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 concept for a safe tritium target for use in Hall A at Jefferson Lab for the approved 12-GeV experiments[1,2,3,4] E12-10-103, E12-11-112, E12-14-009. These experiments have been scheduled tentatively to begin in Fall of 2016. This report describes the overall design and testing of a gas target cell for Hall A at Jefferson Lab following the recommendations of the June 3, 2010, Conceptual Design and Safety Review at Jefferson Lab. Dave Meekins, the Design Authority and Project Manager, for the tritium target has taken this conceptual design to the actual tritium target design that will be used at JLab. This is detailed in a separate report. This report contains many of the details that were necessary to produce the conceptual as well as the actual target design.

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 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. The target will be a completely sealed system that is filled with approximately 13 atmospheres of tritium gas and sealed at a tritium facility (Savannah River National Lab, SRNL) offsite. After the experiments the target will be shipped back to SRNL. This minimizes the risks associated with filling and decommissioning 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. In all cases we followed the guidelines in the DOE Handbook for Tritium Handling and Safe Storage.[5]

Previous tritium targets at electron scattering facilities

Table 1 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, and maximum beam currents 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)
Stanford HEPL	1963	25	0.8	1	0.8
MIT-Bates	1982	180	0.3	20	6.0
Saclay	1985	10	1.2	10	12.0
JLab	(2015)	1	0.08	25	2.0

The proposed JLab target is competitive with the previous gas targets and even compares favorably with the Saclay liquid tritium target.[6] The primary disadvantages of the Stanford HEPL target[7] are the large number of curies (25,000 Ci), the extremely high gas pressure of 200 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[8] 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 beam current. By comparison, the proposed JLab target uses only 1.0 kCi, has a pressure of only 13 atmospheres, and can safely handle 25 μA of beam current. The proposed JLab target makes use of 10 times less target material than even the Saclay target and has the highest luminosity per Ci of target material. The proposed target is completely sealed, isolated in a scattering chamber and cryogenically cooled for beam operation.

Design criteria

The primary design criteria are summarized below:

- Minimize tritium
- Limit beam current
- FEA thermo-mechanical design of the target cell
- ^{3}He, $^2H_2$ and H_2 targets at more than twice the pressure of the $^3H_2$ target
- Minimize tritium handling at JLab – fill target offsite
- Completely sealed cell design
- Secondary containment – isolated scattering chamber
- Hood and ventilation system
- Tritium, vacuum, temperature monitors
- Interlocks on raster, vacuum, tritium monitor, coolant
- Ease of installation and alignment

Target safety optimization

As recommended by the June 3, 2010, review committee, a safety algorithm[9] was developed for the experiment. The approach involved defining the risk level based on the number of curies, beam current, pressure, beam trips, and time for the experiment. The "truth table" for defining the risk level is given in Table 2. Details regarding how these risk levels were set are given in the reference. The basic formula that defines the algorithm is shown below for each parameter p is given by

$$\text{Risk}_P = [1 - \exp(-P/C_P)]\exp(P/C_p).$$

In other words, the risk increases exponentially as the parameter value increases and goes to zero as the parameter decreases. The C_p denotes the high risk value as given in the column labeled "High" in Table 2. The total risk is then the sum of the individual risks as given by

$$\text{Risk} = \Sigma_p \, \text{Risk}_P$$

Table 2. Risk *vs*. operating parameters.

	Risk Level			
Parameter	Extremely Low	Low	Medium	High
Curies	<10	100	1000	5000
Beam current (μA)	<1	5	25	60
Pressure (psi)	<10	100	500	1500
Beam trips	<1000	1E4	1E5	2E5
Time (d)	<10	50	200	365-730

If we assume a 1000 Ci target, then the risk as a function of beam current from this algorithm is given shown in Fig. 1. The absolute minimum occurs at 21 μA, but it is a broad minimum from about 15 to 30 μA. The 1000 Ci was chosen since it is relatively straightforward to ship this amount of tritium gas.

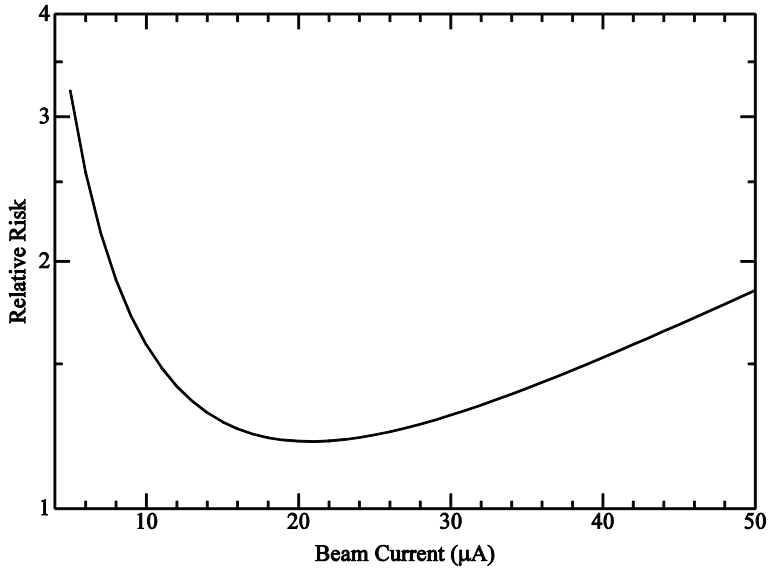


Fig. 1. Relative risk vs. beam current when target is 1000 Ci. The optimum current is 21 μA. This assumes that the high risk value for time is 365 days.

If instead, we choose a beam current of 21 μA and vary the target activity, the result is shown in Fig. 2, where the absolute minimum occurs at 1350 Ci. However, again the minimum is broad.

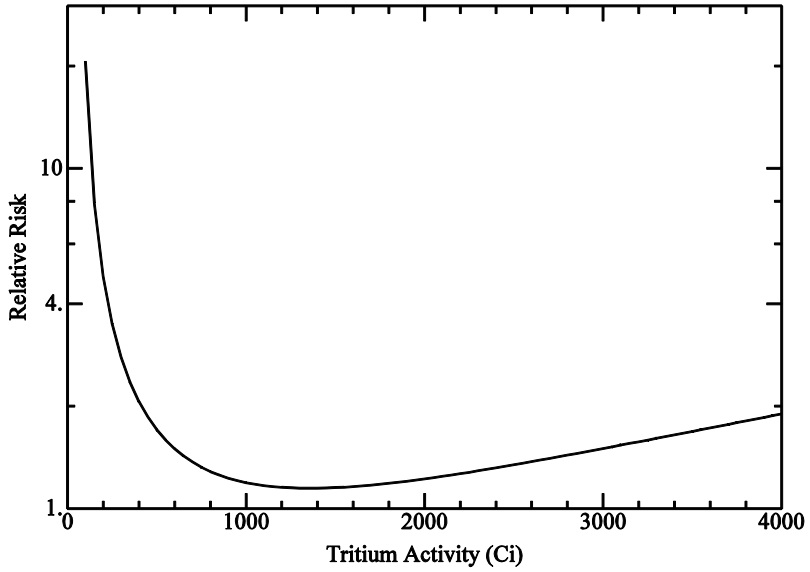


Fig. 2. Relative risk vs. curies when the beam current is 21 mA. The optimum target activity is 1350 Ci. This assumes that the high risk time is 365 days.

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 1000 Ci of tritium gas in a completely sealed system. The tritium gas would be contained in a 25-cm long × 1.27-cm diameter aluminum (7075-T6) cell as shown in Fig. 3. The alloy 7075-T6 was chosen since it is tritium compatible, has high thermal conductivity, has high yield strength, and it is in routine use for target cells at JLab. The windows for beam entrance and exit would be 0.010" and 0.011" thick, respectively, and the windows in the cylindrical body would be 0.018" thick. The resulting absolute tritium gas pressure in the container would be 13.6 atmospheres at room temperature, when the target is fresh and in the vacuum chamber. This pressure would very slowly nearly double 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 (absolute 30 atmospheres) would be more than a factor of two larger than that of the tritium target in order to give similar counting rates. Prototype targets have been pressure and burst tested so that there is an acceptable factor of safety for the tritium and helium targets. This safety factor was also calculated in a 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.

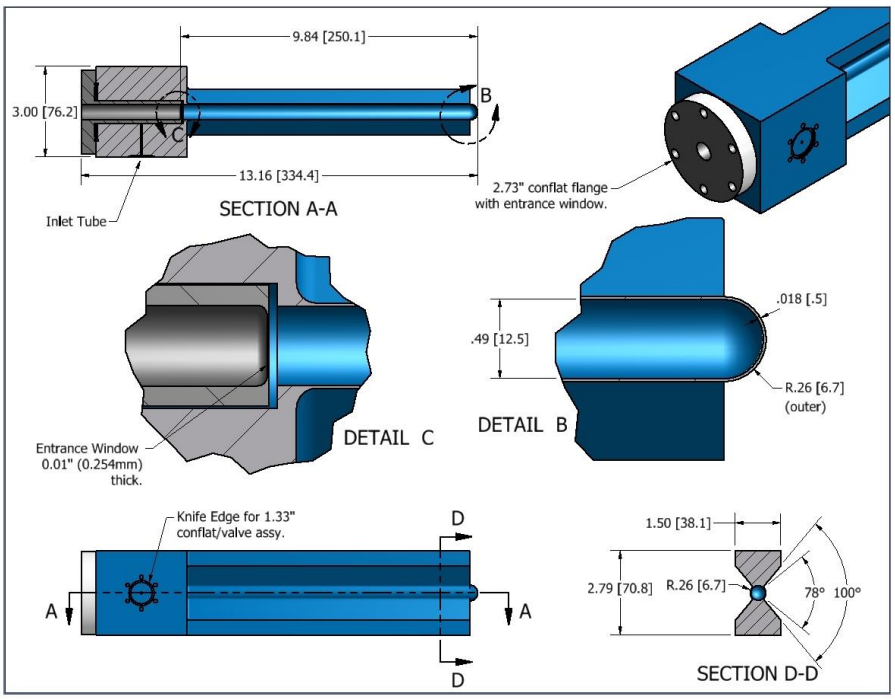


Fig. 3. Engineering design of an individual tritium gas target cell for Jefferson Lab.

The targets would be filled offsite at a tritium facility 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.

The target cells will be fabricated from certified stock which requires certified material test reports (CMTR). The CMTR's will be provided with the parts. If the parts are made from different heat numbers, the numbers must be labeled on the parts. The vessels would then have the filling tubes and valves attached and helium leak tested at a pressure of 450 psi. The upstream window and valve will be attached to the thick part of the target cell with conflat seals. After filling the cells, a s.s. cap will be attached to the valve using a VCR fitting.

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 $^{3}H_2$, ^{3}He, $^{2}H_2$ and H_2 gases, respectively. The main experiment will cycle between the $^{3}H_2$, $^{2}H_2$ and ^{3}He target cells for most of the beam time. Each cell, except for the dummy cell, will be filled individually through valves. The target will be cryo-cooled. Photographs of the prototype target cell and window assembly are shown in Fig. 4.

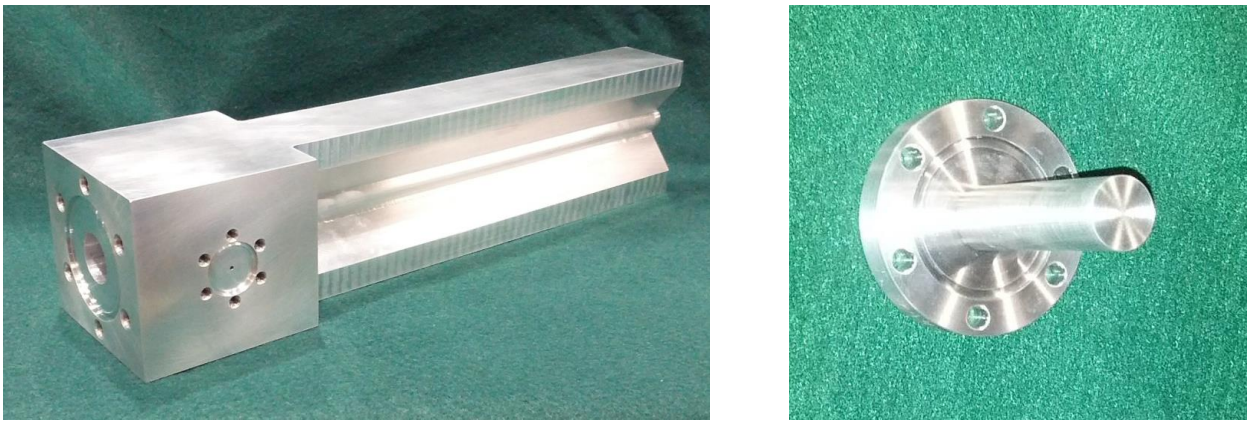


Fig. 4. Left: main target cell body and downstream window. Right: upstream window assembly. The material is aluminum alloy 7075-T6.

Beam current

At JLab the standard administrative procedure for Al targets is to hold the beam current to 40 μA or less. Thus, we propose to have an administrative limit of 25 μA on the beam current for this experiment. Furthermore, it is noted that ion beam studies[10] of static 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 current and this target design, the power density is 34 mW/mm for the ^{3}He, $^2H_2$ and H_2 targets and 15 mW/mm for the $^3H_2$ target which would result in approximately a 15% decrease and 5% decrease in target densities, respectively. In order to avoid significant target density corrections, it is likely that this experiment would not deploy more than 25 μA of beam current on the targets. At the recommendation of the June 3, 2012, JLab Tritium Target Review Committee, an optimization study[11] was performed and it was found that risk is minimized for beam currents between 15 and 30 μA. 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 25 μA. There will be a deposited power of approximately 4.7 W in the 0.010" upstream window, 5.1 W in the 0.011" downstream window, 3.8 W in the tritium gas, approximately 8.6 W in the hydrogen, deuterium and helium gases. The target cell will be fabricated from an Al alloy 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. A thermo-mechanical 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 original conceptual design target cell analyzed is shown in Fig. 5. The analysis was performed using ANSYS 12 FEA software package and was published.[12] The finite element analysis heat transfer calculations are based on the following inputs. The 25-μA electron beam diameter was taken to be 3 mm, while the wall thicknesses were: endcap, 0.45 mm and body, 0.45 mm. The beam generated heat was taken to be: endcaps, 4.7 W (upstream) and 8.4 W (downstream) each; gas - helium, deuterium and hydrogen, 8.6 W; tritium, 3.8 W. The initial net gas pressures: helium, deuterium, hydrogen - 31 bar and tritium - 14 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.

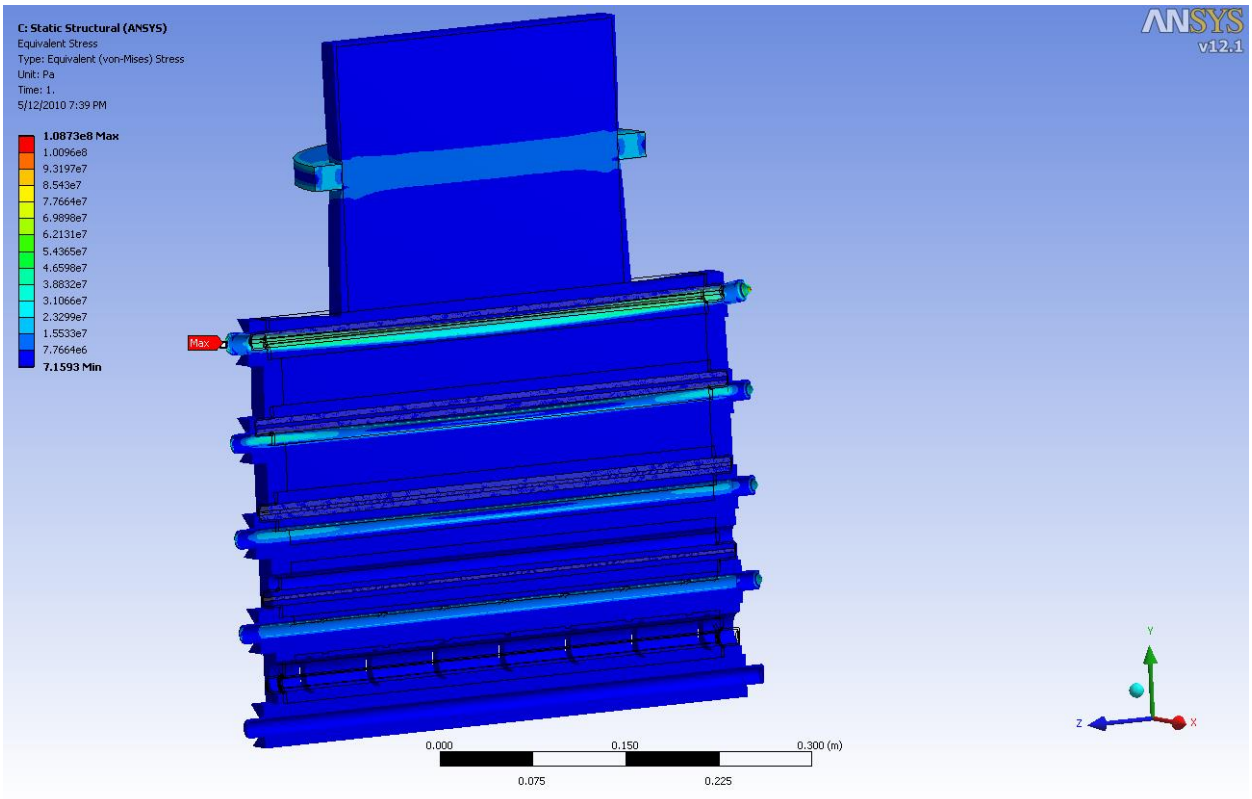


Fig 5. Pressure map of the target cell. The maximum stress is in the target windows.

Please note that these results are not for the present design of the target cell, but rather the previous design and these results are for LN2 cooling and not the planned cryogenic helium gas cooling. The results of the ANSYS 12 analysis are given in Table 3. 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 LN2 cooled heat sink as well as for the tritium target. The LN2 cooling assumed 30 g/s of flow. The factors of safety, based on the yield stress values for

Al 2219 T851 for the hydrogen, deuterium and tritium containers, are large for 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 186 K for the 3 mm diameter beam spot and 20 μA of beam for the ^{3}He target and 170 K for the hydrogenic targets. This is below the temperature for the beam-induced corrosion threshold for the hydrogenic targets.

Table 3. Summary of the results from the FEA heat transfer calculation.

	Max. Temp. (K)	Max. Equiv. Stress (MPa)	Yield Stress (MPa)	Factor of Safety
^{3}He cell exposed to the beam				
^{3}He Cell Endcaps	185.6	61.1	373.5	6.1
^{3}He Cell Side Walls	122.2	35.3	394.2	11.2
$^3H_2$ Cell Endcaps	102.1	17.4	406.2	25.5
$^3H_2$ Cell Side Walls	102.6	26.8	402.4	15.0
$^2H_2$ Cell Endcaps	111.1	16.1	398.7	24.7
$^2H_2$ Cell Side Walls	111.5	34.4	398.5	11.6
H_2 Cell Endcaps	94.1	16.0	406.5	25.5
H_2 Cell Side Walls	94.3	52.9	406.2	7.7
$^3H_2$ cell exposed to the beam				
^{3}He Cell Endcaps	95.6	32.1	405.5	12.6
^{3}He Cell Side Walls	95.6	13.3	405.5	30.4
$^3H_2$ Cell Endcaps	169.9	44.4	377.7	8.5
$^3H_2$ Cell Side Walls	102.0	35.0	405.3	11.5
$^2H_2$ Cell Endcaps	96.3	16.8	405.2	25.0
$^2H_2$ Cell Side Walls	96.3	22.3	405.5	18.1
H_2 Cell End-caps	92.2	15.6	407.1	26.1
H_2 Cell Side walls	92.3	32.2	407.1	12.6
H_2 cell exposed to the beam				
^{3}He Cell Endcaps	89.4	30.0	408.5	13.6
^{3}He Cell Side Walls	89.4	11.1	408.5	36.7
$^3H_2$ Cell Endcaps	90.7	15.7	407.9	26.0
$^3H_2$ Cell Side Walls	90.7	20.3	407.9	20.1
$^2H_2$ Cell Endcaps	89.5	15.7	408.4	26.0
$^2H_2$ Cell Side Walls	89.5	9.7	408.4	42.3
H_2 Cell Endcaps	168.1	43.8	378.3	8.6
H_2 Cell Side Walls	99.6	21.5	403.7	18.8

The maximum temperatures and pressures summarized in Table 3 occur in the end windows. These pressure and temperature results are summarized in Figs. 5 and 6. 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.

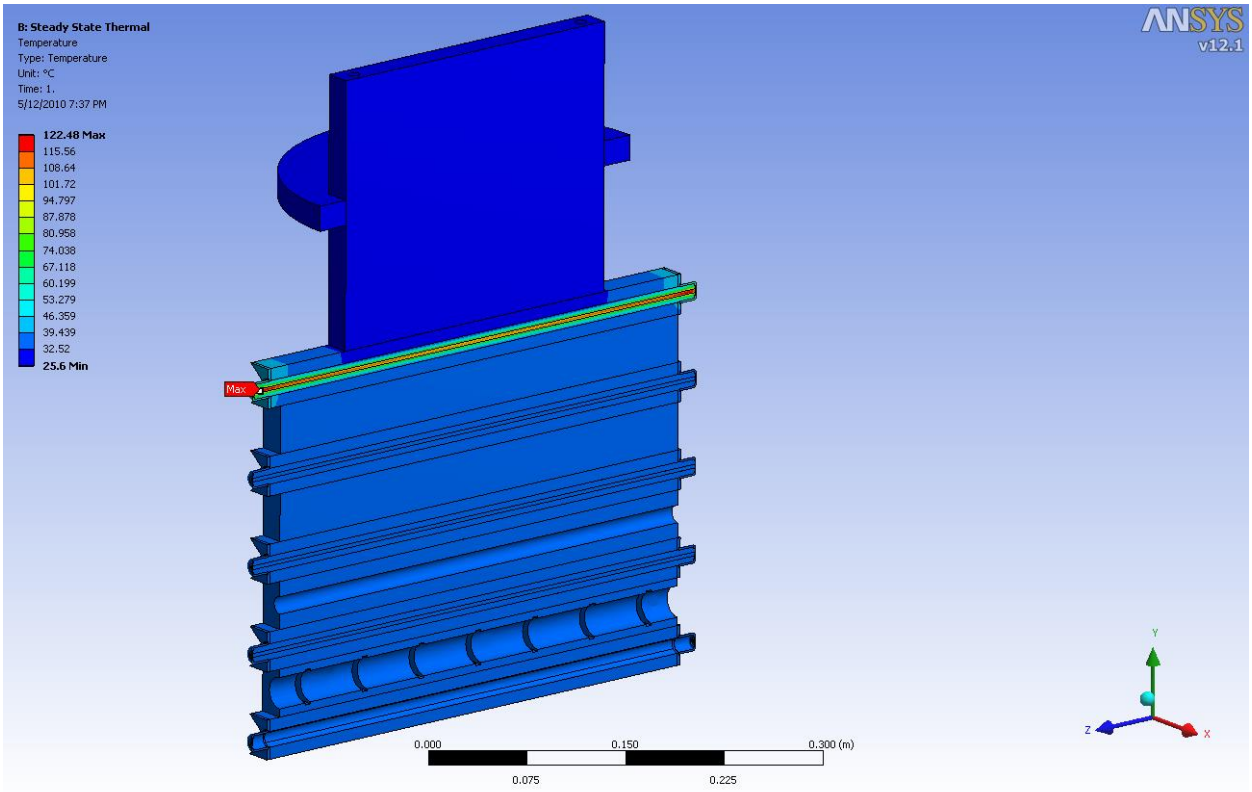


Fig. 6. Temperature map of the target cell. The maximum temperature is in the target windows.

The final engineering design made use of separated target cells. This greatly simplifies the fabrication and installation of the targets. Also, for fabrication reasons, the downstream window is now further from the Al cooling channel. (See Fig. 7.) Even with this design, it was found from an ANSYS14 simulation and a 25 μA beam that with the use of 35 K helium gas coolant that the downstream window could be maintained at 167 K. However, it was found that thinning a 5 mm diameter section of the downstream window as indicated in Fig. 8 could significantly reduce the temperature of the window. With this new downstream window design, the temperature of the downstream window drops to 112 K, well below the goal of less than 180 K.

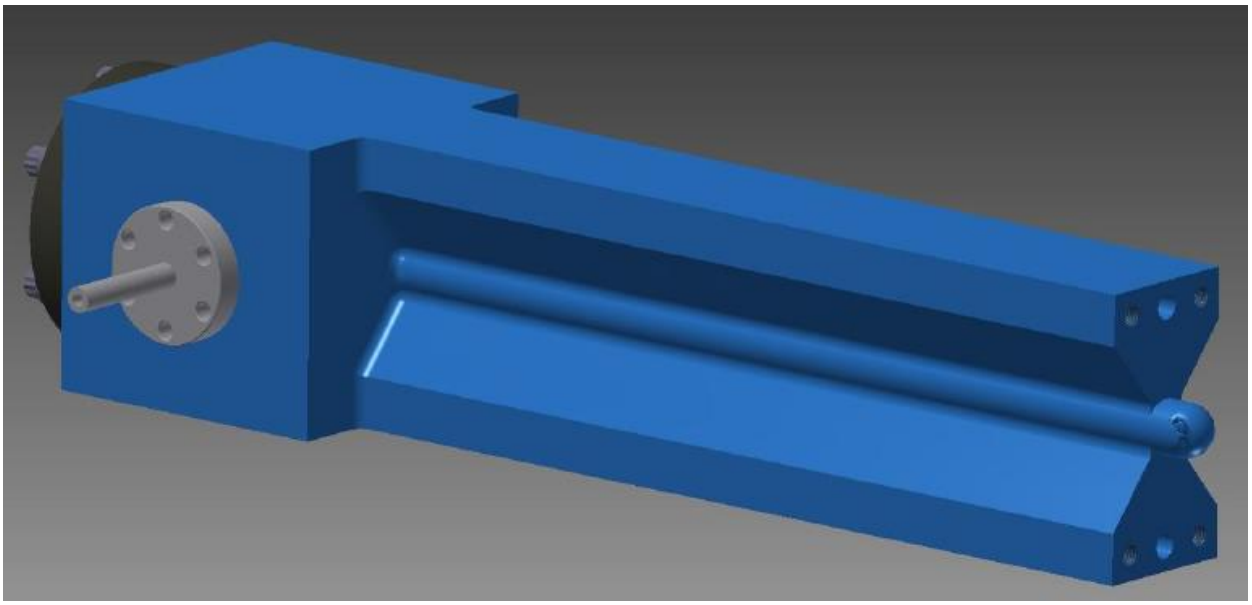


Fig. 7. Drawing of the redesigned single cell with the cooling channel somewhat further from the downstream target window.

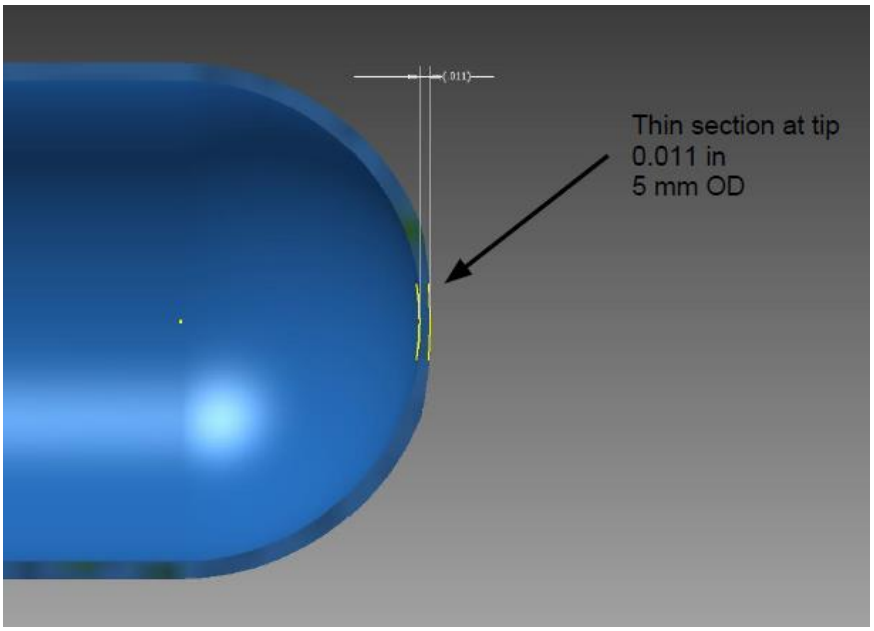


Fig. 8. Detail of the new downstream window design with a 0.011" thick window over a 5 mm diameter. The remaining window is 0.018" thick.

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. 9 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 6.25 mm and the collimator thickness is 25 mm in this figure.

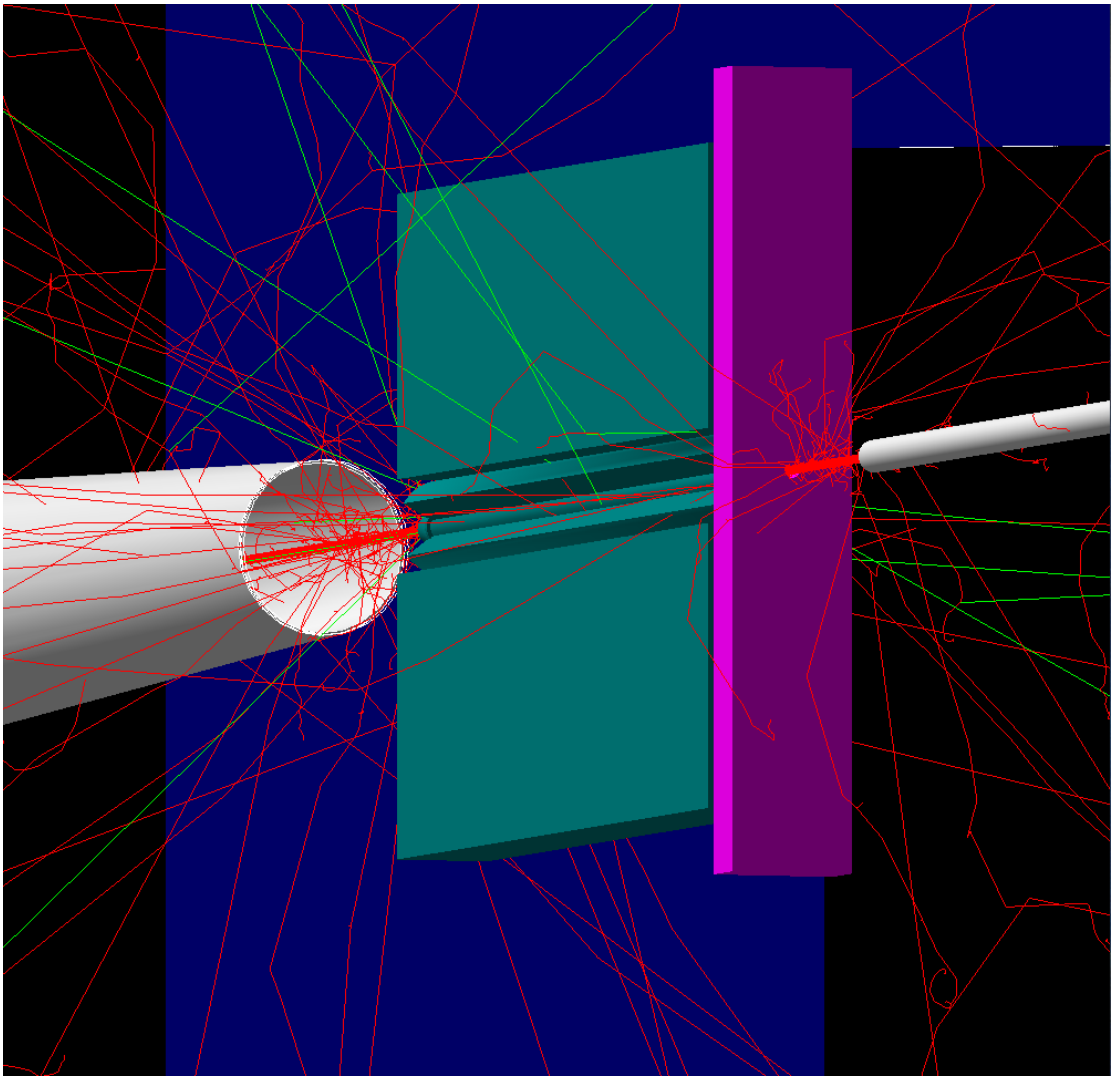


Fig. 9. Side view of the target. The target Aluminum walls and windows are shown in light blue and the collimator in magenta. Red (green) tracks are electrons (photons).

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. 10. Here the Super Bigbite Spectrometer is placed at 30° 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.

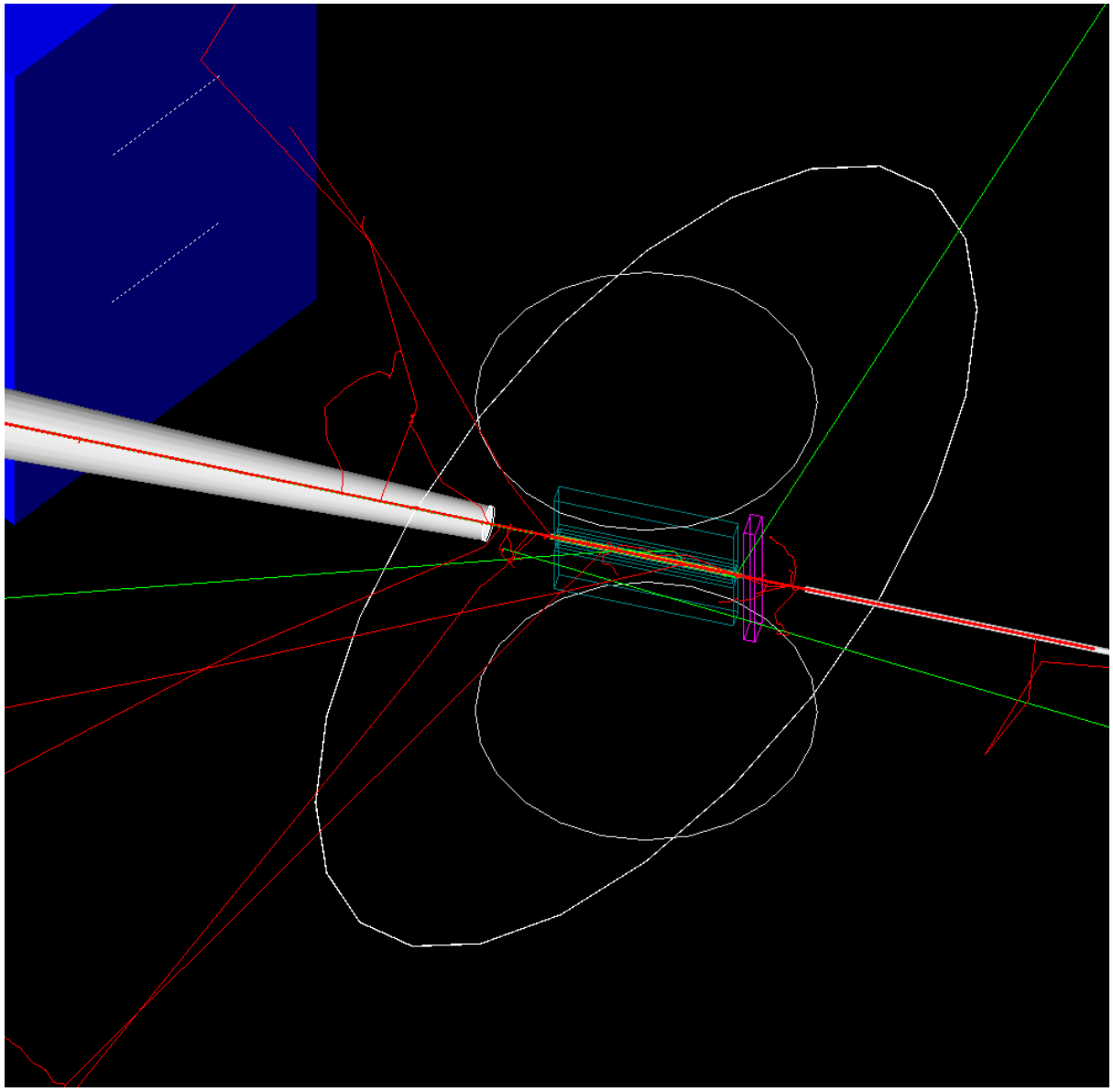


Fig. 10. View of the preliminary experimental setup with the target ladder (light blue), the tritium gas (yellow), the upstream tungsten collimator (magenta), the beam pipe and beam dump (light grey), and the Super-Bigbite Spectrometer magnet (blue).

Target cell pressure tests

Three prototype target cells and two upstream window assemblies were fabricated and were hydraulically tested to burst pressure. Two target cells as fabricated did not meet the design specifications, but these were tested anyway. In particular, an ultrasound thickness gauge indicated that the cells in the area of the downstream windows were as thin as 0.003" in places rather than 0.018". These two cells predictably failed at relatively low pressures of 900 and 1100 psi, respectively. Our calculations indicate that the cell should not fail below 2500 psi when properly fabricated. A third cell closer to design specifications was also tested. This cell had a side window that ranged between 0.014-0.016" rather than 0.018". This cell burst above 3500 psi. The two 0.010" thick upstream windows were properly fabricated, and both failed at 2900 psi. The tritium target would be at an absolute pressure of approximately 206 psi, while the other gas targets will be at approximately 441 psi at room temperature. A new prototype with the newly designed 0.011" downstream window must be tested.

Secondary containment

The scattering chamber will be the secondary container of the tritium target. An engineering drawing of the Big Bite (BB) scattering chamber is shown in Fig. 11. Since the probability for contaminating the scattering chamber is extremely low and we will use the BB spectrometer, we plan to use the BB scattering chamber for the tritium target. The scattering chamber is to be completely isolated from the beam line and an upstream W collimator should be installed as per the recommendations of the June 3, 2010, Review Committee. The isolation will be accomplished with thin Be windows. The engineering detail for a Be window is shown in Fig. 12.

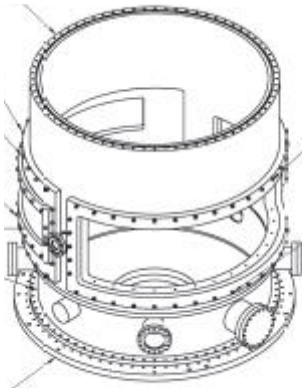


Fig. 11. Engineering drawing of the Bigbite scattering chamber.

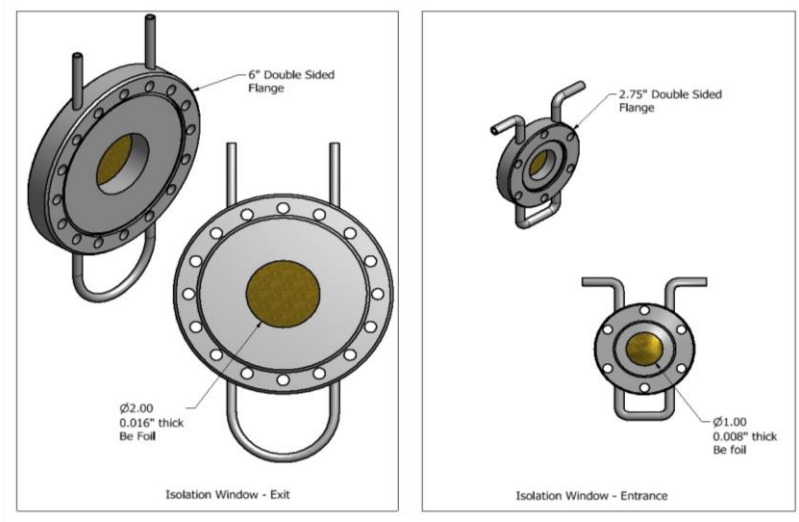
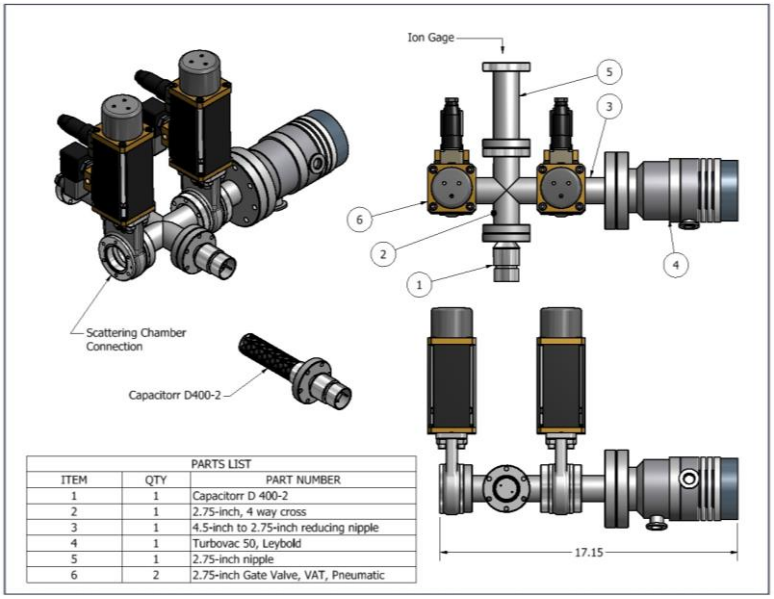


Fig. 12. Detail of the water cooled Be isolation windows for the scattering chamber.

Small levels of tritium can be detected with a rad-hard RGA (Granville-Phillips 835VQM) should a leak occur. In line with the review committee recommendation, a vent hood would be located over the scattering chamber. The vent hood would be exhausted to the outside. Also, according to the Committee recommendation, a getter (NEG) pump[13] will be installed in the system and stand ready to absorb tritium gas in the scattering chamber. A SAES NEG pump with a sorption capacity of 900 torr-liter for H_2 will be activated and in a standby mode. (See Fig. 13.) An automatic valve triggered by the vacuum or RGA will expose the NEG to the scattering chamber. A 1000 Ci sample of tritium represents only 304 torr-liters of gas or about one-third of the NEG pump capacity. As shown in the design the conductance to the pump is approximately 100 l/s. The radiation-hardened RGA and the getter system were already purchased by the ANL group.



PARTS LIST		
ITEM	QTY	PART NUMBER
1	1	Capacitorr D 400-2
2	1	2.75-inch, 4 way cross
3	1	4.5-inch to 2.75-inch reducing nipple
4	1	Turbovac 50, Leybold
5	1	2.75-inch nipple
6	2	2.75-inch Gate Valve, VAT, Pneumatic

Fig. 13. Engineering detail of the getter assembly for the scattering chamber.

Installation of the target at JLab

An outline of a target installation procedure is given below. For protection of the Hall and its equipment, the most important element would be the special ventilation system that is installed for the target since it is vented through a stack.

If this fails, then the Hall A exhaust fans could provide a second line of defense to protect the Hall equipment. A summary[14] of the exhaust fans already installed in Hall A is given below in Table 4. 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.

Table 4. 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

Hydrocarbon based elements in the Hall have the largest tritium absorption rate. For example, the absorption rate[15] 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[16] for stainless steel is an order of magnitude smaller than that of concrete. The administrative or actionable limit for tritium on a surface is 10000 dpm per 100 cm^2. In making an estimate of the worst case incident, we will assume the largest absorption rate, *i.e.*, that for polyethylene. In our estimate, we assume that the entire 1000 Ci sample is lost instantaneously in Hall A. We calculate[17] the dpm in a polyethylene surface as a function of time for various exhaust fan speeds. Note that Table 4 lists the design capacities of the fans and not the actual capacities. Carroll Jones at JLab has stated that the actual values could be measured if necessary.

The dpm for polyethylene is estimated assuming that the fans are turned on 8 hours after a full release. These results are shown in Fig. 15. Here the dpm rises linearly for the 8 hours and then levels out at a value and a time that depend on the fan speed. In this case the value remains well below the actionable level even 6000 cfm, the smallest fan speed.

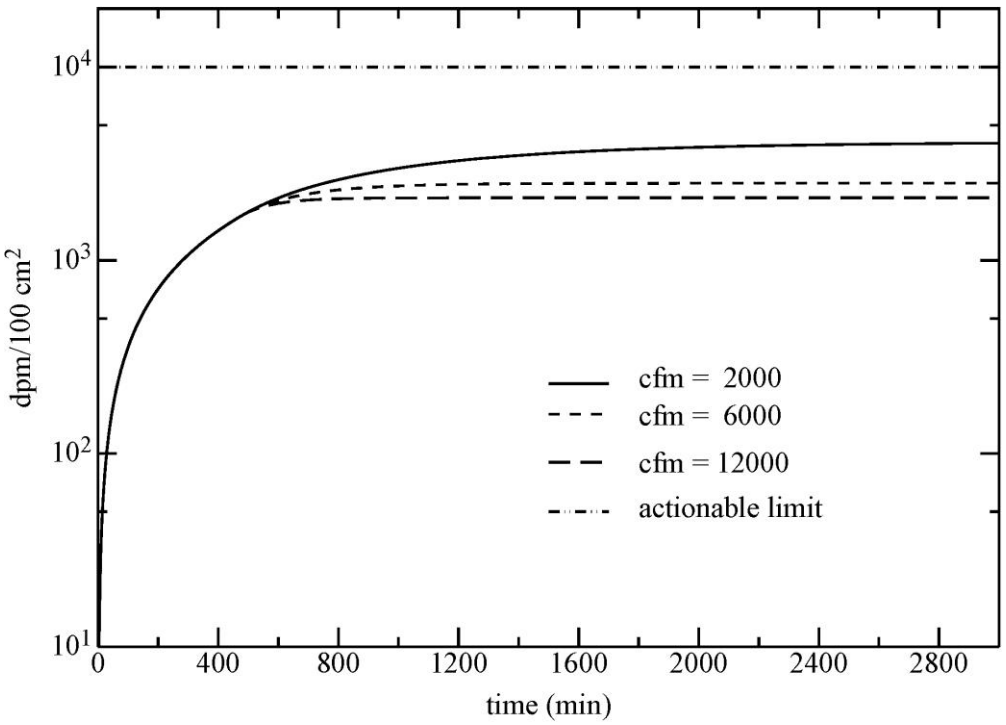


Fig. 15. The dpm per 100 cm^2 in polyethylene in Hall A as a function of time after a full release of 1000 Ci and for various exhaust fan speeds in cubic feet per minute. Here it is assumed that the exhaust fans are turned on 8 hours after the tritium release.

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
- Attach target cell to the frame
- Two target-trained installers with proper PPE will carefully place 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.

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 the two "hole" targets spaced at the positions of the cell exit and entrance will be moved into the target position. This allowed us to measure pitch and yaw angles. Next with the empty target cell 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. In any event, tungsten collimators would precede the targets so that there is no possibility of direct beam hitting the sides of a target cell during this procedure or during the experiment.

Tritium diffusion through aluminum

The tritium diffusion through the Al container was estimated[18] by assuming the hydrogen concentration and diffusion coefficient for Al. The diffusion of tritium into the vacuum chamber is estimated to be approximately 142 mCi per year of continuous operation. The estimated leak rate from the conflat seals and valve is approximately 371 mCi per year. This level of tritium diffusion and leakage 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. A detailed estimate of the X-ray radiation was made[19] for the 1000 Ci target. Most of the X-rays are produced when the betas strike the Al wall and through a bremsstrahlung process, convert to X-rays. A dose rate of 3.6 mrem/hour/cm^2 was found at the surface of the target. At 10 cm from the target, this dose rate drops to 0.06 mrem/hour/cm^2. In any event the target windows should not be touched. These dose rates are small enough to be negligible during the installation of the target cell.

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 25 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

High-strength structural metals are generally more susceptible to hydrogen embrittlement. However, in the case of aluminum alloys in dry hydrogen gas, there is no evidence for hydrogen embrittlement even in the 7000-series alloys. Somerday and San Marchi at Sandia have recently conducted[20] fracture testing on 7000-series alloys in high-pressure hydrogen gas up to 15,000 psi and do not observe any degradation in properties. For comparison, hydrogen embrittlement becomes a problem above 2000 psi for stainless steel. The pressure of the tritium gas target is only 200 psi and for the hydrogen and deuterium targets, 400 psi. Thus, we expect that there should be no problem from hydrogen embrittlement for our target cell when no beam is present.

There is concern that tritium-assisted embrittlement could compromise the mechanical integrity of the Al cell through the following mechanism. First, the tritium atoms diffuse into the Al and subsequently undergo beta decays, thereby implanting ^{3}He atoms into the cell. If sufficient helium atoms are implanted into the cell, then a high pressure could build up that causes the material to swell. Measurements at Savannah River indicate that the swelling threshold for Al is 0.067% He/Al by weight or 0.0046 molar fraction. If we consider storing the tritium in the target cell for one year, then the diffusion and beta decay will result[21] in a molar concentration of 1.8E-10 mol/cm^3 which is more than seven orders of magnitude below the swelling threshold for Al. Thus, this should not be problematic for the tritium target.

The presence of the electron beam could introduce a new factor. For example, the electron beam would be expected[22] to ionize approximately 1E18 tritium atoms per second. This would lead to ions that would migrate to the cell surface and neutralize, possibly producing atomic tritium. Little is known about the effects of atomic hydrogen on surface embrittlement. Studies[23,24] have observed this effect. A simple estimate[19] would indicate that overall there would be an order of magnitude increase in tritium permeation into the Al with the beam on as compared with the beam off. Furthermore, one study[21] indicates that the threshold for corrosion of Al in the presence of an electron beam occurs at a temperature of 180 K. The cryo-cooling of the target when the beam is on is designed to be well under 180 K. Given that the effects of hydrogen embrittlement on Al are negligible and that the operation with beam will occur only when the cell is at low temperature, it is not anticipated that beam-induced corrosion will be problematic.

Finally, we note that the ^{2}H and ^{3}H targets will be operated in an interspersed manner for approximately the same number of beam hours at JLab. The ^{2}H target is more than a factor of two in pressure above the ^{3}H target. This would lead to more than a factor of two more ions produced in the deuterium target compared with the tritium target. Thus, if a problem occurred, it would most likely occur in the deuterium target well before the tritium target.

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.

Chemical energy stored in the target gas

When burned, the tritium would produce about 33 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 1000 Ci of tritium which corresponds to about 0.37 standard liters mixed with 38×10^6 liters of air in the Hall, gives less than 10 ppb tritium by volume. These numbers should be approximately doubled for the hydrogen and deuterium target cells.

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[25] was based[26] on calculations and measurements at SLAC. Radioactive photo-spallation products in ^{27}Al are given in the Table 5. 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 25 μA JLab beam, where a total 13.2 watts is lost in the two target windows, the activity rate immediately after irradiation is 9.1 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 2.5 mR/h and after 4 days, 0.36 mR/h at one meter. The bulk of this activity is from ^{22}Na which has a half-life of 2.62 y and further reasonable cooling times are relatively ineffective in reducing the activity.

Table 5. Photoproduced daughters of aluminum.

Spallation Product	Half life (h)	Saturation exposure rate for 100 W (mR h^{-1} m^2)
^{24}Na	14.96	51
^{24}Ne	0.06	0.1
^{22}Na	22951	30
^{18}F	1.83	8
^{15}O	0.03	4
^{13}N	0.17	0.8
^{11}C	0.34	3.0
^{7}Be	1286	0.4

The rate for Cu in the Al 7075 alloy was estimated[19] and found to be negligible compared with the rate from Al.

Engineered safety features proposed for the tritium target

First, the amount of tritium gas was reduced by about a factor of five from the original proposal. It is envisioned that W collimators will be used so that the target cell diameter could be reduced to 12.7 mm. We note that this target would use about a factor of 180 less tritium than that used

by the MIT-Bates tritium target.[8] 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 offsite. 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 approximately 0.4 liters of gas (STP) would expand into the vacuum chamber which has a volume of approximately 1700 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. The scattering chamber is completely isolated from the beam line by thin Be windows. We would plan to have tritium detection and take the necessary steps to contain the tritium. The RGA or the vacuum gauge should have already opened the valve to the NEG pump which should absorb more than 90% of tritium gas.

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. A transient analysis indicates that burn through would not occur on a short time scale. Most likely, it would take hours to breach the target cell. 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 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.

In line with the June 3, 2010, review committee recommendations, a crash button will be available in the counting house and in the Hall. This crash button should be depressed when tritium has been detected and the normal interlocks have not operated properly. This crash button should initiate a fast shut down of the beam, activation of the target ventilation fan, operation of the pneumatic beam line valves to further ensure that the scattering chamber is isolated, activation of the pneumatic valve on the NEG pump so that tritium that may have entered the scattering chamber can be gettered, and close the pneumatic valve on any roughing pump line that may be in use.

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. The estimates were made[27] using GENII and HotSpot. In the GENII model for public exposure, we assumed an acute release of 1600 Ci of tritium gas with an exit velocity of 1 m/s in an hour up a 15 m stack. Also, 8760 hours of weather data at Norfolk, VA, for the year 2000 were used to determine the 95 percentile meteorology. In other words, the estimated dose of 0.8 mrem at a distance of 300 meters is not exceeded more than 5% of the time in this scenario. This result gives good agreement with that (0.75 mrem scaled from Table 6 below) of HotSpot for similar conditions. The estimates were performed by Bruce Napier using the GENII model at Pacific Northwest National Laboratory.

If one uses HotSpot and takes the "standard" worst case meteorology, *i.e.*, 1 m/s windspeed, class F ("stable atmosphere, minimal dispersion), a sampling time of one hour and an immediate conversion[28] of approximately 100% of the tritium gas to HTO, then the results in Table 6 are obtained.

Table 6. HotSpot calculations with worst case weather scenario, 600 Ci target, 100% conversion to HTO, 60 min sampling time. The right hand column is the maximum dose scaled for a 1000 Ci target.

Stack height (m)	Dose at 300 m (mrem)	Distance at max dose (m)	Max dose 600 Ci (mrem)	Max dose 1000 Ci (mrem)
0	160	<100	890	1483
5	54	200	67	112
10	6.5	500	9.7	16
15	0.28	750	3.2	5.3
20	0.0036	1000	1.4	2.3

The results indicate that for a 1000 Ci target, the maximum dose is significantly less than 10 mrem for a stack height of 15 m. However, even this dose could be reduced by more than a factor of two with a 20 m stack.

Now, we suppose the task fan does not work and all 1000 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 1000 Ci immediately released in a 38,000 m^3 room, that is 0.026 Ci/m^3. A typical worker breathing rate is 1.2 m^3/hour. Thus 1.2 m^3/hr * 0.026 Ci/m^3 * 0.00677 rem/Ci = 0.21 mrem/hour. A worker would be receiving about 0.21 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 0.3 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 "self-powered" 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. Some additional details are given in a technical report.[29] First, let's assume that there is breach of the primary containment and the worker somehow manages to inhale the entire 1000 Ci of gas, an impossible scenario. Only 0.005% of tritium is deposited in the lungs from inhalation of the gas.[30] Then with a committed dose equivalent (CDE) of 64 mrem/mCi ingested, there is a 3.2 rem dose to the body. While this is below the DOE dose limit for a radiation worker for an entire year, it is 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 1000 Ci/10m^3. Then the dose to the worker becomes only 40 mrem. This result is conservative compared with the estimate[31] 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.

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. Although earthquakes in this region are rare, the design will incorporate the usual 15% 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 cryogenic cooling
- 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
- Activated NEG pump in scattering chamber
- "Crash button" in counting house and Hall that shuts off beam, isolates target from beamline, opens activated NEG pump, activates ventilation system if off.

Administrative controls for safe tritium target operation

- The beam current should never exceed 25 μA.
- The overhead crane should be locked out after installing the tritium target and during tritium target operation.
- Trained tritium target operator 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.
- In the event of any target cell failure, the experiment shall be stopped and the failure mode determined before the experiment can continue with the tritium gas.

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