Production of Radioactive Materials

RT4220 – Lecture #5

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Why Produce Radionuclides?

Most naturally occurring radionuclides have VERY long-lived half-lives

Heavy elements, not useful for following biological processes

I believe they have low specific activities *source needed

Methods of Production

Reactor-Produced Radionuclides

- Fission Products
- ${}^{A}_{Z}X(n, \lambda)^{A+1}_{Z}X$ reaction
- ${}^{A}_{Z}X(n, p)_{Z-1}^{A}Y$ reaction

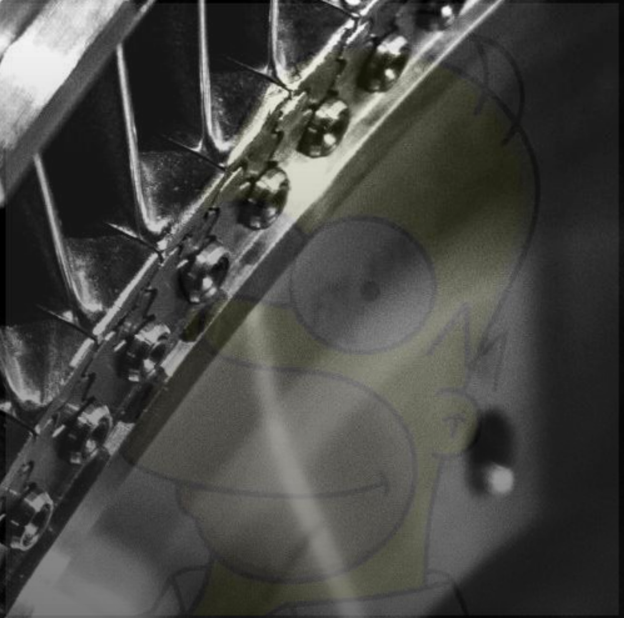
Accelerator-Produced Radionuclides

- Cyclotron
- Synchrocyclotrons

Radionuclide Generators

- Moly Cow

Reactor Produced Radionuclides



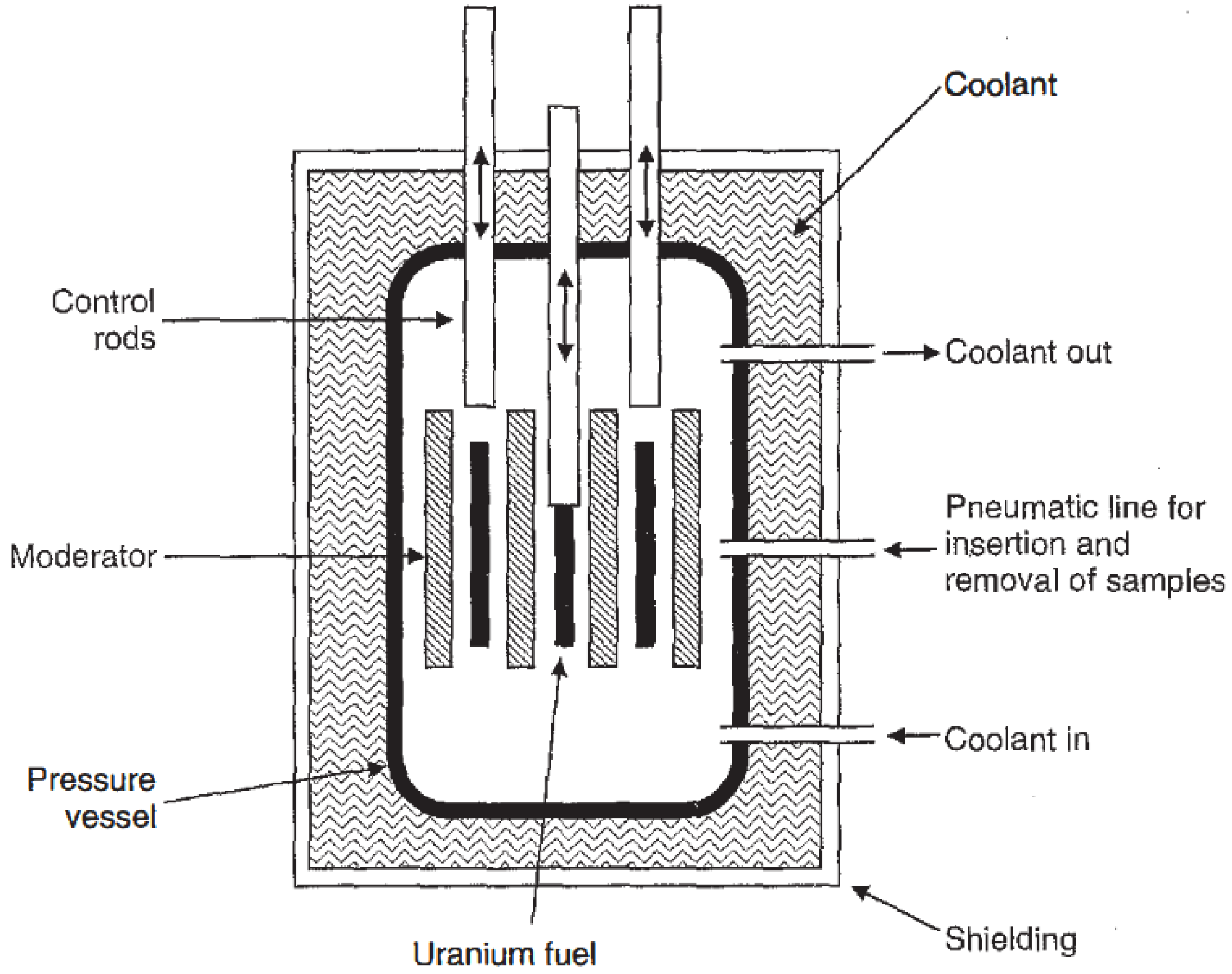
"Doh"

Nuclear Reactor Basics

- Fission of unstable Uranium → chain reaction of excited states and further fission events → excess energy captured by water → SPIN THAT TURBINE
- Neutron excess causes U-235 → U-236 which is even more unstable
  - Neutrons are neutral charge, interact much less than electrons
- Moderators slow down excessively fast neutrons → more likely to react at slower speeds
  - Heavy water (D_2O) or Graphite
- Control rods block fuel cells and prevent meltdown
  - Cadmium or boron

Nuclear Reactor Core Diagram

Schematic representation of a nuclear reactor.



Nuclear Reactor Fission Fragments

- Each fission event results in Q of 200-300 MeV per fragment
- Fission fragments ALWAYS have neutron excess
  - N/Z for U-235 is so high that even after fission, N/Z is too high for fragments
- Energy is deposited in coolant, carried to steam generator/turbine
- If the fission products are long-lived, they can be chemically separated and used for medical purposes
  - Y-99 → Zr-99 → Nb-99 → Mo-99!
- Can be carrier-free! I-131 is not an example, contamination from I-127 and I-129
- Low yield, many different possibilities

U-236* Fission Fragment Mass Distribution

- *Equal mass fragments discouraged*
- *85-105 AMU and 130-150 AMU fragments most likely*
- *20 possible elements, over 100 nuclides*

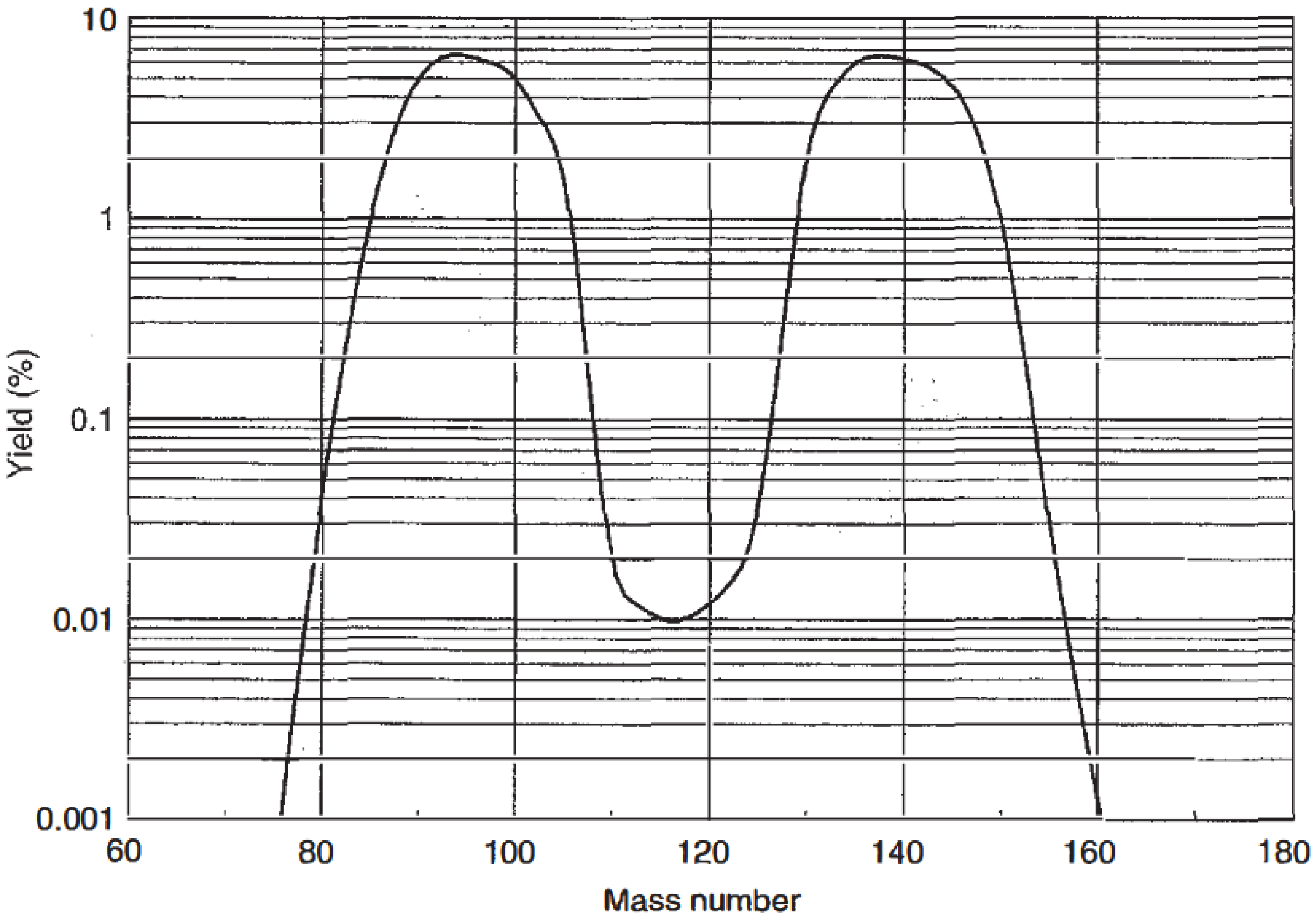


Figure 5–2. Mass distribution of fragments following fission of $^{236}U^*$.

Fission Fragment Practice

The following reaction occurs in a nuclear reactor, determine what the missing part of the equation should be:

$$^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{236}_{92}\mathrm{U} \rightarrow {}^{144}_{56}\mathrm{Ba} + {}^{89}_{36}\mathrm{Kr} + 3\mathrm{n} + \mathrm{Q}$$

The excess 3 neutrons will likely set in motion more events thus continuing the chain-reaction.

Neutron Activation

- Instead of relying on random nature of fission fragments, rely on random nature of neutrons hitting a sample!
- Use pneumatic tubes to place carrier sample near core → bombard sample with neutrons → neutron excess radionuclides
- Two common modes of activation:
  - (n, λ)
  - (n, p)

Neutron Activation: Gamma Reaction

$$^{A}_{Z}X(n, \lambda)^{A+1}_{Z}X$$

Target nucleus $\left({}^{A}_{Z}X\right)$ captures a neutron (n)

Nucleus forms an excited nuclear state $\left({}^{A+1}_{Z}X\right)$

Nucleus emits gamma (λ)

Neutron Activation: Proton Reaction

$$^{A}_{Z}X(n, p)\,{}^{A}_{Z-1}Y$$

Target nucleus $\left(^{A}_{Z}X\right)$ captures a neutron (n)

Nucleus ejects a proton (p)

New element is formed $\left({}^{A}_{Z-1}Y\right)$

Neutron Activation Characteristics

- *Almost always* beta- decay due to neutron excess.
- (n, λ) is the most common reaction, produces sample with carrier
- (n, p) mode can produce carrier-free sample if the product can be chemically separated from the target
- Extremely small proportion of target is activated (1:1000000 at best)
  - (n, λ) yields extremely low specific activity
- Can use complicated process to make proton excess samples, too much hassle, use charged particle accelerators instead!

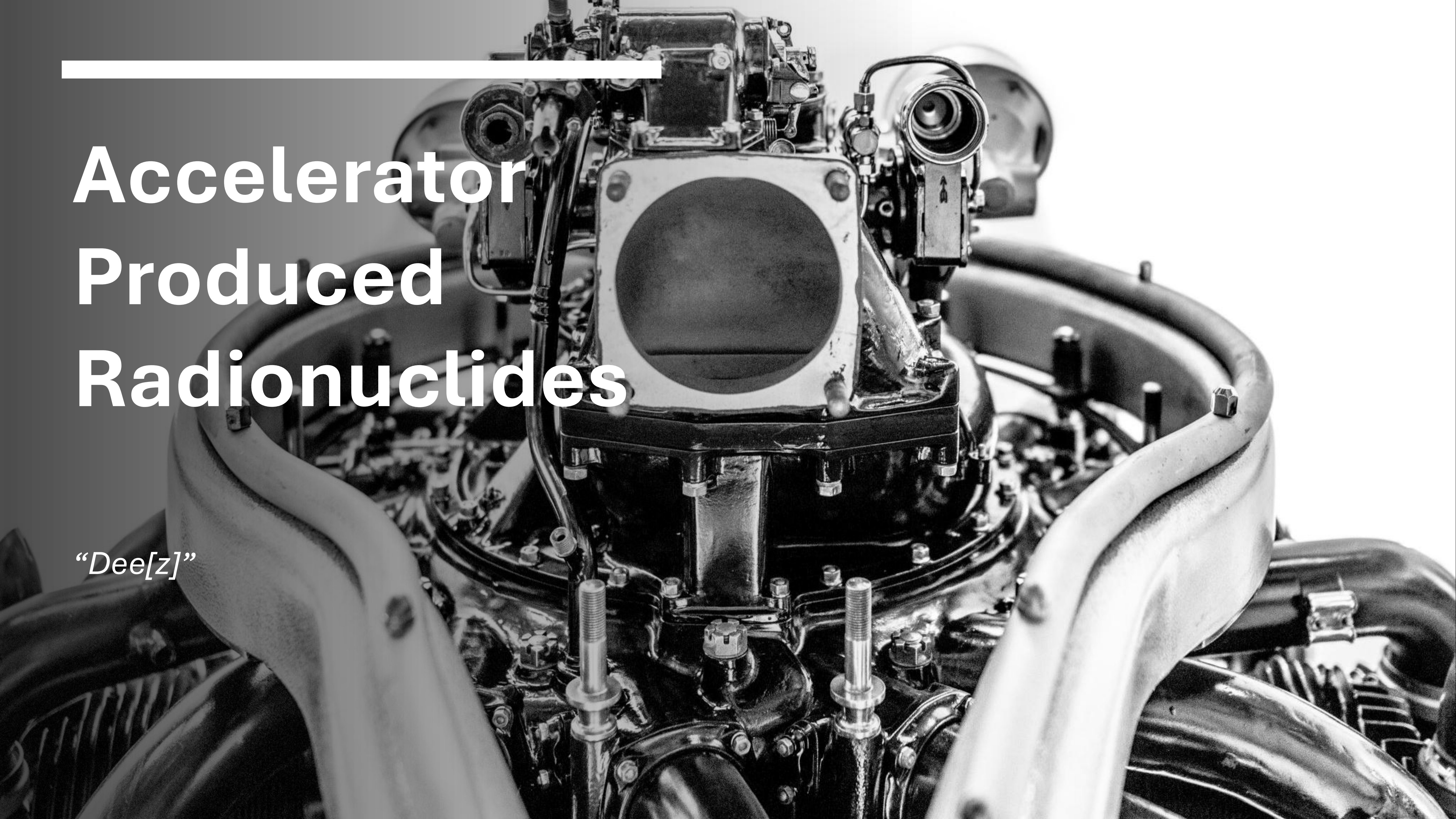
Neutron Activation Practice

A sample of Selenium-74 is placed near the core of a nuclear reactor to undergo nuclear activation. You measure high-energy photons emitting from the during the activation process, and high-energy electrons after taking it out of the core. Determine what nuclear reaction must have occurred and write the extended short-hand form.

$$^{74}_{34}\mathrm{Se}(\mathrm{n}, \lambda)^{75}_{34}\mathrm{Se}$$

Accelerator Produced Radionuclides

“Dee[z]”



Accelerator Principles

- Charged particles must be accelerated to 10-20 MeV to overcome repulsion from nucleus and infiltrate
  - Differs from thermal neutron capture, where energy must be low!
- Easiest way to accelerate charged particles is electric potential (voltage)!
- Cyclotron was one of many attempts to create and control high-energy charged particle beams, general design won, many more improvements since then but same basic design

Cyclotron Principles

- Hollow “D” shaped electrodes positioned between the poles of a large electromagnet
- Narrow gap in the middle
- Ion source in the center
- Low air pressure
- Electric field accelerates ions towards a dee
- Dee has no electric field but a strong magnetic field
- Charged particle in a magnetic field → acceleration!
- When the charged particle reaches the gap it enters electric field, gaining more energy
- Each time ions cross gap → more energy → higher speed → greater radius

Cyclotron Principles - Continued

- When particles reach maximum energy (20-30 MeV) they reach maximum radius too
- Particle is directed to a target inside machine or external target
  - Positive ion cyclotrons deflect beam directly to target (30% efficient)
  - Negative ion cyclotrons pass through thin carbon foil which strips the excess electrons, reverses the direction of acceleration towards target (~100% efficient)
- Constant acceleration of high energy charged particles requires shielding from photons (negative ion requires less, thus called “cold”, but they require even lower air pressure)

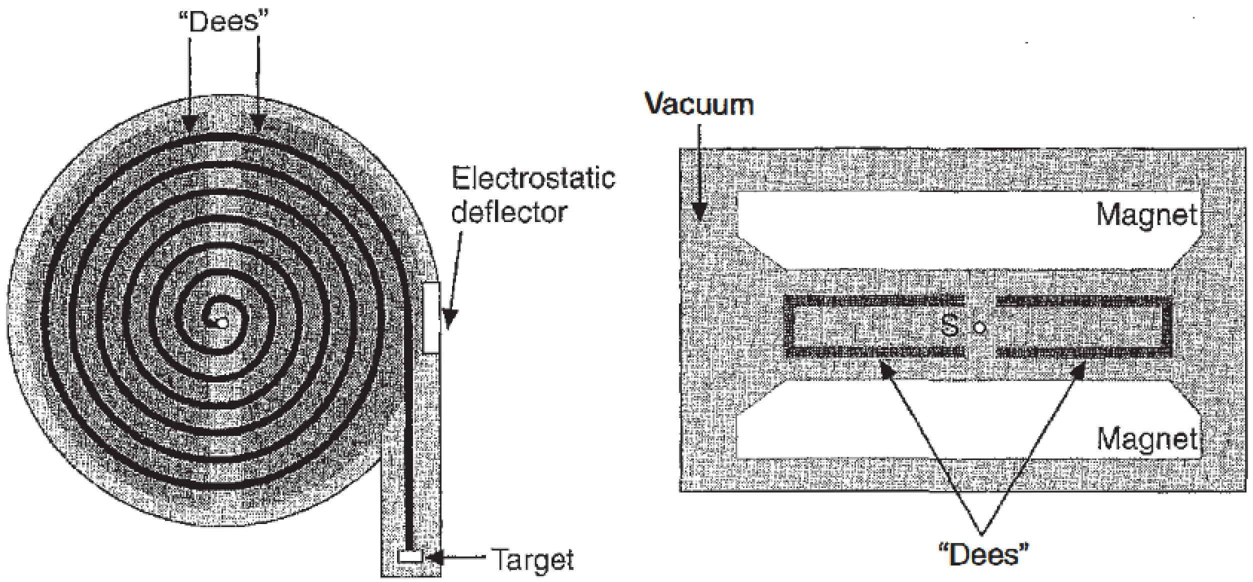


Figure 5–3. Schematic representation of a positive ion cyclotron: top *(left)* and side *(right)* views. The accelerating voltage is applied by a high-frequency oscillator to the two "dees." S is a source of positive ions.

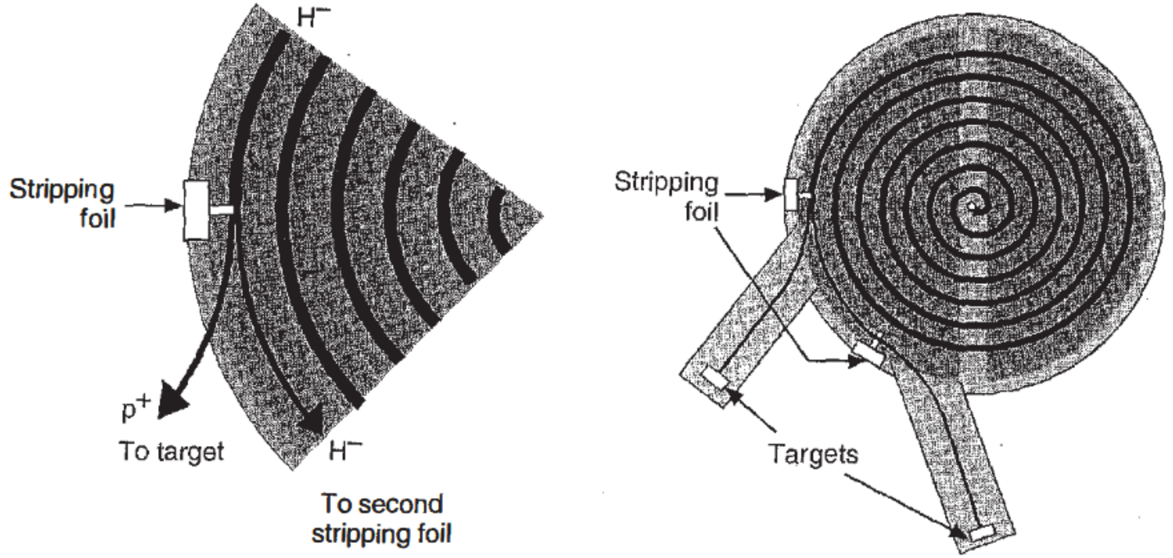


Figure 5–4. *Left,* Schematic representation of a negative ion cyclotron. The carbon stripping foils remove two electrons from negative hydrogen (H^-) ions, converting them into protons (p^+) that bend in the opposite direction in the applied magnetic field. *Right,* The first stripping foil intersects only part of the beam, allowing two beams to be extracted simultaneously.

Cyclotron Radionuclide Characteristics

- Sample is blasted with positive ions
- These radionuclides tend to decay with EC or beta+ (like F-18/FDG!)
- Cyclotron-produced products have a different atomic number, if chemically separated it yields carrier-free sample!
- Cyclotron-produced radionuclides are typically more expensive than neutron due to lower intensity of beams and even lower activation cross-section
- Decay of these emits high-energy photons and positrons → useful for medical imaging (PET!) due to high penetration and low atomic number relevance for biological processes

Cyclotron Practice - Energy

Assuming that a hydrogen atom with two electrons gains 25 keV every time it crosses the gap in a cyclotron, how many times would it have to cross the gap to reach 10 MeV assuming it started from rest?

$$10{,}000\ \text{keV}\ \times \frac{1\ \text{gap crossing}}{25\ \text{keV}} = 400\ \text{gap crossings}$$

Cyclotron Practice - Frequency

The frequency at which the electric field must be turned on/off is a constant at any particle energy for a given particle. Using the following equation, determine the switching frequency of the cyclotron if the cyclotron has a 1.5 Tesla magnet:

$$\mathrm{q} = 1.6\mathrm{E} - 19\ \mathrm{C} \qquad \mathrm{m} = 1.67\mathrm{E} - 27\ \mathrm{kg}$$

$$f = \frac{\mathrm{q}}{\mathrm{m}} \times \frac{\mathrm{B}}{2\pi}$$

$$f = \frac{1.6\mathrm{E} - 19}{1.67\mathrm{E} - 27} \times \frac{1.5}{6.28} \cong 2.3\mathrm{E}7 \text{ or } 23\ \mathrm{MHz}$$

Generator Produced Radionuclides

“Dum?”

Radionuclide Generator Principles

Contains Parent-Daughter pair that permits the extraction of the daughter

Well-shielded and STERILE

Daughter replenishes as parent decays

Technetium Generator (Moly Cow)

Tc-99m decay yields 140 keV photons, low enough to cause minimal damage but high enough to escape the body

Six-hour half-life means the patient can leave safely shortly after the injection

Mo-99 has 67-hour half-life which is just long enough to transport from nuclear reactors to the hospital's on-site Moly Cow

Moly Cow Terminology

- Parent – Mo-99
- Daughter – Tc-99m
- Core – Area of the generator containing the parent
- Elution – The process of separating the daughter from the parent/daughter mixture through washing with a solvent (saline)
- Eluant – Solvent which enters the core
- Eluate – Solvent which exits the core with the washed away material

Elution Principles

- Molybdate ions (MoO_4^{2-} or $MoOOOO$) bound to alumina column (Al_2O_3)
- Pertechnetate (TcO_4^-) does not bind well to the alumina, can be easily washed away with 5-25 mLs normal saline
- Eluate contains contaminants like Mo and aluminum which results in increased rad dose, extra dose to family and public, interferes with chemical labeling, and clumps red blood cells/creates micro-emboli
- Contaminants are regulated by BIG NRC, must be used with 12 hours of elution and contain no pyrogens

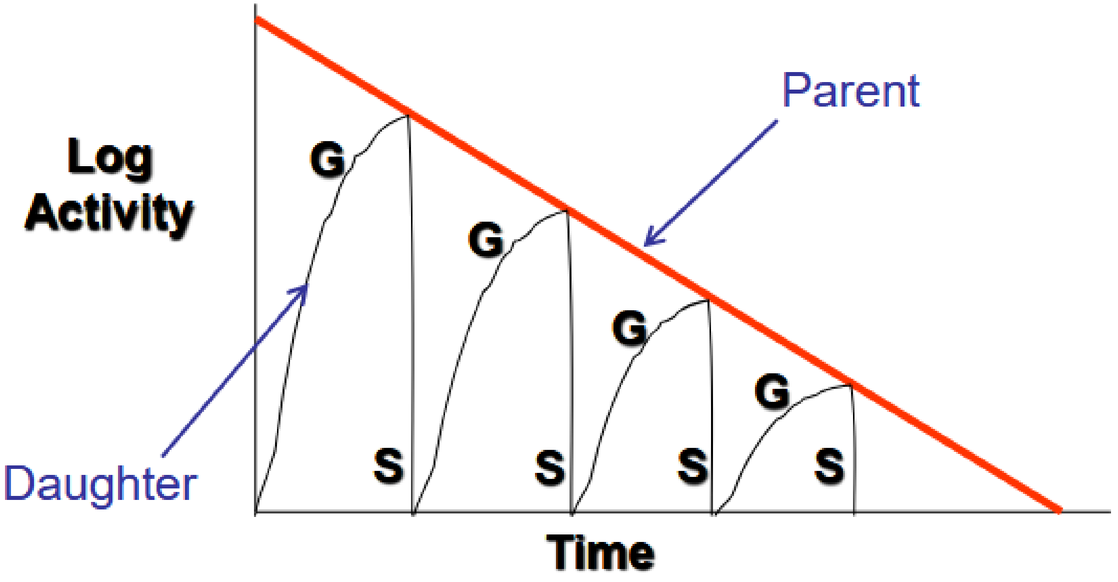
Generator Use-Life

The useful life of a fresh Mo sample for a Moly Cow is 7-10 days.

- At $t = 6\ h$ post elution daughter is ~50% of original parent activity
- … $t = 12\ h$ … ~75%
- … $T = 24\ h$ … ~93%

24 hours is chosen for its ease in routine and sufficient efficiency

G = Growth S = Separation (Elution)



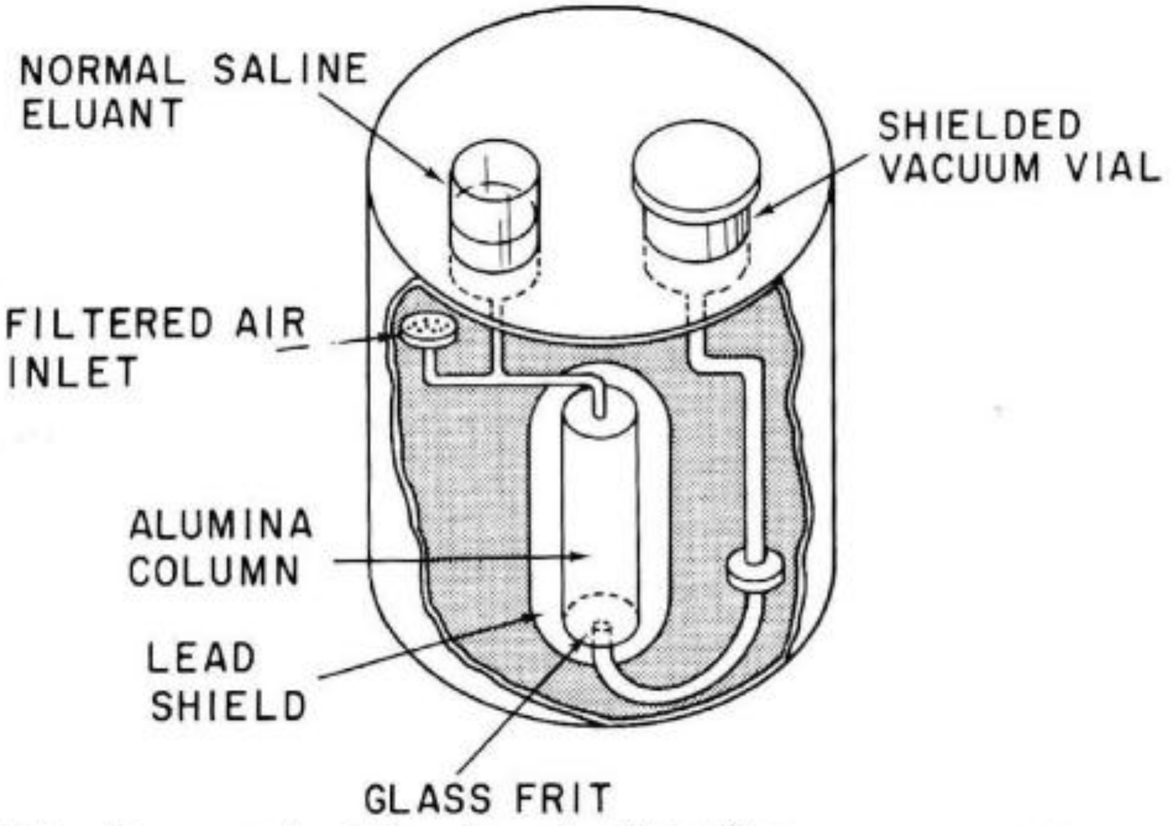
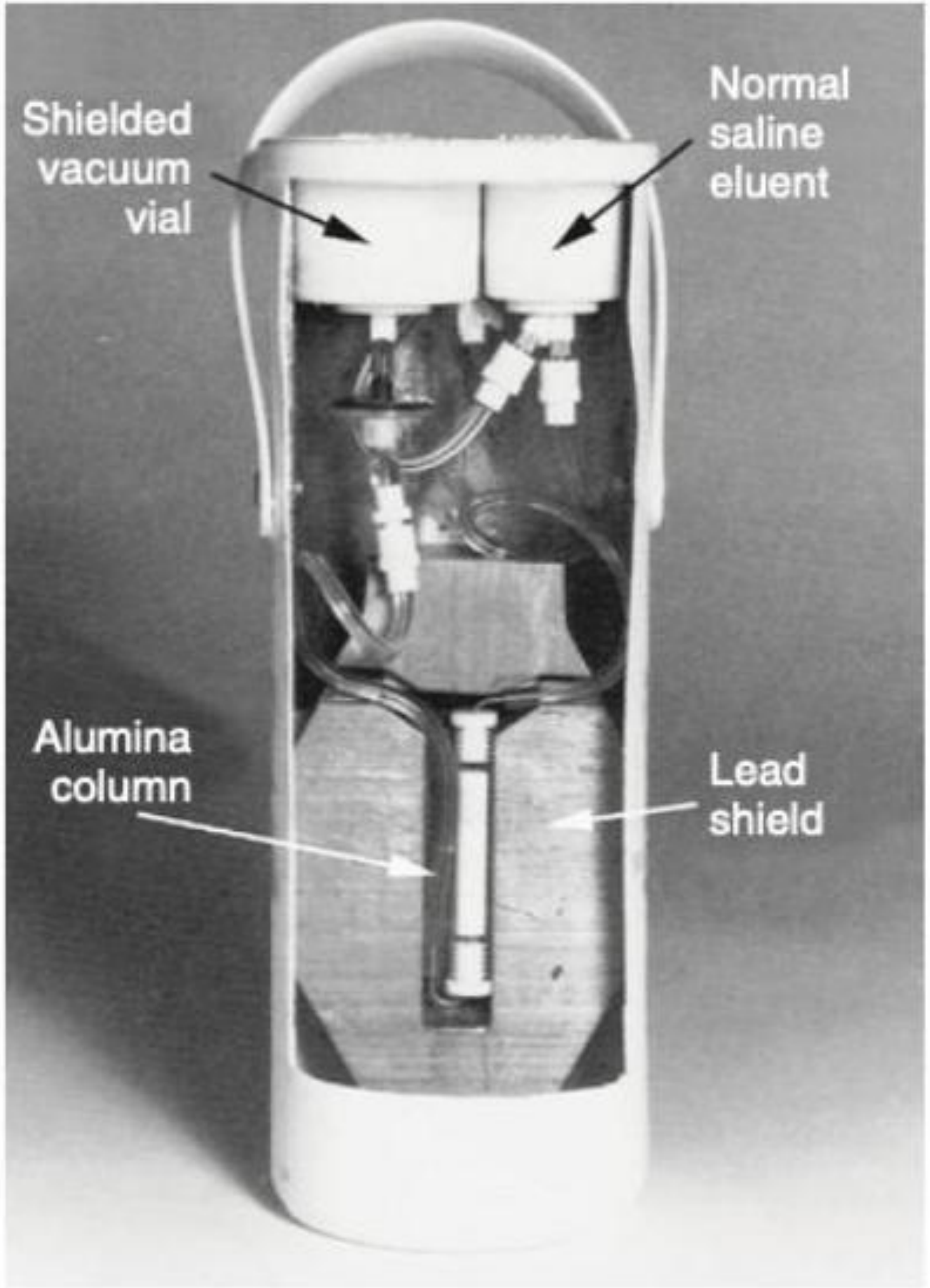


Fig. 7-5. Cross-sectional drawing of a ^{99}Mo-^{99m}Tc generator. (Courtesy Society of Nuclear Medicine and Thomas R. Gnau.)



F-18 Practice Calculations 1: Reaction Equations

Determine the extended short-hand reaction equation for making F-18 in a cyclotron, with the knowledge that they use oxygen as the target:

$$^{18}_{8}\mathrm{O}(\mathrm{p},\mathrm{n})\,^{18}_{9}\mathrm{F}$$

Expand this to the full reaction equation.

$$^{18}_{8}\mathrm{O} + {}^{1}_{1}\mathrm{p} \rightarrow {}^{18}_{9}\mathrm{F} + {}^{1}_{0}\mathrm{n} \ + \ \mathrm{Q}$$

F-18 Practice Calculations 2: Energy Classification

$$^{18}_{8}\mathrm{O} + ^{1}_{1}\mathrm{p} \rightarrow ^{18}_{9}\mathrm{F} + ^{1}_{0}\mathrm{n} + \mathrm{Q}$$

Item	Mass (amu)
O-18	17.994771
p	01.007276
n	01.008665
F-18	17.996000

Using the full reaction equation from the previous problem, calculate the energy Q and determine if it is an exoergic reaction or endoergic reaction.

$$(17.994771 + 1.007276) - (17.996000 - 1.008665) = -0.002618\ \mathrm{u}$$

This process is endoergic as the mass defect is negative (reactants - products). Converting this to energy yields 2.45 MeV. This process consumes 2.45 MeV of extra energy from the kinetic energy of the proton* *citation needed*