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BROOKHAVEN NATIONAL LABORATORY

managed by Brookhaven Science Associates
for the U.S. Department of Energy

Building 911

Memo

date: *January 7, 2013*

to: *C-A Experimental Safety Review RRPL Sub Committee*

from: *Yousef Makdisi*

subject: *Minutes of the Ac-225 Irradiation (2014) review*

Present: D. Beavis, P. Cirnigliaro, L. Evers, Y. Makdisi, L. Mausner, J. McCabe, D. Medvedev, P. Pile, N. Simos, S. Smith

The test will irradiate a single Thorium foil as a target to be irradiated at BLIP using a 200 MeV beam for 17 hours at the maximum available beam current. A RbCl target will also be located behind the Thorium target for continued Sr-82 production. Thus a system of degraders will be employed to assure the correct energy for the Sr-82 production. The review utilized material from OPM 9.1.15.a which provided details of the target preparation and MCNPX isotope production and possible.

A similar irradiation of 3 Thorium foils for 8 days at the same beam energy was carried out last year and the experience from that test was incorporated in this year's test which is geared towards a) understanding the production cross section, and b) measuring the short lived isotopes. The plan calls for shipping the irradiated foil to ORNL within a day after the target is removed from BLIP.

The following are the action items:

- **S. Smith proposed a few changes to better define the TPL effort as well as to improve the documentation to be incorporated in 9.1.15.a (Medvedev Jan 13, 2014) Done see below**

- **Add a check off list with signatures to assure the correct degraders are installed (Medvedev Jan 13, 2014) Done.**

Additional tests with single Thorium foils at lower beam energies are planned for FY14 and the question as to whether it was necessary to carry out additional MCNPX isotope calculations for these as the above represents the maximal production.

- **Beavis and Makdisi will consult with E. Lessard (The process has started)**

cc:

T. Roser
P. Pile
B. Mueller

File

9.1.15.a BLIP Target and Canning Record

Hand Processed Changes

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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 single 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
	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]	10
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]	n/a
9.	**Special Operating Instructions and List of References or Supporting Documents**	n/a
10.	**Appendix** [provide additional support information as required]	13-25

1. Overview

This experiment is part of a three 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 irradiation is 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 six irradiations have already been successfully carried out on Th foil targets at Linac energies of 140 and 200 MeV for periods ranging from 17 hours to 8 days. This irradiation will be at 200 MeV Linac energy (~195 MeV incident on the foil) for a period of 17 hours, at beam currents less than or equal to the maximum available at BLIP. As used previously, thin Th-232 foil will be wrapped in aluminum foil, encapsulated in Al can together with a thin Al foil used to determine actual fluence on target. After irradiation the target can will be transported to the TPL hot cells by standard procedures. In the hot cell the capsule will be opened, the Th foil removed, sealed in a screw top glass vial, and placed in an existing Type A shipping container. The container will then be shipped the same day to ORNL for processing. The goal of this experiment is to measure short lived radioisotopes that are coproduced, that had decayed away in the previous experiments due to long shipping and processing time.

This experiment is the first in the series of experiment planned for FY2014. The next three irradiations will be the same except that the Linac energies will be at 180, 160, and 140 MeV, respectively. The safety submissions for these experiments will be done separately.

2. Target Material and Properties

Target Name:	*Thorium foil_200 MeV*	Target & Canning No. CAJ	CAG

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)	**1.11/28.2**	**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:		Target & Canning No. CAJ	

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)	**1.11/28.2**	**Pressed (Torr)**	**n/a**
Elements (%)	**99.99% Al,**			

Melting Point	**660**	**°C**		**°F**
Boiling Point	**2467**	**°C**		**°F**
Thermal Conductivity	**205 $W.m^{-1}.K^{-1}$**	**Temperature dependence**	***(if available)* 215@125°C, 250@225°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	**Aluminum alloy 6061**			
Can Wall Thickness (inches/mm)	**Refer to drawing** D25-M-3186 attached			
Can Dimensions (inches/mm)	**Can Diameter 2.75/69.9 Can Width 0.5/12.7**			
Melting Point	**660.3**	**°C**	**1221**	**°F**
Thermal Conductivity	**$W.m^{-1}.K^{-1}$ 205**	**Temperature dependence**	*(if available)* **215@125°C, 250@225°C**	
Density	**2.7**	**g/cm^3**		
Specific Heat	**910**		**J/kg.K**	

3. Target Canning Process

Blueprints: D25-M-3292 ; D25-M-3186 attached

General considerations:

1. The aluminum target consists of two parts referred to as upper half (D25-M-3188), normally positioned upstream and lower half (D25-M-3292) positioned downstream that are secured together with eight Allen screws located at the periphery of the target (D25-M-3186)
2. The water-tight seal is ensured by a silver-coated inconel c-ring (refer to D25-M-3186)
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 removed to facilitate better target cooling
5. Packaging and sealing of the target will be carried out in a glove box in Helium atmosphere

Sequence of operations for target closing for irradiation:

a. Create a target card as per C-A-OPM-ATT 19.3.6.2.a
b. Label the upper part of the target placing the letter stamps between the screw holes
c. Machine a well in the center of the lower part d=1.15 inches, depth=0.012+0.001”
d. Cut Th foil and monitor foil to 1.11 inch diameter circles
e. Wrap the Thorium foil in 0.001 Al foil
f. Place the foils inside the well of the lower half with Al monitor foil upstream
g. Position the c-ring in the grove of the lower half
h. Position the upper half of the target on top of the lower half and align the indexing slits
i. Insert eight Allan screws into the holes individually and secure them in the threads.
j. Tighten the Allan screws until the slight resistance is felt in the following sequence: 12-6-9-3-11-4-1-7 o’clock
k. Tighten the Allan screws until the upper and lower halves come in contact in the following sequence: 12-6-9-3-11-4-1-7 o’clock
l. Provide the sealed target to CAD vacuum group for He-leak check
m. Sign off for leak check test on the target card

4. Beam Characteristics		
Maximum Instantaneous Current Desired	**40**	**mA**
Average Current Desired	**90-110**	**µA**
Total Integrated Current Desired	**1530-1870**	**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 and complete CAD OPM 19.4.5.2 a. SOB should commence on or about 3:00 PM January 13. EOB should be on or about 8:00 AM the next morning to ensure same day packaging and shipment.

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

Note: Homogeneous energy distribution on RbCl target is ensured by using shaped degrader (d25m-3452) in the upstream box

See **Appendix 1** for details

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

Table 5c.1 Calculated energy deposition (MeV) in the cladding of Th target at different LINAC energies

Target Layers	200.3 MeV	181.01 MeV	160.53 MeV	138.52 MeV
Aluminum can window (upstream)	0.49	0.53	0.58	0.64
Al monitor foil	0.12	0.13	0.14	0.16
Al wrap	0.02	0.03	0.03	0.03
Th foil	0.33	0.36	0.39	0.43
Al wrap	0.02	0.03	0.03	0.03
Aluminum well bottom	4.23	4.55	4.98	5.59

The array comprised of 3 elements separated by 0.1 inch water gaps (see drawing 3453) and appendix 2 for thermal analysis.

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

Following irradiation the target capsule will be immediately transported to the TPL hot cells by

BLIP staff as per CAD OPM 19.4.5.3. In the main hot cell the bolts will be removed, the capsule opened, the Th foil removed in Aluminum wrapping and sealed in a screw top glass vial. The vial with the wrapped Th foil will be moved to a dispensing cell (hot box 2). The vial will be placed in an existing Type A shipping container by TPL staff. The container will then be turned over to Isotope and Special Materials 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=1.11×0.005 inch) foil will be dissolved in acid (20% stoichiometric access of conc. HCl + few drops of conc. HNO_3) by research staff (hot box 3 or 4). The resulting solution will be assayed for Na-22 on HPGe detector 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

Activation of Aluminum can for 17 h at 100 µA was calculated using activation equation yielding

Na-24 = 3.4 Ci; (T1/2=15 h)

Na-22 =6.68 mCi (T1/2=2.6 years)

Activation of Th foil was calculated using MCNPX code for 1 day irradiation at 192 MeV at EOB and 24 h after was carried out by Albert Hanson (Nuclear Science and Technology Department of BNL).

See Appendix 3

Decay Requirements

No decay at BLIP is required before the transfer to TPL

7. Expected Dose Rate

The dose rates from irradiated target **were measured experimentally** at EOB in 2013 for the following scenario:

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

Irradiation: 191.35 h at 200 MeV, accumulated charge 16486.1 µA-h

Dose measurements at BLIP were done 1 hour after EOB:

- 20 mR/h through the lead glass at operator point
- 22 mR/h through the hot cell shutter (0.5"SS+5"Pb+0.5"SS), 4 feet from the target to the dose point

The proposed irradiation will use **one** Th foil 1.11 ×0.005 and the total accumulated charge is expected to be **1440** µA-h. Therefore, the dose rates will be equal or less, than in previous experiment.

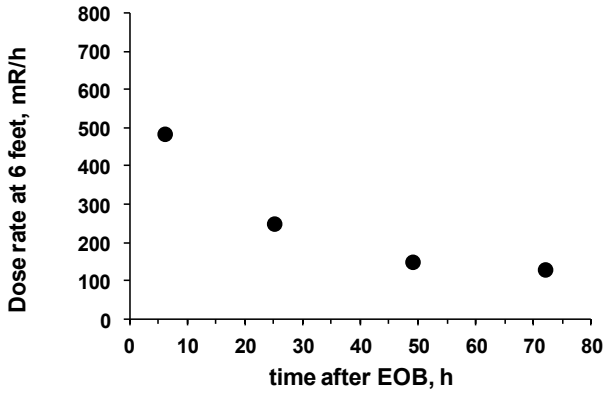


Figure 7.1 Time course of the dose rate from single Th foil irradiated for 8 days at 200 MeV. No shielding between dose point and source

8. Additional Safety Requirements

9. Special Operating Instructions

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-3186, 3188; 3452; 3453

Appendix 1

Table A1.1 Proton Energy Profile for Th target Array at 200 MeV: RbCl in downstream box

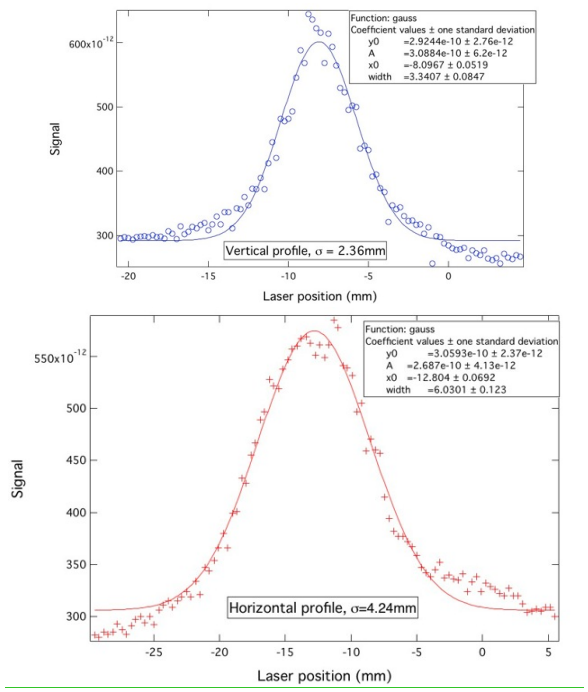
		Energy: 200.3 MeV					
		Layer	Material	density	thickness, inches/mm	Ei, MeV	Eout
	1	Be window	Berillium	1.85	0.012 / 0.3048	200.30	200.09
	2	AlBeMet window	AlBeMet	2.10	0.012 / 0.3048	200.09	199.86
	3	Beamline window	stainless steel	8.00	0.031 / 0.787	199.86	197.88
	4	water gap	water	1.00	0.106 / 2.68	197.88	196.65
Box 1 (upstream)	5	upstream box window	stainless steel	8.00	0.020 / 0.508	196.65	195.37
	6	water gap	water	1.00	0.100 / 2.54	195.37	194.20
	7	Th can window	Al 6061	2.70	0.020 / 0.508	194.20	193.70
	8	Al monitor foil	Al	2.70	0.005 / 0.127	193.70	193.58
	9	Aluminum wrap	Al	2.70	0.001 / 0.0254	193.58	193.56
	10	Th foil	Th	11.70	0.0049 / 0.125	193.56	193.22
	11	Aluminum wrap	Al	2.70	0.001 / 0.0254	193.22	193.20
	12	Aluminum well bottom	Al 6061	2.70	0.170 / 4.32	193.20	189.22
	13	water outside well	water	1.00	0.298 / 7.57	188.90	185.33
	14	cooling channel	water	1.00	0.100/ 2.54	185.33	184.12
	15	Aluminum degrader	Al 6061	2.7	1.736/ 44.09	184.12	135.45
	16	cooling channel	water	1.00	0.100/ 2.54	135.45	133.95
	17	Aluminum degrader (shaped)	Al 6061	2.7	0.354/9.00	133.95	122.40
	18	water end of the box	water	1.00	0.262/ 6.66	122.40	118.13
	19	Upstream box back window	stainless steel	8.00	0.020 / 0.508	118.13	116.31
	20	water gap between box windows	water	1.00	0.150 / 3.82	116.31	113.44
	21	Downstream box front window	stainless steel	8.00	0.020 / 0.508	113.44	111.55
Box 2 (downstream)	22	cooling channel	water	1.00	0.200 / 5.08	111.55	108.11
	23	vacuum box	stainless steel	8.00	0.029 / 0.737	108.11	105.37
	24		vacuum	0.00	0.596/15.14		
	25		stainless steel	8.00	0.029/0.737	105.37	102.37
	26	cooling channel	water	8.00	0.200 / 5.08	102.37	98.70
	27	can window	inconel	8.43	0.012 / 0.3048	98.70	97.40

	28	RbCl salt	RbCl	2.38	0.645 / 16.38	97.40	75.79
	29	can window	inconel	8.43	0.012 / 0.3048	75.79	74.21
	30	cooling channel	water	1.00	0.200 / 5.08	74.21	69.48
	31	can window	inconel	8.43	0.012 / 0.3048	69.48	67.79
	32	RbCl salt	RbCl	2.38	0.500 / 12.7	67.79	45.25
	33	can window	inconel	8.43	0.012 / 0.3048	45.25	42.91
	34	cooling channel	water	1.00	0.200 / 5.08	42.91	35.37
	35	Beam stop	Cu	8.96	0.220/ 5.59	35.37	stop
	36	cooling channel	water	1.00	0.200 / 5.08	0.00	0.00

Table A1.2 Energy on RbCl at different distances from the center

Diameter, inch	**0**	**1.15**	**1.151**	**1.27**	**1.568**	**1.846**	**1.935**	**2.206**
Energy on RbCl	97.40	97.81	97.48	97.48	97.92	98.28	97.89	97.89

Figure A1.1 Measured vertical and horizontal profile of LINAC beam (supplied by Roger Connolly) at 117 MeV



Appendix 2

Thermal analysis

Analysis of Thorium with Aluminum Foil Cladding

Chris Cullen

December 31, 2013

Finite Element Model

- 2D Axi-symmetric model
- (1) x .005" thick Thorium foil
- (1) .001" Aluminum foil on *each face* of Thorium foil
- Aluminum Target
- (1) x .005" Aluminum imaging foil
- Steady-state analysis
- Thermal contact resistance between each layer
- Steady state water cooling on exterior
- Gaussian Internal heat generation for all bodies

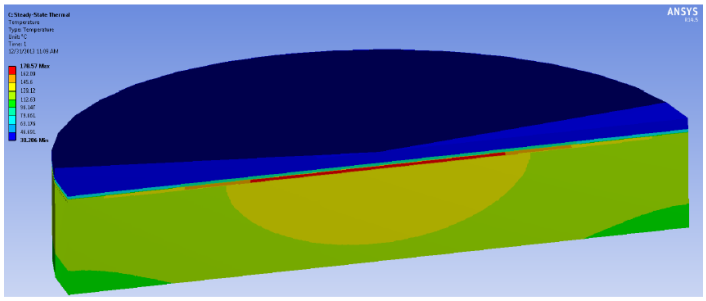
Conditions

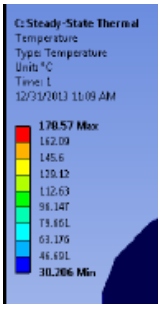
- Instantaneous Current = 40.0 mA
- Pulse width = .000425 sec
- Number of protons = 1.061×10^{14}
- Pulse Frequency = 6.667 Hz
- 140 MeV
  - worst case from 140 – 200 MeV
- 3 targets, (4) .10" water gaps
- 100% beam on target (conservative assumption)

Summary & Conclusion

- Maximum Aluminum temperature = 138 °C
- Aluminum melting temperature = 660 °C
- SAFE
- Maximum Thorium temperature = 179 °C
- Thorium melting temperature = 1755 °C
- SAFE

Target Temperature Profile





Appendix 3

Activation analysis of Th foil

<u>NOTE:</u> Activation analysis of Al can is given in Section 6

Table A3.1 MCNPX calculated spectrum of radionuclides and their activity at EOB produced in 0.125 mm Th foil upon bombardment with 192 MeV protons for 1 day at 100 uA.

Isotope	Z	Activity, Ci	Isotope	Z	Activity, Ci	Isotope	Z	Activity, Ci
th	231	3.35E-01	cs	132	2.86E-03	tb	152	5.18E-04
in	115m	1.13E-01	cu	67	3.10E-03	er	171	1.80E-03
ag	112	2.24E-01	i	124	2.76E-03	ge	71	1.89E-04
cd	115	1.50E-01	cd	111m	2.92E-03	tb	153	2.45E-04
pd	112	2.15E-01	as	76	4.27E-03	se	73	1.98E-03
sn	121	1.69E-01	zr	95	2.16E-03	er	169	2.06E-04
nb	97	4.21E-01	nb	90	6.34E-03	br	83	1.68E-01
zr	97	1.98E-01	gd	159	4.97E-03	cu	64	6.16E-04
nb	97m	1.87E-01	cu	66	4.98E-03	pd	101	1.16E-03
rh	105	8.07E-02	ni	66	2.62E-03	po	210	8.72E-05
y	93	2.99E-01	y	86	4.84E-03	pd	100	1.76E-04
ag	109m	1.92E-01	te	131m	3.11E-03	rb	81	5.42E-03
pd	109	1.92E-01	la	141	1.20E-01	as	74	1.48E-04
sb	127	5.06E-02	rb	86	1.87E-03	in	113m	1.39E-04
br	82	7.22E-02	sr	83	2.91E-03	sn	113	1.39E-04
te	127	6.47E-02	in	117	5.10E-01	yb	175	1.54E-04
i	133	9.59E-02	ce	135	4.32E-03	eu	146	1.43E-04
i	130	1.55E-01	te	119	4.57E-03	sb	125	1.11E-04
ag	113	8.28E-01	cs	131	1.56E-03	y	88	1.17E-04
xe	135	1.14E-01	ba	131	1.62E-03	rb	83	9.92E-05
ac	226	6.44E-02	rh	105m	5.90E-02	po	207	1.78E-04
mo	99	4.57E-02	te	121	1.45E-03	in	109	5.30E-03
ag	111	3.79E-02	i	126	1.49E-03	tm	173	7.32E-04
tc	99m	2.73E-02	kr	79	2.23E-03	ta	183	1.07E-04
po	214	2.10E-01	bi	211	1.64E-01	ce	133	2.77E-03
rn	218	2.10E-01	pb	211	9.85E-04	te	127m	2.89E-05
ra	222	2.10E-01	po	215	9.85E-04	sn	117m	7.39E-05
th	226	2.01E-01	rn	219	9.85E-04	lu	177	8.28E-05
sr	91	1.58E-01	ra	223	9.85E-04	ga	66	4.18E-04
ce	143	4.33E-02	at	211	1.05E-02	ta	184	4.12E-04
pa	229	4.08E-02	tl	207	1.63E-01	er	165	1.73E-04

as	77	2.52E-02	sm	156	7.75E-03	sn	127	2.06E-01
po	216	2.10E-02	sn	123	1.19E-03	zr	88	7.40E-05
rn	220	2.10E-02	pr	140	1.24E-02	fe	59	7.30E-05
ra	224	2.10E-02	nd	140	1.41E-03	at	216	1.41E-02
sb	126	2.15E-02	xe	135m	1.36E-02	fr	220	1.41E-02
xe	133	1.38E-02	nb	95	1.07E-03	rb	82	2.20E-02
bi	212	2.38E-02	tb	154	2.36E-03	sr	82	7.23E-05
pb	212	9.73E-03	br	77	1.41E-03	se	77m	8.07E-05
i	132	8.35E-02	ho	166	1.54E-03	tm	166	3.25E-04
y	91m	9.16E-02	sb	124	1.02E-03	k	42	2.50E-04
te	132	2.10E-02	ga	73	2.86E-02	ca	47	7.17E-05
i	131	1.71E-02	ge	73m	2.82E-02	bi	206	3.85E-05
pa	233	1.49E-02	ru	97	1.15E-03	at	209	1.12E-03
sn	125	1.50E-02	br	76	2.43E-03	cs	134	4.77E-05
po	212	3.71E-02	xe	133m	4.44E-04	cu	62	7.88E-04
bi	210	1.42E-02	rh	99	8.61E-04	re	186	5.66E-05
pa	228	2.52E-02	in	110	2.04E-02	zn	62	2.82E-04
pm	149	1.45E-02	po	211	1.43E-02	yb	169	4.70E-05
bi	213	1.28E-02	xe	127	6.83E-04	lu	172	4.98E-05
at	217	1.28E-02	tb	161	7.89E-04	gd	149	4.81E-05
fr	221	1.28E-02	ac	224	1.38E-01	sc	47	3.87E-05
ac	225	1.23E-02	la	132	2.06E-02	re	189	8.37E-05
pb	209	5.56E-02	cs	128	1.02E-02	k	43	8.90E-05
po	213	5.88E-02	ba	128	9.21E-04	y	85	2.07E-02
pa	232	1.81E-02	kr	83m	1.68E-01	al	28	9.26E-05
nb	96	2.06E-02	rb	84	6.76E-04	pr	138	6.20E-03
la	140	1.07E-02	tc	94	1.88E-02	mg	28	9.26E-05
sb	122	1.17E-02	cd	117	4.80E-01	nd	138	1.14E-03
y	90	1.14E-02	cs	127	8.32E-03	re	181	9.53E-05
sb	128	5.10E-02	ra	225	5.79E-04	sb	117	1.38E-02
pm	151	1.37E-02	eu	156	4.03E-04	tm	165	7.17E-05
pr	142	1.75E-02	te	129m	4.10E-04	as	73	3.48E-05
sb	119	9.60E-03	th	228	4.72E-04	kr	85	3.95E-05
tl	208	8.57E-03	tb	151	1.34E-03	co	55	1.03E-04
ge	77	3.08E-02	rb	88	2.06E-01	kr	76	1.14E-04
ac	228	1.05E-01	i	125	3.93E-04	sc	48	5.34E-05
ga	72	8.41E-03	i	122	5.70E-03	ta	177	4.30E-05
th	227	7.18E-03	xe	122	1.14E-03	yb	166	4.29E-05
i	135	8.64E-02	sb	118	1.29E-02	hf	171	1.26E-04
ba	140	6.50E-03	te	118	5.52E-04	dy	155	1.37E-04
la	135	1.08E-02	sr	85	4.62E-04	ta	175	1.34E-04

sm	153	8.58E-03	er	172	6.77E-04	ga	67	3.23E-05
xe	125	1.58E-02	la	134	9.54E-03	sr	90	2.60E-05
y	92	2.15E-01	ce	134	5.98E-04	mo	90	4.79E-04
cs	129	9.07E-03	at	210	3.68E-03	ho	167	5.04E-03
rh	100	1.21E-02	kr	88	1.58E-01	h	3	2.39E-05
pr	145	8.76E-02	tm	172	3.96E-04	lu	171	1.99E-05
zn	72	7.81E-03	dy	166	5.29E-04	sn	110	1.33E-03
tc	95	1.24E-02	as	72	7.98E-04	tm	167	2.38E-05
ru	105	2.08E-01	te	131	1.54E-01	lu	179	8.21E-04
zr	89	5.97E-03	rh	106	5.09E-02	eu	149	2.15E-05
y	89m	5.96E-03	ru	106	4.15E-04	u	230	6.99E-06
y	87	5.94E-03	la	133	9.04E-03	w	185	2.01E-05
rh	103m	4.83E-03	sr	92	1.72E-01	cd	109	1.80E-05
y	91	3.70E-03	ag	105	3.71E-04	pm	143	1.98E-05
in	111	5.83E-03	tb	156	4.10E-04	dy	157	1.47E-04
nd	147	4.77E-03	ba	136m	3.77E-04	pb	210	1.54E-05
ru	103	4.49E-03	pd	103	3.51E-04	ta	176	1.47E-04
pa	230	4.44E-03	zr	86	8.58E-04	eu	145	1.86E-05
te	129	1.82E-01	tb	155	3.40E-04	hf	181	1.64E-05
i	123	1.28E-02	cd	117m	4.31E-02	xe	131m	5.36E-06
pr	143	2.28E-03	pr	139	1.25E-02	rh	101	1.51E-05
ce	137	2.36E-02	rn	211	9.18E-04	ac	227	1.49E-05
sb	129	1.47E-01	cd	115m	2.92E-04	pm	150	7.24E-03
sr	89	3.23E-03	pr	144	3.10E-02	eu	147	1.44E-05
cs	136	3.37E-03	ce	144	2.90E-04	se	75	1.36E-05
ce	141	2.46E-03	ag	107m	3.42E-03	gd	151	8.09E-06
tc	96	3.56E-03	cd	107	3.43E-03	tb	160	1.29E-05
pm	148	3.15E-03	ge	69	4.10E-04	nd	141	9.25E-03
kr	85m	1.09E-01	as	71	3.42E-04	dy	153	1.56E-04
eu	157	7.70E-03	ce	139	2.49E-04	pm	147	7.72E-06
in	117m	4.38E-01	tl	209	2.68E-04			

Table A3.2 MCNPX calculated spectrum of radionuclides and their activity 24 hours after EOB produced in 0.125 mm Th foil upon bombardment with 192 MeV protons for 1 day at 100 uA.

Isotope	Z	Activity, Ci	Isotope	Z	Activity, Ci	Isotope	Z	Activity, Ci
th	231	1.75E-01	cs	132	2.57E-03	tb	152	2.10E-04
in	115m	1.20E-01	cu	67	2.37E-03	er	171	1.98E-04
ag	112	1.14E-01	i	124	2.34E-03	ge	71	1.96E-04
cd	115	1.11E-01	cd	111m	2.31E-03	tb	153	1.96E-04
pd	112	9.74E-02	as	76	2.27E-03	se	73	1.93E-04
sn	121	9.16E-02	zr	95	2.15E-03	er	169	1.92E-04
nb	97	7.43E-02	nb	90	2.11E-03	br	83	1.78E-04
zr	97	7.39E-02	gd	159	2.07E-03	cu	64	1.66E-04
nb	97m	7.01E-02	cu	66	1.93E-03	pd	101	1.63E-04
rh	105	6.88E-02	ni	66	1.93E-03	po	210	1.60E-04
y	93	5.78E-02	y	86	1.90E-03	pd	100	1.45E-04
ag	109m	5.72E-02	te	131m	1.84E-03	rb	81	1.45E-04
pd	109	5.72E-02	la	141	1.83E-03	as	74	1.43E-04
sb	127	4.63E-02	rb	86	1.80E-03	in	113m	1.38E-04
br	82	4.51E-02	sr	83	1.75E-03	sn	113	1.38E-04
te	127	4.49E-02	in	117	1.71E-03	yb	175	1.32E-04
i	133	4.37E-02	ce	135	1.69E-03	eu	146	1.23E-04
i	130	4.04E-02	te	119	1.63E-03	sb	125	1.22E-04
ag	113	3.75E-02	cs	131	1.56E-03	y	88	1.17E-04
xe	135	3.68E-02	ba	131	1.53E-03	rb	83	1.17E-04
ac	226	3.63E-02	rh	105m	1.43E-03	po	207	1.14E-04
mo	99	3.55E-02	te	121	1.43E-03	in	109	1.01E-04
ag	111	3.50E-02	i	126	1.41E-03	tm	173	9.77E-05
tc	99m	3.33E-02	kr	79	1.39E-03	ta	183	9.75E-05
po	214	3.06E-02	bi	211	1.34E-03	ce	133	9.23E-05
rn	218	3.06E-02	pb	211	1.34E-03	te	127m	8.50E-05
ra	222	3.06E-02	po	215	1.34E-03	sn	117m	8.46E-05
th	226	3.06E-02	rn	219	1.34E-03	lu	177	8.19E-05
sr	91	2.76E-02	ra	223	1.34E-03	ga	66	8.17E-05
ce	143	2.66E-02	at	211	1.34E-03	ta	184	8.03E-05
pa	229	2.49E-02	tl	207	1.34E-03	er	165	7.58E-05
as	77	2.18E-02	sm	156	1.32E-03	sn	127	7.48E-05
po	216	2.10E-02	sn	123	1.19E-03	zr	88	7.37E-05
rn	220	2.10E-02	pr	140	1.15E-03	fe	59	7.19E-05
ra	224	2.10E-02	nd	140	1.15E-03	at	216	7.16E-05
sb	126	2.03E-02	xe	135m	1.12E-03	fr	220	7.16E-05
xe	133	2.02E-02	nb	95	1.09E-03	rb	82	7.03E-05

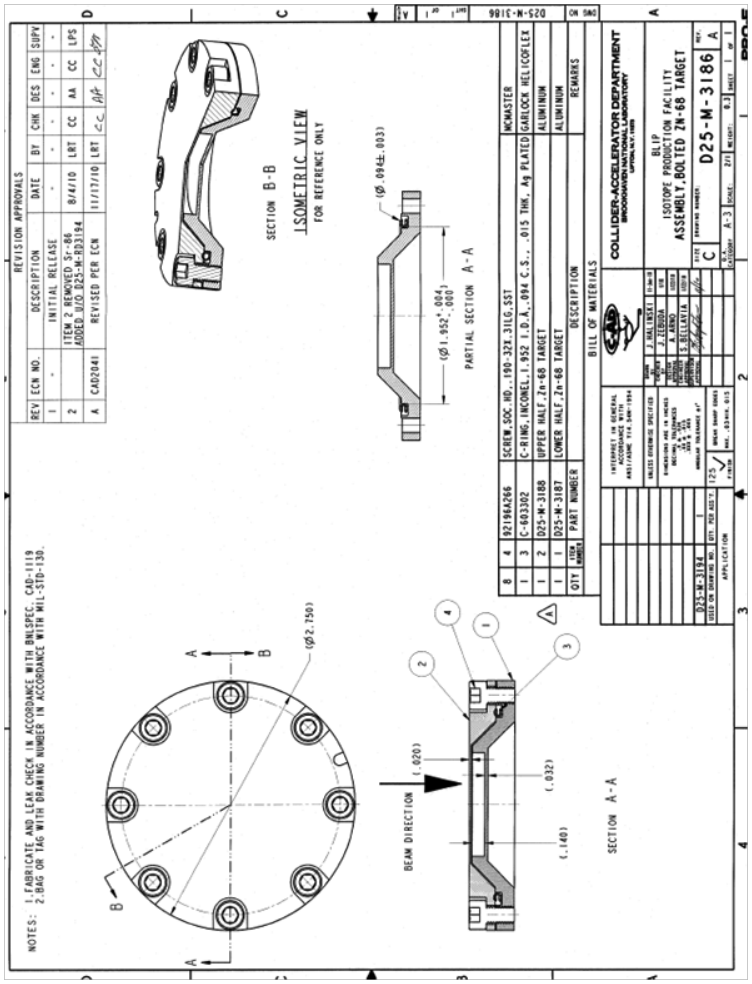
bi	212	1.98E-02	tb	154	1.09E-03	sr	82	7.03E-05
pb	212	1.95E-02	br	77	1.07E-03	se	77m	6.97E-05
i	132	1.76E-02	ho	166	1.05E-03	tm	166	6.88E-05
y	91m	1.75E-02	sb	124	1.01E-03	k	42	6.50E-05
te	132	1.70E-02	ga	73	9.33E-04	ca	47	6.16E-05
i	131	1.64E-02	ge	73m	9.21E-04	bi	206	5.85E-05
pa	233	1.49E-02	ru	97	9.19E-04	at	209	5.19E-05
sn	125	1.40E-02	br	76	9.11E-04	cs	134	4.76E-05
po	212	1.27E-02	xe	133m	8.36E-04	cu	62	4.75E-05
bi	210	1.24E-02	rh	99	8.25E-04	re	186	4.71E-05
pa	228	1.18E-02	in	110	7.91E-04	zn	62	4.67E-05
pm	149	1.18E-02	po	211	7.86E-04	yb	169	4.60E-05
bi	213	1.15E-02	xe	127	7.25E-04	lu	172	4.49E-05
at	217	1.15E-02	tb	161	7.15E-04	gd	149	4.47E-05
fr	221	1.15E-02	ac	224	7.14E-04	sc	47	4.39E-05
ac	225	1.15E-02	la	132	6.96E-04	re	189	4.29E-05
pb	209	1.14E-02	cs	128	6.94E-04	k	43	4.24E-05
po	213	1.13E-02	ba	128	6.94E-04	y	85	4.19E-05
pa	232	1.07E-02	kr	83m	6.79E-04	al	28	4.19E-05
nb	96	1.01E-02	rb	84	6.62E-04	pr	138	4.18E-05
la	140	9.19E-03	tc	94	6.23E-04	mg	28	4.18E-05
sb	122	9.05E-03	cd	117	6.07E-04	nd	138	4.16E-05
y	90	8.82E-03	cs	127	5.88E-04	re	181	4.15E-05
sb	128	8.13E-03	ra	225	5.53E-04	sb	117	4.15E-05
pm	151	7.73E-03	eu	156	5.47E-04	tm	165	4.12E-05
pr	142	7.31E-03	te	129m	5.42E-04	as	73	4.11E-05
sb	119	7.18E-03	th	228	5.25E-04	kr	85	4.06E-05
tl	208	7.12E-03	tb	151	5.21E-04	co	55	4.01E-05
ge	77	7.08E-03	rb	88	5.05E-04	kr	76	3.70E-05
ac	228	7.03E-03	i	125	5.04E-04	sc	48	3.65E-05
ga	72	6.98E-03	i	122	5.00E-04	ta	177	3.20E-05
th	227	6.92E-03	xe	122	4.98E-04	yb	166	3.20E-05
i	135	6.87E-03	sb	118	4.93E-04	hf	171	3.19E-05
ba	140	6.16E-03	te	118	4.93E-04	dy	155	2.87E-05
la	135	6.11E-03	sr	85	4.92E-04	ta	175	2.75E-05
sm	153	6.02E-03	er	172	4.83E-04	ga	67	2.61E-05
xe	125	5.92E-03	la	134	4.82E-04	sr	90	2.60E-05
y	92	5.86E-03	ce	134	4.82E-04	mo	90	2.55E-05
cs	129	5.75E-03	at	210	4.73E-04	ho	167	2.42E-05
rh	100	5.54E-03	kr	88	4.52E-04	h	3	2.39E-05
pr	145	5.48E-03	tm	172	4.36E-04	lu	171	2.38E-05

zn	72	5.46E-03	dy	166	4.32E-04	sn	110	2.32E-05
tc	95	5.41E-03	as	72	4.21E-04	tm	167	2.31E-05
ru	105	5.03E-03	te	131	4.15E-04	lu	179	2.26E-05
zr	89	4.89E-03	rh	106	4.14E-04	eu	149	2.17E-05
y	89m	4.89E-03	ru	106	4.14E-04	u	230	2.03E-05
y	87	4.88E-03	la	133	3.93E-04	w	185	2.01E-05
rh	103m	4.76E-03	sr	92	3.71E-04	cd	109	1.99E-05
y	91	4.58E-03	ag	105	3.65E-04	pm	143	1.98E-05
in	111	4.57E-03	tb	156	3.61E-04	dy	157	1.96E-05
nd	147	4.53E-03	ba	136m	3.58E-04	pb	210	1.93E-05
ru	103	4.42E-03	pd	103	3.46E-04	ta	176	1.88E-05
pa	230	4.26E-03	zr	86	3.13E-04	eu	145	1.66E-05
te	129	4.10E-03	tb	155	3.08E-04	hf	181	1.62E-05
i	123	3.94E-03	cd	117m	3.07E-04	xe	131m	1.55E-05
pr	143	3.88E-03	pr	139	3.01E-04	rh	101	1.54E-05
ce	137	3.81E-03	rn	211	2.94E-04	ac	227	1.50E-05
sb	129	3.37E-03	cd	115m	2.93E-04	pm	150	1.46E-05
sr	89	3.23E-03	pr	144	2.90E-04	eu	147	1.40E-05
cs	136	3.20E-03	ce	144	2.90E-04	se	75	1.39E-05
ce	141	3.04E-03	ag	107m	2.72E-04	gd	151	1.29E-05
tc	96	3.03E-03	cd	107	2.72E-04	tb	160	1.28E-05
pm	148	2.77E-03	ge	69	2.69E-04	nd	141	1.23E-05
kr	85m	2.68E-03	as	71	2.65E-04	dy	153	1.16E-05
eu	157	2.60E-03	ce	139	2.64E-04	pm	147	1.11E-05
in	117m	2.60E-03	tl	209	2.41E-04			

Appendix 4

Drawings

<u>NOTE:</u> The Th bolted target share the same design as Zn-68 target (for production of Cu - 67), except for the well size which is tailored for each run individually. Please, disregard different Ids of the drawings. ***The well size for this run is d×h=1.15×0.012 inch***



D25-M-3186: Conceptual drawing of the assembled Th target. The well is tailored for each experiment according to the cladding size (section 3)

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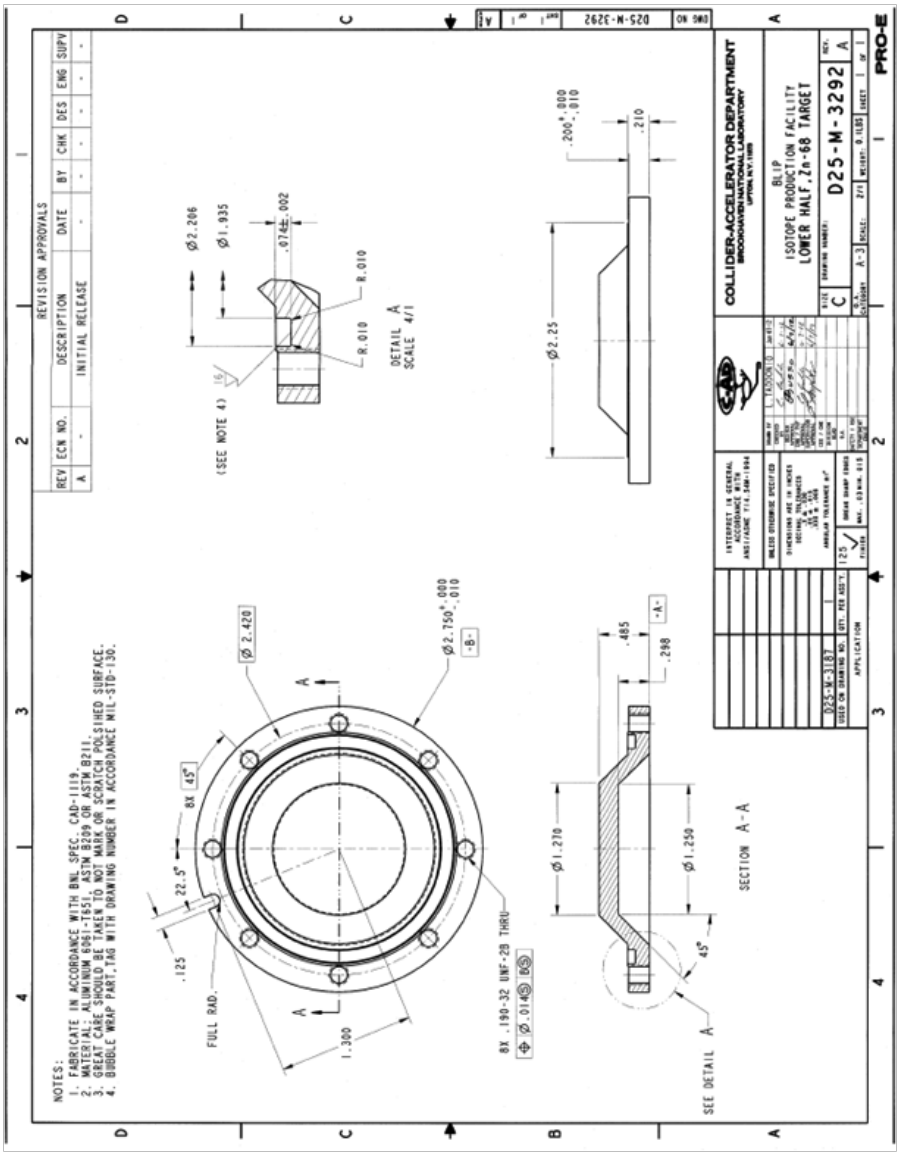

Drawing D25-m-3292: lower part of Th target before well machining

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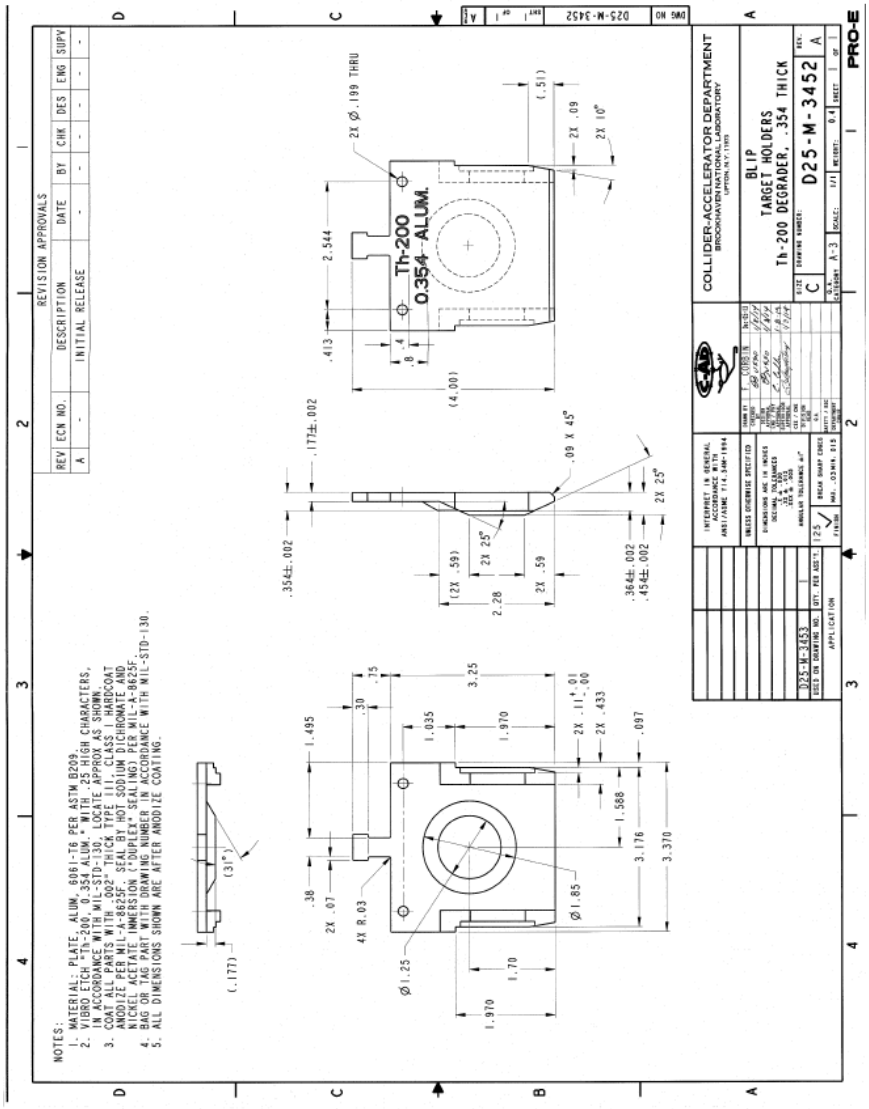

Drawing D25-m-3452: Shaped degrader to ensure homogeneous energy profile on RbCl for 200

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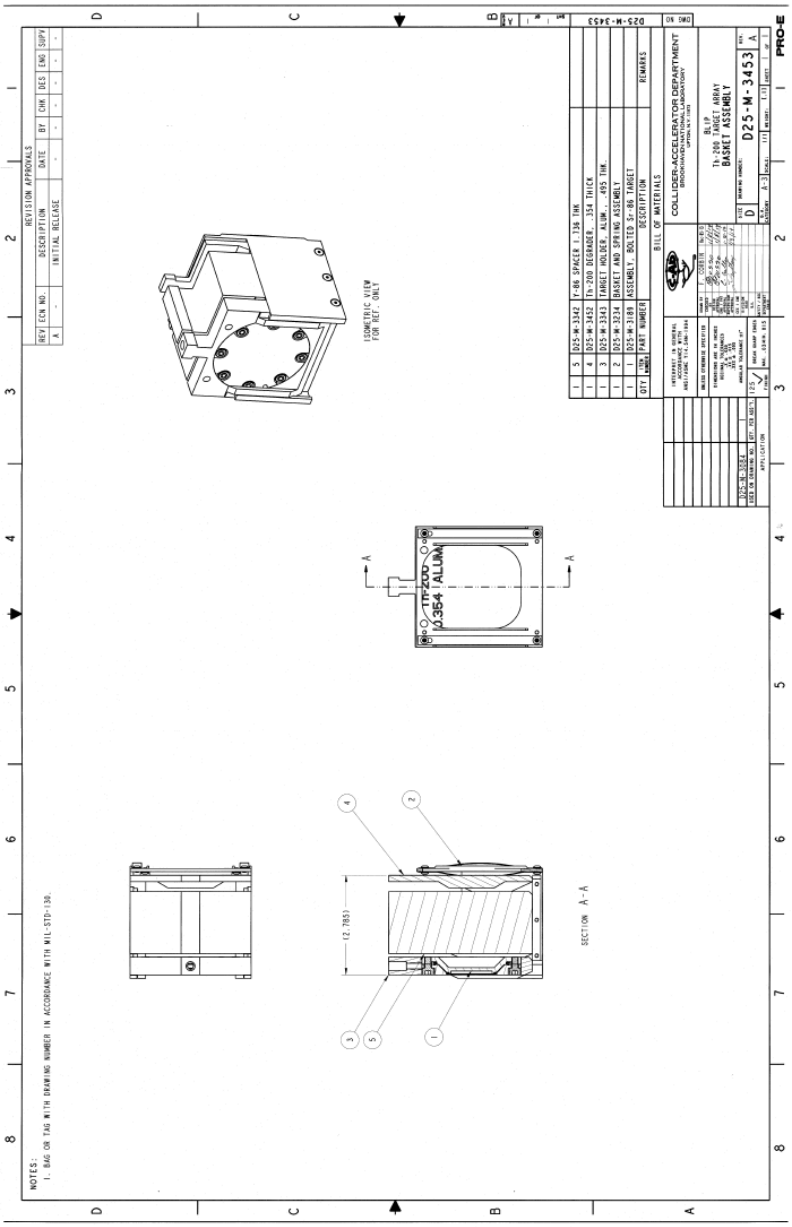
MeV Th array (layer 17)



Drawing D25-m-3453: Target assembly for Th irradiation at 200 MeV: upstream box

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