If you are using a printed copy of this procedure, and not the on-screen version, then you MUST make sure the dates at the bottom of the printed copy and the on-screen version match.
The on-screen version of the Collider-Accelerator Department Procedure is the Official Version.
Hard copies of all signed, official, C-A Operating Procedures are available by contacting the ESSHQ Procedures Coordinator, Bldg. 911A

9.1.15.a BLIP Target and Canning Record

Hand Processed Changes

HPC No.	Date	Page Nos.	Initials

Approved: _____***Signature with Date on File***_____
Collider-Accelerator Department Chairman Date

D. Beavis, S. Smith

Note 1: Uncontrolled copy printed from electronic master that is valid at time of printing. Always check that you have the latest revision of this document before use.

Note2: Leave no blanks. Indicate 'Not Applicable (N/A)', where appropriate.

Title and Preparer
Irradiation of Th foil at 200 MeV, transport to TPL and shipment to ORNL Mausner/Medvedev

Instructions	
Description	**Page No.**
1. Overview [short summary of purpose of experiment; name of principle investigator and researcher involved]	4
2. Target Material and Properties – [Provide physical properties of each component/material to be irradiated]	5-6
3. Target Canning Process – [provide images or drawings and reference the OPM procedures for closing and opening of target can]	7
4. Beam Characteristics [define required beam on target and total current required]	8
5. Proposed Experiment [Provide general description of a) how target will be supplied BLIP, b) target array in box 1 and box 2; c) thermal analysis of target material and target can d) transport of irradiated target to TPL; target opening and processing at TPL and e) disposal of waste. List persons responsible for conducting each task. If others are required to assist in the research irradiation, define level of skill of staff and contact time.]	8
a. Procedure for Irradiation of Target Material BLIP [Summarize steps for experiment including specialist and contact hours required for task]	8
b. Target Array [Define proposed target array for box 1 and box 2 including SRIM calculated entry and exit energy for each layer. Provide physical dimension of degraders, target can, materials and water gaps]	8
c. Thermal Analysis of Target Materials and Target Can [Provide full description of data provide to specialist for calculations and any assumption made on material for calculations]	8

	d. Transport and Processing at TPL [Provide full description of task involved and responsible persons and contact hours required]	8
	e. Disposal of waste. [describe waste to be generated and how it will be disposed of]	9
6.	**Activation Analysis of Target Material and Can** [Provide full list of radionuclide produced and quantities, references used for calculations, as well as decay profiles if the dose rates exceed limit for removal from BLIP hot-cell. Ensure Health Physics has reviewed data and confirms decay requirement if they are dose related. Attach analyses if any.]	10-12
	a. Radioactivity of each nuclide at end of bombardment (EOB), at 8 hours and 24 hours post EOB.	
7.	**Expected Dose Rate (e.g., R/h at 1 m)** [provide expected dose rate using *Microshield or equivalent* calculations for the combined and separate target and can irradiated. Provide expected dose rate at EOB at BLIP and expected dose rate when delivered to TPL]	14
8.	**Additional Safety Requirements** [address hazardous issues related to volatiles and or corrosive materials used and any additional equipment required for this experiment; hazardous materials information must be submitted to the C-AD ESSHQ Division Head for concurrence]	14
9.	**Special Operating Instructions and List of References or Supporting Documents**	14-16
10.	**Appendix** [provide additional support information as required]	17-45

1. Overview

This experiment is part of a five year project to develop production of Ac-225/Bi-213 radiotherapeutic pair (half life 10 d/45.6 min) by proton spallation for cancer therapy of disseminated disease such as leukemia. The project is a collaborative joint effort between BNL, LANL and ORNL. This year's irradiations are a continuation of experiments begun in FY12. They involve irradiating natural thorium metal (half life 14 billion years) in the BLIP in order to produce Ac-225. A total of eleven irradiations have already been successfully carried out on Th foil targets at Linac energies of 140, 160, 180 and 200 MeV for periods ranging from 17 hours to 9.3 days. This year's irradiations will be at 200 MeV Linac energy (~195 MeV incident on the foil) for a period of 9.3 days at beam currents less than or equal to the maximum currently available at BLIP (~115μA). Sustained intensity of >100μA is needed to meet the experimental goal of delivering 2x20mCi Ac-225 generators to hospital and university users after processing by ORNL and 15 days of decay.

These irradiations are essentially a repeat of a BLIP irradiation in June 23 to July 3, 2014, where three Th foils were also irradiated at 200 MeV for 9.3 days. As used previously, three thin Th-232 foils will be individually wrapped in very thin aluminum foil, together with a thin Al foil used to determine actual fluence on target. Thus the contents will be identical to previous irradiations. The reason for this new submission is our decision to make the capsule and needed energy degraders out of copper instead of aluminium. The major activation product of aluminium is Na-24 which emits a very high energy gamma ray of 2.7 MeV. Measurements taken last year demonstrate that over 90% of the dose outside the hot cells was due to the activation of the Al capsule and degrader, not the irradiated Th. MCNPX and Microshield calculations show that the flux and energy distribution of gamma rays from activation products in copper will reduce the dose to staff by about an order of magnitude compared to aluminium. Copper survives well in the BLIP beam, and has been used for several years as a beam stop. It is also a better thermal conductor than aluminum. The mechanical design of the target capsule with copper is identical to the aluminium capsule.

The first such irradiation is scheduled for March 20-30. Maintaining this schedule is important due to the needs of the users, who will be performing time critical experiments with animals. After irradiation the target capsule will be transported to the TPL hot cells by standard procedures. In the hot cell the capsule will be opened, the Th foils removed, sealed in screw top glass vials, and placed individually in existing Type A shipping containers as successfully used previously. They will then be shipped to ORNL for processing when the exterior radiation dose drops below 200mR/h and the DOT requirements for a Type A package are met. This is estimated to take about 7-8 days.

2. Target Material and Properties

Target Name:	*Th #12,13*	**Target & Canning No.** *Assign unique no.* (year-00x)	**CAP, CAR**

Target Material Properties (Thorium foil)				
Purity or Grade	99.5%			
Chemical Formula	Natural Thorium metal, FW=232.038			
Physical Characteristics at 70 °F or 21 °C	**Grey to black metal, odorless, tasteless, radioactive ($T_{1/2}$=1.4*10^{10} years)**			
Physical Form	**Foil**	**yes**	**Powder**	**no**
	Diameter (inches/mm)	**1.93/49**	**Pressed (Torr)**	**n/a**
Elements (%)	**99.5% Th, Al 500ppm, B 0.4, Ca 250, Cd 0.1, Cr 6, Cu 5, Fe 150, Li 0.1, Mg 10, Mn 13, Ni 5, Si 10, U 0.1, Cl 8, N 250, ppm**			
Melting Point	**1750**	**°C**		**°F**
Boiling Point	**4790**	**°C**		**°F**
Thermal Conductivity	**54 $W.m^{-1}.K^{-1}$**	**Temperature dependence**	***(if available)* n/a**	
Density	**11.7**		**g/cm^3**	
Specific Heat	**130**		**J/kg.K**	

Target Material Reactions / Properties						
Does the Target material react with any of the following?	**Aluminium**	**no**	**Air**	**no**	**CO_2**	**no**
	H_2O	**insoluble**	**Lead**	**no**	**Zinc**	**no**
	Inconel 600	**no**	**S/Steel**	**no**	**Copper**	**no**

Target Name:	*Th #12,13*	**Target & Canning No.** *Assign unique no.* (year-00x)	

Target Material Properties (Aluminum foil)				
Purity or Grade	99.99%			
Chemical Formula	Al metal, FW=26.98			
Physical Characteristics at 70 °F or 21 °C	**Grey to white metal, odorless, tasteless, shiny**			
Physical Form	**Foil**	**yes**	**Powder**	**no**
	Diameter (inches/mm)	**1.1”**	**Pressed (Torr)**	**n/a**
Elements (%)	**99.99% Al,**			

Melting Point	**660**	**^{o}C**		**^{o}F**
Boiling Point	**2467**	**^{o}C**		**^{o}F**
Thermal Conductivity	**205 W.m^{-1}.K^{-1}**	**Temperature dependence**	***(if available)* 215@125^{0}C, 250@225^{0}C**	
Density	**2.7**		**g/cm^{3}**	
Specific Heat	**910**		**J/kg.K**	

Target Material Reactions / Properties						
Does the Target material react with any of the following?	**Aluminium**	**no**	**Air**	**no**	**CO_2**	**no**
	H_2O	**insoluble**	**Lead**	**no**	**Zinc**	**no**
	Inconel 600	**no**	**S/Steel**	**no**	**Copper**	**no**

Canning Material Properties				
Chemical Formula	**Copper**			
Can Wall Thickness (inches/mm)	**Refer to drawing** D25-M-3632, 3634 attached			
Can Dimensions (inches/mm)	**Can Diameter 3.37/85.60 Can Width 0.70/17.78**			
Melting Point	**1084**	**^{o}C**	**1984**	**^{o}F**
Thermal Conductivity	**W.m^{-1}.K^{-1} 401**	**Temperature dependence**	*(if available)* **400@125^{0}C, 398@225^{0}C**	
Density	**8.967**	**g/cm^{3}**		
Specific Heat	**385**		**J/Kg K**	

3. Target Canning Process

Blueprints: Target D25-M-3633 ; Target front D25-M-3634, Target back D25-M-3632 Vacuum degrader D25-M-3631 ; Target array D25-M-3629; all attached

General considerations:

1. The cooper target consists of two parts referred to as front, normally positioned upstream and back positioned downstream that are secured together with eight Allen screws located at the periphery of the target.
2. The water-tight seal is ensured by a silver coated Inconel c-ring
3. In the center of the lower half there is a well which is designed to hold the foils/disks for irradiation
4. The material from the back of the lower half of the target is machined thinner to facilitate better target cooling
5. Packaging and sealing of the target (steps b-j below) should be carried out in a glove box in Helium atmosphere

Sequence of operations for target closing for irradiation.

a. Label the front part placing the letter stamps between the screw holes
b. Cut Th foil and monitor foil to 1.1 inch diameter circles
c. Wrap the Thorium individually foils in 0.0005" Al foil
d. Place the foils inside the well of the front part with Al monitor foil upstream
e. Position the c-ring in the groove of the front part.
f. Position the target parts together and align the indexing slits
g. Insert eight Allen screws into the holes individually and secure them in the threads.
h. Tighten the Allen screws until the slight resistance is felt in the following sequence: 12-6-9-3-11-4-1-7 o'clock
i. Tighten the Allan screws to torque 90 inch-pounds until parts come in contact in the following sequence: 12-6-9-3-11-4-1-7 o'clock
j. Provide the sealed target to CAD vacuum group for He-leak check.
k. Create a target card as per C-A-OPM-ATT 19.3.6.2.a
l. Sign off for leak check test on the target card
m. The target is now sealed for irradiation
n. Deliver target to BLIP staff

4. Beam Characteristics		
Maximum Instantaneous Current Desired	**48**	**mA**
Average Current Desired	**100-115**	**µA**
Total Integrated Current Desired	**24000**	**µA - hrs**
Maximum Proton Energy on Target Material	**195**	**MeV**

5. Experiment Description

5.a Procedure for irradiation of target material in BLIP:

BLIP staff shall install and remove target and degraders in BLIP, as per CAD OPM 19.4.5.2. Irradiatoins are planned for ~9.3 days. After EOB let target decay in place for 2 hours before raising the array into the hot cell. Disassemble array and move degraders to storage. Place Th target into secondary containment.

5.b Target array in Box 1 (upstream) and Box 2 (downstream):

Th target and degraders in Box 1, cGMP approved RbCl array in Box 2 with 0.220 inch Cu beamstop

See **Appendix 1** for details of energy loss in these arrays..

5.c Thermal analysis of target material and target can (attach analyses if any):

See Appendix 2.

5.d Transport of irradiated target to TPL, target opening and processing:

Following irradiation the target capsule will be transported to the TPL hot cells by BLIP staff as per CAD OPM 19.4.5.3. In the hot cell the bolts will be removed, the capsule opened, the Th foils removed, sealed in screw top glass vials. After an estimated 7 additional days of decay the vials will be placed individually in existing Type A shipping containers by TPL staff. Dose measurements at cask exterior will be measured. Store containers in storage vault until the exterior contact dose is <200mR/h. At that point alert Hazardous Material Transportation group for survey and preparation of DOT paperwork. The container will then be transported to BNL loading dock for FedEx pick up by early afternoon and shipped to ORNL for processing.

Aluminum monitor (d×h=2×0.005 inch) foil will be dissolved in acid by research staff. The resulting solution will be assayed for Na-22 and the effective proton fluence calculated by research staff.

5.e Disposal of waste:

The Al acid solution from the monitor foil will be neutralised and disposed through D-tank system by research staff as per CAD OPM 19.2.22. Al target body will be disposed with other target bodies as solid non compactable waste as per CAD OPM 19.3.5.6 & 19.3.5.7.

6. Activation Analysis of Target Material and Can

Nuclides and activities produced in the Th foils and Copper degrader are shown in Appendix 4 at EOB and for several decay periods post irradiation:

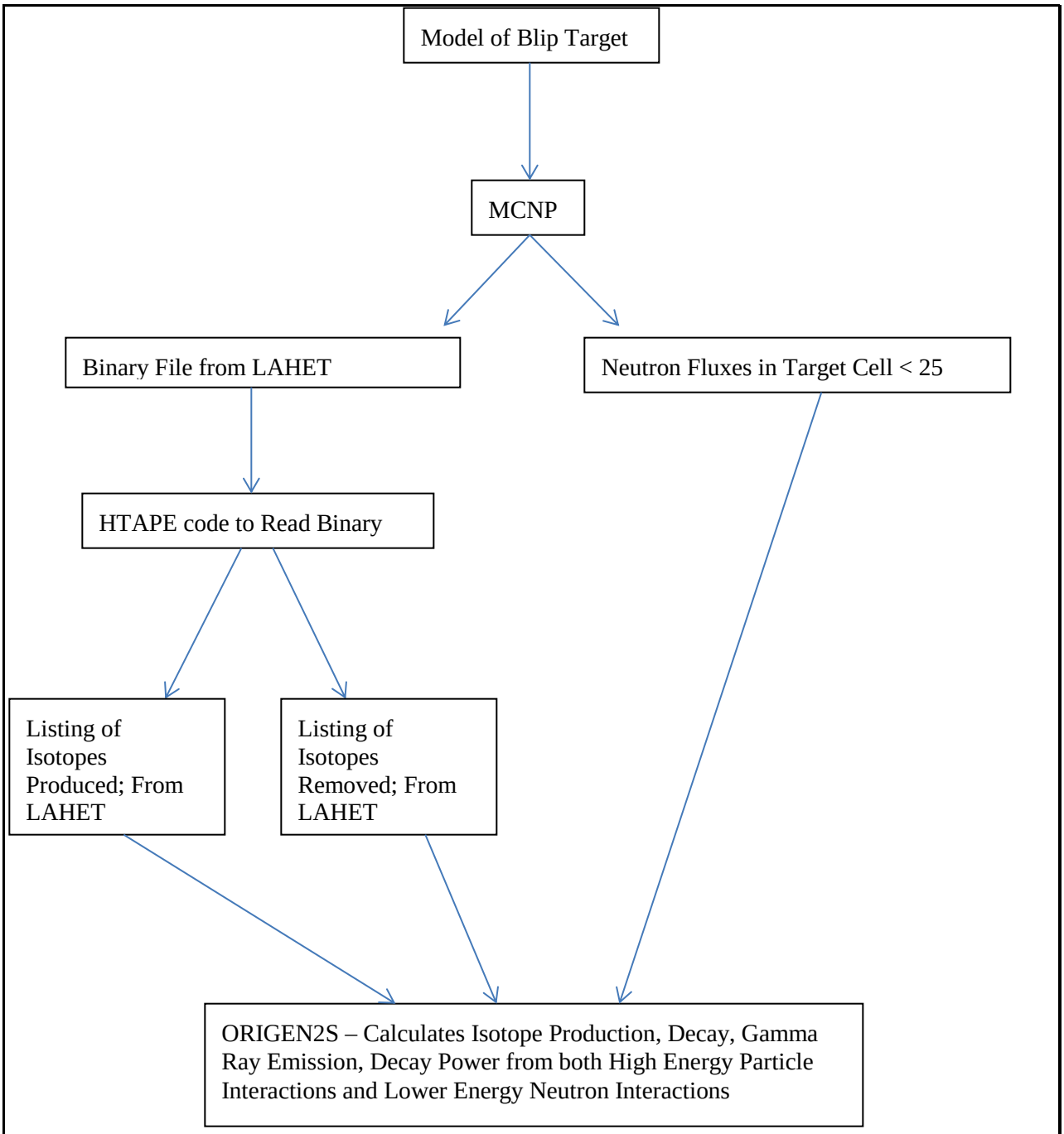
Activation of Th foil and copper was calculated using MCNPX/ORIGEN code for this irradiation at EOB and 24 h after was carried out by Albert Hanson (Nuclear Science and Technology Department of BNL). The methodology is described below.

Calculation of Proton Induced Nuclear Reactions
in ^{232}Th for the production of ^{225}Ac in BLIP

The calculation of proton induced nuclear reactions in ^{232}Th for the production of ^{225}Ac uses a suite of computer programs that consists of MCNPX2.7, HTAPE3X, and ORIGEN2S. A flow chart of the series of computations is shown in Figure 1. One starts modeling the target array which includes the targets, target holders, water gaps, windows, beam degraders and water in the BLIP facility. The target array modeled is as provided by BLIP. The water bath is modeled as a 40 cm diameter cylinder the length of the target assembly with the array of targets submersed in the water. Hence any neutron production in the targets will result in some level of thermal neutrons in the system, which can cause activation. Those interactions are included in one of the calculations and contribute to the output.

In order to understand the series of calculations one should know that the code MCNPX was the merger of two previous Monte Carlo based radiation transport codes, MCNP and LAHET. MCNP was developed by the X Division of LANL and was primarily designed for the transport of neutrons and photons through complex geometries. It is commonly used for neutronic calculations in nuclear reactors. LAHET was the Los Alamos version of the High Energy Transport computer code which modeled the interactions of high energy protons with targets. Upon merger into the code MCNPX, the capabilities were expanded to also include the transport and sourcing of other particles that could be created in high energy interactions. Hence when running MCNPX for a system like BLIP, following the flow chart of Figure 1, the particles and isotopes that are generated by the high energy interactions are sequentially written to a binary file. MCNP simultaneously calculates the fluxes of neutrons in each cell that are below 25 MeV and a subsequent computer program, HTAPE3X, is used to read and interpret the data that is written to the binary file. The outputs of this program are files that contain information about the isotopes generated by the proton interactions along with the isotopes that are removed due to the interactions. A third program, ORIGEN2S, tabulates all of the isotopes generated by the protons reactions, calculates the isotopes generated by the < 25 MeV neutron reactions. It produces a file which contains the masses, activities, decay power and gamma ray emission for each isotope it calculates. The calculations are for the end of beam and any user specified decay time.

The input file for MCNPX includes the materials in the system, the geometry of the system, the size, shape, direction and energy of the proton beam. The input file for ORIGEN2S includes the mass of the target material, in each cell analyzed, the beam proton beam current, the irradiation time and the decay times.



See Appendix 4 for the radioisotope listing.

7. Expected Dose Rate

FY 2014 experiments: the dose rates from irradiated target **were measured experimentally** from the 9.3d 200 MeV irradiation of 3 Th foils at EOB in July 2014 for the following situation:

Target material: three foils each d×h=1.11 ×0.005 inch Th foil wrapped in Al, sealed in an Al can of the same design.

Irradiation: 9.3d at 200 MeV, total accumulated charge 24,348 µA-h

Dose measurements at BLIP were done as follows:

- Al clad Th target with Al degraders measured at operator location outside hot cell (~2ft from wall) = 50mR/h 2.25h post EOB
- Al clad Th target placed at contact with interior and measured at contact with exterior of closed BLIP port hole = 200mR/h 2.25 h post EOB
- Al clad Th target measured at 6'from exterior of closed BLIP port hole = 60mR/h 2.25h post EOB
- Al capsule with Th target at TPL at 6 feet of air = 6R/h 3.5h post EOB
- Al capsule with Th target placed 2 ft. inside TPL hot box 6 = **18mR/h** @contact with exterior wall, **11mR/h** @contact with exterior Pb glass window at 5.5h post EOB
- Th foils (3) only placed 2 ft. inside TPL hot box 6 = **1.8mR/h** @contact with exterior wall, **0.7mR/h** @contact with exterior Pb glass window at 5.75h post EOB.
- Th foils (3) at 6 feet of air = 1.2R/h 6h post EOB

Comparison of the dose outside hot box 6 for the intact Al capsule with Th foils vs. the Th foils alone, indicates that the Al cladding causes 90% of the dose. This is due to the significant amount of induced Na-24 in the aluminium and the resultant 2.7 MeV emitted photons.

FY 2015 experiments: The proposed irradiation will use the same size and mass of Th foils. The total accumulated charge is requested to be ~24500 µA-h, the same as the 2014 irradiation. The difference is the replacement of the Al capsule and degrader with capsule and degrader fabricated from copper. Calculations of activation of the Al degrader and Cu degrader used MCNPX. The output was then organized into photons/sec by gamma ray energy bins. Calculations comparing dose rates at the exterior of the BLIP hot cell of Al clad targets to Cu clad targets were carried out using Microshield 7.02 software using the gamma ray intensity tables. The MicroShield output is provided in **Appendix 3.** The predicted dose rate at the operator location at exterior BLIP hot cell wall for Cu degrader 2h post EOB, when the target array will first be brought into the hot cell, is **19mR/h compared to 227mR/h** for the Al degrader. This order of magnitude reduction in exposure is the motivation to switch from Al to Cu for the cladding and degrader. Copper tolerates underwater long term irradiation well, as evidenced by the use of copper for the existing BLIP target array beam stop without any sign of damage. The dose due to the Th foils alone is expected to be the same as from the similar irradiation in 2014, as listed above.

Estimated personnel doses: Evers 1mR, Nalepa 3mR, Kurczak 5mR, Medvedev1mR, Conley 5mR.

8. Additional Safety Requirements

Gas tight secondary containment of Th target will be used for transport between BLIP and TPL.

See Appendix 4 for complete activation list

Decay Requirements

See section 9 for detailed time line. The target will be left to decay in place for 2 hours after EOB. It will be moved to TPL about 2 hours later. Final shipping is estimated to require 7-8 days of decay. Al monitor foil will be allowed to decay at TPL hot cell for 7-8 days (12 half-lives) before dissolution.

9. Special Operating Instructions

Detailed experiment timing:

Beam off ~08:30. Date to be determined.

Commence pulsing RF for Linac tanks 6-9 for warm up WITHOUT beam at Linac staff discretion 09:00-~13:00

Load 200 MeV dummy arrays in box 1&2 13:00-13:15

Commence tuning with 200 MeV beam. Measure beam position and spot shape with plastic foils and harp to achieve centered, roughly circular spot ~13:15-14:15

Remove dummy arrays and load Th array in box 1 and RbCl array in box 2; ~14:15-14:30

Commence irradiation at 200 MeV and 100-115μA; ~14:30-15:00

Cease irradiation 10 days later at 07:00. Leave targets in place for 2 hours.

Remove Th target array into hot cell; 09:00

Measure radiation dose at various operator locations for entire array and record;09:00

Store degraders and measure dose at operator location for Th capsule alone; ~09:10

Measure dose for Th capsule alone at 6 feet in air and record;~09:15

Reload standard RbCl array in target holder one and retune for 117 MeV operation at BLIP & Linac discretion.

Transport Th target capsule to Target Processing Lab ~10:00-10:30

In TPL measure radiation dose at 6 feet in air of entire capsule and record; ~11:00

Move intact capsule to hot box 6 with capsule ~ 2' from interior wall and measure dose on contact with exterior wall of hot box 6 and at operator location . Record dose and transfer capsule back to main hot cell. ~11:15

Open capsule in main hot cell, move Th foil to port hole, and measure radiation dose 6 feet away and record; ~11:15-12:15.

Bend the foils and put each separately into glass vials and cap. ~12:30.

Transfer glass vials through receiving hot cell port hole into hot box 6 at ~2' from inside wall. ~13:30

Measure dose on contact with exterior wall of hot box 6 and at operator location .Record. ~13:35

Transfer vials back to main hot cell and store 7 days.

On 7th day transfer vials though the hot boxes and out through hot box 1 into separate ORNL drums; ~13:00

Measure dose on contact with drum exteriors and record. ~13:15

Transfer drums into storage vault; ~13:30. Store.

Next day remove drums and measure dose on contact with drum exterior and record. 09:00

If dose is <200mR/h, finish shipping paper work and transfer to Hazardous Material Transport Group. Alert ORNL staff that package is to be shipped by FedEX Heavy Air.

If dose is >200mR/h move drum back to storage vault.

Next day measure dose on contact with drum exterior and record ~09:00

If dose is <200mR/h, finish shipping paper work and transfer to Hazardous Material Transport Group. Alert ORNL staff that package is to be shipped.

Supporting Documentation	
References	
OPMs	19.2.22, 19.3.5.6, 19.3.5.7, 19.4.5.2, 19.4.5.3.
Drawings	D25-M-3629, 3631,3632,3633,3634

Appendix 1

Table 1. Proton Energy Profile for Th target in Cu Array at 200 MeV: RbCl in downstream box

199.05 MeV Thorium 3-1.1inch diameter foils irradiation: target array Calculated Entry and Exit Proton Energies provided by D. Medvedev, verified by P. Pile							
Layer number	Layer	Material	density	inches	mm	Ei	Eout
1	Be window	Beryllium	1.85	0.0120	0.3048	199.05	198.84
2	AlBeMet window	AlBeMet	2.10	0.0120	0.3048	198.84	198.61
3	Beamline window	stainless steel	8.00	0.0310	0.7874	198.61	196.62
4	water gap	water	1.00	0.1060	2.6924	196.60	195.49
5	1st box upstream window	stainless steel	8.00	0.0200	0.5080	195.36	194.19
6	water gap	water	1.00	0.1000	2.5400	194.05	193.01
7	Th can window	Cu	8.96	0.0200	0.5080	193.01	191.57
8	Al monitor foil	Al 99% pure	2.70	0.0050	0.1270	191.57	191.44
9	Aluminum wrap 1a	Al	2.70	0.0005	0.0127	191.44	191.43
10	Th foil 1	Th	11.70	0.0049	0.1245	191.43	191.09
11	Aluminum wrap 1b	Al	2.70	0.0005	0.0127	191.09	191.08
12	Aluminum wrap 2a	Al	2.70	0.0005	0.0127	191.08	191.07
13	Th foil 2	Th	11.70	0.0049	0.1245	191.07	190.73
14	Aluminum wrap 2b	Al	2.70	0.0005	0.0127	190.73	190.72
15	Aluminum wrap 3a	Al	2.70	0.0005	0.0127	190.72	190.71
16	Th foil 3	Th	11.70	0.0049	0.1245	190.71	190.37
17	Aluminum wrap 3b	Al	2.70	0.0005	0.0127	190.37	190.36
18	Copper back plate	Cu	8.96	0.154	3.9174	190.36	178.93
19	Water in target well	water	1.00	0.298	7.5692	178.93	175.21
20	Cooling channel	water	1.00	0.100	2.5400	175.21	173.94
21	Copper degrader (vacuum box)	Cu	8.96	0.303	7.6995	173.94	144.81
22		vacuum	0.00	0.214	5.4304		
23		Cu	8.96	0.303	7.6995	144.81	122.48
24	water gap	water	1.00	0.341	8.6650	122.48	116.89
25	Front box back window	stainless steel	8.00	0.020	0.5080	116.89	115.06
26	water gap between boxes	water	1.00	0.150	3.8100	115.06	112.16
27	Back box front window	stainless steel	8.00	0.020	0.5080	112.16	110.25
28	cooling channel	water	1.00	0.200	5.0800	110.25	106.79
29	vacuum box	stainless	8.00	0.029	0.7370	106.79	104.02

		steel					
30		vacuum	0.00	0.596	15.1400		
31		stainless steel	8.00	0.029	0.7370	104.02	100.99
32	cooling channel	water	8.00	0.200	5.0800	100.99	97.28
33	can window	inconel	8.43	0.012	0.3048	97.28	95.97
34	RbCl salt	RbCl	2.38	0.645	16.3800	95.97	74.77
35	can window	inconel	8.43	0.012	0.3048	74.77	73.18
36	cooling channel	water	1.00	0.200	5.0800	73.18	68.40
37	can window	inconel	8.43	0.012	0.3048	68.40	66.69
38	RbCl salt	RbCl	2.38	0.500	12.7000	66.69	44.02
39	can window	inconel	8.43	0.012	0.305	44.02	41.62
40	cooling channel	water	1.00	0.200	5.080	41.62	33.87
41	Cu block	Cu	8.92	0.220	5.590	33.87	stop
42	cooling channel	water	1.00	0.200	5.080	0.00	0.00

Appendix 2

Thermal analysis of Th target and degrader

Thorium Target, Bolted Cu Holder Thermal Analysis

Chris Cullen

February 18, 2015

Conditions

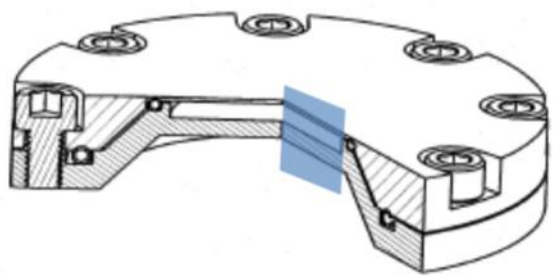
- Instantaneous Current = 40.0 mA
- Steady state average current = 113 µA
- Pulse width = .000425 sec
- Pulse Frequency = 6.667 Hz
- 200 MeV
- 1591 Watts
- 2 targets, (3) .10” water gaps
- Gaussian Beam Distribution
  - FWHM=16 mm
  - FWTM=42 mm

Finite Element Model

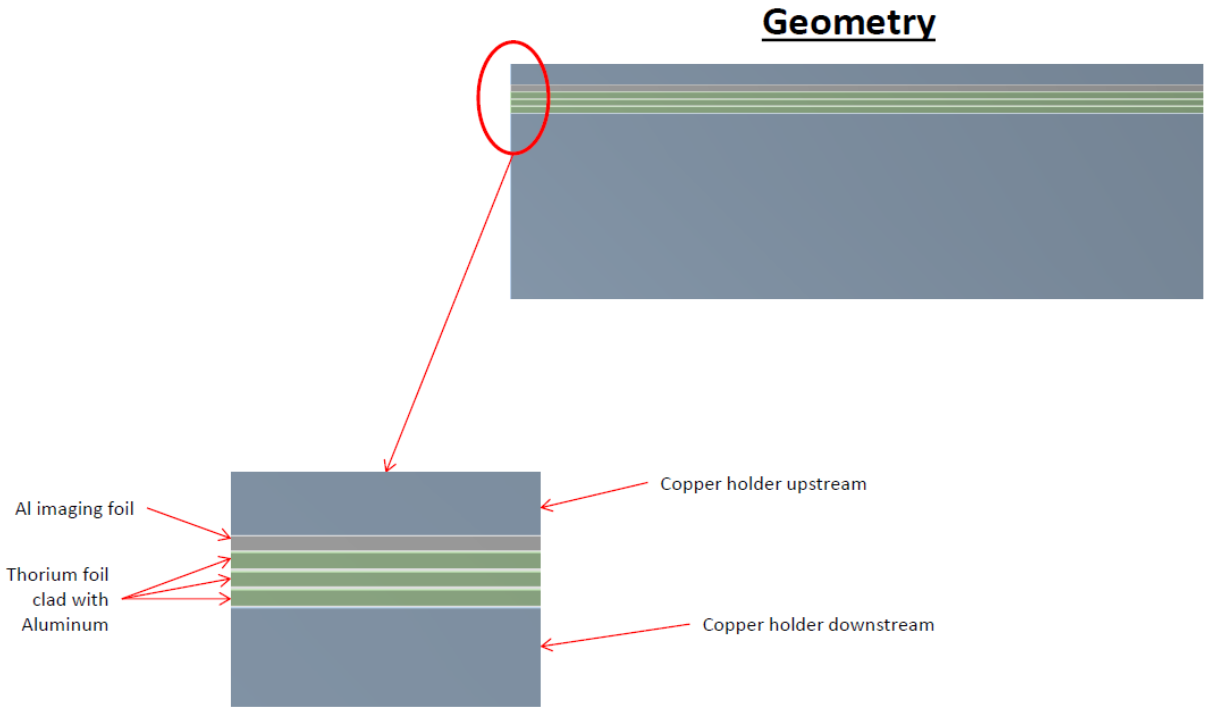
- 2D Axi-symmetric model
- Copper target holder
- (3) x .005” thick Thorium foil
- (1) .0005” Aluminum foil on *each face* of Thorium foil (6 total)
- (1) x .005” Aluminum imaging foil
- Steady-state analysis
- Thermal contact conductance between each layer=2,200 $W/m^2*°C$
- Steady state water cooling on upstream exterior=24,380 $W/m^2*°C$
- Steady state water cooling on upstream exterior=10,000 $W/m^2*°C$
- Gaussian Internal heat generation for all bodies

Generic Target

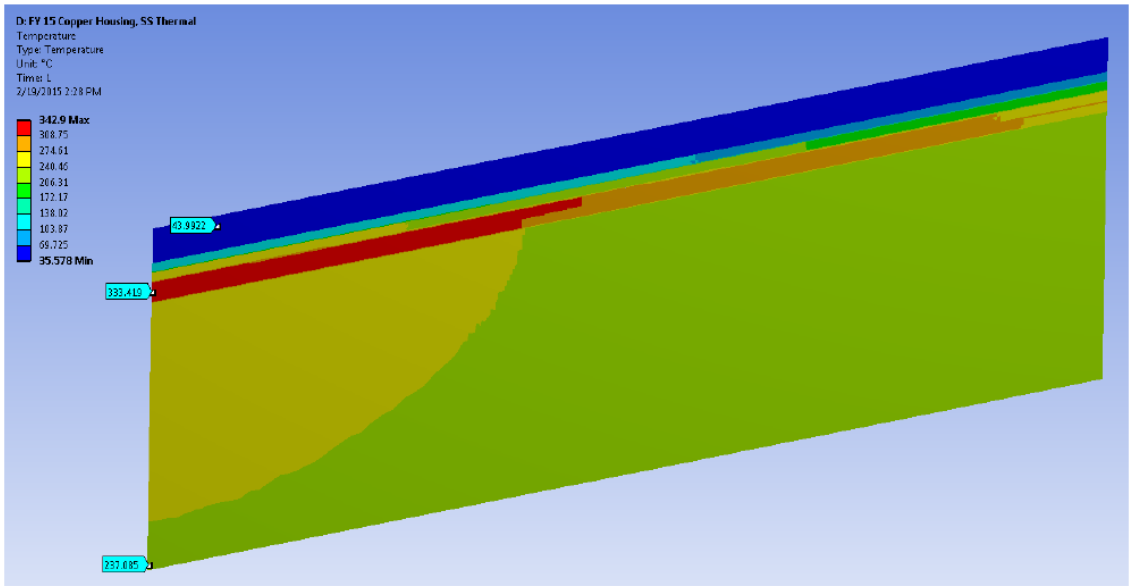
- Axi-symmetric analysis region highlighted in blue
  - Ref. D25-M-3633



Finite Element Model



Target Temperature Profile



Summary & Conclusion

- Maximum Aluminum temperature = 337 °C
- Aluminum melting temperature = 660 °C
- SAFE
- Maximum Thorium temperature = 343 °C
- Thorium melting temperature = 1755 °C
- SAFE
- Maximum Copper temperature = 249 °C
- Copper melting temperature = 1085 °C
- SAFE

<u>Additional contribution to target heating from fission of Th-232:</u> The Th target thickness is 0.15g/cm^2, proton fission cross section at 200 MeV is 1.1b (St. Laurent et al Nucl. Phys. A422, 307-326, 1984), proton flux 100μA, 200 MeV released per fission = 7.5 watts deposited. This is negligible compared to the direct proton heating.

Appendix 3

Comparison of the calculated dose rates for 200 **MeV 9.25d** irradiation of three d×h=1.1×0.005" Th foils and copper degrader

Contents

Table 3.1 Example report for the calculation of the dose rate from the Th foil only to the BLIP operator station based on data in the Table A4.1.

Table 3.2 Example of the report for the calculation of the dose rate from the Cu degrader only at operator location of the BLIP hot cell based on activation data in the Table A4.3. Dose from Th foils not included.

Table 3.3 Example of the report for the calculation of the dose rate from the Al degrader only at operator location of the BLIP hot cell based on activation data in the Table A4.4. Dose from Th foils not included.

Calculation methodology:

1) The dose rate to the operator at BLIP from Box 1 is comprised of the dose rate from:
   - Th target can (copper)
   - Th foil
   - Copper degraders positioned behind the Thorium can
2) Activation of Th foil is calculated using MCNPX-ORIGEN code in Appendix 4, Table A.4.1&4.2 Activation data for the copper degrader is shown in Appendix 4, Table 4.3. The data for the dose calculation is provided in a form of gamma energy bins (Table 3)
3) Dose rate calculation carried out in Microshield 7.02 (Grove Engineering)
4) Dose calculation at BLIP assumes the following geometry:
   - Wall thickness: 0.5 inch SS/6 inches Pb/0.5 inch SS
   - Source point –inside the hot cell, 12 inches away from the interior wall
   - Dose point – outside the hot cell at 12 inches. Report is attached

Conclusions:

1) Estimation of the dose rates to the operator station at BLIP (using Microshield 7.02) due to copper degrader is much less than due to the previously used aluminum degrader.

Table 3.1 Example report for the calculation of the dose rate from the Th foil only to the BLIP operator station based on data in the Table A4.1

MicroShield 7.02

BNL (7.02-0000)

Date	By	Checked	
Filename	**Run Date**	**Run Time**	**Duration**
180 MeV BLIP_foil_2h.ms7	June 2, 2014	9:37:19 AM	00:00:00

Project Info	
Case Title	Th foil 2 h blip
Description	180 MeV from Th foil 2h at BLIP to operator_lead
Geometry	8 - Cylinder Volume - End Shields

Source Dimensions	
Height	0.013 cm (0.0 in)
Radius	2.794 cm (1.1 in)

Dose Points			
A	**X**	**Y**	**Z**
#1	0.0 cm (0.0 in)	80.01 cm (2 ft 7.5 in)	0.0 cm (0.0 in)

Shields			
Shield N	**Dimension**	**Material**	**Density**
Source	.019 in³	Thorium	11.7
Shield 1	12.0 in	Air	0.00122
Shield 2	.5 in	Iron	8
Shield 3	6.0 in	Lead	11.34
Shield 4	.5 in	Iron	8
Air Gap	12	Air	0.00122

Source Input: Grouping Method - User Defined Energies				
Group #	**Energy (MeV)**	**Activity (Photons/sec)**	**Volume Source Photons/sec/cm³**	**% Energy Activity**
1	0.005	1.1900e+009	3.8207e+009	0.018%

2	0.02	9.4800e+009	3.0437e+010	0.587%
3	0.045	1.5200e+009	4.8802e+009	0.212%
4	0.08	2.7300e+009	8.7651e+009	0.676%
5	0.15	5.3800e+009	1.7273e+010	2.498%
6	0.25	4.4600e+009	1.4320e+010	3.452%
7	0.4	6.0500e+009	1.9424e+010	7.491%
8	0.5125	1.7900e+009	5.7471e+009	2.840%
9	0.638	9.9500e+009	3.1946e+010	19.651%
10	0.875	7.3000e+009	2.3438e+010	19.773%
11	1.165	3.6200e+009	1.1623e+010	13.055%
12	1.495	2.6700e+009	8.5724e+009	12.356%
13	1.83	1.0200e+009	3.2749e+009	5.778%
14	2.25	1.0900e+009	3.4996e+009	7.592%
15	2.75	3.6300e+008	1.1655e+009	3.090%
16	3.5	8.2000e+007	2.6327e+008	0.888%
17	4.5	3.0800e+006	9.8888e+006	0.043%
18	5.5	5.1500e+003	1.6535e+004	0.000%
19	6.5	4.4700e+000	1.4352e+001	0.000%

Buildup: The material reference is Shield 3
Integration Parameters

Radial	20
Circumferential	10
Y Direction (axial)	10

Results

Energy (MeV)	Activity (Photons/sec)	Fluence Rate MeV/cm²/sec No Buildup	Fluence Rate MeV/cm²/sec With Buildup	Exposure Rate mR/hr No Buildup	Exposure Rate mR/hr With Buildup
0.005	1.190e+09	0.000e+00	6.475e-25	0.000e+00	3.968e-25
0.02	9.480e+09	0.000e+00	2.063e-23	0.000e+00	7.147e-25
0.045	1.520e+09	0.000e+00	7.975e-24	0.000e+00	2.652e-26
0.08	2.730e+09	1.528e-162	3.042e-23	2.419e-165	4.814e-26
0.15	5.380e+09	1.212e-142	2.737e-21	1.996e-145	4.507e-24

0.25	4.460e+09	1.065e-39	1.971e-22	1.965e-42	3.636e-25
0.4	6.050e+09	2.226e-13	5.444e-13	4.337e-16	1.061e-15
0.5125	1.790e+09	2.308e-08	6.902e-08	4.530e-11	1.355e-10
0.638	9.950e+09	1.109e-04	3.690e-04	2.156e-07	7.174e-07
0.875	7.300e+09	3.297e-02	1.290e-01	6.200e-05	2.426e-04
1.165	3.620e+09	5.031e-01	2.147e+00	9.004e-04	3.842e-03
1.495	2.670e+09	2.659e+00	1.170e+01	4.478e-03	1.971e-02
1.83	1.020e+09	2.917e+00	1.302e+01	4.635e-03	2.069e-02
2.25	1.090e+09	6.682e+00	3.004e+01	9.952e-03	4.474e-02
2.75	3.630e+08	3.800e+00	1.693e+01	5.302e-03	2.363e-02
3.5	8.200e+07	1.314e+00	5.652e+00	1.698e-03	7.303e-03
4.5	3.080e+06	6.179e-02	2.716e-01	7.340e-05	3.226e-04
5.5	5.150e+03	1.077e-04	5.098e-04	1.199e-07	5.675e-07
6.5	4.470e+00	8.896e-08	4.808e-07	9.447e-11	5.106e-10
Totals	**5.870e+10**	**1.797e+01**	**7.990e+01**	**2.710e-02**	**1.205e-01**

Table 3.2 Example of the report for the calculation of the dose rate from the Cu degrader only at operator location at the BLIP hot cell based on activation Data in the Table A4.3. Dose from Th foils not included.

MicroShield 7.02
BNL (7.02-0000)

Date	By	Checked

Filename	Run Date	Run Time	Duration
Cu_deg_2h_EOB_BLIP.ms7	January 30, 2015	10:45:08 AM	00:00:01

Project Info	
Case Title	Cu degrader_2h_BLIP
Description	Dose rate from Cu degrader 200 MeV BLIP 2h after EOB
Geometry	13 - Rectangular Volume

Source Dimensions	
Length	1.839 cm (0.7 in)
Width	7.62 cm (3.0 in)
Height	7.62 cm (3.0 in)

Dose Points			
A	X	Y	Z
#1	78.74 cm (2 ft 7.0 in)	0.0 cm (0.0 in)	0.0 cm (0.0 in)

Shields			
Shield N	Dimension	Material	Density
Source	6.516 in³	Copper	8.96
Shield 1	12.0 in	Air	0.00122
Shield 2	.5 in	Iron	8
Shield 3	5.0 in	Lead	11.34
Shield 4	.5 in	Iron	8
Air Gap		Air	0.00122

Source Input: Grouping Method - User Defined Energies				
Group #	Energy (MeV)	Activity (Photons/sec)	Volume Source	% Energy Activity

			Photons/sec/cm³	
1	0.005	6.7400e+011	6.3122e+009	0.084%
2	0.02	2.9500e+009	2.7627e+007	0.001%
3	0.045	4.7900e+010	4.4859e+008	0.053%
4	0.08	1.2500e+011	1.1707e+009	0.248%
5	0.15	1.9400e+011	1.8169e+009	0.721%
6	0.25	1.9400e+011	1.8169e+009	1.202%
7	0.4	5.4000e+010	5.0572e+008	0.535%
8	0.513	3.1400e+012	2.9407e+010	39.914%
9	0.638	6.8700e+011	6.4339e+009	10.861%
10	0.875	8.1600e+011	7.6420e+009	17.692%
11	1.17	1.3700e+011	1.2830e+009	3.972%
12	1.5	5.6400e+011	5.2820e+009	20.963%
13	1.83	4.1300e+010	3.8678e+008	1.873%
14	2.25	1.3800e+010	1.2924e+008	0.769%
15	2.75	7.8900e+009	7.3892e+007	0.538%
16	3.5	6.4600e+009	6.0499e+007	0.560%
17	4.5	1.3600e+008	1.2737e+006	0.015%
18	5.5	2.2000e+005	2.0603e+003	0.000%
19	6.5	7.2700e-003	6.8085e-005	0.000%
20	7.5	8.7900e-006	8.2320e-008	0.000%

Buildup: The material reference is Shield 3 Integration Parameters	
X Direction	10
Y Direction	20
Z Direction	20

Results					
Energy (MeV)	Activity (Photons/sec)	Fluence Rate MeV/cm²/sec No Buildup	Fluence Rate MeV/cm²/sec With Buildup	Exposure Rate mR/hr No Buildup	Exposure Rate mR/hr With Buildup
0.005	6.740e+11	0.000e+00	3.854e-22	0.000e+00	2.361e-22
0.02	2.950e+09	0.000e+00	6.747e-24	0.000e+00	2.337e-25

0.045	4.790e+10	0.000e+00	2.641e-22	0.000e+00	8.783e-25
0.08	1.250e+11	1.929e-135	1.464e-21	3.053e-138	2.316e-24
0.15	1.940e+11	8.752e-118	1.037e-19	1.441e-120	1.708e-22
0.25	1.940e+11	1.801e-31	9.007e-21	3.323e-34	1.662e-23
0.4	5.400e+10	5.241e-10	1.237e-09	1.021e-12	2.410e-12
0.513	3.140e+12	1.551e-03	4.418e-03	3.043e-06	8.670e-06
0.638	6.870e+11	1.047e-01	3.298e-01	2.035e-04	6.411e-04
0.875	8.160e+11	2.191e+01	8.009e+01	4.121e-02	1.506e-01
1.17	1.370e+11	7.631e+01	3.003e+02	1.365e-01	5.369e-01
1.5	5.640e+11	1.782e+03	7.149e+03	2.998e+00	1.203e+01
1.83	4.130e+10	3.346e+02	1.353e+03	5.318e-01	2.150e+00
2.25	1.380e+10	2.276e+02	9.211e+02	3.391e-01	1.372e+00
2.75	7.890e+09	2.172e+02	8.649e+02	3.031e-01	1.207e+00
3.5	6.460e+09	2.721e+02	1.036e+03	3.516e-01	1.339e+00
4.5	1.360e+08	7.367e+00	2.829e+01	8.751e-03	3.360e-02
5.5	2.200e+05	1.290e-02	5.250e-02	1.436e-05	5.845e-05
6.5	7.270e-03	4.228e-10	1.924e-09	4.489e-13	2.043e-12
7.5	8.790e-06	4.820e-13	2.630e-12	4.925e-16	2.688e-15
Totals	**6.705e+12**	**2.939e+03**	**1.173e+04**	**4.710e+00**	**1.882e+01**

Table 3.3 Example of the report for the calculation of the dose rate from the Al degrader only at operator location at the BLIP hot cell based on activation Data in the Table A4.4. Dose from Th foils not included.

MicroShield 7.02 BNL (7.02-0000)		
Date	**By**	**Checked**

Filename	Run Date	Run Time	Duration
Case1	October 30, 2014	10:32:01 AM	00:00:01

Project Info	
Case Title	Al degraders_2h_BLIP
Description	Dose rate from Al degraders 200 MeV BLIP 2h after EOB
Geometry	13 - Rectangular Volume

Source Dimensions	
Length	5.309 cm (2.1 in)
Width	7.62 cm (3.0 in)
Height	7.62 cm (3.0 in)

Dose Points			
A	X	Y	Z
#1	81.28 cm (2 ft 8.0 in)	0.0 cm (0.0 in)	0.0 cm (0.0 in)

Shields			
Shield N	Dimension	Material	Density
Source	18.81 in³	Aluminum	2.7
Shield 1	12.0 in	Air	0.00122
Shield 2	.5 in	Iron	8
Shield 3	5.0 in	Lead	11.34
Shield 4	.5 in	Iron	8
Air Gap		Air	0.00122

Source Input: Grouping Method - User Defined Energies				
Group #	Energy (MeV)	Activity (Photons/sec)	Volume Source Photons/sec/cm³	% Energy Activity

1	0.005	4.1400e+009	1.3431e+007	0.000%
2	0.02	2.2400e+006	7.2670e+003	0.000%
3	0.045	3.1900e+008	1.0349e+006	0.000%
4	0.08	6.4600e+008	2.0958e+006	0.001%
5	0.15	2.1000e+009	6.8129e+006	0.005%
6	0.25	4.7900e+008	1.5540e+006	0.002%
7	0.4	1.1600e+009	3.7633e+006	0.008%
8	0.513	5.7000e+011	1.8492e+009	5.044%
9	0.638	6.8000e+009	2.2061e+007	0.075%
10	0.875	1.4600e+010	4.7366e+007	0.220%
11	1.17	2.4300e+010	7.8835e+007	0.490%
12	1.5	1.2900e+012	4.1850e+009	33.376%
13	1.83	3.9600e+008	1.2847e+006	0.012%
14	2.25	2.1400e+008	6.9426e+005	0.008%
15	2.75	1.2800e+012	4.1526e+009	60.716%
16	3.5	6.7500e+008	2.1898e+006	0.041%
17	4.5	1.0500e+006	3.4064e+003	0.000%
18	5.5	1.7100e+003	5.5476e+000	0.000%
19	6.5	7.2700e-003	2.3585e-005	0.000%
20	7.5	2.5600e-004	8.3052e-007	0.000%

Buildup: The material reference is Shield 3 Integration Parameters	
X Direction	10
Y Direction	20
Z Direction	20

Results					
Energy (MeV)	**Activity (Photons/sec)**	**Fluence Rate MeV/cm²/sec No Buildup**	**Fluence Rate MeV/cm²/sec With Buildup**	**Exposure Rate mR/hr No Buildup**	**Exposure Rate mR/hr With Buildup**
0.005	4.140e+09	0.000e+00	2.321e-24	0.000e+00	1.423e-24
0.02	2.240e+06	0.000e+00	5.024e-27	0.000e+00	1.740e-28
0.045	3.190e+08	0.000e+00	1.725e-24	0.000e+00	5.736e-27

0.08	6.460e+08	4.020e-137	7.418e-24	6.362e-140	1.174e-26
0.15	2.100e+09	1.471e-119	1.101e-21	2.422e-122	1.813e-24
0.25	4.790e+08	5.132e-34	2.181e-23	9.468e-37	4.024e-26
0.4	1.160e+09	1.200e-11	2.831e-11	2.338e-14	5.517e-14
0.513	5.700e+11	2.949e-04	8.395e-04	5.788e-07	1.648e-06
0.638	6.800e+09	1.075e-03	3.383e-03	2.090e-06	6.577e-06
0.875	1.460e+10	4.028e-01	1.470e+00	7.576e-04	2.764e-03
1.17	2.430e+10	1.382e+01	5.424e+01	2.470e-02	9.698e-02
1.5	1.290e+12	4.147e+03	1.659e+04	6.978e+00	2.791e+01
1.83	3.960e+08	3.263e+00	1.315e+01	5.185e-03	2.089e-02
2.25	2.140e+08	3.595e+00	1.449e+01	5.354e-03	2.158e-02
2.75	1.280e+12	3.599e+04	1.427e+05	5.022e+01	1.991e+02
3.5	6.750e+08	2.919e+01	1.106e+02	3.772e-02	1.429e-01
4.5	1.050e+06	5.883e-02	2.243e-01	6.988e-05	2.664e-04
5.5	1.710e+03	1.044e-04	4.214e-04	1.163e-07	4.692e-07
6.5	7.270e-03	4.433e-10	1.996e-09	4.707e-13	2.119e-12
7.5	2.560e-04	1.480e-11	7.976e-11	1.513e-14	8.151e-14
Totals	**3.196e+12**	**4.019e+04**	**1.595e+05**	**5.727e+01**	**2.272e+02**

Appendix 4

Activation analysis of Th foil and copper degrader

Table A4.1 MCNPX calculated spectrum of radionuclides and their activity at EOB produced in the d×h=2”×0.005” Th foil upon bombardment with 192 MeV (200 MeV LINAC) protons for 9.2 days at a 100 µA.

Isotope	Z	Activity, Ci
th	231	4.93E-01
ag	113	3.65E-01
ag	112	3.45E-01
in	115m	3.28E-01
cd	115	3.28E-01
pd	112	3.12E-01
sn	121	3.03E-01
in	117m	2.55E-01
in	117	2.31E-01
ag	111	2.03E-01
ag	109m	1.80E-01
pd	109	1.80E-01
po	214	1.73E-01
rn	218	1.73E-01
ra	222	1.73E-01
th	226	1.70E-01
rh	105	1.70E-01
nb	97	1.65E-01
y	92	1.53E-01
rb	88	1.50E-01
te	129	1.41E-01
y	93	1.40E-01
ru	105	1.38E-01
sr	91	1.32E-01
mo	99	1.26E-01
i	133	1.26E-01
pa	233	1.26E-01
te	127	1.23E-01
xe	133	1.20E-01
sb	129	1.20E-01
i	132	1.18E-01
te	131	1.17E-01
zr	97	1.15E-01

Isotope	Z	Activity, Ci
xe	135	1.12E-01
tc	99m	1.11E-01
nb	97m	1.09E-01
bi	211	1.01E-01
tl	207	1.01E-01
sb	127	9.51E-02
ac	226	9.20E-02
pb	209	9.09E-02
po	213	8.97E-02
ac	224	8.71E-02
i	131	8.37E-02
la	141	8.09E-02
bi	212	8.02E-02
kr	85m	7.71E-02
y	91m	7.68E-02
ac	228	7.60E-02
pb	212	7.15E-02
po	216	7.15E-02
rn	220	7.15E-02
ra	224	7.15E-02
ce	143	7.13E-02
i	135	6.91E-02
pr	145	6.71E-02
po	212	6.43E-02
te	132	6.36E-02
pa	229	6.31E-02
ac	225	5.98E-02
at	217	5.98E-02
fr	221	5.98E-02
bi	213	5.98E-02
as	77	5.56E-02
i	130	4.83E-02
rh	106	4.69E-02

Isotope	Z	Activity, Ci
bi	210	4.50E-02
sb	128	4.46E-02
la	140	4.46E-02
th	227	4.13E-02
rh	105m	3.91E-02
cd	117m	3.76E-02
ga	73	3.54E-02
ge	73m	3.49E-02
ba	140	3.41E-02
sb	122	3.39E-02
br	82	3.36E-02
pa	228	3.24E-02
y	90	3.16E-02
ce	137	3.14E-02
sb	126	3.14E-02
rn	217	3.11E-02
pm	149	3.08E-02
tl	208	2.88E-02
ge	77	2.85E-02
rh	103m	2.83E-02
pa	232	2.82E-02
nb	96	2.76E-02
pr	143	2.76E-02
y	87	2.73E-02
ru	103	2.64E-02
pr	144	2.58E-02
pr	142	2.57E-02
nd	147	2.56E-02
pm	151	2.31E-02
pa	230	2.26E-02
sb	119	2.19E-02
zr	89	2.14E-02
y	89m	2.14E-02

Isotope	Z	Activity, Ci
in	110	2.13E-02
sn	125	2.12E-02
cs	129	1.97E-02
ga	72	1.95E-02
cs	136	1.92E-02
y	91	1.85E-02
sr	89	1.85E-02
ce	141	1.78E-02
la	135	1.76E-02
sm	153	1.65E-02
pm	148	1.60E-02
tc	96	1.57E-02
sb	118	1.45E-02
zn	72	1.41E-02
zr	95	1.32E-02
pb	211	1.31E-02
po	215	1.31E-02
rn	219	1.31E-02
ra	223	1.31E-02
cs	131	1.25E-02
po	211	1.25E-02
rb	86	1.21E-02
ba	131	1.11E-02
xe	135m	1.09E-02
te	121	9.82E-03
i	123	9.79E-03
i	124	8.98E-03
at	211	8.78E-03
nb	95	8.74E-03
at	216	8.71E-03
fr	220	8.71E-03
la	134	8.30E-03
sb	124	8.14E-03
eu	157	7.67E-03
cs	132	7.61E-03
pr	140	7.60E-03
rh	100	7.46E-03
cu	66	7.04E-03
cu	67	6.80E-03

Isotope	Z	Activity, Ci
xe	125	6.75E-03
ce	135	6.75E-03
sm	156	6.50E-03
nb	90	6.41E-03
pr	139	6.24E-03
te	119	6.08E-03
la	133	6.08E-03
ni	66	6.02E-03
rb	82	6.00E-03
tc	95	5.74E-03
y	86	5.74E-03
la	132	5.74E-03
te	131m	5.68E-03
kr	79	5.67E-03
i	126	5.62E-03
cs	128	5.57E-03
in	111	5.44E-03
i	122	5.40E-03
gd	159	5.36E-03
te	118	5.08E-03
xe	127	4.77E-03
in	109	4.73E-03
as	76	4.38E-03
sr	83	4.35E-03
br	77	4.09E-03
at	210	4.05E-03
te	129m	3.72E-03
tb	154	3.71E-03
ru	97	3.60E-03
xe	133m	3.43E-03
pd	101	3.38E-03
rb	81	3.21E-03
th	228	3.20E-03
pd	100	3.07E-03
cs	127	3.04E-03
tc	94	3.04E-03
eu	156	2.92E-03
sr	85	2.75E-03
cd	111m	2.72E-03

Isotope	Z	Activity, Ci
cd	107	2.70E-03
ag	107m	2.70E-03
ru	106	2.61E-03
ra	225	2.60E-03
sn	123	2.55E-03
er	169	2.51E-03
i	125	2.44E-03
se	73	2.36E-03
ce	133	2.36E-03
ba	128	2.19E-03
cd	115m	2.18E-03
ba	136m	2.15E-03
ho	166	2.07E-03
tb	152	2.03E-03
br	76	2.03E-03
tm	173	2.03E-03
pd	103	2.01E-03
nd	140	1.86E-03
re	182	1.84E-03
ce	144	1.78E-03
po	210	1.73E-03
dy	166	1.72E-03
xe	122	1.69E-03
ce	139	1.64E-03
tb	161	1.63E-03
rb	84	1.55E-03
ge	71	1.39E-03
tm	172	1.38E-03
tl	209	1.26E-03
dy	157	1.18E-03
tb	156	1.06E-03
sc	47	1.03E-03
er	171	1.01E-03
w	187	1.01E-03
er	165	1.01E-03
rh	99	9.94E-04
er	172	9.67E-04
tb	153	9.46E-04
ce	134	8.78E-04

Isotope	Z	Activity, Ci
rb	83	8.50E-04
sb	125	7.23E-04
ga	68	6.83E-04
zr	86	6.75E-04
k	43	6.74E-04
as	72	6.73E-04
at	209	6.71E-04
tm	165	6.71E-04
te	127m	6.02E-04
y	88	5.98E-04
sr	82	5.96E-04
gd	149	5.00E-04
cs	134	4.07E-04
as	74	4.07E-04
bi	206	3.87E-04
ag	105	3.87E-04
yb	169	3.66E-04
zr	88	3.48E-04
ga	66	3.38E-04
ta	180	3.38E-04
re	189	3.37E-04
ho	160	3.36E-04
er	160	3.36E-04
ge	69	3.31E-04
sc	48	3.27E-04
fe	59	3.16E-04
u	230	3.15E-04
as	71	3.05E-04
eu	148	2.98E-04
ga	67	2.90E-04
sn	117m	2.72E-04
yb	175	2.64E-04
ca	47	2.55E-04
ta	183	2.43E-04
in	113m	2.37E-04
sn	113	2.37E-04
tb	155	2.36E-04
xe	131m	2.29E-04

Isotope	Z	Activity, Ci
eu	145	2.23E-04
as	73	1.80E-04
se	77m	1.78E-04
tm	167	1.68E-04
cd	109	1.66E-04
rh	101	1.53E-04
sc	46	1.48E-04
dy	159	1.46E-04
hf	181	1.41E-04
pm	147	1.27E-04
pb	210	1.24E-04
ta	182	1.09E-04
eu	149	1.08E-04
sr	90	1.02E-04
kr	85	9.30E-05
ac	227	8.87E-05
eu	147	7.89E-05
nb	95m	7.88E-05
pm	143	7.22E-05
se	75	7.00E-05
h	3	6.74E-05
pm	144	6.46E-05
cs	137	5.72E-05
ba	133	5.53E-05
ba	137m	5.40E-05
re	184	5.22E-05
sn	119m	4.75E-05
eu	155	4.08E-05
rh	102	3.85E-05
gd	153	3.49E-05
tm	170	3.27E-05
hf	175	2.94E-05
co	58	2.90E-05
tb	160	2.85E-05
w	185	2.75E-05
ca	45	2.58E-05
pr	144m	2.56E-05
tm	168	2.23E-05

Isotope	Z	Activity, Ci
ra	228	2.15E-05
sm	145	2.13E-05
w	181	1.73E-05
tm	171	1.53E-05
v	49	1.26E-05
w	183m	1.22E-05
eu	154	1.10E-05
po	208	1.01E-05
bi	205	9.38E-06
te	125m	8.56E-06
lu	173	8.56E-06
pm	146	8.51E-06
ge	68	7.86E-06
cd	113m	7.66E-06
sn	121m	7.59E-06
mn	54	6.83E-06
co	60	6.70E-06
u	232	5.65E-06
fr	222	5.52E-06
pm	145	5.00E-06
eu	152	4.86E-06
fe	55	4.30E-06
sm	151	4.05E-06
ta	179	3.22E-06
bi	207	1.98E-06
fr	223	1.23E-06
u	233	7.18E-09

Table A4.2 MCNPX calculated spectrum of radionuclides and their activity 24 h after produced in the **single** d×h=2×0.005" Th foil upon bombardment with 192 MeV (200 MeV LINAC) protons for 9.2 days at a 100 µA.

Isotope	Z	Activity, Ci
in	115m	2.63E-01
th	231	2.57E-01
cd	115	2.41E-01
ag	111	1.86E-01
ag	112	1.66E-01
sn	121	1.64E-01
pd	112	1.41E-01
pa	233	1.23E-01
rh	105	1.18E-01
xe	133	1.16E-01
mo	99	9.81E-02
tc	99m	9.43E-02
sb	127	8.03E-02
te	127	8.01E-02
i	131	7.75E-02
bi	212	6.89E-02
pb	212	6.73E-02
po	216	6.20E-02
rn	220	6.20E-02
ra	224	6.20E-02
i	133	5.73E-02
at	217	5.60E-02
fr	221	5.60E-02
bi	213	5.60E-02
ac	225	5.60E-02
po	213	5.48E-02
pb	209	5.43E-02
ag	109m	5.37E-02
pd	109	5.35E-02
i	132	5.31E-02
ac	226	5.19E-02
te	132	5.14E-02
po	212	4.41E-02
po	214	4.41E-02
rn	218	4.41E-02
ra	222	4.41E-02

Isotope	Z	Activity, Ci
th	226	4.41E-02
ce	143	4.33E-02
nb	97	4.33E-02
zr	97	4.31E-02
as	77	4.12E-02
nb	97m	4.09E-02
la	140	4.07E-02
th	227	3.98E-02
bi	210	3.92E-02
pa	229	3.85E-02
xe	135	3.27E-02
ba	140	3.23E-02
sb	126	2.96E-02
pr	143	2.90E-02
rh	103m	2.78E-02
y	93	2.72E-02
sb	122	2.63E-02
ru	103	2.59E-02
tl	208	2.48E-02
y	90	2.44E-02
nd	147	2.41E-02
pm	149	2.32E-02
sr	91	2.31E-02
y	87	2.23E-02
pa	230	2.17E-02
br	82	2.10E-02
sn	125	1.97E-02
y	91	1.91E-02
sr	89	1.83E-02
cs	136	1.82E-02
ce	141	1.78E-02
zr	89	1.74E-02
y	89m	1.74E-02
pa	232	1.66E-02
ag	113	1.65E-02
sb	119	1.54E-02

Isotope	Z	Activity, Ci
pa	228	1.52E-02
bi	211	1.47E-02
pb	211	1.47E-02
po	215	1.47E-02
rn	219	1.47E-02
ra	223	1.47E-02
tl	207	1.47E-02
y	91m	1.47E-02
pm	148	1.40E-02
ga	72	1.39E-02
nb	96	1.36E-02
tc	96	1.33E-02
zr	95	1.31E-02
pm	151	1.29E-02
i	130	1.26E-02
cs	131	1.24E-02
cs	129	1.20E-02
rb	86	1.17E-02
sm	153	1.16E-02
pr	142	1.08E-02
ba	131	1.05E-02
zn	72	9.86E-03
la	135	9.84E-03
te	121	9.45E-03
nb	95	8.83E-03
sb	124	8.05E-03
i	124	7.61E-03
sb	128	7.10E-03
cs	132	6.84E-03
ge	77	6.55E-03
i	135	5.50E-03
te	129	5.46E-03
i	126	5.33E-03
cu	67	5.20E-03
ce	137	5.11E-03
ac	228	5.10E-03

Isotope	Z	Activity, Ci
rh	100	4.87E-03
xe	127	4.70E-03
sb	118	4.53E-03
te	118	4.53E-03
cu	66	4.45E-03
ni	66	4.44E-03
in	111	4.26E-03
pr	145	4.19E-03
y	92	4.07E-03
te	129m	3.76E-03
kr	79	3.53E-03
ru	105	3.33E-03
te	131m	3.31E-03
th	228	3.24E-03
xe	133m	3.17E-03
br	77	3.06E-03
eu	156	2.93E-03
i	123	2.88E-03
ru	97	2.84E-03
sb	129	2.74E-03
sr	85	2.73E-03
ce	135	2.65E-03
rh	106	2.61E-03
ru	106	2.61E-03
sr	83	2.60E-03
eu	157	2.58E-03
tc	95	2.55E-03
xe	125	2.55E-03
pd	100	2.54E-03
sn	123	2.53E-03
ra	225	2.48E-03
i	125	2.47E-03
er	169	2.33E-03
as	76	2.33E-03
gd	159	2.22E-03
te	119	2.17E-03
cd	111m	2.15E-03
cd	115m	2.15E-03
y	86	2.12E-03

Isotope	Z	Activity, Ci
nb	90	2.11E-03
ba	136m	2.04E-03
po	210	1.94E-03
pd	103	1.93E-03
kr	85m	1.90E-03
ho	166	1.82E-03
pr	144	1.78E-03
ce	144	1.78E-03
tb	154	1.71E-03
cs	128	1.65E-03
ba	128	1.65E-03
ce	139	1.64E-03
pr	140	1.52E-03
nd	140	1.52E-03
rb	84	1.52E-03
in	117m	1.51E-03
tb	161	1.47E-03
re	182	1.42E-03
dy	166	1.40E-03
ge	71	1.33E-03
tm	172	1.25E-03
la	141	1.24E-03
tl	209	1.18E-03
ga	73	1.16E-03
ge	73m	1.14E-03
in	117	1.11E-03
sm	156	1.11E-03
rh	99	9.52E-04
rh	105m	9.49E-04
tb	156	9.29E-04
xe	135m	8.98E-04
sc	47	8.78E-04
at	211	8.75E-04
rb	83	8.71E-04
tb	152	7.83E-04
te	131	7.44E-04
i	122	7.40E-04
xe	122	7.38E-04
sb	125	7.37E-04

Isotope	Z	Activity, Ci
in	110	7.36E-04
br	76	7.25E-04
la	134	7.06E-04
ce	134	7.05E-04
tb	153	7.04E-04
te	127m	6.96E-04
er	172	6.90E-04
ac	224	6.29E-04
y	88	5.97E-04
er	165	5.86E-04
rb	82	5.80E-04
sr	82	5.80E-04
po	211	5.50E-04
at	210	5.21E-04
w	187	5.05E-04
pd	101	4.80E-04
gd	149	4.64E-04
cs	134	4.07E-04
as	74	3.91E-04
tm	165	3.86E-04
rb	88	3.86E-04
ag	105	3.80E-04
u	230	3.73E-04
bi	206	3.73E-04
yb	169	3.58E-04
as	72	3.55E-04
zr	88	3.45E-04
la	132	3.45E-04
k	43	3.20E-04
la	133	3.12E-04
fe	59	3.11E-04
eu	148	2.94E-04
tm	173	2.70E-04
cd	117m	2.68E-04
sn	117m	2.66E-04
xe	131m	2.65E-04
zr	86	2.46E-04
as	71	2.37E-04
in	113m	2.35E-04

Isotope	Z	Activity, Ci
sn	113	2.35E-04
ga	67	2.34E-04
se	73	2.30E-04
sc	48	2.24E-04
yb	175	2.24E-04
ca	47	2.19E-04
ge	69	2.16E-04
ta	183	2.15E-04
cs	127	2.13E-04
ag	107m	2.12E-04
cd	107	2.11E-04
tb	155	2.07E-04
eu	145	1.98E-04
ho	160	1.91E-04
er	160	1.88E-04
as	73	1.87E-04
re	189	1.71E-04
cd	109	1.68E-04
dy	157	1.56E-04
tm	167	1.56E-04
rh	101	1.54E-04
pr	139	1.48E-04
sc	46	1.47E-04
dy	159	1.45E-04
pm	147	1.45E-04
hf	181	1.39E-04
se	77m	1.32E-04
pb	210	1.30E-04
er	171	1.11E-04
eu	149	1.11E-04
ta	182	1.09E-04
tc	94	1.03E-04
sr	90	1.02E-04
kr	85	9.38E-05
nb	95m	9.06E-05
in	109	8.95E-05
ac	227	8.88E-05
rb	81	8.46E-05
ce	133	7.86E-05

Isotope	Z	Activity, Ci
ga	66	7.68E-05
eu	147	7.66E-05
pm	143	7.20E-05
se	75	6.98E-05
h	3	6.73E-05
pm	144	6.45E-05
at	216	6.30E-05
fr	220	6.30E-05
cs	137	5.72E-05
ba	133	5.56E-05
ba	137m	5.40E-05
re	184	5.12E-05
sn	119m	4.74E-05
ta	180	4.39E-05
eu	155	4.09E-05
rh	102	3.85E-05
gd	153	3.71E-05
tm	170	3.25E-05
at	209	3.11E-05
hf	175	2.91E-05
co	58	2.87E-05
tb	160	2.82E-05
w	185	2.74E-05
ca	45	2.57E-05
pr	144m	2.49E-05
tm	168	2.22E-05
sm	145	2.16E-05
ra	228	2.15E-05
w	181	1.72E-05
tm	171	1.57E-05
v	49	1.26E-05
eu	154	1.10E-05
w	183m	1.07E-05
te	125m	1.05E-05
po	208	1.02E-05
bi	205	9.34E-06
lu	173	8.54E-06
pm	146	8.50E-06
cd	113m	7.92E-06

Isotope	Z	Activity, Ci
ga	68	7.84E-06
ge	68	7.84E-06
sn	121m	7.59E-06
mn	54	6.81E-06
rn	217	6.72E-06
co	60	6.69E-06
u	232	6.24E-06
pm	145	5.00E-06
eu	152	4.86E-06
sm	151	4.42E-06
fe	55	4.30E-06
ta	179	3.22E-06
fr	222	3.14E-06
bi	207	2.07E-06
fr	223	1.23E-06
u	233	8.67E-09

Table A4.3 MCNPX calculation of Activation products in copper degrader at times post EOB from 7 d irradiation at 100µA and 200MeV.

						Decay Time post EOB					
		A(Ci)	1.0hr	2.0hr	3.0hr	4.0hr	5.0hr	6.0hr	7.0hr	8.0hr	1.0d
cu	62	1.20E+02	7.57E+00	5.57E+00	5.15E+00	4.77E+00	4.43E+00	4.11E+00	3.81E+00	3.54E+00	1.07E+00
he	5	1.16E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
cu	61	5.73E+01	4.68E+01	3.82E+01	3.12E+01	2.54E+01	2.07E+01	1.69E+01	1.38E+01	1.13E+01	4.35E-01
cu	64	3.45E+01	3.27E+01	3.09E+01	2.93E+01	2.77E+01	2.63E+01	2.49E+01	2.36E+01	2.23E+01	9.31E+00
mn	52	1.24E+01	1.24E+01	1.23E+01	1.22E+01	1.22E+01	1.21E+01	1.21E+01	1.20E+01	1.19E+01	1.10E+01
cu	60	1.09E+01	1.97E+00	3.58E-01	6.51E-02	1.18E-02	2.15E-03	3.90E-04	7.09E-05	1.29E-05	1.81E-17
zn	63	6.73E+00	2.26E+00	7.58E-01	2.55E-01	8.54E-02	2.87E-02	9.63E-03	3.23E-03	1.09E-03	2.82E-11
zn	62	6.33E+00	5.87E+00	5.45E+00	5.05E+00	4.69E+00	4.35E+00	4.04E+00	3.75E+00	3.48E+00	1.05E+00
co	61	5.80E+00	3.81E+00	2.51E+00	1.65E+00	1.08E+00	7.11E-01	4.67E-01	3.07E-01	2.02E-01	2.42E-04
co	58	5.33E+00	5.33E+00	5.33E+00	5.33E+00	5.32E+00	5.32E+00	5.32E+00	5.32E+00	5.32E+00	5.28E+00
co	62	2.82E+00	7.17E-10	3.59E-11	1.81E-12	9.09E-14	4.57E-15	2.30E-16	1.16E-17	5.82E-19	0.00E+00
mn	56	2.52E+00	1.93E+00	1.48E+00	1.13E+00	8.61E-01	6.58E-01	5.03E-01	3.85E-01	2.94E-01	3.98E-03
ni	57	1.61E+00	1.58E+00	1.55E+00	1.52E+00	1.49E+00	1.46E+00	1.44E+00	1.41E+00	1.38E+00	1.01E+00
co	56	1.09E+00	1.09E+00	1.09E+00	1.09E+00	1.09E+00	1.09E+00	1.09E+00	1.09E+00	1.09E+00	1.08E+00
zn	61	1.01E+00	6.94E-13	4.77E-25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
co	57	9.94E-01	9.95E-01	9.95E-01	9.95E-01	9.95E-01	9.95E-01	9.95E-01	9.95E-01	9.95E-01	9.95E-01
co	55	9.30E-01	8.94E-01	8.60E-01	8.26E-01	7.94E-01	7.64E-01	7.34E-01	7.06E-01	6.78E-01	3.60E-01
cr	51	9.11E-01	9.11E-01	9.10E-01	9.09E-01	9.08E-01	9.07E-01	9.06E-01	9.05E-01	9.04E-01	8.89E-01
cu	59	6.97E-01	3.52E-14	1.77E-27	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
fe	53	6.44E-01	4.86E-03	3.66E-05	2.76E-07	2.09E-09	1.57E-11	1.19E-13	8.95E-16	6.76E-18	0.00E+00
co	63	5.85E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
mn	57	5.63E-01	3.41E-12	2.06E-23	1.64E-34	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
mn	51	3.32E-01	1.35E-01	5.48E-02	2.23E-02	9.05E-03	3.68E-03	1.50E-03	6.08E-04	2.47E-04	1.37E-10
mn	54	3.23E-01	3.23E-01	3.23E-01	3.23E-01	3.23E-01	3.23E-01	3.23E-01	3.23E-01	3.23E-01	3.22E-01
v	52	2.90E-01	4.45E-06	6.78E-11	1.04E-15	1.58E-20	2.41E-25	3.68E-30	7.03E-35	0.00E+00	0.00E+00
mn	58	2.34E-01	5.94E-18	2.42E-34	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
fe	55	1.80E-01	1.80E-01	1.80E-01	1.80E-01	1.80E-01	1.80E-01	1.80E-01	1.80E-01	1.80E-01	1.80E-01
v	48	1.64E-01	1.64E-01	1.63E-01	1.63E-01	1.63E-01	1.62E-01	1.62E-01	1.62E-01	1.62E-01	1.57E-01
cr	49	1.60E-01	5.97E-02	2.23E-02	8.35E-03	3.12E-03	1.17E-03	4.37E-04	1.64E-04	6.12E-05	9.01E-12
fe	59	1.22E-01	1.22E-01	1.22E-01	1.22E-01	1.22E-01	1.22E-01	1.21E-01	1.21E-01	1.21E-01	1.20E-01
cr	55	7.89E-02	6.45E-07	5.27E-12	4.30E-17	3.52E-22	2.87E-27	2.35E-32	0.00E+00	0.00E+00	0.00E+00
co	60	7.88E-02	7.88E-02	7.88E-02	7.88E-02	7.88E-02	7.88E-02	7.88E-02	7.88E-02	7.87E-02	7.87E-02
ni	56	6.57E-02	6.54E-02	6.51E-02	6.48E-02	6.45E-02	6.42E-02	6.39E-02	6.36E-02	6.33E-02	5.87E-02
co	54	5.53E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
v	53	5.49E-02	3.33E-13	2.01E-24	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
fe	61	5.15E-02	4.91E-05	4.69E-08	4.47E-11	4.27E-14	4.07E-17	3.89E-20	3.71E-23	3.54E-26	0.00E+00
cu	58	4.98E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
zn	65	4.83E-02	4.83E-02	4.83E-02	4.83E-02	4.83E-02	4.83E-02	4.83E-02	4.83E-02	4.83E-02	4.82E-02
zn	60	4.09E-02	1.08E-09	2.85E-17	7.53E-25	1.99E-32	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
v	47	3.88E-02	1.08E-02	3.03E-03	8.45E-04	2.36E-04	6.59E-05	1.84E-05	5.14E-06	1.43E-06	1.96E-15

sc	47	3.55E-02	3.52E-02	3.49E-02	3.46E-02	3.43E-02	3.40E-02	3.37E-02	3.35E-02	3.32E-02	2.90E-02
fe	52	2.91E-02	2.68E-02	2.46E-02	2.26E-02	2.08E-02	1.92E-02	1.76E-02	1.62E-02	1.49E-02	3.90E-03
v	49	2.62E-02	2.62E-02	2.62E-02	2.62E-02	2.62E-02	2.62E-02	2.62E-02	2.62E-02	2.62E-02	2.62E-02
sc	44	2.57E-02	2.16E-02	1.81E-02	1.52E-02	1.27E-02	1.07E-02	8.93E-03	7.48E-03	6.27E-03	3.72E-04
mn	50	2.36E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
sc	48	1.96E-02	1.93E-02	1.90E-02	1.87E-02	1.84E-02	1.81E-02	1.78E-02	1.76E-02	1.73E-02	1.34E-02
cr	56	1.60E-02	1.45E-05	1.31E-08	1.18E-11	1.07E-14	9.65E-18	8.72E-21	7.87E-24	7.11E-27	0.00E+00
fe	62	1.52E-02	1.76E-18	2.33E-34	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ni	65	1.48E-02	1.12E-02	8.52E-03	6.47E-03	4.92E-03	3.73E-03	2.84E-03	2.15E-03	1.64E-03	2.01E-05
mn	59	1.31E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
sc	46	1.29E-02	1.29E-02	1.29E-02	1.29E-02	1.29E-02	1.29E-02	1.29E-02	1.29E-02	1.29E-02	1.28E-02
ti	45	1.22E-02	9.77E-03	7.80E-03	6.23E-03	4.97E-03	3.97E-03	3.17E-03	2.53E-03	2.02E-03	5.52E-05
cr	48	8.40E-03	8.13E-03	7.88E-03	7.63E-03	7.39E-03	7.15E-03	6.93E-03	6.71E-03	6.50E-03	3.88E-03
sc	49	7.17E-03	3.47E-03	1.68E-03	8.10E-04	3.91E-04	1.89E-04	9.14E-05	4.42E-05	2.14E-05	1.89E-10
ti	51	5.49E-03	4.01E-06	2.94E-09	2.15E-12	1.57E-15	1.15E-18	8.41E-22	6.15E-25	4.50E-28	0.00E+00
h	3	5.46E-03	5.46E-03	5.46E-03	5.46E-03	5.46E-03	5.46E-03	5.46E-03	5.46E-03	5.46E-03	5.46E-03
v	46	3.38E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
mn	60	2.53E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
v	54	2.11E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
v	55	1.69E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ti	52	1.27E-03	3.00E-14	7.13E-25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ni	63	1.16E-03	1.16E-03	1.16E-03	1.16E-03	1.16E-03	1.16E-03	1.16E-03	1.16E-03	1.16E-03	1.16E-03
co	64	8.44E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
sc	43	8.44E-04	7.06E-04	5.91E-04	4.95E-04	4.14E-04	3.46E-04	2.90E-04	2.43E-04	2.03E-04	1.17E-05
ca	47	5.54E-04	5.51E-04	5.47E-04	5.44E-04	5.40E-04	5.37E-04	5.34E-04	5.30E-04	5.27E-04	4.76E-04
k	42	4.22E-04	3.99E-04	3.77E-04	3.57E-04	3.37E-04	3.19E-04	3.01E-04	2.85E-04	2.69E-04	1.10E-04
ti	53	4.22E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
fe	51	4.22E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ni	55	4.22E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
cu	57	4.22E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
cu	66	4.22E-04	1.21E-07	3.49E-11	1.00E-14	2.88E-18	1.09E-21	2.61E-22	2.58E-22	2.55E-22	2.08E-22
zn	57	4.22E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
zn	59	4.22E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ca	45	1.97E-04	1.97E-04	1.97E-04	1.97E-04	1.97E-04	1.97E-04	1.97E-04	1.97E-04	1.97E-04	1.96E-04
co	58m	1.48E-04	1.37E-04	1.27E-04	1.18E-04	1.10E-04	1.02E-04	9.41E-05	8.72E-05	8.09E-05	2.41E-05
co	60m	1.45E-04	2.74E-06	5.45E-08	3.90E-09	2.95E-09	2.93E-09	2.93E-09	2.93E-09	2.93E-09	2.93E-09
ni	59	1.30E-05	1.30E-05	1.30E-05	1.30E-05	1.30E-05	1.30E-05	1.30E-05	1.30E-05	1.30E-05	1.30E-05

Table 4.4 Calculated activity of Na-22 and Na-24 produced in the individual elements of the target array (Box 1) after 9.2 d irradiation

time since EOB, h	**0.0**	**1.0**	**2.0**	**5.0**	**15.0**	**24.0**
Th can	0.069	0.069	0.069	0.069	0.069	0.069
1.734 Al vacuum degrader	0.137	0.137	0.137	0.137	0.137	0.137
Al deg. 0.354	0.055	0.055	0.055	0.055	0.055	0.055
total Na-22	0.262	0.262	0.262	0.262	0.262	0.262
time since EOB, h	**0.0**	**1.0**	**2.0**	**5.0**	**15.0**	**24.0**
Th can	5.3	5.1	4.9	4.3	2.7	1.8
1.734 Al vacuum degrader	9.9	9.4	9.0	4.1	7.8	3.3
Al deg. 0.354	3.8	3.6	3.5	3.0	1.9	1.3
total Na-24	19.0	18.1	17.4	11.4	12.4	6.4

Estimation of U-233 production

Radioisotope U-233 can be produced in the foil by the Th-232 (n,γ) Th-233(22.3 min, β-)→ Pa-233(27.4 d, β-)→U-233. The indirect production of U-233 was calculated using MCNPX code for a 9 day irradiation at 100μA at 200 MeV on a Th foil. The total yield of U-233 was found to be ~9nCi for each foil, or ~27nCi total at EOB. Since the tables above are truncated for products at less than 1.0μCi this amount of U-233 is not listed. Fission of U-233 is also not included in the fission fragment heating calculation above due to its insignificant contribution. At EOB the U-233 mass from this irradiation is only 2 μg (~5.6 x10^{15} atoms). To fission these nuclei must interact with a proton just as the Th-232 nuclei (~2.4x10E21 atoms) do. The proton fission cross section of U-233 is 1.6 barn at these energies (Kotov et al, Physical Review, Part C, Nuclear Physics Vol.74, p.034605) vs 1.1 barn for Th-232. Hence, the contribution to heat from U-233 fission is many orders of magnitude less than from the Th fission discussed above in Appendix 2.

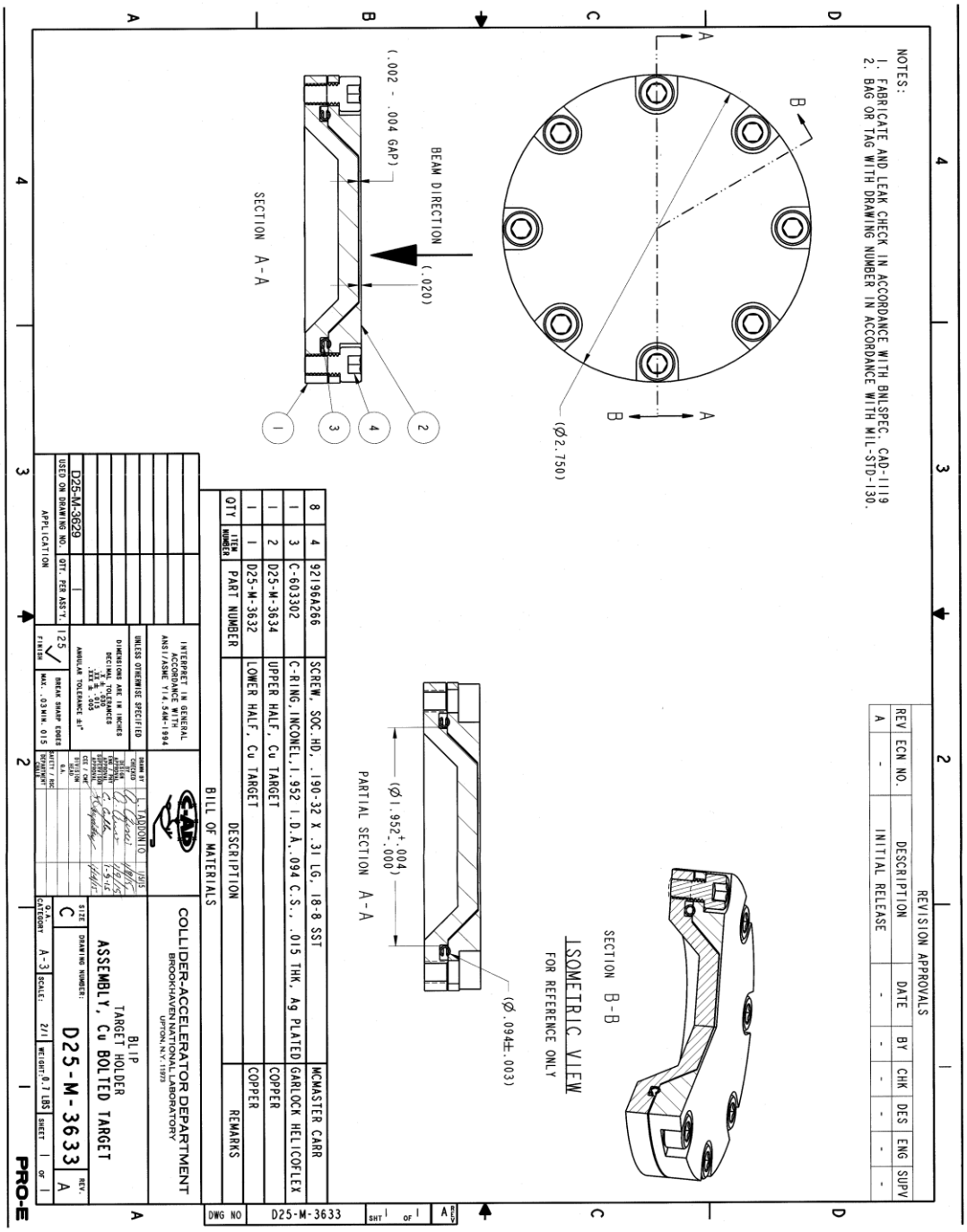
Production of noble gases

A total of ~1.5-2Ci of radioactive noble gases, radiobromines and radioiodines are predicted to be present in the three Th foils at time of transport from BLIP to building 801 (~2-3h post EOB). The sealed target capsule will be put into a sealed stainless steel secondary container for transport to building 801. In the extremely unlikely event of a serious transport accident involving ejection of the target from the cask, subsequent steel container rupture and target penetration, followed by a fire, and assuming 100% release of volatiles (also unlikely because the melting point of thorium is much higher than flame temperature), the maximum dose at the site boundary will be no more than 30μR (proportionally scaled from previous H. Kahnhauser calculation). Since the wrapped foil is placed intact in a capped glass vial immediately after opening the target capsule, it is not likely that any of these products are driven out of the foil and released. The ORNL shipping drums are also sealed and meet DOT Type A regulations.

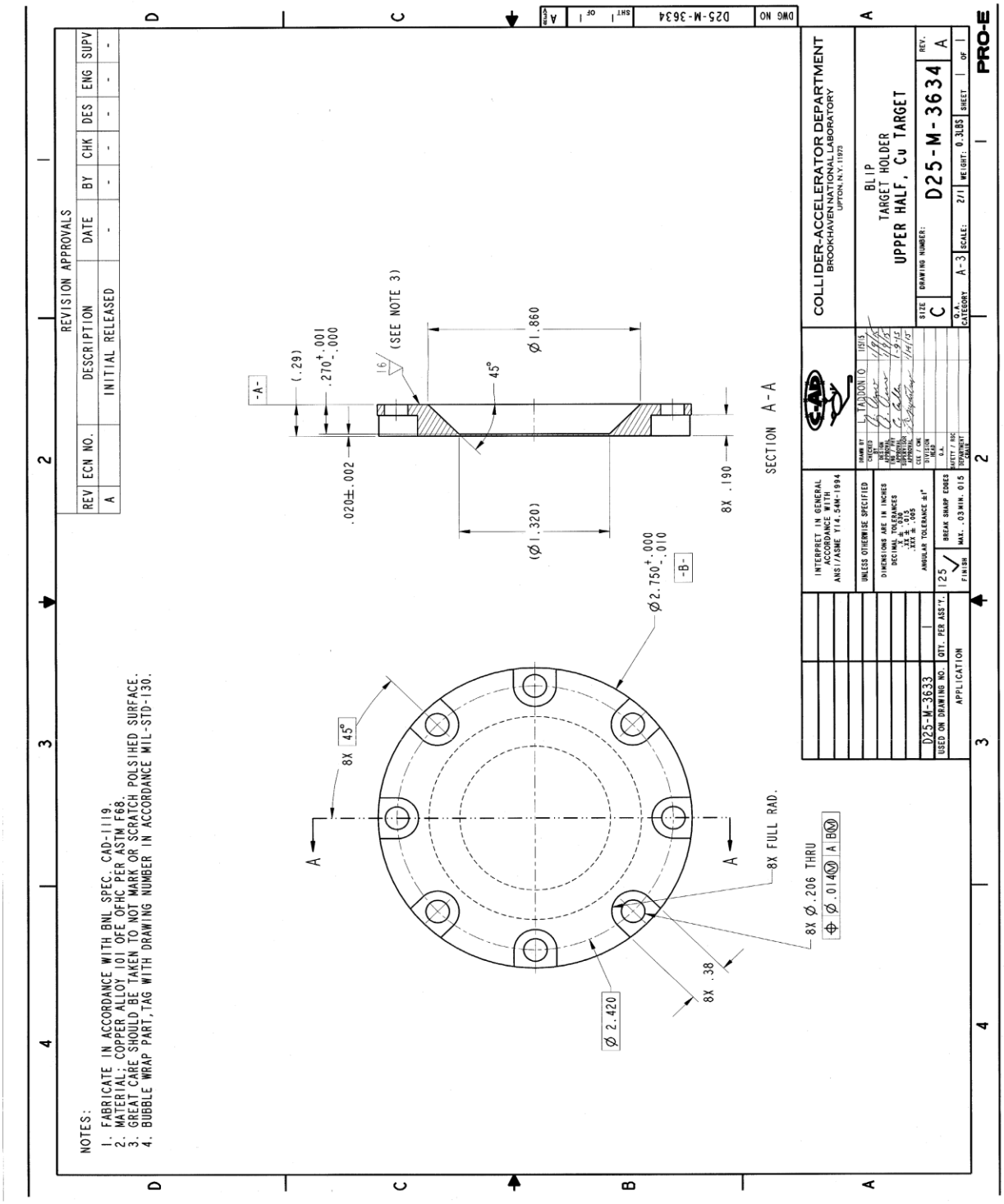
Appendix 5

Drawings

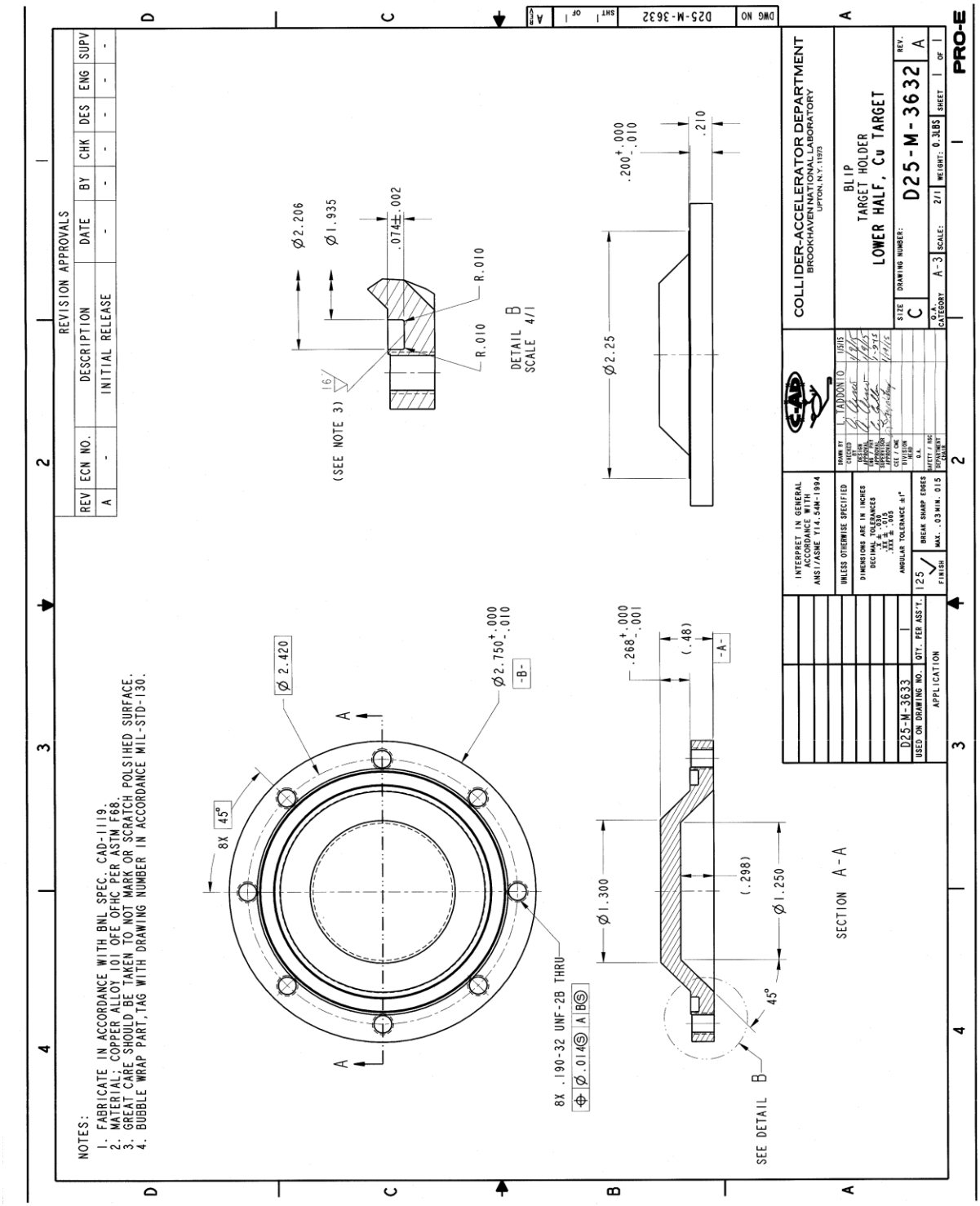
D25-M-3633: Drawing of the assembled Th target with Cu capsule.



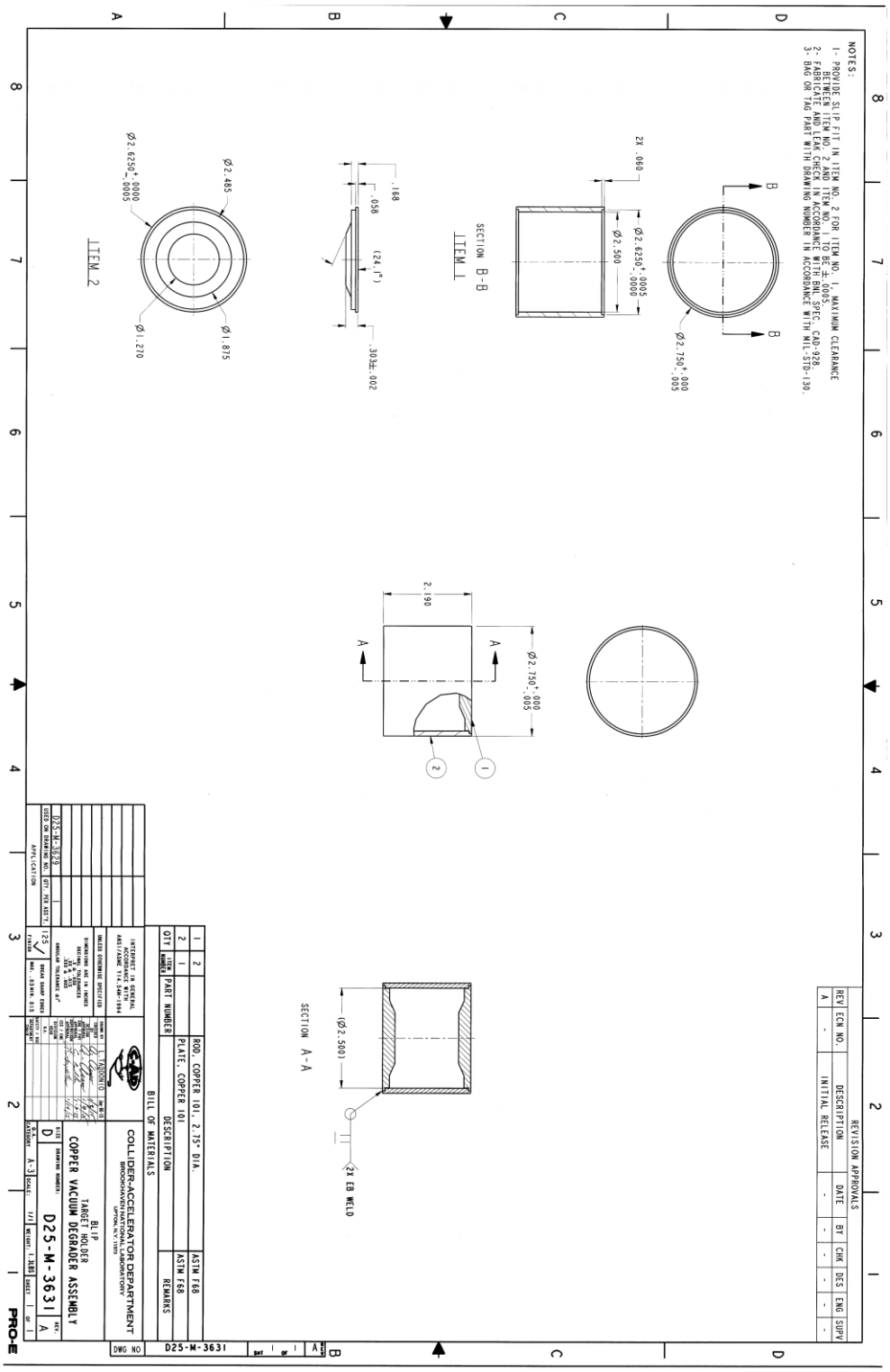
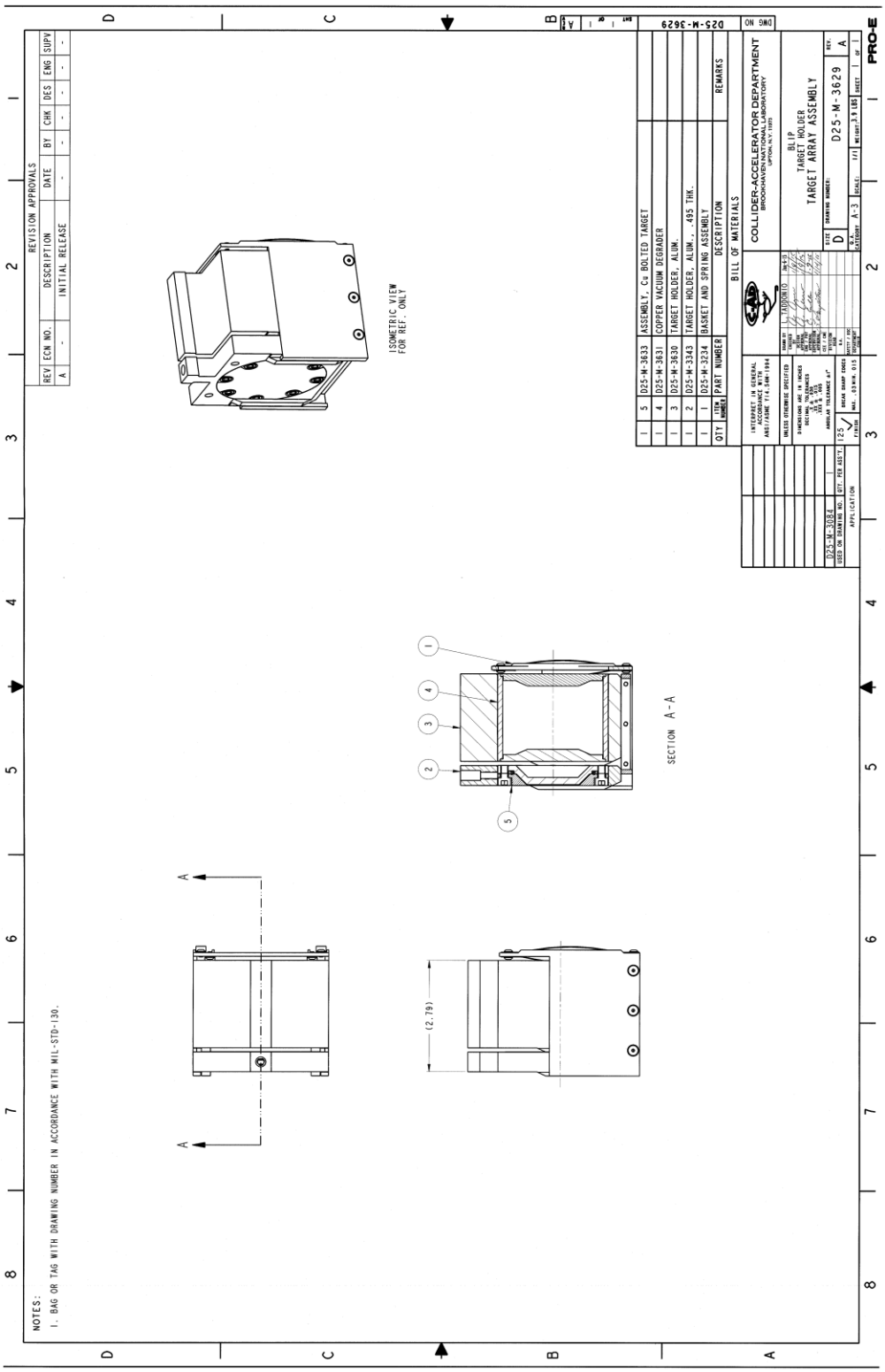
Drawing D25-m-3634: Th target capsule upstream section



Drawing D25-m-3632: Th target capsule downstream section



Drawing D25-M-3631: Th target array Cu vacuum degrader



Drawing D25-M-3629: Th target array