BNL-210939-2019-TECH
C-A/BLIP/002

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E. Lessard

May 2019

Collider Accelerator Department
Brookhaven National Laboratory

U.S. Department of Energy
USDOE Office of Science (SC), Nuclear Physics (NP) (SC-26)

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RSC Technical Note, Target Sub-Committee

June 2018

Estimates of Radionuclide Activity in Irradiated Radium Targets at TR19 Cyclotron

E. Lessard

Collider-Accelerator Department
Brookhaven National Laboratory
Upton, N.Y. 11973

RSC Technical Note, Target Sub-Committee

Abstract

By congressional mandate the National Isotope Development Center (NIDC) and the Medical Isotope Research and Production (MIRP) Program at C-AD are tasked to develop production methods for radioisotopes that are needed for the Nation and then produce them. However, the MIRP Program is not allowed to compete with commercial radiopharmaceutical companies should they decide to produce any specific radionuclide. Currently the MIRP Program is repurposing the TR19 Cyclotron in Building 901 for use as an alternate source of research radionuclides. This conversion requires changeover from aqueous targets producing very short-lived radio-nuclides (minutes) used by the former BNL Medical Department to solid targets producing longer-lived radionuclides (days to months) used by the medical community in the United States for diagnostic and therapeutic purposes.

Initial interest is to use the TR19 cyclotron to produce Ac-225 from solid Ra-226 at low energies free or nearly free from Ac-227. This Technical Note addresses the radioactivity produced in these targets so that safety analyses, handling, processing and waste management activities can be addressed.

INTRODUCTION

The target is 300 mg Ra-226, or 7.99E20 atoms. The proton current from TR19 is 200 microA, which is 1.25E15 protons/s. The total absorption cross section for 16 MeV protons interacting with radium is 600 mb or 6.00E-25 cm^2/atom. The target atom loss rate is 5.99E11 atoms/s. Thus, there is minimal loss of target atoms during 40 hours of proton irradiation.

The radium is deposited on a 1.58 cm by 4.45 cm aluminum backing plate (Figure 1). The density of radium is 5.0 g cm^{-3} and the density of aluminum is 2.7 g cm^{-3}. The range of 16 MeV protons in radium is about 0.7 g cm^{-2} (0.14 cm) and in aluminum it is 0.4 g cm^{-2} (0.15 cm).[1] The thickness of the aluminum plate is 0.234 cm. The thickness of the radium deposit is 0.0086 cm. Thus, the proton beam penetrates the radium layer and is completely stopped in the aluminum backing plate.

Figure 1

[1] https://physics.nist.gov/PhysRefData/Star/Text/PSTAR.html

The plan is to irradiate the radium target in a fully-enclosed, removable target holder with 16 MeV proton beam entering through a thin window on the sealed target holder for four consecutive days. The irradiation period each day would be 10 hours. On the fifth day, the target and target holder would be moved to Building 801 for processing in a hot cell.

The spallation products listed in Table 1 are expected for p,Ra-226 interactions at 16 MeV. Cross sections were from TALYS.[2]

Table 1 Effective Production Rate of Spallation Product Nuclides at TR19 for Ra-226 Targets

Spallation Product Nuclide	Cross-section, cm^2 $atom^{-1}$	Maximum Calculated Atom Production Rate, atoms s^{-1}	Half-life, s	Maximum Calculated Activity for 40-Hour Irradiation, Ci	Observed Ac-225/Ra-226 Activity Ratio at 45 Hours,[3] %	Effective Production Rate, atoms s^{-1}
Ac-227	4.77E-28	4.76E+08	6.87E+08	1.87E-06		2.14E+08
Ac-226	2.51E-26	2.51E+10	1.06E+05	4.14E-01		1.13E+10
Ac-225	4.46E-25	4.46E+11	8.64E+05	1.31E+00	45	2.00E+11
Ac-224	1.28E-26	1.28E+10	7.23E+03	3.46E-01		5.75E+09
Ra-225	1.05E-27	1.05E+09	1.29E+06	2.11E-03		4.72E+08
Ra-224	8.46E-29	8.45E+07	3.14E+05	6.22E-04		3.80E+07

Some systematic errors and losses are expected (beam energy variance, beam/target mis-alignment, beam loss in window, etc.). Reference 3 indicates Ac-225 production was such that 45% was measured for the Ac-225 activity relative to the Ra-226 activity for a 45-hour irradiation of 30 mg Ra-226 targets using a 50-microA 16-MeV proton-beam. Reference 3 produced 13 mCi of Ac-225, and one would calculate a maximum of 33 mCi based on beam current and cross -section. TR19 will irradiate 300 mg with 200 microA, and one would expect a factor of 40 increase in the Reference 3 result or 590 mCi using the Ac-225/Ra-226 ratio. Due to various beam loss mechanisms, one would not expect the maximin calculated activity of 1.31 Ci for the TR19 irradiations as shown in Table 1. Thus, the relative activity ratio from Reference 3 was assumed here and an effective production rate for TR19 irradiations is listed in Table 1. These effective production rates listed in Table 1 were used as inputs to calculate estimates of radioactivity in the TR19 target as a function of time. It is noted that the incremental style of TR19 irradiations, 10-hour periods each day for four consecutive days reduces activity at end of bombardment (EOB) due to the additional increments of radioactive decay between consecutive irradiations; that is, decay further reduces the estimate to 558 mCi for Ac-225 at EOB at TR19.

KINETICS MODEL

[2] RSICC Computer Code Collection, TALYS 1.2, Nuclear Model Code System for Analysis and Prediction, of Nuclear Reactions and Generation of Nuclear Data, ORNL

[3] C. Apostolidis, R. Molinet, J. McGinley, K. Abbas, J. Möllenbeck, A. Morgenstern, Cyclotron Production of Ac-225 for Targeted Alpha Therapy, Applied Radiation and Isotopes 62 (2005) 383–387

The equation for production for the quantity of the n^{th} nuclide in a decay chain occurring at irradiation time *t*, assuming radioactive decay, ingrowth of daughters and production of parent during irradiation, is[4]

$$N_n(t) = \sum_{i=1}^{n} P_i \prod_{j=i}^{n-1} f_{j+1}\lambda_j \sum_{j=i}^{n} \frac{\left(1 - e^{-\lambda_j t}\right)}{\lambda_j \prod_{\substack{p=i \\ p\neq j}}^{p=n} (\lambda_p - \lambda_j)}$$

where $N_n\ (t)$ is the quantity of the nth nuclide in the decay chain present at time *t*; P_i is the atom production rate of the *ith* nuclide present during irradiation; f_{j+1} is the fraction of nuclide *j* disintegrations that produce nuclide *j+1*; and λ_j is the decay constant for nuclide *j*.

The equation for the quantity of the *nth* nuclide in a decay chain occurring at time *T* after EOB, assuming radioactive decay and ingrowth of daughters, is

$$N_n(T) = \sum_{i=1}^{n} N_i\,(0) \prod_{j=i}^{j=n-1} f_{j+1}\lambda_j \sum_{j=i}^{n} \frac{e^{-\lambda_j T}}{\prod_{\substack{p=i \\ p\neq j}}^{p=n} (\lambda_p - \lambda_j)}$$

where $N_n\ (T)$ is the quantity of the nth nuclide in the decay chain present at time *T*; $N_i(0)$ is the quantity of the *ith* nuclide present at time 0 (EOB); f_{j+1} is the fraction of nuclide *j* disintegrations which produce nuclide j+1; and λ_j is the decay constant for nuclide *j*. The value of an empty Π product is equal to one, so that:

$$\prod_{j=i}^{n-1} (f_{j+1}\lambda_j) = 1 \quad if\ i = n$$

RESULTS

The following Tables and Figures show the activity at EOB after four 10-hour irradiations on four consecutive says, and the subsequent daughter ingrowth and decay. The activity estimates are for bombardment with 16 MeV, 200 microA proton beam on 300 mg of Ra-226. Again, the calculated activities were reduced 45% based on the observed Ac-225 to Ra-226 activity ratio in Reference 3. That is, it was assumed the bombardment was not 100% efficient.

Figure 2 shows the gross radioactivity in an TR19 target following irradiation. Schematics of the decay chains are illustrated are on page 23.

[4] K. Skrable, C. French, G. Chabot and A. Major, A General Equation for the Kinetics of Linear First Order Phenomena and Suggested Applications, Health Physics, Vol. 27 (July), pp155-157

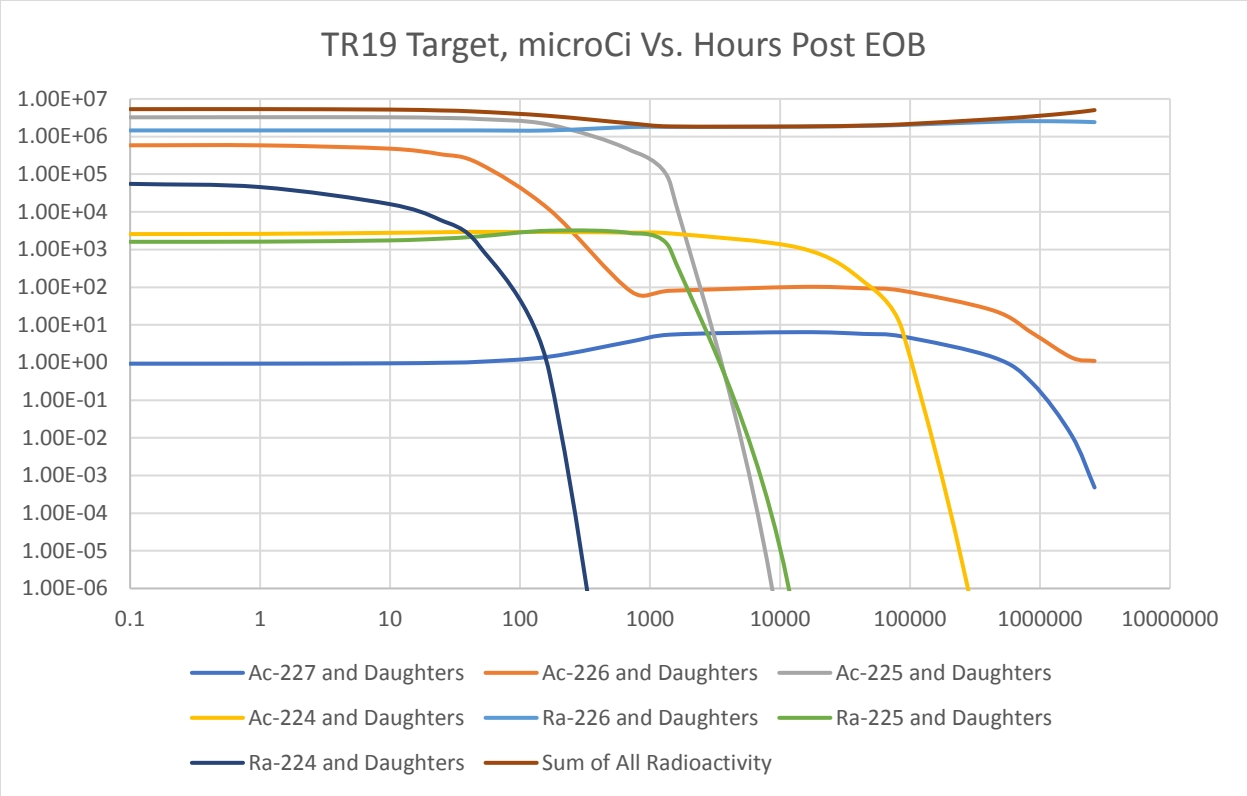

Figure 2 Assuming a 1-week old Ra-226 target, Ingrowth and Decay of Target post EOB

CONSIDERATIONS

- 300 mg of Ra-226 and its daughters' radioactivity peak at 2.57 Ci; while 300 mg of pure Ra-226 is 0.3 Ci at time 0; at 3.5 days with daughters' radioactivity it is 1 Ci; at one week with daughters' radioactivity is 1.5 Ci
- Gross target radioactivity at EOB is 5.3 Ci assuming a 1-week old Ra-226 target
- Ac-225 activity at EOB is 0.558 Ci
- Ra-225 and its daughters' radioactivity peak at 1 week at 3.1 mCi and is essentially gone after 600 days
- Ra-224 and daughter activity at EOB is 55 mCi and is essentially gone after 1 week
- Ac-225 and daughter activity is 3.24 Ci at EOB, 2.07 Ci at 1 week, 55 mCi at 60 days and essentially gone after 600 days
- Ac-224 and daughter activity is about 3 mCi for 60 days, 1 mCi at 600 days and 7 microCi at 10 years
- Ac-226 and daughter activity is 0.58 Ci at EOB, 11 mCi at 1 week and 80 microCi at 10 years
- Ac-227 and daughter activity is 0.93 microCi at EOB and 4.9 microCi at 10 years
- Radon gas primarily from decay of Ra-226 will be constantly produced; although, weekly targets will produce radon isotopes in significant quantities from other parent nuclides such as Ra-224 and Ac-225

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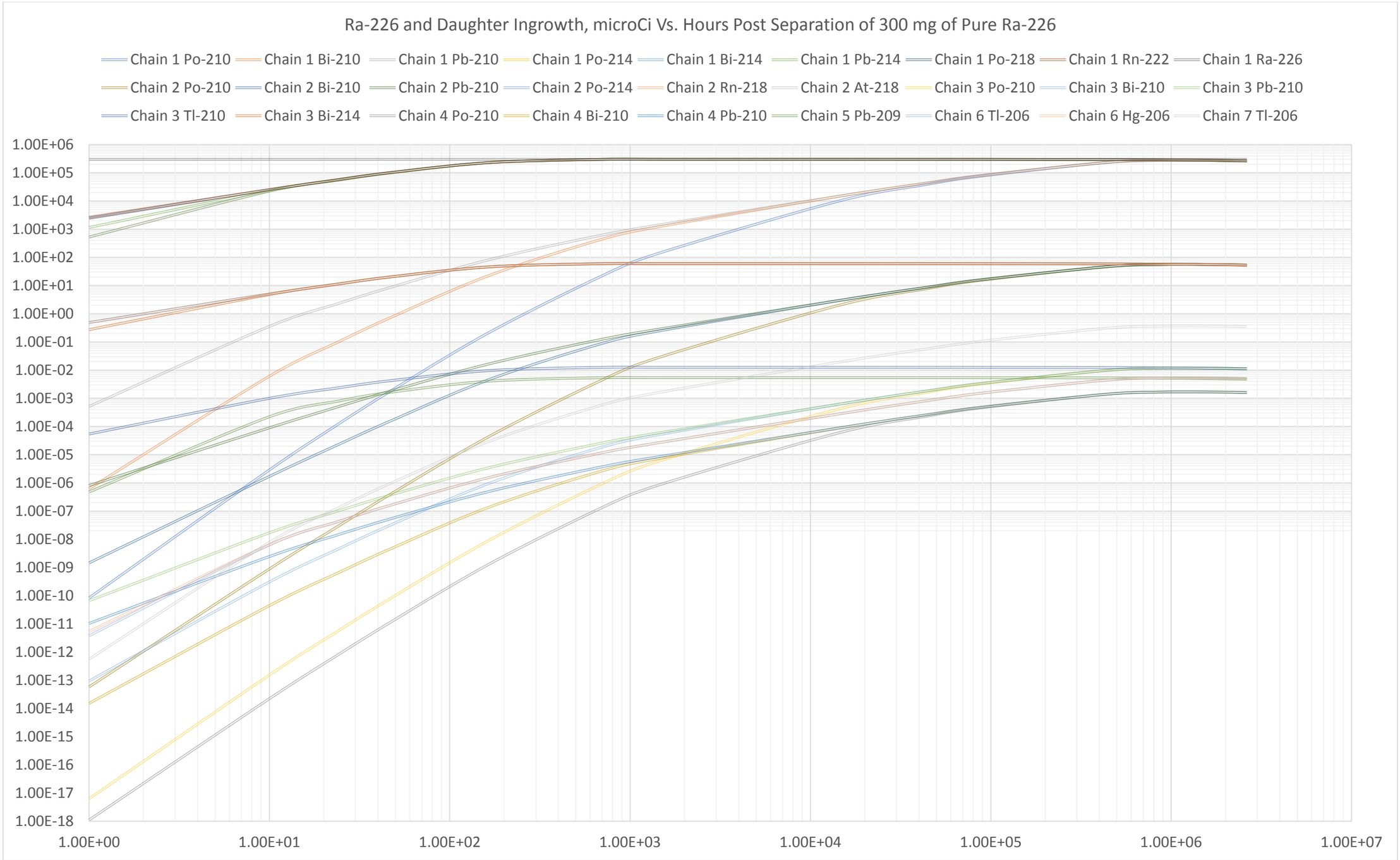
Target Ra-226 and Daughter Ingrowth, microCi Vs. Hours Post Separation of 300 mg Pure Ra-226

			1.00	10.00	24.00	48.00	168.00	720.00	1440.00	14400.00	43800.00	87600.00	438000.00	876000.00	1752000.00	2628000.00
Chain 1	Po-210		8.28E-11	2.87E-06	1.19E-04	1.97E-03	2.28E-01	2.42E+01	1.40E+02	9.96E+03	3.83E+04	7.58E+04	2.32E+05	2.77E+05	2.78E+05	2.67E+05
	Bi-210		6.17E-07	6.07E-03	9.84E-02	7.79E-01	2.36E+01	4.66E+02	1.22E+03	1.46E+04	4.28E+04	7.96E+04	2.33E+05	2.77E+05	2.78E+05	2.67E+05
	Pb-210		5.13E-04	3.56E-01	2.28E+00	8.97E+00	8.43E+01	6.42E+02	1.40E+03	1.48E+04	4.29E+04	7.97E+04	2.33E+05	2.77E+05	2.78E+05	2.67E+05
	Po-214		5.27E+02	2.23E+04	5.44E+04	1.01E+05	2.30E+05	2.99E+05	2.99E+05	2.99E+05	2.99E+05	2.98E+05	2.93E+05	2.87E+05	2.74E+05	2.63E+05
	Bi-214		5.27E+02	2.23E+04	5.45E+04	1.01E+05	2.30E+05	2.99E+05	2.99E+05	2.99E+05	2.99E+05	2.98E+05	2.93E+05	2.87E+05	2.75E+05	2.63E+05
	Pb-214		1.15E+03	2.35E+04	5.55E+04	1.02E+05	2.31E+05	2.99E+05	2.99E+05	2.99E+05	2.99E+05	2.98E+05	2.93E+05	2.87E+05	2.75E+05	2.63E+05
	Po-218		2.44E+03	2.51E+04	5.70E+04	1.03E+05	2.32E+05	2.99E+05	3.00E+05	3.00E+05	2.99E+05	2.99E+05	2.94E+05	2.87E+05	2.75E+05	2.63E+05
	Rn-222		2.63E+03	2.53E+04	5.71E+04	1.03E+05	2.32E+05	2.99E+05	3.00E+05	3.00E+05	2.99E+05	2.99E+05	2.94E+05	2.87E+05	2.75E+05	2.63E+05
	Ra-226		3.00E+05	3.00E+05	3.00E+05	3.00E+05	3.00E+05	3.00E+05	3.00E+05	3.00E+05	3.00E+05	3.00E+05	3.00E+05	3.00E+05	3.00E+05	3.00E+05
Chain 2	Po-210		5.76E-14	8.86E-10	2.87E-08	4.31E-07	4.69E-05	4.87E-03	2.80E-02	2.00E+00	7.68E+00	1.52E+01	4.64E+01	5.55E+01	5.57E+01	5.34E+01
	Bi-210		1.45E-09	1.70E-06	2.26E-05	1.67E-04	4.81E-03	9.36E-02	2.45E-01	2.93E+00	8.57E+00	1.59E+01	4.67E+01	5.55E+01	5.57E+01	5.34E+01
	Pb-210		8.06E-07	8.97E-05	5.01E-04	1.88E-03	1.71E-02	1.29E-01	2.82E-01	2.96E+00	8.60E+00	1.60E+01	4.67E+01	5.55E+01	5.57E+01	5.34E+01
	Po-214		4.87E-01	5.02E+00	1.14E+01	2.06E+01	4.63E+01	5.99E+01	6.00E+01	5.99E+01	5.99E+01	5.97E+01	5.87E+01	5.74E+01	5.50E+01	5.27E+01
	Rn-218		4.87E-01	5.02E+00	1.14E+01	2.07E+01	4.63E+01	5.99E+01	6.00E+01	6.00E+01	5.99E+01	5.97E+01	5.87E+01	5.75E+01	5.50E+01	5.27E+01
	At-218		4.87E-01	5.02E+00	1.14E+01	2.07E+01	4.63E+01	5.99E+01	6.00E+01	6.00E+01	5.99E+01	5.97E+01	5.87E+01	5.75E+01	5.50E+01	5.27E+01
Chain 3	Po-210		6.22E-18	1.53E-13	5.55E-12	8.69E-11	9.73E-09	1.02E-06	5.87E-06	4.19E-04	1.61E-03	3.19E-03	9.75E-03	1.16E-02	1.17E-02	1.12E-02
	Bi-210		9.38E-14	3.07E-10	4.46E-09	3.40E-08	1.00E-06	1.96E-05	5.14E-05	6.15E-04	1.80E-03	3.35E-03	9.79E-03	1.17E-02	1.17E-02	1.12E-02
	Pb-210		6.61E-11	1.70E-08	1.01E-07	3.86E-07	3.57E-06	2.70E-05	5.91E-05	6.22E-04	1.81E-03	3.35E-03	9.79E-03	1.17E-02	1.17E-02	1.12E-02
	Tl-210		5.43E-05	1.00E-03	2.35E-03	4.30E-03	9.71E-03	1.26E-02	1.26E-02	1.26E-02	1.26E-02	1.25E-02	1.23E-02	1.21E-02	1.15E-02	1.11E-02
	Bi-214		2.72E-01	4.78E+00	1.12E+01	2.05E+01	4.62E+01	5.98E+01	5.99E+01	5.99E+01	5.98E+01	5.97E+01	5.87E+01	5.74E+01	5.50E+01	5.26E+01
Chain 4	Po-210		1.10E-18	2.21E-14	7.96E-13	1.24E-11	1.39E-09	1.46E-07	8.39E-07	5.99E-05	2.30E-04	4.55E-04	1.39E-03	1.66E-03	1.67E-03	1.60E-03
	Bi-210		1.51E-14	4.43E-11	6.40E-10	4.87E-09	1.43E-07	2.80E-06	7.34E-06	8.78E-05	2.57E-04	4.78E-04	1.40E-03	1.66E-03	1.67E-03	1.60E-03
	Pb-210		1.03E-11	2.45E-09	1.44E-08	5.53E-08	5.10E-07	3.86E-06	8.44E-06	8.88E-05	2.58E-04	4.79E-04	1.40E-03	1.66E-03	1.67E-03	1.60E-03
Chain 5	Pb-209		4.76E-07	2.22E-04	7.91E-04	1.67E-03	4.09E-03	5.38E-03	5.39E-03	5.39E-03	5.38E-03	5.37E-03	5.27E-03	5.16E-03	4.94E-03	4.73E-03
Chain 6	Tl-206		3.77E-12	6.33E-09	4.21E-08	1.68E-07	1.59E-06	1.22E-05	2.66E-05	2.80E-04	8.13E-04	1.51E-03	4.41E-03	5.25E-03	5.26E-03	5.05E-03
	Hg-206		5.32E-12	6.46E-09	4.25E-08	1.69E-07	1.59E-06	1.22E-05	2.66E-05	2.80E-04	8.13E-04	1.51E-03	4.41E-03	5.25E-03	5.26E-03	5.05E-03
Chain 7	Tl-206		5.54E-13	7.76E-09	1.28E-07	1.02E-06	3.10E-05	6.13E-04	1.61E-03	1.92E-02	5.63E-02	1.05E-01	3.06E-01	3.65E-01	3.66E-01	3.51E-01


Ra-226 and Daughter Ingrowth, microCi Vs. Hours Post Separation of 300 mg of Pure Ra-226
Chain 1 Po-210
Chain 1 Bi-210
Chain 1 Pb-210
Chain 1 Po-214
Chain 1 Bi-214
Chain 1 Pb-214
Chain 1 Po-218
Chain 1 Rn-222
Chain 1 Ra-226
Chain 2 Po-210
Chain 2 Bi-210
Chain 2 Pb-210
Chain 2 Po-214
Chain 2 Rn-218
Chain 2 At-218
Chain 3 Po-210
Chain 3 Bi-210
Chain 3 Pb-210
Chain 3 Tl-210
Chain 3 Bi-214
Chain 4 Po-210
Chain 4 Bi-210
Chain 4 Pb-210
Chain 5 Pb-209
Chain 6 Tl-206
Chain 6 Hg-206
Chain 7 Tl-206
1.00E+06
1.00E+05
1.00E+04
1.00E+03
1.00E+02
1.00E+01
1.00E+00
1.00E-01
1.00E-02
1.00E-03
1.00E-04
1.00E-05
1.00E-06
1.00E-07
1.00E-08
1.00E-09
1.00E-10
1.00E-11
1.00E-12
1.00E-13
1.00E-14
1.00E-15
1.00E-16
1.00E-17
1.00E-18
1.00E+00
1.00E+01
1.00E+02
1.00E+03
1.00E+04
1.00E+05
1.00E+06
1.00E+07

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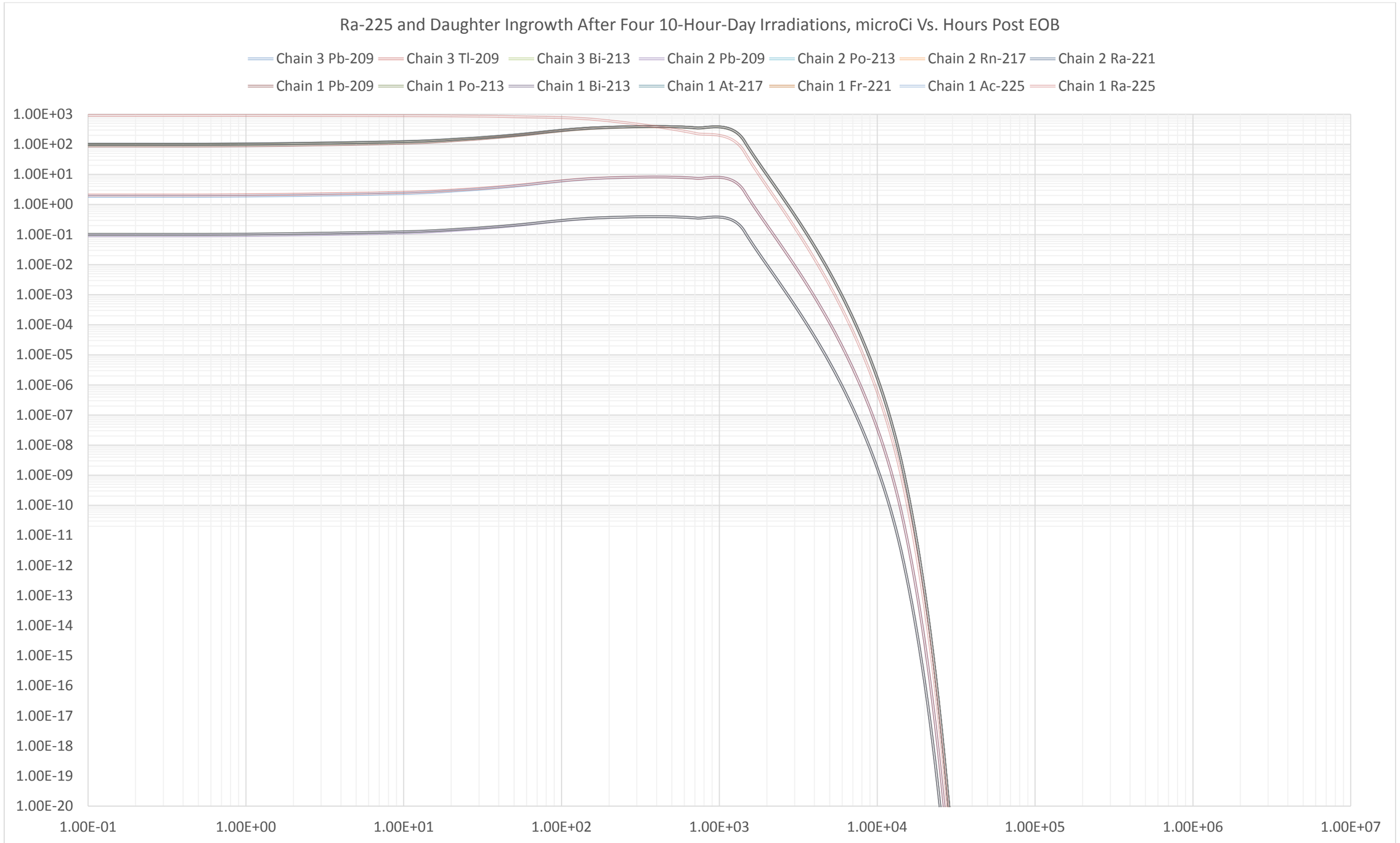
Four 10-Hour Irradiations on Four Consecutive Days; 16 MeV, 200 microA Beam from TR19 on 300 mg Ra-226

Ra-225 and Daughter Ingrowth After Four Consecutive 10-Hour-Day Irradiations, microCi Vs. Hours Post EOB

		0.10	1.00	10.00	24.00	48.00	168.00	720.00	1440.00	14400.00	43800.00	87600.00	438000.00	876000.00	1752000.00	2628000.00
Chain 3	Pb-209	1.87E+00	1.91E+00	2.32E+00	2.97E+00	3.97E+00	7.38E+00	7.44E+00	2.71E+00	4.44E-11	7.90E-36	1.06E-72	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Tl-209	2.07E+00	2.11E+00	2.54E+00	3.18E+00	4.16E+00	7.47E+00	7.40E+00	2.69E+00	4.40E-11	7.83E-36	1.05E-72	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Bi-213	9.87E+01	1.01E+02	1.22E+02	1.52E+02	1.99E+02	3.57E+02	3.54E+02	1.29E+02	2.10E-09	3.75E-34	5.04E-71	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Chain 2	Pb-209	9.19E-02	9.38E-02	1.14E-01	1.45E-01	1.93E-01	3.55E-01	3.56E-01	1.30E-01	2.12E-12	3.78E-37	5.08E-74	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Po-213	1.02E-01	1.04E-01	1.24E-01	1.55E-01	2.01E-01	3.59E-01	3.54E-01	1.29E-01	2.10E-12	3.74E-37	5.04E-74	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Rn-217	1.02E-01	1.04E-01	1.24E-01	1.55E-01	2.01E-01	3.59E-01	3.54E-01	1.29E-01	2.10E-12	3.74E-37	5.04E-74	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Ra-221	1.02E-01	1.04E-01	1.24E-01	1.55E-01	2.01E-01	3.59E-01	3.54E-01	1.29E-01	2.10E-12	3.74E-37	5.04E-74	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Chain 1	Pb-209	8.77E+01	8.95E+01	1.09E+02	1.39E+02	1.86E+02	3.46E+02	3.48E+02	1.27E+02	2.08E-09	3.70E-34	4.98E-71	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Po-213	9.70E+01	9.91E+01	1.19E+02	1.49E+02	1.95E+02	3.50E+02	3.47E+02	1.26E+02	2.06E-09	3.67E-34	4.94E-71	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Bi-213	9.87E+01	1.01E+02	1.22E+02	1.52E+02	1.99E+02	3.57E+02	3.54E+02	1.29E+02	2.10E-09	3.75E-34	5.04E-71	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	At-217	1.02E+02	1.04E+02	1.24E+02	1.54E+02	2.01E+02	3.58E+02	3.54E+02	1.29E+02	2.10E-09	3.74E-34	5.03E-71	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Fr-221	1.02E+02	1.04E+02	1.24E+02	1.55E+02	2.01E+02	3.59E+02	3.54E+02	1.29E+02	2.10E-09	3.74E-34	5.04E-71	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Ac-225	1.02E+02	1.04E+02	1.25E+02	1.55E+02	2.02E+02	3.59E+02	3.54E+02	1.29E+02	2.10E-09	3.74E-34	5.04E-71	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Ra-225	9.15E+02	9.13E+02	8.97E+02	8.73E+02	8.33E+02	6.61E+02	2.27E+02	5.61E+01	6.91E-10	1.23E-34	1.66E-71	0.00E+00	0.00E+00	0.00E+00	0.00E+00

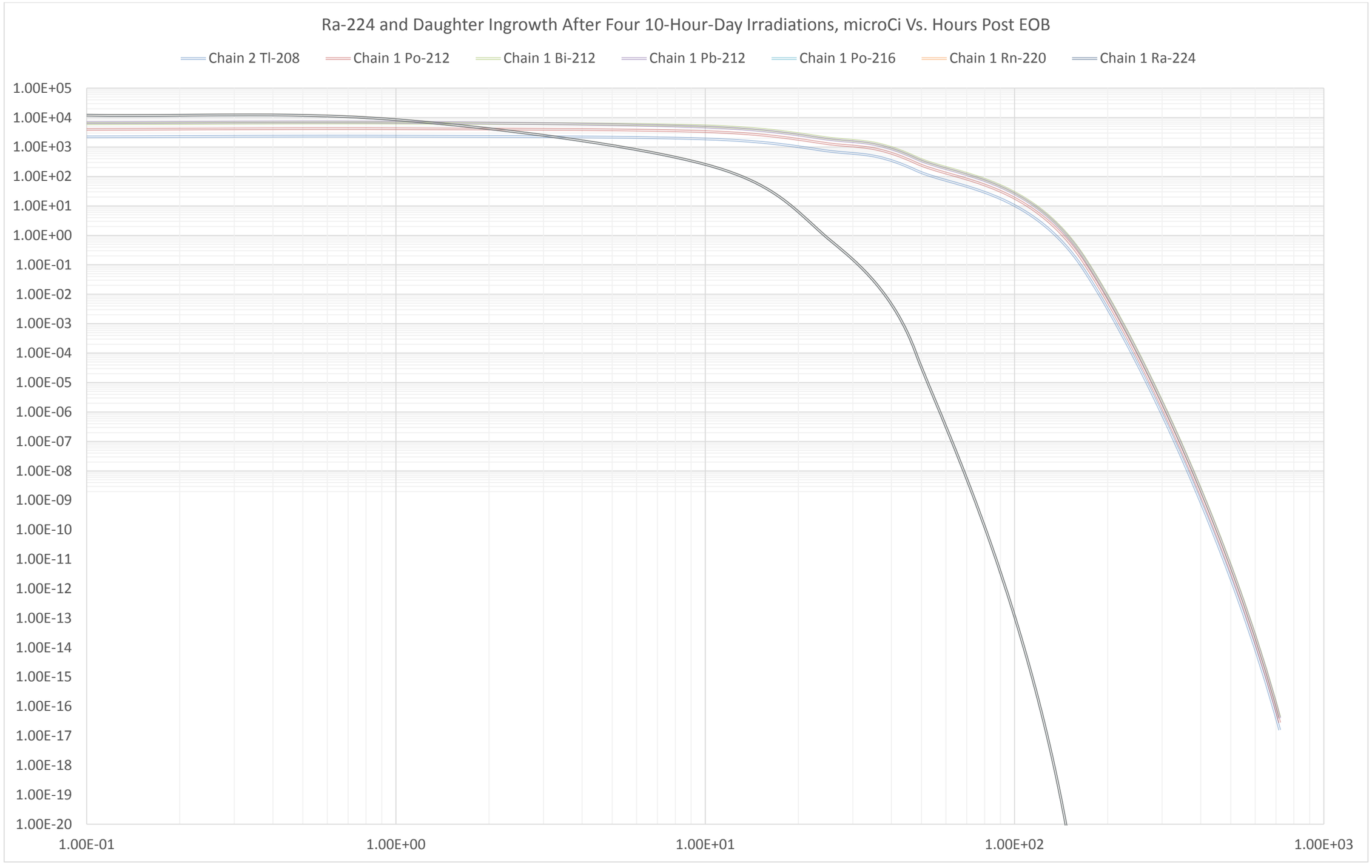

Ra-225 and Daughter Ingrowth After Four 10-Hour-Day Irradiations, microCi Vs. Hours Post EOB
Chain 3 Pb-209
Chain 3 Tl-209
Chain 3 Bi-213
Chain 2 Pb-209
Chain 2 Po-213
Chain 2 Rn-217
Chain 2 Ra-221
Chain 1 Pb-209
Chain 1 Po-213
Chain 1 Bi-213
Chain 1 At-217
Chain 1 Fr-221
Chain 1 Ac-225
Chain 1 Ra-225
1.00E+03
1.00E+02
1.00E+01
1.00E+00
1.00E-01
1.00E-02
1.00E-03
1.00E-04
1.00E-05
1.00E-06
1.00E-07
1.00E-08
1.00E-09
1.00E-10
1.00E-11
1.00E-12
1.00E-13
1.00E-14
1.00E-15
1.00E-16
1.00E-17
1.00E-18
1.00E-19
1.00E-20
1.00E-01
1.00E+00
1.00E+01
1.00E+02
1.00E+03
1.00E+04
1.00E+05
1.00E+06
1.00E+07

RSC Technical Note, Target Sub-Committee

Four 10-Hour Irradiations on Four Consecutive Days; 16 MeV, 200 microA Beam from TR19 on 300 mg Ra-226/

Ra-224 and Daughter Ingrowth After Four Consecutive 10-Hour-Day Irradiations, microCi Vs. Hours Post EOB

		0.10	1.00	10.00	24.00	48.00	168.00	720.00	1440.00	14400.00	43800.00	87600.00	438000.00	876000.00	1752000.00
Chain 2	Tl-208	2.22E+03	2.34E+03	1.89E+03	7.75E+02	1.62E+02	6.53E-02	1.58E-17	6.72E-38	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Chain 1	Po-212	3.98E+03	4.18E+03	3.35E+03	1.37E+03	2.88E+02	1.16E-01	2.80E-17	1.19E-37	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Bi-212	6.21E+03	6.53E+03	5.22E+03	2.15E+03	4.49E+02	1.81E-01	4.37E-17	1.86E-37	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Pb-212	6.77E+03	6.97E+03	4.78E+03	1.94E+03	4.07E+02	1.64E-01	3.95E-17	1.68E-37	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Po-216	1.21E+04	8.55E+03	2.59E+02	1.12E+00	9.96E-05	5.52E-25	3.66E-118	1.06E-239	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Rn-220	1.21E+04	8.55E+03	2.59E+02	1.12E+00	9.96E-05	5.52E-25	3.66E-118	1.06E-239	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Ra-224	1.20E+04	8.47E+03	2.56E+02	1.11E+00	9.87E-05	5.47E-25	3.63E-118	1.05E-239	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00


Ra-224 and Daughter Ingrowth After Four 10-Hour-Day Irradiations, microCi Vs. Hours Post EOB
Chain 2 Tl-208
Chain 1 Po-212
Chain 1 Bi-212
Chain 1 Pb-212
Chain 1 Po-216
Chain 1 Rn-220
Chain 1 Ra-224
1.00E+05
1.00E+04
1.00E+03
1.00E+02
1.00E+01
1.00E+00
1.00E-01
1.00E-02
1.00E-03
1.00E-04
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1.00E-10
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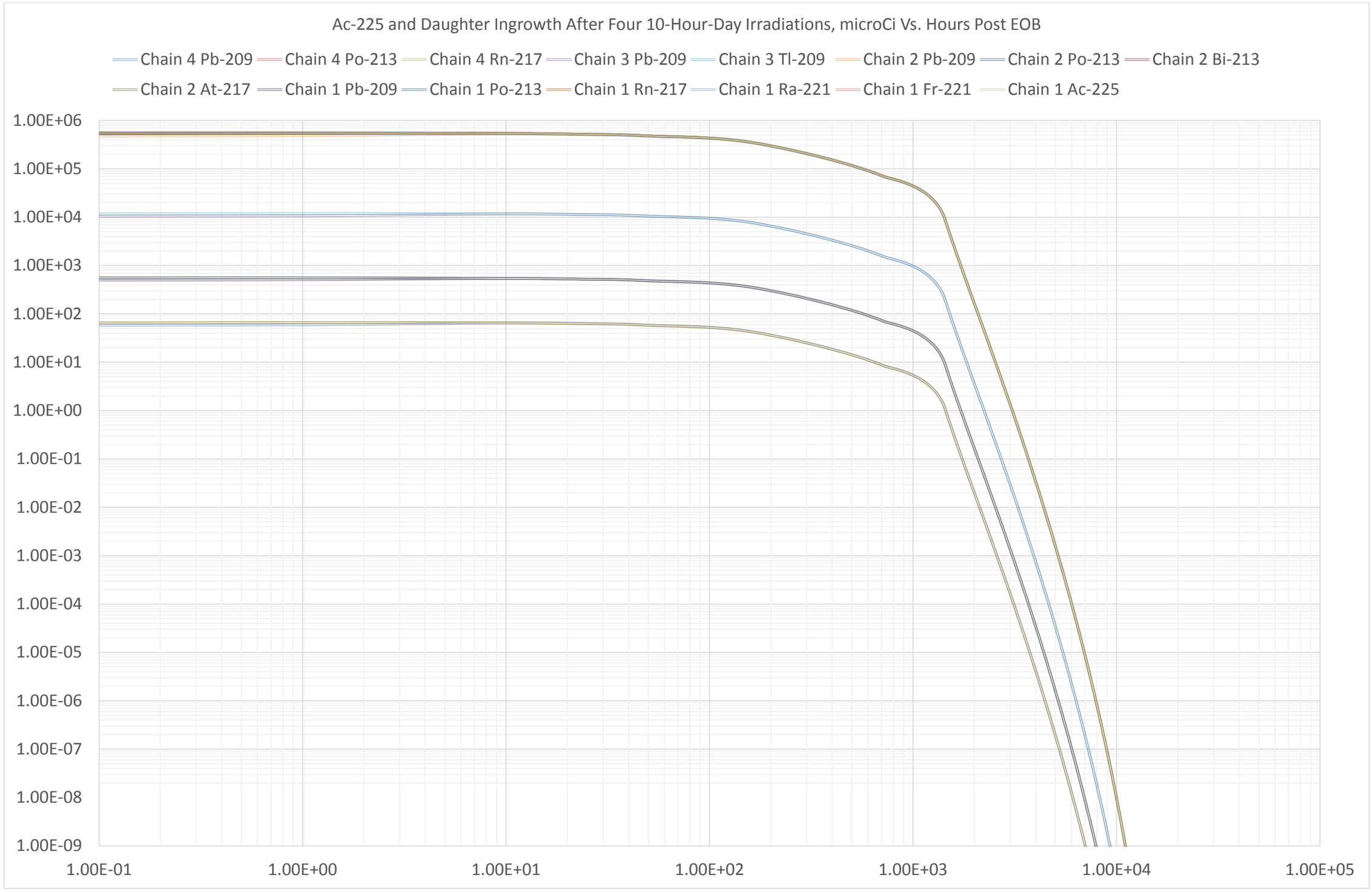
1.00E-14
1.00E-15
1.00E-16
1.00E-17
1.00E-18
1.00E-19
1.00E-20
1.00E-01
1.00E+00
1.00E+01
1.00E+02
1.00E+03

RSC Technical Note, Target Sub-Committee

Four 10-Hour Irradiations on Four Consecutive Days; 16 MeV, 200 microA Beam from TR19 on 300 mg Ra-226/

Ac-225 and Daughter Ingrowth After Four Consecutive 10-Hour-Day Irradiations, microCi Vs. Hours Post EOB

		0.1	1	10	24	48	168	720	1440	14400	43800	87600	438000	876000	1752000	2628000
Chain 4	Pb-209	5.82E+01	5.94E+01	6.48E+01	6.34E+01	5.92E+01	4.19E+01	8.50E+00	1.06E+00	5.90E-17	7.85E-54	9.05E-109	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Po-213	6.49E+01	6.59E+01	6.52E+01	6.26E+01	5.84E+01	4.13E+01	8.39E+00	1.05E+00	5.82E-17	7.74E-54	8.93E-109	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Rn-217	6.49E+01	6.59E+01	6.52E+01	6.26E+01	5.84E+01	4.13E+01	8.39E+00	1.05E+00	5.82E-17	7.74E-54	8.93E-109	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Chain 3	Pb-209	1.05E+04	1.07E+04	1.17E+04	1.14E+04	1.07E+04	7.54E+03	1.53E+03	1.91E+02	1.06E-14	1.41E-51	1.63E-106	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Tl-209	1.17E+04	1.19E+04	1.17E+04	1.13E+04	1.05E+04	7.43E+03	1.51E+03	1.89E+02	1.05E-14	1.39E-51	1.61E-106	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Chain 2	Pb-209	4.75E+05	4.85E+05	5.28E+05	5.17E+05	4.83E+05	3.41E+05	6.93E+04	8.66E+03	4.81E-13	6.40E-50	7.38E-105	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Po-213	5.29E+05	5.38E+05	5.31E+05	5.10E+05	4.76E+05	3.37E+05	6.84E+04	8.55E+03	4.74E-13	6.31E-50	7.28E-105	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Bi-213	5.41E+05	5.49E+05	5.43E+05	5.22E+05	4.87E+05	3.44E+05	6.99E+04	8.74E+03	4.85E-13	6.45E-50	7.44E-105	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	At-217	5.56E+05	5.56E+05	5.42E+05	5.20E+05	4.85E+05	3.43E+05	6.97E+04	8.71E+03	4.83E-13	6.43E-50	7.42E-105	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Chain 1	Pb-209	4.99E+02	5.09E+02	5.41E+02	5.27E+02	4.92E+02	3.48E+02	7.07E+01	8.84E+00	4.91E-16	6.52E-53	7.53E-108	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Po-213	5.57E+02	5.56E+02	5.42E+02	5.21E+02	4.86E+02	3.43E+02	6.97E+01	8.72E+00	4.84E-16	6.44E-53	7.42E-108	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Rn-217	5.57E+02	5.56E+02	5.42E+02	5.21E+02	4.86E+02	3.43E+02	6.97E+01	8.72E+00	4.84E-16	6.44E-53	7.42E-108	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Ra-221	5.57E+02	5.56E+02	5.42E+02	5.21E+02	4.86E+02	3.43E+02	6.97E+01	8.72E+00	4.84E-16	6.44E-53	7.42E-108	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Fr-221	5.57E+05	5.56E+05	5.42E+05	5.21E+05	4.86E+05	3.43E+05	6.97E+04	8.72E+03	4.84E-13	6.44E-50	7.42E-105	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Ac-225	5.58E+05	5.56E+05	5.42E+05	5.20E+05	4.86E+05	3.43E+05	6.97E+04	8.71E+03	4.84E-13	6.43E-50	7.42E-105	0.00E+00	0.00E+00	0.00E+00	0.00E+00


Ac-225 and Daughter Ingrowth After Four 10-Hour-Day Irradiations, microCi Vs. Hours Post EOB
Chain 4 Pb-209
Chain 4 Po-213
Chain 4 Rn-217
Chain 3 Pb-209
Chain 3 Tl-209
Chain 2 Pb-209
Chain 2 Po-213
Chain 2 Bi-213
Chain 2 At-217
Chain 1 Pb-209
Chain 1 Po-213
Chain 1 Rn-217
Chain 1 Ra-221
Chain 1 Fr-221
Chain 1 Ac-225
1.00E+06
1.00E+05
1.00E+04
1.00E+03
1.00E+02
1.00E+01
1.00E+00
1.00E-01
1.00E-02
1.00E-03
1.00E-04
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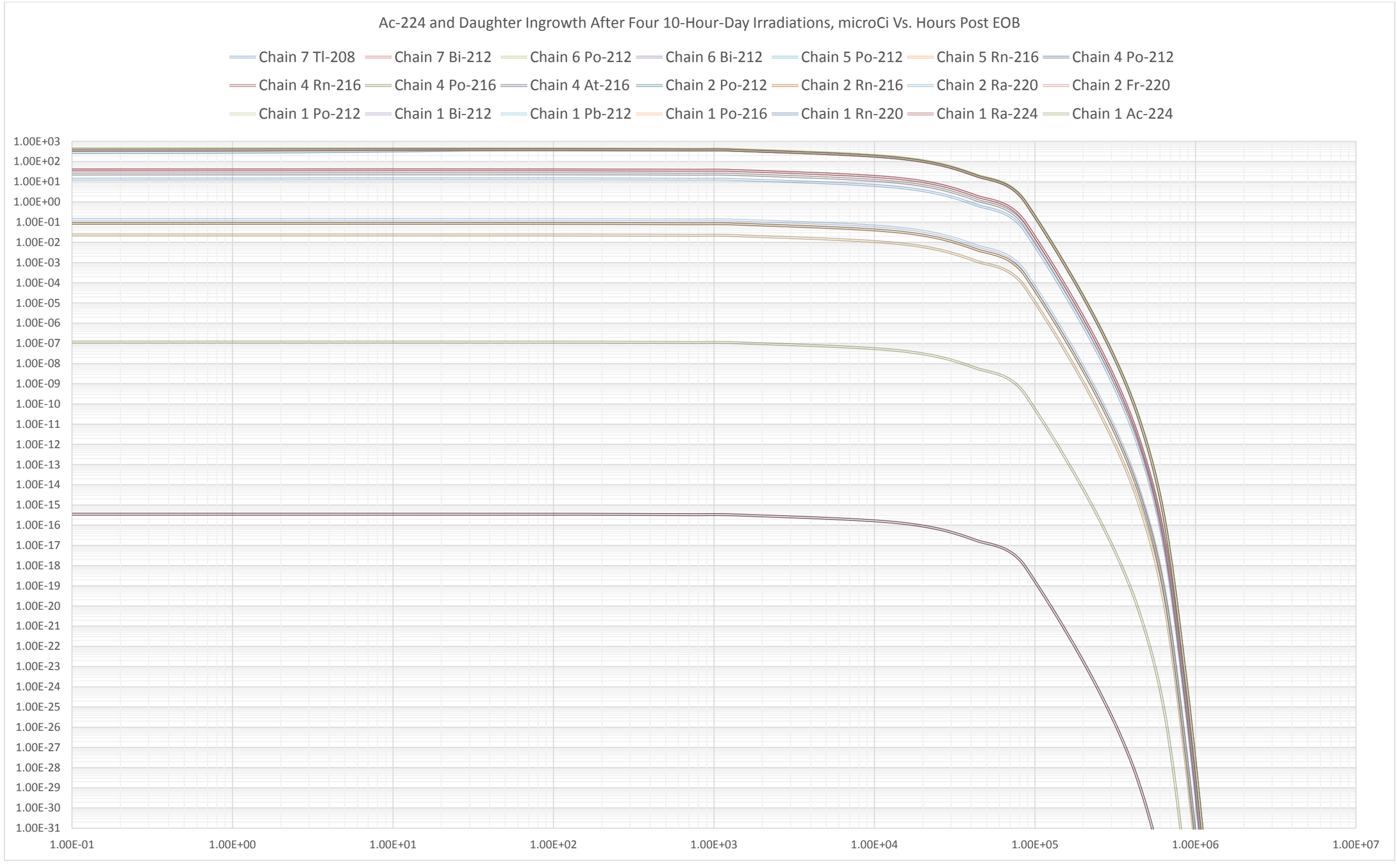
1.00E-06
1.00E-07
1.00E-08
1.00E-09
1.00E-01
1.00E+00
1.00E+01
1.00E+02
1.00E+03
1.00E+04
1.00E+05

RSC Technical Note, Target Sub-Committee

Four 10-Hour Irradiations on Four Consecutive Days; 16 MeV, 200 microA Beam from TR19 on 300 mg Ra-226

Ac-224 and Daughter Ingrowth After Four Consecutive 10-Hour-Day Irradiations, microCi Vs. Hours Post EOB

		0.10	1.00	10.00	24.00	48.00	168.00	720.00	1440.00	14400.00	43800.00	87600.00	438000.00	876000.00	1752000.00
Chain 7	Tl-208	1.35E+01	1.37E+01	1.40E+01	1.40E+01	1.39E+01	1.38E+01	1.33E+01	1.27E+01	5.16E+00	6.74E-01	3.24E-02	9.36E-13	6.26E-26	2.80E-52
	Bi-212	3.76E+01	3.82E+01	3.89E+01	3.89E+01	3.88E+01	3.85E+01	3.70E+01	3.52E+01	1.44E+01	1.87E+00	9.02E-02	2.60E-12	1.74E-25	7.80E-52
Chain 6	Po-212	2.41E+01	2.45E+01	2.49E+01	2.49E+01	2.49E+01	2.46E+01	2.37E+01	2.26E+01	9.20E+00	1.20E+00	5.78E-02	1.67E-12	1.12E-25	5.00E-52
	Bi-212	2.41E+01	2.45E+01	2.49E+01	2.49E+01	2.49E+01	2.46E+01	2.37E+01	2.26E+01	9.20E+00	1.20E+00	5.78E-02	1.67E-12	1.12E-25	5.00E-52
Chain 5	Po-212	2.34E-02	2.34E-02	2.33E-02	2.33E-02	2.33E-02	2.31E-02	2.22E-02	2.11E-02	8.62E-03	1.12E-03	5.41E-05	1.56E-15	1.05E-28	4.68E-55
	Rn-216	2.34E-02	2.34E-02	2.33E-02	2.33E-02	2.33E-02	2.31E-02	2.22E-02	2.11E-02	8.62E-03	1.12E-03	5.41E-05	1.56E-15	1.05E-28	4.68E-55
Chain 4	Po-212	3.50E-16	3.50E-16	3.50E-16	3.50E-16	3.49E-16	3.46E-16	3.33E-16	3.17E-16	1.29E-16	1.69E-17	8.12E-19	2.34E-29	1.57E-42	7.02E-69
	Rn-216	3.50E-16	3.50E-16	3.50E-16	3.50E-16	3.49E-16	3.46E-16	3.33E-16	3.17E-16	1.29E-16	1.69E-17	8.12E-19	2.34E-29	1.57E-42	7.02E-69
	Po-216	1.17E-07	1.17E-07	1.17E-07	1.17E-07	1.16E-07	1.15E-07	1.11E-07	1.06E-07	4.31E-08	5.62E-09	2.71E-10	7.81E-21	5.23E-34	2.34E-60
	At-216	3.89E+01	3.89E+01	3.89E+01	3.89E+01	3.88E+01	3.85E+01	3.70E+01	3.52E+01	1.44E+01	1.87E+00	9.02E-02	2.60E-12	1.74E-25	7.80E-52
Chain 2	Po-212	8.76E-02	8.76E-02	8.75E-02	8.74E-02	8.73E-02	8.66E-02	8.33E-02	7.93E-02	3.23E-02	4.22E-03	2.03E-04	5.86E-15	3.92E-28	1.75E-54
	Rn-216	8.76E-02	8.76E-02	8.75E-02	8.74E-02	8.73E-02	8.66E-02	8.33E-02	7.93E-02	3.23E-02	4.22E-03	2.03E-04	5.86E-15	3.92E-28	1.75E-54
	Ra-220	1.37E-01	1.37E-01	1.37E-01	1.37E-01	1.36E-01	1.35E-01	1.30E-01	1.24E-01	5.04E-02	6.58E-03	3.17E-04	9.15E-15	6.12E-28	2.74E-54
	Fr-220	3.91E+01	3.91E+01	3.90E+01	3.90E+01	3.89E+01	3.86E+01	3.72E+01	3.54E+01	1.44E+01	1.88E+00	9.06E-02	2.61E-12	1.75E-25	7.83E-52
Chain 1	Po-212	2.82E+02	2.87E+02	3.30E+02	3.66E+02	3.84E+02	3.86E+02	3.72E+02	3.54E+02	1.44E+02	1.88E+01	9.06E-01	2.61E-11	1.75E-24	7.83E-51
	Bi-212	2.82E+02	2.87E+02	3.30E+02	3.66E+02	3.84E+02	3.86E+02	3.72E+02	3.54E+02	1.44E+02	1.88E+01	9.06E-01	2.61E-11	1.75E-24	7.83E-51
	Pb-212	2.89E+02	2.94E+02	3.35E+02	3.68E+02	3.85E+02	3.86E+02	3.72E+02	3.54E+02	1.44E+02	1.88E+01	9.06E-01	2.61E-11	1.75E-24	7.83E-51
	Po-216	3.71E+02	3.78E+02	3.90E+02	3.90E+02	3.89E+02	3.86E+02	3.71E+02	3.53E+02	1.44E+02	1.88E+01	9.05E-01	2.61E-11	1.75E-24	7.82E-51
	Rn-220	3.71E+02	3.78E+02	3.90E+02	3.90E+02	3.89E+02	3.86E+02	3.71E+02	3.53E+02	1.44E+02	1.88E+01	9.05E-01	2.61E-11	1.75E-24	7.82E-51
	Ra-224	3.71E+02	3.78E+02	3.90E+02	3.90E+02	3.89E+02	3.86E+02	3.71E+02	3.53E+02	1.44E+02	1.88E+01	9.05E-01	2.61E-11	1.75E-24	7.82E-51
	Ac-224	4.29E+02	4.29E+02	4.29E+02	4.29E+02	4.28E+02	4.24E+02	4.08E+02	3.89E+02	1.58E+02	2.07E+01	9.95E-01	2.87E-11	1.92E-24	8.60E-51


Ac-224 and Daughter Ingrowth After Four 10-Hour-Day Irradiations, microCi Vs. Hours Post EOB
Chain 7 Tl-208
Chain 7 Bi-212
Chain 6 Po-212
Chain 6 Bi-212
Chain 5 Po-212
Chain 5 Rn-216
Chain 4 Po-212
Chain 4 Rn-216
Chain 4 Po-216
Chain 4 At-216
Chain 2 Po-212
Chain 2 Rn-216
Chain 2 Ra-220
Chain 2 Fr-220
Chain 1 Po-212
Chain 1 Bi-212
Chain 1 Pb-212
Chain 1 Po-216
Chain 1 Rn-220
Chain 1 Ra-224
Chain 1 Ac-224
1.00E+03
1.00E+02
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1.00E+01
1.00E+02
1.00E+03
1.00E+04
1.00E+05
1.00E+06
1.00E+07

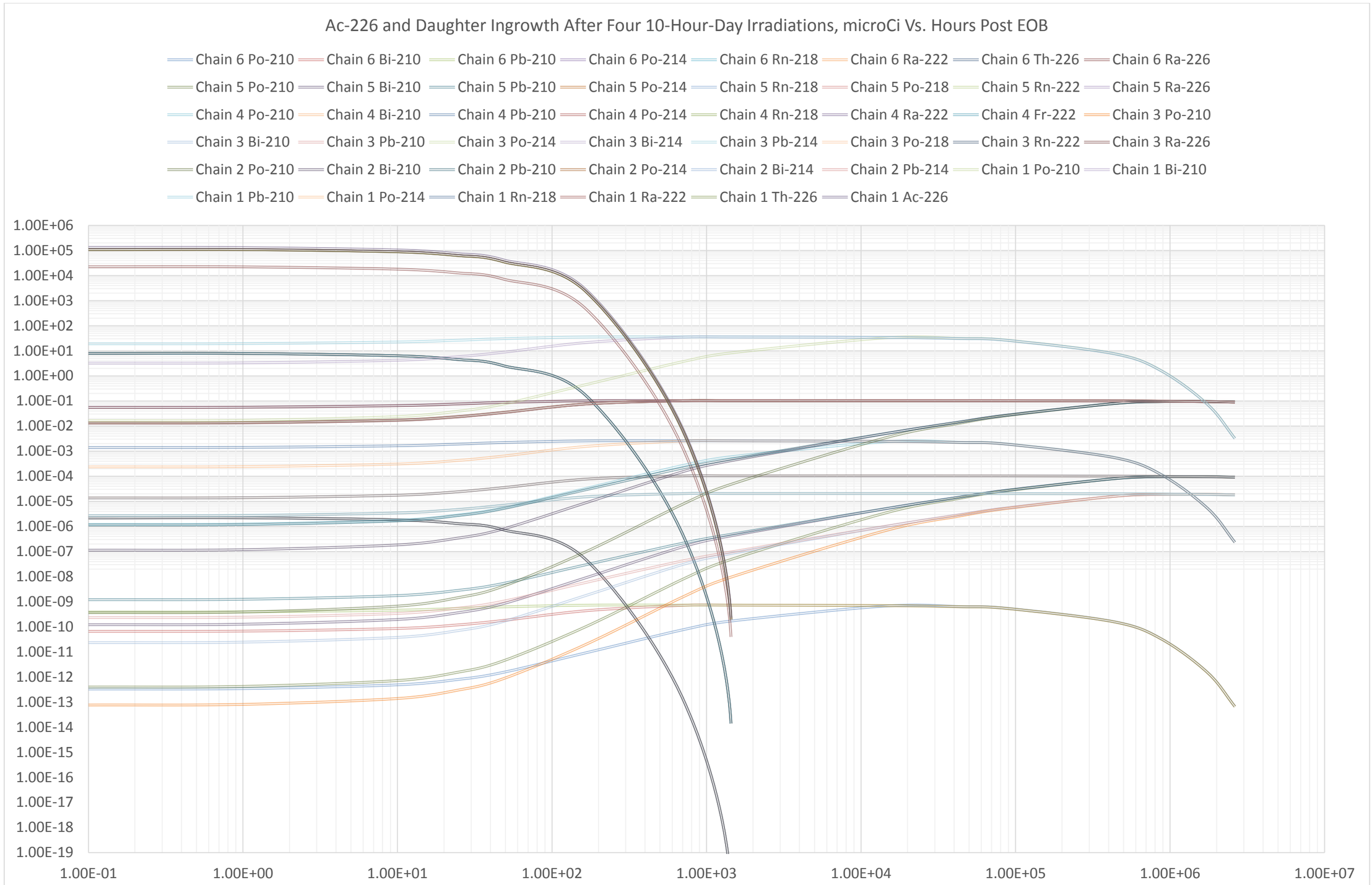
RSC Technical Note, Target Sub-Committee

Four 10-Hour Irradiations on Four Consecutive Days; 16 MeV, 200 microA Beam from TR19 on 300 mg Ra-226

Ac-226 and Daughter Ingrowth After Four Consecutive 10-Hour-Day Irradiations, microCi Vs. Hours Post EOB

		0.1	1	10	24	48	168	720	1440	14400	43800	87600	438000	876000	1752000	2628000
Chain 6	Po-210	3.31E-13	3.44E-13	4.86E-13	7.81E-13	1.52E-12	9.39E-12	7.89E-11	1.70E-10	6.73E-10	6.41E-10	5.49E-10	1.58E-10	3.35E-11	1.49E-12	6.68E-14
	Bi-210	6.56E-11	6.73E-11	8.56E-11	1.18E-10	1.78E-10	4.40E-10	7.22E-10	7.32E-10	7.00E-10	6.30E-10	5.40E-10	1.56E-10	3.29E-11	1.47E-12	6.57E-14
	Pb-210	3.88E-10	3.95E-10	4.60E-10	5.38E-10	6.23E-10	7.29E-10	7.34E-10	7.32E-10	6.99E-10	6.30E-10	5.39E-10	1.56E-10	3.29E-11	1.47E-12	6.56E-14
	Po-214	2.19E-06	2.22E-06	1.83E-06	1.32E-06	7.47E-07	4.40E-08	9.67E-14	4.04E-21	5.91E-154	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Rn-218	2.19E-06	2.22E-06	1.83E-06	1.32E-06	7.47E-07	4.40E-08	9.67E-14	4.04E-21	5.91E-154	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Ra-222	2.19E-06	2.22E-06	1.83E-06	1.32E-06	7.47E-07	4.40E-08	9.67E-14	4.04E-21	5.91E-154	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Th-226	2.19E-06	2.22E-06	1.83E-06	1.32E-06	7.47E-07	4.40E-08	9.67E-14	4.03E-21	5.90E-154	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Ra-226	2.24E+04	2.22E+04	1.80E+04	1.29E+04	7.34E+03	4.32E+02	9.50E-04	3.96E-11	5.80E-144	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Chain 5	Po-210	3.98E-13	4.22E-13	7.20E-13	1.51E-12	4.33E-12	1.06E-10	8.46E-09	4.84E-08	3.45E-06	1.33E-05	2.63E-05	8.03E-05	9.60E-05	9.63E-05	9.24E-05
	Bi-210	1.21E-10	1.27E-10	1.96E-10	3.55E-10	8.24E-10	9.28E-09	1.62E-07	4.23E-07	5.07E-06	1.48E-05	2.76E-05	8.07E-05	9.61E-05	9.63E-05	9.24E-05
	Pb-210	1.21E-09	1.25E-09	1.75E-09	2.78E-09	5.29E-09	3.03E-08	2.23E-07	4.87E-07	5.13E-06	1.49E-05	2.76E-05	8.07E-05	9.61E-05	9.63E-05	9.24E-05
	Po-214	1.36E-05	1.40E-05	1.76E-05	2.39E-05	3.52E-05	7.73E-05	1.04E-04	1.04E-04	1.04E-04	1.04E-04	1.03E-04	1.02E-04	9.94E-05	9.51E-05	9.11E-05
	Rn-218	1.36E-05	1.40E-05	1.76E-05	2.39E-05	3.52E-05	7.73E-05	1.04E-04	1.04E-04	1.04E-04	1.04E-04	1.03E-04	1.02E-04	9.94E-05	9.51E-05	9.11E-05
	Po-218	1.36E-02	1.40E-02	1.76E-02	2.39E-02	3.52E-02	7.73E-02	1.04E-01	1.04E-01	1.04E-01	1.04E-01	1.03E-01	1.02E-01	9.94E-02	9.51E-02	9.11E-02
	Rn-222	1.37E-02	1.40E-02	1.76E-02	2.39E-02	3.52E-02	7.73E-02	1.04E-01	1.04E-01	1.04E-01	1.04E-01	1.03E-01	1.02E-01	9.94E-02	9.51E-02	9.11E-02
	Ra-226	5.60E-02	5.70E-02	6.59E-02	7.66E-02	8.83E-02	1.03E-01	1.04E-01	1.04E-01	1.04E-01	1.04E-01	1.03E-01	1.02E-01	9.94E-02	9.51E-02	9.11E-02
Chain 4	Po-210	1.21E-06	1.25E-06	1.76E-06	2.82E-06	5.45E-06	3.34E-05	2.79E-04	6.00E-04	2.38E-03	2.26E-03	1.94E-03	5.59E-04	1.18E-04	5.28E-06	2.36E-07
	Bi-210	2.37E-04	2.43E-04	3.08E-04	4.22E-04	6.36E-04	1.56E-03	2.55E-03	2.58E-03	2.47E-03	2.22E-03	1.90E-03	5.49E-04	1.16E-04	5.19E-06	2.32E-07
	Pb-210	1.39E-03	1.42E-03	1.64E-03	1.91E-03	2.21E-03	2.57E-03	2.59E-03	2.58E-03	2.47E-03	2.22E-03	1.90E-03	5.49E-04	1.16E-04	5.18E-06	2.32E-07
	Po-214	7.90E+00	7.84E+00	6.35E+00	4.56E+00	2.59E+00	1.53E-01	3.35E-07	1.40E-14	2.05E-147	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Rn-218	7.90E+00	7.84E+00	6.35E+00	4.56E+00	2.59E+00	1.53E-01	3.35E-07	1.40E-14	2.05E-147	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Ra-222	7.90E+00	7.84E+00	6.35E+00	4.56E+00	2.59E+00	1.53E-01	3.35E-07	1.40E-14	2.05E-147	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Fr-222	7.91E+00	7.84E+00	6.35E+00	4.56E+00	2.59E+00	1.52E-01	3.35E-07	1.40E-14	2.05E-147	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Chain 3	Po-210	7.64E-14	8.09E-14	1.39E-13	2.91E-13	8.39E-13	2.07E-11	1.67E-09	9.56E-09	6.83E-07	2.63E-06	5.19E-06	1.59E-05	1.90E-05	1.90E-05	1.83E-05
	Bi-210	2.34E-11	2.45E-11	3.79E-11	6.89E-11	1.60E-10	1.82E-09	3.19E-08	8.36E-08	1.00E-06	2.93E-06	5.45E-06	1.60E-05	1.90E-05	1.90E-05	1.83E-05
	Pb-210	2.34E-10	2.43E-10	3.41E-10	5.42E-10	1.03E-09	5.97E-09	4.40E-08	9.62E-08	1.01E-06	2.94E-06	5.46E-06	1.60E-05	1.90E-05	1.90E-05	1.83E-05
	Po-214	2.66E-06	2.73E-06	3.44E-06	4.67E-06	6.91E-06	1.52E-05	2.05E-05	2.05E-05	2.05E-05	2.05E-05	2.04E-05	2.01E-05	1.96E-05	1.88E-05	1.80E-05
	Bi-214	2.66E-06	2.73E-06	3.44E-06	4.67E-06	6.91E-06	1.52E-05	2.05E-05	2.05E-05	2.05E-05	2.05E-05	2.04E-05	2.01E-05	1.96E-05	1.88E-05	1.80E-05
	Pb-214	2.69E-06	2.76E-06	3.48E-06	4.72E-06	6.95E-06	1.53E-05	2.05E-05	2.05E-05	2.05E-05	2.05E-05	2.04E-05	2.01E-05	1.96E-05	1.88E-05	1.80E-05
	Po-218	1.35E-02	1.38E-02	1.74E-02	2.36E-02	3.47E-02	7.64E-02	1.02E-01	1.03E-01	1.02E-01	1.02E-01	1.02E-01	1.00E-01	9.82E-02	9.40E-02	9.00E-02
	Rn-222	1.35E-02	1.38E-02	1.74E-02	2.36E-02	3.48E-02	7.64E-02	1.02E-01	1.03E-01	1.02E-01	1.02E-01	1.02E-01	1.00E-01	9.82E-02	9.40E-02	9.00E-02
	Ra-226	5.53E-02	5.63E-02	6.52E-02	7.57E-02	8.73E-02	1.02E-01	1.03E-01	1.03E-01	1.02E-01	1.02E-01	1.02E-01	1.00E-01	9.82E-02	9.40E-02	9.00E-02
Chain 2	Po-210	3.67E-10	3.88E-10	6.68E-10	1.41E-09	4.09E-09	1.02E-07	8.32E-06	4.78E-05	3.41E-03	1.31E-02	2.60E-02	7.94E-02	9.49E-02	9.52E-02	9.13E-02
	Bi-210	1.13E-07	1.19E-07	1.84E-07	3.36E-07	7.86E-07	9.04E-06	1.59E-04	4.18E-04	5.00E-03	1.47E-02	2.73E-02	7.97E-02	9.49E-02	9.51E-02	9.13E-02

	Pb-210	1.14E-06	1.18E-06	1.67E-06	2.66E-06	5.09E-06	2.97E-05	2.20E-04	4.80E-04	5.06E-03	1.47E-02	2.73E-02	7.98E-02	9.49E-02	9.51E-02	9.13E-02
	Po-214	1.31E-02	1.34E-02	1.69E-02	2.31E-02	3.42E-02	7.61E-02	1.02E-01	1.03E-01	1.02E-01	1.02E-01	1.02E-01	1.00E-01	9.82E-02	9.40E-02	9.00E-02
	Bi-214	1.31E-02	1.34E-02	1.69E-02	2.31E-02	3.42E-02	7.61E-02	1.02E-01	1.03E-01	1.02E-01	1.02E-01	1.02E-01	1.00E-01	9.82E-02	9.40E-02	9.00E-02
	Pb-214	1.33E-02	1.36E-02	1.71E-02	2.33E-02	3.44E-02	7.62E-02	1.02E-01	1.03E-01	1.02E-01	1.02E-01	1.02E-01	1.00E-01	9.82E-02	9.40E-02	9.00E-02
Chain 1	Po-210	1.64E-02	1.70E-02	2.40E-02	3.85E-02	7.44E-02	4.59E-01	3.84E+00	8.27E+00	3.28E+01	3.12E+01	2.67E+01	7.71E+00	1.63E+00	7.28E-02	3.25E-03
	Bi-210	3.23E+00	3.31E+00	4.21E+00	5.78E+00	8.73E+00	2.15E+01	3.52E+01	3.57E+01	3.41E+01	3.07E+01	2.63E+01	7.58E+00	1.60E+00	7.16E-02	3.20E-03
	Pb-210	1.90E+01	1.94E+01	2.25E+01	2.63E+01	3.04E+01	3.55E+01	3.57E+01	3.57E+01	3.41E+01	3.07E+01	2.63E+01	7.57E+00	1.60E+00	7.15E-02	3.20E-03
	Po-214	1.08E+05	1.08E+05	8.85E+04	6.36E+04	3.61E+04	2.12E+03	4.67E-03	1.95E-10	2.85E-143	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Rn-218	1.08E+05	1.08E+05	8.85E+04	6.36E+04	3.61E+04	2.12E+03	4.67E-03	1.95E-10	2.85E-143	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Ra-222	1.08E+05	1.08E+05	8.85E+04	6.36E+04	3.61E+04	2.12E+03	4.67E-03	1.95E-10	2.85E-143	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Th-226	1.08E+05	1.08E+05	8.84E+04	6.35E+04	3.61E+04	2.12E+03	4.67E-03	1.95E-10	2.85E-143	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Ac-226	1.33E+05	1.30E+05	1.05E+05	7.54E+04	4.28E+04	2.52E+03	5.54E-03	2.31E-10	3.38E-143	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

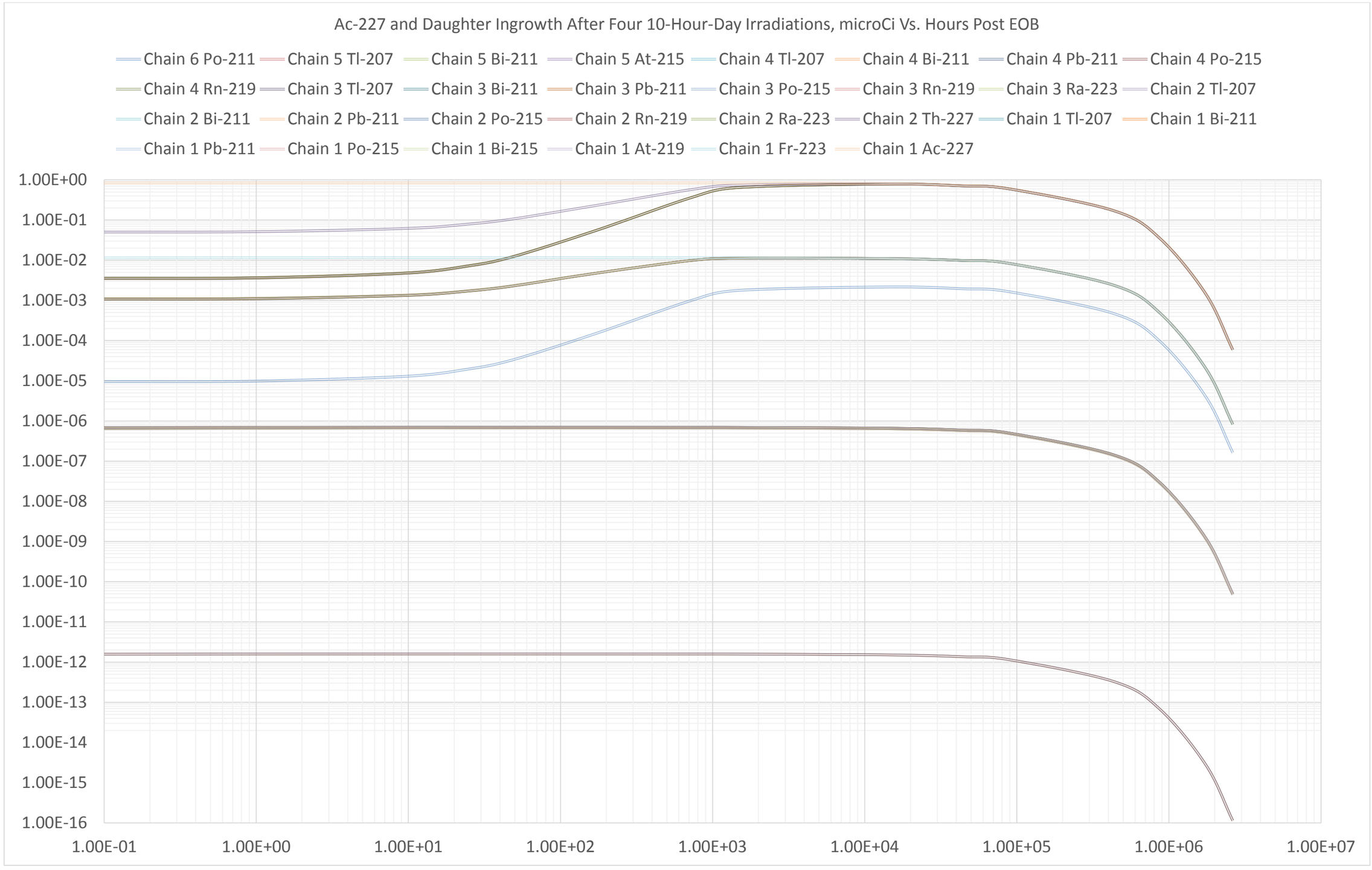

Ac-226 and Daughter Ingrowth After Four 10-Hour-Day Irradiations, microCi Vs. Hours Post EOB
Chain 6 Po-210
Chain 6 Bi-210
Chain 6 Pb-210
Chain 6 Po-214
Chain 6 Rn-218
Chain 6 Ra-222
Chain 6 Th-226
Chain 6 Ra-226
Chain 5 Po-210
Chain 5 Bi-210
Chain 5 Pb-210
Chain 5 Po-214
Chain 5 Rn-218
Chain 5 Po-218
Chain 5 Rn-222
Chain 5 Ra-226
Chain 4 Po-210
Chain 4 Bi-210
Chain 4 Pb-210
Chain 4 Po-214
Chain 4 Rn-218
Chain 4 Ra-222
Chain 4 Fr-222
Chain 3 Po-210
Chain 3 Bi-210
Chain 3 Pb-210
Chain 3 Po-214
Chain 3 Bi-214
Chain 3 Pb-214
Chain 3 Po-218
Chain 3 Rn-222
Chain 3 Ra-226
Chain 2 Po-210
Chain 2 Bi-210
Chain 2 Pb-210
Chain 2 Po-214
Chain 2 Bi-214
Chain 2 Pb-214
Chain 1 Po-210
Chain 1 Bi-210
Chain 1 Pb-210
Chain 1 Po-214
Chain 1 Rn-218
Chain 1 Ra-222
Chain 1 Th-226
Chain 1 Ac-226
1.00E+06
1.00E+05
1.00E+04
1.00E+03
1.00E+02
1.00E+01
1.00E+00
1.00E-01
1.00E-02
1.00E-03
1.00E-04
1.00E-05
1.00E-06
1.00E-07
1.00E-08
1.00E-09
1.00E-10
1.00E-11
1.00E-12
1.00E-13
1.00E-14
1.00E-15
1.00E-16
1.00E-17
1.00E-18
1.00E-19
1.00E-01
1.00E+00
1.00E+01
1.00E+02
1.00E+03
1.00E+04
1.00E+05
1.00E+06
1.00E+07

RSC Technical Note, Target Sub-Committee

Four 10-Hour Irradiations on Four Consecutive Days; 16 MeV, 200 microA Beam from TR19 on 300 mg Ra-226

Ac-227 and Daughter Ingrowth After Four Consecutive 10-Hour-Day Irradiations, microCi Vs. Hours Post EOB

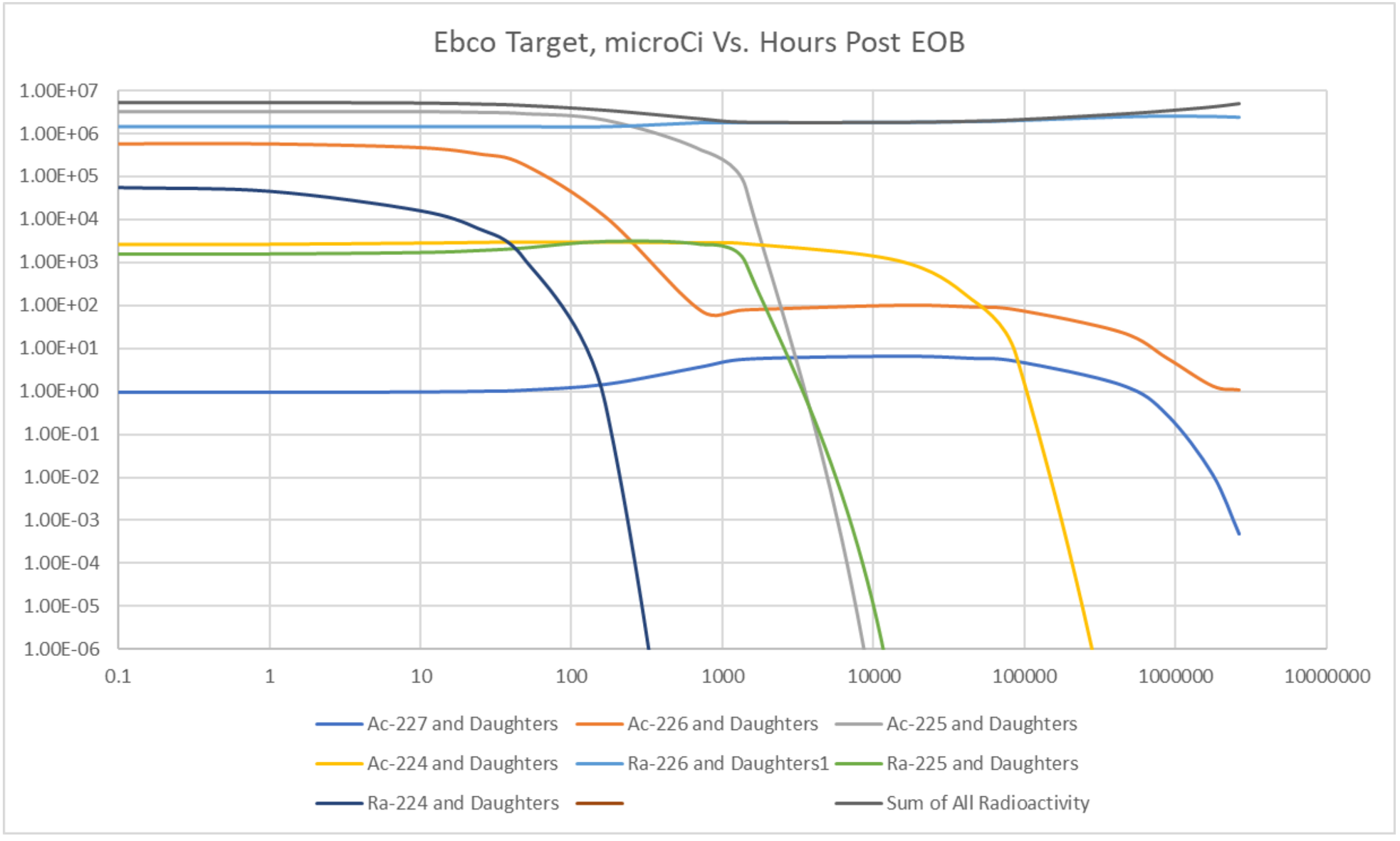
		1.00E-01	1.00E+00	1.00E+01	2.40E+01	4.80E+01	1.68E+02	7.20E+02	1.44E+03	1.44E+04	4.38E+04	8.76E+04	4.38E+05	8.76E+05	1.75E+06	2.63E+06
Chain 6	Po-211	9.55E-06	9.84E-06	1.31E-05	1.92E-05	3.29E-05	1.47E-04	9.91E-04	1.76E-03	2.17E-03	1.95E-03	1.67E-03	4.66E-04	9.50E-05	3.94E-06	1.63E-07
Chain 5	Tl-207	1.57E-12	1.59E-12	1.60E-12	1.60E-12	1.60E-12	1.60E-12	1.59E-12	1.59E-12	1.51E-12	1.36E-12	1.16E-12	3.25E-13	6.62E-14	2.74E-15	1.14E-16
	Bi-211	1.58E-12	1.59E-12	1.60E-12	1.60E-12	1.60E-12	1.60E-12	1.59E-12	1.59E-12	1.51E-12	1.36E-12	1.16E-12	3.25E-13	6.62E-14	2.74E-15	1.14E-16
	At-215	1.58E-12	1.60E-12	1.60E-12	1.60E-12	1.60E-12	1.60E-12	1.60E-12	1.59E-12	1.52E-12	1.37E-12	1.16E-12	3.26E-13	6.64E-14	2.75E-15	1.14E-16
Chain 4	Tl-207	6.68E-07	6.82E-07	6.94E-07	6.94E-07	6.94E-07	6.94E-07	6.92E-07	6.90E-07	6.59E-07	5.92E-07	5.05E-07	1.41E-07	2.88E-08	1.19E-09	4.95E-11
	Bi-211	6.70E-07	6.83E-07	6.94E-07	6.94E-07	6.94E-07	6.94E-07	6.92E-07	6.90E-07	6.59E-07	5.92E-07	5.05E-07	1.41E-07	2.88E-08	1.19E-09	4.95E-11
	Pb-211	6.73E-07	6.86E-07	6.96E-07	6.96E-07	6.96E-07	6.96E-07	6.94E-07	6.92E-07	6.60E-07	5.94E-07	5.06E-07	1.42E-07	2.89E-08	1.20E-09	4.96E-11
	Po-215	6.88E-07	6.95E-07	6.96E-07	6.96E-07	6.96E-07	6.95E-07	6.94E-07	6.92E-07	6.60E-07	5.94E-07	5.06E-07	1.42E-07	2.89E-08	1.20E-09	4.96E-11
	Rn-219	6.88E-07	6.95E-07	6.96E-07	6.96E-07	6.96E-07	6.95E-07	6.94E-07	6.92E-07	6.60E-07	5.94E-07	5.06E-07	1.42E-07	2.89E-08	1.20E-09	4.96E-11
Chain 3	Tl-207	1.08E-03	1.10E-03	1.33E-03	1.69E-03	2.27E-03	4.70E-03	9.85E-03	1.12E-02	1.10E-02	9.88E-03	8.43E-03	2.36E-03	4.80E-04	1.99E-05	8.26E-07
	Bi-211	1.08E-03	1.10E-03	1.34E-03	1.69E-03	2.27E-03	4.70E-03	9.85E-03	1.12E-02	1.10E-02	9.88E-03	8.43E-03	2.36E-03	4.80E-04	1.99E-05	8.26E-07
	Pb-211	1.08E-03	1.11E-03	1.34E-03	1.70E-03	2.28E-03	4.72E-03	9.88E-03	1.13E-02	1.10E-02	9.91E-03	8.45E-03	2.37E-03	4.82E-04	2.00E-05	8.28E-07
	Po-215	1.11E-03	1.13E-03	1.36E-03	1.72E-03	2.30E-03	4.73E-03	9.88E-03	1.13E-02	1.10E-02	9.91E-03	8.45E-03	2.37E-03	4.82E-04	2.00E-05	8.28E-07
	Rn-219	1.11E-03	1.13E-03	1.36E-03	1.72E-03	2.30E-03	4.73E-03	9.88E-03	1.13E-02	1.10E-02	9.91E-03	8.45E-03	2.37E-03	4.82E-04	2.00E-05	8.28E-07
	Ra-223	1.11E-03	1.13E-03	1.36E-03	1.72E-03	2.30E-03	4.73E-03	9.88E-03	1.13E-02	1.10E-02	9.91E-03	8.45E-03	2.37E-03	4.82E-04	2.00E-05	8.28E-07
Chain 2	Tl-207	3.45E-03	3.55E-03	4.72E-03	6.95E-03	1.19E-02	5.33E-02	3.59E-01	6.39E-01	7.87E-01	7.08E-01	6.04E-01	1.69E-01	3.44E-02	1.43E-03	5.91E-05
	Bi-211	3.46E-03	3.56E-03	4.73E-03	6.97E-03	1.19E-02	5.34E-02	3.59E-01	6.39E-01	7.87E-01	7.08E-01	6.04E-01	1.69E-01	3.44E-02	1.43E-03	5.91E-05
	Pb-211	3.48E-03	3.58E-03	4.75E-03	7.00E-03	1.20E-02	5.35E-02	3.60E-01	6.41E-01	7.90E-01	7.10E-01	6.05E-01	1.69E-01	3.45E-02	1.43E-03	5.93E-05
	Po-215	3.58E-03	3.68E-03	4.88E-03	7.15E-03	1.22E-02	5.39E-02	3.60E-01	6.41E-01	7.90E-01	7.10E-01	6.05E-01	1.69E-01	3.45E-02	1.43E-03	5.93E-05
	Rn-219	3.58E-03	3.68E-03	4.88E-03	7.15E-03	1.22E-02	5.39E-02	3.60E-01	6.41E-01	7.90E-01	7.10E-01	6.05E-01	1.69E-01	3.45E-02	1.43E-03	5.93E-05
	Ra-223	3.58E-03	3.68E-03	4.88E-03	7.15E-03	1.22E-02	5.39E-02	3.60E-01	6.41E-01	7.90E-01	7.10E-01	6.05E-01	1.69E-01	3.45E-02	1.43E-03	5.93E-05
	Th-227	5.03E-02	5.14E-02	6.21E-02	7.85E-02	1.06E-01	2.28E-01	5.72E-01	7.42E-01	7.88E-01	7.09E-01	6.04E-01	1.69E-01	3.44E-02	1.43E-03	5.92E-05
Chain 1	Tl-207	6.45E-07	6.59E-07	6.73E-07	6.73E-07	6.73E-07	6.73E-07	6.71E-07	6.70E-07	6.39E-07	5.74E-07	4.90E-07	1.37E-07	2.79E-08	1.16E-09	4.80E-11
	Bi-211	6.47E-07	6.61E-07	6.73E-07	6.73E-07	6.73E-07	6.73E-07	6.71E-07	6.70E-07	6.39E-07	5.74E-07	4.90E-07	1.37E-07	2.79E-08	1.16E-09	4.80E-11
	Pb-211	6.50E-07	6.63E-07	6.75E-07	6.75E-07	6.75E-07	6.75E-07	6.73E-07	6.72E-07	6.41E-07	5.76E-07	4.91E-07	1.37E-07	2.80E-08	1.16E-09	4.81E-11
	Po-215	6.64E-07	6.73E-07	6.75E-07	6.75E-07	6.75E-07	6.75E-07	6.73E-07	6.72E-07	6.41E-07	5.76E-07	4.91E-07	1.37E-07	2.80E-08	1.16E-09	4.81E-11
	Bi-215	6.64E-07	6.73E-07	6.75E-07	6.75E-07	6.75E-07	6.75E-07	6.73E-07	6.72E-07	6.41E-07	5.76E-07	4.91E-07	1.37E-07	2.80E-08	1.16E-09	4.81E-11
	At-219	6.88E-07	6.95E-07	6.96E-07	6.96E-07	6.96E-07	6.95E-07	6.94E-07	6.92E-07	6.60E-07	5.94E-07	5.06E-07	1.42E-07	2.89E-08	1.20E-09	4.96E-11
	Fr-223	1.15E-02	1.16E-02	1.16E-02	1.16E-02	1.16E-02	1.16E-02	1.16E-02	1.15E-02	1.10E-02	9.89E-03	8.44E-03	2.36E-03	4.81E-04	1.99E-05	8.27E-07
	Ac-227	8.40E-01	8.40E-01	8.40E-01	8.40E-01	8.40E-01	8.40E-01	8.38E-01	8.36E-01	7.98E-01	7.17E-01	6.11E-01	1.71E-01	3.48E-02	1.45E-03	5.99E-05


Ac-227 and Daughter Ingrowth After Four 10-Hour-Day Irradiations, microCi Vs. Hours Post EOB
Chain 6 Po-211
Chain 5 Tl-207
Chain 5 Bi-211
Chain 5 At-215
Chain 4 Tl-207
Chain 4 Bi-211
Chain 4 Pb-211
Chain 4 Po-215
Chain 4 Rn-219
Chain 3 Tl-207
Chain 3 Bi-211
Chain 3 Pb-211
Chain 3 Po-215
Chain 3 Rn-219
Chain 3 Ra-223
Chain 2 Tl-207
Chain 2 Bi-211
Chain 2 Pb-211
Chain 2 Po-215
Chain 2 Rn-219
Chain 2 Ra-223
Chain 2 Th-227
Chain 1 Tl-207
Chain 1 Bi-211
Chain 1 Pb-211
Chain 1 Po-215
Chain 1 Bi-215
Chain 1 At-219
Chain 1 Fr-223
Chain 1 Ac-227
1.00E+00
1.00E-01
1.00E-02
1.00E-03
1.00E-04
1.00E-05
1.00E-06
1.00E-07
1.00E-08
1.00E-09
1.00E-10
1.00E-11
1.00E-12
1.00E-13
1.00E-14
1.00E-15
1.00E-16
1.00E-01
1.00E+00
1.00E+01
1.00E+02
1.00E+03
1.00E+04
1.00E+05
1.00E+06
1.00E+07

Radionuclide Parent and Daughter Radioactivity After EOB (Four 10-Hour-Day Irradiations), microCi Vs. Hours Post EOB

	0.1	1	10	24	48	168	720	1440	14400	43800	87600	438000	876000	1752000	2628000
Ac-227 and Daughters	9.30E-01	9.32E-01	9.51E-01	9.83E-01	1.04E+00	1.43E+00	3.64E+00	5.50E+00	6.40E+00	5.75E+00	4.90E+00	1.37E+00	2.80E-01	1.16E-02	4.81E-04
Ac-226 and Daughters	5.86E+05	5.85E+05	4.77E+05	3.43E+05	1.94E+05	1.15E+04	7.57E+01	8.05E+01	1.02E+02	9.36E+01	8.03E+01	2.40E+01	6.01E+00	1.35E+00	1.10E+00
Ac-225 and Daughters	3.24E+06	3.27E+06	3.25E+06	3.13E+06	2.93E+06	2.07E+06	4.20E+05	5.25E+04	2.91E-12	3.88E-49	4.47E-104	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ac-224 and Daughters	2.57E+03	2.61E+03	2.77E+03	2.88E+03	2.93E+03	2.92E+03	2.81E+03	2.67E+03	1.09E+03	1.42E+02	6.85E+00	1.98E-10	1.32E-23	5.92E-50	2.65E-76
Ra-226 and Daughters[5]	1.46E+06	1.46E+06	1.46E+06	1.46E+06	1.46E+06	1.46E+06	1.80E+06	1.80E+06	1.84E+06	1.92E+06	2.03E+06	2.46E+06	2.57E+06	2.51E+06	2.42E+06
Ra-225 and Daughters	1.61E+03	1.62E+03	1.75E+03	1.94E+03	2.23E+03	3.16E+03	2.71E+03	9.59E+02	1.54E-08	2.75E-33	3.70E-70	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ra-224 and Daughters	5.54E+04	4.56E+04	1.60E+04	6.24E+03	1.31E+03	5.26E-01	1.27E-16	5.41E-37	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Sum of All Radioactivity	5.34E+06	5.36E+06	5.21E+06	4.94E+06	4.58E+06	3.54E+06	2.22E+06	1.86E+06	1.85E+06	1.96E+06	2.11E+06	2.90E+06	3.44E+06	4.26E+06	5.04E+06

[5] Assumes 1-week old Ra-226 target


Ebco Target, microCi Vs. Hours Post EOB
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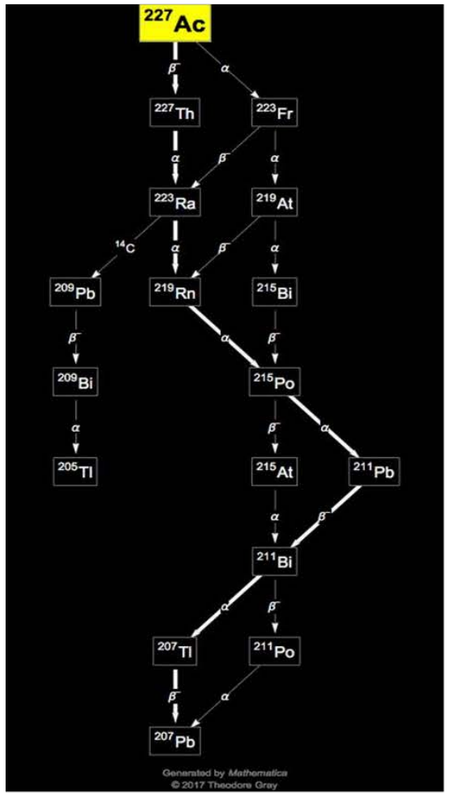
1.00E+06
1.00E+05
1.00E+04
1.00E+03
1.00E+02
1.00E+01
1.00E+00
1.00E-01
1.00E-02
1.00E-03
1.00E-04
1.00E-05
1.00E-06
0.1
1
10
100
1000
10000
100000
1000000
10000000
Ac-227 and Daughters
Ac-226 and Daughters
Ac-225 and Daughters
Ac-224 and Daughters
Ra-226 and Daughters1
Ra-225 and Daughters
Ra-224 and Daughters
Sum of All Radioactivity


227Ac
227Th
223Fr
223Ra
219At
209Pb
219Rn
215Bi
209Bi
215Po
205Tl
215At
211Pb
211Bi
207Tl
211Po
207Pb
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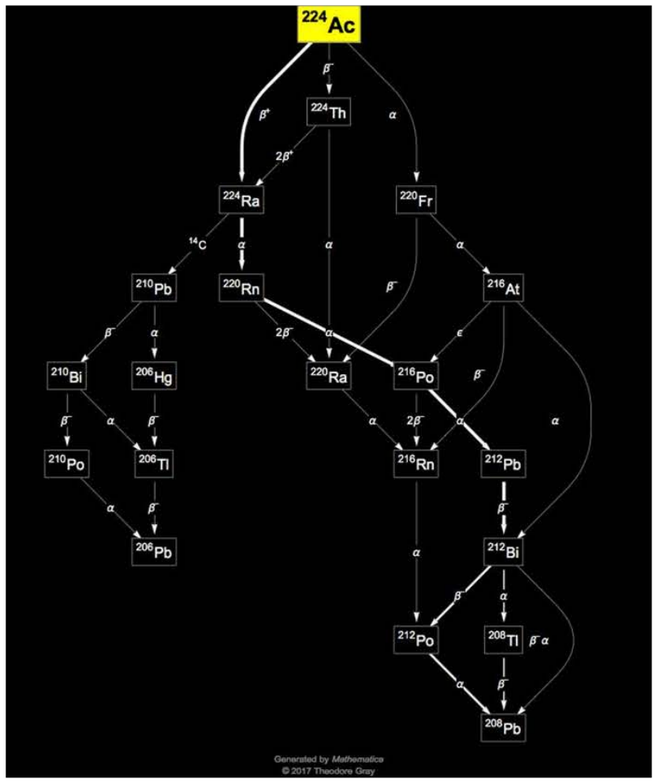
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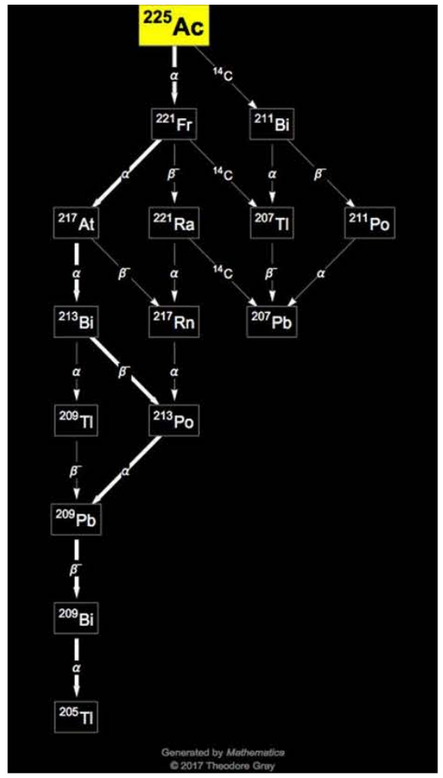
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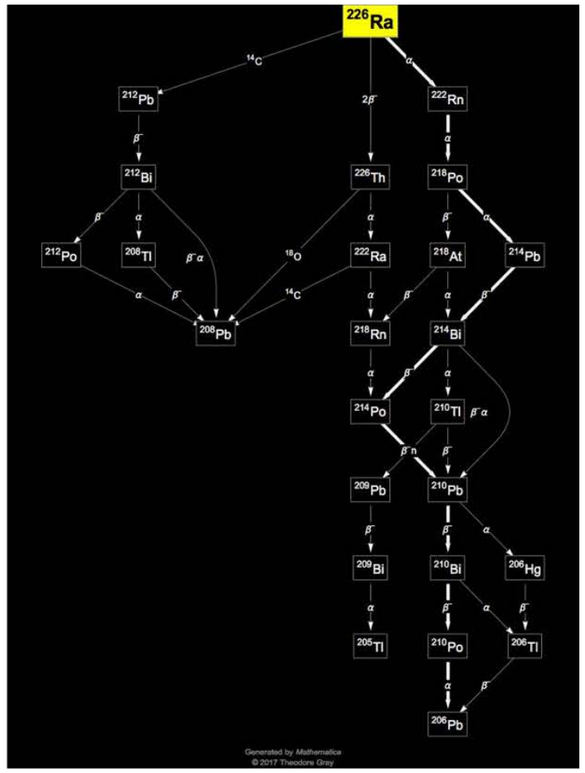
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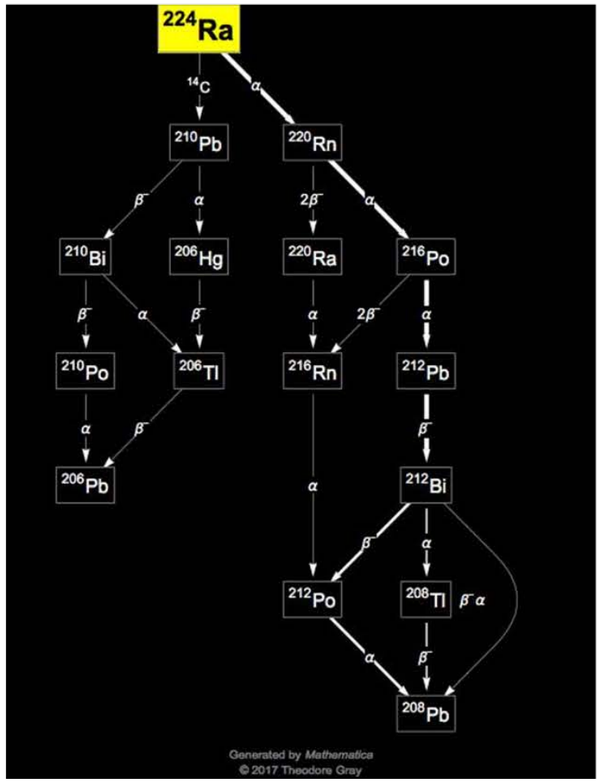
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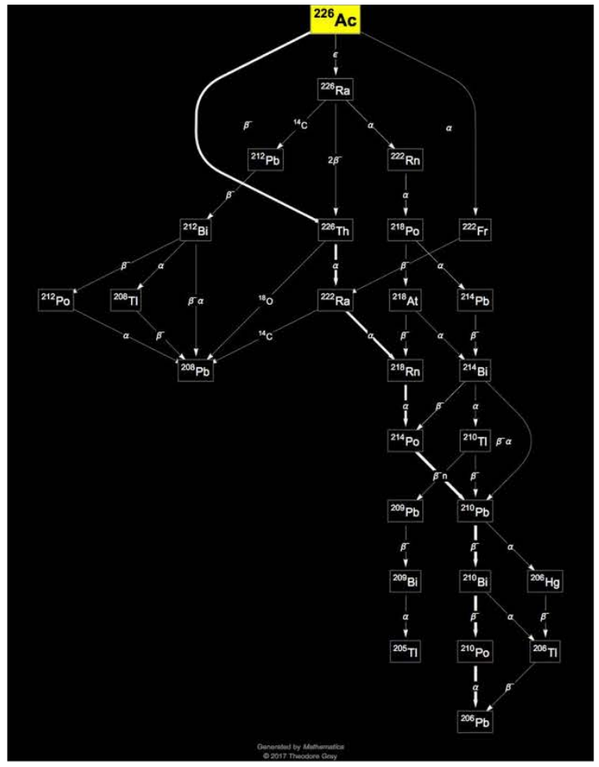
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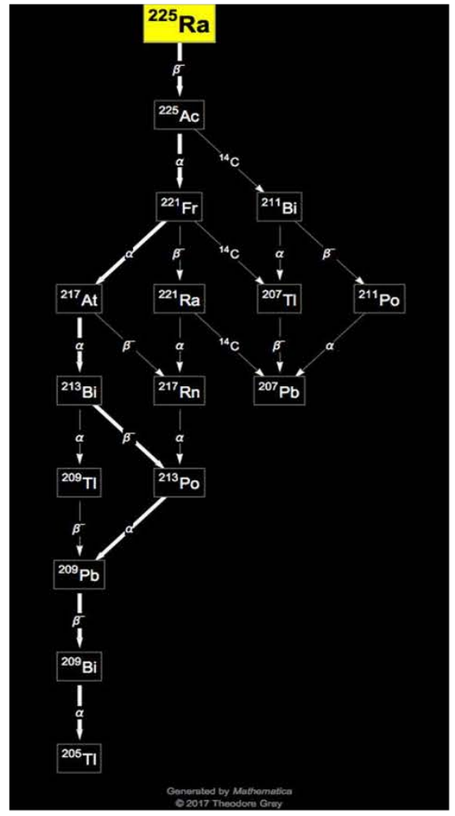
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