The following electrical items are in close proximity to or are actually in the hydrogen system.

Axial Circulation Fan The fans which circulate the hydrogen in the target are AC induction motors and therefore contain no brushes and are practically immune to sparking. The three phase power for these fans is delivered to them by 18 gauge stranded copper wire with Kapton insulation. The maximum current that we anticipate that the fans will have is 5 Amps and a maximum power consumption of 200 Watts when pumping liquid hydrogen/deuterium. The current and voltage drawn by the fans is monitored by the control system.

Fan Motor Tachometer The fans have a tachometer associated with them which consist of a coil that views the flux change caused by a permanent magnet attached to the motor rotor. The tachometer signals are carried on 22 gauge stranded wire with Kapton insulation. This is a low power signal. The control system monitors the frequency of the fans.

Low Power Heater This is a "hair dryer" style heater (it resembles the heater elements found in hair dryers and heat guns) that is immersed in the hydrogen. The heater is made of 0.0179 inch diameter Nichrome wire with a resistance of 1.993 Ωs per foot wrapped on a G10 carrier board. The maximum power available to this heater is 80 Watts. The power for the low power heater is supplied by a Oxford ITC-502 temperature controller. The heater lead wire is 18 gauge Kapton insulated copper stranded wire. The heaters have a DC resistance of 20 Ωs and hence will draw a maximum of 2 Amps. The power supplied to this heater is monitored by the control system.

High Power Heater There are two kapton enclosed incoloy heater foils wrapped on the inside wall of each heat exchanger. The maximum power available to each heater is 500 Watts. The heater has a DC resistance of 26 Ωs and two heaters in parallel are driven by a 150 Volts, 7 Amps power supply. The current and voltage supplied to this heater are monitored by the control system and there is a software power maximum enforced on the power setting of this heater. The heater is connected to the outside world by 18 gauge stranded wire with kapton insulation.

Resistors There are two Allen Bradley and four Cernox resistors immersed in each target loop. These resistors provide temperature measurements of the target fluid. The temperature controllers that read them use a current of less than 30 μA to excite them (actually they are excited with a constant voltage which for our resistors is of order 30 mV). The Cernox resistors are connected to the outside world with quad strand 36 gauge phosphor bronze wire with Formvar insulation.

The Allen Bradley resistors are wired with 30 gauge Kapton insulated copper stranded wire.

Target Lifter There are two AC servo motors which provide the power to lift the target ladder. These motors are powered by three phase 208 Volt power and are equipped with fail safe brakes (the brakes are **released** by a 24 Volt DC control voltage) and 50 to 1 gear reducers. On power up there is a delay relay that insures that the motors are always energized before the brakes are released.

Vacuum Pumps The scattering chamber is evacuated by two Leybold 1000 liter per second turbo pump that is backed by a Leybold 65 cfm mechanical pump. The turbo pumps are powered by 120 Volt AC power while the backing pump requires three phase 208 Volt AC power. The motor on the backing pump is explosion proof and approved for use in NEC Class 1, Division 1, Group D (hydrocarbons **but not** hydrogen) environments. An identical mechanical pump is used in the pump and purge system of the gas panels. Both the scattering chamber backing pump and the pump and purge system's mechanical pump exhaust to the vent line.

Vacuum Gauges the chamber vacuum is monitored by a HP cold cathode gauge. This gauge has a maximum operating voltage of 4000 Volts and a maximum current of 133 μA. The pressure at the entrance to the roughing pump is measured by a convectron gauge.

2.2 Flammable Gas Detectors

There are four flammable gas detectors installed (one on top of the target, one each on top of the hydrogen and deuterium gas panels, one on top of the gas tanks) to provide early detection of hydrogen/deuterium leaks. These detectors are sensitive (and calibrated) over the range from 0 to 50 % Lower Explosive Limit (LEL) of hydrogen. The electrochemical sensors were manufactured by Crowcon Detection Instruments LTD and the readout (four channels) was purchased from CEA Instruments, Inc (The Gas Master Four System). The readout unit provides two alarm levels per channel. The low level alarm is tripped at 20 % LEL while 40 % LEL activates the high level alarm. Each channel has a relay output for both low and high level alarm states and there is also a set of common relays for both alarm levels (these common relays respond to the "logical or" of the sensor inputs). The common relays will be connected to the Fast Shut Down System, FSD, which removes the beam from the hall by disabling a grid bias at the injector.

2.3 Pressure

The most important aspect of hydrogen safety is to minimize the possibility of explosive mixtures of hydrogen and oxygen occurring. To this end the gas handling system has been made of stainless steel components (wherever possible) and as many junctions as possible have been welded.

The pressure in the gas handling system is monitored in numerous places. Most importantly the absolute pressure of the target is viewed by two pressure transducers, one on the fill line, PT127 for H_2 and PT136 for D_2, and one on the return line, PT131 for H_2 and PT140 for D_2. These pressures are also measured by manual gauges. The fill line gauges are PI126 for H_2 and PI135 for D_2. The return line gauges are designated PI130, H_2 and PI139, D_2. The gas tanks are viewed with both pressure transducers (PT133 for hydrogen and PT142 for deuterium) and pressure gauges (PI123 for hydrogen and PI112 for deuterium).

2.3.1 Target Cells

The target cells themselves represent the most likely failure point in the hydrogen system. The outer walls and downstream window of the cells are made of $\approx$ 0.03 to 0.045 inch thick 3004 aluminum (Coors beer cans in a former incarnation) (all the final ones are above 0.035 inch). There are two cells soldered to each cell block, one 15 cm long and one 4 cm long. Both cells have an outer diameter of approximately 2.5 inches. The upstream windows of the cells are made from 0.0028 inch thick 5052 aluminum. These windows are soldered to 1.75 inch diameter (0.065 inch wall) upstream window tubes which are in turn soldered to the cell block.

Since all the components are made of aluminum it is necessary to plate them before soldering. The final components were copper plated before assembly.

The cell block components have been pressure tested hydrostatically at Jefferson Lab. We chose the thinnest beer cans to have pressure burst test. Results are listed in the summary table. Upstream windows have been tested to similar pressures. Finally, the entire completed cell block assemblies were pressurized to 85 PSID with helium gas. A summary of the testing program to date is presented in table:

2.3.2 Pressure Relief

The gas handling and controls system have been designed to prevent excessive pressure build up in the system in order to protect the target cells from rupture.

In the event that the pressure in the system begins to rise there are multiple vent

Object	P (PSIG)	thickness (in)	size	test method
Can	55	0.003	short	test (J)ig, (D)estructive
Can	80	0.0035	short	(J), (D)
Can	80	0.0035	long	(J), (D)
Can	60	0.0038	long	(V)acuum, (D)
Can	85	0.0039	long	(V), (D)
Window	110	0.028		(J),(D)
Window	125	0.028		(J),(D)
Window	125	0.028		(J),(D)
Window	115	0.028		(J),(D)
Window	147	0.028		(J),(D)
Window	150	0.028		(J),(D)
Complete Blocks	85			(V), Non-Destructive

Table 1: A summary of the cell block pressure testing to date.

paths to release it. The first line of defense is the recovery tank. The second line of defense is a small orifice solenoid valve which is slaved to a pressure transducer. This valve, CSV28 for H_2 and CSV57 for D_2, is normally controlled by the limit output of the computer (via a VME based relay) readout of the pressure transducer that views the target relief line, PT131 for H_2 and PT140 for D_2. The valve itself is mounted in the fill line relief assembly. The separation of the valve from its controlling pressure gauge should provide some dampening of the response and the small orifice of the valve also ensures that it will be able to make pressure adjustments gently if need be. There is a separate relief valve on the fill side of the target, CRV30 for H_2 and CRV59 for D_2. This relief is mounted in parallel with the small orifice solenoid valve. Right on top of the cryocan, on the return side of the target, there is a large size (one inch) relief valve. All target pressure reliefs are connected to the nitrogen vent line of the Hall A superconducting magnets. This is a 3.5 inch diameter copper pipe which is filled with nitrogen gas at atmospheric pressure. Thus any vented target gas is placed in an inert environment until it is released outside of Hall A. Each gas tank has one relief valve and one rupture disk (CRV43 and CRD44 for hydrogen, and CRV72 and CRD143 for deuterium).

In addition to the reliefs on the gas handling system described above, the scattering chamber itself has a four-inch one PSIG relief, VRV01. This is the path that the hydrogen will take in the event of a cell failure.

The target pressure reliefs are summarized in table 2.

Name	Target	Location	Diameter (inch)	Pressure (PSIG)
CSV28	H_2	FRA	0.125	40
CRV30	H_2	FRA	0.5	40
CRV82	H_2	RL	1	40
CRV43	H_2	TANK	1	55
CRD44	H_2	TANK	1	55
CSV57	D_2	FRA	0.125	40
CRV59	D_2	FRA	0.5	40
CRV64	D_2	RL	1	40
CRV72	D_2	TANK	1	55
CRD143	D_2	TANK	1	55
CRV35	He	RL	1	40
CRV01		SC	4	2

Table 2: A summary of the pressure relieving devices on the hydrogen/deuterium targets and the scattering chamber. FRA is an abbreviation for Fill Line Relief Assembly. and RL is an abbreviation for Relief Line. SC stands for Scattering Chamber.

2.3.3 Scattering Chamber Vacuum Failure

The scattering chamber will be leak checked before service but obviously the possibility of vacuum loss can not be eliminated. The most likely sources of vacuum failure are:

Spectrometer Windows Initially the scattering chamber will have two aluminum windows, one for each side of the beam line.

Target Cell Failure This is a multiple loop system. If a target cell fails then the remaining targets will have their insulating vacuum spoiled.

The two spectrometer windows are both made from aluminum. Each window is seven inches high and sustends 170 degrees on the 43 inch outer diameter of the scattering chamber. This window is made of 0.016 inch thick 5052 H34 Aluminum foil.

The scattering chamber was evacuated (and cycled several times) with both windows covered by the same 0.016 inch material. The foil forms regularly spaced vertical ridges when placed under load. The window had an inter ridge spacing of 3 inches. If the window is treated as a collection of smaller rectangular windows which have the full vertical height of 7 inches and the inter ridge spacing as a width, then stress formulas predict that the 0.016 inch material would reach ultimate stress at a pressure higher than 35 PSI. There is a gate valve between the scattering chamber and the beam entrance (exit) pipe. Both valves will be closed automatically in the event that the chamber vacuum begins to rise and a FSD will be caused (this is done via a relay output of the scattering chamber vacuum gauge). If either valve is closed an FSD will result.

In the unlikely event of a catastrophic vacuum failure it is important that the relief line of the targets be sized such that it can handle the mass flow caused by the sudden expansion of its cryogenic contents due to exposure to the heat load. A calculation has been performed which models the response of the system to sudden vacuum failure. That calculation indicates that the relief plumbing is sized such that the flow remains subsonic at all times and that the maximum pressure in the cells remains well below their bursting point.

The calculation was performed by following methods in an internal report from the MIT Bates laboratory [2]. The formulas and algorithm in the report were incorporated in two computer codes and those codes were able to reproduce results in the report (hence they represent an accurate implementation of the Bates calculation).

The calculation can be logically broken into two parts. First, the mass evolution rate is calculated from geometric information and the properties of both the target material and vacuum spoiling gas. The principal results of this first stage are the heat transferred per unit area, q, the boiloff time, t_b, and the mass evolution rate, w. Second, the capability of the plumbing to handle the mass flow is checked. The principle result of this second step is the maximum pressure in the target cell during the discharge, P_1.

The formula involved will not be repeated (readers are refered to the Bates report for detail). The information that was used as input to the calculation is given in the tables 3, 4 and 5.

For the calculation of the boiloff rate the target was split into two pieces, the cells plus cell block, both aluminum, and the heat exchangers plus the connecting plumbing, all steel. The mass evolution rates for the two pieces where then added in order to find the total mass flow rate.

The calculation of the pressure drop includes all the plumbing up to the large relief valve. The calculation assumes that all the mass flow is carried out the relief side of the target gas handling system (no flow out of the fill line reliefs). The friction factor for each diameter was taken from a Moody plot. A typical value was $f = 0.017$. The effective K values, K_{eff}, were adjusted to the average tube inner diameter which was taken to be 0.71 in. The final K_{eff} value was 40. The minor losses are from bends, expansions and contractions in piping.

The final result gives the cells subjected to 58 PSIA during the boiloff. Which is comparable to the 75 PSIA pressure that the assembled cell blocks were tested at and is significantly below the tested pressure of the cell components.

Fluid and Phase	Property	Symbol	Value
Hydrogen/Liquid	Temperature	T(K)	22
	Density	ρ (kg/m^3)	67.67
	Specific Heat	C_p (J/(kg K))	11520
	Enthalpy of Vaporization	H_v J/kg	428,500
Hydrogen/Vapor	Temperature	T(K)	22
	Density	ρ (kg/m^3)	2.4991
	Viscosity	μ (kg/(s m))	$1.29*10^{-6}$
	Specific Heat	C_p (J/(kg K))	13,550
	Thermal Conductivity	k (W/(K m))	0.02
	Volume Expansivity	β K^{-1}	0.00366
Air	Temperature	T(K)	273
	Pressure	P (Torr)	760
	Density	ρ (kg/m^3)	1.224
	Viscosity	μ (kg/(s m))	$1.8*10^{-5}$
	Specific Heat	C_p (J/(kg K))	1005
	Thermal Conductivity	k (W/(K m))	0.0244
	Volume Expansivity	β K^{-1}	0.00367

Table 3: The properties of the gases used to calculate the heat transferred to the target during a catastrophic vacuum failure.

The scattering chamber has a volume of about 2,100 liters with perhaps an additional 200 liters of volume in the bellows and the cryo can. If one target cell were to rupture and the chamber were unrelieved the chamber pressure would rise to about 2 Atm. It takes approximately 150 seconds to bring 5 liters of 22 degree hydrogen to room temperature by conductive heat transfer with the scattering chamber walls. In order that the maximum pressure in the chamber stay near one atmosphere it is necessary to vent one half of the target mass in approximately one half of the total expansion time. Therefore the relief valve for the scattering chamber should be capable of venting about three grams per second at a low pressure difference (say two PSIG). If one considers the case where all three targets fail at once, the vent must be capable of handling three times that amount. A four inch diameter relief placed near top of the scattering chamber would be capable of handling this rate. A rise in the chamber vacuum will stop the beam, FSD, and cause the gate valves on either side of the scattering chamber to close. In addition the valves that connect the targets to their gas supplys will be closed.

In the unlikely event that a line which carries helium coolant were to rupture the four inch chamber relief valve is capable of handling the full coolant flow rate.

Quantity	Cell Block	Piping	Heat Exchanger	Total
D	2.5 in (0.063 m)	1.5 in (0.038 m)	7 in (0.1778 m)	
k	55 W/(K m)	6.5 W/(K m)	6.5 W/(K m)	
A	0.146 m^2	0.185 (m^2)	0.216 m^2	0.510 m^2
V	0.001 m^3	0.0019 (m^3)	0.002 m^3	0.0054 m^3
x	0.004 in (0.0001 m)	0.065 in (0.00165 m)	0.12 in (0.003 m)	
q	14903 W/m^2	10526 W/m^2	11235 W/m^2	
t_b	26.78 s	28.29 s	23.89 s	26.3 s
w	0.0038 kg/s	0.0045 kg/s	0.0056 kg/s	0.014 kg/s (0.03 lbs/s)

Table 4: The geometric quantities needed for and the results of calculations of the mass evolution rate after a catastrophic vacuum failure.

3 Temperature Regulation

This is really more an issue of target stability than one of safety. However, a target with a carefully regulated temperature will presumably not undergo worrisome pressure changes.

Each target contains six quality temperature measurements, four Cernox resistors and two hydrogen vapor pressure thermometers. The primary temperature regulation is done with a dedicated temperature controller (an Oxford ITC-502) which slaves a heater (the "low power heater") to the temperature read by one of the Cernox resistors. This is a three parameter control loop (Proportional, Integral and Differential Control or PID).

In addition, the return temperature of the target systems coolant gas is used to regulate the supply of coolant from ESR.

Finally the heat load from the beam will be compensated in the "active" target loop by use of the high power heater. This is not a true regulation but rather a one for one replacement of the beam load should the beam disappear for whatever reason. The beam load is calculated from the target length, the beam current as read from a current monitor and the target material.

Excursions of the target temperature outside acceptable limits will cause the control system to take action. In the case of a high temperature alarm the beam will be inhibited by issuing an FSD. Finally the redundancy of temperature measurements can be used by the control system to pick up the failure of a sensor or its readout channel. A more complete discussion of target temperature regulation is available in reference [3].

Inner Diameter	Length	K (K_{eff})
0.44 in tube	10 ft	4.64 (31.5)
0.88 in tube	10 ft	2.32 (0.98)
Quantity		Value
Minor Losses		7.4
K_{eff}^{total}		40
Average Diameter		0.71 in
xmax		0.890
w_{sonic}		0.065 lbs/s
m		0.323
x		0.748
P_2		14.7 PSIA
P_1		58.3 PSIA
P_1		43.6 PSIG

Table 5: Tubing sizes, and other information needed to analyse relief line response. The mass flow rate was 0.03 lbs/s.

3.1 Target Freezing

Solid hydrogen is more dense than the liquid phase so freezing does not endanger the mechanical integrity of a closed system. The chief hazard is that relief routes out of the system will become clogged with hydrogen ice making the behavior of the system during a warmup unpredictable. However, since we are using 15 K coolant, while the hydrogen freezing point is about 13.8 K, hydrogen target should not get frozen. The freezing point of deuterium is higher than that of hydrogen and higher than the temperature of the gas used for cooling (15 K). There could be a chance that the deuterium target start to freeze.

The coolant flow through the three target heat exchangers is connected in parallel for the three target loops. The entire target system will be run so that it represents a constant heat load on the ESR. For instance, the ESR will deliver a constant mass flow of helium cryogen at a constant temperature, about 15 K, and the coolant will be returned at an approximately constant but higher temperature, usually about 20 K.

The targets are always temperature regulated by temperature controllers. Also high power heater will be in the PID loop to compensate any large temperature fluctuations to keep the temperature constant. In the unlikely event of target temperature drops to too low, an alarm will sound and the target operator will turn down the corresponding J-T valve(s).

4 ODH

The total volume of the targets is relatively small with the entire scattering chamber containing only 9,000 STP liters of target fluid when all three targets are full. As the scattering chamber is located in the middle of Hall A (ie. not in a confined area) and the total Hall A volume is 40,000 m^3, the ODH hazard is minimal.

5 Controls

The target controls have been implemented with the EPICS control system and with hardware very similar to that employed by the accelerator. The basic control functions reside on a VME based single board computer. The graphical interfaces to the control system uses a PC, and also requires the Hall A Hewlett Packard, HP, computer for control (HAC) to be present as well.

All of the instrumentation for the target is downstairs in Hall A. Most of the equipment (in fact all of the 120 V AC equipment) is on an Uninterruptable Power Supply, UPS. The equipment whose power is not on UPS is

- The scattering chamber vacuum pumps and the gas panel backing pump.
- The target lifting mechanism
- The target circulation fans.

This is a 7 kVA zero switching time UPS which is dedicated to the target. The PC, HAC and the counting house target X-terminal are on Uninterruptable Power as well. The targets dedicated UPS provides 18 minutes of power at full load (or 50 min at one half load). The status of the UPS, online or offline, is read by the control system and after ten minutes the control system will initiate an orderly shut down of the targets.

The principal functions that the control system performs are:

Pressure Monitoring The pressure at various places in the system is monitored and alarm states are generated if a transducer returns a value that is outside user defined limits. High pressures will cause the small orifice solenoid valve to open and cause an FSD.

Temperature Monitoring The temperature of the target is read from resistors and vapor pressure bulbs and alarm states are activated when any temperature sensor returns a value outside the user defined limits. High temperatures will cause an FSD to occur.

Temperature Regulation The control system allows the target temperature to be regulated. In the default operating scenario this regulation is performed by a stand alone temperature controller.

Solenoid Valve Control The gas systems have a number of solenoid valves that must be switched.

J-T Valve Control The flow of coolant through the heat exchangers is controlled by a set of J-T valves. These valves control the coolant helium flow through the three loop heat exchangers and the precool heat exchanger.

Circulation Fan Monitoring and Control The fans which circulate the target fluid are monitored (current, voltage, frequency). The voltage supplied to the fans is adjustable and alarm states can be set on out of range frequency, voltage or current values.

Vacuum Monitoring The scattering chamber vacuum is monitored by the control system. Unacceptable values will generate an FSD and close the upstream and downstream scattering chamber valves.

Target Lifter The target lifting mechanism is controlled by the computer. This allows one to place the desired target in the beam.

6 Conclusion

The principal problem in hydrogen safety is the prevention of explosive hydrogen and air mixtures. The mechanical aspects of this system have been built to minimize the possibility of a hydrogen release. The components that are most susceptible to failure have been tested and the results of these test indicate that the system should stay in tact under the most extreme conditions that are likely to be encountered.

In the unlikely event that hydrogen is released a mechanism is in place to detect its presence quickly and remove at least the beam as a possible ignition source.

A control system has been developed to allow the careful monitoring of the target systems behavior and it will respond to any aberrant behavior in order to minimize the consequences. Essentially the entire control system has been placed on uninterruptable power so that short power outages can be waited out.

References

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[2] W. Schmitt and C. Williamson " Boiloff Rates of Cryogenic Targets Subjected to Catastrophic Vacuum Failure", Bates Internal Report # 90-02, Sept 1990

[3] F. Duncan, K. McCormick, and J. Goity "A User's Guide to the Hall A Cryotarget Control System", Sept 1997