OAK RIDGE National Laboratory

Production and Distribution of Isotopically Enriched and Radioactive Isotopes for Research

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ORNL Isotope Program

ORNL is managed by UT-Battelle, LLC for the US Department of Energy

U.S. DEPARTMENT OF ENERGY

Outline

- DOE Isotope Program Overview
- ORNL Isotope Program
- Stable Isotopes
  - Development of Isotope Enrichment Capabilities at ORNL
- Radioisotopes
  - Details on selected radioisotopes (mostly actinides)
- ^{225}Ac production and availability

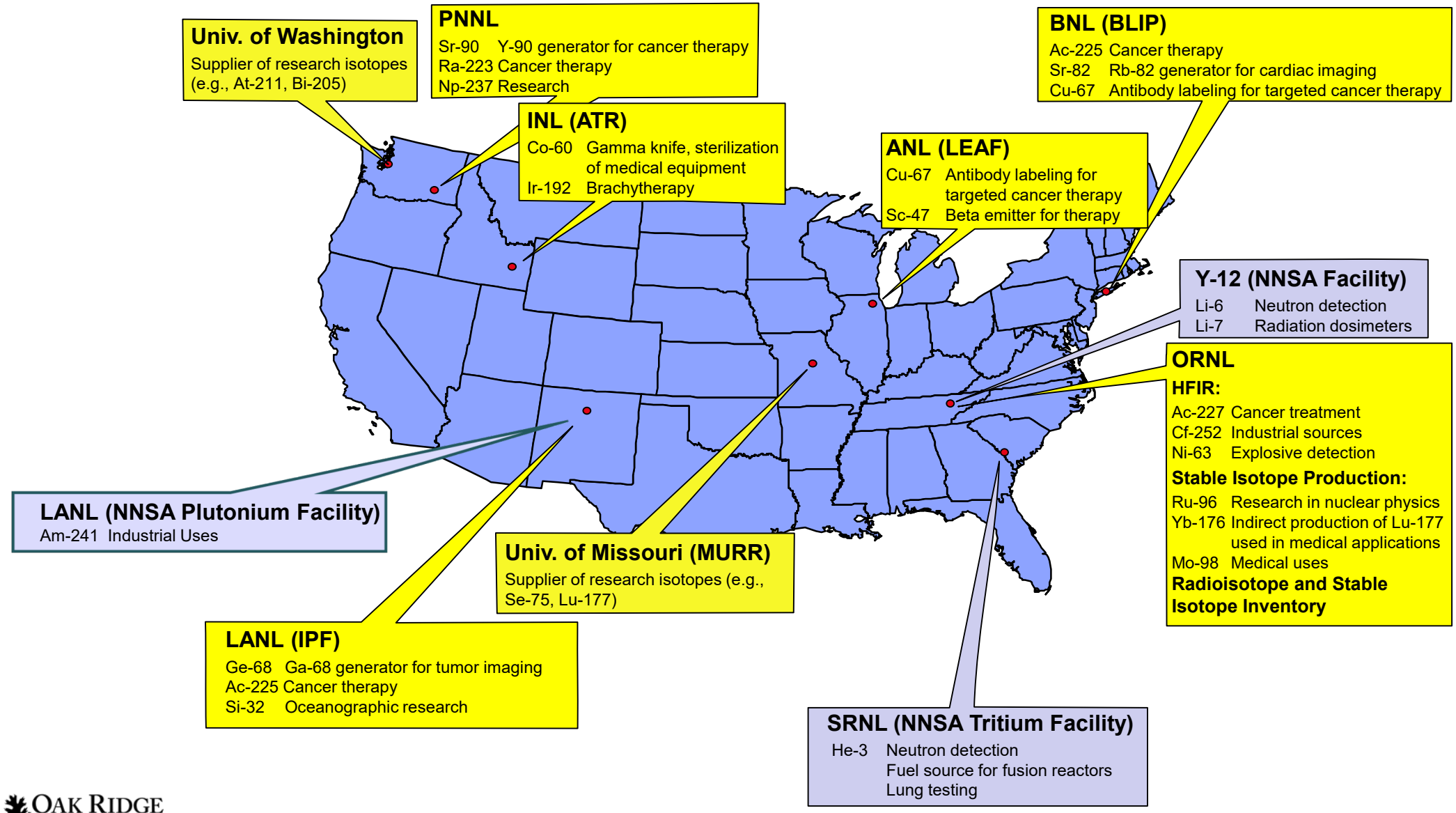
US Department of Energy Isotope Program

DOE Isotope Program Mission

- Produce and/or distribute priority enriched stable and radioactive isotopes, especially those that are in short supply
- Maintain the infrastructure required to produce and supply isotope products and related services
- Conduct R&D on new and improved isotope production and processing techniques which can make available new isotopes for research and applications

Managed by Office of Nuclear Physics (NP) in the DOE Office of Science

DOE Isotope Program Production Sites



ORNL Isotope Program

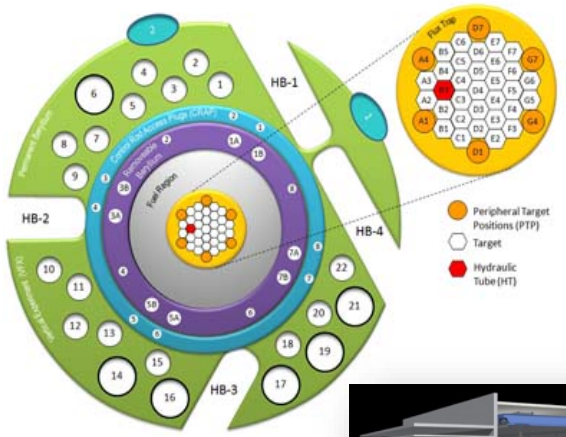
ORNL Isotope Program Mission

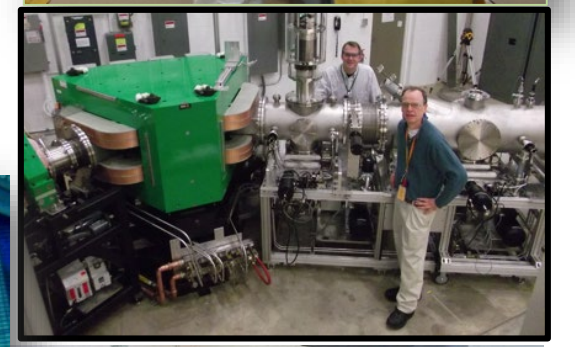
- Utilize unique resources at ORNL to meet the DOE need to produce and/or distribute **stable and radioactive isotopes** that are in short supply and conduct R&D to create new isotope products that are not currently available

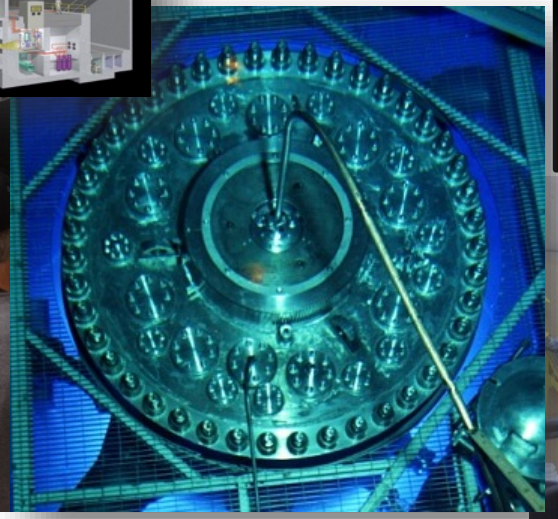
Enriched Stable Isotope Prototype Plant (ESIPP)

High Flux Isotope Reactor (HFIR)

Radiochemical Engineering Development Center (REDC)







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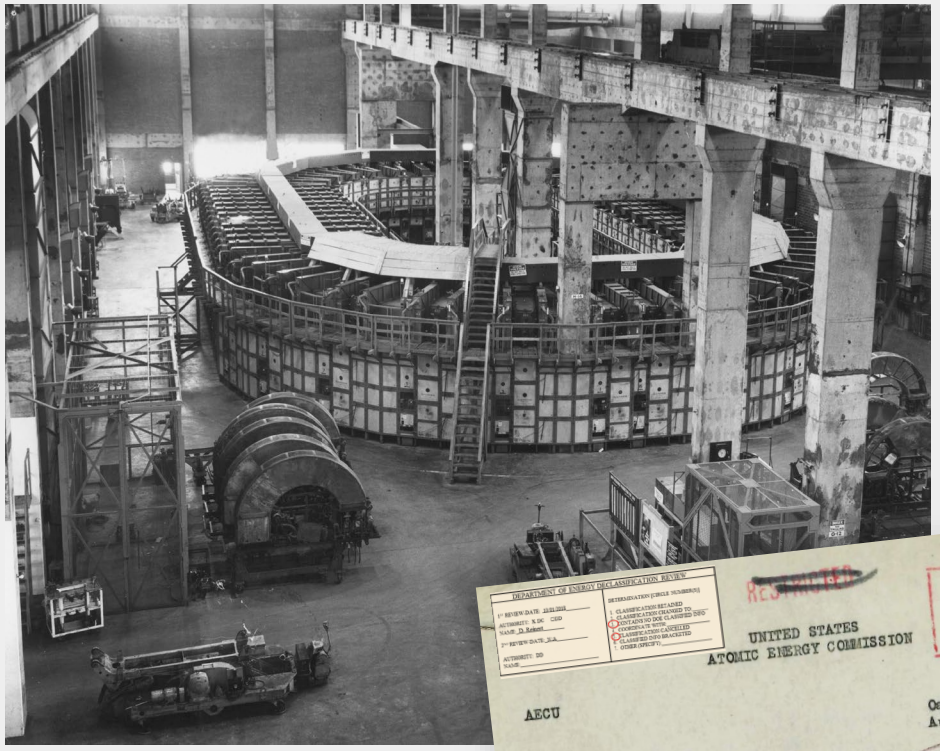
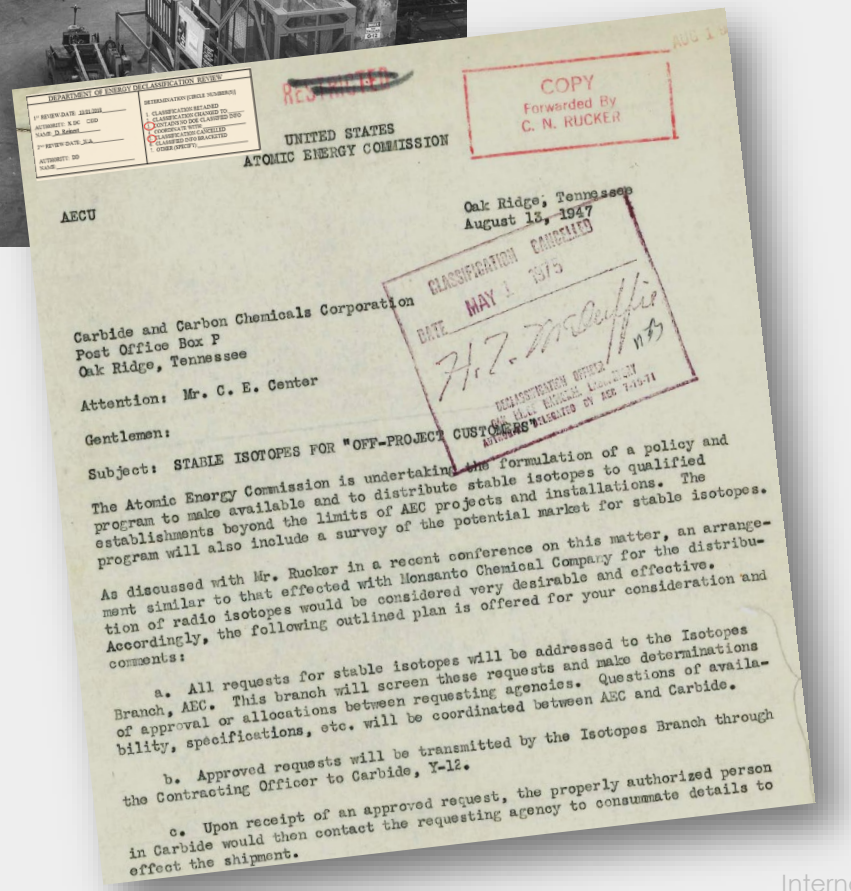
Isotope production, enrichment and distribution began at Oak Ridge in 1946





DEPARTMENT OF ENERGY DECLASSIFICATION REVIEW

RESTRICTED

COPY
Forwarded By
C. N. RUCKER

UNITED STATES
ATOMIC ENERGY COMMISSION

AECU

Oak Ridge, Tennessee
August 13, 1947

CLASSIFICATION CANCELLED
DATE MAY 1 1975

Carbide and Carbon Chemicals Corporation
Post Office Box P
Oak Ridge, Tennessee

Attention: Mr. C. E. Center

Gentlemen:

Subject: STABLE ISOTOPES FOR "OFF-PROJECT CUSTOMERS"

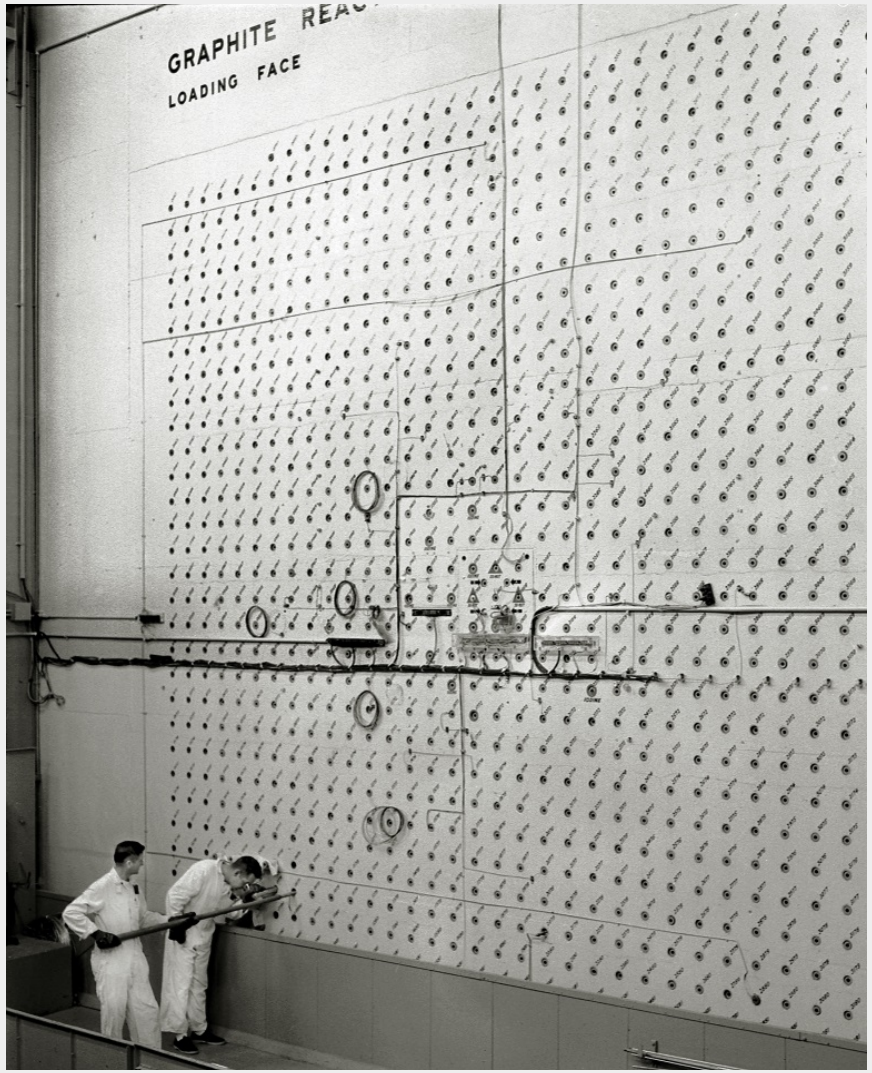
The Atomic Energy Commission is undertaking the formulation of a policy and program to make available and to distribute stable isotopes to qualified establishments beyond the limits of AEC projects and installations. The program will also include a survey of the potential market for stable isotopes.

As discussed with Mr. Rucker in a recent conference on this matter, an arrangement similar to that effected with Monsanto Chemical Company for the distribution of radio isotopes would be considered very desirable and effective. Accordingly, the following outlined plan is offered for your consideration and comments:

a. All requests for stable isotopes will be addressed to the Isotopes Branch, AEC. This branch will screen these requests and make determinations of approval or allocations between requesting agencies. Questions of availability, specifications, etc. will be coordinated between AEC and Carbide.

b. Approved requests will be transmitted by the Isotopes Branch through the Contracting Officer to Carbide, Y-12.

c. Upon receipt of an approved request, the properly authorized person in Carbide would then contact the requesting agency to consummate details to effect the shipment.



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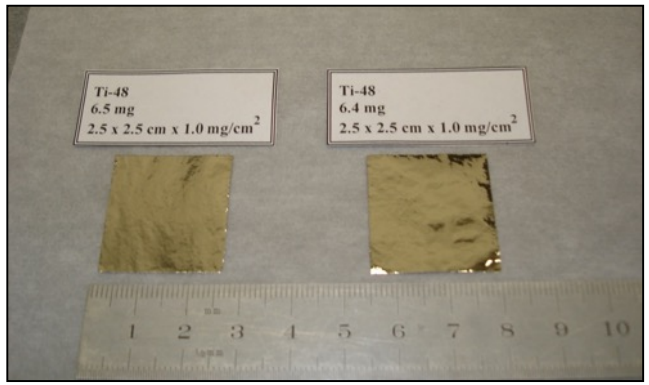
Stable Isotopes

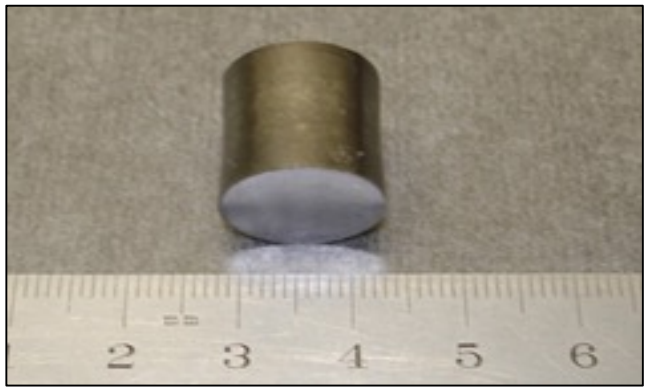
New Production in Enriched Stable Isotope Prototype Plant (ESIPP)

- Electromagnetic Isotope Separator (EMIS)
- Gas Centrifuge Isotope Separator (GCIS)Cascade

US DOE Inventory Stewardship & Dispensing

Technical Services





Electromagnetic Isotope Separator (EMIS)

EMIS Performance Metrics

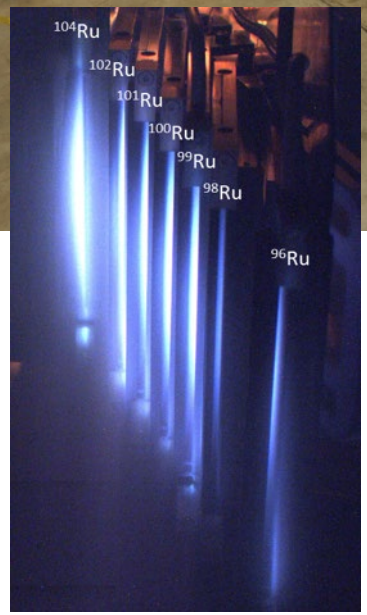
- **High ion current (throughput)**

Ion Beam Element	# of Naturally Occurring Isotopes	Total Ion Current, mA
Ar	3	93
Mo	7	30
Ru	7	6.5

Previously reported ion current for Ar using commercial Freeman ion source was 11 mA (***Egle, INTDS 2012, Mainz, Germany***)

- **High enrichment per pass (isotopic purity)**

Isotope	Enrichment Product Assay, %	Beam Stats
^{102}Ru	99.2	1.35 mA (ave.), 1000 hours
^{58}Ni	99.9	6.4 mA (ave.)



Non-Ambipolar Electron Driven Ion Source (NEDIS)

NEDIS Metrics

- **Greatly improved mean-time-between-maintenance**
  - MTBM (600+ hours)
  - Prior commercial Freeman ion source was ca. 10 hours
- **Much higher electron current obtained per W of rf power and sccm gas load** (see table at right)
- **Potential for higher ion current (throughput)**
  - 200+ mA of Ar ion current potentially available based on plasma density measurements
- **Direct evaporation of refractory metals using solid targets**

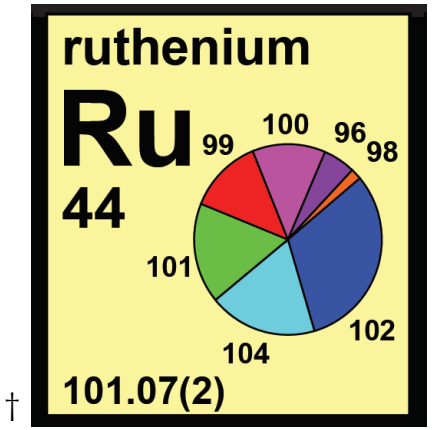
Electron Current (A)	Rf Power (W)	Gas Flow (sccm)
20+	<1000	8
10	500	5

High ion beam stability and repeatability achieved for Ru and other elements

- **24/7 reliable operation for 46 continuous days, averaging 17 hours of collection per day**
- **Some elements such as Ru require daily maintenance to clean high voltage insulators but typically this is not required for most elements**

Ru-96

- Applications [1]
  - Fundamental nuclear physics experiments at Relativistic Heavy Ion Collider at Brookhaven National Laboratory using Zr-96 and Ru-96
  - "chiral magnetic effect"
  - First proof of "anomalous electric currents in QCD matter"
- No global source for Ru-96
  - 6.1 grams of total Ru and 371 milligrams of Ru-96 collected in 1646 hours at ESIPP
  - Remainder of 500 mg produced by purification of some reserve inventory material
- Challenges
  - Volatilizing Ru and plasma chemistry



†

Isotope	Natural Abundance, %
96	5.54
98	1.87
99	12.76
100	12.60
101	17.06
102	31.55
104	18.62

††

[1] Berndt Mueller, RHIC Bulletin, January, 2018; H. Huang, et. al, "Operation of RHIC Injectors with Isobaric Ruthenium and Zirconium Ions", 9th International Particle Accelerator Conference, IPAC 2018, Vancouver, BC, Canada

Sources: † IUPAC Periodic Table of the Isotopes; †† IAEA data

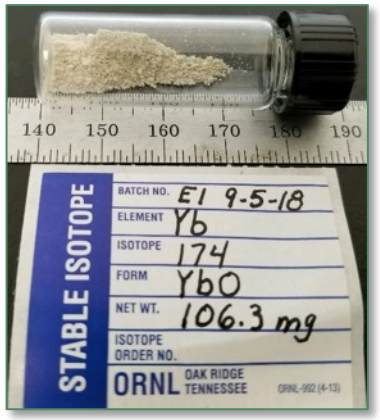
First Successful New EMIS Production Since 2009

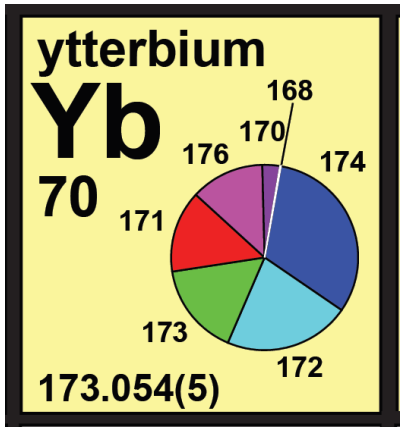
Front Row: Jay Pruitt, Kevin Hart, Joe Tracy, Brian Egle, Brian Ticknor, Cole Hexel, Jack McCollister, Claude Sampson
Back Row: David Dean, Bobby Whitus, Adam Stevenson, Derek Byrd, Gerald Mills, Alan Tatum, Clint Ausmus, Mike Zach

DOE Office of Science Appreciation Award, April 2018

Yb-176

- Applications
  - Target for indirect production of Lu-177
- US has some inventory but additional source of material is needed
- Preliminary production R&D has begun
- Challenges
  - Higher mass requires higher resolution to separate adjacent isotopes
  - Target material requires very high assay (99%+)





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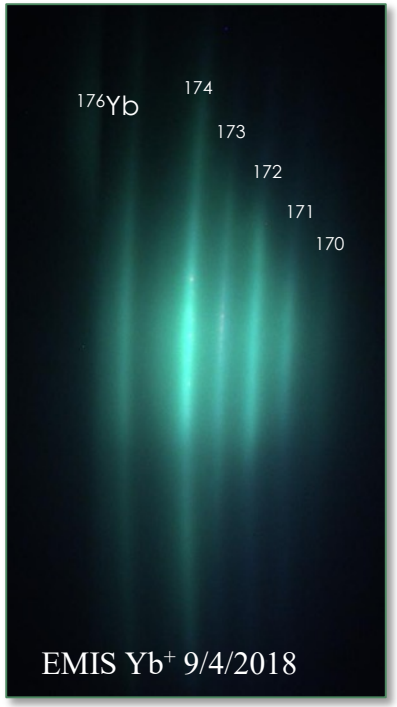


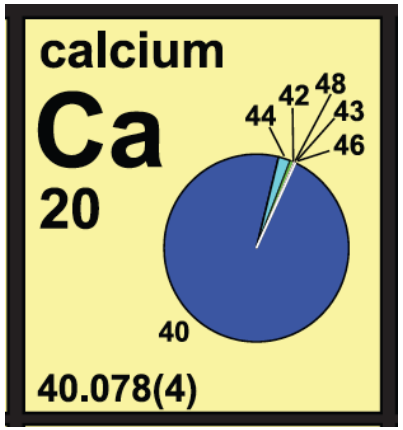
Isotope	Natural Abundance, %
168	0.123
170	2.982
171	14.09
172	21.68
173	16.103
174	32.026
176	12.996

††

Sources: † IUPAC Periodic Table of the Isotopes; †† IAEA data

Ca-48

- Applications
  - Production of Super Heavy Elements
  - Lightest nucleus to undergo neutrinoless double beta decay
- US has some inventory but the need for additional production is being considered
- Challenges
  - 20% mass difference between low and high mass isotope
  - Extremely low natural abundance of the main isotope of interest, ^{48}Ca



†

Isotope	Natural Abundance, %
40	96.94
42	0.647
43	0.135
44	2.09
46	0.004
48	0.187

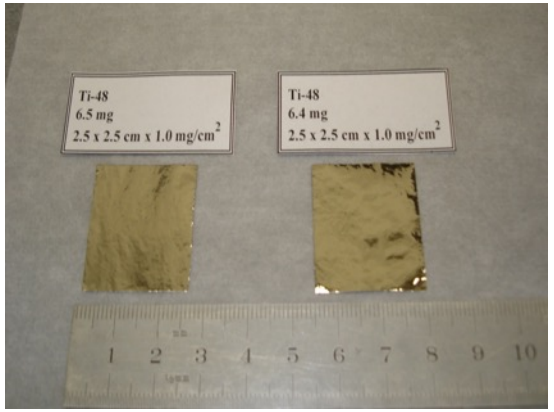
††

Sources: † IUPAC Periodic Table of the Isotopes; †† IAEA data

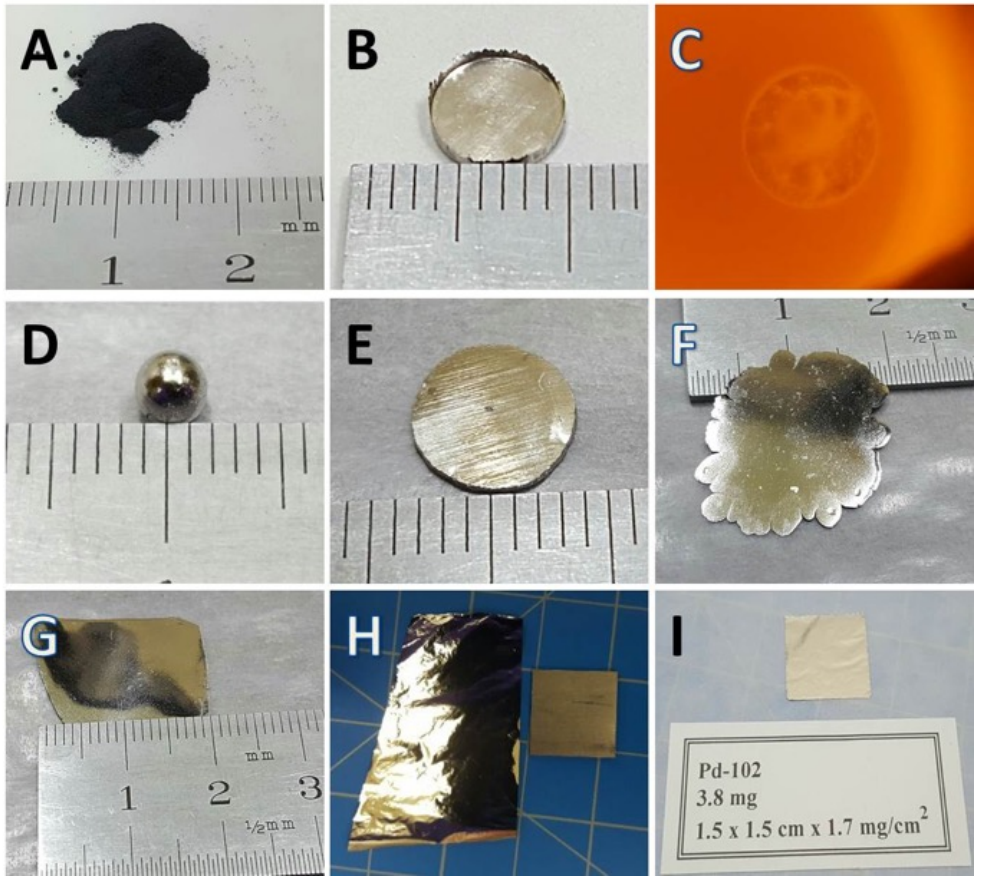
Distribution and Technical Services

- DOE Stable Isotope Inventory Management
- Dispensing
- Reserve Inventory Processing
- Custom Chemical and Physical Form Preparation

Ni-62 pellets (>45 g) for irradiation to Ni-63



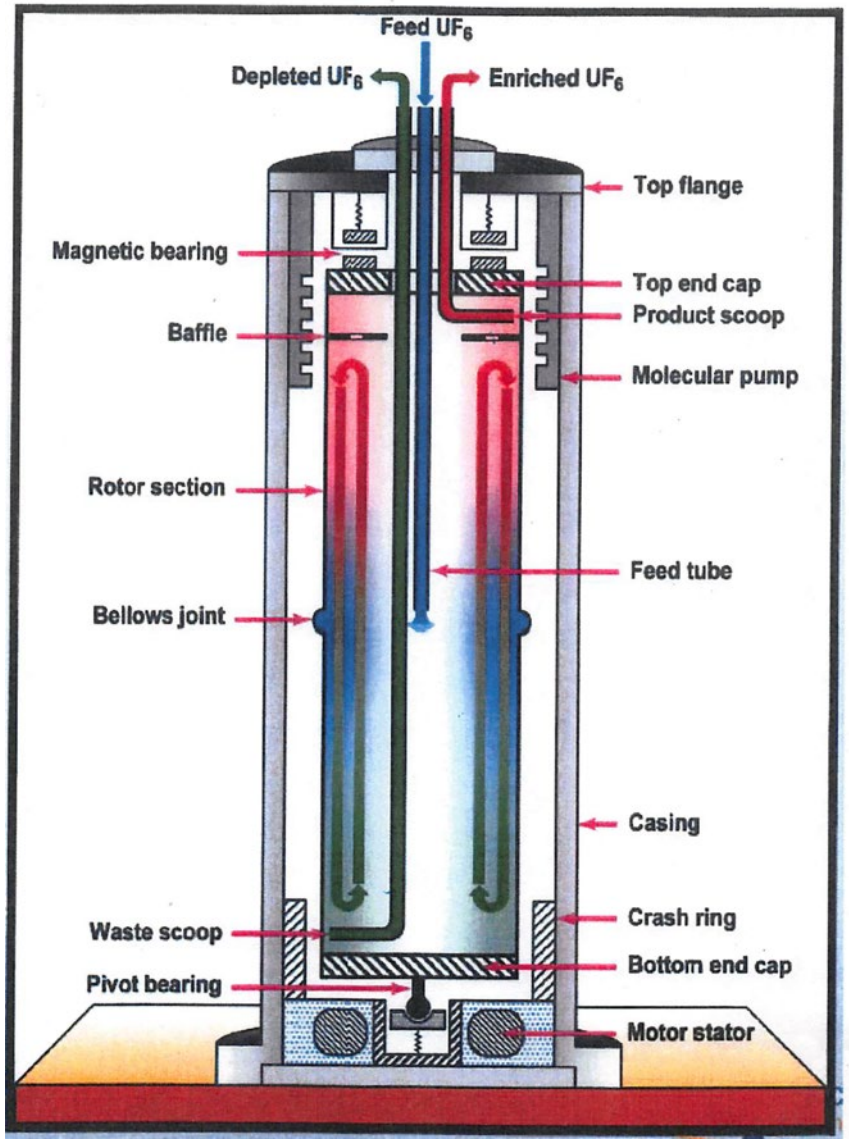
Ti-48 foils – 2.5 cm x 2.5 cm x 1 mg/cm^2



- Mike Zach, "Preparing Enriched Stable Isotope Targets at Oak Ridge National Laboratory", INTDS 2018

Gas Centrifuge Isotope Separator (GCIS)

- ORNL developed a small scale gas centrifuge optimized for separation of stable isotopes from 2013 to 2016
  - For elements with volatile compounds meeting the vapor pressure, thermodynamic stability and isotopic complexity requirements
- A small pilot production cascade was also built to demonstrate enrichment of Mo isotopes using MoF_6 as the process gas
  - Cascade designs may vary depending on isotope of interest and desired assay of the product
- A pilot production of enriched Mo-100 / Mo-98 will be initiated later this year

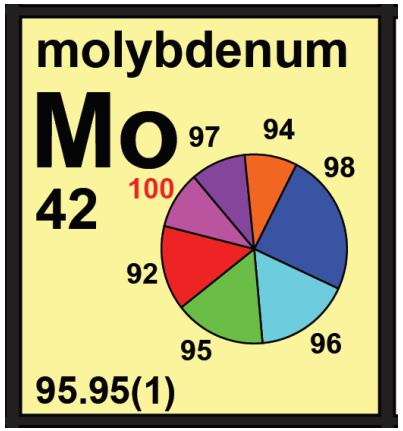


Stable Isotope Production Facility (SIPF)

- DOE has identified a mission need to increase the production capacity of the existing ESIPP to "greater than 1 kg annually"
- CD-1 for a Major Item of Equipment project was approved in May 2018
- Investment of up to $28M has been approved that will support multiple production cascades
- Final design is scheduled for 2019
- Project completion is scheduled for 2024

Mo-98 / Mo-100

- The separation of Mo-98 and Mo-100 is aided by the fact that they are the two heaviest stable isotopes
- A pilot separation of these two isotopes from natural Mo using MoF_6 as the process gas is planned for FY19 using multiple step passes through a small scale cascade
- Data and material obtained from this pilot production run will aid in the development of larger scale stable isotope production by gas centrifuges
- Enriched Mo-98 and Mo-100 targets are needed to support production of Mo-99 and Tc-99m



†

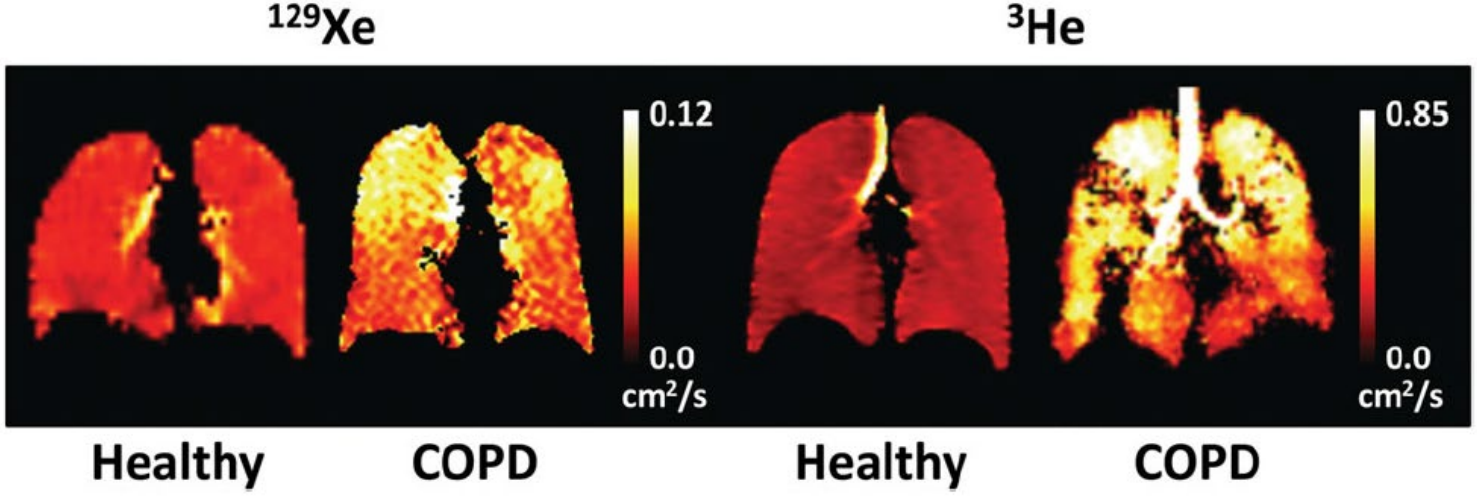
Isotope	Natural Abundance, %
92	14.53
94	9.15
95	15.84
96	16.67
97	9.6
98	24.39
100	9.82

††

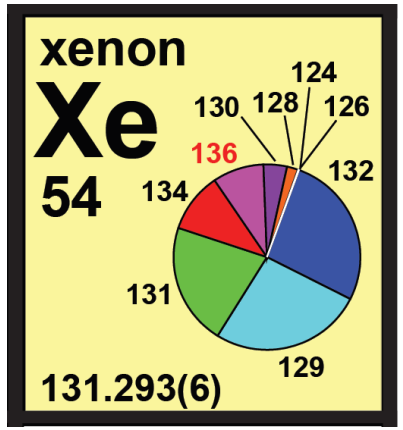
Sources: † IUPAC Periodic Table of the Isotopes; †† IAEA data

Xe-129

- Domestic production of Xe-129 is of interest due to the utility of this isotope as a ^{3}He replacement for pulmonary MRI
- The separation of Xe-129 from the other Xe isotopes is aided by the fact that the lower mass naturally occurring isotopes are low in abundance
- A byproduct of the Xe-129, an enriched Xe-136 gas, may also be of interest since enrichment of this isotope may be needed to support neutrinoless double beta decay experiments



J.P. Mugler, III, et. al., *J. Mag. Res. Imag.*, 37, 313 (2013)



†

Isotope	Natural Abundance, %
124	0.0952
126	0.0890
128	1.9102
129	26.4006
130	4.0710
131	21.2324
132	26.9086
134	10.4357
136	8.8573

††

Sources: † IUPAC Periodic Table of the Isotopes; †† IAEA data

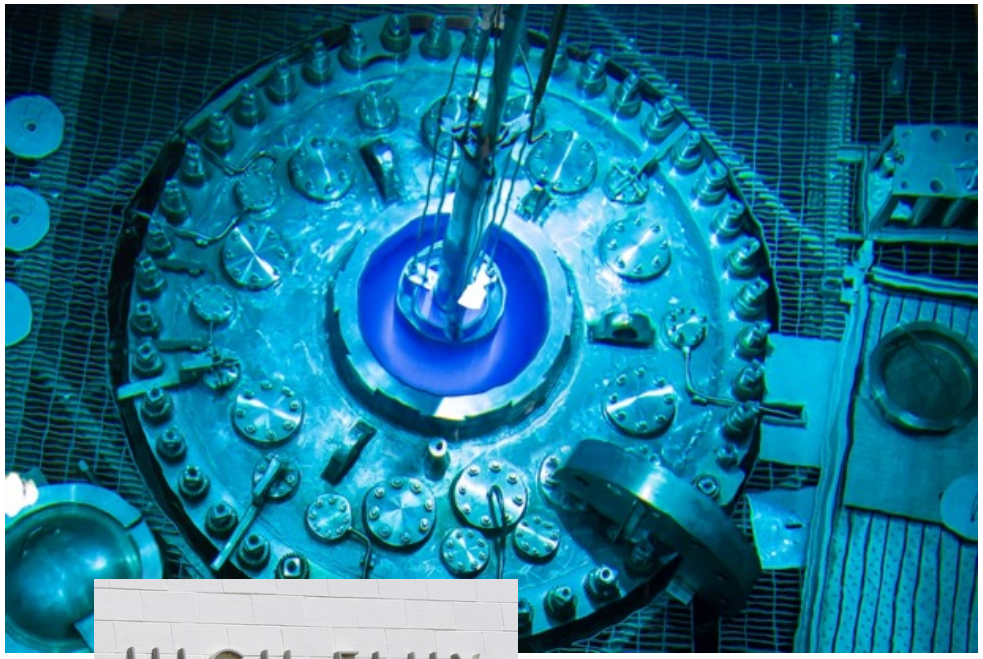
Radioisotopes dispensed at ORNL

Produced at HFIR or harvested from inventory

- $^{249,251,252}Cf$
- ^{249}Bk
- $^{253,254}Es$
- ^{63}Ni
- ^{75}Se
- ^{248}Cm
- $^{242,244}Pu$
- $^{238,239}Pu$
- ^{209}Po
- $^{233,234}U$
- $^{241,243}Am$
- ^{99}Tc
- ^{239}Pu
- ^{133}Ba
- ^{212}Pb
- ^{188}W
- ^{89}Sr
- $^{225,227}Ac$
- $^{227,228,229}Th$
- $^{223,225}Ra$

High Flux Isotope Reactor (HFIR)

- Highest thermal flux in Western world
  - 2.1×10^{15} n/cm^2-s thermal
  - 1×10^{14} n/cm^2-s epithermal (< 1 MeV)
  - 4.7×10^{14} n/cm^2-s fast (> 1 MeV)
- Neutron scattering research
- Brightest cold neutron source in world
- Isotope production
- Material irradiation
- Neutron activation analyses
- 6–7 cycles (24 days) per year



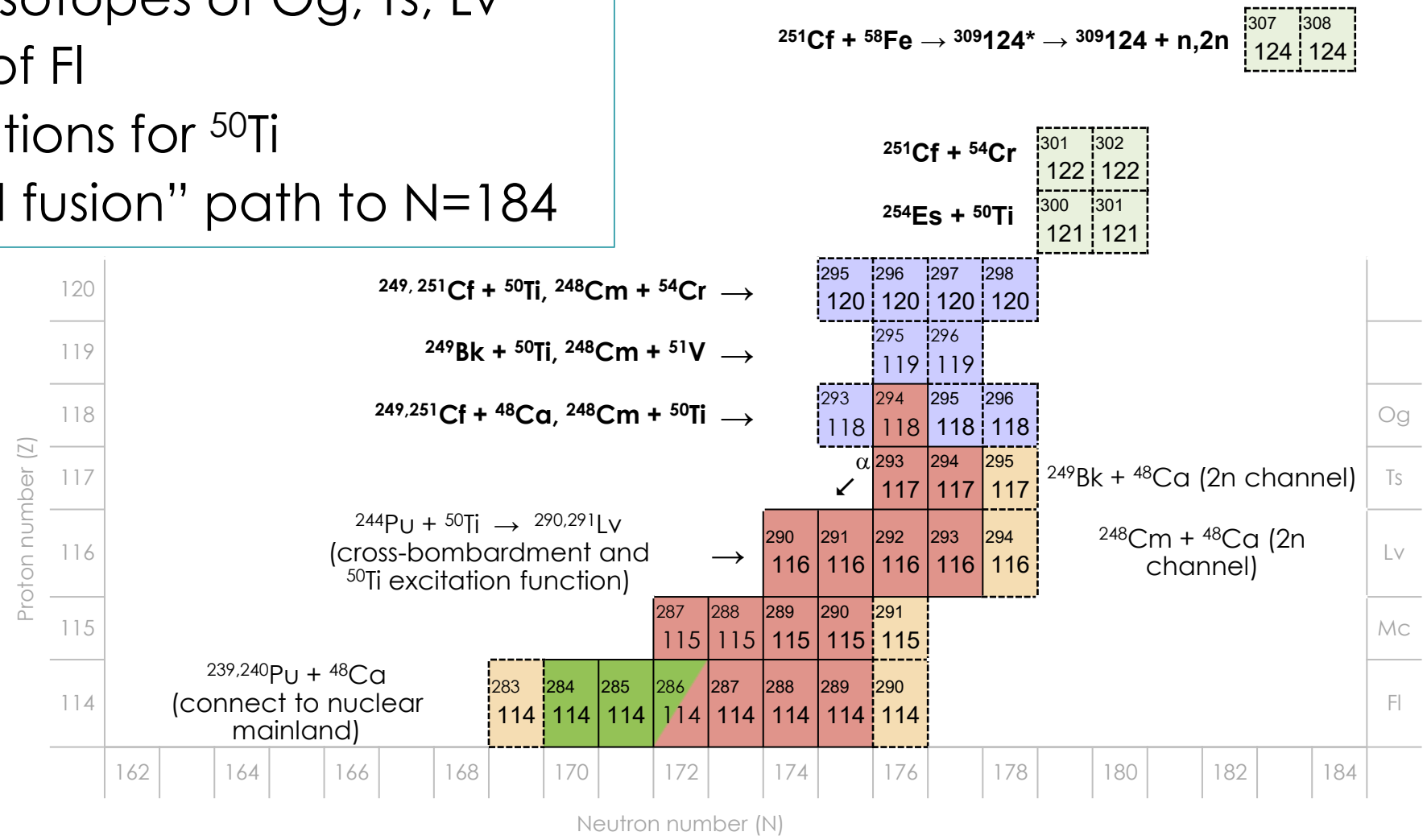
Lu-177 for targeted cancer therapy

- Recently approved by FDA for the use in treatment of certain types of pancreatic cancer (Lutathera®)
- Can be produced at HFIR
  - Irradiation of enriched ^{176}Lu targets
  - Irradiation of enriched ^{176}Yb targets (followed by β-decay of ^{177}Yb)
- Two enriched ^{176}Yb (97.6%) targets irradiated recently
  - Develop challenging Yb/Lu separations chemistry
  - Evaluate production yield
  - Measure specific activity

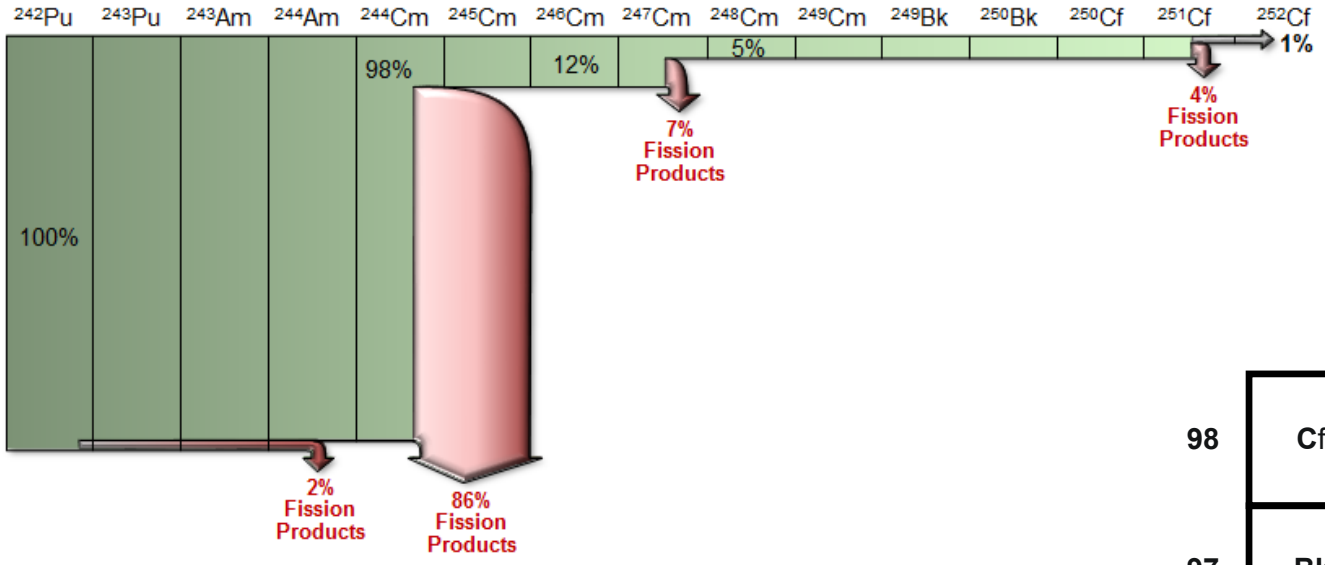
Two small Yb targets prior to loading and post irradiation

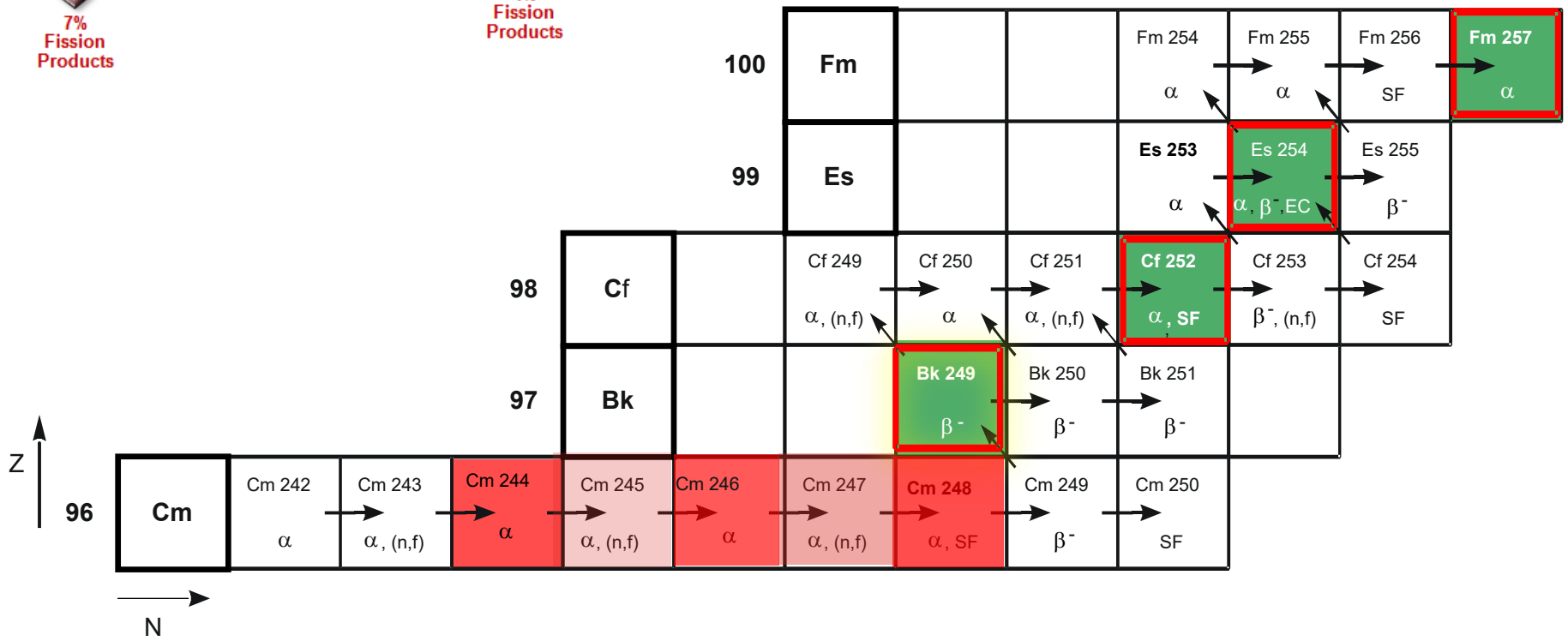
Significant research opportunities using actinide targets

- New elements 119 and 120
- New heaviest isotopes of Og, Ts, Lv
- Light isotopes of Fl
- Excitation functions for ^{50}Ti
- Potential "cold fusion" path to N=184



Heavy element production by neutron irradiation of Cm feedstock target in HFIR





- Cm feedstock isotopics: 244 (30%), 246 (55%), 248 (12.3%)
- Irradiation: 4–6 cycles in HFIR (8–14 months)
- Cool 3 months before processing

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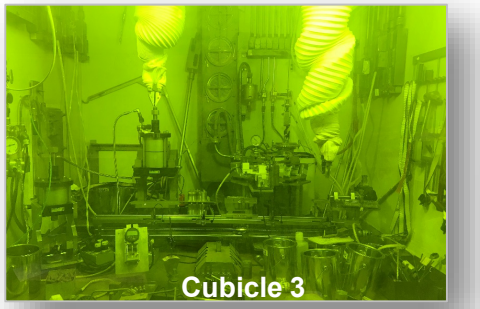
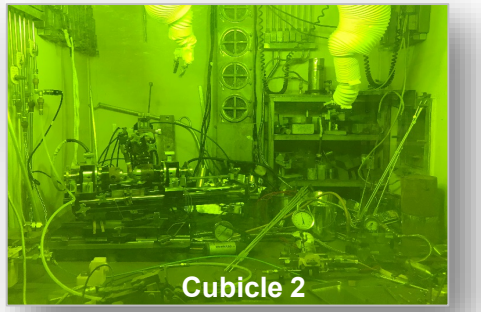
ORNL DWG 98C-20

Cm target assembly

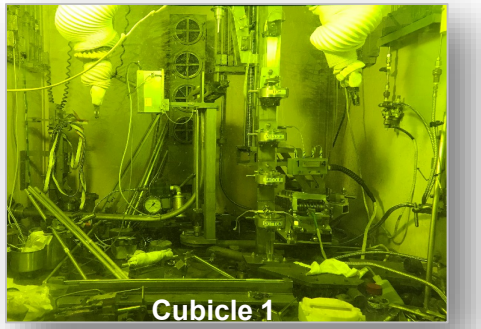
- Each target rod holds 30–35 pellets, which is ~ 7 g of ^{244,246,248}Cm
- All work performed inside of hot cells
- Assembly requires several months



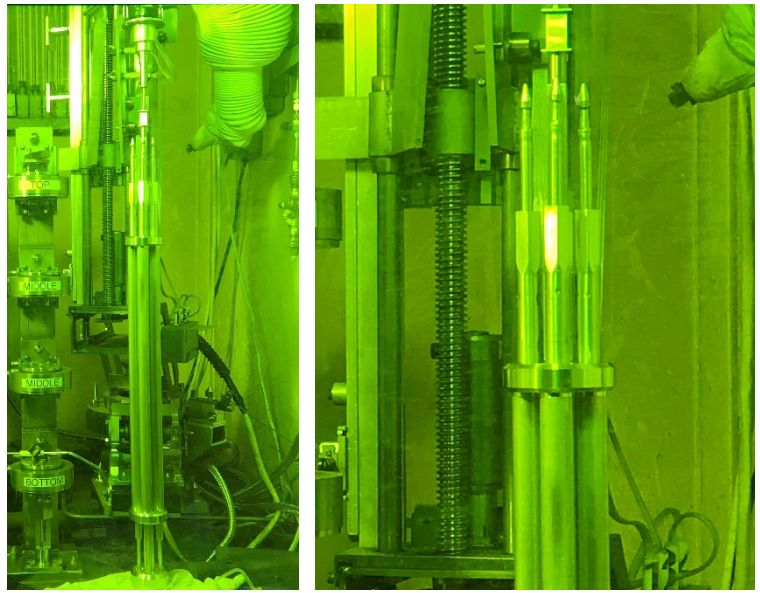
Curium oxide and Al pressed into pellets



Pellets loaded into target rods and welded



Assembled target rods evaluated by x-ray

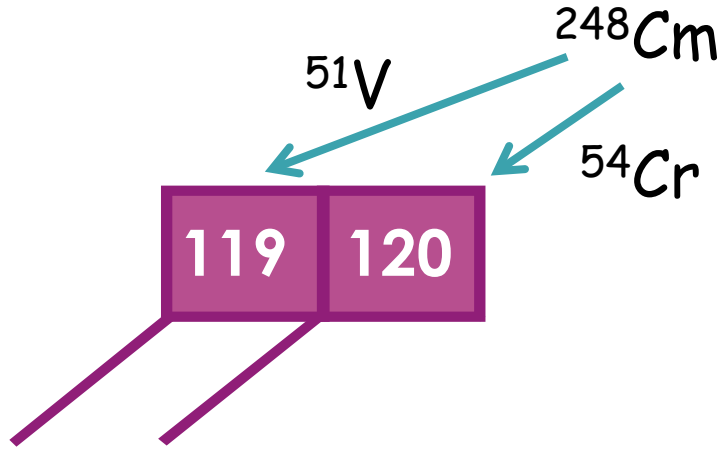


Assembled target bundle will go into reactor core.

22.6 ton carrier transports targets to HFIR

Recovery of high weight percent ^{248}Cm

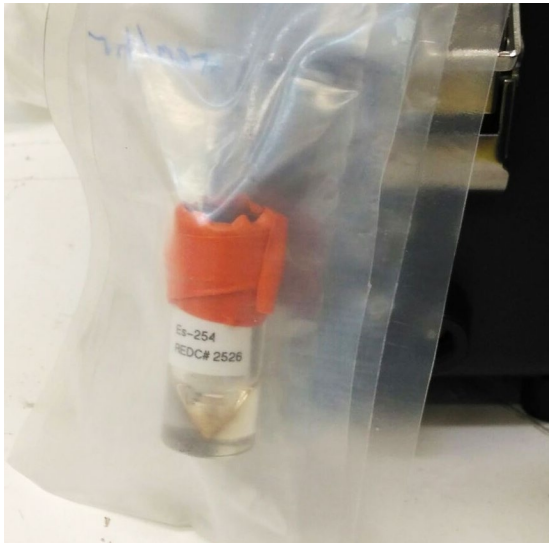
- 30 mg ^{248}Cm (~95 wt%) in stock at ORNL
- SHE projected needs are ~110 mg



- Two recovery paths:

1. **Recover ^{248}Cm from routine ^{252}Cf production**
   - Separate Cm ingrowth within 2 years of Cf purification
   - Yields >90 wt% ^{248}Cm (~10 mg/y)
2. **Recover ^{248}Cm (>83 wt%) from old ^{252}Cf sources**

Packaging and shipping ^{254}Es

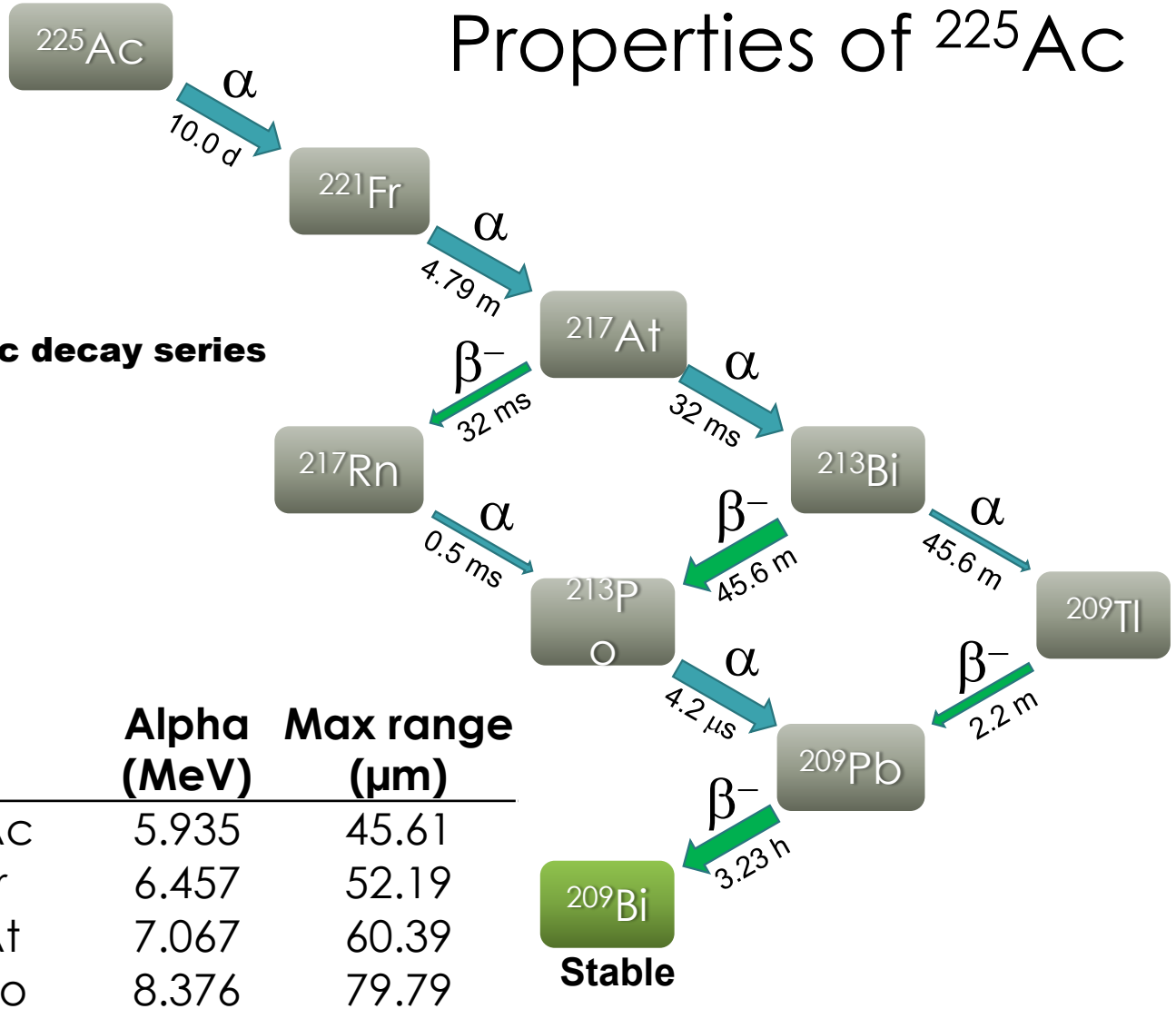


Arrival in Japan – JAEA, Tokai (K. Nishio)

- ~0.5 μg of ^{254}Es ($T_{1/2}$ = 276 days) separated at REDC and transferred to JAEA at Tokai, Japan
- Heaviest isotope used as target for in-beam reaction studies
- Chemistry (atomic radius) and physics (fusion cross-sections and fission barriers) experiments

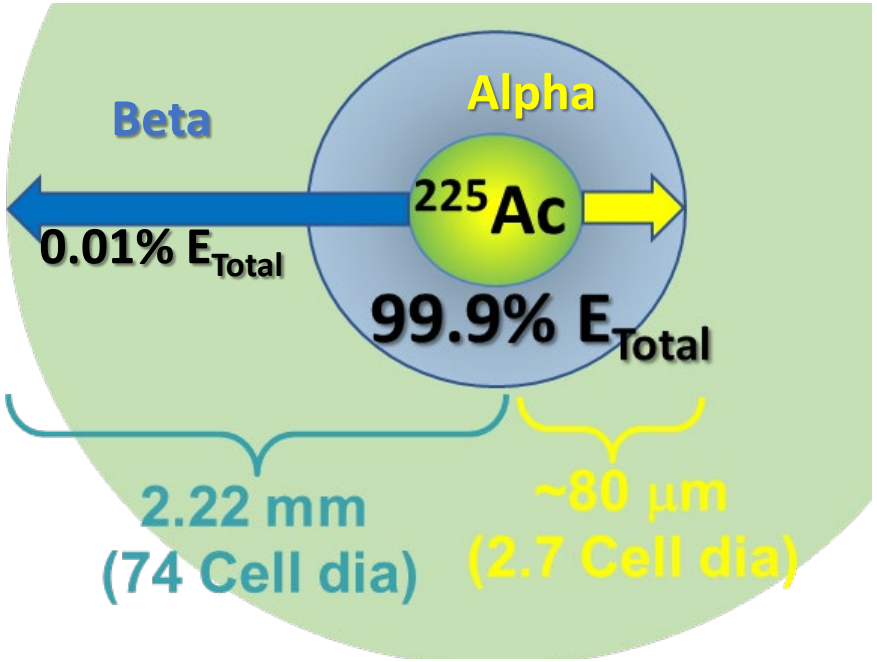
Properties of ^{225}Ac

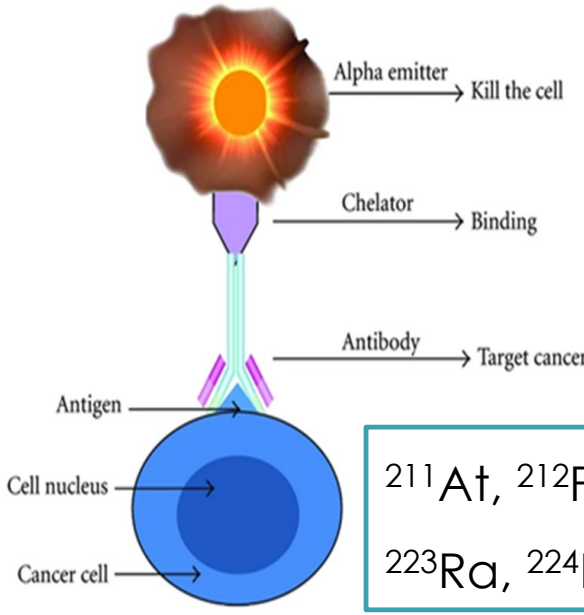
^{225}Ac decay series



	Alpha (MeV)	Max range (μm)
^{225}Ac	5.935	45.61
^{221}Fr	6.457	52.19
^{217}At	7.067	60.39
^{213}Po	8.376	79.79
^{213}Bi	0.4922	1.53

	Beta (MeV)	Max range (mm)
^{209}Pb	0.644	2.22
^{213}Bi	0.4922	1.53

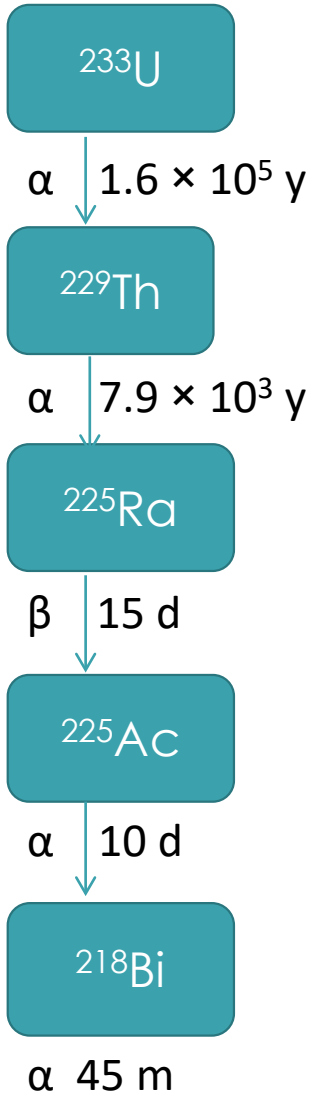




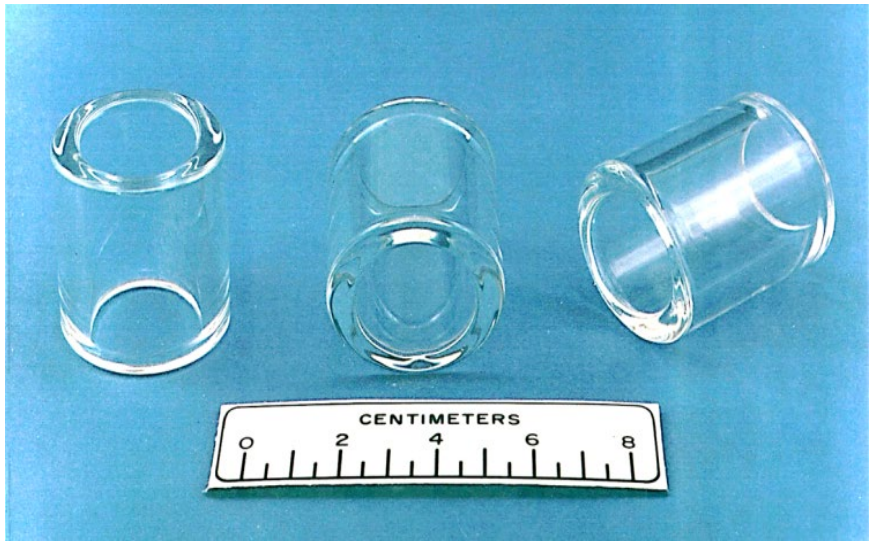
^{211}At, ^{212}Pb, ^{213}Bi,

^{223}Ra, ^{224}Ra, ^{225}Ac, ^{227}Th

ORNL ^{225}Ac history - ^{229}Th recovery



- Early 1990s, ~90 mCi recovered from ^{233}U processing remnants, specific activity 0.36%

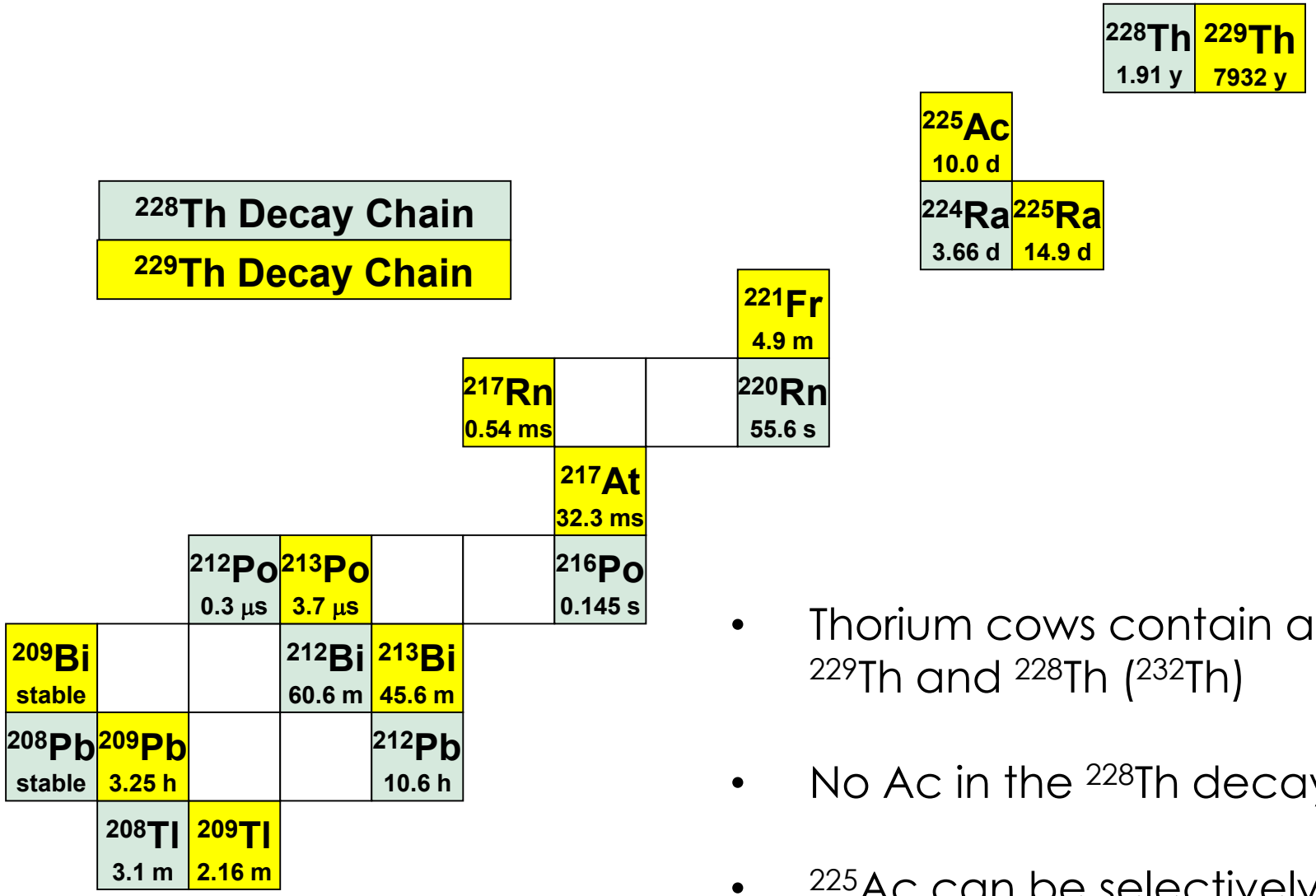


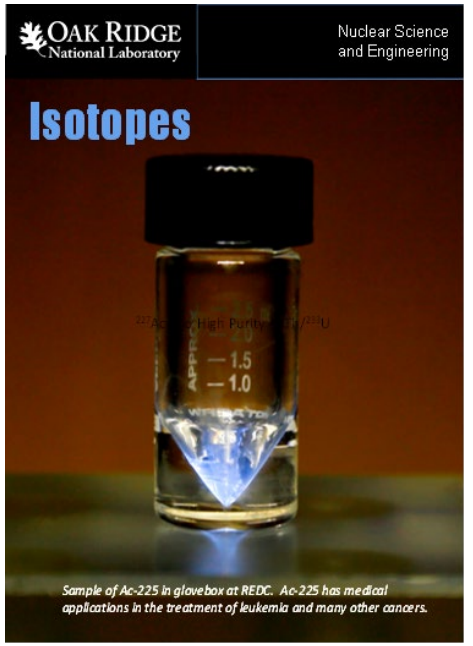
Borosilicate glass (Raschig rings)

Glass with Th adsorbed

- Late 1990s, ~50 mCi recovered from purified ^{233}U material, specific activity 24.4%
- Recovered ^{229}Th stored as four fractions ("cows")
- Limited supply – no new ^{229}Th available

ORNL ^{225}Ac history - ^{229}Th recovery

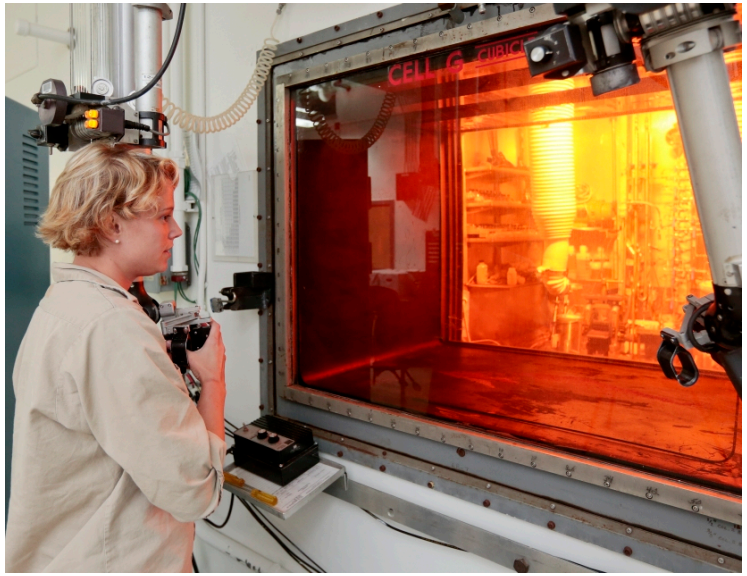




- Thorium cows contain a mixture of ^{229}Th and ^{228}Th (^{232}Th)
- No Ac in the ^{228}Th decay chain
- ^{225}Ac can be selectively isolated

^{225}Ac processing – Chemical separation and purification

Anion and cation exchange chromatography used to produce chemically and isotopically pure ^{225}Ac for medical applications



- Hot cell
  - ✓ (1) Ac/Ra from bulk Th
  - ✓ (2) Ac/Ra from trace Th
  - ✓ (3) Ac/Ra from Fe
    (Iron is critical since it completes with Ac on labeling)
  - ✓ (4) Ac from bulk Ra and other mono- and di-valent cations

- Glove box
  - ✓ (5) Ac/Ra from trace Th
  - ✓ (6) Ac from trace Ra and other cations

Accelerator-based production of ^{225}Ac is ramping up

- DOE funded development of an accelerator-based ^{225}Ac production method
- This is a joint venture between 3 National Labs (LANL, BNL, and ORNL)
  - Thick ^{232}Th targets are irradiated with high-energy, high-intensity proton beams at LANL and BNL and shipped to ORNL for processing
- The project is currently in Stage 2
  - R&D is complete and ^{225}Ac production is ramping up
  - 50 – 100 mCi of ^{225}Ac available per batch (irradiated target)
  - 8 – 12 batches per year for the next 2-3 years
- In Stage 3 (starting in 2021), production will ramp up by at least a factor of 10

The ^{229}Th 'cows' can only provide a limited quantity of ^{225}Ac (~750 mCi/year).

Patient doses are estimated at:
^{225}Ac: 0.3-5 μCi per patient kg (25-400 μCi/patient)
^{213}Bi: 1 mCi per patient kg

Demand projected to be 30-50 Ci/year

News item received yesterday from NIDC

Notice #99 – October 9, 2018

NIDC | NATIONAL ISOTOPE DEVELOPMENT CENTER
Managed by the US Department of Energy's Office of Nuclear Physics

AVAILABILITY ALERT: Accelerator-produced Actinium-225 in December

A new batch of accelerator-produced actinium-225 (Ac-225) will be available through the U.S. Department of Energy Isotope Program (DOE IP) in early December 2018. This alpha-emitting radionuclide and its decay product bismuth-213 (Bi-213), from an Ac-225/Bi-213 generator, have gained considerable interest within the medical community for their radioimmunotherapy applications.

The Ac-225 (half-life of 10.0 days) is produced with the DOE IP's high-energy accelerators at both Los Alamos and Brookhaven National Laboratories through the proton bombardment of natural thorium targets, and then separated and purified at Oak Ridge National Laboratory. It has a theoretical specific activity of 5.8 x 10^4 Ci/g at EOB and a radionuclidic purity of ≥98% (~0.12% Ac-227 at EOB).

The DOE IP has completed accelerator production campaigns for Ac-225 approximately every other month since early 2018, and the program plans to continue this schedule (depending on market demand) to ensure a reliable and abundant supply for research efforts and clinical trials. Additional batches can be produced upon demand.

Quotation requests for Ac-225 may be placed through the National Isotope Development Center's (NIDC) product catalog. For further inquiries about the availability of Ac-225, please contact Dr. Wolfgang Runde, Associate Director for Production Planning and Customer Relations, NIDC.

National Isotope Development Center
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www.isotopes.gov

Radioisotope Groups

Medical, Industrial, and Research Isotope Group

Nuclear and Radiochemistry Group

Summary

- The ORNL Isotope Program supports the DOE Isotope Program mission to produce and distribute enriched stable isotopes and radioactive isotopes for research
- Recent DOE investments in the stable isotope component of the program will greatly expand the annual production capacity for stable isotopes to the "kg level"
- The radioisotope component of the program continues to deliver unique radioisotopes for a variety of fundamental research, medical and national security applications
- The ORNL Isotope Program also hosts significant target fabrication capabilities utilizing these rare isotopes