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Author(s): Kelsey, Charles T. IV

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Activation, Heating and Exposure Rates for Mo-99 Experiments with 25-Disk Targets

Charles Kelsey

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An MCNPX model of the 25-disk target assembly inside the vacuum cube inside the shielded box was prepared. This was used to calculate heating and photon and neutron fluxes throughout the model. Production rates for photonuclear reaction products were calculated using the photon fluxes and ENDF/B-VII cross sections. Measured isomer to ground state yield ratios were used where available. Where not available the new correlation between spin deficit and isomer to ground state yield ratios presented at AccApp'11 was used. The photonuclear production rates and neutron fluxes were input to CINDER2008 for transmutation calculations. A cross section update file was used to supply (n,n') reactions missing from CINDER2008 libraries. Decay photon spectra produced by CINDER2008 were then used to calculate exposure rates using the MCNPX model.

Two electron beam irradiations were evaluated. The first was for a thermal test at 15 MeV with 1300 μ A incident on one target end and the second was for a production test at 35 MeV with 350 μ A incident on both target ends (700 μ A total current on target). For the thermal test 1, 2, 3, 4, 5 and 6 h irradiation times were simulated, each followed by decay time steps out to 42 days. For the production test 6, 12, 18, 24, 30 and 36 h irradiation times were simulated followed by the same decay periods. For all simulations beam FWHMs in x and y were both assumed to be 6 mm. Simulations were run for Mo-100 enriched and natural Mo targets for both tests. It is planned that thermal test will be run for 4 h with natural target disks and production test will be run for 24 h with enriched target disks. Results for these two simulations only are presented in this report. Other results can be made available upon request.

Post irradiation exposure rates were calculated at 30 cm distances from left, right, front and back of the following configurations:

1. Shielded box with everything in it (beam pipes, cooling pipes, vacuum cube, target housing weldment and target assembly),
2. Shielded box with everything in it except the target assembly,
3. Shielded box with nothing in it,
4. Target assembly taken outside of shielded box,
5. Target disks in cradle (target assembly with thermocouple weldment and flange removed),
6. Empty cradle, and
7. Target disks alone.

Decay photon spectra from the CINDER2008 calculations were used as sources for the exposure rate calculations in the same model used for the flux calculations with beam on. As components were removed to simulate the seven cases considered the material compositions were changed to air and their respective sources were turned off. The MCNPX model geometry is plotted in Figure 1. The left and right detector locations for cases 1, 2 and 3 were 30 cm from the shielded box walls and 30 cm from the beam pipe openings in the left and right sides of the model (they are not in the beam line). A zoomed in plot of the target assembly alone is in Figure 2.

Figure 1: MCNPX model of shielded box with target assembly installed.

Figure 2: MCNPX model of target assembly.

Exposure rates for the seven cases are plotted as a function of time after irradiation in Figures 3, 4 and 5. To aid in comparison between the cases, all of these figures have been plotted using the same scale. Figures 3 and 4 are respectively the thermal and production test results for cases 1 through 6. Figure 5 includes case 7 results for both. Differences between cases 1 and 2 for both tests are not statistically significant showing that activation of components other than the target assembly, many of which are also shielding the target assembly, dominates exposure rates outside the shielded box. Case 3 shows the contribution from activation of the shield box itself. In front where shielded box wall is thickest box activation accounts for essentially all of the exposure rate outside. Differences between cases 4 and 5 are also minimal, showing that the contribution to target assembly exposure rates from the thermocouple flange and weldment are small compared to the target disks and cradle. From the numerical results the contribution is about 1%. Results for case 6, the cradle itself, are initially about half of the target assembly exposure rates.

For the thermal test maximum shielded box exposure rates with or without the target assembly in it are about 1 mR/h 1 h after shutdown versus 65 mR/h for the production test. In front of the shielded box where a person would be positioned for target removal activities the calculated exposure rate is about 20% of the maximum for the production test, and after a few hours of decay is less than 1 mR/h. However, the window was not modeled. Typically lead glass is about one quarter as effective as solid lead for the same thickness and drawing indicates a window thickness about double the front wall thickness suggesting exposure rate in front of the window will likely be comparable to what it is in the back, 25 mR/h 1 h after shutdown and about 10 mR/h at 1 d. The unshielded target assembly exposure rates at 30 cm, 1 h after shutdown are about 170 mR/h for the thermal test and about 50 R/h for the production test.

Tables 1 and 2 list calculated 30 cm exposure for decayed individual target disks for the thermal test and production test respectively. Table 3 lists the end of irradiation Mo-99 activities. Total Mo-99 activities are 80 mCi for the thermal test and 36 Ci for the production test. Table 4 lists heating tally results. About 58% of beam power is deposited in the target disks for the thermal test versus 44% for production test. Other significant fractions are 16% for thermal and 19% for production in the target disk cradle, 7% for thermal and 10% for production in the vacuum cube, and 8% for thermal and 14% for production in the shielded box's inner lead material. Table 5 for thermal and Table 6 for production list radionuclide inventories at EOB. The radionuclides listed are those with activities greater than 1 nCi. At EOB the total sum-of-fractions of DOE STD 1027 Hazard Category 3 thresholds is $4.8\text{E-}5$ (73% in target assembly) for the thermal test and $1.9\text{E-}2$ (84% in target assembly) for the production test.

1. Shielded box with everything in it

4. Target assembly taken outside of shielded box

2. Shielded box with everything in it except the target assembly

5. Target disks in cradle

3. Shielded box with nothing in it

6. Empty cradle

Figure 3: Exposure rates after 4 h natural target irradiation at 15 MeV, 1300 uA.

1. Shielded box with everything in it

4. Target assembly taken outside of shielded box

2. Shielded box with everything in it except the target assembly

5. Target disks in cradle

3. Shielded box with nothing in it

6. Empty cradle

Figure 4: Exposure rates after 24 h enriched target irradiation at 35 MeV, 700 uA.

Figure 5: Post irradiation exposure rates for target disks alone.

Table 1: Thermal test decayed target disk exposure rates.

disk	exposure rate (R/h)							
	1 h	3 h	7 h	15 h	31 h	63 h	127 h	255 h
1	7.43E-03	5.08E-03	5.34E-03	5.39E-03	4.80E-03	3.46E-03	1.77E-03	4.70E-04
2	1.02E-02	7.75E-03	8.17E-03	8.25E-03	7.35E-03	5.31E-03	2.72E-03	7.18E-04
3	1.02E-02	7.91E-03	8.34E-03	8.44E-03	7.52E-03	5.43E-03	2.78E-03	7.34E-04
4	9.54E-03	7.26E-03	7.66E-03	7.74E-03	6.90E-03	4.98E-03	2.55E-03	6.73E-04
5	8.66E-03	6.53E-03	6.88E-03	6.95E-03	6.20E-03	4.47E-03	2.29E-03	6.05E-04
6	7.83E-03	5.86E-03	6.17E-03	6.23E-03	5.56E-03	4.01E-03	2.05E-03	5.43E-04
7	7.09E-03	5.26E-03	5.54E-03	5.60E-03	4.99E-03	3.60E-03	1.84E-03	4.87E-04
8	6.50E-03	4.73E-03	4.98E-03	5.04E-03	4.49E-03	3.24E-03	1.66E-03	4.38E-04
9	5.87E-03	4.25E-03	4.47E-03	4.52E-03	4.03E-03	2.91E-03	1.49E-03	3.93E-04
10	5.29E-03	3.82E-03	4.02E-03	4.06E-03	3.62E-03	2.61E-03	1.34E-03	3.54E-04
11	4.83E-03	3.44E-03	3.62E-03	3.66E-03	3.26E-03	2.35E-03	1.20E-03	3.19E-04
12	4.38E-03	3.11E-03	3.27E-03	3.30E-03	2.94E-03	2.12E-03	1.09E-03	2.87E-04
13	3.93E-03	2.81E-03	2.95E-03	2.98E-03	2.65E-03	1.92E-03	9.80E-04	2.60E-04
14	3.68E-03	2.55E-03	2.68E-03	2.71E-03	2.41E-03	1.74E-03	8.90E-04	2.36E-04
15	3.33E-03	2.31E-03	2.43E-03	2.45E-03	2.18E-03	1.58E-03	8.06E-04	2.14E-04
16	3.02E-03	2.10E-03	2.20E-03	2.22E-03	1.98E-03	1.43E-03	7.32E-04	1.94E-04
17	2.79E-03	1.91E-03	2.01E-03	2.03E-03	1.81E-03	1.30E-03	6.67E-04	1.77E-04
18	2.58E-03	1.75E-03	1.84E-03	1.85E-03	1.65E-03	1.19E-03	6.10E-04	1.62E-04
19	2.31E-03	1.59E-03	1.67E-03	1.69E-03	1.50E-03	1.09E-03	5.55E-04	1.47E-04
20	2.11E-03	1.46E-03	1.53E-03	1.54E-03	1.37E-03	9.92E-04	5.07E-04	1.35E-04
21	1.97E-03	1.34E-03	1.40E-03	1.42E-03	1.26E-03	9.10E-04	4.66E-04	1.23E-04
22	1.84E-03	1.23E-03	1.29E-03	1.30E-03	1.16E-03	8.36E-04	4.28E-04	1.13E-04
23	1.66E-03	1.12E-03	1.18E-03	1.19E-03	1.06E-03	7.65E-04	3.91E-04	1.04E-04
24	1.53E-03	1.03E-03	1.08E-03	1.09E-03	9.72E-04	7.02E-04	3.59E-04	9.52E-05
25	1.39E-03	9.48E-04	9.97E-04	1.00E-03	8.94E-04	6.46E-04	3.30E-04	8.76E-05
sum	1.20E-01	8.71E-02	9.17E-02	9.26E-02	8.25E-02	5.96E-02	3.05E-02	8.07E-03

Table 2: Production test decayed target disk exposure rates.

disk	exposure rate (R/h)							
	1 h	3 h	7 h	15 h	31 h	63 h	127 h	255 h
1	6.93E-01	6.75E-01	6.76E-01	6.52E-01	5.67E-01	4.07E-01	2.08E-01	5.42E-02
2	1.13E+00	1.10E+00	1.11E+00	1.07E+00	9.28E-01	6.67E-01	3.40E-01	8.87E-02
3	1.50E+00	1.48E+00	1.48E+00	1.43E+00	1.24E+00	8.93E-01	4.56E-01	1.19E-01
4	1.81E+00	1.78E+00	1.79E+00	1.72E+00	1.50E+00	1.08E+00	5.50E-01	1.43E-01
5	2.03E+00	2.00E+00	2.00E+00	1.94E+00	1.68E+00	1.21E+00	6.18E-01	1.61E-01
6	2.15E+00	2.12E+00	2.13E+00	2.05E+00	1.79E+00	1.28E+00	6.55E-01	1.71E-01
7	2.19E+00	2.16E+00	2.16E+00	2.09E+00	1.82E+00	1.31E+00	6.67E-01	1.74E-01
8	2.16E+00	2.13E+00	2.14E+00	2.06E+00	1.80E+00	1.29E+00	6.58E-01	1.72E-01
9	2.10E+00	2.07E+00	2.08E+00	2.00E+00	1.75E+00	1.25E+00	6.40E-01	1.67E-01
10	2.04E+00	2.00E+00	2.01E+00	1.94E+00	1.69E+00	1.21E+00	6.20E-01	1.61E-01
11	1.98E+00	1.94E+00	1.95E+00	1.88E+00	1.64E+00	1.18E+00	6.01E-01	1.57E-01
12	1.94E+00	1.91E+00	1.91E+00	1.85E+00	1.61E+00	1.16E+00	5.90E-01	1.54E-01
13	1.93E+00	1.89E+00	1.90E+00	1.84E+00	1.60E+00	1.15E+00	5.86E-01	1.53E-01
14	1.94E+00	1.91E+00	1.91E+00	1.85E+00	1.61E+00	1.16E+00	5.90E-01	1.54E-01
15	1.98E+00	1.94E+00	1.95E+00	1.89E+00	1.64E+00	1.18E+00	6.01E-01	1.57E-01
16	2.04E+00	2.00E+00	2.01E+00	1.94E+00	1.69E+00	1.21E+00	6.20E-01	1.61E-01
17	2.10E+00	2.07E+00	2.08E+00	2.00E+00	1.75E+00	1.25E+00	6.40E-01	1.67E-01
18	2.16E+00	2.13E+00	2.14E+00	2.06E+00	1.80E+00	1.29E+00	6.58E-01	1.72E-01
19	2.19E+00	2.15E+00	2.16E+00	2.09E+00	1.82E+00	1.31E+00	6.66E-01	1.74E-01
20	2.15E+00	2.12E+00	2.13E+00	2.06E+00	1.79E+00	1.29E+00	6.56E-01	1.71E-01
21	2.03E+00	2.00E+00	2.00E+00	1.94E+00	1.68E+00	1.21E+00	6.18E-01	1.61E-01
22	1.81E+00	1.78E+00	1.79E+00	1.72E+00	1.50E+00	1.08E+00	5.50E-01	1.43E-01
23	1.50E+00	1.48E+00	1.48E+00	1.43E+00	1.25E+00	8.95E-01	4.57E-01	1.19E-01
24	1.13E+00	1.11E+00	1.11E+00	1.07E+00	9.31E-01	6.69E-01	3.41E-01	8.89E-02
25	6.94E-01	6.77E-01	6.78E-01	6.54E-01	5.69E-01	4.09E-01	2.09E-01	5.44E-02
sum	4.54E+01	4.46E+01	4.48E+01	4.32E+01	3.76E+01	2.70E+01	1.38E+01	3.60E+00

Table 3: End of irradiation Mo-99 activities.

disk	end of irradiation Mo-99 activity (Ci)	
	thermal	production
1	4.55E-03	5.38E-01
2	6.99E-03	8.81E-01
3	7.15E-03	1.18E+00
4	6.56E-03	1.42E+00
5	5.89E-03	1.60E+00
6	5.28E-03	1.70E+00
7	4.74E-03	1.73E+00
8	4.26E-03	1.70E+00
9	3.83E-03	1.66E+00
10	3.44E-03	1.60E+00
11	3.10E-03	1.56E+00
12	2.79E-03	1.53E+00
13	2.52E-03	1.52E+00
14	2.29E-03	1.53E+00
15	2.08E-03	1.56E+00
16	1.88E-03	1.60E+00
17	1.72E-03	1.66E+00
18	1.57E-03	1.70E+00
19	1.43E-03	1.73E+00
20	1.31E-03	1.70E+00
21	1.20E-03	1.60E+00
22	1.10E-03	1.43E+00
23	1.01E-03	1.18E+00
24	9.23E-04	8.83E-01
25	8.49E-04	5.40E-01
total	7.84E-02	3.57E+01

Table 4: Heating tally results.

component	thermal test			production test		
	W/ μ A	relative error	fraction of total	W/ μ A	relative error	fraction of total
cooling channel 1	4.16E-04	0.0467	0.003%	2.29E-04	0.0379	0.001%
cooling channel 2	5.51E-04	0.0470	0.004%	2.12E-04	0.1490	0.001%
cooling channel 3	6.55E-04	0.0208	0.004%	2.73E-04	0.0396	0.001%
cooling channel 4	5.07E-04	0.0438	0.003%	2.34E-04	0.2242	0.001%
cooling channel 5	3.56E-04	0.0347	0.002%	2.62E-04	0.0866	0.001%
cooling channel 6	2.16E-04	0.0284	0.001%	2.75E-04	0.0654	0.001%
cooling channel 7	9.10E-05	0.0768	0.001%	2.52E-04	0.0621	0.001%
cooling channel 8	1.59E-05	1.0000	0.000%	2.56E-04	0.0377	0.001%
cooling channel 9	1.67E-05	0.1967	0.000%	1.93E-04	0.1094	0.001%
cooling channel 10	1.59E-05	0.1386	0.000%	1.79E-04	0.0931	0.001%
cooling channel 11	1.25E-05	0.1986	0.000%	1.38E-04	0.1272	0.000%
cooling channel 12	9.37E-06	0.3009	0.000%	1.22E-04	0.0975	0.000%
cooling channel 13	3.90E-06	1.0000	0.000%	8.93E-05	0.1891	0.000%
cooling channel 14	7.38E-06	0.5621	0.000%	1.25E-04	0.0641	0.000%
cooling channel 15	1.75E-06	1.0000	0.000%	1.15E-04	0.1156	0.000%
cooling channel 16	2.04E-06	1.0000	0.000%	1.46E-04	0.0616	0.000%
cooling channel 17	7.75E-06	0.1431	0.000%	1.71E-04	0.0900	0.000%
cooling channel 18	5.67E-06	0.2710	0.000%	1.83E-04	0.1332	0.001%
cooling channel 19	3.58E-06	0.1858	0.000%	2.14E-04	0.1030	0.001%
cooling channel 20	1.19E-05	0.7874	0.000%	2.60E-04	0.0369	0.001%
cooling channel 21	4.88E-06	0.2129	0.000%	2.91E-04	0.0415	0.001%
cooling channel 22	4.30E-06	0.3432	0.000%	2.78E-04	0.0790	0.001%
cooling channel 23	2.16E-06	1.0000	0.000%	2.83E-04	0.0521	0.001%
cooling channel 24	3.02E-06	0.1289	0.000%	2.32E-04	0.1419	0.001%
cooling channel 25	2.81E-06	0.3872	0.000%	2.66E-04	0.0418	0.001%
cooling channel 26	1.75E-07	1.0000	0.000%	1.92E-04	0.1589	0.001%
target disk 1	1.64E+00	0.0006	10.954%	7.06E-01	0.0020	2.014%
target disk 2	1.98E+00	0.0005	13.184%	7.70E-01	0.0020	2.196%
target disk 3	1.86E+00	0.0005	12.406%	8.16E-01	0.0020	2.327%
target disk 4	1.39E+00	0.0006	9.259%	8.45E-01	0.0019	2.411%
target disk 5	8.56E-01	0.0008	5.709%	8.28E-01	0.0020	2.363%
target disk 6	4.36E-01	0.0012	2.904%	7.76E-01	0.0022	2.214%
target disk 7	1.82E-01	0.0024	1.213%	6.91E-01	0.0023	1.971%
target disk 8	7.23E-02	0.0051	0.482%	5.91E-01	0.0027	1.687%
target disk 9	3.91E-02	0.0087	0.261%	4.95E-01	0.0031	1.413%

component	thermal test			production test		
	W/ μ A	relative error	fraction of total	W/ μ A	relative error	fraction of total
target disk 10	3.04E-02	0.0103	0.203%	4.13E-01	0.0036	1.178%
target disk 11	2.61E-02	0.0112	0.174%	3.53E-01	0.0041	1.008%
target disk 12	2.23E-02	0.0130	0.149%	3.11E-01	0.0045	0.889%
target disk 13	1.98E-02	0.0137	0.132%	2.95E-01	0.0049	0.843%
target disk 14	1.74E-02	0.0152	0.116%	3.10E-01	0.0046	0.884%
target disk 15	1.53E-02	0.0156	0.102%	3.48E-01	0.0041	0.994%
target disk 16	1.40E-02	0.0160	0.093%	4.14E-01	0.0035	1.181%
target disk 17	1.19E-02	0.0179	0.079%	4.96E-01	0.0031	1.414%
target disk 18	1.09E-02	0.0188	0.072%	5.92E-01	0.0027	1.688%
target disk 19	9.65E-03	0.0199	0.064%	6.89E-01	0.0023	1.967%
target disk 20	8.85E-03	0.0216	0.059%	7.75E-01	0.0021	2.212%
target disk 21	8.19E-03	0.0207	0.055%	8.32E-01	0.0020	2.374%
target disk 22	7.43E-03	0.0222	0.050%	8.44E-01	0.0020	2.407%
target disk 23	6.41E-03	0.0258	0.043%	8.18E-01	0.0020	2.334%
target disk 24	5.73E-03	0.0303	0.038%	7.68E-01	0.0020	2.193%
target disk 25	5.27E-03	0.0314	0.035%	7.04E-01	0.0020	2.010%
target cradle	2.44E+00	0.0005	16.251%	6.67E+00	0.0005	19.025%
coolant gap between target cradle and housing	1.59E-04	0.0328	0.001%	1.63E-04	0.0443	0.000%
target housing	5.00E-01	0.0013	3.335%	1.23E+00	0.0016	3.517%
front window	6.27E-01	0.0011	4.179%	3.07E-01	0.0029	0.877%
back window	2.05E-03	0.0515	0.014%	3.08E-01	0.0029	0.879%
coolant in inlet and outlet	5.12E-04	0.0281	0.003%	1.47E-03	0.0334	0.004%
coolant inlet and outlet walls	1.11E-01	0.0027	0.740%	3.80E-01	0.0026	1.084%
thermocouple flange to target holder	1.75E-02	0.0049	0.116%	3.94E-02	0.0055	0.112%
thermocouple flange	1.88E-03	0.0174	0.013%	5.05E-03	0.0159	0.014%
coolant in inlet cone	7.50E-04	0.0207	0.005%	1.87E-03	0.0169	0.005%
coolant inlet cone walls	6.49E-02	0.0032	0.432%	2.47E-01	0.0028	0.704%
coolant in outlet cone	7.35E-04	0.0213	0.005%	1.87E-03	0.0188	0.005%
coolant outlet cone walls	6.47E-02	0.0032	0.431%	2.47E-01	0.0027	0.706%
vacuum cube	1.01E+00	0.0007	6.738%	3.48E+00	0.0007	9.924%
bottom port cover	8.44E-03	0.0088	0.056%	3.47E-02	0.0060	0.099%
coolant in horizontal inlet line	4.49E-04	0.0285	0.003%	1.00E-03	0.0178	0.003%
horizontal inlet line wall	2.54E-02	0.0048	0.170%	7.29E-02	0.0045	0.208%
coolant in horizontal outlet line	4.51E-04	0.0263	0.003%	9.87E-04	0.0225	0.003%
horizontal outlet line wall	2.52E-02	0.0051	0.168%	7.26E-02	0.0042	0.207%

component	thermal test			production test		
	W/ μ A	relative error	fraction of total	W/ μ A	relative error	fraction of total
coolant in vertical inlet line	1.39E-04	0.0548	0.001%	2.75E-04	0.0478	0.001%
vertical inlet line wall	1.66E-02	0.0058	0.111%	3.80E-02	0.0057	0.108%
coolant in vertical outlet line	1.39E-04	0.0426	0.001%	3.11E-04	0.0399	0.001%
vertical outlet line wall	1.64E-02	0.0064	0.109%	3.84E-02	0.0060	0.110%
beam pipes	1.12E-01	0.0032	0.748%	7.48E-01	0.0024	2.134%
shielded box inside lead	1.17E+00	0.0006	7.811%	5.01E+00	0.0005	14.308%
shielded box steel walls	2.01E-02	0.0062	0.134%	9.22E-02	0.0054	0.263%
shielded box outside lead	5.35E-02	0.0033	0.357%	2.50E-01	0.0027	0.713%
air in shielded box	3.12E-03	0.0233	0.021%	1.51E-02	0.0149	0.043%
neutron escape	1.53E-04		0.001%	5.20E-03		0.015%
photon escape	2.74E-02		0.183%	2.48E-01		0.709%
electron escape	8.39E-04		0.006%	9.25E-03		0.026%
proton escape	0.00E+00		0.000%	4.51E-08		0.000%
total	1.50E+01		100.000%	3.50E+01		100.000%

Table 5: Thermal test EOB activities for all radionuclides > 1 nCi.

nuclide	half-life (s)	EOB activity (Ci)				
		all target disks	target assembly without disks	shielded box	air inside box	remainder of model
Be 8	8.18E-17		1.92E-09	1.86E-09		1.41E-09
B 12	2.02E-02		1.22E-07			5.95E-08
N 13	5.98E+02				4.94E-05	
N 16	7.13E+00				8.80E-09	
O 19	2.69E+01				6.32E-09	
Na 24	5.39E+04	5.68E-07				
Al 26m1	6.35E+00		4.70E-05			1.64E-05
Mg 27	5.67E+02		2.80E-06	6.62E-09		2.45E-06
Al 28	1.34E+02		2.37E-04	2.39E-05		1.28E-04
Al 29	3.94E+02		5.56E-08	1.36E-06		6.75E-07
Si 31	9.44E+03		6.04E-06	9.16E-05		4.42E-05
P 32	1.23E+06		7.97E-08	8.74E-07		5.20E-07
P 33	2.19E+06		2.02E-09	8.80E-09		1.01E-08
P 34	1.24E+01			3.63E-09		1.21E-09
S 37	3.03E+02					1.02E-09
Cl 39	3.37E+03				6.71E-09	
Ar 41	6.58E+03				1.76E-06	
Sc 45m1	3.18E-01		7.86E-05			2.84E-05
Ti 45	1.11E+04		5.40E-05			1.88E-05
Sc 46	7.24E+06		1.78E-08			6.80E-09
Sc 46m1	1.88E+01		2.16E-06			9.31E-07
Sc 47	2.89E+05		3.95E-07			1.96E-07
Sc 48	1.57E+05		4.28E-08			1.51E-08
Sc 49	3.43E+03		6.51E-08			5.12E-08
V 49	2.85E+07		2.25E-06	4.11E-08		4.03E-06
Cr 49	2.54E+03		1.67E-04	3.35E-06		3.18E-04
Ti 51	3.46E+02		9.54E-06	1.20E-08		4.73E-06
Cr 51	2.39E+06		3.32E-04	2.46E-05		5.53E-04
V 52	2.25E+02		8.25E-05	1.93E-05		1.64E-04
V 53	9.60E+01		4.83E-07	2.40E-06		1.72E-06
Fe 53	5.11E+02	1.00E-06	5.28E-04	4.33E-05		3.59E-03
Fe 53m1	1.52E+02	2.55E-08	1.34E-05	1.10E-06		9.14E-05
V 54	4.98E+01			1.45E-09		
Mn 54	2.70E+07		2.06E-06	2.41E-06		1.76E-05
Cr 55	2.10E+02		1.91E-04	2.22E-04		2.33E-04

nuclide	half-life (s)	EOB activity (Ci)				
		all target disks	target assembly without disks	shielded box	air inside box	remainder of model
Fe 55	8.64E+07	3.61E-08	2.86E-05	3.36E-06		1.71E-04
Mn 56	9.28E+03	1.47E-08	3.06E-03	9.36E-03		1.02E-02
Mn 57	8.54E+01		8.21E-08	3.07E-06		1.38E-06
Co 57	2.35E+07		6.45E-05	2.33E-07		4.22E-05
Ni 57	1.28E+05		5.24E-03	1.83E-05		3.29E-03
Mn 58	3.00E+00			1.89E-09		
Co 58	6.12E+06		2.55E-05	2.57E-05		2.78E-05
Co 58m1	3.25E+04		2.47E-03	6.54E-04		1.39E-03
Fe 59	3.84E+06		1.64E-07	7.81E-07		5.53E-07
Ni 59	2.40E+12		1.02E-09			
Co 60	1.66E+08		1.91E-06	1.13E-09		9.26E-07
Co 60m1	6.28E+02		2.08E-02	7.97E-08		1.01E-02
Co 61	5.94E+03		3.15E-06	1.55E-06		2.94E-06
Co 62	9.00E+01			5.77E-09		1.50E-09
Co 62m1	8.35E+02			2.51E-09		
Cu 62	5.80E+02		3.91E-03			1.45E-03
Co 63	2.74E+01		1.87E-09			1.26E-09
Ni 63	3.16E+09		9.44E-08	5.23E-09		5.62E-08
Zn 63	2.31E+03	1.84E-05				
Cu 64	4.57E+04	1.16E-08	5.88E-04			2.42E-04
Ni 65	9.06E+03		4.39E-04	9.38E-05		2.76E-04
Zn 65	2.11E+07	1.15E-08				
Cu 66	3.07E+02	2.41E-07	1.75E-04			8.86E-05
Cu 67	2.23E+05	2.67E-09				
Cu 67m1	2.40E-09	3.21E-09				
Zn 69	3.38E+03	2.27E-06				
Zn 69m1	4.95E+04	4.67E-08				
Zn 71	1.47E+02	4.11E-09				
Sr 86m1	4.55E-07	2.42E-07				
Sr 87m1	1.01E+04	2.89E-08				
Y 88	9.21E+06	4.24E-09				
Zr 88	7.21E+06	7.84E-06	7.78E-08			2.76E-08
Y 89m1	1.57E+01	1.24E-05	7.84E-04			3.10E-04
Zr 89	2.82E+05	2.91E-06				
Zr 89m1	2.51E+02	4.80E-05	2.11E-09			1.88E-09
Y 90	2.30E+05	9.87E-09	3.05E-08			2.29E-08

nuclide	half-life (s)	EOB activity (Ci)				
		all target disks	target assembly without disks	shielded box	air inside box	remainder of model
Y 90m1	1.15E+04	2.23E-08	8.07E-08			6.22E-08
Zr 90m1	8.09E-01	3.98E-02	8.15E-04			3.77E-04
Y 91m1	2.98E+03	1.91E-08				
Zr 91m1	4.35E-06	1.25E-03	1.66E-05			6.34E-06
Nb 91	2.15E+10	3.12E-07	3.92E-09			1.47E-09
Nb 91m1	5.26E+06	5.28E-04	6.79E-06			2.56E-06
Nb 91m2	3.76E-06	2.65E-01	3.45E-03			1.31E-03
Mo 91	9.29E+02	7.32E-02	6.46E-04			2.25E-04
Mo 91m1	6.46E+01	4.14E-02	3.65E-04			1.27E-04
Sr 92	9.58E+03	1.08E-08				
Y 92	1.27E+04	3.80E-09				
Nb 92m1	8.77E+05	7.69E-07	1.44E-03			5.55E-04
Y 93	3.66E+04	1.17E-09				
Nb 93m1	5.09E+08	7.36E-08	5.57E-08			4.05E-08
Mo 93	1.26E+11	6.14E-08				
Mo 93m1	2.47E+04	4.84E-04	6.30E-06			2.38E-06
Nb 94m1	3.76E+02	1.35E-03	3.72E-03			2.24E-03
Zr 95	5.53E+06	3.44E-08				
Nb 95	3.02E+06	2.48E-06	2.40E-08			8.52E-09
Nb 95m1	3.12E+05	4.89E-05	4.73E-07			1.67E-07
Nb 96	8.41E+04	2.23E-05	2.00E-07			6.98E-08
Zr 97	6.03E+04	4.76E-09				
Nb 97	4.33E+03	4.72E-05	3.93E-07			1.37E-07
Nb 97m1	5.27E+01	2.18E-05	1.81E-07			6.31E-08
Nb 99	1.50E+01	2.66E-07	1.94E-09			
Nb 99m1	1.56E+02	2.09E-07	1.52E-09			
Mo 99	2.37E+05	7.84E-02	1.12E-03			4.39E-04
Tc 99m1	2.17E+04	1.38E-02	1.97E-04			7.71E-05
Mo101	8.77E+02	4.92E-03	9.58E-05			6.11E-05
Tc101	8.53E+02	4.92E-03	9.58E-05			6.11E-05
Hg203	4.03E+06			2.14E-08		
Pb203	1.87E+05			2.69E-07		
Pb203m1	6.21E+00			2.59E-07		
Pb204m1	4.03E+03			3.49E-02		
Hg205	3.08E+02			8.96E-07		
Pb205m1	5.55E-03			4.10E-01		

nuclide	half-life (s)	EOB activity (Ci)				
		all target disks	target assembly without disks	shielded box	air inside box	remainder of model
Tl206	2.52E+02			2.88E-04		
Tl206m1	2.24E+02			3.47E-06		
Tl207	2.86E+02			1.54E-04		
Tl207m1	1.33E+00			1.64E-05		
Pb207m1	8.06E-01			1.08E+00		
Pb209	1.17E+04			2.43E-02		

Table 6: Production test EOB activities for all radionuclides > 1 nCi.

nuclide	half-life (s)	EOB activity (Ci)				
		all target disks	target assembly without disks	shielded box	air inside box	remainder of model
H 3	3.89E+08	3.27E-07	2.13E-07	1.63E-08	9.74E-08	3.12E-07
He 6	8.07E-01					1.16E-09
Be 7	4.60E+06		1.68E-08			3.15E-08
Li 8	8.40E-01		1.67E-06			1.31E-06
Be 8	8.18E-17		8.43E-06	3.61E-06	2.58E-05	2.48E-05
B 9	8.44E-19		2.88E-07		2.57E-05	2.29E-07
Be 11	1.38E+01		5.16E-08			4.43E-08
C 11	1.22E+03		1.07E-03	9.35E-06	2.03E-05	1.87E-03
B 12	2.02E-02		1.42E-05	2.68E-07	4.32E-06	2.20E-05
B 13	1.73E-02		1.09E-07	8.99E-08		5.01E-07
N 13	5.98E+02				8.96E-03	
C 14	1.80E+11				2.68E-08	
O 14	7.06E+01				2.44E-07	
C 15	2.45E+00				2.05E-07	
O 15	1.22E+02				1.17E-03	
N 16	7.13E+00				2.73E-05	
N 17	4.17E+00				3.30E-06	
N 18	6.30E-01				2.14E-08	
O 19	2.69E+01				1.14E-07	
Na 22	8.21E+07	5.67E-09	2.41E-07			7.05E-08
Ne 23	3.72E+01		3.15E-09			2.92E-09
Mg 23	1.13E+01	2.17E-07	2.41E-06	5.18E-08		1.26E-05
Na 24	5.39E+04	1.64E-06	3.15E-04			2.40E-04
Na 24m1	2.02E-02	1.20E-06	2.27E-04			1.74E-04
Na 25	5.91E+01	4.37E-07	1.86E-05			5.47E-06
Al 25	7.18E+00	3.20E-06	1.39E-04	3.72E-08		4.86E-05
Al 26m1	6.35E+00	7.70E-04	5.30E-02	1.54E-05		2.12E-02
Mg 27	5.67E+02	6.84E-06	1.29E-03	7.75E-06		1.03E-03
Si 27	4.17E+00	1.43E-03	3.46E-02	1.02E-03		1.52E-01
Mg 28	7.53E+04	5.47E-08	7.71E-07	1.79E-08		3.67E-06
Al 28	1.34E+02	2.44E-04	9.97E-03	4.50E-03		3.46E-02
Al 29	3.94E+02	4.64E-05	1.13E-03	1.42E-04		5.19E-03
P 29	4.14E+00		2.12E-06	3.52E-08		6.99E-06
Al 30	3.60E+00	1.01E-08	8.11E-07	1.53E-06		6.78E-06
P 30	1.50E+02		1.28E-04	3.15E-06		4.17E-04

nuclide	half-life (s)	EOB activity (Ci)				
		all target disks	target assembly without disks	shielded box	air inside box	remainder of model
S 30	1.18E+00		2.38E-06	3.65E-08		8.50E-06
Si 31	9.44E+03	2.31E-06	3.17E-04	2.09E-03		3.35E-03
S 31	2.57E+00		1.23E-03	2.67E-05	1.20E-08	3.94E-03
P 32	1.23E+06		3.03E-05	1.08E-04		2.22E-04
Si 33	6.18E+00					1.55E-09
P 33	2.19E+06		4.23E-06	9.84E-07		1.54E-05
P 34	1.24E+01		5.88E-07	9.70E-07		4.22E-06
Cl 34	1.53E+00				8.28E-08	
Cl 34m1	1.92E+03				2.25E-08	
P 35	4.73E+01		6.40E-08	1.37E-09		2.05E-07
S 35	7.56E+06		4.67E-08	3.11E-08	3.22E-07	9.84E-08
Ar 35	1.78E+00				2.27E-07	
S 37	3.03E+02		1.07E-08	1.30E-08	1.27E-06	2.08E-08
Ar 37	3.03E+06				3.59E-08	
S 38	1.02E+04				6.91E-09	
Cl 38	2.23E+03				1.03E-05	
Cl 38m1	7.15E-01				1.29E-06	
Cl 39	3.37E+03				5.30E-05	
Ar 39	8.49E+09				8.92E-09	
Cl 40	8.10E+01				2.73E-07	
Ar 41	6.58E+03				4.32E-05	
Sc 43	1.40E+04		1.51E-06			4.64E-07
Sc 44	1.43E+04		7.71E-04			2.32E-04
Sc 44m1	2.11E+05		1.88E-05			5.65E-06
Ti 44	1.89E+09		1.09E-08			3.38E-09
Ca 45	1.41E+07		1.50E-06			5.91E-07
Sc 45m1	3.18E-01		1.04E-02			3.67E-03
Ti 45	1.11E+04		1.83E-02	1.01E-05		8.40E-03
Sc 46	7.24E+06		5.19E-05			1.87E-05
Sc 46m1	1.88E+01		1.42E-03			5.11E-04
Ca 47	3.92E+05		1.07E-07			6.34E-08
Sc 47	2.89E+05		6.25E-03			2.20E-03
V 47	1.96E+03		1.39E-05	1.09E-07		2.94E-05
Sc 48	1.57E+05		6.59E-04			2.47E-04
V 48	1.38E+06		8.95E-04	7.63E-06		1.57E-03
Cr 48	7.76E+04		1.85E-03	1.58E-05		3.25E-03

nuclide	half-life (s)	EOB activity (Ci)				
		all target disks	target assembly without disks	shielded box	air inside box	remainder of model
Sc 49	3.43E+03		4.63E-04			1.63E-04
V 49	2.85E+07		1.19E-03	1.56E-05		2.18E-03
Cr 49	2.54E+03	1.82E-09	2.21E-01	2.58E-03		3.97E-01
Sc 50	1.03E+02		5.75E-07			4.74E-07
Ti 51	3.46E+02		2.88E-04	1.08E-05		2.74E-04
Cr 51	2.39E+06	7.63E-08	2.32E-01	4.13E-03		4.19E-01
Mn 51	2.77E+03	1.00E-08	8.55E-06	2.58E-07		7.06E-05
Ti 52	1.02E+02		1.00E-06	8.25E-09		1.87E-06
V 52	2.25E+02		1.89E-01	7.69E-03		3.54E-01
Mn 52	4.83E+05	6.92E-07	1.15E-03	3.90E-05		7.14E-03
Mn 52m1	1.27E+03	3.27E-06	5.42E-03	1.84E-04		3.37E-02
Fe 52	2.98E+04	6.20E-07	1.03E-03	3.50E-05		6.37E-03
Fe 52m1	4.59E+01	7.22E-09	1.20E-05	4.08E-07		7.43E-05
V 53	9.60E+01		1.34E-02	4.99E-04		2.50E-02
Mn 53	1.18E+14					2.67E-09
Fe 53	5.11E+02	1.25E-04	3.52E-01	1.63E-02		2.03E+00
Fe 53m1	1.52E+02	3.17E-06	8.95E-03	4.13E-04		5.16E-02
V 54	4.98E+01		1.02E-05	7.84E-06		3.96E-05
Mn 54	2.70E+07	1.62E-07	7.71E-04	3.72E-04		6.19E-03
Cr 55	2.10E+02	2.89E-09	3.80E-03	3.78E-03		6.16E-03
Fe 55	8.64E+07	2.26E-06	6.26E-03	4.83E-04		3.88E-02
Co 55	6.31E+04		8.18E-04	1.19E-06		5.25E-04
Cr 56	3.56E+02		6.46E-09			4.46E-08
Mn 56	9.28E+03	7.18E-06	1.14E-01	1.56E-01		5.32E-01
Co 56	6.67E+06		5.16E-03	8.51E-06		3.02E-03
Ni 56	5.25E+05		1.08E-02	1.79E-05		6.31E-03
Mn 57	8.54E+01	1.54E-07	4.87E-04	4.46E-04		3.75E-03
Co 57	2.35E+07		4.65E-02	1.24E-04		2.98E-02
Ni 57	1.28E+05		2.50E+00	6.33E-03		1.60E+00
Mn 58	3.00E+00		1.77E-06	4.39E-06		1.89E-05
Co 58	6.12E+06		1.35E-02	3.59E-03		1.53E-02
Co 58m1	3.25E+04		3.91E-01	4.96E-02		2.99E-01
Fe 59	3.84E+06	9.79E-09	3.72E-05	6.55E-05		8.11E-05
Ni 59	2.40E+12		2.48E-07	1.08E-08		1.46E-07
Co 60	1.66E+08		2.47E-04	8.88E-07		8.11E-05
Co 60m1	6.28E+02		4.15E-01	4.64E-05		1.25E-01

nuclide	half-life (s)	EOB activity (Ci)				
		all target disks	target assembly without disks	shielded box	air inside box	remainder of model
Fe 61	3.59E+02		2.48E-06	3.90E-07		3.65E-06
Co 61	5.94E+03		5.33E-02	1.94E-04		3.35E-02
Cu 61	1.20E+04		4.55E-03			1.47E-03
Fe 62	6.80E+01		4.10E-08			2.50E-08
Co 62	9.00E+01		4.10E-04	7.58E-06		2.75E-04
Co 62m1	8.35E+02		7.58E-05	3.80E-06		6.39E-05
Cu 62	5.80E+02		1.26E-01			4.66E-02
Co 63	2.74E+01		1.66E-03	3.28E-06		1.01E-03
Ni 63	3.16E+09		1.30E-05	3.07E-07		6.23E-06
Co 64	3.00E-01		3.94E-06	6.15E-07		5.81E-06
Cu 64	4.57E+04		5.37E-02			1.93E-02
Ni 65	9.06E+03		1.26E-02	2.01E-03		5.91E-03
Cu 66	3.07E+02		3.35E-03			1.07E-03
Sr 87m1	1.01E+04	1.25E-07	2.64E-06			7.77E-07
Y 87	2.87E+05	1.68E-07	3.51E-06			1.03E-06
Y 87m1	4.81E+04	1.42E-06	2.73E-05			8.01E-06
Zr 87	6.05E+03	2.24E-06	4.16E-05			1.22E-05
Zr 87m1	1.40E+01	9.95E-07	1.85E-05			5.40E-06
Y 88	9.21E+06	7.66E-09	1.32E-05			4.12E-06
Y 88m1	3.01E-04		1.57E-03			4.87E-04
Zr 88	7.21E+06	2.36E-06	8.17E-05			2.99E-05
Zr 88m1	1.32E-06		7.84E-09			7.29E-09
Y 89m1	1.57E+01		2.19E-02			8.08E-03
Zr 89	2.82E+05	1.89E-06	3.76E-05			1.30E-05
Zr 89m1	2.51E+02	4.54E-06	9.53E-05			3.15E-05
Nb 89	7.31E+03	1.86E-08	2.19E-07			6.79E-08
Nb 89m1	3.96E+03	1.49E-08	1.74E-07			5.42E-08
Y 90	2.30E+05		2.57E-05			1.96E-05
Y 90m1	1.15E+04		3.95E-05			3.03E-05
Zr 90m1	8.09E-01	3.66E-04	1.05E-02			3.59E-03
Nb 90	5.25E+04	1.54E-04	3.78E-03			1.15E-03
Nb 90m1	1.88E+01	1.37E-05	5.15E-04			1.53E-04
Mo 90	2.00E+04	9.25E-05	2.14E-03			6.59E-04
Y 91	5.06E+06		9.23E-08			2.72E-08
Y 91m1	2.98E+03		3.95E-06			1.16E-06
Zr 91m1	4.35E-06	9.46E-06	4.33E-03			1.39E-03

nuclide	half-life (s)	EOB activity (Ci)				
		all target disks	target assembly without disks	shielded box	air inside box	remainder of model
Nb 91	2.15E+10	3.34E-08	2.32E-06			8.17E-07
Nb 91m1	5.26E+06	3.53E-05	5.15E-03			1.78E-03
Nb 91m2	3.76E-06	2.21E-03	4.21E-01			1.45E-01
Mo 91	9.29E+02	6.22E-03	2.09E-01			7.57E-02
Mo 91m1	6.46E+01	3.51E-03	1.18E-01			4.27E-02
Nb 92m1	8.77E+05	2.12E-06	2.09E-01			7.79E-02
Nb 93m1	5.09E+08	3.63E-08	1.40E-05			1.03E-05
Mo 93	1.26E+11	5.42E-09	1.45E-07			5.34E-08
Mo 93m1	2.47E+04	1.06E-04	2.71E-03			9.26E-04
Nb 94	6.41E+11		1.19E-08			5.69E-09
Nb 94m1	3.76E+02	2.71E-04	7.88E-02			3.79E-02
Zr 95	5.53E+06	7.65E-04	9.16E-07			3.15E-07
Nb 95	3.02E+06	9.99E-06	1.32E-04			4.57E-05
Nb 95m1	3.12E+05	2.52E-05	2.10E-03			7.24E-04
Nb 96	8.41E+04	4.56E-03	2.76E-03			9.19E-04
Zr 97	6.03E+04	6.76E-05	2.25E-07			1.88E-07
Nb 97	4.33E+03	4.36E-02	5.76E-03			1.92E-03
Nb 97m1	5.27E+01	1.92E-02	2.39E-03			7.96E-04
Zr 98	3.07E+01	8.54E-07				
Nb 98	2.86E+00	3.75E-01	3.29E-04			1.00E-04
Nb 98m1	3.08E+03	5.41E-02	4.81E-05			1.49E-05
Nb 99	1.50E+01	6.46E-01	7.31E-04			2.39E-04
Nb 99m1	1.56E+02	5.08E-01	5.74E-04			1.87E-04
Mo 99	2.37E+05	3.57E+01	5.80E-02			2.25E-02
Tc 99	6.66E+12	9.80E-08				
Tc 99m1	2.17E+04	2.13E+01	3.46E-02			1.34E-02
Nb100	1.50E+00	1.95E-04	6.34E-07			5.55E-07
Nb100m1	2.90E+00	6.02E-05	1.96E-07			1.71E-07
Tc100	1.58E+01	2.59E-05	2.17E-09			
Mo101	8.77E+02	8.65E-01	1.81E-03			1.15E-03
Tc101	8.53E+02	8.65E-01	1.81E-03			1.15E-03
Hf177m1	1.08E+00	3.66E-08				
Hf177m2	3.08E+03	2.39E-09				
Ta177	2.03E+05	1.75E-08				
W 177	7.92E+03	6.35E-08				
Hf178m1	4.00E+00	6.88E-07				

nuclide	half-life (s)	EOB activity (Ci)				
		all target disks	target assembly without disks	shielded box	air inside box	remainder of model
Ta178	5.57E+02	1.11E-07				
W 178	1.87E+06	1.06E-07				
Hf179m1	1.87E+01	3.01E-06				
Ta179	5.08E+07	5.14E-08				
W 179	2.22E+03	4.19E-05				
W 179m1	3.84E+02	1.86E-05				
Ta180	2.94E+04	3.03E-06				
W 180m1	5.47E-03	1.54E-09				
Hf181	3.66E+06	1.90E-08				
W 181	1.05E+07	2.86E-05				
Hf182m1	3.69E+03	2.42E-07				
Ta182	9.89E+06	1.48E-07				
Ta182m1	2.83E-01	4.10E-06				
Ta182m2	9.50E+02	5.47E-07				
Hf183	3.84E+03	4.90E-09				
Ta183	4.41E+05	1.04E-06				
W 183m1	5.25E+00	6.00E-04				
Ta184	3.13E+04	1.92E-06				
Ta185	2.96E+03	2.21E-05				
W 185	6.49E+06	3.49E-05				
W 185m1	1.00E+02	3.96E-04				
W 187	8.54E+04	6.57E-04				
Hg199m1	2.53E+03			2.60E-09		
Hg201m1	9.40E-05			1.46E-08		
Tl202	1.06E+06			8.97E-07		
Pb202m1	1.29E+04			3.69E-06		
Hg203	4.03E+06			1.19E-05		
Pb203	1.87E+05			2.77E-02		
Pb203m1	6.21E+00			1.21E-02		
Pb203m2	4.80E-01			3.15E-04		
Tl204	1.19E+08			6.80E-07		
Tl204m1	6.17E-05			2.08E-04		
Pb204m1	4.03E+03			7.42E-01		
Hg205	3.08E+02			1.98E-04		
Pb205	4.83E+14			5.69E-09		
Pb205m1	5.55E-03			3.44E+00		

nuclide	half-life (s)	EOB activity (Ci)				
		all target disks	target assembly without disks	shielded box	air inside box	remainder of model
Hg206	4.89E+02			1.64E-06		
Tl206	2.52E+02			2.38E-02		
Tl206m1	2.24E+02			2.72E-04		
Tl207	2.86E+02			2.79E-02		
Tl207m1	1.33E+00			3.11E-03		
Pb207m1	8.06E-01			1.10E+01		
Tl208	1.83E+02			9.47E-05		
Pb209	1.17E+04			7.26E-01		