Oak Ridge National Laboratory

ORNL Isotope Production and Radiation Protection

MIRION Connect 2025
Radiopharmaceutical Track

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Oak Ridge National Laboratory

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U.S. DEPARTMENT OF ENERGY

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FOR THE US DEPARTMENT OF ENERGY

A new approach for nuclear research

Albert Einstein
Old Grove Road
Nassau Point
Peconic, Long Island

August 2nd, 1939

F. D. Roosevelt,
President of the United States,
White House
Washington, D.C.

Sir:

Some recent work by E. Fermi and L. Szilard, which has been communicated to me in manuscript, leads me to expect that the element uranium may be turned into a new and important source of energy in the immediate future. Certain aspects of the situation which has arisen seem to call for watchfulness and, if necessary, quick action on the part of the Administration. I believe therefore, that it is my duty to bring to your attention the following facts and recommendations:

In the course of the last four months it has been made probable - through the work of Joliot in France as well as Fermi and Szilard in America - that it may become possible to set up a nuclear chain reaction in a large mass of uranium, by which vast amounts of power and large quantities of new radium-like elements would be generated. Now it appears almost certain that this could be achieved in the immediate future.

This new phenomenon would also lead to the construction of bombs, and it is conceivable - though much less certain - that extremely powerful bombs of a new type may thus be constructed. A single bomb of this type, carried by boat and exploded in a port, might very well destroy the whole port together with some of the surrounding territory. However, such bombs might very well prove to be too heavy for transportation by air.

The United States has only very poor ores of uranium in moderate quantities. There is some good ore in Canada and the former Czechoslovakia, while the most important source of uranium is Belgian Congo.

In view of this situation, you may think it desirable to have some permanent contact maintained between the Administration and the group of physicists working on chain reactions in America. One possible way of achieving this might be for you to entrust with this task a person who has your confidence and who could perhaps serve in an inofficial capacity. His task might comprise the following:

a) to approach Government Departments, keep them informed of the further development, and put forward recommendations for Government action, giving particular attention to the problem of securing a supply of uranium ore for the United States;

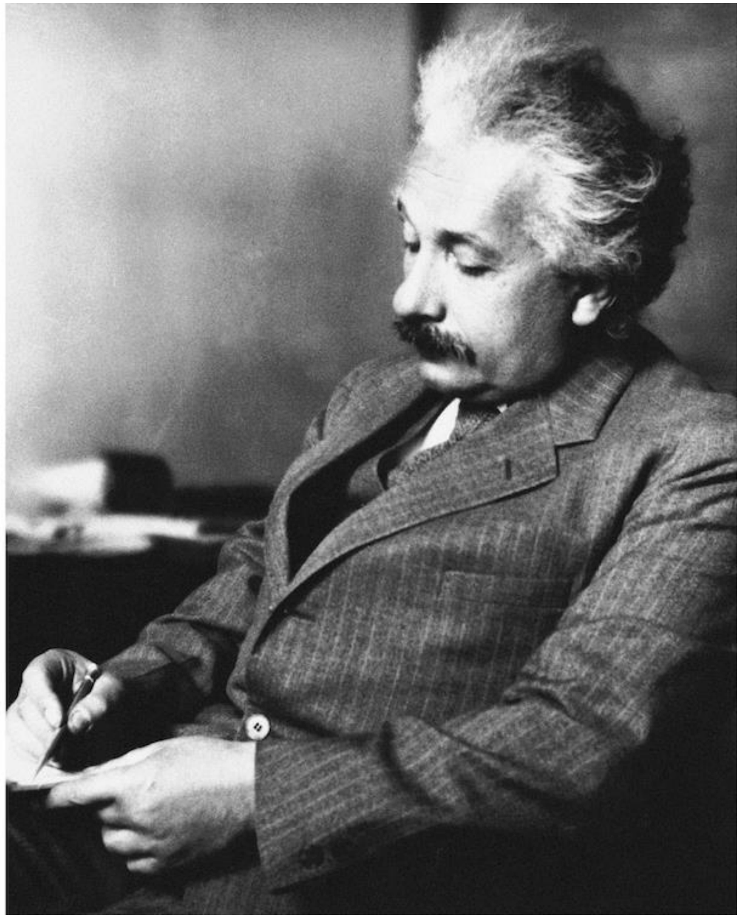
b) to speed up the experimental work, which is at present being carried on within the limits of the budgets of University laboratories, by providing funds, if such funds be required, through his contacts with private persons who are willing to make contributions for this cause, and perhaps also by obtaining the co-operation of inductrial laboratories which have the necessary equipment.

I understand that Germany has actually stopped the sale of uranium from the Czechoslovakian mines which she has taken over. That she should have taken such early action might perhaps be understood on the ground that the son of the German Under-Secretary of State, von Weizsacker, is attached to the Kaiser-Wilhelm-Institute in Berlin where some of the American work on uranium is now being repeated.

Yours very truly,

A. Einstein

(Albert Einstein)

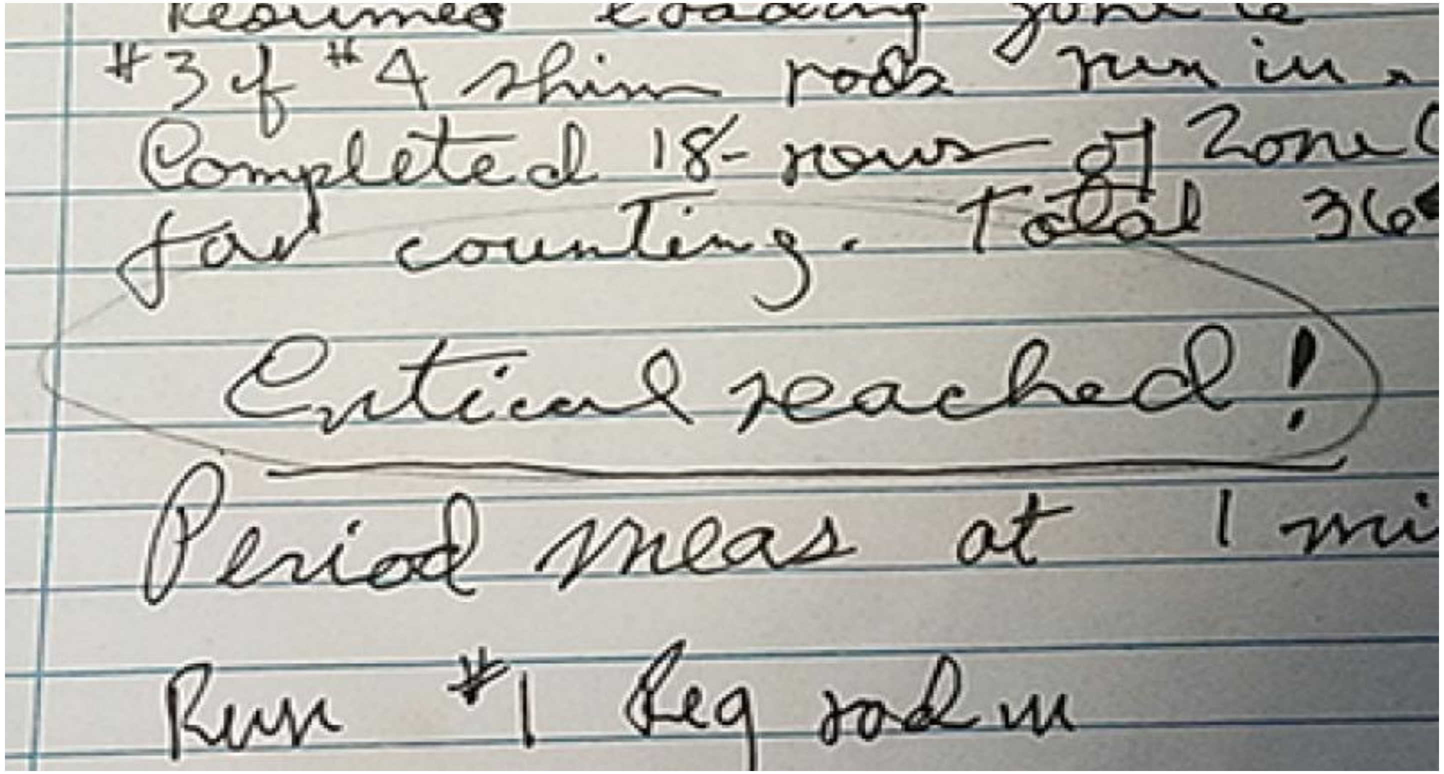


Oak Ridge was developed as part of the secret mission to expand and accelerate the United States nuclear program

- Manhattan Project to manage construction of plants for producing fissionable materials
- General Leslie Groves buys 59,000 of East Tennessee that will become known as Oak Ridge
- K-25 and Y-12 to separate Uranium, X-10 to demonstrate plutonium production and separation
- DuPont mobilized construction to build an air-cooled graphite reactor and a plutonium-separation pilot plant (1943) at X-10
- Pilot plant is built for separating plutonium and other isotopes from irradiated fuels
- X-10 facilities served as a pilot plant for the plutonium production complex at Hanford, Washington

The X-10 Graphite Reactor was designed and built in ten months

Nov. 4, 1943, at 5:00 am, the X-10 Graphite Reactor reached self-sustained criticality



World War II Ends: Transition to a Peacetime Laboratory

Legacy in technology for nuclear reactor produced radioisotopes

- Established in 1943 as the Clinton Laboratories, or X-10, as part of the Manhattan Project
- Constructed the first continuously operated nuclear reactor
- The Graphite Reactor was the first reactor to produce gram quantities of plutonium and to demonstrate the production of electricity using nuclear energy

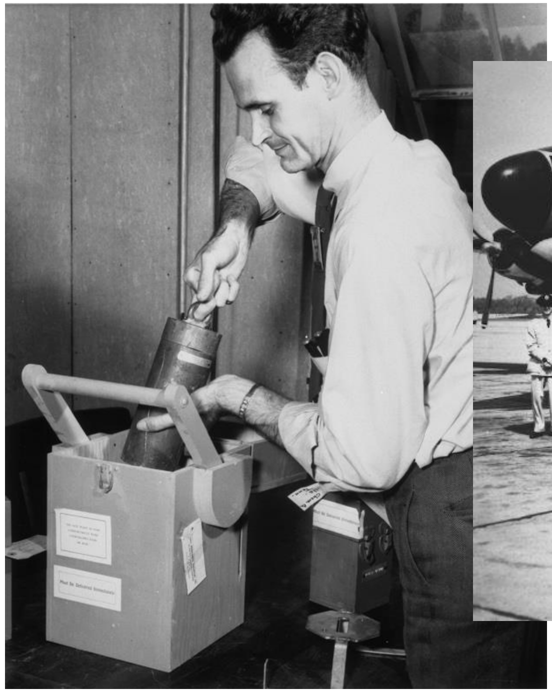
1946-1947 ORNL Timeline in Brief

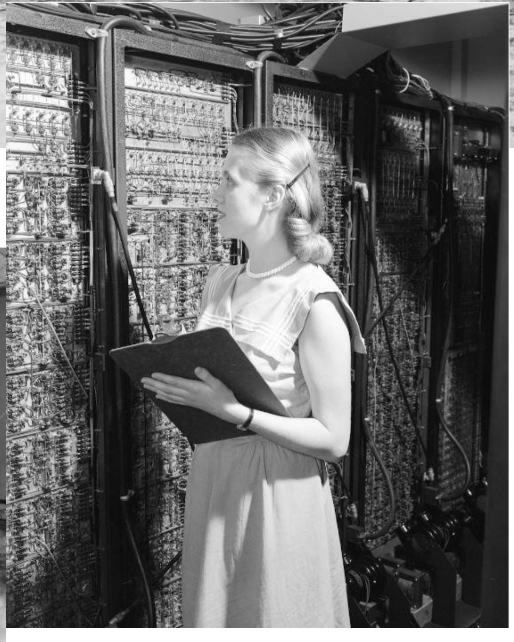
- 1946: The first official shipment of a radioisotope produced at a nuclear reactor, carbon-14, is produced at the Graphite Reactor and shipped to Barnard Free Skin and Cancer Hospital in St. Louis in August 1946.

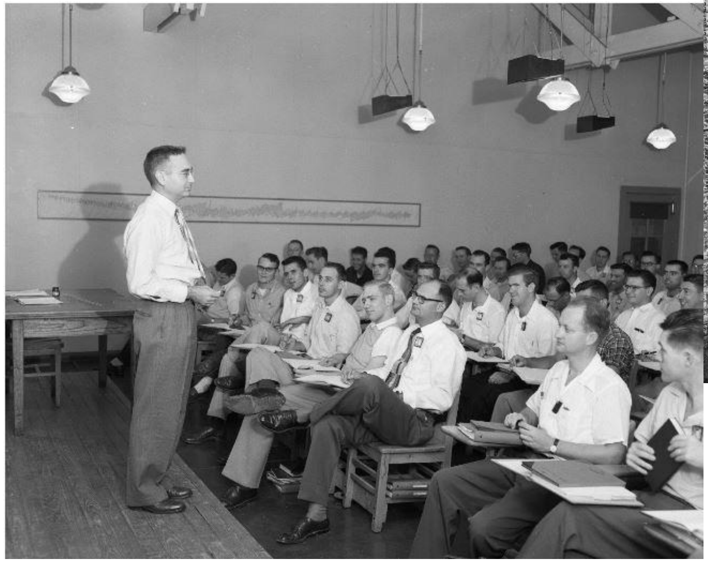
- During the program's first year, more than 1,000 shipments of 60 different radioisotopes are used for cancer treatment and other research applications.

- 1946: US Army Air Force starts the Nuclear Energy for the Propulsion of Aircraft project. ORNL supports research into shielding, heat transfer, metallurgy and materials, and radiation damage.

- ORNL operates Clinton Training School from 1946 to 1947, providing nuclear science and technology training for the military, academia, and industry.







*https://www.ornl.gov/timeline

ORNL was first to formalize the discipline of “Health Physics”

- 1945: Graphite Reactor, researchers produce the rare-earth element 61, promethium
- 1946: Radiation protection (Health Physics) research develops to protect people from exposure to unsafe levels of radiation
  - focusing on radiation monitoring, tolerance, radiation protection concepts, and training
  - Developing new methods to measure radiation exposure
- 1946: Health Physics Division began
  - K.Z. Morgan was the first division director

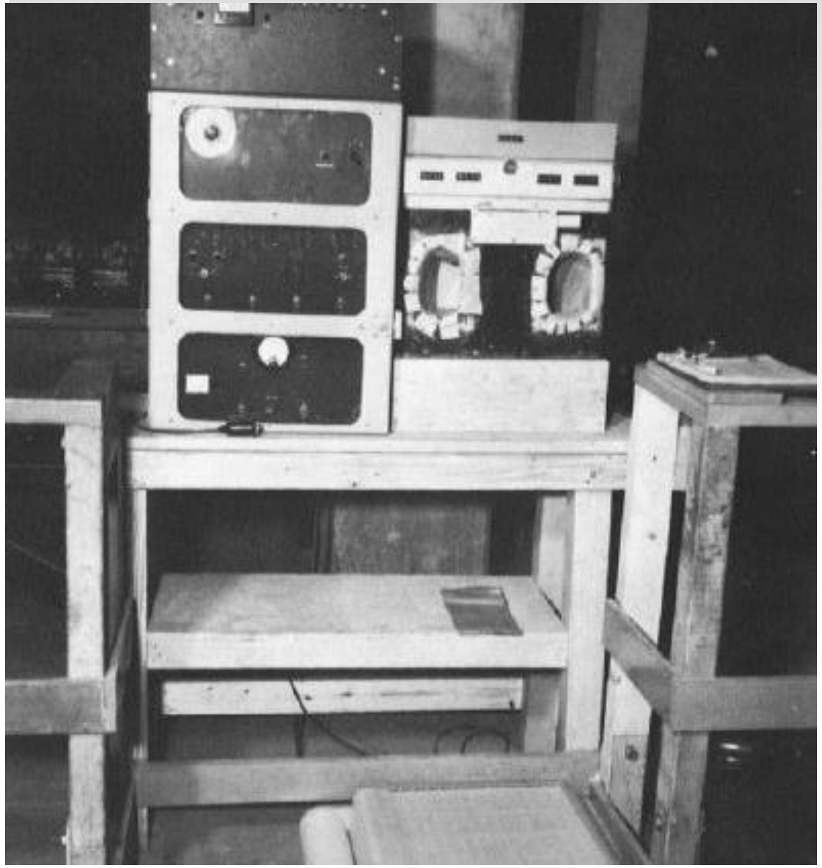
X-10 Health Physics Division

https://www.ornl.gov/timeline

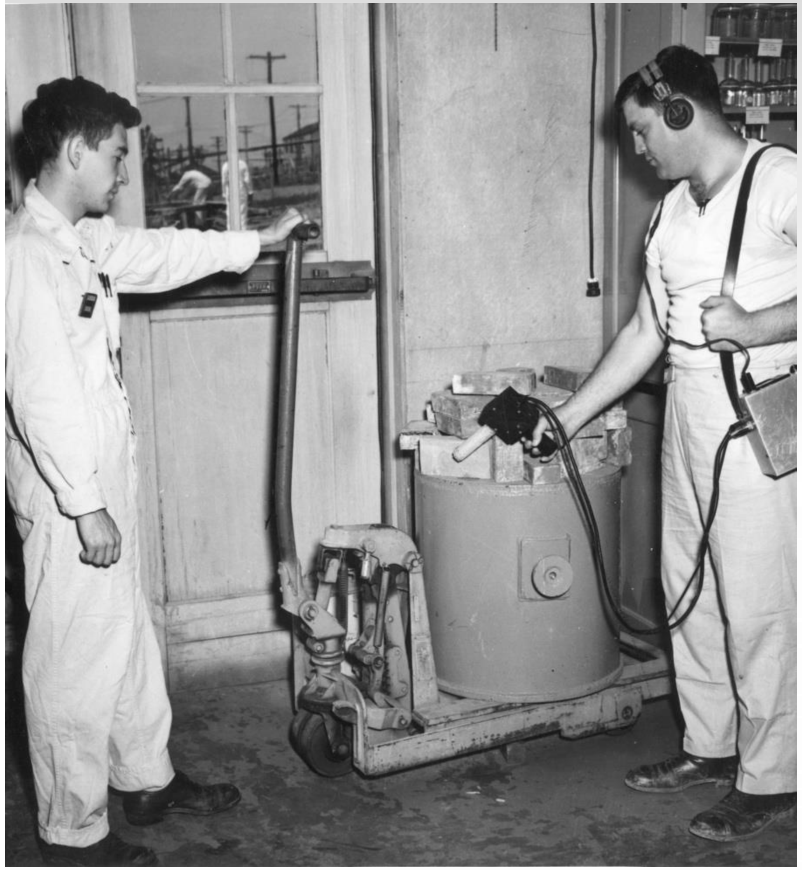
ORNL Radiation Detection surveys and monitoring

Walkie Talkie Survey Meter 1944

Hand and Foot Counter 1944



Cutie-Pie Survey Meter 1947



Handwritten note regarding personal contamination event

Mr 'head was checked with a
G M Probe counter after the final washing
on 8/14/45 with the following results:

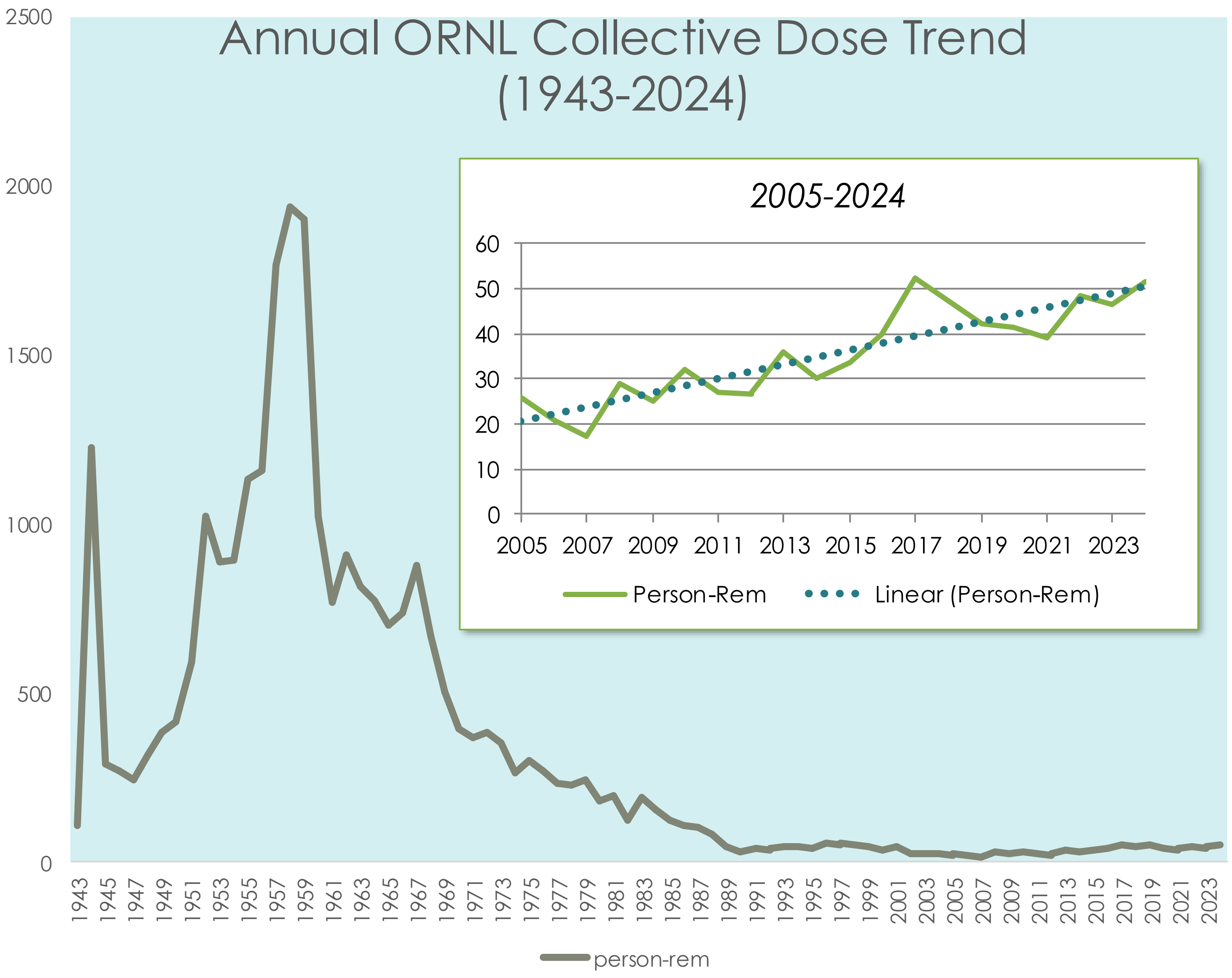
no absorber between probe and head 717 c/m
1 mm Al " " " " 163
2 " " " " " " 83

These readings were corrected for background.

K. Z. Morgan

ORNL HISTORICAL DOSE TREND

- 1943-1945 dose levels correspond with activities of major facilitates, such as the X-10 Pile, Separations Plant, Radiochemistry Labs and Tank Farms
- Drop off at the end of 1945 signaled by the end of WWII
- 1951-1959: increase corresponds with operation of reactors: Aqueous homogeneous reactor experiment, Molten salt reactor experiment, and water cooled (ORR,LITR,BSR,TSF) reactors
- 1961–1979: non-nuclear energy sources, ecological and biological sciences
- 1980 – Current: end of Cold War and increased regulatory oversight/ALARA



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ORNL's Isotope Production Program utilizes the unique facilities and scientific expertise to support the goals of the Department of Energy.

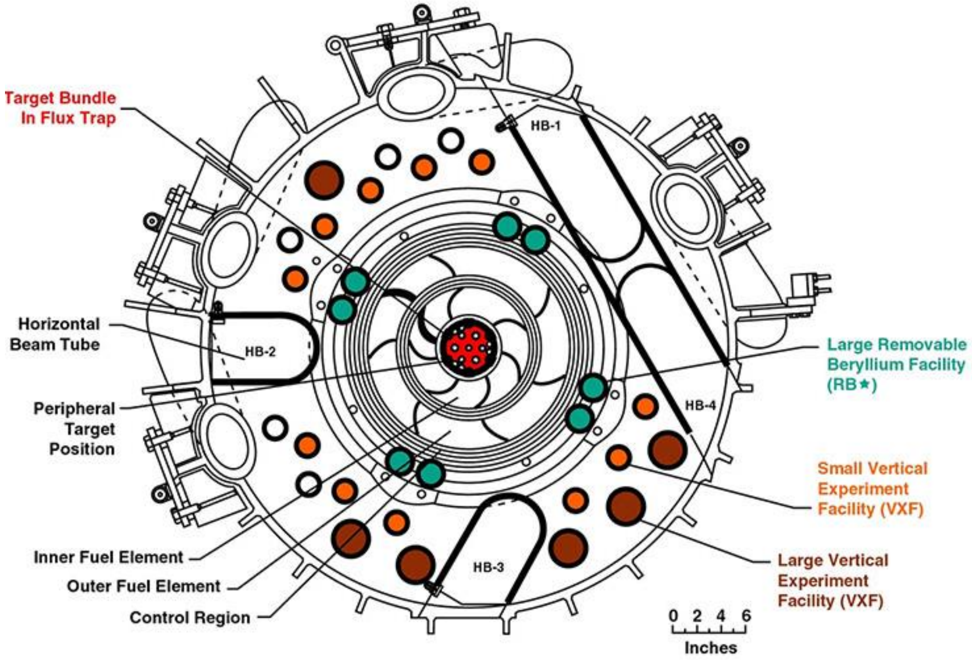
- The primary goal is to make critical isotopes more readily available to meet domestic U.S. needs
- Enrichment Technology
- Element Discovery
- Produces Medical, Industrial, and Stable Isotopes
- Produces Isotopes for Security
- Unique Nuclear Facilities
- Production of PU-238

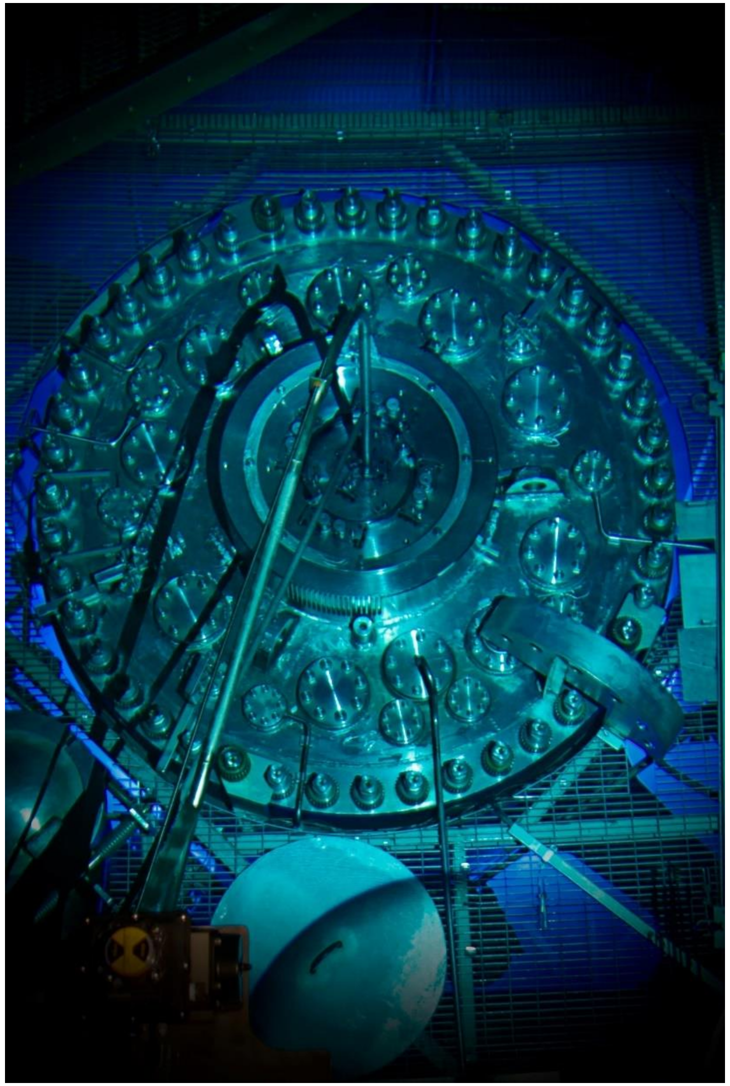
High Flux Isotope Reactor (HFIR)

- Criticality was achieved on August 25, 1965
- 85 MW steady state neutron source provides 3,900 hours of beam time annually
- Peak thermal flux of 2.6 x 10^{15} neutrons/cm^2/sec
- Produces medical- and industry-grade isotopes
- The cold source increases neutron wavelength from 4 to 12 Å for studying large-scale structures
- 15 state-of-the-art neutron scattering instruments; 7 exclusively for cold neutron experiments

The High Flux Isotope Reactor generates the highest steady state neutron flux environment in the world

- The HFIR is an 85 MW highly enriched uranium (HEU) fueled reactor containing an ~13 cm diameter flux trap.
- The flux trap contains 37 target irradiation sites with a neutron flux of ~2×10^{15} n·cm^{-2}s^{-1}.
- One target site contains a hydraulic tube, which can pass targets up to 6.5 cm in height in and out of the reactor during operation





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Product Catalog

Welcome to the NIDC online catalog. Elements shown in blue indicate that isotopes are available for quotation.

Select your isotopes and add them to the cart. Once all isotopes are added to your cart, click on the cart button to complete your quote request

If the isotope you are interested in is not listed in the catalog, click here to submit your request: Request a New Product

Periodic Table View | List View

H																	**He**
Li	**Be**											B	C	**N**	**O**	F	**Ne**
Na	**Mg**											**Al**	**Si**	P	**S**	**Cl**	**Ar**
K	**Ca**	**Sc**	**Ti**	**V**	**Cr**	**Mn**	**Fe**	**Co**	**Ni**	**Cu**	**Zn**	**Ga**	**Ge**	**As**	**Se**	**Br**	**Kr**
Rb	**Sr**	**Y**	**Zr**	Nb	**Mo**	**Tc**	**Ru**	Rh	**Pd**	**Ag**	**Cd**	**In**	**Sn**	**Sb**	**Te**	I	**Xe**
Cs	**Ba**		**Hf**	**Ta**	**W**	**Re**	**Os**	**Ir**	**Pt**	**Au**	**Hg**	**Tl**	**Pb**	**Bi**	**Po**	**At**	Rn
Fr	**Ra**		Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Nh	Fl	Mc	Lv	Ts	Og
		La	**Ce**	Pr	**Nd**	**Pm**	**Sm**	**Eu**	**Gd**	Tb	**Dy**	**Ho**	**Er**	Tm	**Yb**	**Lu**	
		Ac	**Th**	Pa	**U**	**Np**	**Pu**	**Am**	**Cm**	**Bk**	**Cf**	**Es**	**Fm**	Md	No	Lr	

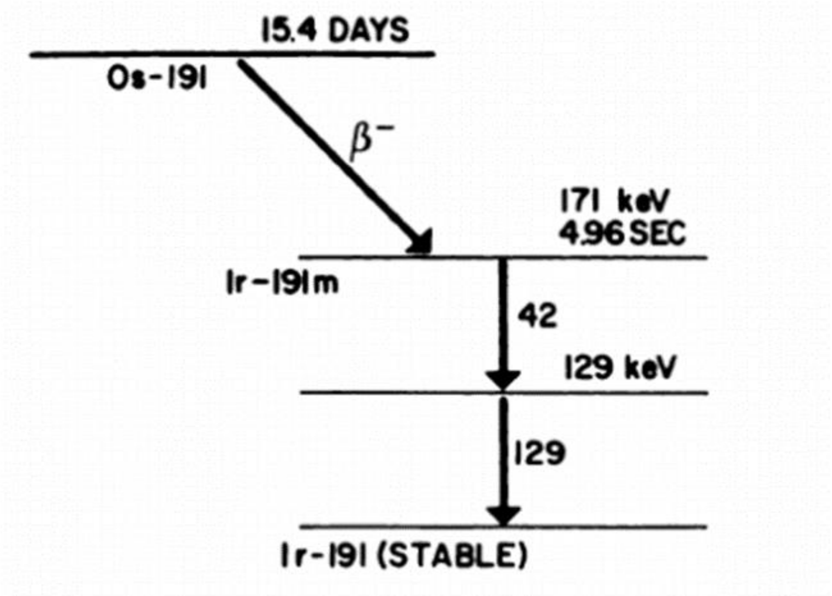
Selected Isotopes and their Uses from ORNL

Californium-252	Californium-252 is an intense neutron source used in detecting impurities in coal and cement, determining productivity of oil wells, calibrating radiation detection instruments in port security operations, and starting up nuclear reactors. ORNL is the only US producer of this isotope and one of two producers in the entire world.
Plutonium-238	Full-scale production—expected by 2026—will provide electrical and thermal energy for NASA's deep space missions, as it did for Mars 2020.
Actinium-225	In clinical trials for targeted radiotherapy cancer treatments
Actinium-227	Actinium-227 is the source for Bayer's FDA-approved treatment for metastasized prostate cancer, Xofigo. ORNL is the only near-term production site for actinium-227.
Berkelium-249	A by-product of californium-252 production, berkelium-249 was essential in the discovery of tennessine, one of several new elements on the periodic table.
Selenium-75	Selenium-75 is a gamma emitter used by industry for weld inspections and other nondestructive tests.
Nickel-63	Explosives detectors at airports and narcotics detectors use nickel-63.
Strontium-89	Strontium-89 is used to relieve bone pain during the treatment of various metastasized cancers.
Tungsten-188	Researchers continue to use tungsten-188 in numerous clinical trials, with promising treatments for bone pain and lung and liver cancers.
Promethium -147	Recovered by ORNL from the waste streams of plutonium-238 production, promethium-147 is used in nuclear batteries, thin film measurement instruments, light sources, and luminous paints.

Tungsten-188 is used to generate Rhenium-188 Labeled Radiopharmaceuticals

- W-188 is difficult to produce since it requires a W-186 target to be subjected to high neutron flux – HFIR
- ORNL is currently the only source
- Rhenium-188 (^{188}Re) is a high energy beta-emitting radioisotope that is used in therapeutic nuclear medicine

Osmium-191 is a byproduct of reactor produced W-188

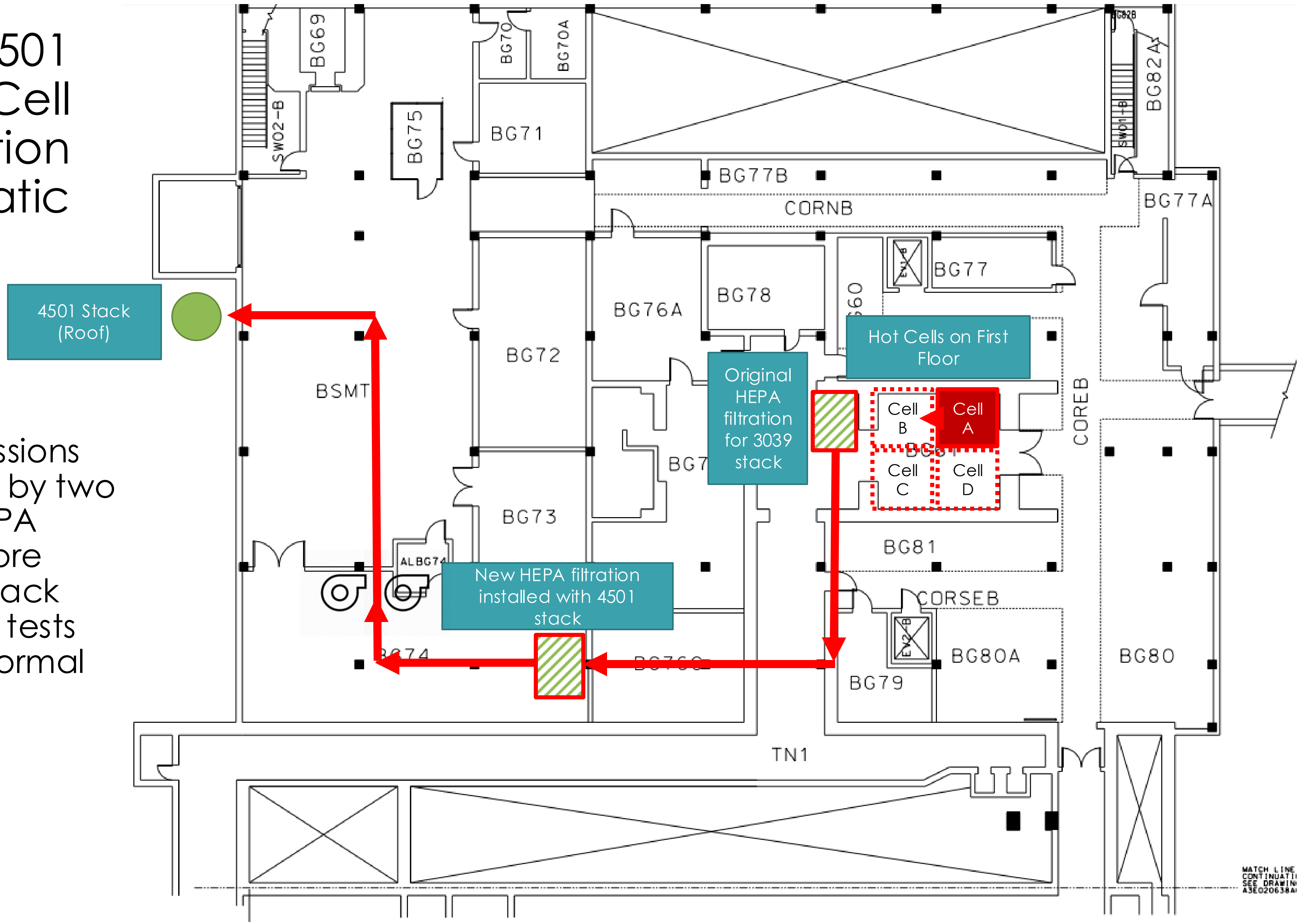


Os-191 has a short 15.4-day half-life

During neutron irradiation of enriched W-186, both Os-191 and Ir-192 are produced in varying amounts depending on the neutron flux characteristics and other irradiation parameters.

Building 4501 Hot Cell Ventilation Schematic

- Hot Cell emissions are serviced by two stages of HEPA filtration before exiting the stack
- Recent DOP tests confirmed normal operation



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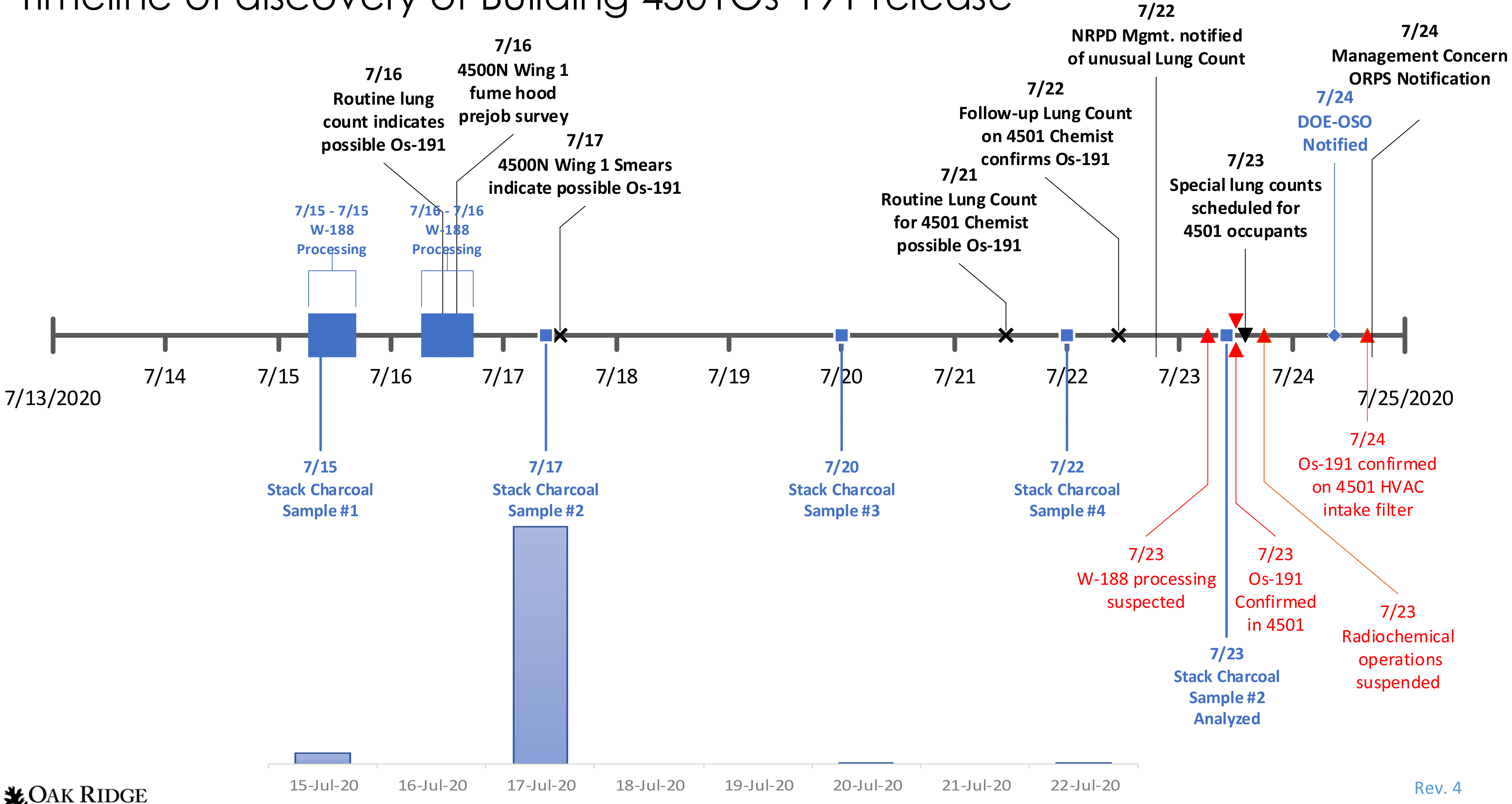
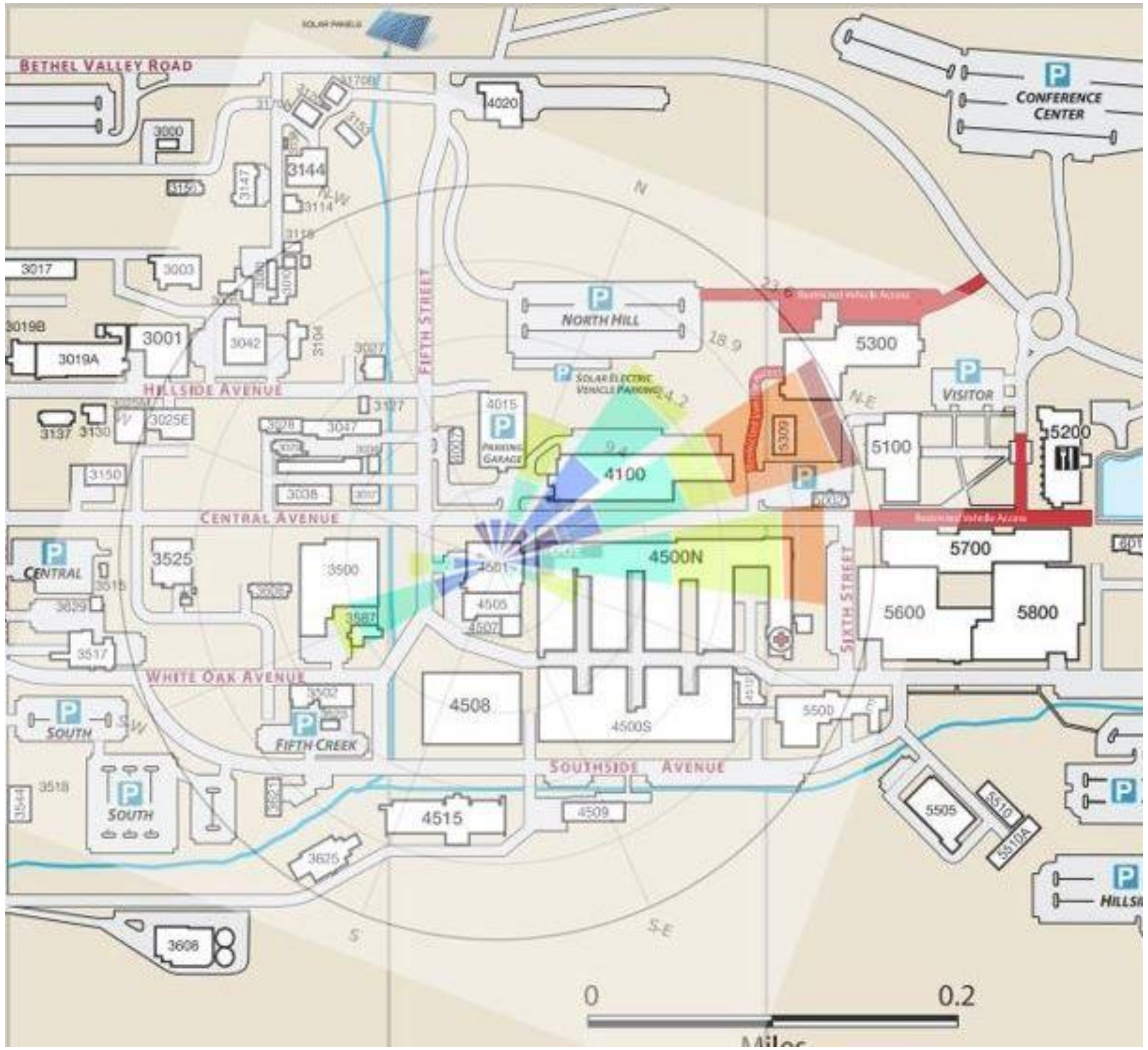
Timeline of discovery of Building 4501Os-191 release



Plume modeling was performed to evaluate potential Os-191 dispersion

- Used actual meteorological data recorded July 15 – 18th
- Most conservative dispersion projections indicate maximum onsite dose was in the range of 1 mrem
- Contamination was detected on several building HVAC fresh air intake filters
- Low-levels of Os-191 was detected inside some buildings using Large Area Smears (≥100 ft²) and gamma spectroscopy



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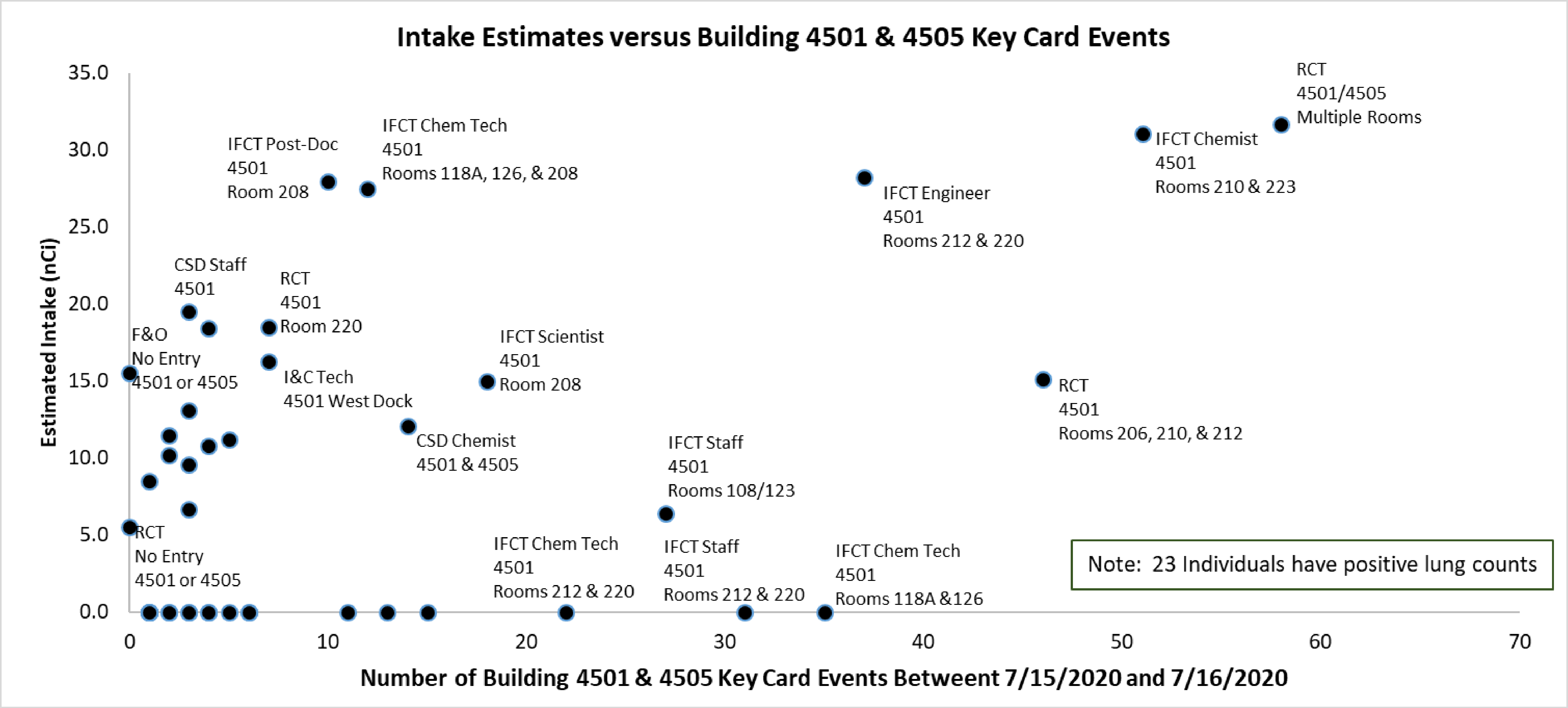

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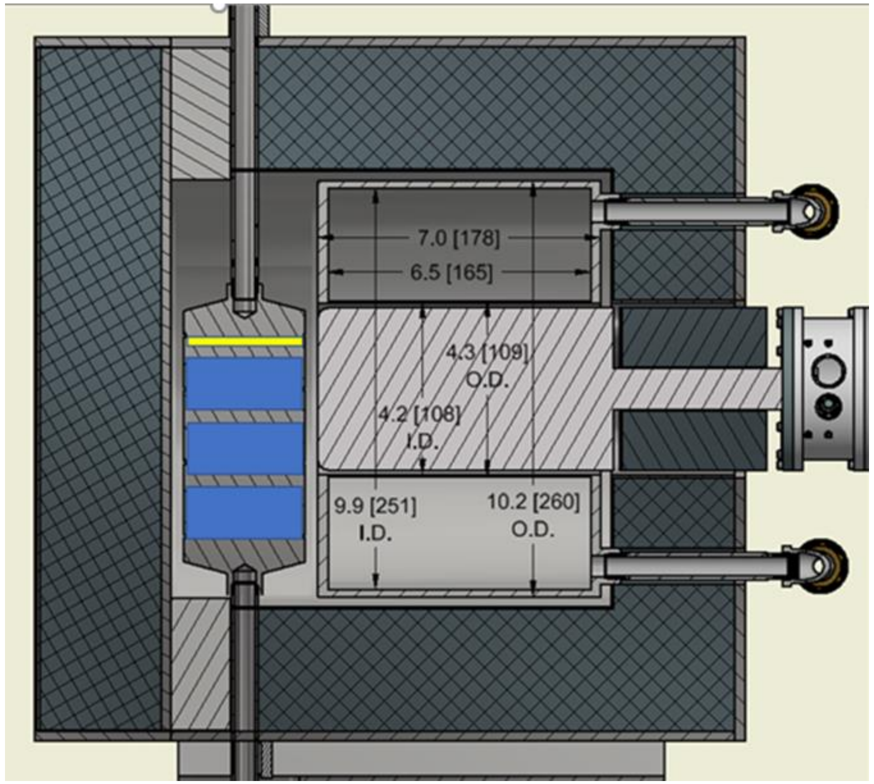
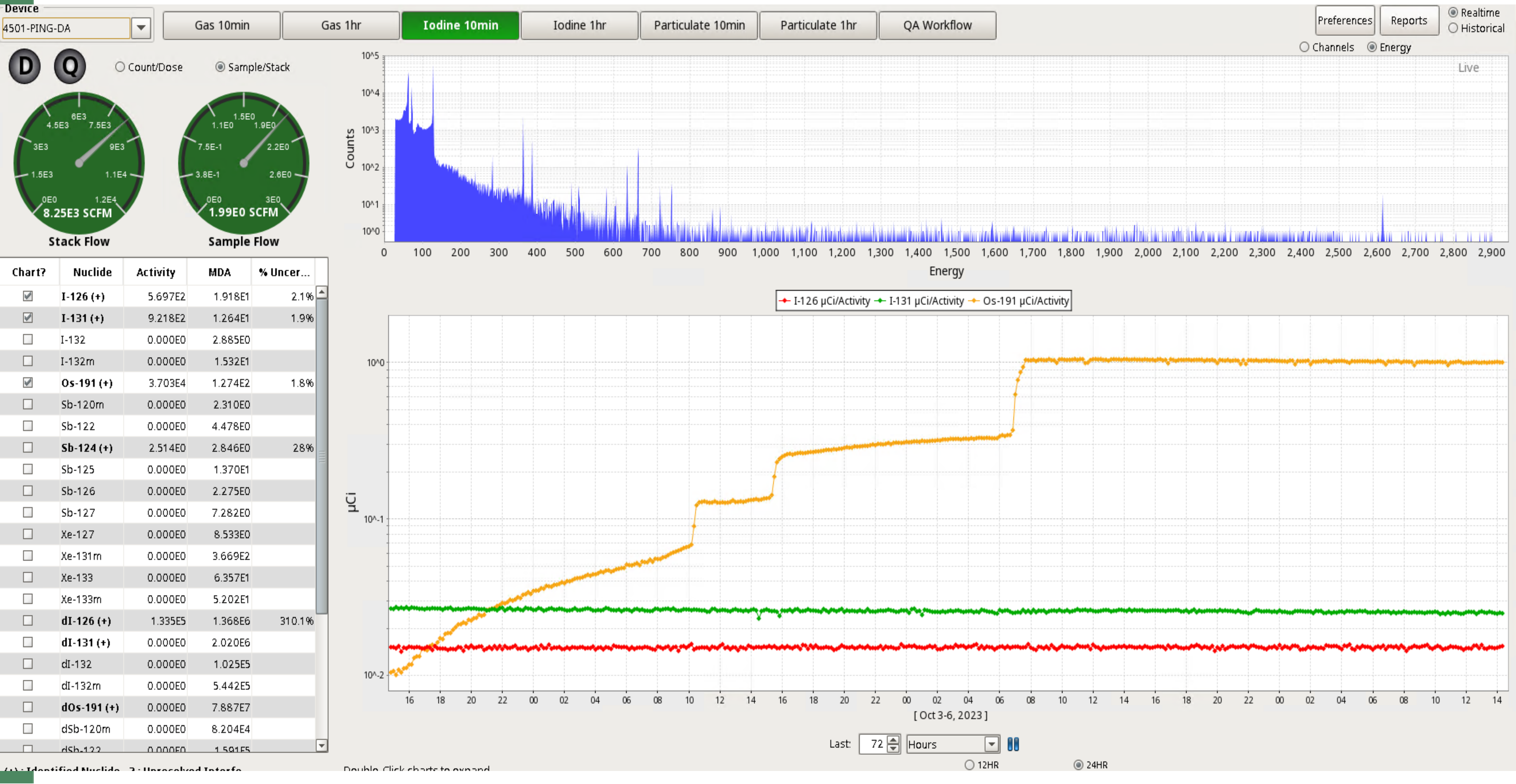
4501 Spectroscopic Particulate, Iodine, Noble Gas (SPING) cabinet and skid

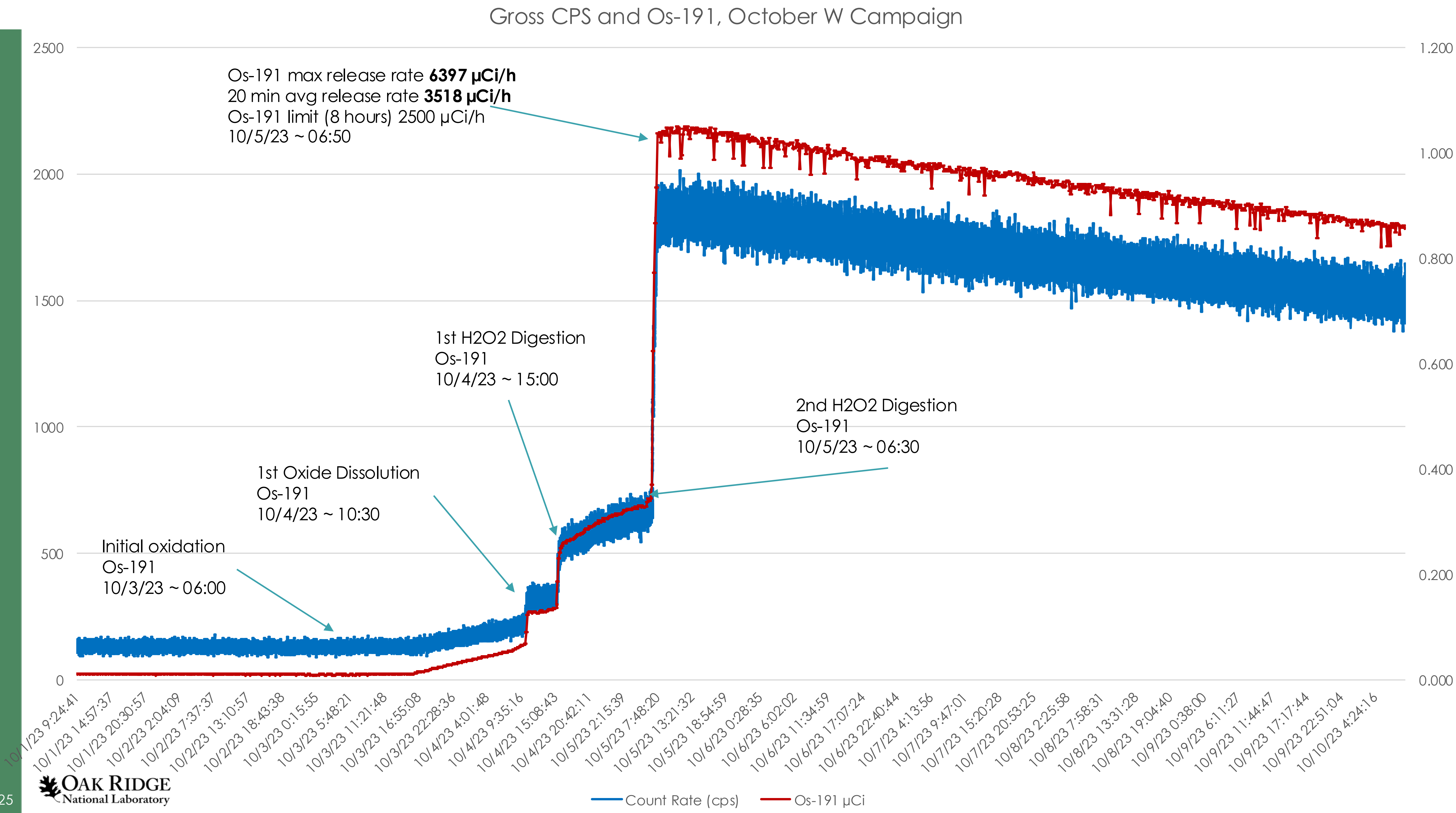


Our new 4501 SPING ….

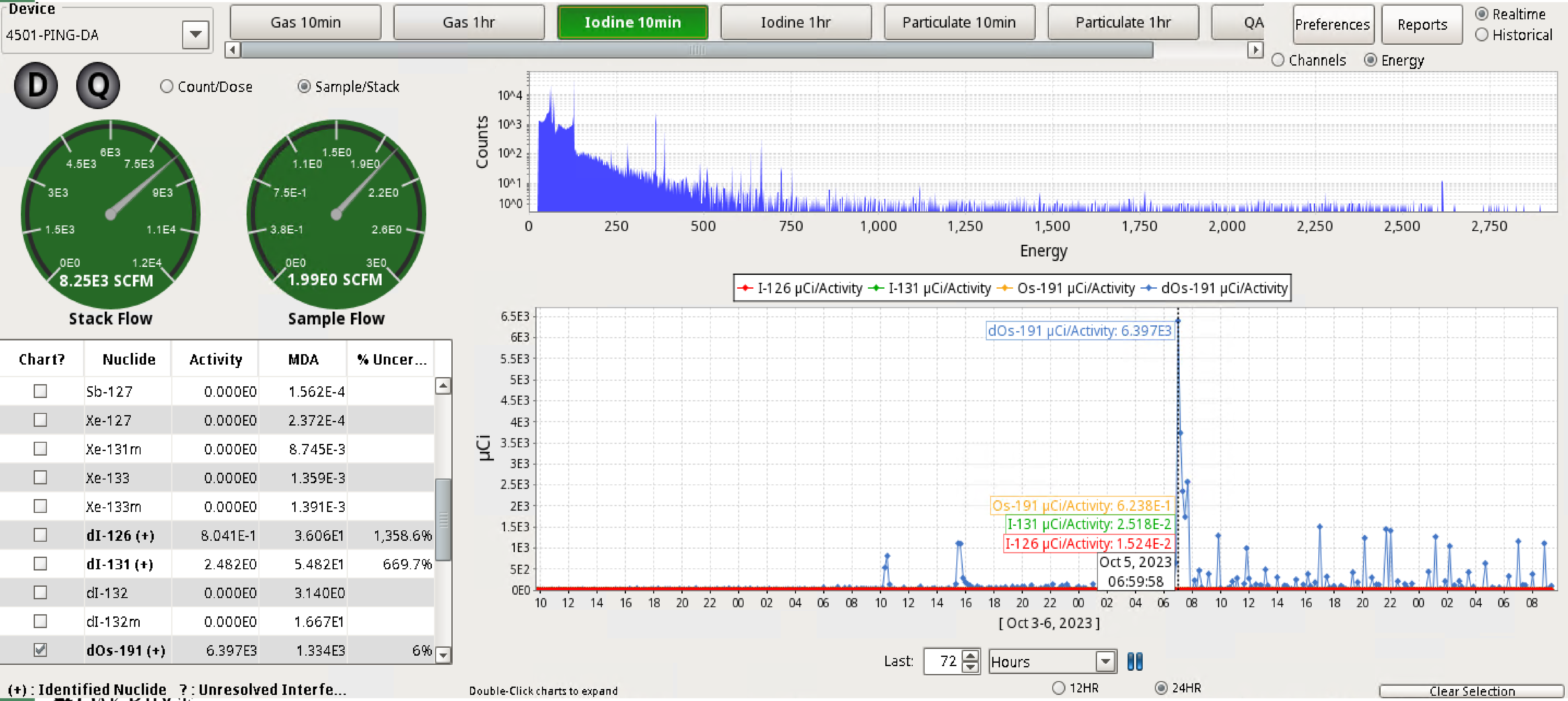


Chart?	Nuclide	Activity	MDA	% Uncer…
☑	**I-126 (+)**	5.697E2	1.918E1	2.1%
☑	**I-131 (+)**	9.218E2	1.264E1	1.9%
☐	I-132	0.000E0	2.885E0	
☐	I-132m	0.000E0	1.532E1	
☑	**Os-191 (+)**	3.703E4	1.274E2	1.8%
☐	Sb-120m	0.000E0	2.310E0	
☐	Sb-122	0.000E0	4.478E0	
☐	**Sb-124 (+)**	2.514E0	2.846E0	28%
☐	Sb-125	0.000E0	1.370E1	
☐	Sb-126	0.000E0	2.275E0	
☐	Sb-127	0.000E0	7.282E0	
☐	Xe-127	0.000E0	8.533E0	
☐	Xe-131m	0.000E0	3.669E2	
☐	Xe-133	0.000E0	6.357E1	
☐	Xe-133m	0.000E0	5.202E1	
☐	**dI-126 (+)**	1.335E5	1.368E6	310.1%
☐	**dI-131 (+)**	0.000E0	2.020E6	
☐	dI-132	0.000E0	1.025E5	
☐	dI-132m	0.000E0	5.442E5	
☐	**dOs-191 (+)**	0.000E0	7.887E7	
☐	dSb-120m	0.000E0	8.204E4	
☐	dSb-122	0.000E0	1.591E5	

(+) : Identified Nuclide ? : Unresolved Interfe…


Gross CPS and Os-191, October W Campaign
Os-191 max release rate **6397 µCi/h**
20 min avg release rate **3518 µCi/h**
Os-191 limit (8 hours) 2500 µCi/h
10/5/23 ~ 06:50
1st H2O2 Digestion
Os-191
10/4/23 ~ 15:00
2nd H2O2 Digestion
Os-191
10/5/23 ~ 06:30
1st Oxide Dissolution
Os-191
10/4/23 ~ 10:30
Initial oxidation
Os-191
10/3/23 ~ 06:00
2500
2000
1500
1000
500
0
1.200
1.000
0.800
0.600
0.400
0.200
0.000
10/1/23 9:24:41
10/1/23 14:57:37
10/1/23 20:30:57
10/2/23 2:04:09
10/2/23 7:37:37
10/2/23 13:10:57
10/2/23 18:43:38
10/3/23 0:15:55
10/3/23 5:48:21
10/3/23 11:21:48
10/3/23 16:55:08
10/3/23 22:28:36
10/4/23 4:01:48
10/4/23 9:35:16
10/4/23 15:08:43
10/4/23 20:42:11
10/5/23 2:15:39
10/5/23 7:48:20
10/5/23 13:21:32
10/5/23 18:54:59
10/6/23 0:28:35
10/6/23 6:02:02
10/6/23 11:34:59
10/6/23 17:07:24
10/6/23 22:40:44
10/7/23 4:13:56
10/7/23 9:47:01
10/7/23 15:20:28
10/7/23 20:53:25
10/8/23 2:25:58
10/8/23 7:58:31
10/8/23 13:31:28
10/8/23 19:04:40
10/9/23 0:38:00
10/9/23 6:11:27
10/9/23 11:44:47
10/9/23 17:17:44
10/9/23 22:51:04
10/10/23 4:24:16
Count Rate (cps)
Os-191 µCi

The 4501 SPING gives us release rate in addition to accumulated activity



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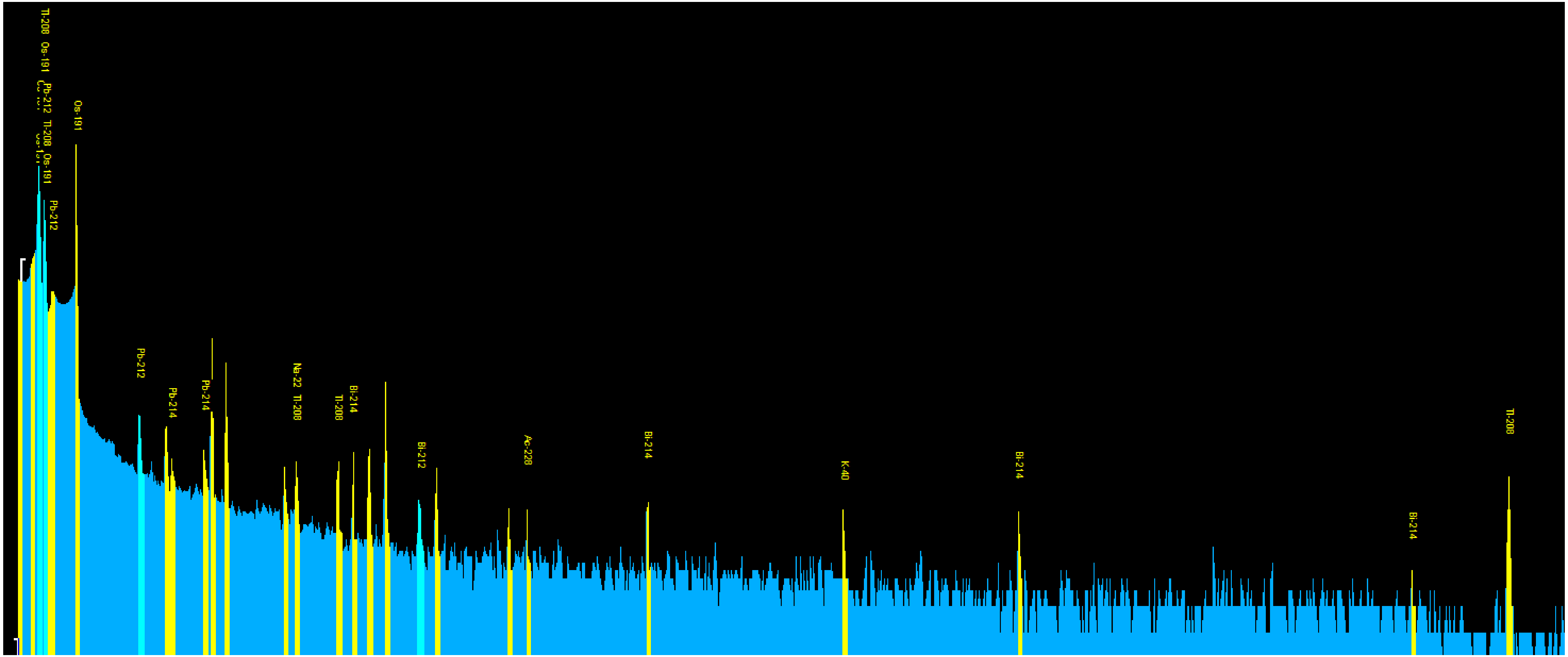
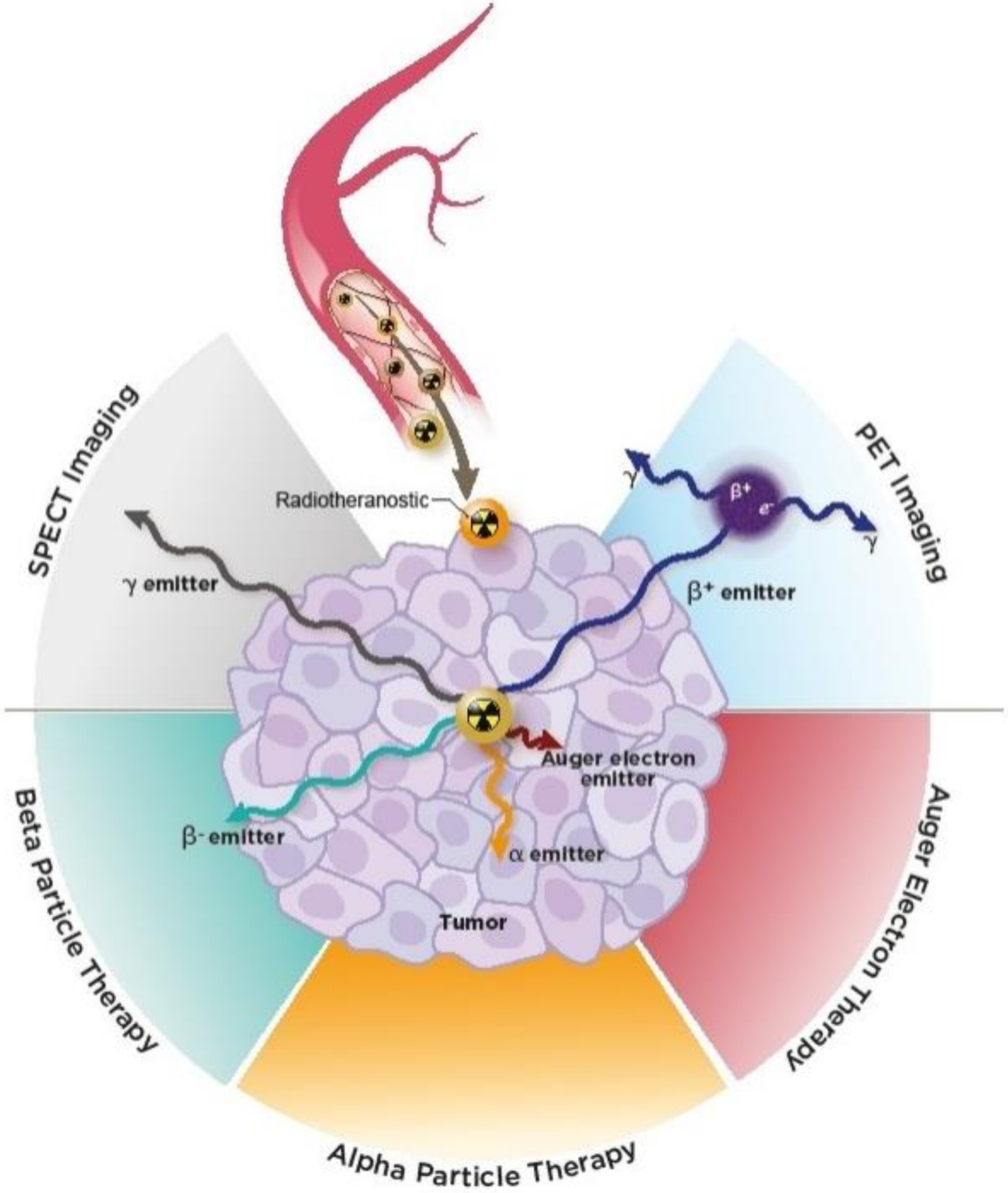
Example Spectrum from Re-188 Campaign



Targeted Radiotherapy, Imaging and Diagnostics



Recent Advances in Radiometals for Combined Imaging and Therapy in Cancer; 2021 Dr. Natalia Herrero Álvarez, Dr. David Bauer, Dr. Javier Hernández-Gil, Prof. Dr. Jason S. Lewis https://chemistry-europe.onlinelibrary.wiley.com/doi/10.1002/cmdc.202100135

The ORNL Molten Salt Reactor Experiment (MSRE) was the first reactor to operate on U-233

- MSRE achieved a self-sustained chain reaction on October 8, 1968, when AEC Chairman Glenn Seaborg (co-discoverer of ^{233}U) threw the switch in the control room
- MSRE was permanently shut down on December 12, 1969
- On February 1973, the U.S. AEC terminated the development program for molten salt reactors
- The was a significant stockpile of surplus ^{233}U containing material with "no-defined-use"

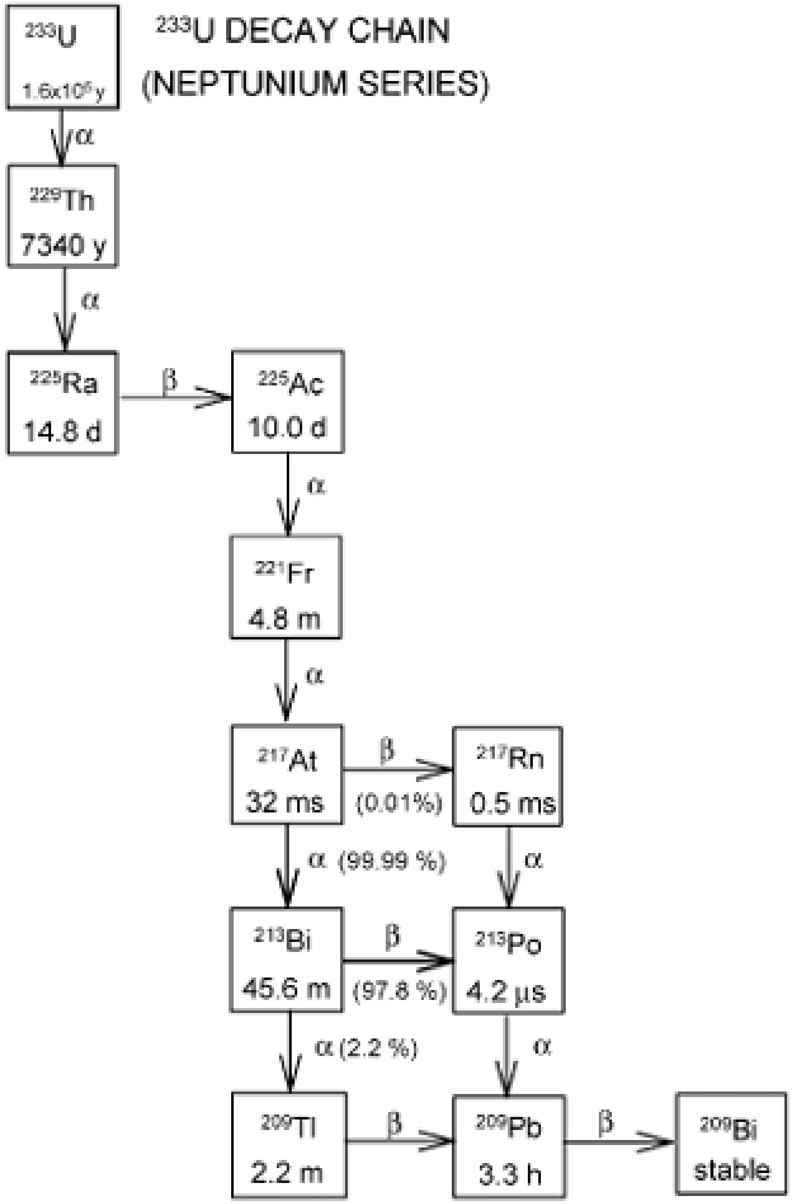
AEC chair Glenn Seaborg operates the controls of the MSRE—running on U-233 fuel—on October 8, 1968. (Photo: ORNL)

$$^{232}_{90}Th + ^{1}_{o}n \rightarrow ^{233}_{90}Th \rightarrow ^{233}_{91}Pa + \beta^{-} \rightarrow ^{233}_{92}U + \beta^{-}$$

14 billion yrs | 22 min | 27 days | 160,000 yrs

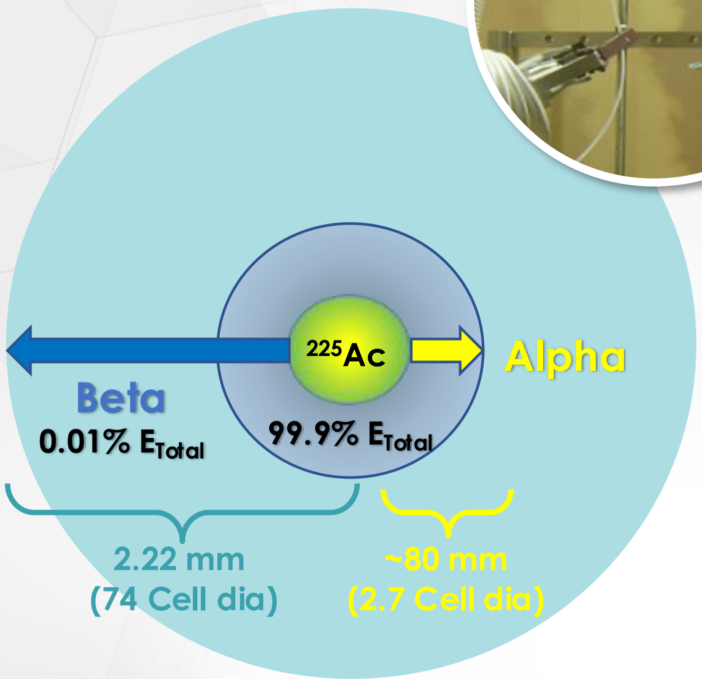
Preclinical studies in the late 1990s showed promising results using ^{213}Bi and ^{225}Ac (parent) for targeted radiotherapy

- The 8-MeV alpha particles from ^{213}Bi can penetrate 6–10 nearby cell layers, killing everything in their short path (100mm) including tumor cells
- During the 1995–1996 period, ^{229}Th was extracted from pre-existing ^{233}U waste material which was stored at ORNL for about 35 years
- Boll, et al. showed that ^{225}Ac could be separated and purified with an average isotopic purity of 99.6 ± 0.7%
  - Results provided a limited supply for a proof-of-principle that ^{225}Ac was a promising therapeutic agent for cancer and infectious diseases
- ^{229}Th slow in-growth rate of from ^{233}U and the increasing difficulties associated with safeguards made routine processing of ^{233}U impractical
- LANL (IPF) and BNL (BLIP) proton accelerators are being used to produce ^{225}Ac via spallation of thorium metal with 480 MeV protons



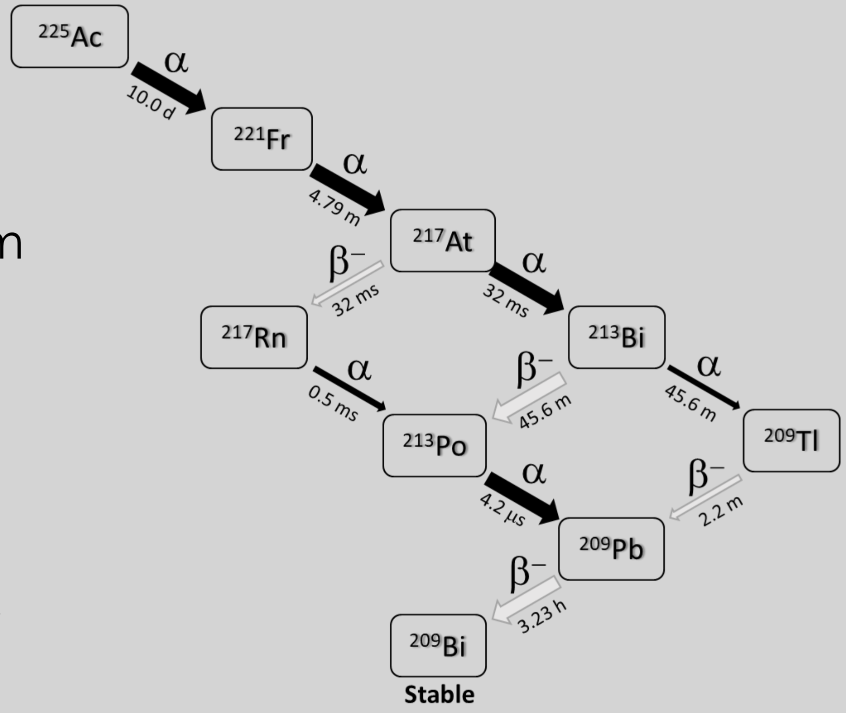
Boll, Rose & Murphy, Karen & Groover, Greg & Mirzadeh, Saed. (2008). *Production of Ac-225 for Alpha Particle Radioimmunotherapy.*

Chemical recovery process



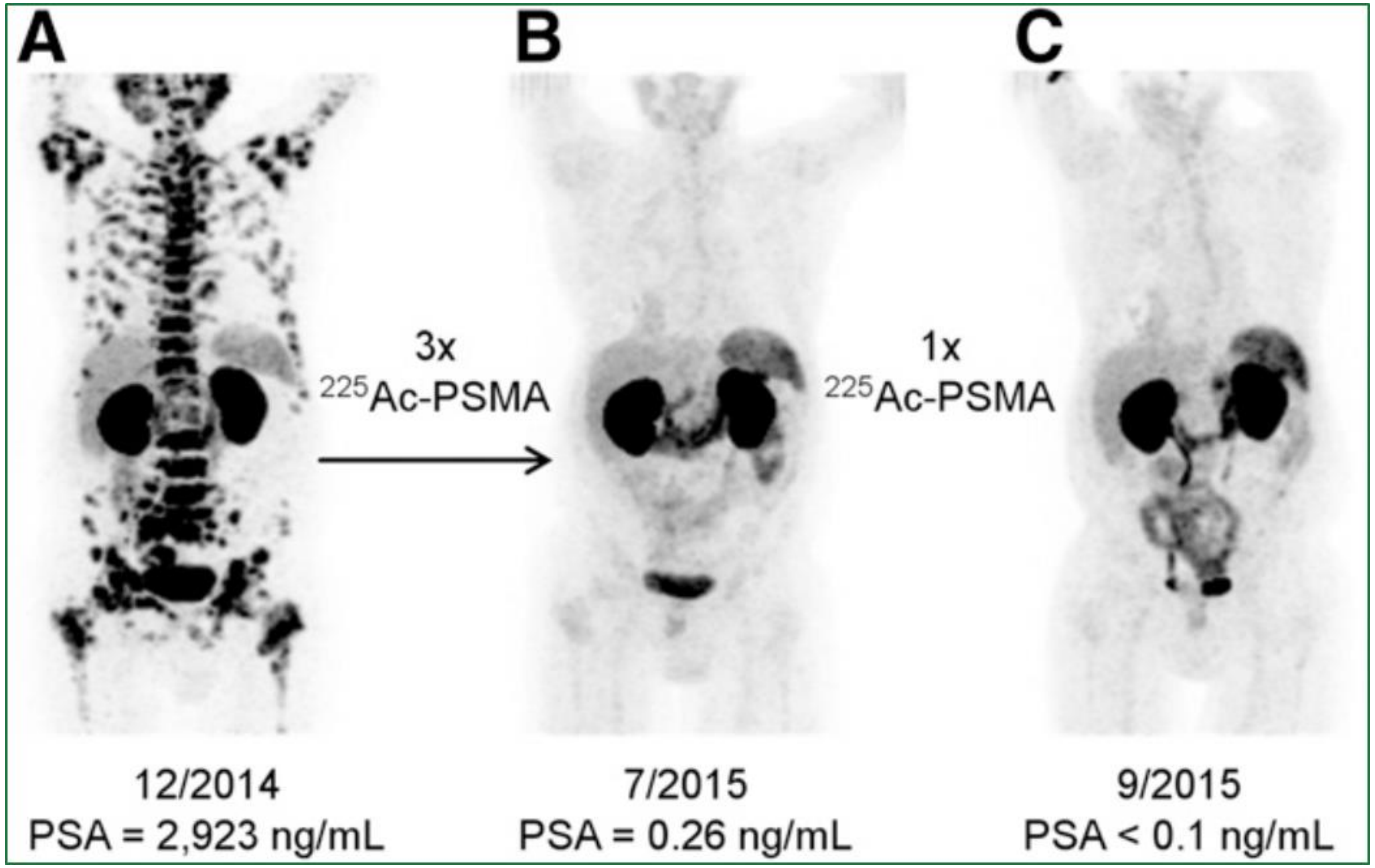
Ac-225 ($t_{1/2}$ 9.92 d) from Th-229

- Th-229 material recovered from storage tanks
- Series of separations to isolate Ac-225 from Ra-225 and Th-229 precursors
- Ac-225 multi-decay (α, β) TAT therapy
- Weekly shipments to customers all over the world

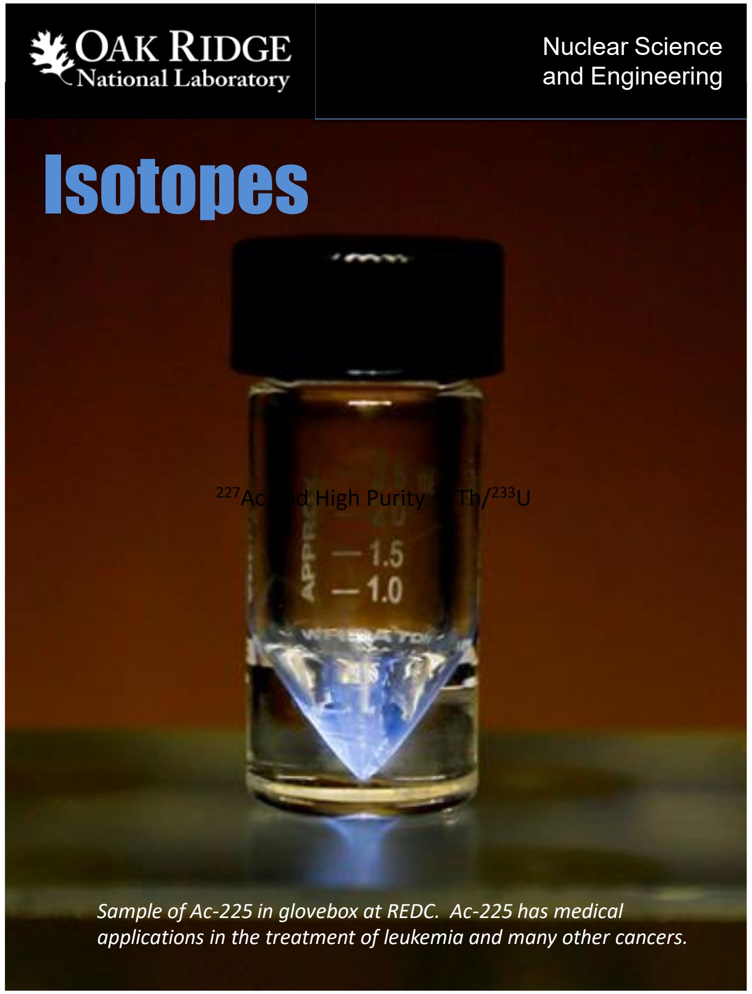


*Rasching rings are made of borosilicate glass to absorb neutrons to help prevent potential criticality

Clinical Trials for ^{225}Ac therapy for metastasized cancer have originated the field of targeted alpha therapy

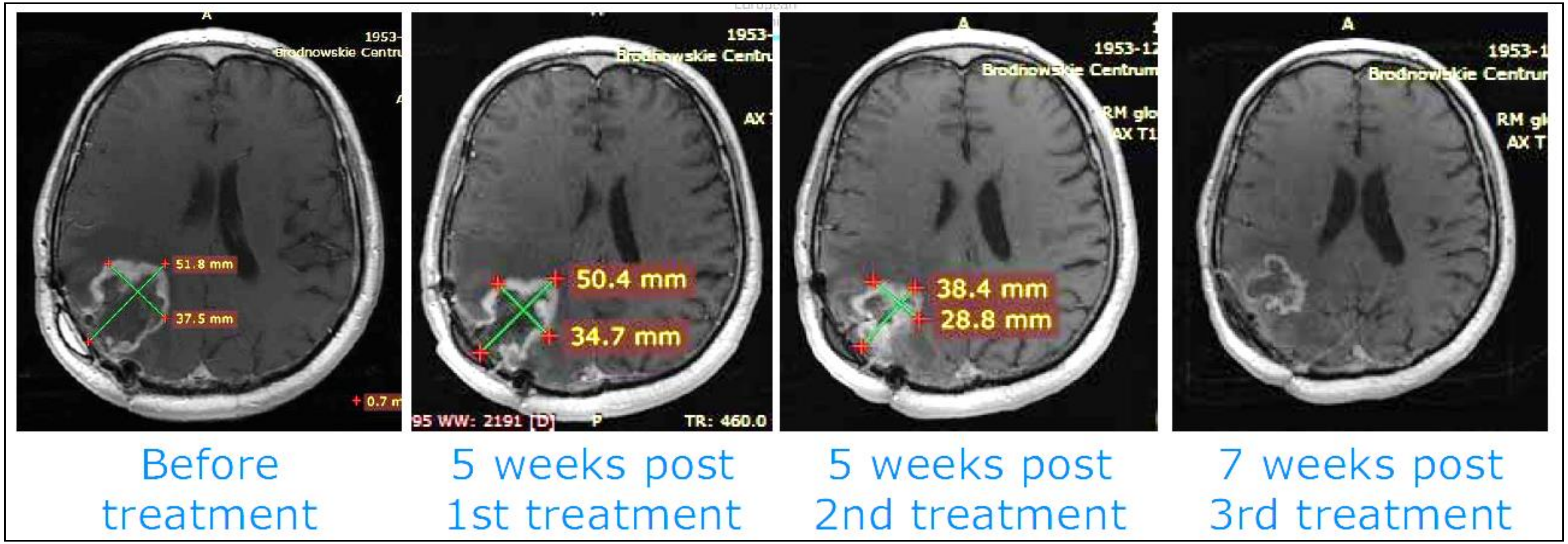


Clemens Kratochwil, University Hospital Heidelberg – *J. Nuc. Med.*, v57, 2016, pp 1941-1944



Clinical trials for treatment of glioblastoma using $^{225}Ac/^{213}Bi$

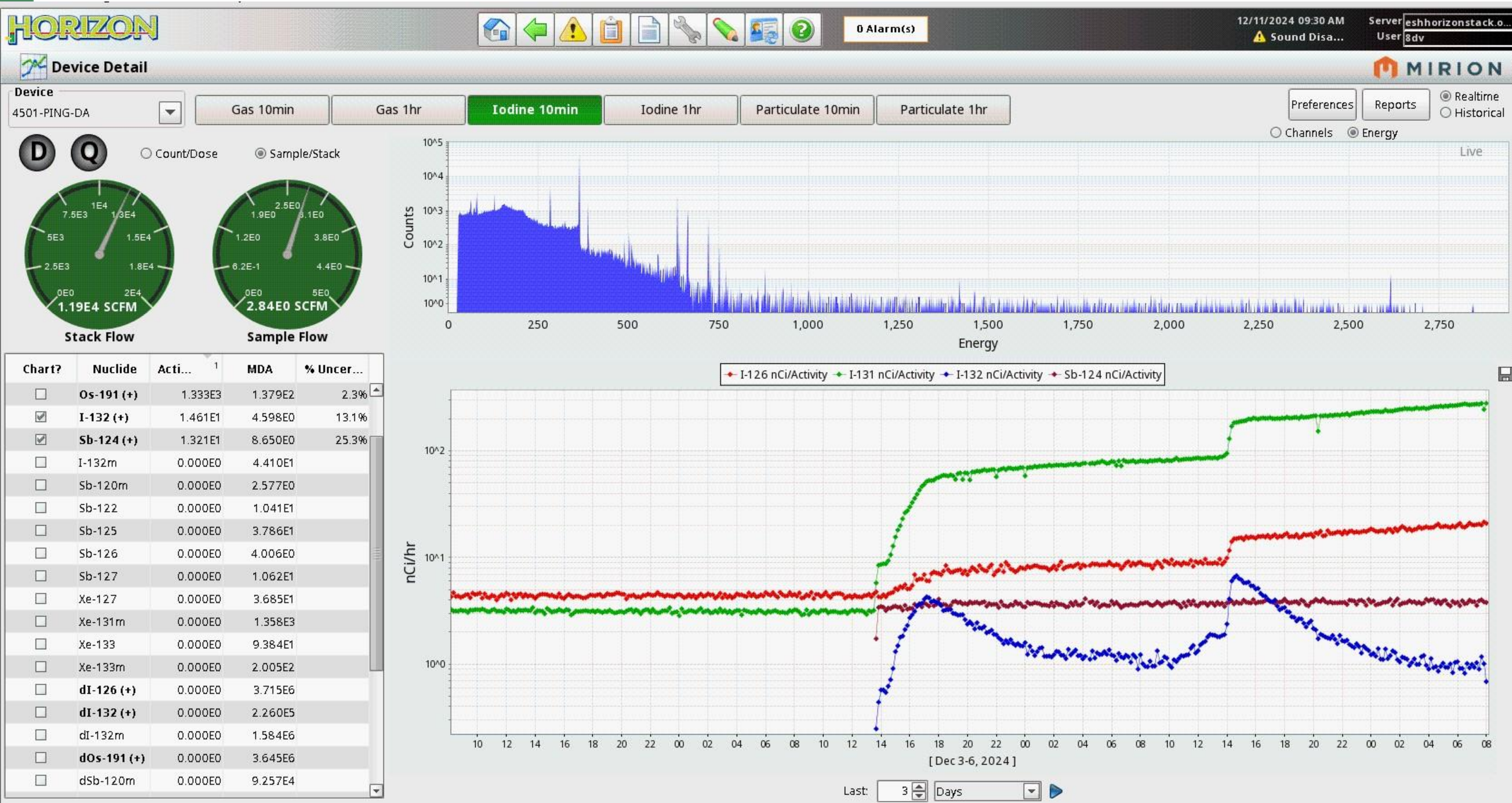
- Glioblastoma multiforme (GBM) is the most common and aggressive malignant primary brain tumor in humans
- ^{213}Bi-DOTA-Substance P kills GBM cells and GBM stem cells effectively *in vitro*



A. Morgenstern (et al), European Commission, Joint Research Centre, Institute for Transuranium Elements, Karlsruhe, Germany

Continued treatment improved overall survival >23 months

Snapshot of the recent Tri-Lab campaign emissions



Ac-227 from Irradiated Ra-226

Ac-227
$t_{1/2}$ = 21.7 y

↓ α *decay*

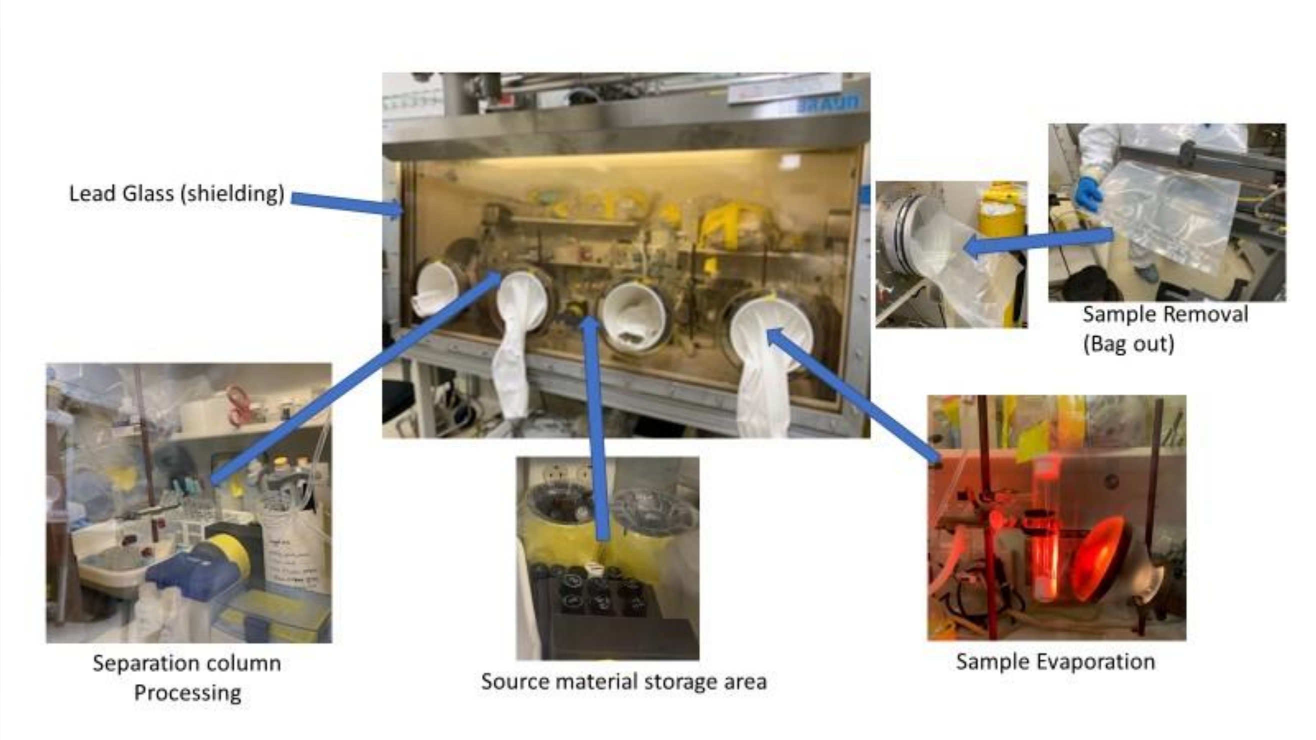
Th-227
$t_{1/2}$ = 18.68 d

↓ α *decay*

Ra-223
$t_{1/2}$ = 11.4 d

↓ β^- *decay*

Decay products



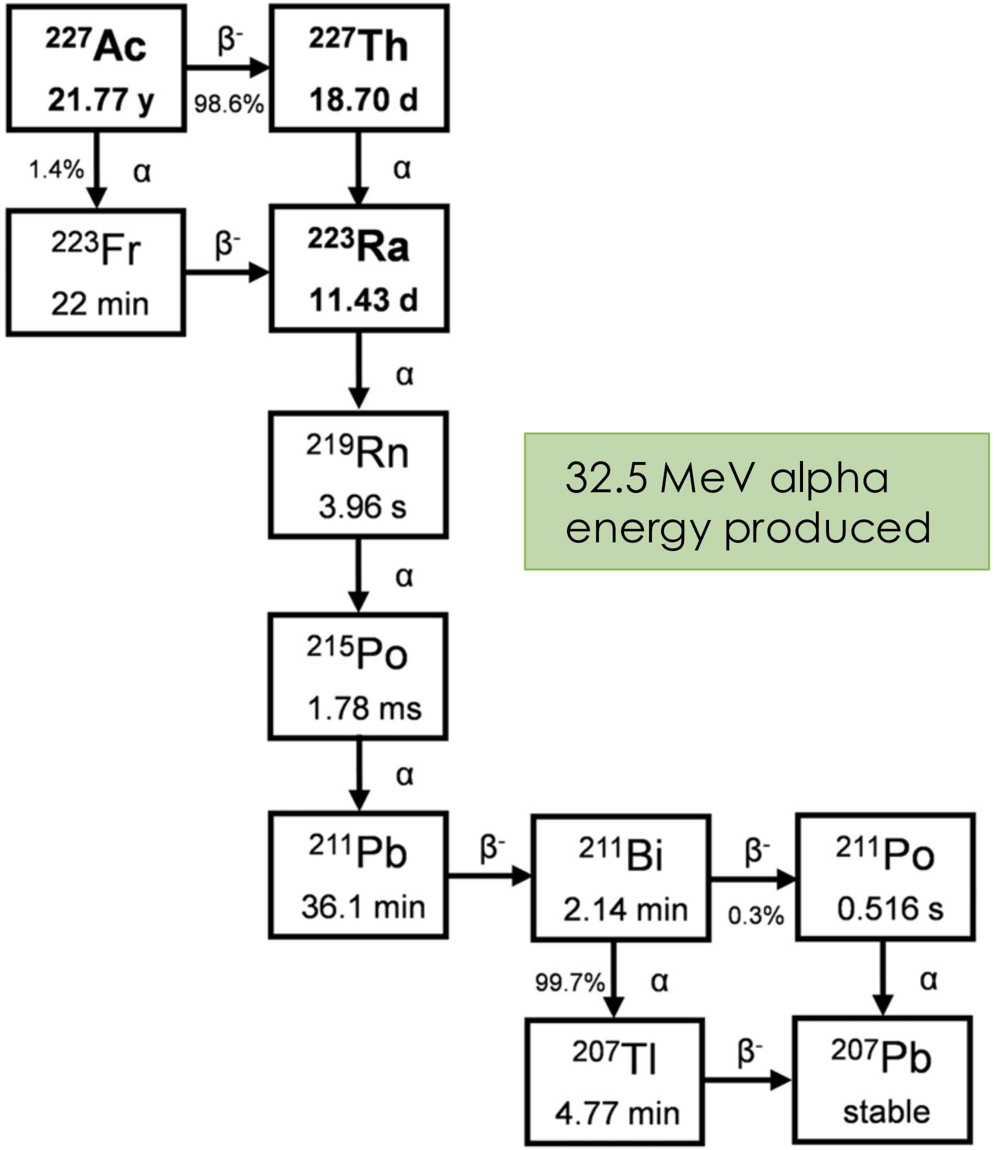
- Th-227 and Ra-223 progenies
- Multi-decay (α, β)
- Emerging TAT and systemic in vivo applications
- Isolated by anion exchange chromatography
- Alternative TAT radioisotopes with varied chemical and biological behavior

ORNL is also producing ^{227}Ac as longer-lived feedstock for a ^{223}Ra generator for targeted alpha therapy

Xofigo® ^{223}Ra dichloride is being used for treatment of certain metastatic prostate cancer patients

wwww.mims.com

Bayer Pharmaceutics Company



32.5 MeV alpha energy produced

^{227}Ac Production Process

Ra-226 Target Production	Radium recovered from surplus brachytherapy needles	Oxide powder pressed into pellets	Pellets loaded into aluminum rabbit and welded	Welded rabbits transferred to HFIR for irradiation
HFIR Irradiation	HFIR Irradiation 1×10^{15} cm^{-2} sec^{-1}	Irradiation time optimized to limit Th-228 production	Irradiated rabbits are returned for processing	
Post-irradiation Processing	Pellets are dissolved to separate Ac-227	Repeat purification steps as necessary to meet specification	Convert purified form to nitrate for shipment	Transfer product to a DOT Special Form capsule for shipment

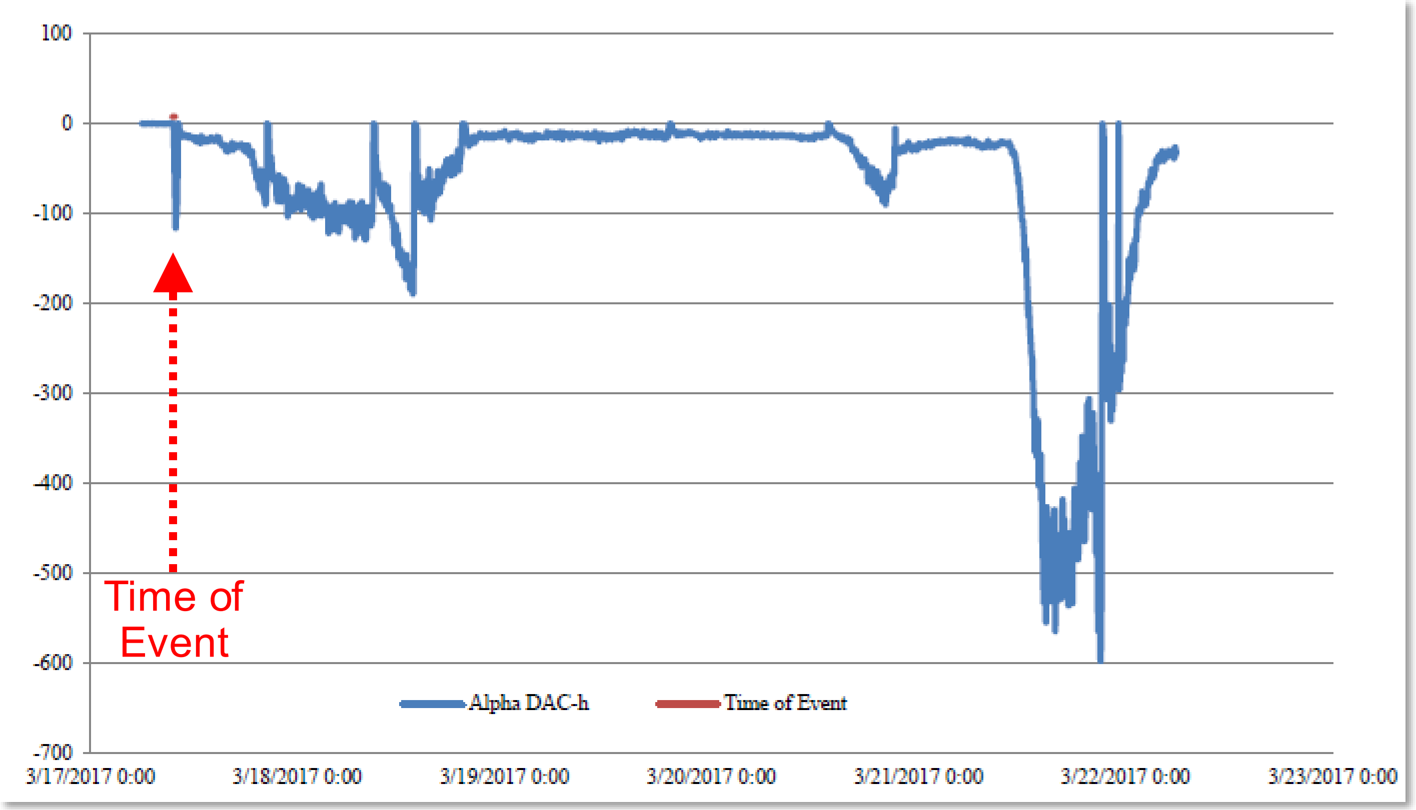
Readiness to Respond to an Ac-227 Event was Tested

- On March 17, 2017 an inspection and inventory of stored radioactive specimens was performed in a glovebox lab
- A lead pig containing two glass vials of Ac-227 in double plastic bags was opened for inspection
  - Note: Ac-227 in secular equilibrium with progeny (> 100 days)
- The plastic bag had deteriorated and Ac-227 contamination quickly spread on work surfaces, protective clothing, etc.
- The lab was evacuated and the iCAM did not alarm
- Personnel contamination detected on finger tips (4,729 dpm alpha) and hair (86,229 dpm/100cm^2 alpha and 129,500 dpm/100cm^2 beta)
  - Note: Contamination had diffused through 3 layers of gloves
- The event was reported to the Occurrence Reporting System:
  - SC-ORO—ORNL-X10NUCLEAR-2017-0002; 6D(3) - Identification of onsite personnel or clothing contamination… that exceeds 10 times the total contamination values identified in 10 CFR Part 835, Appendix D

The iCAM Displayed Negative DAC Values

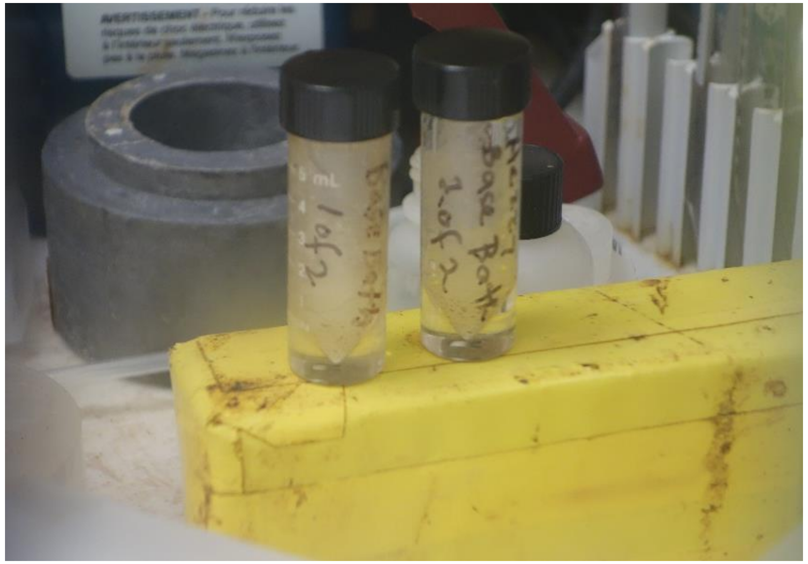
- Negative DAC values were an indication Rn-219 progeny
  - Needed to better understand airborne contamination before re-entry and recovery
  - iCAM data downloaded and filter paper retrieved
  - Th-227 and Ra-223 confirmed by alpha spectroscopy
- A long cable was used to connect a laptop to download archived spectrum data and monitor ongoing data without entering the lab

iCAM 1916 response March 17 through March 22, 2017

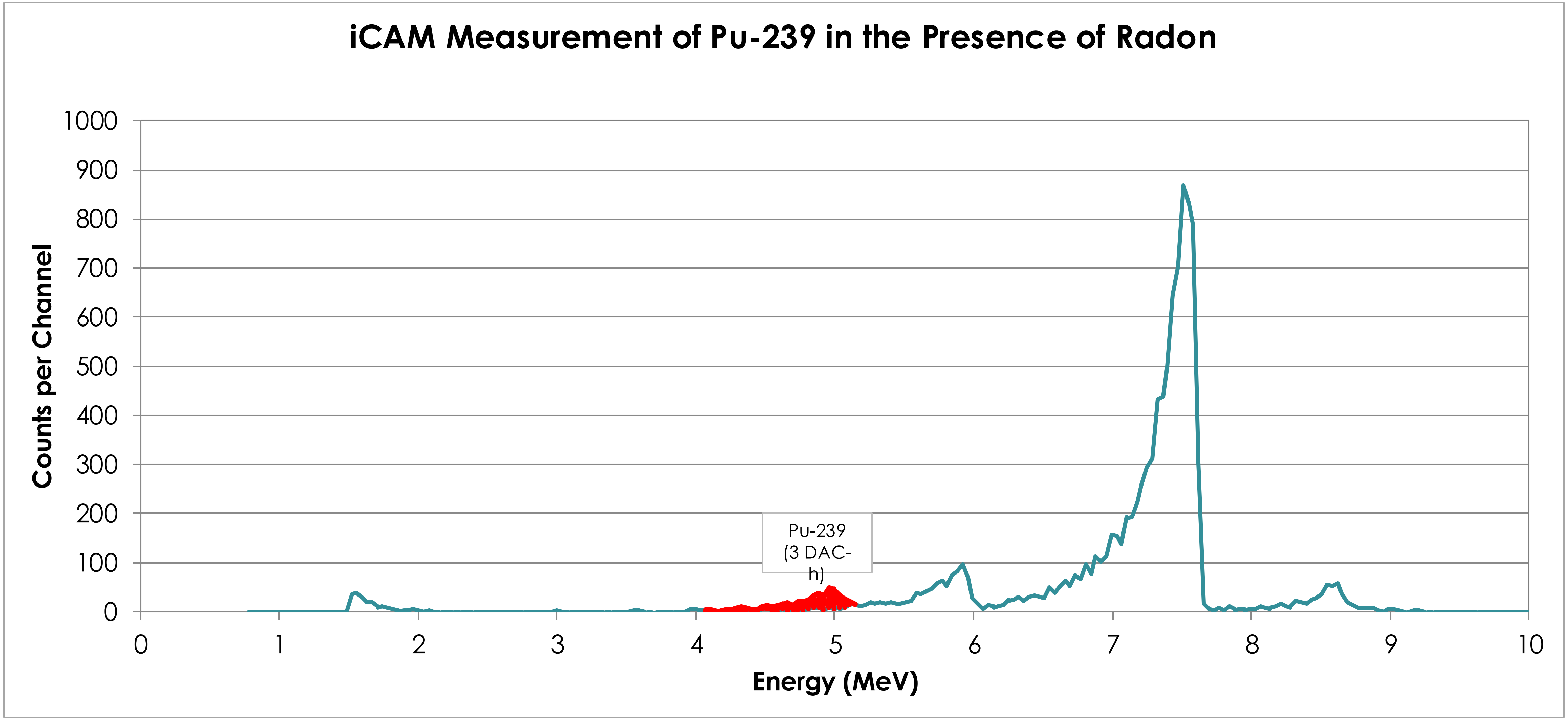


Internal Exposure Needed to be Evaluated

- Unclear whether the personnel contamination resulted from Ac-227 or Rn-219 progeny
  - Ac-227 is virtually nondetectable
  - Radioactivity from personnel decontamination was not preserved for analysis
- Neither respiratory protection or personal air sampling were used during the event;
  - Urine sampling performed
  - The Ac-227 specimens were verified to be in secular equilibrium and in a nitrate form which corresponds to a DAC value of 1 E-12 μCi/ml

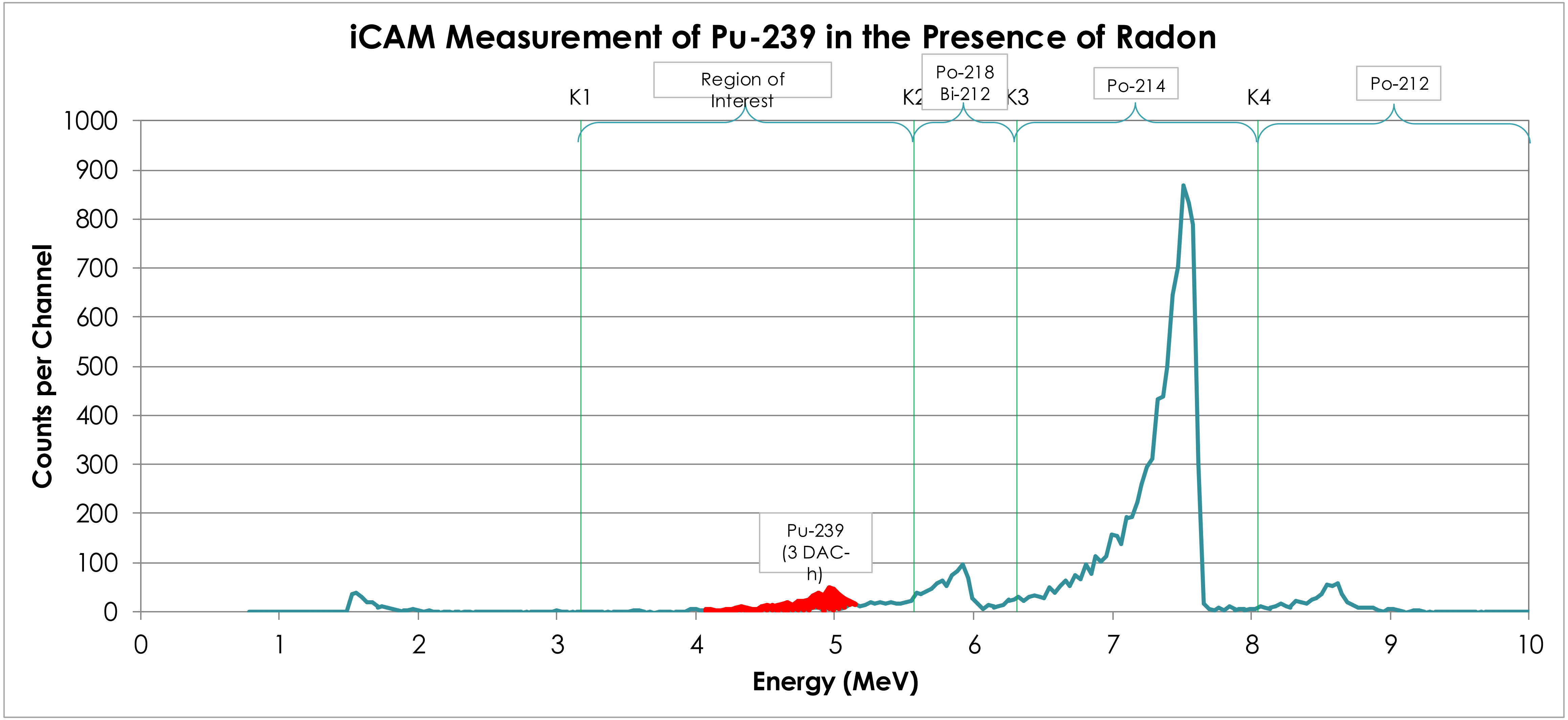


Measuring Plutonium in the Presence of Radon



Level 1 alarm = 3 DAC-h (~75 dpm for Pu-239)

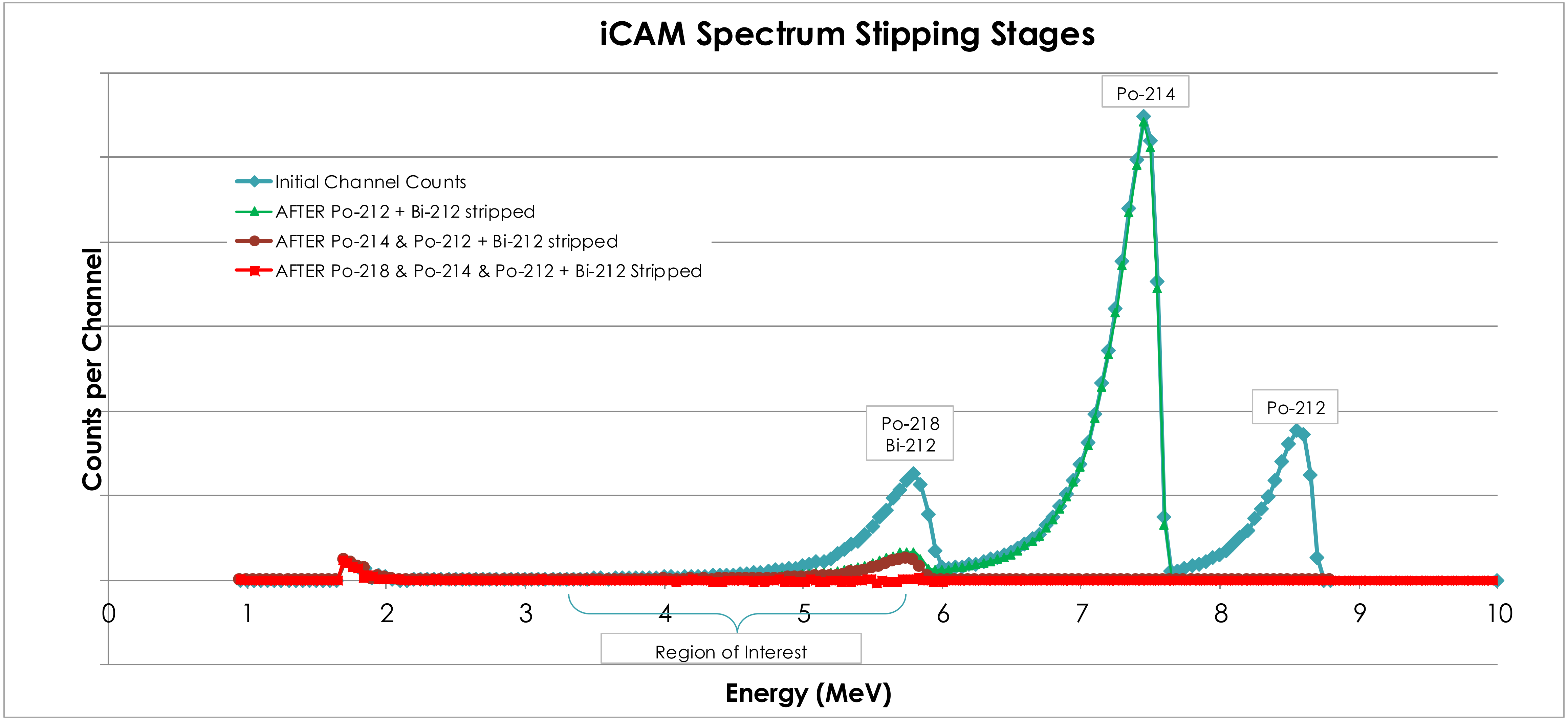
iCAM Compensation Regions



iCAM uses K-factors to define regions of interest for radon compensation

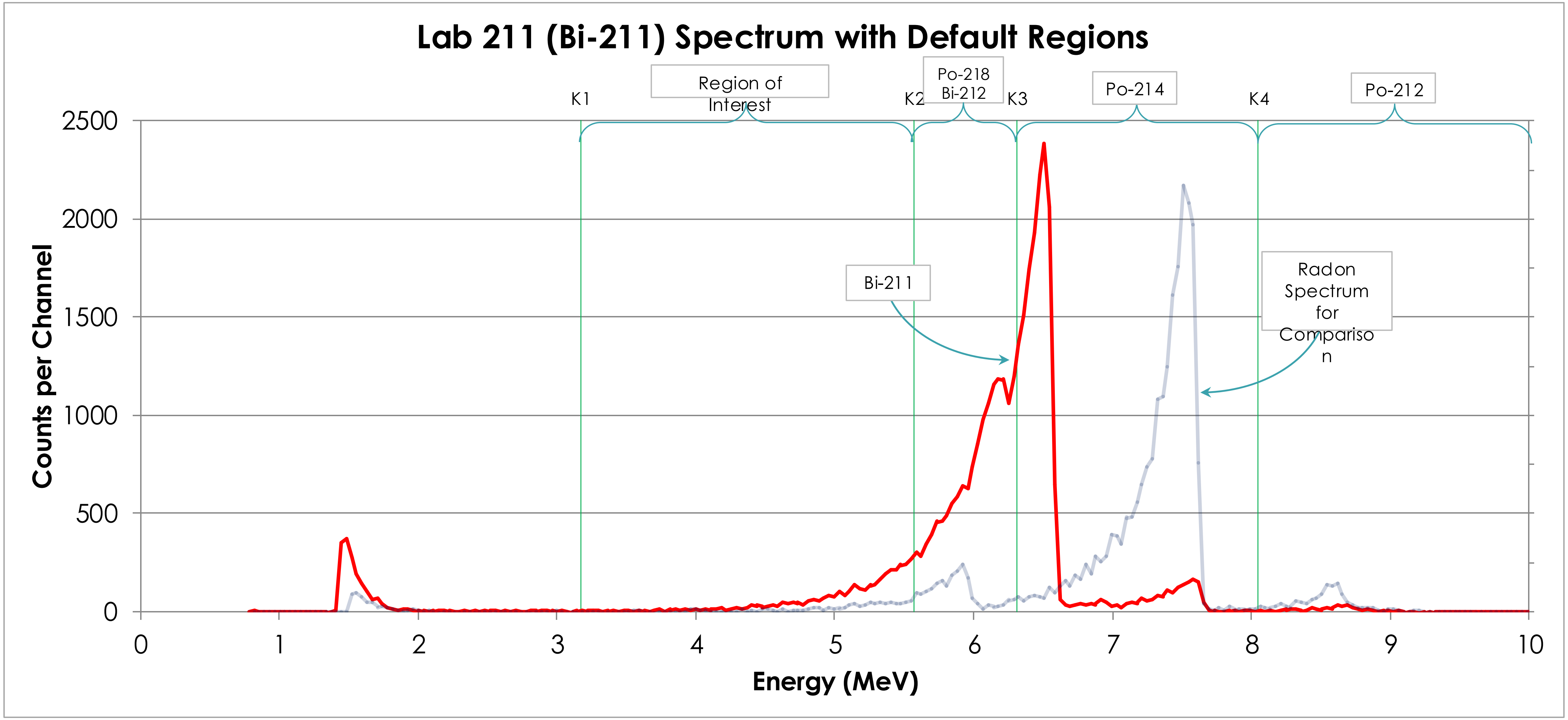
Measurement ROI ranges from 3.2 – 5.6 MeV

iCAM™ Radon Compensation



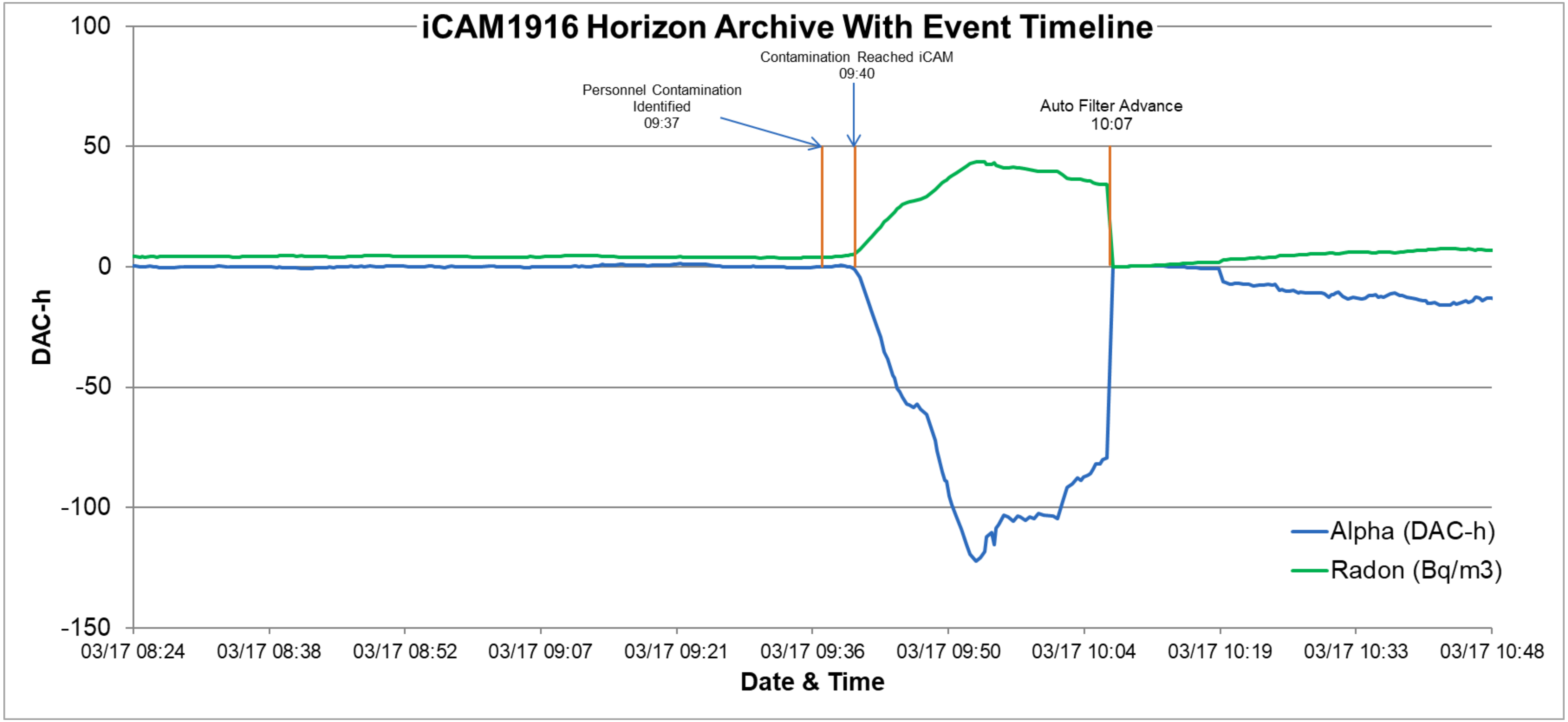
Canberra uses a three-stage stripping process

iCAM Spectrum Following Lab 211 Event



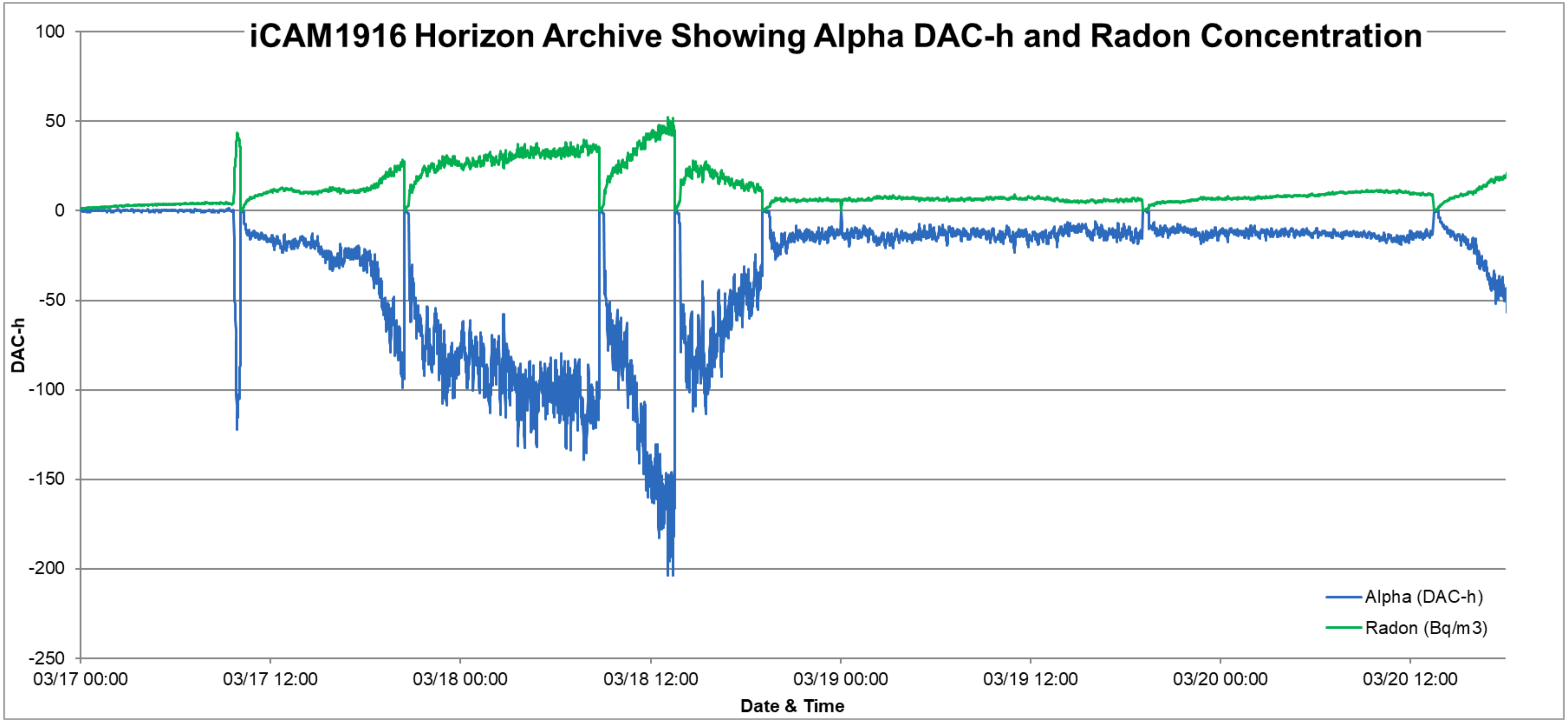
- Bi-211 peak(s) sit across compensation ROIs
- Unexpected Po-214 tail shape causes overcompensation

iCAM Response to Ac-227 Release



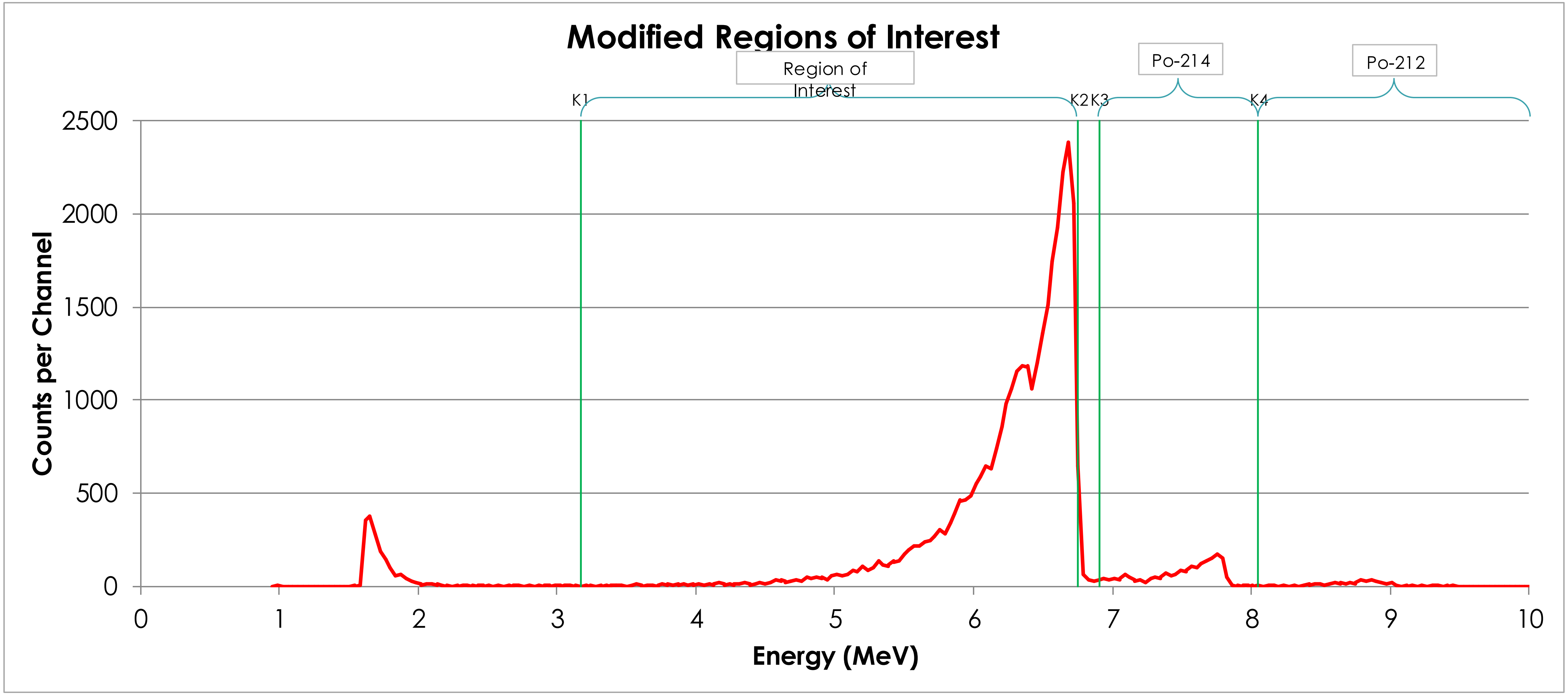
- March 17, 2017 Airborne release resulted in negative DAC-h display
- No alarm indications

Response Continued to Indicate the Presence of Ac-227



- Laboratory analysis confirmed Ac-227 on a single iCAM filter
- All subsequent filters indicated the presence of Bi-211 only

Proposed Solution – Modified Region of Interest



- Resulted in positive DAC-h for Ac-227 progeny
- Requires higher alarm set points to avoid false alarms
- Limited application to specific nuclides/energies

Summary

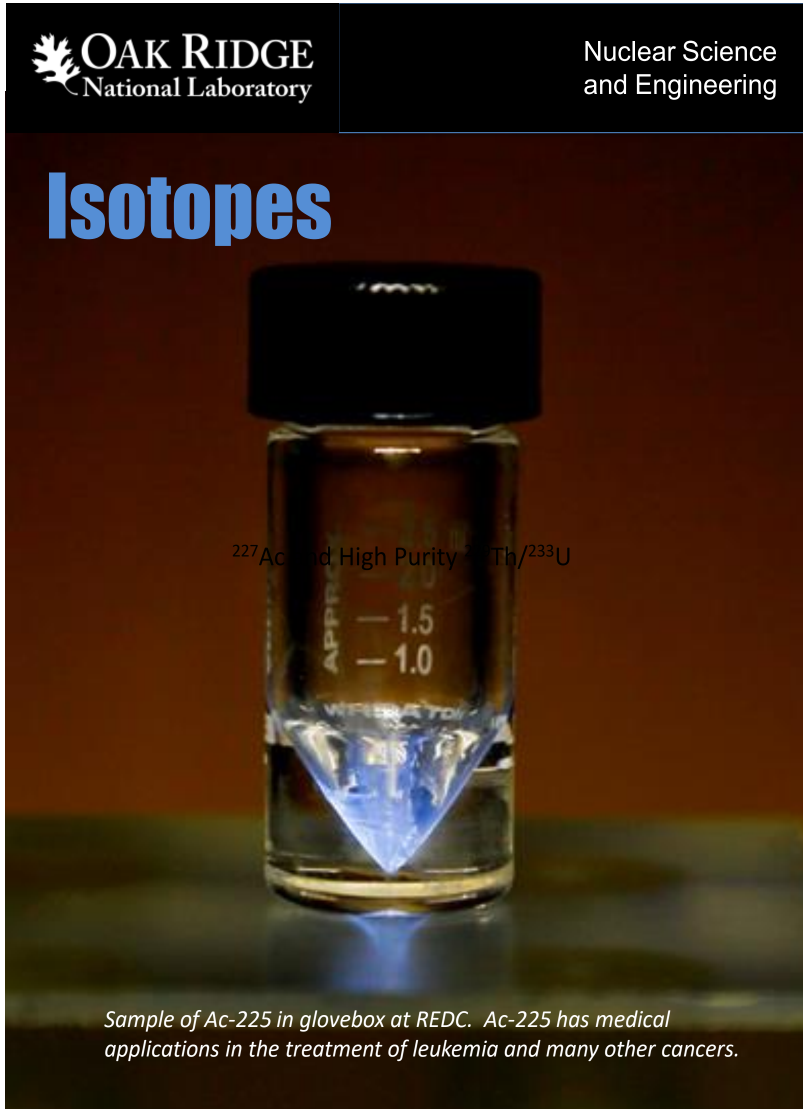
- The iCAM was designed to measure airborne alpha emitters with energies up to 5.6 MeV.
- When exposed to an alpha spectrum dominated by energies greater than 6 MeV, the iCAM's radon compensation algorithm can cause unexpected results.
- Modification of compensation regions can improve the response, but may only work for specific nuclides.
- The implementation of a negative activity alarm capability is the most promising solution for ORNL.

Other Potentially Problematic Nuclides

Parent / Decay Chain	Nuclide	$t_{1/2}$ (days)	$t_{1/2}$ (h)	$t_{1/2}$ (m)	Energy (KeV)	Notes
Ac-225	Ac-225	1.00E+01	2.40E+02	1.44E+04	5.83E+03	alpha energy is very close to Cm-244 energy (5.8 MeV)
	At-217	3.74E-07	8.97E-06	5.38E-04	7.07E+03	Ac-225 Progeny - 7 MeV alpha may interfere with Po-214 peak and radon discrimination algorithm
	Fr-221	3.33E-03	8.00E-02	4.80E+00	6.34E+03	Ac-225 Progeny - 6.3 MeV alpha may interfere with radon discrimination algorithm (Falls between Bi-212/Po-218 and Po-214 peaks)
	Po-213	4.86E-11	1.17E-09	7.00E-08	8.38E+03	Ac-225 Progeny - 8.4 MeV alpha may interefere with Po-212 Peak and radon discrimination algorithm
	Bi-213	3.17E-02	7.61E-01	4.56E+01	5.87E+03	Ac-225 Progeny Very low alpha decay yield - Energy close to Cm-244 alpha
At-211	At-211	3.01E-01	7.21E+00	4.33E+02	5.87E+03	alpha energy is very close to Cm-244 energy - May interfere with radon discrimination (decays to Bi-207 41.7% and Po-211 58.3%)
	Po-211	5.97E-06	1.43E-04	8.60E-03	7.45E+03	At-211 Progeny -(At-211 E.C.) 7.5 MeV alpha may interefere with Po-214 peak
Ac-227	Bi-211	1.48E-03	3.55E-02	2.13E+00	6.62E+03	Ac-227 Progeny - 6.6 MeV alpha intereferes with radon discrimination algorithm (Falls between Bi-212/Po-218 and Po-214 peaks)
	Po-211	5.97E-06	1.43E-04	8.60E-03	7.45E+03	Ac-227 Progeny -(Bi-211 beta decay) low branching probability
	Po-215	2.06E-08	4.94E-07	2.96E-05	7.39E+03	Ac-227 Progeny - 7.4 MeV alpha may interefere with radon discrimination algorithm (Bi-211 will be present with this nuclide)
Cf-248	Cf-248	3.34E+02	8.00E+03	4.80E+05	6.26E+03	6.3 MeV alpha may interefere with radon discrimination algorithm (Decays to Cm-244)
Cf-249	Cf-249	1.28E+05	3.07E+06	1.84E+08	5.81E+03	Primary alpha (84.4%) energy close to Cm-244 (5.8 MeV)
Cf-250	Cf-250	4.78E+03	1.15E+05	6.88E+06	6.03E+03	6 MeV alpha may interfere with Bi-212/Po-218 peak
Cf-252	Cf-252	9.64E+02	2.31E+04	1.39E+06	6.12E+03	6.1 MeV alpha may interfere with Bi-212/Po-218 peak
Cm-242	Cm-242	1.63E+02	3.92E+03	2.35E+05	6.11E+03	6.1 MeV alpha may interfere with Bi-212/Po-218 peak
Es-253	Es-253	2.05E+01	4.91E+02	2.95E+04	6.63E+03	6.6 MeV alpha may interefere with radon discrimination algorithm
Es-254	Es-254	2.76E+02	6.62E+03	3.97E+05	6.43E+03	6.5 MeV alpha may interefere with radon discrimination algorithm
Es-254m	Es-254m	1.64E+00	3.93E+01	2.36E+03	6.38E+03	Very low alpha decay yield - may interfere with radon discrimination algorithm - Beta Decays to Fm-254
	Fm-254	1.35E-01	3.24E+00	1.94E+02	7.19E+03	7.2 MeV alpha may interfere with Po-214 peak and radon discrimination algorithm
Es-255	Es-255	3.98E+01	9.55E+02	5.73E+04	6.30E+03	6.3 MeV alpha may interefere with radon discrimination algorithm
	Fm-255	8.36E-01	2.01E+01	1.20E+03	7.02E+03	7 MeV alpha may interfere with Po-214 peak and radon discrimination algorithm (Es-255 daughter)
Fm-256	Fm-256	1.09E-01	2.63E+00	1.58E+02	6.92E+03	6.9 MeV alpha may interfere with Po-214 peak and radon discrimination algorithm
U-230/Th-226	Th-226	2.15E-02	5.15E-01	3.09E+01	6.34E+03	6.3 MeV alpha may interfere with radon discrimination algorithm (Falls between Bi-212/Po-218 and Po-214 peaks) - also includes progeny that is in the U-238 decay chain (Ra-222, Rn-218, Po-214...)

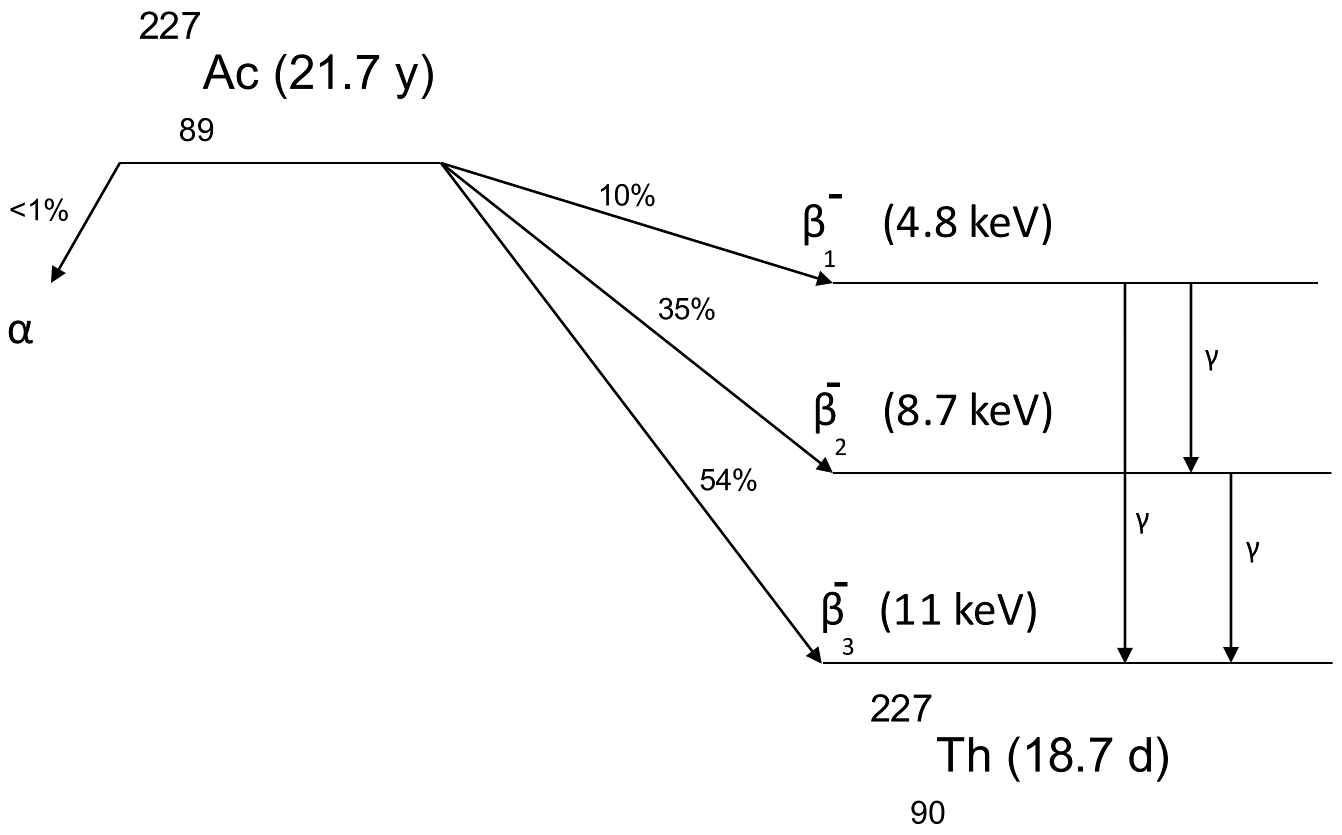
Radiobioassay for Ac-227 presented challenges

- ORNL produces Curie-level quantities of radioactive actinium to support research and clinical use.
- Bioassay methods for radioactive actinium are limited and it is difficult to demonstrate regulatory exposure limits.
- Primary exposure control and internal dose assessment is achieved using air monitoring.



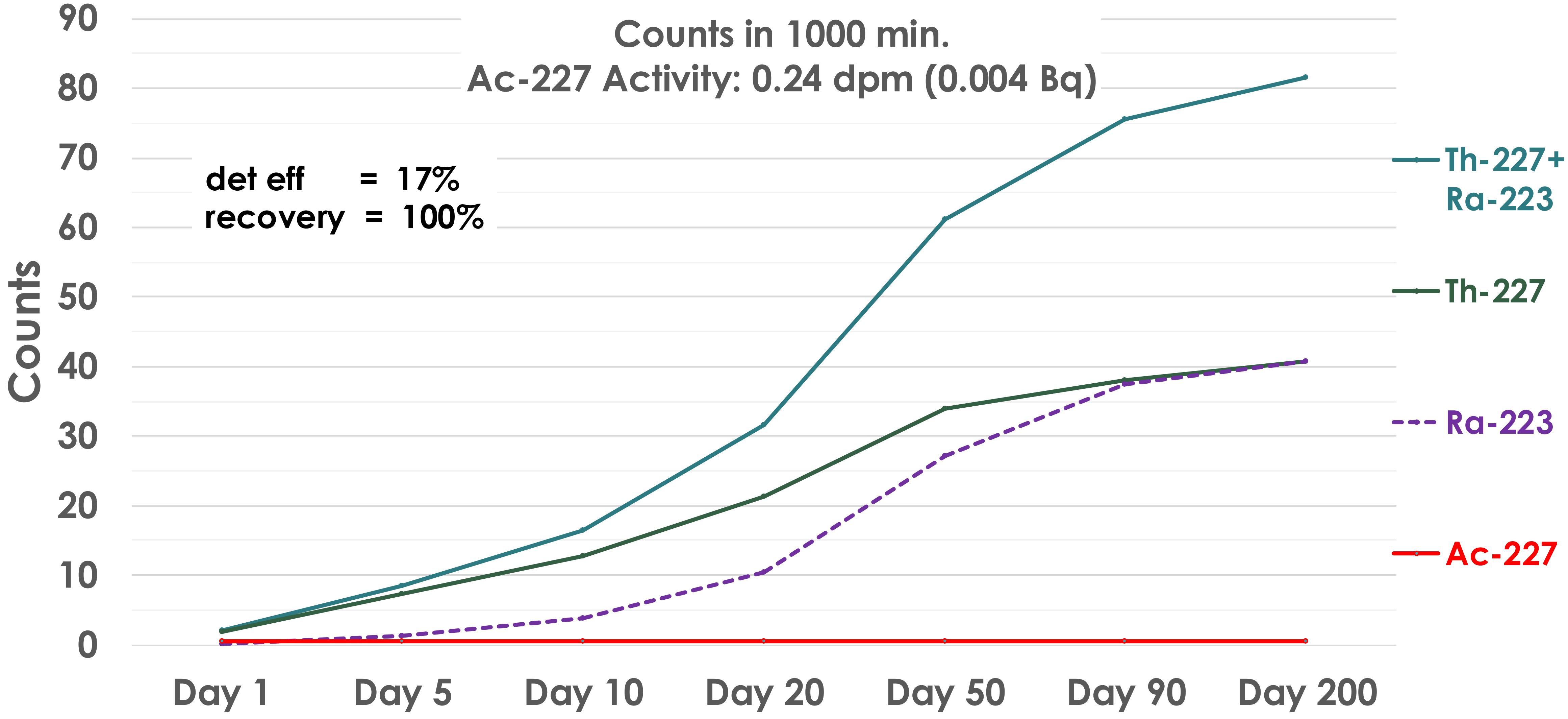
Sample of Ac-225 in glovebox at REDC. Ac-225 has medical applications in the treatment of leukemia and many other cancers.

Freshly separated ^{227}Ac is essentially invisible to measure



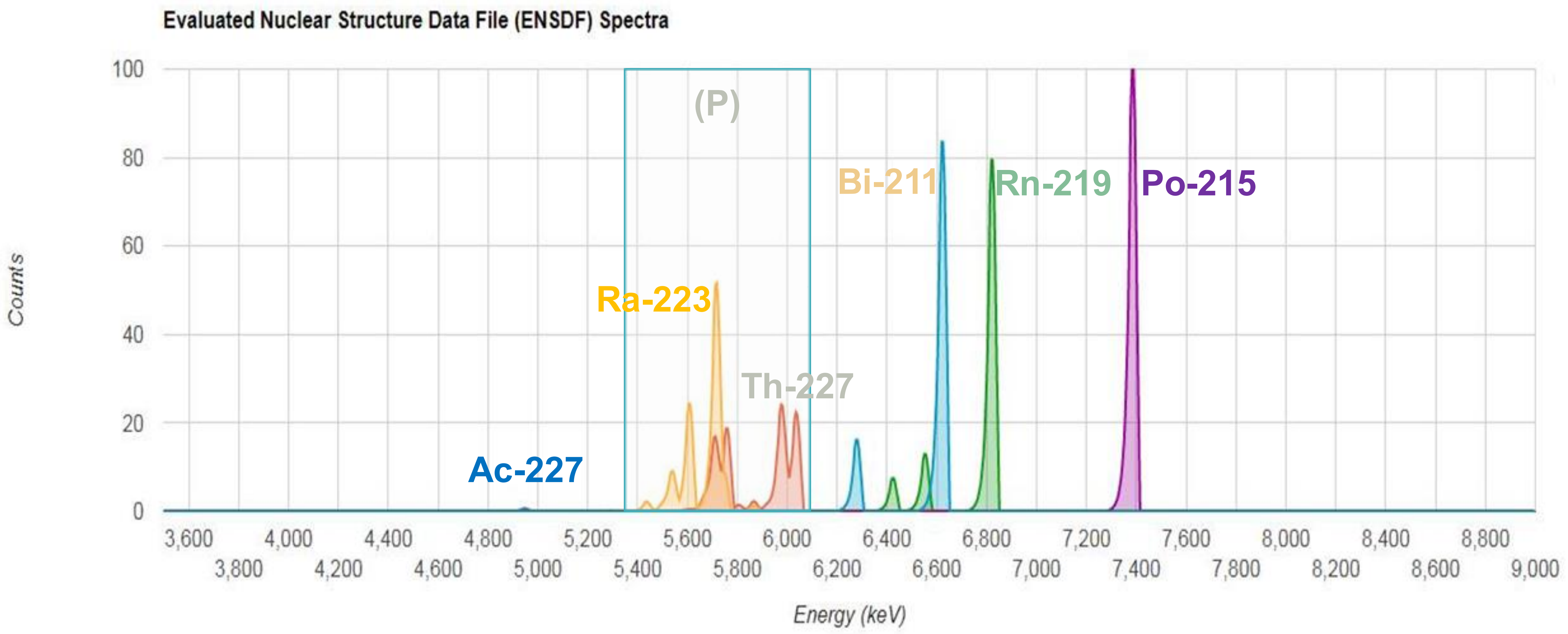
Average Beta Emission: 9.6 keV (99%)

Ingrowth of Th-227 and Ra-223



OAK RIDGE National Laboratory

Ac-227 and Progeny in Equilibrium, and Primary ROI (P)



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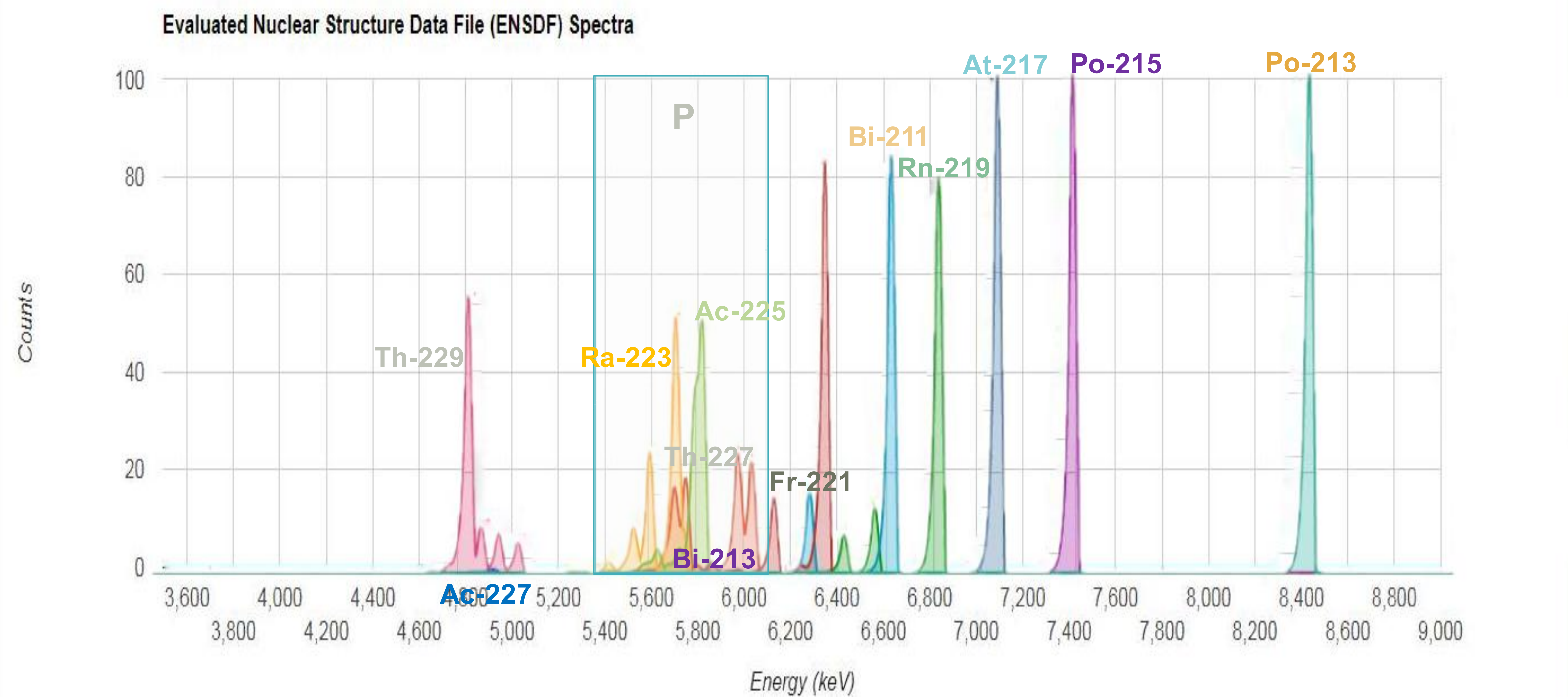
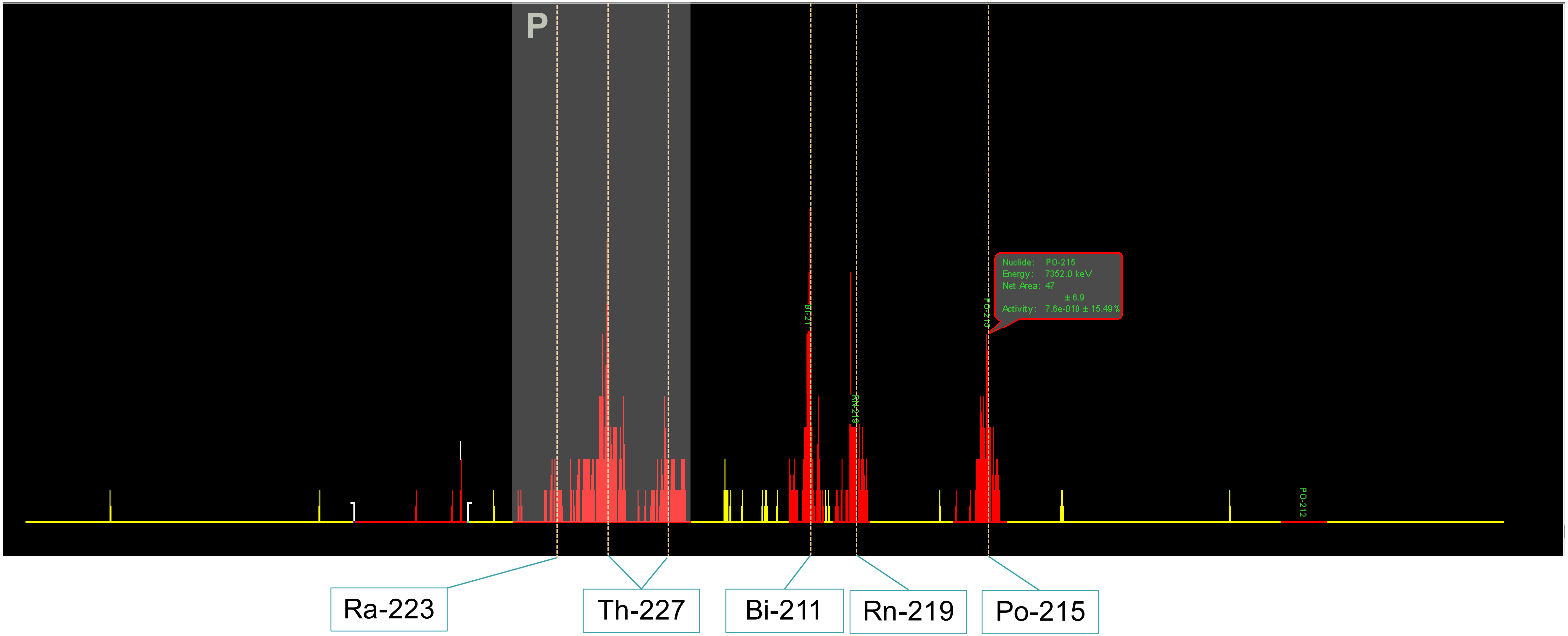
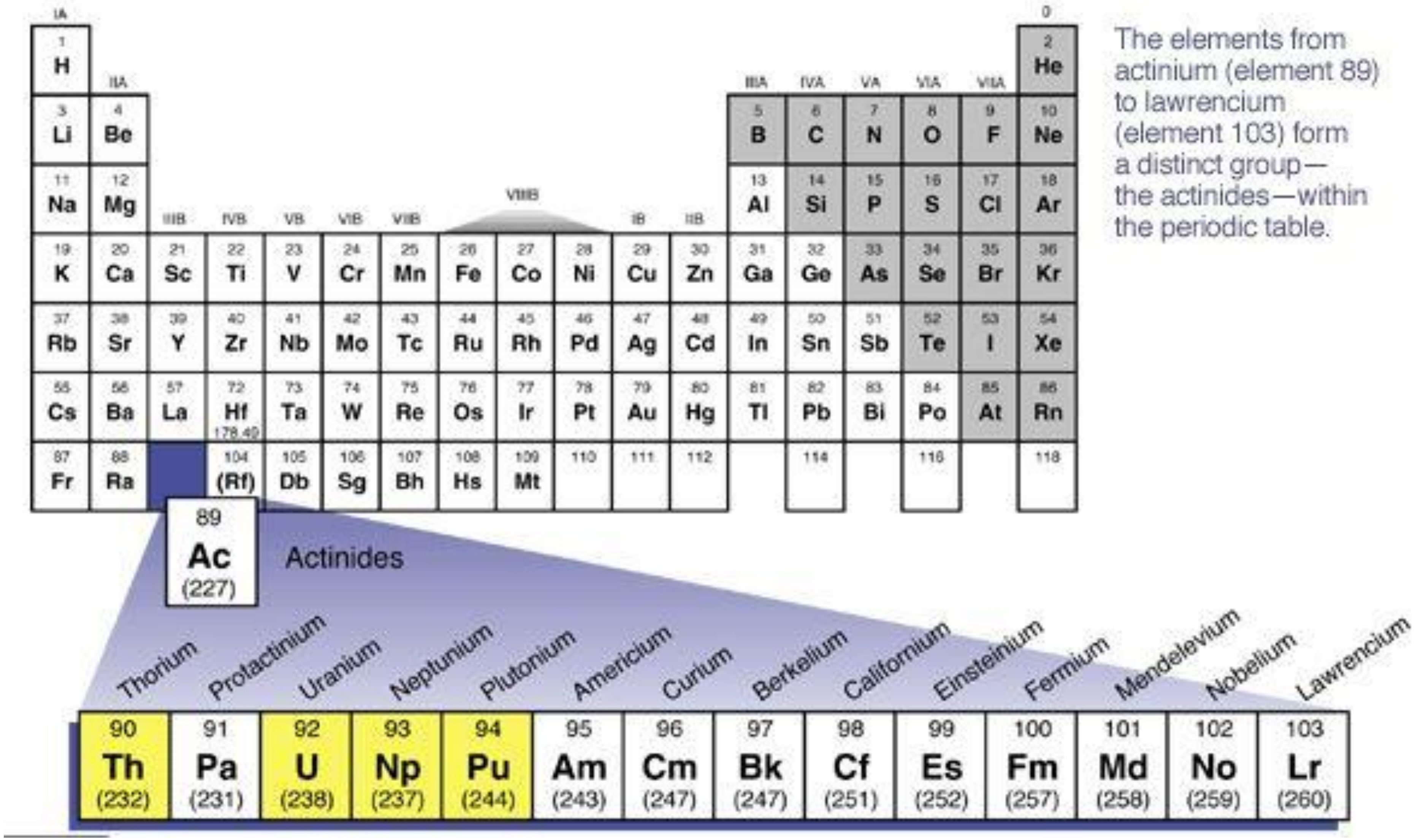
Ac-227, Th-229 and Progenies in Equilibrium

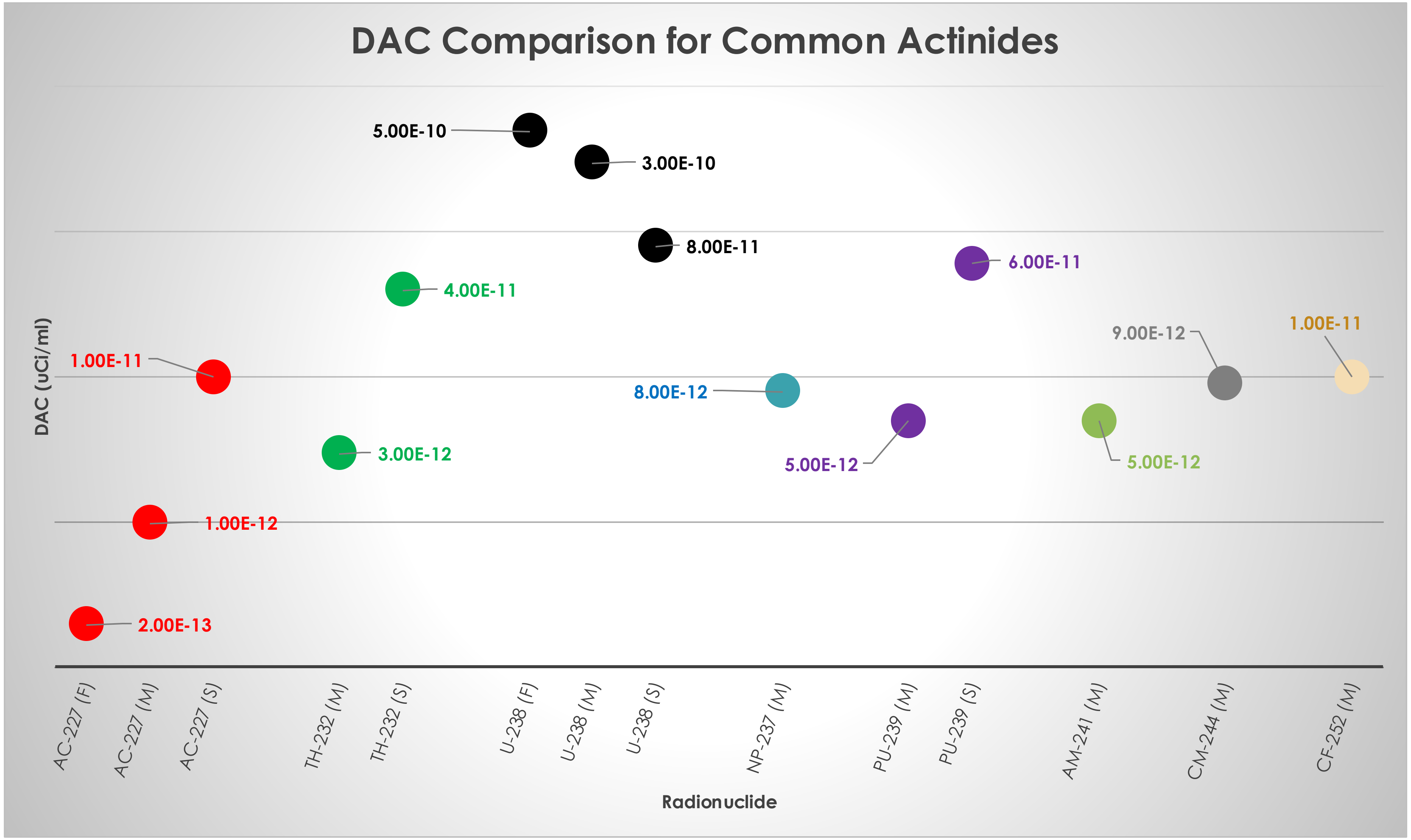


Direct Measurement – Ac-227 (0.004 Bq) in Equilibrium



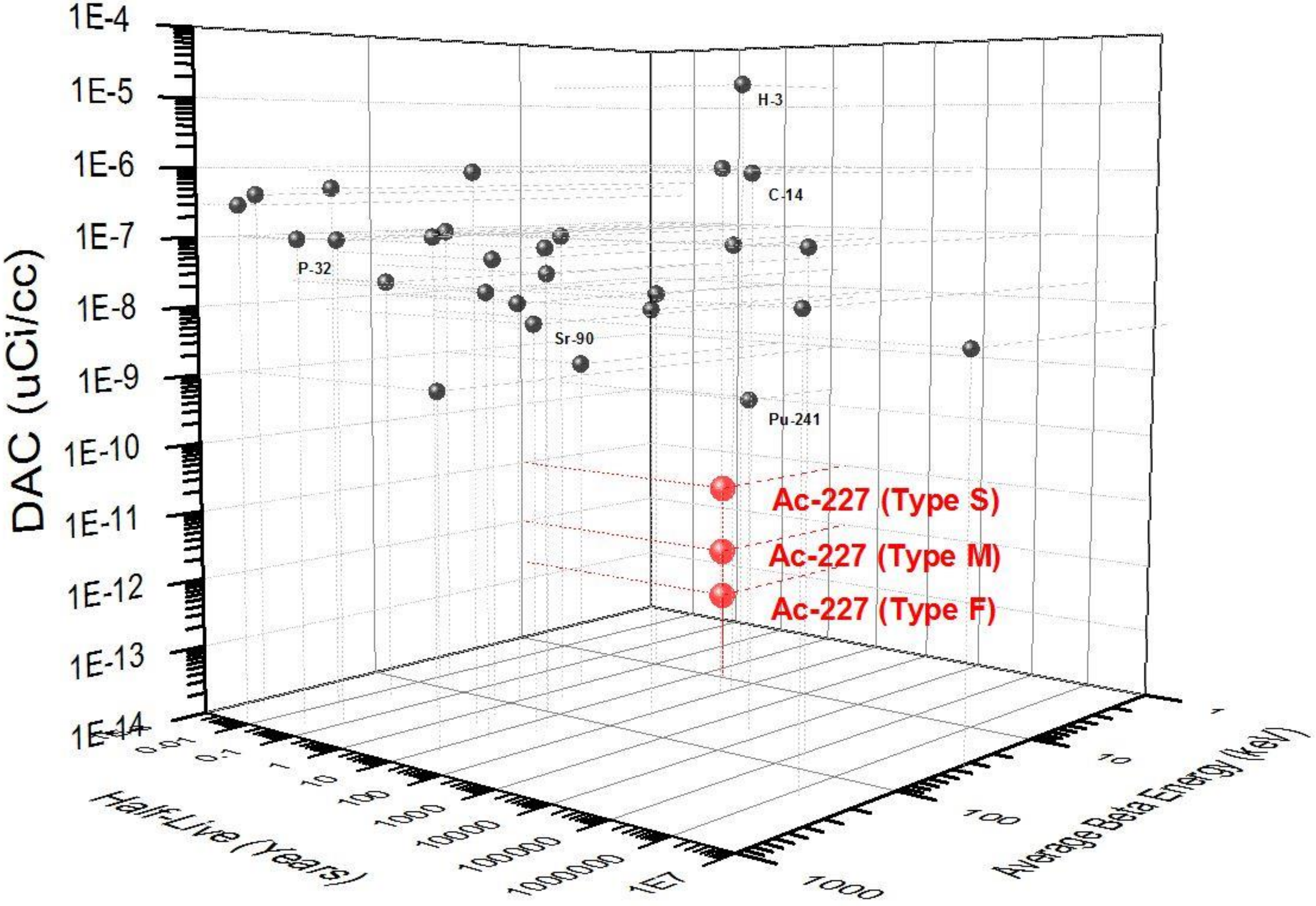


The elements from actinium (element 89) to lawrencium (element 103) form a distinct group—the actinides—within the periodic table.



DAC Comparison for Common Actinides
DAC (uCi/ml)
Radionuclide
5.00E-10
3.00E-10
8.00E-11
6.00E-11
4.00E-11
1.00E-11
9.00E-12
1.00E-11
8.00E-12
3.00E-12
5.00E-12
5.00E-12
1.00E-12
2.00E-13
AC-227 (F)
AC-227 (M)
AC-227 (S)
TH-232 (M)
TH-232 (S)
U-238 (F)
U-238 (M)
U-238 (S)
NP-237 (M)
PU-239 (M)
PU-239 (S)
AM-241 (M)
CM-244 (M)
CF-252 (M)

Ac-227 Derived Air Concentration Comparison



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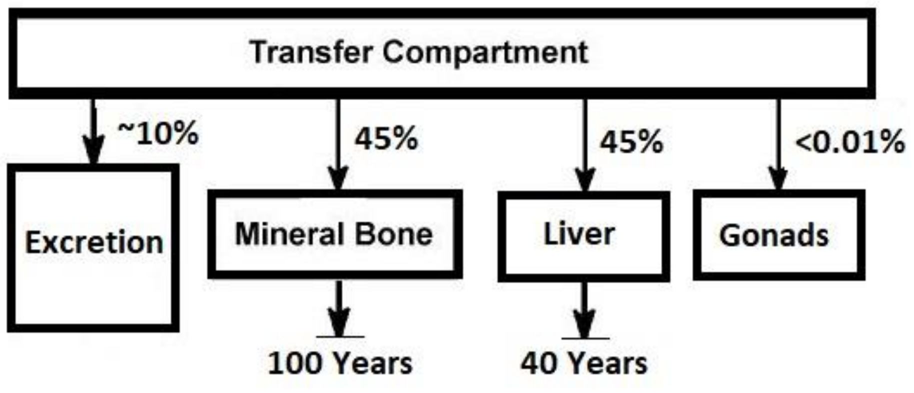
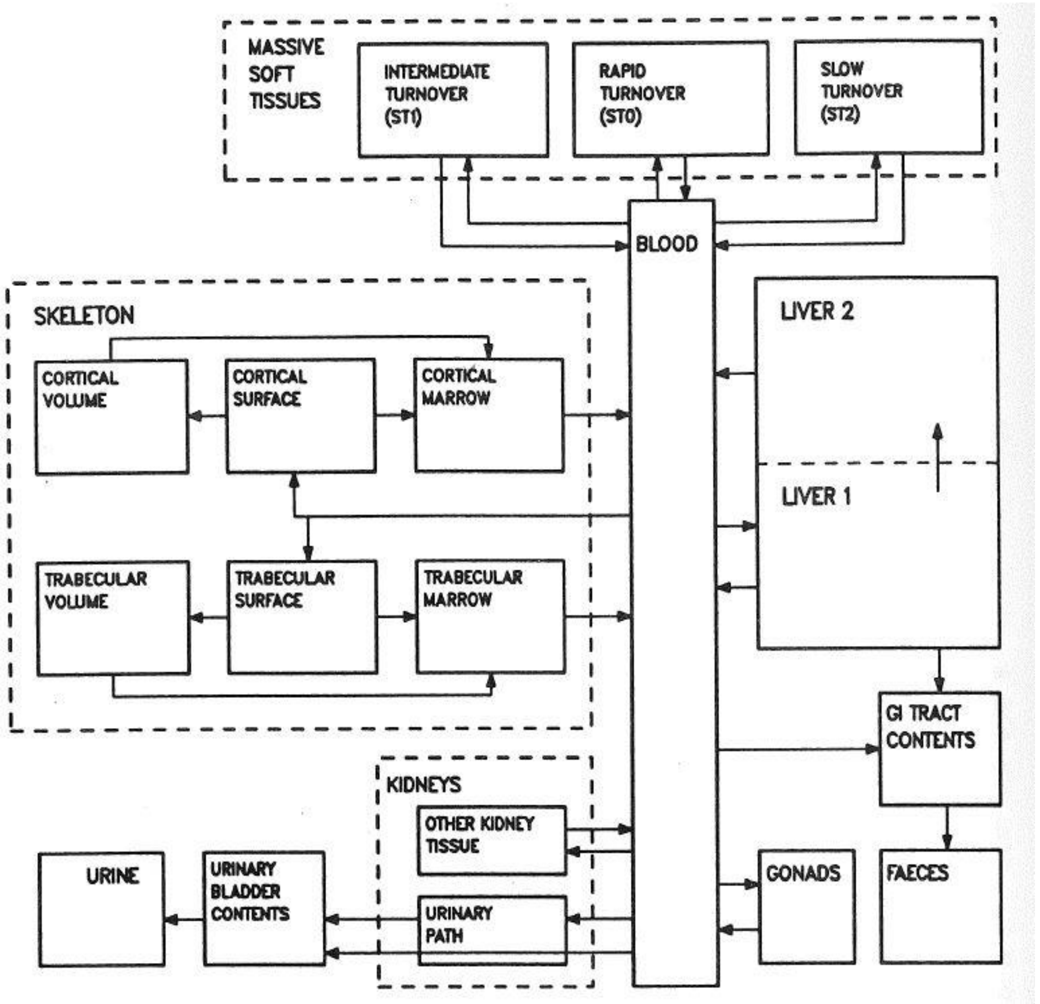
National Laboratory

Metabolic Modeling for Actinium



Current Regulatory Model

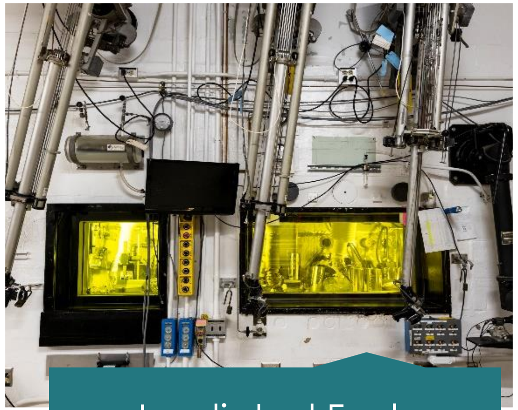


Proposed Update

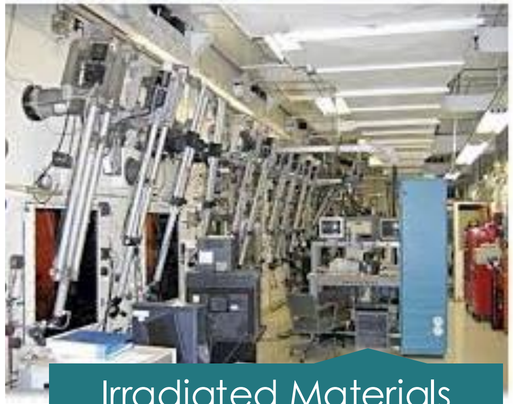
DOE approved our regulatory exemption request to increase DAC values using more advance biokinetic modeling)

Radionuclide	Absorption Type (µCi/ml)			Stochastic or Organ/Tissue
	F	M	S	(F/M/S)
Ac-224	**2E-08 (2x increase)**	**7E-09 (1.2x increase)**	**6E-09 (1.2x increase)**	ET/St/St
Ac-225	*2E-10*	*9E-11*	*8E-11*	BS/St/St
Ac-226	*1E-09*	*6E-10*	*5E-10*	ET/St/St
Ac-227	**1E-12 (5x increase)**	**4E-12 (4x increase)**	*1E-11*	BS/BS/St
Ac-228	**1E-08 (1.7x increase)**	**6E-08 (2x increase)**	*4E-08*	BS/BS/St

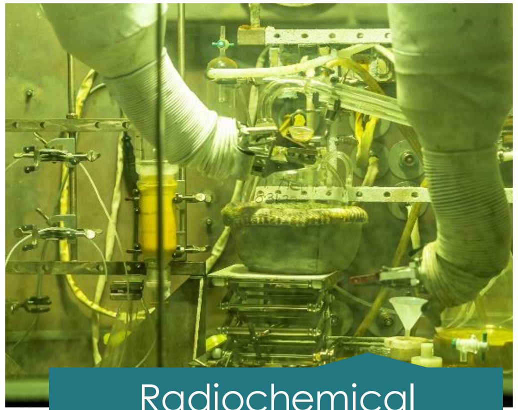
Oak Ridge National Laboratory



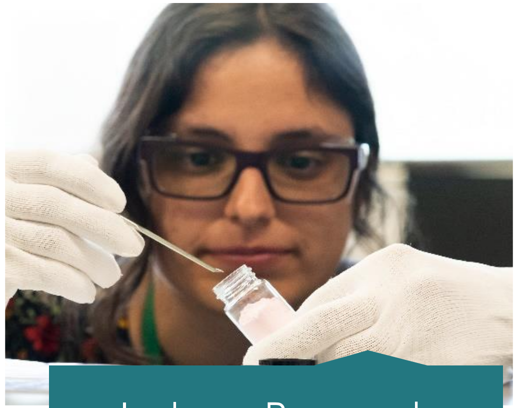
Irradiated Fuels Examination Laboratory



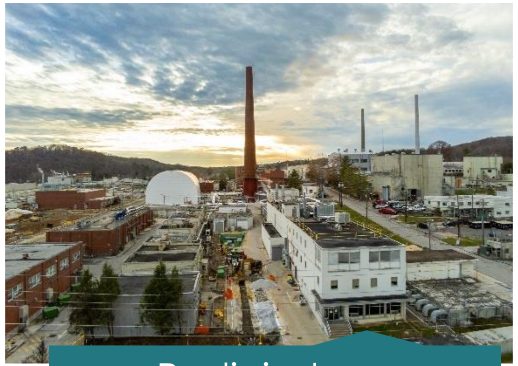
Irradiated Materials Examination and Testing Laboratory



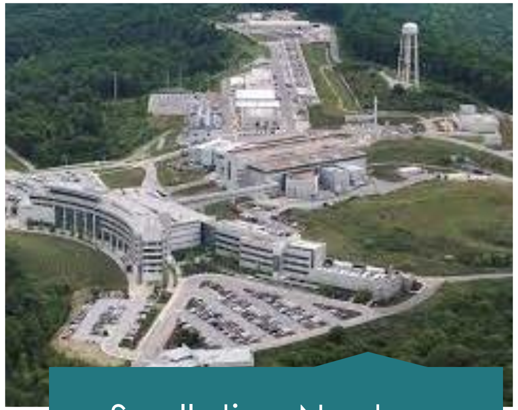
Radiochemical Engineering Development Center



Isotope Research Materials Laboratory



Radioisotope Development Laboratory



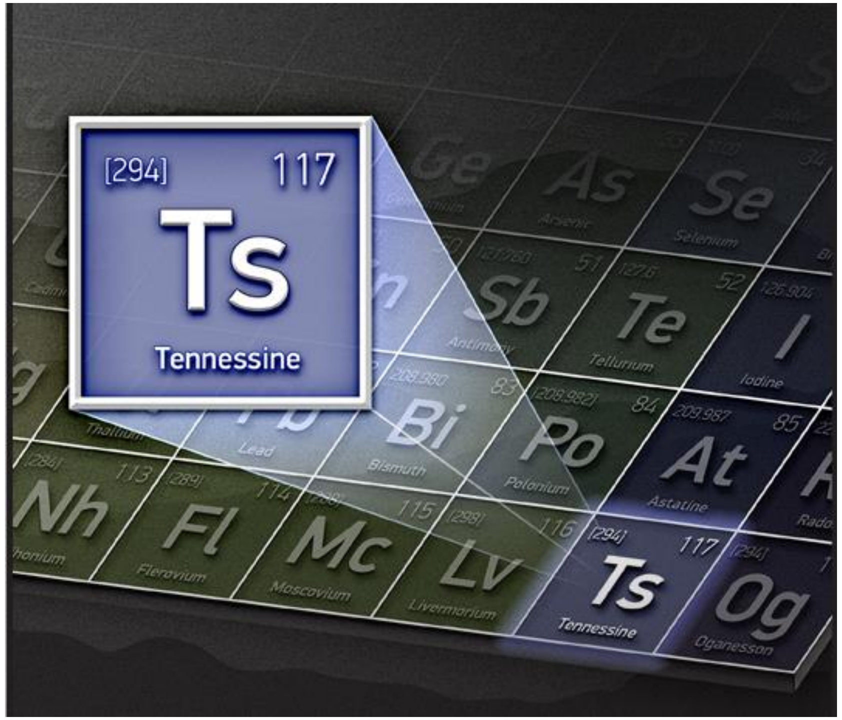
Spallation Neutron Source

High Flux Isotope Reactor

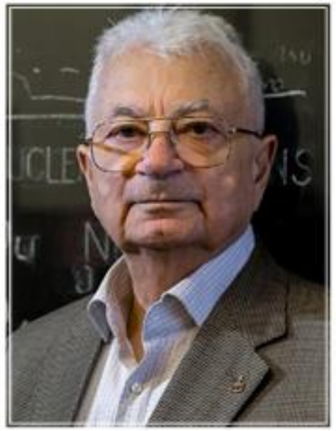
Radioisotope Processing Facility

Tennessee is one of two US states with an element namesake: Tennessine

- Produced by bombarding ^{249}Bk (T ½ 320 days) with an intense beam of ^{48}Ca for 150 days using the heavy ion accelerator at the Joint Institute for Nuclear Research in Dubna, Russia
- Berkelium is a byproduct of californium production at ORNL
  - Neutron capture of ^{248}Cm (“heavy curium”)
  - Produced through 250 days of irradiation at HFIR
- The idea came to fruition when californium production resumed at ORNL in 2008
  - Vanderbilt University physics professor Joe Hamilton introduced ORNL’s Jim Roberto to Russian physicist Yuri Oganessian
  - Pioneered the “hot fusion” approach to synthesize superheavy elements by bombarding actinide targets with heavy ions



Jim Roberto



Yuri Oganessian