SAND2015-3430PE

NCSP
NUCLEAR CRITICALITY SAFETY PROGRAM

United States Department of Energy
Nuclear Criticality Safety Program (NCSP)

Hands-On Training

Water Moderated Critical Experiments
Sandia National Laboratories

SAND2015-XXXX

NCERC NATIONAL CRITICALITY EXPERIMENTS RESEARCH CENTER

Oak Ridge National Laboratory

Sandia National Laboratories

Lawrence Livermore National Laboratory

Los Alamos NATIONAL LABORATORY

NUCLEAR CRITICALITY SAFETY PROGRAM

Module 00
Course Logistics

Presented by:

Gary Harms

Logistics

- Restrooms
- Emergency Exit/Meeting Point (6585 and TA-V)
- Schedule for the Week
  - Start at 8:00 AM Tuesday through Friday
  - Lunch at about 12:00 PM for 1 hour
  - Finish around 5:00 PM

Administrative Specialists

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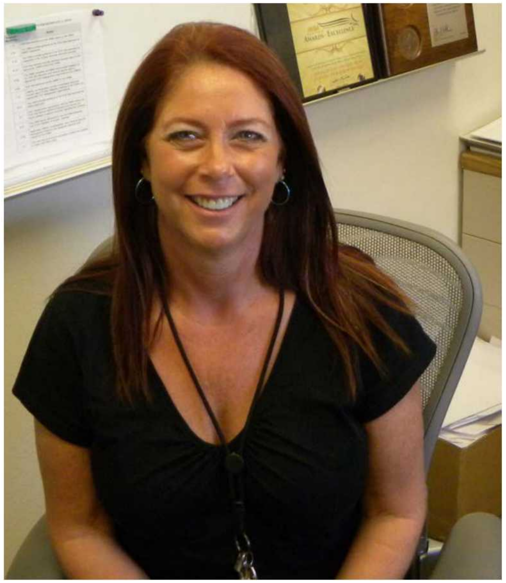
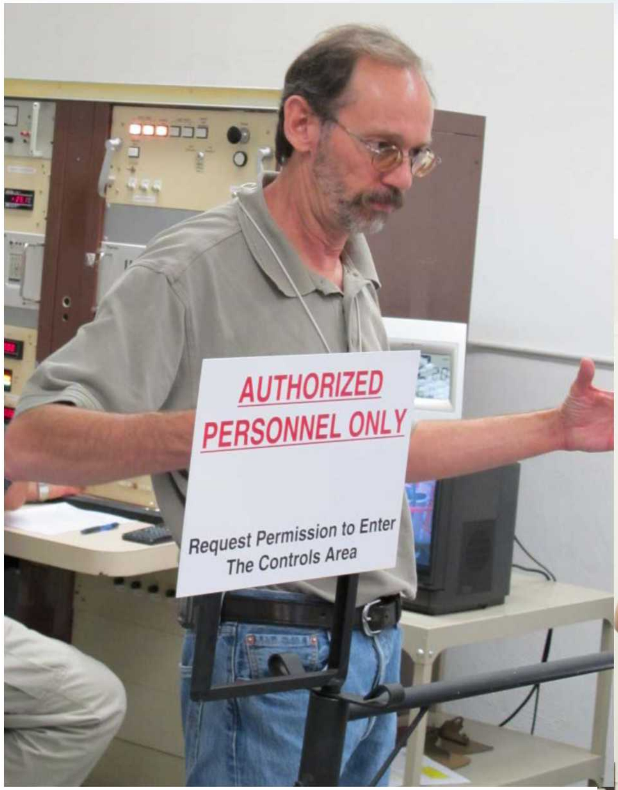


Nancy Collins

Operations

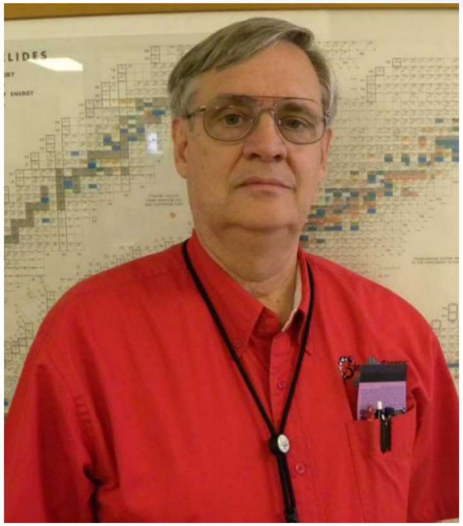


John Ford

Rafe Campbell

?

Instructors



Ron Knief

John Miller

Shean Monahan

Kerstan Cole

Experimenters

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?

Class Contacts

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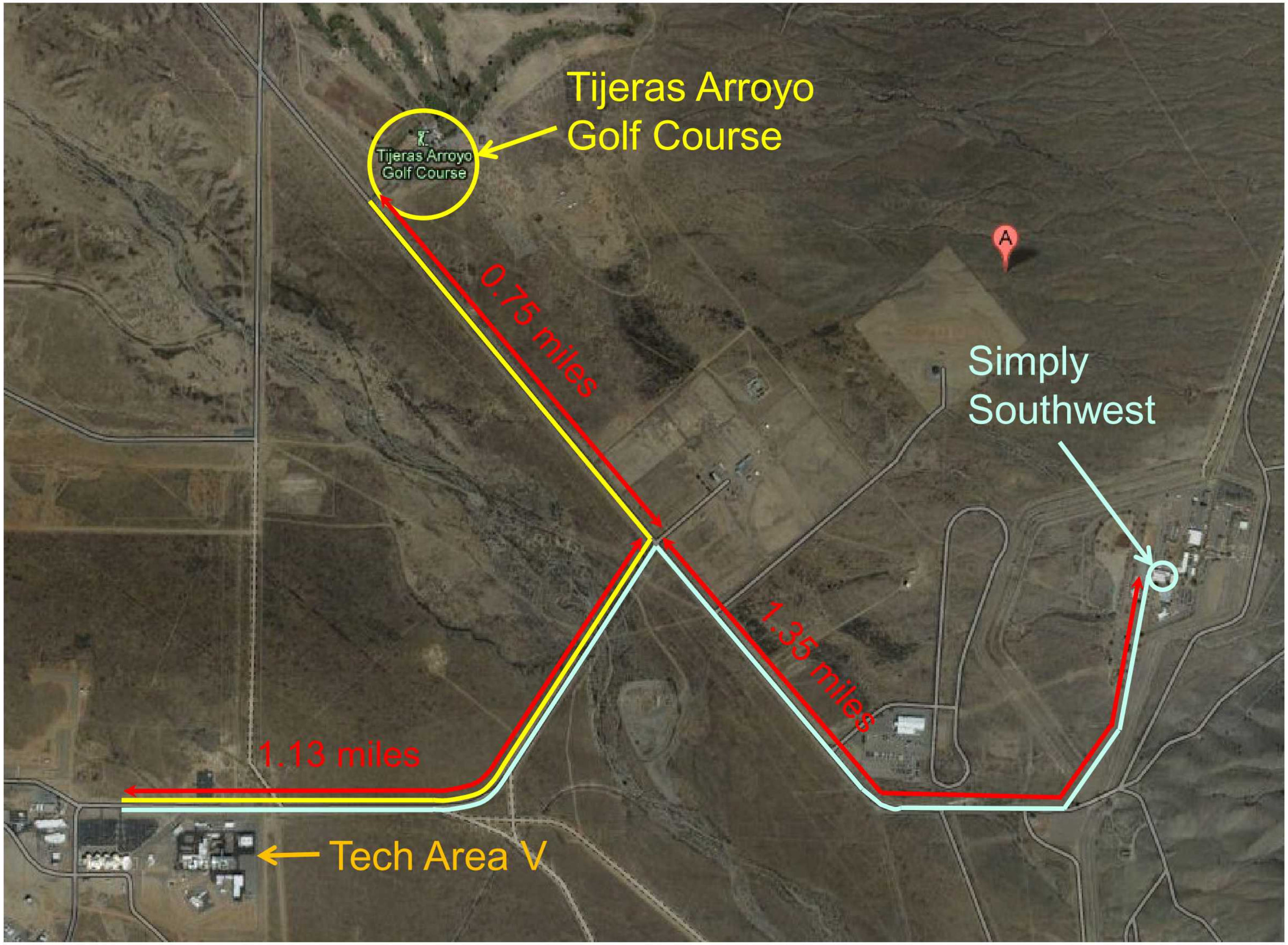
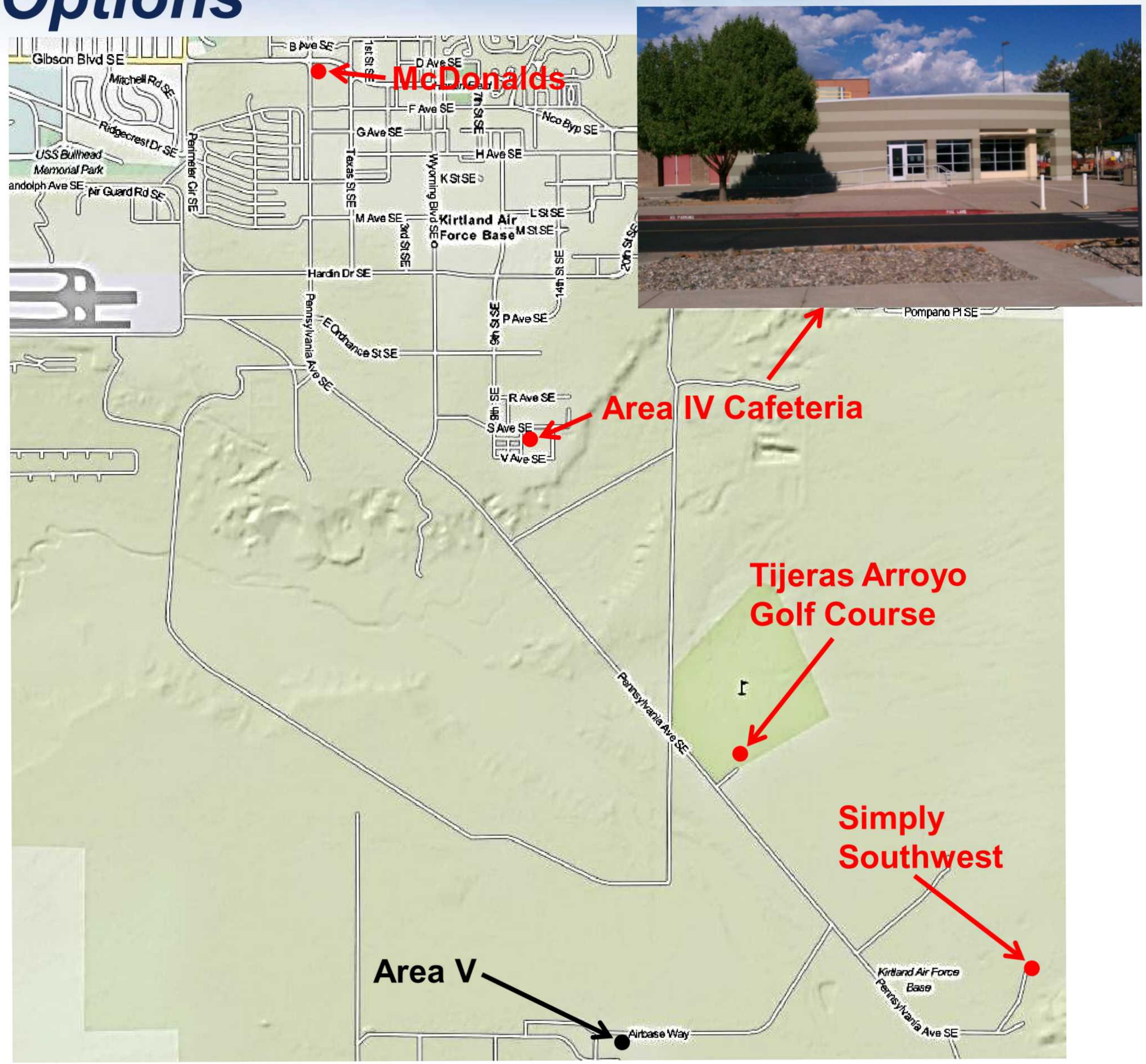
Lunch Options

- Tijeras Arroyo Golf Course (1.9 miles)
  - Golf course food: burgers, hot dogs, etc.
- Simply Southwest (2.5 miles) – **cash only**
  - New Mexican grill food: burgers, burritos, sandwiches, salads, green chile stew, etc.
- Area IV Cafeteria (4.3 miles) – **cash only**
  - Sandwiches, salads, soup, burritos, etc.
- McDonald’s (5.5 miles)
- BYO (0 miles)
  - Refrigerator and microwave are available

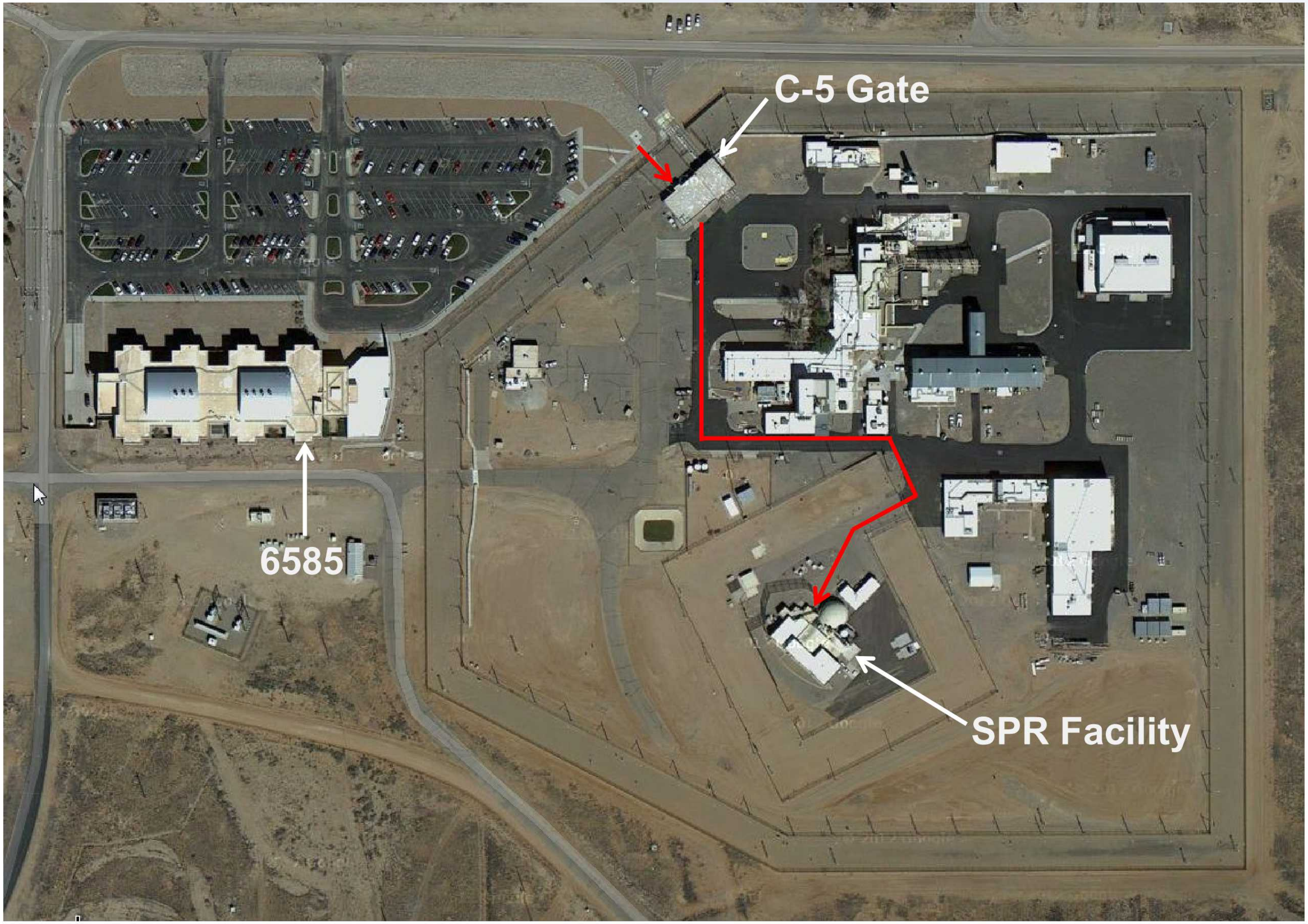
Lunch Options



Lunch Options



Access to the Experiment Facility



COURSE SYLLABUS

Tuesday, May 5, 2015		
	Module 00	Logistics
	Module 01	Fundamentals of Nuclear Criticality Safety
	Module 02	Criticality Accidents (Introduction)
	Module 03	Design of Sandia Critical Experiment
	Module 04	Human Factors
	Module 05	Approach on Fuel Loading
	Accidents	Accidents (4,6)
Wednesday, May 6,2015		
	Module 06	Conduct of Operations
	Module 07	Experiment 2 – Approach on Water Height
	Module 08	Experiment 3 –Fuel Separation Effects
	Accidents	Accidents (9,11,14, 3, 5, 17, 20)
Thursday, May 7, 2015		
	Module 09	Review of Experiments
	TOUR	Tour of TA-V (Reactor Facilities and Criticality Safety Areas)
	Exam	Closed Book Exam

TESTING!!

- There will be a closed-book exam on Friday
  - It could cover any of the material presented in the course
  - All test questions are covered throughout the week
  - Please ask questions about any of the material
- Final grade is determined based on the exam (70%) and class participation (30%)
- An overall grade of 80% is required to pass the course

Survey

- Turn-about is fair play
- Survey is for you to grade us
  - Included in your notebook with envelope to mail or feel free to hand to any instructor at the end of the course
- We will use your responses to improve the course
- If you have real-time feedback, please don't hesitate to speak up

NUCLEAR CRITICALITY SAFETY PROGRAM

Module 1

Nuclear Criticality Safety Fundamentals

Presented by:
Shean P. Monahan

Rapid Development & Challenges

1932	Neutron Discovered
1939	Fission Discovered
1942	First Chain Reaction (CP1)
Hanford Plutonium Production	
1943	Construction Started
1944	Reactor Operation
1945	3 Reactors, Pu Processing
Oak Ridge Isotope Separation	
1943	Construction Started
1945	Diffusion Plant Operation

Early Safety Challenges and Philosophy

- Oppenheimer established safety as the responsibility of group leaders and supervisors
  - Criticality safety was a major concern
    - critical parameters were largely unknown
    - measurements had to be made for designing
      - weapons
      - process equipment
      - material staging and transport
      - SNM assemblies were hands-on
- Everyone had a real appreciation for

Risk versus Benefit

Safety

- Attitude & common sense
  - Institutional management
    - responsible for overall safety
    - provide resources for safety program implementation
  - Line Managers
    - responsible for safety of operations under their control
    - safety cannot be controlled remotely
      - encourages the attitude “someone else is responsible”
    - must seek guidance from appropriate safety professionals
  - Implementation
    - employ people with the right safety attitude
    - facilitate efficient operations through effective systems
    - effective formality of operations
      - particularly procedures (ConOps) and training

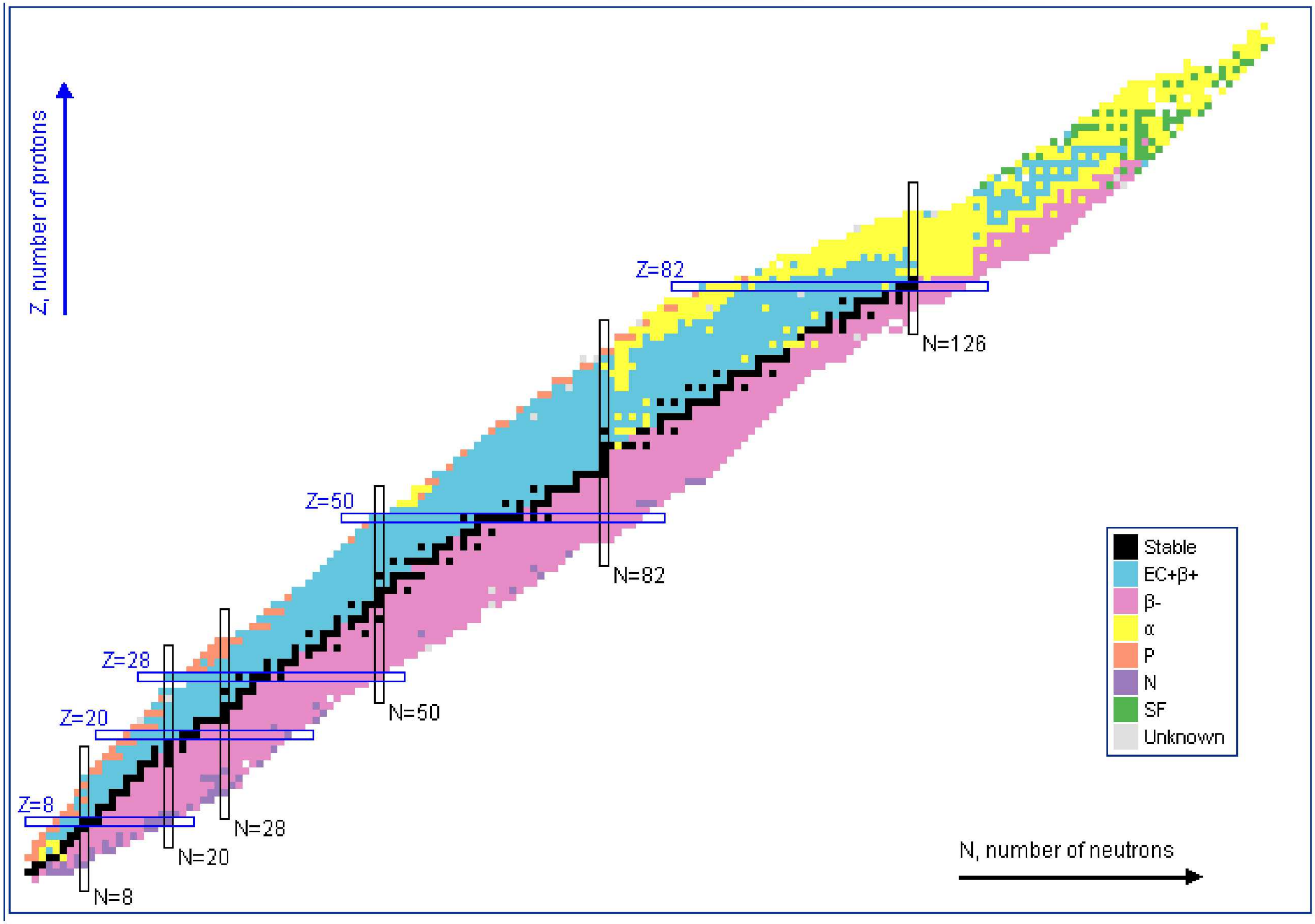
Governing Philosophy

- Safety has no meaning when isolated from other goals
  - risks and benefits must be balanced
  - **practical** and **economic** considerations still apply
  - risk can not be eliminated
    - It is dangerous to think that it can!
  - Supervisors (closest to operations) must have the responsibility and authority over safety provisions
    - simple & convenient safety provisions are preferred over complex or awkward arrangements
  - Workers have a responsibility to themselves and their co-workers
    - follow procedures
    - stop work if the procedures cannot be followed

Radiological Safety vs Nuclear Criticality Safety

- Thousands of radioactive materials (isotopes)
  - most exist in nature; some are artificial
  - all pose a hazard to human health
    - each one is unstable and emits radiation (α,β,γ,n) at predictable levels
    - damages the human body at the cellular level
- Radioactivity **cannot be altered** by physical properties or the environment
  - mass, volume, geometry,
  - temperature, pressure,
- Personnel protection is effective via simple rules
  - Time
  - Distance
  - Shielding

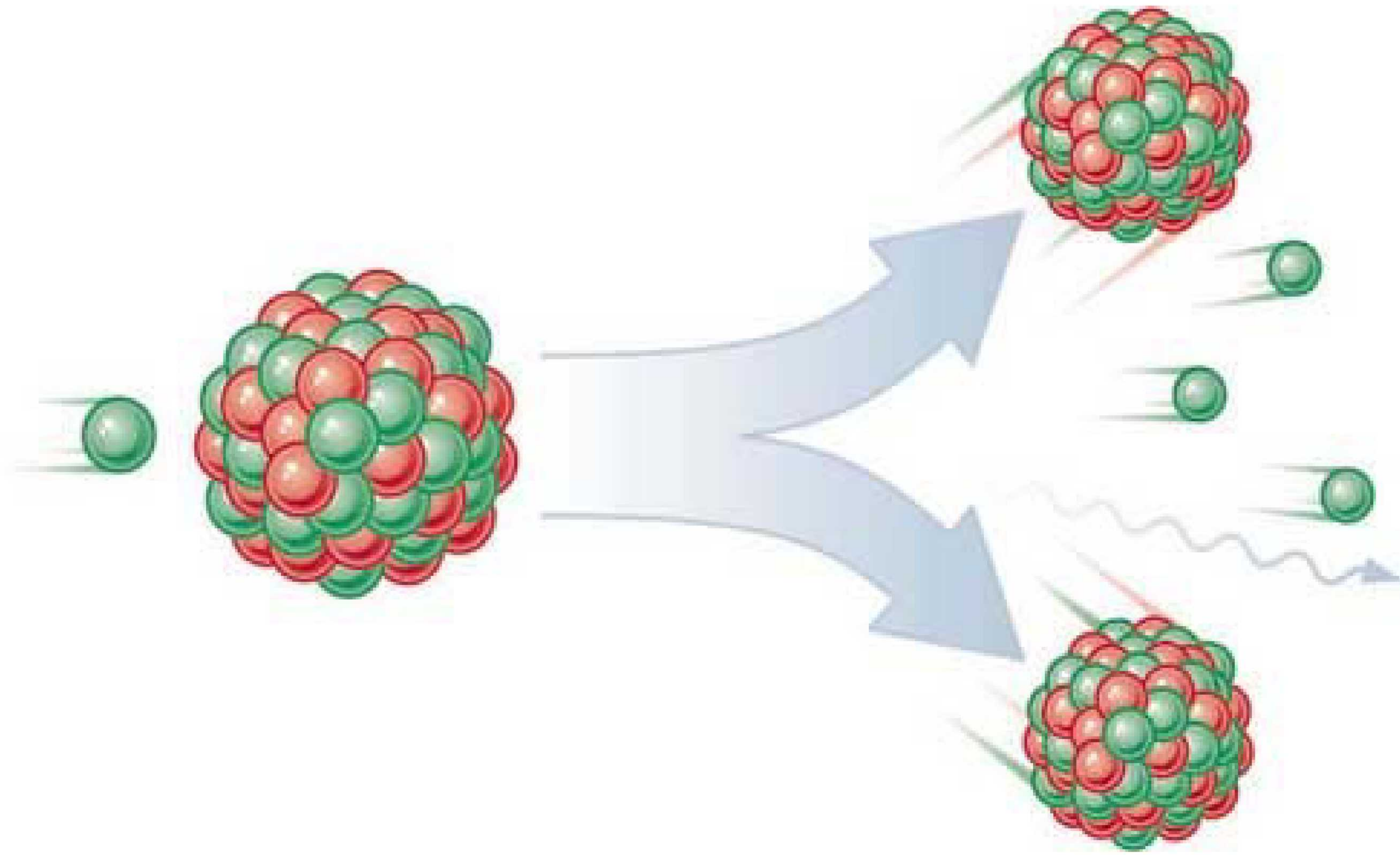
Chart of the Nuclides



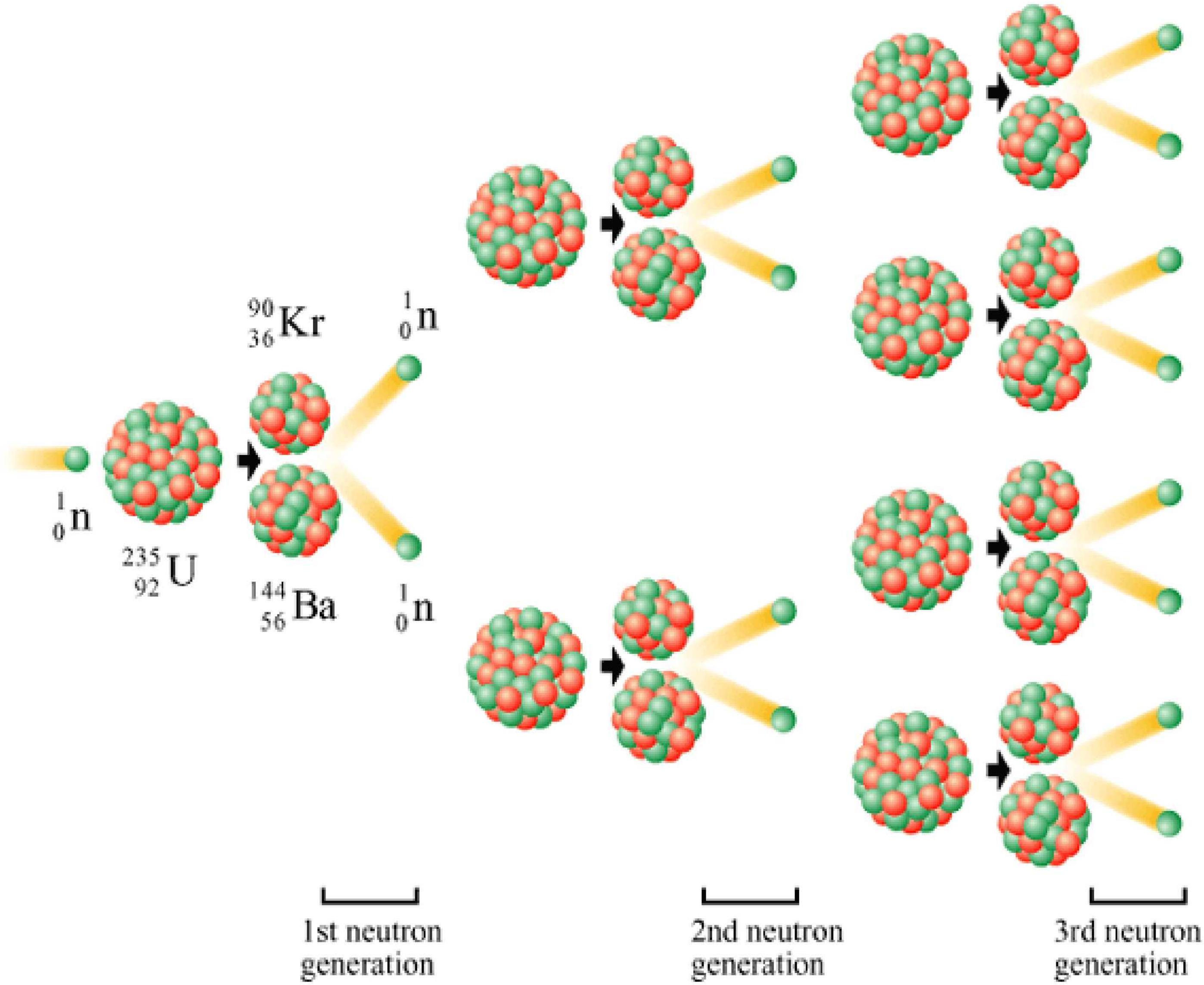
Fission

- A subset of these materials also “fission”
  - uranium and plutonium are the most common in the NNSA
- Fission is NOT a radioactive decay process
  - it is caused by particles striking the nucleus
    - e.g., neutrons
  - As such, **<u>it can be altered</u>** by physical and environmental properties
    - Mass, volume, geometry, temperature, pressure, etc.
- Furthermore because fission releases new neutrons
  - it is possible for fission to feed itself
  - chain reactions can result
    - large energy release, in the form of radiation, is possible
    - life threatening to personnel and organisms *nearby*

Fission Conceptually



Chain Reaction In Concept



Chain Reactions

- Self-sustaining chain reactions that occur at a time and place of our choosing are known as:

Nuclear reactors

Critical assemblies

Nuclear Weapons

- Self-sustaining chain reactions that occur during the handling (transport, processing, storage) of fissionable materials are known as

Criticality Accidents

Criticality Safety

Protection against the consequences of a criticality accident, preferably by prevention of the accident

- It is no different than any other safety discipline
  - Implementation at the floor level is by procedures and controls
  - Underlying principles can be complex and counter to *rational judgment*
    - Adding or removing water from fissionable material may be both be unsafe
    - Effects of adding non-fissionable material are not always straightforward
    - Behavior of material may change depending on its distribution and location
- Criticality safety evaluations establish controls for avoiding a self-sustaining chain reaction under both
  - normal &
  - **CREDIBLE** abnormal process conditions

The Atom

- Electrons around a nucleus of protons/neutrons
  - Protons have +1 charge
    - symbol Z
    - ^{1}H has one proton & 1 electron
    - ^{235}U has 92 protons & 92 electrons
    - ^{239}Pu has 94 protons & 94 electrons
  - Neutrons have no charge,
    - symbol N
    - determine nuclear behavior
      - radioactivity and interactions (fission, scattering, etc.)
      - ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu (Isotopes)
  - The sum of the protons and neutrons is the Atomic Number
    - $A = Z + N$
    - Essentially the mass of the nucleus

The Nucleus

- Should "not exist"
  - Protons repulse one another
    - Ordinarily this would destabilize a nucleus
    - *Strong nuclear force—glue between protons/neutrons*
      - Overcomes the electrical repulsive force
      - However, its acts only over ~10^{-15}m
        - 1 to 2 protons/neutrons
      - As nuclei get heavier more neutrons are needed to overcome electrical repulsion
  - Very small compared to the atom as a whole
    - About 20,000 to 100,000 times smaller
      - Nuclei radii ~10^{-15} meters, $\propto A^{1/3}$
      - Atomic radii ~10^{-10}meters
    - Matter is mostly empty space

Relative Scales

- A is the relative mass of a nucleus
  - Each proton & neutron = 1 relative mass unit
    - ^{1}H : ~the same mass as a single neutron
    - ^{16}O : ~16 larger mass than a single neutron
    - ^{239}Pu : ~239 larger mass than a single neutron
  - Nuclear radius, $R_N \propto A^{1/3}$
    - ^{1}H : ~ the same size as a single neutron
    - ^{16}O : ~2.5 times the size of a single neutron
    - ^{239}Pu : ~6 times the size of a single neutron

Fission Process

- When a neutron is strikes a nucleus
  - it sometimes sticks (absorption)
    - the nucleus becomes unstable (neutron energy)
    - two possibilities
      - nucleus readjusts and semi-stabilizes
        - releases a small amount of radiation and stays intact
        - A+1 isotope, e.g.,
          - $^{26}Al \rightarrow {}^{27}Al$
          - $^{239}Pu \rightarrow {}^{240}Pu$,$^{235}U \rightarrow {}^{236}U$, $^{238}U \rightarrow {}^{239}U$
          - ~20% of the time for ^{239}Pu & ^{235}U
      - nucleus splits (fissions) releasing
        - large amounts of energy
          - two or more major pieces known as fragments
          - γ-rays & **some number of additional free neutrons**
          - ~80% of the time for ^{239}Pu & ^{235}U

For our purposes the neutron either causes fission or is lost

Fissile versus Fissionable

- Fissile
  - Nuclei that fission regardless of how fast a neutron is moving
    - ^{235}U, ^{239}Pu, ^{233}U, ^{241}Pu, ^{242}Am are fissile
- Fissionable
  - Nuclei that fission only if the neutron is traveling above a particular speed (threshold)
    - ^{238}U, ^{238}Pu, ^{240}Pu, ^{242}Pu, ^{237}Np are fissionable
- Whether a self-sustaining chain reaction is possible is not part of either definition, but
  - All fissile material can self-sustain a chain reaction
  - Most, but not all fissionable materials, also can
    - ^{238}U is fissionable but cannot, by itself, sustain a chain reaction
  - For NCS purpose
    - "Fissionable" is used generically to refer to SNM that that contribute to criticality safety concerns

Neutrons and Chain Reactions

- In any fission, 0 to 10 neutrons may result
  - average, $\bar{\upsilon}$, for ^{235}U is ≈ 2.5
  - average, $\bar{\upsilon}$, for ^{239}Pu is ≈ 3.0
- This is why chain reactions are possible
  - Should be easier of ^{239}Pu than for ^{235}U
- Follow the neutrons
  - Chain reactions are propagated by neutrons
  - Whatever affects the fate of a neutron will affect the type of chain reaction that is possible

Types of Chain Reactions

- **Subcritical**
  - Fission balance is not maintained
  - Each fission leads to less than one future fission
  - Fission chain and neutron population dies in time
- **Critical (self-sustaining chain reaction)**
  - Fission balance is exactly maintained
  - Each fission leads to exactly one future fission
  - Fission chain and neutron population is constant (“never ends”)
- **Supercritical (self-promoting chain reaction)**
  - Fission balance is not maintained
  - Each fission leads to more than one future fission
  - Fission chain and neutron population grow in time

Key Concepts

- k_{eff}
  - A single value used to describe the type of chain reaction

$$k_{\text{eff}} = \frac{\text{Fissions in generation } i + 1}{\text{Fissions in generation } i}$$

- Reactivity
  - The relative departure of the system from k_{eff}=1

$$\rho = \frac{k_{eff} - 1}{k_{eff}}$$

- Subcritical, reactivity is negative
- Critical, reactivity is zero
- Supercrtical, reactivity is positive

The Fate of Neutrons

- Neutron life
  - begins at fission
  - ends when it is *removed* from the system
- As a neutron travels through a material it can
  - Miss the nuclei until it reaches the surface and leaks out
  - Collide with a nucleus and

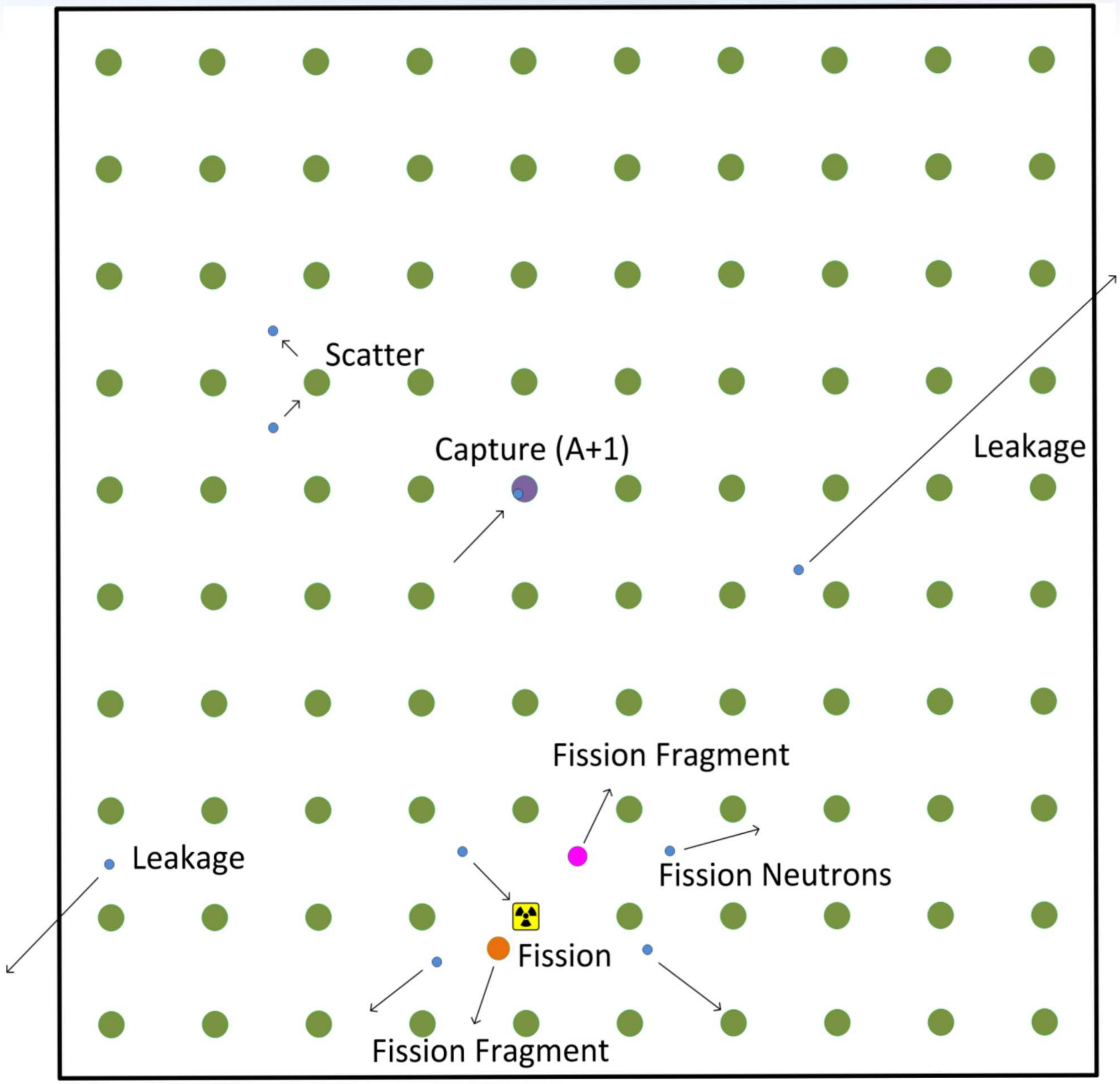
Stick (Absorbed)

or

Bounce off (scatter)

  - If it sticks it may cause fission or be lost forever (A+1 isotope)

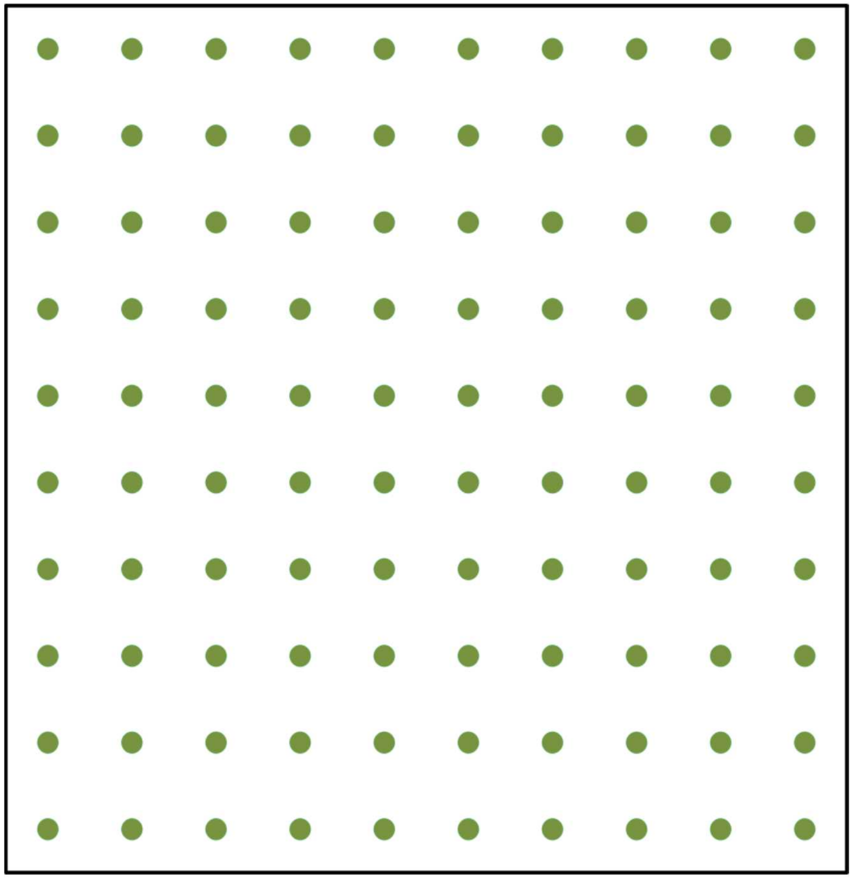
Possible Fates

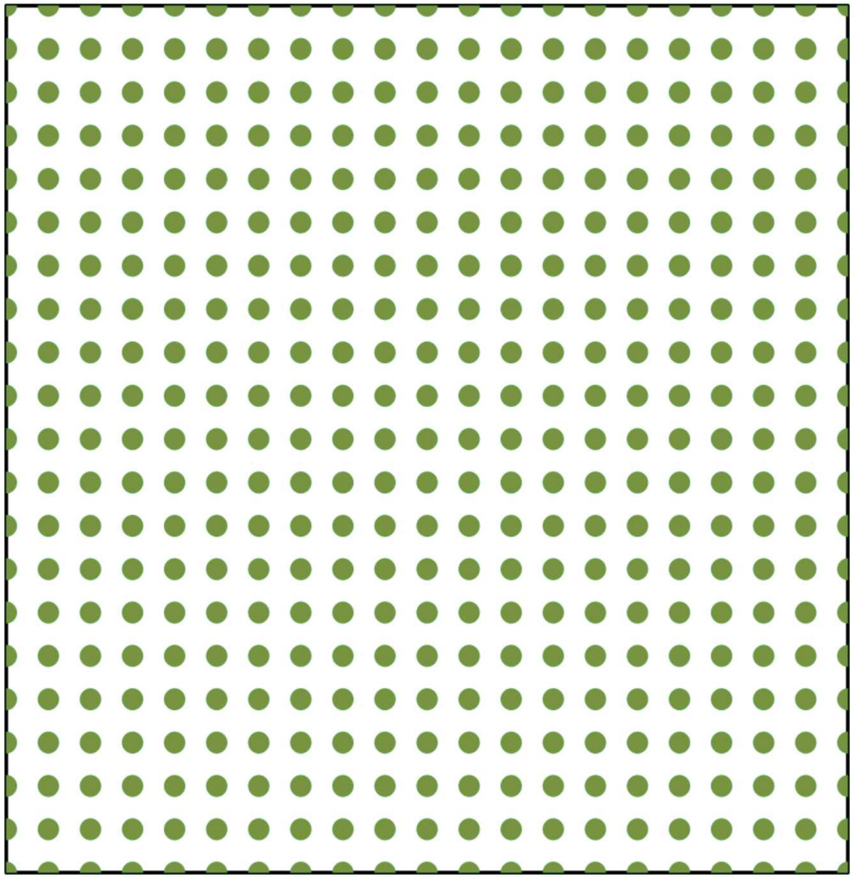


Micro and Macro Properties

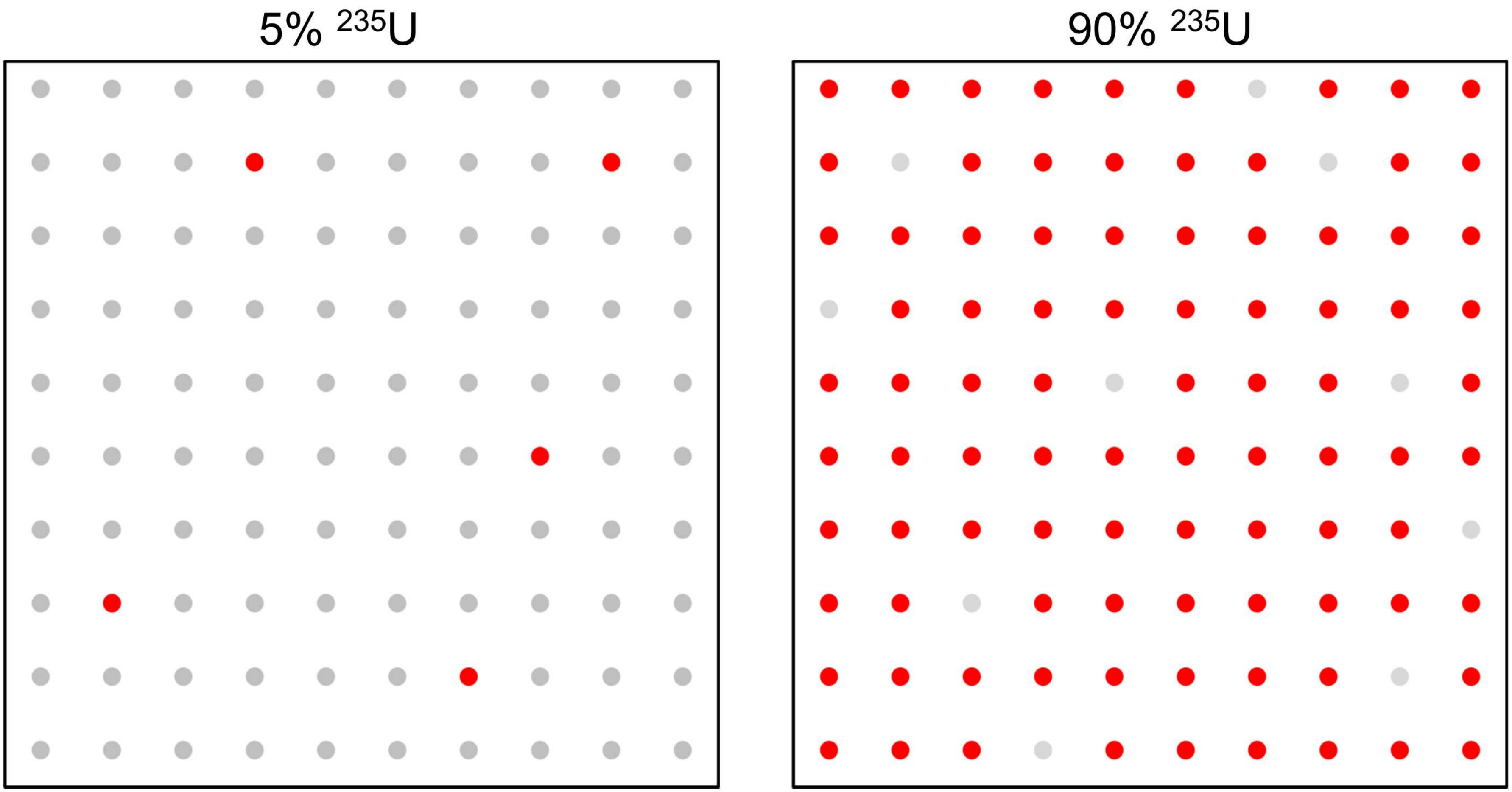
- What any one neutron will do is not knowable
- The average neutron behavior is very predictable
  - identical conditions=identical results
    - e.g., a 6 kg, α-phase, ^{239}Pu sphere, thick water reflected, is always supercritical
  - depends on both
    - macro-properties
      - size (volume, mass), shape (geometry), density, enrichment, etc.
    - micro-properties of individual nuclei
      - what things can happen
      - the size of the nucleus (cross section)
    - shorthand way of saying this is *everything*

Density

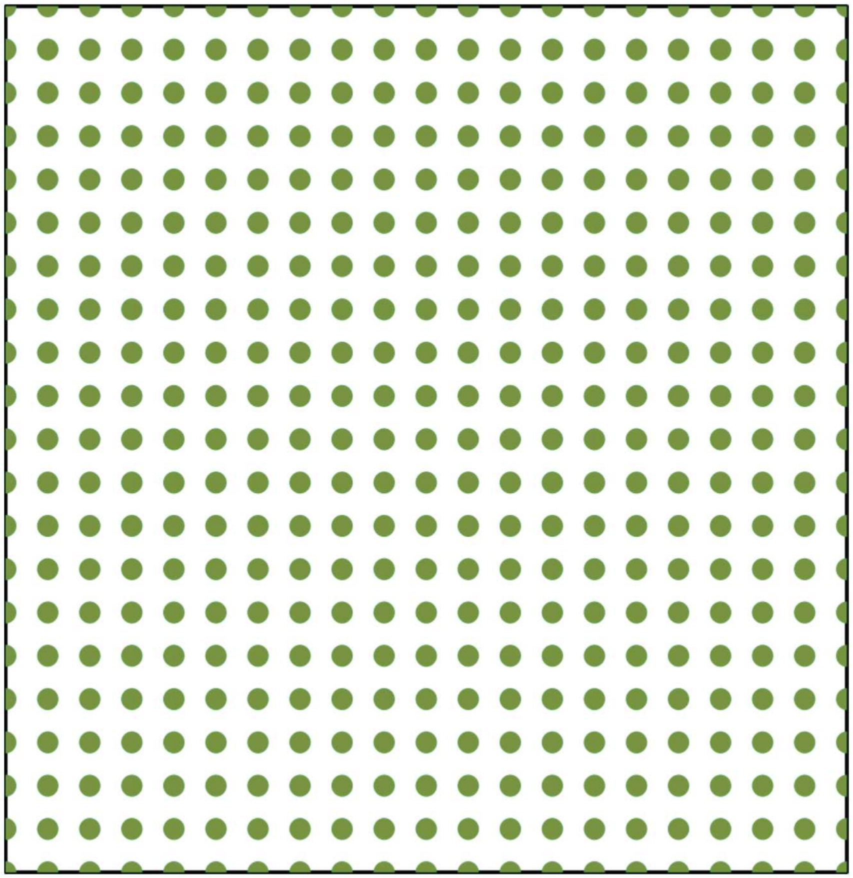


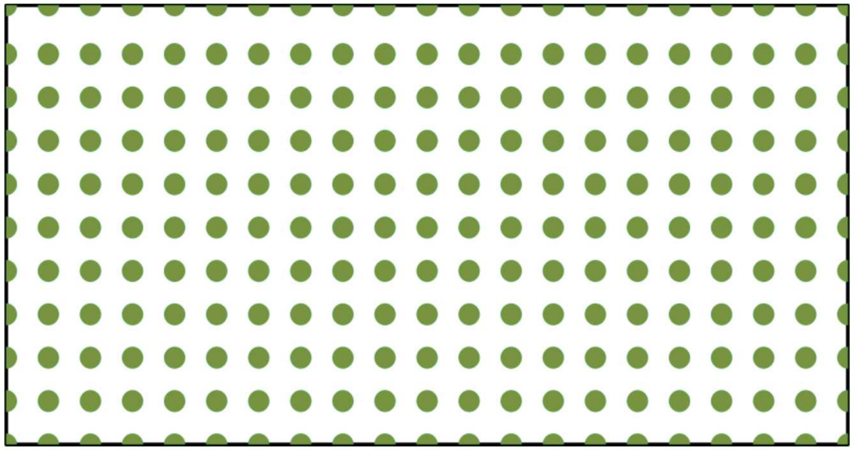


Enrichment

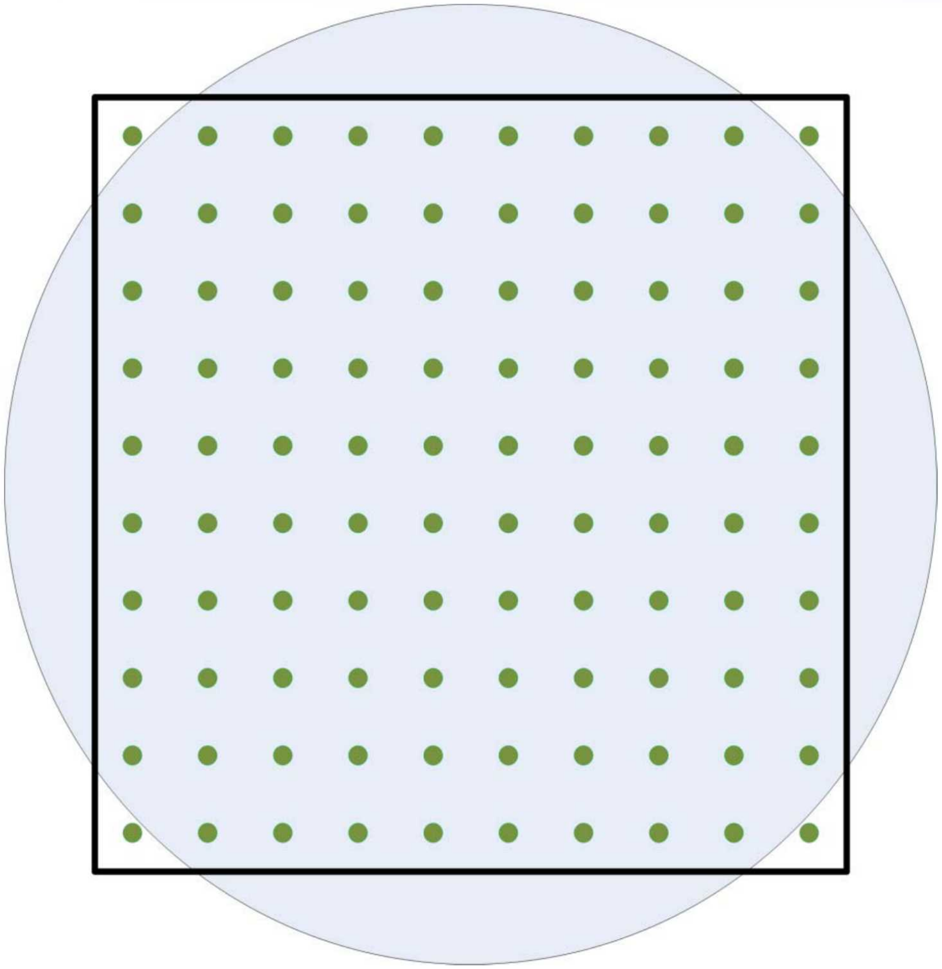


Size (Volume & Mass)



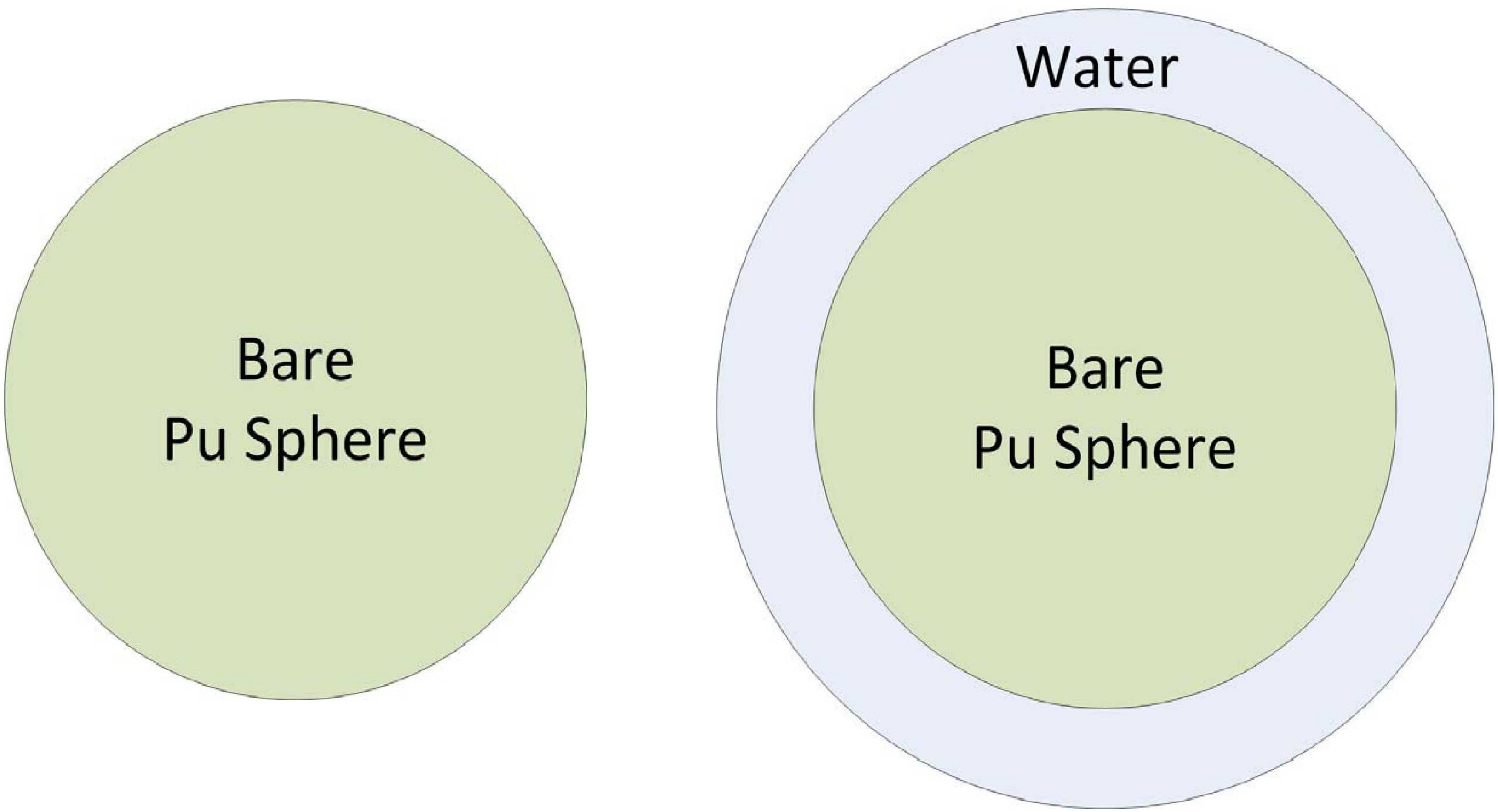


Shape

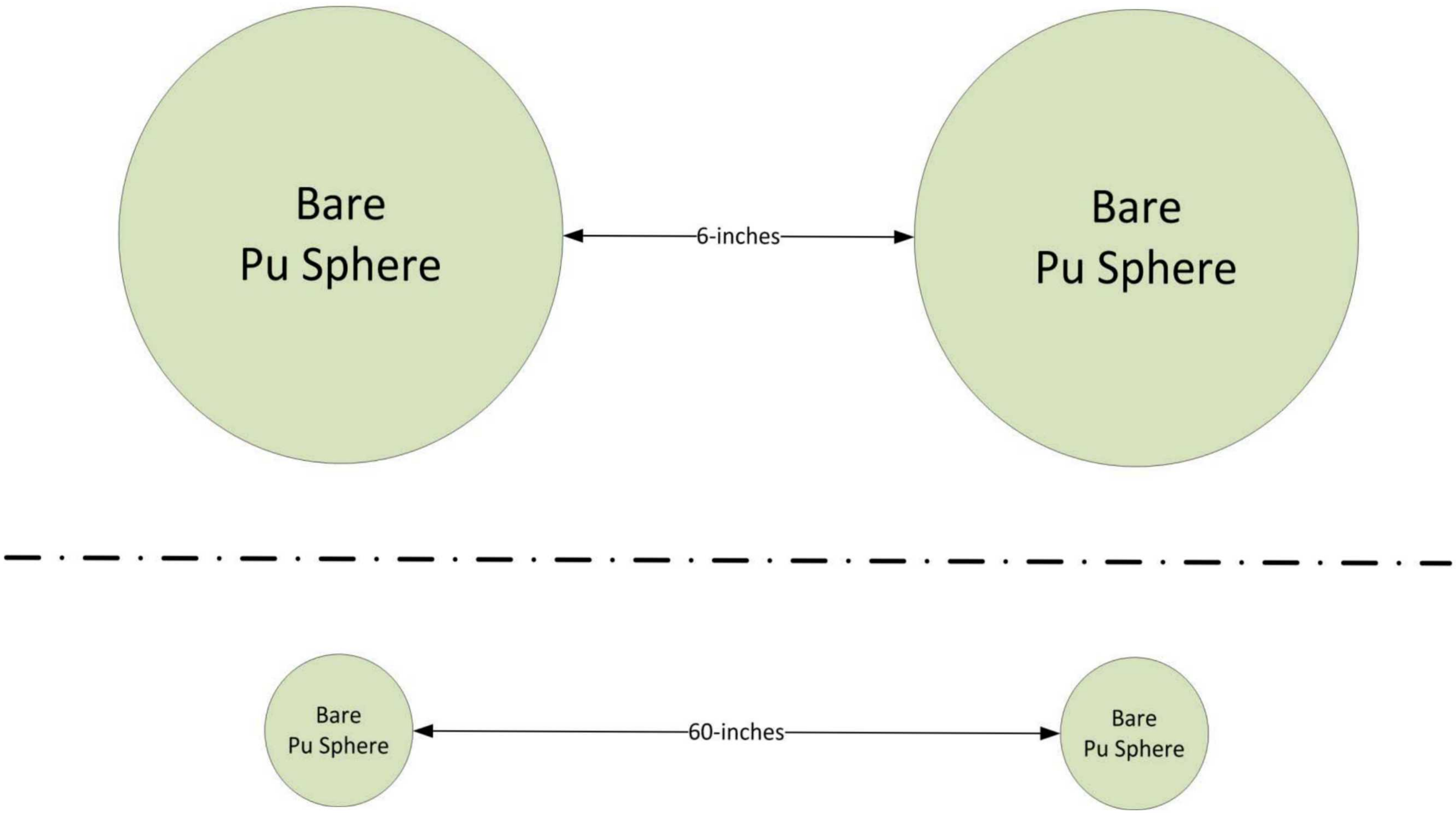


- Equivalent volumes
  - Cube surface area is 600 units
  - Sphere surface area is 483.6 units
  - S/C surface area ratio = 0.81
  - Sphere has 19% less surface area for the same enclosed material
  - Cube leakage is higher

Reflection



Spacing


Bare
Pu Sphere
6-inches
Bare
Pu Sphere
Bare
Pu Sphere
60-inches
Bare
Pu Sphere

Parameters

- Mass---almost always requires explicit control
- Geometry---most effective engineered features
- Volume---common for vessels and containers
- Spacing---always necessary (implicit/explicit)
- Reflection---almost always implicitly limited
- Moderation---almost always implicit for dry operations
- Density---usually implicit
- Enrichment---usually at a facility level
- Poisons---rarely used, extra measures usually required

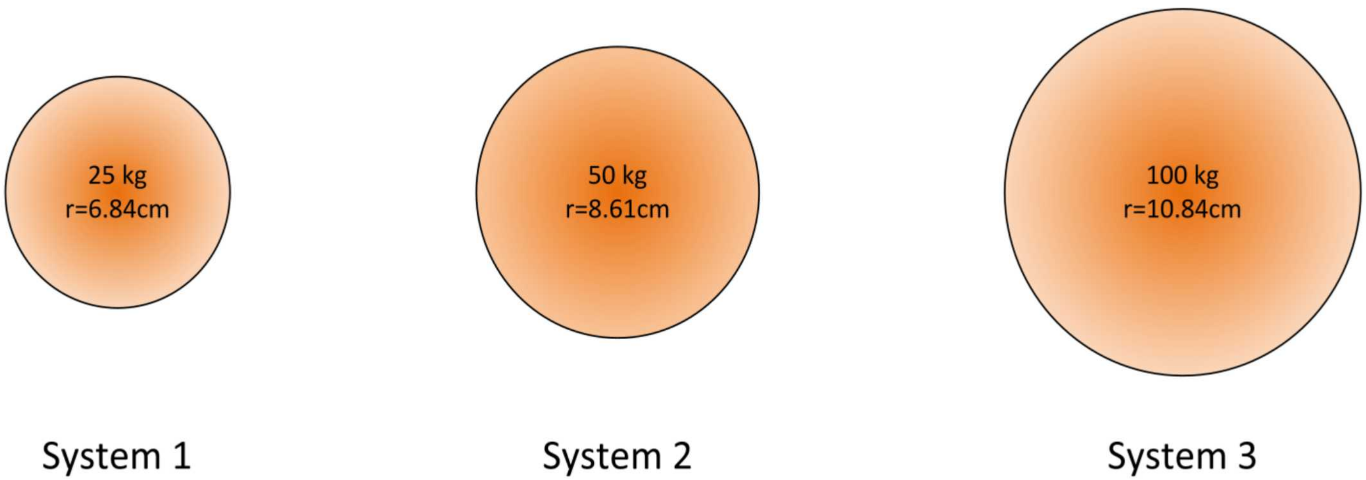
Dealing with Everything

- For any fissionable material accumulation
  - the particular value of each parameter will act to either make a self-sustaining chain reaction
    - Easier
      - Enhances absorption of neutrons in fissionable material
      - Reduces leakage from the system
    - More difficult
      - Reduces absorption of neutrons in fissionable material
      - Increases leakage from the system

As fissionable material is handled the parameters change

Parameters and Chain Reactions

- Consider three different metal systems
  - Bare (no reflector)
  - U(100) metal at α-phase density (18.8 g/cc)
  - Spherical geometry
- Place 100 fission G_0 neutrons into the system and see what happens



System 1

- Radius = 6.84 cm, 25 kg U(100)
- The system properties combine such that
  - 60 of G_0 neutrons leak from the system (lost forever)
  - 40 of G_0 neutrons are absorbed in ^{235}U
    - 20% form ^{236}U (lost forever)
    - 80% cause fission, 0.8*40 = 32 fissions
      - 32 fissions result in 32 x 2.5 = 80 G_1 neutrons

$$k_{eff} = G_1/G_0 = 80/100 = 0.8$$

The system is SUBCRITICAL

System 2

- Radius = 8.61 cm, 50 kg U(100)
- The system properties combine such that
  - 50 of G_0 neutrons leak from the system (lost forever)
  - 50 of G_0 neutrons are absorbed in ^{235}U
    - 20% form ^{236}U (lost forever)
    - 80% cause fission, 0.8*50 = 40 fissions
      - 40 fissions result in 40 x 2.5 = 100 G_1 neutrons

$$k_{eff} = G_1/G_0 = 100/100 = 1.0$$

The system is CRITICAL

System 3

- Radius = 10.84 cm, 100 kg U(100)
- The system properties combine such that
  - 40 of G_0 neutrons leak from the system (lost forever)
  - 60 of G_0 neutrons are absorbed in ^{235}U
    - 20% form ^{236}U (lost forever)
    - 80% cause fission, 0.8*60 = 48 fissions
      - 48 fissions result in 48 x 2.5 = 120 G_1 neutrons

$$k_{eff} = G_1/G_0 = 120/100 = 1.2$$

The system is SUPERCRITICAL

Summary

Radius (cm)	U(100) Mass (kg)	k_{eff}
6.84	25	0.8
8.61	50	1.0
10.84	100	1.2

- As mass is added the systems gets larger
  - More fission sites available
  - Leakage decreases (surface to volume ratio decreases)
  - Absorption increases
  - Fission increases
  - Eventually, chain reactions become self-sustaining (critical) and then self-promoting (supercritical)

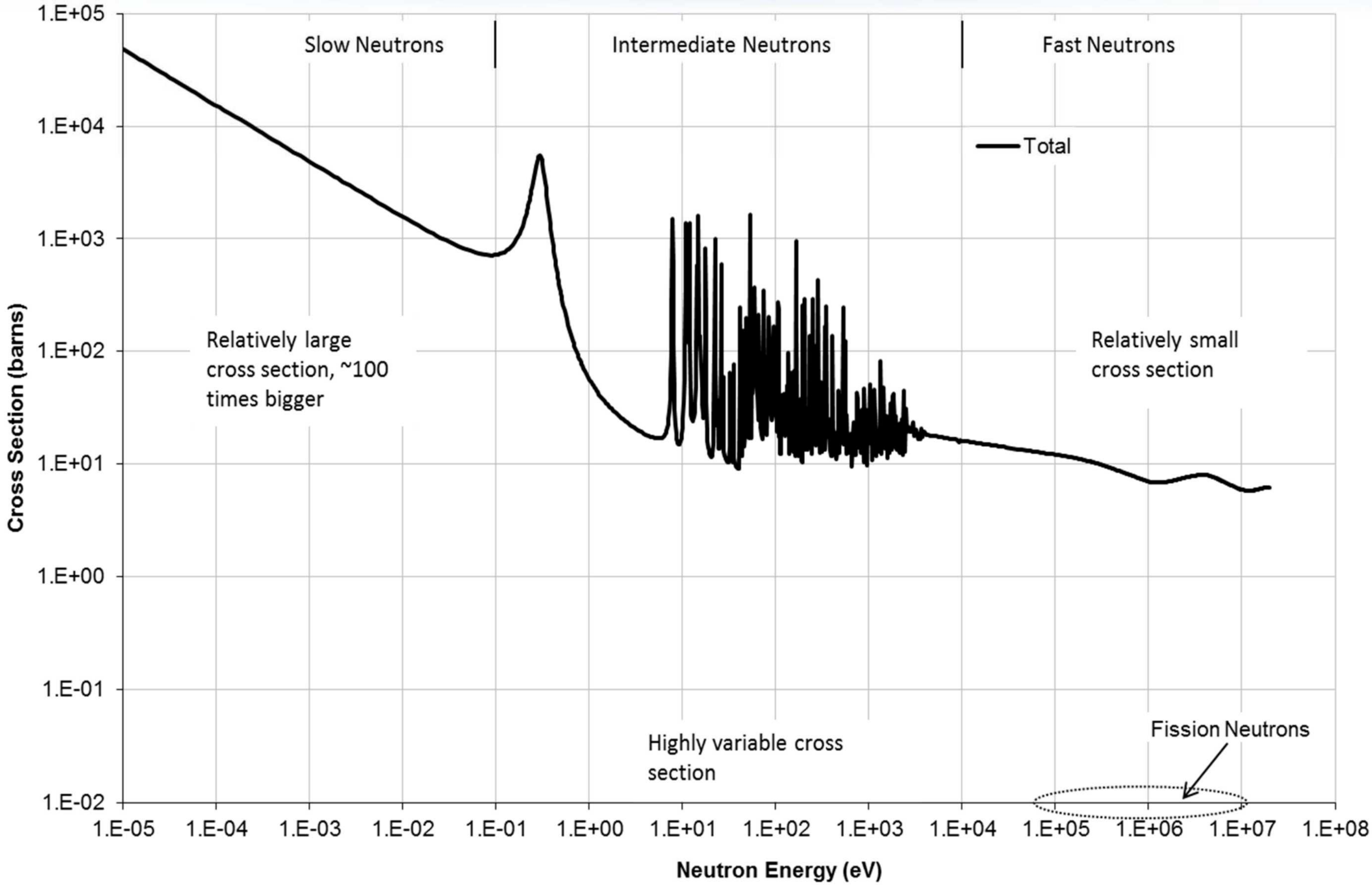
The Effect of Parameters

- What would happen to System 2 (critical) if
  - An identical sphere was placed next to and in contact with the first sphere?
  - The shape was changed to a long skinny rod?
  - It was surrounded by
    - A pair of hands?, Water?, Beryllium?
  - It was placed on a glovebox floor?
  - The density was dropped by a factor of two?
  - The enrichment was dropped to 50%
  - *The metal was dispersed (mixed) in water?*
    - *To understand how this would affect the system, we must understand something about nuclei*
    - *This is not straightforward or common sense*

Nuclear Microscopic Cross Section

- Whether a neutron collides with a nucleus or not depends on the size of the nucleus
  - Microscopic **cross section**
    - Units of area, cm^2 or barns
    - 1 barn = 10^{-24} cm^2
    - Relative unit is more understandable
  - Physically atoms are very small, nuclei smaller still
    - Matter is mostly empty space
      - Punctuated by regions of incredible density (nuclei)
    - You could conclude that neutron-nuclei reactions would be very rare
    - You could but you would be wrong!

^{239}Pu

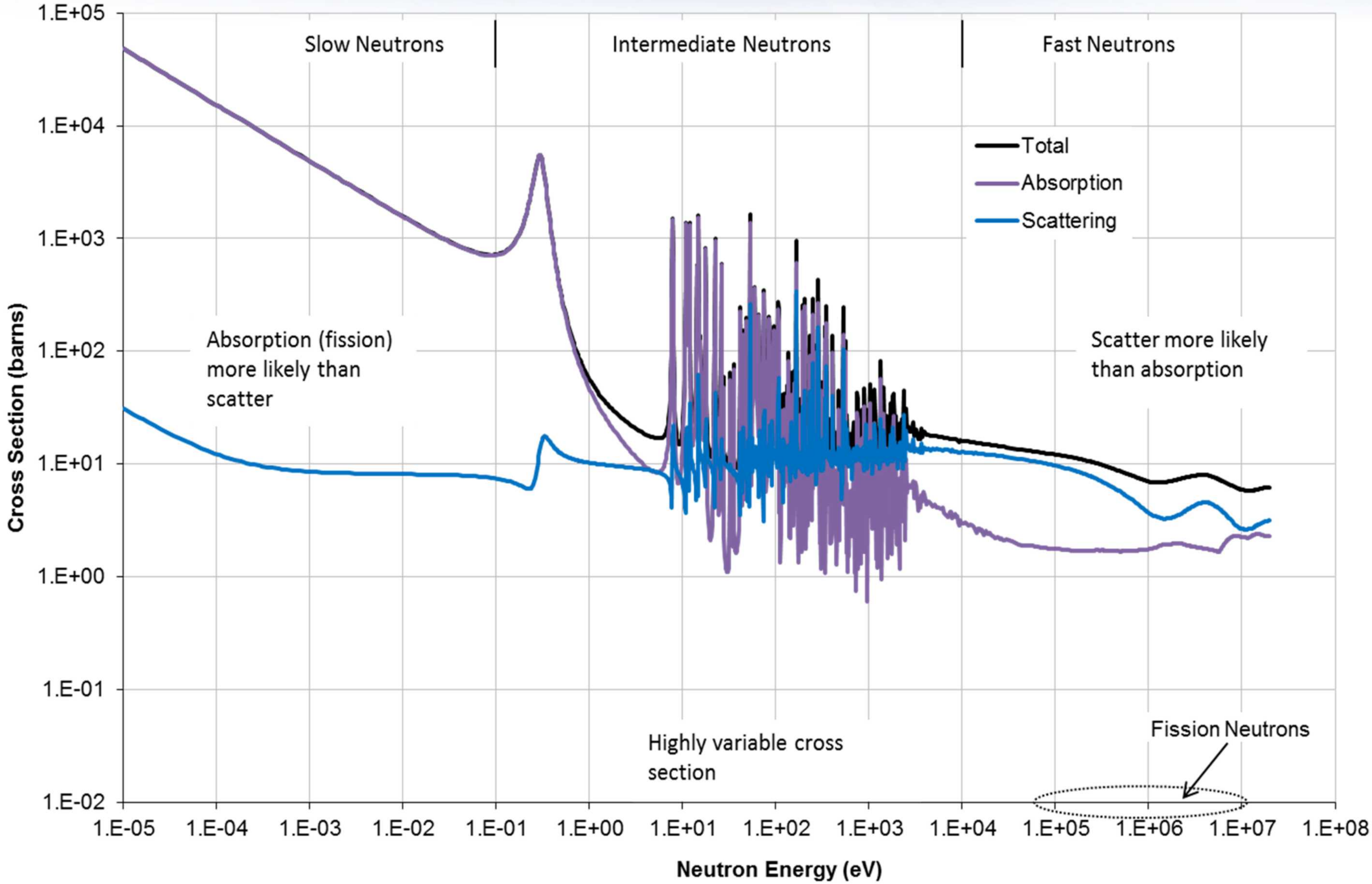


1.E+05
1.E+04
1.E+03
1.E+02
1.E+01
1.E+00
1.E-01
1.E-02
Cross Section (barns)
Slow Neutrons
Intermediate Neutrons
Fast Neutrons
Total
Relatively large cross section, ~100 times bigger
Relatively small cross section
Highly variable cross section
Fission Neutrons
1.E-05
1.E-04
1.E-03
1.E-02
1.E-01
1.E+00
1.E+01
1.E+02
1.E+03
1.E+04
1.E+05
1.E+06
1.E+07
1.E+08
Neutron Energy (eV)

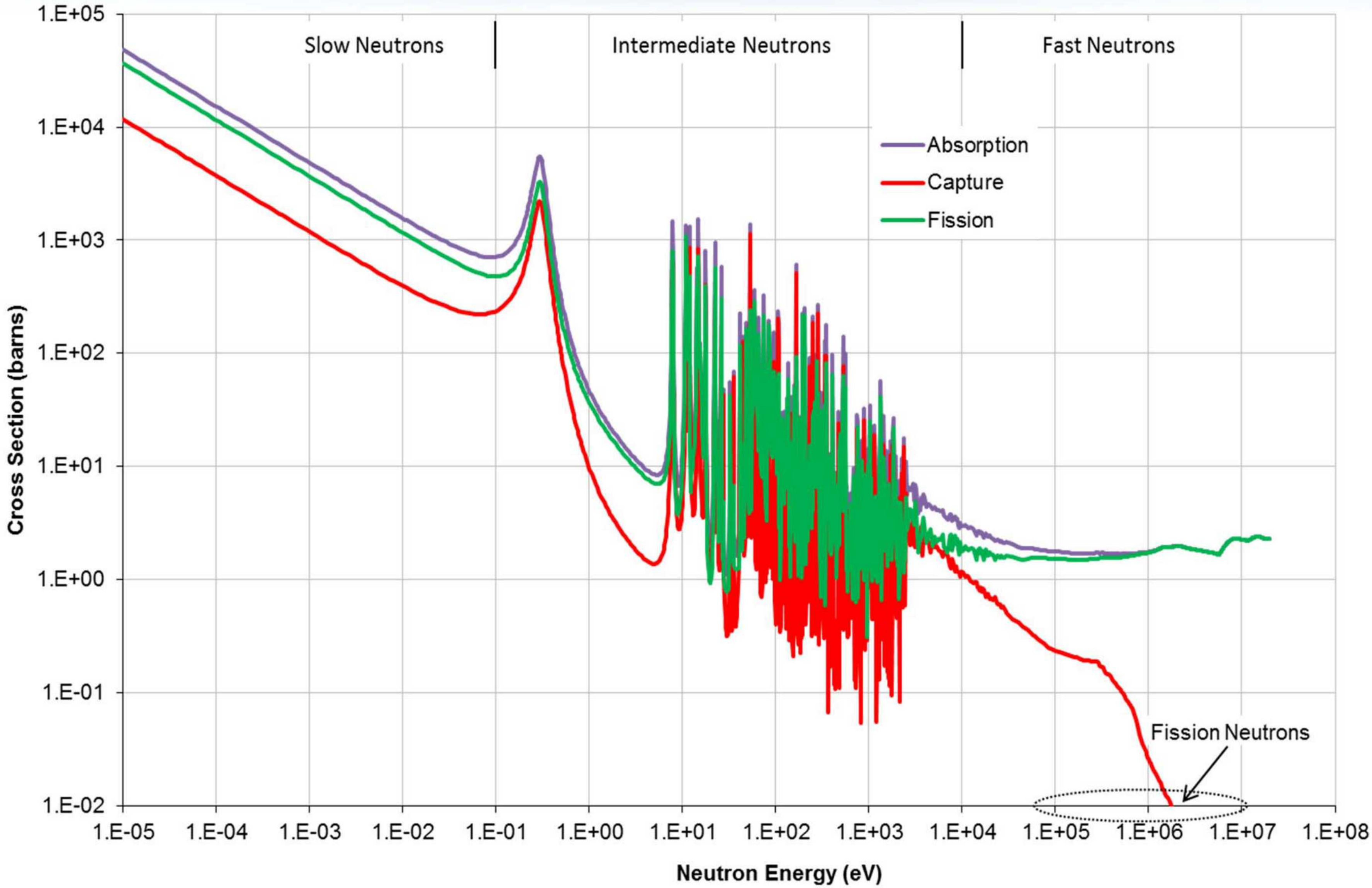
Microscopic Total Cross Section

- A single nuclei appears to grow or shrink depending on how fast a neutron is moving!!!!
  - The reality is more complex but the end result is the same
  - Any one neutron only has one speed, so it only sees one size of nuclei but
    - Different speed=different nuclei size
- The total microscopic cross section can be divided into parts based on what can happen
  - Sometimes the neutrons stick (absorbed)
    - Can be further divided into fission and non-fission absorption
  - Sometimes the neutrons bounce off (scatter)

^{239}Pu


Slow Neutrons
Intermediate Neutrons
Fast Neutrons
Total
Absorption
Scattering
Absorption (fission) more likely than scatter
Scatter more likely than absorption
Highly variable cross section
Fission Neutrons
Cross Section (barns)
Neutron Energy (eV)
1.E+05
1.E+04
1.E+03
1.E+02
1.E+01
1.E+00
1.E-01
1.E-02
1.E-05
1.E-04
1.E-03
1.E-02
1.E-01
1.E+00
1.E+01
1.E+02
1.E+03
1.E+04
1.E+05
1.E+06
1.E+07
1.E+08

^{239}Pu


Slow Neutrons
Intermediate Neutrons
Fast Neutrons
Absorption
Capture
Fission
Fission Neutrons
Cross Section (barns)
Neutron Energy (eV)
1.E+05
1.E+04
1.E+03
1.E+02
1.E+01
1.E+00
1.E-01
1.E-02
1.E-05
1.E-04
1.E-03
1.E-02
1.E-01
1.E+00
1.E+01
1.E+02
1.E+03
1.E+04
1.E+05
1.E+06
1.E+07
1.E+08

Moderation

- For fissile nuclei, the total cross section is larger (~100) for slow as opposed to fast moving neutrons
  - The likelihood of absorption is larger
  - The likelihood of fission is larger
  - However, all fission neutrons are born moving fast
- For this to matter there would have to be a way of slowing neutrons down
  - How can this be done?
    - Neutrons that bounce off nuclei (scatter) slow down as a result of the collision
    - That slowing down is known as “moderation”

Scattering

- The neutron energy loss per collision depends on the mass (A) of the nuclei being hit
  - Heavy (A > 16) nuclei cannot slow neutrons down effectively
    - Billiard ball hitting a bowling ball is a good analogy
    - Nuclei heavier than oxygen are just not good at slowing neutrons
  - Light ($A \leq 16$) can be somewhat effective
    - H, He, Li, Be, B, C, N, O
    - The lighter the better
    - Hydrogen is best of all at slowing neutrons
      - ~ Equal mass to a neutron
      - Billiard ball hitting another billiard ball is a good analogy

Scattering Energy Loss versus Nuclei Mass

Maximum and Average Energy Lost

Nucleus	Mass No.	ΔE_{max} %	ΔE_{avg} %
^{1}H	1	100	50.0
^{2}H	2	88.9	44.0
^{9}Be	9	36.0	18.0
^{16}O	16	22.1	11.0
^{56}Fe	56	6.9	3.45
^{235}U	235	1.7	0.9
^{239}Pu	239	1.7	0.9

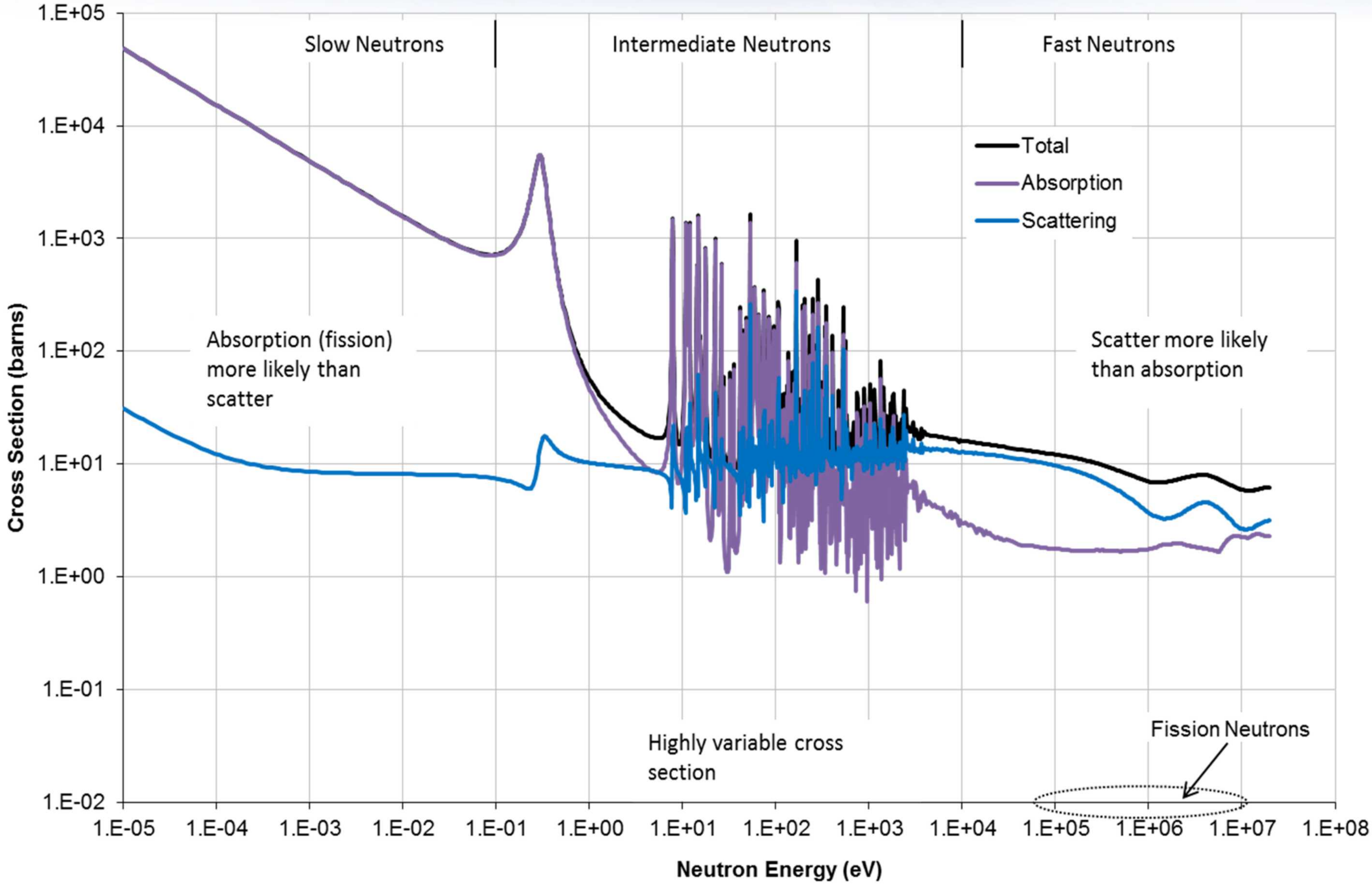
Average # of collisions from 2 MeV to 0.02 eV)

H	D	^{9}Be	^{16}O	^{56}Fe	^{235}U	^{239}Pu
18	25	89	152	509	2143	2179

Importance of Moderation

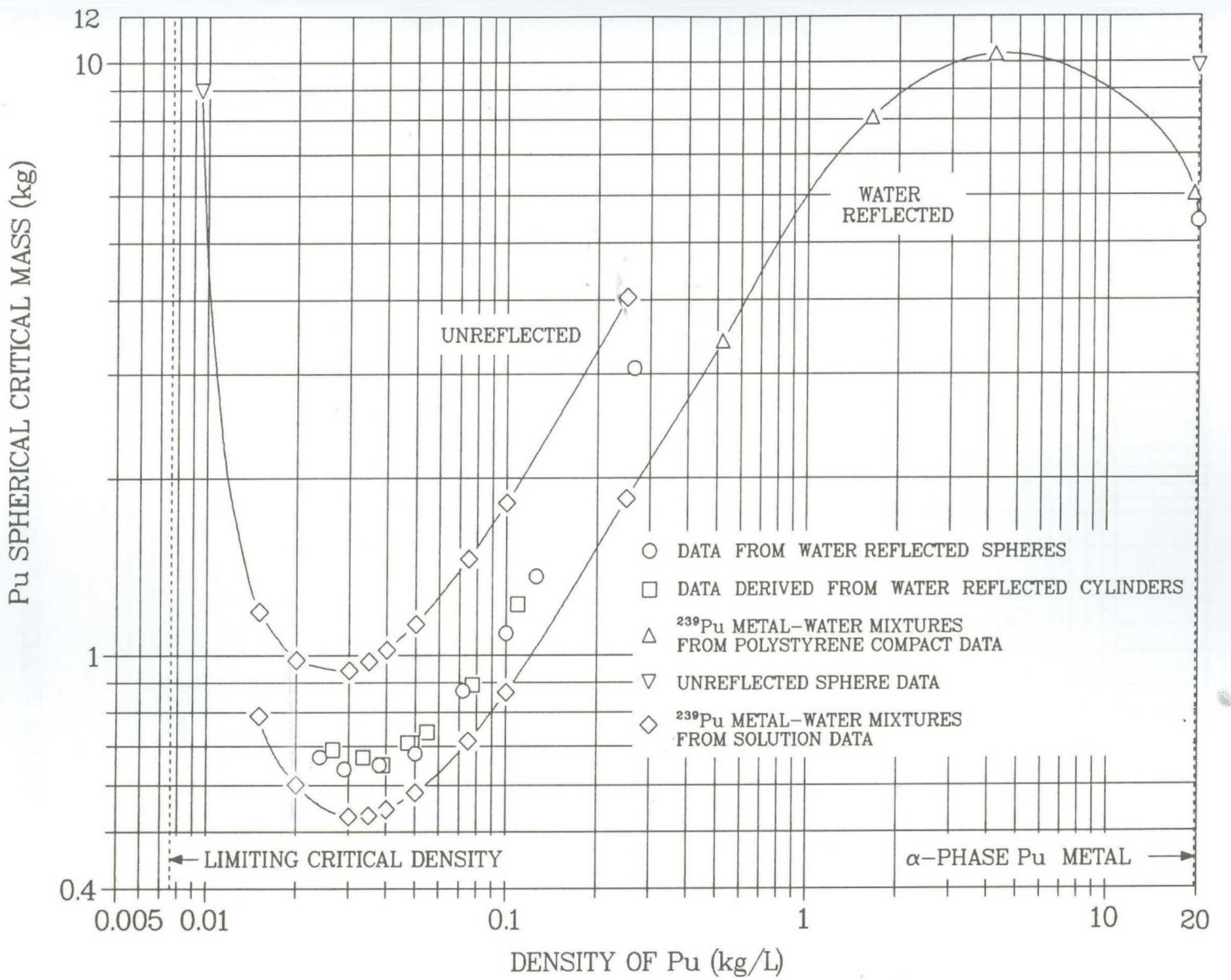
- Moderating material slows neutrons down
  - More slow neutrons means more fissionable material absorption
  - More absorption means more fissions
  - More fissions makes a self-sustaining chain reaction easier
- Mixing fissionable material with lighter materials causes moderation
  - Moderation is a macro system property like mass, density, etc.
  - Varies depending on the amount of light material
    - Measured by concentration, i.e., g/l of ^{239}Pu or ^{235}U
    - Lower concentration means more moderating material per fissile nuclei

^{239}Pu

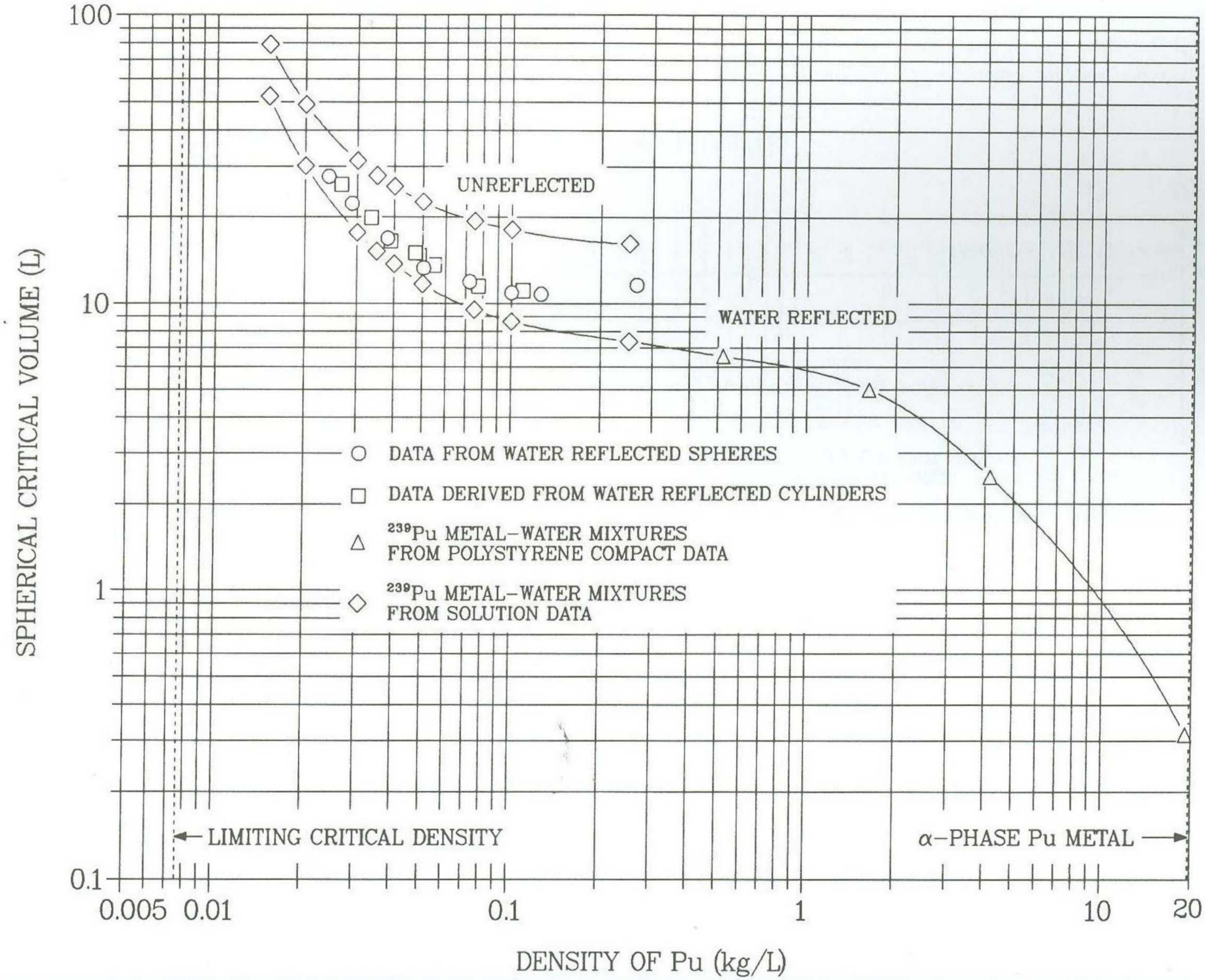


Slow Neutrons
Intermediate Neutrons
Fast Neutrons
Total
Absorption
Scattering
Absorption (fission) more likely than scatter
Scatter more likely than absorption
Highly variable cross section
Fission Neutrons
Cross Section (barns)
Neutron Energy (eV)
1.E+05
1.E+04
1.E+03
1.E+02
1.E+01
1.E+00
1.E-01
1.E-02
1.E-05
1.E-04
1.E-03
1.E-02
1.E-01
1.E+00
1.E+01
1.E+02
1.E+03
1.E+04
1.E+05
1.E+06
1.E+07
1.E+08

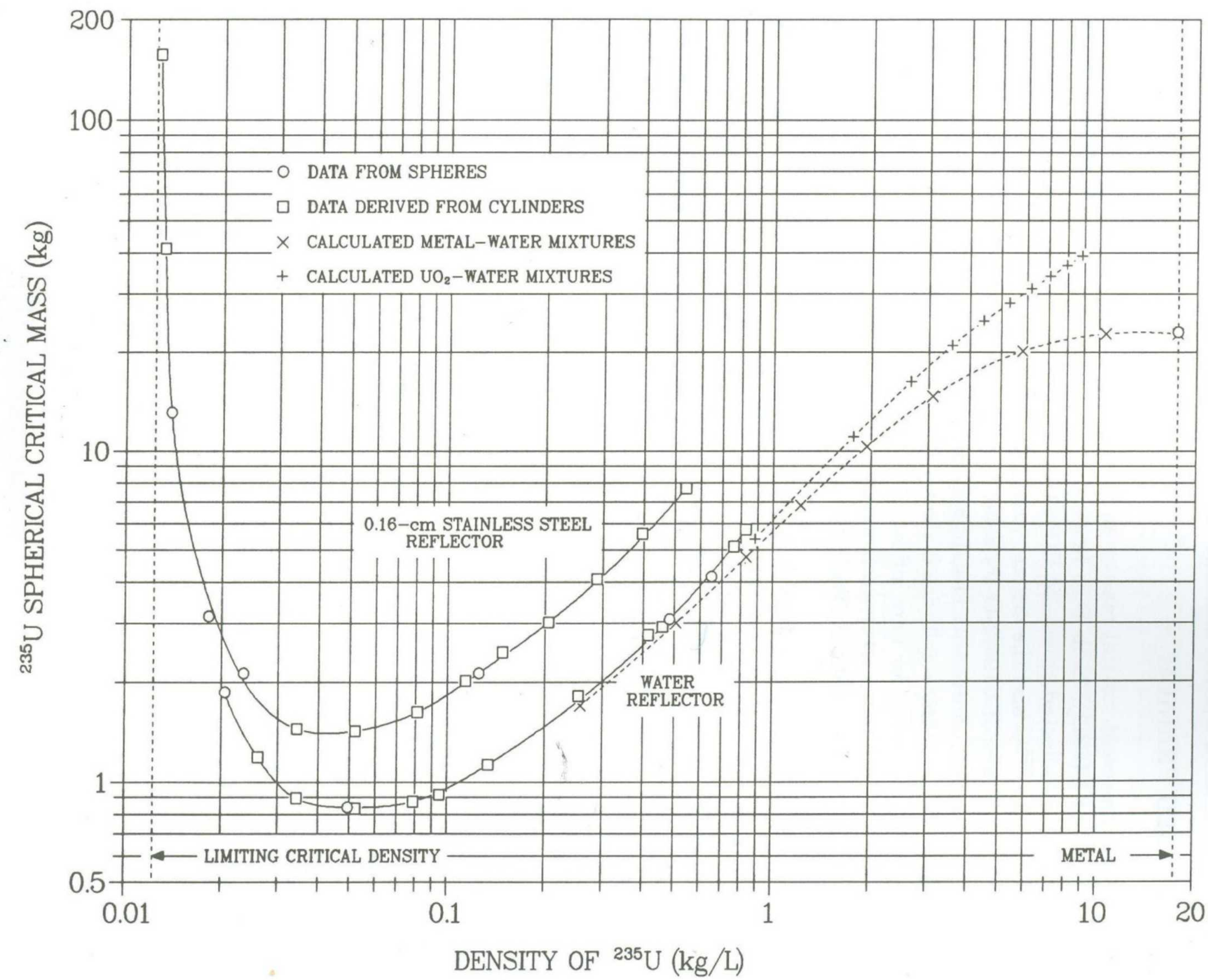
^{239}Pu Metal-Water Critical Mass Curves



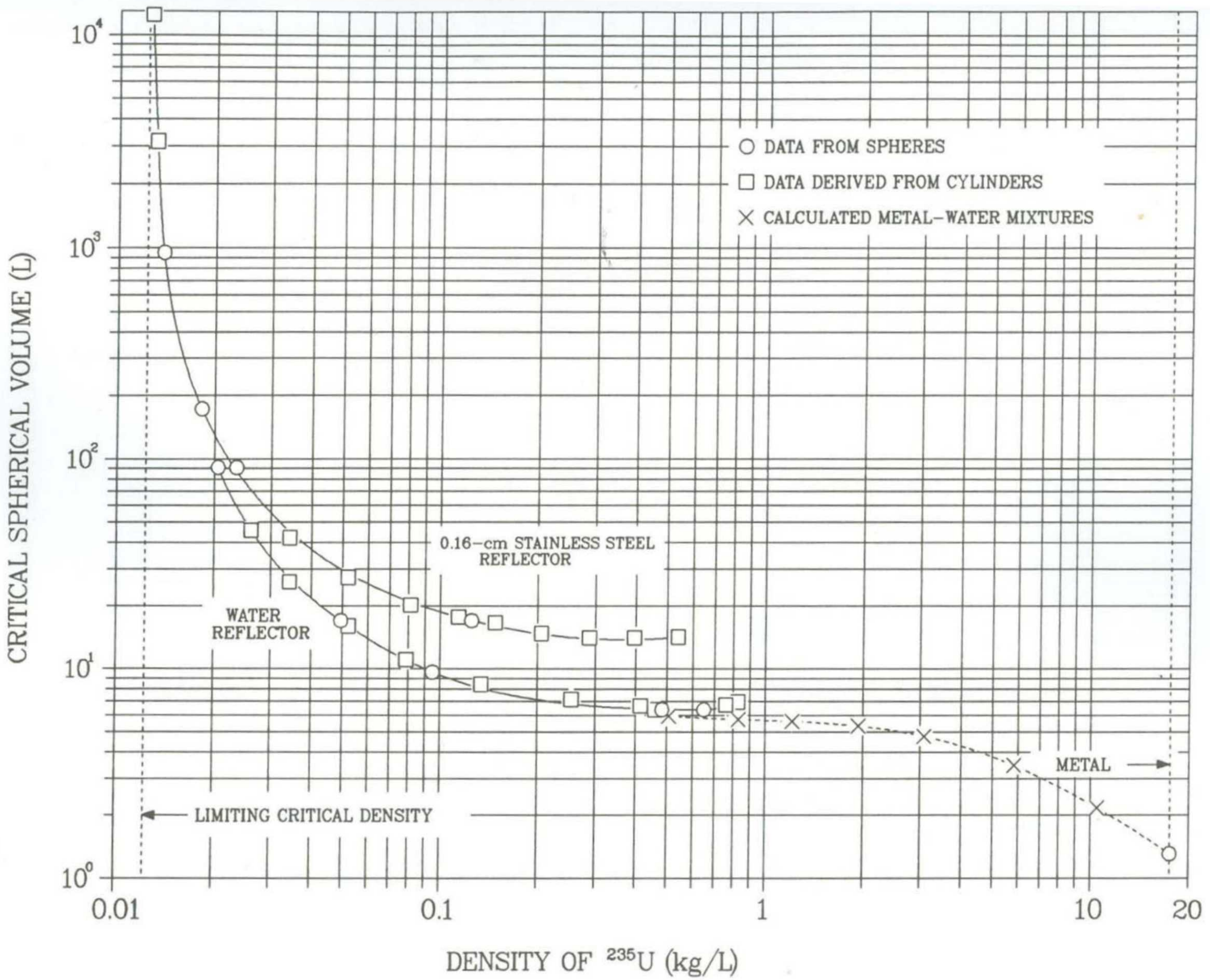
^{239}Pu Metal-Water Critical Volume Curves



^{235}U Metal-Water Critical Mass Curves



^{235}U Metal-Water Critical Volume Curves



Fast, Slow, and Dual Systems

- Fissionable material systems
  - Fast systems
    - Fissions are caused by fast moving neutrons
      - Metals, ceramics, oxide
  - Slow systems
    - Most fissions caused by slow moving neutrons
      - Liquids
      - Contaminated plastic, oil, water
  - Dual systems (bi-modal)
    - Fissions are caused by both slow and fast moving neutrons
      - Water/poly reflected metal, ceramics, or oxide systems
      - High concentration solutions or mixtures

Fast Systems

- Neutrons are born and die fast
  - Neutrons do not slow down
  - Fission is inefficient
    - Large mass is needed to sustain the chain reaction
    - Critical mass are in the 10’s of kilograms
  - Higher density means more efficient fission
    - Less material is required
    - α-phase ^{239}Pu metal = 10.2 kg critical mass
  - Lower density means less efficient fission
    - More material is required
    - δ-phase ^{239}Pu metal = 15.6 kg critical mass

Slow Systems

- Neutrons are born fast
  - Die fast or slow down by scattering off light nuclei
  - Slow neutron fission is material efficient
    - Small masses required to sustain a chain reaction
    - Critical masses on the order of hundreds of grams
- Examples include
  - Fissionable material solutions
    - Uranyl nitrate, uranyl fluoride, Pu nitrate, Pu chloride, etc.
  - Fissionable material mechanically mixed with
    - Plastic, oil, water, Be, C
      - Process criticality accident 9 [SCC, U(22.6) in oil]
      - Process criticality accident 15 [ES, U(6.5) in water]

Critical Mass Comparison

Material	Metal System Mass (kg)		Solution System Mass (g)	
	Bare	Water Reflected	Bare	Water Reflected
α-Pu(5)	10.2	5.8	1200	600
δ-Pu(5)	15.6	8.0		
α-U(93)	50.0	25.0	1600	800

- The critical mass of a
  - water reflected system is about ½ that of a bare system
  - moderated systems require less fissionable material
    - ~10 times less for optimally moderated systems
- 21 of the 22 process accidents have occurred with solution
  - Where would you put most of your criticality safety efforts?

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Safety Margin

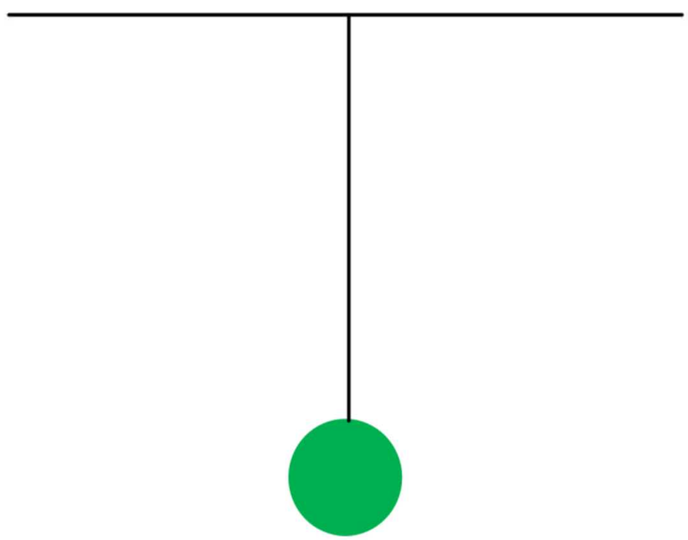
Presented by:
Shean P. Monahan

Measuring Safety Margin

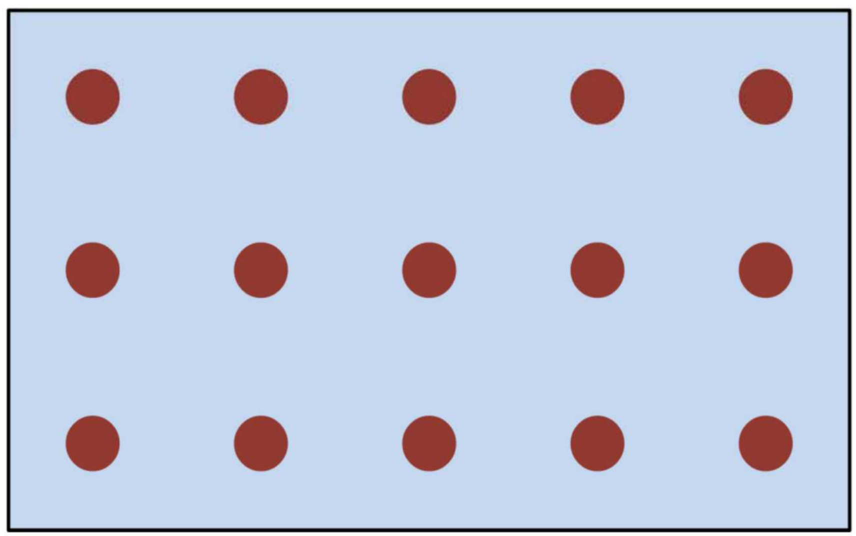
- k_{eff} and safety margin
  - it is common belief that k_{eff} is a measure of safety margin
    - e.g., that the serious of an event can be expressed in terms of the change in k_{eff}
    - **Such efforts are not very valuable and in fact can obscure the seriousness of an event**
  - experienced NCS advisors avoid this descriptor in discussing degrees of
    - subcriticality
    - safety margin, and
    - acceptable levels of risk

Two Fissionable Material Systems

6kg α-phase ^{239}Pu
Sphere
$k_{eff} = 0.84$



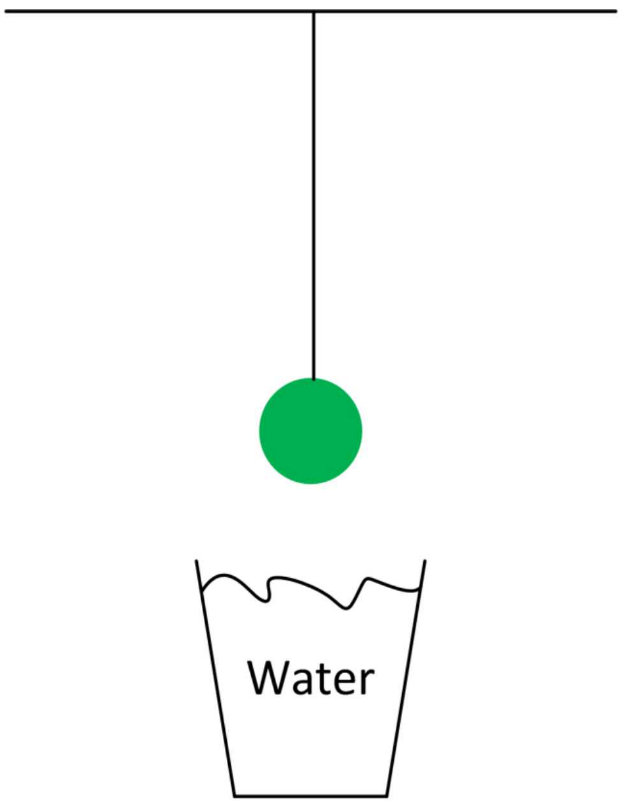
Natural U rods
In Water
$k_{eff} = 0.97$

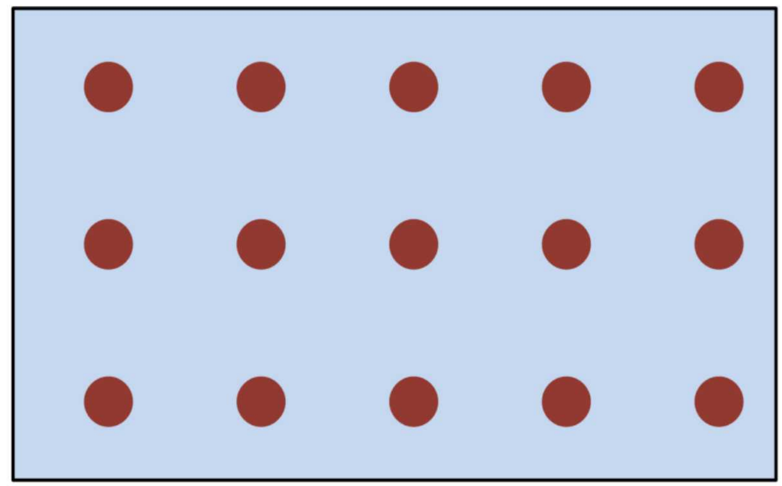


Natural Uranium in Water

- Experimentally and from first principles
  - natural uranium in water cannot achieve a self-sustaining chain reaction
    - ^{235}U density is insufficient
    - hydrogen absorption always wins
- Safety margin is infinite
  - universities perform experiments with natural Uranium and water
    - controls are not necessary despite high k_{eff}
    - imposing controls or k_{eff} limits would be
      - costly
      - inappropriate, and
      - result in no health or safety benefits

Pu Sphere





Actual Safety Margin

- What is the safety margin of this operation?
  - Measured solely by the likelihood of the support failure

- Safety margin is measured by the **likelihood** and **consequences of changes in process conditions**

  - If failure of the support is likely or even unlikely
    - the safety margin is unacceptable

  - The failure of the support structure must be
    - incredible to meet the safety margin requirement

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Time Behavior of Criticality Accidents

Presented by:
Shean P. Monahan

Criticality Accident Mitigation

- Operators can be trained to respond to many off normal events
  - Fires can occur in operations
    - Operators are trained to
      - Assess the situation
      - Take mitigating action if possible
        - Smother fire with graphite powder or magnesium oxide
- Can the same be true of criticality accidents?
  - Can operators be trained to
    - Stop accidents?

    or
    - Mitigate the consequences?

Generation Time

$$k_{eff} = \frac{Fissions\ in\ generation\ i+1}{Fissions\ in\ generation\ (i)}$$

- The definition of k_{eff} begs two questions
  - How long is a generation?
    - i.e., what is the generation time?
  - What affects the generation time?
    - Intuitively, generation time will affect how fast changes to a system occur
    - Shorter generations mean faster changes

Generation Time

- Human and fission generations are exactly analogous
  - Both are fabrications used to mathematically describe populations in which children are produced by parents
    - Average human generations are ~20 years
    - Average fission generation times range from 10^{-8} to 10^{-3} seconds
    - Depends on
      - System properties
        - Size, shape, moderation, etc.
      - Relative departure of k_{eff} from the value of 1.0
        - How far above critical is the system
        - Relative importance of *prompt* versus *delaye*d neutrons in the system

Time Evolution At and Above Critical

- The speed of the fission chain growth is exponential

$$n(t) = n_o e^{t\left(\frac{k_{eff}-1}{\ell_g}\right)}$$

- Where:
  - e = natural log base, 2.718…
  - ℓ_g = average prompt neutron lifetime
  - n_o = initial neutron population
  - t = time from the change in k_{eff}

Example: 1958 Los Alamos Process Accident

- Solution (moderated) system, slowing down time extended generation time
- Even so, there was simply no time to react
  - Changes in the system caused k_{eff} to change from subcritical to above critical almost instantly
  - k_{eff} ~ 1.01

$$\text{For } \ell_g = 10^{-3} \text{ and } \ell_g = 10^{-4}$$

$$n(0.1) = n_0 e^{1.0} = 2.72 n_0$$

$$n(0.2) = n_0 e^{2.0} = 7.39 n_0$$

$$n(1.0) = n_0 e^{10} = 22{,}026 n_0$$

$$n(0.1) = n_0 e^{10} = 22{,}026 n_0$$

$$n(0.2) = n_0 e^{20} = 4.85 \times 10^{8} n_0$$

$$n(1.0) = n_0 e^{100} = 2.69 \times 10^{43} n_0$$

Metal (fast) Systems

- Had this been a fast fission system, neutrons don't need to slow down
- Generation times is even shorter

$$\text{For } \ell_g = 10^{-5} \text{ and } \ell_g = 10^{-8}$$

$$n(0.1) = n_0 e^{100} = 2.69 \times 10^{43} n_0 \qquad n(0.1) = n_0 e^{100,000}$$

$$n(0.2) = n_0 e^{200} = 7.23 \times 10^{86} n_0 \qquad n(0.2) = n_0 e^{200,000}$$

$$n(1.0) = n_0 e^{1000} = 1.97 \times 10^{434} n_0 \qquad n(1.0) = n_0 e^{1,000,000}$$

Conclusions

- Process operations must be designed to be well subcritical
  - criticality safety hands-on must be about prevention
  - under both normal and credible abnormal conditions
- Once the critical point is exceeded there is no time to react
  - the consequences cannot be mitigated
  - stop work and back away if controls are suspected to be compromised
  - the difference between subcritical and supercritical in term of physical properties could be very small
    - spacing between objects or
    - the height of solution
- **Alarm systems do nothing to protect personnel from the consequences of first exceeding the critical point**

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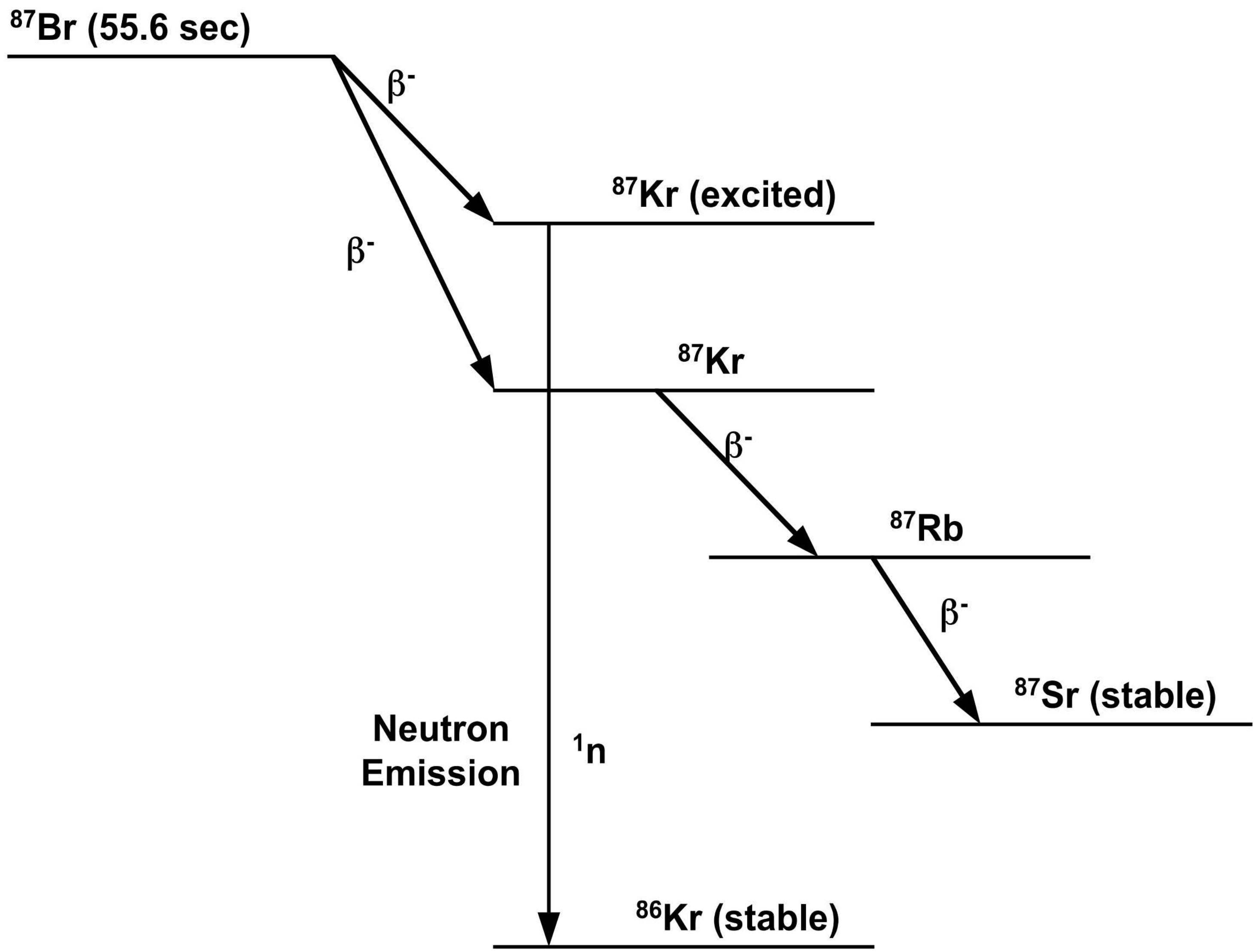
Experimental Considerations
Subcritical Multiplication & Reactor Period

Presented by:
Shean P. Monahan

Neutron Flavors

- Prompt neutrons
  - nearly all fission neutrons appear instantaneously
    - within 10^{-14} seconds of the fission event
    - Greater than 99% of the fission neutrons
    - All are born moving very fast
- Delayed neutrons
  - a small fraction neutrons are born *long* after the fission event
    - tenths of seconds to minutes after
      - released by the decay of fission fragments
      - known as delayed neutron precursors
  - amount to less than 1% of the total fission neutrons
    - known as the delayed neutron fraction β

Example of delayed neutron emission



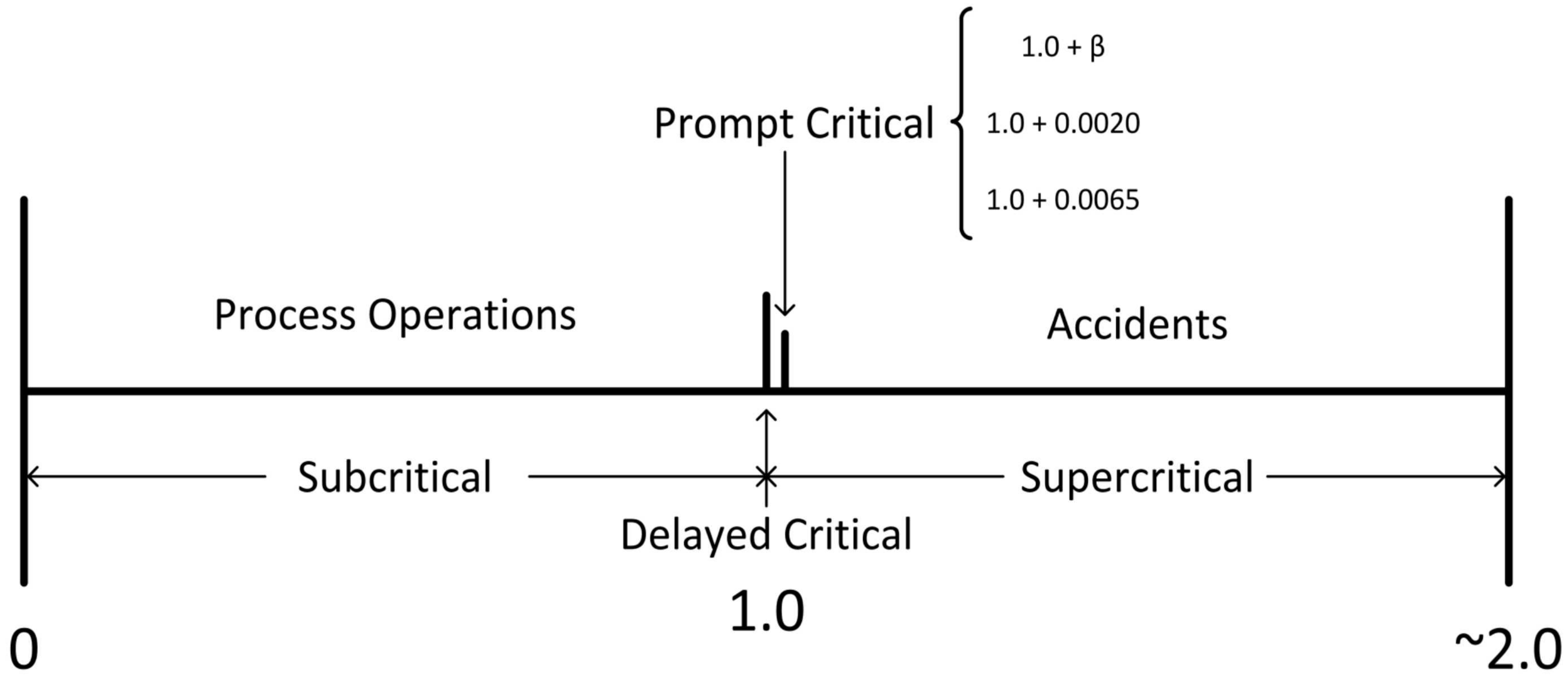
Delayed Neutron Fractions

- Delayed neutron precursor fraction is material and system dependent
  - β=0.0065 for ^{235}U
  - β=0.0020 for ^{239}Pu
- Though a small fraction
  - it is possible for delayed neutrons to dominate the time behavior of systems
    - delayed neutrons can be used to control fission chains
      - critical assemblies
      - reactors (thermal, intermediate, fast)
    - effectively lengthen the generation time
  - without them weapons and accidents would be the only viable nuclear systems

Three Categories of Multiplying Systems

- Subcritical; $k_{eff} < 1$
  - fission chains die out
  - characterized by neutron multiplication, M
  - process operations
- Delayed critical window; $1.0 \leq k_{eff} < 1.0 + \beta$
  - both prompt and delayed neutrons are required to maintain the chain
  - time behavior is characterized by a “reactor period”
    - time for fission rate to increase by a factor of e
  - critical assemblies and reactors operate here
- Super prompt critical; $k_{eff} \geq 1.0 + \beta$
  - Prompt neutrons dominate the system
    - delayed neutrons are not needed to sustain the chain reaction
    - characterized by extremely fast increases in fission rate
    - weapons, criticality accidents

Range of k_{eff}



Subcritical Systems & Neutron Multiplication, M

- Fission chains are part of every subcritical fissionable material system
  - chains start and die out continuously
    - neutrons are multiplied by fission
      - insufficient for constant or divergent chain
      - leakage > absorption (fission) in any generation
  - the amount of multiplication is a characteristic of subcritical systems
    - distinct from but related to k_{eff}
    - designated by the symbol M
      - terminology is unfortunate
      - *amplification* is closer to the concept
  - only has meaning for subcritical systems

Subcritical Chain Multiplication

t	G_0	G_1	G_2	G_3	G_4	G_5	G_6	G_7	G_8	G_9		Total
1	1000	500	250	125	63	32	16	8	4			
2		1000	500	250	125	63	32	16	8		……	
3			1000	500	250	125	63	32	16		……	
4				1000	500	250	125	63	32		……	
5					1000						……	2000
										⋮		
										2000		

Example: $k_{eff} = 0.5$

- Assume we have a non-fission source inserting a 1000 neutrons at the start of each generation
  - As the chain dies out, those original source neutrons create children in each generation
  - Eventually each chain ends but not before multiplying the original value
- M=2000/1000 = 2
- Mathematically

$$M = \frac{1}{1-k}$$

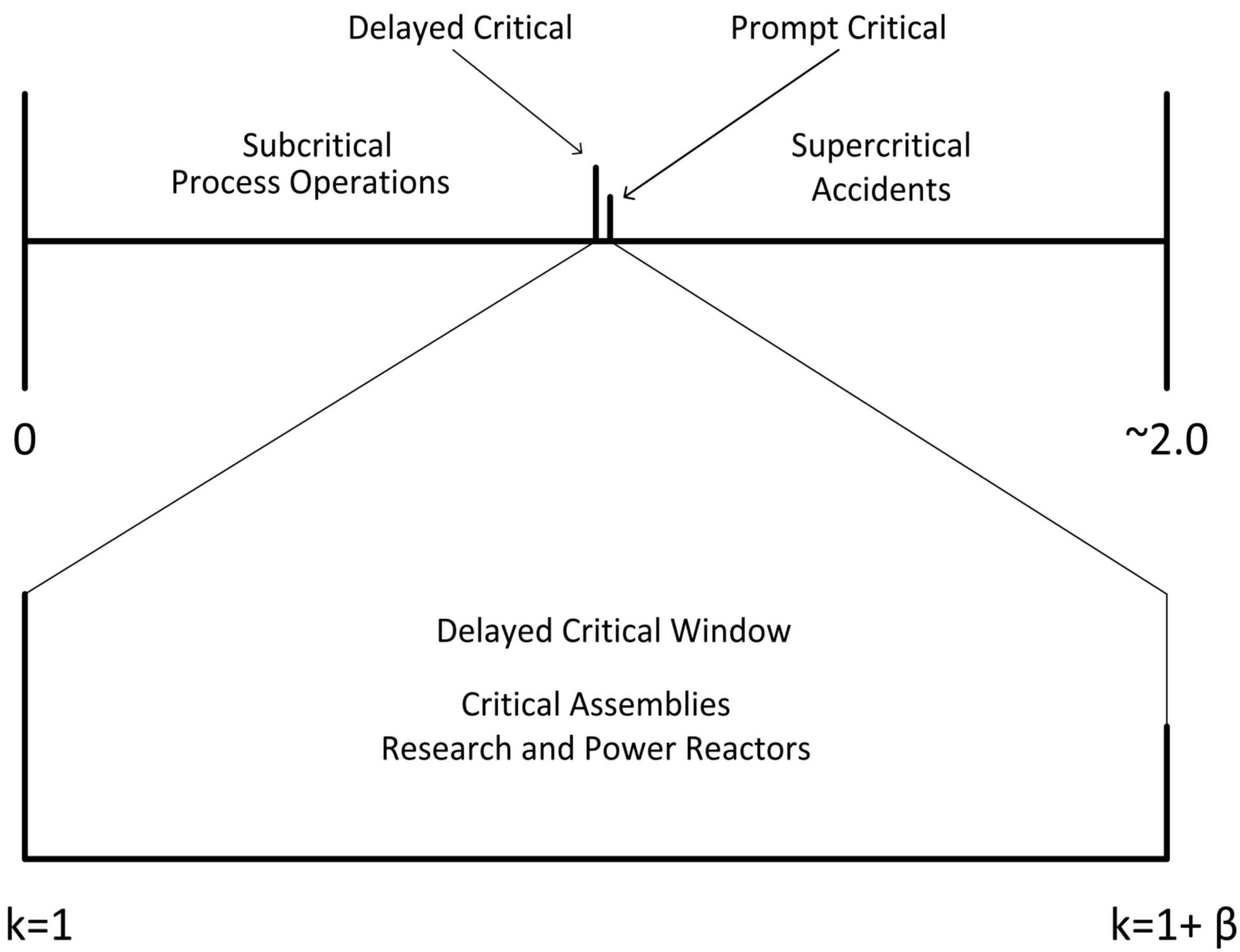
M versus k_{eff}

- This very simple relationship will be used to approach the critical point carefully
  - how critical experiments are done

k_{eff}	M	1/M
0.5	2	0.5
0.8	5.0	0.2
0.9	10.0	0.1
0.95	20.0	0.05
0.99	100.0	0.01
0.999	1000.0	0.001
1.0	∞	0

Delayed Critical Window

- $k_{eff} = 1.0$
  - delayed critical, a.k.a. critical
  - as the name implies every single delayed is necessary to sustain the chain reaction
  - a "generation" is not complete until the delayed neutrons are released, scatter, and cause fission
    - generation time increases
- Inside the DC window: $1.0 \leq k_{eff} < 1.0 + \beta$
  - critical assemblies and reactors
  - as PC is approached less and less delayed neutrons are required
    - wait time is less, generation time decreases
    - kinetics speed up


Delayed Critical
Prompt Critical
Subcritical
Process Operations
Supercritical
Accidents
0
~2.0
Delayed Critical Window
Critical Assemblies
Research and Power Reactors
k=1
k=1+ β

Reactivity

- Relative departure of a system from the critical point, or mathematically

$$\rho = \frac{k_{eff} - 1}{k_{eff}}$$

  - Negative for subcritical systems
  - Positive for supercritical systems
  - ZERO for critical systems
    - The system is non-reactive
      - The neutron population, fission rate, power, leakage rate, etc., are constant
  - No units;
    - Common practice is to assign the DC window as being $1 of reactivity, i.e., 100 cents

$$\rho_{\$} = \frac{\rho}{\beta}$$

Period

- Above DC, ρ>0

$$n(t) = n_o e^{t\left(\frac{k-1}{\ell_g}\right)} = n_o e^{\left(\frac{t}{\tau}\right)} = n_o e^{\omega t}$$

  - in which τ is the system or *reactor period*
    - the time it takes for the power to increase by a factor of e (2.7)
    - obtained from the Inhour equation relating reactivity to period
      - arises from kinetics equations relating neutron population to time
        - includes delayed neutron effects
  - ω the inverse (1/ τ) of the reactor period

- At DC, ρ =0, and the neutron population is constant
  - the period is infinite

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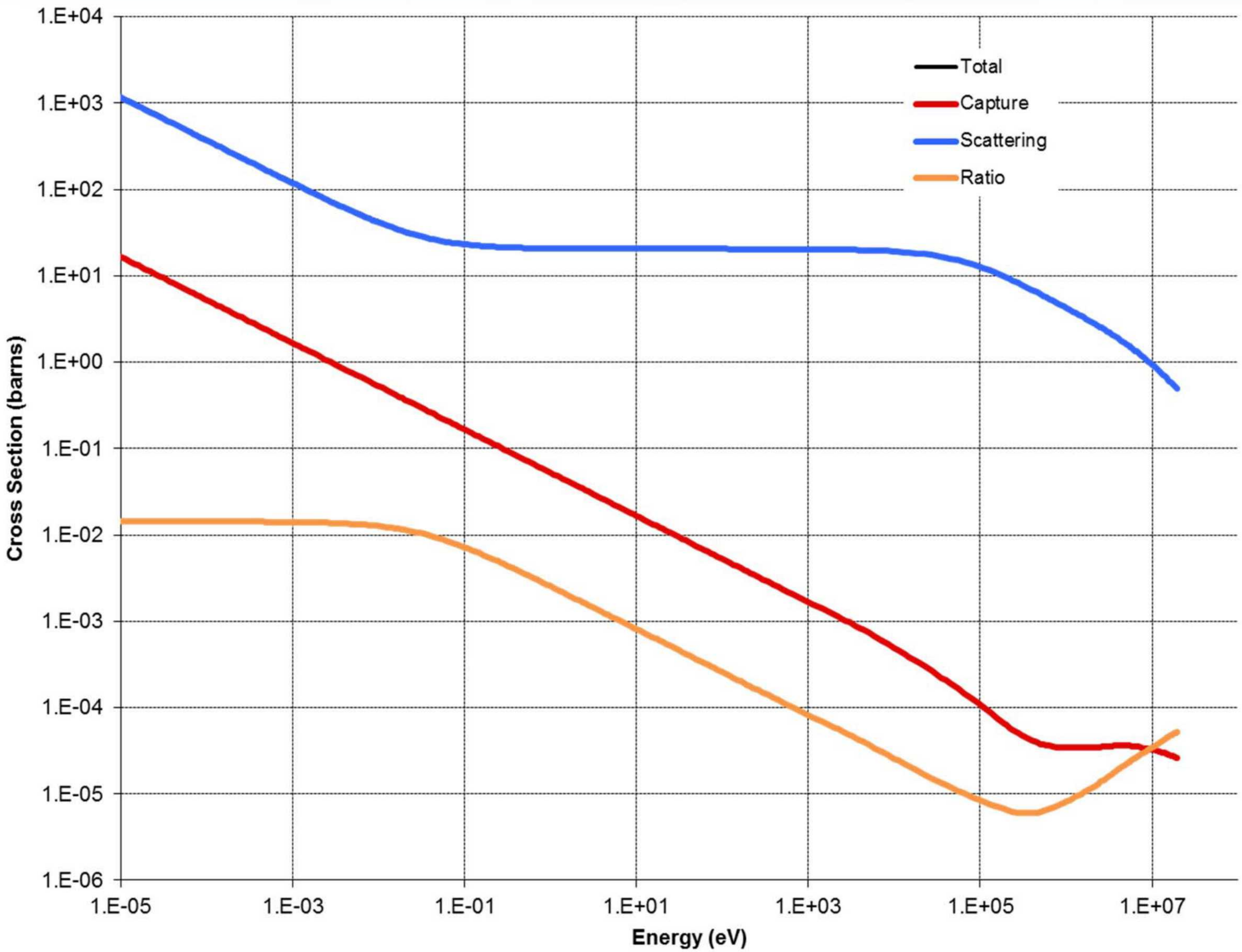
Supplemental Materials

Presented by:

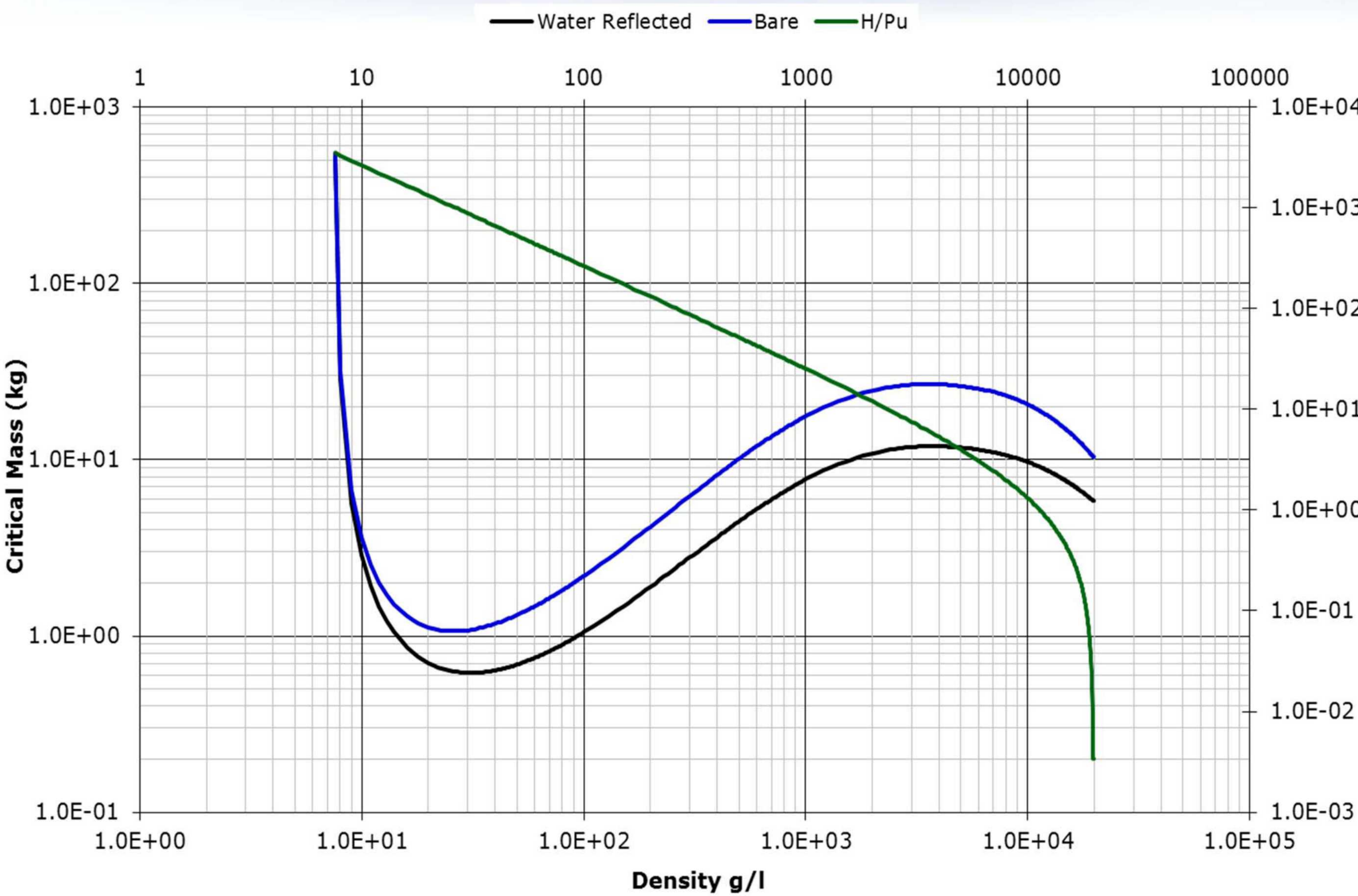
Shean P. Monahan

^{1}H

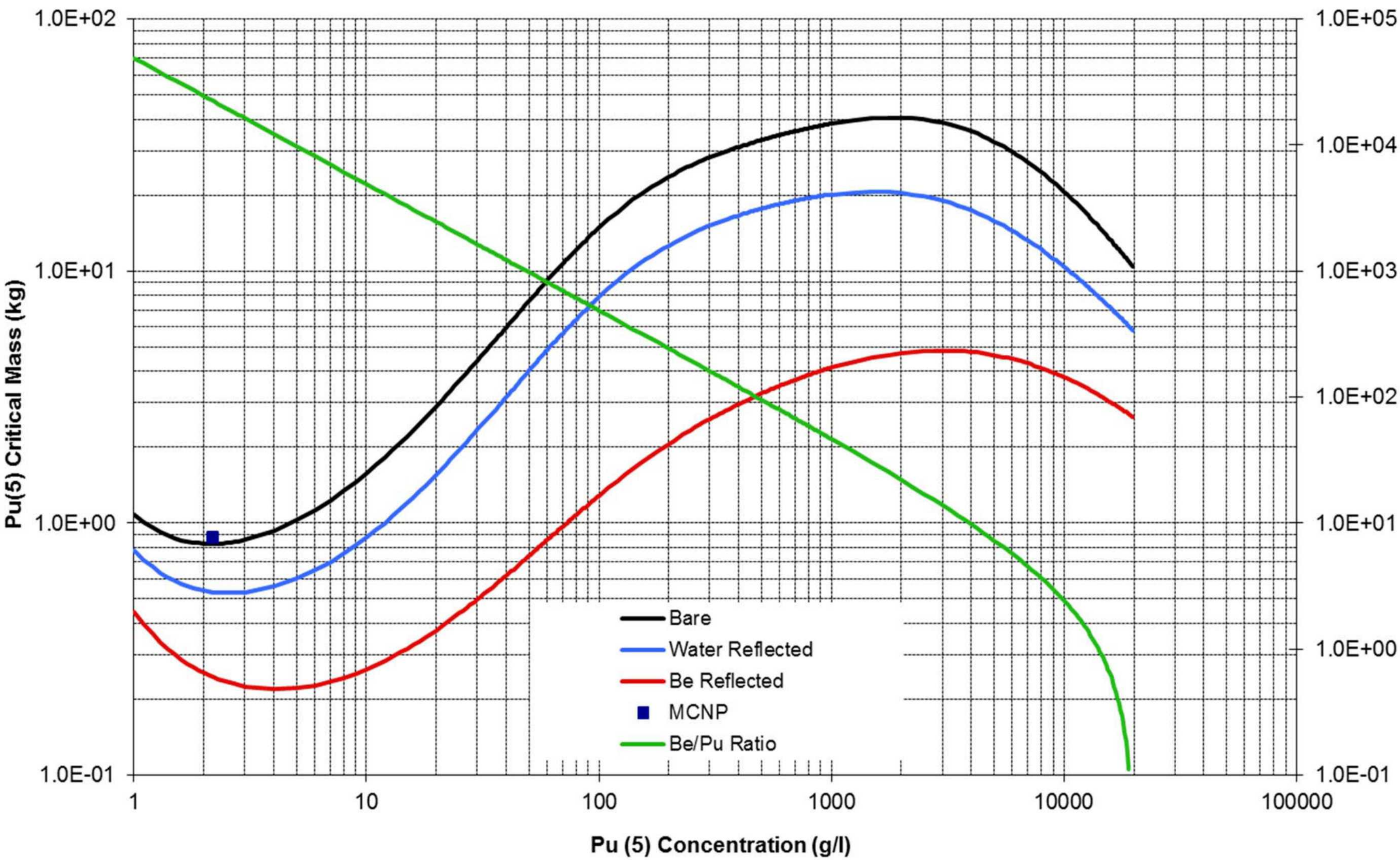


Total
Capture
Scattering
Ratio
Cross Section (barns)
Energy (eV)
1.E+04
1.E+03
1.E+02
1.E+01
1.E+00
1.E-01
1.E-02
1.E-03
1.E-04
1.E-05
1.E-06
1.E-05
1.E-03
1.E-01
1.E+01
1.E+03
1.E+05
1.E+07

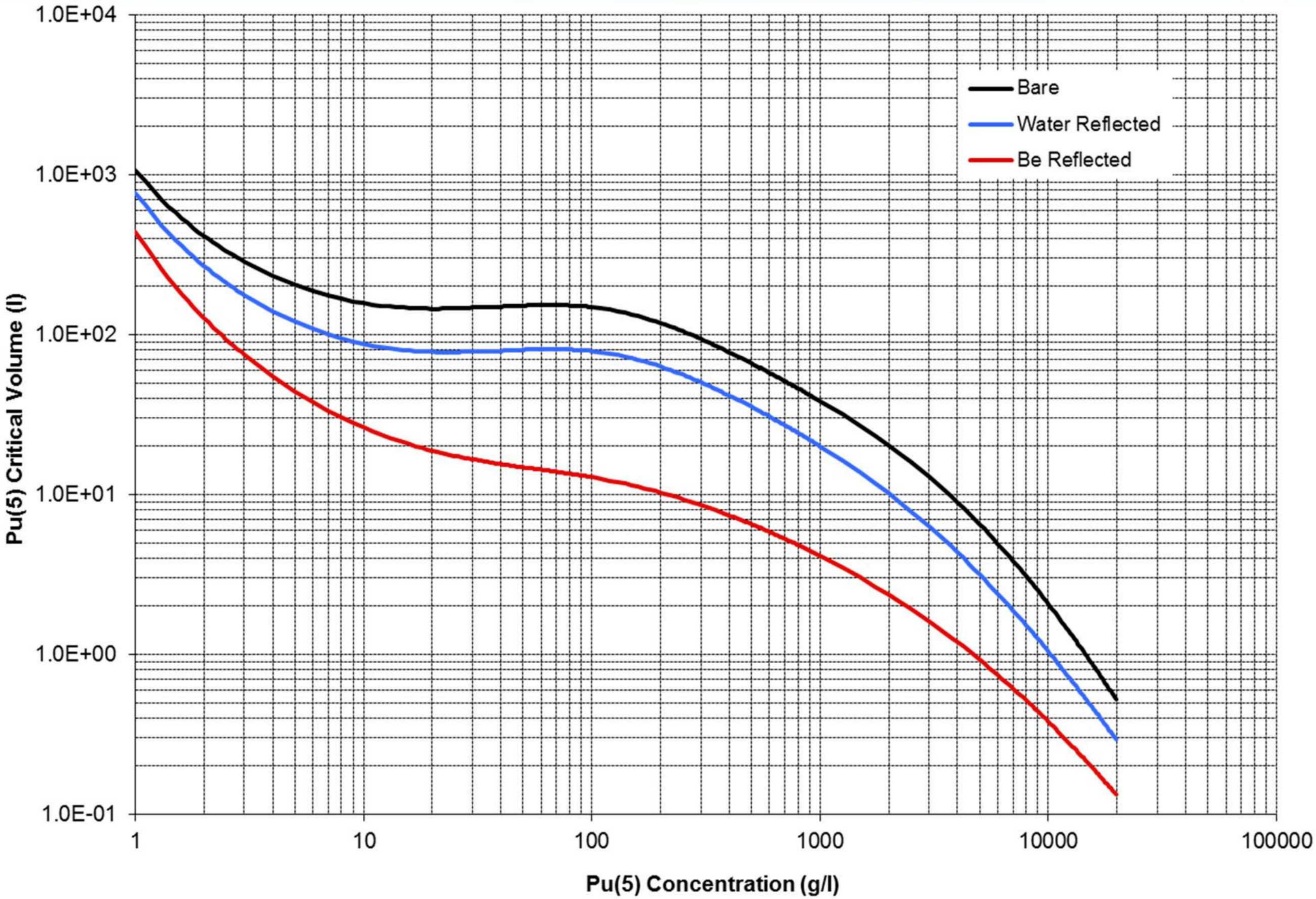
Pu(5) Critical Mass Curve



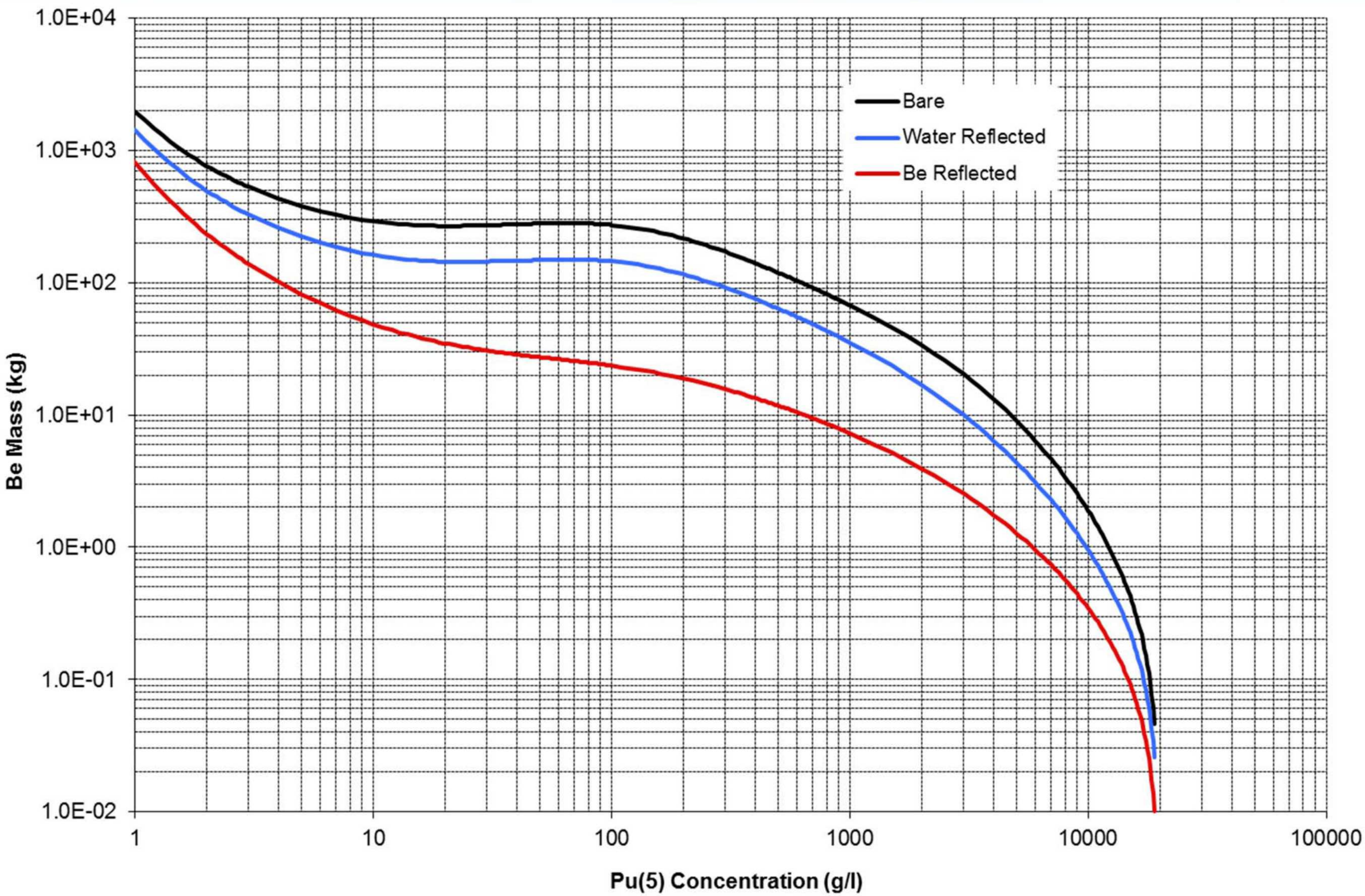
Critical Mass vs. Concentration For a Pu/Be Mixture

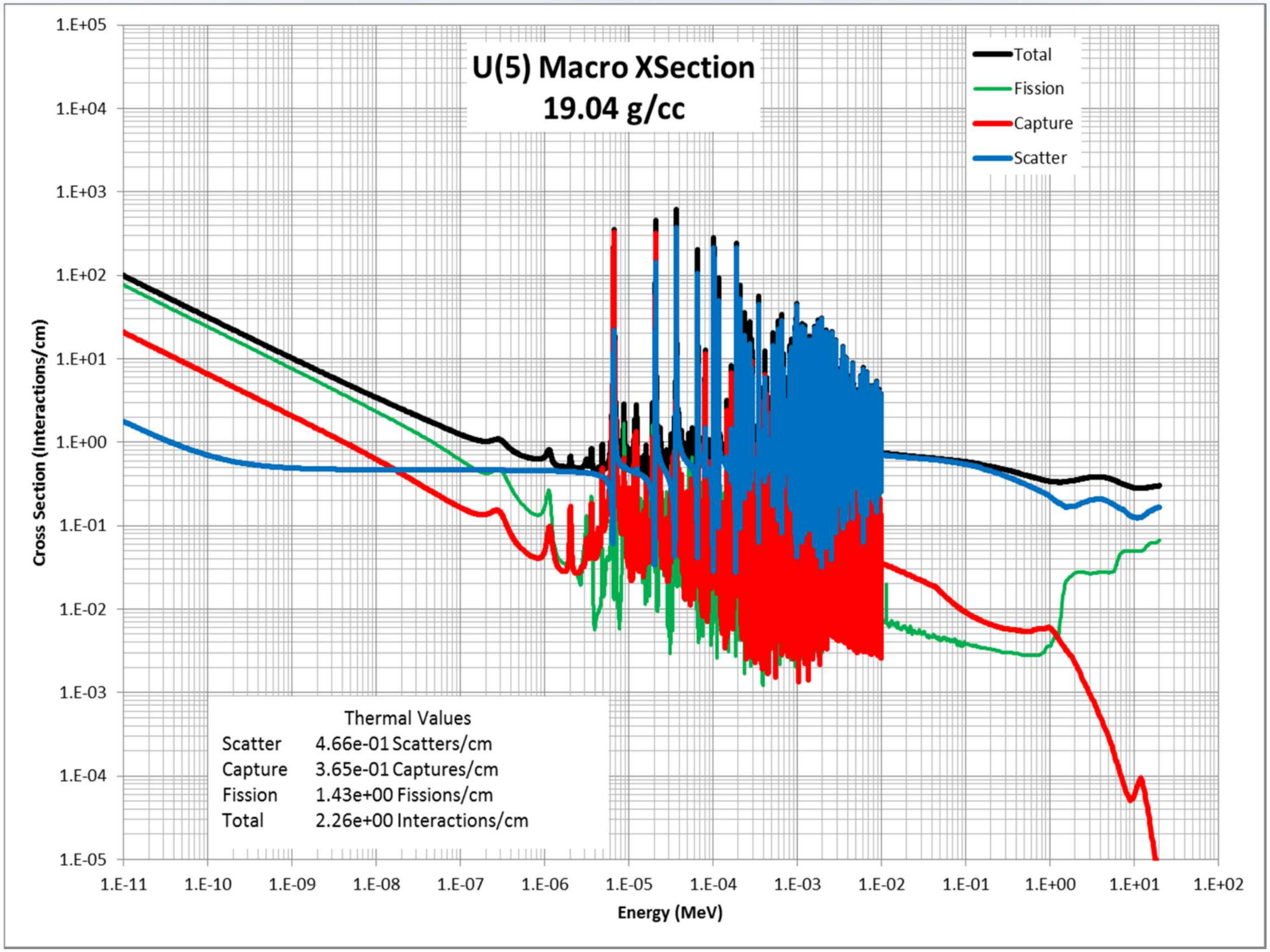


Critical Volume vs. Concentration For a Pu/Be Mixture

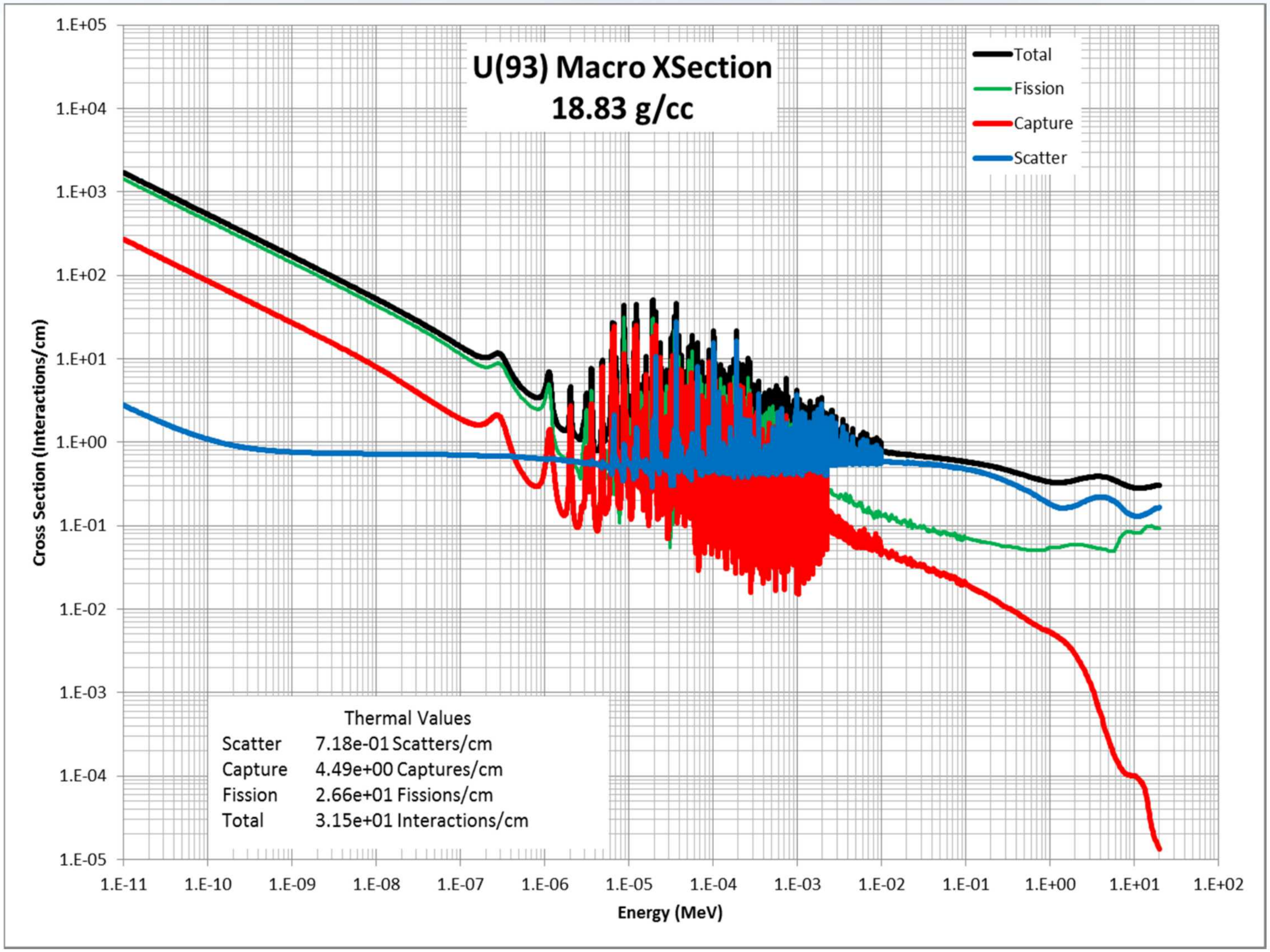


Core Be Mass vs. Concentration For a Pu/Be Mixture





U(5) Macro XSection
19.04 g/cc
Total
Fission
Capture
Scatter
Cross Section (Interactions/cm)
1.E+05
1.E+04
1.E+03
1.E+02
1.E+01
1.E+00
1.E-01
1.E-02
1.E-03
1.E-04
1.E-05
Energy (MeV)
1.E-11
1.E-10
1.E-09
1.E-08
1.E-07
1.E-06
1.E-05
1.E-04
1.E-03
1.E-02
1.E-01
1.E+00
1.E+01
1.E+02
Thermal Values
Scatter 4.66e-01 Scatters/cm
Capture 3.65e-01 Captures/cm
Fission 1.43e+00 Fissions/cm
Total 2.26e+00 Interactions/cm


U(93) Macro XSection
18.83 g/cc
Total
Fission
Capture
Scatter
Thermal Values
Scatter 7.18e-01 Scatters/cm
Capture 4.49e+00 Captures/cm
Fission 2.66e+01 Fissions/cm
Total 3.15e+01 Interactions/cm
Cross Section (Interactions/cm)
Energy (MeV)
1.E+05
1.E+04
1.E+03
1.E+02
1.E+01
1.E+00
1.E-01
1.E-02
1.E-03
1.E-04
1.E-05
1.E-11
1.E-10
1.E-09
1.E-08
1.E-07
1.E-06
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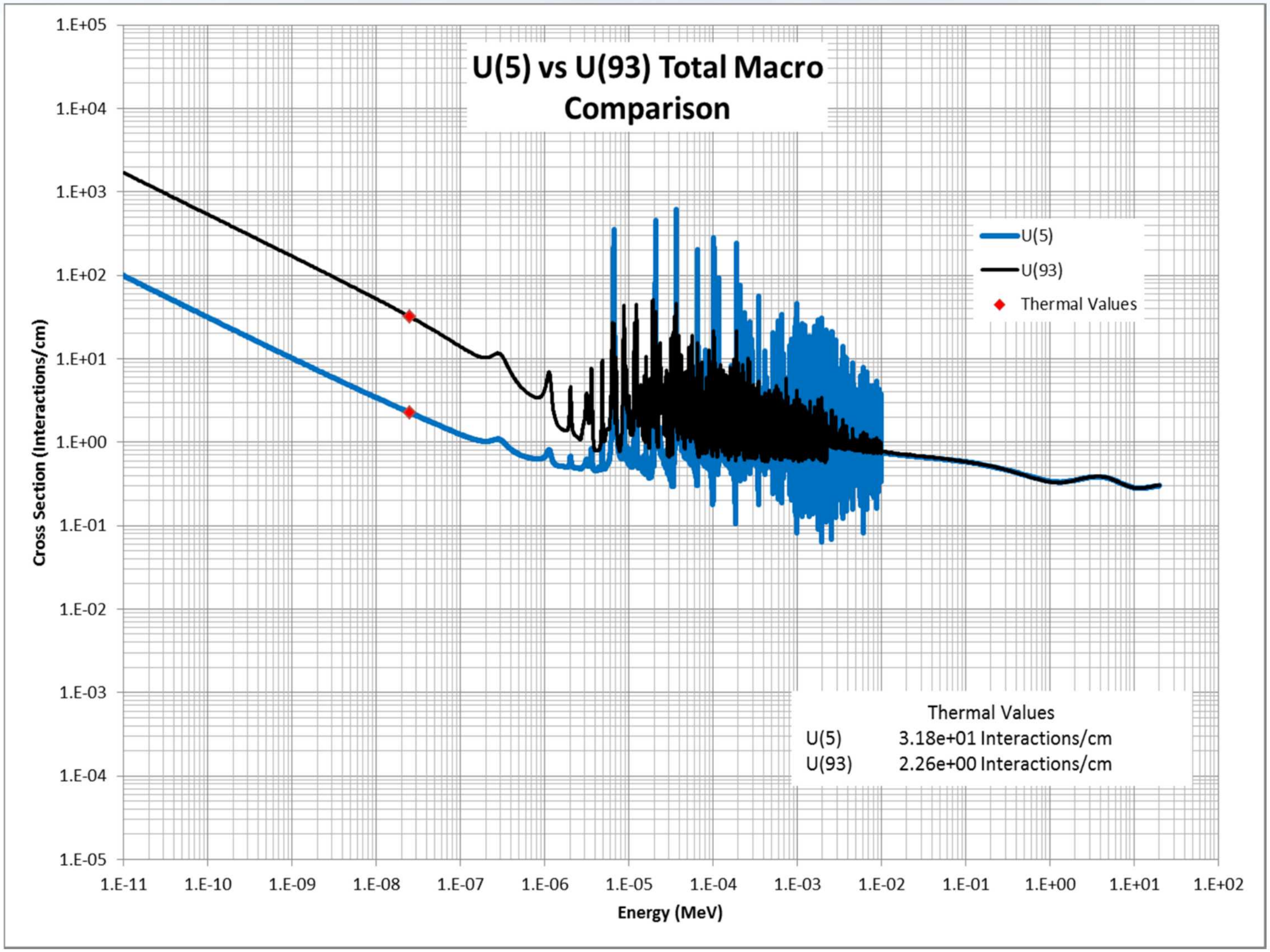
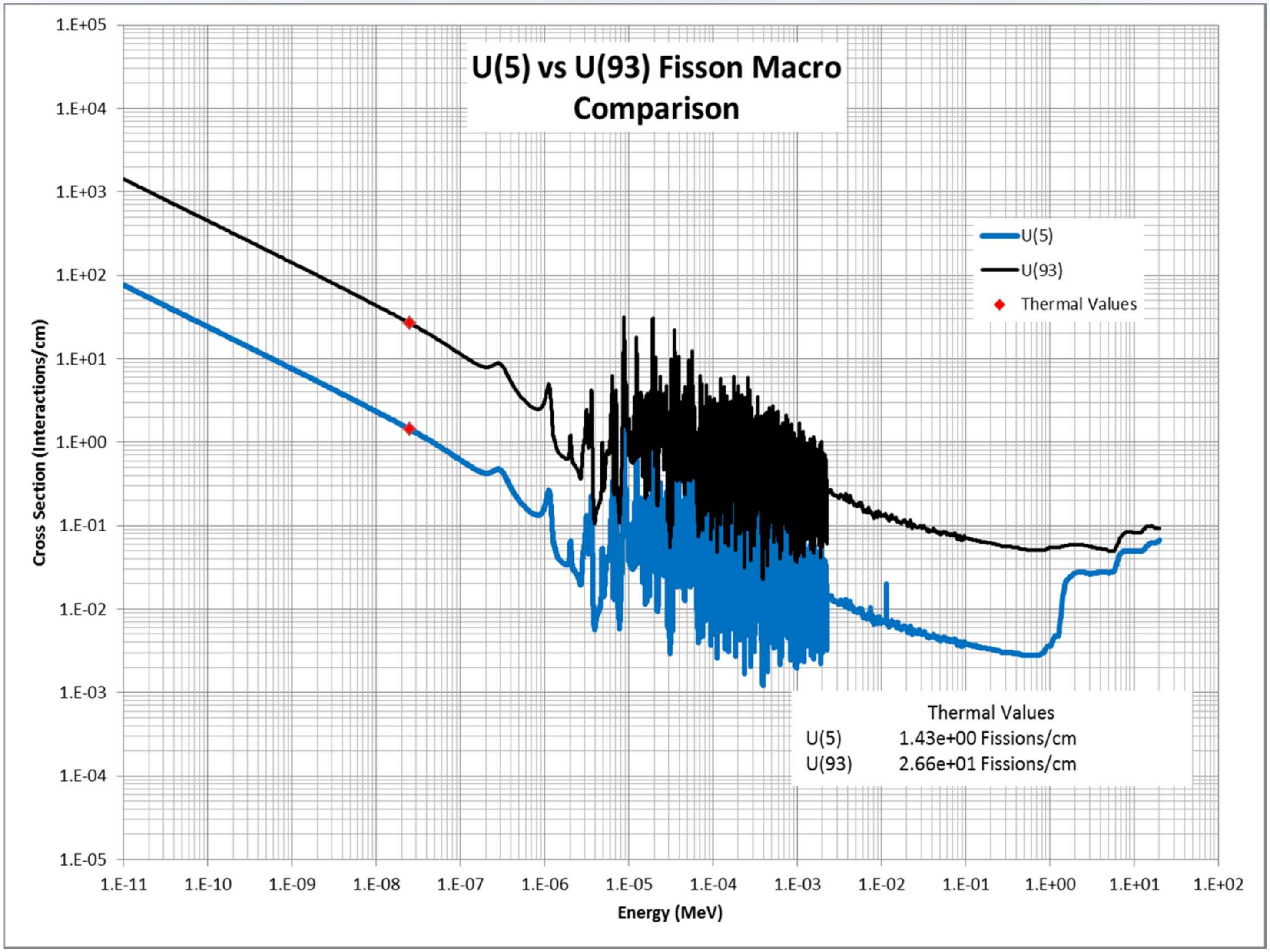
1.E+00
1.E+01
1.E+02



U(5) vs U(93) Total Macro Comparison
U(5)
U(93)
Thermal Values
Thermal Values
U(5) 3.18e+01 Interactions/cm
U(93) 2.26e+00 Interactions/cm
Cross Section (Interactions/cm)
Energy (MeV)
1.E+05
1.E+04
1.E+03
1.E+02
1.E+01
1.E+00
1.E-01
1.E-02
1.E-03
1.E-04
1.E-05
1.E-11
1.E-10
1.E-09
1.E-08
1.E-07
1.E-06
1.E-05
1.E-04
1.E-03
1.E-02
1.E-01
1.E+00
1.E+01
1.E+02



U(5) vs U(93) Fisson Macro Comparison
U(5)
U(93)
Thermal Values
Thermal Values
U(5) 1.43e+00 Fissions/cm
U(93) 2.66e+01 Fissions/cm
Cross Section (Interactions/cm)
Energy (MeV)
1.E+05
1.E+04
1.E+03
1.E+02
1.E+01
1.E+00
1.E-01
1.E-02
1.E-03
1.E-04
1.E-05
1.E-11
1.E-10
1.E-09
1.E-08
1.E-07
1.E-06
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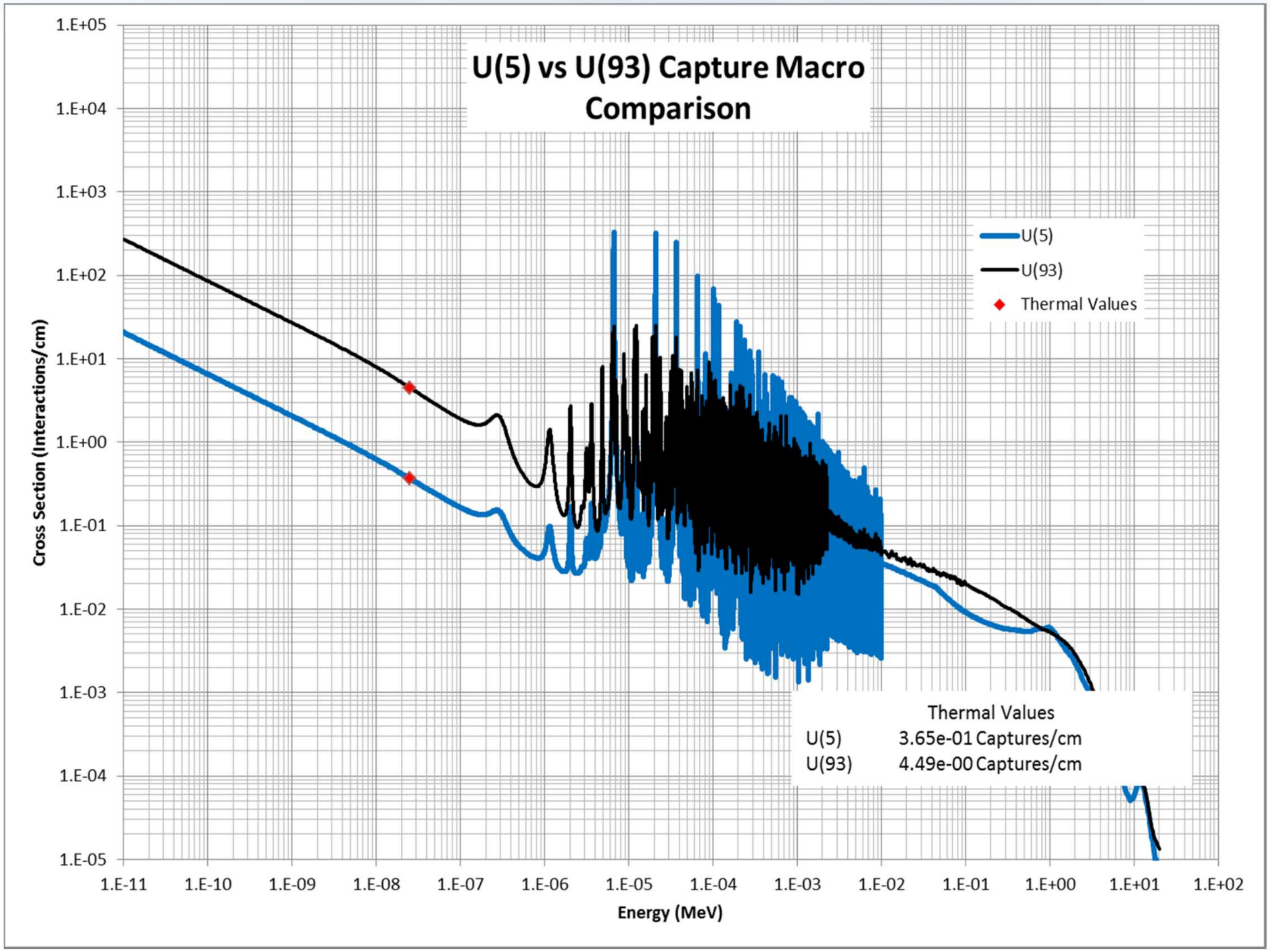
1.E-02
1.E-01
1.E+00
1.E+01
1.E+02


U(5) vs U(93) Capture Macro Comparison
Cross Section (Interactions/cm)
Energy (MeV)
1.E+05
1.E+04
1.E+03
1.E+02
1.E+01
1.E+00
1.E-01
1.E-02
1.E-03
1.E-04
1.E-05
1.E-11
1.E-10
1.E-09
1.E-08
1.E-07
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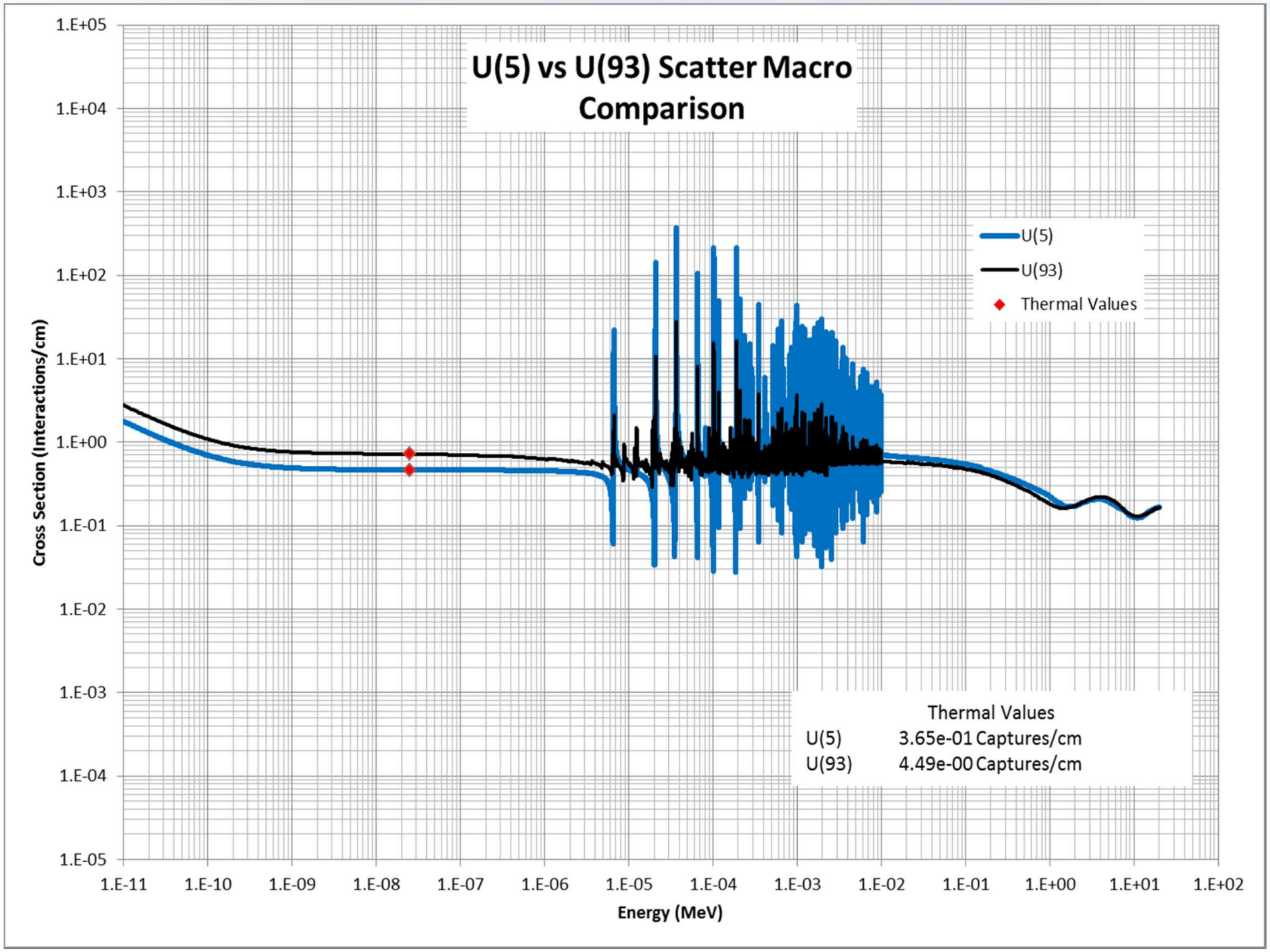
U(5)
U(93)
Thermal Values
Thermal Values
U(5) 3.65e-01 Captures/cm
U(93) 4.49e-00 Captures/cm



U(5) vs U(93) Scatter Macro Comparison
U(5)
U(93)
Thermal Values
Thermal Values
U(5) 3.65e-01 Captures/cm
U(93) 4.49e-00 Captures/cm
Cross Section (Interactions/cm)
Energy (MeV)
1.E+05
1.E+04
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1.E-05
1.E-04
1.E-03
1.E-02
1.E-01
1.E+00
1.E+01
1.E+02

NUCLEAR CRITICALITY SAFETY PROGRAM

Module 2
Criticality Accidents
Section 1: LA-13638

Presented by:
Shean P Monahan

Objectives

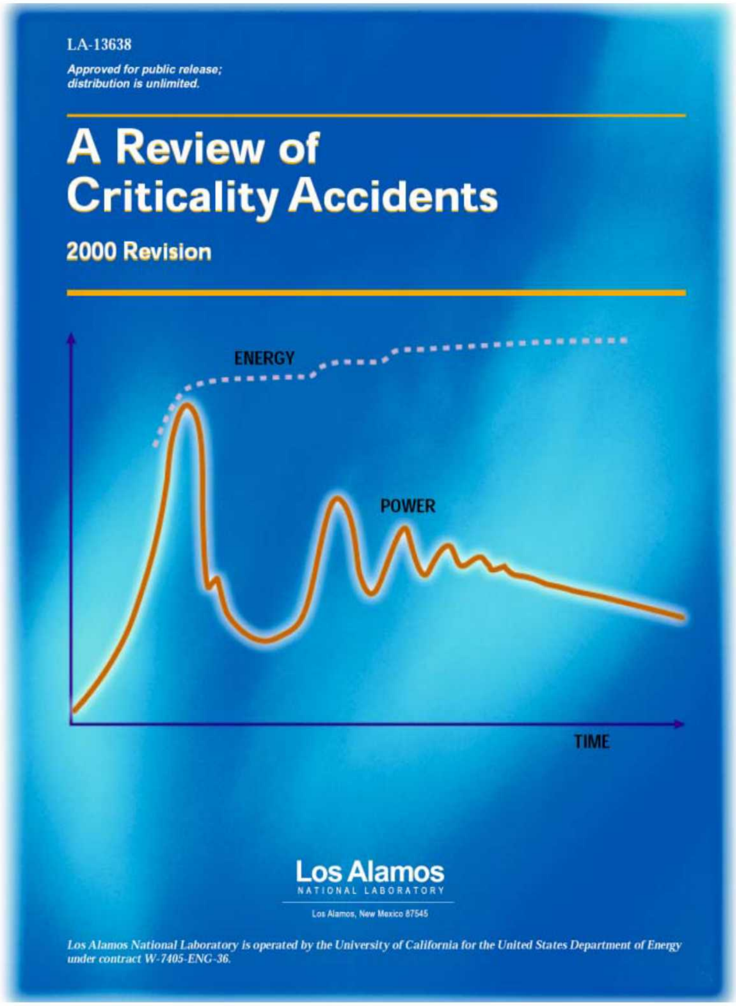
- Introduce LA-13638 “A Review of Criticality Accidents” published in 2000
- Learn about the 1953 accident at Mayak in the USSR (first process criticality accident)
- Learn about the 1999 accident at Tokai-mura in Japan (last process accident)
- Understand the common characteristics of the process criticality accidents and lessons learned

Historical Criticality Accidents

- Basic reference: LA-13638
  - Reactors
  - Critical-measurement facilities
  - Processing plants

T. P. McLaughlin et al., "A Review of Criticality Accidents 2000 Revision," Los Alamos National Laboratory report **LA-13638** (May 2000).

http://ncsp.llnl.gov/basic_ref/la-13638.pdf



LA-13638 Part I

- Chronological presentation of process criticality accidents
  - Overview
  - Summary description of each accident
    - References to more in depth documents when available
  - Physical and neutronic characteristics section
  - Observations and Lessons Learned

LA-13638 Part II

- Chronological presentation of reactor and experimental accidents
  - Overview
    - A. Fissile solution systems
    - B. Bare and reflected metal assemblies
  - Will be discussed later in this presentation

Nuclear Criticality Accident

The release of energy as the result of inadvertently producing a self-sustaining or divergent chain reaction

Process Facility Criticality Accidents

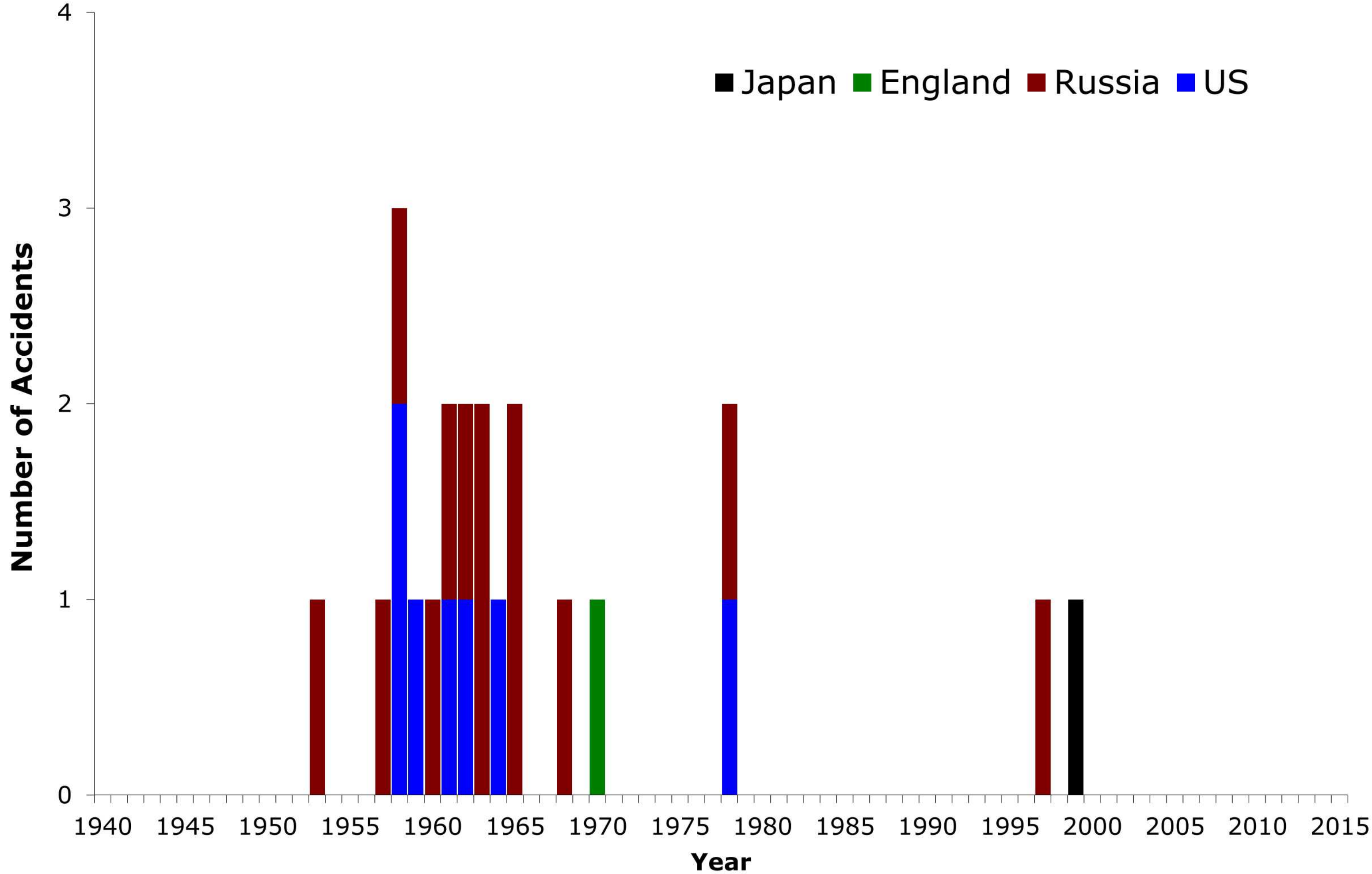
- Millions of operations since 1943
  - Designed with largest practical safety margins
- 22 accidents
  - 21 involving solution/slurry
    - 4 involving chemistry “gone bad”
  - 1 involving metal ingots
  - 0 involving powders
  - 0 in transportation
  - 0 in storage

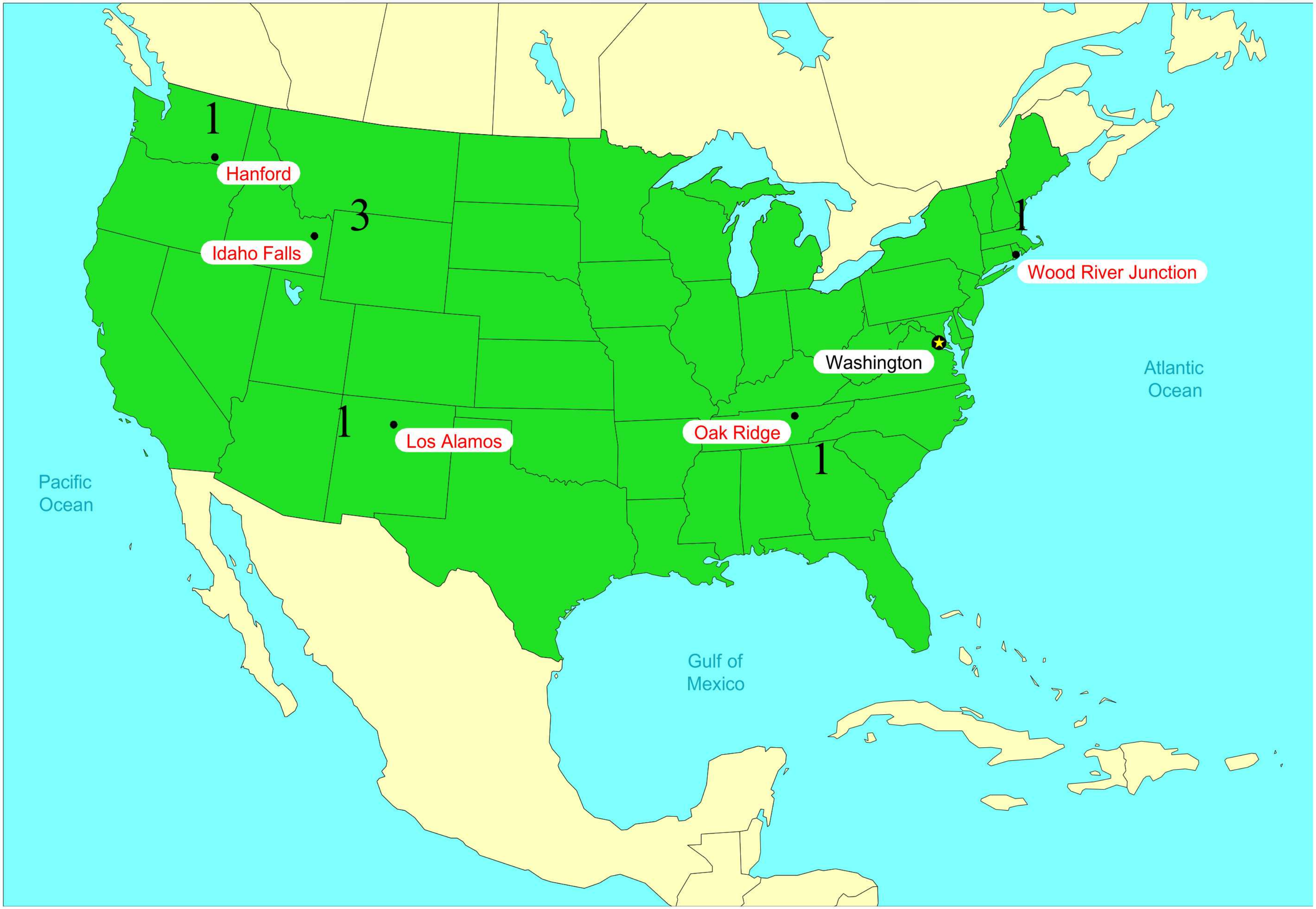
Process Facility Criticality Accidents

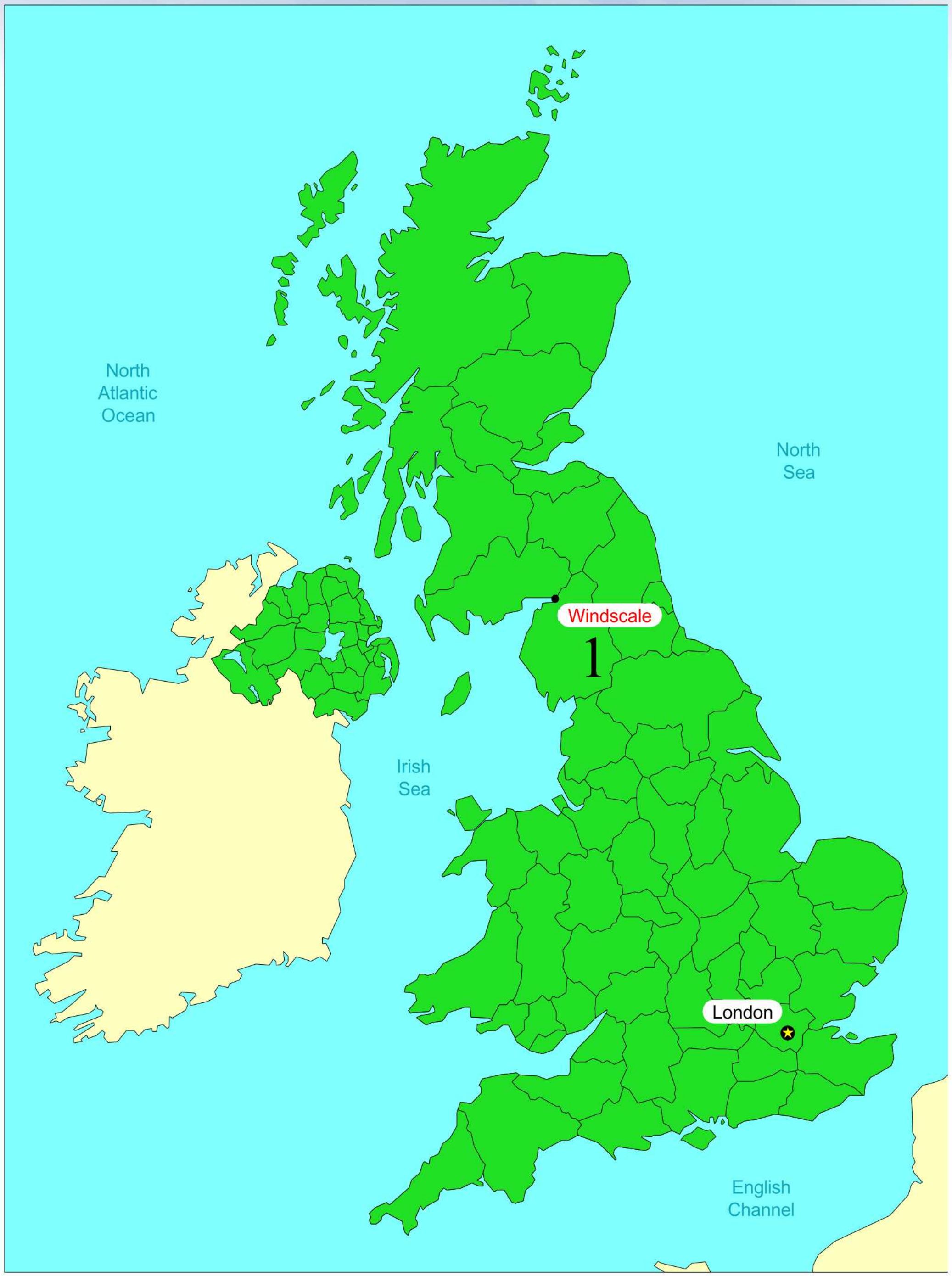
- By Country
  - 7 United States
    - 6 @ government facilities
    - 1 @ commercial facility, UNFR Plant
  - 1 United Kingdom
  - 1 Japan
  - 13 in the Former Soviet Union

- Frequency
  - 1957-1970; ~1 to 2 per year
  - 1970+; ~1 every 10 years

Process Facility Criticality Accidents




1
Hanford
3
Idaho Falls
1
Wood River Junction
Washington
Atlantic
Ocean
1
Los Alamos
Oak Ridge
1
Pacific
Ocean
Gulf of
Mexico


North
Atlantic
Ocean
North
Sea
Windscale
1
Irish
Sea
London
English
Channel


Sea of
Japan
Tokai Mura
Tokyo
1
North
Pacific
Ocean
Philippine Sea


Norwegian Sea
Bering Sea
Baltic Sea
Moscow
Obninsk
Electrostal
1
Black Sea
Mayak
7
4
Tomsk
Novosibirsk
1
Sea of Okhotsk
Sea of Japan

Process Facility Consequences

- 9 deaths
  - 2 United States
  - 2 Japan
  - 5 Former Soviet Union
- 3 personnel required limb amputations
- Negligible environmental contamination
- No physical damage to equipment or facilities
- Measured public exposures
  - 1999 Japan accident only
  - Not health threatening

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NUCLEAR CRITICALITY SAFETY PROGRAM

Module 2
Section 2: Process Facility Criticality Accidents
The First Accident

Presented by:
Shean P Monahan

Background Information

- Union of Soviet Socialist Republics
  - Mayak Production Association
  - Sunday, 15 March 1953
  - Facility was not equipped with an alarm system

- Pu extraction (fuel) and purification facility
  - $Pu(NO_3)_4$ solution interim staging area
  - Sampling (purity, concentration), mixing, dilution, and volume measurement

- First process criticality accident in history
  - Inevitable the day the facility was opened

Pu Nitrate Staging Vessels

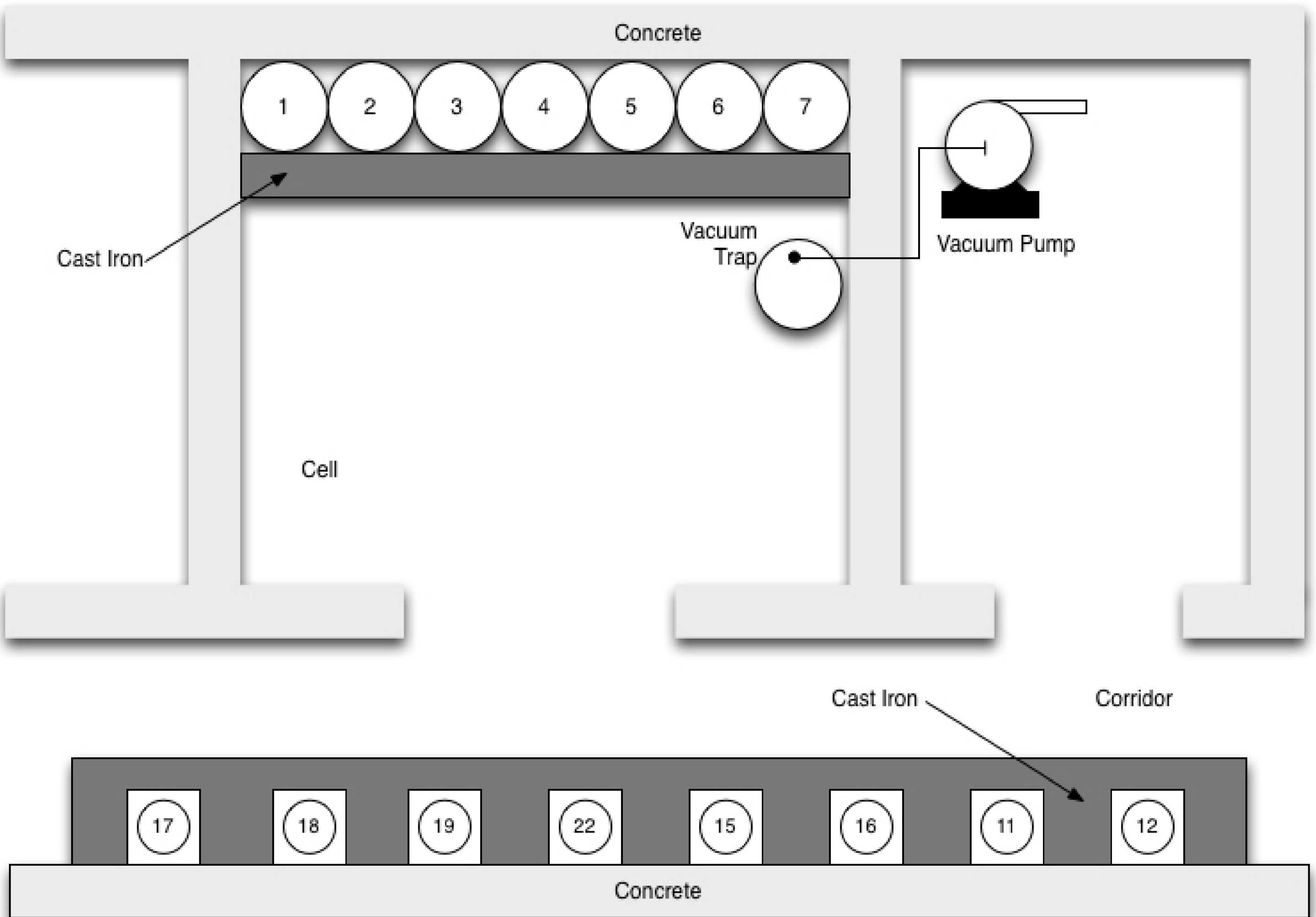
- 15 identical steel vessels
  - 40-cm (15.75-inches) in diameter
  - 32-cm (12.6-inches) high
  - H/D ratio = 0.8
  - Shielded by thick cast iron, ~2.2 mt/vessel
    - Cut-outs in the top cast iron shields allowed for access to the vessel connection ports

Physical Layout

- 7 vessels located in a concrete cell
  - 3 by 2 by 2.5 meters in size
  - original vessels installed in 1952
  - fixed piping for feeds, water, and nitric acid

- 8 vessels located in the adjacent corridor
  - installed when the first seven proved inadequate
  - no fixed piping or utility services

- Transfers between the cell and corridor vessels
  - hand-held hoses and a vacuum system



Concrete
1
2
3
4
5
6
7
Cast Iron
Vacuum
Trap
Vacuum Pump
Cell
Cast Iron
Corridor
17
18
19
22
15
16
11
12
Concrete

Criticality Safety

- Written instructions
  - Operations were directed through shift orders
- Each vessel was limited to 500-grams of Pu
  - contents were recorded in an operational log
- Use of vessels 2, 4, and 6 was <u>not</u> allowed
  - cadmium sheets installed between vessels
- Review of sample analysis was required
  - Recorded in log book approved by supervisors

15 March 1953 Operating Log

Tank Number	Volume (L)	Pu Mass (g)	Concentration (g/L)
5	0.0	0.0	0.0
6	0.0	0.0	0.0
7	0.0	0.0	0.0

15 March 1953 Operating Log

Tank Number	Volume (L)	Pu Mass (g)	Concentratio n (g/L)
1	15.0	**672.0**	44.8
5	0.0	0.0	0.0
6	0.0	0.0	0.0
7	0.0	0.0	0.0

15 March 1953 Operating Log

Tank Number	Volume (L)	Pu Mass (g)	Concentration (g/L)
1	15.0	**672.0**	44.8
2	**10.0**	**58.0**	**5.8**
5	0.0	0.0	0.0
6	0.0	0.0	0.0
7	0.0	0.0	0.0

15 March 1953 Operating Log

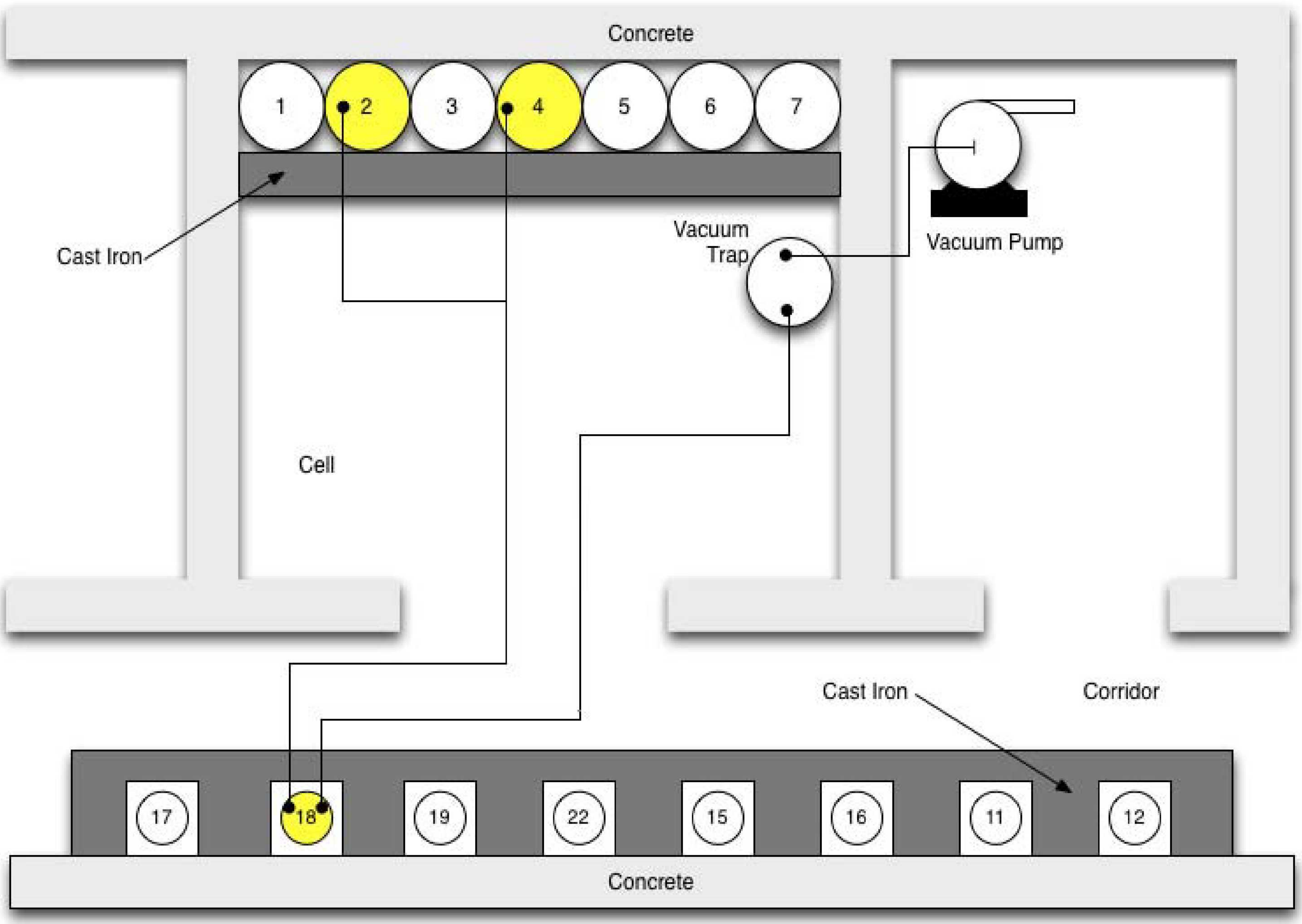
Tank Number	Volume (L)	Pu Mass (g)	Concentration (g/L)
1	15.0	**672.0**	44.8
2	**10.0**	**58.0**	**5.8**
3	15.5	**567.0**	36.6
5	0.0	0.0	0.0
6	0.0	0.0	0.0
7	0.0	0.0	0.0

15 March 1953 Operating Log

Tank Number	Volume (L)	Pu Mass (g)	Concentration (g/L)
1	15.0	**672.0**	44.8
2	**10.0**	**58.0**	**5.8**
3	15.5	**567.0**	36.6
4	**16.0**	**566.0**	**35.4**
5	0.0	0.0	0.0
6	0.0	0.0	0.0
7	0.0	0.0	0.0

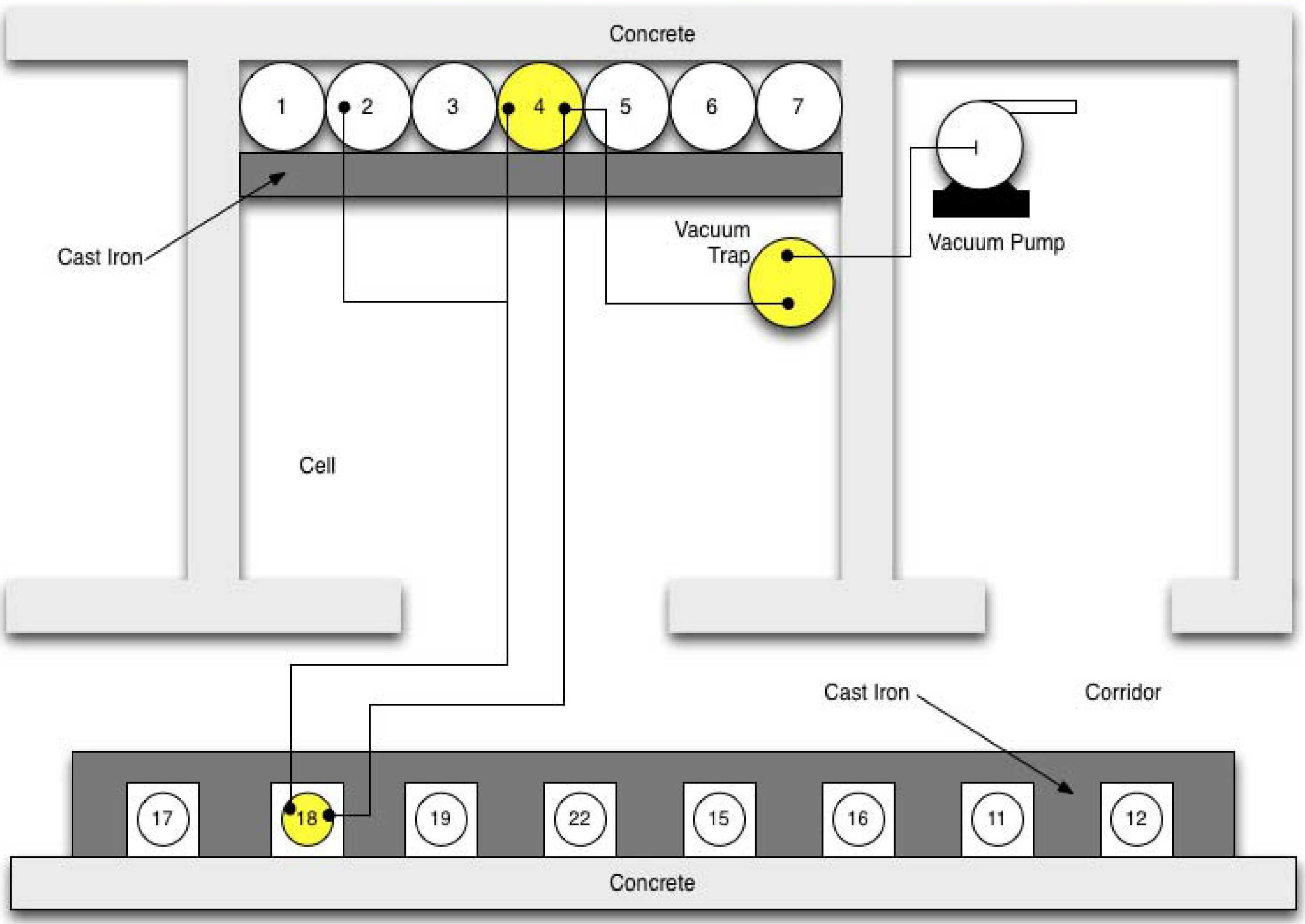
Lead-Up Activities

- Shift orders
  - two incoming transfers to the concrete cell
- Operators needed to make room in the cell for incoming solution
  - Apparently vessels 5, 6, and 7 were inoperable
  - Operators decided to transfer contents of vessels 2 and 4 to vessel 18
    - vessel 18 was listed as empty in the operating log
- Transfer would result in 624g Pu in 26 liters; 23.8g/l


Concrete
1
2
3
4
5
6
7
Cast Iron
Vacuum
Trap
Vacuum Pump
Cell
Cast Iron
Corridor
17
18
19
22
15
16
11
12
Concrete

The Transfer

- One operator was stationed in the concrete cell
  - at vessels 2 and 4
- One operator was stationed in the corridor
  - at vessel 18
- Hoses were held in place by hand
- Vacuum was applied to vessel 18 via 5-liter glass trap in the cell
  - Vessel contents 2 transferred
  - Vessel contents 4 transferred


Concrete
1
2
3
4
5
6
7
Cast Iron
Vacuum Trap
Vacuum Pump
Cell
Cast Iron
Corridor
17
18
19
22
15
16
11
12
Concrete

The Accident

- After the transfer
  - Corridor operator (vessel 18)
    - disconnected the hose
    - observed an energetic gas release and foaming
    - noticed a significant rise in the temperature of the vessel
      - Estimated 60 °C above ambient (30 °C)
    - reconnected the hose
  - Cell operator (vessels 2 and 4)
    - observed a slug of solution entering the vacuum trap (5 liters)

The Aftermath

- The operators did not recognize that a criticality accident had just occurred
  - No alarm system
- However
  - considered the situation unusual
  - agreed and completed a course of action
    - transferred the solution back into vessel 4
    - diluted it with water and nitric acid for cooling purposes
  - continued to work and finished the shift
    - received 15.5-liters containing 614 grams of Pu to vessel 5

The Aftermath

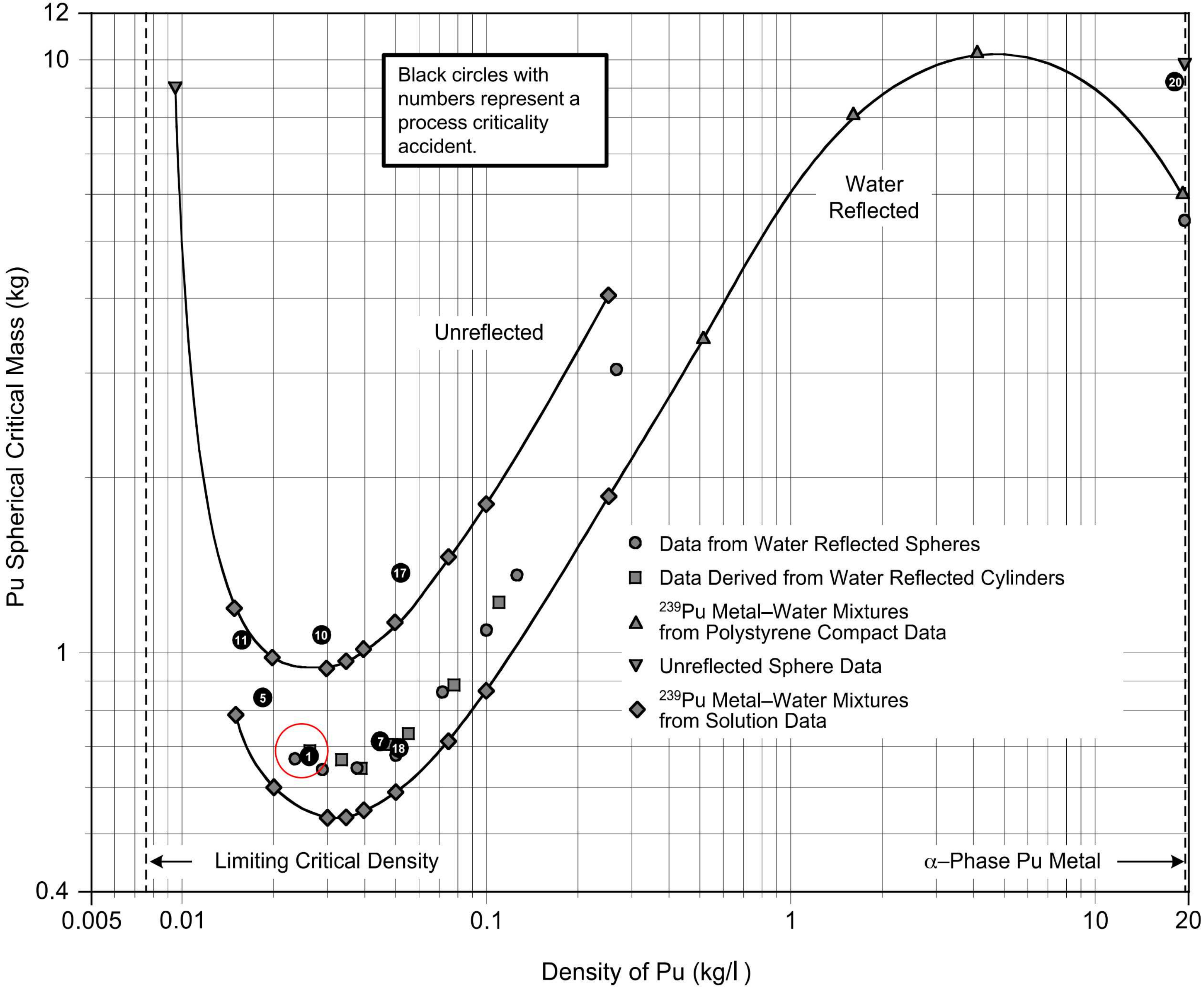
- Two days later:
  - One of the operators “abruptly” became ill
    - corridor operator (vessel 18)
    - requested medical assistance
  - Symptoms were recognized as radiation sickness
  - Investigation initiated

The Details

- Vessel 18 had not been empty on 15 March
  - Contained 5 liters of solution (218g Pu)
  - Unrecorded transfer from vessel 1 to 18 on some earlier shift
    - responsible person was never identified
  - Therefore after the transfer of the contents of vessels 2 and 4, vessel 18 contained

31 liters @ 27.2 g/l; 842 grams

^{239}Pu Critical Mass Curve (from LA-13638)



Causes

- Supervisors and operators
  - **Had no knowledge or understanding of plutonium**
  - **Had no training or knowledge of criticality safety**

- From their point of view the rules were nonsensical & interfered with production

- 1953
  - Stalin had just died (10 days earlier, 5 March 1953)
  - Production took precedence over safety

Consequences

- 2 x 10^{17} Fissions
  - based on a 60 °C temperature rise
  - more likely 2 to 4 x 10^{16} fissions
    - 10^{15} fissions/liter

- 100 rad dose to cell operator
  - No long-term effects

- 1000 rad dose to corridor operator
  - legs amputated
  - died 35 years later

1 Sievert = 100 rem (dose equivalent)

1 Gray = 100 rad (absorbed dose)

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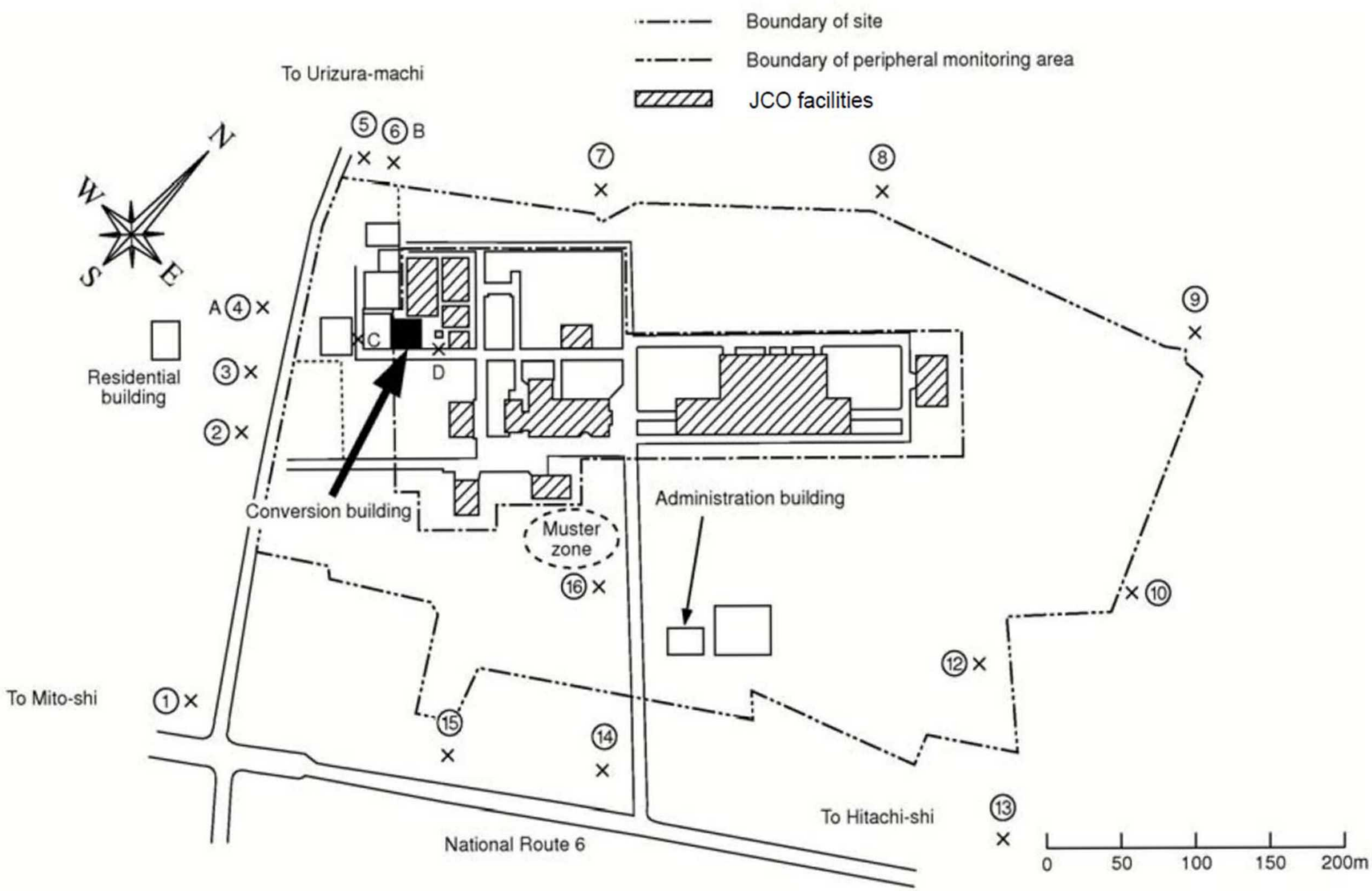
Module 2
Section 3: Process Facility Criticality Accidents
The Last Accident

Presented by:
Shean P Monahan

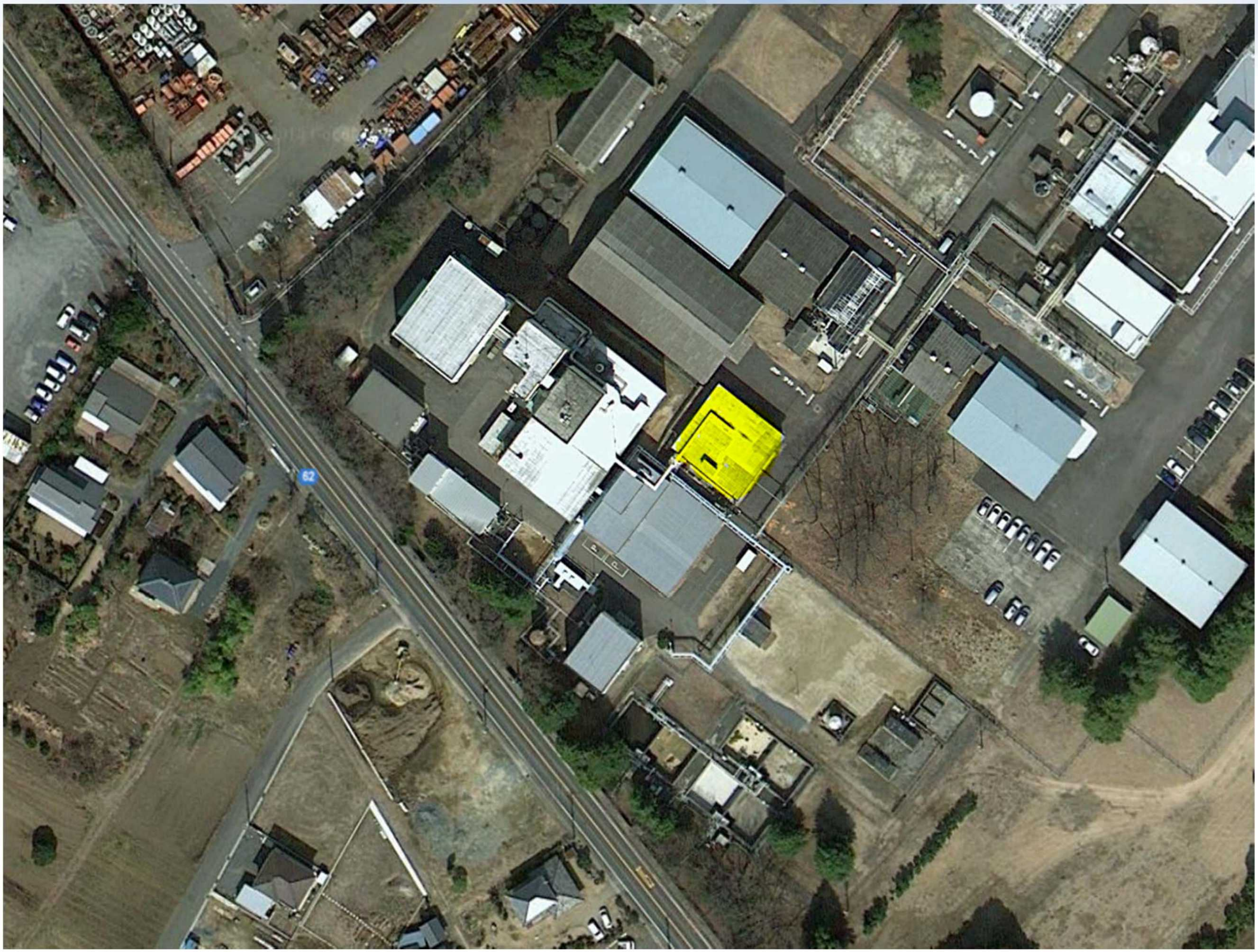
Background Details

- Tokai-Mura, Ibaraki-ken Prefecture, Japan
  - JCO Fuel Fabrication Plant
  - 30 September 1999
  - Facility was not equipped with a criticality accident alarm system
  - Facility was equipped with a high radiation alarm

- JCO Fuel Fabrication Plant
  - 3 fissionable material handling facilities
    - 2 main buildings for UO_2 production from UF_6
      - processed up to U(5)
    - Fuel Conversion Test Building (FCTB)
      - processed up to U(20)
      - infrequently used


Boundary of site
Boundary of peripheral monitoring area
JCO facilities
To Urizura-machi
N
W
S
E
Residential building
Conversion building
Muster zone
Administration building
To Mito-shi
To Hitachi-shi
National Route 6
A
B
C
D
0
50
100
150
200m

ジェー・シー
オー労働組合
Rikuzenhama Hwy
二軒茶屋


62


管理区域
許可なくして
立ち入りを禁ず
入禁止

The Task

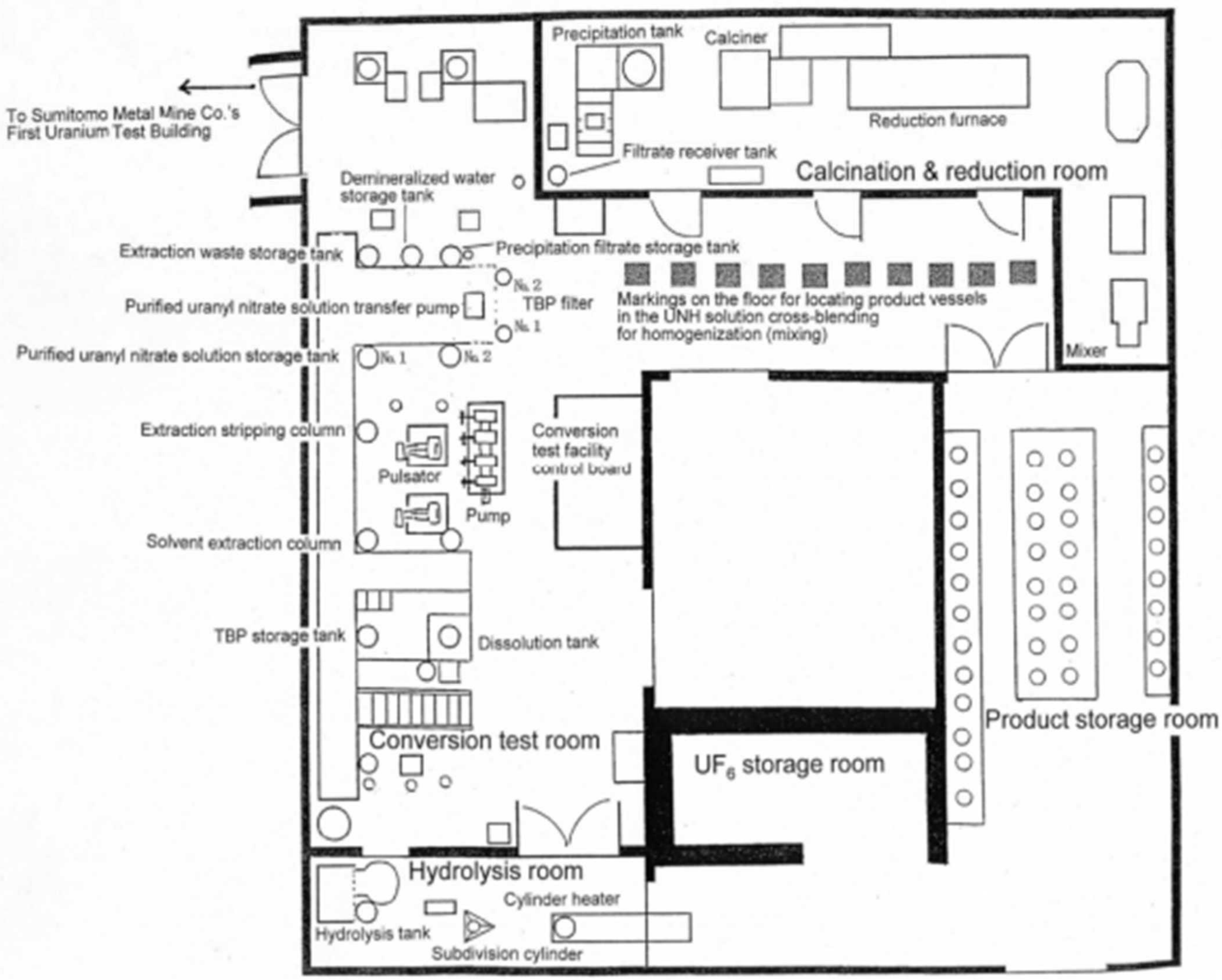
- JOYO reactor fuel production
  - Infrequent
    - Ninth time in facility history
  - 2 operators and a supervisor were assigned to the FCTB
    - uniform uranyl nitrate packaged it into 4 liter bottles

- Feed material was 16.8 kg of $U_3(18.8)O_8$ powder
  - Procedures for U(16) to U(20) limited the batch mass
    - 2.4 kg per batch

- Uniform uranyl nitrate, 45.4l @ 370 g/l
  - Package in 4 liters bottles (12 total)

FCTB

The layout in the JCO conversion test building



The Approved and Licensed Procedure

- Dissolution via dissolver vessel
  - Batches were limited to of 2.4kg

- Each batch was to be transferred to a single geometrically favorable vessel
  - Achieved uniformity of concentration

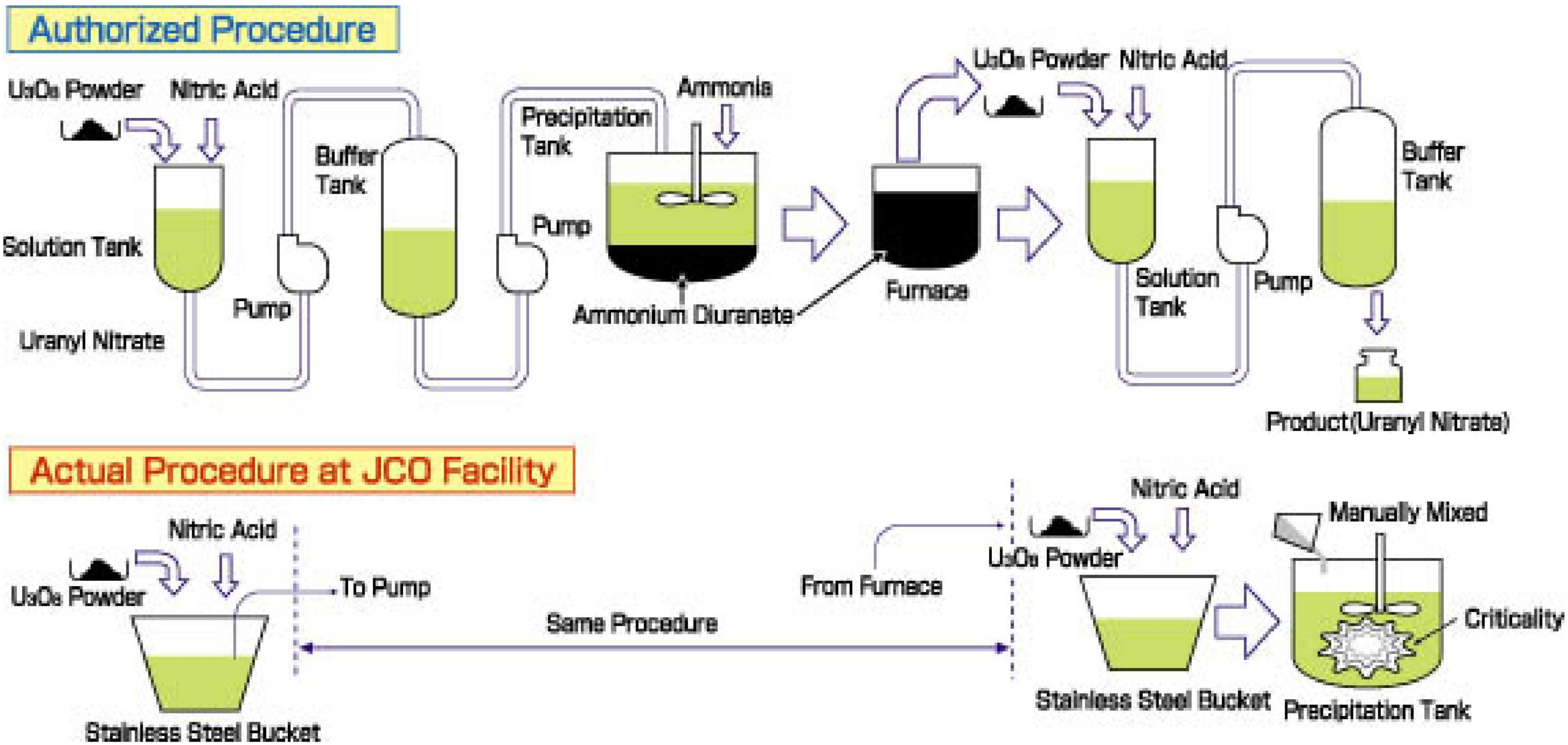
- Once all the batches had been completed
  - the solution would then be drained into four liter bottles through a valve located about 10-cm (~4-inches) above the floor
    - this did not allow for filling the bottles directly
    - solution would first have to be drained into a ladle, and then the ladle emptied into the bottles

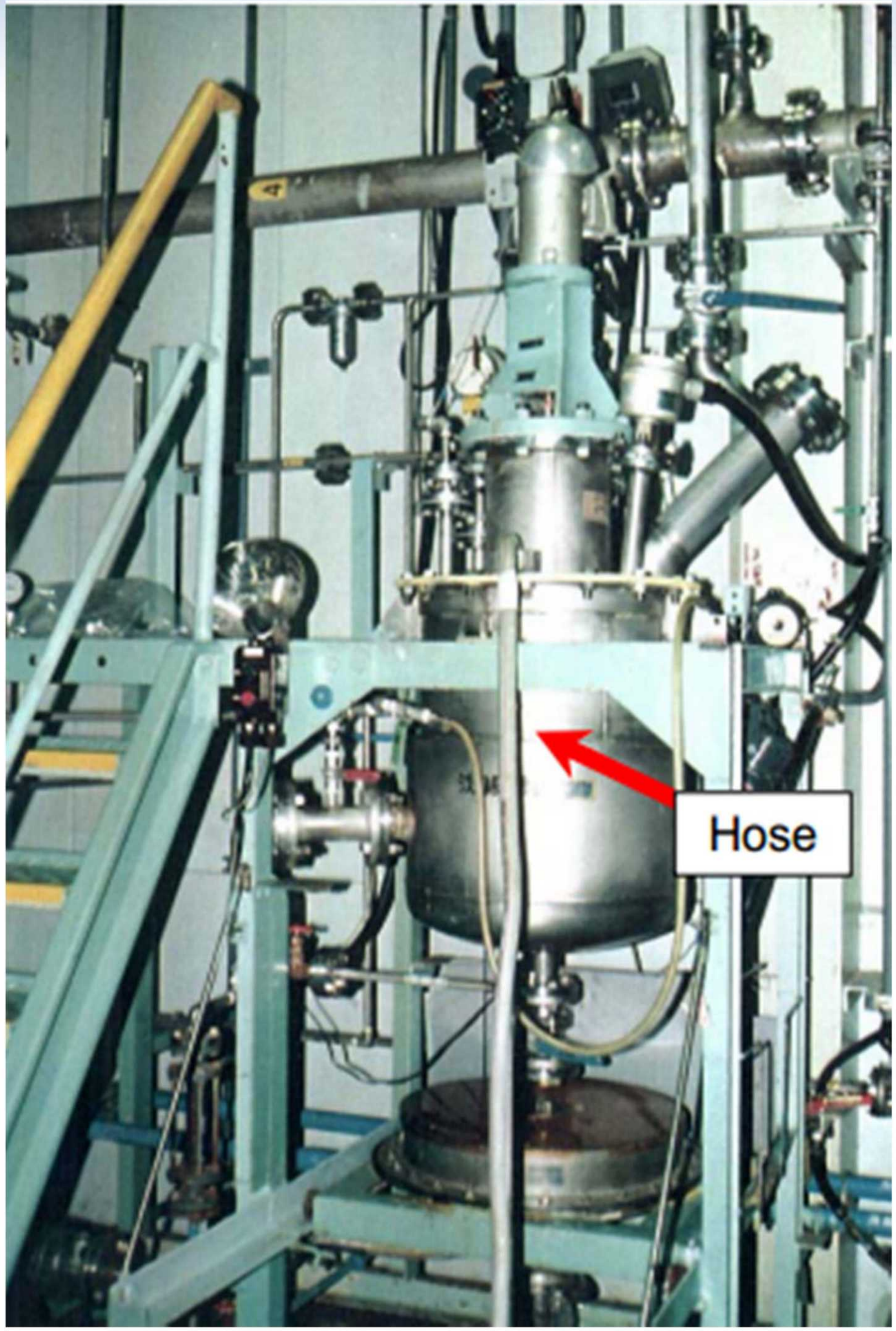
Process Deviations

- 10-liter stainless steel buckets
  - Earlier in the facility history management had approved this deviation,
    - JCO wide (not just in the FCTB)
  - Process was more efficient by about 1-hour per batch

- The supervisor approved using a precipitation vessel
  - larger volume
  - equipped with stirring rod to facilitate uniformity
  - better method of directly filling each bottle
  - equipped with a 1-inch thick water jacket for cooling purposes for precipitation process

The Authorized Process and Deviation



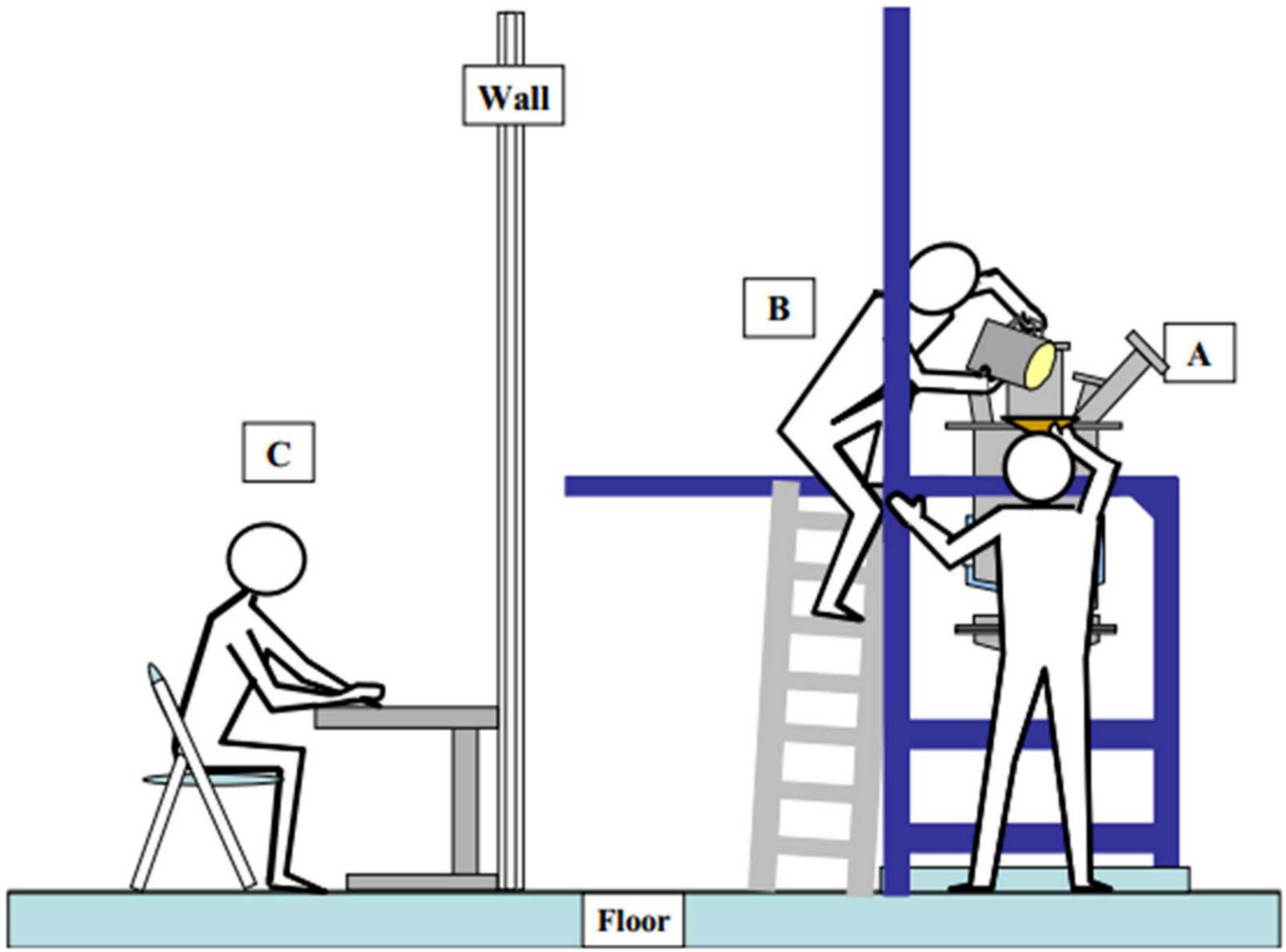

Hose

The Accident

- September 29th
  - Using the 10-liter stainless steel buckets
    - **dutifully** dissolved 4 batches (2.4 kg), one at time
    - transferred the solution to the precipitation vessel using a 5-liter flask

- September 30th
  - 3 additional batches were dissolved and transferred to the tank
  - The accident occurred near the end of the pouring of the final batch ~10:35 a.m.
    - 183g U remain left in 5-liter flask
    - Beyond prompt critical burst
    - High radiation (γ) alarms sounded in **all** fissionable material handling buildings

Operator Positions



The Reaction

- Operators evacuated FCTB
  - two began showing signs of radiation sickness immediately
- Two other processing buildings evacuated
  - Muster location moved due to high radiation levels
- JCO was unprepared for the accident
  - Expertise and detectors had to come from a nearby facility, JAERI
- The accident did not self-terminate

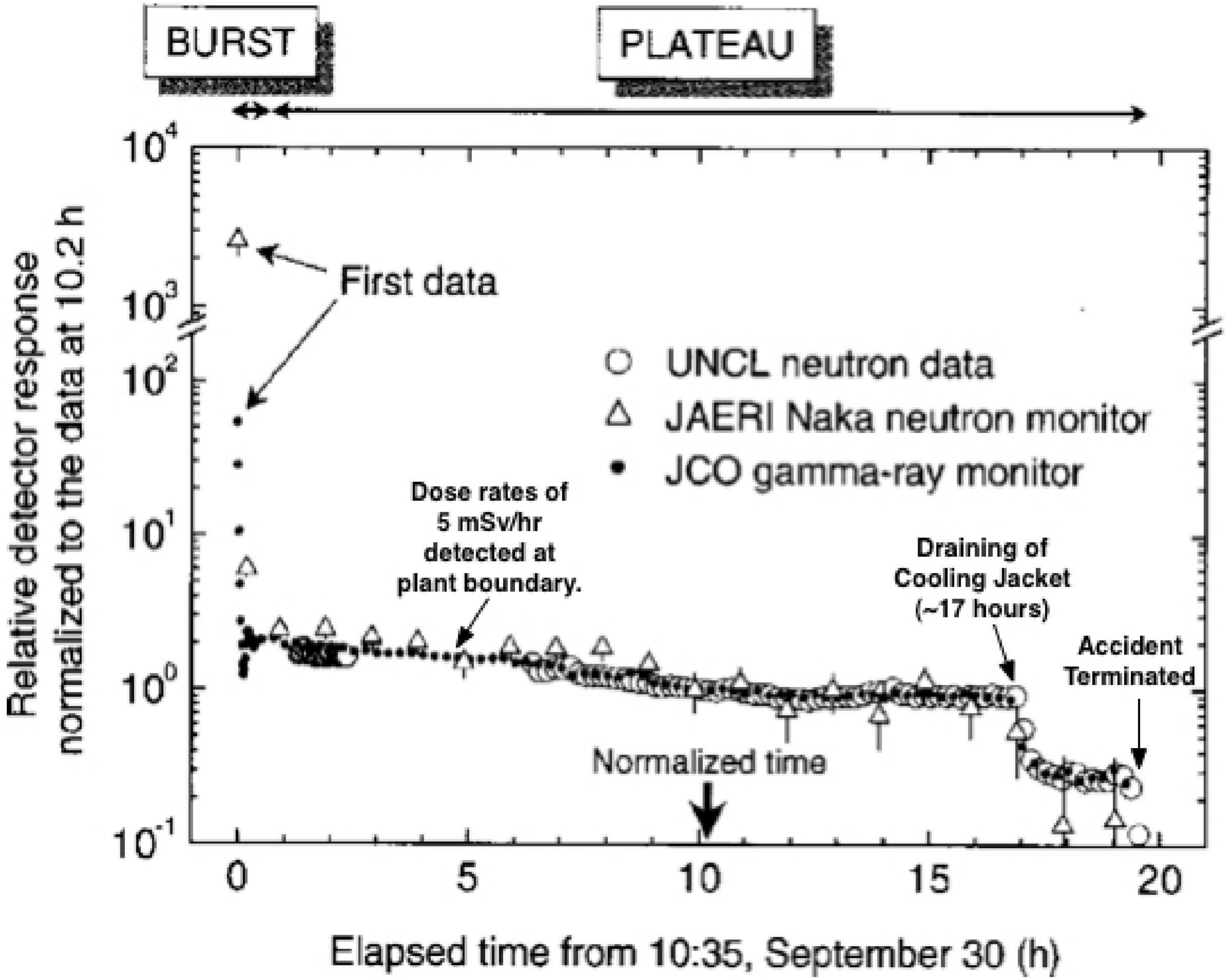
- 4.5 hours into the accident
  - the Mayor recommended evacuation of the residents living within 350-meters of the site evacuate

The Reaction

- ~12 hours
  - the prefecture officials recommended sheltering in place to residents within a 10-km radius
- ~14 hours
  - actions directed and authorized by the government
    - teams of operators attempted to drain the cooling jacket
    - ~17 hours succeeded in draining about half of water from cooling jacket
      - opened water line outside of the facility
    - accident was not terminated
      - power level did decrease by about a factor of 4
- ~20 hours
  - termination achieved by forcing remaining water out via argon gas

Outside Access

Accident Power History



The Consequences

- 2.5 x 10^{18} fissions
  - 4-8 x 10^{16} first spike
- 3 operators exposed
  - (A) 1600-2000 rad – died after 82 days
  - (B) 600-1000 rad – died after 210 days
  - Supervisor 100 to 450 rad
- 235 members of the public exposed
  - 208 0.0 to 0.5 rem
  - 18 0.5 to 1.0 rem
  - 6 1.0 to 1.5 rem
  - 2 1.5 to 2.0 rem
  - 1 2.0 to 2.5 rem

1 Sievert = 100 rem (dose equivalent)

1 Gray = 100 rad (absorbed dose)

Contributing factors

- Operators weak understanding of criticality parameters
  - no criticality safety training
- Company pressure to operate more efficiently
  - The use of the 10-liter buckets was a company approved deviation from the license
- Difficult method of filling the 4-liter bottles
- Mind set of JCO **and** the regulatory authority
  - A criticality accident was incredible
    - Inadequate facility review
      - 10 years since their last review
    - Inadequate procedural review
    - Inadequate plans and equipment layout
    - Inadequate assessment of human factors

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NUCLEAR CRITICALITY SAFETY PROGRAM

Module 2
Section 4: Process Facility Criticality Accidents Lessons Learned

Presented by:
Shean P Monahan

Process Criticality Accident Lessons-Learned

- General considerations
  - No single failure accidents
  - No accidents attributed to hardware failure
  - No accidents attributed to faulty calculations
  - Human factors dominated all accidents
    - Communications
    - Understanding
    - Procedural violations

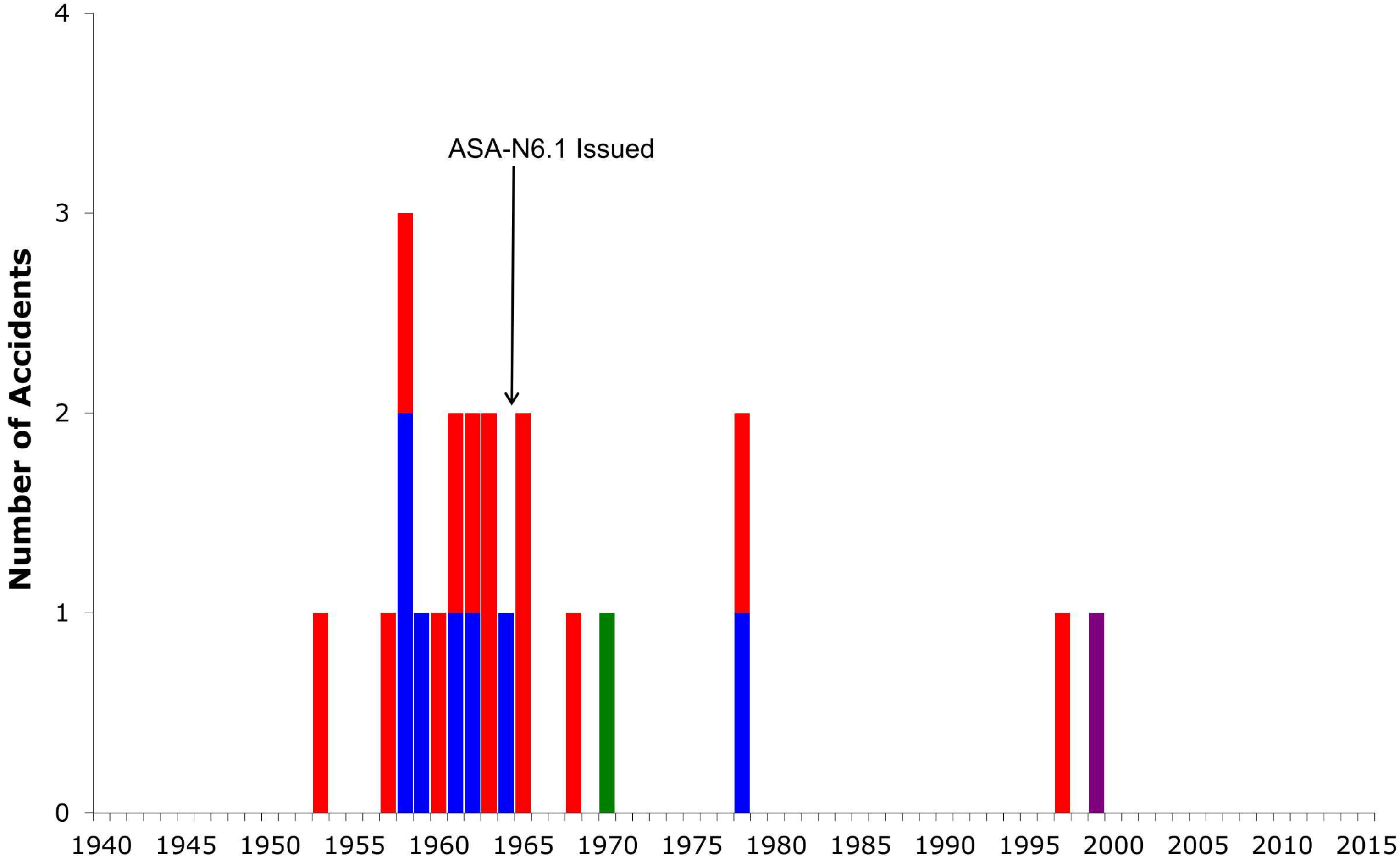
Process Accident Lessons

- Management (Program) Issues
  - Avoid unfavorable geometry equipment
  - Avoid cumbersome procedures
    - Make execution of the safe job easy
  - Important instructions must be in writing
  - Regularly observe operations
  - Evaluate operators understanding
    - Consequences of violating
      - Procedures
      - Limits

Process Accident Lessons

- Operators
  - Understanding of and willingness to follow
  - Written procedures
  - Controls
  - Postings
  - Stop work policy
- Accidents occur when the lessons of the past are forgotten
- National standards incorporate the lessons from accidents
  - ASA N6.1-1964

    Safety Standard for Operations with Fissionable Materials Outside Reactors



ASA-N6.1 Issued
Number of Accidents
0
1
2
3
4
1940
1945
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
2015

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Module 03

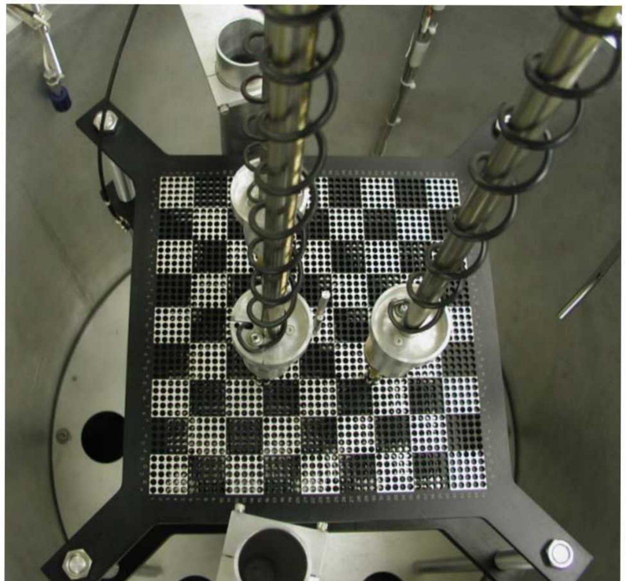
Design of the Sandia Critical Experiments (SCX)

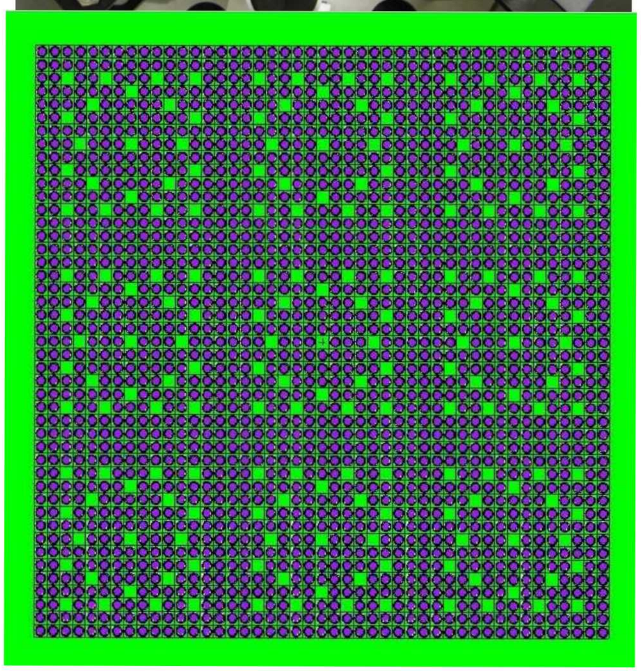
Presented by:
Gary Harms

What is ahead

- A description of recent Sandia critical experiments
  - 7uPCX (the one we will be using)
- A description of the critical assembly
- A description of how we operate the 7uPCX
- An introduction to the approach-to-critical experiment process

The Seven Percent Critical Experiment (7uPCX) is our current experiment





Project Objective: ***Design, perform, and analyze critical benchmark experiments for validating reactor physics methods and models for fuel enrichments greater than 5-wt% ^{235}U***

- We built new 7% enriched experiment fuel
- We built critical assembly hardware to accommodate the new core
- The core is a 45x45 array of rods to simulate 9 commercial fuel elements in a 3x3 array
- The experiment is a reactor physics experiment as well as a critical experiment
- Additional measurements will be made
  - Fission density profiles
  - Soluble poison worth

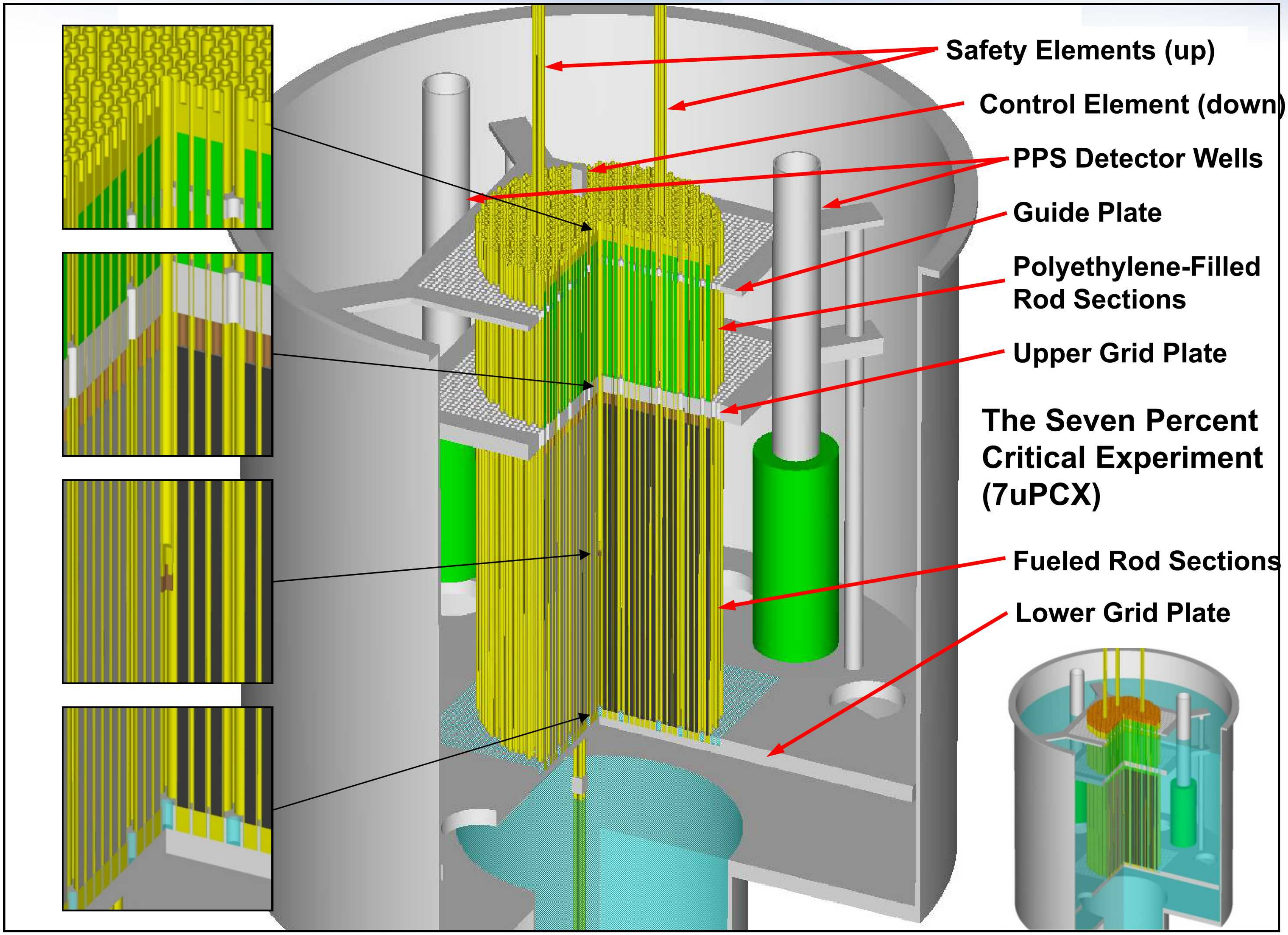
The 7uPCX experiment matrix

- We have two grid plate sets
  - The sets were chosen to bound the fuel-to-water ratio of commercial PWRs
  - A full set of experiments will be done at each pitch
- We have completed a set of fully-reflected benchmark critical experiments with each grid plate set

Full reflection: Adding a thicker reflector does not change k_{eff} appreciably – about 6 inches of water on all sides

  - We loaded fuel into the assembly in an "approach-to-critical" experiment
  - We loaded fuel until the assembly became supercritical
- We are performing experiments with larger fuel arrays
  - We will find the water level that makes the larger arrays critical
  - The arrays will not be fully reflected

The critical assembly in person

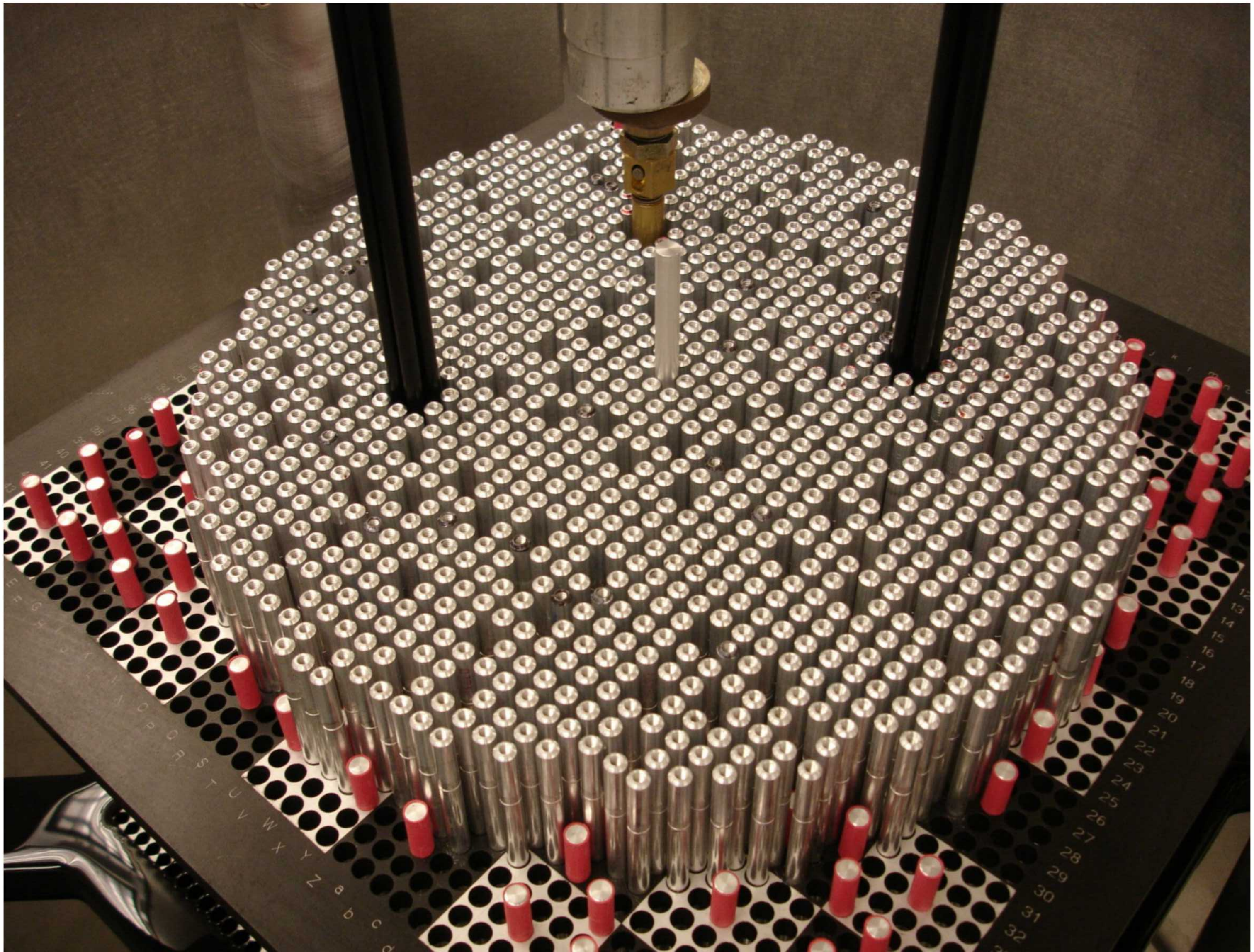

Safety Elements (up)
Control Element (down)
PPS Detector Wells
Guide Plate
Polyethylene-Filled Rod Sections
Upper Grid Plate
The Seven Percent Critical Experiment (7uPCX)
Fueled Rod Sections
Lower Grid Plate

Characteristics of the Sandia Critical Experiments

Critical Experiment	BUCCX		7uPCX	
Fuel	UO_2		UO_2	
Enrichment (%)	4.306		6.903	
Moderator	Light Water		Light Water	
Fuel OD (cm)	1.265		0.526	
Fuel Length (cm)	48.7		48.8	
Fuel Density (g/cm^3)	10.4		10.3	
Fuel Rod OD (cm)	1.382		0.635	
Array Configuration	Triangular Pitch		Square Pitch	
Pitch (cm)	2.0	2.8	0.800	0.855
Fuel to Water Volume Ratio	0.640	0.238	0.672	0.524
H to ^{235}U Atom Ratio	131	332	62.0	79.5
H to U Atom Ratio	4.48	12.1	4.33	5.55

Values for the core we will use are highlighted.

The first 7uPCX core at the end of the approach



How is a critical assembly different from a reactor?

- **A critical experiment looks like a reactor from the outside**

Except:

- ***The reactor is the experiment***
  - **The core may undergo significant configuration changes**

"Critical assemblies are special nuclear devices designed and used to sustain nuclear reactions. Critical Assemblies may be subject to frequent core and lattice configuration change and are used frequently as mockups of reactor configurations." **[DOE Order 5480.30 Chg 1 – *Nuclear Reactor Safety Design Criteria*, Attachment 2, p. 4]**

- ***The fission product inventory is low***
  - **This limits the potential consequences of an accident**

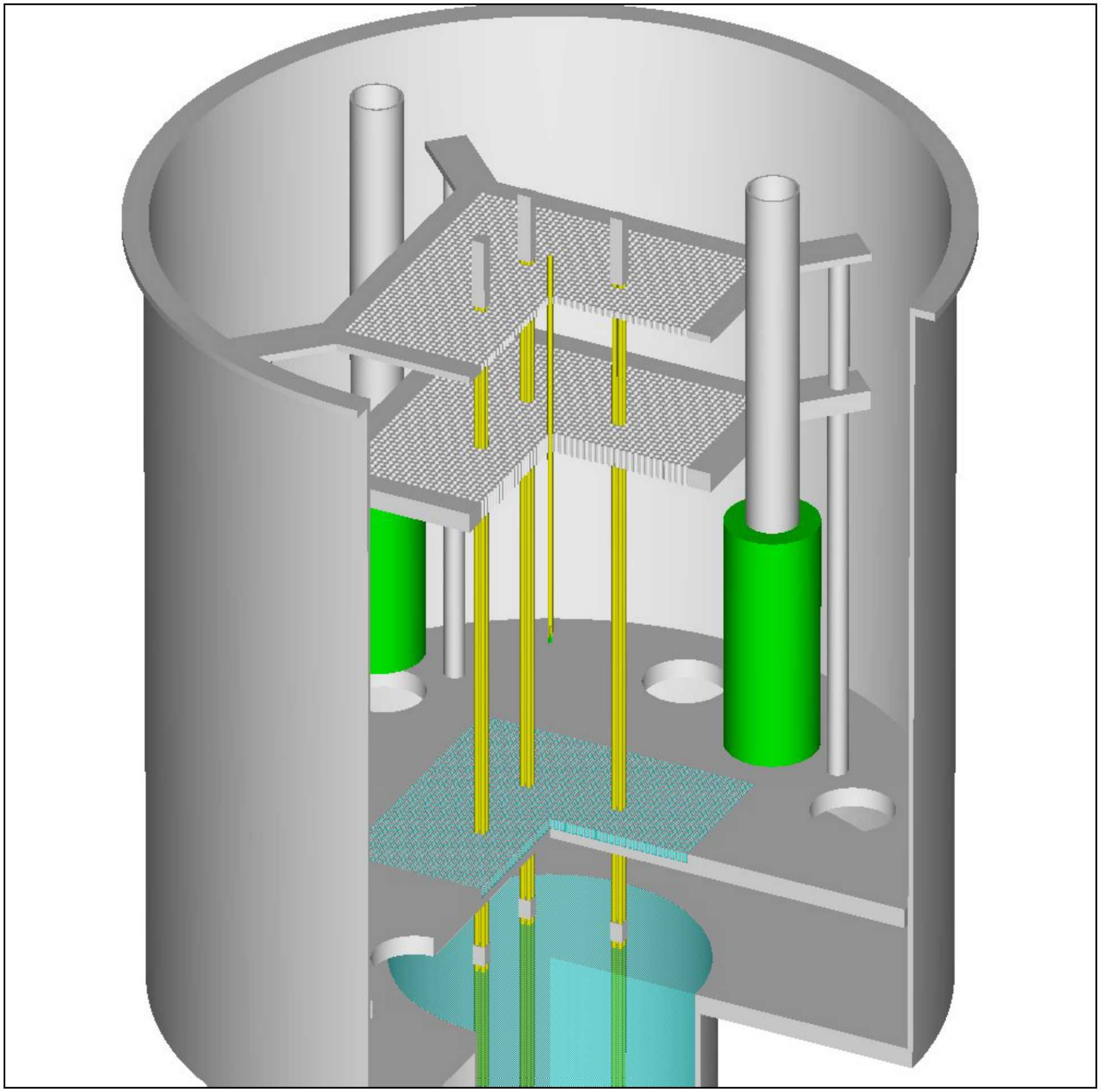
"critical assembly. ***a device or physical system for performing critical experiments. In a critical assembly, the energy produced by fission is insufficient to require auxiliary cooling and the power history is such that the inventory of long-lived fission products is insignificant."***

[ANSI/ANS-1-2000 – *Conduct of Critical Experiments*, Section 2.3]

Access controls ensure personnel safety

- We have limited ourselves to low-enriched (<20%) fuel
  - 1000 kg of the fuel is subcritical without water moderator
  - Reactor room is limited to 500 kg of fuel
  - **The fuel cannot go critical without water**
- When out of storage, the fuel is in the core tank that is connected to the dump tank through two large-diameter normally-open dump valves
  - **Water cannot collect in the core tank if the dump valves are open**
- The key that closes the dump valves and allows water to accumulate in the core tank is tied to the key to the facility door
  - When people are in the reactor room, the key is out of the console and the dump valves are open (core tank cannot hold water)
  - When the dump valves are closed, the reactor area is locked and people are excluded from the reactor room
  - **FUEL – WATER – PEOPLE** – **pick any TWO**

The Shut-Down Configuration of the Assembly



Fuel: 12 - CE/SE only

k_{eff} ≈ 0.139

Safety Elements: Down

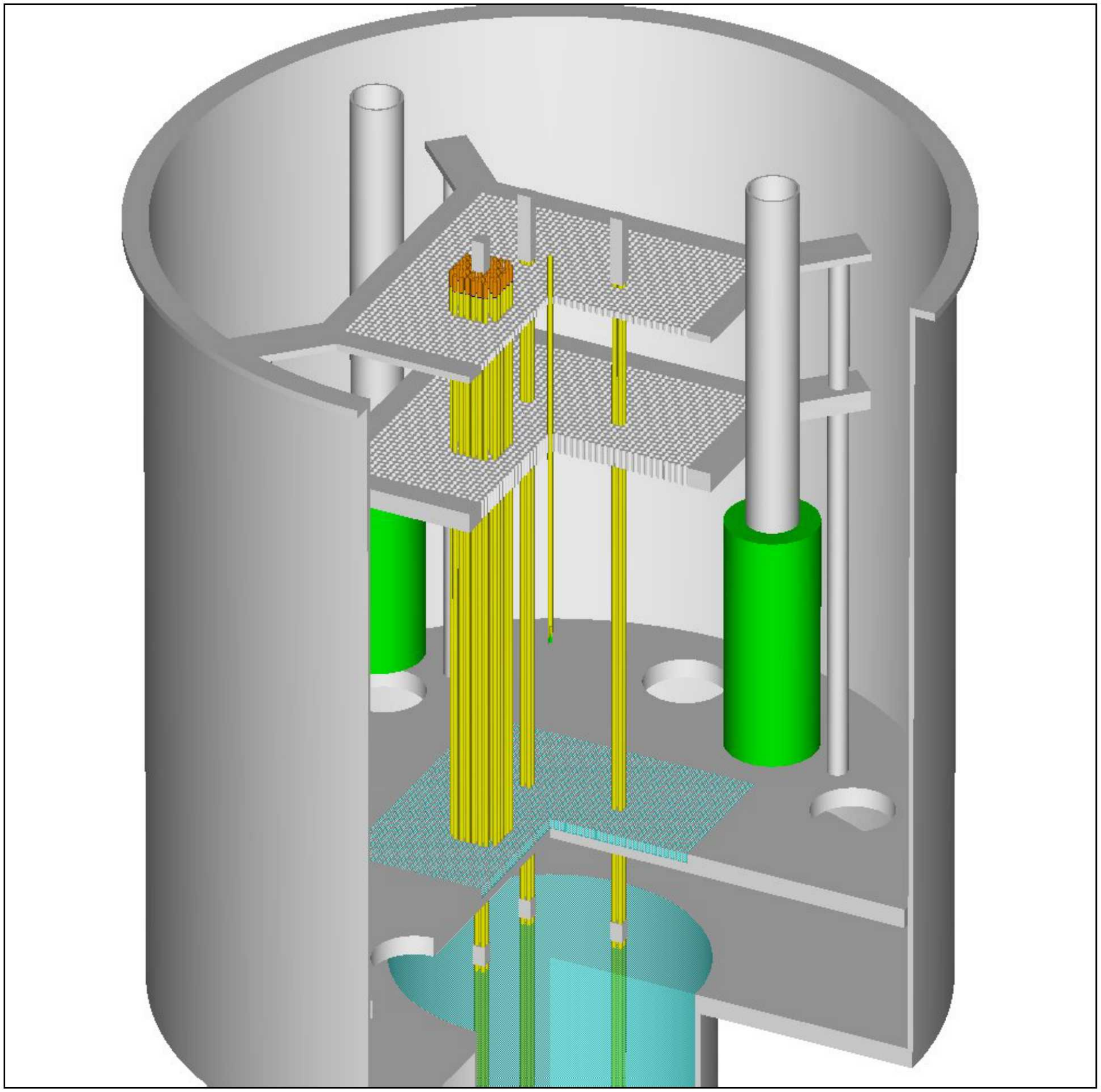
Control Element: Down

Core Tank: Empty

Personnel: Allowed

In this condition, the assembly is "shut down." Entry into the reactor room is allowed. The control system need not be manned. Fuel may be added to or removed from the array.

Load Fuel



Fuel: 64

$k_{eff} \approx 0.139$

Safety Elements: Down

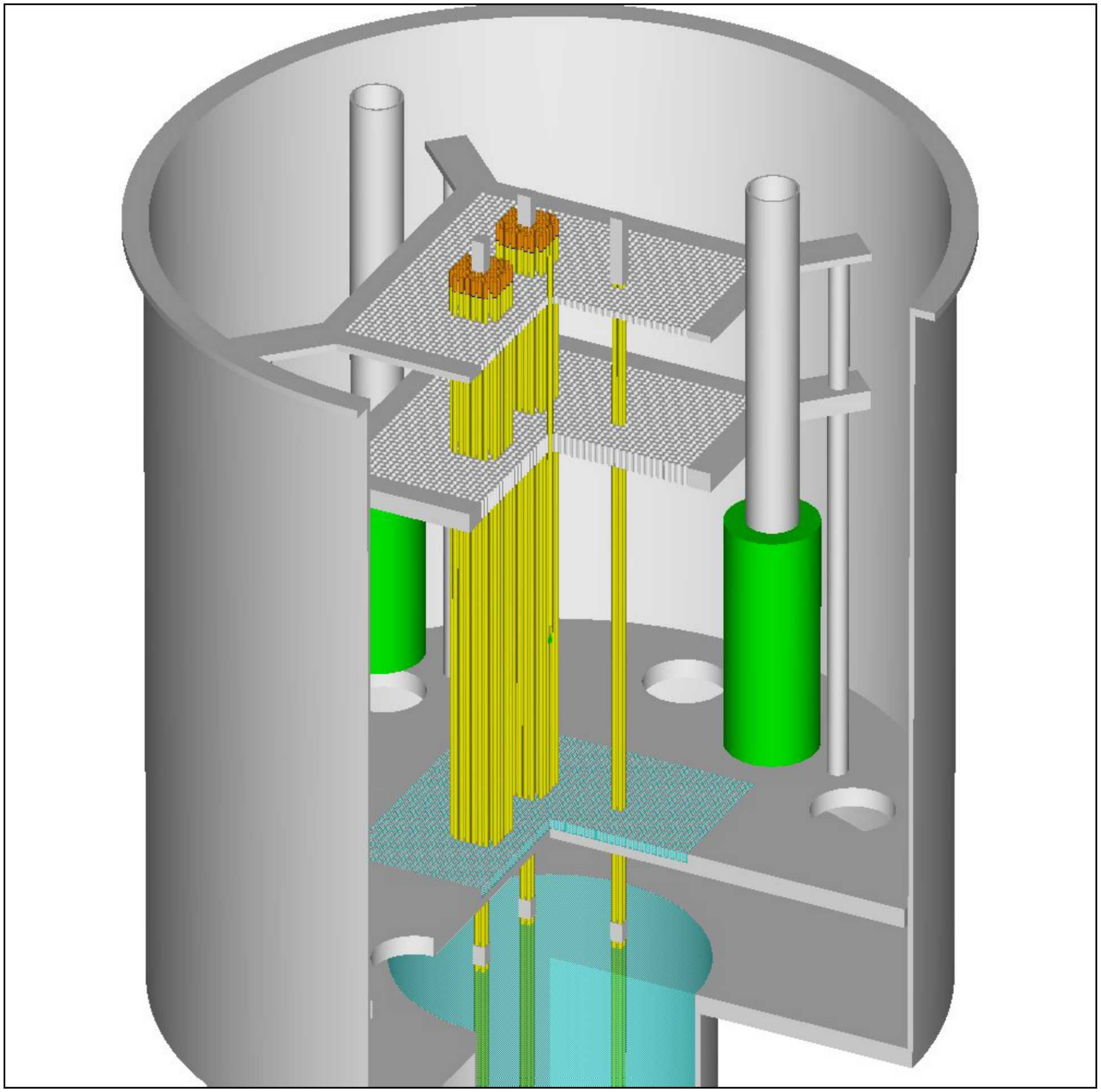
Control Element: Down

Core Tank: Empty

Personnel: Allowed

In this condition, the assembly is "shut down." Entry into the reactor room is allowed. The control system need not be manned. Fuel may be added to or removed from the array.

Load Fuel



Fuel: 116

$k_{eff} \approx 0.139$

Safety Elements: Down

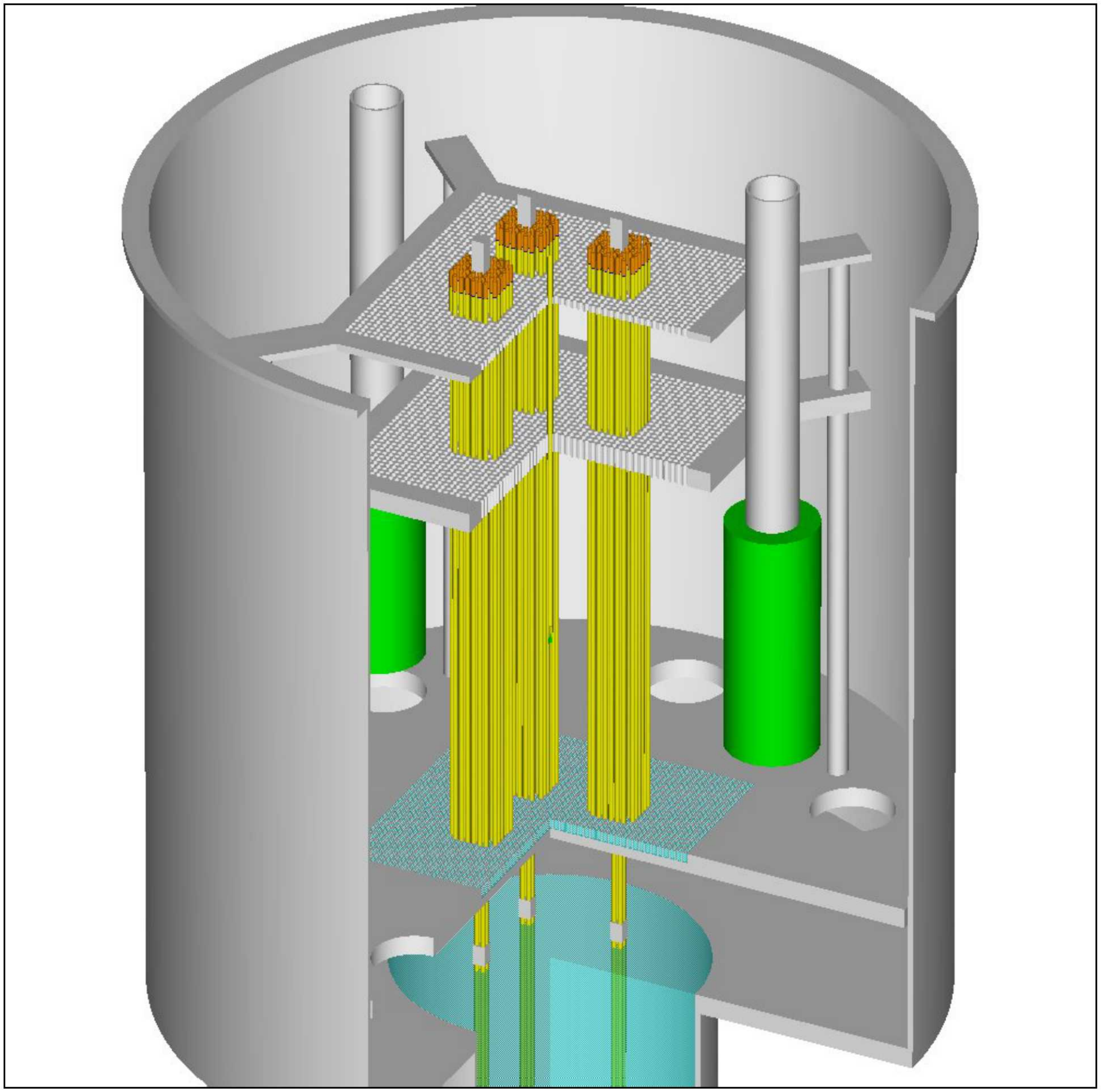
Control Element: Down

Core Tank: Empty

Personnel: Allowed

In this condition, the assembly is "shut down." Entry into the reactor room is allowed. The control system need not be manned. Fuel may be added to or removed from the array.

Load Fuel



Fuel: 168

k_{eff} ≈ 0.139

Safety Elements: Down

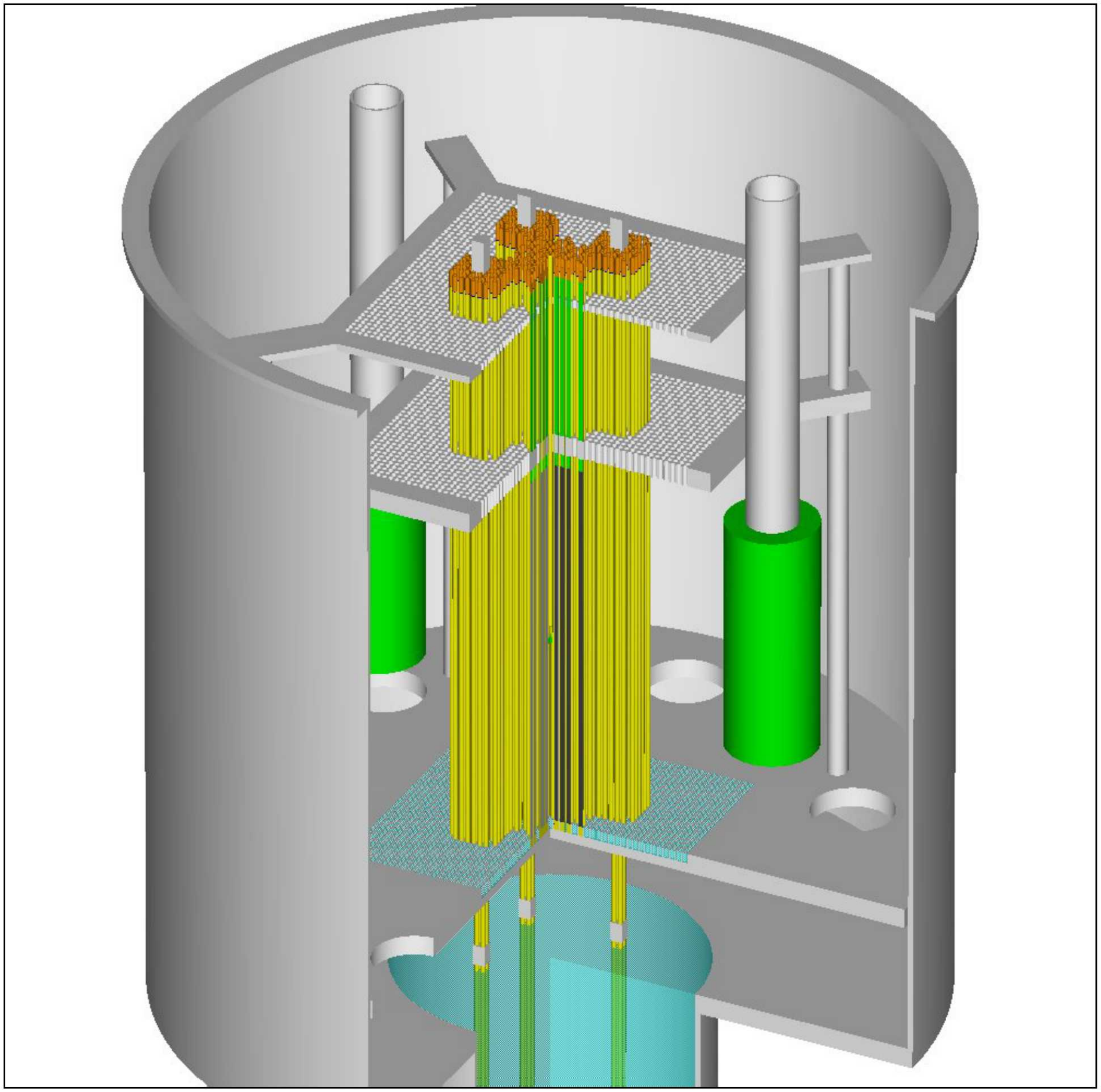
Control Element: Down

Core Tank: Empty

Personnel: Allowed

In this condition, the assembly is "shut down." Entry into the reactor room is allowed. The control system need not be manned. Fuel may be added to or removed from the array.

Load Fuel



Fuel: 318

$k_{eff} \approx 0.140$

Safety Elements: Down

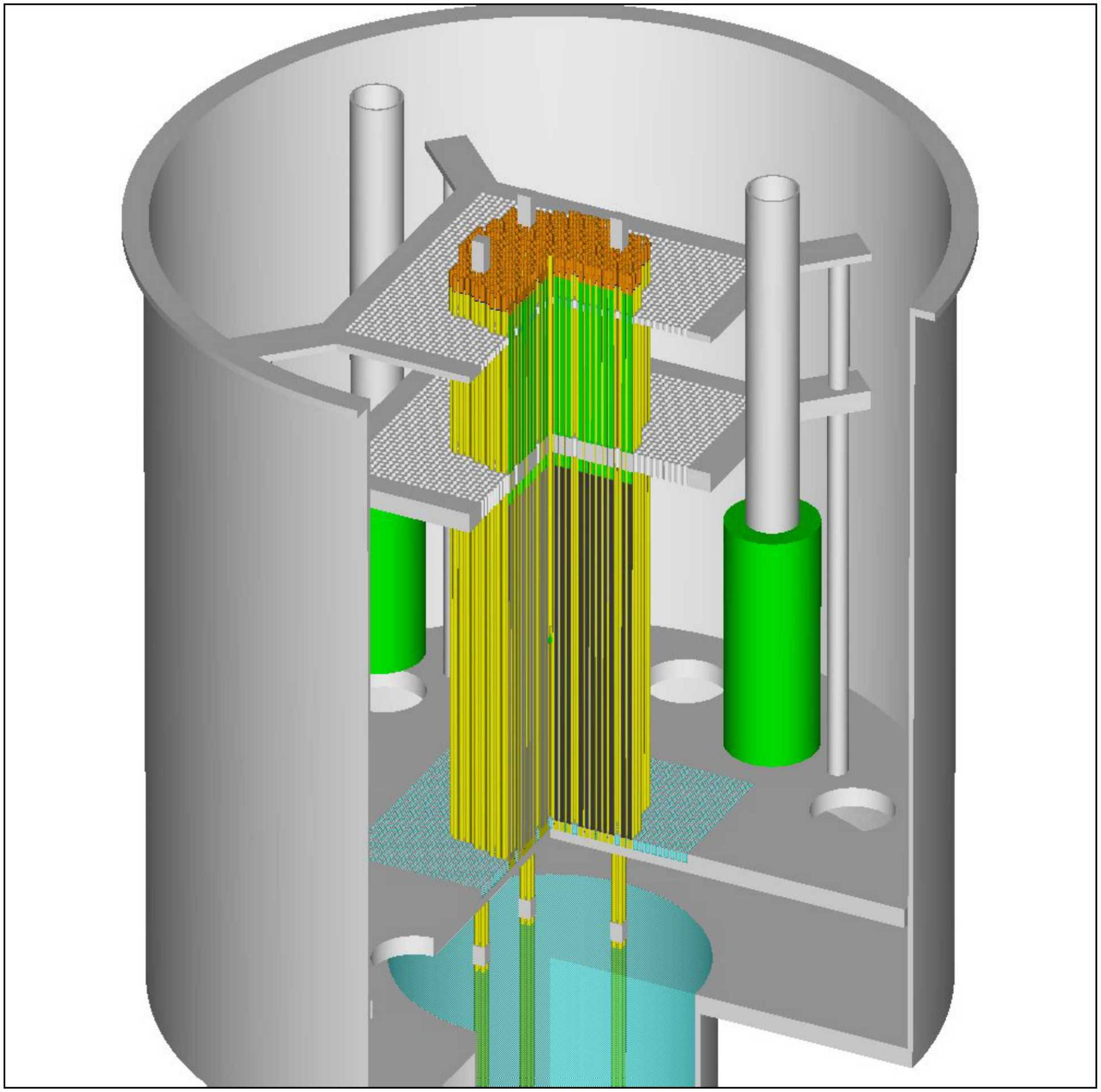
Control Element: Down

Core Tank: Empty

Personnel: Allowed

In this condition, the assembly is "shut down." Entry into the reactor room is allowed. The control system need not be manned. Fuel may be added to or removed from the array.

Load Fuel



Fuel: 548

$k_{eff} \approx 0.140$

Safety Elements: Down

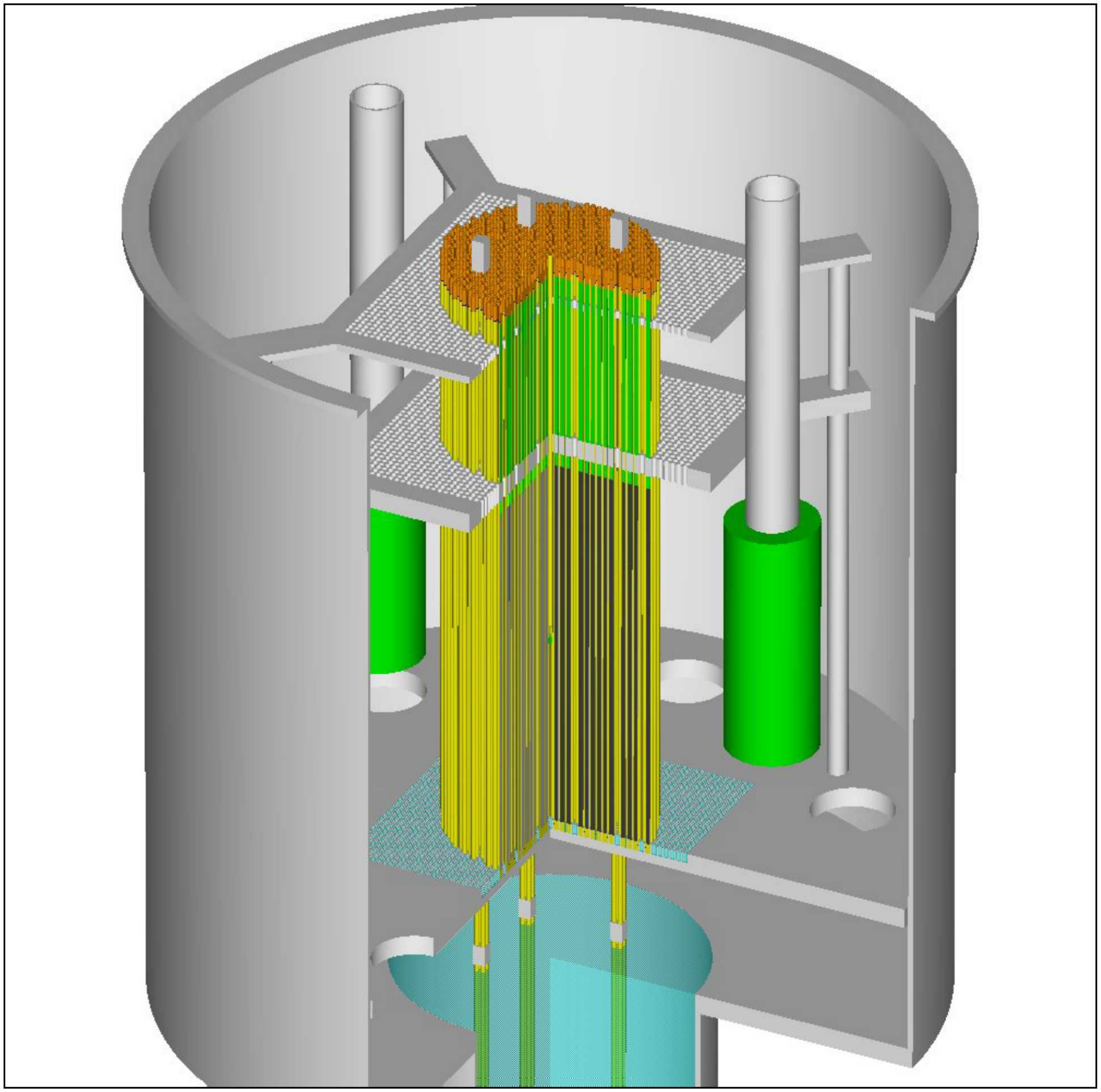
Control Element: Down

Core Tank: Empty

Personnel: Allowed

In this condition, the assembly is "shut down." Entry into the reactor room is allowed. The control system need not be manned. Fuel may be added to or removed from the array.

Load Fuel



Fuel: 740

$k_{eff} \approx 0.140$

Safety Elements: Down

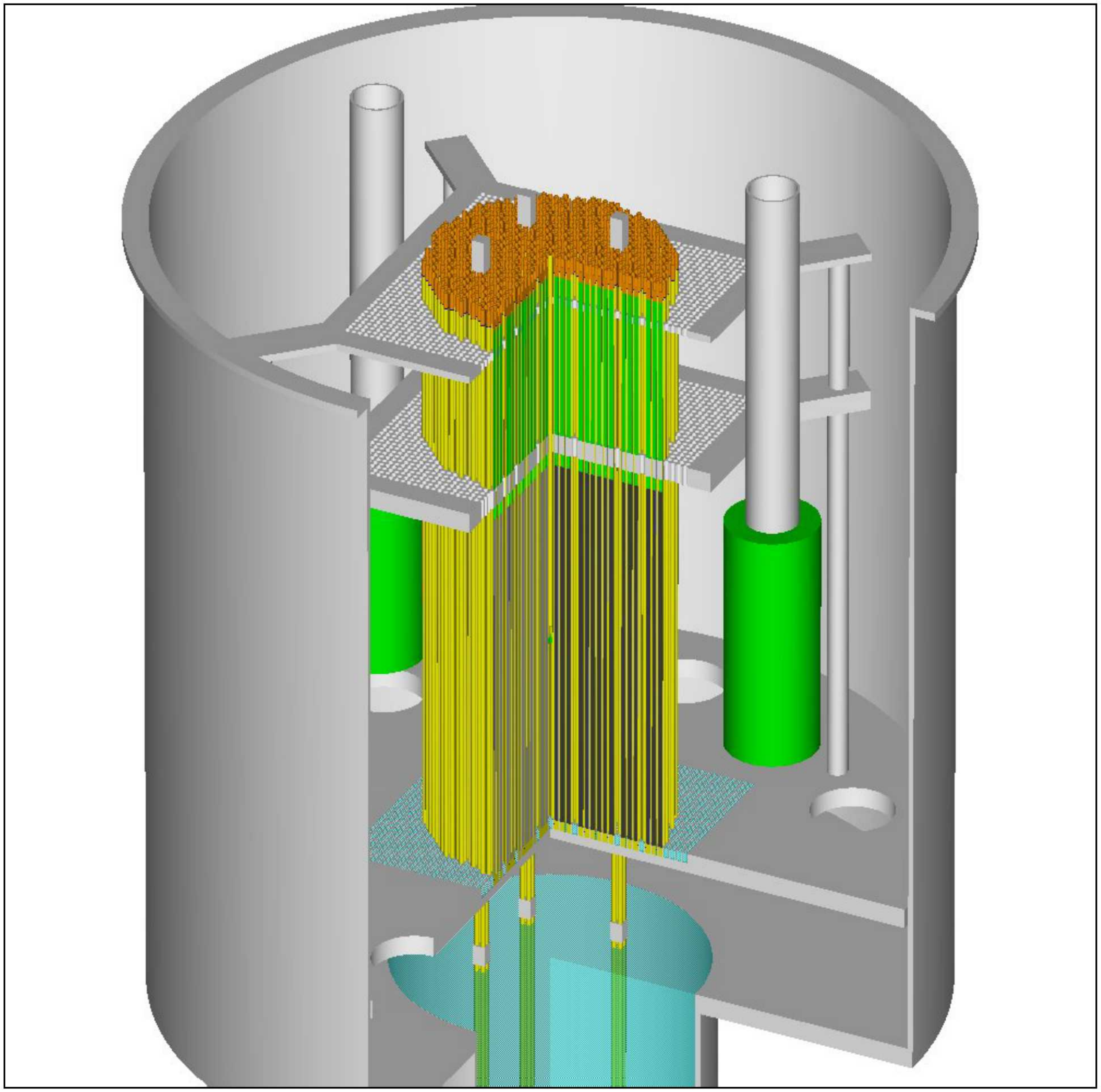
Control Element: Down

Core Tank: Empty

Personnel: Allowed

In this condition, the assembly is "shut down." Entry into the reactor room is allowed. The control system need not be manned. Fuel may be added to or removed from the array.

Load Fuel



Fuel: 956

$k_{eff} \approx 0.140$

Safety Elements: Down

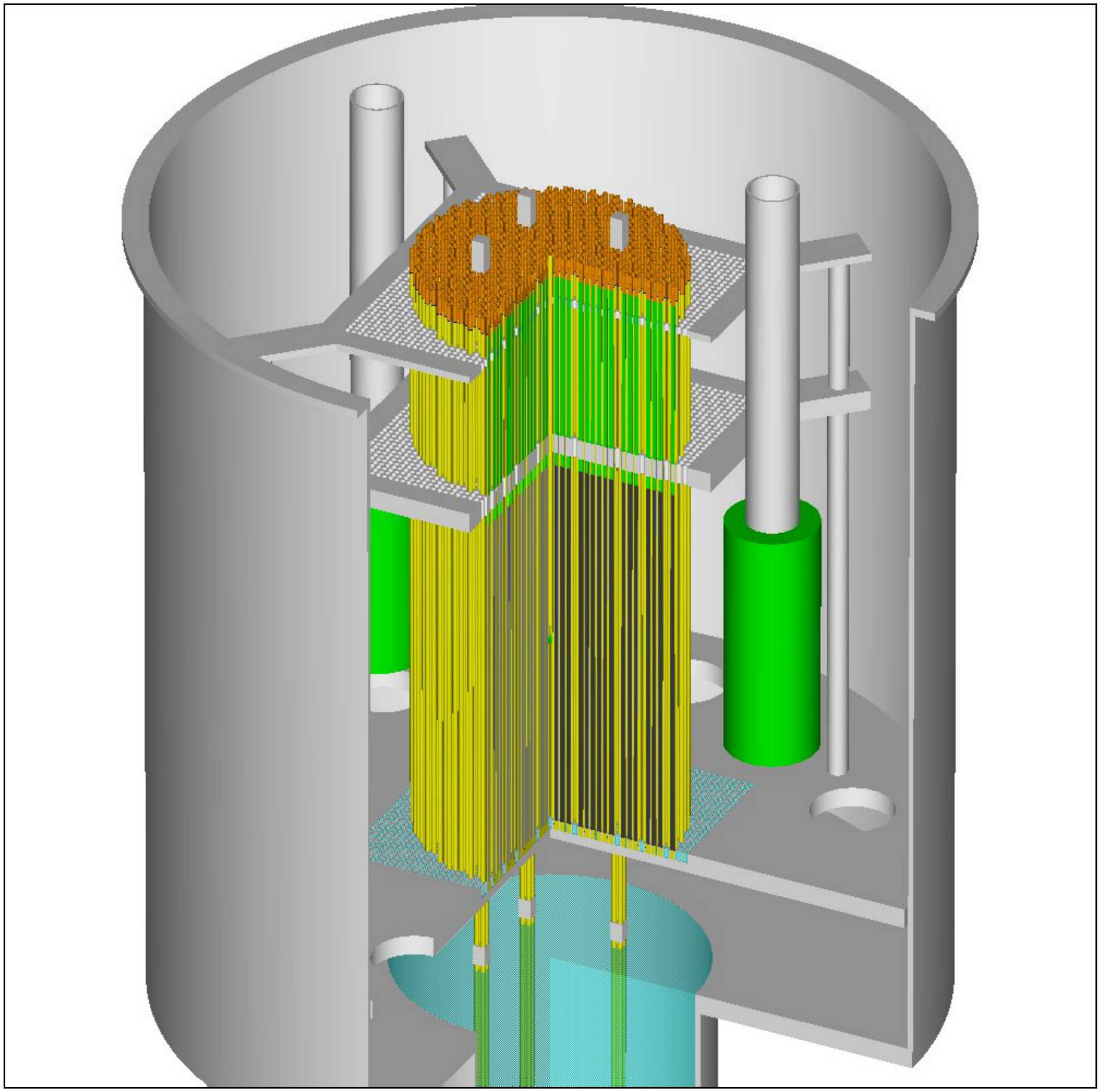
Control Element: Down

Core Tank: Empty

Personnel: Allowed

In this condition, the assembly is "shut down." Entry into the reactor room is allowed. The control system need not be manned. Fuel may be added to or removed from the array.

The Desired Fuel Array is Complete



Fuel: 1136

$k_{eff} \approx 0.140$

Safety Elements: Down

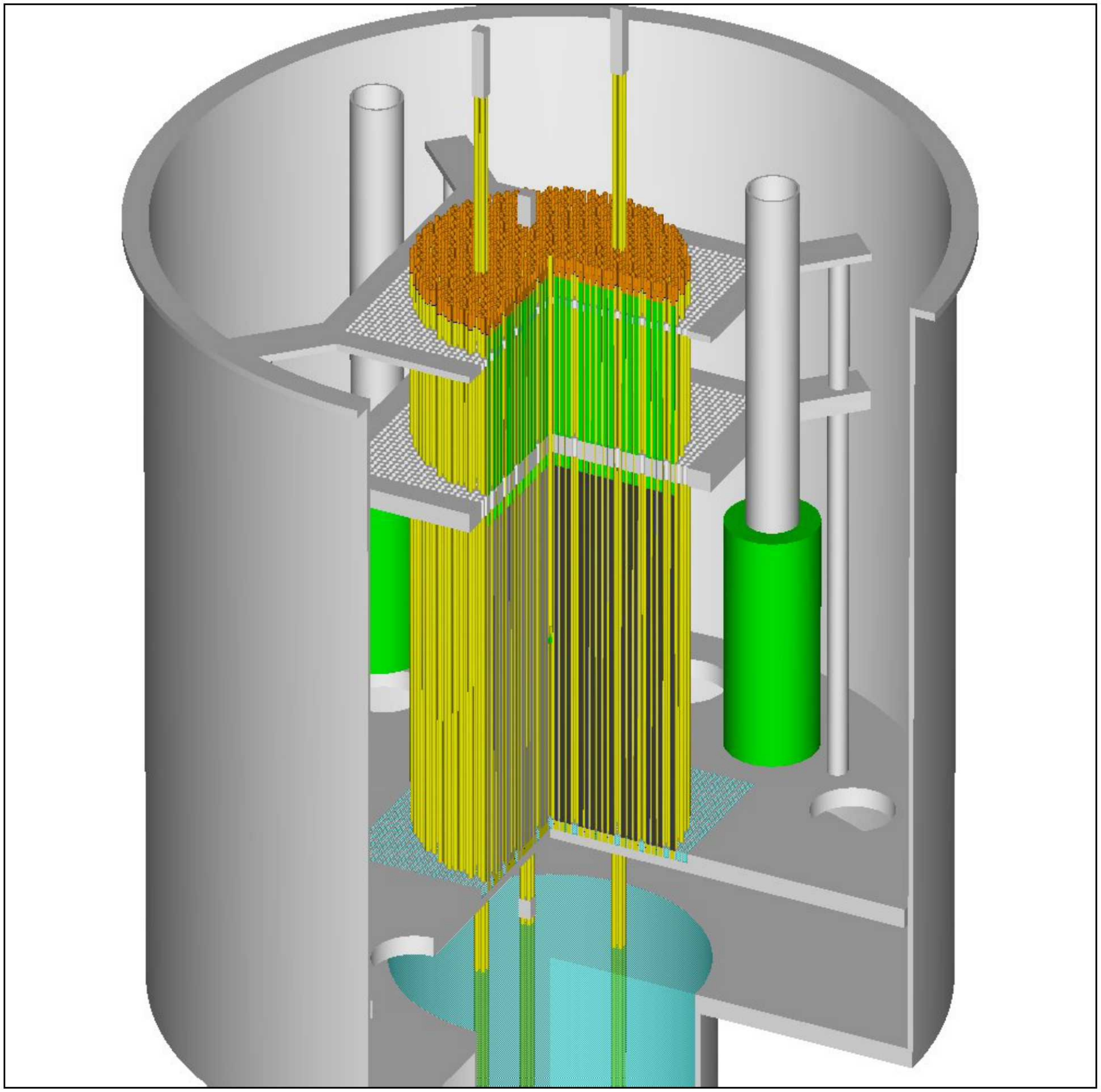
Control Element: Down

Core Tank: Empty

Personnel: Allowed

In this condition, the assembly is "shut down." Entry into the reactor room is allowed. The control system need not be manned. Fuel may be added to or removed from the array.

Raise the Safety Elements



Fuel: 1136

$k_{eff} \approx 0.132$

Safety Elements: Raising

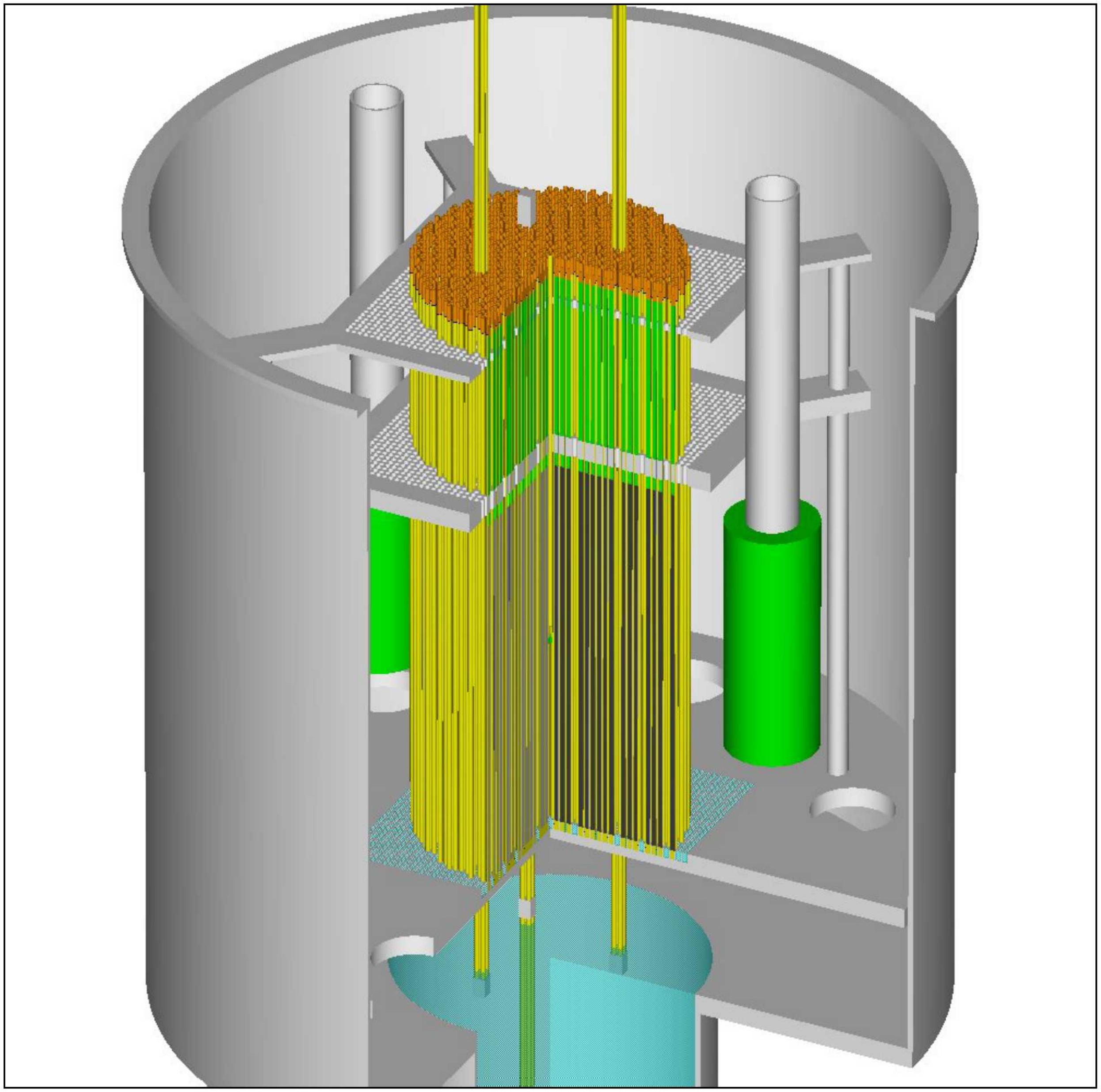
Control Element: Down

Core Tank: Empty

Personnel: Allowed

In this condition, the assembly is "operating" and a qualified operator must be at the controls at all times. Entry into the reactor room is allowed. Fuel may be added to or removed from the array.

Raise the Safety Elements



Fuel: 1136

$k_{eff} \approx 0.127$

Safety Elements: Raising

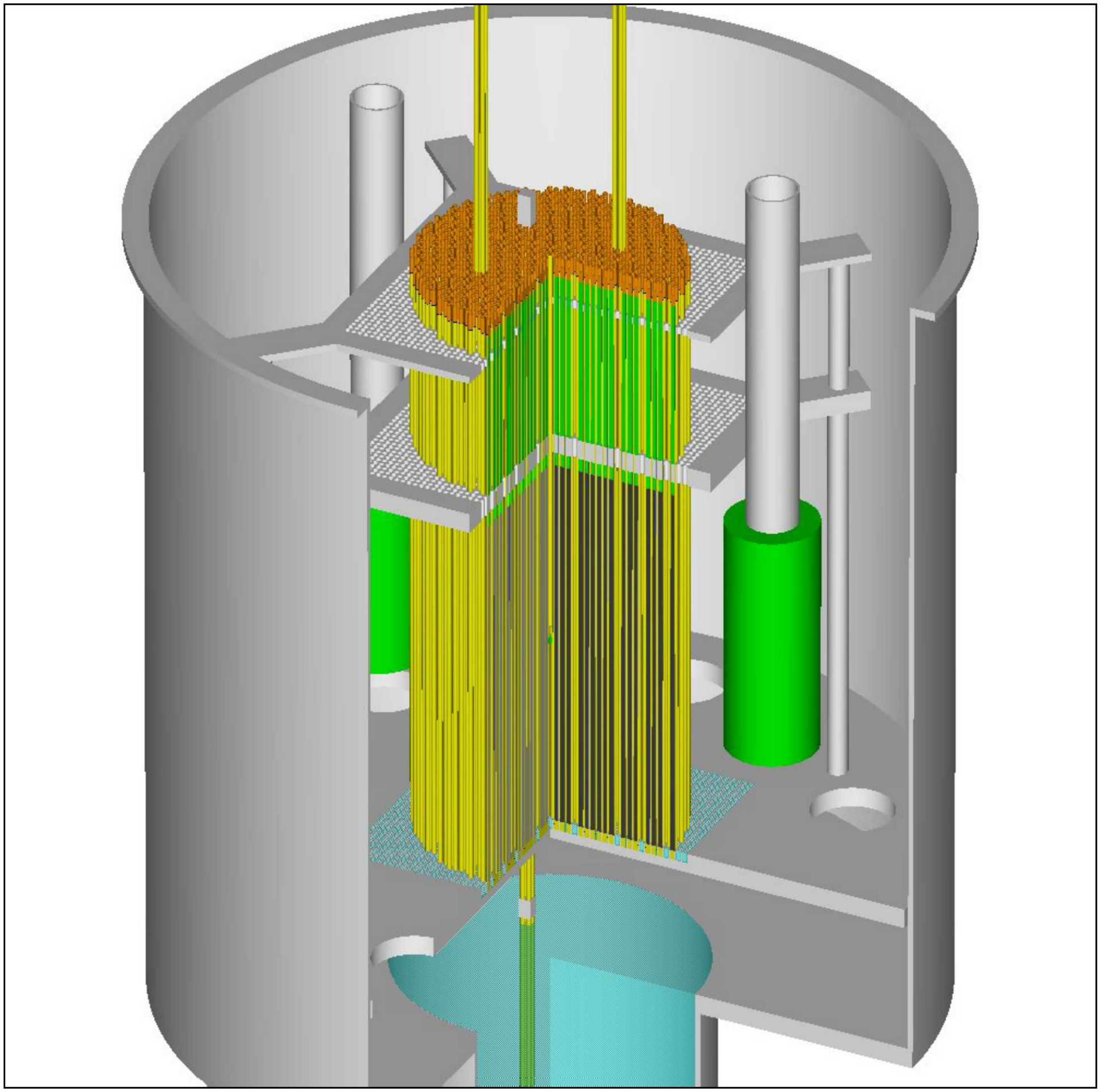
Control Element: Down

Core Tank: Empty

Personnel: Allowed

In this condition, the assembly is "operating" and a qualified operator must be at the controls at all times. Entry into the reactor room is allowed. Fuel may be added to or removed from the array.

The Safety Elements are Up



Fuel: 1136

$k_{eff} \approx 0.128$

Safety Elements: Up

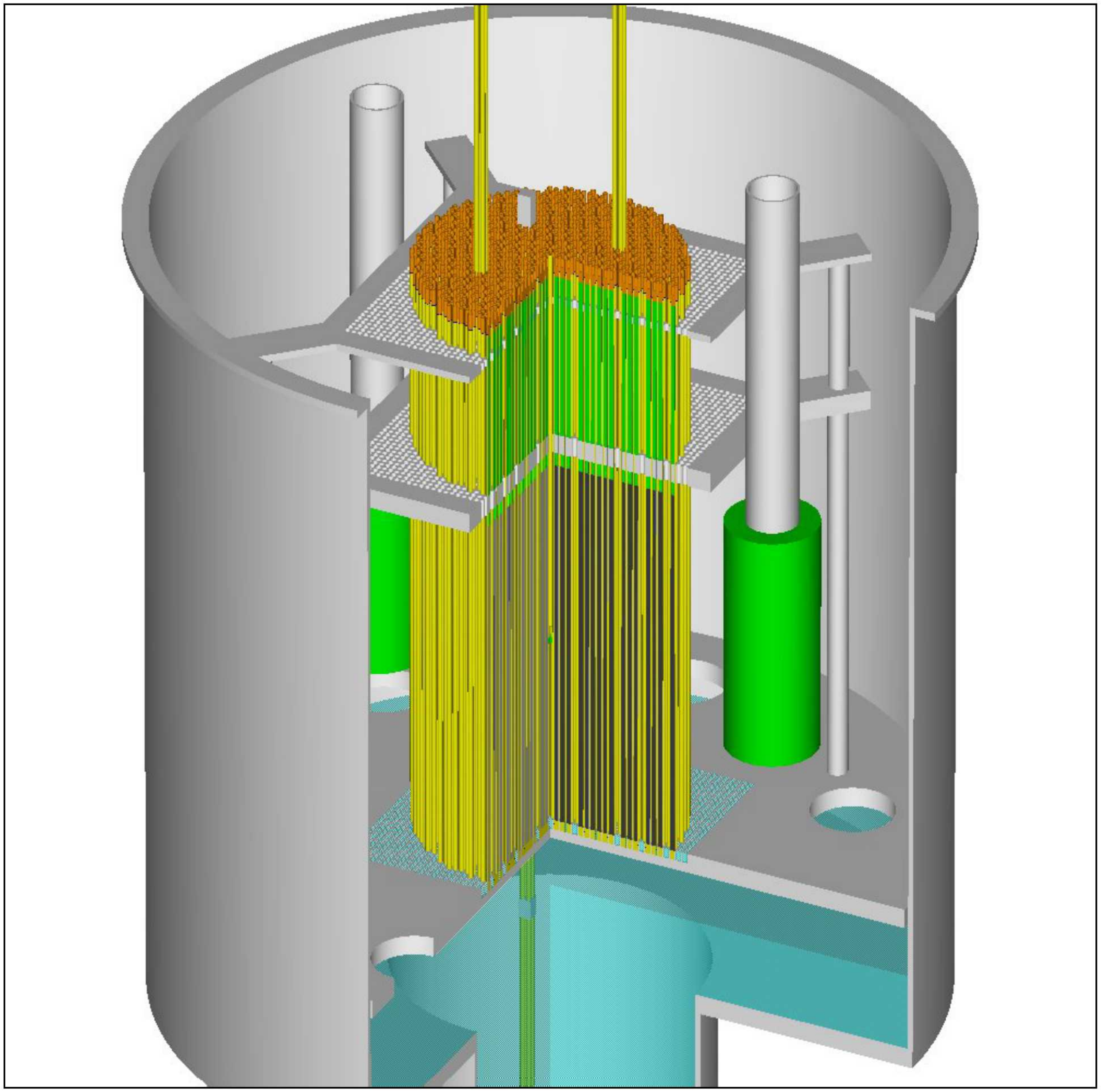
Control Element: Down

Core Tank: Empty

Personnel: Allowed

In this condition, the assembly is "operating" and a qualified operator must be at the controls at all times. Entry into the reactor room is allowed. Fuel may be added to or removed from the array.

Fill the Core Tank



Fuel: 1136

$k_{eff} \approx 0.139$

Safety Elements: Up

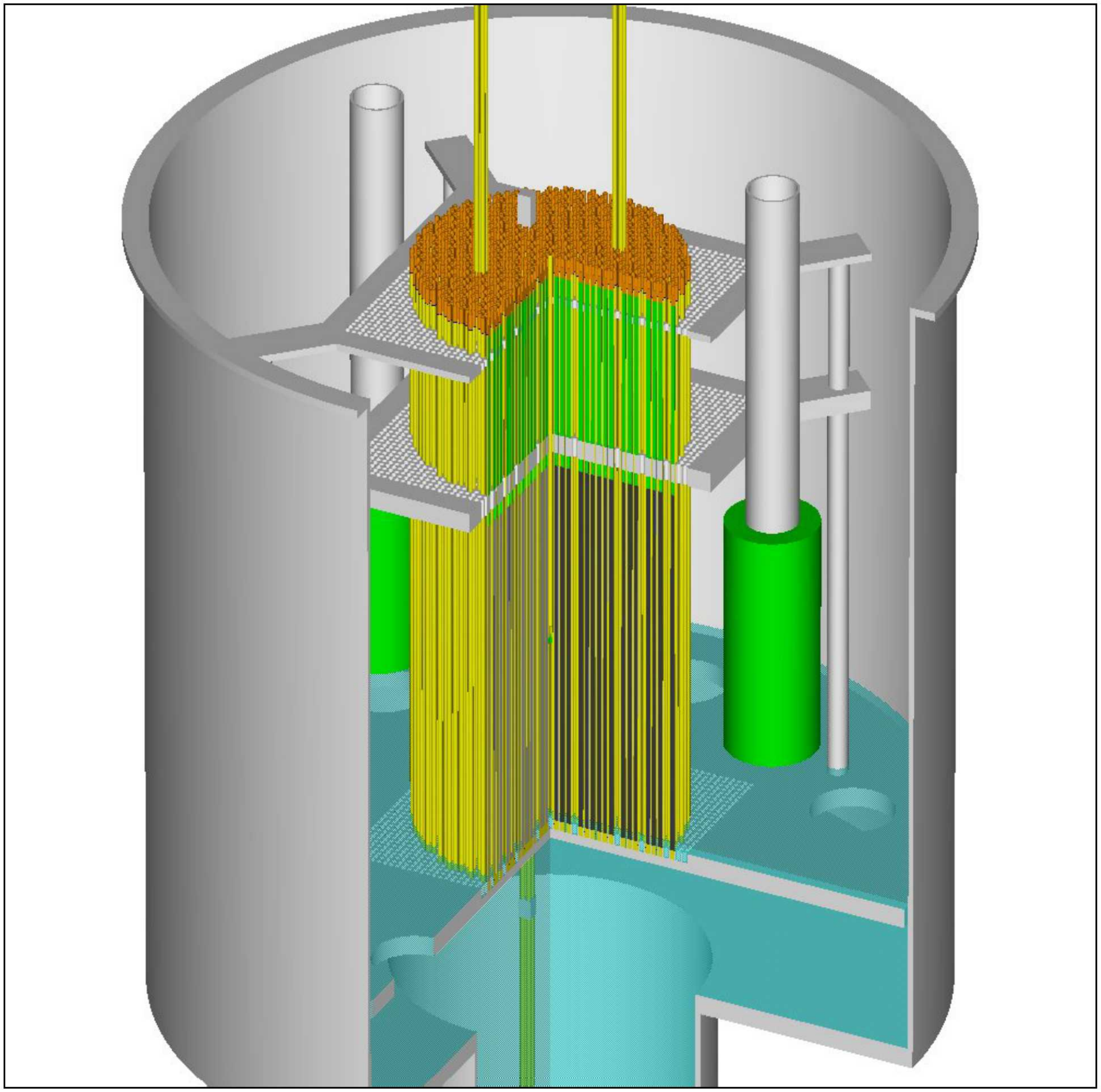
Control Element: Down

Core Tank: Filling

Personnel: Excluded

The water level changes by about 1 mm per second. Filling the core tank requires about 15 minutes.

Fill the Core Tank



Fuel: 1136

$k_{eff} \approx 0.178$

Safety Elements: Up

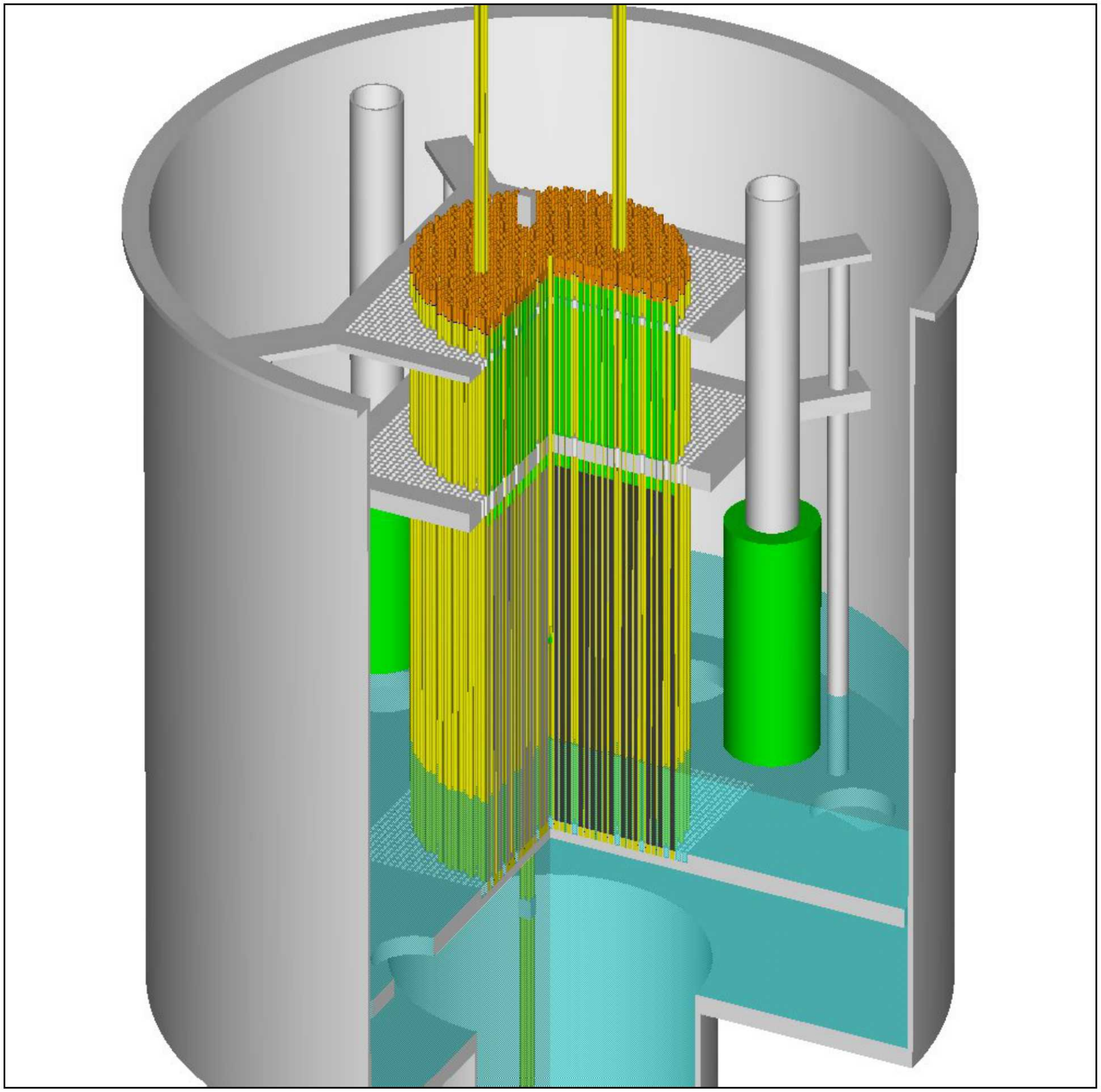
Control Element: Down

Core Tank: Filling

Personnel: Excluded

The water level changes by about 1 mm per second. Filling the core tank requires about 15 minutes.

Fill the Core Tank



Fuel: 1136

k_{eff} ≈ 0.594

Safety Elements: Up

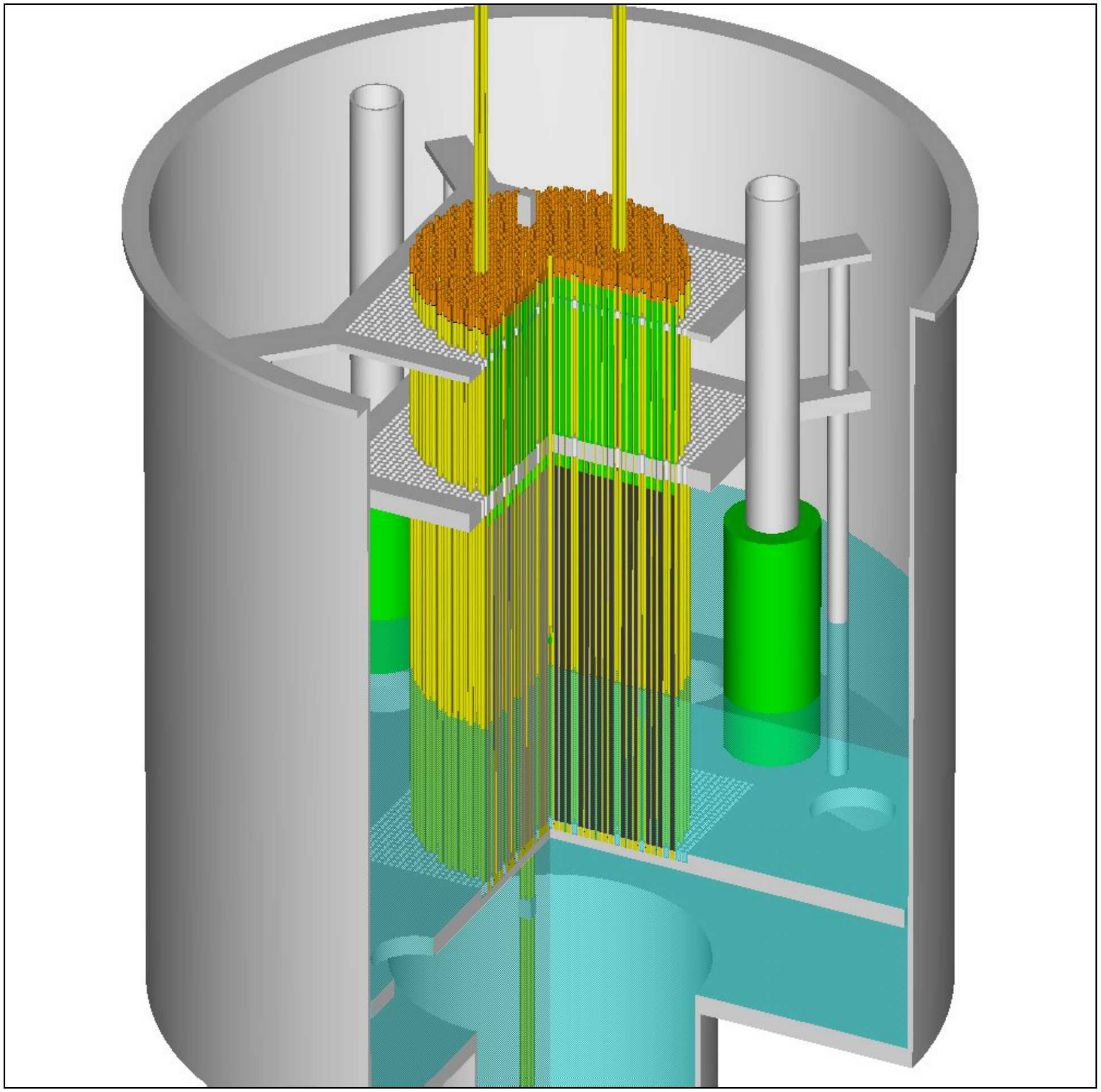
Control Element: Down

Core Tank: Filling

Personnel: Excluded

The water level changes by about 1 mm per second. Filling the core tank requires about 15 minutes.

Fill the Core Tank



Fuel: 1136

$k_{eff} \approx 0.804$

Safety Elements: Up

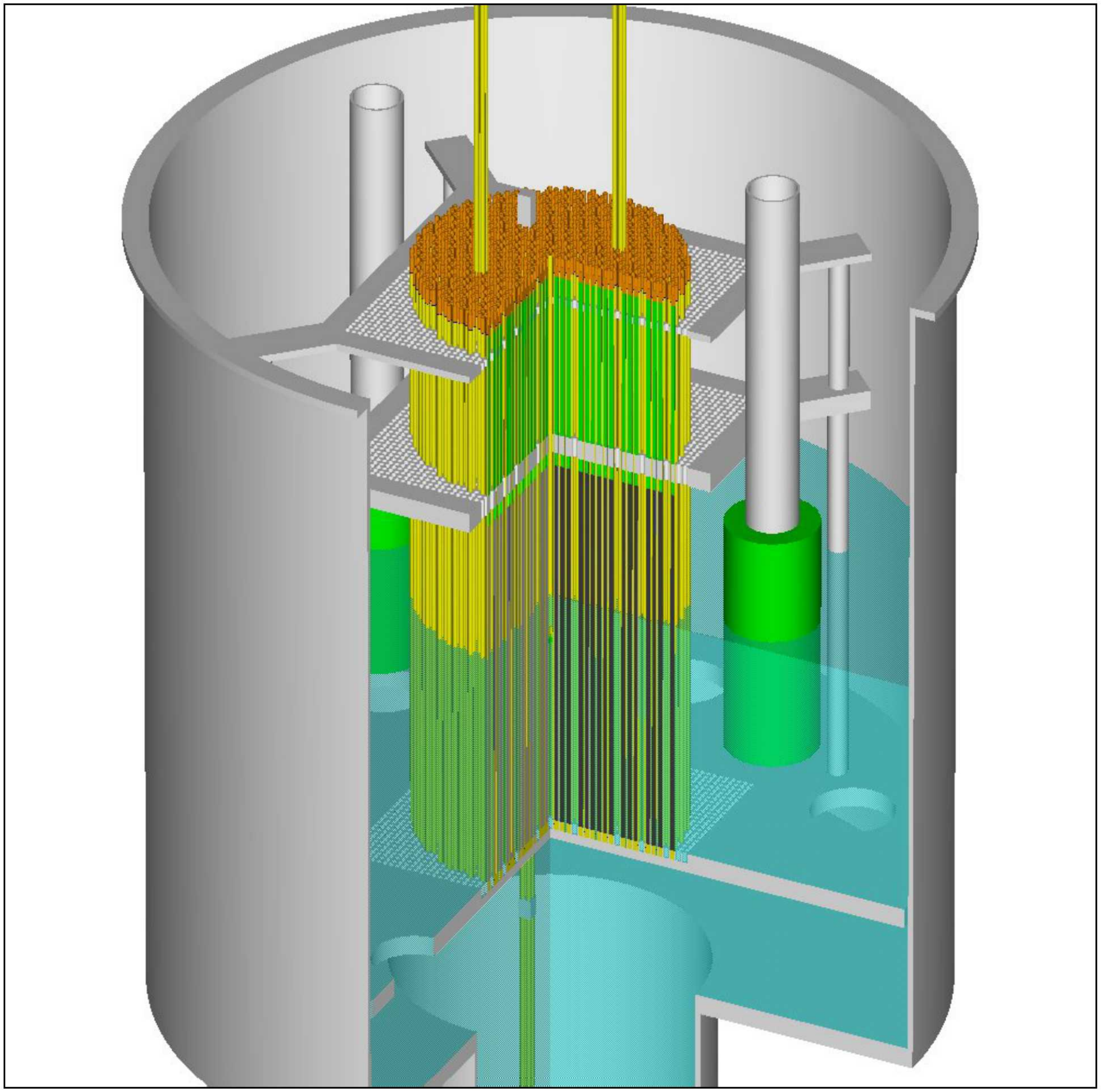
Control Element: Down

Core Tank: Filling

Personnel: Excluded

The water level changes by about 1 mm per second. Filling the core tank requires about 15 minutes.

Fill the Core Tank



Fuel: 1136

$k_{eff} \approx 0.901$

Safety Elements: Up

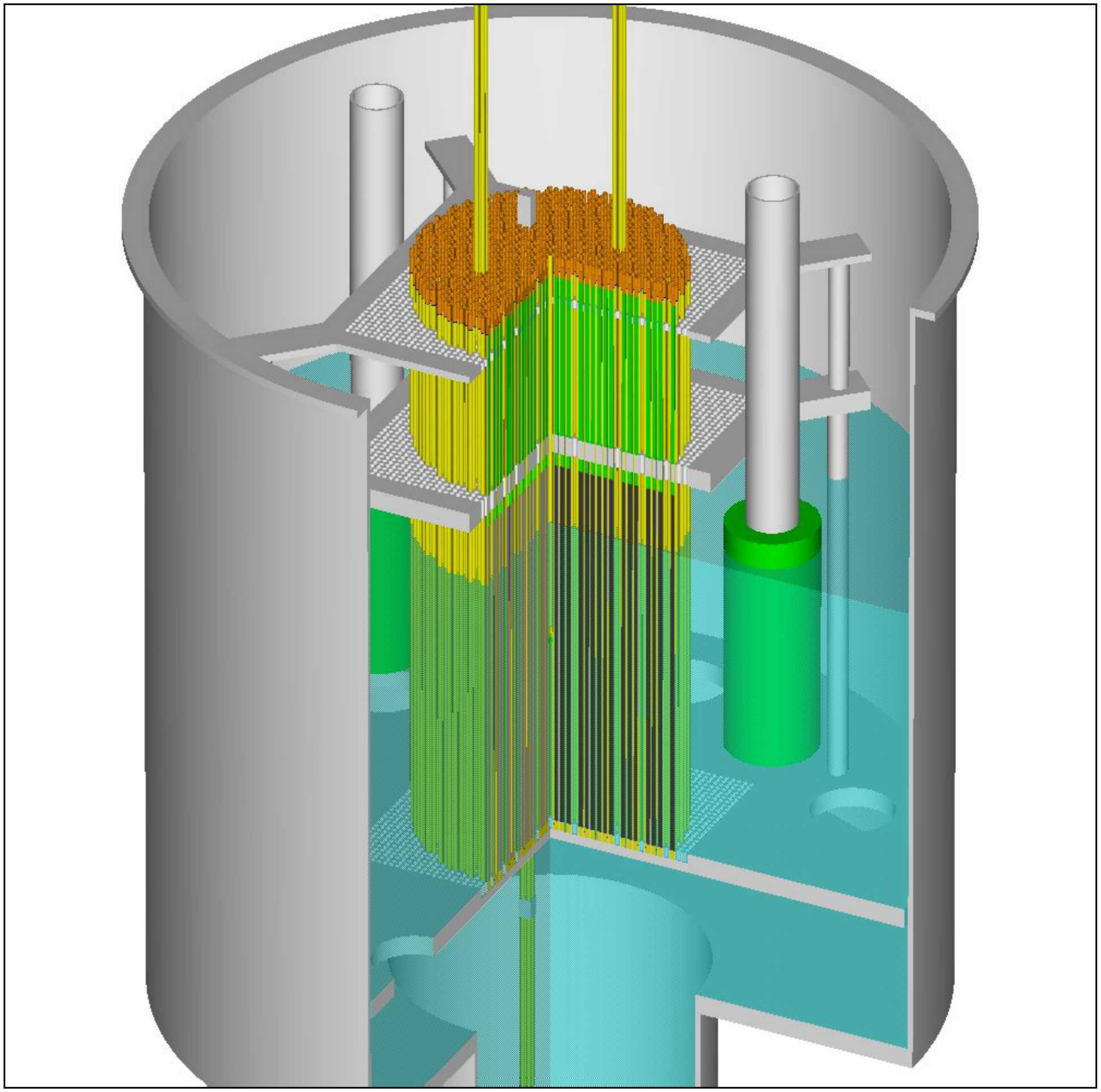
Control Element: Down

Core Tank: Filling

Personnel: Excluded

The water level changes by about 1 mm per second. Filling the core tank requires about 15 minutes.

Fill the Core Tank



Fuel: 1136

k_{eff} ≈ 0.953

Safety Elements: Up

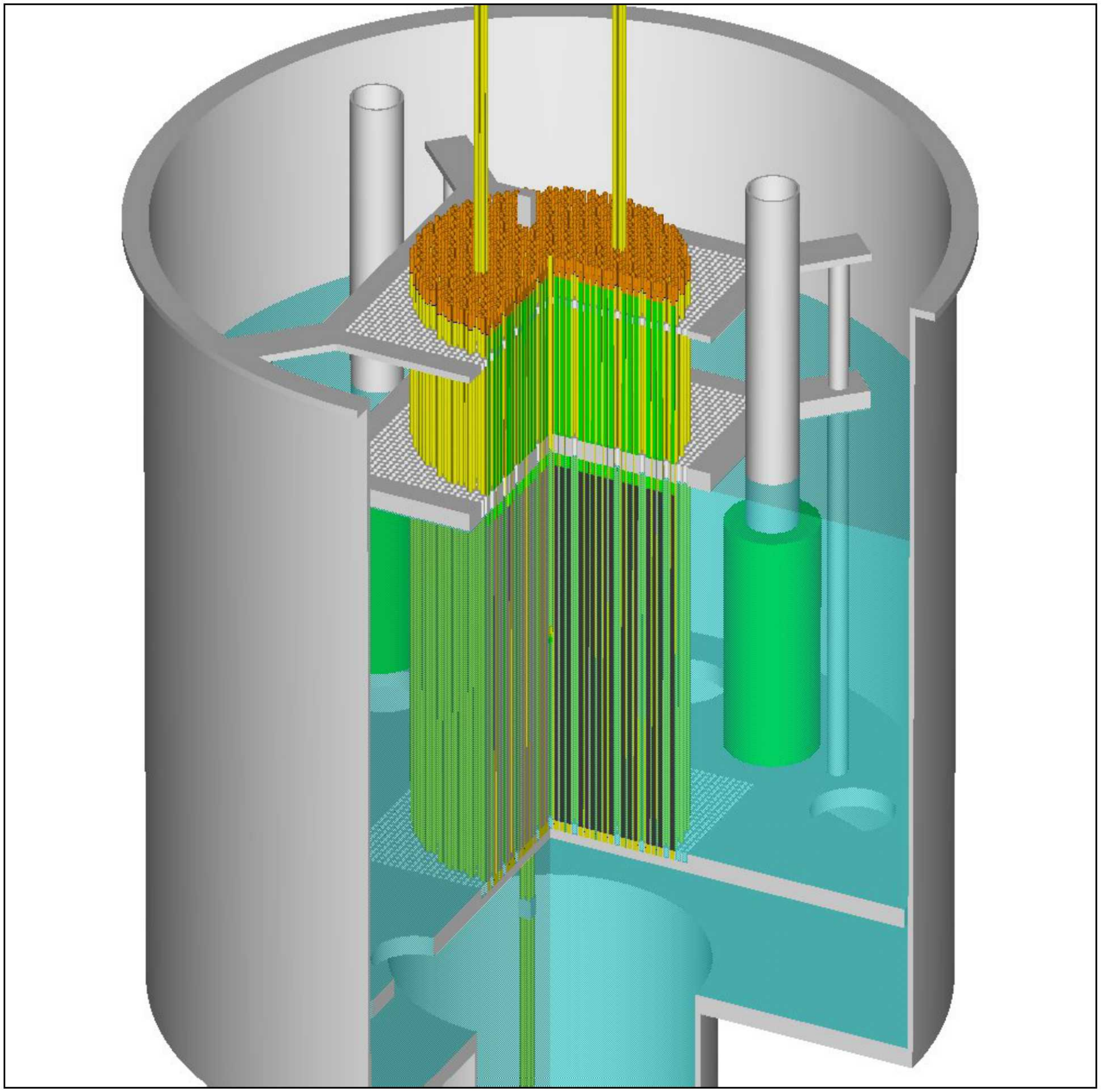
Control Element: Down

Core Tank: Filling

Personnel: Excluded

The water level changes by about 1 mm per second. Filling the core tank requires about 15 minutes.

Fill the Core Tank



Fuel: 1136

$k_{eff} \approx 0.981$

Safety Elements: Up

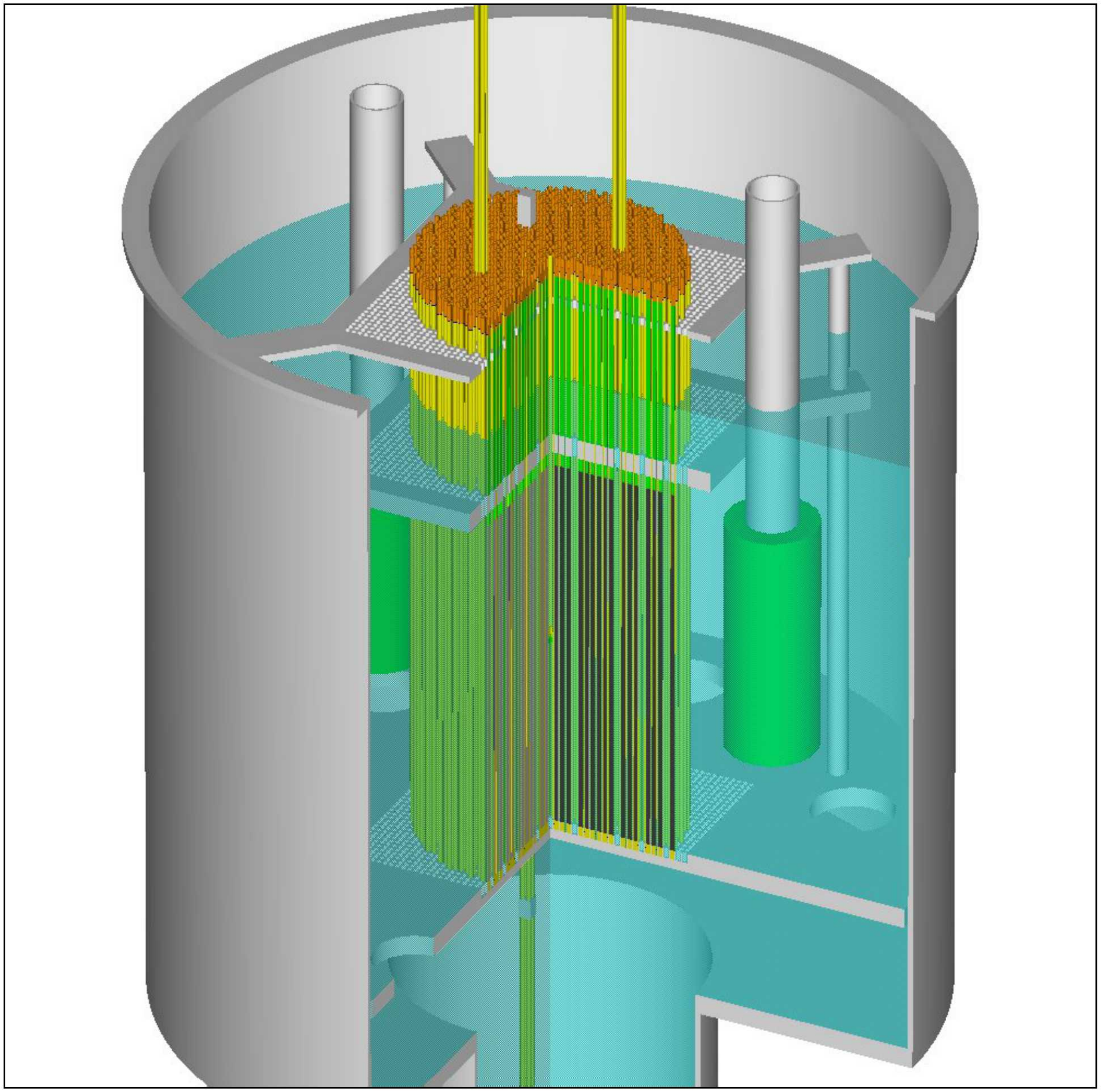
Control Element: Down

Core Tank: Filling

Personnel: Excluded

The water level changes by about 1 mm per second. Filling the core tank requires about 15 minutes.

Fill the Core Tank



Fuel: 1136

$k_{eff} \approx 0.986$

Safety Elements: Up

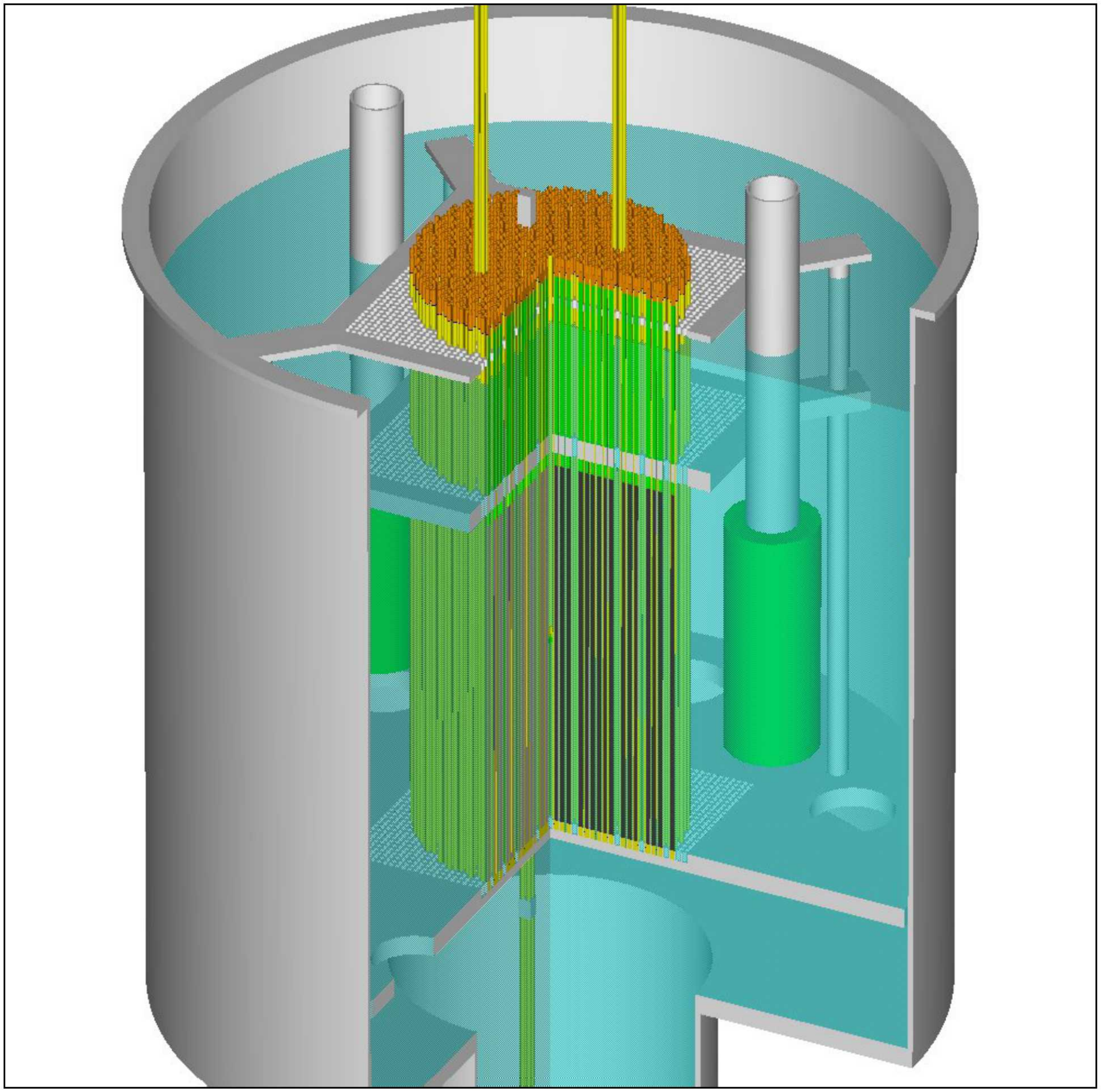
Control Element: Down

Core Tank: Filling

Personnel: Excluded

The water level changes by about 1 mm per second. Filling the core tank requires about 15 minutes.

The Core Tank is Full



Fuel: 1136

k_{eff} ≈ 0.986

Safety Elements: Up

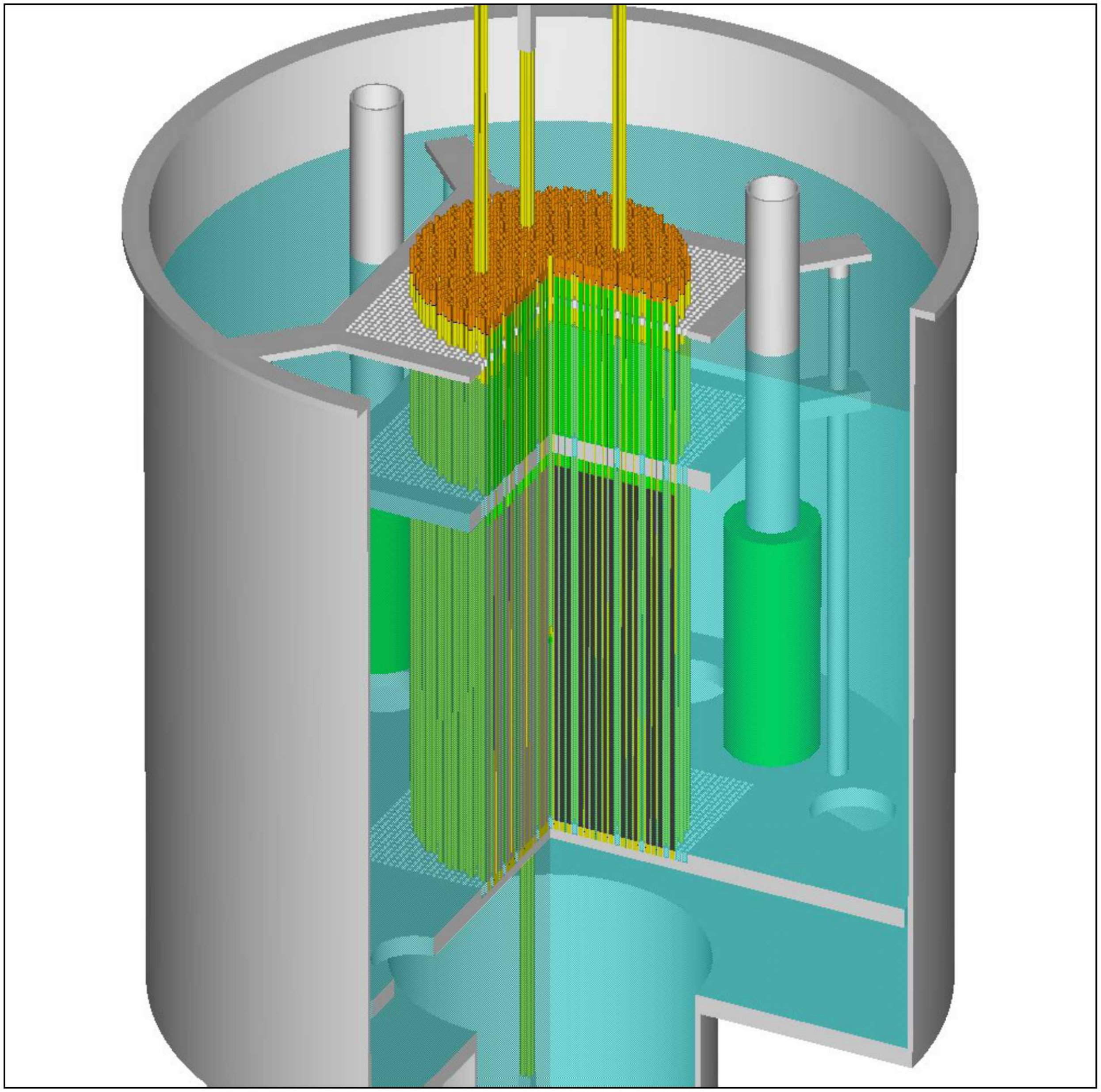
Control Element: Down

Core Tank: Full

Personnel: Excluded

At this point, the “fast” fill pump is disabled by an interlock and the recirculation pump is turned on. Moderator enters under the water’s surface and drains to the dump tank through a standpipe.

Raise the Control Element



Fuel: 1136

$k_{eff} \approx 0.992$

Safety Elements: Up

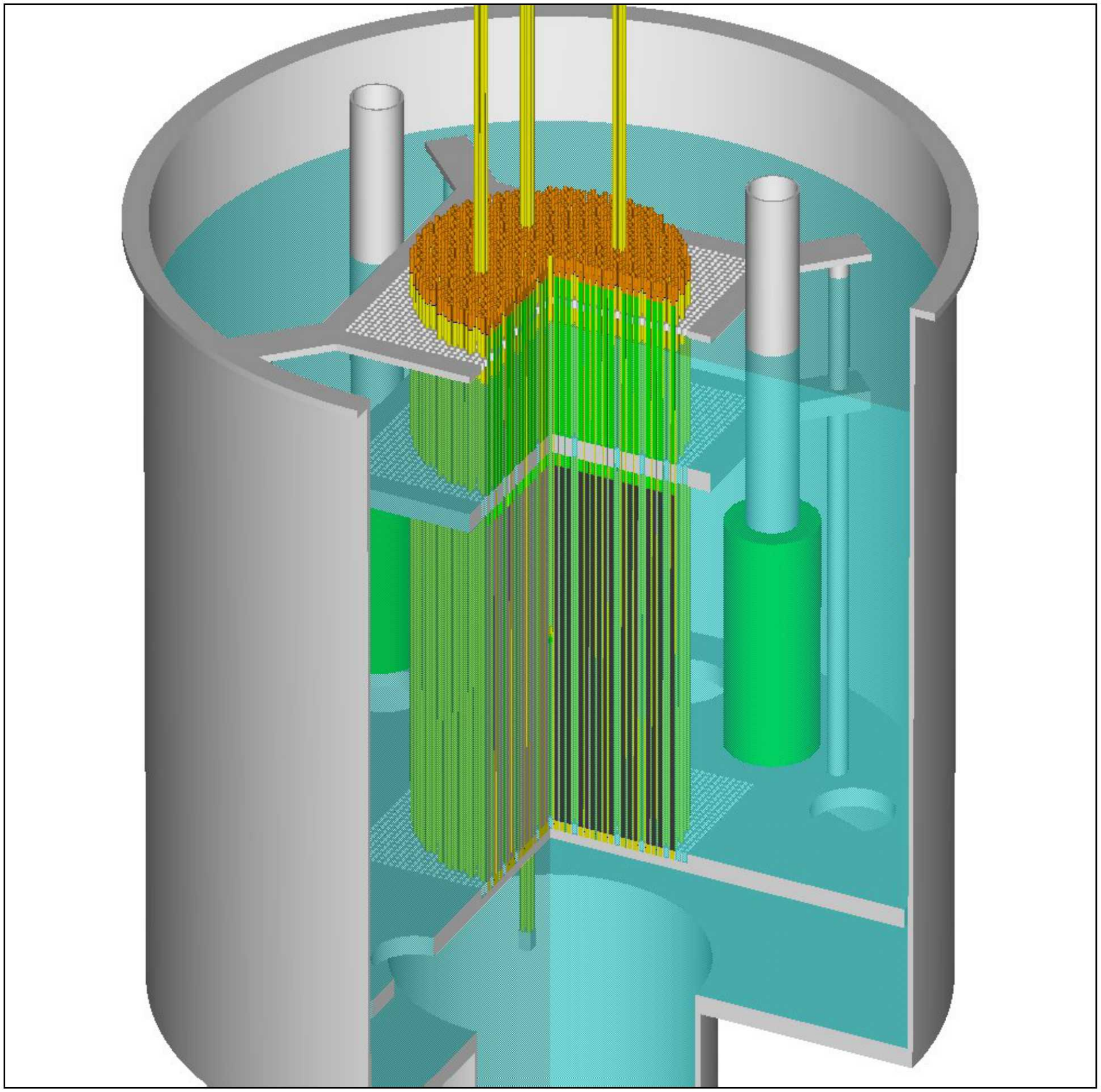
Control Element: Raising

Core Tank: Full

Personnel: Excluded

It takes about 90 seconds to raise the control element. The maximum reactivity insertion rate during control element withdrawal is less than 4 ¢ per second.

Raise the Control Element



Fuel: 1136

k_{eff} ≈ 0.998

Safety Elements: Up

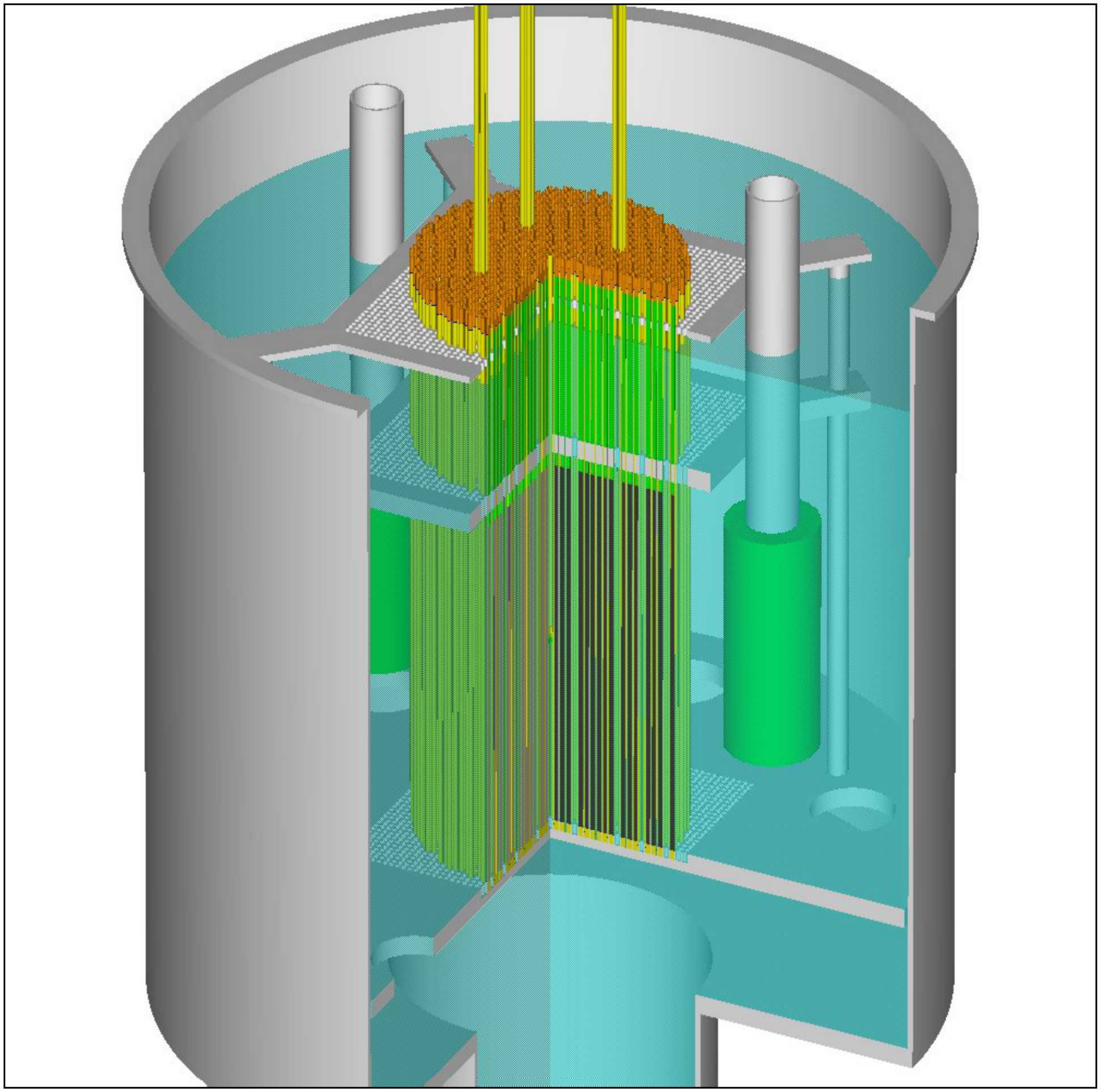
Control Element: Raising

Core Tank: Full

Personnel: Excluded

It takes about 90 seconds to raise the control element. The maximum reactivity insertion rate during control element withdrawal is less than 4 ¢ per second.

The Assembly Reaches Its Most Reactive State



Fuel: 1136

$k_{eff} \approx 0.999$

Safety Elements: Up

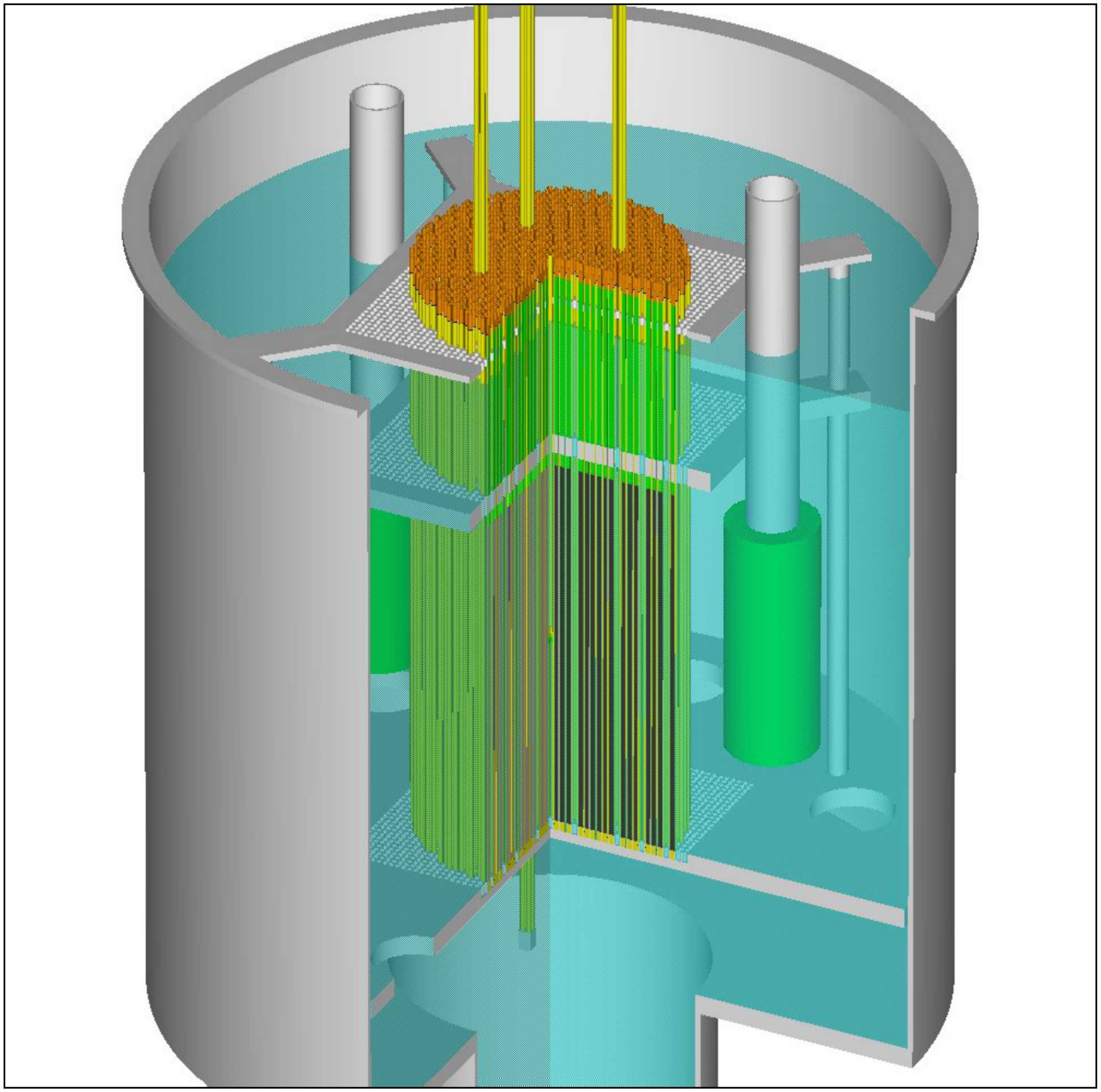
Control Element: Up

Core Tank: Full

Personnel: Excluded

With all control and safety elements up and full reflection (>6 in. of water on all sides), this is the highest reactivity state of the assembly. Multiplication measurements are made in this configuration.

Lower the Control Element



Fuel: 1136

$k_{eff} \approx 0.998$

Safety Elements: Up

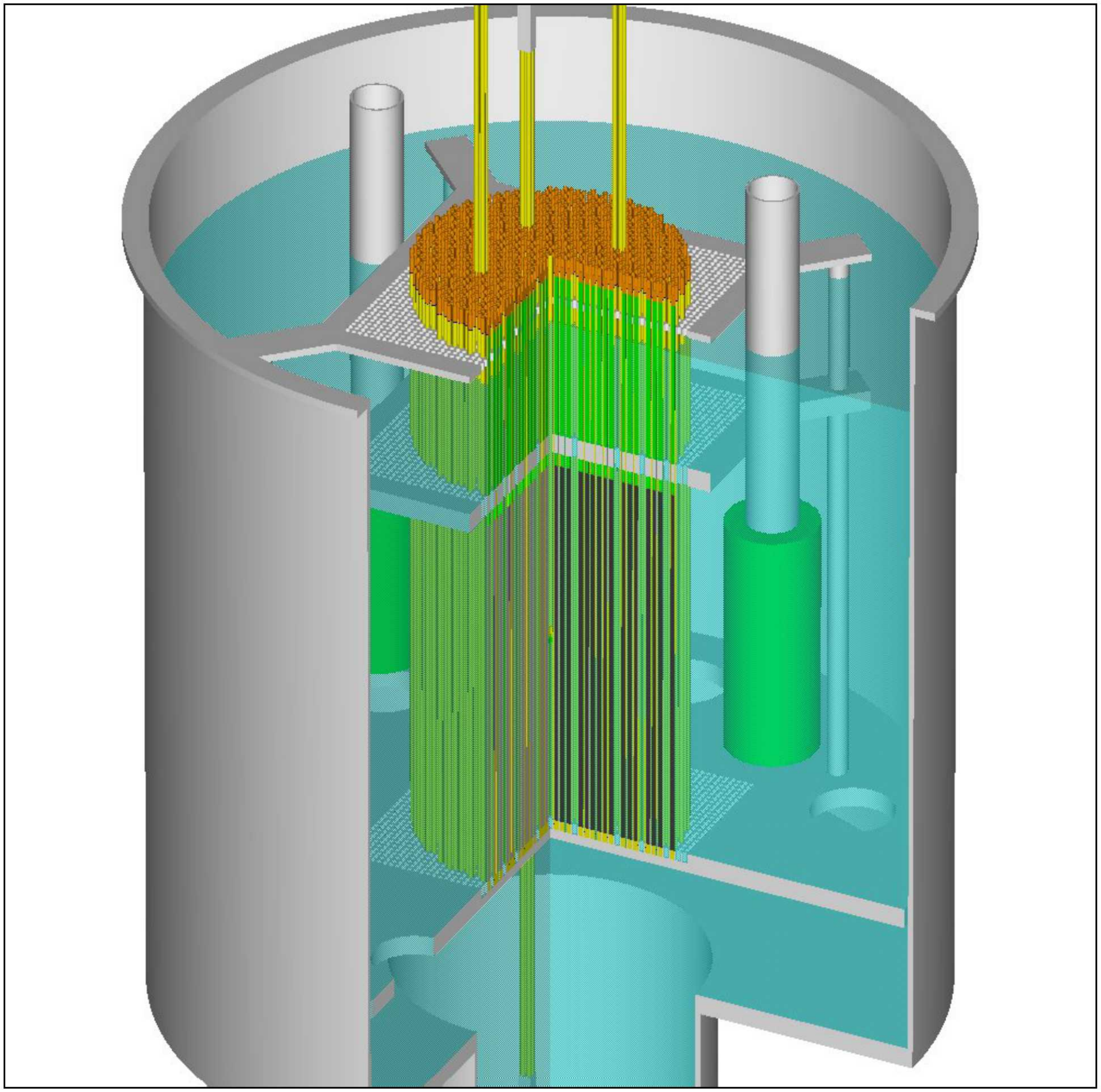
Control Element: Lowering

Core Tank: Full

Personnel: Excluded

It takes about 90 seconds to lower the control element.

Lower the Control Element



Fuel: 1136

$k_{eff} \approx 0.992$

Safety Elements: Up

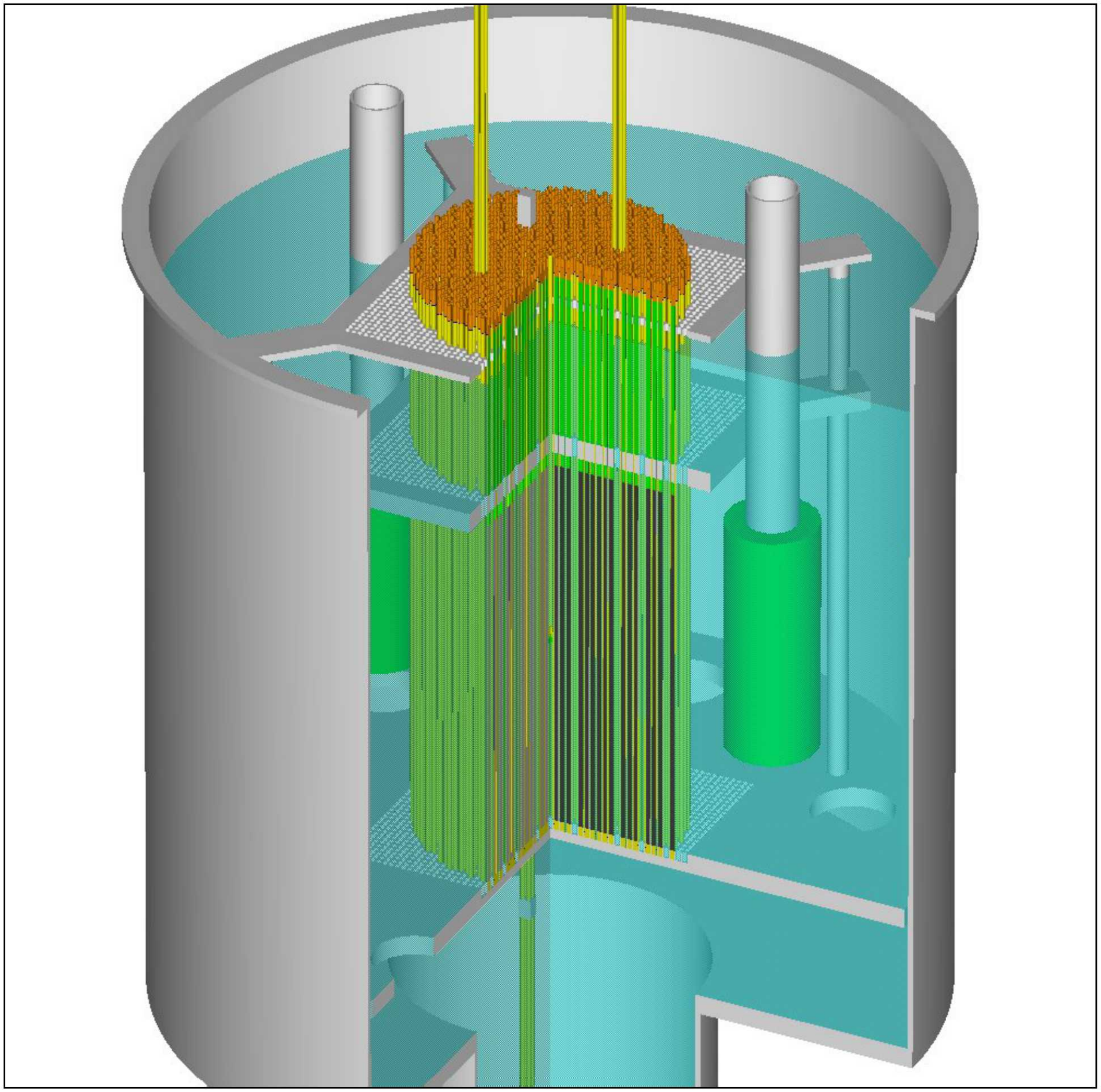
Control Element: Lowering

Core Tank: Full

Personnel: Excluded

It takes about 90 seconds to lower the control element.

Lower the Control Element



Fuel: 1136

k_{eff} ≈ 0.986

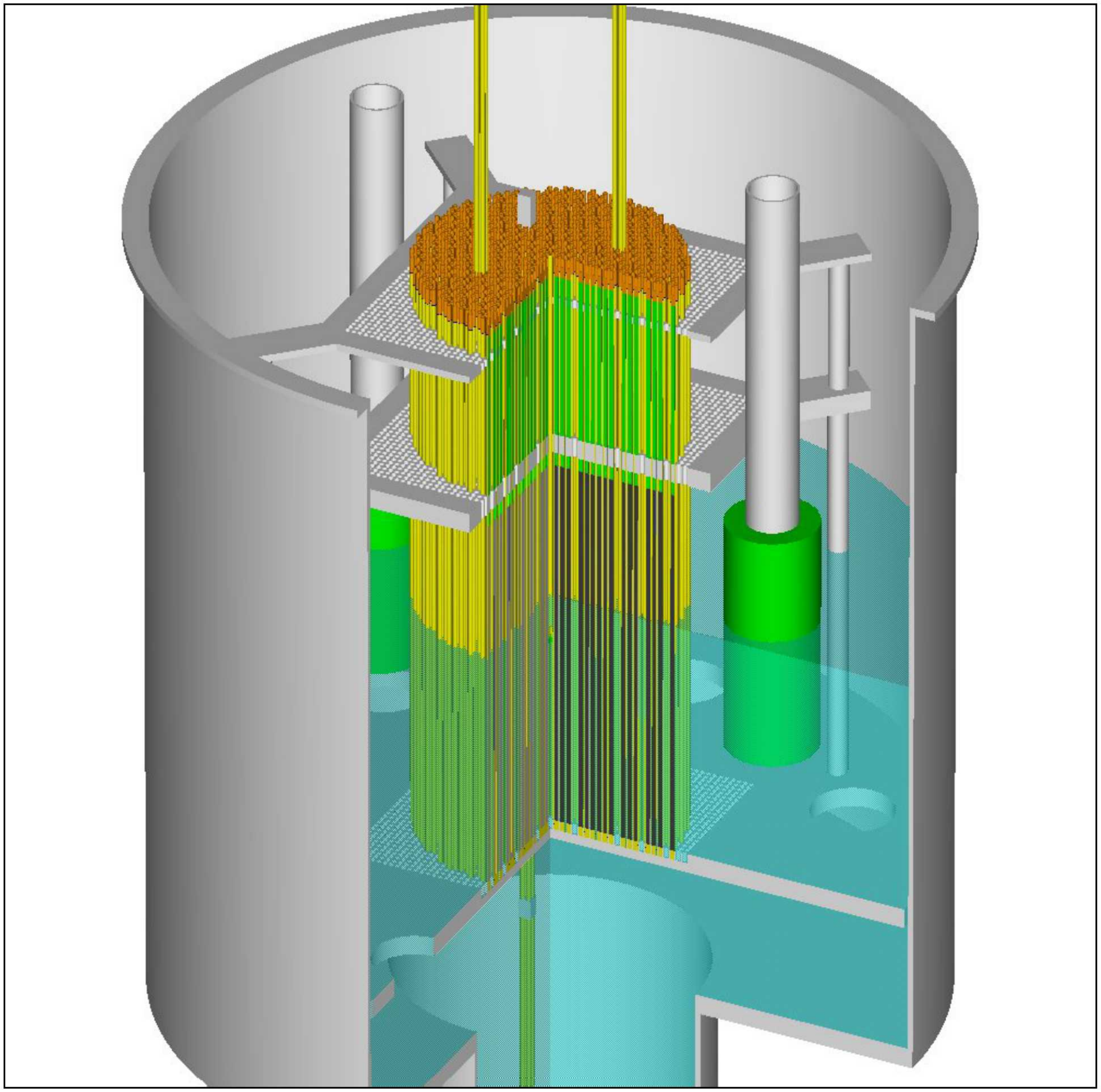
Safety Elements: Up

Control Element: Down

Core Tank: Full

Personnel: Excluded

Drain the Core Tank



Fuel: 1136

$k_{eff} \approx 0.901$

Safety Elements: Up

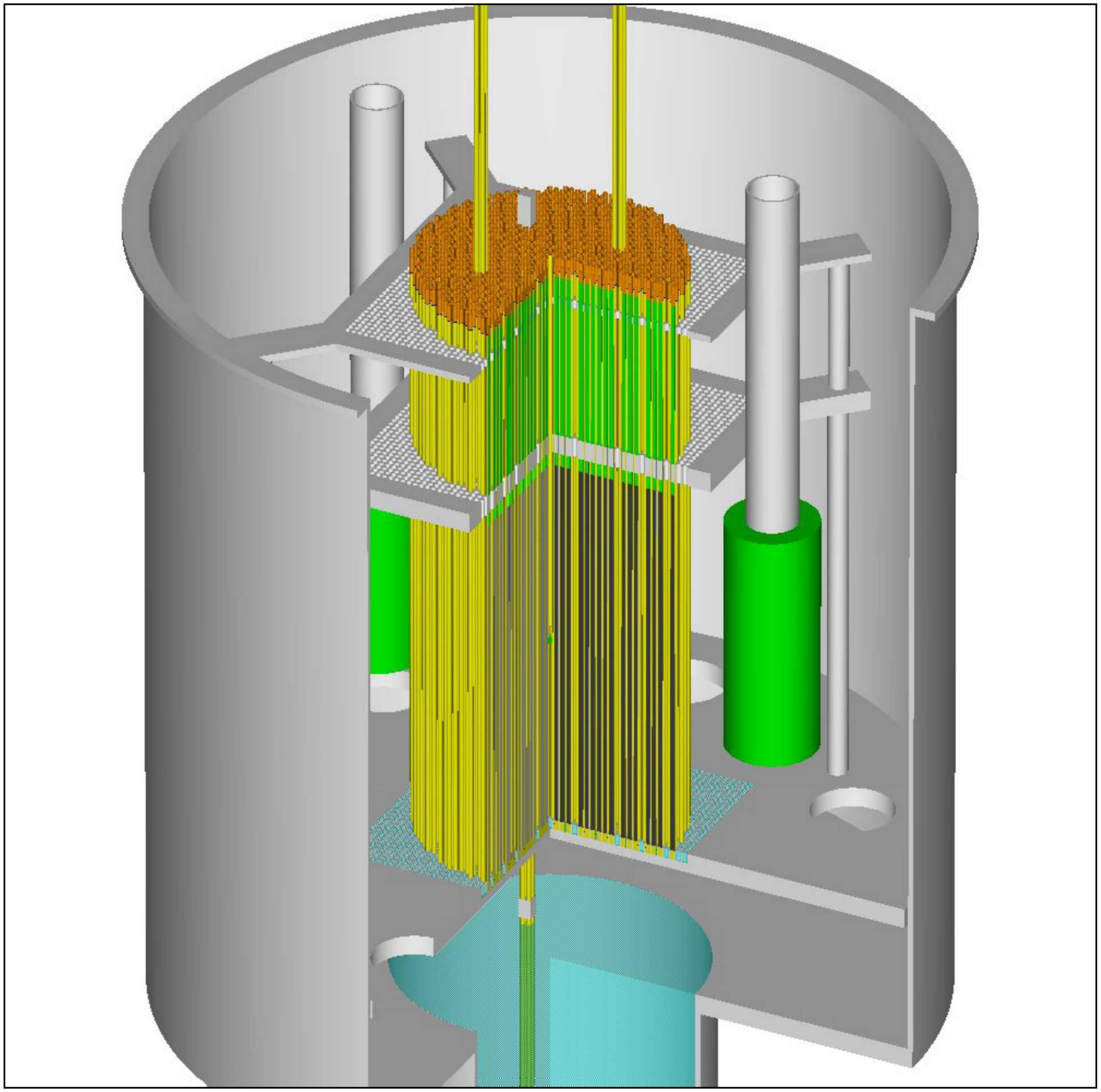
Control Element: Down

Core Tank: Draining

Personnel: Excluded

It takes about 15 seconds to completely drain the core tank.

Drain the Core Tank



Fuel: 1136

$k_{eff} \approx 0.128$

Safety Elements: Up

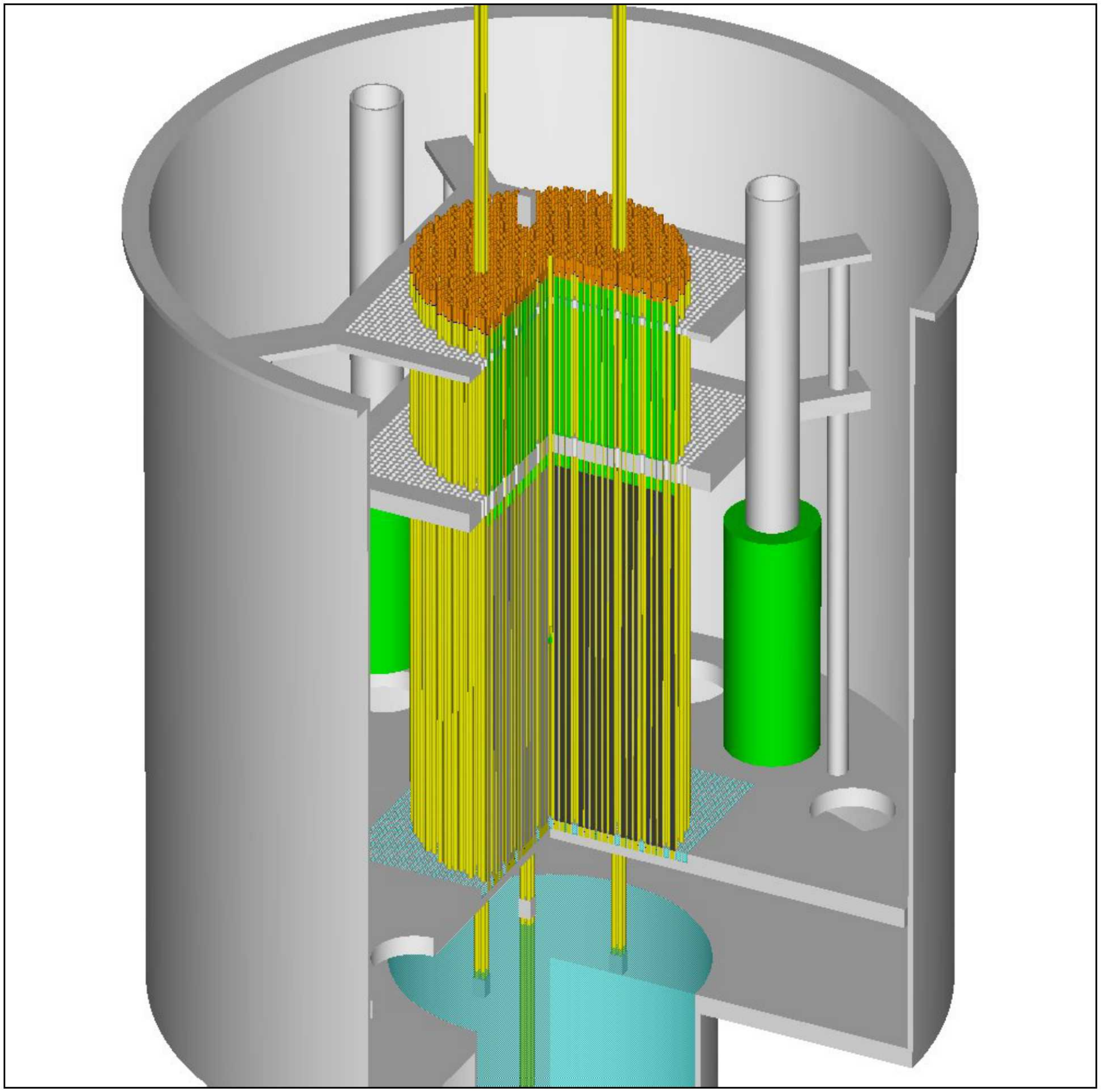
Control Element: Down

Core Tank: Empty

Personnel: Allowed

Now we are back to a condition where fuel may be added to or removed from the array.

Lower the Safety Elements



Fuel: 1136

$k_{eff} \approx 0.127$

Safety Elements: Lowering

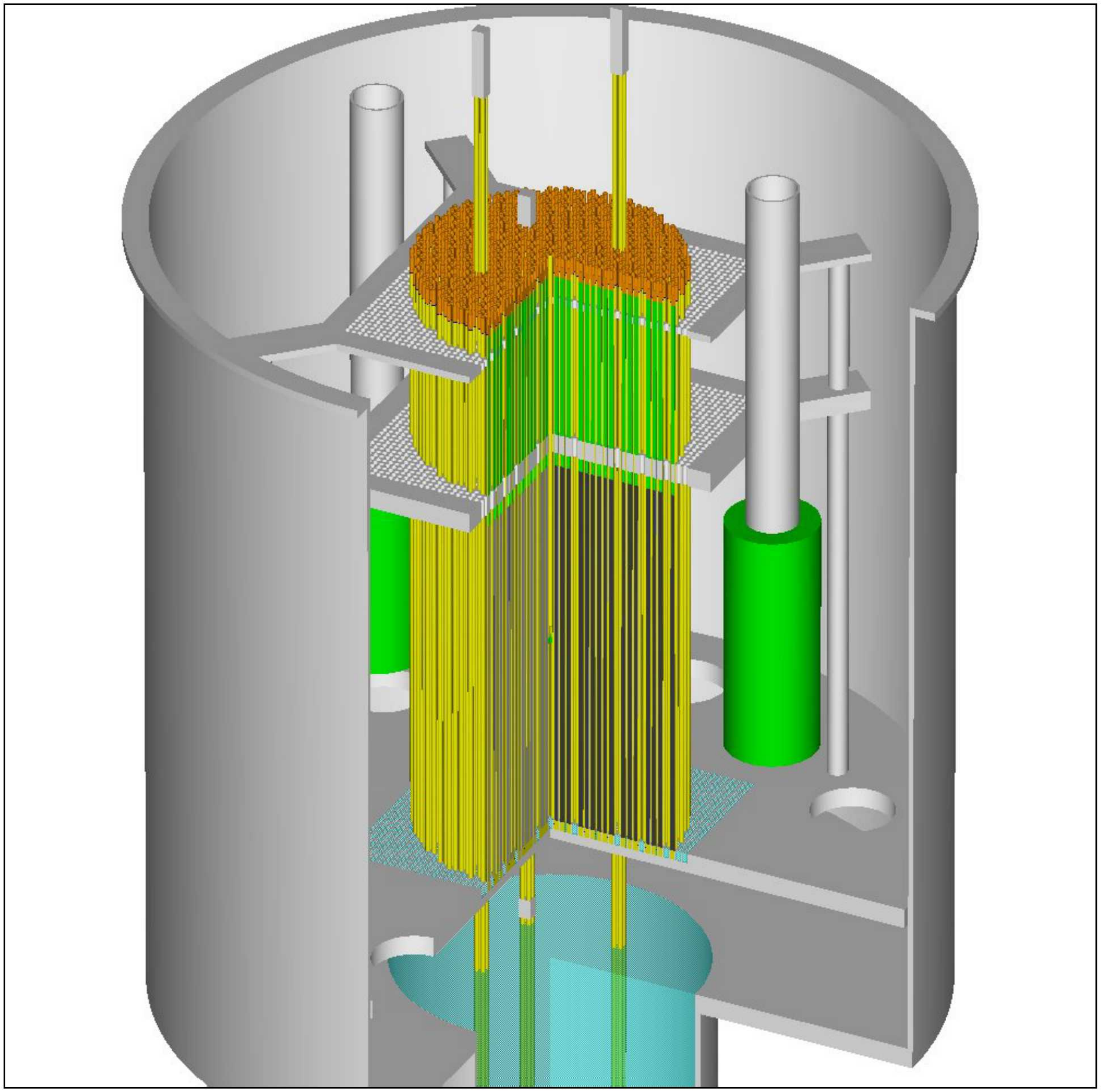
Control Element: Down

Core Tank: Empty

Personnel: Allowed

Now we are back to a condition where fuel may be added to or removed from the array.

Lower the Safety Elements



Fuel: 1136

k_{eff} ≈ 0.132

Safety Elements: Lowering

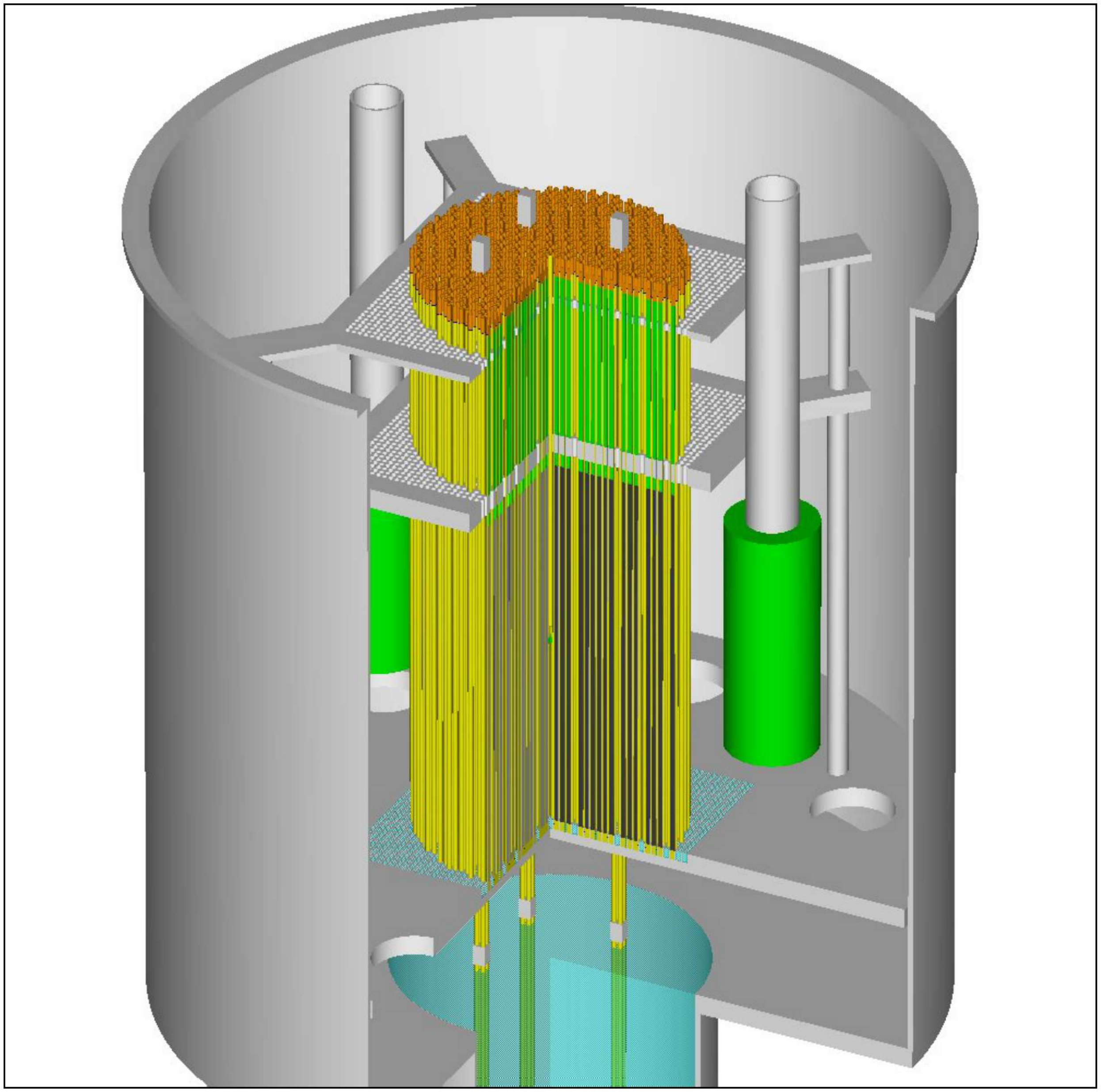
Control Element: Down

Core Tank: Empty

Personnel: Allowed

Now we are back to a condition where fuel may be added to or removed from the array.

The Assembly Reaches its Shutdown Condition



Fuel: 1136

k_{eff} ≈ 0.140

Safety Elements: Down

Control Element: Down

Core Tank: Empty

Personnel: Allowed

In this condition, the assembly is "shut down." Entry into the reactor room is allowed. The control system need not be manned. Fuel may be added to or removed from the array.

Approach to Critical

- We determine critical conditions for a given set of assembly conditions in an "approach-to-critical" experiment
- The goal of the experiment is to find the conditions where the multiplication of the assembly is infinite
- Under those conditions, the inverse of the multiplication is zero
- Count-rate measurements are made on the assembly as the approach variable is changed to make the system more reactive
- When the assembly is nearly critical, the count rates follow the assembly multiplication
- Estimates are made of the critical condition of the assembly from the measurements

$$M = \frac{1}{1 - k_{eff}}$$

Subcritical Multiplication

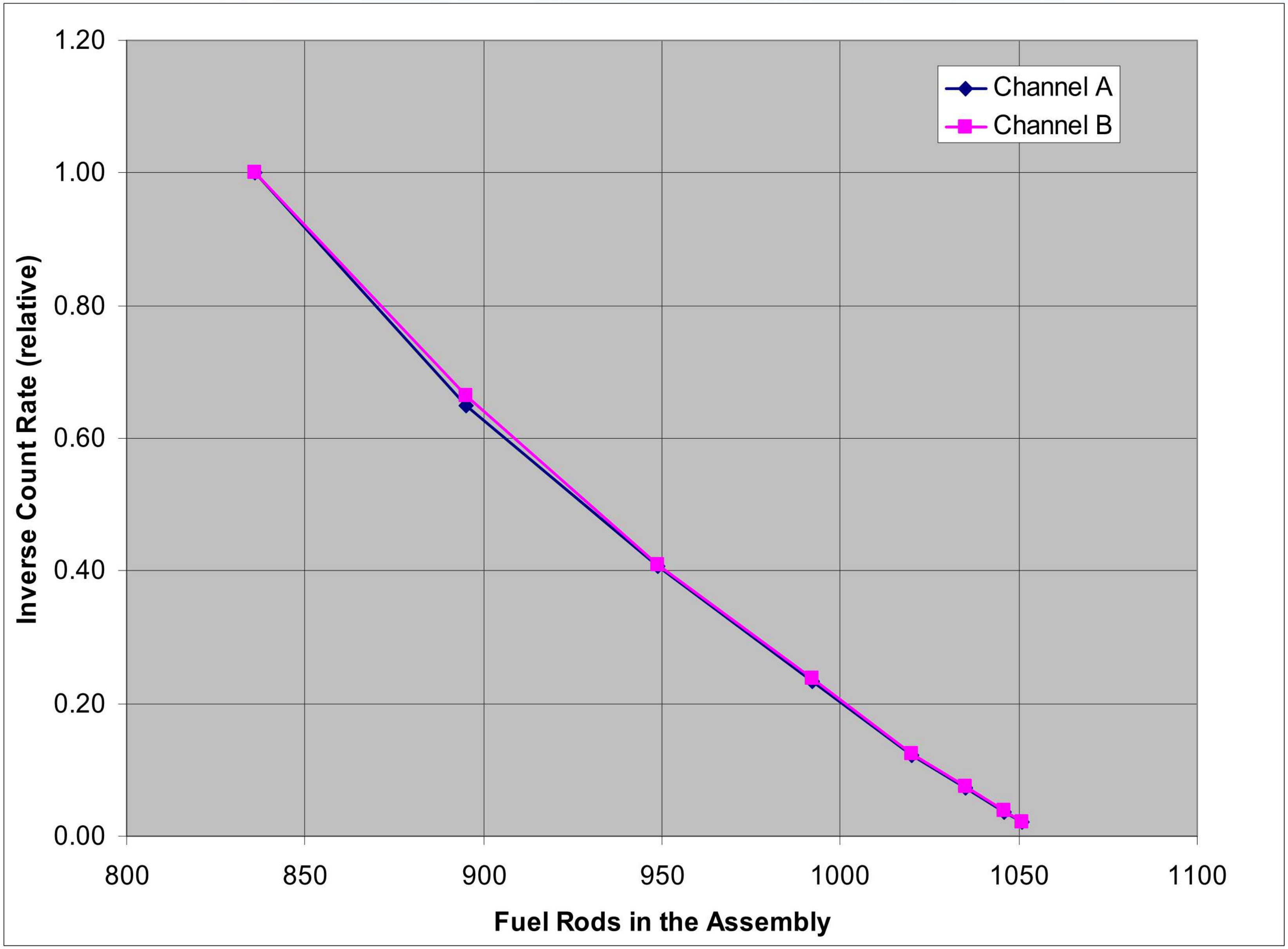
$$\frac{1}{M} = 1 - k_{eff}$$

Inverse Subcritical Multiplication

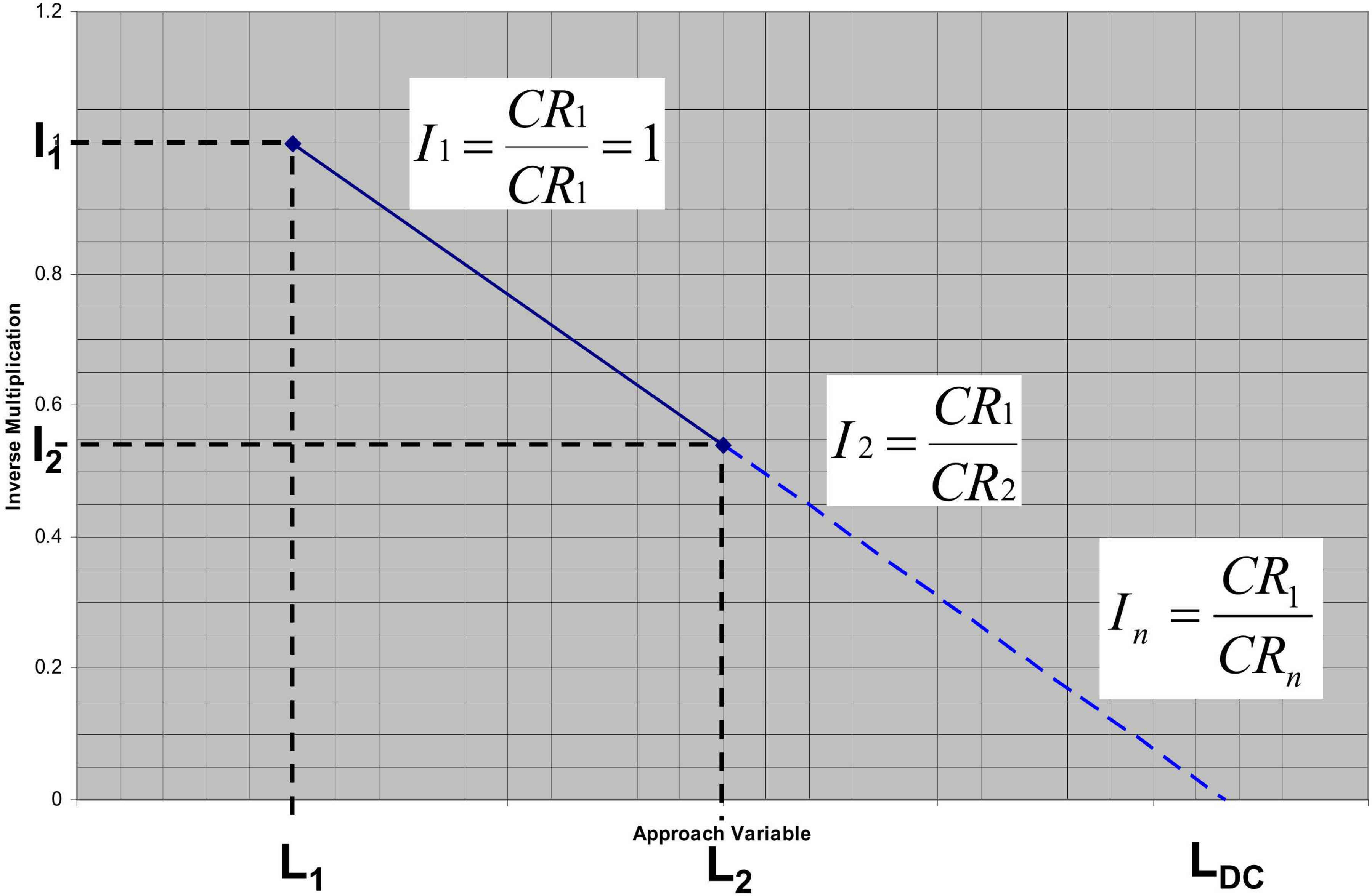
$$I_n = \frac{Constant}{CR_n}$$

Inverse Count Rate

Inverse Count Rate Plot



Determining the Next Fuel Increment

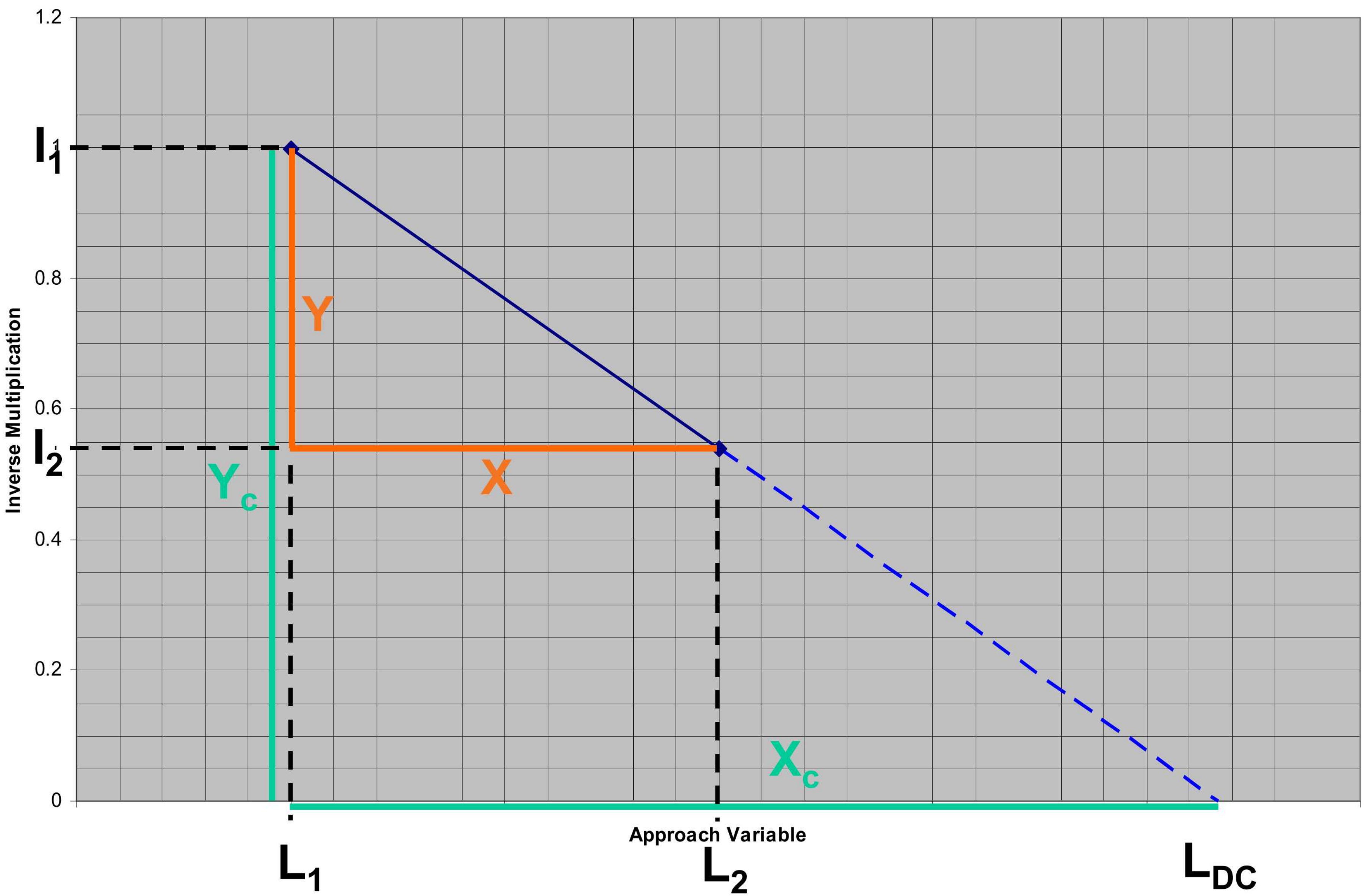


$$I_1 = \frac{CR_1}{CR_1} = 1$$

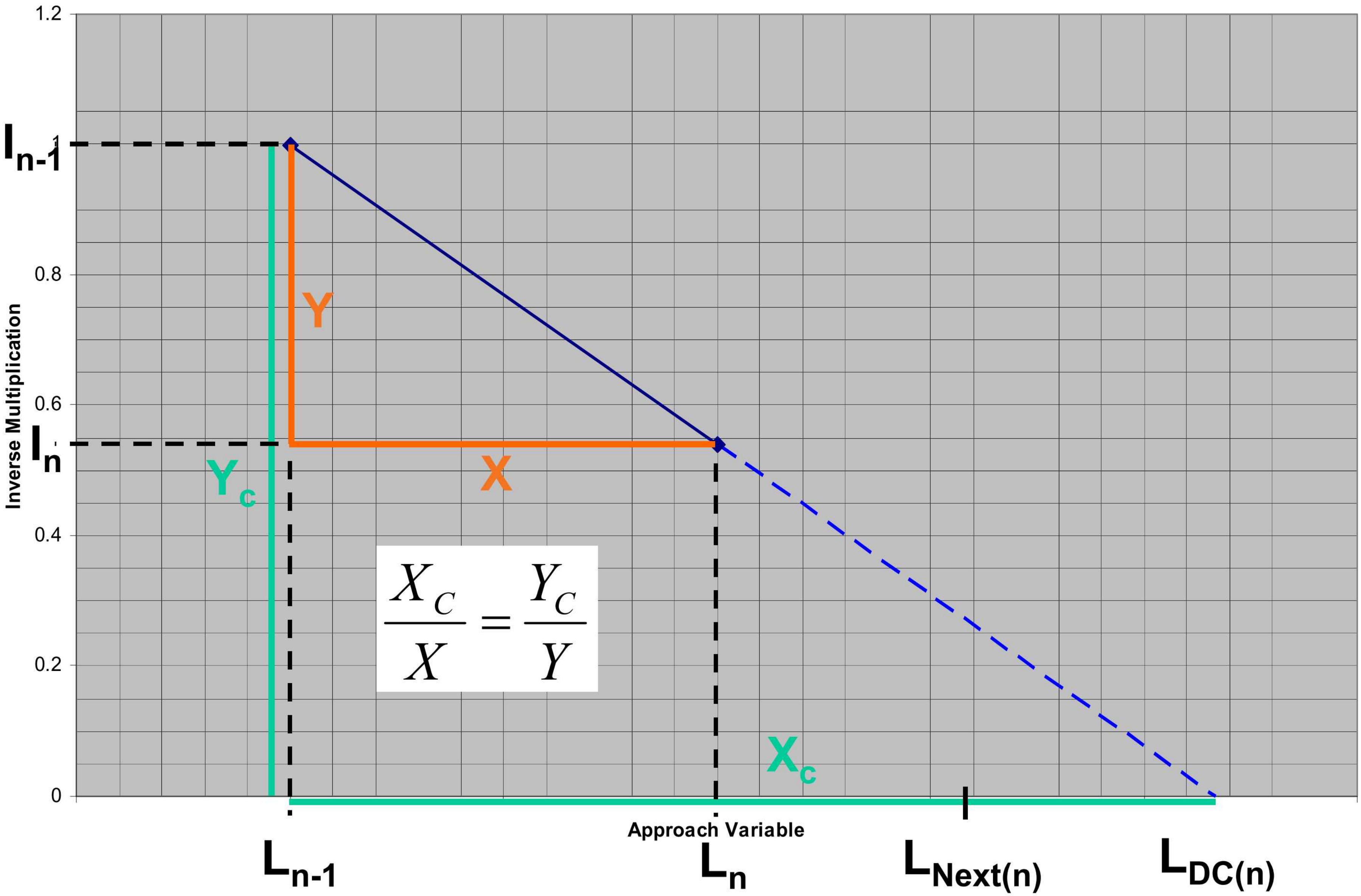
$$I_2 = \frac{CR_1}{CR_2}$$

$$I_n = \frac{CR_1}{CR_n}$$

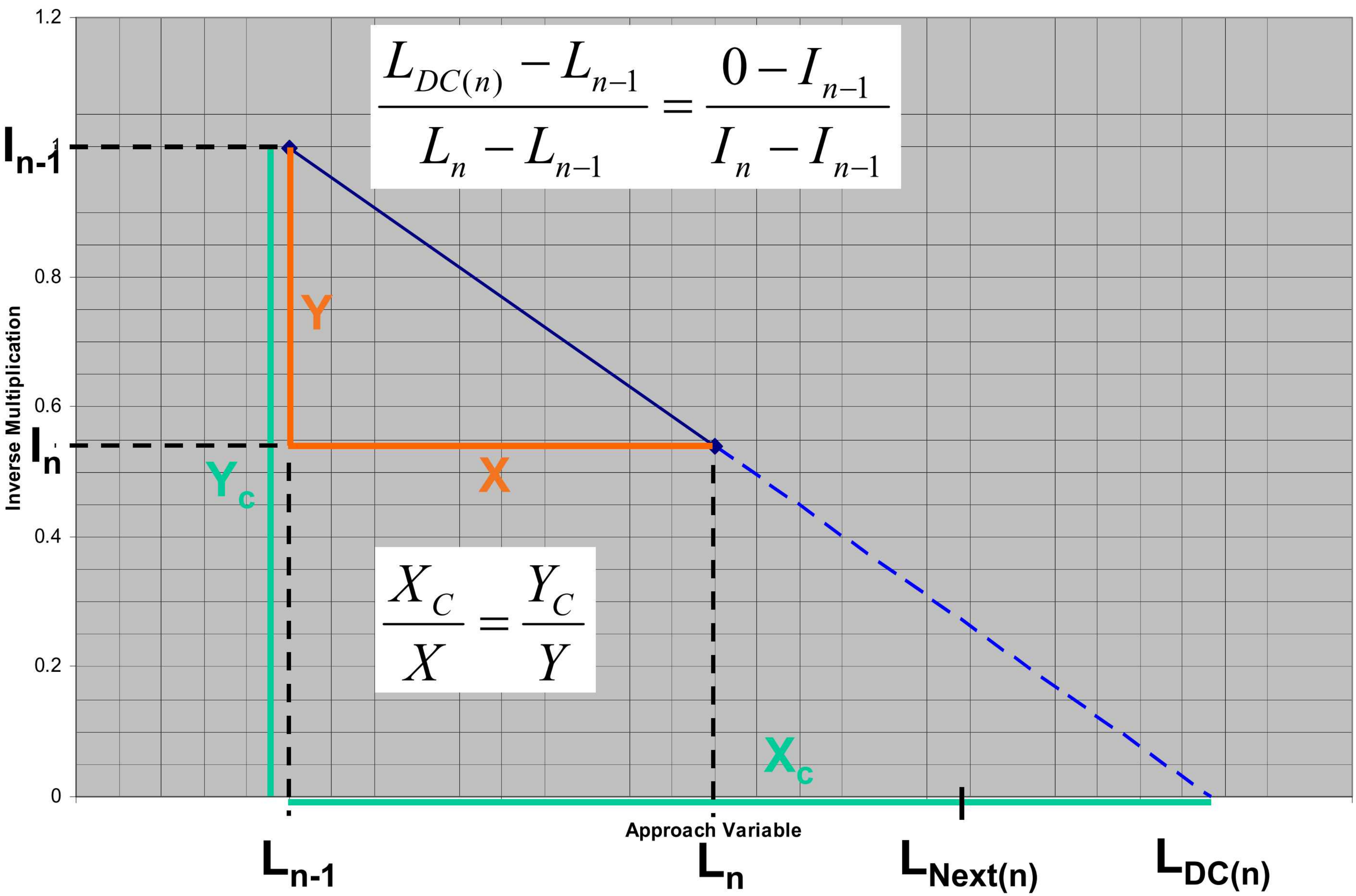
Determining the Next Fuel Increment



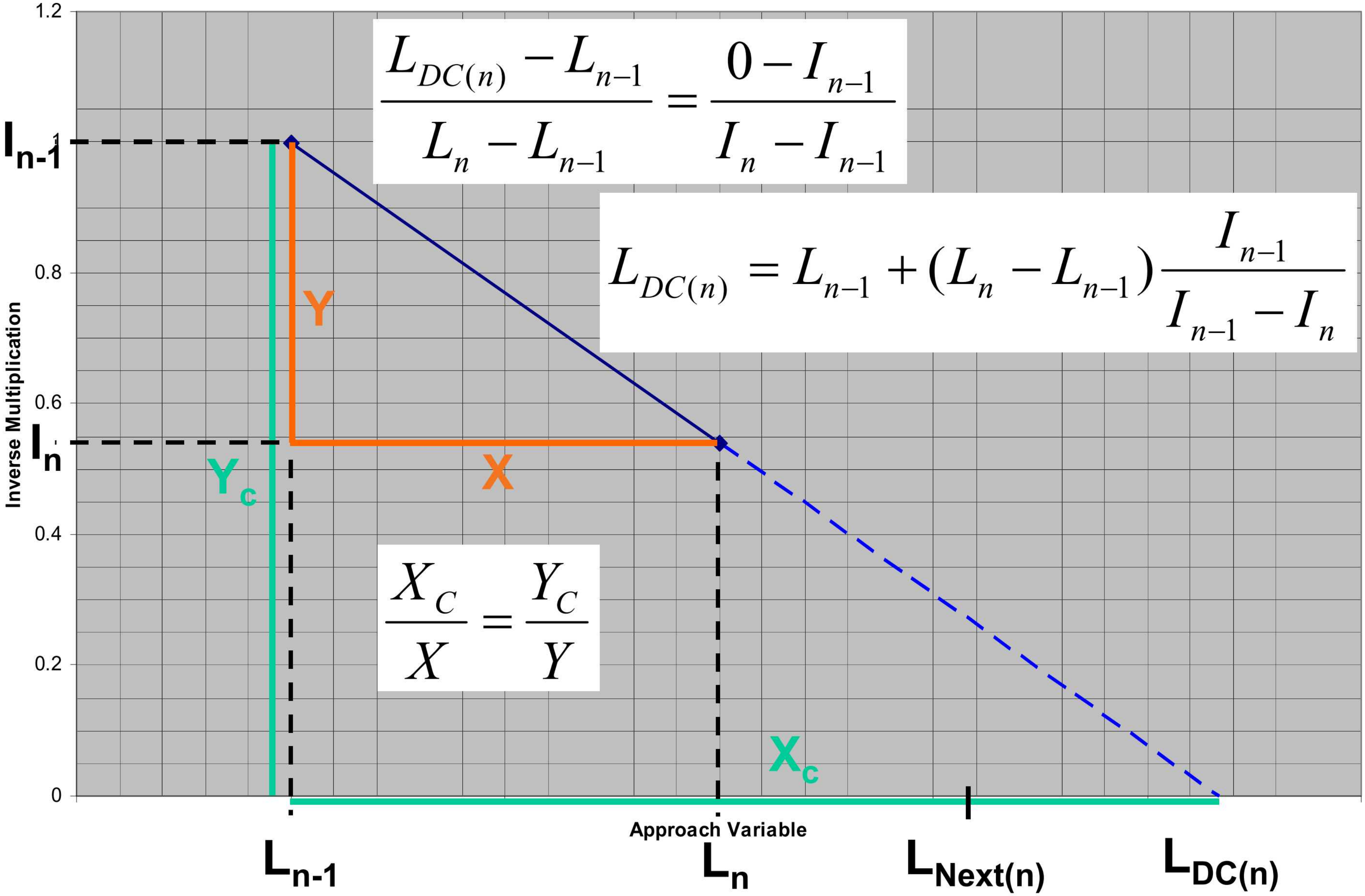
Determining the Next Fuel Increment



Determining the Next Fuel Increment



Determining the Next Fuel Increment



$$\frac{L_{DC(n)} - L_{n-1}}{L_n - L_{n-1}} = \frac{0 - I_{n-1}}{I_n - I_{n-1}}$$

$$L_{DC(n)} = L_{n-1} + (L_n - L_{n-1})\frac{I_{n-1}}{I_{n-1} - I_n}$$

$$\frac{X_C}{X} = \frac{Y_C}{Y}$$

NUCLEAR CRITICALITY SAFETY PROGRAM

Module 04
Human Factors and Reliability Principles for Criticality Safety Evaluations

Presented by:
Kerstan Cole
Sandia National Laboratories
Albuquerque, New Mexico

Course Purpose

- Fulfill elements of Nuclear Criticality Safety Program (NCSP) mission and vision
  - Support safe, efficient fissionable material operations within DOE
  - Provide continually improving, adaptable, and transparent program
  - Communicate and collaborate globally
  - Respond to technical needs of criticality safety personnel
- Mission and vision identifies five-year goals in five technical program elements
  - Analytical methods
  - Information preservation and dissemination
  - Integral experiments
  - International criticality safety benchmark evaluation project
  - Nuclear data
  - Training and education

Course Purpose

- Training and education program element mission and vision
  - Offer hands-on training courses as needed by DOE
  - Identify and develop training needs and resources
  - Maintain technical capabilities of criticality safety professionals
  - Provide training and education for people new to criticality safety
  - Foster competency in art, science, and implementation of nuclear criticality safety
- Training and education five-year goals
  - International Handbook of Evaluated Criticality Safety Benchmark Experiments
  - Nuclear data
  - Analytical methods
  - Integral experiments
  - Other
    - Tutorial on human factors related to criticality safety

Course Objectives

- Understand basic human factors and reliability principles important for criticality safety evaluations
  - Identify critical human factors and reliability issues to look for, based on previous accidents
  - Understand importance of reliability for criticality safety evaluations
  - Create awareness of how humans relate to the effectiveness of administrative and engineering controls
  - Provide available resources for human factors support

What this course will NOT do:

- ***Provide exhaustive coverage of the field of human factors***
- ***Transform criticality safety engineers into human factors experts***

Course Modules

- 05.1: Introduction
- 05.2: Procedural Instructions
- 05.3: Human Machine Interface
- 05.4: Attention
- 05.5: Reliability
- 05.6: Summary and Application
- 05.7: Examples and Discussion

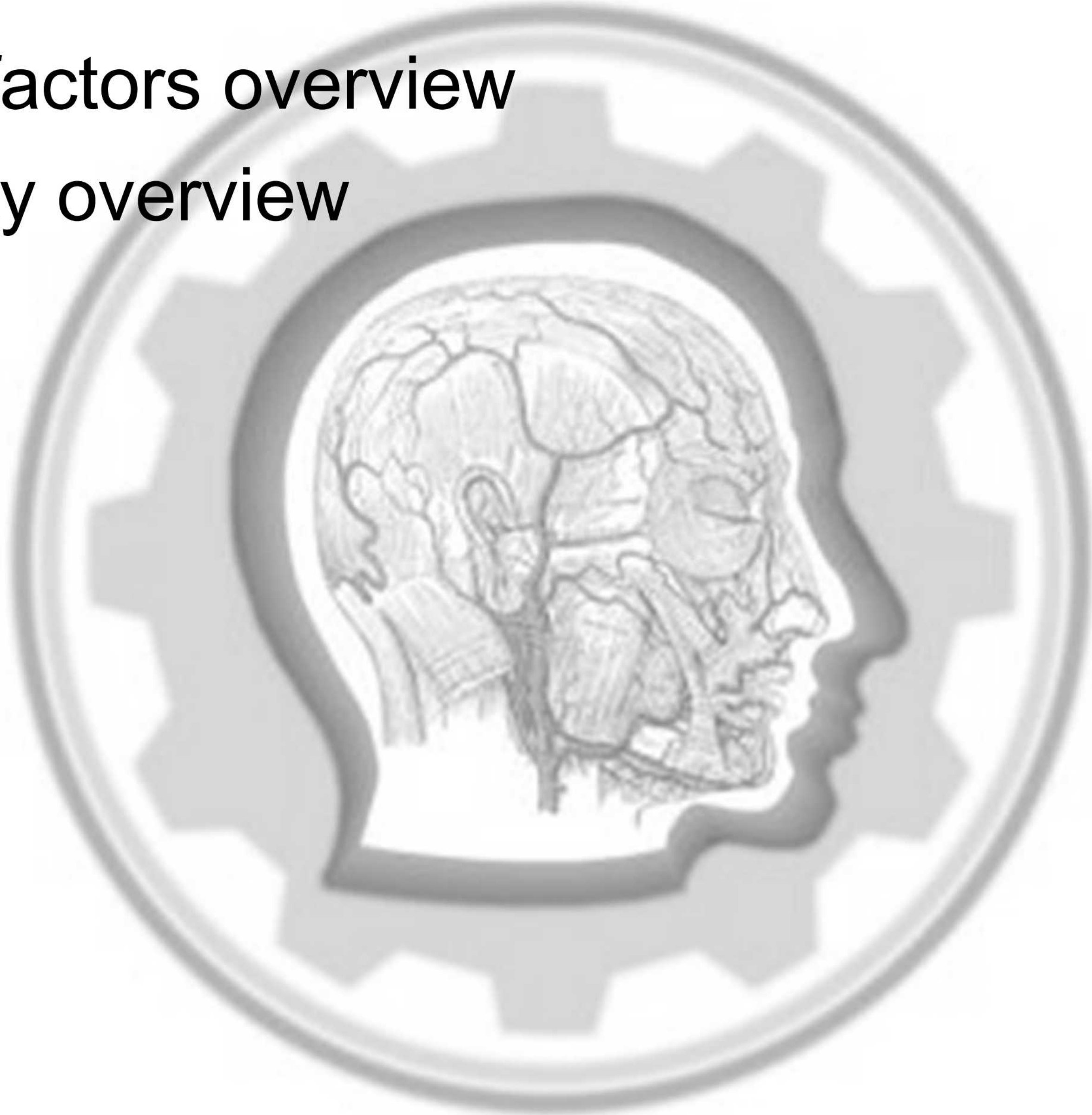
Part 1
Introduction

Presented by:

Kerstan Cole

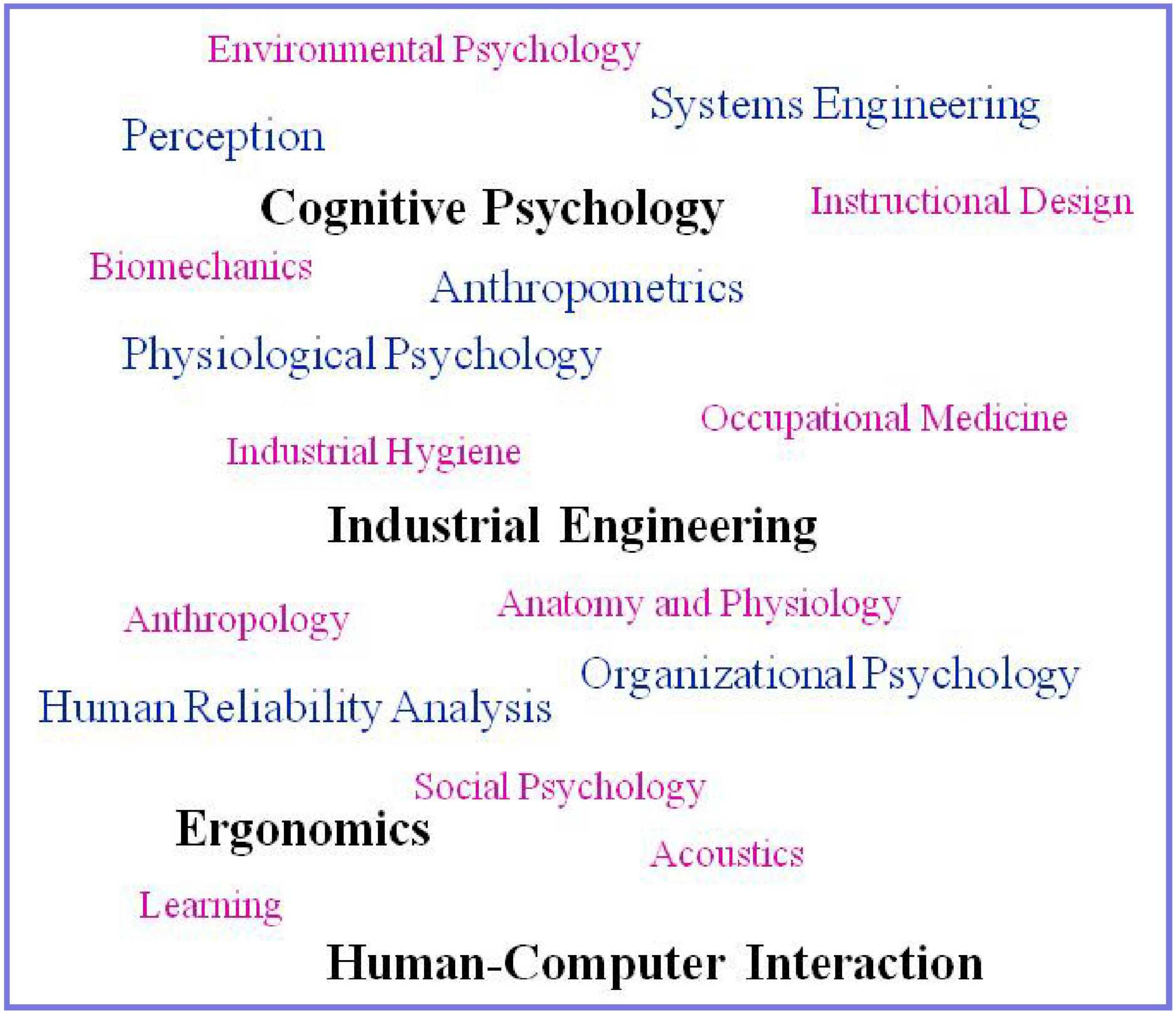
Introduction

- Human factors overview
- Reliability overview



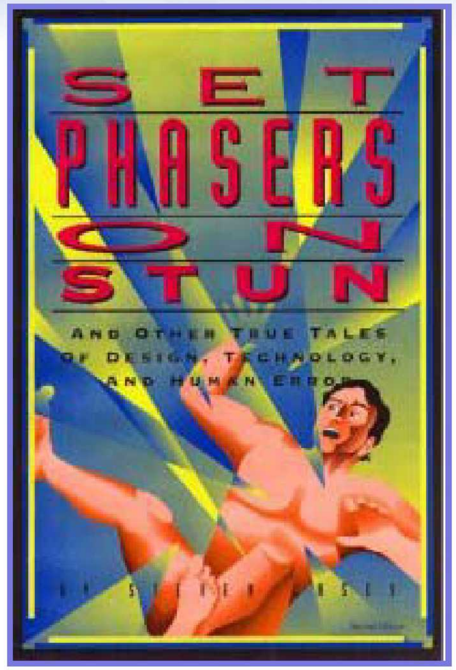
Definition of Human Factors

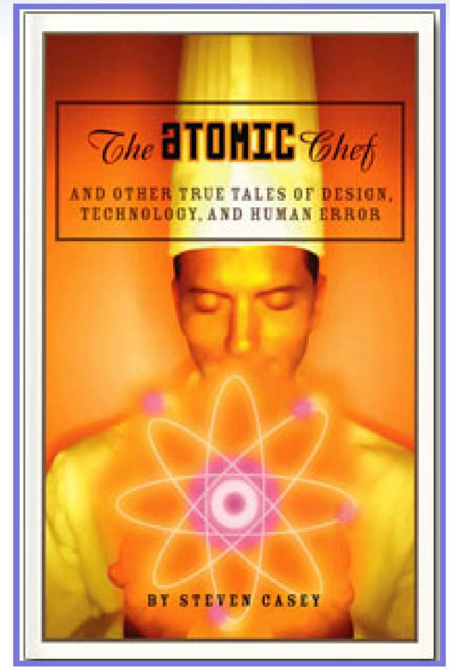
- Scientific discipline that applies knowledge about human abilities, characteristics, and limitations to design jobs, equipment, and environments
- A.K.A. ergonomics and human-centered design



Importance of Human Factors

- Reduced errors
- Usability
- Productivity
- Personnel satisfaction
- Safety





Structurally sound aircraft plummet to earth, ships run aground in calm seas, industrial machines run awry, and the instruments of medical science maim and kill unsuspecting patients, *all because of incompatibilities between the way things are designed and the way people perceive, think, and act.*

~Steven Casey, 1993

Human Factors Techniques

- Observation and task analysis
- Surveys and interviews
- Experimentation
- Assessment of workload and situational awareness
- Environmental measurements (illumination, noise, and temperature)
- Anthropometry (postures, forces, and load demands)
- Physiological measurements (heart rate, blood pressure)
- Analysis of records

Human Factors in the Complex

Organization	Contact	Phone
SNL/NM	Courtney Dornburg	505-284-1432
LANL	Walter Gilmore	505-667-2461
ORNL	Jack Schryver	865-574-4710
INL	Ronald Boring	208-526-0966
PNNL	Frank Greitzer	509-372-4251
BNL	John O'Hara	631-344-3638

BNL = Brookhaven National Laboratory; INL = Idaho National Laboratory; LANL = Los Alamos National Laboratory; ORNL = Oak Ridge National Laboratory; PNNL = Pacific Northwest National Laboratory; SNL = Sandia National Laboratories

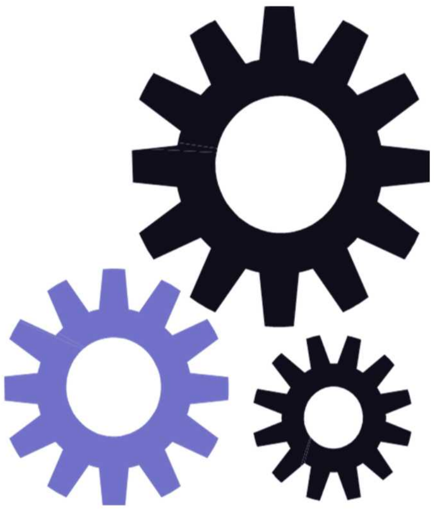
Human Factors for NCSP

- Fissile material operations represent a high-risk, high-consequence system
- Operations rely heavily on human involvement
  - Administrative controls require correct human action
  - Humans must read and interpret procedures
  - Humans execute the process
  - Humans bring a host of issues to work with them that can impact quality of work
- Review of 60 criticality accidents from 1953 to 1999 concluded that the *human element was not only present, but the dominant cause in all of the accidents* (LA-13638)

> ***Ensuring that a criticality accident never happens again in a DOE facility is one key facet of the DOE mission...***
>
> **~Mission and Vision for FY09-18**

Reliability Overview

- Probability that a system will perform its intended function satisfactorily.
- Equipment reliability
  - Hardware reliability
  - Software reliability
- Human reliability
  - Active failures
  - Latent conditions



Reliability in the Complex

Organization	Contact	Phone
SNL/NM	Stacey Hendrickson	505-284-2665
SNL/NM	Janet Sjulin	505-844-3902
LANL	Mike Hamada	505-667-1843
LLNL	Tom Bennett	925-422-5497
INL	John Forester	505-869-0238

INL = Idaho National Laboratory
LANL = Los Alamos National Laboratory
LLNL = Lawrence Livermore National Laboratory
SNL = Sandia National Laboratories

Reliability for NCSP

- Fissile material operations represent a high-risk, high-consequence system
- Reliability issues may have dire consequences
- Equipment must perform reliably
  - Vessels, valves, stirrers, dials, and switches
  - Generators, lighting, HVAC
  - Maintenance practices
- People must perform reliably
  - Adherence to administrative controls
  - Interpretation and use of procedures
  - Process execution
- Controls must be reliable

Part 2
Procedural Instructions

Presented by:

Kerstan Cole

Procedural Instructions

- Procedure is a tool that provides administrative control to help prevent hazards
- Effective procedures make the users' tasks as easy and straightforward as possible
  - Support different users and different users' tasks
  - Provide specific "how to" information
  - Provide only the content the user needs
  - Organize the content to match the users' tasks
  - Use layout, typography, and graphics that support user performance
  - Use clear and unambiguous language
  - Assure consistency and quality of human actions

Procedures

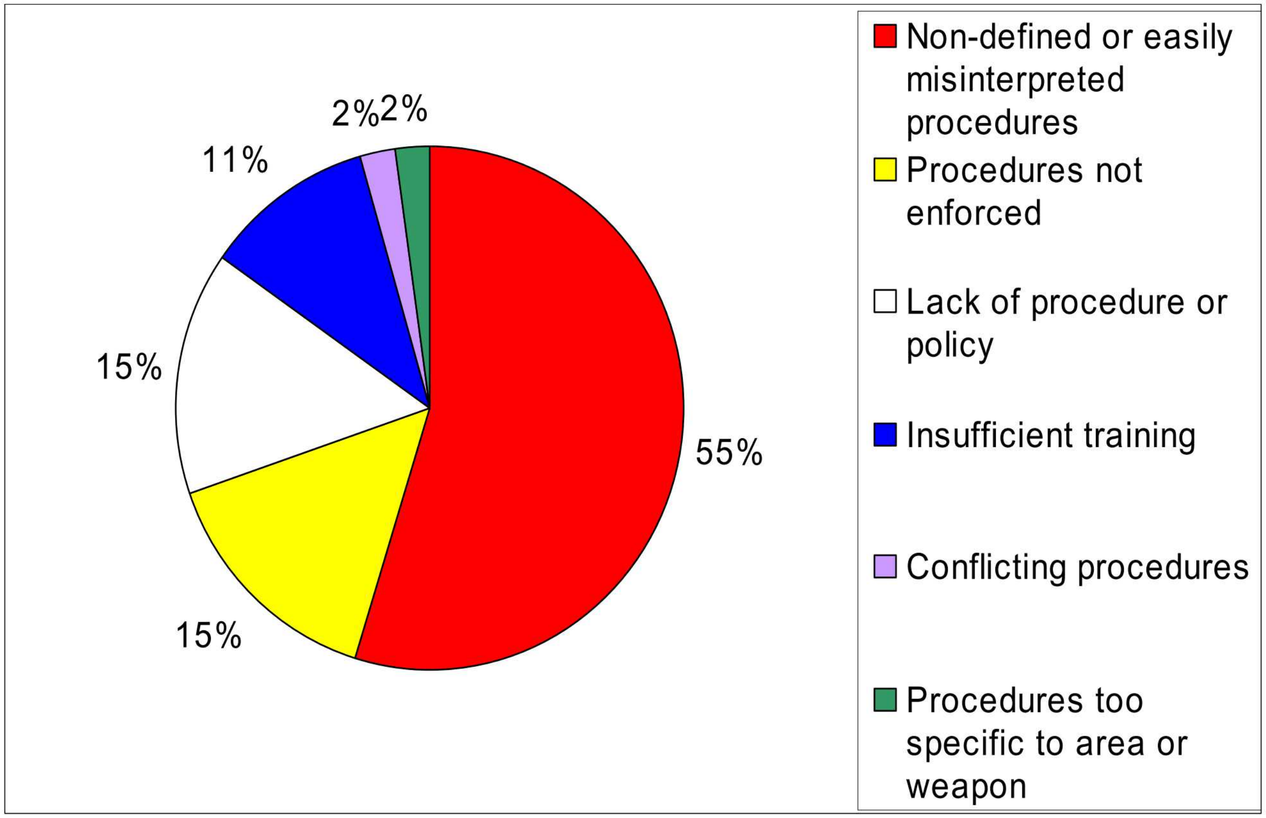
- ANSI/ANS-8.19, Section 7 discusses Operating Procedures
  - 7.1 The purpose of written operating procedures is to facilitate and to document the safe and efficient conduct of the operation. Procedures should be organized for convenient use by operators and be conveniently available. They should be free of extraneous material.
  - 7.2 Procedures shall include those controls and limits significant to the nuclear criticality safety of the operation. Procedures should be written such that no single, inadvertent departure from a procedure can cause a nuclear criticality accident.
  - 7.3 Supplementing and revising procedures as improvements become desirable shall be facilitated.

Common Issues in Procedures

- Ambiguous or vague steps
- Technically inaccurate information
- Mismatch between procedural steps and the order in which tasks need to be performed
- Critical information that is missing
- Lack of graphics for complex steps
- References to other procedures
- More than one instruction in a step
- Overuse of critical steps

Error Pathways from Procedures

- 526 of 1434 reported incidents (37%) at one DOE facility over a 13-year period from procedural issues
- Most issues involved vague procedures



From SAND2004-5416, *Human Error Mitigation Initiative (HEMI) Summary Report*

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SAFETY PROGRAM

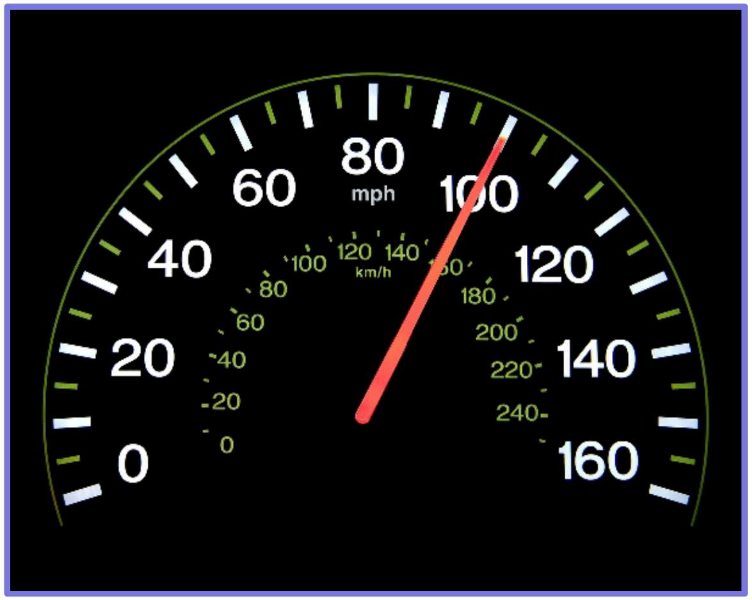
Part 3
Human-Machine Interface

Presented by:

Kerstan Cole

Human-Machine Interface

- Human-machine interface consists of displays and controls to assist in accomplishing a given task
  - Displays allow machines to convey information to humans
  - Controls allow humans to provide inputs to machines



Failure to understand the needs and requirements of the users will preclude effective design and increase the likelihood of use error, device misuse, and adverse events.

~Wiklund and Wilcox, 2005

HMI Potential Issues

- Poorly designed interfaces can result in errors because:
  - Not transparent to user
  - Violates user expectations/mental model
  - Hidden functions
  - No user testing/inadequate user testing
  - Require workarounds
  - No engineering controls (i.e., allows users to make mistakes through inputs)

Real World Example

- Multiple personnel at one DOE facility have inadvertently pressed the alarm button to call in armed guards when they really only wanted to exit the facility.

- These incidents occur because similar red buttons are used for different functions throughout the facility.

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Part 4
Attention

Presented by:

Kerstan Cole

- http://www.youtube.com/watch?v=IGQmdoK_ZfY
- http://www.youtube.com/watch?v=FWSxSQsspiQ

Attention

- Multiple studies similar to gorilla video
- ~50% of observers do not notice highly salient, ongoing, unexpected events
- Observers who do notice typically cannot accurately report details
- More observers notice unexpected events if the task is easy (number of passes) versus hard (separate counts of aerial and bounce passes)
- Observers may be more likely to notice if basic visual features are shared

> ***There is no conscious perception without attention.***
> ***~Simons and Chabris, 1999***

Selective Attention

- Concepts of selective attention and inattentional blindness apply to criticality safety evaluations
- What-if checklist is a common approach to identify potential criticality safety problems
  - What if something goes wrong?
  - Variations in parameters important to criticality safety
  - CSE may miss the gorilla in the process
- Subsequent development of controls may also be subject to inattentional blindness
  - CSE may attend heavily to one control to the exclusion of others
- Controls that take into account biases as well as limited attentional capacity are useful

Attention: Real-World Example

- On September 12, 2008, a freight train and a commuter train collided head-on in Chatworth, CA
- 25 people were killed
- National Transportation Safety Board determined that the commuter train engineer was distracted by text messaging wh the accident occurred

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Part 5
Reliability

Presented by:
Kerstan Cole

Reliability

- Conditional **probability**, at a given **confidence level**, that equipment will **satisfactorily perform** its intended function, given **predefined circumstances**
  - Operating environment
  - Limitations such as operating time
  - Frequency and thoroughness of maintenance
  - Specified period of time
  - Failure data often have a large degree of uncertainty!
- Reliability and safety of a process can be impacted by two components of reliability
  - Equipment reliability (hardware and software)
  - Human reliability

Equipment Reliability

Equipment is not 100% reliable

Component	Failures Per Million Hours
Switch - Toggle	1
Switch - Pushbutton	10
Valve - Globe	2
Valve - Gate	30
Differential Pressure Sensor (flow meter)	200
Generator – Diesel Set	4000

From *Reliability, Maintainability, and Risk* by David J. Smith (2005)

Causes of Equipment Failures

Infant Mortality	Random Failures	Wearout Failures
Poor manufacturing	Conflict in designed strength and operational stress	Aging
Poor quality control	Insufficient designed-in safety factors	Wear
Poor workmanship	Higher than expected loads	Degradation in strength
Insufficient burn-in	Lower than expected strengths	Fatigue
Substandard materials	Human error in usage	Creep
Improper storage/transit	Misapplication	Corrosion
Contamination	Abuse	Mechanical, electrical, or chemical

From *Reliability Engineering Handbook, Volume 1* by Dimitri Kececioglu (2002)

Equipment Failure Example

- Operations were suspended this week when an incorrectly installed lifting and rotating fixture containing a unit prevented subsequent steps from being performed. The lifting fixture was 180 degrees out from its procedurally required position and thus could not be loaded into the transportation cart. The lifting fixture is used on several weapon programs. This is another example of tooling that is not designed to preclude improper installation.

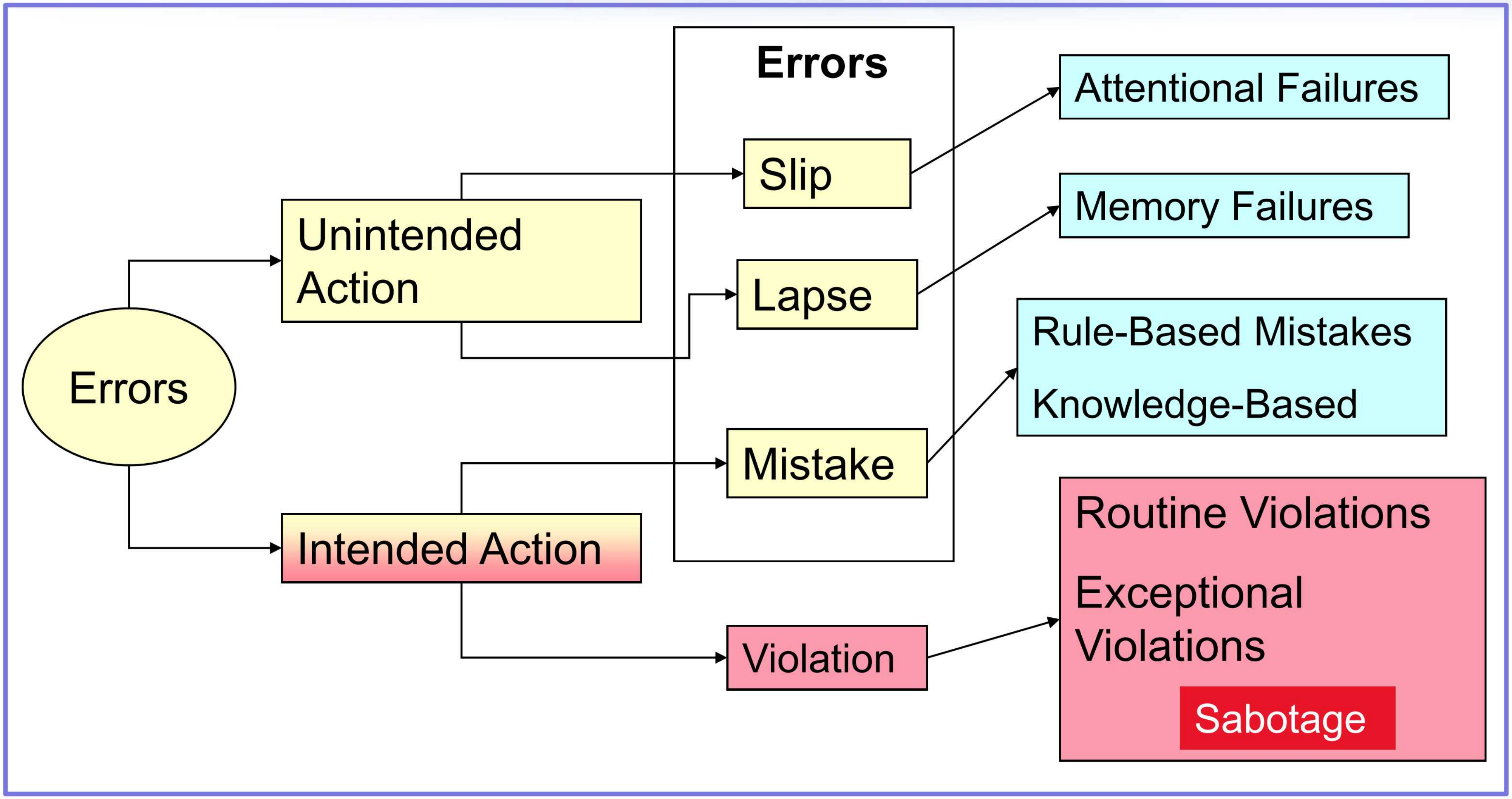
DNFSB Weekly Report (April 15, 2005)

Human Reliability

Probability that an individual, team, or human organization will accomplish a mission under the given conditions, within acceptable limits, for a certain duration.

Traditional View	Human Factors View
Human error is inevitable and little can be done to prevent human error	Human is reliable in certain conditions, and performance is predictable
Explanation of failures: find people's inaccurate assessments, wrong decisions, and bad judgments (blame)	Explanation of failures: discover how people's assessments and actions made sense under the given circumstances
Causes: carelessness, poor attitudes, and inattention to detail	Causes: increases in system complexity and ambiguity in external systems
Cures: training and punishment	Cures: manage causes of error

Human Reliability



People cannot easily avoid actions they did not intend to perform in the first place.

Human Reliability

Error Type	Description
Slip	• Person does something, but not what they intended • Poor display-control compatibility or deviation from routine • Fixed by better displays/controls • Example: uranium recorded as 8 liters instead of 18 liters
Lapse	• Person forgets to do something they intended to do • Caused by failure of prospective memory • Fixed by checklists, procedures, explicit reminders • Example: forgetting to close a valve
Mistake	• Person does what they intended, but act is inappropriate • Caused by lack of knowledge • Fixed by training to improve knowledge or better displays • Example: turning right but did not see one-way street sign
Violation	• Person intentionally commits an inappropriate act • Caused by inadequate safety culture • Fixed by emphasis on safety culture or remedial training • Example: intentionally ignoring uranium mass limit

What caused the failure?

- During operations on Monday, a procedural step was misread and technicians removed the wrong piece of tooling from the unit.

DNFSB Weekly Report (April 15, 2005)

What caused the failure?

- Two plumbers were removing the coupling from what they believed to be a depressurized and drained fire sprinkler water supply pipeline. As they loosened the two bolts on the pipe coupling, hydraulic fluid under pressure sprayed out. The pipeline from what they were removing the coupling was actually a hydraulic fluid supply pipeline for a nearby elevator. Both the fire sprinkler water supply and hydraulic fluid supply pipelines and couplings were identical and unlabeled, and were adjacent to each other.

ORPS report (2010)

Human Reliability: Improvisation

- Improvisation occurs when well-meaning personnel attempt to complete tasks with minimal disruption and delay in the absence of sufficient guidance/materials
- Improvisation may be classified as mistakes or violations

Reliability and Controls

- Controls are methods designed to eliminate or reduce hazards
- Engineering controls are more reliable than administrative controls
- Engineering controls eliminate hazard through system design – about 90%+ effectiveness
- Administrative controls use procedures or training to reduce hazards – about 50% effectiveness
  - Redundant administrative controls often necessary
  - Effort to ensure administrative controls work

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Part 6
Summary and Application

Presented by:
Kerstan Cole

Summary and Application

- Fissile material operations are high-risk and high-consequence operations that rely heavily on humans
- Human factors issues have played a major role in previous criticality accidents
  - Procedural Instructions
  - Human machine interface (usability)
  - Attention
  - Reliability (equipment and human)
- **Where do these issues apply to your operations?**

Understanding basic human factors/reliability principles and establishing controls to prevent common human factors issues helps ensure that a criticality accident will never happen again.

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NUCLEAR CRITICALITY SAFETY PROGRAM

Part 7
Examples and Discussion

Presented by:
Kerstan Cole

Example 1

- In one facility, an incident occurred because fissile material was being weighed and was left unattended on a balance.
  - Criticality Safety Limit Approval requires that specified fissile material “must be staged” individually in a container with an insert
  - During conditions that are considered “safe and stable,” workers can walk away from the material.
  - However, the procedure was unclear as to whether this staging condition was considered “safe and stable.”

- An oversight person noticed an item on the balance inside a glovebox with no one physically attending to the item and reported the incident.
  - Operators felt that they were working within their procedure.
  - The CSO agreed with the operators.
  - Employees believed that “staging” referred to a longer-term set up and that they didn’t have to stage every time that they walked away to complete other shorter term tasks

Discussion Questions: Example 1

- What were the factors that contributed to the incident described in the previous example?
- Why did the workers in this example deviate from the procedures? What are other reasons that people may deviate from procedures?
- What are the human limitations and capabilities that are associated with the previous example?
- Have you seen incidents like this at your facility?
- How could incidents like these be prevented in the future?

Example 2

- An incident occurred because a Material At Risk (MAR) limit was exceeded.
- Workers were using a database that contained the MAR limits.
  - However, the database did not alert them when the MAR was exceeded.
  - They were also using a procedure to complete their work.
    - This procedure only contained the criticality safety value
    - Workers thought that the MAR limit was the same as the criticality safety value

Discussion Questions: Example 2

- What factors contributed to the incident described in the previous example?
- What type of error was made (e.g., knowledge-based, rule-based, slip, lapse, violation)? How do you know?
- How could the interface be improved to support the workers?
- Are there poorly designed interfaces that you currently use? If so, how would you improve them?
- How could incidents like these be prevented in the future?

Example 3

- An incident occurred because the plastic bags used for contamination control exceeded the volume allowed for criticality safety
  - Workers obtained plastic bags from the warehouse in order to control contamination, a radiological safety requirement
    - However, in order to meet the criticality safety requirement, a maintenance procedure specified that 1 gallon bags should be used
    - The warehouse only stocked 1.4 gallon bags
    - Workers did not check the volume of the bags before they started work
  - Later, a supervisor determined that the volume of the plastic bags was 1.4 gallons rather than 1 gallon and reported the incident

Discussion Questions: Example 3

- What factors contributed to the incident?
- What role did the warehouse play in this incident? The workers? Management?
- What type of error occurred (e.g., knowledge-based mistake, rule-based mistake, slip, lapse, violation)? How do you know?
- Have you seen similar incidents in your facility?
- How could incidents like these be prevented in the future?

Example 4

- An incident occurred because the water level on a sight glass exceeded the required level
  - A procedure specified that the water level on a sight glass for a pencil tank did not rise above a particular level
  - Workers were expected to continuously monitor the sight glass while performing the other tasks
  - While they were performing their other tasks, the water level rose above the specified level in the procedure.
  - Workers recognized this as an abnormal condition and paused work
  - An incident was reported

Discussion Questions: Example 4

- What factors contributed to the incident described in the previous example?
- How is the requirement “to continuously monitor the sightglass” while performing other tasks representative of an inherent human limitation?
- How would you rewrite the procedure to more appropriately support the workers?
- Have you seen incidents like this in your facility?

Example 5

- Workers continually refilled a limited volume system from an unlimited volume source resulting in an incident
  - There were indications that there might be a leak into the glovebox
  - Workers did not consider the indications of a leak into the glovebox as an “unusual condition”
  - So, they troubleshooted by tightening a fitting and subsequently added 1-2 gallons of water to a limited volume circulating chilled water system from the positive pressure unlimited source
  - The same workers kept refilling the system every day because the water level kept receding

Discussion Questions: Example 5

- What factors contributed to the incident described in the previous example?
- What type of error did the workers make (e.g., knowledge-based mistake, rule-based mistake, slip, lapse, violation)? How do you know?
- What cues could the workers have relied on to determine whether the conditions they were experiencing represented something “unusual”?
- What two criticality parameters were affected by the change in process conditions in the previous example? Could this have resulted in a criticality accident?
- How can incidents like these be prevented in the future?

Example 6

- A LVCCWS did not meet criticality safety requirements
  - The system was limited to 4L of water but actually held more than 4L
  - The supervisor was required to verify that the system met the requirements before use
    - Supervisor did not do this because other systems in the facility always met the requirements

Discussion Questions: Example 6

- What factors contributed to the incident described in the previous example?
- Could this have resulted in a criticality accident? Why or why not?
- What type of error did the supervisor make during this incident (knowledge-based, rule-based, slip, lapse, violation)?
- Have you seen incidents like this at your facility?
- How can incidents like these be prevented in the future?

Module 05

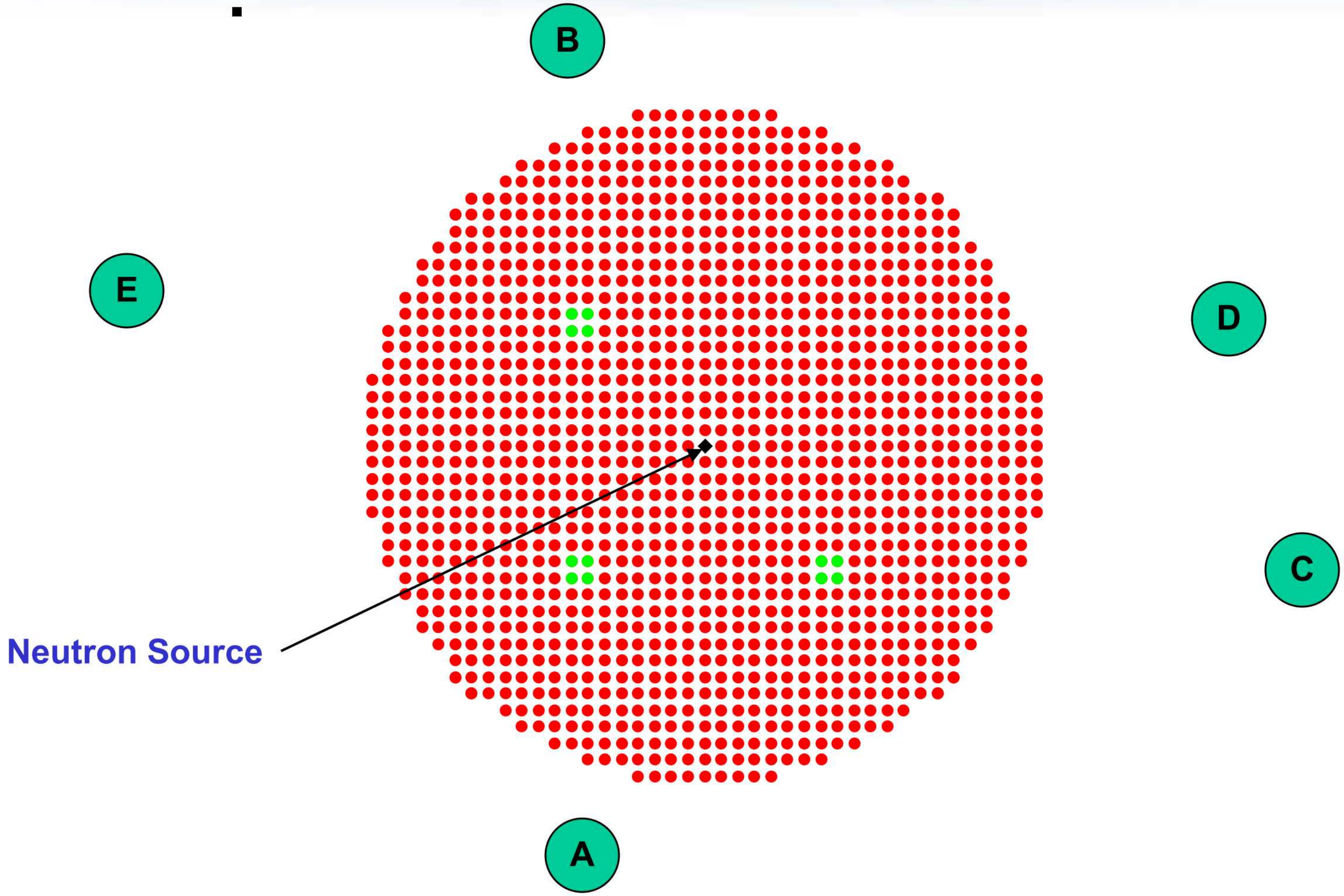
Experiment 1
Approach to Critical on Fuel Loading

Presented by:
Gary Harms

Experiment 1 Overview

- We will do an approach-to-critical experiment by loading fuel into the assembly
- This is the way we normally perform experiments
- Criticality safety parameters that are in play:
  - Mass
  - Moderation
  - Reflection
  - Absorption
- Application to criticality safety:
  - What happens when the number of fuel lumps in an array increases?
- This is the process used in most experiments that are used to calibrate the analysis methods used in criticality safety
  - The array size is the variable in this experiment

Core Loading Experiment Configuration 1

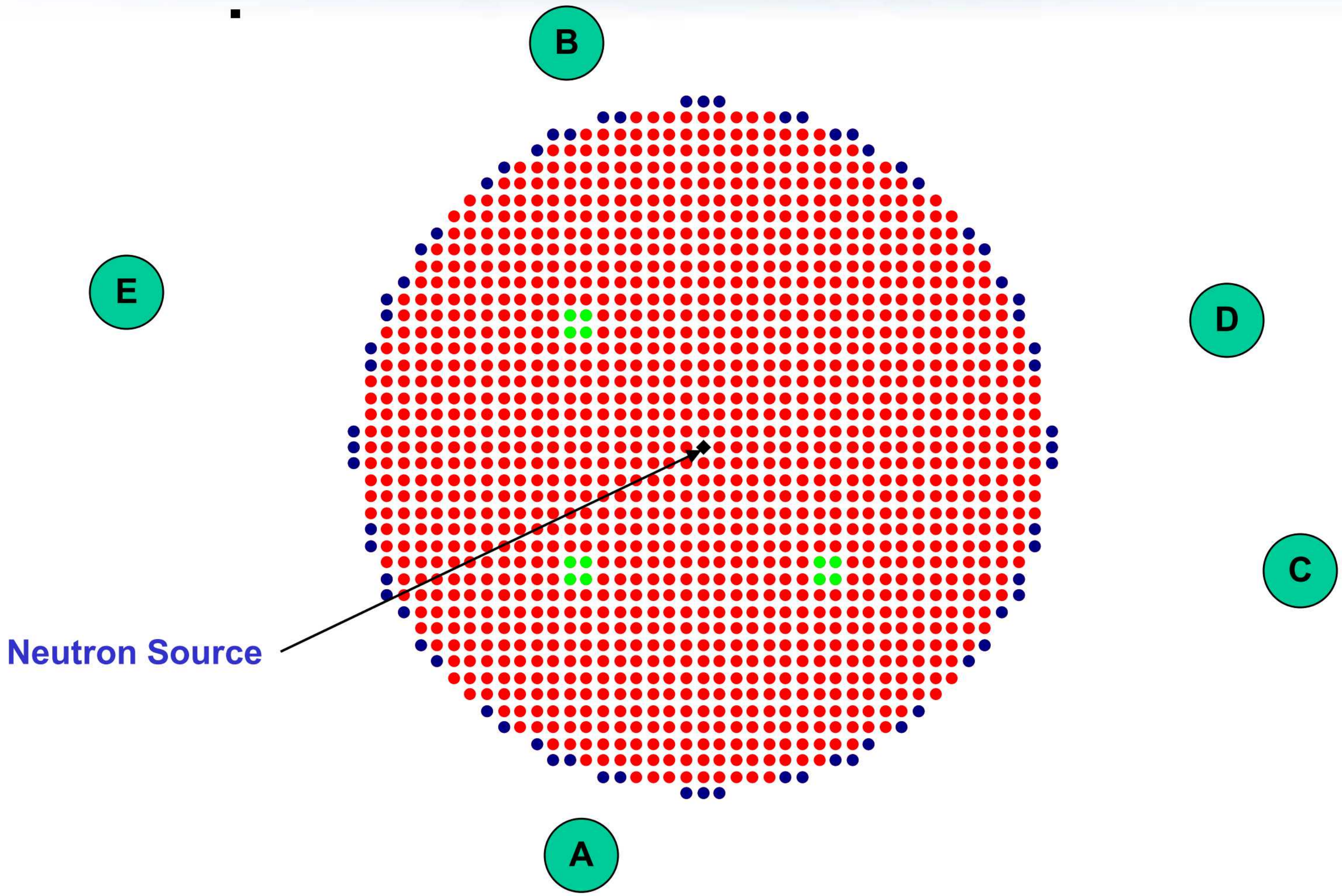


Fuel Rods: 1320

k ~ 0.98

X = Fission Chamber

Core Loading Experiment Configuration 2

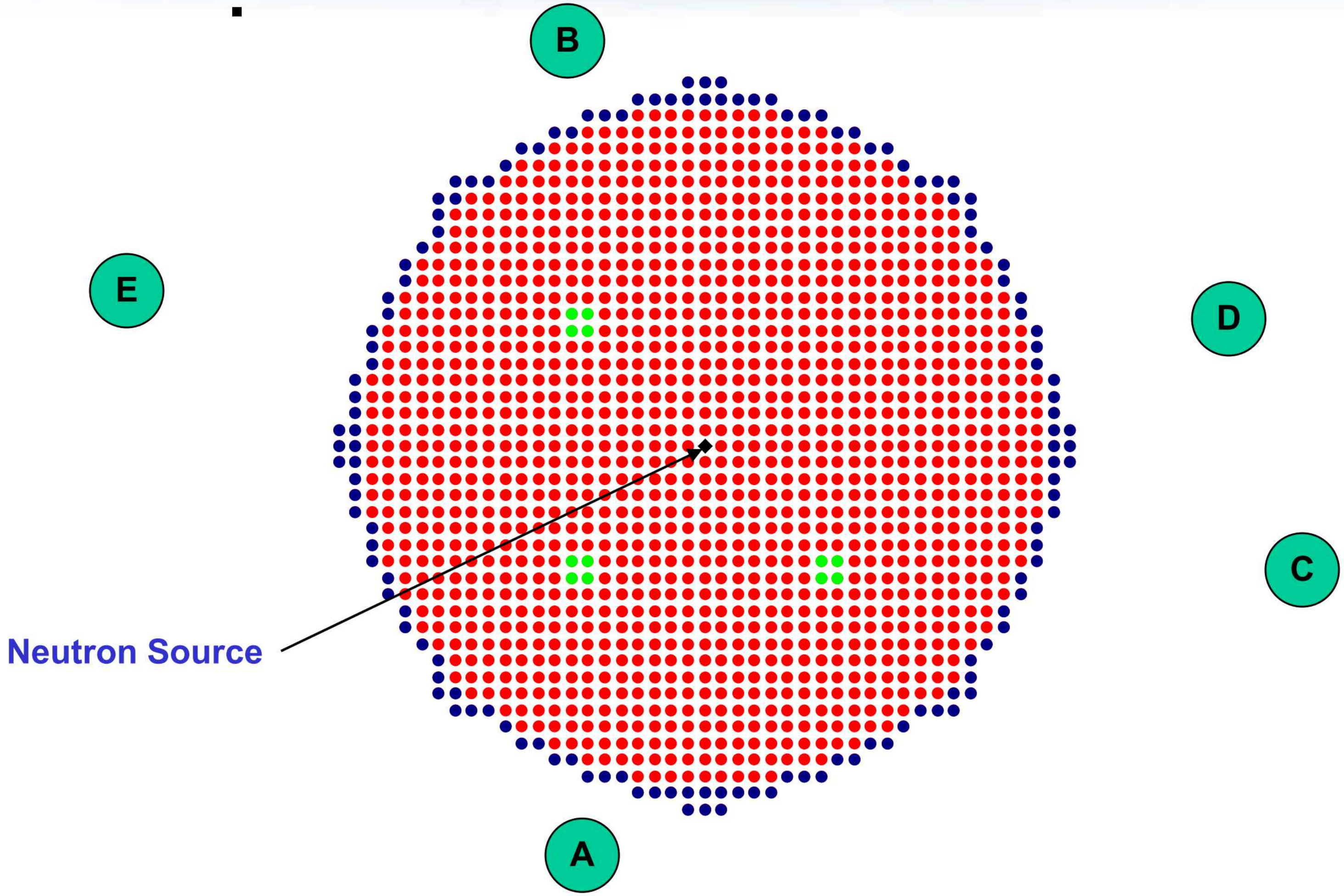


Fuel Rods: 1388

k ~ 0.99

X = Fission Chamber

~Critical Core Loading



Fuel Rods: about 1460

k ~ 1.00

X = Fission Chamber

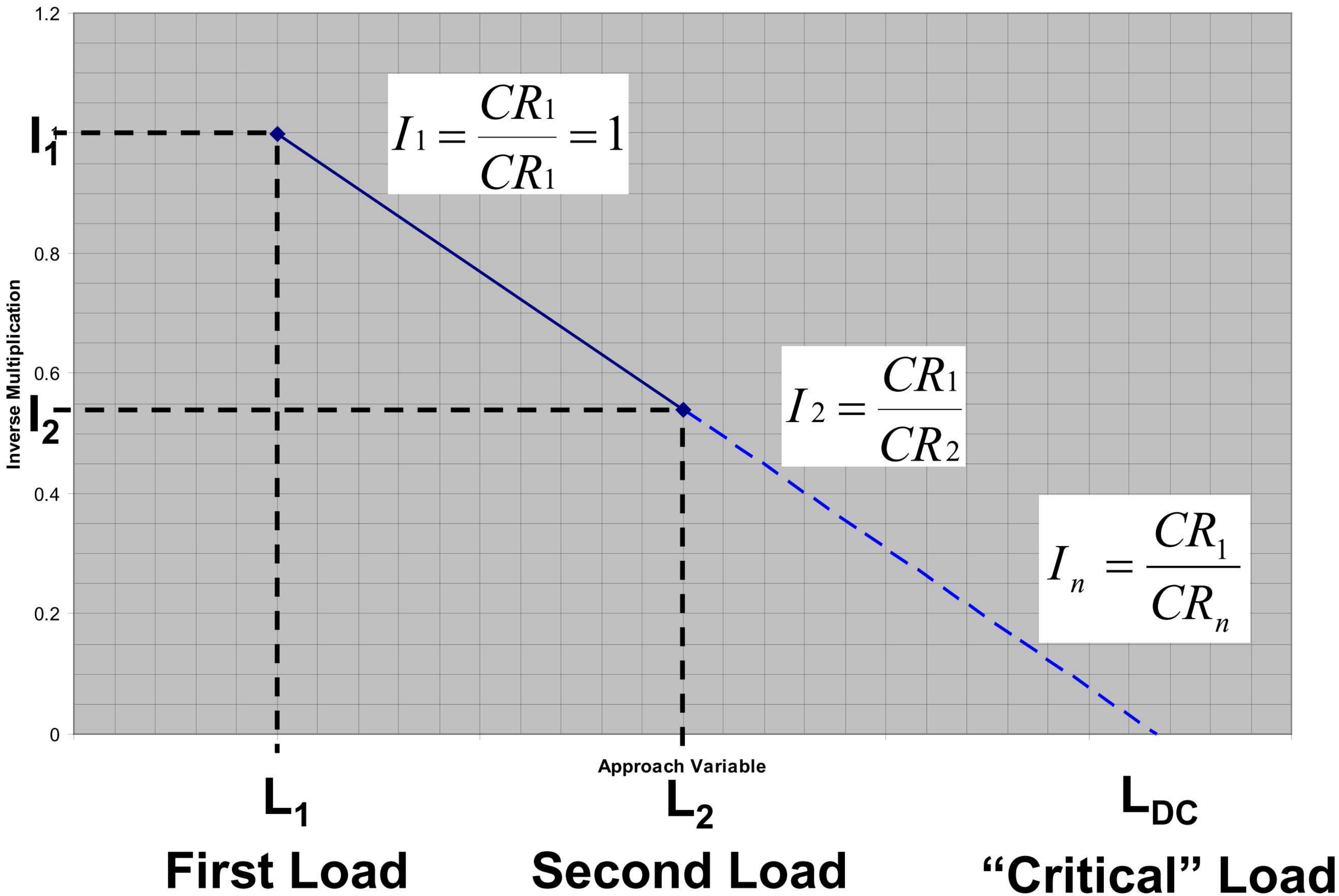
Mechanics of the Experiment

- The number of fuel rods in the core will be changing
- The fuel configurations will be guided by the count rates
- The class will sort the fuel rods and pass them to the operations staff
- The operations staff will place fuel rods in the core
- The minimum fuel increment will be eight rods

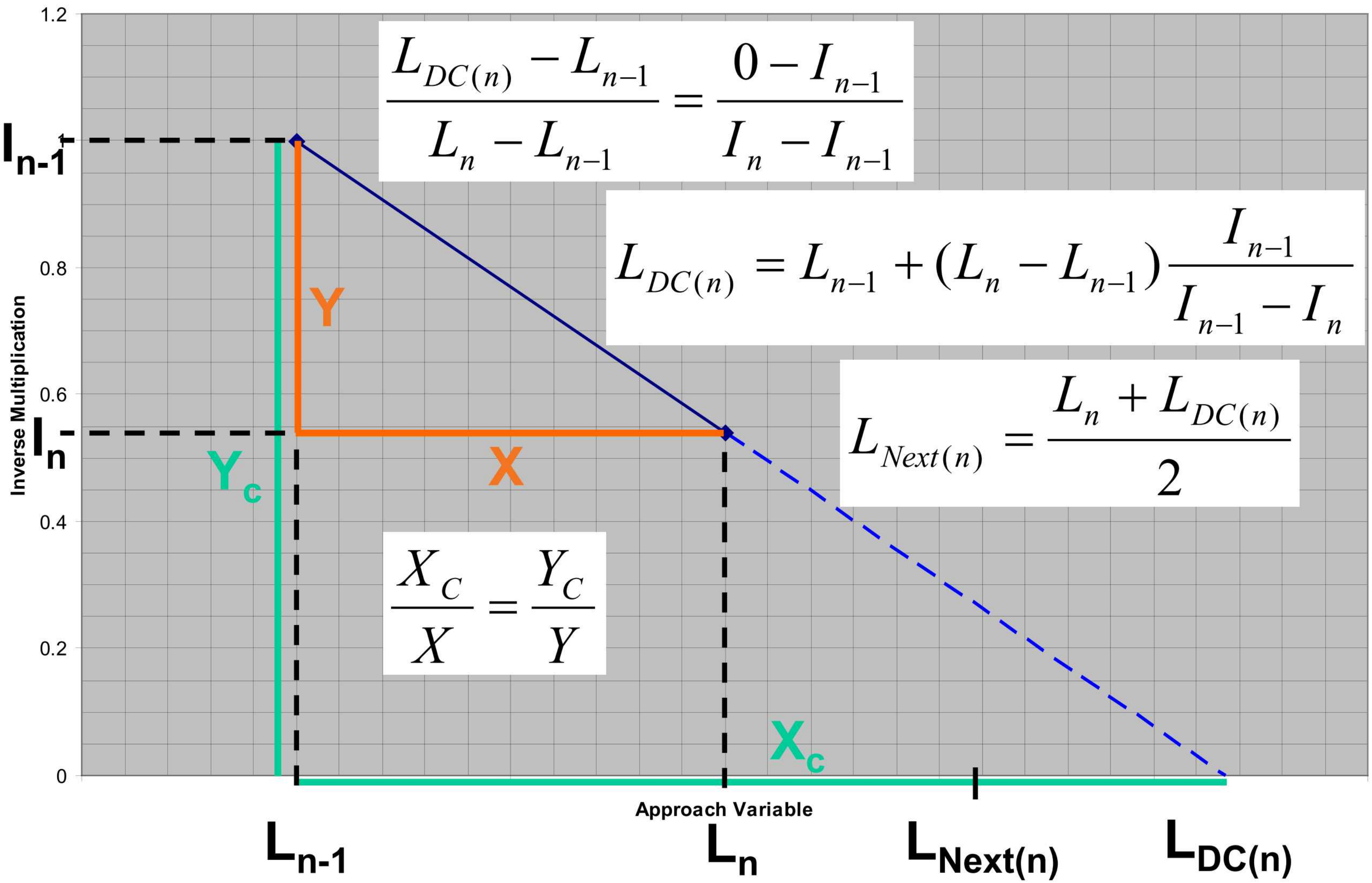
The Experiment Process

- The desired fuel rod array will be loaded
- The safety rods will be “cocked”
- The reactor room will be cleared
- The core tank will be filled with water
- The control rod will be raised – this puts the assembly in its most reactive condition in this operational mode
- Counts will be taken
- The core tank will be drained
- The control rod will be lowered
- The safety rods will be dropped
- The next fuel increment will be determined from the count rates
- The reactor room will be opened
- Loop back to the first step on this page

Determining the Next Fuel Increment



Determining the Next Fuel Increment

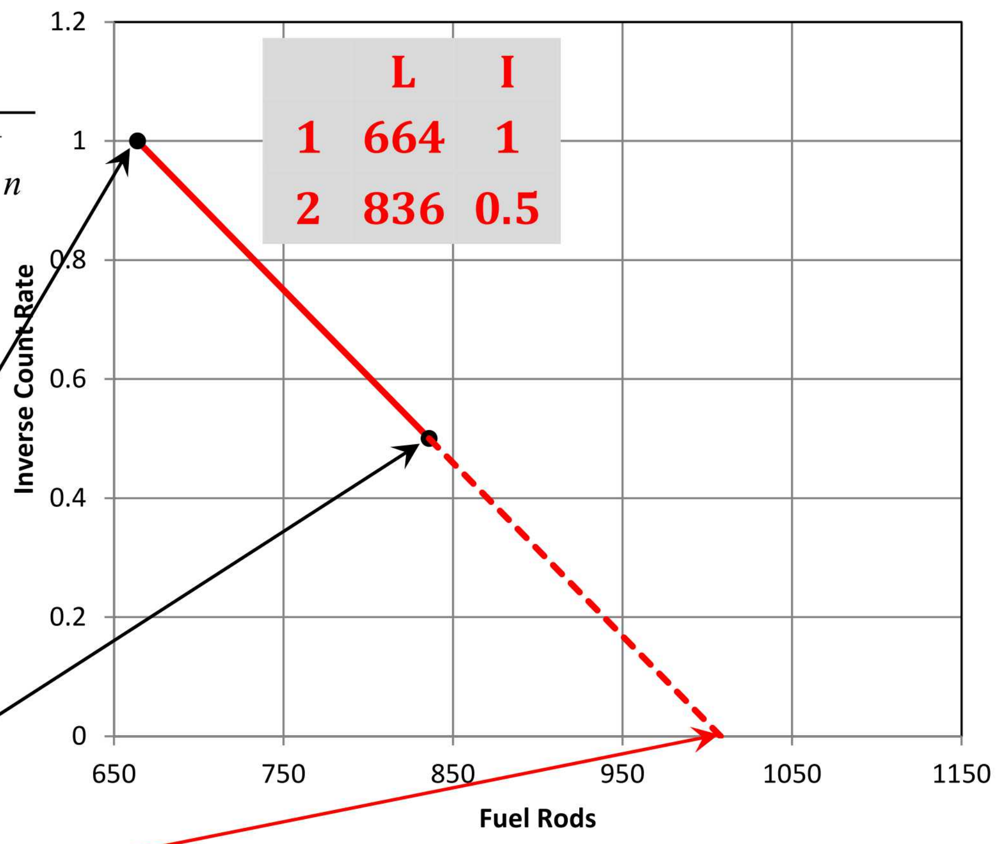


Constructing an Inverse Count Rate Plot

$$L_{DC(n)} = L_{n-1} + (L_n - L_{n-1})\frac{I_{n-1}}{I_{n-1} - I_n}$$

$$I_n = \frac{CR_1}{CR_n}$$

Fuel Rods (L)	Count Rate	Inverse Count Rate (I)	Projection (L_{DC})
664	1000	1	
836	2000	0.5	1008
922	3333	0.3	1051
987	5000	0.2	1117



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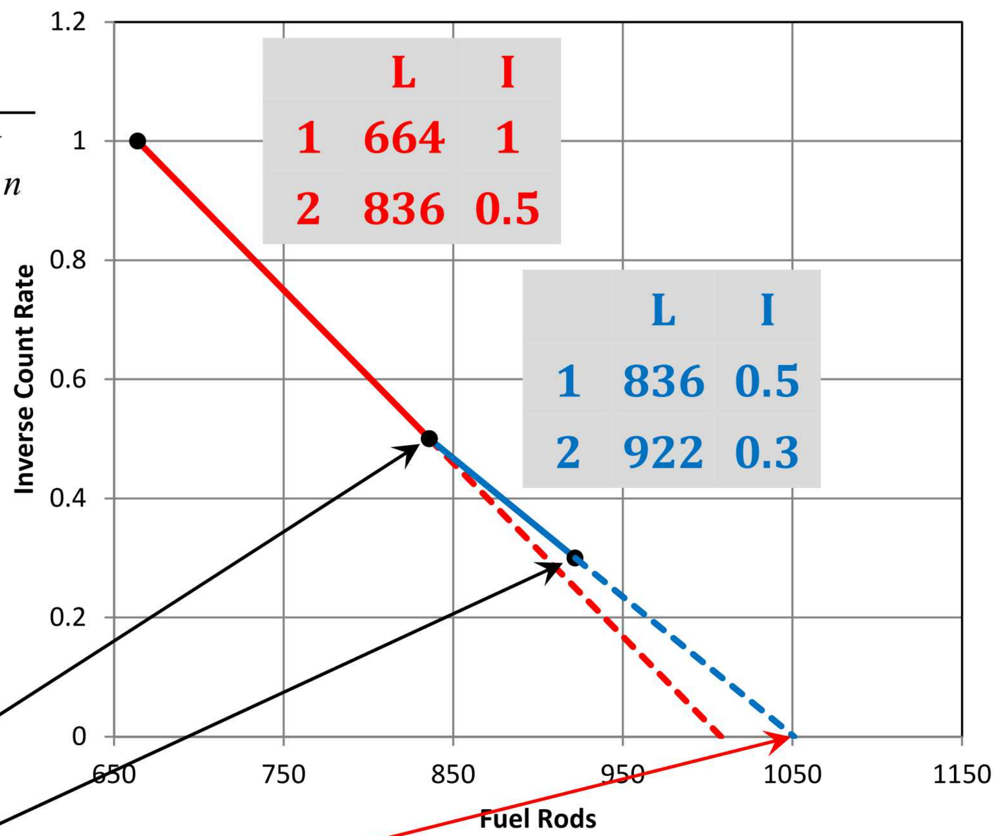

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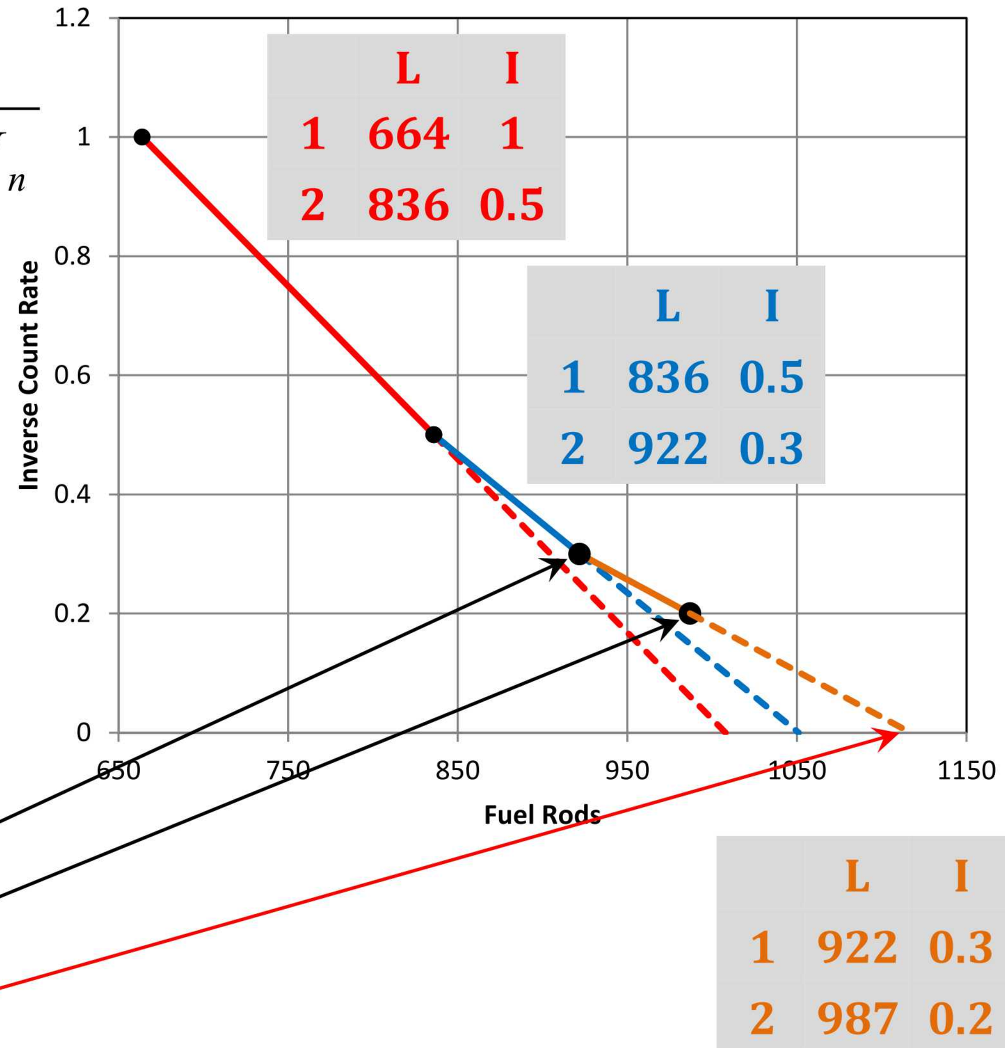
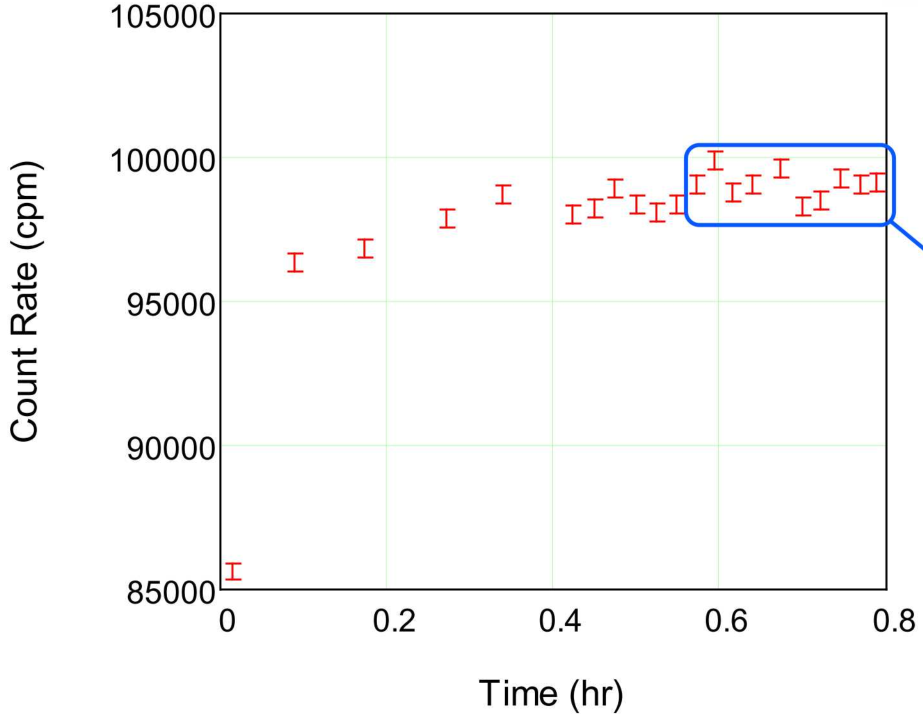
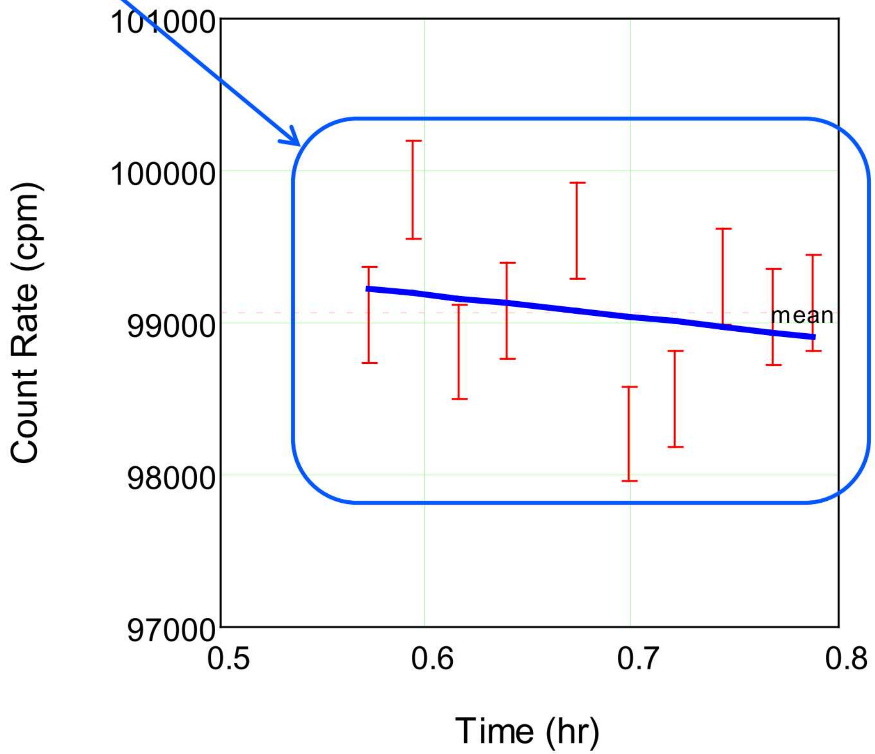


How do we know if the count rate is stable?



For a detector giving a reading of N counts, the uncertainty in the reading is √N
Looking at the last 10 measurements:



Look at the mean value – between 6 and 7 error bars should touch the mean (it's a random process – could be more or less . . .)
Look at the slope of a linear fit to the data – is it "relatively flat?"
For our experiments, count until you see the value drop, then take a few more counts.

Pre-Job Brief

- The operations folks will brief you on the hazards of the experiment

Conduct of Operations

Universal Concepts for Excellence

November 2014

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CR Richardson, LANL MET-DO
Unclassified and Not UCNI
11/19/14

LA-UR-14-29074

UNCLASSIFIED

Conduct of Operations

- Conduct of Business
- Formality of Operations
- Formality of Business

Conduct of Operations

A rose by any other name still smells good.

What do you call it?

Conduct of Operations

Can be defined as…

Effective implementation
and control
of normal everyday activities.

Conduct of Operations

Why follow Conduct of Operations?

First, because it is the law!

In June of 2010, DOE Order 422.1, *Conduct of Operations*, superseded DOE Order 5480.19 and was added to the Laboratory contract in January of 2011.

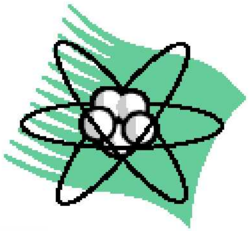
Conduct of Operations

Has helped the nuclear industry (since mid-80s) achieve

- Exemplary record of safety,
- Reduced liabilities
- Reduced regulatory oversight

With the following results

- Keeps plants running at high capacity factor,
- Keeps electricity costs low



Conduct of Operations

P315, The Conduct of Operations Manual, is the main document driving implementation at LANL.

Other implementation documents include:

- Implementing Formality of Operations
- Roles, Responsibilities, Authorities, and Accountability
- Management Observation and Verification

Conduct of Operations

Contrary to popular belief, Conduct of operations does not apply only to Operators.

According to P-315, *Conduct of Operations Manual*

"This document applies to all Laboratory workers (e.g., employees, subcontractors, and other assigned personnel) performing facility or programmatic work, in integration with Integrated Work Management and other institutional program and system requirements referenced by this document."

Conduct of Operations

- Reliable performance of activities and daily operations
- A culture…
  - **it is the way you present yourself to your internal and external customers**
  - **your customers perception of you**
  - **a sense of pride and accomplishment**

Conduct of Operations

Consistent performance

- Human performance can be highly variable, and that variability can lead to inefficiencies, errors, and incidents
- Incidents most often are near misses which are pre- cursors to more serious accidents, but less frequently, the serious accidents themselves.

Conduct of Operations

A “Control System" for human performance

– **Even “Highly Disciplined” people doing everyday activities make “Honest Mistakes”**

– **ConOps provides layers of protections such that an honest mistake has minimum consequences**

Conduct of Operations

A Systematic Approach to doing daily business

- **Establish a sound "Lessons Learned" Program**
  - **Taking actions to prevent reoccurrences**
- **It is "Self-Assessment"**
  - **Routinely looking "Critically" at yourself**

Conduct of Operations

The protection of the Safety Envelope

- **It is rigor in normal performance**

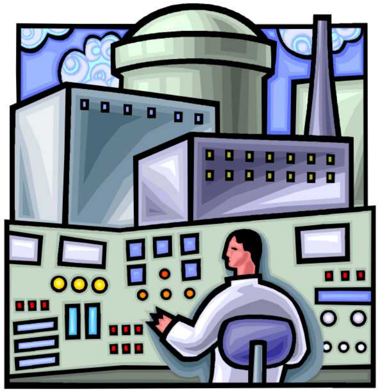
- **It permits human intervention in abnormal situations**

- **It controls activities within the desired safety envelope**

Conduct of Operations

Disciplined Professionals

- It **encourages and supports a culture of "disciplined professionals",** which is paramount to establishing a sound safety culture



UNCLASSIFIED

Conduct of Operations

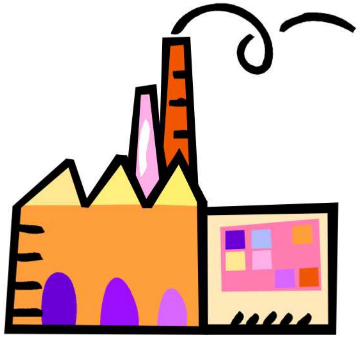
- The implementation of Integrated Safety Management
- The implementation of Safe Work Practices
- The implementation of the Integrated Work Management Process

Conduct of Operations

Saying what you are going to do!!

and

Doing what you said you were going to do!!



Conduct of Operations

A Continuous Improvement Process

- Many before have doubted the worthiness of the program but have experienced the benefit after going through the process
- Experienced significant increases in
  - Safety
  - Productivity
  - Performance

Conduct of Operations

Experience has shown that the better operating organizations

- control the activities by having well-defined and effectively administered policies and programs

This concept improves performance indicators by:

- Reducing cost, down time, rework, occurrences
- Improves safety, quality, productivity

What's In It For Me?

- Improved Personnel Safety
- Increased Personal Productivity
- Feeling Good about what you do

Conduct of Operations

- Different approaches or methods may be used based upon:
  - Analyzed Hazards
  - Perceived Risk
  - Activity Duration

Conduct of Operations

The intent of the process must be implemented

"Graded" <u>Does Not Mean</u> "Non-Existent"

Conduct of Operations

Implementing conduct of operations uses three principles

- You Cannot Tell What is Wrong If You Don't Know What is Right

- Experience Is A Good Teacher

- What one Does Speaks Louder Than What One Says

Conduct of Operations

- Identify the work (i.e. study your operations)
- Identify the Hazards
  - Rank highest to lowest risk
- Identify mitigation methods
  - Hardware, Personnel, Training, Processes and Procedures
  - Prioritize based on cost/benefit
- Implement proven mitigation & operational methods
  - Straightforward and cost/beneficial
- Document what you did to show due diligence
- Periodically review your status or when an abnormal event occurs
  - Continuously improve

Conduct of Operations

Who better to make it happen than "YOU"?

Questions?

Module 07

Experiment 2
Approach to Critical on Moderator Height

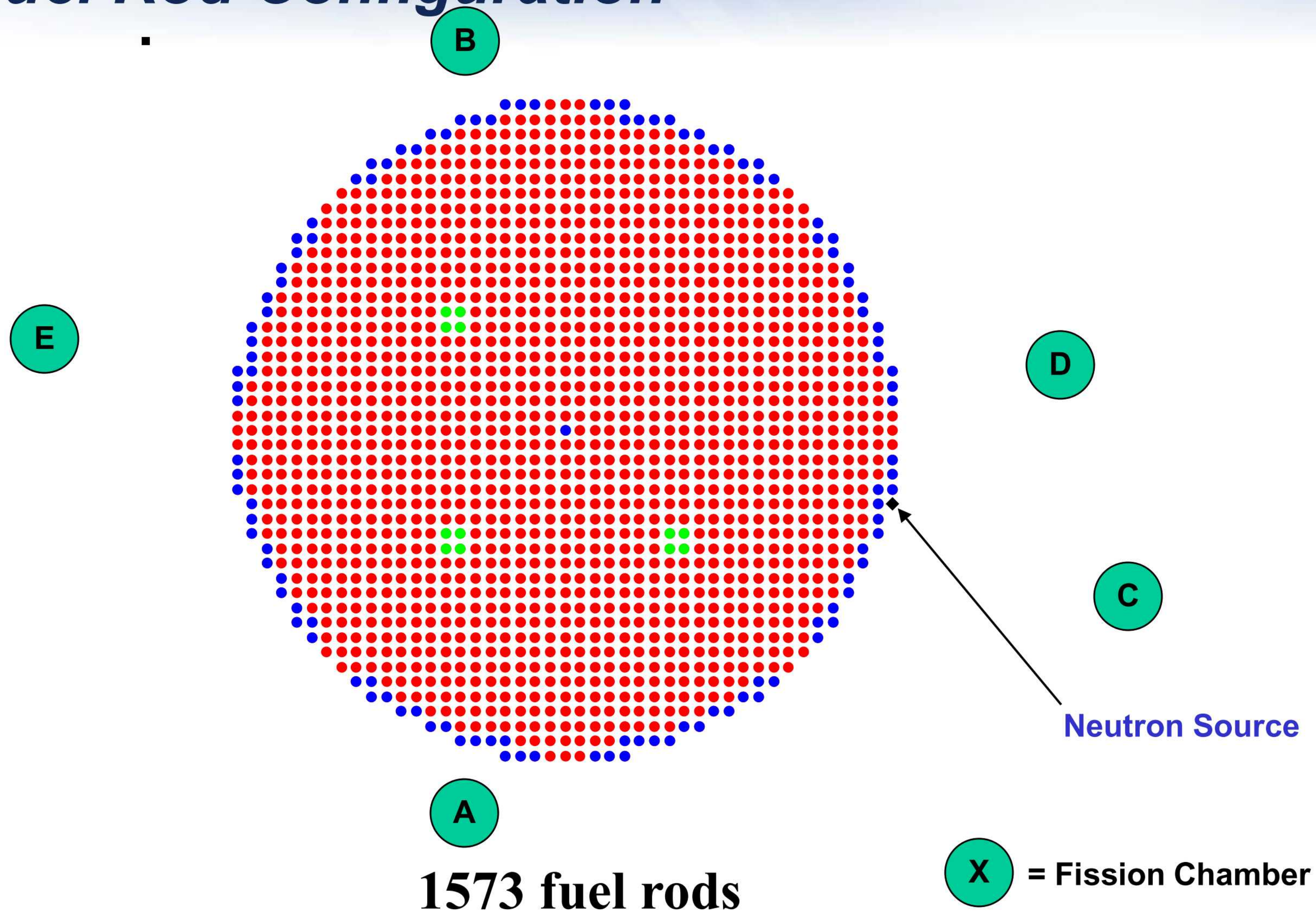
Presented by:
Gary Harms

Experiment 2 Overview

- We will do an approach-to-critical experiment by increasing the moderator height in the assembly
- Criticality safety parameters that are in play:
  - Moderation
  - Geometry
  - Absorption
  - Mass

- Application to criticality safety:
  - What happens to an array that becomes flooded?
- This is the process used in most experiments that are used to calibrate the analysis methods used in criticality safety
  - The depth of the water in the tank is the variable in this experiment

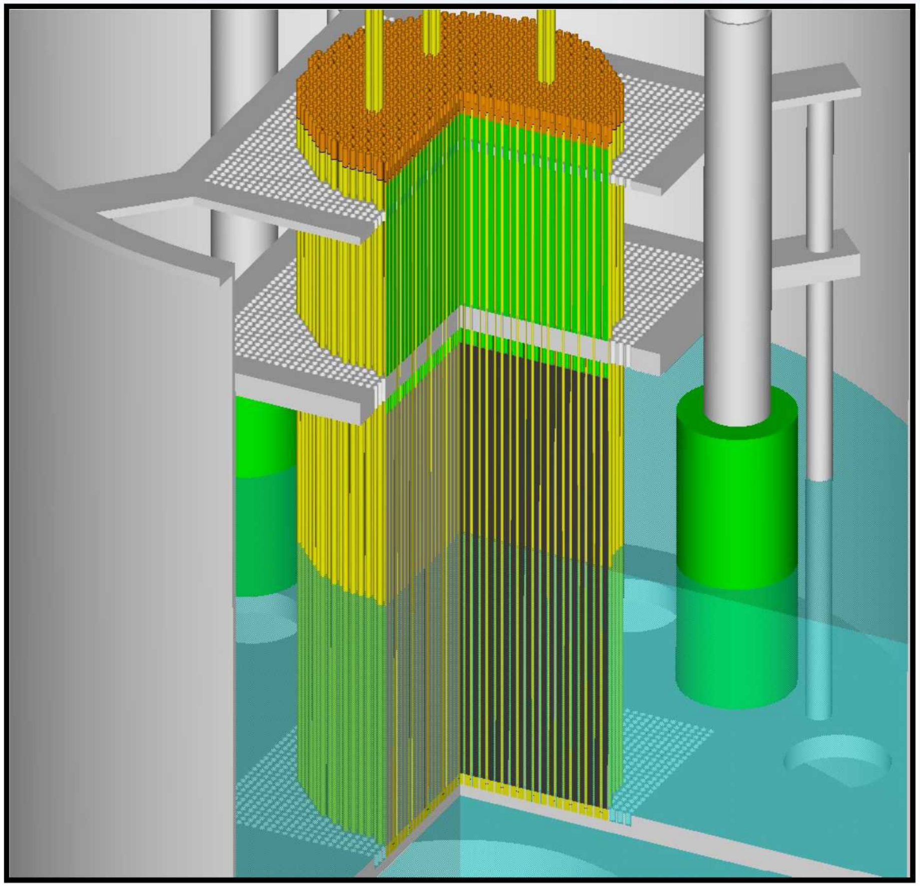
The Fuel Rod Configuration



1573 fuel rods

The blue rods are the difference from yesterday's critical array

Moderator Height Experiment Configuration 1

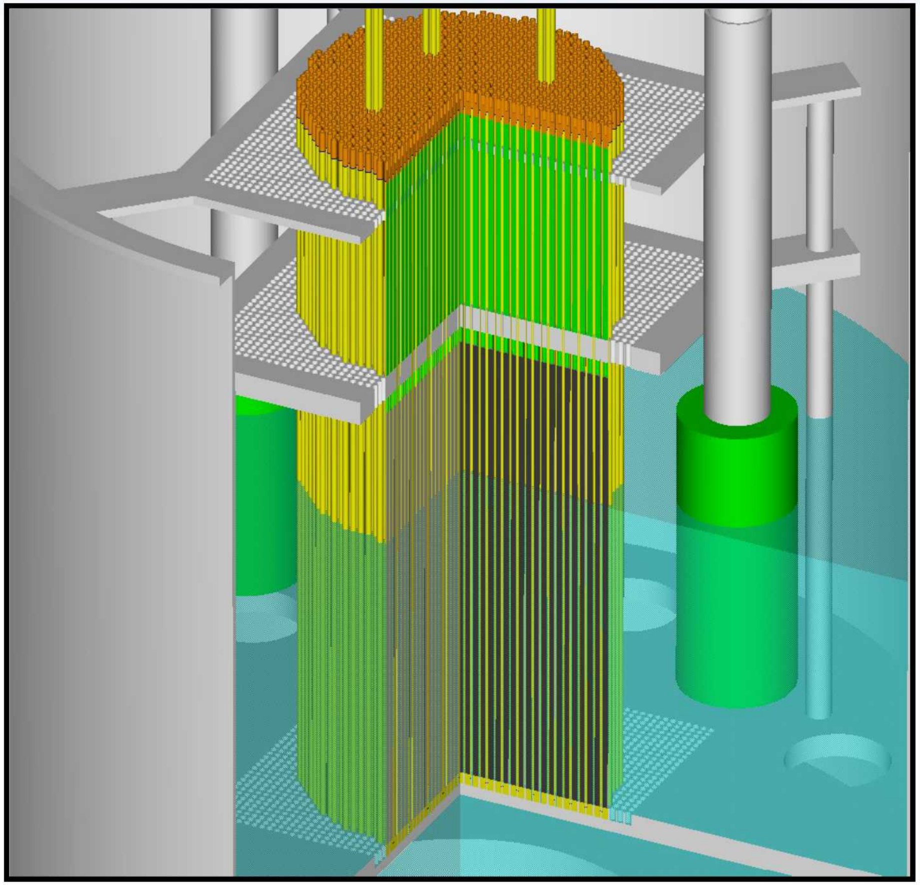


Fuel Rods: 1573

k_{eff}: ~0.90

Water Depth: 274 mm

Moderator Height Experiment Configuration 2

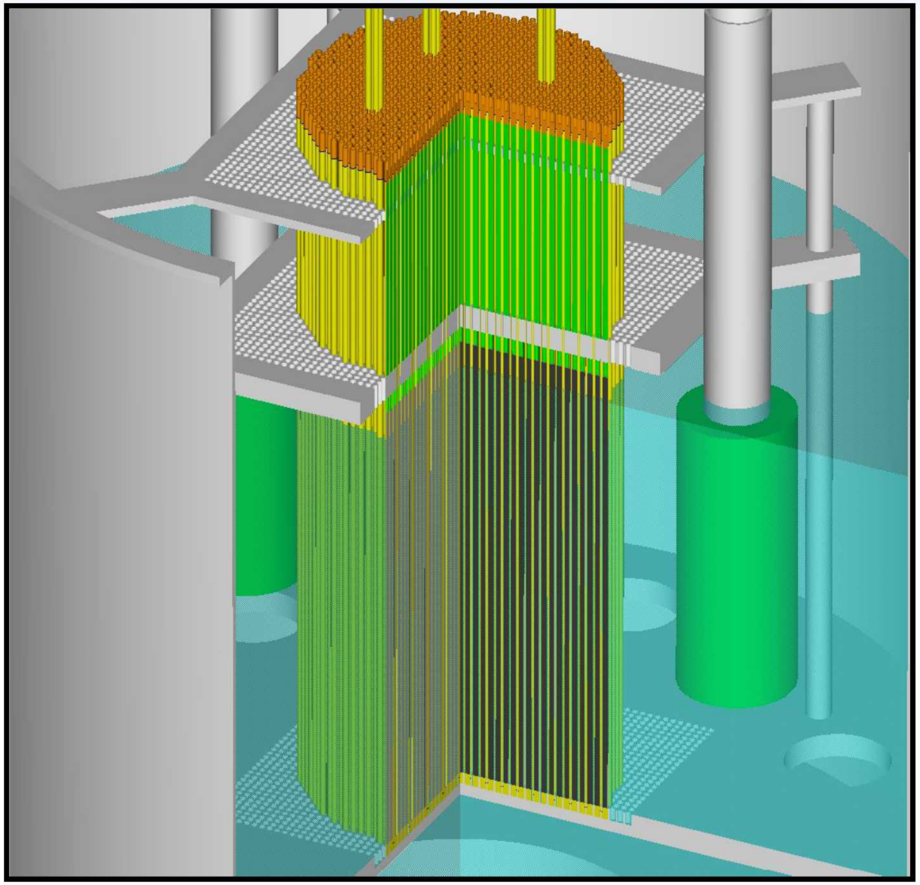


Fuel Rods: 1573

k_{eff}: ~0.95

Water Depth: 345 mm

Moderator Height Experiment at DC



Fuel Rods: 1573

k_{eff}: ~1.0

Water Depth: about 465 mm

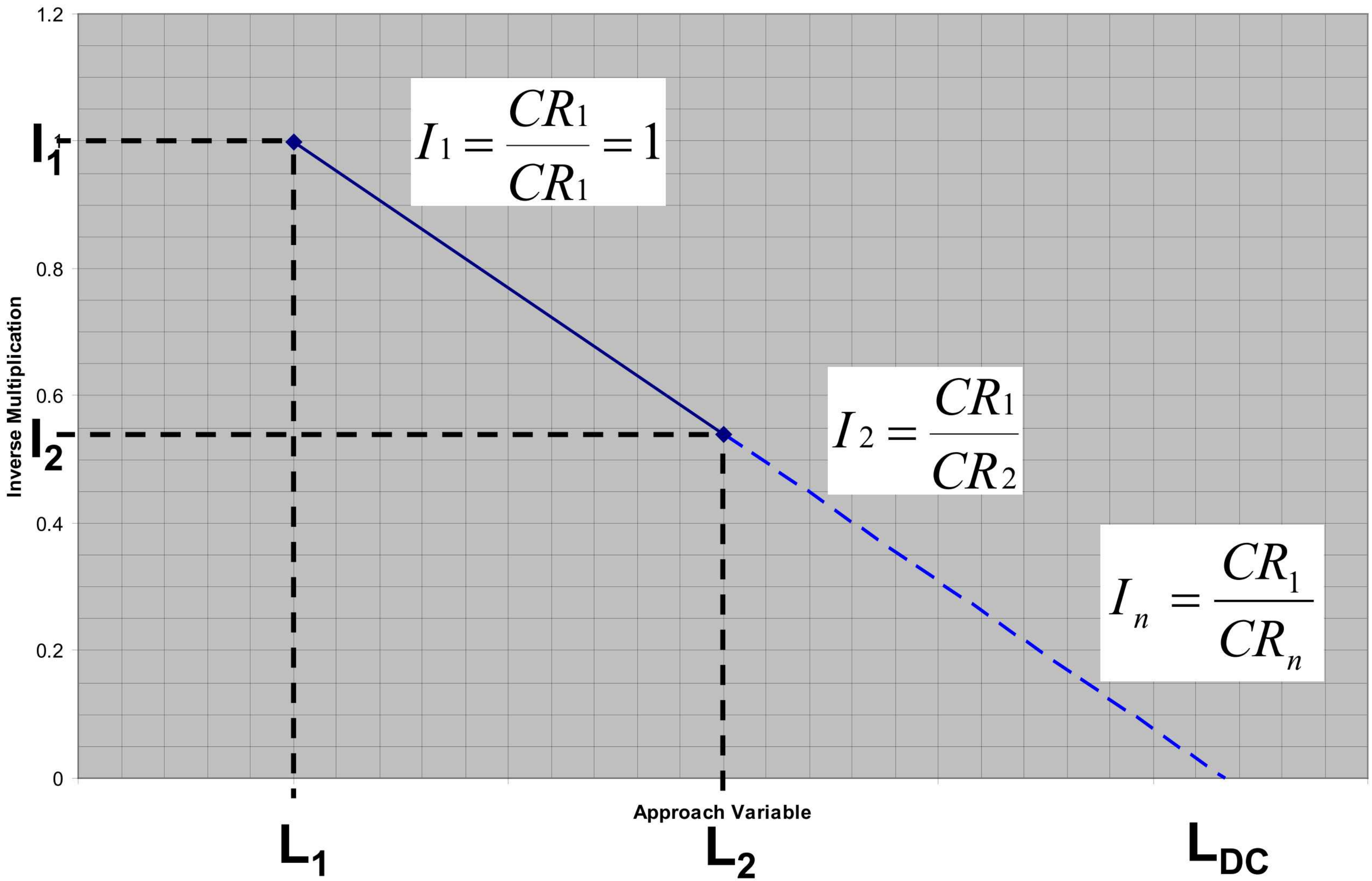
Mechanics of the Experiment

- The number of fuel rods in the core will be constant
- The approach-to-critical will be done with the depth of the moderator in the core tank as the free parameter
- The choice of water depth will be guided by the count rates
- This approach will be done remotely (we won't go into the reactor room)
- The minimum water height increment will be 5 mm

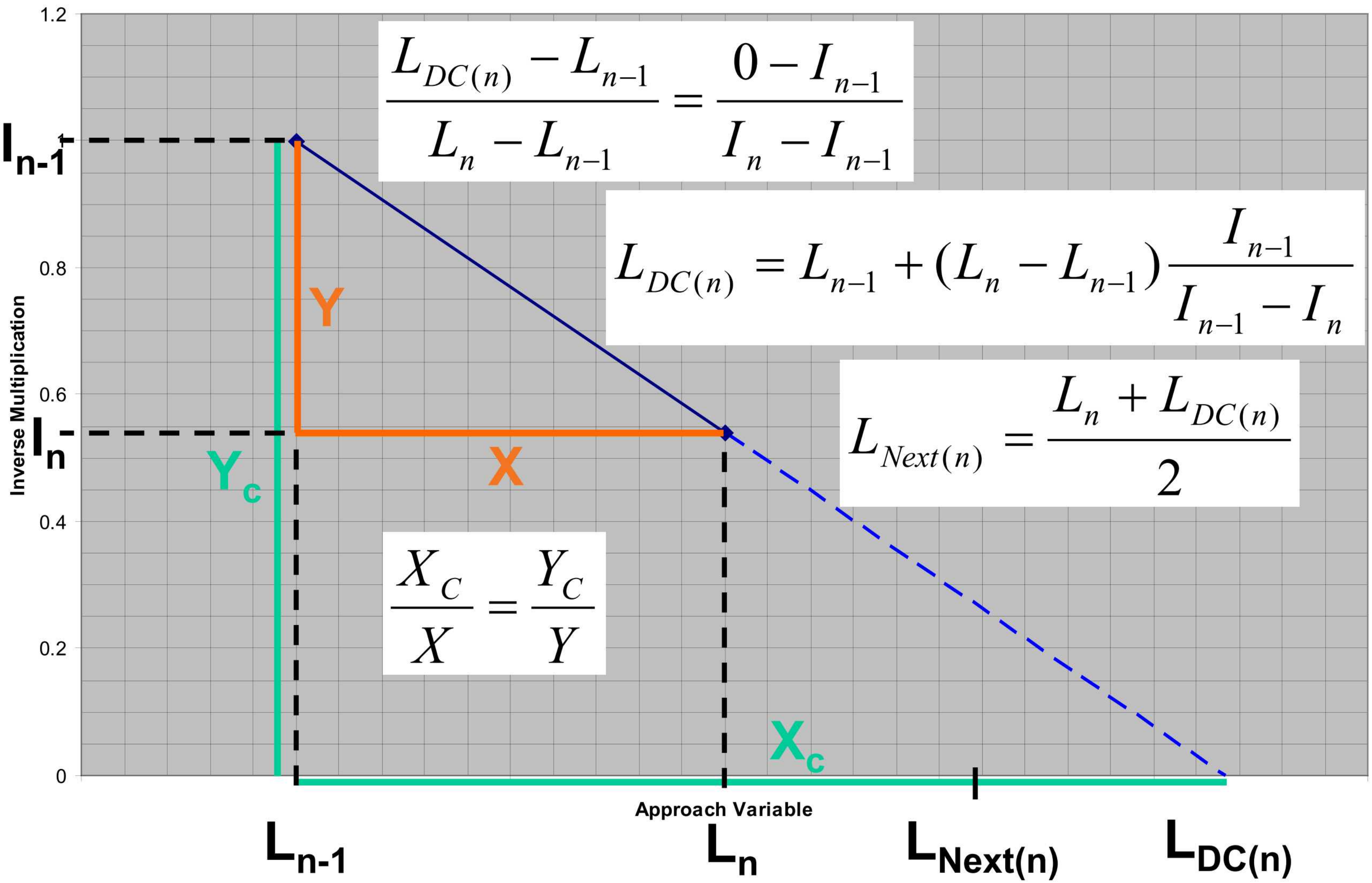
The Experiment Process

- The desired fuel rod array will be loaded
- The safety rods will be “cocked”
- The reactor room will be cleared
- The core tank will be filled with water to the height that gives a calculated k_{eff} of about 0.90
- The control rod will be raised
- The slow pump will be turned on – the water height in the core will be controlled by the setting of the overflow standpipe
- When the water level in the core tank reaches the standpipe, counts will be taken **[A]**
- The next water level will be determined from the previous two counts
- The standpipe will be set for the new water level
- Loop back to the step marked **[A]**

Determining the Next Water Increment



Determining the Next Fuel Increment



$$\frac{L_{DC(n)} - L_{n-1}}{L_n - L_{n-1}} = \frac{0 - I_{n-1}}{I_n - I_{n-1}}$$

$$L_{DC(n)} = L_{n-1} + (L_n - L_{n-1})\frac{I_{n-1}}{I_{n-1} - I_n}$$

$$L_{Next(n)} = \frac{L_n + L_{DC(n)}}{2}$$

$$\frac{X_C}{X} = \frac{Y_C}{Y}$$

Pre-Job Brief

- The operations folks will brief you on the hazards of the experiment

Module 08

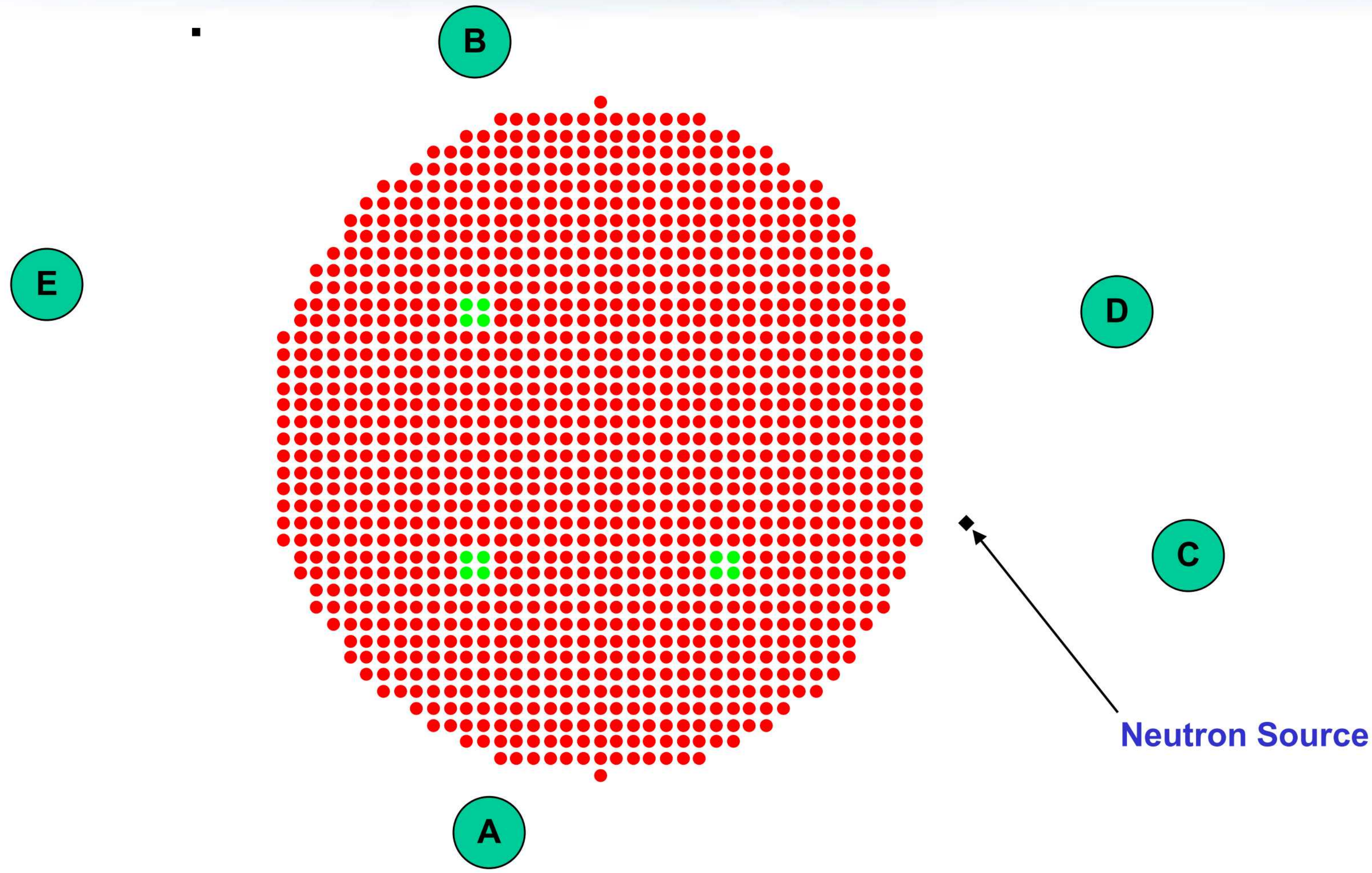
Experiment 3
Approach to Critical on Fuel Lump Separation

Presented by:
Gary Harms

Experiment 3 Overview

- We will do an approach-to-critical experiment by moving two roughly equal fuel lumps toward each other
- This simulates experiments done with a horizontal split table machine
- Criticality safety parameters that are in play:
  - Interaction
  - Moderation
- Application to criticality safety:
  - What happens as two fuel masses are moved progressively closer to one another?
  - What happens when two neighboring fuel masses are moved apart?
- This experiment is applicable to many accident configurations.

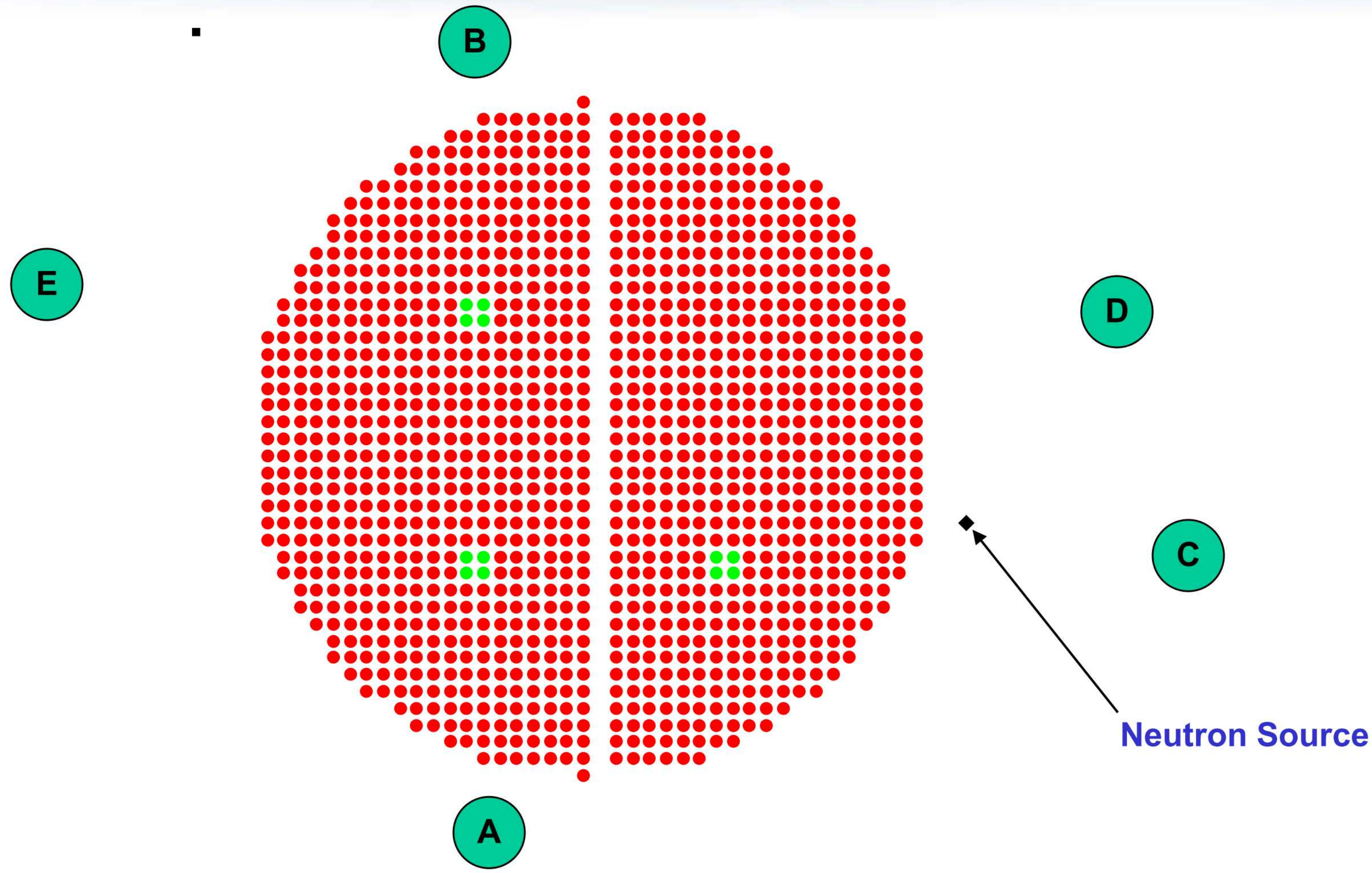
Core Separation Experiment Configurations



Fuel Rods: 1247

X = Fission Chamber

Core Separation Experiment Configurations

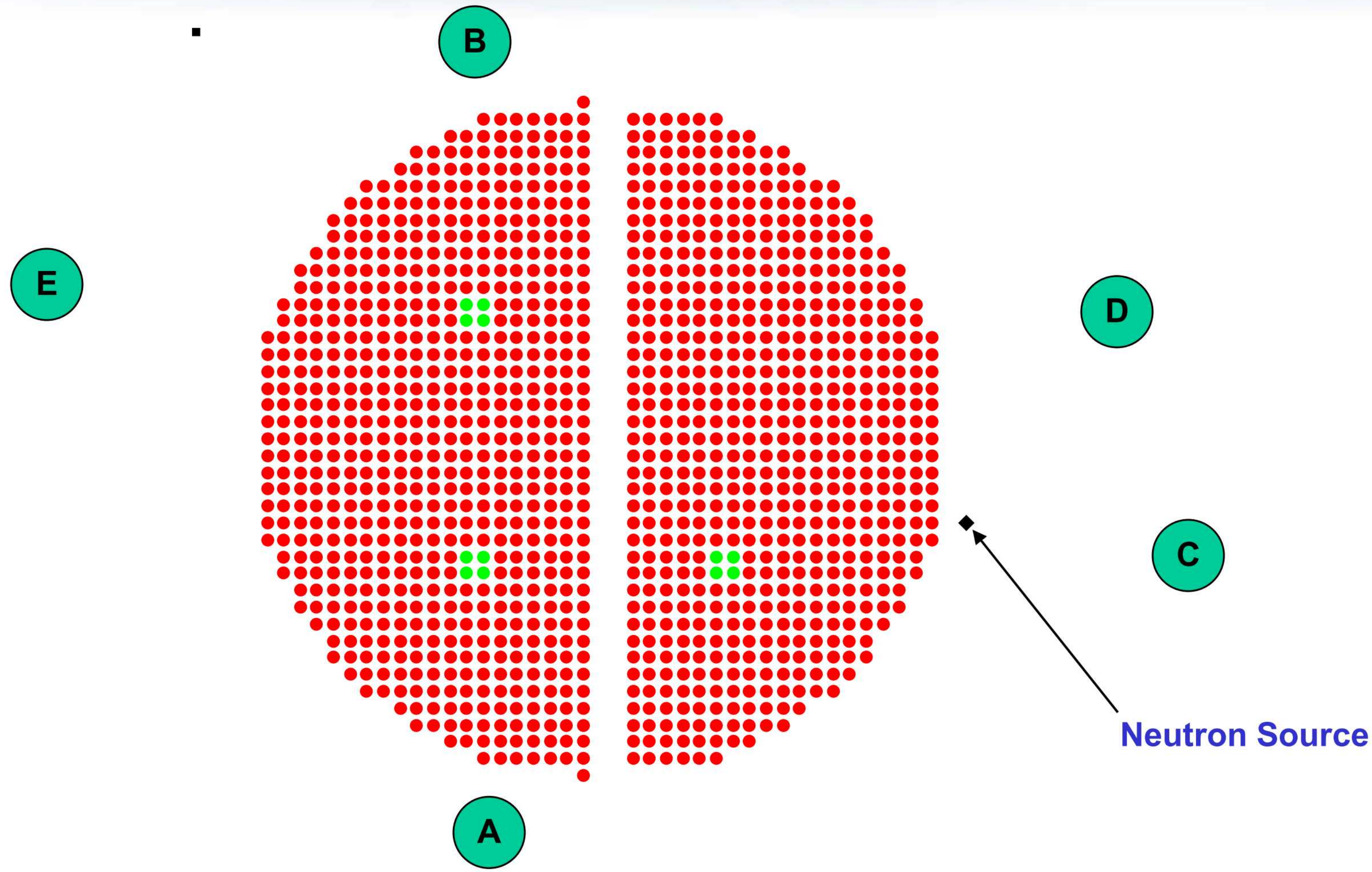


Fuel Rods: 644 (left) + 603 (right) = 1247 (total)

Separation: 0.80 cm

X = Fission Chamber

Core Separation Experiment Configurations

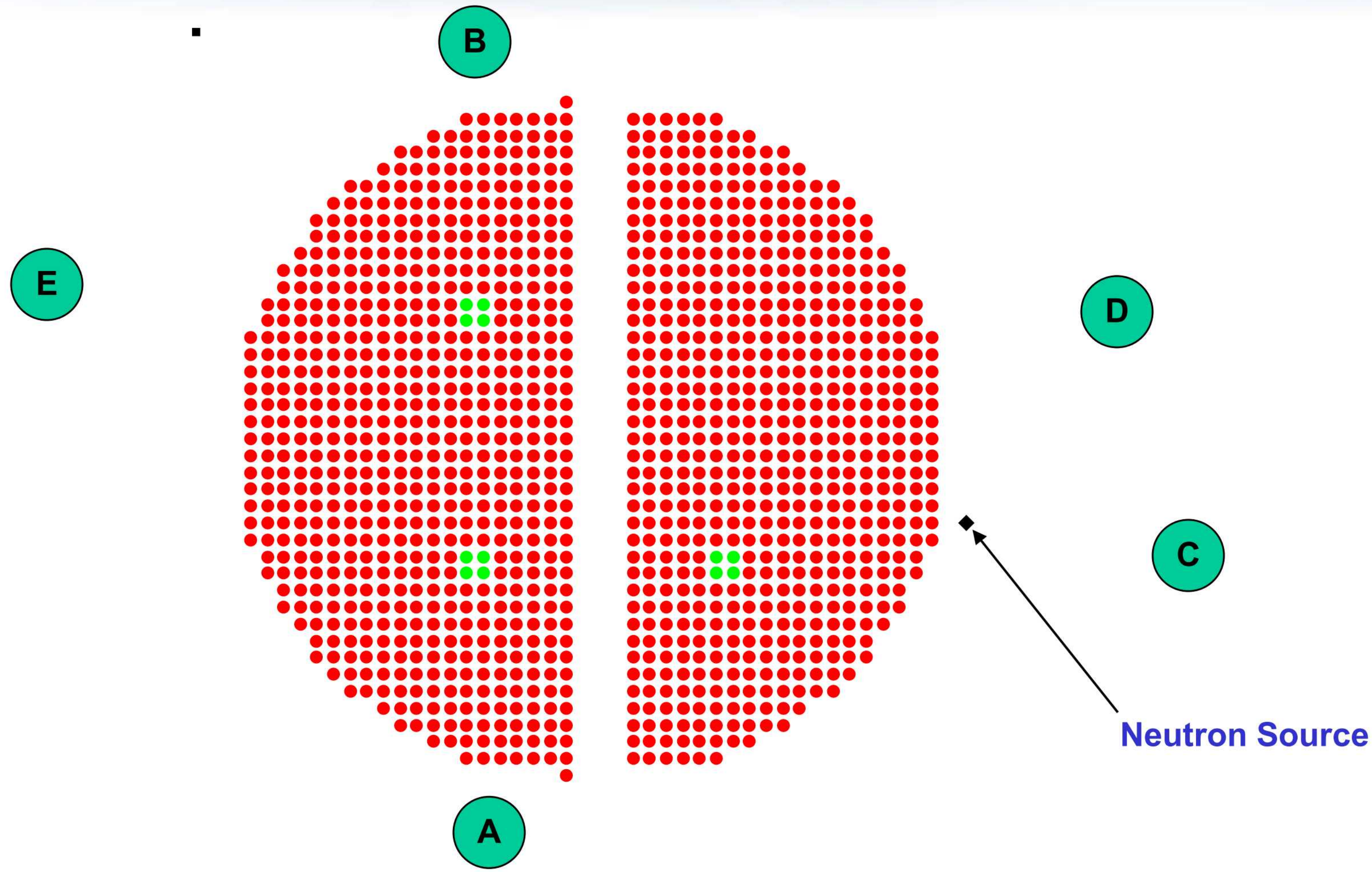


Fuel Rods: 644 (left) + 603 (right) = 1247 (total)

Separation: 1.60 cm

X = Fission Chamber

Core Separation Experiment Configurations

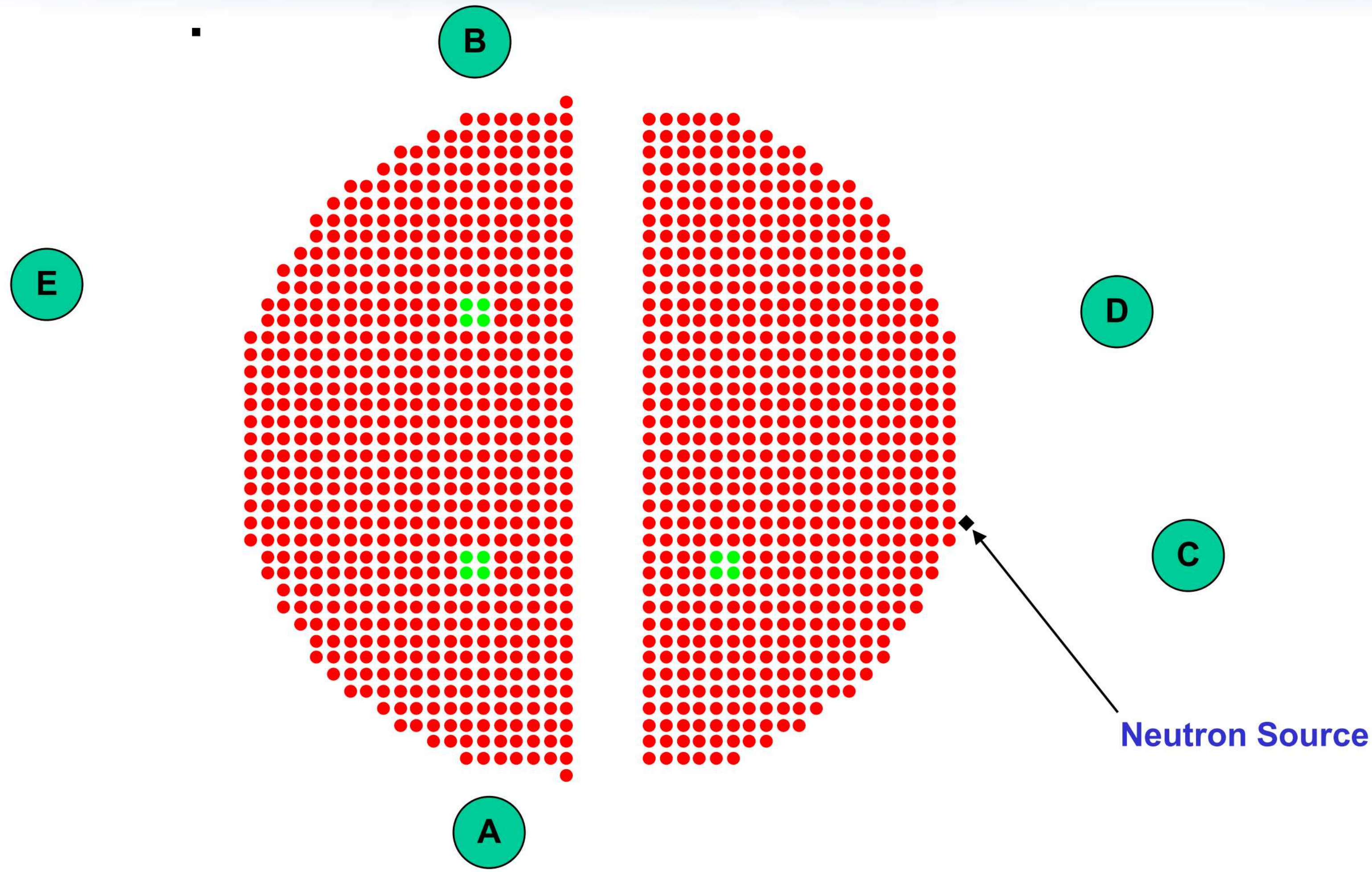


Fuel Rods: 644 (left) + 603 (right) = 1247 (total)

Separation: 2.40 cm

X = Fission Chamber

Core Separation Experiment Configurations

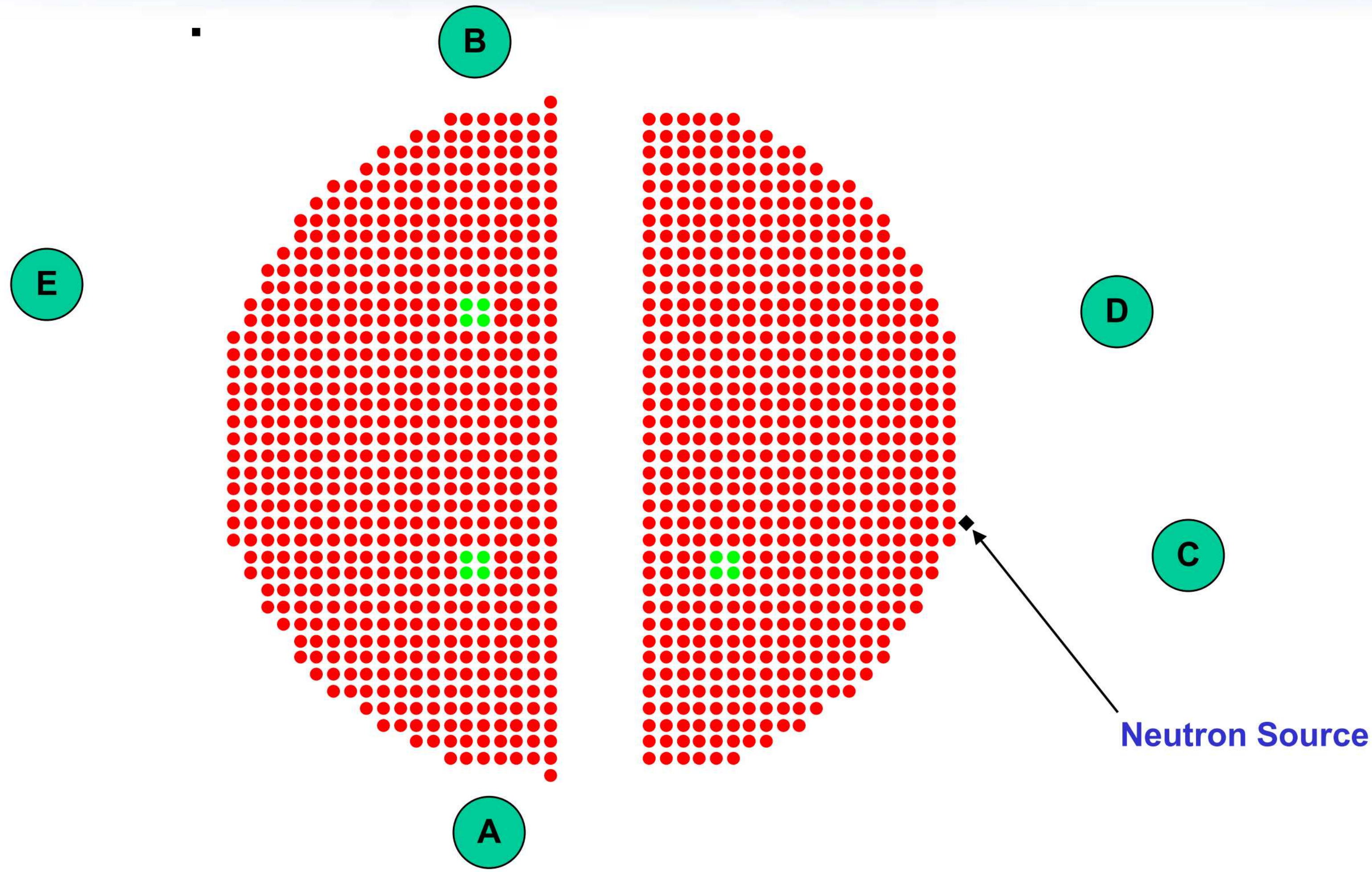


Fuel Rods: 644 (left) + 603 (right) = 1247 (total)

Separation: 3.20 cm

X = Fission Chamber

Core Separation Experiment Configurations



Fuel Rods: 644 (left) + 603 (right) = 1247 (total)

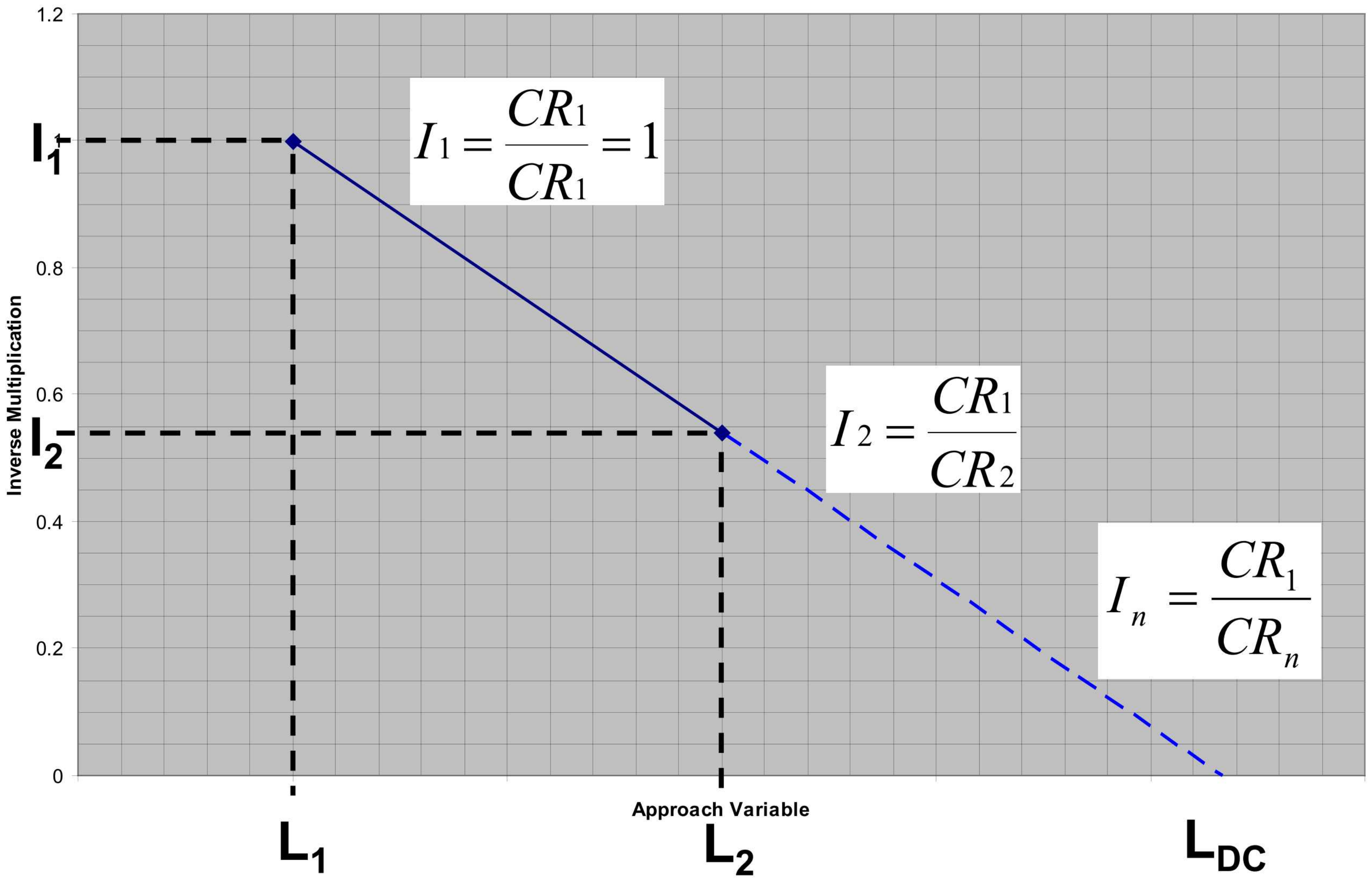
Separation: 4.00 cm

X = Fission Chamber

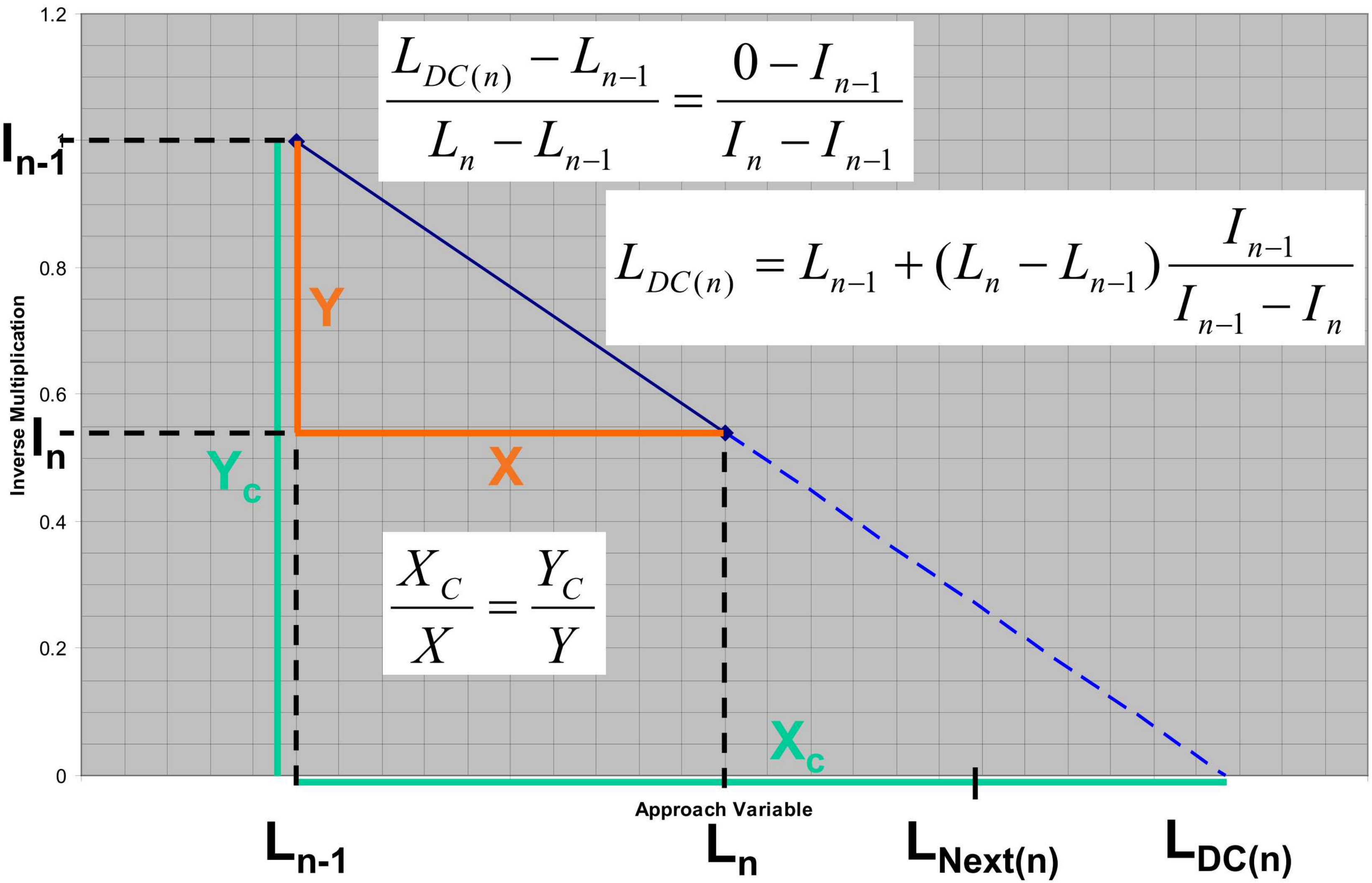
Mechanics of the Experiment

- The number of fuel rods in the core will be constant
- The separation of the fuel masses will be adjusted by moving fuel rods from location to location in the core
- The operations staff will perform all the fuel movements
- This is a DEMONSTRATION
  - We will record data and make projections to critical as we would in an approach-to-critical experiment
  - We will change the separation by full rows of fuel rods, not according to the results of our projections

Determining the Next Step



Determining the Next Fuel Increment



$$\frac{L_{DC(n)} - L_{n-1}}{L_n - L_{n-1}} = \frac{0 - I_{n-1}}{I_n - I_{n-1}}$$

$$L_{DC(n)} = L_{n-1} + (L_n - L_{n-1})\frac{I_{n-1}}{I_{n-1} - I_n}$$

$$\frac{X_C}{X} = \frac{Y_C}{Y}$$

Pre-Job Brief

- The operations folks will brief you on the hazards of the experiment

NCSP
NUCLEAR CRITICALITY
SAFETY PROGRAM

Module 09

Review of the Experiments

Presented by:
Gary Harms, John Ford, Rafe Campbell, Ron Knief, and John Miller

Summary

- The material for this presentation will be developed during the four experiments we will do during the class.
- The slides in this presentation will give an overview of the experiments that were performed during the class.

United States Department of Energy
Nuclear Criticality Safety Program (NCSP)

Process Criticality Accident Number 3

Union of Soviet Socialist Republics

Mayak Production Association

02 January 1958

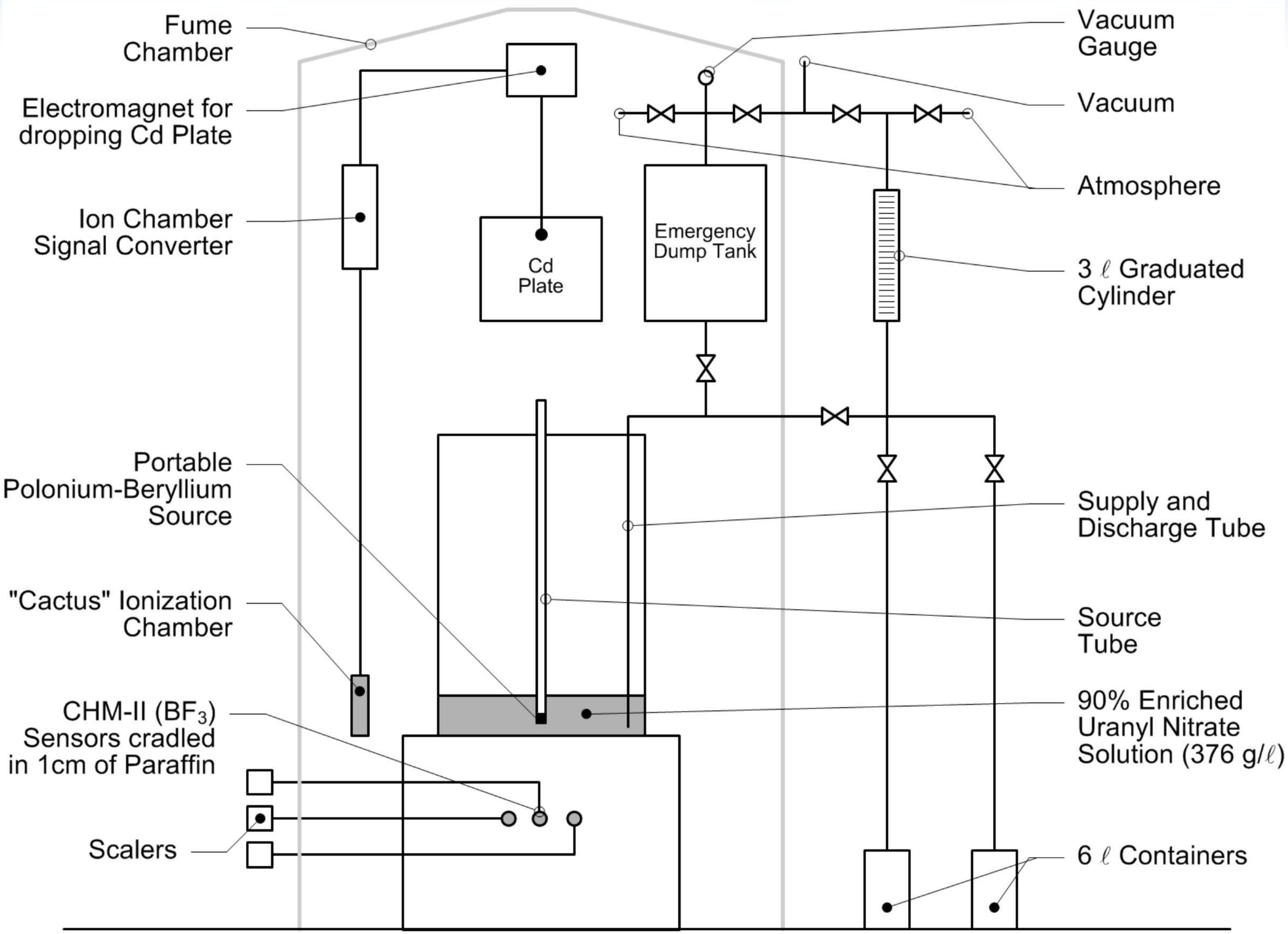
NCERC · Oak Ridge National Laboratory · Sandia National Laboratories · Lawrence Livermore National Laboratory · Los Alamos National Laboratory

Background Information

- Union of Soviet Socialist Republics
  - Mayak Production Association
  - Thursday, 2 January, 1958
  - First day of work after New Year Holiday
  - Facility was not equipped with an alarm system
- Two previous accidents
  - one death, one amputation
  - wide-spread use of large process vessels
- Critical experiment operation
  - experiments began in November 1957
  - single team of experimenters working one shift
    - 13:00 to 19:00

The Setting

- Dedicated room within the process facility
  - vessels and U(90) solution was readily
  - experimenters remained in the room
    - shielded by 0.5m water wall
- Experiments were supposed to be progressive in two respects
  - Small to large diameter vessels
  - High to low concentrations
- First experiment with new tank
  - 75 cm (2.5 feet) diameter cylindrical tank
  - 2 to 4 mm thick SS
  - bolted to stand 80 cm (2.6 feet) off concrete floor
  - immediately prior series (completed just before the holiday) involved a relatively smaller diameter vessel


Fume Chamber
Electromagnet for dropping Cd Plate
Ion Chamber Signal Converter
Cd Plate
Emergency Dump Tank
Vacuum Gauge
Vacuum
Atmosphere
3 ℓ Graduated Cylinder
Portable Polonium-Beryllium Source
"Cactus" Ionization Chamber
CHM-II (BF_3) Sensors cradled in 1cm of Paraffin
Scalers
Supply and Discharge Tube
Source Tube
90% Enriched Uranyl Nitrate Solution (376 g/ℓ)
6 ℓ Containers

The Accident

- After each experiment a written procedure required
  - uranyl nitrate solution to be drained into 6 liter containers
    - dimensions were critically safe in a planar array
  - one at a time
- First set of measurements completed
  - Four experimenters using a 1/M approach
  - 418 g/l of U(90), 64.4 liters, H_c=14.6 cm
  - one or more 6 liter bottles had been filled
- Improvisation
  - draining was apparently a slow and tedious process
  - experimenters discussed and decided on a more expeditious draining plan

The Accident

- Unbolted the tank from the stand
  - 3 of them lifted the tank off the stand
  - moved it to an area where the contents could be poured into the bottles
- While the tank was being tilted to pour out the contents
  - Prompt criticality was exceeded
  - The experimenters saw
    - a flash of light
    - violent ejection of solution from the tank
      - reached the ceiling 5 meters (~16 ft) above
  - Vessel was immediately dropped
  - All experimenters evacuated the room
    - Eventually all four were sent to a hospital

The Causes

- Violation of procedures
  - Poor judgment on the part of the experimenters
  - physical and mental state unknown
- Geometry change
  - assuming only one 6 liter bottle had been filled
    - a 5 degree tilt would have been sufficient to achieve prompt criticality
      - not likely since sloshing alone would have caused this to occur
  - large changes for H/D<<1
  - possibly added reactivity from human and floor reflection
- Lessons
  - engineered features are ultimately "administrative requirements"
  - tedious processes invite improvisation
  - intentional acts cannot be adequately addressed in criticality safety analysis
  - there is no substitute for reliable personnel

The Consequences

- ~2 x 10^{17} fissions
- Estimated doses
  - 3 @ 6000 rad
    - all died within 5 to 6 days
  - 1 @ 600 rad, ~2.5 meters away
    - Radiation sickness
    - Ongoing health problems
    - Cataracts**
- Experimental facility was dismantled

United States Department of Energy
Nuclear Criticality Safety Program (NCSP)

Process Criticality Accident Number 4

United States of America

Y-12 Oak Ridge Plant

16 June 1958

Background Information

- United States of America
  - Y-12 Oak Ridge Plant
  - Monday, 16 June 1958
  - Facility was equipped with an alarm system

- C-1 Wing, Building 9212
  - Uranium recovery operations
    - Solid waste dissolved into Uranyl (93) nitrate solution
    - Purified by solvent extraction
    - Concentrated
    - Converted to UF_4

9212 Inventory

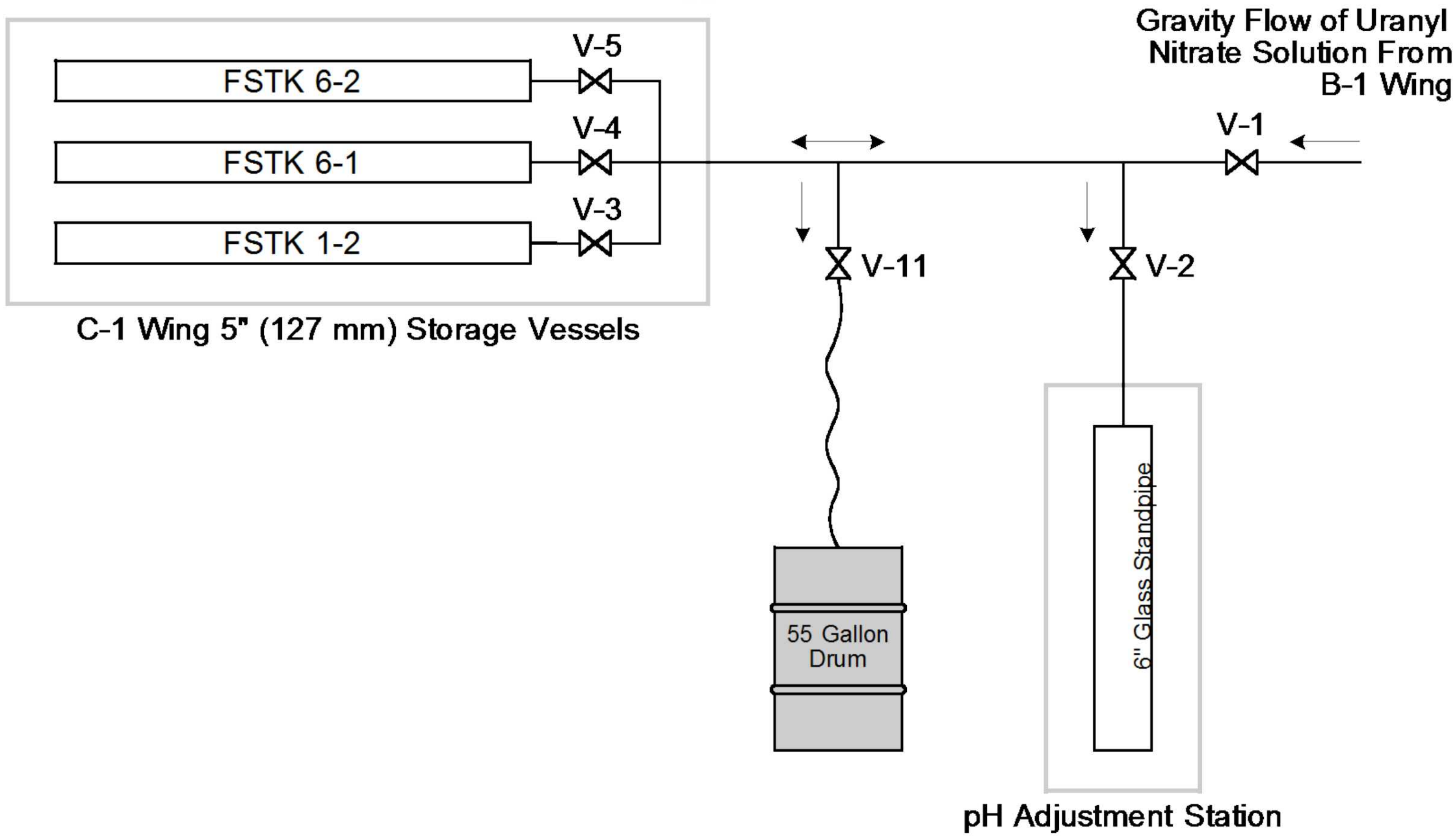
- B-1 and C-1 Wings had been shutdown for inventory
  - Several days to complete
  - Processes were restarted incrementally
  - By June 16th
    - B-1 Wing was operating
    - C-1 Wing still shutdown
- B-1 Wing
  - Newer technology recently installed
  - UF_4 conversion equipment delayed
  - Solution temporarily piped to C-1 Wing

C-1 Wing Inventory

- The process equipment C-1 Wing included three 5-inch (127mm) diameter "pencil tanks"
  - FSTK 1-2, FSTK 6-1, FSTK 6-2

- By procedure the inventory required that these tanks be
  - Disassembled
  - Cleaned
  - Reassembled
  - Leak tested

- The process was non-trivial and required several 8-hour shifts to complete


Gravity Flow of Uranyl Nitrate Solution From B-1 Wing
V-5
FSTK 6-2
V-4
FSTK 6-1
V-3
FSTK 1-2
C-1 Wing 5" (127 mm) Storage Vessels
V-1
V-11
V-2
55 Gallon Drum
6" Glass Standpipe
pH Adjustment Station

Preceding Shift (2300-0700)

- 1:00 a.m.
  - C-1 Wing Supervisor
    - Noted uranyl nitrate in 6-inch pH station glass standpipe
    - Ordered draining
- 5:00 a.m.
  - C-1 Wing Supervisor
    - Again noted Uranyl nitrate in glass standpipe
    - Operator confirmed that the standpipe had been drained earlier
    - An investigation determined that valve V-2 was leaking (partially open)
    - Supervisor closed valve V-2
    - Valve V-1 leading to the B-1 Wing was not checked
    - Believed that the leak checking of the FSTK tanks had been completed on Friday

Shift Change

- 7:00 a.m.
  - C-1 Wing supervisor change
    - Conflicting accounts as to whether information concerning V-2 was reported
    - In any case there was no mention of the issue in the operating log
- 8:00 a.m.
  - Additional C-1 Wing supervisor arrived
    - In charge of certain specific operations carried our only on the day shift
    - Duties included overseeing tank leak checks and return to service
  - This supervisor knew that FSTK 1-2, FSTK 6-1, and FSTK 6-2
    - Had been disassembled, cleaned, and reassembled the previous week
    - No part of the C-1 Wing had yet been operational
    - He considered checking the vessel level panel indicator unnecessary
    - Further the condition (open) of the valve V-3 was insignificant

NCSP
NUCLEAR CRITICALITY SAFETY PROGRAM

The Accident

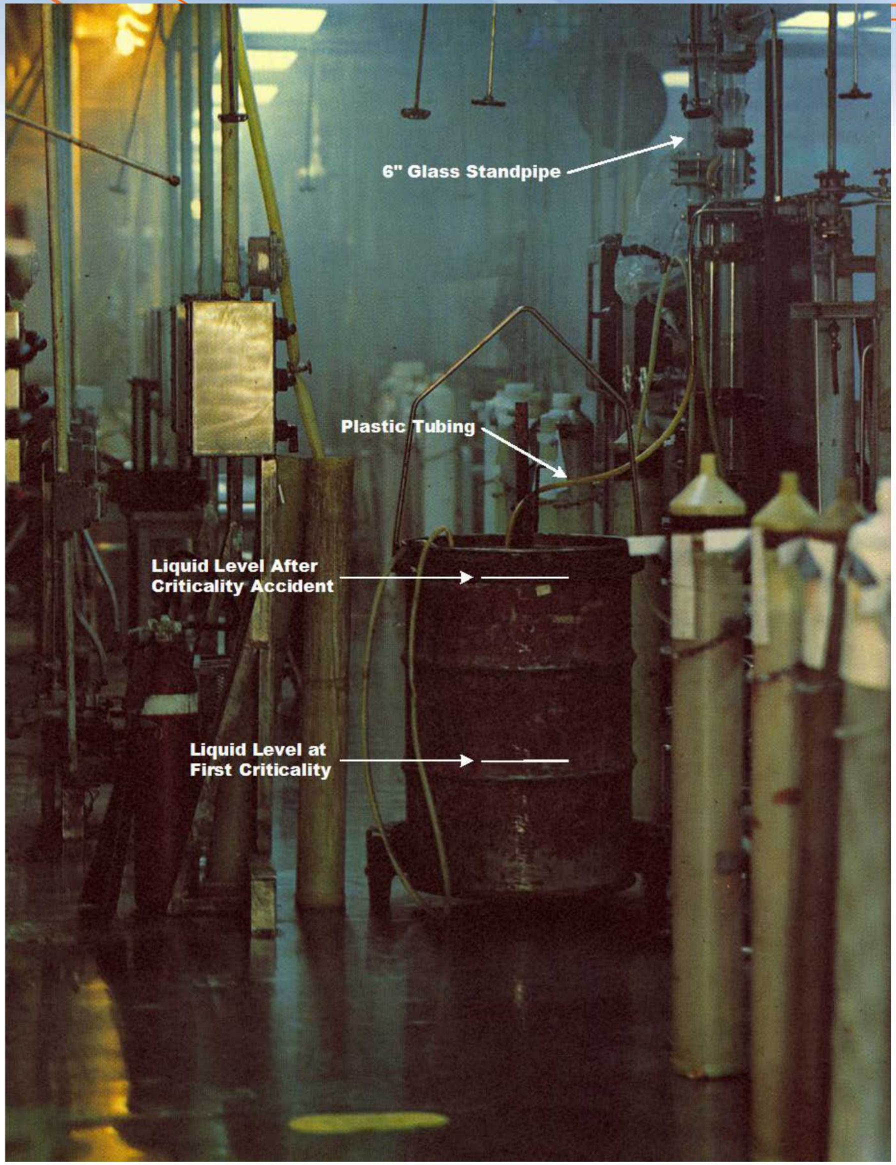
- ~1:50 p.m.
  - FSTK 6-1, and 6-2 had been filled with water
  - Leak check was complete
  - Supervisor instructed the operators to check valve V-1
    - The valve was reported closed by an operator, “a large and powerful man” who checked it by applying vigorous pressure to the handle
  - Operators opened V-4, V-5, V-11 to drain water into a 55-Gallon drum
  - V-3 was already opened
    - Flow pattern ensured tank FSTK 1-2 drained first
  - Operator stationed about 3-feet from the 55-Gallon drum
    - The operator was tasked with observing the draining and to safeguard against any unusual development
    - Part of the leak check process

The Accident

- ~2:05 p.m.
  - The operator looked into the drum and noticed yellow-brown fumes rising
  - He stepped back and within a few seconds noted an odd blue flash
  - Almost immediately thereafter the criticality accident alarm sounded
- All of Building 9212 was then evacuated
- Uranyl nitrate solution continued to drain into drum, followed by water from FSTK 6-1 and 6-2
  - ~20 minutes after the accident began the solution was diluted to below a critical concentration
- A detector 430 meters distant was immediately driven off scale and again about 15 seconds later
  - For the next 2.6 minutes the detector oscillated an indeterminate number of times
  - This was followed by and 18 minute ramp down

The Cause & Details

- B-1 Wing was operational before C-1 Wing
  - Valves V-1 (from B-1 Wing) & V-2 (to standpipe) had both been partially open
  - Valve V-3 had been left open after reassembly
  - Solution leaked via gravity from B-1 Wing through valves V-1 and V-2 to the pH station standpipe
  - At 5:00 a.m. valve V-2 was closed which diverted solution to FSTK 1-2 through valve V-3
- At first critical the drum contained
  - 2.1 kg ^{235}U in ~56 liters (37.5 g/l)
  - 55.2 cm diameter, 23.45 cm (~9-inches) height
- Additional 0.4 kg ^{235}U added by continued flow


6" Glass Standpipe
Plastic Tubing
Liquid Level After Criticality Accident
Liquid Level at First Criticality

Consequences

- ~1.3x10^{18} total fission yield
  - 6x10^{16} initial spike
- Eight personnel received significant doses
  - 461, 428, 413, 341, 298, 86.5, and 28.8 rem
  - None were fatally exposed
    - 14.5 years
    - 17.5 years
    - 5 alive after 29 years
    - Status of one operator was unknown
- Plant was returned to service in 3 days
- Leak check procedures were modified
  - Unfavorable geometry vessels were excluded from the process floor

Missed opportunities

- Earlier shift standpipe solution incidents
  - Should have indicated that the solution was leaking from B-1 Wing
  - Valves V-1 & V-2 had to be open or leaking
- Skipped tank level check
- Valve V-1 check and tightening
- ~15 minutes for solution to reach critical height
  - Operator was educated and experienced
    - 1 year of college
    - 6 years of uranium solution processing
      - Yellow color of uranyl nitrate was distinctive and well known to the operator

"It would thus appear that Operator A had an opportunity to shut off the flow of solution prior to the accident"

Human Factors and Criticality Safety

- Good safety is not possible without appropriate attention to human factors
  - Investigations that end attributing events/accidents to *human error* demonstrate inadequate understanding (bad apple view)
  - Human error is almost always the result of deeper system faults (bad systems view)
- As managers you will be called upon to establish controls on process operations
  - Natural process constraints, engineered features, administrative features
- Don't set operators up with poor tools and inadequate systems
  - If operators must decide how to
    - implement controls
    - interpret controls
    - work around difficult controls
    - work with inadequate/broken equipment

The evaluation process has failed

Human Factor Aspects

- What aspects of human factors are illustrated by the Y-12 accident?
  - Systemic
    - B-1 wing not fully operational; temporary piping to C-1 wing
    - Phased restart; B-1 wing back before C-1 wing
  - Inadequate communication
    - Night supervisor *assumed* leak check was complete
  - Poor administrative control (HF Category: Attention)
    - Equivalent to asking someone to watch paint dry
      - How many times had this been done before?
      - What were the lighting conditions?
      - Did expectations lead the operator to see water?

United States Department of Energy
Nuclear Criticality Safety Program (NCSP)

Process Criticality Accident Number 5

United States of America

Los Alamos Scientific Laboratory

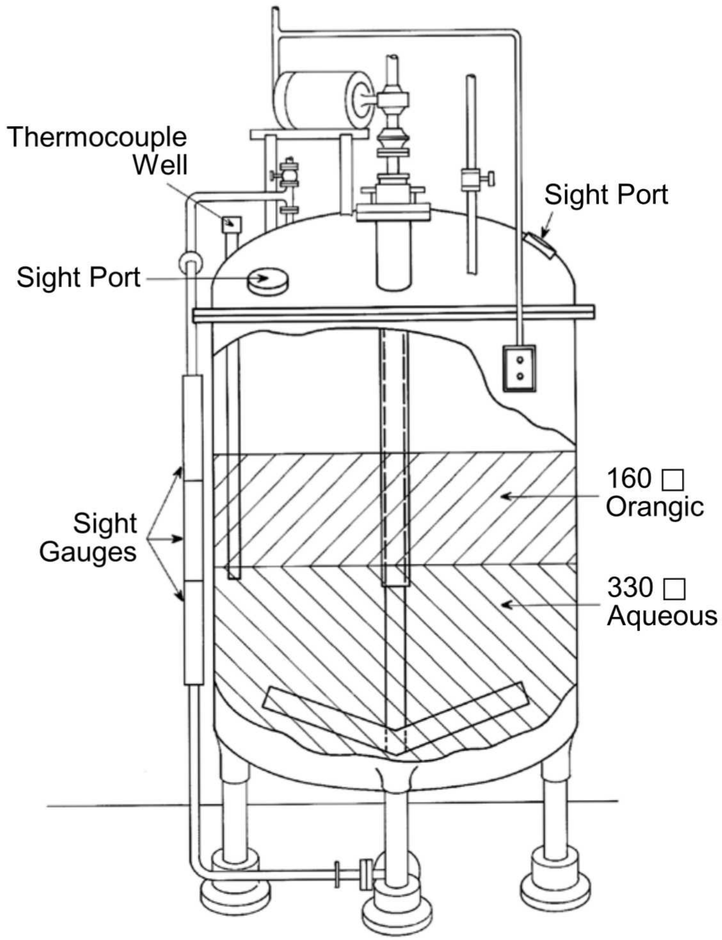
30 December 1958

Background Information

- **United States of America**
  - Los Alamos Scientific Laboratory
  - Tuesday, 30 December 1958
  - Facility was not equipped with an alarm system
- **Plutonium recovery operations**
  - Lean waste solution processing
    - Waste from sand, slag, crucible dissolution and recovery
  - Typical solutions contained < 0.1 g/liter
- **Year end inventory in progress**
  - Normal flow was interrupted
  - Vessel and piping cleanout

Precursors

- **Each tank was to be cleaned individually**
  - **Instead contents of four tanks were transferred to a single tank**
    - Mix of solids, solvents, and nitric acid
    - Solids likely had accumulated over 7.5 years of operations
  - **Filtering for solids was not performed during transfers**
- **Solvent treatment tank (~40-inch outside diameter)**
  - After transfer/mixing two phases separated
    - 160 liters organic
      - 3.27 kg of Pu
        - ~20.4 g/L
      - 20.3-cm (8-inches) thick
        - T_c ~ 21 cm (8.25-inches)
    - 330 liters of nitric acid
      - 60 grams of Pu


Thermocouple
Well
Sight Port
Sight Port
160 □
Orangic
Sight
Gauges
330 □
Aqueous

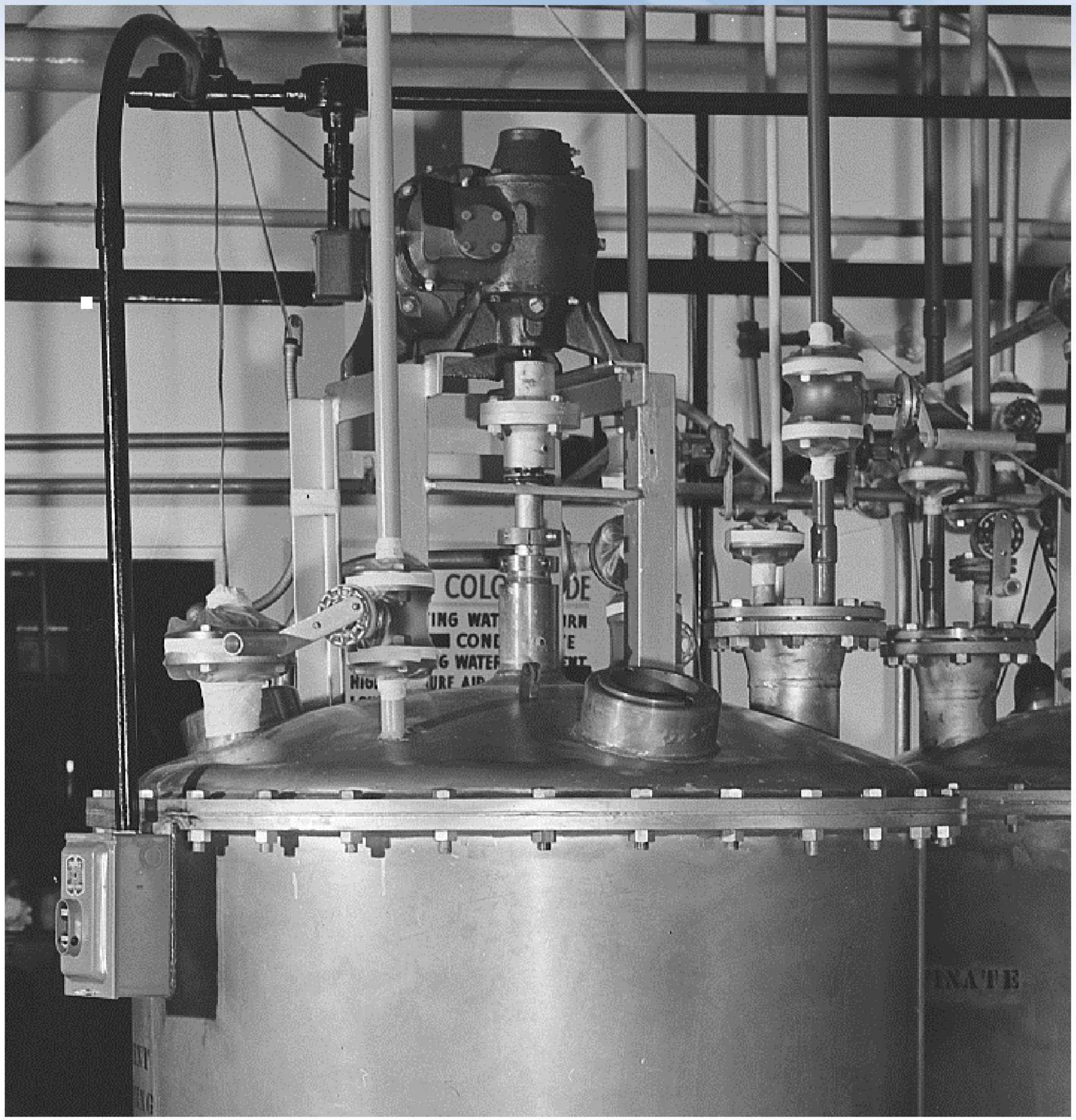
The Accident

- **At ~ 4:35 p.m. the operator**
  - Stood on a ladder next to the tank
  - Looked into the site port
  - Turned a mixing stirrer on
- **Forced aqueous phase up the tank walls**
- **Pulled organic layer down**
  - Very rapid change in geometry
    - 5$/sec reactivity insertion rate
  - Thick central region reflected by aqueous
- **In about one second**
  - The system was well above prompt critical
  - Single excursion ~ 1.5 x 10^{17} fissions
  - Permanent shutdown in about ~3 seconds; <7 g/l from mixing

The Accident

- **Operator was knocked or fell to the floor**
  - Huge shock to the nervous system
  - Recovered footing and ran out a nearby door
  - Later reported seeing a flash of light
- **In an adjacent room another operator**
  - Saw a bright flash of light
    - Believed it to be a photo flash bulb/electrical shorting accident
  - Heard a thumping sound
  - Felt a floor vibration
- **Co-workers came to his aid**
  - Complained of “***burning up***”
  - Assisted him to an emergency shower
  - Walked several times by the tank
  - A responding nurse commented his “***nice pink skin***”


RAFFINATE
C/C-9: 59111



NCSP
NUCLEAR CRITICALITY SAFETY PROGRAM

Missed Opportunity

- **NCSC reviewed operations ~1 month earlier**
  - Recommended vessels be changed
    - Favorable geometry
  - Operations had agreed
    - Planned to switched to banks of 6-inch diameter vessels
  - Budgeted for May/June of 1959 installation
    - If accident had not occurred when it did, it likely never would have
  - Procurement accelerated
    - 5 and 6-inch vessels were used for recovery
    - Eventually permanently installed

The Consequences

- **Two nearby operators**
  - 134, 53 rem
  - No ill effects reported
- **No physical damage**
  - Tank was displaced by ~10 mm
- **Operator fatality**
  - Operator ~12,000 ± 6000 rad
  - Died 35 hours later
  - Cecil Kelley
    - Decorated WW-II veteran
    - 38 years old
    - 11.5 years at Los Alamos
      - 19 nanocuries Pu burden from 1946 to 1949
      - ~6 years as a Pu worker

Cecil Kelley

United States Department of Energy
Nuclear Criticality Safety Program (NCSP)

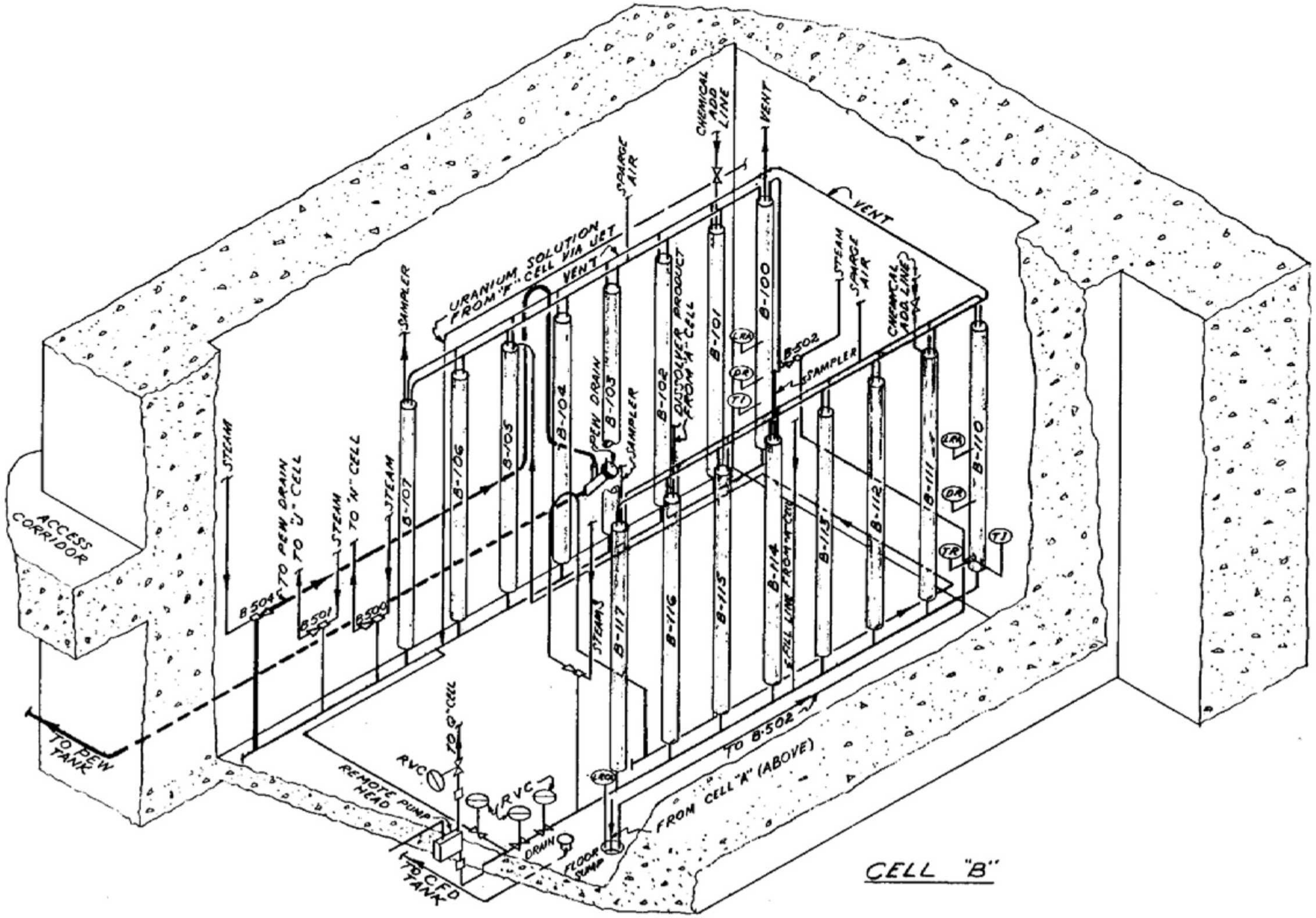
Process Criticality Accident Number 6

United States of America
Idaho Chemical Processing Plant

Background Information

- United States of America
  - Idaho Chemical Processing Plant
  - Friday, 16 October 1959
  - Facility was not equipped with an criticality accident alarm system

- Spent fuel chemical processing plant
  - Uranium recovery operations
    - Spent fuel was dissolved
    - Purified by solvent extraction in pulse columns
    - Three stage purification---normally only two are used
    - Staging between stages was afforded by banks of pencil tanks



CELL "B"
URANIUM SOLUTION FROM "F" CELL VIA JET
VENT
SPARGE AIR
CHEMICAL ADD LINE
STEAM
SAMPLER
DISSOLVER PRODUCT FROM "A" CELL
PEW DRAIN
TO PEW DRAIN TO "J" CELL
STEAM TO "H" CELL
ACCESS CORRIDOR
TO PEW TANK
TO CFD TANK
REMOTE PUMP HEAD
RVC
DRAIN
FLOOR SUMP
FROM CELL "A" (ABOVE)
TO B-502
B-100
B-101
B-102
B-103
B-104
B-105
B-106
B-107
B-110
B-111
B-112
B-113
B-114
B-115
B-116
B-117
B-502
B-504
B-501
B-500

Pencil Tanks

- Two banks of pencil tanks (B-Cell) were used for temporary staging of uranyl nitrate solution
  - Designation bank B-100, and B-110
  - Interconnected via a bottom drain manifold
  - 8 tanks per bank
  - 5-inches in diameter
  - 10-feet long
  - ~150 liters in volume each
  - Each tank was vented by a 1-inch tube at the top that lead to a 1-inch manifold leading to a off-gas system
- Tanks were rarely used
  - Only three other uses since installation in 1952
    - July 1952, December 1956, and December 1957

Process Underway

- Beginning in mid-July 1959 ICPP had been engaged in processing stainless steel clad fuel rods
  - Different than the normal fuel processed
  - Additional solvent extraction cycle
  - Second and third extraction cycles took place in an area common to other than stainless steel clad fuel rods
    - Capacities of the these cycles were several times greater than the first stage extraction
    - Consequently, the first stage product was staged in B-Cell temporary staging pencil tanks

Process Underway

- On 15 October, the banks of tanks were nearing the capacity
  - ~80% full with U(91) at 170 g/L (~150 g^{235}U/L)
  - Decision was made to measure the solution density to more accurately assess the volume
    - Measurement was performed using an air purged in-line density probe that read out on a chart recorder
  - The tanks were briefly (~10 minutes) sparged that afternoon

Process Underway

- Final preparations for the measurement, however, were not completed until the midnight to 0800 shift on 16 October
  - Sampling procedure required sparging for
    - 30 minutes prior to density measurement
    - 15 minutes while the solution circulated through the probe region
  - The air line pressure upstream sparge valve was 50 psig
    - Several years earlier flow restricting devices had been installed elsewhere in the plant
    - B-Cell was omitted because of its limited use

The Accident

- ~02:30 two operators entered cell B to measure the density in each bank
  - Each turned on one of the air sparge systems
    - B-100 was operated by manual globe valve
      - Turned until the gauge read 2 psig and the chart recorder began oscillating
    - B-110 was a remotely operated pneumatic valve
      - As the operator opened the valve he noted that the pressure gauge was inoperative
      - Closed the valve and reopened it carefully until he saw the chart recorder oscillating
      - Neither operator was apparently aware that there was an additional pressure gauge for this line near the cell wall
  - The operators returned to their stations

The Accident

- Shortly after the start of sparging
  - The liquid level and density in B-110 began dropping uniformly for about 15 minutes
  - Uranyl nitrate was lost from system
  - The solution was being forced out of the system through an attached waste line
    - The line had a hydrostatic pressure barrier, i.e., a 4-foot high extension of the waste line above the highest point in the tanks
    - Once above that point siphoning took over and the solution entered the waste system

NCSP
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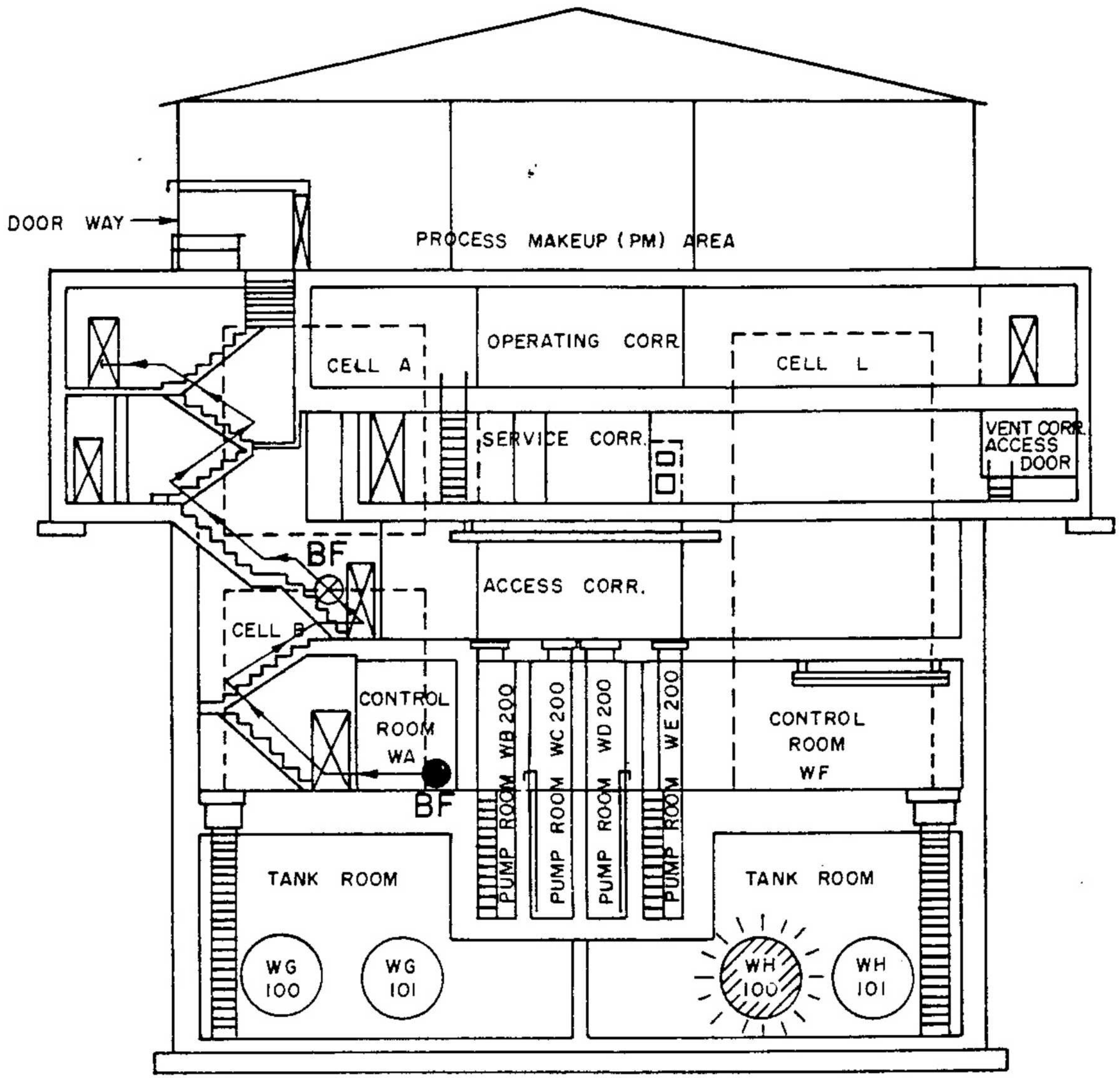


The Accident

- Waste system solution accumulated in a set of tanks in the basement depending on valve line-up
  - The waste receiving tank (WH-100) being used at the time was a 5000-gallon cylindrical tank oriented on its side
- ~200 liters of 170 gU/L (34kg U) solution was transferred at an average rate of 13-Liters/second
  - The tank already contained about 600-Liters of dilute aqueous waste solution
- 15-minutes after the sparging began radiation alarms sounded and the building was evacuated

Consequences

- The excursion history is a matter of conjecture
  - It is likely that there was an initial spike and follow spikes followed by quasi-equilibrium boiling for 15 to 20 minutes
  - Nearly half of the 800-liters evaporated
  - The total yield was estimated to be about $4x10^{19}$ fissions
- Prompt neutron and γ-ray doses were negligible
- Some personnel received doses during evacuation from airborne fission products
  - One 50 rem,
  - One 32 rem, and
  - Seventeen persons with smaller doses

Human Factor Aspects

- What aspects of human factors are illustrated by this accident?
  - Human factors categories
    - Instructions
    - Human/machine interface
  - Systemic
    - The operators were not familiar with the seldom used equipment
      - Inadequate preparation
    - There was not an anti-siphon device on the waste line
      - poor system design
    - Operating procedures were not current
      - Failed to call for careful adjustment of the air sparge valve
      - Regardless this was a poor substitute for an engineered feature
    - There was no pressure regulating device on the air sparge system
      - Adequate implementation of the control was not possible
        - Not repeatable or reliable

United States Department of Energy
Nuclear Criticality Safety Program (NCSP)

Module 02
Process Criticality Accident Number 9

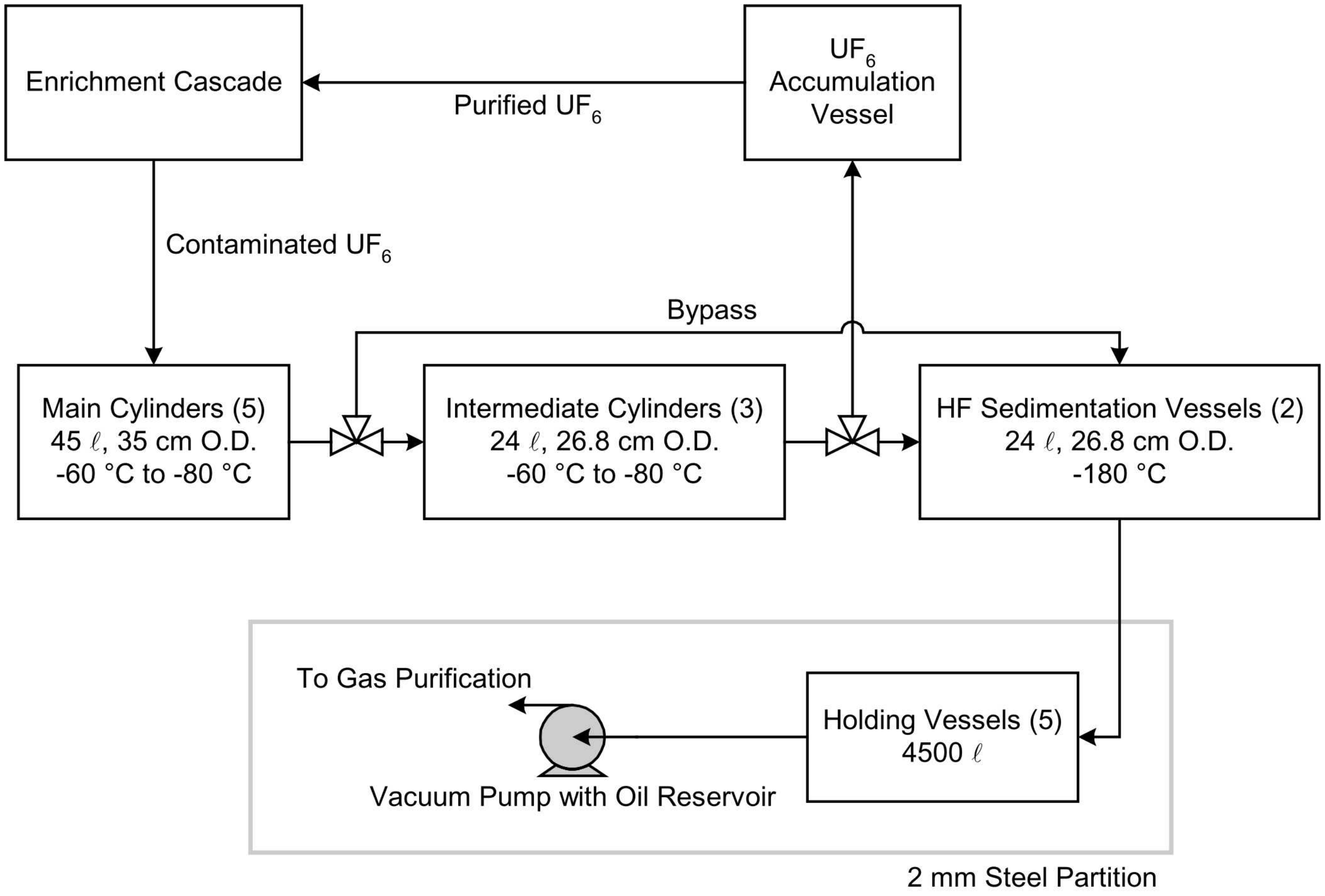
Union of Soviet Socialist Republics
Siberian Chemical Combine

NCERC NATIONAL CRITICALITY EXPERIMENTS RESEARCH CENTER
Oak Ridge National Laboratory
Sandia National Laboratories
Lawrence Livermore National Laboratory
Los Alamos National Laboratory

Tomsk, 14 July 1961

- Union of Soviet Socialist Republics
  - Siberian Chemical Combine, a.k.a., Tomsk
  - Friday, 14 July, 1961
  - Continuous 24 hour operation
  - Facility was equipped with an alarm system
- Only enrichment facility and oil-mixture accident
- Intermediate purification stage (DSS-6)
  - $U(22.6)F_6$
  - Removed air and excess HF
  - 7.2 meters by 18.2 meters room (24 by 60 feet)

The Process



Enrichment Cascade
Purified UF6
UF6 Accumulation Vessel
Contaminated UF6
Bypass
Main Cylinders (5)
45 ℓ, 35 cm O.D.
-60 °C to -80 °C
Intermediate Cylinders (3)
24 ℓ, 26.8 cm O.D.
-60 °C to -80 °C
HF Sedimentation Vessels (2)
24 ℓ, 26.8 cm O.D.
-180 °C
To Gas Purification
Vacuum Pump with Oil Reservoir
Holding Vessels (5)
4500 ℓ
2 mm Steel Partition

The Process

- Continuous diversion of part of the cascade stream
- UF de-sublimation occurred in main (MC) and intermediate cylinders (IC)
  - -60 °C to -80 °C (Cooled by liquid nitrogen , -196 °C)
- HF condensing occurred in sedimentation vessels
  - -180 °C (Also cooled by liquid nitrogen)
- In both systems the liquid nitrogen coolant
  - Flowed through coils embedded in iron–shot filled jackets
    - uniform temperature distribution
  - Flow was automatically activated by a temperature sensor

Oxygen liquefies at -183°C

The Process

- Impurities including air were collected in holding vessels
  - Five 4500 liter tanks (in a separate room)
  - Emptied by vacuum pump with an oil reservoir
  - Pump was activated manually
  - Pump was isolated from the tanks by a valve
- UF_6 was known to accumulate in the vacuum pump oil
  - Changed every 15 days
  - Primarily an operational consideration as the density increased in the oil
    - 0.90 to 0.92 g/cc reduced the pumps efficiency
    - ~20 gU/L, or ~4.5 g^{235}U/L

The Vacuum Pump

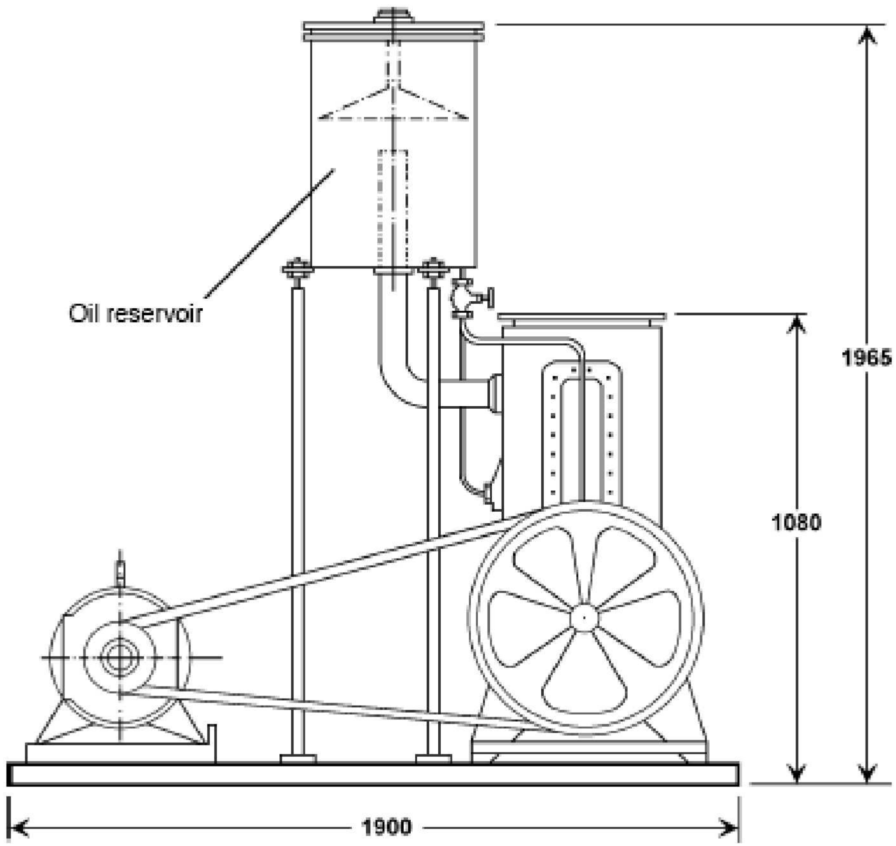


Figure 15. Vacuum pump diagram showing oil reservoir (Dimensions are in mm)

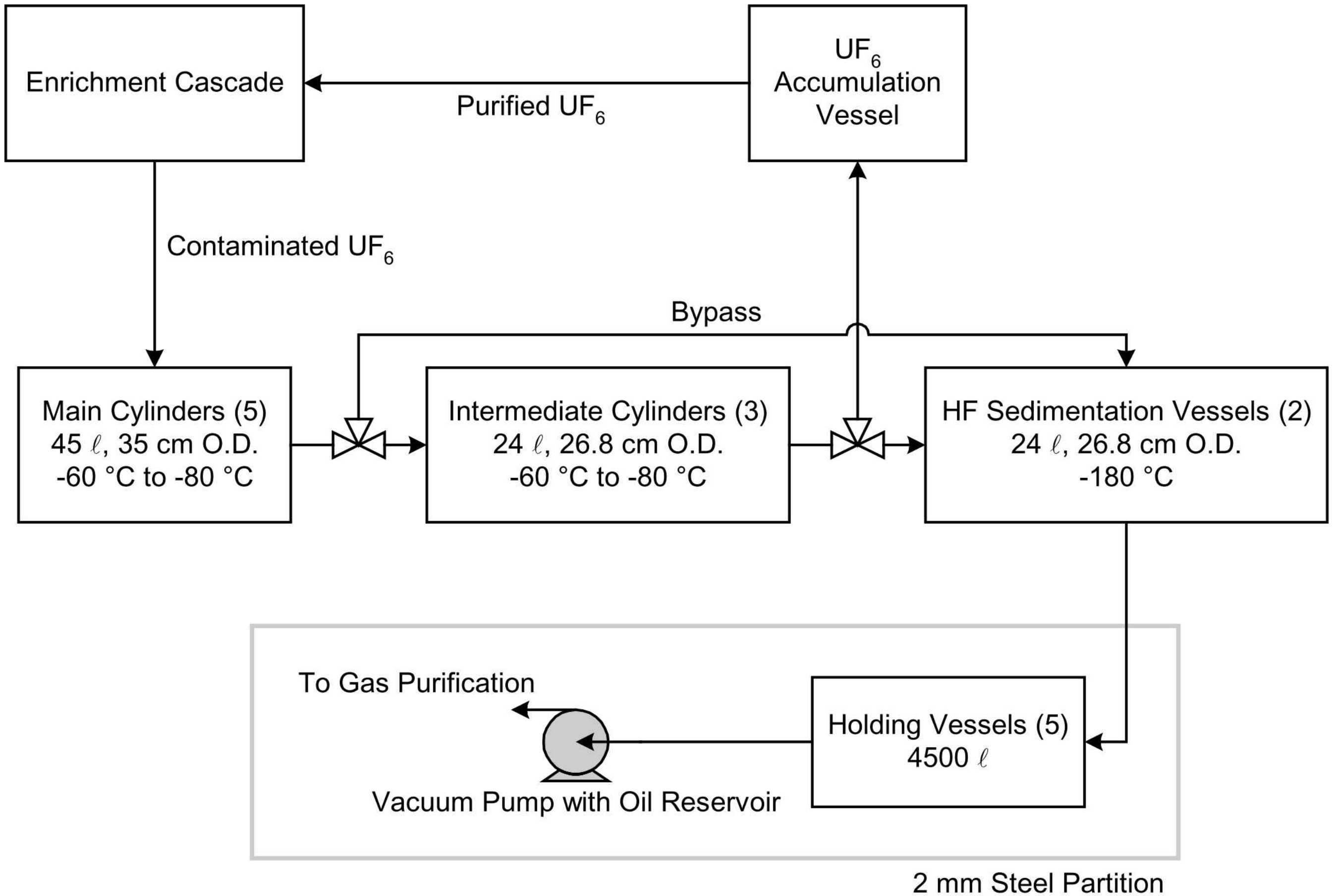
Deviations

- 1 July
  - Failures at the liquid nitrogen (LN) facility cut its output by 50%
    - operating procedures were altered
      - automatic nitrogen flow to the MCs was disable
      - LN was added manually as needed to the MC
  - In addition cooling of the ICs was discontinued in violation of procedures
  - UF accumulation in the pump oil was increased

Deviations

- 10 July
  - A regulator within the main enrichment cascade began leaking
    - stream became much more contaminated with air
    - to compensate a greater fraction of cascade was diverted to the purification stage, DSS-6

  - UF accumulation in the pump oil was increased yet again



Enrichment Cascade
Purified UF_6
UF_6 Accumulation Vessel
Contaminated UF_6
Bypass
Main Cylinders (5)
45 ℓ, 35 cm O.D.
-60 °C to -80 °C
Intermediate Cylinders (3)
24 ℓ, 26.8 cm O.D.
-60 °C to -80 °C
HF Sedimentation Vessels (2)
24 ℓ, 26.8 cm O.D.
-180 °C
To Gas Purification
Holding Vessels (5)
4500 ℓ
Vacuum Pump with Oil Reservoir
2 mm Steel Partition

The Accident

- 14 July; 04:45
  - A high radiation alarm sounded within DSS-6 and operations were halted

  - A radiation control officer (RCO) responded and surveyed the main room and equipment
    - where the alarm was located
    - average exposure rates ~9 mR/hr
    - the criticality accident alarm system had not activated,
      - 7 mR/hr trip point
    - radiation levels fell rapidly and as a result the RCO authorized resumption of activities

The Accident

- 14 July; 07:30
  - an operator turned on the vacuum pump from the control panel
  - as he approached the isolation valve (~0.5m) to open it the criticality accident alarm sounded
    - The operator later reported having seen a flash of light
    - Turned off the pump and ran to a phone 200 meters away
  - alarms in 3 other buildings sounded simultaneously
    - 160 to 320 meters (~500 10 1000 feet) from DSS-6
  - exposure rates
    - 0.7 mR/h at 100 meters from building
    - 36 mR/h adjacent to building

The Investigation

- Two excursions had occurred in the vacuum pump oil reservoir
  - First excursion was at 04:45
    - it is not known if the pump had just been switched on or was running
      - suspect that is was just turned on
    - actual configuration, quantities, concentration, etc., are unknown and unknowable
    - yield was roughly estimated to be ~2×10^{14} fissions
  - Second excursion at 07:30 when the pump was switched on
    - oil was ejected from the pump into the reservoir
    - terminated by
      - radiolytic gas
      - temperature
      - ejection of oil back into the pump and other equipment

The Oil Reservoir

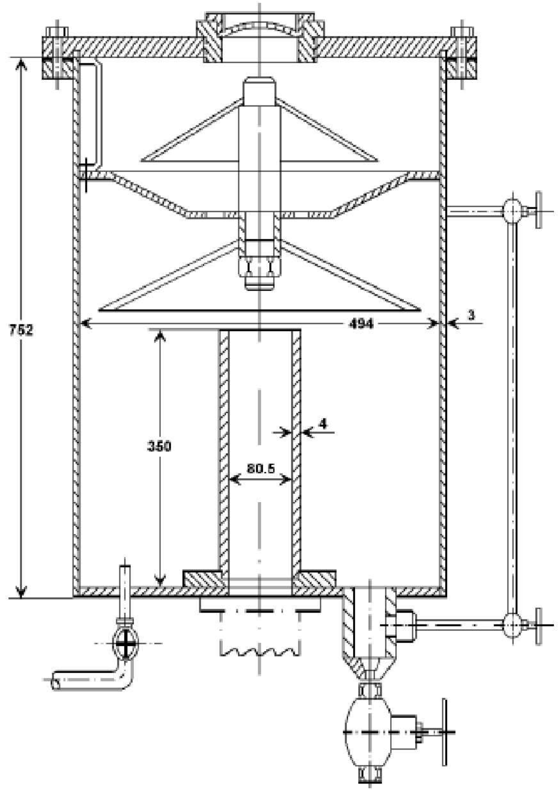


Figure 16. Oil reservoir (Dimensions are in mm).

Reservoir Contact Exposure Rates

Date	Time	Elapsed Time (hours)	Rate (R/h)	Note
14 July	12:00	4.5	36.0	
	13:30	6.0	25.2	
	15:25	7.9	14.4	
	17:30	10.0	14.4	
	20:10	12.6	11.2	
	23:15	15.75	9.0	
15 July	12:00	28.5	3.6	
16 July	10:00	50.5	1.8	
	15:00	55.5	1.8	
17 July	11:00	75.5	1.1	
	15:00	79.5	1.1	
18 July	07:00	95.5	0.9	Draining started
19 July	08:00	120.5	0.3	Draining ended

Consequences

- 18 and 19 July
  - A total of 42.95 liters were drained into 5-Liter bottles
  - Analysis (luminescence method) indicated 173 gU/L ± 30 to 40%
    - 39 $g^{235}U/L$
    - 70 gU/L to 242 gU/L
      - 16 $g^{235}U/L$ to 55 $g^{235}U/L$
- ~1.2 x 10^{15} fissions
- Operator received and estimated 200 rad and experienced mild radiation sickness

Causes

- Beginning on 1 July (LN plant failures)
  - Written procedure was altered
    - the temperature sensors and recording instruments on the Main Cylinders (MCs) were turned off
    - the MCs were cooled manually in an undoubtedly difficult process
  - In violation of the new procedure
    - LN was poured directly onto the iron shot and not through the coils
      - significant temperature gradients resulted
      - erroneous temperature readings because the sensor (thermometer) was directly adjacent to the pour point
    - cooling of the Intermediate Cylinders (ICs) had been discontinued altogether

Causes

- Probably of more significance (kinetically speaking)
  - The air leak in the main cascade accelerated the UF build-up
    - greater fraction of the stream was diverted
  - It is was not reported when the oil was last changed
    - could have been on 1 July
    - anytime between 1 and 10 July or
    - even after 10 July
    - buildup could have resulted anywhere from 2 to 14 days
  - In any case the increase in the diverted stream increased the build-up rate from the previous 10 days
  - If the oil was fresh on 1 July, it was due to be changed the following day

Human Factor Aspects

- What aspects of human factors are illustrated by this accident?
  - Human factors categories
    - Instructions
    - Human/machine interface
  - Systemic faults
    - Operators were tasked with working
      - around inadequate nitrogen supplies
        - undoubtedly pressured operators to shutdown IC cooling
      - around broken equipment (cascade air leak)
    - Control implementation too difficult
      - Operators were forced to find a work around
        - Pouring directly over iron shot rather than into the coil

United States Department of Energy

Nuclear Criticality Safety Program (NCSP)

Module 02
Process Criticality Accident
Number 11

Union of Soviet Socialist Republics

Mayak Production Association

Mayak, 7 September 1962

- Union of Soviet Socialist Republics
  - Mayak Production Association
  - Friday, 7 September 1962
  - Facility was equipped with an alarm system
  - Purification and conversion facility

- This accident is not well described in LA-13638
  - Some information is presented as if it was known at the time when in fact it was not;
    - the information is not aligned with the time line
    - operators believed they were working with low-equity residues

Residues

- Each step of the purification and conversion process produced Pu bearing residues
  - Sand, Slag, Crucible, molds
  - Accident occurred in a nitric acid dissolution process
    - part of the Pu recovery process

- Residues from the various processes were collected, canned, and staged pending introduction in the recovery process

- There was no practical method for assaying the residue containers

- Fissionable material mass was estimated based on process knowledge, i.e., historical averages
  - Arrived at from records of assays conducted on the solutions generated in previous recovery operations

Residues

- 1% by weight was the value assigned to these residues, e.g., 50 grams in a 5kg batch
  - This included the statistical deviation
  - The particular recovery operation involved in the accident was limited to these low level residues
    - Compliance to the criticality mass limits was based on applying the 1% rule to a batch of residue

- Occasionally upstream process deviations lead to a much higher loading, i.e., significantly > 100 grams per 5kg batch
  - These items were not supposed to be part of the recovery operation

- **Both high and low level residues would be staged in the same glovebox awaiting disposition**

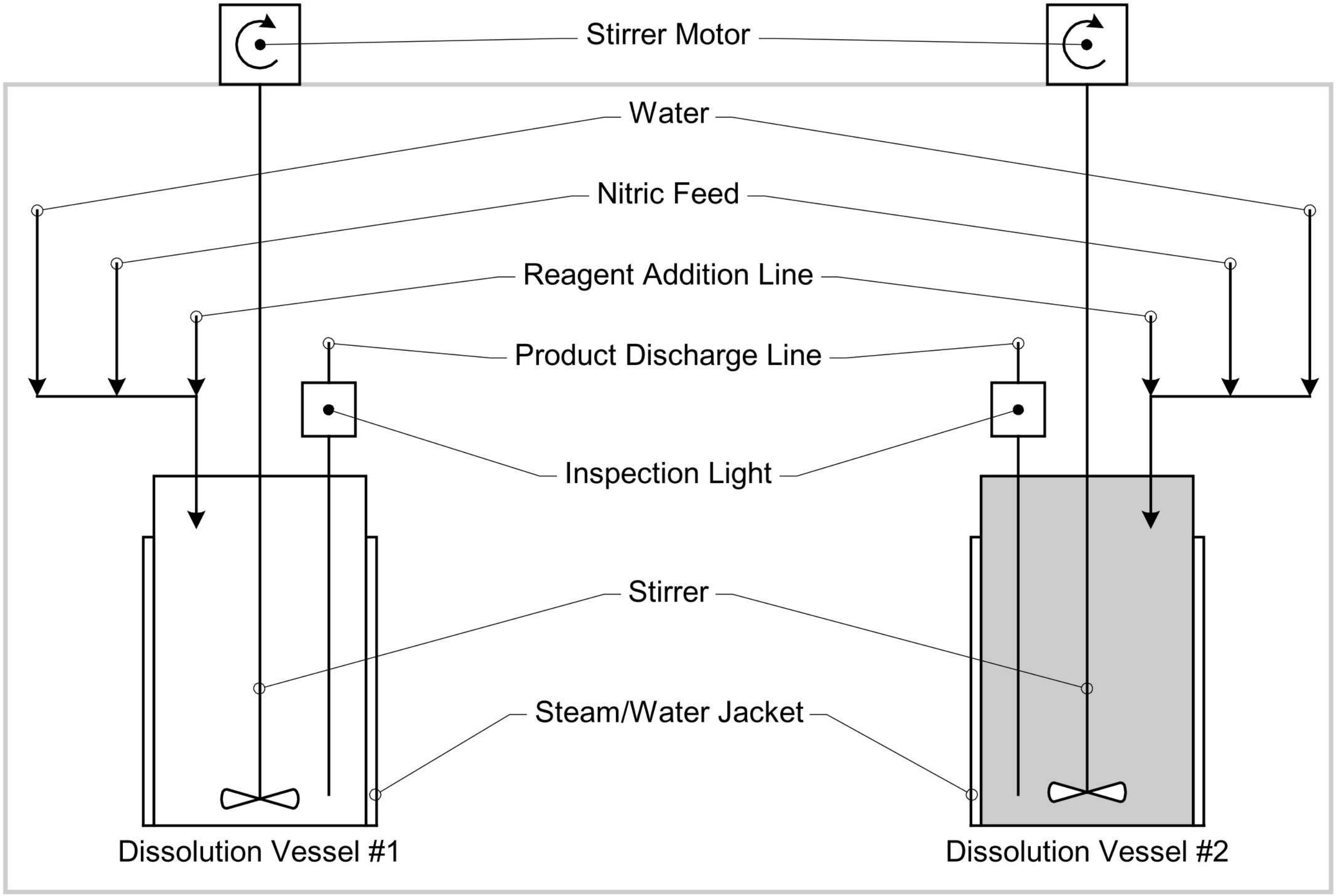
The Process and Equipment

- Residues were dissolved in nitric acid
- Procedures limited the number of source cans to 6
  - Typically operators would use only 5
- The vessels were cylindrical in shape
  - 45-cm (~18-inches) in diameter
  - 62-cm (~24-inches) in height
  - ~100-liters in volume

The Process and Equipment

- Each vessel was
  - equipped with a stirrer and 6-cm (2.4-inch) thick heating jacket that used circulating hot water
  - open topped which allowed residues to be manually added
  - equipped with fixed lines for adding acids, water, and reagents
  - equipped with a sampling device to help monitor acidity (pH)
    - important to maintain a specified acidity level
    - high acidity was reduced by charging the system with additional residue

The Process and Equipment



Lead-Up Activities

- Evening shift of 6 September
  - A batch of residue was dissolved in vessel 2
    - residue was from reduction smelting operation
    - the operation was new and still in the research phase
    - inefficient and produced high level residue
  - The batch contained 318 grams of Pu, much higher than the 1% limitation
    - Likely that the operator believed this to be low-equity
  - After dissolution, the Pu nitrate stream discharged contained only 11 grams
    - Not necessarily inconsistent with low-equity residues

The Accident

- Another batch of residue containing 352 grams of Pu was introduced for dissolution

  - This batch was not dissolved according to procedure
    - Vessel 2 had been down for maintenance immediately preceding this operation
    - The liquid transfer lines were all not operating, only nitric acid was initially added to the vessel
    - Water was added several hours later; should have been added first
    - The quantities of both acid and water were also outside of the procedural requirements

The Accident

- After several hours of mixing the solution was determined to be acidic
  - Further mixing eventually resolved the acidity
  - It is likely, but not documented in the process records, that additional residue was added to the vessel to help adjust the pH
- The process was halted and the solution was drained (decanted) from the vessel
- The process was repeated two additional times with new residue feed batches

The Accident

- After the completion of the fourth batch the heating and mixing were then stopped to allow for solids to settle

- About 3 hours later, i.e., 00:15 on September 7th
  - The criticality alarms sounded
  - All personnel evacuated to the emergency muster location
  - Trip level of the detectors was set at 110 mR/hr
    - Spaced a maximum of 30 meters apart
    - Generally much closer together
  - 15 minutes later the radiation levels “in the vicinity” of the glovebox were about 2.2R/h
  - 30 minutes after, the levels were 1.8 R/h

Recovery Operations

- Actions were conducted remotely from the supervisor's office about 30m distant
  - 15 minutes after the accident an unsuccessful attempt was made to empty vessel 2 by opening a drain line remotely
  - The heating and mixing were switched back on
    - Temporarily reduced reactivity but did not stop the reaction
  - The heating and mixing were then switched off, and a 1:10 a second spike of about the same size occurred
    - Based on alarm activation

Recovery Operations

- Shortly thereafter, the plant, building, and safety manager, along with criticality safety personnel arrived and took charge
  - Continued the effort to remotely drain the vessel
  - Despite the efforts at 01:55 a third excursion occurred tripping detectors further away
    - Excursion was larger than the first two
  - The mixer and heater were then switched back on as a mitigating action

Recovery Operations

- The vessel was finally drained in a two part procedure
  - Half the contents were transferred to an aqueous collection vessel where it was transferred into bottles
  - Once the bottles were filled, the process was repeated
  - Bottles were isolated and processed only after the radiation levels had dropped

Consequences

- Analysis later determined that Vessel 2 contained 1324g of Pu
  - 933 grams in solution
  - 391 grams as precipitate (660 grams total solids, mostly graphite)
  - More than 3 times the limit (likely 400g)

- No personnel over exposures
  - the workers were otherwise occupied when the first excursion occurred (break)

- 2 x 10^{17} fissions estimated

Causes

- Unfavorable geometry vessel
- High level residues charged to the vessel despite the 1% limitation
- Failure to segregate high and low level residues
- Unclear and difficult to read labeling of the residues
- Procedural violations in the dissolution process in terms of adding reagents
  - The correct order may have led to better dissolution and therefore reduced accumulation from batch to batch
- Inadequate supervision
- Inadequate material accounting
  - Lack of real time NDA technique for the residues

Human Factor Aspects

- What aspects of human factors are illustrated by this accident?
  - Human factors categories
    - Instructions
  - Systemic faults
    - Inadequate equipment
      - unfavorable geometry vessels
      - inoperative equipment (water supply)
      - acidity controlled by adding residue rather than reagent
    - Inadequate administrative requirements
      - 400 gram limitation was not enforceable operator
      - Segregation and labeling of residues was poor

United States Department of Energy
Nuclear Criticality Safety Program (NCSP)

Process Criticality Accident Number 14

United States of America

United Nuclear Fuels Recovery Plant

Wood River Junction, Rhode Island

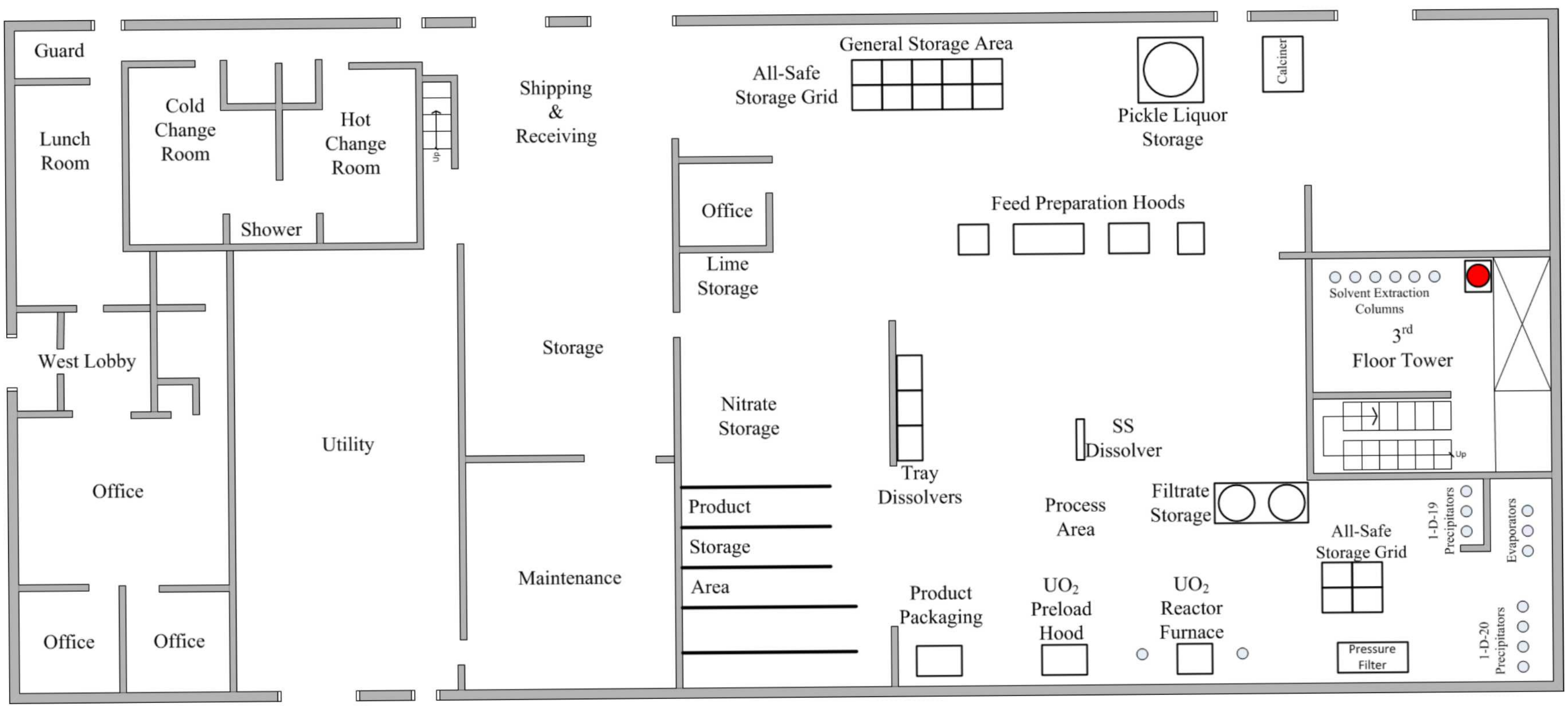
United Nuclear Fuels Recovery Plant

- United States of America
  - United Nuclear Fuels Recovery Plant
  - Friday, 24 July 1964
  - Facility was equipped with an alarm system
  - Uranium recovery plant
- Only commercial facility criticality accident
  - Uranium recovery from scrap fuel and waste solution
  - Operated three 8 hours shifts 5 days a week
      - 1 supervisor and 3 operators
      - 1 guard
    - One superintendent on the day shift only
  - Accident occurred on the 4pm to Midnight shift
- Facility had only been open for about 4 months
  - 16 March 1964

The Process

- Feed
  - Uranyl nitrate solution (or scrap UO_2)
  - Shipped to the plant in 55-gallon drums
    - 1 to 5 grams/liter (1 gram of Cd for every gram of ^{235}U)
- Solvent extraction
  - Solution was purified using extraction columns
    - TBP/kerosene organic wash
  - After acid stripping
    - Uranyl nitrate bubbled through a trichloroethane (TCE) column
      - 4 to 6 liters of TCE
      - Removed TBP/kerosene remnants
    - Concentrated via an evaporator to ~100 g/l
- Product
  - Precipitated to ammonium diuranate and then burned to UO_2

Facility Layout



Tricholorethane Difficulties

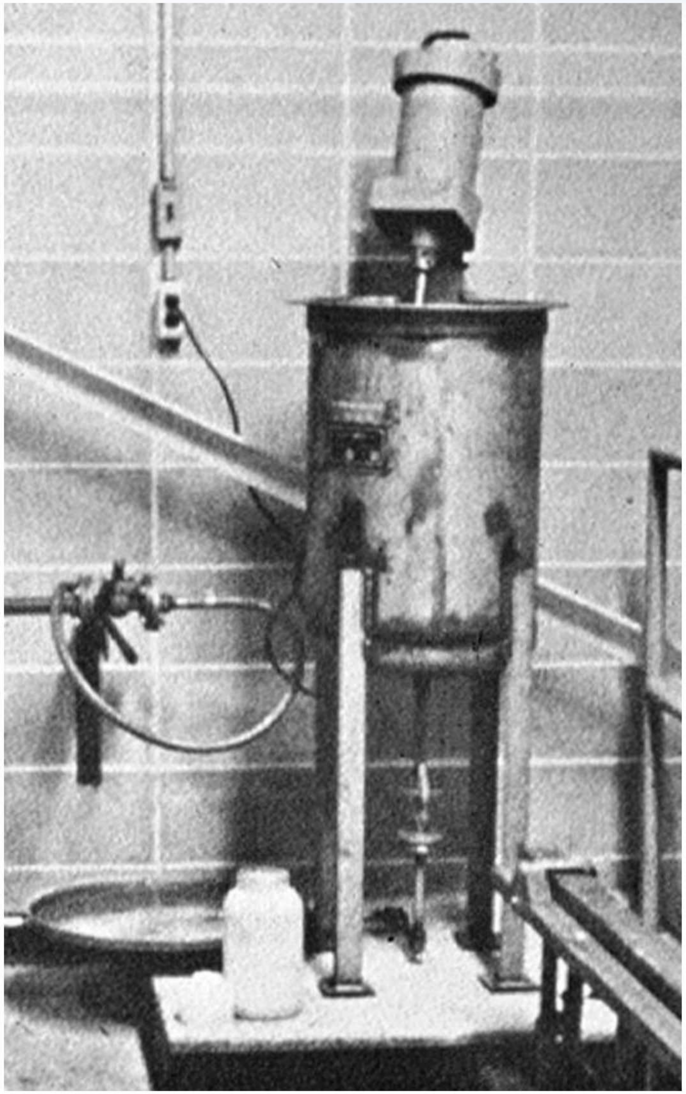
- Projected lifetime
  - ~6 months
- Startup difficulties resulted-TCE accumulated much faster
  - Inefficiencies in acid stripping led to
    - Higher solvent carryover
    - Higher retention of uranium
      - 400 to 800 ppm (~1 to 2 g/l)
- TCE wash procedure developed
  - Sodium carbonate added to 11-liter “safe” bottles
  - 30 to 40 lb bottles were agitated by operator(s) for ~20 minutes
  - Uranium would separate out into the sodium carbonate
    - Manually separated and sent to recovery
  - Often needed to be repeated 2 to 3 times per bottle
  - Washed TCE/solvent poured out along the facility fence line to kill weeds

TCE Washing

- In early July process issues led to accelerated TCE accumulation
  - In-bottle process was difficult
    - Unwieldy, slippery, heavy
    - Time consuming
- A more efficient process was developed on July 16th
  - A reagent (sodium carbonate) makeup tank was used
    - Had a stirrer
    - **18-inch diameter, 26.375-inches deep**
  - Supervisor approved the process change for <800 ppm
  - From July 16 to 24 two operators had washed 10 to 12 bottles each in this tank

❖ **Washing of TCE via any method was not part of the operating license**

Sodium Carbonate Make-Up Tank



Changes in Process Conditions

- On July 23rd
  - Plant process evaporator plugged 12:00am to 8:00am shift
    - Disassembled on the 8:00am to 4:00pm shift
      - Overseen by superintendent
      - Uranyl nitrate and nitrate crystals removed from various parts of the system
      - Solution was collected in 11-liter "safe" bottles
        - ~5 bottles generated over the course of two shifts
          - First instance of the bottles being used for high concentration solution
        - All such bottles were labeled "concentrated OK liquor"
        - Scattered around the process floor
        - Some in "safe-carts" others in racks
  - Evaporator clean-out and reassembly was completed on the 4pm to midnight shift
    - Same staff that was present during the accident

Fits and Starts

- For several shifts
  - Processes were being re-started
  - Concentrated solution was being loaded and unloaded because of dissolver and precipitator problems
- July 24th 4pm to Midnight shift
  - Several bottles of high concentration uranyl nitrate solution were still scattered around the process floor
  - Each operator was assigned a subset of processes
    - Dissolvers
    - Extraction columns
    - Evaporator and precipitator
  - At around 6pm the extraction column operator asked the supervisor if TCE needed washing
    - Because plans called for the used TCE to be used for column rinsing he was told no

The Accident

- At around 6pm
  - The extraction column operator inquired if TCE needed washing
    - Because plans called for the used TCE to be used for column rinsing he was told no
- Regardless
  - Operator proceeded to locate a bottle of used TCE
    - Perhaps to obtain an empty bottle
    - Transported a bottle and cart to the stairwell
    - Carried the bottle up to the third floor make-up tank
    - Bottle label was found later by the cart
      - Concentrated “OK liquor”
  - The operator proceeded to pour the bottle contents into the tank
    - Already contained 41-liters of sodium carbonate
    - Stirrer was on, valve on the bottom the tank was open
  - **Near the end of the pour prompt criticality was exceeded**

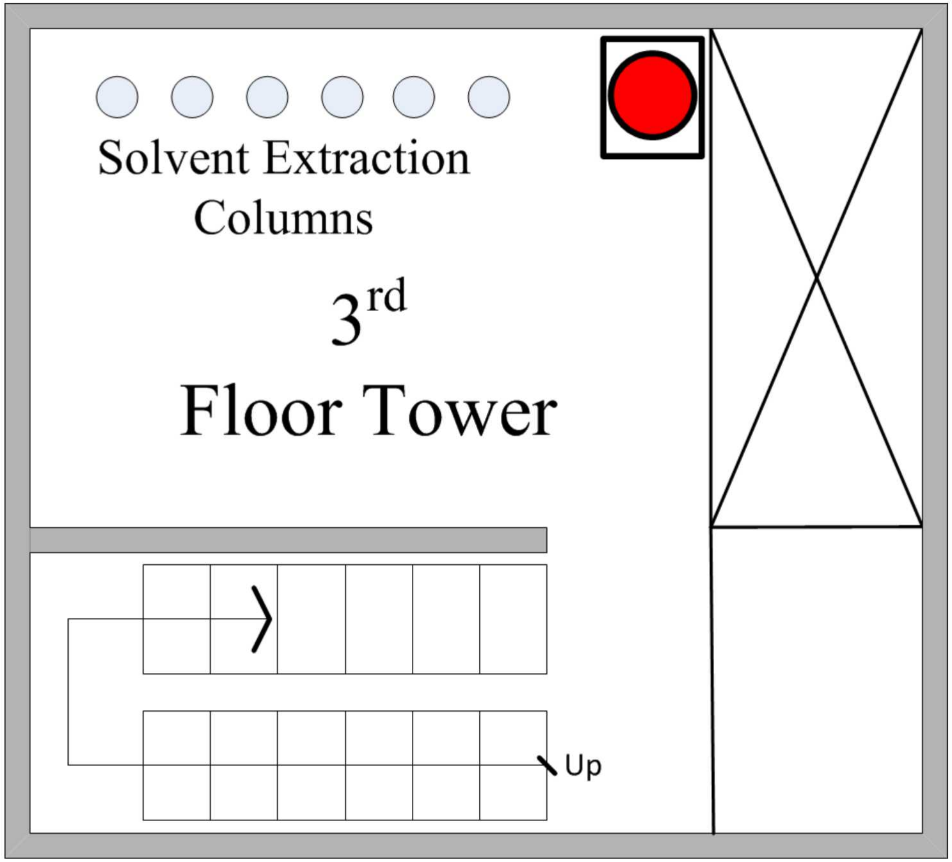
The Excursion

- Operator
  - Saw a flash of bluish-white light
  - Fell to the floor
  - Regained his footing, evacuated, and ran to the emergency shack
- ~20% of the solution was immediately ejected from the tank
- The criticality alarms system was activated
  - All personnel evacuated to the emergency shack
- Immediately obvious to everyone that an accident had occurred
  - Calls for help and notifications were made
  - Superintendent arrived about ½ hour later

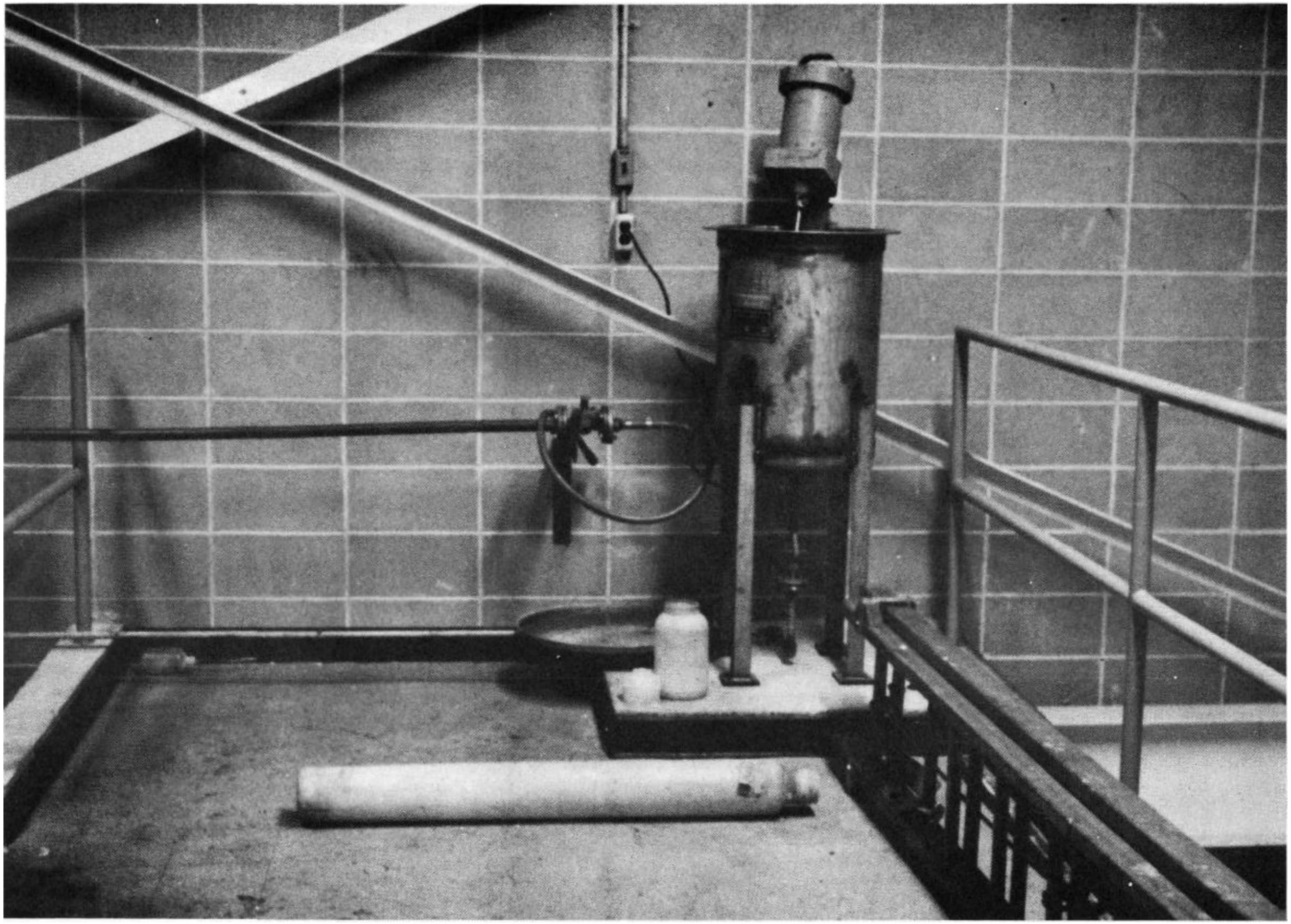
Recovery?

- Victim transported to a hospital
- About an hour after the accident
  - Superintendent and supervisor re-entered the building to drain the tank
  - Alarms were still sounding
  - On the third floor
    - Supervisor remained in the doorway
    - Superintendent approached tank
    - Removed the 11-liter bottle (still up-ended in the tank)
    - Switched off the stirrer
    - Exited the room passing by the supervisor and preceded him down the stairs
- Superintendent
  - Returns to the tank shortly after and switches the stirrer back on because something was preventing the tank from draining

3^{rd} Floor Tower



Sodium Carbonate Make-Up Tank



Bottle Labeling Difficulties

- Bottle tags
  - originally color coded pressure sensitive gummed labels
    - did not adhere well
  - new tags held on by scotch tape were tried
    - also failed
  - bottles would inevitably have organic on the surface
  - settled on tags held on by rubber bands
    - this too had issue as the organic would degrade the rubber bands
  - tags were not always completed as required by the license
    - originated as sample tag that traveled with sample
      - sample tag # and results recorded in lab analysis logbook and on tag
      - sample and tag returned to the bottle of origin

Consequences and Mystery

- 3 significant exposures
  - 1 fatality
    - Robert Peabody received about 10,000 rad
      - father of nine children
      - second job
        - auto mechanic during the day
  - Inconsistent doses
    - Superintendent
      - ~60 rad?
    - Supervisor
      - ~100 rad?
  - Superintendent had twice approached the vessel?

Fools Go Where Others Fear to Tread

- There were actually 2 excursions
  - 1.0×10^{17} fissions
  - 3.0×10^{16} fissions
  - 1.3×10^{17} fissions total
- System was subcritical when the superintendent approached the tank
  - Shape induced by the stirrer and the ejected solution had driven the system subcritical
- After the stirrer was turned off
  - The vortex collapsed and the system went through a supercritical geometry just after the superintendent passed-by the supervisor in the stairwell
  - Later when the superintendent switched the stirrer back on, the distribution never reached critical by pure chance

Back Then

Now

United States Department of Energy
Nuclear Criticality Safety Program (NCSP)

Process Criticality Accident Number 15

Union of Soviet Socialist Republics
Electrostal Machine Works
3 November 1965

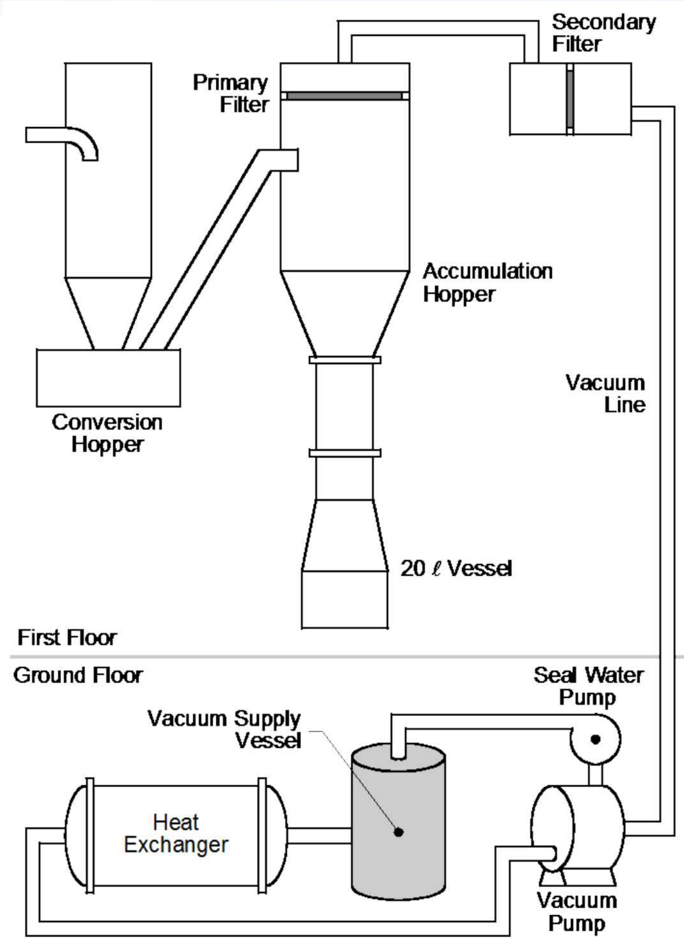
NCERC NATIONAL CRITICALITY EXPERIMENTS RESEARCH CENTER
Oak Ridge National Laboratory
Sandia National Laboratories
Lawrence Livermore National Laboratory
Los Alamos NATIONAL LABORATORY

Background Information

- Union of Soviet Socialist Republics
  - Electrostal Machine Works
  - Wednesday, 3 November 1965
  - Facility was equipped with an alarm system
- UF_6 to UO_2 conversion facility
  - Originally designed to process 2% enriched uranium
    - September 23, 1964 to October 19,1965
- Only oxide-water slurry accident
  - Pseudo-solution

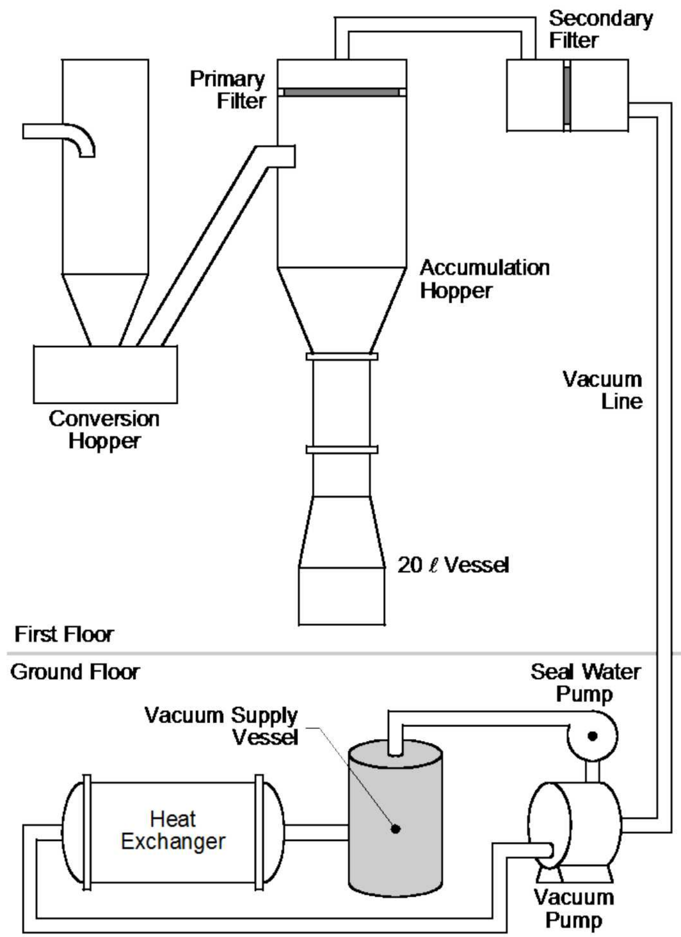
SATURN

- UF_6 to UO_2 conversion system
  - UF_6 was burned in a conversion hopper
    - Atmosphere rich in hydrogen
    - Uranium oxide accumulated at the bottom of the hopper
- UO_2 was vacuum transferred to an accumulation hopper
- Gravity transferred to geometrically favorable 20 liter bottles


Secondary Filter
Primary Filter
Accumulation Hopper
Vacuum Line
Conversion Hopper
20 ℓ Vessel
First Floor
Ground Floor
Seal Water Pump
Vacuum Supply Vessel
Heat Exchanger
Vacuum Pump

The Vacuum System

- Location
  - one physical floor beneath SATURN
- Equipment
  - Vacuum pump and water pump
  - Vacuum supply vessel
    - 65 cm diameter; 90 cm height
    - 300 liter capacity---operated half full
    - Equipped with glass site gauge
  - Shell and tube heat exchanger
- Vacuum pump was protected by
  - Primary filter on top of the accumulation hopper
  - Secondary filter in the vacuum line
  - Filters constructed of Lavsan, a fluorinated plastic woven into a fabric


Secondary
Filter
Primary
Filter
Accumulation
Hopper
Conversion
Hopper
Vacuum
Line
20 ℓ Vessel
First Floor
Ground Floor
Seal Water
Pump
Vacuum Supply
Vessel
Heat
Exchanger
Vacuum
Pump

Criticality Safety

- Each shift
  - Visually inspect secondary filter
    - Determine level of oxide accumulation
    - Examine for defects or tears
  - If the operator could not see through the filter
    - Filter was replaced
    - Primary filter was inspected
  - Obtain and analyze vacuum system water sample (1.5 hours to receive results)

The Switch

- Beloyarskaya Nuclear Power Plant
  - Two new uranium-graphite reactors were being commissioned
  - Required 6.5% enriched fuel
- Conversion facility was shutdown on October 19, 1965
  - All systems were thoroughly cleaned out
- Conversion restarted on October 22,1965
  - At 11:10 on 3 November 1965
    - Building 242 criticality accident alarm system activated
    - All personnel evacuated
    - Alarm systems of adjacent buildings did not activate
  - ~50 minutes after the alarm
    - Chief Physicist re-entered building
    - Performed survey with portable γ-ray instrument
    - Determined accident site was vacuum supply system vessel
      - 3.6 R/h @ 1.5 meters from vessel surface

The Recovery

- Vessel drained
  - Geometrically favorable trays were positioned below the vessel
    - Site gauge was broken with a long pole
    - ~60 liters of liquid was collected
      - 85 g/l of uranium
      - 5.1 kg U
        - 331g ^{235}U
  - 8 days later (11/11/65)
    - Vacuum supply vessel was opened
      - 51kg of U additional recovered
        - 3.32 kg ^{235}U
    - Balance of system (S&T HE, piping)
      - 13.9kg U
        - 0.904 kg ^{235}U
- 70kg U total; 4.6kg ^{235}U

The Causes

- Records review confirmed that on 19 Oct
  - Filters had been replaced
    - Primary
    - Secondary
  - 150 liters of water had been drained and replaced in vacuum system
  - Plans to install a third filter could not be completed

So What Happened?

- Records confirmed that on 19 Oct
  - Filters had been replaced
    - Primary
    - Secondary
  - 150 liters of water had been drained and replaced in vacuum system
  - Plans to install a third filter could not be completed on time
- Multiple violations of procedure
  - No primary filter was in place
    - Investigation could not determine how long it had been absent
  - Secondary filter was not properly secured
    - Not all swivel locks were properly positioned
  - Operators did not note missing product
  - Since 19 Oct the vacuum system water had been sampled
    - 0 times

The Consequences

- Fission yield estimates
  - 5×10^{15} fissions
    - Based on 3.6 R/h at 1.5 meters 50 minutes after the accident
  - 1×10^{16} fissions
    - Based on ^{64}Cu activation of a nearby wire
- Excursion most likely
  - Occurred during settling
    - Vacuum system had been shut off shortly before
  - Was not delayed
    - Background source estimated at 800 n/s
  - Terminated by
    - Continued settling
    - Ejection of material into process piping

United States Department of Energy
Nuclear Criticality Safety Program (NCSP)

Process Criticality Accident Number 16

Union of Soviet Socialist Republics
Siberian Chemical Combine
16 December 1965

NCERC NATIONAL CRITICALITY EXPERIMENTS RESEARCH CENTER
Oak Ridge National Laboratory
Sandia National Laboratories
Lawrence Livermore National Laboratory
Los Alamos National Laboratory

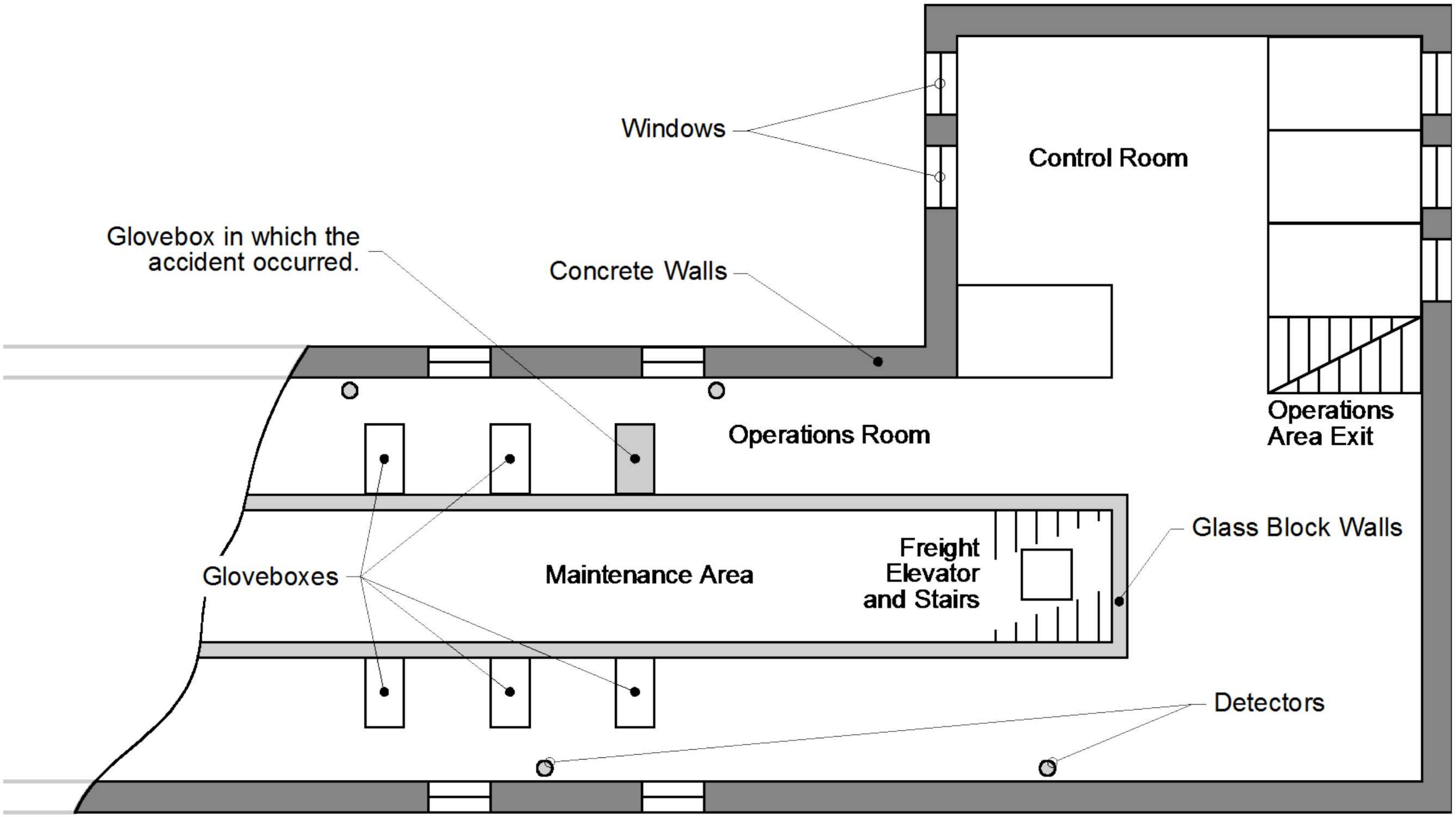
Background Information

- Union of Soviet Socialist Republics
  - Mayak Production Association
    - sixth accident
  - Thursday, 16 December 1965
  - Facility was equipped with an alarm system
- Residue recovery process area
  - Residues generated from dissolution/precipitation/reduction processes
    - Difficult to recover
  - Dissolution vessel
    - Uranyl Nitrate solution
- Hands-on actions were required to terminate the accident

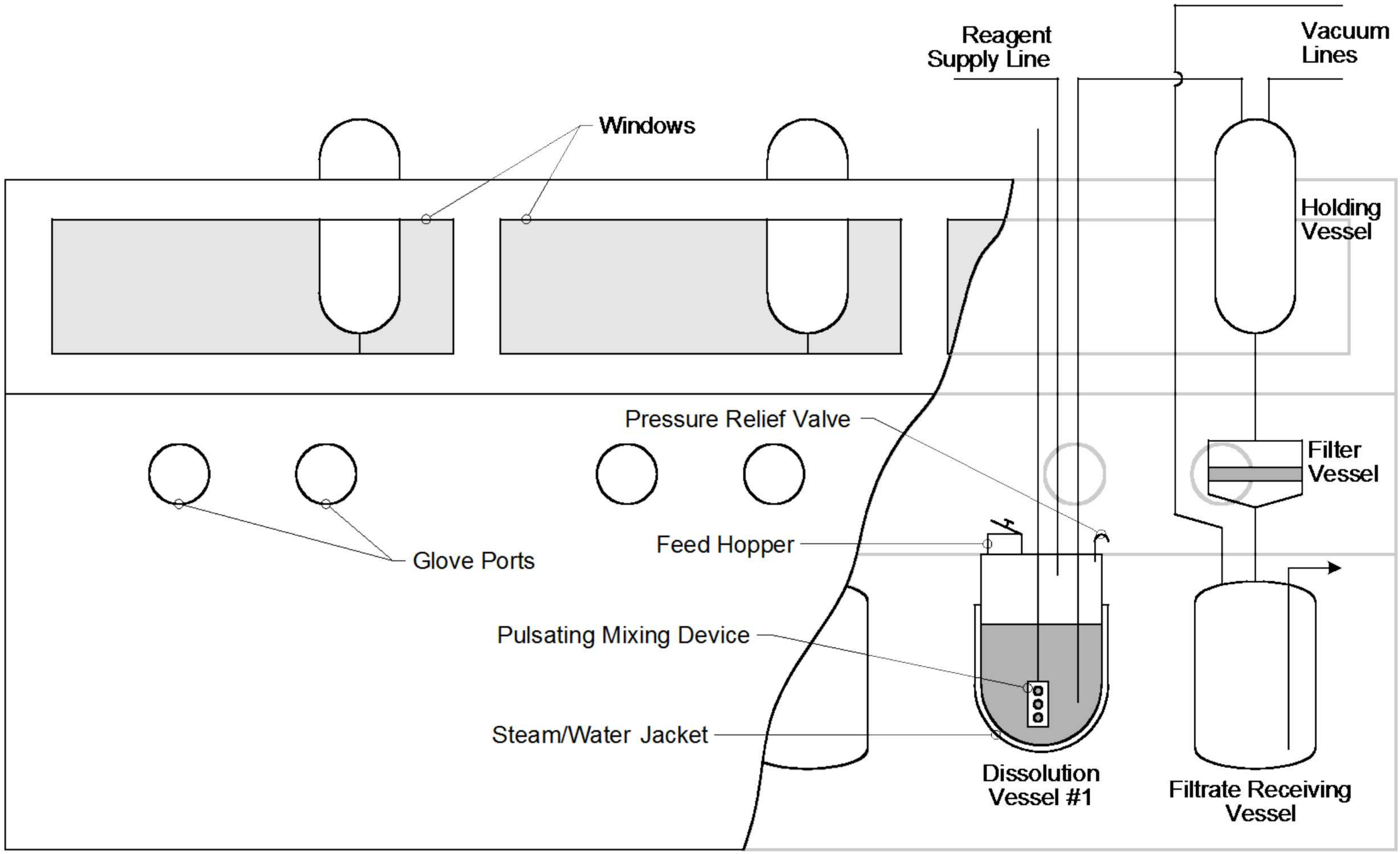
The Setting

- Residue dissolution glovebox
  - Three identical sets of process equipment
    - Parallel operation
    - Dissolution vessel
    - Holding vessel
    - Filter vessel
    - Filtrate receiving vessel
- Dissolution vessels were cylindrical
  - Elliptical bottom; 45-cm (18-inches) in diameter; 100 liters in volume
  - Pulsating mixer and feed hopper with sealable flat cover plate
  - Pressure relief valve
  - 2.5 cm (~1-inch) steam water jacket for heating

The Facility Layout



The Glovebox



The Process

- Residue introduced via a feed hopper
  - lid that could be sealed in locked closed
- Acid and heat were added to the system
- Normal dissolution process
  - 100 ºC
  - 1.5 hours
  - constant mixing
- After dissolution
  - transferred to a holding vessel
  - filtered to remove any solids
  - Finally staged in the filtrate receiving vessel

15 December 1965

- In a related operation
  - Contrary to the criticality safety controls, a supervisor had ordered the calcining (burning) of a batch residue
    - Batch #1726 had >1% by weight U
    - The furnace was limited to residue ≤ 1% by weight U
  - After burning batch #1726 was
    - Sampled per procedure
    - Sent immediately to the dissolution feed staging glovebox
      - Multiple residue containers were already present
      - This was done before the sample results were received
  - The analysis determined the U content to be 44% U by weight
    - Result was recorded in the laboratory sample book but had not been transmitted back to floor for recording on the batch accountability card

15 December 1965

- Batch #1726
  - An operator, preparing material for dissolution, discovered the missing analysis results
  - Phoned the analytical laboratory
  - Informed batch #1726 was 0.32% by weight uranium
    - In fact this was the content of batch #1826
    - The actual content was 138 times larger, i.e., 44% by weight
    - The erroneous results were recorded on the container accountability card
    - The error has been attributed to poor communications complicated by differences in dialects

16 December 1965

- 5 kg from batch #1726
  - loaded into dissolution vessel #1
    - Believed to contain around 20 grams
    - In reality it had 2.2kg of U(90) or 1980 g of ^{235}U
  - Criticality safety limit was 300 grams
  - Inadvertently the limit was violated by > 6 times
- After 40 minutes
  - the process was halted to accommodate cleaning for a shift change
- ~10 minutes later (~10:00 p.m.)
  - Nearest criticality alarm sounded briefly and then stopped
  - The operator reported to the control room as per procedure
    - While at the control room the alarm activated again
    - Shortly thereafter, ~10:10 p.m., additional more distant alarms began sounding
    - The building was evacuated (tunnel muster point)

The Response

- Initial actions
  - Prior to emergency personnel response
    - the situation was monitored from an adjacent building
      - ~50-meters distant
      - remote radiation readouts, both gamma and neutron
    - 4 additional excursions were noted separated by 15 to 20 minutes
- At 11:00 p.m. emergency personnel arrived
  - Senior criticality safety specialist, facility management, health physics
  - Based on a radiation survey the team judged it was safe to occupy the control room of the affected building
    - relocated
  - Based on interviews, accountability records, and system schematics the accident location was narrowed to either
    - **dissolution vessel #1 OR the holding vessel**

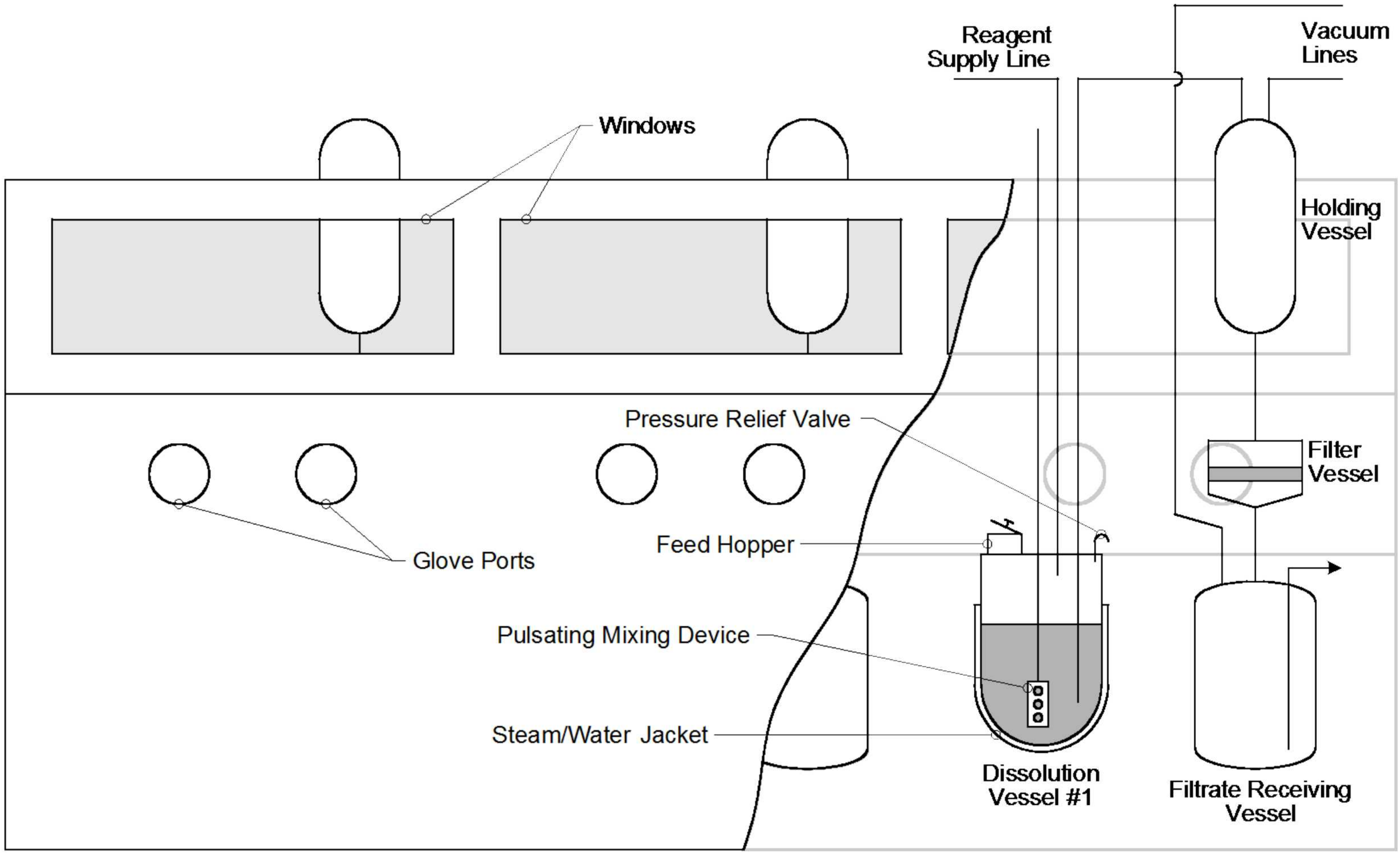
The Response

- Continuing excursion
  - System continued to oscillate
    - instruments and surveys indicated radiation minima of ~8 R/h @ 2m from the glovebox
- After the 9th excursion
  - Cd poisoned solution was remotely pumped to the holding vessel
  - An argument between the criticality safety specialist and process supervision ensued
    - Process supervision wanted to re-occupy the area and begin recovery and cleanup
  - After ~20 minutes, while the argument was still on-going, a 10th excursion occurred
    - The argument quickly terminated
    - Established the most likely accident site as dissolution vessel #1

The Response

- Remote addition of Cd solution was not possible
- Draining was considered too dangerous
  - Required multiple operators at the glovebox
  - Time intensive valve manipulations
- The Plan
- Send personnel in one at a time with one specific task each
  - One operator would remove the gloves from two glovebox ports
  - One operator would unlock and open the feed hopper lid
  - The final operator would then very CAREFULLY insert a wadded up piece of Cd foil into the nitric acid solution through the hopper
    - Careful placement required that his hand and part of his arm would be inside the vessel itself

The Glovebox



The Response

- After preparation
  - Tasks 1 and 2 were accomplished
    - Two specially chosen operators each proficient at their chosen task
    - ~30 and ~60 seconds, respectively
  - The effort was then halted as radiation reading indicated that an 11th excursion was underway
  - After the radiation levels had again fallen
    - a senior engineer/physicist quickly went to the glovebox and placed the Cd foil ball onto the surface of the acidic solution
      - Was careful not to disturb the solution surface
      - The foil began dissolving almost immediately
      - ~20 seconds from beginning to end

The Response

- Excursions terminated by the foil
  - Gamma radiation exposure rates fell continuously
  - None of the termination team received more than 0.3 rem
- Follow-on actions
  - Later that day the solution was transferred to favorable geometry containers using temporary piping
    - Sent to a special facility and eventually recovered
- Note: The senior engineer/physicist that terminated the accident was the criticality safety specialist that had argued with the operations supervisor

Consequences

- 5.5 x 10^{17} fissions total
  - 26 liters, 69 g^{235}U/l
- Exposures
  - Recovery team members limited to 0.3rem
  - 17 @ 0.1 REM or less
  - 7 between 0.1 and 0.2 REM
  - 3 between 0.2 and 0.27 REM
- Limited operations resumed the next day
  - complete resumption within several days
- 94% of process equipment was replaced with favorable geometry over the next 2 to 3 years

United States Department of Energy
Nuclear Criticality Safety Program (NCSP)

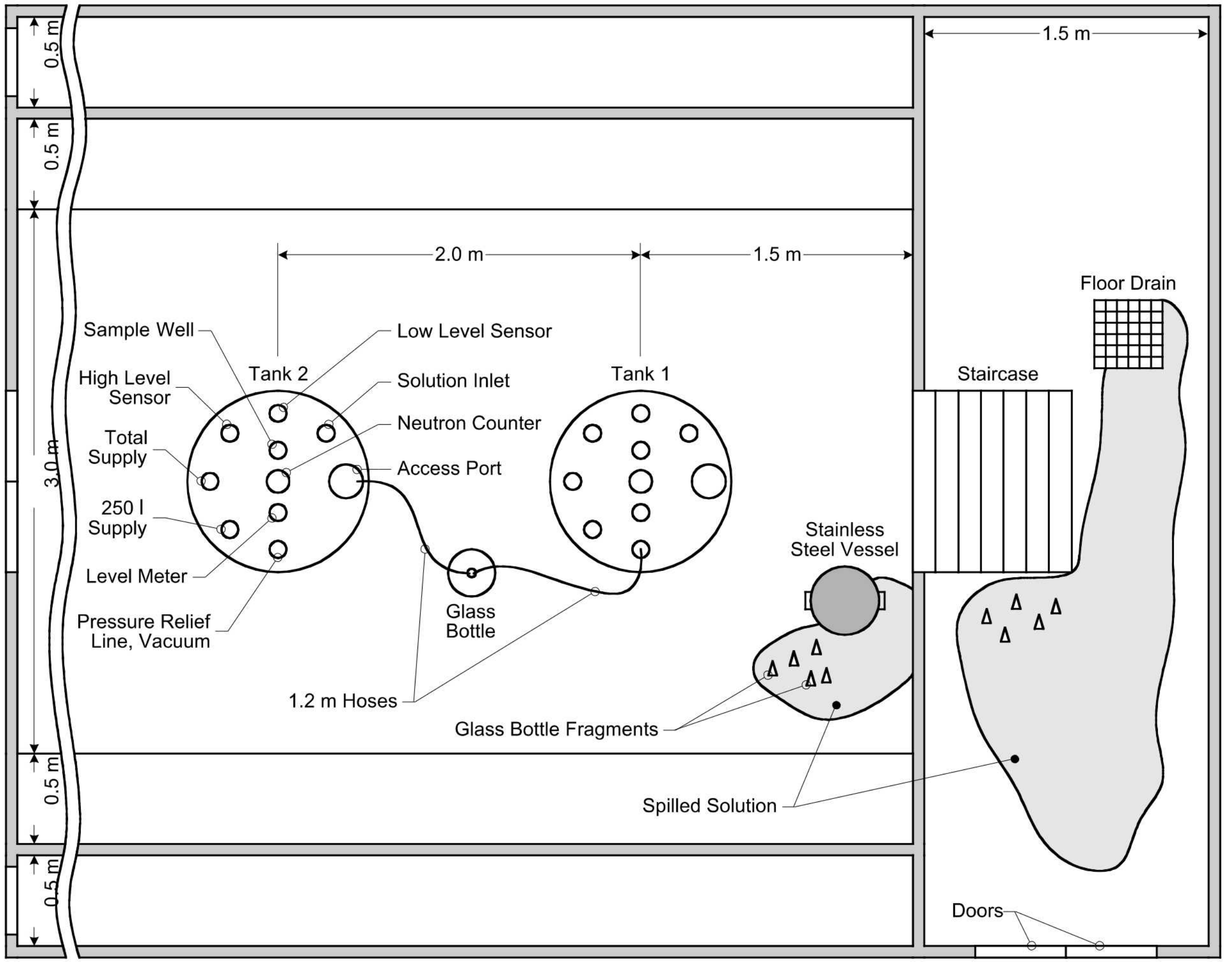
Process Criticality Accident Number 17

Union of Soviet Socialist Republics
Mayak Production Association
10 December 1968

Background Information

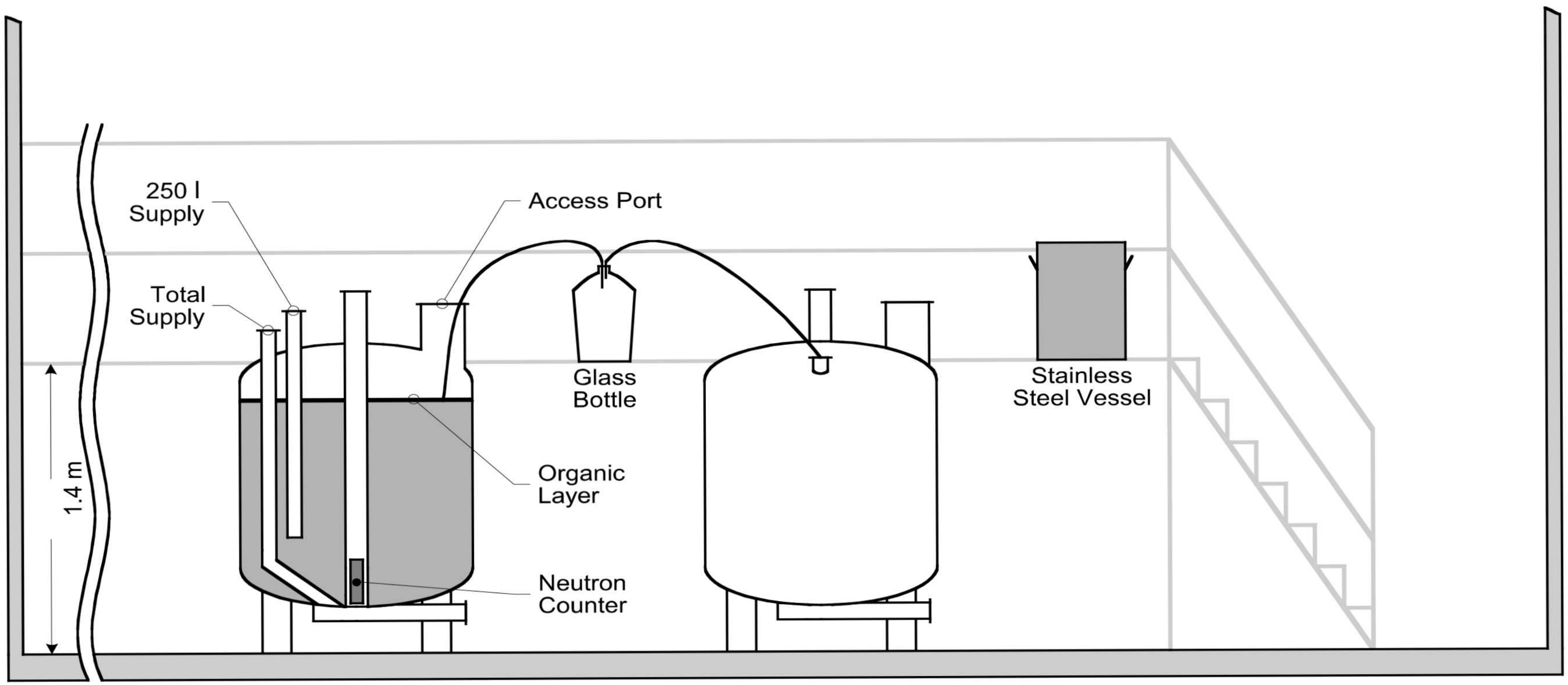
- Union of Soviet Socialist Republics
  - Mayak Production Association
    - Seventh and last accident at Mayak
  - Tuesday, 10 December 1968
  - Facility was equipped with an alarm system
- Improvised procedure for the removal of Pu organic solution
  - Two 1000-liter tanks
    - Storage of lean Pu-nitrate waste prior to ion-exchange recovery
    - 800-liter operational volume
    - 400g Pu criticality safety limit
      - Neutron detectors mounted on bottom of tanks
- Nearby
  - An experimental organic purification had been installed and was operating in an adjacent room

Plan View



0.5 m
0.5 m
3.0 m
0.5 m
0.5 m
1.5 m
2.0 m
1.5 m
Floor Drain
Sample Well
Low Level Sensor
High Level Sensor
Tank 2
Tank 1
Solution Inlet
Staircase
Neutron Counter
Total Supply
Access Port
250 l Supply
Stainless Steel Vessel
Level Meter
Glass Bottle
Pressure Relief Line, Vacuum
1.2 m Hoses
Glass Bottle Fragments
Spilled Solution
Doors

Side View



250 l
Supply
Total
Supply
Access Port
Glass
Bottle
Stainless
Steel Vessel
Organic
Layer
Neutron
Counter
1.4 m

10 December, 19:00 Shift

- Supervisor ordered sampling of Tank 2
  - Automatic sampling device was inoperative
  - Sample extracted by lowering a vial on a string through an open port
- Sample results, ~0.6 g/l
  - ~800 liters, 480g Pu
- Ordered two additional samples
  - Organics present in second set of samples
    - Tank 2 access port opened and visual inspection confirmed organic layer
    - Supervisor ordered decanting of organics prior to submitting for analysis
    - The supervisor ordered two operators to
      - remove organic layer and
      - transfer part of the solution to Tank 1

The Improvised Procedure

- Using
  - a 20-liter glass bottle, two hoses, and a cloth plug
    - Drew vacuum on the glass bottle using Tank 1
    - Extracted ~17 liters of organic into glass bottle
  - The bottle was essentially (operationally) full
- Visual inspection
  - indicated that Tank 2 still contained organic
  - draining needed to continue
- Operators obtained an open top 60-liter SS vessel
  - Could not be used directly from decanting
  - Was used to collect batches from the glass bottle
    - Emptied the glass bottle contents

The Accident

- Extraction was repeated
  - Part way through the second extraction
    - Solution became a mix of organic and aqueous
  - Operators stopped work
    - sought additional guidance from the supervisor
- Supervisor
  - Ordered for the second extraction to continue
  - Only one operator need finish the job
- The remaining single operator
  - completed the second "fill" of the 20-liter bottle and
  - transferred the contents into 60-liter SS vessel

The Accident

- Toward the end of the pour, ~22:35
  - the operator sensed a flash of light and extreme heat to his body
    - dropped the glass bottle and evacuated
  - the criticality alarm system activated (two buildings)
  - all other personnel, supervisor included, evacuated to the same underground tunnel
    - Radiological Control Supervisor (RCS)
      - collected dosimeters and
      - ordered the operator to the medical facility
- ~15 minutes (23:50) later
  - a second excursion occurred
  - At this time the supervisor insisted that RCS accompany him back into the work area
  - As they approached the tank room the radiation detector pegged
  - Supervisor convinced the RCS to leave to get a detector with a greater range

Third Excursion

- Shortly thereafter
  - a third, very large excursion occurred
- The supervisor
  - returned to tunnel covered in Pu organic solution
  - had attempted to empty 60-liter vessel into a floor drain
- His motivation was never disclosed
  - Cover-up? Recovery?
  - only evidence of motivation was that some equipment was replaced to its original location

The Details

- 19.14 liters remained in 60-liter vessel
  - 12.83(l) organic @ 55g/l
  - 6.31(l) aqueous @ 0.5 g/l
- Ejected matter, ~16 liters, ~880 grams
- ~1590 grams total involved in excursions
  - Installation of organic purification research facility piping had lead to organic overflow into these tanks
  - In fact, all the material was missing from this operation

The Consequences

- Initial burst 3×10^{16}
- 10^{17} third burst
- Hands-on operator
  - 700rem, both legs and hand amputated
  - died 31 years later
- Supervisor
  - 2450rem
  - died one month later
- Organic purification research halted

Missed opportunities

- There were many stop work opportunities
  - Initial limit violation
  - Discovery of organics
  - Departure from procedures
  - etc.
- Tank 2 neutron detector was inoperative
  - Tank 1 neutron detector was thought to be broken
    - Each time solution was drained from Tank 2, the neutron counter on Tank 1 experienced increased counts
- Organic was missing from experimental operations but was not tracked down

Abnormal process conditions are cause to STOP WORK

Not a license to Improvise!

United States Department of Energy
Nuclear Criticality Safety Program (NCSP)

Process Criticality Accident Number 20

Union of Soviet Socialist Republics

Siberian Chemical Combine

13 December 1978

NCERC NATIONAL CRITICALITY EXPERIMENTS RESEARCH CENTER
Oak Ridge National Laboratory
Sandia National Laboratories
Lawrence Livermore National Laboratory
Los Alamos NATIONAL LABORATORY

Background Information

- Union of Soviet Socialist Republics
  - Siberian Chemical Combine (Tomsk)
  - Wednesday, 13 December 1978
  - Facility was equipped with an alarm system
  - Building 901 Department 1
- Only process criticality accident in history involving solid material
  - α-phase Pu metal ingots
  - storage container

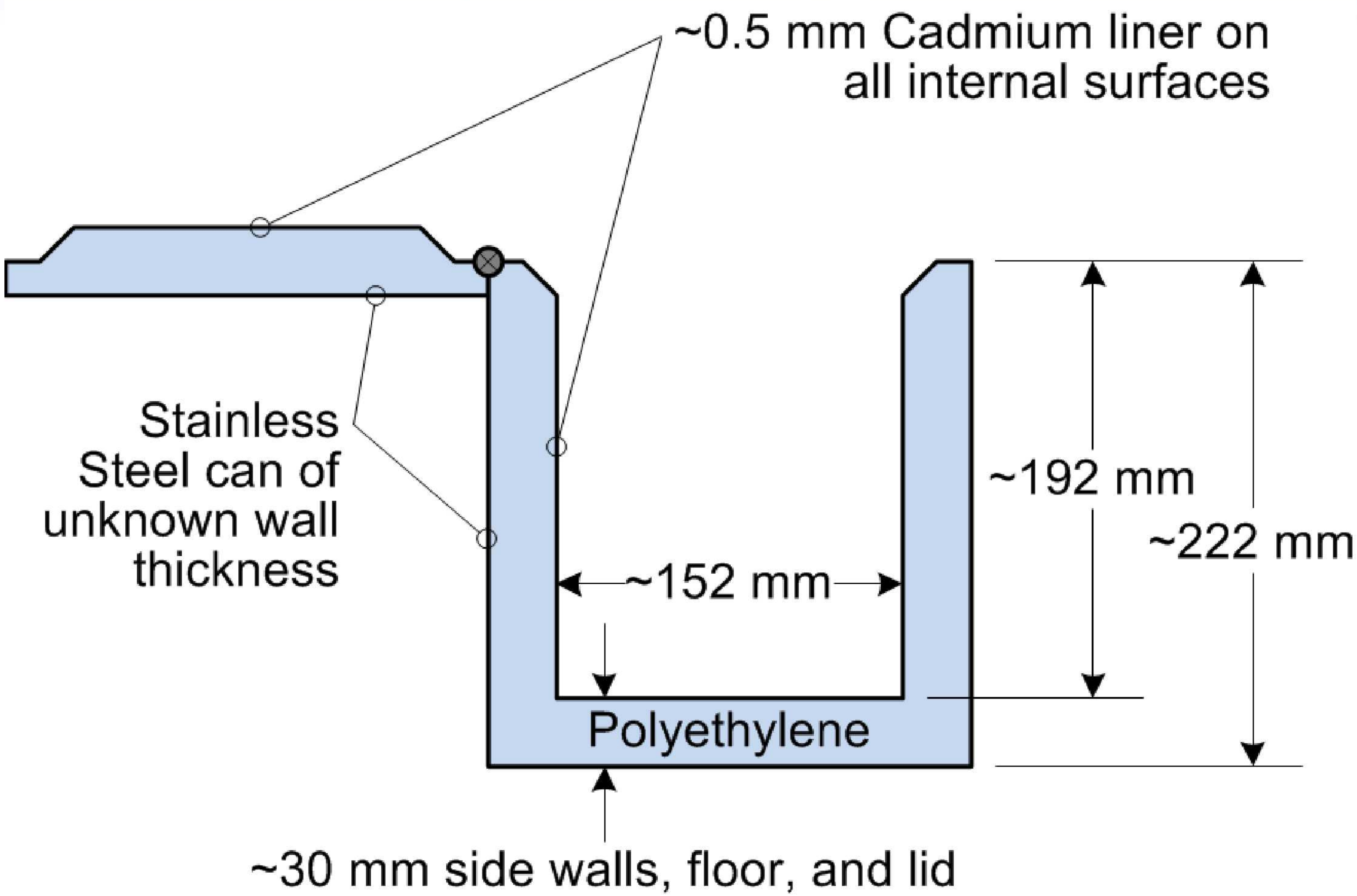
Building 901, Department 1

- 16 gloveboxes for oxide to metal conversion
  - Produced ingots
    - Dimensions no longer known
    - Shape was that of a cone frustrum (rubber stopper)
  - Ingot mass process limitations
    - 2 kg for impure (waste recovery) oxide feed
    - 4 kg for relatively pure oxide feed
- 7 operators per shift
  - Operators were
    - Trained on each process in the department
    - Assigned only one process per shift
  - Written procedures prohibited
    - Switching of operations during a shift
    - Operators to assist one another

Specially Designed Storage Containers

- Cylindrical containers
  - 15.2 cm (~6”) inside diameter cavity
  - 19.2 cm (~7.5”) inside depth
  - Lined with 0.5 mm Cd sheets
  - 3 cm (~1.2”) polyethylene layer encased in stainless steel on all sides
  - Hinged lid
- Designed such that
  - Infinite planar arrays were criticality safe

Storage container



Criticality Safety

- Administrative requirements

≤ 2 ingots

AND

≤ 4 kg total mass

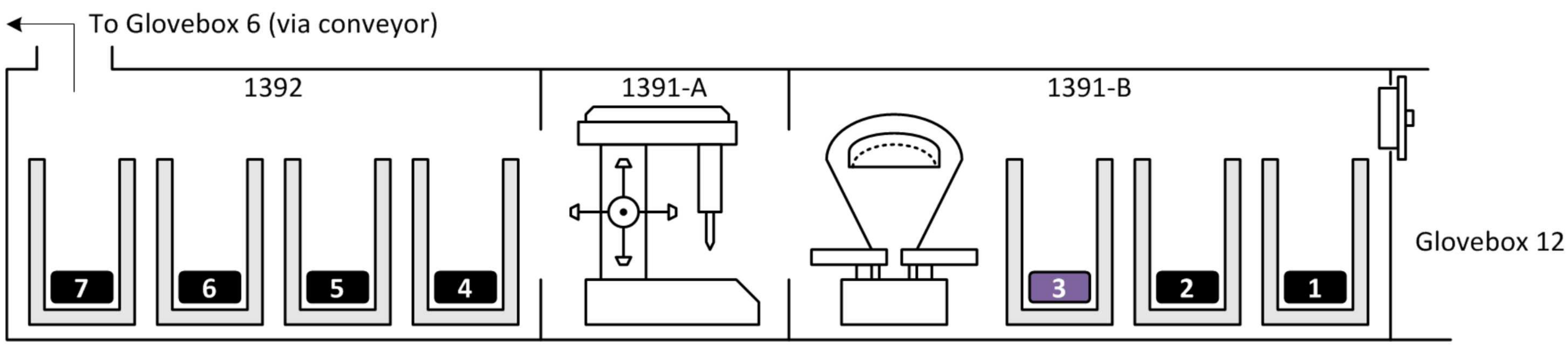
- Changes in process conditions
  - Inadvertent over-mass, i.e., > 8 kg was considered an incredible abnormal condition
    - Operator training
    - Oversight
  - Internal volume did not preclude this overloading

Glovebox 13 Ingot Characterization

- Three workstations
  - 1391-A Sample extraction
    - 0.1gram samples, impurity analysis
  - 1391-B Weighing and staging
  - 1392 Dimensional measurements
- Connected to
  - Glovebox 12 by pass-through port
  - Glovebox 6 by conveyor
- For analysis tracking reasons
  - containers were limited to a single ingot regardless of mass
  - Ingots removed, handled, and returned to original container

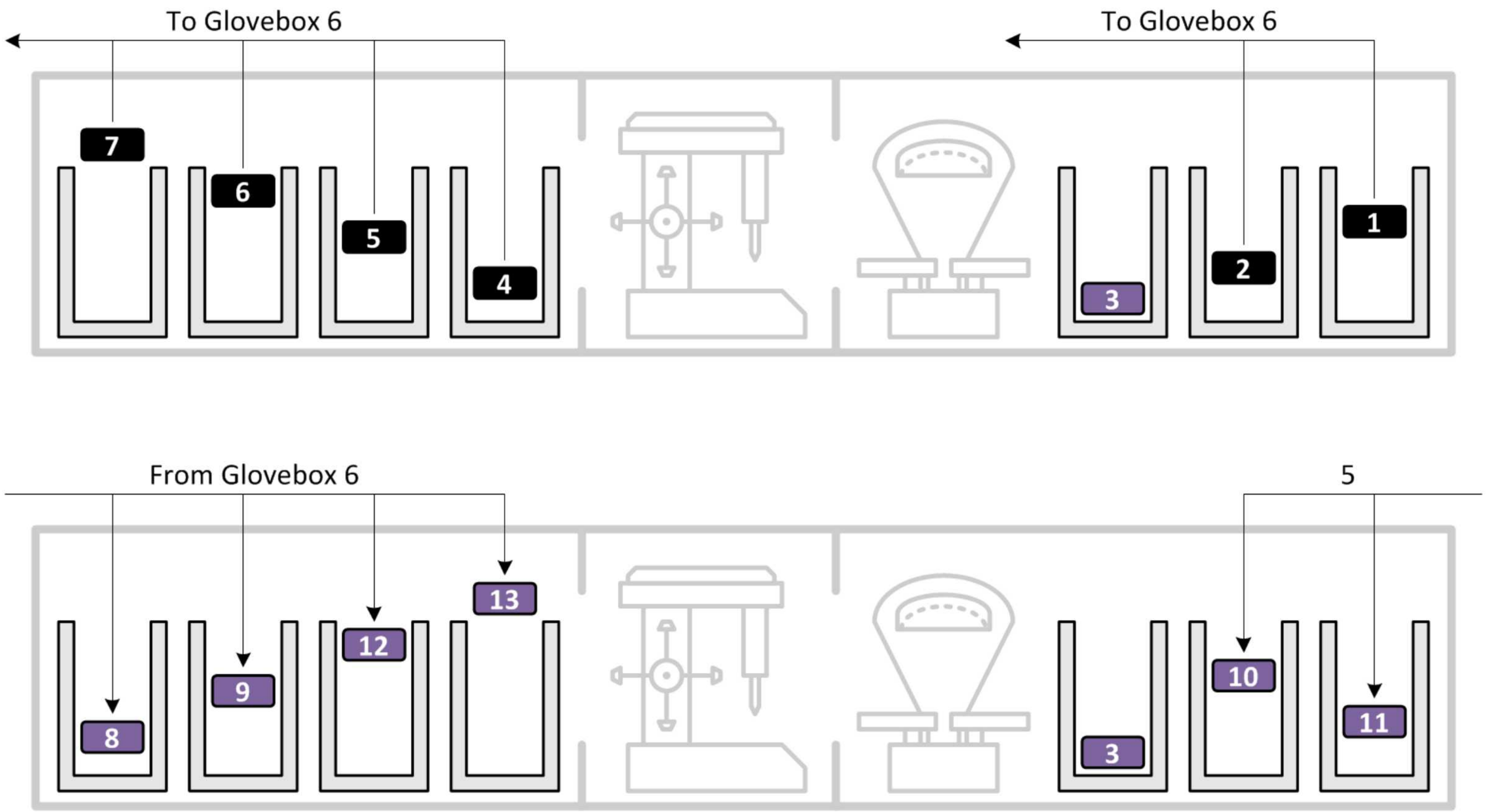
13 December 1978

- 4 containers in workstation 1392
  - 6 & 7 physically behind 4 & 5
- 3 containers in workstation 1391-B
- Ingots 1,2,4,5,6&7 characterization complete
  - Ingot 3 (1391-B) was awaiting sample analysis



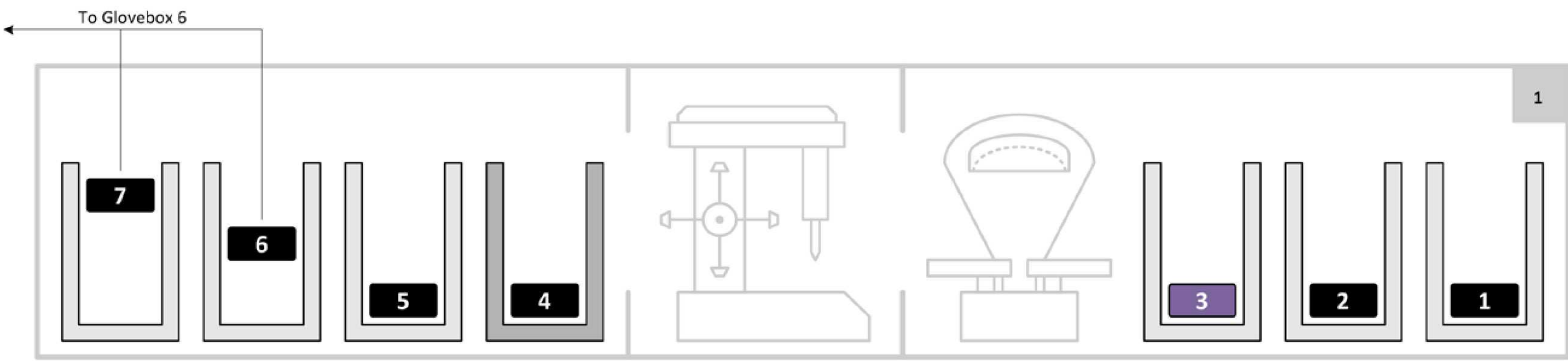
Shift Orders

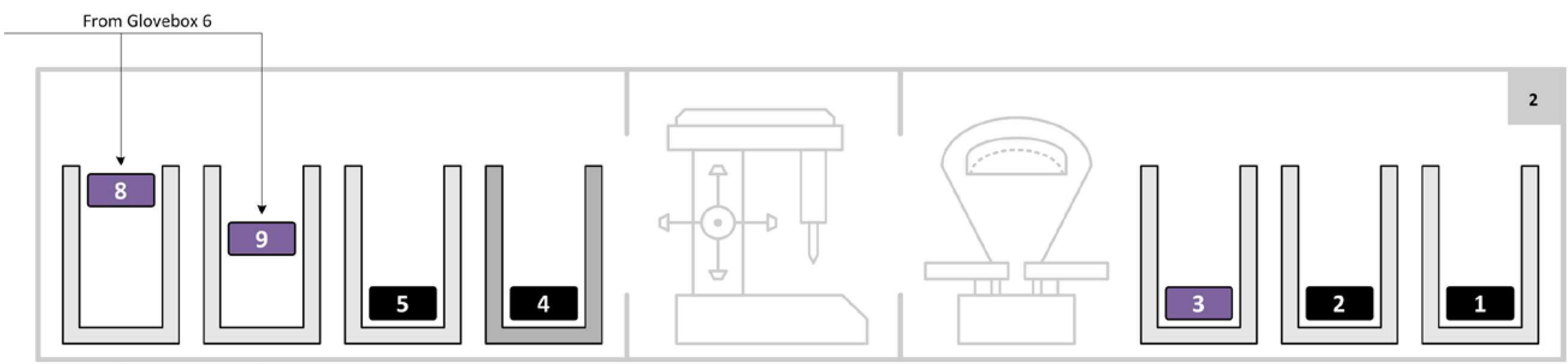
- Shift instructions for GB 13 worker (Operator A)
  - Move ingots 1, 2, 4, 5, 6 & 7 to GB 6
  - Replace with four ingots from GB 6 and two from GB 12



Course of Events

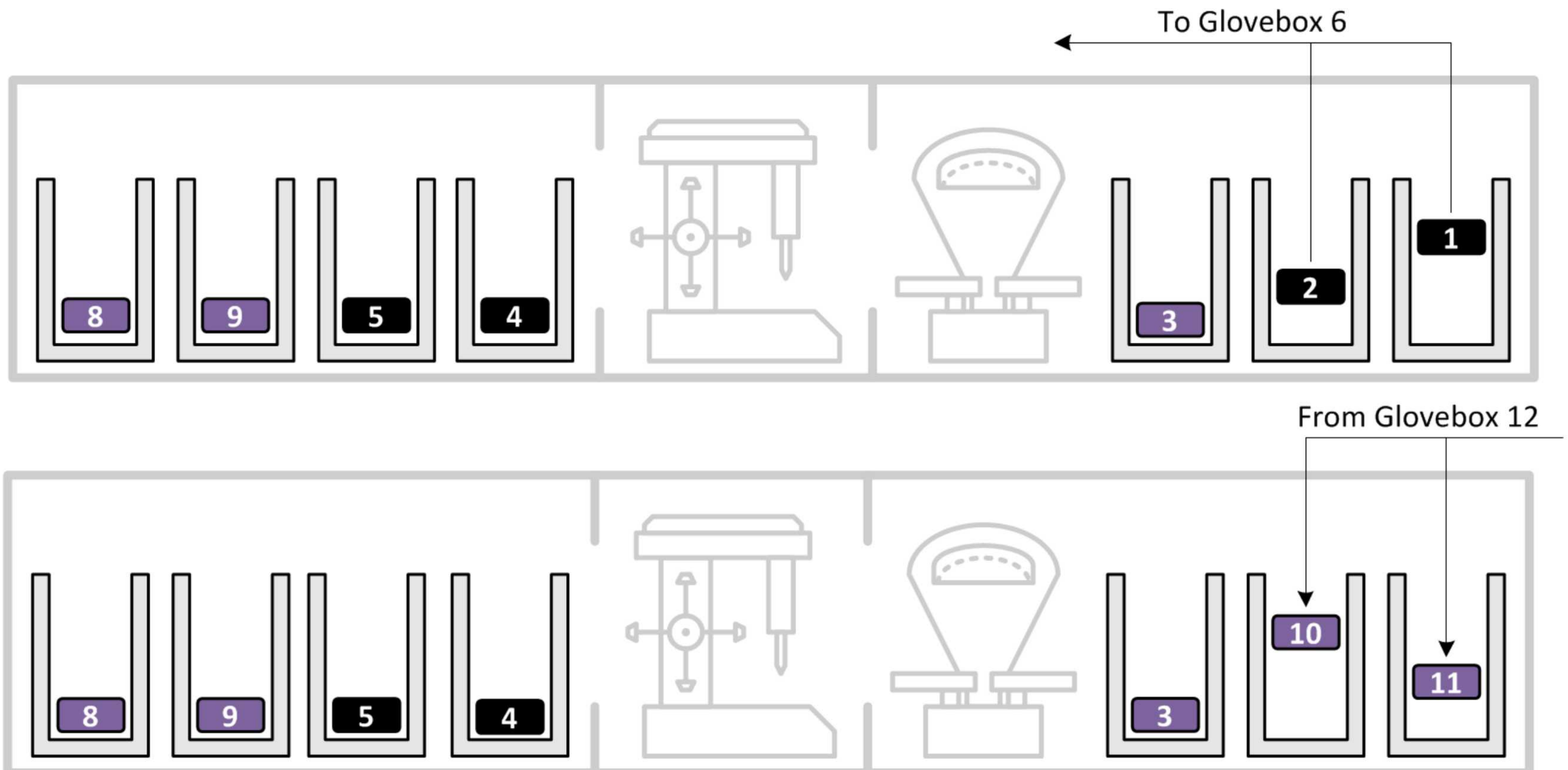
- Operator A
  - Transferred ingots 6 & 7 to GB 6
  - Transferred two ingots (8 and 9) from GB 6 to GB 13
  - Both actions were in accordance with instructions





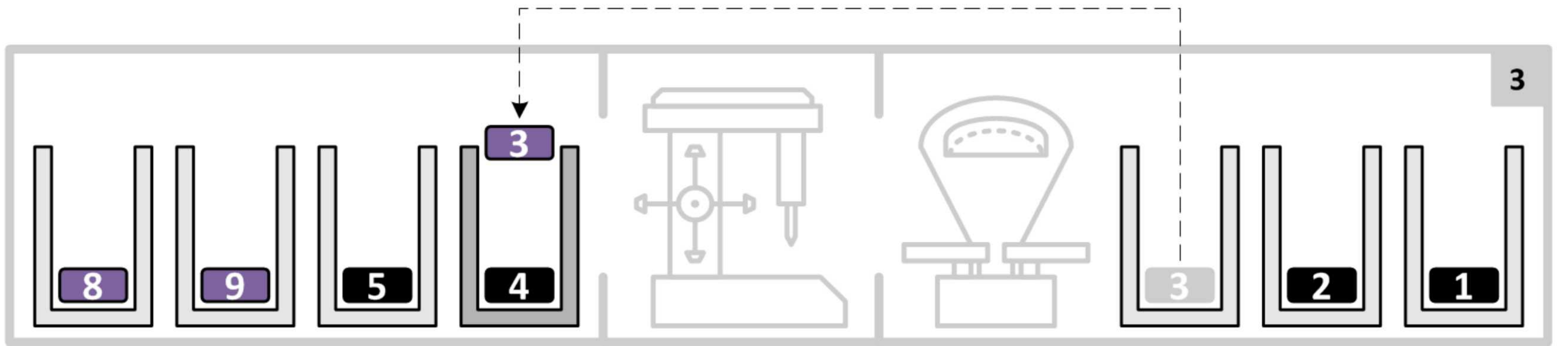
Production Pressures?

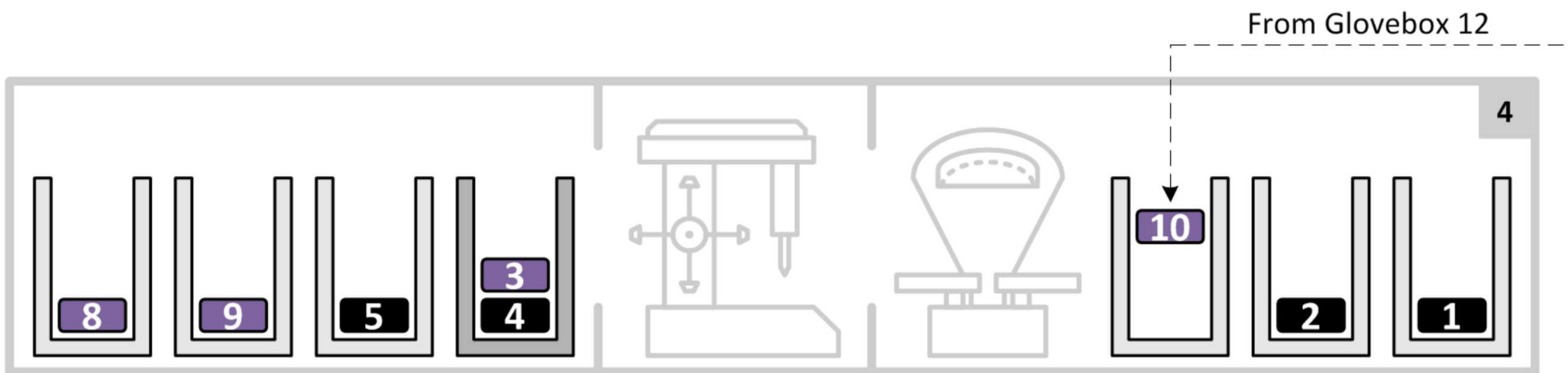
- In violation of procedures, Operator A asked Operator B for help in moving ingots (motivation unknown)
  - transfer ingots 1 & 2 to GB 6
  - replace with two ingots (10 & 11) from GB 12



Course of Events

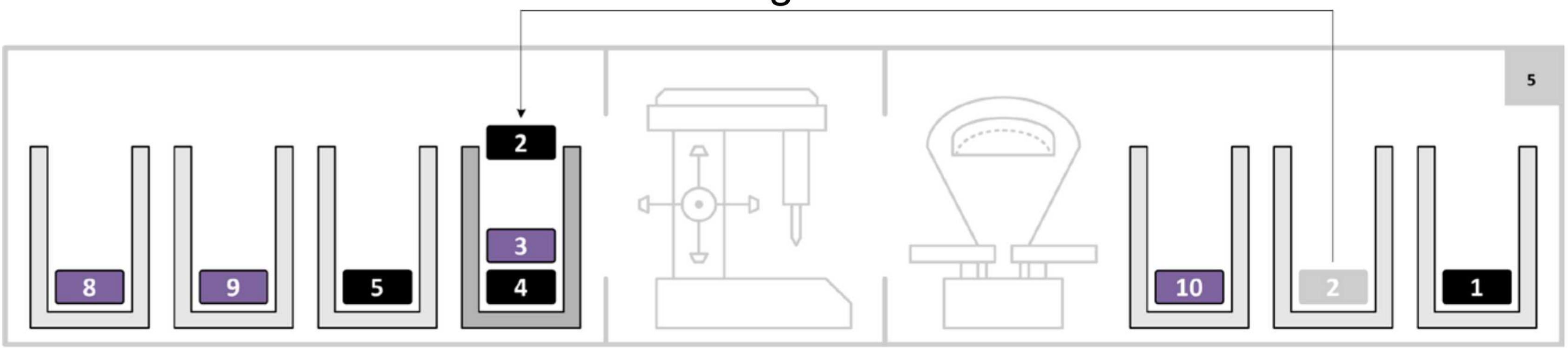
- Operator B
  - Moved ingot 3 (should not have been touched) to container holding ingot 4
  - Moved ingot 10 from GB 12 to the container originally holding ingot 3
    - Ingot 10 misplaced

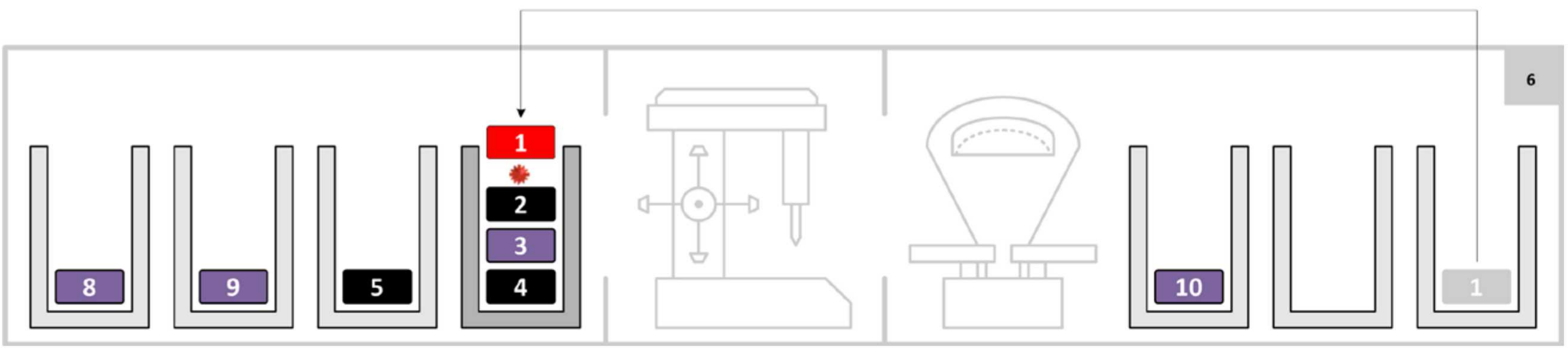




Course of Events

- Operator A returned
  - did not confirm Operator B actions
  - transferred ingots 2 & 1 to the container already holding ingots 4 and 3
    - Should have known that it had ingot 4





The Accident

- While placing the Ingot #1
  - Prompt criticality was exceeded
  - Alarms in two buildings activated
  - An ingot was ejected or immediately removed by Operator A
- Operator A
  - sensed a flash of light and heat to his hands and arms
  - removed two of three remaining ingots from the container
  - placed one in 1391-A and one in 1391-B
- Total mass 10.68kg
  - 4 Ingots
  - Individual masses not well known

Consequences

- $3x10^{15}$ fissions
  - ^{140}La γ-ray spectrometry estimate
- Operator A
  - 250 rad whole-body
  - 2000 rad to hands and arms
    - Amputation of both arms up to the elbows
    - Eventually developed vision problems
- 7 additional personnel received doses from 5 to 60 rad
- Failure of conduct of operations
  - **Such behavior cannot be evaluated**
    - Engineered features could have precluded overloading
    - Container was redesigned--no more than 4 kg vertically