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Title: Why We Need Nuclear Safety

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Why We Need Nuclear Safety

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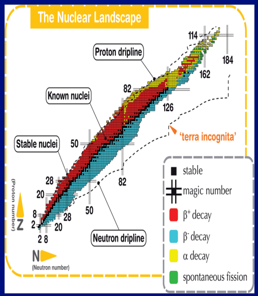
Nuclear Criticality Safety Division

Researcher placing a nuclear material item for measurement with SOFIA.

Los Alamos National Laboratory developed a tool called SOFIA (Spectrometer Optimized for Facility Integrated Applications) by capitalizing on key advances in ultra-high-resolution microcalorimeter technology.

Overview of Presentation

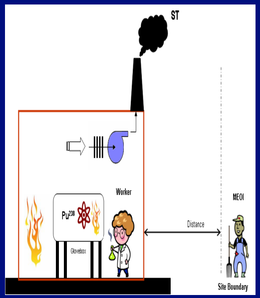
Radiation



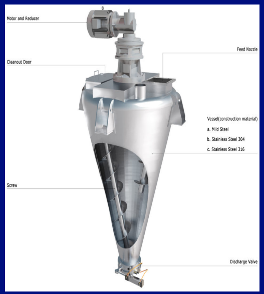
Pictures of Safety

Why We Need Radiation Protection

Why We need Safety Basis/ Licensing



Why We need Criticality Safety

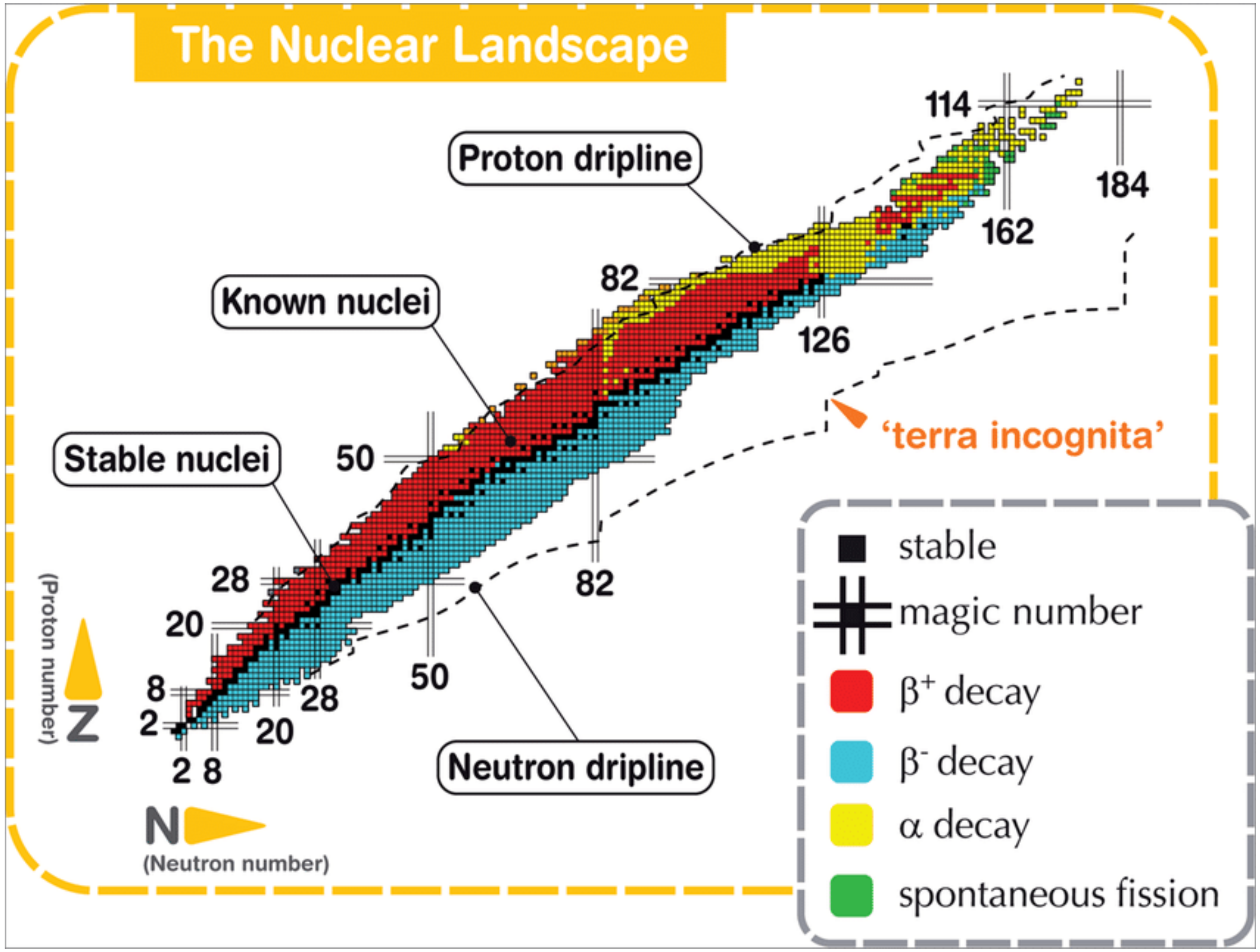


Safety Controls In Action

Radiation

A lot of isotopes inherently create their own hazard.

- Alpha
- Beta
- Gamma
- Neutron



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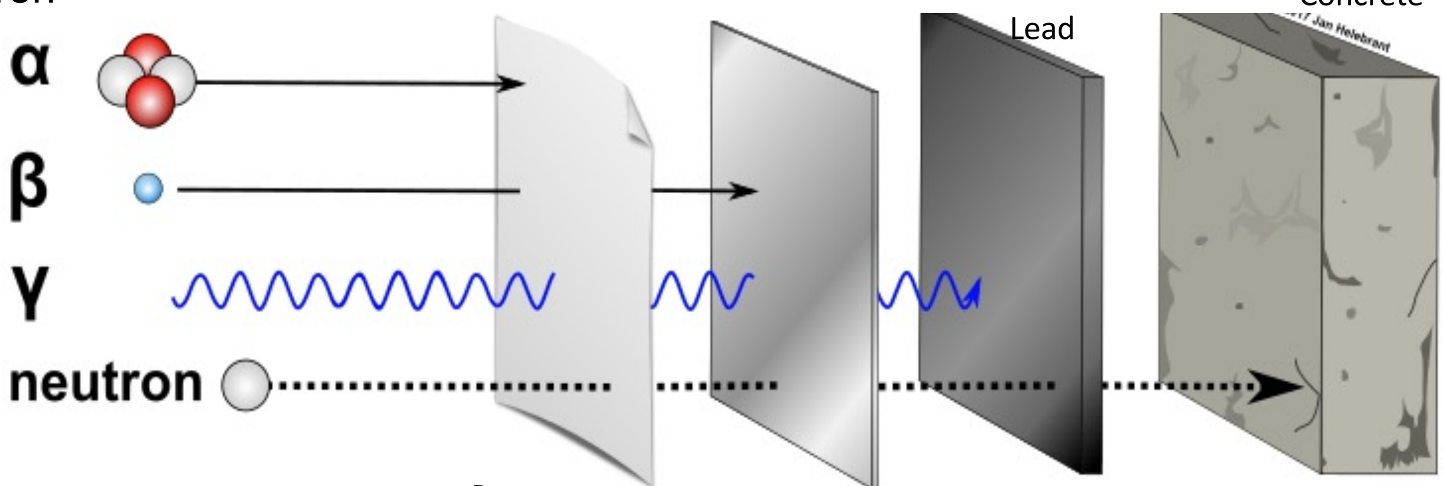
Alpha, Beta, Gamma, and Neutron Radiation

Alpha particles - produced by plutonium and americium radioactive decay

Gamma-rays - decay product nucleus is usually left in an excited state, which emits energy as the nucleus transitions to the ground state

Neutrons - produced through an "alpha-n" reaction: an alpha particle from Pu or Am decay hits a "low-Z" material such as carbon, oxygen, chlorine, or beryllium, and produces a neutron



Major Safety Management Programs

- Radiation Protection (including Radiation Control)
- Safety Basis/Licensing
- Nuclear Criticality Safety

Nuclear Safety In Pictures

Negative pressure glovebox containment to control alpha emitting materials

Worker holding a disc of highly enriched uranium

Leaded windows – good for shielding whole-body from all gammas from something like Pu

Containerized radioactive material

2-inch polyethylene shielding on a glovebox surface to reduce neutron exposure

Leaded gloves – good for shielding hands from low-energy gammas from something like Pu & Am-241

Bad Things Happen to Good Plutonium

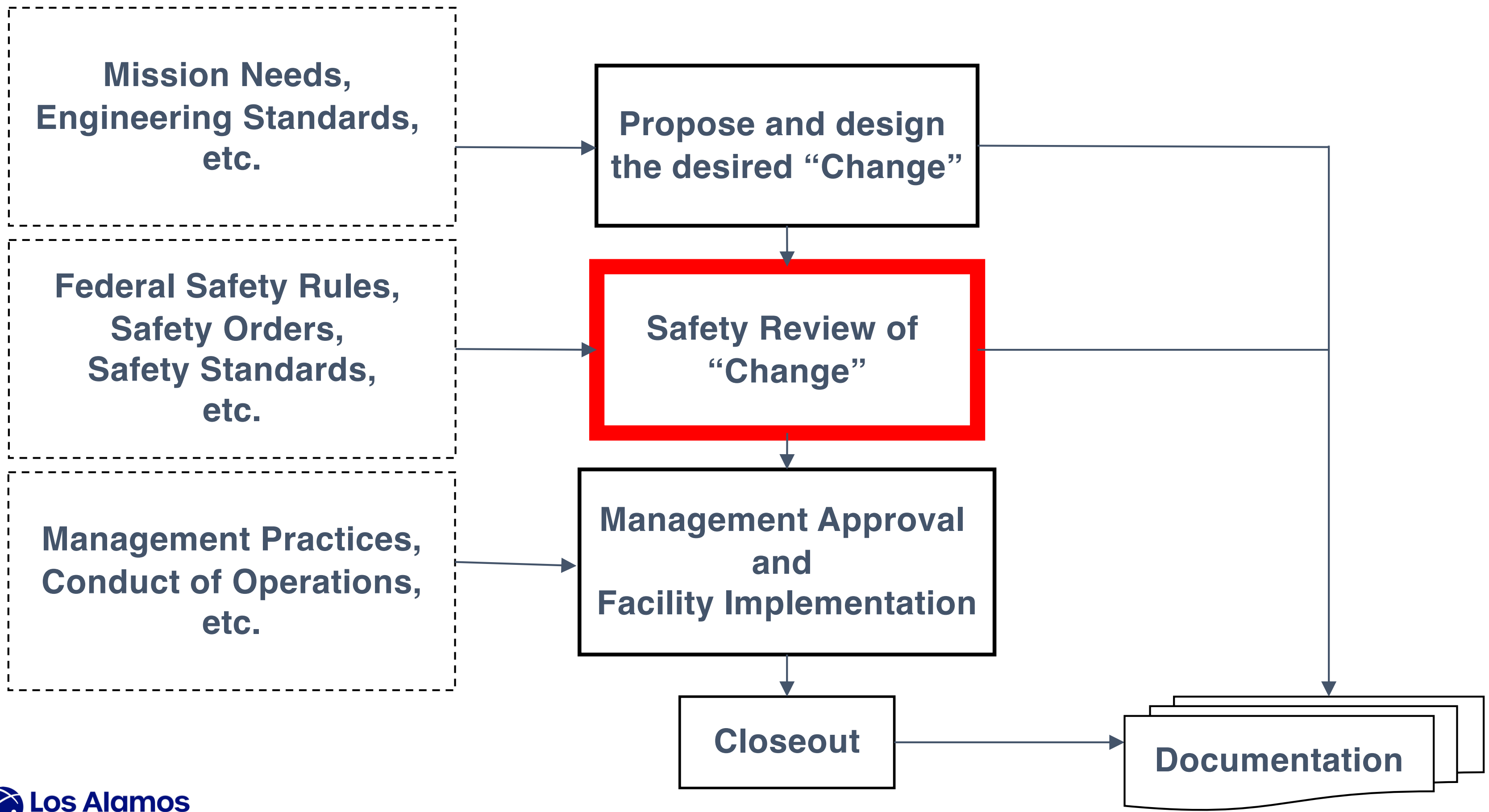
Rocky Flats had major plutonium-related fires in 1957 and 1969

- Initiated by plutonium's pyrophoric properties
- A key result was the inerting (nitrogen) of the glovebox lines in their main newly constructed facility that began operations in 1970

Mechanisms for mitigating the fire hazards

- Inert glovebox atmospheres, especially in areas where small particles/items of plutonium are generated (e.g., machining)
- Maximizing use of containers
- Reducing combustible materials in gloveboxes
- Fire suppression systems

Relationship between Design, Safety, and Implementation



Why We Need Radiation Protection

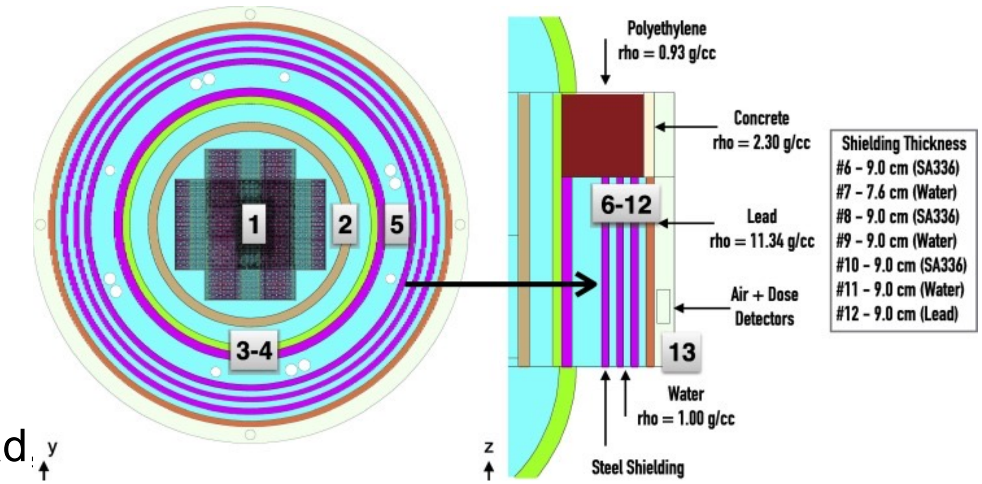
Radiation Protection

Maintain worker exposure as low as reasonably achievable (ALARA) by controlling:

- External Dose
- Contamination
- Airborne radioactivity

External Radiation Dose

- Minimizing **Time**
  - Mockup training
- Maximizing **Distance**
  - Long reach tools
- Using appropriate **Shielding**
  - Gamma – High density materials (lead
  - Beta – Thick piece of plastic, thin sheet of aluminum
  - Neutron – Hydrogenous material (water, concrete, polyethylene, etc.)
  - Alpha – Will not penetrate outer layer of skin



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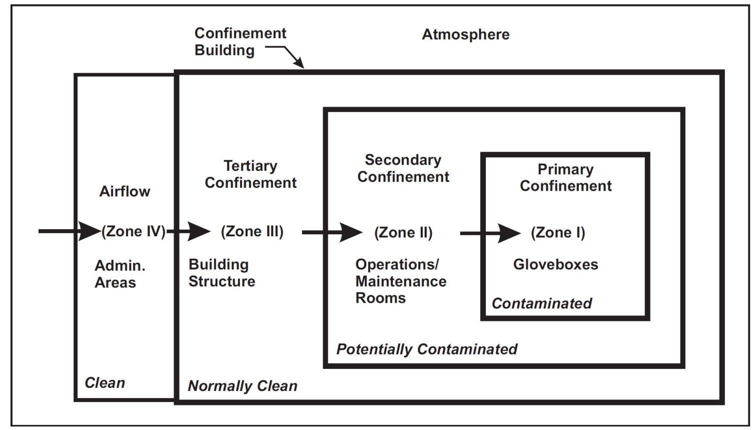
Contamination Control

- Engineered controls
  - Containments (Gloveboxes, glovebags, tents)
  - Localized ventilation (pull air down and away from the worker)
- Personnel Monitoring
  - Instruments used for detecting contamination prior to leaving the job-site, controlled area, and/or facility
- Personal Protective Equipment (PPE)
  - Gloves, coveralls, booties
  - Donning/doffing procedures
- Work practices
  - Decontaminate low to high
  - Survey newly exposed surfaces

Airborne Radioactivity

- Facility Ventilation Design
  - Differential pressure between areas of higher contamination and lower contamination
  - HEPA filtration
  - Separate systems for breathing air and contaminated areas (gloveboxes)



- Airborne monitoring equipment
  - Instruments continuously monitoring breathing air for radioactivity

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Dose Equivalent

- Absorbed Dose (D): Denotes energy absorbed per unit mass; Si units **Gy** [J/kg] or English **rad** [1.0E-2]
- Quality Factor (Q): Value assigned to quantify each type of radiation's biological damage, based upon that radiation's Linear Energy Transfer and Relative Biological Effectiveness.
- Dose Equivalent (H): Quantifies the biological risk associated from a given Absorbed Dose (D) with respect to the incident's radiation's Radiation Weighting Factor (Q); Si units **Sv** or English **Rem**.

$$H = DQ(N)$$

Note: N refers to any other modifying factors…a common example is dose fractionation.

Internal Dosimetry

- Tissue Weighting Factor (W_t) = Stochastic Risk associated with radiation damage to an individual organ.
- Committed Dose Equivalent ($H_{t,50}$) = The Dose Equivalent (D_t) an individual organ accrues during a 50 yr time frame due to an intake of radioactive material.
- Committed Effective Dose Equivalent ($H_{E,50}$) = The sum of all Committed Dose Equivalents multiplied by their respective Tissue Weighting Factors.

$$H_{E,50}=\sum(W_t H_{t,50})$$

Note: The sum of all Tissue Weighting Factors = 1

Derived Annual Concentration

- Annual Limit on Intake (ALI): Amount of a specific radionuclide, which if committed internally, would result in a dose equal to the limits set forth by the ICRP for each year of occupational exposure
  - 5 rem Whole-Body, 50 rem Individual Organ/Tissue.

- ALI for Stochastic (Whole-Body) (Bq/yr):

$$ALI \leq \frac{5 \text{ rem}}{\sum(W_t H_t{,}50) \text{ (per}-\text{intake unit activity)}}$$

  - Derived Annual Concentration (DAC): The concentration of a radioactive material that if inhaled, would result in a dose equal to the limits set forth by the ICRP for each year of occupational exposure.
  - DAC(Bq/m^3) = $\frac{ALI}{(\frac{2000hr}{yr})(\frac{1.2m^3}{hr})}$
  - DAC-hr: The integrated Dose Committed to an individual due to spending any amount of time (hr) in a given DAC field.
  - Knowing the ICRP Annual Stochastic Dose limit for Radiation Workers is 5 rem, we can derive that 1 DAC-hr = 2.5 mrem

Example Problem

- Jimmy is working in a 40 DAC field for 15 minutes with a general area dose of 15 mrem/hr photon. What is his Total Effective Dose Equivalent due to this job?
  - Hint: TEDE = Dose Dose External Exposure(1000 mg/cm^2) + Dose From Internal Exposure
  - Hint: Photon Radiation Weighting Factor = 1

$$\text{TEDE} = \frac{40\ DAC * 15\ min * 2.5\frac{mrem}{DAC-hr}}{(60\frac{min}{hr})} + \frac{15\frac{mrem}{hr} * 15\ min * 1}{(60\frac{min}{hr})} = 28.75\ mrem$$

Why We Need Safety Basis/Licensing

Safety Basis/Licensing

- Identify accident scenarios for which controls are necessary to prevent or mitigate doses to the Public
  - Source Term Development
  - Consequence Determination
  - Safety Controls Development

DOE Safety Basis Process Expanded

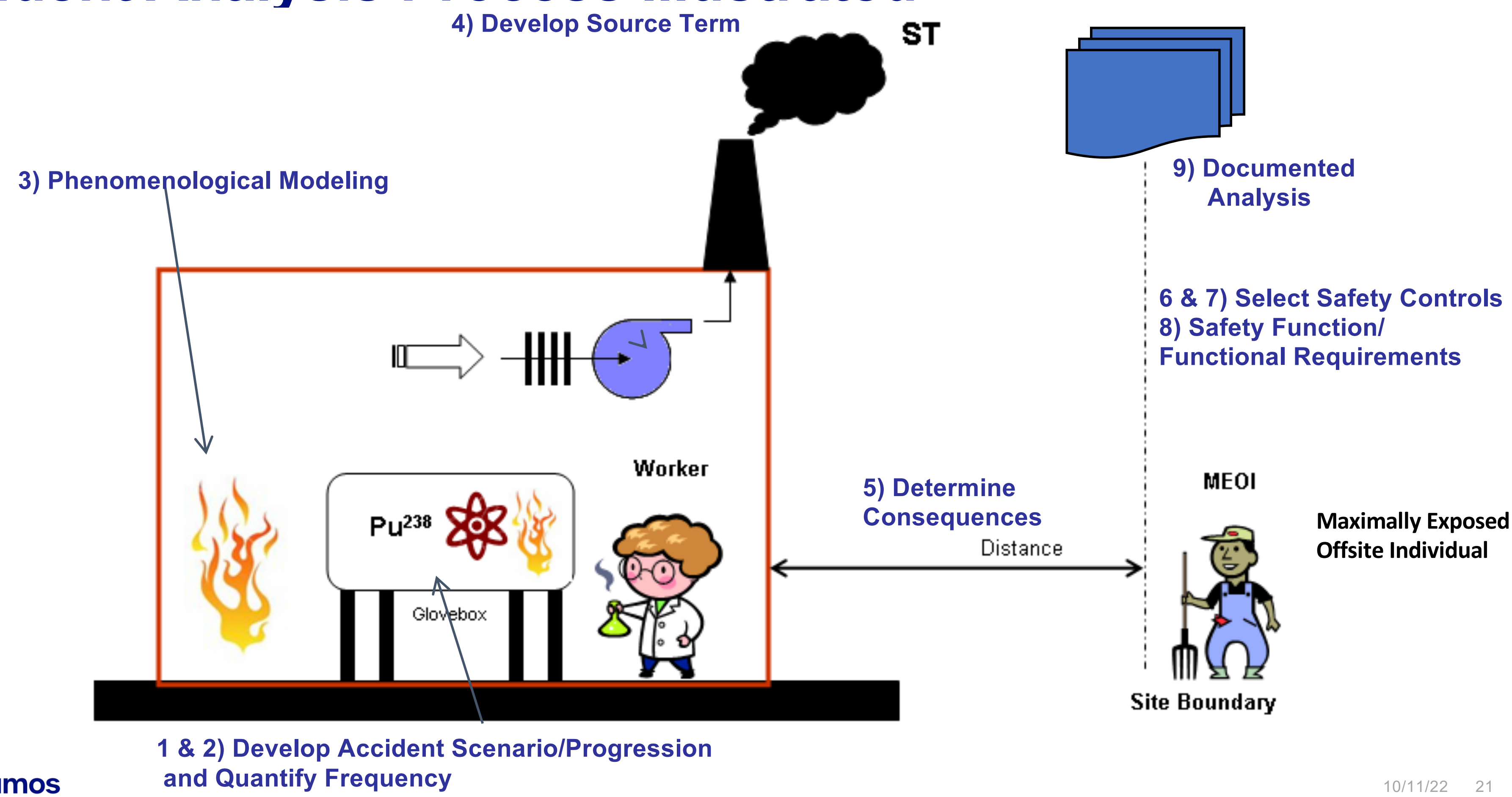
Safety Analysis

1. Develop Accident Scenario
2. Quantify Frequency
   Used for describing the logic of the accident progression
3. Perform Phenomenological Modeling
   IF/WHEN it is necessary
4. Develop Source Term (g, Ci)
5. Determine Consequence (dose)

Safety Controls

6. Does the Dose Consequence Challenge Evaluation Guideline?
7. Select Safety Controls
8. Define Safety Controls' Function and Functional Requirements
9. Documented the Results

Accident Analysis Process Illustrated



Source Term Analysis

The source term is the amount of respirable radioactive material released to the air either at the accident source or to the environment, depending on the target receptor. (DOE-HDBK-3010)

$$ST = MAR \cdot DR \cdot ARF \cdot RF \cdot LPF$$

MAR = Material-at-Risk (g, Ci)
DR = Damage Ratio
ARF = Airborne Release Fraction
RF = Respirable Fraction
LPF = Leak Path Factor

Consequence Determination

Our measure of consequence is typically the chronic radiological dose received from the inhalation of radionuclides by a hypothetical Maximally Exposed Offsite Individual.

$$\mathbf{Dose = ST \cdot X/Q \cdot BR \cdot DCF \cdot SA}$$

ST	= Source term (developed previously) (g or Ci)
X/Q	= Dispersion coefficient (s/m^3)
BR	= Breathing rate (derived from ICRP, FGR)
DCF	= Dose conversion factor (from ICRP, FGR)
SA	= Specific activity

- SA Not Needed if ST in already in units of Ci

Safety Controls Selection

Alan Swain giving of the Christensen Safety Control Hierarchy (Training Course on Prevention of Significant Nuclear Events, US DOE June 25-27, 1986) for designing safety into the operation

– Design the System	(Strongest) (Passive Engineered)
– Remove the Human	
– Guard the Hazard	↓ ↓ ↓ ↓
– Warn Personnel	
– Train the Operator	(Weakest) (Administrative)

Why We Need
Nuclear Criticality Safety

Nuclear Criticality Safety

Nuclear criticality safety is a multifaceted discipline with three major components

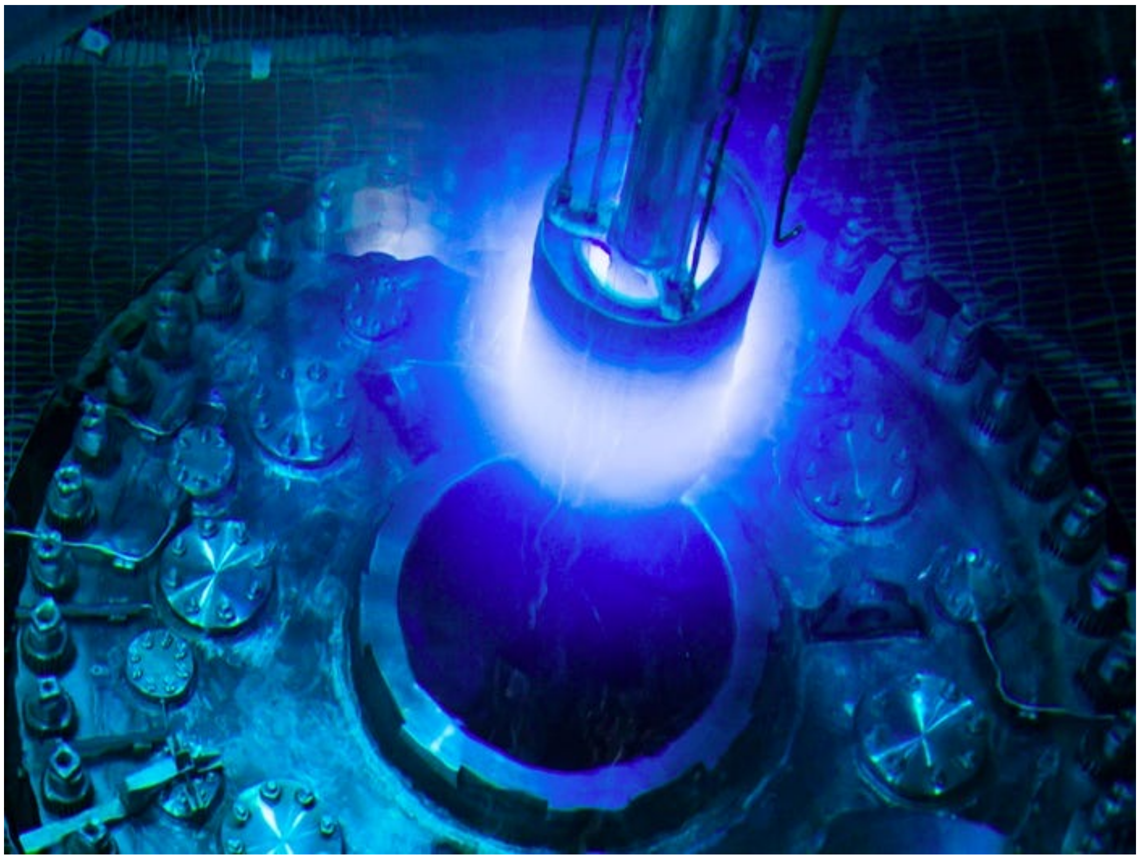
- Neutron physics,
- Engineering, and
- Administration.

Only with proper interaction among the three can the ultimate safety goals be expected to be met.

- Knief, *Nuclear Criticality Safety (1985)*, p. 4

- Alcorn, NCS - *Current Theory and Practice*, **ANS Topical Mtg** (1975)

What Does a Bunch of Neutrons Looks Like



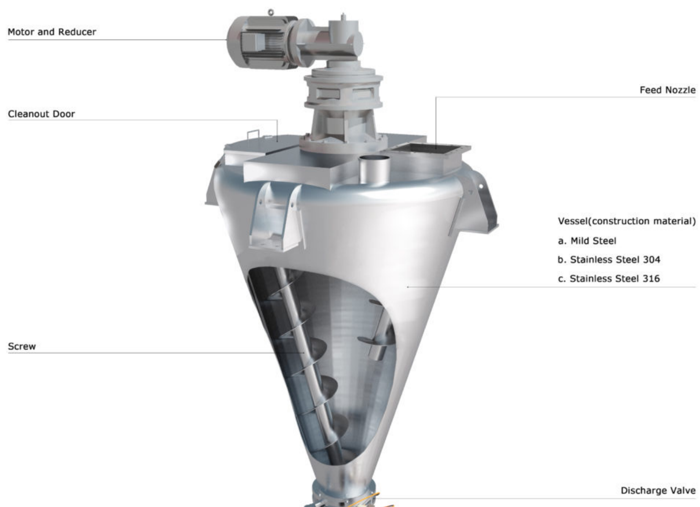
Cherenkov radiation (blue) emanates from spent fuel being removed from the High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory. Oak Ridge National Laboratory

It basically boils down to this:
"The science is easy.
The engineering is hard."
– Gougar, Petti at INL

Less Dramatic – But of Equal Concern

Plutonium ring after refining

UO_2 Powder Homogenization & Blending



https://www.incmachine.com/products/conical-screw-mixernauta-mixer/

https://www.youtube.com/watch?v=iuCkwX_Zwhc

Population of Neutrons

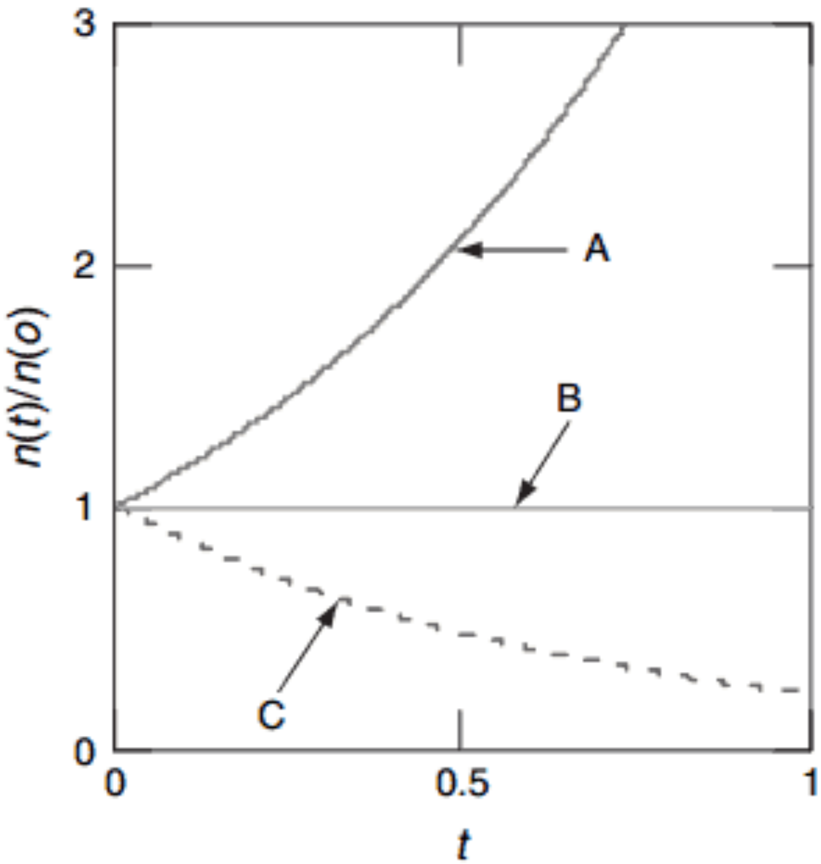
$$\Delta\, k_{eff} = k_{eff} - 1$$

$$\frac{dn}{dt} = n_o \frac{\Delta k}{l}$$

l = average n lifetime
~10^{-6} for fast reactors
~10^{-4} for thermal reactors

$$Power \;\approx neutron\; flux \;\approx n(t) = n_o e^{\left(\frac{\Delta k}{l}\right)t}$$

Simple Power Curve of a “Reactor”



Six Factor Formula

$$k = \eta \varepsilon p f P_{FNL} P_{ThNL}$$

Where:

η = number of n produced per n absorbed in fuel

ε = fast fission factor

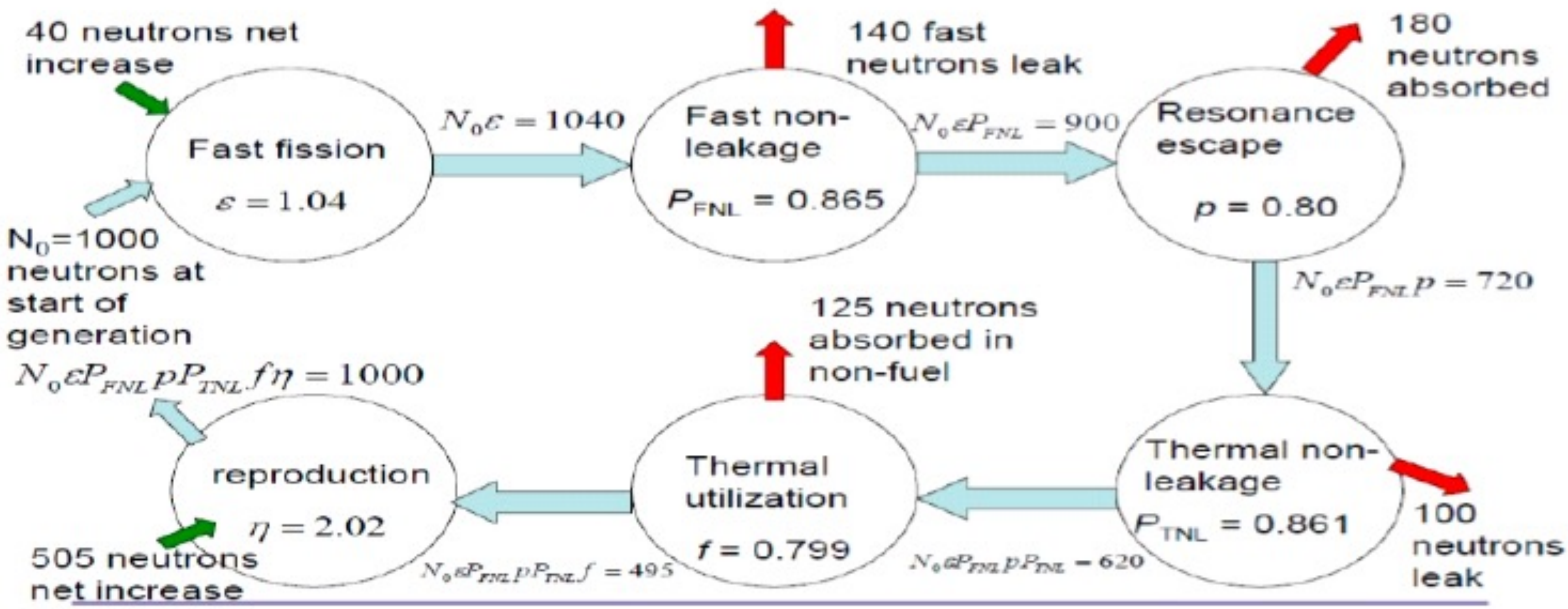
p = resonance escape probability

f = thermal utilization

P_{FNL} = fast neutron nonleakage probability

P_{ThNL} = slow neutron nonleakage probability

Six Factor Formula



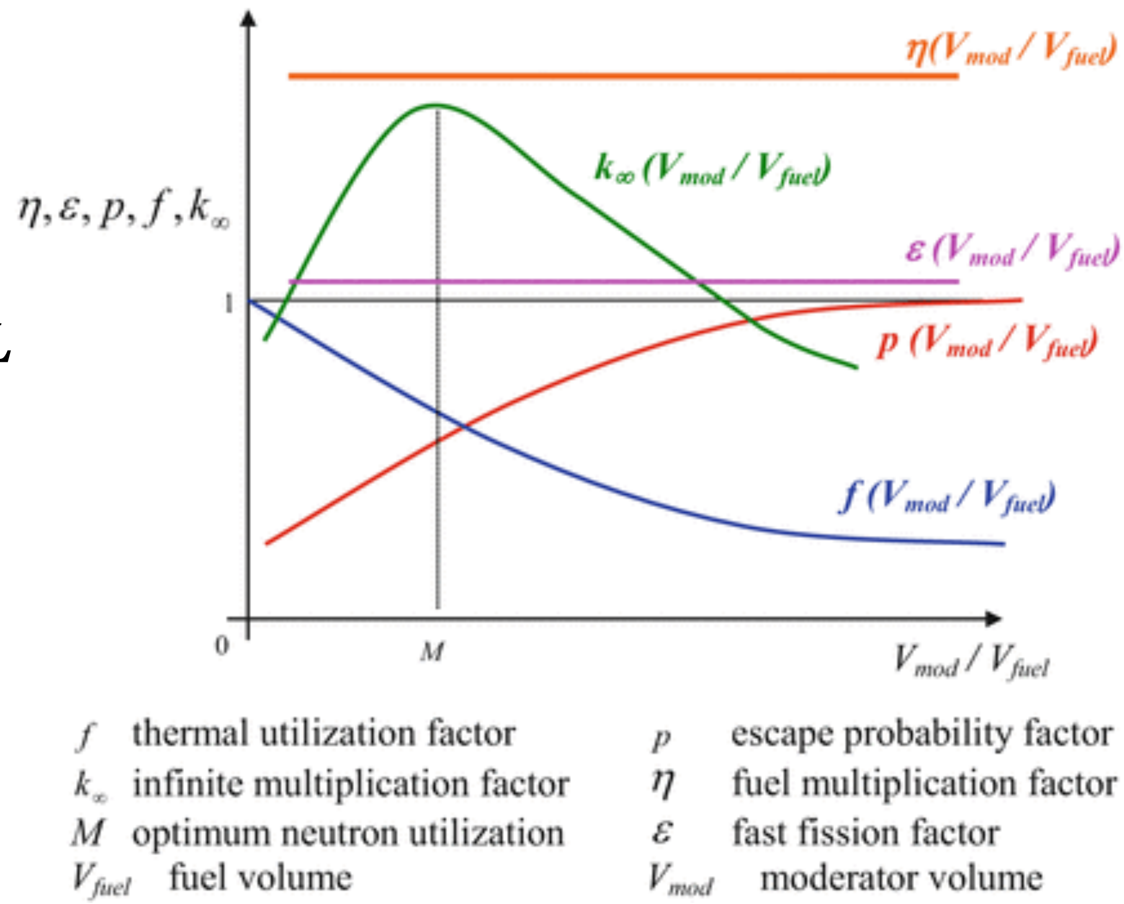
Fast n ~ 2Mev
Thermal n ~ 0.02eV

Taken from: Conceptual Study and Analysis of Neutron Diffusion and Moderation in Nuclear Reactor, T. Mollik, M.M. Hossain, et. al.

Six Factor Formula

$$k = \eta \varepsilon p f P_{FNL} P_{ThNL}$$

Taken from: Nuclear Reactor Reactivity,
Serge Marguet , Figure 11.9



Two Factor Formula

$$k_{eff} = \frac{Neutron\ production\ rate}{Neutron\ loss\ rate}$$

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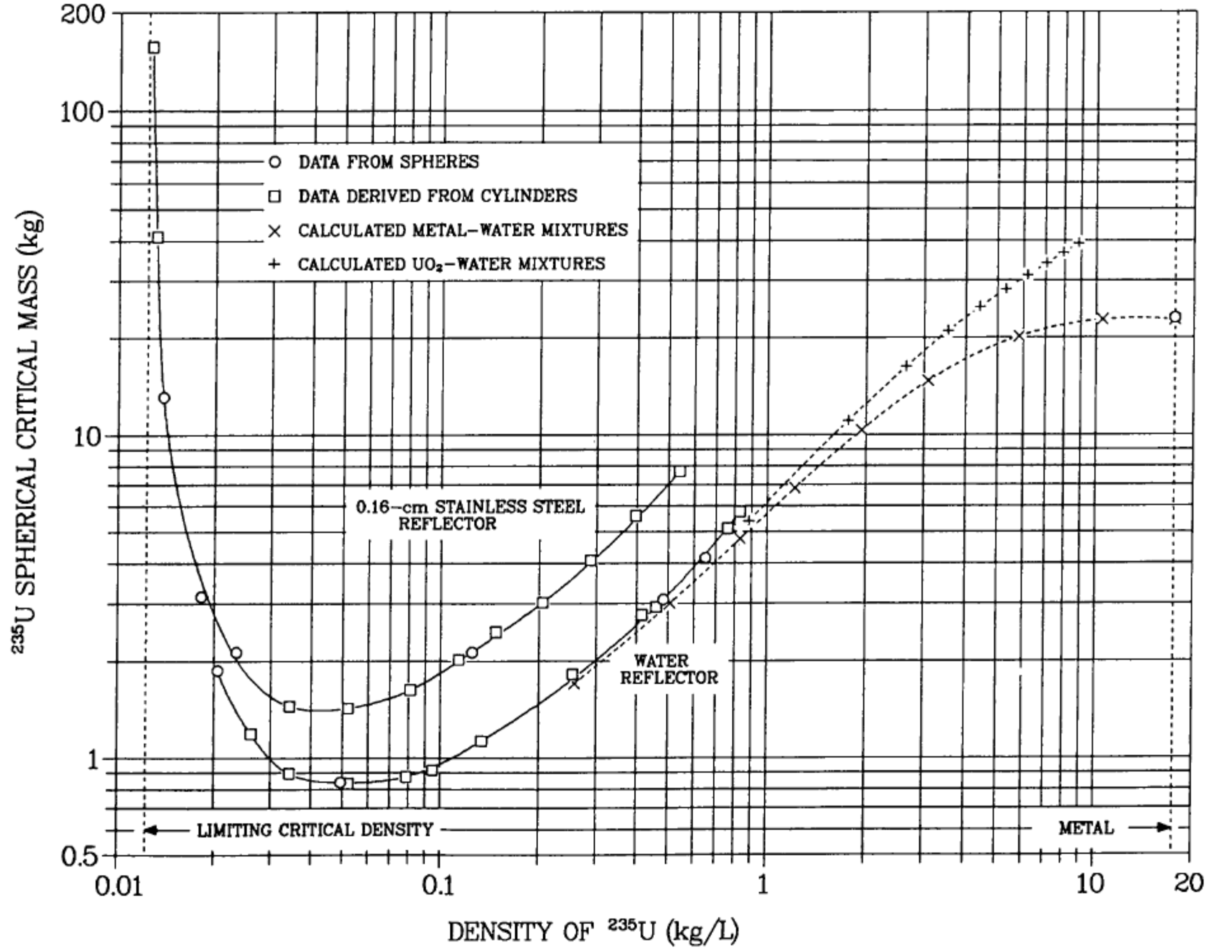
K-eff in Terms of Parameters

PARAMETER	n PROD	n LOSS	AFFECT ON K		
			WHEN PARAMETER ↓	OPTIMUM	WHEN PARAMETER ↑
MASS	X		↓		↑
DENSITY		X	↓		↑
ENRICHMENT/ASSAY	X		😃	😃	😃
ABSORPTION	X	X	😃		😃
VOLUME		X			↓
GEOMETRY/SHAPE		X	↓	😃	↓
REFLECTION		X			↑
SPACING		X	↑	😃	↓
MODERATION (CONCENTRATION)	X	X	🤬	🤬	🤬

NCS Controls Development

Parameter	Subcritical Limit	Process Change	Safety Control/ Implementing Measure	Quality Control (Type of Control)
NCS parameter	Limit from Reference or MCNP	From hazard analysis	Control that will prevent/mitigate the process change	Engr or Admin
Mass	< 4,500 g Plutonium	Operator brings in too much mass	Batch sizes are established upstream	Administrative
Geometry	Solution diameter < 5-in diameter	Operator adds too much mass	Tanks are <4-in diameter	Engineered
Etc.	Etc.	Etc.	Etc.	Etc.

Why Moderation is the BANE of NCS - URANIUM



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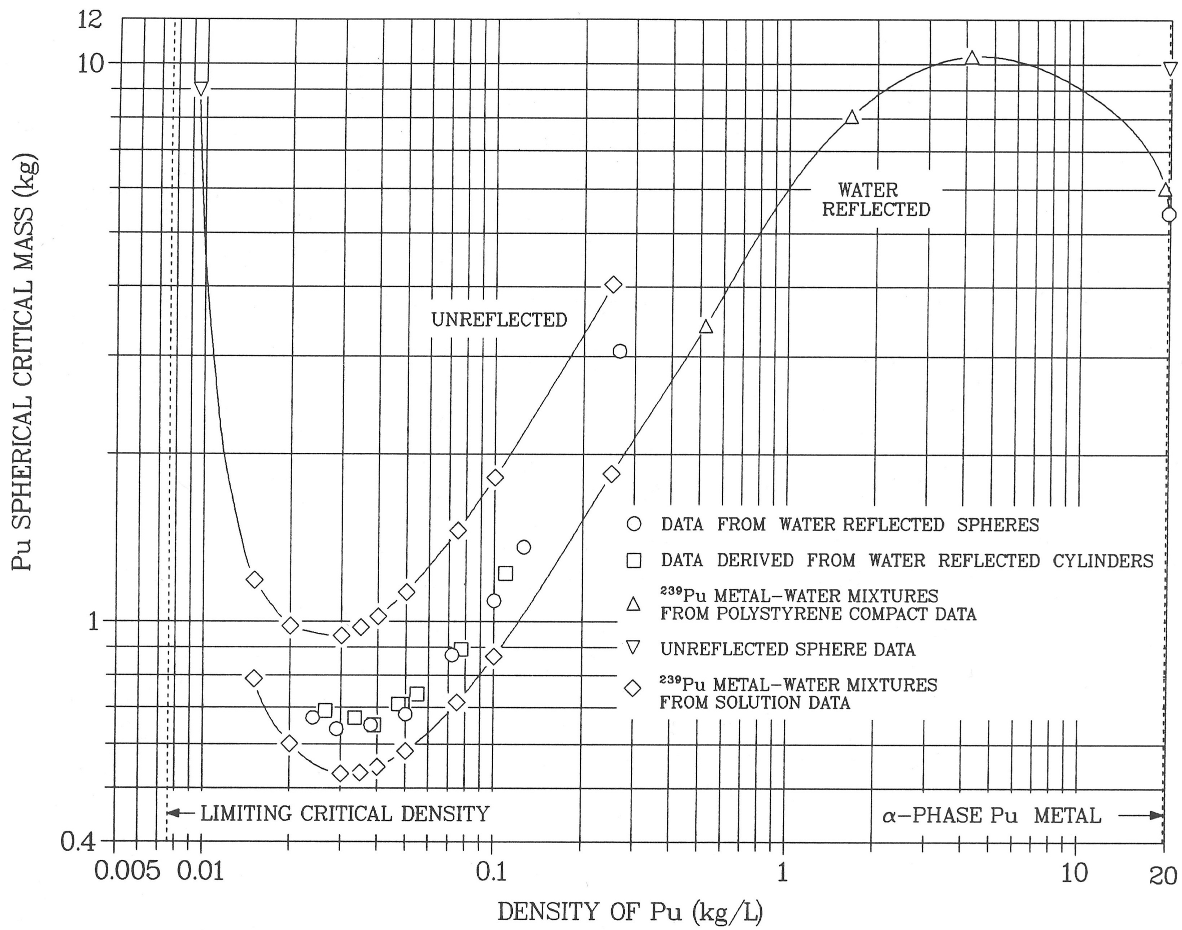
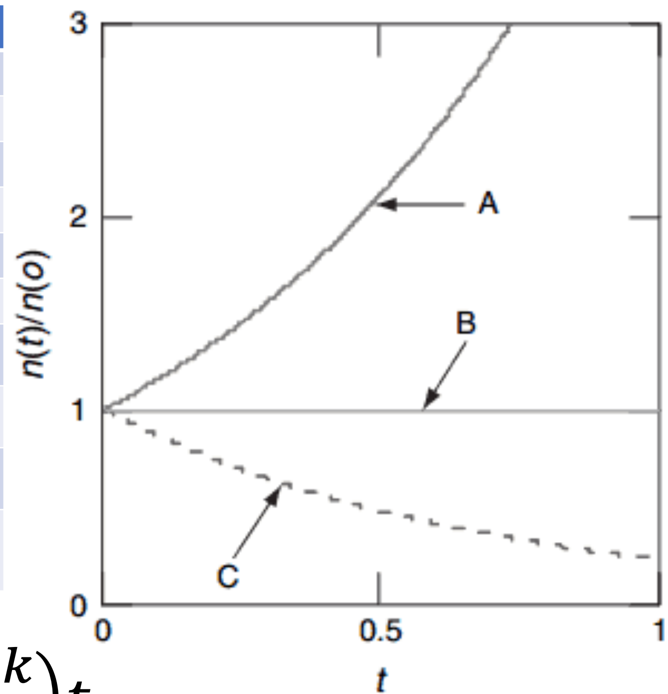
Why Moderation is the BANE of NCS - PLUTONIUM



Tying it Back to Controlling Neutrons

PARAMETER	n PROD	n LOSS	AFFECT ON K		
			PARAMETER ↓	OPTIMUM	PARAMETER ↑
MASS	X		↓		↑
DENSITY		X	↓		↑
ENRICHMENT/ASSAY	X				
ABSORPTION		X			↓
VOLUME		X			↓
GEOMETRY/SHAPE		X	↓	😃	↓
REFLECTION		X			↑
SPACING		X	↑	😃	↓
MODERATION (CONCENTRATION)	X		🤬	🤬	🤬



$$Power \approx flux \approx n(t) = n_o e^{\left(\frac{\Delta k}{l}\right)t}$$

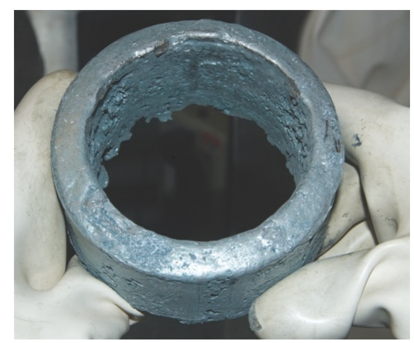
Nuclear Safety Controls In Action

Material Supply: Metal Preparation

- Plutonium purification is mainly performed via pyrochemistry (high-temperature, molten-salt, environment). Purification is primarily related to
  - Americium (Am-241) removal (to reduce subsequent worker radiation exposure) via metal chlorination
  - Removal of “everything else” via electrorefining (ER)

Metal chlorination salt containing 3-5% Am and remainder Pu

ER setup (left to right): Crucible, salt, feed metal, $PuCl_3$



ER ring of purified Pu metal

Material Supply: Aqueous Recovery

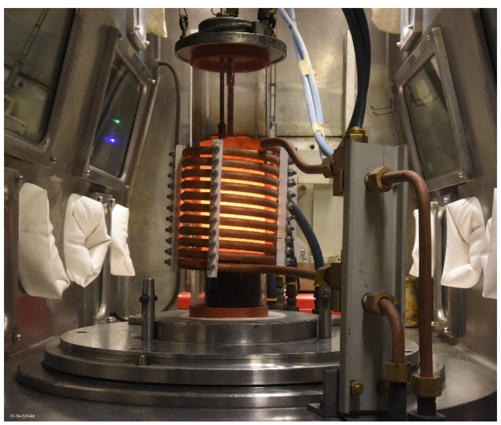
- Pyrochemical operations produce chloride-based residues and other oxides that contain sufficient plutonium to warrant recovery by traditional chemical (aqueous) means.
  - Nitrate recovery: generally, for oxides. Uses dissolution, ion exchange, oxalate precipitation, and calcination.
  - Chloride recovery: generally, for chloride salts. Dissolution, solvent extraction, oxalate precipitation, hydroxide precipitation, and calcination.

Nitrate dissolution vessel and ion exchange

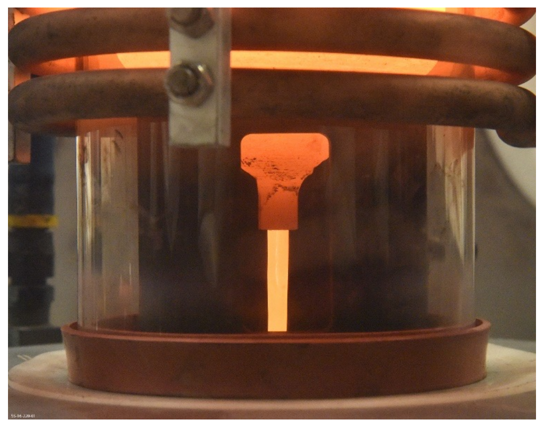
Chloride dissolution vessel, oxalate cake, and calcined oxide

Foundry

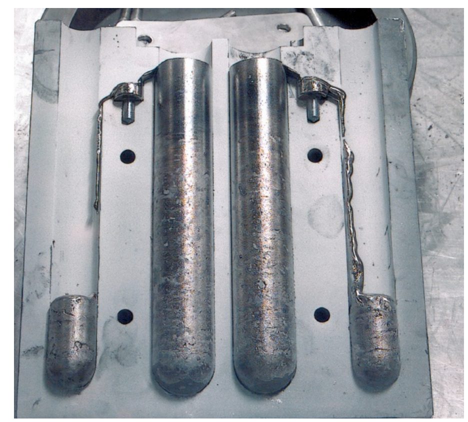
- Similar to any commercial foundry, the primary processes are
  - Casting
  - Heat treatment
- Casting primarily involved ingots, rods, and components



Melt vessel



Plutonium pour



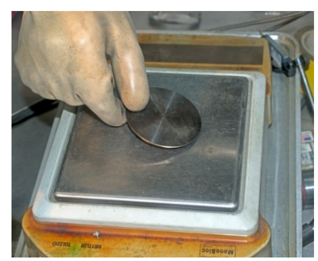
Mold breakout showing product (rods)

Machining and Inspection

- Similar to any commercial machine shop, the primary processes are
  - Lathe and mill metal cutting, often with computer-numerical controlled (CNC) systems
- Various dimensional and other inspections
- Machining generates the fine plutonium materials that must be handled carefully, and in inert atmospheres (e.g., argon, nitrogen), to mitigate plutonium's pyrophoricity.

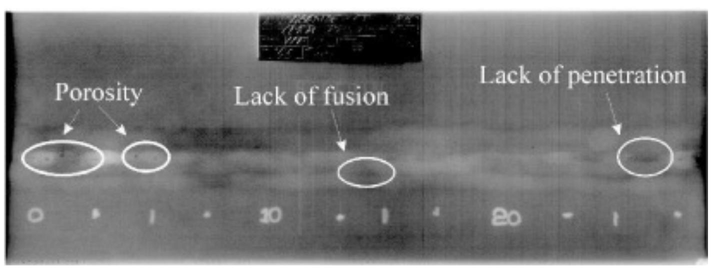
Plutonium item machining and resultant machining turnings

Types of dimensional inspections and mass measurement

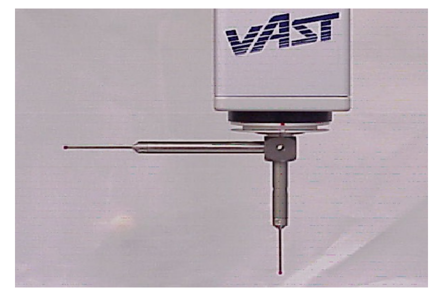


Post-Assembly/Nondestructive Testing (NDT)

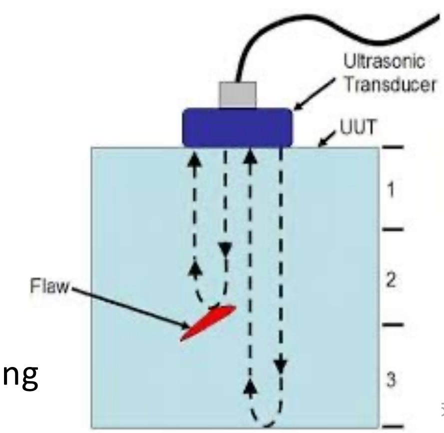
- After assembly and joining, the component undergoes a suite of analyses to ensure it is of sufficient quality.
  - Leak testing
  - Radiography
  - Dye penetrant testing
  - Dimensional inspection
  - Ultrasonic testing
  - Weighing



Sample radiograph of a weld region



Coordinate Measuring Machine (CMM) & probes



Conceptual operation of ultrasonic testing

Why We Need Nuclear Safety

BECAUSE

Nuclear technologies provides exciting

real world solutions

for **real world challenges**

that we will continue to pursue. Hence, we have a **professional obligation to do so safely.**

COROLARY

In order to support Nuclear –

effective Nuclear Safety Professionals are needed.