***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***

C-A OPERATIONS PROCEDURES MANUAL

# 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 Ga target at BLIP to produce Ge-68/Zn-65<br><br>[MIRP-CAD] |

**Instructions**

## 1. Overview

The purpose of this experiment is to irradiate Ga to produce radionuclide Ge-68 at the request of DOE isotope program

## 2. Target Material and Properties

| | | | |
|---|---|---|---|
| **Target Name:** | | **Target & Canning No.** *Assign unique no.* (year-00x) | **TBD** |

### Target Material Properties

| | | | | |
|---|---|---|---|---|
| **Purity or Grade** | 99.999% | | | |
| **Chemical Formula** | Ga | | | |
| **Physical Characteristics at 70 ºF or 21 ºC** | **Solid (melting point 29.78 $^0$C)** | | | |
| **Physical Form** | **Foil** | **n/a** | **Powder** | **n/a** |
| | **Diameter (inches/mm)** | **2.250** | **Pressed (Torr)** | **n/a** |
| **Elements (%)** | **Ga** | | | |
| **Melting Point** | **29.78** | **ºC** | **n/a** | **ºF** |
| **Boiling Point** | **2403** | **ºC** | **n/a** | **ºF** |
| **Thermal Conductivity** | 40.6 **W.m$^{-1}$.K$^{-1}$** | **Temperature dependence** | ***(if available)*** | |
| **Density** | **Sol. 5.904, liq. 6.095** | | **g/cm$^3$** | |
| **Specific Heat** | **25.86** | | **J/mol.K** | |

### Target Material Reactions / Properties

| | | | | | | |
|---|---|---|---|---|---|---|
| **Does the Target material react with any of the following?** | **Aluminium** | **no** | **Air** | **oxide** | **$CO_2$** | **no** |
| | **$H_2O$** | **no** | **Lead** | **no** | **Zinc** | **no** |
| | **Inconel 600** | **np** | **S/Steel** | **no** | **Niobium** | **Yes at 400$^0$C[1]** |

### Canning Material Properties

| | | | | |
|---|---|---|---|---|
| **Chemical Formula** | **Nb** | | | |
| **Can Wall Thickness (inches/mm)** | **0.012 (0.3048 )** | | | |
| **Can Dimensions (inches/mm)** | **Can Diameter 2.75 (69.85)** | | **Can Width: 0.220 (5.588)** | |
| **Melting Point** | **2468** | **ºC** | **n/a** | **ºF** |
| **Thermal Conductivity** | **54 W.m$^{-1}$.K$^{-1}$** | **Temperature dependence** | *(if available)n/a* | |
| **Density** | **8.57** | **g/cm$^3$** | | |
| **Specific Heat** | **24.60** | | **J/mol.K** | |

[1] Kelman L.R., Wilkinson, W.D., Yagee, F.L. Resistance of Metals to Attack by Liquid Metals, Argonne National Laboratory report ANL-4417, July 1950, pp139.

## 3. Target Canning Process

The target has been beam-welded by EB industries, following CAD OPM 19.17.1

| 4. Beam Characteristics | | |
|---|---|---|
| **Beam shape:** | Rastered | |
| **Raster parameters:** | Gaussian beam spot 12mm FWHM, rotation frequency 5kHz , 4 sweeps 15mm radius per one sweep 5.5mm radius | |
| **Power density:** | 110 watt/mm2 | |
| **Maximum Instantaneous Current Desired** | **145** | **µA** |
| **Average Current Desired** | **145** | **µA** |
| **Total Integrated Current Desired** | **97440 (4 weeks at 145 MeV)** | **µA-hrs** |
| **Maximum Proton Energy on Target Material** | **28** | **MeV** |

## 5. Experiment Description

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

Irradiate target at BLIP in the low energy slot for 4 weeks at 145 uA and transport to BLIP after irradiation. Follow CAD OPM 19.17.20 to install or remove the target.

**5.b Target array in Box 1:**

Target array is given in the Appendix 1. Briefly, upstream to downstream: [vacuum degrader], [1$^{st}$ RbCl] [2$^{nd}$ RbCl], [Ga target] with 5 mm water gaps

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

The summary of successfully irradiated and processed targets is given under 9. Special Operating Instructions. See details of thermal analysis in the appendix 2

### Summary & Conclusion

- Maximum Gallium temperature = 433 °C
- Ga boiling temperature = 2400 °C
- SAFE
- Maximum Niobium temperature = 379 °C
- Nb reacts with Ga at 400°C
- SAFE
- Maximum Nb heat flux at water surface = 207 W/cm$^2$
- Critical Heat Flux = 227 W/cm$^2$
- Safe

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

Follow CAD OPM 19.17.30 to transport the target from BLIP in a pig

Follow CAD OPM 19.9.4. to open the target using target cutter

Follow 19.18.30 Ge-68 from Ga Metal Targets for target processing

**5.e Disposal of waste:**

Liquid waste will be neutralized and disposed in D tank system. Target body will be disposed as TPL solid waste CAD OPM 19.30.3

## 6. Activation Analysis of Target Material and Can

**Target material:**

The activation of Ga metal was calculated **using activation equation[2] and cross section data assuming 4 week** irradiation. See Appendix 3 for cross section data. The Table contains the list of the nuclides contributing to the dose rate.

| Nuclide | T1/2, d | Activity EOB, Ci | Activity 24 h past EOB, Ci | Activity 7 d past EOB, Ci |
|---|---|---|---|---|
| **Ge-68** | 287 | 2.81 | 2.80 | 2.76 |
| **Ga-68** | 0.047 | 2.81 | 2.80 | 2.76 |
| **Ge-69** | 1.625 | 36.34 | 23.74 | 1.84 |
| **Ga-67** | 3.263 | 2.53 | 2.05 | 0.57 |
| **Zn-65** | 244 | 0.57 | 0.57 | 0.56 |

**Target cladding:**

Since the beam will stop in Ga metal and will not reach downstream window only the upstream Nb window will be activated. Activation of the upstream Nb window is **insignificant** compared to activation of Ga metal due to small thickness and unfavourable cross section data (see appendix 4). Nuclides produced in the Nb window are Zr-88 (83.4 d, E=392.8 keV (I=94.5%)), Zr-89 (78.4 h, 909.2 keV, (I=99.87%)).

**Decay Requirements**

Decay At BLIP for 7 days is required

## 7. Expected Dose Rate

The dose rate was calculated using Microshied 7.02 based on the data for Ga target.

The dose rate to the operator at BLIP after 28 days irradiation at 145 μA is 0.73 mR/h

[2]Helus, F., Wobler, G., 1983. Activation techniques, in: Helus, F., Colombetti, L.G. (Eds.), Radionuclide Production. CRC Press, Inc, p. 95

The dose rate after 24 h cool off time is 0.48 mR/h
The dose rate after 7 days cool off time is 0.045 mR/h
See appendix 5 for Microshield reports.

## 8. Additional Safety Requirements

Target needs to undergo visual inspection 1 h after bombardment commencement, at the end of the day, and next day, weekly, and every time it is lifted. BLIP Cooling water will be monitored for Zn-65 peak at 1115 keV

## 9. Special Operating Instructions/Additional considerations

### Summary of irradiated and processed Ga metal targets

**(provided by J. Fitzsimmons)**

| | 06/01/ 2012 | 07/02/ 2012 | 08/09/ 2012 | 05/23/ 2013 | 08/26/ 2013 |
|---|---|---|---|---|---|
| **Target name** | BQR | BQQ | BQU | BPR | BPS |
| **Irradiation charge µA-h*** | 36008 | 40352 | 24950 | 44814 | 31916 |
| **Ge (mCi) Leached** | 700 | 610 | 257 | 410 | 359-430 |
| **Total Ge-68 recovered mCi** | 666 | 595 | 257 | 420 | 408 |
| **Ge activity recovered by fraction mCi** | 666 | 128/465[c]/<5 | 257 | 140/274 | 408 |
| **mCi/ µA-h** | 0.0194 | 0.0151 | 0.0103 | 0.0091 | 0.0135 |
| **µCi/ µA-h** | 19.44 | 15.12 | 10.30 | 9.15 | 13.47 |

*irradiated according to production schedule

| Supporting Documentation | |
|---|---|
| **References** | |
| | |
| | |

## Appendix 1.

Proton Energy Profile for Ga target Array

| layer number | Layer | Material | density | inches | mm | Ei | Eout |
|---|---|---|---|---|---|---|---|
| 1 | Be window | Berillium | 1.85 | 0.012 | 0.305 | 116.50 | 116.20 |
| 2 | AlBeMet window | AlBeMet | 2.10 | 0.012 | 0.305 | 116.20 | 115.86 |
| 3 | Beamline window | stainless steel | 7.99 | 0.031 | 0.787 | 115.86 | 113.00 |
| 4 | water gap | water | 1.00 | 0.106 | 2.692 | 113.00 | 111.18 |
| 5 | BOX front window | stainless steel | 7.99 | 0.020 | 0.508 | 111.18 | 109.26 |
| 6 | water gap | water | 1.00 | 0.200 | 5.080 | 109.26 | 105.72 |
| 7 | stainless steel | stainless steel | 7.99 | 0.058 | 1.473 | 105.72 | 99.88 |
| 8 | water gap | water | 1.00 | 0.200 | 5.080 | 99.88 | 96.08 |
| 9 | can window | inconel | 8.43 | 0.012 | 0.305 | 96.08 | 94.71 |
| 10 | RbCl salt | RbCl | 2.20 | 0.670 | 17.018 | 94.71 | 74.19 |
| 11 | can window | inconel | 8.43 | 0.012 | 0.305 | 74.19 | 72.53 |
| 12 | water gap | water | 1.00 | 0.200 | 5.080 | 72.53 | 67.64 |
| 13 | can window | inconel | 8.43 | 0.012 | 0.305 | 67.64 | 65.86 |
| 14 | RbCl salt | RbCl | 2.20 | 0.524 | 13.309 | 65.86 | 43.72 |
| 15 | can window | inconel | 8.43 | 0.012 | 0.305 | 43.72 | 41.23 |
| 16 | water gap | water | 1.00 | 0.200 | 5.080 | 41.23 | 33.25 |
| 17 | Can window | Nb | 8.57 | 0.012 | 0.305 | 33.25 | 30.40 |
| 18 | Ga metal | Ga | 6.10 | 0.196 | 4.979 | 30.40 | stop |
| 19 | Can window | Nb | 8.57 | 0.012 | 0.305 | 0.00 | 0.00 |
| 20 | water gap | water | 1.00 | 0.200 | 5.080 | 0.00 | 0.00 |
| 21 | Copper | Cu | 8.96 | 0.348 | 8.839 | 0.00 | 0.00 |
| 22 | water gap | water | 1.00 | 0.200 | 5.08 | 0.00 | 0.00 |

**Appendix 2**

Heal load analysis

**provided by Chris Cullen**

## Gallium Target, Niobium Holder Thermal Analysis

Chris Cullen

January 13, 2016

## Conditions

- Steady state average current = 145 µA, 116 MeV
- Pulse width = .000450 sec
- Pulse Frequency = 6.667 Hz
- 4820 Watts (32.3 MeV) total power deposited
- Assumed RbCl density = 2.20 gm/cc
- 5 targets, (6) .20" water gaps
- Target placed in upstream box
- Gaussian Beam FWHM=12.0 mm
- Z axis energy deposition gradient included to account for Bragg Peak
- Raster pattern 15 mm & 5.5 mm radii (4:1)

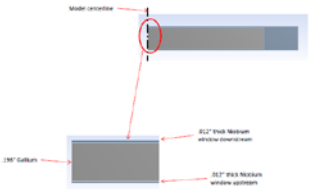
## Finite Element Model

- 2D Axi-symmetric model
- Niobium target holder
- Steady-state analysis
- Steady state water cooling = 5604 W/m²*°C (22.5 gpm mass flow)

## Generic Target

- Axi-symmetric analysis region highlighted in blue
  - Ref. D25-M-3095

## Finite Element Model Target Geometry



## Summary & Conclusion

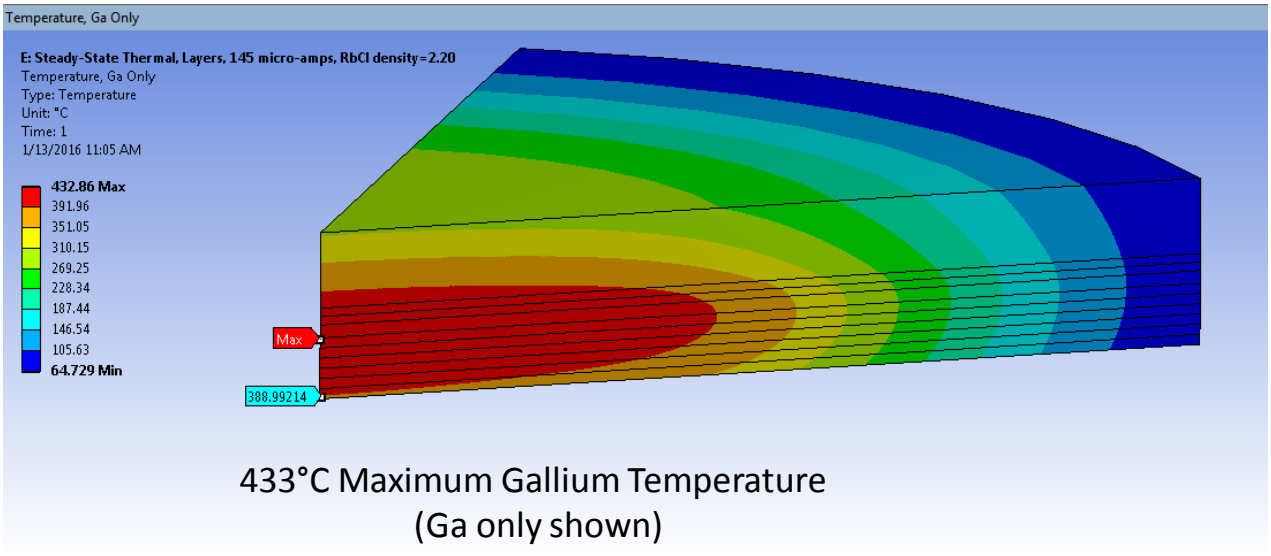
- Maximum Gallium temperature = 433 °C
- Ga boiling temperature = 2400 °C
- SAFE
- Maximum Niobium temperature = 379 °C
- Nb reacts with Ga at 400°C
- SAFE
- Maximum Nb heat flux at water surface = 207 W/cm²
- Critical Heat Flux = 227 W/cm²
- Safe

## Reference Slides

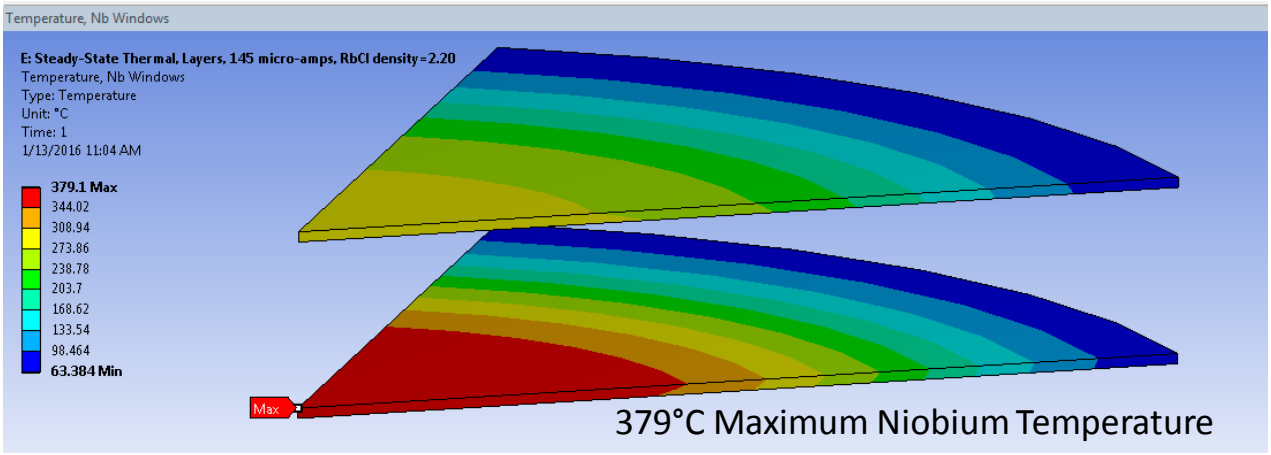
- Files
  - D:\Jobs - Active\BLIP\Target Analyses\FY 16\Ga\Ga Thermal with Raster. wbpj
  - D:\Jobs - Active\BLIP\Target Analyses\FY 16\Ga\BLIP-HTC-R2 Ga Thermal.xlsx, CHFs Bernath Correlation
  - D:\Jobs - Active\BLIP\Target Analyses\FY 16\Ga\FY2016 RbCl energy propogation_raster_Cu_stop_10_28.xlsx

**Target drawing is on the page 13: D25-M-3095**

# Target Temperature Profile

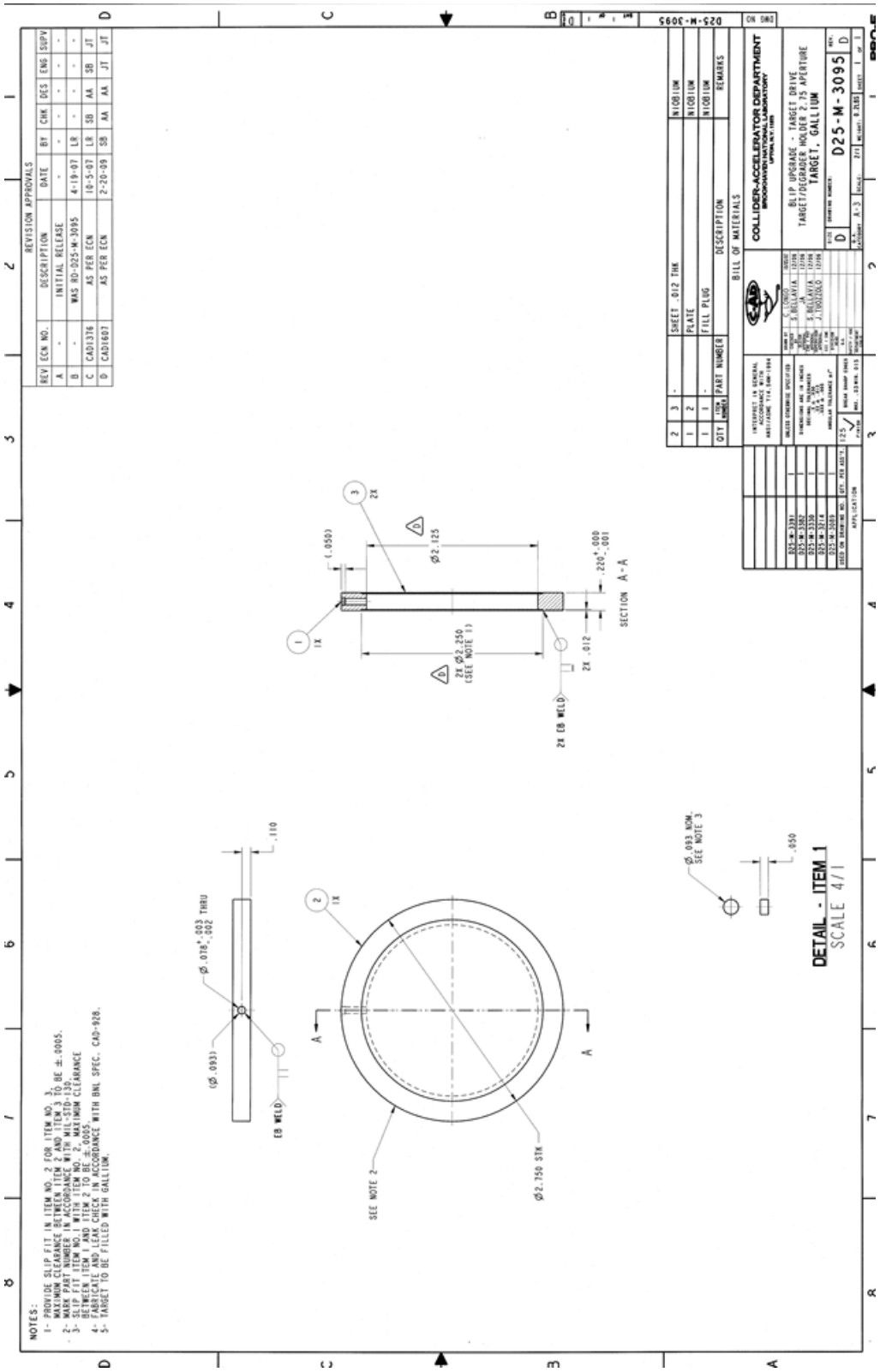



433°C Maximum Gallium Temperature
(Ga only shown)




379°C Maximum Niobium Temperature

**Ga target drawing**



**Appendix 3**

**Cross section data for activation of Ga metal target for energies ~27→0 MeV**

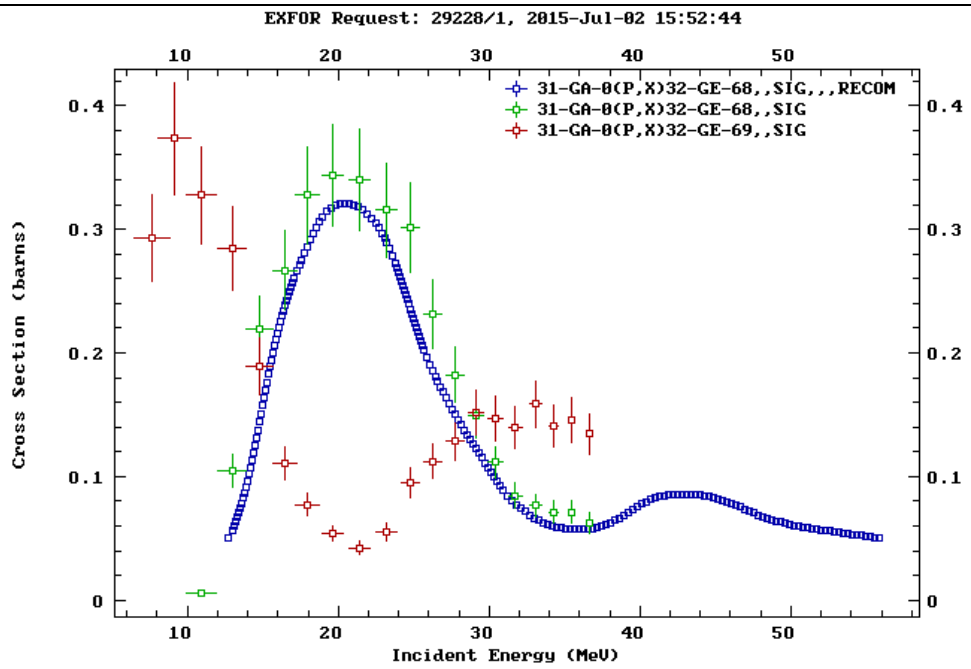



**Figure A3-1.** Cross section data for production of Ge-68 and Ge-69 isotopes from natural Ga

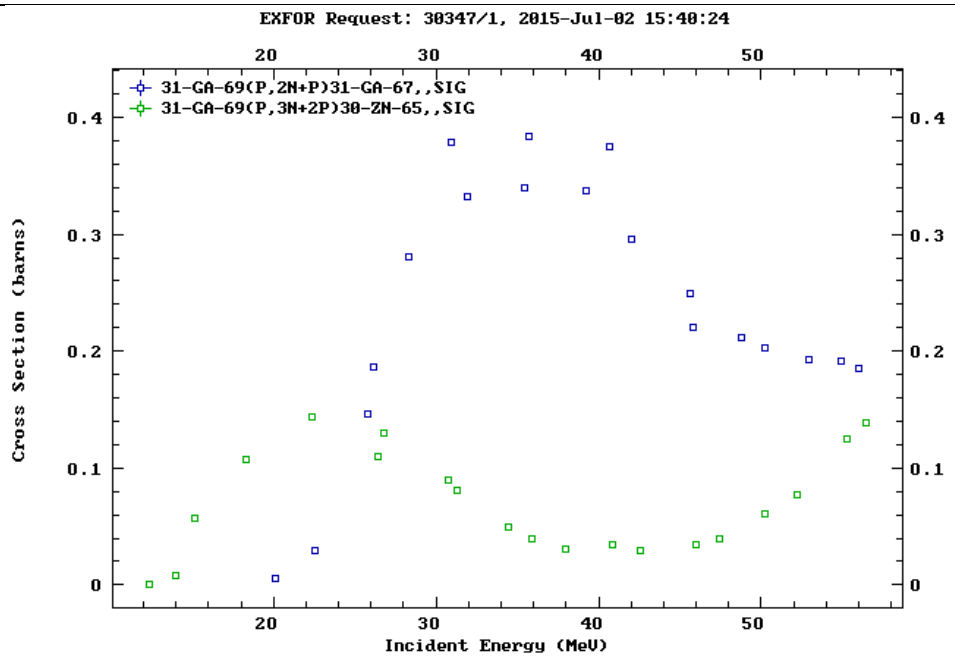



**Figure A3-2.** Cross section data for production of Ga-67 and Zn-65 isotopes from Ga-69

**Appendix 4**

**Cross section data for activation of Nb window for proton energy ~30→27 MeV**

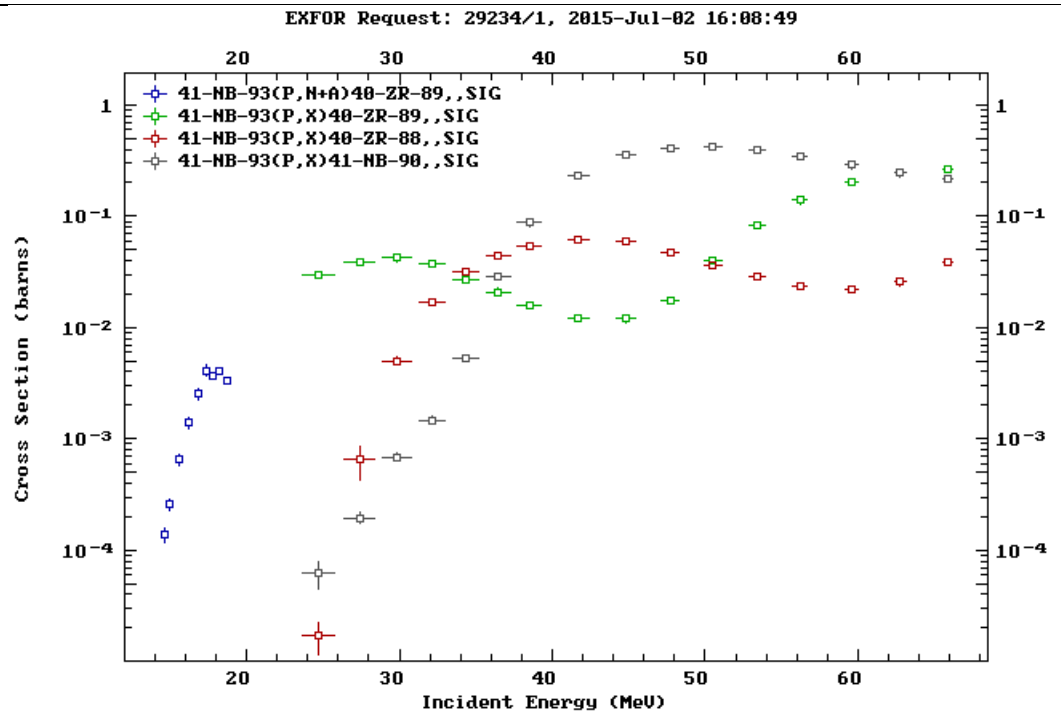



**Figure A4-1**. Cross section data for activation of the upstream Nb window. The energy is 30→27 MeV

**Appendix 5**

**Microshield reports**

**Dose rate to the operator from Ga target at BLIP at EOB**

| MicroShield 7.02<br>BNL (7.02-0000) |
|---|

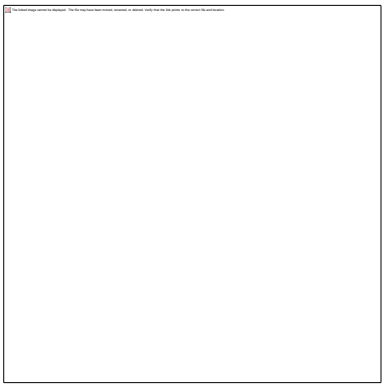
| Date | By | Checked |
|---|---|---|
| | | |

| Filename | Run Date | Run Time | Duration |
|---|---|---|---|
| Ga target EOB_28d 145 uA beam.ms7 | January 4, 2016 | 4:22:51 PM | 00:00:00 |

| Project Info | |
|---|---|
| Case Title | Ga BLIP @EOB |
| Description | Dose rate EOB after 4 weeks at 145 uA |
| Geometry | 8 - Cylinder Volume - End Shields |

| Source Dimensions | |
|---|---|
| Height | 0.498 cm (0.2 in) |
| Radius | 3.493 cm (1.4 in) |

| Dose Points | | | |
|---|---|---|---|
| A | X | Y | Z |
| #1 | 0.0 cm (0.0 in) | 76.2 cm (2 ft 6.0 in) | 0.0 cm (0.0 in) |



| Shields | | | |
|---|---|---|---|
| Shield N | Dimension | Material | Density |
| Source | 1.164 in³ | Gallium | 6.095 |
| Shield 1 | 12.0 in | Air | 0.00122 |
| Shield 2 | .5 in | Stainless steel | 8 |
| Shield 3 | 6.0 in | Lead | 11.34 |
| Shield 4 | .5 in | Stainless steel | 8 |
| Air Gap | | Air | 0.00122 |

**Source Input: Grouping Method - Standard Indices**
**Number of Groups: 25**
**Lower Energy Cutoff: 0.015**
**Photons < 0.015: Excluded**
**Library: ICRP-38**

| Nuclide | Ci | Bq | µCi/cm³ | Bq/cm³ |
|---|---|---|---|---|
| Ga-67 | 2.5300e+000 | 9.3610e+010 | 1.3262e+005 | 4.9069e+009 |
| Ga-68 | 2.8100e+000 | 1.0397e+011 | 1.4730e+005 | 5.4500e+009 |
| Ge-68 | 2.8100e+000 | 1.0397e+011 | 1.4730e+005 | 5.4500e+009 |
| Ge-69 | 3.6340e+001 | 1.3446e+012 | 1.9049e+006 | 7.0481e+010 |
| Zn-65 | 5.6700e-001 | 2.0979e+010 | 2.9721e+004 | 1.0997e+009 |

| Buildup: The material reference is Shield 3<br>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 |
|---|---|---|---|---|---|
| 0.1 | 3.869e+10 | 0.000e+00 | 1.909e-05 | 0.000e+00 | 2.920e-08 |
| 0.2 | 2.793e+10 | 5.473e-68 | 1.045e-21 | 9.660e-71 | 1.845e-24 |
| 0.3 | 3.382e+10 | 6.452e-25 | 2.307e-21 | 1.224e-27 | 4.375e-24 |
| 0.4 | 5.435e+09 | 1.968e-13 | 4.818e-13 | 3.835e-16 | 9.387e-16 |
| 0.5 | 1.121e+12 | 5.423e-06 | 1.602e-05 | 1.064e-08 | 3.144e-08 |
| 0.6 | 1.584e+11 | 3.554e-04 | 1.147e-03 | 6.936e-07 | 2.238e-06 |
| 0.8 | 1.387e+11 | 1.563e-01 | 5.901e-01 | 2.973e-04 | 1.122e-03 |
| 1.0 | 3.684e+11 | 1.007e+01 | 4.147e+01 | 1.857e-02 | 7.644e-02 |
| 1.5 | 4.731e+10 | 5.011e+01 | 2.218e+02 | 8.431e-02 | 3.732e-01 |
| 2.0 | 9.411e+09 | 4.042e+01 | 1.824e+02 | 6.251e-02 | 2.820e-01 |
| 3.0 | 5.147e+05 | 6.826e-03 | 3.028e-02 | 9.261e-06 | 4.108e-05 |
| **Totals** | **1.949e+12** | **1.008e+02** | **4.462e+02** | **1.657e-01** | **7.327e-01** |

**Dose rate to the operator at BLIP 24 hours past EOB, 28 d of beam**

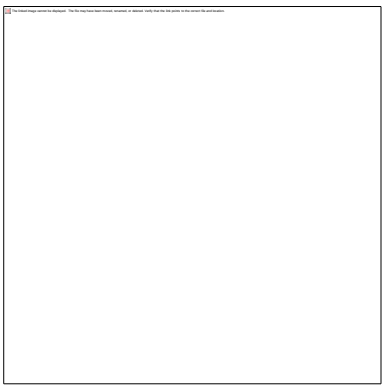
| MicroShield 7.02<br>BNL (7.02-0000) | | |
|---|---|---|
| **Date** | **By** | **Checked** |
| | | |

| Filename | Run Date | Run Time | Duration |
|---|---|---|---|
| Ga target EOB_28d 145 uA beam.ms7 | January 4, 2016 | 4:24:49 PM | 00:00:00 |

| Project Info | |
|---|---|
| Case Title | Ga BLIP @EOB |
| Description | Dose rate EOB after 4 weeks at 145 uA |
| Geometry | 8 - Cylinder Volume - End Shields |

| Source Dimensions | |
|---|---|
| Height | 0.498 cm (0.2 in) |
| Radius | 3.493 cm (1.4 in) |

| Dose Points | | | |
|---|---|---|---|
| **A** | **X** | **Y** | **Z** |
| #1 | 0.0 cm (0.0 in) | 76.2 cm (2 ft 6.0 in) | 0.0 cm (0.0 in) |



| Shields | | | |
|---|---|---|---|
| **Shield N** | **Dimension** | **Material** | **Density** |
| Source | 1.164 in³ | Gallium | 6.095 |
| Shield 1 | 12.0 in | Air | 0.00122 |
| Shield 2 | .5 in | Stainless steel | 8 |
| Shield 3 | 6.0 in | Lead | 11.34 |
| Shield 4 | .5 in | Stainless steel | 8 |
| Air Gap | | Air | 0.00122 |

**Source Input: Grouping Method - Standard Indices**
**Number of Groups: 25**
**Lower Energy Cutoff: 0.015**
**Photons < 0.015: Excluded**
**Library: ICRP-38**

| Nuclide | Ci | Bq | µCi/cm³ | Bq/cm³ |
|---|---|---|---|---|
| Ga-67 | 2.0455e+000 | 7.5684e+010 | 1.0722e+005 | 3.9673e+009 |

| | | | | |
|---|---|---|---|---|
| Ga-68 | 2.8037e+000 | 1.0374e+011 | 1.4697e+005 | 5.4378e+009 |
| Ge-68 | 2.8032e+000 | 1.0372e+011 | 1.4694e+005 | 5.4369e+009 |
| Ge-69 | 2.3734e+001 | 8.7816e+011 | 1.2441e+006 | 4.6032e+010 |
| Zn-65 | 5.6539e-001 | 2.0919e+010 | 2.9637e+004 | 1.0966e+009 |

| **Buildup: The material reference is Shield 3<br>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** |
| 0.1 | 3.128e+10 | 0.000e+00 | 1.543e-05 | 0.000e+00 | 2.361e-08 |
| 0.2 | 2.163e+10 | 4.239e-68 | 8.094e-22 | 7.482e-71 | 1.429e-24 |
| 0.3 | 2.453e+10 | 4.679e-25 | 1.673e-21 | 8.877e-28 | 3.173e-24 |
| 0.4 | 4.233e+09 | 1.533e-13 | 3.752e-13 | 2.987e-16 | 7.311e-16 |
| 0.5 | 7.961e+11 | 3.851e-06 | 1.138e-05 | 7.560e-09 | 2.233e-08 |
| 0.6 | 1.034e+11 | 2.321e-04 | 7.490e-04 | 4.531e-07 | 1.462e-06 |
| 0.8 | 9.062e+10 | 1.022e-01 | 3.857e-01 | 1.943e-04 | 7.336e-04 |
| 1.0 | 2.455e+11 | 6.711e+00 | 2.763e+01 | 1.237e-02 | 5.093e-02 |
| 1.5 | 3.094e+10 | 3.277e+01 | 1.450e+02 | 5.513e-02 | 2.440e-01 |
| 2.0 | 6.198e+09 | 2.662e+01 | 1.201e+02 | 4.117e-02 | 1.857e-01 |
| 3.0 | 5.135e+05 | 6.811e-03 | 3.021e-02 | 9.240e-06 | 4.099e-05 |
| **Totals** | **1.354e+12** | **6.621e+01** | **2.932e+02** | **1.089e-01** | **4.814e-01** |

**Dose rate to the operator at BLIP 7 days past EOB, 28 d of beam**

**MicroShield 7.02**
**BNL (7.02-0000)**

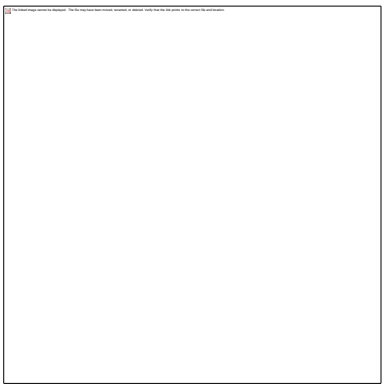
| Date | By | Checked |
|---|---|---|
| | | |

| Filename | Run Date | Run Time | Duration |
|---|---|---|---|
| Ga target EOB_28d 145 uA beam.ms7 | January 4, 2016 | 4:27:53 PM | 00:00:00 |

| Project Info | |
|---|---|
| Case Title | Ga BLIP @EOB |
| Description | Dose rate after 7 days, 4 weeks at 145 uA |
| Geometry | 8 - Cylinder Volume - End Shields |

| Source Dimensions | |
|---|---|
| Height | 0.498 cm (0.2 in) |
| Radius | 3.493 cm (1.4 in) |

| Dose Points | | | |
|---|---|---|---|
| A | X | Y | Z |
| #1 | 0.0 cm (0.0 in) | 76.2 cm (2 ft 6.0 in) | 0.0 cm (0.0 in) |



| Shields | | | |
|---|---|---|---|
| Shield N | Dimension | Material | Density |
| Source | 1.164 in³ | Gallium | 6.095 |
| Shield 1 | 12.0 in | Air | 0.00122 |
| Shield 2 | .5 in | Stainless steel | 8 |
| Shield 3 | 6.0 in | Lead | 11.34 |
| Shield 4 | .5 in | Stainless steel | 8 |
| Air Gap | | Air | 0.00122 |

**Source Input: Grouping Method - Standard Indices**
**Number of Groups: 25**
**Lower Energy Cutoff: 0.015**
**Photons < 0.015: Excluded**
**Library: ICRP-38**

| Nuclide | Ci | Bq | µCi/cm³ | Bq/cm³ |
|---|---|---|---|---|
| Ga-67 | 5.7135e-001 | 2.1140e+010 | 2.9950e+004 | 1.1081e+009 |

| | | | | |
|---|---|---|---|---|
| Ga-68 | 2.7635e+000 | 1.0225e+011 | 1.4486e+005 | 5.3598e+009 |
| Ge-68 | 2.7631e+000 | 1.0223e+011 | 1.4484e+005 | 5.3589e+009 |
| Ge-69 | 1.8420e+000 | 6.8156e+010 | 9.6558e+004 | 3.5726e+009 |
| Zn-65 | 5.5583e-001 | 2.0566e+010 | 2.9136e+004 | 1.0780e+009 |

| **Buildup: The material reference is Shield 3<br>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 |
|---|---|---|---|---|---|
| 0.1 | 8.737e+09 | 0.000e+00 | 4.310e-06 | 0.000e+00 | 6.594e-09 |
| 0.2 | 5.237e+09 | 1.026e-68 | 1.959e-22 | 1.811e-71 | 3.458e-25 |
| 0.3 | 4.466e+09 | 8.520e-26 | 3.046e-22 | 1.616e-28 | 5.778e-25 |
| 0.4 | 1.046e+09 | 3.787e-14 | 9.270e-14 | 7.380e-17 | 1.806e-16 |
| 0.5 | 2.300e+11 | 1.113e-06 | 3.287e-06 | 2.185e-09 | 6.452e-09 |
| 0.6 | 8.060e+09 | 1.808e-05 | 5.835e-05 | 3.530e-08 | 1.139e-07 |
| 0.8 | 7.157e+09 | 8.069e-03 | 3.046e-02 | 1.535e-05 | 5.794e-05 |
| 1.0 | 3.177e+10 | 8.687e-01 | 3.576e+00 | 1.601e-03 | 6.592e-03 |
| 1.5 | 2.504e+09 | 2.652e+00 | 1.174e+01 | 4.462e-03 | 1.975e-02 |
| 2.0 | 6.172e+08 | 2.651e+00 | 1.196e+01 | 4.100e-03 | 1.849e-02 |
| 3.0 | 5.061e+05 | 6.713e-03 | 2.978e-02 | 9.108e-06 | 4.040e-05 |
| **Totals** | **2.996e+11** | **6.186e+00** | **2.733e+01** | **1.019e-02** | **4.493e-02** |