ODH Assessment

DATE: 11/10/2016 (Revision 2, 01/26/21)

DIVISION: Accelerator & Engineering Divisions

LOCATION: Upgrade Injector Test Facility (UITF) at Building 58

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APPROVAL: ______________________________________
Chris Perry for the Engineering Division Head

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EHS IH Group, MS 52C
EHS Documentation, MS 52C

Revision History:

2/1/21; M. McCaughan (Rev. 2)

- Figure reorganization & update from Rev.1 & addition of several figures for clarity
- Content added for cave 1 vent chimneys, cable enclosure cable trenches, and HDice venting.
- Section added describing installed ODH monitoring system
- Update QCM/Booster section in risk analysis section with as-installed mitigations.

2/13/18, W. Oren (Rev. 1)

- Eliminated "Preliminary" on assessment location
- Modified venting requirements for parallel plate and burst disk relief valves on the ¼ cryomodule.
- Changed ODH conditions for Mode 3 Operational Conditions

Document Approval: (from Rev. 1)

From mis-webapps@jlab.org
Subject **ODH form #74180 approved**
To Me <poelker@jlab.org>, stuart@jlab.org, Dave Fazenbaker, John C. Hansknecht

This email is to inform you that the following ODH form has been fully approved.

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Oxygen Deficiency Review 74180

Calculated % Oxygen Level: 0

Affected Area(s)

- 58_1.1127 - Test Lab - 1127

ODH Risk Assessment, UITF

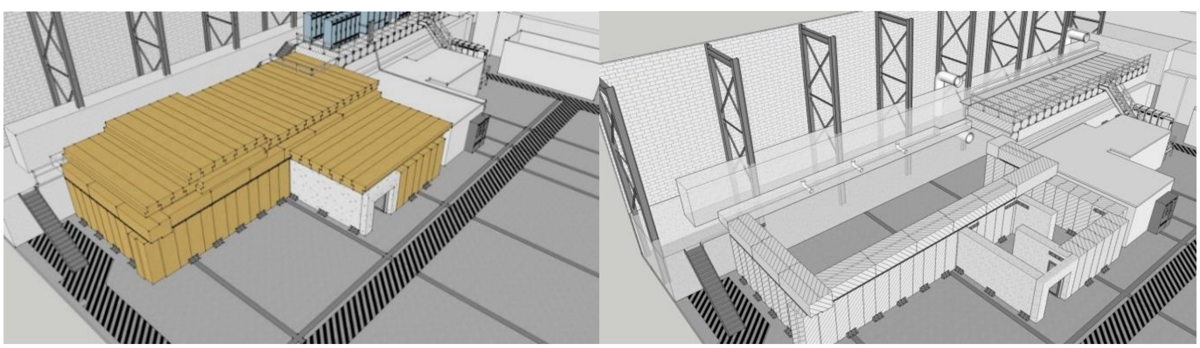
Introduction

This assessment addresses the risk of oxygen deficiency hazard for the Upgrade Injector Test Facility (UITF). The assessment is conducted according to Jefferson Lab's ODH Risk Assessment Process (ODHRAP). This assessment addresses the cryogens and gas (Helium, Nitrogen and Sulfur Hexafluoride [SF_6]) ODH hazards associated with the facility. These gases and cryogenic fluids are sources of gases which can dilute the normal oxygen content with health effects as outlined in the Lab's ODH Risk Assessment Process. However, according to the Safety Data Sheet (SDS) the maximum exposure of SF_6 is 1000ppm and therefore should not be considered here as an asphyxiant. A separate industrial hygiene assessment addresses SF_6 as a toxic hazard other than what is covered here as an ODH hazard.

The following sections cover the modeling scope and methodology for a cryogen or gas dispersion release, a description of the work space, operational modes which affect the risk factors, failure rates of the components, and the resultant area classification.

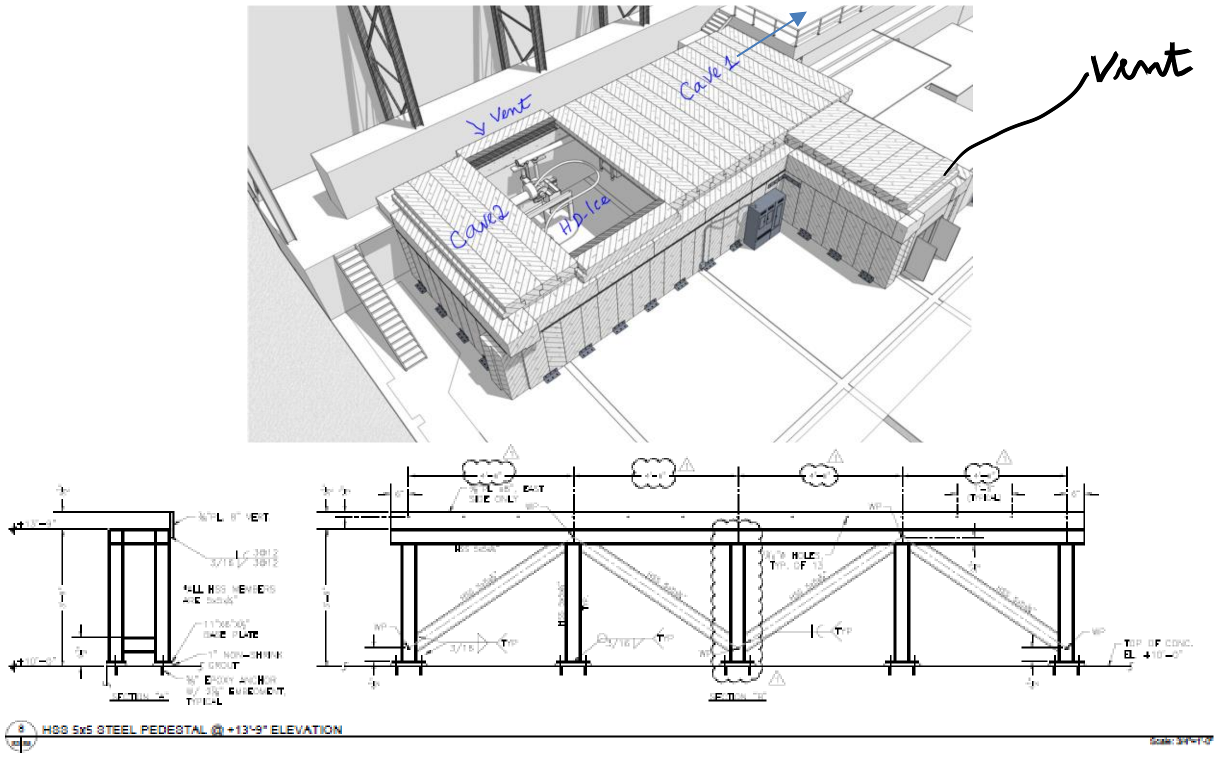
UITF Configuration

The facility description is depicted in Figures 1 - 5, shown below where the entire complex is within the Test Lab, Bldg 58. The work areas covered in this analysis include the UITF enclosure which is composed of Cave 1 and Cave 2, the adjacent Test Lab high bay area and the tops of Caves 1 and 2.



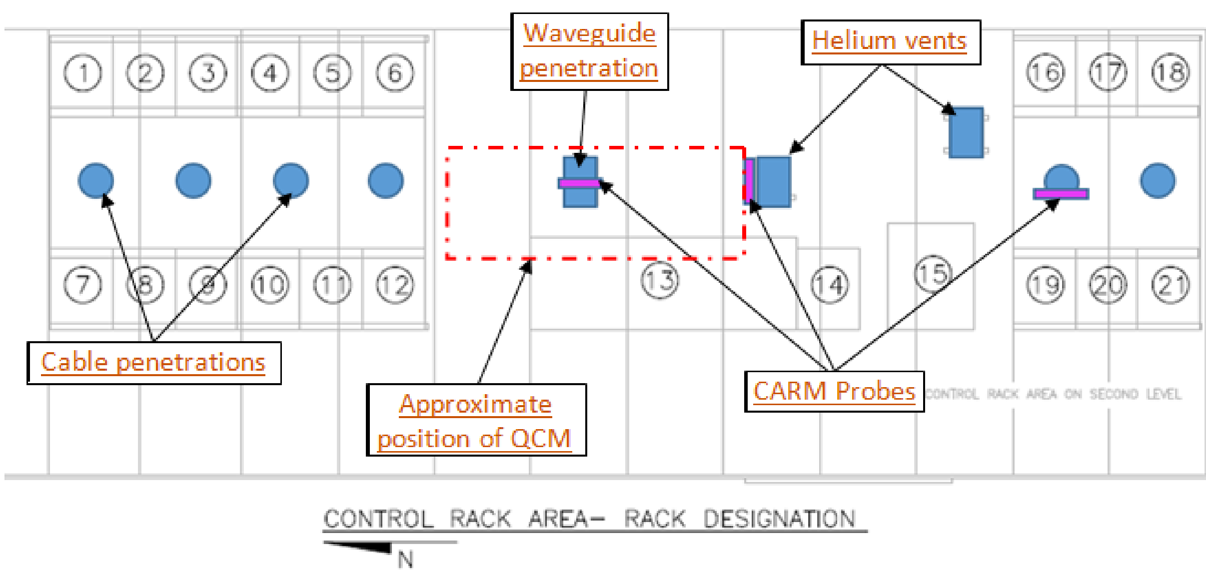
(Fig. 1/2: UITF with ceiling in place and removed from Cave 2)

Cave 1 has a volume of 207 m^3 and Cave 2 has a volume of 441 m^3 for a grand total of 648 m^3 for the combined space. These areas, while they have differing ceiling heights with a 1 m divider between them, will be treated as a combined space. The bottom of this divider is 3m (10') from the floor.



(Fig. 3: 5.6 m^2 vent area at the ceiling in Cave2)

Cave 1 has six 0.25 (10") diameter ceiling penetrations, all of which can be used for cable routing as seen in Fig. 4. All six of these penetrations emerge under an expanded metal grating that spans the space between 2 sets of electronics racks on the top of the cave. None of these will be considered as possible vents for helium in this analysis. They must be blocked so that helium cannot escape through them preventing the possibility that workers in the racks will be exposed to an oxygen deficient environment.

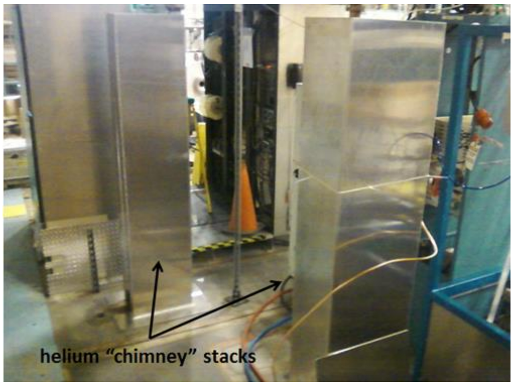


(Fig. 4: Rack & Waveguide Penetrations and Helium Venting)

Additionally, in Cave 1 there are two 0.76m (30”) diameter ventilation tubes, with active fans, on the east wall approximately 2.1m (7’) above the floor: one tube vents to the exterior of the building (capacity of 2.1m^3/s – 4400CFM), and the other vents (capacity of 3.5m^3/s – 7400CFM) to the high bay region. (See Fig. 5) Because of the need to power the fans, these vents will not be used in this analysis which assumes that powered active controls may fail. The discharge of the northern most exhaust fan is directed away from the electrical support racks on the top of the cave to avoid personnel exposure to helium/nitrogen during a spill event. In addition, there are three 0.15m (6”) diameter vent holes on the west wall near the ceiling which go to the High Bay area. Finally, there are three 0.30m x 0.46m (12”x18”) penetrations that go through the ceiling terminating outside the access area to the electronics racks. One of these is filled with RF waveguide but the other two are used as vents.

(Figure 5: Vents in Cave 1)

The total area in Cave1 available for venting helium, includes the two 0.30m X 0.46m penetrations and one of the 0.15m diameter vent holes on the west side, is 0.30m^2 (3.2ft^2). The two remaining 0.15 diameter holes on the west side are reserved for dedicated use to house a vent line coming from the ¼ cryomodule’s primary Circle Seal relief. Since the two 0.30m X 0.46m ceiling penetrations are used as vents, chimney stacks have been installed on the cave roof to direct any vented helium above the heads of anyone in the area. (Fig. 6) Within Cave2, there is a 5.6 m^2 (60ft^2) area at approximately 3.7 m (12’) under the raised part of ceiling available for venting into the high bay volume. This raised portion can be seen in Fig. 3 (as well as below in Fig. 7) and corresponds to the area overhead of the HDice target and refrigerator location.

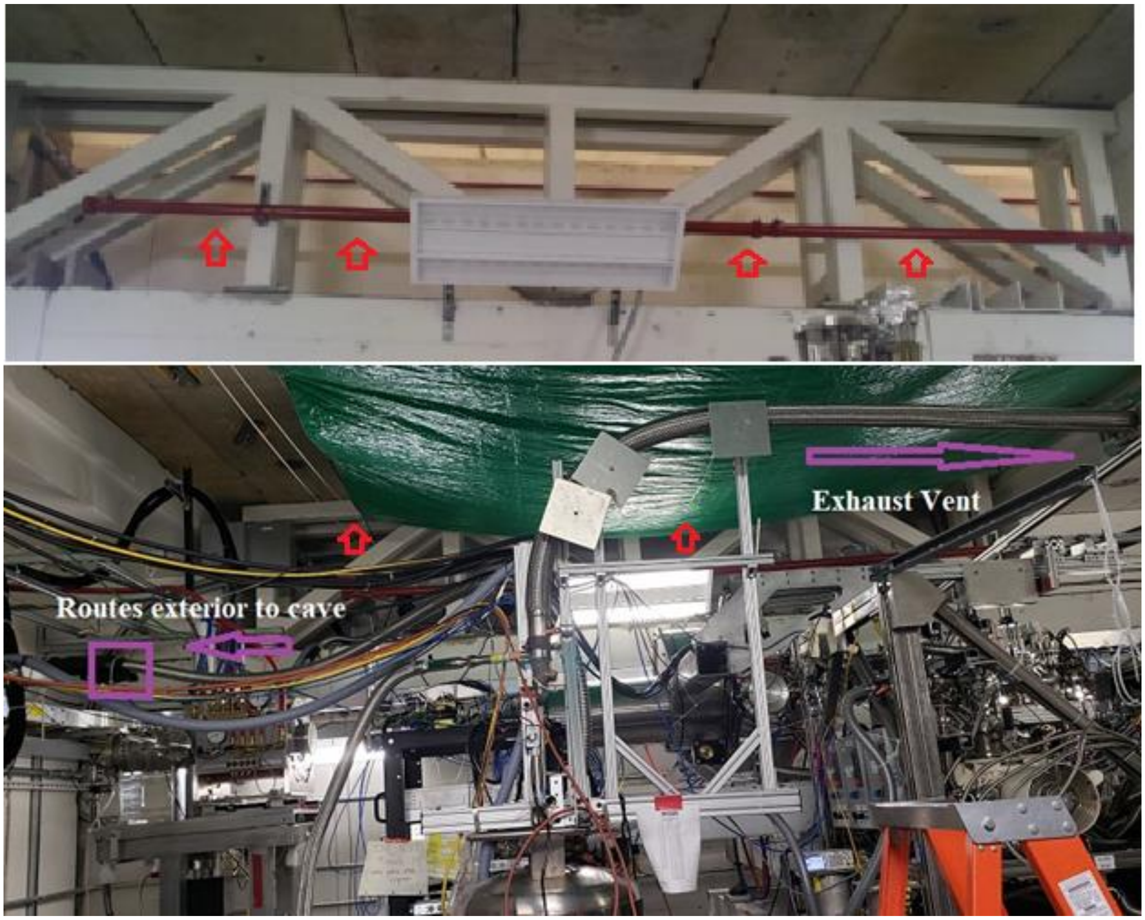


(Fig. 6: UITF Cave 1 roof Helium chimney stacks) **(Fig. 7: Cave 2 Helium Vents)**

Trenches also exist in the cave floor as a means of passing electrical conduit and control cables into the UITF from the Test Lab High Bay, Drive Laser Room, UITF Control Room, etc. These trenches represent a potential pathway for the release of ODH gases, and as such have been filled with layers of foam to isolate the enclosure as well as lead bricks and gravel bags for purposes of radiation shielding. (Fig. 8)

(Fig. 8: Sealed UITF cave cable trenches)

The main entry/exit to UITF is through a labyrinth with a chain-link fence gate, approximately 1.8m (6') wide and 2.4m (8') tall, which also provides an escape path for helium gas and/or a path for makeup air. (Fig. 14) The penetrations and chain-link fence gate allow lighter than air mixtures of ODH gases to leave the enclosure to the high bay. (Fig. 9) If desired, a more detailed description of the Hall B – CLAS HDIce In-Beam Cryostat may be found in the experiments cryogenic flow schematic drawing: B00000-09-01-0203



(Fig. 9: HDIce Gas Venting [internal to beam enclosure] | Purple = Target Boil off / Red = Catastrophic loss)

(Fig. 10: HDIce Gas exhaust port into the Test Lab High Bay)

Model and Sources for Cryogen and Gas Dispersion Release

Helium spill tests within the JLab accelerator tunnel and the CHL vent stack test apparatus have shown that rising helium gas interacts with the surrounding air, mixing with it as it rises to predominately produce a mixture with 16.5-17% oxygen. Once combined with air, the helium does not readily separate out of the air/helium mixtures thus is not reversible. It will retain the same helium to air percentages as long as it does not further interact with additional sources of air (dilution) or high concentrations of helium (enrichment). Since the helium/air gas mixture is "lighter than air", the mixture rises but at a substantially slower rate than pure helium gas since the mixture is heavier. When natural convection ventilation (in the form of vertical vent tubes) is provided, both oxygen and helium are purged from the enclosure area. The helium/air mixture will displace more of the enclosed space in a vertical downward direction from the ceiling if no additional sources of air are provided to replace the escaping helium/air mixture. Calculations indicate for ideal conditions, where the vented mixture is replaced by air, that we can expect a passive vent capacity of 0.26 kg (He)/m^2/s. (Reference: Internal memo – "Helium Vent Investigation, July 9, 2001, Dana Arenius)

The possible sources of ODH producing gases or cryogens in Cave 1 are based on a fully operational quarter-cryomodule with 400L of 2K liquid helium and the associated cryogenic distribution system at 4K located within the UITF accelerator enclosure. Liquid helium is supplied to the quarter-cryomodule from the Cryomodule Test Facility (CTF) refrigerator located adjacent to building 58. The UITF ODH sources of pressurized helium gas are a cryogen distribution 3 atm 4k supply line, a 4K .034/1 atm return line, a warm (300K) 3 atmosphere helium supply line and the component failures associated with the quarter-cryomodule. The cryogen transfer line relief valves are located outside the UITF enclosure either outdoors (supply and shield return lines), in the CTF (primary supply line) or inside the Test Lab (shield supply) and do not contribute as a source for ODH for the UITF accelerator enclosure. The quarter-cryomodule has a cryogenic shield circuit with liquid nitrogen supplied from outside the UITF enclosure at a rate of 6.2 liquid liters/minute.

In addition to the quarter-cryomodule, this ODH assessment considers: a fully functional HDIce target attached to an In-Beam-Cryostat of 50L LHe, a 500L LHe buffer dewar, a 500L or 1000L LHe supply dewar and a 100L LN2 service dewar. The helium gas boil off from the HDIce target is captured and vented into the second floor of the Test Lab High Bay via a marked and isolated exhaust port. (see Fig. 9/10) As discussed below this is equivalent to venting to the outdoors and does not pose an ODH hazard.

Additionally, gaseous nitrogen is available from a supply line originating at the LN2 dewar that services the Test lab. An ODH analysis, using a smaller cave volume, is documented in JLab Tech note "JLAB-TN-07-075" for Room 127 (old cave room number) and requires an orifice bore of 0.114in and an interlock from active fans to a solenoid cut off valve on the N2 supply line that limits the area to an ODH 0 state. These features have been installed in the N2 supply line system.

ODH Analysis

The Test Lab high bay volume is large, roughly 40220 m^3 (81.4m L x 40.5m W x 12.2m H - 1.4 million cubic feet, 267' L × 133' W × 40' H), the high bay is considered to be equivalent to the outdoors. To justify the assumption that the high bay volume is large enough to be considered equivalent to the outdoors, consider 1,900 L of LHe released simultaneously from the quarter cryomodule (400L) and from the HDIce target (500L buffer dewar and a 1000L fill dewar). This amount of LHe would expand to 1481m^3 (52,315 $ft^3$of gas) with a resulting O2 concentration of 20.2% in the Test Lab high bay.

This ODH analysis is based on the premise that the passive venting capacity built into the UITF cave is large enough that ODH gases from failure of any component in the supply circuits will never accumulate to the level where the O2 content will go below 18.5% outside the spill plume. If the O2 content never goes below 18.5% then the fatality factor will be 0 for all failure cases where the passive vent rate is greater than the failure flow rate. Of course, O2 levels will be less than 18.5% in the vent plume but the layout of the equipment in the cave does not restrict access to the point where those qualified for ODH work cannot move away to a point where there is no ODH danger. The tables below quantify the flow rates upon failure of any of the circuits associated with the UITF cave with the HDice target and the ¼ cryomodule fully functional. (Note: an alternative analysis methodology is present by Hari Areti in Appendix A which confirms the conclusions from the table below)

Equipment failure and passive vent rates

Item and Event	Spill Rate kg/sec	Passive Vent Rate kg/sec based on 5.9m^2 vent area	Ratio (Spill Rate)/(Vent Rate)	If <1 "Ok", If >/=1 "Issue"
Rupture 4K Supply	0.02	1.50	0.013	Ok
Blocked 4K Return	0.02	1.50	0.013	Ok
Rupture Shield Supply	.015	1.50	0.010	Ok
Blocked Shield Return	.015	1.50	0.010	Ok
¼ CM Insul Vac Loss	0.22	1.50	0.147	Concern$^+$
¼ CM Beam Line Vac Loss	0.89	1.50	0.593	Concern$^+$
Rupture 300K Helium Supply	0.01	1.50	0.007	Ok

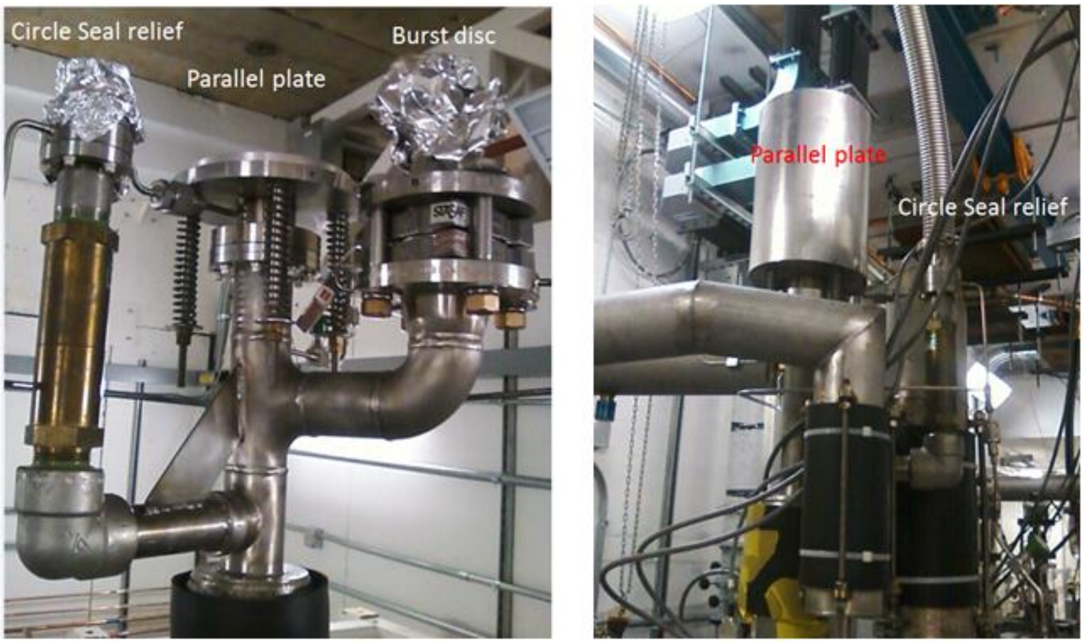
Rupture HDice 50L IBC	NA*	1.50	NA	Ok
Rupture transfer line 500L Buffer Dewar	0.06	1.50	0.040	Ok
Rupture transfer line Supply Dewar	0.25	1.50	0.167	Ok
Rupture 500L Dewar	63kg**	1.50	NA	<u>Issue</u>
Helium Dewar Relief – Spoiled Insulating Vacuum	0.23	1.50	0.153	Ok
Rupture 1000L Dewar	125kg**	1.50	NA	<u>Issue</u>
Rupture HDice boil off return line	0.0003	1.50	<<1	Ok
Rupture 100L LN2 Dewar	81kg***	NA	NA	Ok
LN2 shield line rupture	0.084****	NA	NA	Ok

<u>Notes:</u>
+ Because of the direction of discharge and distance to substantial passive venting these events remain a concern
*Instantaneous failure of 50L IBC results in a 19.9% O2 concentration in the cave with a fatality factor of 0.
** Instantaneous failure of dewar dumping entire contents results in O2 concentration for 500L of 8.8%, 1000L inerts the cave – Initial operations will be with a 500L supply dewar.
*** Instantaneous failure of dewar dumping entire contents results in O_2 concentration of 18.7% resulting in a fatality factor of 0.
**** This is a release rate of 0.07m^3/s. It will take 10 minutes before the oxygen content in the cave goes down to 19.5%. See the figure and discussion in Appendix B.

Referring to the table above one sees that two concerns and two issues need to be addressed:

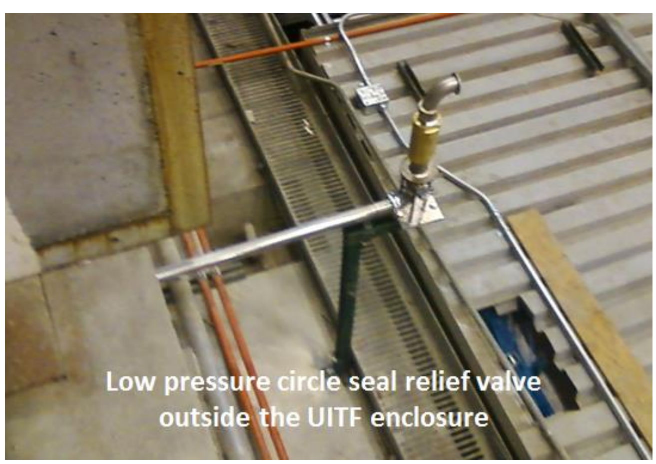
<u>Quarter Cryomodule / Booster:</u>
While the passive venting is able to accommodate a full venting of the ¼ cryomodule, the direction of flow from the reliefs (close to head height) and the long distance to the majority of available venting in Cave 2 is a concern if an actual event were to occur. The venting of the entire helium inventory upon the loss of beam line vacuum in the ¼ cryomodule will take place

in approximately 70secs with a large discharge plume. To ensure clear egress and clear flow of the spill out of the cave, the primary relief on the new ¼ CM must be diverted to the outside of the cave. A penetration on the west wall of Cave 1 has been reserved for that function.



(Fig. 11: Cryomodule relief vents)

There are three main vent pathways by which helium gas can escape from the QCM, and each vent pathway is located on the QCM vent stack: a) circle seal relief which opens at 17 psi, b) a parallel plate relief valve which opens at 45 psig and c) a burst disk which opens at 51 psig.   See Figure 11, above. If a venting incident should occur, the circle seal relief would open first. For this reason, the exhaust of the circle seal relief is piped outside of the UITF enclosure and into the high bay as is seen in Figure 12. Sheet metal wrapped around the parallel-plate relief serves to direct gaseous helium upward, and not toward personnel walking near the QCM. A 90 degree elbow has been installed onto the burst disk for the same purpose.



(Fig. 12: Circle seal relief valve exhaust port)

Dewar Failures:
The two issues involving dewar failures must be dealt with in a traditional ODH risk analysis considering fatality factors and failure rates. The median failure rate for a dewar from the old EH&S manual chapter 6500-T3 indicates 1 x 10^{-6}/hr but with a fatality factor of 1 in this case. This results in a P_iF_i product of 10^{-6} and an ODH 1 rating from the presence of a 500L helium dewar or larger. The failure of insulating vacuum on a 500L dewar would trigger the release of gas through the relief valve at a rate which is less than a rupture in the transfer line to the target as quantified in the above table. For this analysis, it is recognized that the most probable failure that would result in an instantaneous dumping of the entire dewar contents would involve the movement of such a dewar. This is considered in the analysis of ODH states for the configurations enumerated below. The dewars and target apparatus are seen below in Fig. 13.

(Fig. 13: HDIce Target Apparatus Installation and Supporting Dewars)

ODH Ratings and Operational Configuration

Mode 1: The ODH rating of the UITF cave is **ODH 1** when a 500L helium dewar or larger is being moved into/out of the cave or the supply transfer line is being installed into the supply dewar with the roof fully installed.

Mode 2: The ODH rating of the UITF cave is **ODH 0** from the floor to an elevation of 9ft (The height of the bottom of the lintel separating Cave 1 from Cave 2) with the roof fully installed, the primary relief of the ¼ Cryomodule diverted outside the cave and the passive vent areas outlined above free and clear for the passage of helium gas. From 9ft up to the ceiling the ODH rating is **ODH 1**. Additionally, the access labyrinth must have a chain-link fence gate allowing free passage of air.

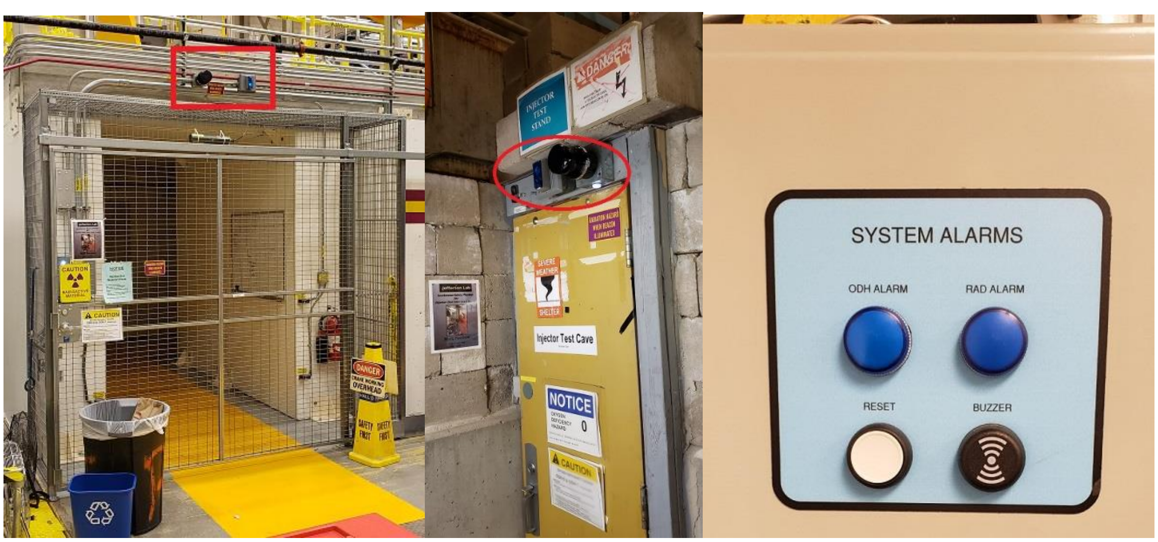
Also, the two 0.30m x 0.46m (12”x18”) penetrations on the roof of Cave 1 must have chimneys installed to divert any vented helium above the heads of anyone working in the vicinity of the electronics racks. (See Fig. 6) The six 0.25 (10”) diameter ceiling penetrations in Cave 1 must be sealed to prevent the passage of helium.

Mode 3: When the Cave 2 roof is partially removed for work on the HDice target the entirety of Cave 2 is rated as **ODH 0** but from 9ft up to the ceiling in Cave 1 remains at an **ODH 1** rating with all gas and cryogen sources available and the ¼ cryomodule primary relief diverted outside the cave.

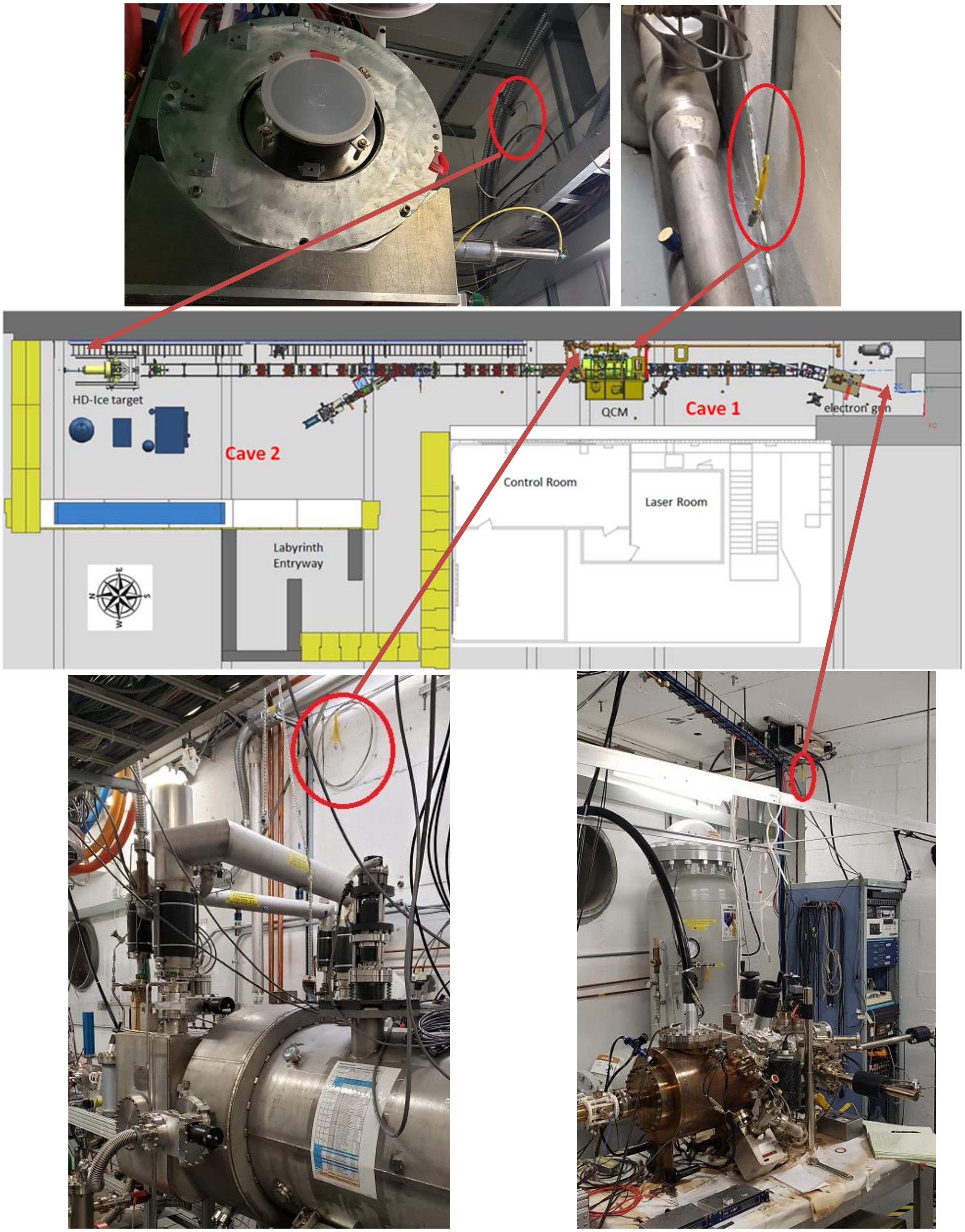
Mode 4: When the cave roof is fully installed, during u-tube operations to connect or disconnect the ¼ Cryomodule the entire cave will be rated **ODH 2.** The ODH 2 rating reflects the poor egress conditions from the ¼ Cryomodule during u-tube operations.

ODH Monitoring System

An ODH Monitoring System has been established in the UITF enclosure. Presently it contains 4 sensor inputs: 3 for Helium & 1 for Nitrogen as seen in Fig. 15. Helium sensors are distributed approximately uniformly along the enclosure length near ceiling level at positions near the keV beamline, Booster cryomodule, and HDIce target location. The Nitrogen sensor is located at floor level near to the cryomodule. ODH alarm systems are located both internal to and at the entryways into the enclosure, as well as within the UITF control room. (See Fig. 14/16) A separate monitoring system also exists to monitor SF_6 tank pressure, but as mention above it will not be discussed herein for ODH purposes.



(Fig. 14: ODH alarm system indicators outside the UITF enclosure & within the Control Room)



(Fig. 15: Positioning of the ODH Sensors in the UITF; 3 He + 1 Nitrogen – seen at top right)

(Fig. 16: ODH Warning Strobes & Sirens internal to the beam enclosure)

Appendix A

Assessment: Cave2 – HDIce Area – Using ceiling vent and chain link entrance gate

Helium:

Helium released in the cave tends to rise towards the ceiling. The ceiling vent is located close to the cryogenic dewars facilitating the venting of cryogenic gases into the high bay. The pressure increase in an enclosure due to release of cryogenic gas is given by $\Delta P = n\,RT/V_c$, where n is moles of the released gas, R is the gas constant, T is gas temperature in K and V_c is the volume into which the gas is released. N = m/M, where m is the mass of the released gas and M is its molecular weight. This equation could be rewritten as $\Delta P = mRT/MV_c$. Since m/V_c is the density of gas, rearranging the equation gives, $\rho = M\,\Delta P/RT$ or, $\Delta P/\rho = RT/M$. Recognizing that $\Delta P/\rho$ is related to the volume flow, we find that volume flow of gas is given by

$$V = A\,C\sqrt{\frac{2\Delta P}{\rho}}\text{. Or, } V = A\,C\sqrt{\frac{RT}{M}}.$$

There will be no ODH hazard in cave2 if the volume of the released gas is replaced by the air entering the cave from the openings. No ODH condition then is,

$$A_d\,C_d\sqrt{\frac{2\Delta P}{\rho}} < A_c\,C_c\sqrt{\frac{RT}{M}}\text{, where}$$

A_d is the area of the dewar's transfer tube, ΔP is the pressure in the dewar and ρ is the density of liquid in the dewar, A_c is the area of the ceiling vent and C_d and C_c are discharge coefficients. Using the values for expansion factor of Helium (750) and the gas constant $R = 0.0083\ m^3\cdot Kpa.mol^{-1}K^{-1}$,

$$\sqrt{\frac{2\Delta P}{\rho}} < B\sqrt{\frac{T}{M}}\text{, where}$$

$B = (1/750)(A_c/A_d)\,(C_c/C_d)\,\sqrt{R}$. Substituting values for gas constant R, $B = 1.2\ 10^{-4}\,(A_c/A_d)\,(C_c/C_d)$.

Note that for any gas mixture in this document $\sqrt{\frac{T}{M}}$ is never less than 1 - even when T is 5K, for Helium its value is 35 and, for air its value is 13.

If we make a reasonable assumption that C_c/C_d is 1, the condition for no ODH reduces to

$$\sqrt{\frac{2\Delta P}{\rho}} < 1.2\ 10^{-4}\,(A_c/A_d)\sqrt{\frac{T}{M}}$$

Dewar	$\sqrt{\frac{2\Delta P}{\rho}}$	$1.2\ 10^{-4}\,(A_c/A_d)$
1000L LHe	0.22	2.7
500L LHe	0.22	10.6

The above table shows that the openings in UITF exclude ODH conditions in Cave2 due to transfer pipe ruptures of the Helium dewars, even without the $\sqrt{\frac{T}{M}}$ factor. Note that this analysis is valid even when the two caves are considered together. In the coupled cave case, T will be larger than if only Cave2 is considered because the gas released has to warm up a larger volume.

Rupture of the In-Beam-Cryostat will increase the pressure in the cave and move the gas towards the ceiling vent. This requires a different calculation, based on the gas law, and calculating the pressure increase in the cave. One can use this pressure increase in the formula for volume flow to find the flow rate of Helium through the ceiling vent. However, in this document we will not take credit for venting of this small amount of Helium. At 19.3% oxygen content due to In-Beam-Cryostat rupture, (if only Cave2 is considered), the fatality factor for this incidence is zero. If the entire UITF volume is used, the oxygen content is higher (19.9%) and again there is no ODH.

An earlier leak test has established a volume vent rate for Helium as 0.26kg/m^2/s. (Ref. 1). The 5.6 m^2 ceiling vent of UITF can vent 1.4 kg/s. The 1.5m^3/s of Helium spill from 1000L dewar is equivalent to 0.25kg/s of spill. Thus, both the calculations shown in this document and the data from spill test show no ODH due to Helium spill from dewars in Cave2. (The conditions for the test are different from those in UITF. There was a 10.7m chimney but the enclosure did not have a chain link fence type opening that UITF. Not having such an opening limits the flow of gas mixture through the chimney).

Relevant Data:

Percentage of Oxygen in ambient air = 21%
Oxygen level below which ODH exists = 19.5%
Cave2 ambient temperature = 300K
Cave2 Volume = 441 m^3
Ceiling vent area = 5.6 m^2

Pressure in liquid Helium dewars = 13.8KPa
Transfer pipe diameter of 1m^3 dewar = 0.00635m
Transfer pipe diameter of 0.5m^3 dear = 0.003175m
Expansion factor for 4K He = 750
Expansion factor liquid N_2 = 700
Pressure in liquid Nitrogen dewar = 139KPa
Transfer Pipe diameter of Nitrogen dewar = 0.003175m

From Reference 1:
Rate of escape of Helium = 250g/s/m^2
Volume of Helium venting through 1m^2 vent= 0.002 m^3/s
Volume Helium venting capacity of 5.6 m^2 vent in Cave2 = 0.0112 m^3/s

Formulas and constants Used:

Volume flow of fluid $V = A\ C\sqrt{\frac{2\Delta P}{\rho}}$, where A is the area of the opening, C is the discharge coefficient, ΔP is the pressure differential and ρ is the density of the fluid.

The value of C will be less than 1 due to friction. In this document, we assume C to be 1 for liquid Helium and liquid Nitrogen venting from the dewars which dilutes the oxygen content of ambient air more quickly.

Mass flow $M = V^* \rho$
% Oxygen Content in a volume = $(V – V_r)/V$, where V is the volume of the cave and V_r is the volume of the released gas.

$R = 0.0083 m^3 \cdot Kpa.mol^{-1}K^{-1}$
Molecular Weight of Helium = 0.004kg/mol
Molecular Weight of Nitrogen = 0.028kg/mol
Molecular Weight of air = 0.029kg/mol
Density of Liquid Helium = 125kg/ m^3
Density of Helium at 300K = 0.165kg/ m^3
Density of Liquid Nitrogen = 810kg/m^3
Density of Nitrogen at 300 K = 1.165kg/m^3

Appendix B

Nitrogen:

There are two sources of nitrogen. One is the 100 L Nitrogen dewar and the other is the liquid nitrogen shield supply to the quarter-cryomodule.

Instantaneous rupture of the 100L dewar dumps all of nitrogen into the cave which amounts to 70 m^3 of nitrogen in the cave's volume of 648 m^3. The percentage of oxygen in the cave is

21 * (1- nitrogen volume/cave volume), where 21 is the percentage of oxygen in air.

In the case of shield supply transfer line failure, the amount of nitrogen that will enter the cave is 6.2 L/min, which is equal to 4.34 m^3/min of gas. Since the UITF has a large vent and an open entrance (chain link gate), we assume that the volume of gas in UITF stays the same though the oxygen content is going down. The rate of loss of oxygen in air is calculated as follows:
The original, (at time = 0 minutes) percentage of O_2 is X (%)/648 m^3 (Vol. of UITF). The rate at which O_2 is leaving UITF (due to N_2) is 4.34 m^3/min. giving the rate at which O_2 is depleted from UITF as 4.34/648 per minute. Therefore, the rate of change in O_2 concentration in the cave with time is $dX/dt = -X* 4.34/648$. Thus, the percentage of O_2 in UITF after time t minutes is
$X = C * \exp(-4.34t/648)$, where C is the constant of integration which can be valuated as 21 at time t= 0.

The graph below shows the concentration of Oxygen with time in case of a rupture. ODH alarms are set to alert occupants when the oxygen level reaches 19.5%. The occupants have 17 minutes to exit UITF before the oxygen level falls to 18.5%.