Conceptual Design of a Tritium Gas Target for Jefferson Lab

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Tritium Target Task Force

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Introduction

The goal of the tritium target task force is to develop a safe tritium target for use in Hall A at Jefferson Lab for the conditionally approved 12-GeV experiment[1] E12-06-118. This experiment is aimed at resolving the large uncertainty in the down and up quark distributions in the proton at high Bjorken *x*. Although this is a decades-old problem, an accurate measurement of the down to up quark ratio is essential for our understanding the flavor structure of the nucleon.

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. The relatively low density in the target permits the concept of minimal cooling. It is envisioned that the amount of tritium will be minimized by reducing the diameter of the cell and using a collimator for the beam to minimize beam scraping on the target cell walls. Thus, the target will be a completely sealed system that is filled with 10 atmospheres of tritium gas and sealed at the Safety and Tritium Applications Research Facility (STAR) at Idaho National Lab (INL). This minimizes the risks associated with filling operations on the JLab site. The secondary containment would be a dedicated vacuum chamber that can be completely isolated from the accelerator and beam dump pipe.

Previous tritium targets at electron scattering facilities

The table below gives a summary of tritium target properties used at previous electron scattering facilities. The bottom entry indicates the parameters for the proposed JLab target. The number of curies, target thicknesses, maximum beam currents and a safe figure of merit (FOM) based on the luminosity divided by the number of curies are given.

Table 1. Parameters for previous tritium targets and the proposed JLab target.
(Note that the Saclay target is a liquid target, the other targets are gas targets.)

Lab	Year	Quantity (kCi)	Thickness (g/cm^2)	Current (μA)	Current *x* thickness (μA-g/cm^2)	Safe FOM (μA-g/cm^2/kCi)
Stanford HEPL	1963	25	0.8	1	0.8	0.03
MIT-Bates	1982	180	0.3	20	6.0	0.03
Saclay	1985	10	1.2	10	12.0	1.2
JLab	201?	1.6	0.13	30	3.9	2.4

The proposed JLab target is competitive with the previous gas targets and even compares favorably with the Saclay liquid tritium target.[2] When one divides the luminosity by the total number of curies of tritium, then the JLab target has a superior safe figure of merit. The primary disadvantages of the Stanford HEPL target[3] are the large number of curies, the extremely high pressure of 100 atmospheres and the low beam current. Because of target heating considerations, this target could not have handled very much more beam current. The MIT target[4] has the main disadvantage of using 180 kCi, the largest activity of any of the targets and it has a target thickness that is less than the Stanford target. The Saclay target is a static liquid target and consequently, it is severely limited in the total amount of beam current. By comparison, the proposed JLab target uses only 1.6 kCi, has a pressure of only 10 atmospheres, can safely handle at least 30 μA of beam current and represents the best safe FOM when the total number of curies are taken into account. The proposed target is completely sealed, doubly enclosed and is cooled by heat sinking to a cooled surface.

Design criteria

The primary design criteria are summarized below.

- Minimize tritium
- Limit beam current
- FEA thermo-mechanical design of the target cell
- ^{3}He target = twice the pressure of the ^{3}H target
- Minimize tritium handling at JLab – STAR facility at INL
- Completely sealed cell design
- Minimize active cooling requirements
- Secondary containment
- Hood and ventilation system
- Tritium, vacuum, temperature monitors
- Interlocks on raster, vacuum, tritium monitor, coolant flow
- Ease of installation and alignment

Tritium cell construction

The plan is to develop a tritium gas target for use in Hall A at Jefferson Lab during the 12-GeV era. The target cell would consist of 1563 Ci of tritium gas in a completely sealed system. This target cell should qualify for the sealed source designation. The tritium gas would be contained in a 40-cm long x 1.25-cm diameter aluminum (2219) cell as shown in Fig. 1. The alloy 2219 was chosen since it is tritium compatible, weldable, age hardens after welding and has a relatively high yield strength. The windows for beam entrance and exit would be 0.018" thick and the windows in the cylindrical body would be 0.018" thick. The resulting tritium gas pressure in the container would be 10 atmospheres at room temperature, when the target is fresh, but would very slowly double in pressure as tritium decays with a half life of 12.3 years into helium-3.

A ^{3}He target is also necessary for the experiment. The ^{3}He pressure (20 atmospheres) would be approximately a factor of two larger than that of the tritium target in order to give similar counting rates. The target assembly would be pressure and burst tested so that there should be an acceptable factor of safety for the tritium and helium targets. This safety factor was calculated in an thermo-mechanical FEA which takes into account heating of the target gas as well as heat stress in the target cell from the electron beam. These factors of safety (FOS) are recorded in Table 2.

The targets would be filled at the STAR Facility at INL and shipped in a special container to JLab. The target cells will be unpacked at JLab and installed in the scattering chamber at the pivot in Hall A. INL has prepared and shipped[5] gas sample sizes up to 1080 Ci.

Before the individual parts are welded, the parts would be tested by fluorescent dye penetrant and radiography. These tests could reveal possible cracks, voids, inclusions as well as other imperfections. The parts would then be assembled and electron beam welded. This method produces a joint that has the same composition as the base material. The vessels would then have the filling tubes welded on and helium leak tested at a pressure of 300 psi. The cells would then be radiographed again to make sure that all the welds were sound. Low profile valves will be welded to the fill tubes. After filling the cells, a s.s. cap will be attached to the valve using a VCR fitting.

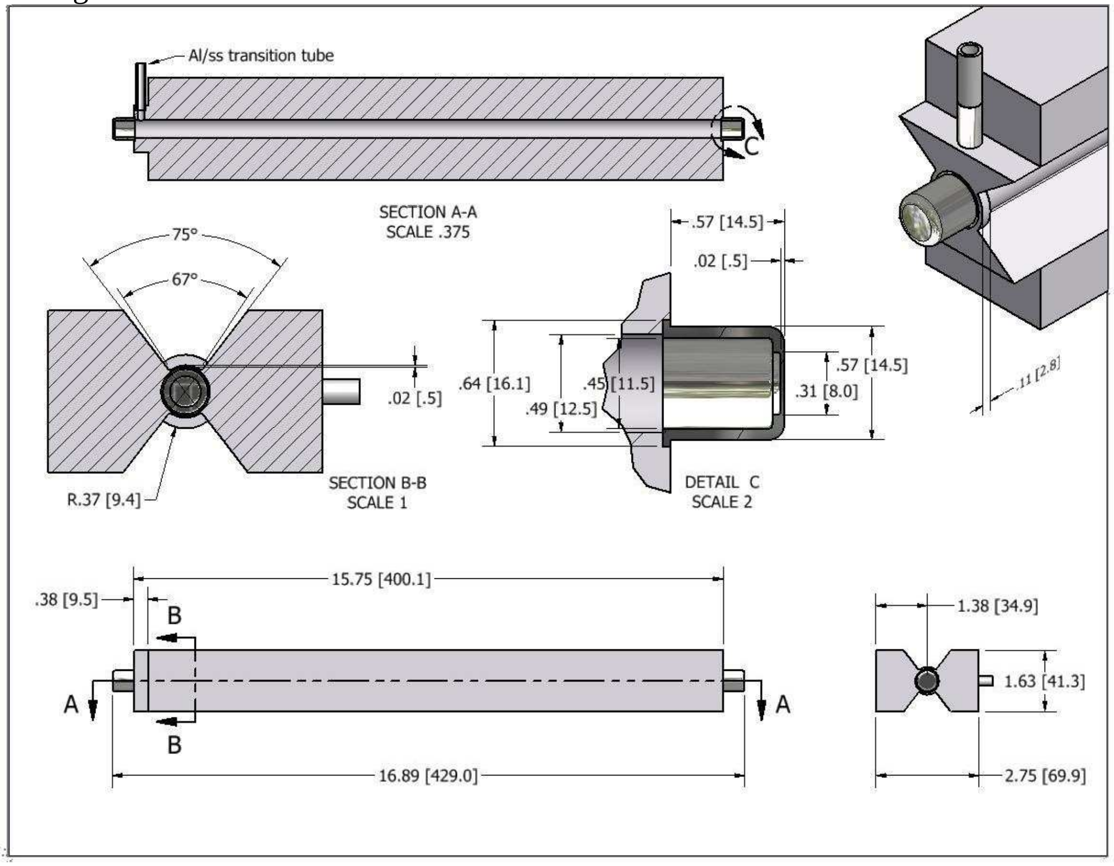

Fig. 1. Conceptual design of an individual tritium gas target cell for Jefferson Lab.

Fig. 2 shows three individual cells that have been coupled together. There will be a total of five cells, where one cell will be a dummy target for background measurement. The other four cells will contain ^{3}H, ^{3}He, ^{2}H and H gases, respectively. The main experiment will cycle between the ^{3}H and ^{3}He target cells for most of the beam time. It may be practical to machine these cells out of one piece to maximize thermal conductivity to the heat sink at the top of the drawing. Each cell, except for the dummy cell, will be filled individually through the valves indicated on the drawing. The valve bodies are s.s. so that an Al to s.s. transition tube is necessary. The valves will be mounted to the thick portion of the Al body. The coolant can be cryogenic nitrogen gas or water.

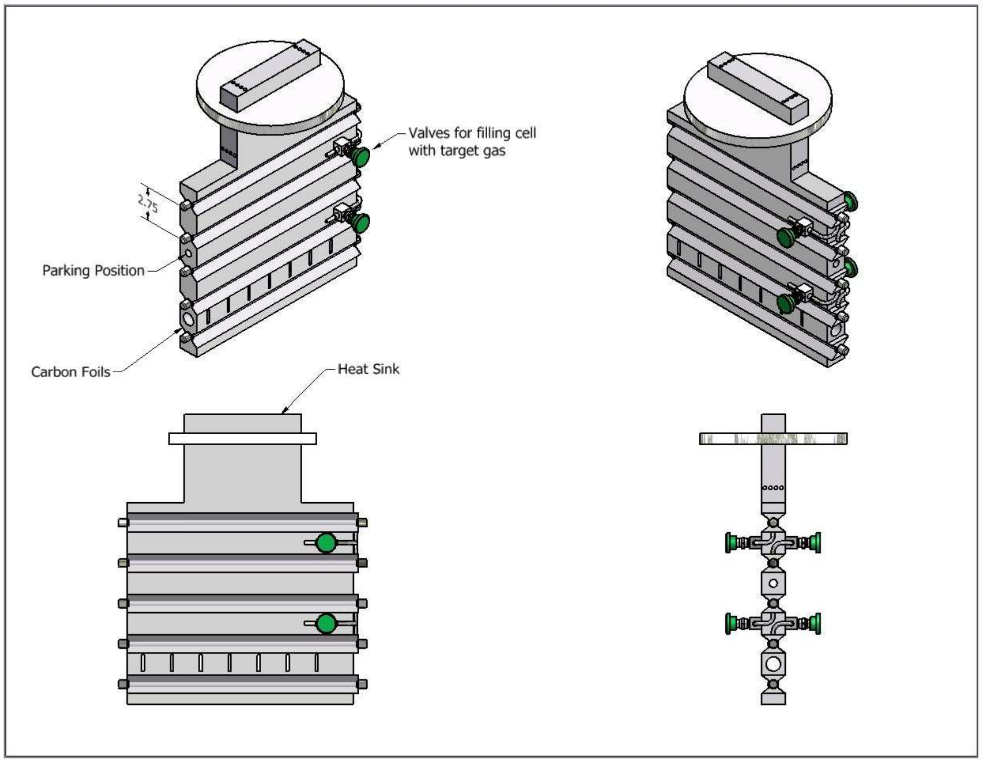

Fig. 2: Conceptual design of the coupled target cells. The filling valves have green handles. The massive piece of Al at the top of the drawing is a heat sink that will be cooled.

Beam current

At JLab the standard procedure for Al targets is to hold the beam current to 40 μA or less. Thus, we propose to have an administrative limit of 30 μA on the beam current for this experiment. Furthermore, it is noted that ion beam studies[6] of cooled-gas targets have found a threshold in beam current power density where the gas target density drops rather dramatically from beam heating. This threshold is approximately 10 mW per mm of target length. For an electron beam and this target design, this threshold value would correspond to a beam current of 24 μA. In order to avoid significant target density corrections, it is likely that this experiment would not deploy more than 24 μA of beam current on this target. Target heating considerations are discussed below. A finite element analysis heat transfer calculation was performed for the target design.

Target heating

The heat generated by the tritium decay is very small, about 50 mW. The power deposited in the windows and gas is also relatively small with a beam current of 30 μA. There will be a loss of approximately 8.2 W per window, 6.6 W in the hydrogen gases and 17.4 W in the helium gas. The target cell is to be fabricated from Al because of the high thermal conductivity, low tritium diffusion rate and compatibility with tritium gas. One must consider heat stress in the target windows as well as the temperature rise. An analysis of a stainless steel target cell was performed and eliminated from consideration as a result of the large heat stress.

Heat transfer calculations

The target cell analyzed is shown in Fig. 2. The analysis was performed using ANSYS 12 FEA software package. The finite element analysis heat transfer calculations are based on the following inputs. The 30-μA electron beam diameter was taken to be 3 mm, while the wall thicknesses were: endcap, 0.45 mm and body, 0.456 mm. The beam generated heat was taken to be: endcaps, 8.2 W each; gas - tritium, deuterium and hydrogen, 6.6 W; helium, 17.4 W. The initial net gas pressures: tritium, deuterium, hydrogen - 11 bar and helium - 21 bar. Toloukhian's values for thermal conductivity were used for hydrogen, deuterium and helium. For tritium a thermal conductivity that was 60% of hydrogen thermal conductivity was assumed. The results indicate that the temperatures and stresses do not depend much on the conductivity of the gases. This means that the error that was introduced by estimating the thermal conductivity of tritium cannot be large.

The results of the ANSYS 12 analysis are given in Table 2. The calculations are shown for the helium target case which has the largest energy loss and for the hydrogen target case which is furthest from the water cooled heat sink as well as for the tritium target. Two temperatures for the water cooling are considered. The differences between using 25.6 C and 20 C cooling water are not large. The factors of safety, based on the yield stress and ultimate tensile strength values of Al 2219 T851 for the hydrogen, deuterium and tritium containers, have large safety factors in the endcaps and the thin side walls of the container. For helium, due to the larger initial pressure and due to the larger amount of heat generated in the gas the safety factors are lower, but are near a factor of three or larger in the endcaps and very large for the thin side walls of the container. The finite element analysis heat transfer calculation for the target cell design indicates that the hottest spot on the target window is near 100 C for the 3 mm diameter beam spot and 30 μA of beam. This is well below the temperature (150 C) where the yield strength of Al 2219 becomes problematic.

Table 2: Summary of the results from the FEA heat transfer calculation.

	Max. temperature	Max. Equiv. Stress	Factor of Safety	
	℃	MPa	yield stress	ultimate strength
Helium Cell exposed to the beam				
Coolant: Water at 25.6℃				
Helium Cell End-caps	96.98	108.73	2.99	3.83
Helium Cell Thin Sidewalls	43.55	63.65	5.36	7.03
Tritium Cell End-caps	37.36	54.05	6.34	8.33
Tritium Cell Thin Sidewalls	37.37	49.89	6.87	9.02
Coolant: Water at 20℃				
Helium Cell End-caps	91.30	107.64	3.04	3.90
Helium Cell Thin Sidewalls	38.08	60.65	5.60	7.42
Tritium Cell End-caps	31.85	53.07	6.48	8.53
Tritium Cell Thin Sidewalls	31.86	48.57	7.08	9.32
Tritium Cell exposed to the beam				
Coolant: Water at 25.6℃				
Helium Cell End-caps	34.95	101.80	3.37	4.43
Helium Cell Thin Sidewalls	35.35	48.84	7.02	9.24
Tritium Cell End-caps	94.95	72.40	4.50	5.77
Tritium Cell Thin Sidewalls	41.92	69.15	4.94	6.48
Coolant: Water at 20℃				
Helium Cell End-caps	29.74	99.94	3.44	4.54
Helium Cell Thin Sidewalls	29.82	57.56	5.98	7.88
Tritium Cell End-caps	89.79	71.88	3.66	4.68
Tritium Cell Thin Sidewalls	36.44	68.41	5.01	6.58
Hydrogen Cell exposed to the beam				
Coolant: Water at 25.6℃				
Helium Cell End-caps	34.71	101.76	3.37	4.43
Helium Cell Thin Sidewalls	34.80	54.73	6.27	8.24
Hydrogen Cell End-caps	103.82	72.85	4.43	5.63
Hydrogen Cell Thin Sidewalls	52.59	47.81	7.08	9.27
Coolant: Water at 20℃				
Helium Cell End-caps	29.18	99.90	3.45	4.54
Helium Cell Thin Sidewalls	29.27	64.20	5.37	7.07
Hydrogen Cell End-caps	99.79	72.32	4.49	5.73
Hydrogen Cell Thin Sidewalls	47.18	47.81	7.11	9.32

The maximum temperatures and pressures summarized in Table 2 occur in the end windows. These pressure and temperature results are summarized in Figs. 3 and 4. Here one can see that the hottest part of the cells and the highest stresses are in the end windows. Furthermore, the temperatures and pressures were determined for a loss of coolant accident for an hour after the coolant loss. There are relatively small temperature and pressure rises under these conditions. The design is reasonably "forgiving" in the case of coolant loss.

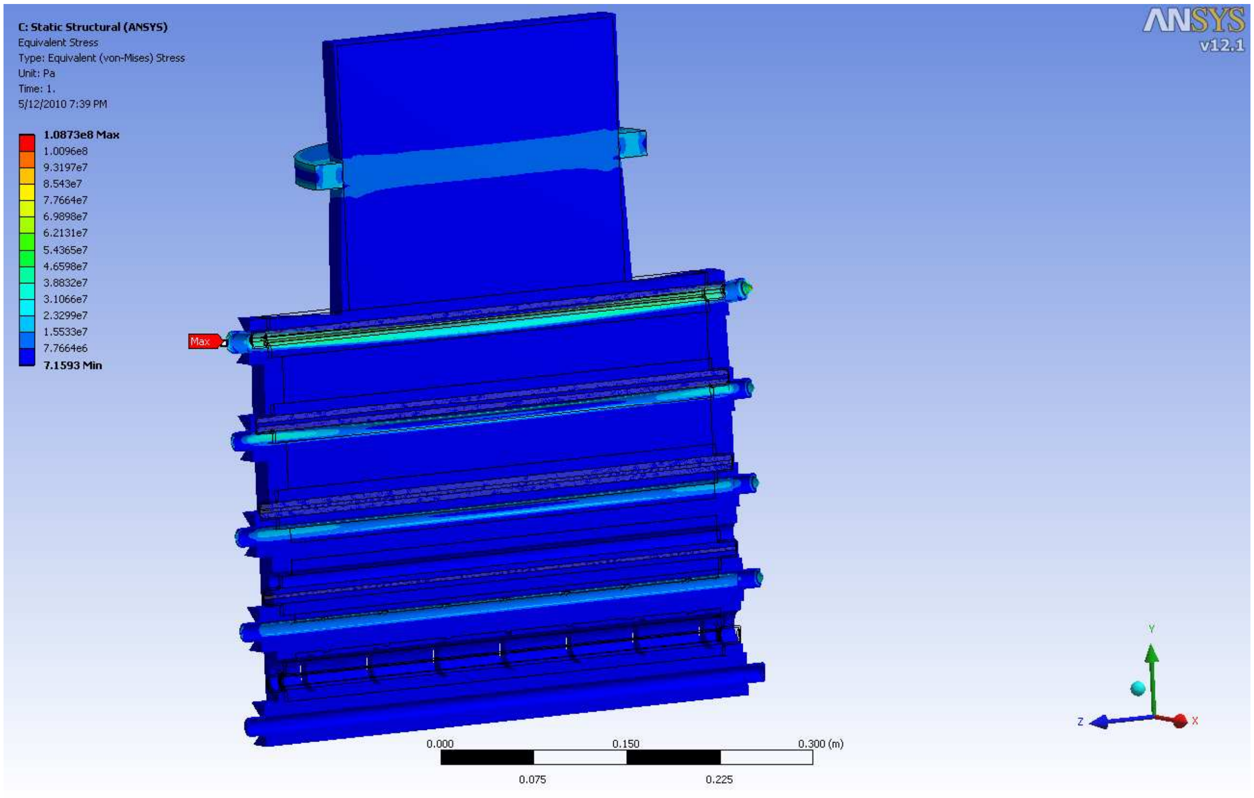

Fig 3. Pressure map of the target cell. The maximum stress is in the target windows.

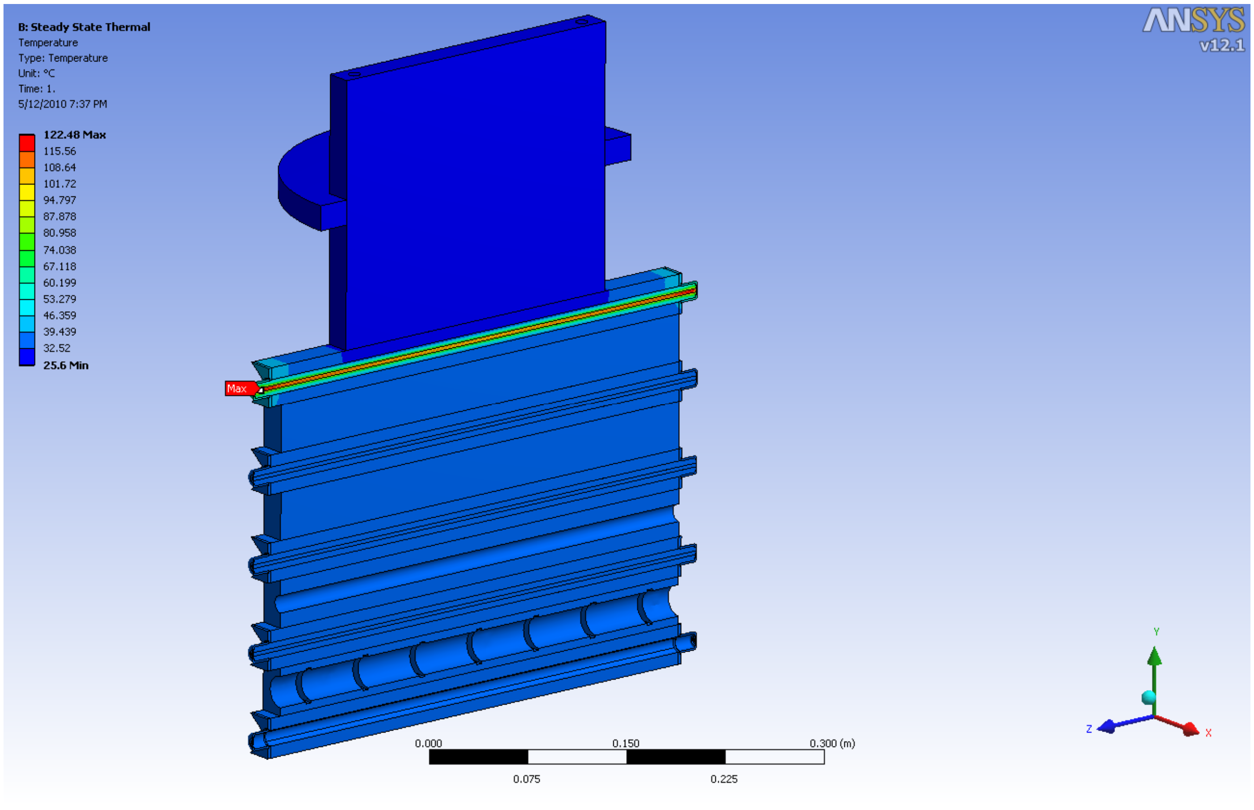

Fig. 4. Temperature map of the target cell. The maximum temperature is in the target windows.

GEANT4 Simulation

After having established an optimum design from the heat transfer calculation and basic considerations for electron scattering, a Monte Carlo simulation is underway using GEANT4. An upstream collimator has already been designed which will protect the target from unexpected offset of the beam position and, therefore, avoid beam scrapping on the wall of the target. It is expected that the beam halo scraping on the collimator would trigger the radiation monitors and shut down the beam. Fig. 5 shows a 3 mm diameter electron beam going through the upstream tungsten collimator, and further interacts with the target windows and the target gas. The collimator opening has a diameter of 6.25mm and the collimator thickness is 25mm in this figure.

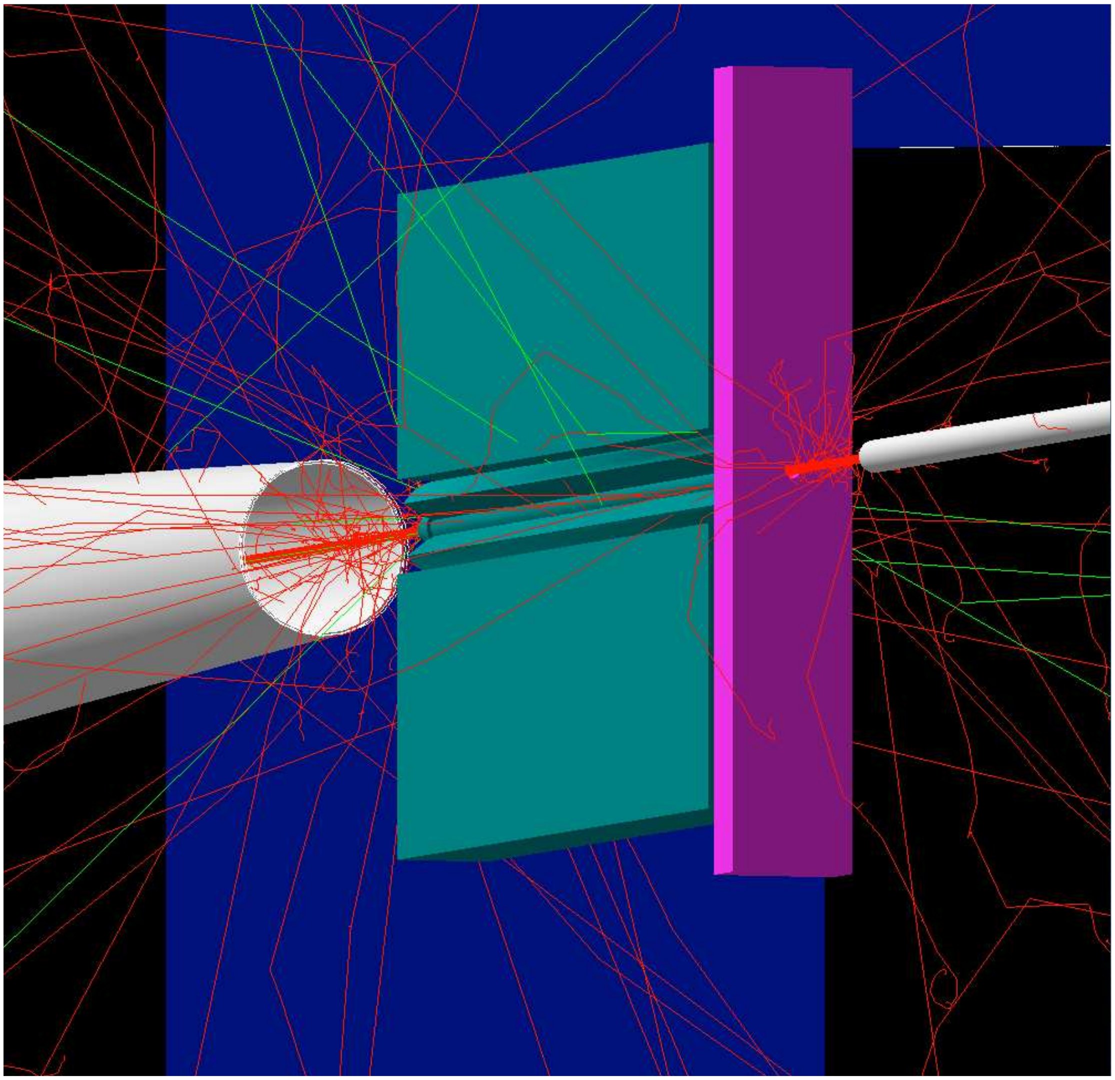

Fig. 5. Side view of the target. The target Aluminum walls and windows are shown in light blue and the collimator in magenta. Red (green) tracks are electrons (photons).

For an 11 GeV incident electron passing through the collimator full thickness, the energy absorbed in the collimator will be 4.2 GeV, in the Aluminum ladder and container 1.08 GeV, and the tritium gas 29 MeV.

A top view of the expected experimental setup is shown in Fig. 6. Here the Super Bigbite Spectrometer is placed at 30^o angle and at a distance of about 1.5 meters with respect to the center of the scattering chamber. Work is underway to estimate the rates for scattering from the upstream collimator, the target cell windows and walls, and the tritium gas. This study will determine whether collimators need to be added on the sides of the target in order to mask events scattering from the target windows and making their way through the entrance of the spectrometer. Also the simulation will provide the target-collimator alignment sensitivity.

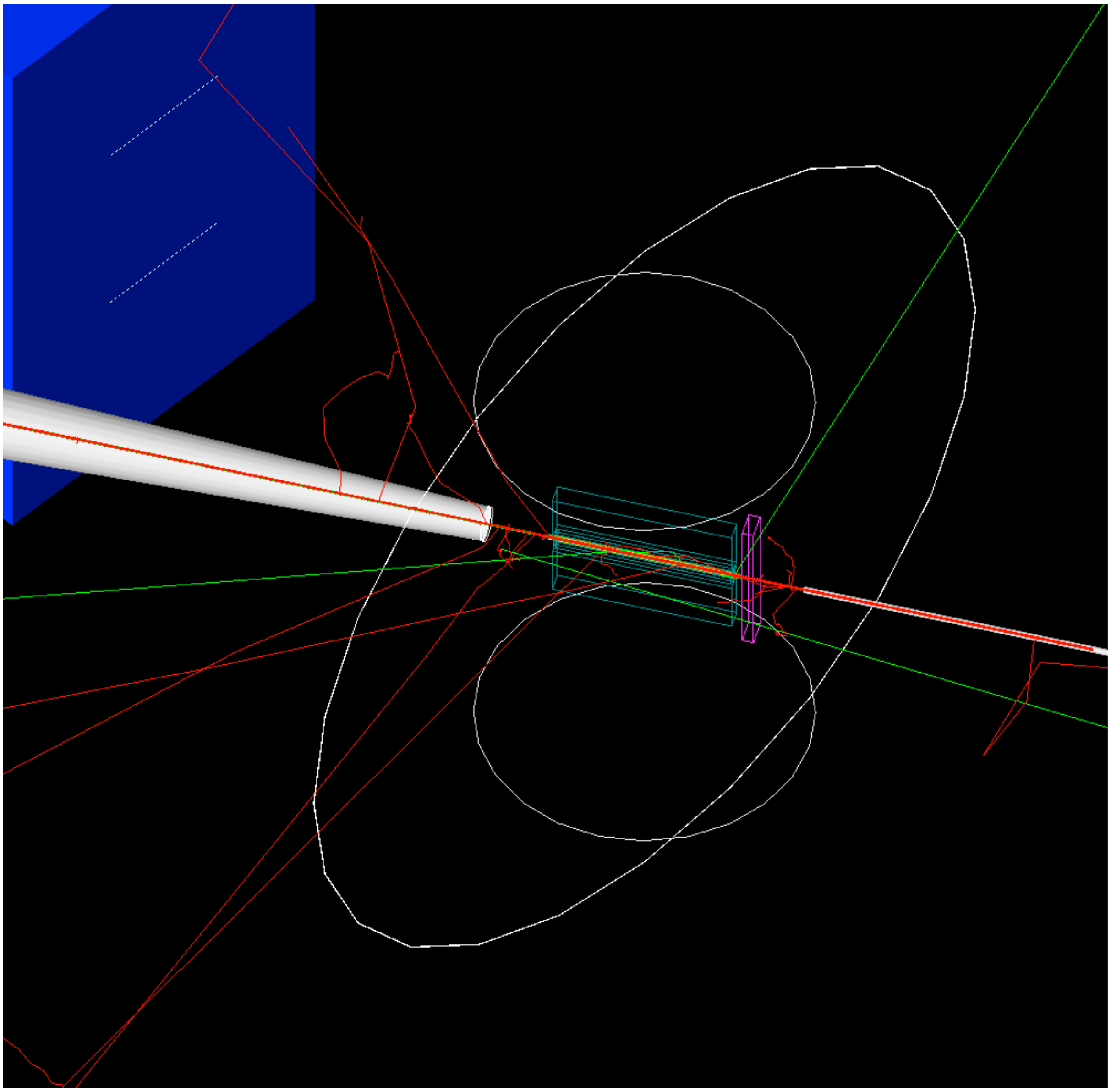

Fig.6. View of the preliminary experimental setup with the target ladder (light blue), the tritium gas (yellow), the upstream tungsten collimator (magenta), the beam pipe and beam dump (light grey) and the Super-Bigbite Spectrometer magnet (blue).

Thermal radiative cooling of the target cell window

Using the Stefan-Boltzmann Law for radiative cooling, the amount of cooling depends strongly on how hot the foil window actually gets. Here if we assume that the maximum temperature is 150 C for the target window whereas the surrounding vacuum can is 25 C, the amount of radiation from the target windows is much less than a watt and is thus negligible. Thus, we cannot depend on radiative cooling of the target cell windows.

Gaseous conductive and convective cooling of the target window

Estimates indicate that the thermal conductivity of the gas and convection are negligible in cooling the cell or the target windows. For example, the thermal conductivity of helium is only 0.15 W/(m-K) compared with about 120 W/(m-K) for Al.

Secondary Containment

At present the scattering chamber rather than a helium box is being considered as the secondary container of the tritium target. The advantages of the vacuum chamber are: less multiple scattering of the primary and secondary beams, no possibility for oxidation of the target cell windows, no entrance and exit windows for the beam since the chamber would be vacuum coupled to the beam line, easy detection of small levels of tritium should a leak occur, use of the existing target lifter system design, and the use cryogenic gas for cooling. A dedicated vacuum chamber concept is shown in Fig. 7. With the vacuum chamber, fast acting valves must be interlocked to protect the accelerator beam line from a target rupture or leak. The windows of the vacuum chamber for secondary beams must handle one atmosphere and tend to leak so that one must have continuous pumping and exhausting of the forepump. A vent hood would be located over the scattering chamber as indicated in Fig. 7. The vent hood would be exhausted to the outside.

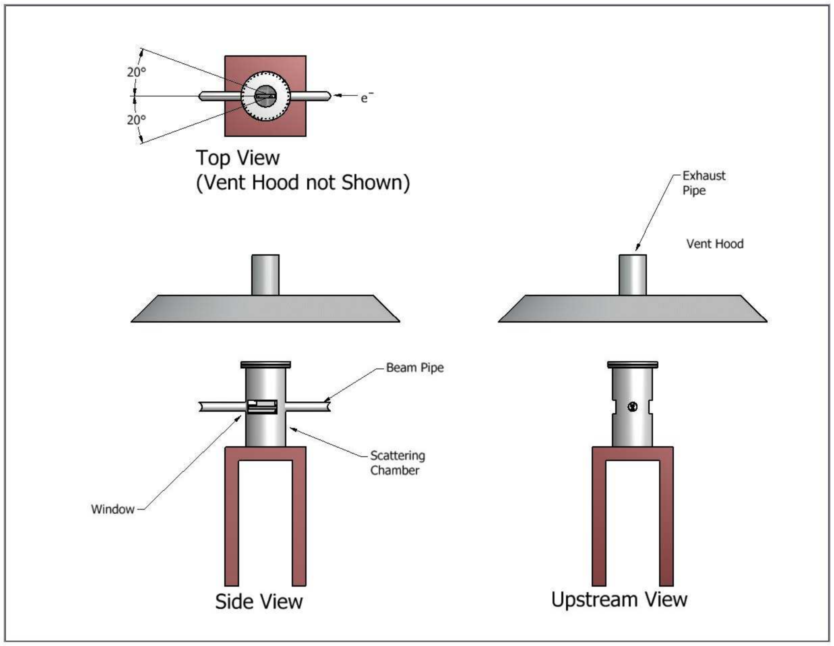

Fig. 7. Conceptual design of the dedicated scattering chamber for the tritium target.

Installation of the target at JLab

An outline of a target installation procedure is given below. The detailed procedure will be developed after the design of the target cell and scattering chamber become more established. For protection of the Hall and its equipment, the most important element is the Hall A ventilation system. A summary[7] of the exhaust fans already installed in Hall A is given below in Table 3. Fan EF-3 is a dual speed fan that can operate at either 6000 or 12000 cfm. The lowest speed fan (6000 cfm) can be operated with the truck access doors closed. The higher fan speeds operate with the truck access doors open.

Hydrocarbon based elements in the Hall have the largest tritium absorption rate. For example, the absorption rate[8] for elemental tritium (T_2 + ½ HT) for polyethylene is 0.13 mCi/s/m^2, while that for concrete is 0.01 mCi/s/m^2. The concrete estimate is especially conservative since the HT must convert to HTO before uptake in the concrete. The uptake rate[9] for stainless steel is an order of magnitude smaller than that of concrete. The administrative or actionable limit for tritium on a surface is 1000 dpm per 100 cm^2. In making an estimate of the worst case incident, we will assume the largest absorption rate, *ie* that for polyethylene. In our estimate, we assume that the entire 1600 Ci sample is lost instantaneously in Hall A. We calculate the dpm in a polyethylene surface as a function of time for various exhaust fan speeds and present these results in Fig. 8.

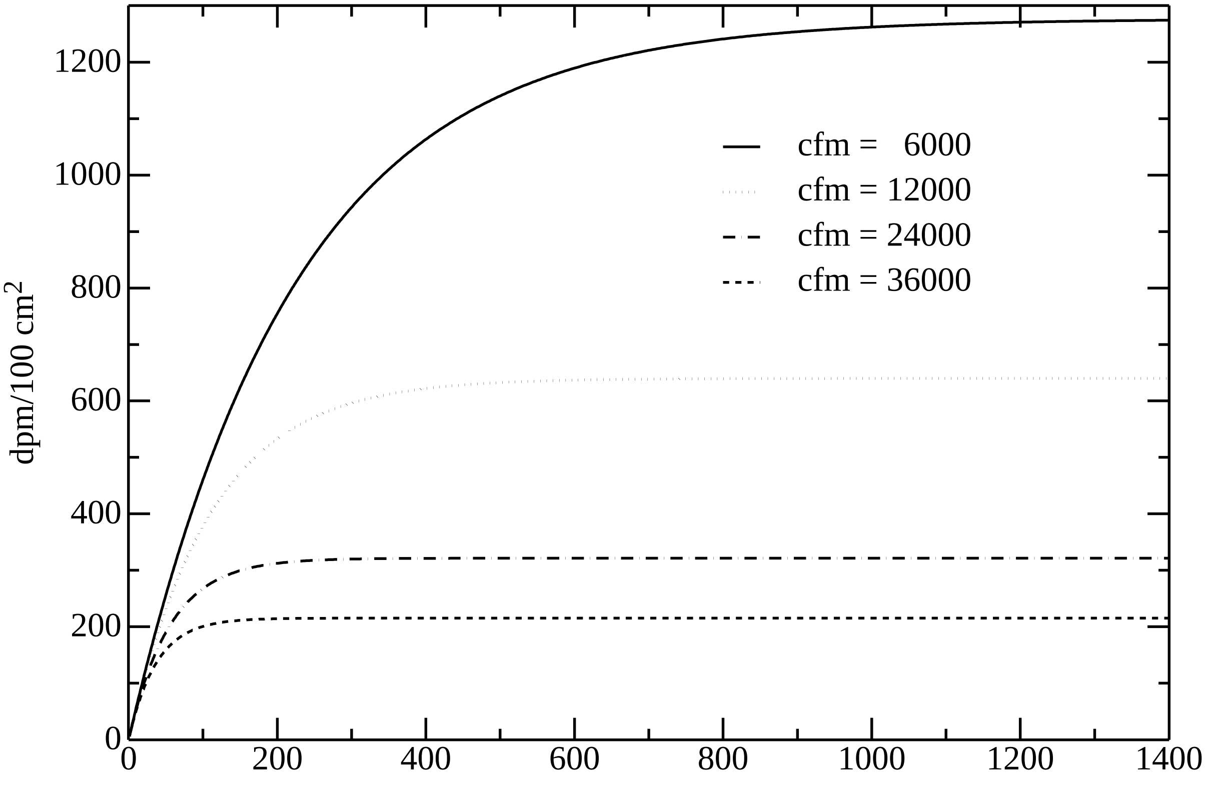

Figure 8. The dpm per 100 cm^2 in polyethylene in Hall A as a function of time after a full release of 1600 Ci of tritium and for various exhaust fan speeds in cubic feet per minute.

It is clear from Fig. 8 that if the exhaust fan speed is greater that 12000 cfm then the actionable limit is not exceeded. Thus, our first and most important proposed step in the installation is to ensure that at least a 12000 cfm exhaust fan speed is turned on when the target container arrives in Hall A and is being installed. Note that Table 3 lists the design capacities of the fans and not the actual. Carroll Jones at JLab has stated that the actual values could be measured if necessary.

For reference, the dpm for polyethylene is estimated assuming that the fans are turned on one hour after a full release. These results are shown in Fig. 9. Here the dpm rises linearly for the first hour and then levels out at a value and a time that depend on the fan speed. In this case the value remains below the actionable level with the 12000 cfm fan speed.

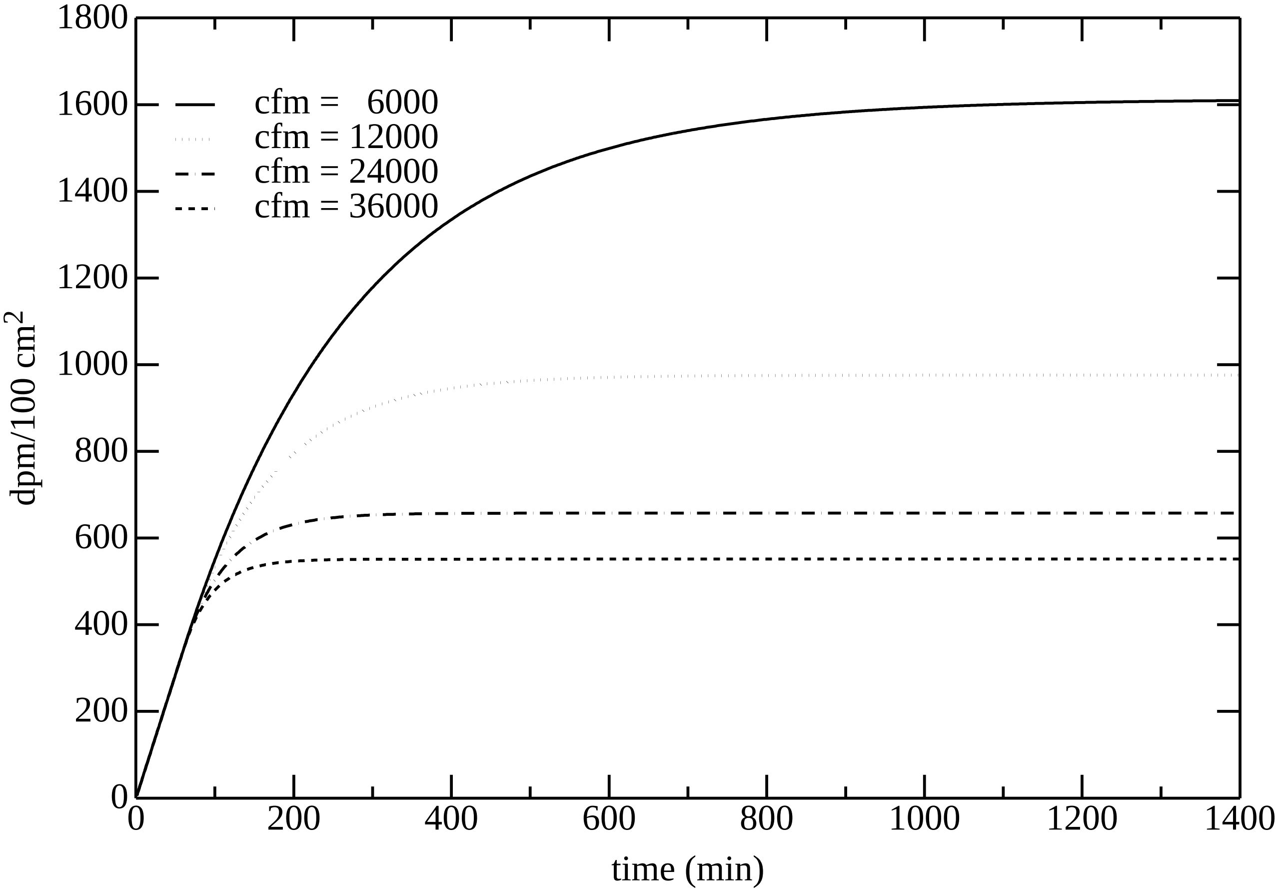

Figure 9. The dpm per 100 cm^2 in polyethylene in Hall A as a function of time after a full release of 1600 Ci and for various exhaust fan speeds in cubic feet per minute. Here it is assume that the exhaust fans are turned on one hour after the tritium release.

Table 3. Design capacity of existing Hall A exhaust fans. Capacity is in cubic feet per minute.

Exhaust fan Hall A	Design capacity (cfm)
EF-1	12000
EF-2	12000
EF-3	6000/12000

Outline of proposed target installation procedure:

- Turn on Hall A exhaust fans (>24000 cfm should be sufficient)
- When target container is received at JLab, survey with a hand-held tritium monitor
- When opening the target cask, survey with hand-held monitor
- Survey for x-rays if not done at INL
- Swipe target in several places for tritium
- Carefully unpack target, one person continuously surveying for tritium
- Remove protective shipping covers
- Load solid targets into frame if this has not been done prior to shipment
- Attach W mask to target frame if this has not been done prior to shipment
- Attach scattering chamber top flange to target assembly if not done prior to shipment
- Attach crane to top flange
- Lift target to position directly above scattering chamber
- Two target-trained installers with proper ppe will carefully guide target into chamber
- When target is seated, remove crane and begin bolting target flange to chamber
- Place vent hood over target and activate exhaust fan
- 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 MKS rad-hard RGA (QTC54537) 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 – described below

The de-installation of the target would be approximately the reverse steps with the one major exception that the Hall A exhaust fans should be turned on before the target vent hood is removed.

Alignment of the Tritium Target

The alignment procedure described in the following assumes that the tritium target has been surveyed by the Jefferson Lab survey and alignment group, so the absolute position of the target is known. Further we assume that the beam is "roughly" aligned with respect to the target. This can be achieved by using a BeO target close to the tritium target location. In order to minimize background generated by scattering off the target walls, the following procedure is proposed.

At the beginning one has to make sure that the raster is at nominal setting. Then the beam current has to be reduced to ~2 μA. Next an x-y scan is performed with the beam in ~0.5 mm steps, measured at the target. The rates in the spectrometers have to be monitored carefully and the scan should be stopped if the rates start rising significantly. The increase in rate indicates that the beam halo starts hitting the wall or any other obstruction. As soon as the x-y scan is finished the beam should be moved to the position which yields the lowest rates. After this scan a raster size study should be performed. The raster size should be increased in small steps (~ 1 mm) and the spectrometer rates should be monitored. As soon as the rates increase significantly the scan should be stopped. This procedure will allow us to estimate the background due to wall scattering. The nominal raster setting should generate a small enough beam size that any background from the walls is small. It is likely that these alignment procedures would be performed with the ^{3}He target in the beam position and then the ^{3}H target moved into the beam position and checked with the low current beam.

Tritium diffusion through aluminum

The tritium diffusion through the Al container was estimated[10] by assuming the hydrogen concentration and diffusion coefficient for Al. The diffusion of tritium into the vacuum chamber is less than 50 μCi/month of continuous operation. This level of tritium diffusion would have negligible radiological impact.

X-ray emission from the tritium target

Tritium nuclei beta decay with a 12.3 year half life. The emitted betas have a maximum energy of 18.6 keV. An estimate of the X-ray radiation from the tritium target can be made by assuming that the betas are 10 keV in energy. The X-rays are produced when the betas strike the Al wall and through a bremsstrahlung process, convert to X-rays. For a 1563 Ci target, there are approximately 6×10^{13} betas/sec. If we make an extreme assumption that 100% of these betas convert to a 10 keV X-ray, then the total radiation produced in the cell is about 10 rads/sec. Assuming a solid angle of 0.1 sr and a distance of about 30 cm from the target cell, the dose rate would be less than 0.6 mrem/hr outside the Al container. The X-ray radiation level should be measured from the target, but it is likely to be much less than the estimate above.

Radiation damage considerations of the target cell from the JLab beam

Measurements indicate that the fast neutron fluence necessary to give problematic radiation damage to aluminum is approximately 10^{21}-10^{22} neutrons/cm^2. A beam of 30 μA for several months produces a neutron fluence in the target windows that is 5 to 6 orders of magnitude below this critical value. Thus, we expect no problems from radiation-induced embrittlement of the target cell. Aluminum target cells for hydrogen and helium isotopes have been in routine use at JLab and no failure from radiation damage has been noted to date.

Hydrogen embrittlement

Hydrogen embrittlement becomes an issue[11] at very high gas pressures, *i.e.*, above 2000 psi. The pressure in our target cell will be more than an order of magnitude below this value, *i.e.*, 150 psi. Thus, we expect that there should be no problem from hydrogen embrittlement for our target cell.

Energy stored in the pressurized gas

The stored energy in the pressurized gas in the tritium target is estimated to be 50 J. This value is comparable to that of the polarized ^{3}He target which has been in routine use at JLab. We would expect to use similar procedures necessary for the polarized ^{3}He target.

Chemical energy stored in the target gas

When burned, the tritium would produce about 22 kJ of energy. Any release of the tritium from the primary containment cell would expand into the evacuated scattering chamber and be pumped away. However, if gas leaks outside the scattering chamber, an explosion proof fan, triggered by the detection of tritium would immediately ventilate the target area to the outside. If these systems fail, the tritium gas would readily mix with room air and be diluted well below the lower flammable limit of 4% hydrogen to air by volume. The target capacity is 1563 Ci of tritium which corresponds to about 0.5 standard liters mixed with 38 x 10^6 liters of air in the Hall, gives less than 150 ppb tritium by volume.

Activation of the target

The Al target cells will become activated in the JLab electron beam. The photon induced saturation rate was estimated for the Al target windows. This estimate was based[11] on calculations and measurements at SLAC. Radioactive photo-spallation products in ^{27}Al are given in the Table 4. The metastable and ground states of ^{26}Al, although produced, are not considered because the lifetime is too short and too long, respectively, to have an impact. For a 90 day irradiation of a target cell in a 30 μA JLab beam, where a total 17 watts is lost in the two target windows, the activity rate immediately after irradiation is 14.5 mR/h at a distance of one meter. The short lived daughters are responsible for this relatively high activity. After cooling for one day, the rate is 4.9 mR/h and after 4 days, 3.0 mR/h at one meter. The bulk of this activity is from ^{22}Na which has a half-life of 2.6 y and further reasonable cooling times are relatively ineffective in reducing the activity.

Table 4. Photoproduced daughters of aluminum.

Spallation Product	Half life (h)	Saturation exposure rate for 17 W (mR h^{-1} m^2)
^{24}Na	14.96	8.7
^{24}Ne	0.06	0.02
^{22}Na	22950	5.1
^{18}F	1.83	1.36
^{15}O	0.03	0.68
^{13}N	0.17	0.14
^{11}C	0.34	0.51
^{7}Be	1286	0.07

Engineered safety features proposed for the tritium target

First, the amount of tritium gas was reduced by about a factor of three from the original proposal. It is envisioned that a collimator will be used so that the target cell diameter could be reduced to

12.5 mm. We note that this target would use about a factor of 100 less tritium than that used by the MIT-Bates tritium target.[4] The target is completely sealed and has secondary containment. Independent sensors would be interlocked to protect the target from cooling loss, over-temperature or tritium leaks. Complex procedures such as filling the target cell are performed at the STAR Facility at INL. Risk occurs when the target is being removed from the shipping container and installed in the target ladder at JLab as well as the reverse steps.

The target has both primary and secondary containment. If the primary containment were breached, the gas would expand into the vacuum chamber which has a volume of approximately 100 liters. This means that the pressure in the scattering chamber would be much less than an atmosphere and the tritium gas would be contained in the scattering chamber. We would plan to have tritium detection and take the necessary steps to contain the tritium.

A possible failure mode could occur if the beam is on, but the beam raster is off. In this case, the 100 μm diameter beam could burn-through the target cell windows. It is estimated that the probability of putting beam on the target without the raster on is about 3×10^{-4} based on experience. We would mitigate this problem by developing an independent raster monitor with a battery-backup-based electronics unit that would be used on the beam raster. In order to minimize beam interlock failure rate, we would also develop a parallel and independent Fast Shut Down (FSD) for the injector beam. With these improvements, we expect to reduce the probability for this type of incident by at least another factor of 100. Administrative controls, described later, should further mitigate this risk.

A high velocity task fan (1000-2000 cfm) that could quickly move air from the target region to the outside would be installed and vent the target region if tritium or helium were detected in the scattering chamber. This task fan and the JLab beam would be interlocked to the tritium detector. Normally, the existing Hall ventilation fans are disabled when the beam is on. The task fan should also be in operation when the scattering chamber is first pumped out. The exhaust of the roughing pump should be vented with the task fan.

Extreme case radiological considerations

Here we make some drastic assumptions where the entire tritium gas target is lost from all levels of containment. We consider two extreme cases: one case where the task fan works properly and the other case where even this fails.

First, we assume that the task fan works properly. In this case tritium is detected, the beam is shut off and the task fan is turned on. In the GENII model[12] for public exposure, we assumed an acute release of 1600 Ci of tritium gas in about an hour up a 5 m stack. We chose a 5 m stack since the present target vent stack[13] is 5 m. We chose 300 m as the closest point since the nearest site boundary is about 300 m from Hall A. The estimates were performed by Bruce Napier using the GENII v. 2.09 model at Pacific Northwest National Laboratory. The dose to a person at the site boundary can range between about 0.8 mrem and 10 mrem depending critically on the meteorology. For example, if one takes the GENII model with 95 percentile meteorology for Norfolk in 2000 over 8960 hours, then the answer is 0.8 mrem. The 95th percentile in this case means that only 5% of the values are worse than this result. If one uses HOTSPOT and takes the "standard" worst case meteorology, *ie* 1 m/s windspeed, class F ("stable atmosphere, minimal dispersion), a sampling time of one hour and an immediate conversion[14] of approximately 6% of the tritium gas to HTO, then a person at the site boundary would receive a 10 mrem dose[15]. When the same meteorology is used for the HOTSPOT and GENII models, similar results are obtained[15]. In the GENII model, the dose at 100 m is approximately a factor of 7 larger than that at 300 m from the vent stack. Also, with a 10-m stack instead of the 5-m stack there is a factor of approximately 1.6 reduction in the dose at 300 m.

Now, we suppose the task fan does not work and all 1563 Ci were released into Hall A at JLab. Assuming that the release was elemental hydrogen (HT), the dose conversion factor for inhalation is 1.83E-15 Sv/Bq = 0.00677 rem/Ci. Hall A has a diameter of 53.5 m and a height to crane of about 16.9 m. If you have 1563 Ci immediately released in a 38,000 m^3 room, that is 0.041 Ci/m^3. A typical worker breathing rate is 1.2 m^3/hour. Thus 1.2 m^3/hr * 0.041 Ci/m^3 * 0.00677 rem/Ci = 0.33 mrem/hour. A worker would be receiving about 0.33 mrem/hour. Likely this value is exaggerated since most of the tritium gas would collect near the ceiling. In this case, the usual exhaust fans for the Hall should be used to clear as much tritium out of the hall as quickly as possible. If we assume that the Hall A exhaust fans are turned on and produce 20,000 cfm, then the meantime to exhaust Hall A is about 67 minutes. (The actual peak capacity of all three Hall A fans in simultaneous operation is 36,000 cfm.) The level of activity should be reduced to the 0.5 Ci level after about 8 mean times or nine hours of operation. The ~1 Ci level is the estimated level of tritium release from a previous cryogenic ^{3}He target leak in Hall C. (For reference, a typical portable exit sign contains from 10 to 20 Ci of tritium gas.) The impact of using the Hall A exhaust fans is discussed in more detail in the subsection entitled “Installation of the target at JLab”.

As mentioned earlier, the installation and removal of the target cell from the scattering chamber at JLab poses a potential risk. Here we estimate the dose that a worker installing the target might receive during the installation. First, let’s assume that there is breach of the primary containment and the worker somehow manages to inhale the entire 1563 Ci of gas, an impossible scenario. Only 0.005% of tritium is deposited in the lungs from inhalation of the gas[16]. Then with a committed dose equivalent (CDE) of 64 mrem/mCi ingested, there is a 5 rem dose to the body. This is essentially the DOE dose limit for a radiation worker for an entire year and clearly not acceptable at JLab. A more reasonable estimate would be to assume that the worker breathes tritium gas at a breathing rate of 1.2 m^3/hour for 3 minutes before a tritium alarm sounds. In this case we assume that on average the tritium gas over the three minutes has a concentration of 1563 Ci/10m^3. Then the dose to the worker becomes only 63 mrem. This result is conservative compared with the estimate[17] made by R. Wayne Kanady for the TMIST-2 facility at Idaho National Lab. In this situation, a 1422 Ci sample of gaseous elemental tritium (T_2) was considered. For a confinement factor of 10 for an open work area with unknown ventilation conditions, the dose to a worker was estimated to be 1.19E-5 of the Annual Limit on Intake, or 59.5 μrem. The main difference between these two estimates is that the more conservative estimate assumed that somehow 6% of the T_2 gas was immediately converted to HTO.

Proposed testing of target cell prototype at JLab

We plan an in-beam test of a hydrogen/helium filled prototype of a target cell in the JLab beam. In this case, we would verify our heat transfer calculations. In addition, we would turn off the raster systems and verify our safety interlocks and controls for the burn-through condition of the target cell.

Unrelated fire, natural disaster and other incidents

The tritium target containment is thermally well insulated and mechanically well protected. In case of fire, a normal evacuation of the room should be performed. Access to Hall A by the fire department should be permissible after a check for tritium as well as other radiological hazards has been conducted. Earthquakes and tornadoes of exceptional scale that could cause problems are extremely rare in the area. Nevertheless, the design will incorporate the usual 10% transverse load requirement. Hurricanes cause power outages and flooding. The completely-sealed target system should not be adversely affected by these types of events.

Summary of proposed engineering controls for safe tritium target operation

- Completely sealed source of tritium
- Vacuum chamber provides secondary containment of tritium target
- Active cooling with either cryogenic nitrogen gas or water
- Fast Shut Down (FSD) system on low raster signal
- FSD on loss of coolant
- FSD on vacuum in scattering chamber
- FSD on tritium detector
- FSD on target over-temperature
- Vent hood with exhaust fan ready for activation

Administrative controls for safe tritium target operation

- The beam current should never exceed 30 uA.
- The overhead crane should be locked out after installing the tritium target and during tritium target operation.
- Trained tritium target operators should be on shift at all times that the target is installed.
- The beam condition, raster pattern and target parameters should be continuously monitored by the target operator.

- Accelerator operators should be given special instructions regarding operations during the experiment. For example, the crew chief should double check that the raster and all beam interlocks are energized before putting beam on the tritium target.

- Full written and approved procedures for all operations with the target: target installation and removal, target motion, beam on target, and storage, if necessary, of target on site.

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