Tritium Target Safety Review Report – June 3, 2010 Review

A proposal E12-06-118 to study the F_2^n/F_2^p, d/u Ratios and A=3 EMC Effect in DIS off ^3H and ^3He has been conditionally approved subject to a safety review of a Conceptual Design of the proposed tritium target. To complete the initial evaluation of the proposed experiment, a Tritium Target Safety Review was held on June 3rd, 2010 at Jefferson Lab.

The committee's concerns with the presence of tritium at a DOE national laboratory were to large extent alleviated with the experience and expertise with tritium at the Idaho National Laboratory (INL). The committee was presented with information that a) tritium up to a volume of 1000 Curie could even be shipped with shipping services such as Fedex, and that b) INL as a user laboratory allowed users in their facilities containing such tritium cylinders after proper training. The collaboration presented a plan where the tritium (and other target gases) would be filled in one massive target block containing various target cells at INL, and then shipped to Jefferson Lab, where also the handling of the tritium targets there would be handled by experienced INL personnel.

In principle this plan is sound. Given that the amount of tritium planned is small when compared to other DOE Laboratories that handle tritium, and an overestimate of a worst-case scenario in a non-credible accident resulted in a "first-pass" estimate of 5 REM personnel exposure, the committee did not see a direct show stopper to operate a tritium target at a DOE national laboratory.

Nonetheless, the situation for using a tritium target in an electron beam environment presents multiple pitfalls, and a large engineering effort is needed to mitigate risks. Folded with this, the collaboration did not present a true risk assessment that combined safety consequences of a tritium target and operation in a high-current electron beam environment. A safety figure-of-merit presenting a balance of amount of tritium used and running time required for the potential experiment needs to be developed. We do note that the committee was presented with an estimate for a tritium run period of six months maximum (calendar time), with a 25 μA maximum beam current and tritium target cell of 1600 Curie total.

The committee's main worries will reflect the need to establish an engineering team and framework with a designated lead person; the need for multiple engineering measures to mitigate risk and define both active and passive control and safety systems – here we wish to add that a systematic development of the physics design, engineering, safety protocols, etc., must be undertaken. For successful operation of a tritium target an engineering approach, and not only a physicist approach, is needed to *e.g.* define cell walls and containment units; and the fact that when developing a hazard analysis it may prove impractical to assume a 1600 Curie tritium target.

Since this is only an initial tritium target safety review, with still many quantitative questions to be settled, and with the expected DOE sensitivity to a release of tritium in any form and or amount, folding in the aftermath of cleanup after a significant tritium leak in the current DOE climate, especially of reputation, we believe all text should be regarded as recommendations.

Charge Item 1. Review the conceptual design of the Tritium Target design from an operational safety point of view

The Committee strongly recommends a modular target design rather than the presented one-piece design (see also charge item 2 below). This recommended change complicates detailed comments on the design from an operational standpoint. However:

1. A secondary "sealed" containment vessel with thin windows for beam and scattered particles should be considered. The Committee strongly recommends against relying on fast valves. A secondary containment, or any type of sealing of the scattering chamber with windows, would remove the reliance on valves to protect the target.
2. The connection between the tungsten collimator and the target should be strengthened, and we strongly recommend the use of a strongback.
3. The target would not be a sealed source. For DOE regulatory purposes, sealed sources are built or used explicitly for the radiation emitted by the radioactive material. A target is not a sealed source by 10CFR835 definitions. Therefore, the material in the target is not an accountable sealed source, and would not be subject to inventory for 10CFR835 purposes, and it would not be an accountable quantity in the Nuclear Material Safeguard & Security program (with a threshold of 1 gram).
4. The risks associated with using a 1600 Curie source vs. a 1000 Curie source should be evaluated. Using a lesser amount of Tritium will allow the material to be shipped as a DOT Type A quantity, and have a moderate reduction in the consequences of an incident. This needs to be balanced against the risk of a mishap as a longer running time may be needed to collect sufficient data.
5. Make some provision such that if the H or He target fails, a failure mode determination is made and applied to the tritium target before the experiment continues with the tritium gas.
6. Establish baseline values for detectable tritium at the JLab site before the arrival of a tritium target. Having data points for tritium above MDA within the facility soils and other facility locations, is paramount to validate and track actual changes to the environment or facility after the arrival of the tritium cell, should changes occur.

Charge Item 2. Review the tritium target design as engineered and its anticipated performance characteristics.

A *systematic* development of the physics design, engineering, safety protocols, etc. must be undertaken. The collaboration is commended for putting forward a novel conceptual design that appears sound and for initiating FEA calculations to demonstrate viability in a number of beam scenarios. Nonetheless, there has been not nearly enough careful work done in such a systematic direction folding in exceptional circumstances. For example, beginning with the physics, there must be solid justification for, ultimately, the total tritium inventory, the window thicknesses, etc. The engineering and safety analyses must carefully follow established practice and protocol for safe handling of tritium. This project will therefore be significantly more expensive in personnel cost than usual projects. It was not clear to the Committee whether the DOE Tritium Handbook, and other DOE cross references for tritium, were consulted as much as possible and at all times.

The current Jefferson Lab policy considers a system a pressure system if the internal pressure exceeds 15 psi, the fluid contained is hazardous or if it is flammable. All three conditions have been met in this case and thus the Tritium cell shall be considered a pressure system. In fact all three cells shall be considered pressure systems. A JLab design authority should be assigned the overall responsibility for the design, fabrication, procurement, installation, and operation of this system. Following the guidance of the JLab EHS&Q Manual Chapter 6151 and Appendices, the cell design shall meet the following:

1. The appropriate governing code should be ASME Boiler and Pressure Vessel Code Section VIII Div 2 2007.
2. Where this code cannot be specifically applied equivalent measures shall be applied. This requires at least two JLAB design authorities to concur that the design and fabrication methods are safe. This committee suggests that in this particular case concurrence by a separate safety committee should be considered.

The cell shall be designed to provide safe operation for both normal and off-normal conditions. The off-normal conditions need not be considered to act simultaneously. The target design (cell and mounting/motion system) shall meet the following base requirements:

1. Complete containment of tritium with the exception of standard permeation through cell walls.
2. Cell shall be filled at a facility other than JLAB. Recommend STAR at INL.
3. Survive transport via ground to and from JLAB.
4. Secondary shipping container shall have environmental sampling taps to check cell integrity upon receipt.

5. Shipping loads shall be considered in the design of the cell or target stack if choosing not to have modular system.
6. At minimum the following loads must be considered at worst case temperature and pressure.
   a. Pressure
   b. Vibration from shipment (mitigated by packing)
   c. Cyclic loading due to temperature and pressure cycles (beam trips). Empirical beam trip rates should be considered. Trip rate shall be part of operational restriction.
   d. Raster off condition for time duration 3x larger than expected to trip beam by some reliable device.
   e. Seismic loading (ASCE-7 05). This is, in effect, a 5-10% load in all directions.
   f. Thermal
7. Valves with all metal wetted parts shall be used.
8. Code of record shall be ASME Boiler and Pressure Vessel Code Div 1 or 2 (most likely if using FEA).
9. Cell shall be designed to sustain full vacuum load

Heat transfer

A simple model for heat transfer to the cooling fluid should be performed. This ensures the proper amount of surface area and specifies the properties of the cooling fluid required. It is recommended that the cell be cooled with 90K N2. This lowers operating pressure and increases the normal operating tensile strength of the material. The N2 source should be the cryogenics group at JLab.

Material and Welding Requirements for Cell

Aluminum 2219 is a copper alloy and should be suitable for tritium. This shall be verified either through testing (difficult) or through literature. An authority in the field of tritium containment and metallurgy should be consulted for this. The consultation should be formalized if possible. It is understood that this alloy is suitable for hydrogen containment. Note that NASA uses this for H2 fuel storage.

The strength of the welded 2219 shall be determined. Tests of this material have been performed by and agent of JLab and have shown that the welded material has an ultimate tensile strength of 34 ksi. This is far lower than the material tables give and is consistent with testing performed by NASA.

Weld coupons (3 each) shall be made by the E-beam process at whatever facility is performing all the welds. These coupons shall be tensile tested and bend tested as required by ASME Section IX. The bend test results shall be examined but failure of a bend test should not disqualify the weld process. The tensile strength of the welded and heat affected material shall be determined from the pull tests and used in the final design calculations.

The aluminum-stainless steel transition should be purchased, not self-made, given the amount of space available in the design. It should probably not be bent, but rather elbows should be welded to it as necessary, following established protocols to prevent damage to the transition bond itself.

Cell Design

a) Weld design

The cell design must consider the weld joint geometry and weld effectiveness. Several weld samples with exact geometry shall be made and section tested for quality and weld depth. These samples must yield consistent results before WPS approval. This WPS must be subject to JLAB oversight. Cyclic pressure and temperature loading on the endcap weldment shall be considered.

b) Modular design

More consideration of a modular cell design should be given. This design would have a number of advantages.

1. Simplify the machine process.
2. Simplify alignment
3. Simplify installation and handling
4. One cell shipped in a smaller container with less consideration given to shipping loads
5. Cells can be attached to a stable heat sink/frame.
6. Motion and other systems can be checked out with tritium cell removed
7. Installation and removal procedures can be simplified with minimum exposure to workers

c) FEA model

The FEA model of the cell design is conservative. It is recommended that the analysis include a non linear model for the cell material. An elastic plastic model of the cell (i.e. ASME D2 5.2.4) should be used. This will most likely show that the cell design is conservative. The model includes temperature effects on the material properties. This should continue, however it can be simplified to hold the bulk material faces of the cell at constant temperature neglecting convection and conduction effects to the fluid. Similar cells to these at JLAB, with 0.005 in thick windows have been shown to burst above 600 psi. With these thicker walls and windows this should improve dramatically. A slight yielding of the material will allow the window to form a spherical section. The stresses in such a section are greatly reduced for equivalent loads.

d) Proof testing

Proof tests, with several samples (greater than 3), are required to substantiate the model results. The proof tests can be performed on smaller endcap weldments but at least one proof test is required for a completely fabricated cell. This requirement is additional to the code requirements.

Initially, a real cell, including all welds and valves, correct window thicknesses, etc., should be filled (at INL) with tritium, and go through a procedure of thermal cycling of windows and time exposure to tritium (e.g., the full six-month duration the tritium target is assumed to be at JLab later on), unless directly applicable data can be shown to be available from other sources. It is impossible to foresee the structural consequences of diffusion and subsequent decay of tritium, especially in weld regions where material chemistry will not be uniform.

For reference or information regarding tritium deposition and diffusion through metals a source of information is the Fusion Science and Technology journal (American Nuclear Society). July 2008 could be a good starting point. Walter Schmayda of the University of Rochester may be a good resource for this subject matter. Wayne Kanady is in possession of some information written by Schmayda and can provide it to the collaboration.

e) Other requirements

An extensive engineering review of the final cell design and test results should be performed by competent JLAB, Argonne, and outside individuals. Some of these individuals should be engineers preferably personnel from labs like Savannah River. A responsible engineer from JLAB must take the lead in ensuring that proper documentation, testing, design calculations, etc. are performed and archived in the required manner for pressure systems here at JLAB. It should be expected that this engineer will need to travel and may also need fabrication and design support from JLAB. It should also be expected that this engineer will require support from other JLAB engineers. These engineers should be formally assigned to this project in some matrixed capacity. This should be considered in any budget for this target.

f) Raster and beam steering

The failure of the raster presents the most critical loading scenario. Beam spot size should be increased if possible and reliable methods for raster detection and beam FSD interlock must be employed. A copper (or other suitable material) plug should be installed upstream of the target to protect the target from beam steering issues. These are the only realistic operational failure modes.

Charge Item 3. Review the Installation Plan including safety checkout plans both prior to installation (specifically including the transportation of the target to JLab), during installation, and after installation has been completed.

It is possible that the only possible shipping options will be either 1) an approved DOT/UN cylinder; or 2) in a uranium or other metal getter bed. This may be directly applicable to, but not solely limited to, transport of target material above the 1.1 kCi "Type A" quantity limit. If so, the target would have to be filled at JLab (either from cylinder(s) or a DU bed). At present, none of the safety or operational plans addressed this possibility, and hence this aspect of the experiment could not be sufficiently examined. Hence, the committee can not judge whether local target preparation is seen as a "non-starter", which may rule out any possibilities of a target beyond the "Type A" quantity limit at Jefferson Lab. This would have to be the topic of a renewed tritium target safety review, might this situation arise. This assessment is based upon our knowledge of the DOT shipping regulations – a shipping expert should be further consulted.

Beyond this, there needs to be a clear definition, as alluded to above, what will be the responsibility of INL, what will be the responsibility of the collaboration, and who will sign off on the safety checkout plans.

Charge Item 4. Review both the passive and active control and safety systems.

The failure analysis for various beam and target components affecting and compromising the tritium containment was begun, but a lot of work remains to define the safe operations procedures including a multitude of active and passive controls.

The collimator design seems inadequate (not thick enough). This could be resolved by complimentary stationary collimator(s) further upstream since the weight of the movable target assembly is likely an issue. This solution would have the benefit of locating sources of accidental mis-steering further upstream from the target and detectors. Given that beam mis-steering presented the largest risk to the tritium target operation, addition of an upstream long collimator system is strongly recommended.

The ANSYS FEA calculation presents static stress situation. The effect of very rapid "shockwave" effect of sudden heating on the material structure is unknown. This would be best determined by in-beam test. A number of in-beam irradiations with the purpose of studying material failure were conducted at SLAC by Dieter Walz and collaborators. Some data from these experiments may be useful. Specifically, tungsten components are known to shatter as a result of high temperature gradients induced by short beam pulses.

Beyond beam mis-steering, a fast raster failure would present the next largest risk. We recommend investigating the use of so-called blown-up beam optics, at Jefferson Lab often used for various precision Rosenbluth-separation experiments, where unrastered beam spot sizes could be reached factors of 2-3 larger than the nominal beam sizes. In addition, there should be a double protection system against possible fast raster failures.

We recommend implementing a beam shutdown system when any levels of tritium are detected in the exhaust pipes above the Hall A dome, rather than interlocking with the tritium air monitors. The latter is rather a monitoring system to increase pump speed.

Charge Item 5. Review the initial estimates provided of the impact of a catastrophic failure of the target, either during installation or operation, on the general environment and on Hall A specifically.

To first order, the site boundary dose in the event of a catastrophic failure and release does not appear prohibitive.

The approach in estimating impact of accidental rupture on a) personnel present (during installation), b) contamination of Hall A and c) public and environment is sound, taking into account the large uncertainties involved. However, at this stage it is better to refrain from any overly conservative scenarios. Auditors and the DOE site office may not always understand or appreciate this approach. Keep in mind that the design goal of 10 mrem at the site boundary was established by Jefferson Lab and DOE. The administrative limit for a radiation worker at Jefferson Lab is 1000 mrem/year.

Anticipated and worst-case scenarios for worker exposure during installation and removal should be considered and analyzed by qualified personnel, in close cooperation with the JLab Radiation Control Group. This should be reviewed by outside experts experienced with tritium handling and beam operations. Budgeting for RadCon personnel training should be considered.

Regarding release of radioactivity to the environment, the 15 m elevation of the Hall A dome should be factored in any planned height of stack. A stack on top of Hall A should be installed to lower the possible dose at the site boundary. Based on initial estimates, not much of additional height will be required. However, the stack should vent upwards (unlike the current release point) in order to take advantage of vertical momentum rise. Calculations assuming anticipated and worst-case scenarios using standard models must be performed. It should be included that the ICRP-68 dose coefficient of 1.8E-11 Sv/Bq is the reference used for the exposure evaluations. These calculations should be reviewed or performed by qualified personnel. An outside review of this should be performed.

The risk analysis should be clarified by including both severity of consequence and probability of any considered event. A good example of this approach is illustrated in tables 4.2 through 4.5 of JLab's Final Safety Analysis Document (FSAD, rev. 6). In particular, scenarios 2d, 3a and 3e may serve as an example. (a copy can be found on www/jlab.org/~vylet/ for those who cannot access docushare from the outside).

More detailed analysis of cell failure shall be considered. The addition of small vacuum break windows protecting the accelerator from tritium exposure should be used. This would allow for a secondary containment of tritium in the event of both a slow leak and catastrophic failure.

The scattering chamber vacuum pumps shall be vented to the outside through the tritium stack. Monitoring of this stack for tritium is required. Monitoring of the scattering chamber for low and high level tritium should be required. Dedicated vent pumps/fans and lines should be installed over the scattering chamber and should be utilized for installation and removal procedures.

The affects of tritium contamination in Hall A to equipment and infrastructure in the hall were not discussed in great detail. This needs to be considered in a formal analysis and reviewed by qualified personnel. Airborne radioactivity detectors interlocked with the vent/fan stack system should be used to monitor release conditions. Manual "scram" buttons should also be available in the counting house and in the hall.

A uranium getter bed should be attached to the scattering chamber in the event of a cell failure during normal operations.

Given shipping and other constraints, it seems prudent to limit the size of the target to 1 kCi. This would drop the site boundary and worker exposure doses by a significant 30%.

Charge Item 6. Review the proposed procedure to establish a firm prediction of the impacts of such a catastrophic failure.

The Hazard Risk Matrix and resulting summary of hazards and proposed mitigation needs major refinement. Following the template provided in the JLab FSAD will allow for consistent (and acceptable by JLab and DOE) use of terminology and hazard and probability designation.

For your reference, see (particle data format) pages 42-43, and 46 of:
https://jlabdoc.jlab.org/docushare/dsweb/Get/Document-21395/FSAD%20Rev6.pdf

Similarly, realistic cell failure probabilities should be estimated and folded into this hazard risk matrix. For instance, Jefferson Lab encountered one cell rapture in 15 years of operation in Halls A and C, which corresponds to about a 1% probability.