Tritium Gas Target Hazard Analysis for Jefferson Lab

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Introduction

The goal is to develop a safe tritium target for use in Hall A at Jefferson Lab for the 12-GeV experiments[1,2] E12-10-103 and E12-11-112. Our overall philosophy for developing the conceptual design and safety devices has been to minimize the amount and density of tritium necessary for the experiment and to keep the systems and procedures as simple and reliable as possible. In this report we present a hazard analysis that outlines the risks and mitigation of risk for operation of a tritium target in Hall A at JLab.

The tritium target consists of two subsystems: the target cells which provide primary containment of the target material and the scattering chamber which provides the secondary containment. David Meekins at Jefferson Lab is the Design Authority for the tritium target. Prototype target cells will be designed, fabricated and tested before the final target is designed and constructed. The final target will be installed in Hall A, then commissioned and operated.

In this document we define the hazards that will be encountered at the JLab site during assembly, commissioning, operation and decommissioning of the target. We also discuss the corresponding engineering and administrative controls to mitigate these hazards. The focus of the hazard analysis presented here is on hazards unique to the tritium target. Standard industrial hazards are not addressed because they are controlled through existing JLab policies and procedures.

Hazard Analysis Methodology

Hazard analysis includes the following steps: (1) hazard identification and screening, (2) assessment of the potential consequences of unmitigated risk, (3) identification of relevant and effective mitigation or preventative measures, and (4) assessment of mitigated risk. It is desirable to identify and apply safety measures that make the risks associated with JLab, including the tritium target, fall into the "extremely low" category.

The steps in the hazard analysis process and general decision criteria are shown below. Hazard identification produces a comprehensive list of the hazards present in a process or facility. The screening phase removes from consideration all hazards below a threshold of concern or which are covered by recognized industrial codes and standards. For each hazard retained for hazard analysis, the unmitigated risk is first evaluated in terms of frequency and consequence. This places it on the risk matrix. The following assumptions govern the determinations of unmitigated risk:

- The unmitigated risk does not include safety or control systems or administrative controls.
- Assigned frequencies are based on engineering judgment. For the unmitigated evaluation, the frequency is that of the unmitigated initiating event.
- Assigned consequence can be qualitative but must be conservative.
- If the unmitigated risk is extremely low, the process can stop at this point. Otherwise, proceed to the evaluation of mitigated risk.

In assigning a risk level, we follow the JLab ESH Manual with Document ID: 3210 T3 Risk Code Assignment[3]. In defining the level of risk, first the consequence level is determined from Table 1.

Table 1: Consequence Levels

Consequence Level	Severity	Property Loss ($)
High (H)	Serious impact on site. May cause death or loss of facility operation. Major impact on the environment.	>100,000
Medium (M)	Significant impact on site. May cause severe injury, severe occupational illness to personnel, major damage to facility operation, or impact on the environment.	>50,000
Low (L)	Minor impact on site. May cause minor injury, minor occupational illness, or minor impact on the environment.	>500
Extremely Low (EL)	Insignificant injury, occupational illness or impact on the environment.	<500

The next step is assigning a probability level for an incident. This level is assigned from Table 2.

The next step is to make a risk code assignment. Table 3 is used for this process.

At this point, each risk is reevaluated considering mitigating factors that would either reduce the consequence or make the hazard less frequent. This should move the location on the risk matrix based on assumed conditional probabilities of failure for the mitigating systems.

At this point, the mitigated risk should be either low or extremely low. For low risk, the evaluation should be reviewed to determine if there are preventive or mitigating features that could be credited to bring the risk to extremely low. The risk of serious consequences should be made extremely low if that is reasonably achievable.

Table 2: Probability of Incident

Probability Level	Description	Occurrence per Year
High (H)	An incident is likely to occur several times during a task.	$>10^{-1}$
Medium (M)	An incident may occur during the task.	10^{-2} to 10^{-1}
Low (L)	Probability of an incident occurring is unlikely to happen during the task.	10^{-4} to 10^{-2}
Extremely Low (EL)	Probability of an incident occurring is extremely unlikely to happen during the task.	10^{-6} to 10^{-4}

Table 3: Risk Code Assignment

Consequence Level	H	1	3	4	4
	M	1	2	3	4
	L	N	1	2	3
	EL	N	N	1	1
		EL	L	M	H
		Probability Level			

Hazard Identification and Analysis

Vacuum, pressure and activation hazards

As with most experiments at JLab the scattering chamber will be operated under vacuum. Implosion of vacuum components could present a potential hazard from flying objects. Vacuum systems at the JLab must be designed to meet, withstand, or eliminate the full range of stresses encountered in vacuum service and are subject to the general instrument safety-review process. Vacuum components, except for windows, are constructed of heavy-walled material per the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section VIII, to minimize the threat of implosion when evacuated. Vacuum window lifetime is evaluated conservatively so that windows are changed before they fail accidentally in service.

The target cells will be pressurized with H_2, D_2, ^{3}He or ^{3}H gas. The H_2, D_2 and ^{3}He cells will be pressurized to 25-30 atmospheres at room temperature. As an additional safety precaution, the ^{3}H cell will not exceed 14 atmospheres of pressure although this cell will be constructed to the same dimensions and standards as the hydrogen and helium cells. The transport, installation and de-installation of the target cells into the scattering chamber represent a potential hazard to personnel and for loss of the tritium gas. The risk code assignment for the H_2, D_2 and ^{3}He target cells is 3 based on a medium consequence level and probability level without mitigation. The risk code for the ^{3}H target is 4 based on a high consequence level and a medium probability level. Here the risk level of 4 is based on the potential loss of > $100k of equipment from potential contamination of the Hall as well as the loss of the target and experiment. However, the radiological aspects will be discussed in a separate section. Here, we just deal with the pressure vessel aspects of the target. The mitigation would be the design of the target cells to have a significant safety factor, to design the target for easy installation and removal from the scattering chamber, proper personnel protective equipment (PPE), and well-thought-out procedures. The risk codes and mitigations are summarized in Table 4.

Table 4: Risk Codes and Mitigation for Pressure Hazards

Hazard Type	Presence	Unmitigated Risk Code	Mitigation	Mitigated Risk Code
Vacuum	Scattering chamber	2	1. Follow code and design parameters for previous scattering chambers	1
Pressure	Target cell rupture during installation and removal	4	1. Design for simple installation, removal, alignment 2. ventilation 3. Procedures 4. PPE	1
Pressure	Target cell rupture during normal operation	3	1. FEA design studies 2. pressure testing 3. material selection 4. Secondary containment 5. pressure vessel standards 6. Interlocks on beam	1
Activation	Target cell exposure to beam	2	1. Rad control procedures for beam activated components 2. Aluminum cell	1

Of course, the target cell can rupture during normal operation. During normal operation there will be secondary containment from the scattering chamber, thus there should be no injuries from this possible failure mode. For this case, an unmitigated risk code would be 3 largely due to the cost of replacing the cell, while the mitigated risk code is 1. The mitigations involve extensive FEA design calculations, pressure testing of prototypes, selection of the material (certified plate stock), presence of secondary containment, pressure vessel standards and interlocks on the beam to protect against off-normal beam operation, *e.g.*, raster failure.

When the target is being disassembled, the residual beam-induced activity in the target cells can pose a potential hazard. The activation of Al in the target cell windows was estimated[4] in a separate report. The activity of the target cell windows was found to be 9.1 mR/h at one meter immediately following a 92 day irradiation at 25 μA, a worst case estimate. After waiting one day, the activity would drop to 2.5 mR/h for Al 7075. For these reasons, it would be best to wait a day or two before removing the target cell from the scattering chamber to minimize radiation exposure. Here, ease of removal of the target as well as radiation control procedures should be followed to mitigate the risk. Aluminum cells have been in use at JLab for the past 15 years and have not presented a serious problem for target maintenance.

Cryogenic and fire hazards

The risk codes and mitigation for cryogenic and fire hazards are summarized in Table 5. The plan is to cryogenically cool the tritium target. The use of cryogenic coolants has become standard practice at JLab, particularly for cryotargets. Appropriate personnel protective equipment is required when handling cryogenic liquids. Personnel involved in complex cryogenic operations are required to receive adequate cryogenic safety training. The probability of occurrence for cryogenic hazard initiator events is medium. The consequence of an unmitigated cryogenic accident is low. With application of appropriate JLab procedures, standards, and training for handling cryogenic fluids, and experiment review as required, the mitigated risk of cryogenic hazards is extremely low.

Table 5: Risk Codes and Mitigations for Fire and Cryogenic

Hazard Type	Presence	Unmitigated Risk Code	Mitigation	Mitigated Risk Code
Cryogenic	Target cooling system	2	1. Safety training for cryogenic operations 2. Procedures and PPE	1
Fire	Minor amounts of combustible materials; total of 1.9 liters (STP) of hydrogenic gas	1	1. Standard JLab fire protection procedures 2. Standard safety procedures for cryotarget	N

Experience indicates that there have been six cryotarget failures in 30 Hall-years of operation at JLab. Since this target will be in operation for about ¼ of a year, this would suggest a probability for failure at approximately 0.05, which would place it in the medium probability of incident range.

The risk code for fire is based on the additional risk for fire that the hydrogenic materials in the target bring to the Hall. Of course, there are the usual sources of fires in experimental areas such as overheating power supplies and electrical insulation that we are not considering here. Rather, the H_2 and D_2 targets contain only 0.8 liters (STP) each of hydrogen gas, while the tritium target contains only 0.4 liters (STP) of tritium gas. This is roughly a factor of 10,000 less hydrogenic gas than that used in the typical cryotargets in Hall A. Nevertheless, the risk of fire can be mitigated in the same way as with the cryotargets, *i.e.*, a well-ventilated target region as well as the standard procedures for JLab fire protection and the cryotarget.

Hazards during normal operations

The unmitigated risk code for the full release of the 1000 Ci tritium target into Hall A during normal operations was assigned to be 4 in Table 6. This risk is primarily based on the consequence level of H from loss of property being greater than $100k. This unmitigated property loss could potentially result from contamination[5] of the Hall beyond the actionable limit of 10,000 dpm per 100 cm^2. This could result in a rather costly decontamination effort. The unmitigated probability for occurrence was selected as M since the probability for a cryotarget failure during the run would be approximately 0.05. For these reasons there are significant steps taken toward mitigation of the risk and probability of occurrence. In particular, a careful thermo-mechanical study of the target cell has led to the selection of aluminum rather than stainless steel as the primary target container. Stainless steel because of its lower thermal conductivity has significant risk of thermal stresses[6] in the windows. Further, significant safety factors were built into the choice of window thicknesses. The windows are significantly thicker than previous target cells that have been used already in Hall A. There will be extensive pressure testing of target windows and prototype cells. The H_2, D_2 and ^{3}He targets will be approximately 2 to 2.5 times the pressure of the T_2 target. If any cell ruptures during normal operation, the experiment stops and an extensive review would be conducted before the experiment could be scheduled again. Secondary containment would be provided by a scattering chamber under vacuum. The scattering chamber will be isolated from the beamline through the use of thin Be windows. Attached to the vacuum chamber through a normally closed pneumatic valve would be an activated NEG pump that could be used to absorb any tritium that leaked into the secondary containment. A hood with ventilation would be installed in the target region. An exhaust stack would be necessary. Interlocks would be available on beam current, raster, scattering chamber vacuum, tritium monitor, and radiation level in the Hall that would provide a fast shut down. A tungsten beam collimator system would be installed to prevent the beam from striking the sides of the target cells. Beam striking the W collimator or the target cell should trip the high radiation interlock.

Administratively, the beam current would be limited to 25 μA. The Hall A exhaust fans could be used as a last resort if all other precautions fail. When these steps are taken, the mitigated risk code could be assigned as 1. This assignment is based on both the consequence level and probability of occurrence being assigned L. The consequence level should just be limited to the loss of the tritium and target cell and should be under the $50k level, while the probability for an event should be reduced by the additional interlocks, administrative procedures and training.

Installation and de-installation of the target cell

Installation and de-commissioning of the target at JLab represents a separate risk since the target cell must be handled. The unmitigated risk code is set at 4 in Table 7, primarily because of a potential consequence level of H, *i.e.*, the possibility of contamination of the Hall, and a probability level of H. Thus, mitigation becomes extremely important. First, the engineered controls would be easily removable covers on the target cell windows that would survive an accidental drop of the cell. The tritium target ventilation system will already be in place. One should also be mindful[7] of the X-rays produced by tritium beta decay and subsequent bremsstrahlung in the Al target cell windows. One should not touch the target cell windows in any case.

Clearly, procedures will be essential for installing and de-installing the target in order to minimize risk. The target cell must be removed from its shipping cask and installed in the scattering chamber on the pivot. To minimize damage to the Hall, either a 12000 cfm Hall A fan should be turned on or the target ventilation system should be used during this procedure. After the target cell is moved to the pivot, the target ventilation system should be used. An outline of possible procedures is illustrated below.

Table 6: Risk Codes and Mitigation for Uncontrolled Release of the Tritium Gas, Normal Operations

Hazard Type	Presence	Unmitigated Risk Code	Mitigation	Mitigated Risk Code
Radio-logical	Release of 1000 Ci of tritium gas in Hall A, normal operations	4	1. Thermo-mechanical FEA design 2. Pressure testing 3. ^{3}He cell twice pressure of ^{3}H cell 4. Secondary containment 5. Hood with ventilation, stack 6. Interlocks on current, raster, vacuum, temperature, tritium monitor, radiation level 7. Activated NEG pump 8. Beam collimator 9. Tritium monitor 10. Beam current limit 11. Exhaust fans 12. Rad control and procedures 13. Target operator training	1

Table 7: Risk Codes and Mitigation for Uncontrolled Release of Tritium Gas during Installation

Hazard Type	Presence	Unmitigated Risk Code	Mitigation	Mitigated Risk Code
Radio-logical	1000 Ci of tritium gas released during target installa-tion, removal	4	1. Rad procedures and control based on expected dose to worker 2. Target ventilation system, stack 3. Hand held tritium monitor 4. Two trained target installers 5. Design for ease of installation 6. possible PPE	1
Radio-logical	X-rays from target cell	1	1. Survey target cell for X-rays 2. Possible PPE and special procedures	N

Outline of proposed target installation procedure:

- Turn on target ventilation system
- When target container is received at JLab, survey with a hand-held tritium monitor
- When opening the target cask, survey with hand-held monitor
- Carefully unpack target, one person continuously surveying for tritium
- Remove protective shipping covers
- Attach W mask to target frame if this has not been done prior to shipment
- Attach target cell to the frame
- Two target-trained installers with proper PPE will carefully guide target into chamber
- Check target alignment, make adjustments as necessary
- Begin pumpdown of target in chamber after all seals have been made
- Begin monitoring pump exhaust for tritium
- Set up rad-hard RGA on mass 6 peak and remote monitor/interlock
- Hook up target cooling, monitors and all interlocks; activate cooling and interlocks
- Test all monitors and interlocks
- Perform special checklist before leaving hall – two target operators
- Target should be ready for beam alignment

The de-installation of the target would be approximately the reverse steps.

Uncontrolled release of tritium target to the environment

Table 8 summarizes the risk code assignments in the event of a full uncontrolled release of the tritium target where the ventilation system exhausts the target to the environment. Also, the tritium diffusion through the thin windows and seals is considered here. For the tritium release to the environment we are assuming that the ventilation system is working and that there is a ~20 m stack in place. The unmitigated risk code of 2 was chosen based on the consequence level of L and a probability level of M. Here we chose the same mitigations that are summarized in Table 6. GENII and HotSpot estimates[8] indicate that the dose rate will not exceed 10 mrem/h at maximum provided that there is at least a 15 m stack. The assumptions that went into the estimates were conservative. We assumed that 100% of the T_2 target converted immediately to HTO, an acute release occurred over 60 minutes, and conservative weather conditions were chosen.

The tritium diffusing through the thin Al windows, conflat seals and valve was estimated[9] to be substantially less than 1 Ci per year in the worst case. Thus, this risk mitigated with normal leak checking procedures and ventilated exhaust from the scattering chamber is judged to be negligible.

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Table 8: Risk Codes and Mitigations for Uncontrolled Release and Diffusion of Tritium Gas

Hazard Type	Presence	Unmitigated Risk Code	Mitigation	Mitigated Risk Code
Radio-logical	1000 Ci of tritium gas release, beyond site boundary	2	1. Same mitigation for radiological under normal operations 2. Rad control and procedures based on estimates of dose to person at site boundary	1
Radio-logical	Tritium diffusion through Al cell, seals	1	1. Leak checking 2. Normal vacuum chamber exhaust venting	N

[1] G. G. Petratos *et al.*, JLab MARATHON Collaboration, JLab Experiment E12-10-103, 2010.
[2] P. Solvignon *et al.*, JLab Experiment E12-06-112, 2011.
[3] http://www.jlab.org/ehs/ehsmanual/3210T3.htm
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