LA-UR-19-31373
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Title: Nuclear Criticality Safety Fundamentals

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Intended for: Stabilization Training

Issued: 2019-12-13 (rev.1)

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Nuclear Criticality Safety Fundamentals

Stabilization Training

George (Geordie) McKenzie

November 13, 2019

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Take Aways

- Criticality safety can be complicated and non-intuitive
- You cannot stop an accident once it has started - best to avoid an accident from starting
- Important criticality safety parameters: MAGIC MERV

- Mass
- Absorption
- Geometry
- Interaction/Spacing
- Concentration

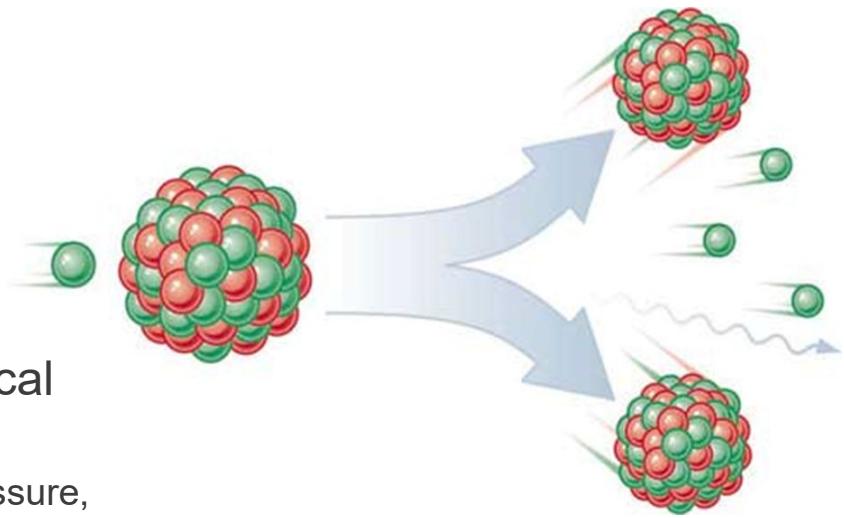
- Moderation
- Enrichment
- Reflection
- Volume

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 <u>cannot be altered</u> by physical properties or the environment**
  - mass, volume, geometry, temperature, pressure,
- **Personnel protection is effective via simple rules**
  - Time
  - Distance
  - Shielding
- **These controls and principles are not effective for criticality safety**

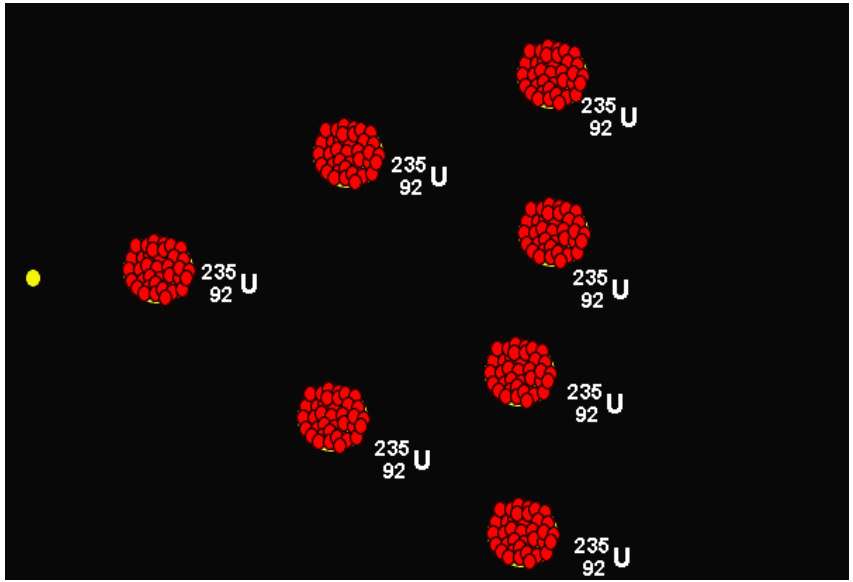
Fission

- **A subset of these radioactive 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 (ie, a trigger)
    - e.g., neutrons
  - As such, **it can be altered** by physical and environmental properties
    - Mass, volume, geometry, temperature, pressure, etc.
    - Fission process can be reduced (or intensified!) by adjusting trigger



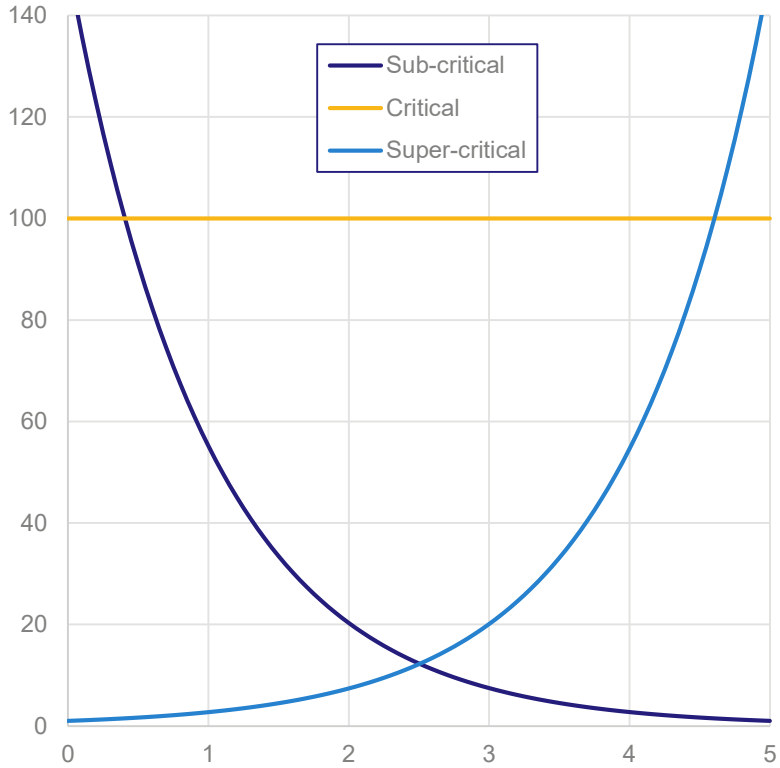
Chain Reactions

- **Because fission releases new neutrons (potential triggers)**
  - 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*



Types of Chain Reactions

- **Subcritical (self-extinguishing chain reaction)**
  - Each fission leads to less than one future fission
  - Fission chain and neutron population dies in time
- **Critical (self-sustaining chain reaction)**
  - Each fission leads to exactly one future fission
  - Fission chain and neutron population is constant (“never ends”)
- **Supercritical (self-promoting chain reaction)**
  - Each fission leads to more than one future fission
  - Fission chain and neutron population grow in time



Criticality Accident

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

Nuclear reactors

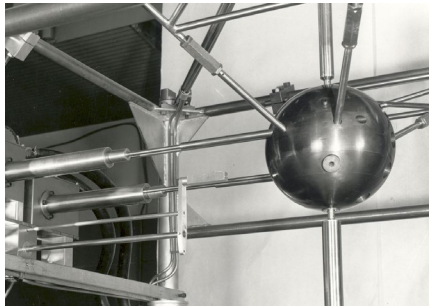
Critical assemblies

Nuclear Weapons

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

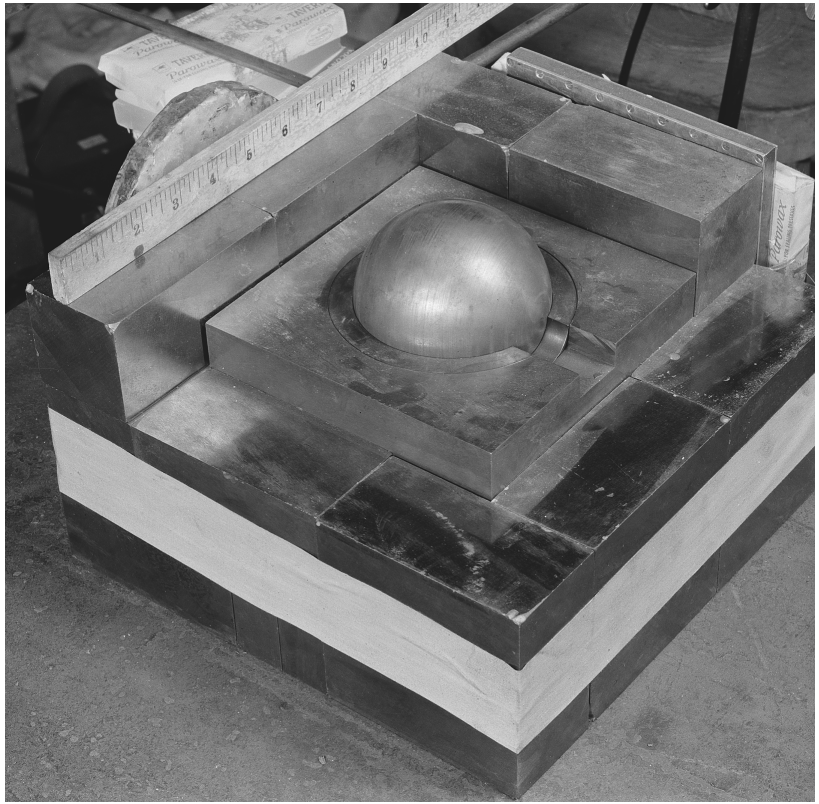
Criticality Incident (Omega) Aug.30, 1945
11:00 A.M.

Criticality Accidents



Chain Reactions

- **Self-sustaining chain reactions can be started any number of ways**
  - Mixing the fissionable materials with
    - Acid, water, plastic, oil, beryllium, carbon, foam
  - Placing shielding nearby
    - Realistically any material
    - Common materials include: gel blocks, polyethylene, your body, metal sheets
  - Collocating containers or items of fissionable material
  - Altering the shape of the fissionable material unit



Consequences of Criticality Accidents

- **Large energy release in the form of radiation**
- **Life threatening to personnel and organisms *nearby***
  - Significant effects within ~5 meters (~15 feet)
  - You and your teammates!
- **Potential for public exposures or offsite workers**
- **Important Note: Criticality accidents happen very quickly**
  - Less than a second, typically milliseconds or microseconds for initial burst
    - Majority of dose from initial burst
  - No chance to make any changes or stop accident
  - Criticality Safety (ie, avoiding criticality accidents) is important!

What is Criticality Safety?

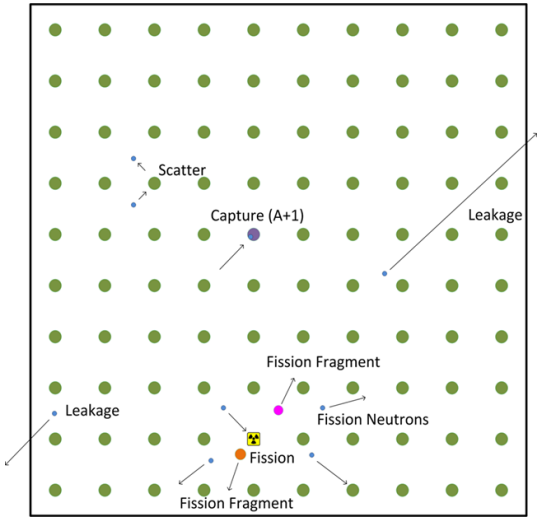
Protection against the consequences of a criticality accident, preferably by prevention of the accident

- **Limiting chance for self-sustaining chain reaction**
- **It is no different than any other safety discipline**
  - Implemented for Stabilization through technical guidance from the Diagnostician or Home Team
  - Underlying principles can be complex and counter to *rational judgment*
    - Adding or removing water from fissionable material may both be unsafe
    - Effects of adding non-fissionable material are not always straightforward
    - Behavior of material may change depending on its distribution and location

Who Are Criticality Safety?

- **The mission space we exist in does not allow for full evaluations of every situation**
  - No procedures
  - Expert Guidance
- **The Diagnostician and the Home Team are able to give criticality safety guidance**
- **The team lead is responsible for the safety of the overall operation**
- **You**
  - You are the one at the IPC
  - Your team relies on you to perform the correct actions

The Fate of Neutrons



- **Neutron life**
  - Begins at fission
  - Continues as the neutron moves through the system
  - Ends when it is **removed** from the system
- **How are neutrons removed?**
  - Leakage – neutrons fly out of the system, never to return
  - Absorption – neutrons can collide with an atom and “stick” (maybe causing a fission)
- **What else can happen to a neutron as it flies through a system?**
  - Scatter – neutrons can collide with an atom and “bounce” off
- **The number of neutrons that are absorbed (and cause a fission) versus the number of neutrons that leak out or are absorbed (and do not cause a fission) tells us if a chain reaction is possible!**

Fission Process

- **Fission can be induced by free neutrons "*colliding*" with nuclei**
  - The neutron brings energy to the nucleus, making it unstable
    - Two types of energy
      - Kinetic (speed) and binding ($E=mc^2$)
  - This sometimes results in splitting of the nucleus
    - two or more major pieces known as fragments
    - **some number of additional free neutrons**
    - γ-rays
    - Lots of energy carried by all these products
  - Some isotopes can only fission with collisions with high energy neutrons (ie, traveling fast)
  - Some isotopes can fission with any energy neutrons

Neutrons and Chain Reactions

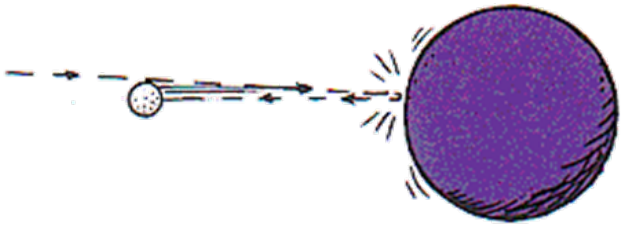
- **Anywhere from 0 to 10 neutrons may result from one fission**
  - average, $\bar{\upsilon}$, for ^{235}U is ≈ 2.5
  - average, $\bar{\upsilon}$, for ^{239}Pu is ≈ 3.0
- **Conceptually this makes a chain reaction possible**
  - Should be easier of ^{239}Pu than for ^{235}U
- **Follow the neutrons**
  - Chain reactions are propagated by neutrons
  - You can design your system (reactor, assembly, weapon, process, etc) to stop or enhance a chain reaction
  - What types of things can happen to a neutron in a system?

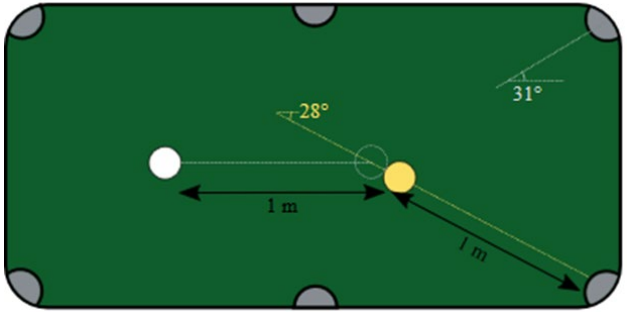
Scattering and Moderation

- **Neutron cross sections (ie, what happens when a neutron "collides" with an atom) depend upon energy of the neutron**
- **If the neutron is moving slower (or faster!), the criticality of the system can change**
- **Can we slow neutrons down? Can we speed neutrons up?**
- **Yes – neutrons will lose energy when scattering (ie, "bouncing")**
  - Cannot really speed neutrons up – but they start off pretty fast to begin with!
- **Scattering neutrons off of nuclei to slow the neutrons down is called Neutron Moderation and is very important in criticality safety**
- **Are certain nuclei (atoms) better in slowing neutrons down?**
- **What are the overall effects of neutron moderation on our systems?**

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 ≤ 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

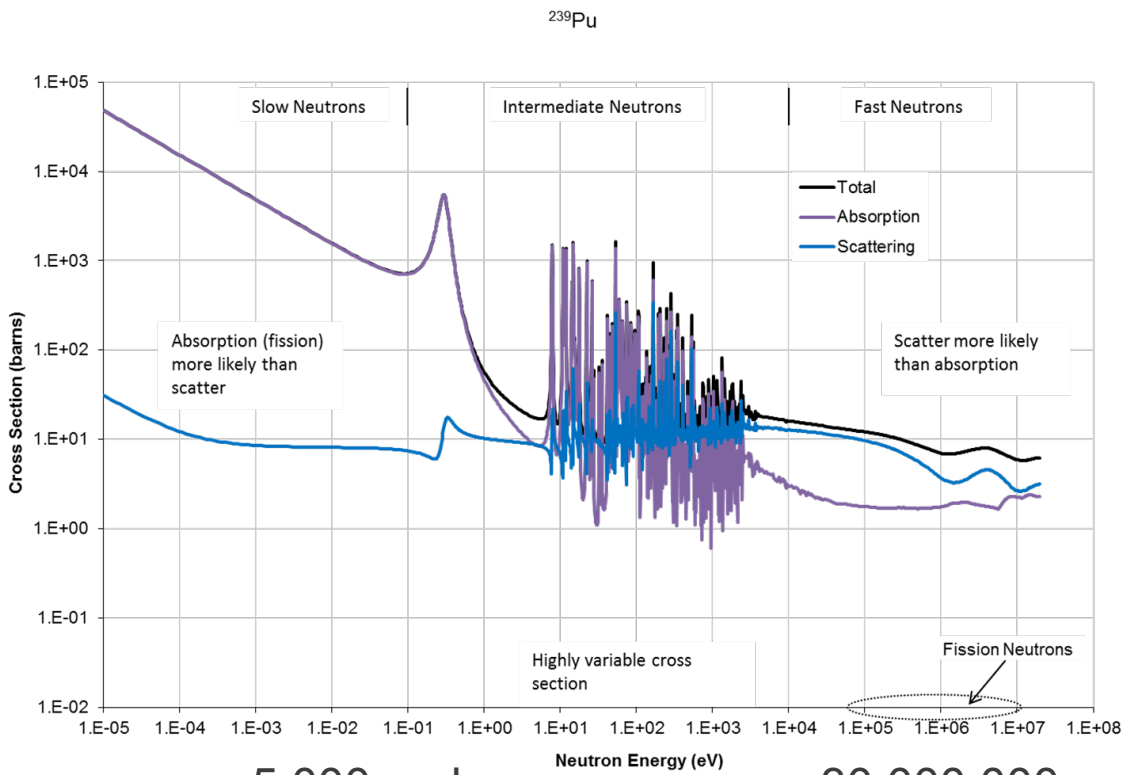




Importance of Moderation

- **What is moderation?**
  - The slowing down of neutrons through scattering
- **Why does moderation matter?**
  - Scattering off light nuclei slows a neutron down
    - Slower neutrons are more likely to be absorbed than scatter in fissionable material
  - More slow neutrons means more absorption
  - More absorption means more fissions
  - More fissions means greater likelihood that self-sustaining chain reaction will occur
    - Less fissionable material is required
- **Mixing fissionable material with lighter materials causes moderation**
  - The degree of moderation is a macro system property like density
    - Varies depending on the amount of light material

Cross Section



~5,000 mph ~30,000,000 mph

Criticality Safety Parameters

- **The list of parameters can have large effect upon criticality of a system**
  - Some we can easily adjust – some are harder to adjust
  - Adjusting parameters can be complicated and non-intuitive!
  - MAGIC MERV

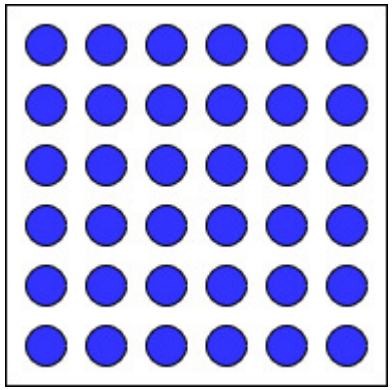
- **Mass**
- **Absorption**
- **Geometry**
- **Interaction/Spacing**
- **Concentration**

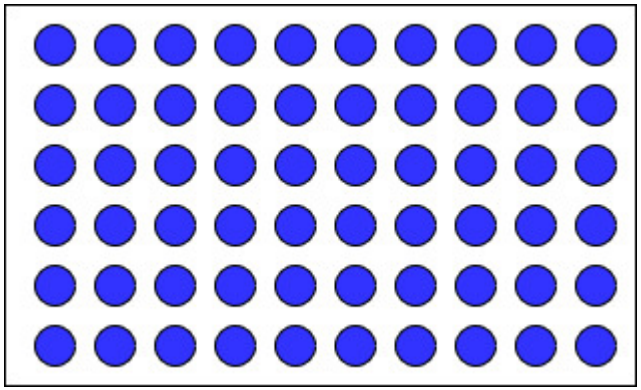
- **Moderation**
- **Enrichment**
- **Reflection**
- **Volume**

Criticality Safety Parameters

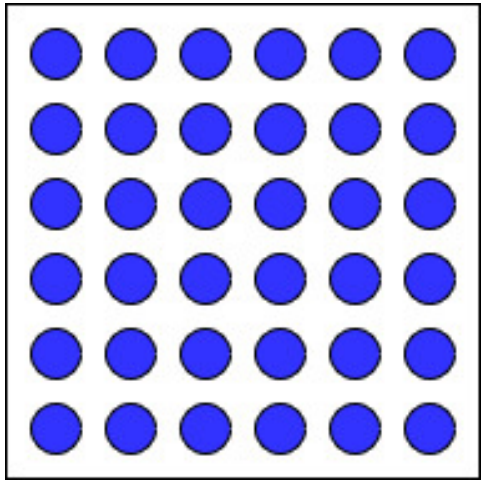
- **Mass - the amount of material that is in the IPC**
- **Absorption – removal of some absorbing material near IPC**
- **Geometry – shape of material and IPC**
- **Interaction/Spacing – distance between multiple IPCs**
- **Concentration – amount of material in a solution**
- **Moderation – slowing neutrons down**
- **Enrichment – amount of the "good stuff"**
- **Reflection – addition of materials around IPC**
  - including you and your buddy
- **Volume – size of IPC**

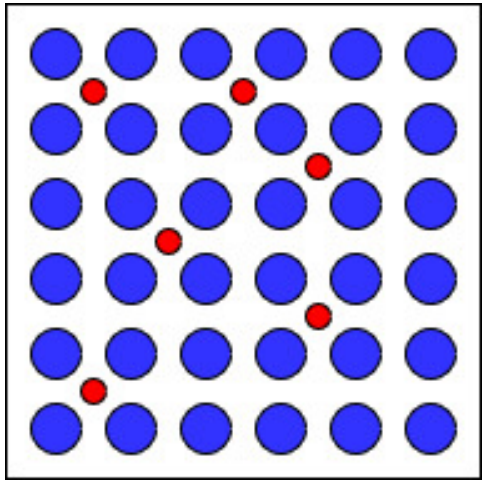
Mass



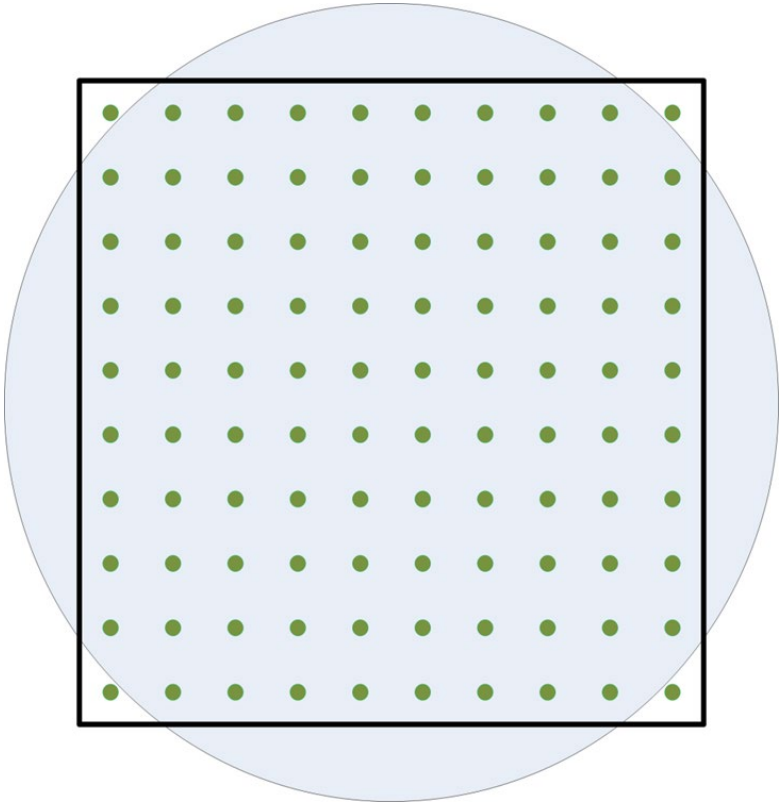


Absorption



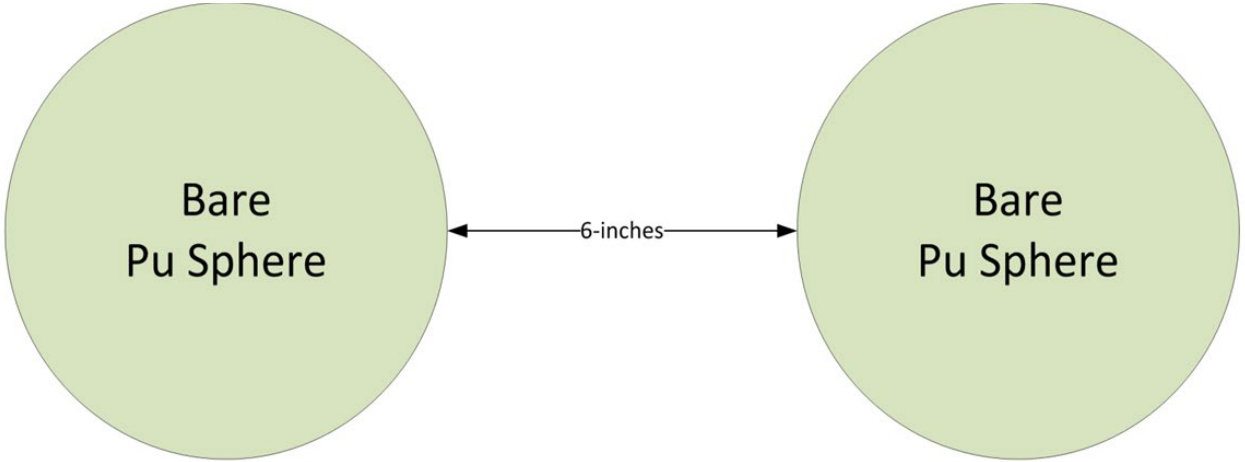


Geometry

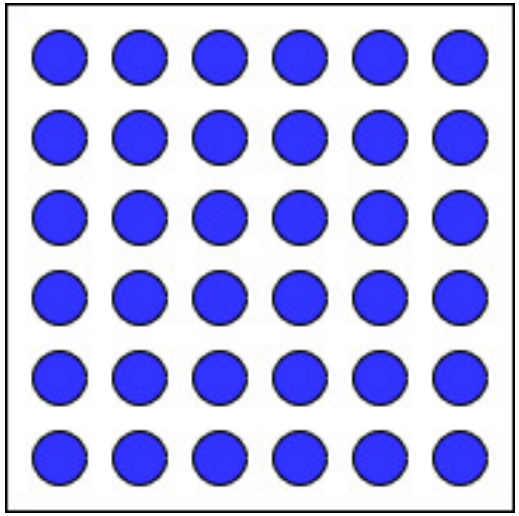


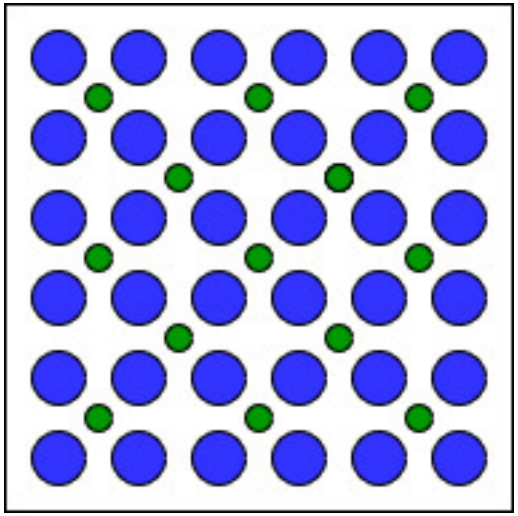
- **Equivalent volumes**
  - S/C surface area ratio = 0.81
  - Sphere has 19% less surface area for the same enclosed material
  - Cube leakage is higher

Interaction/Spacing

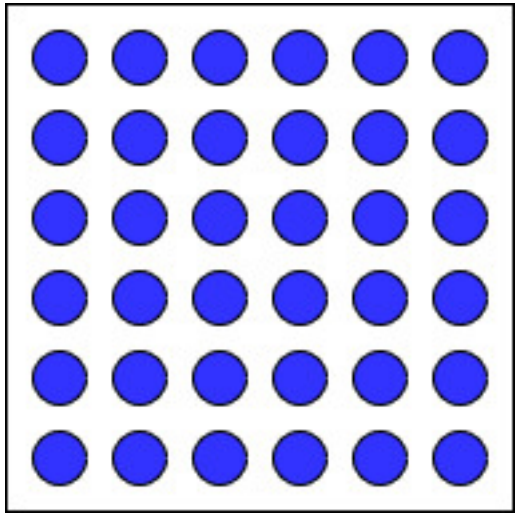


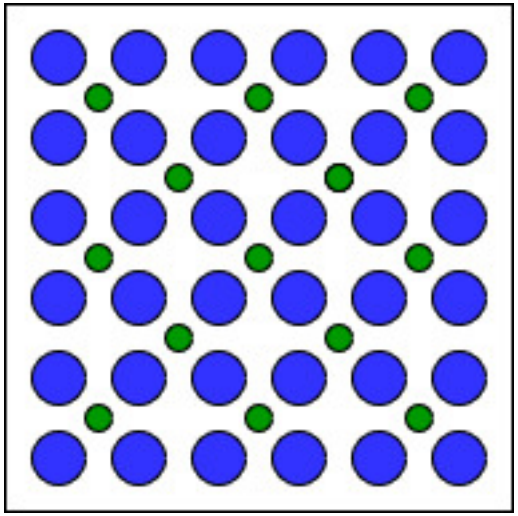
Interaction/Spacing



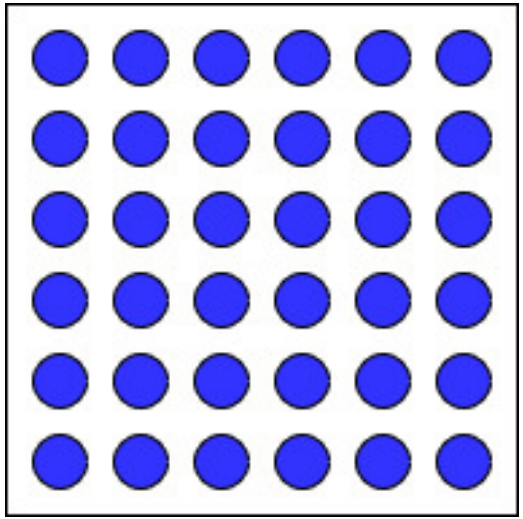


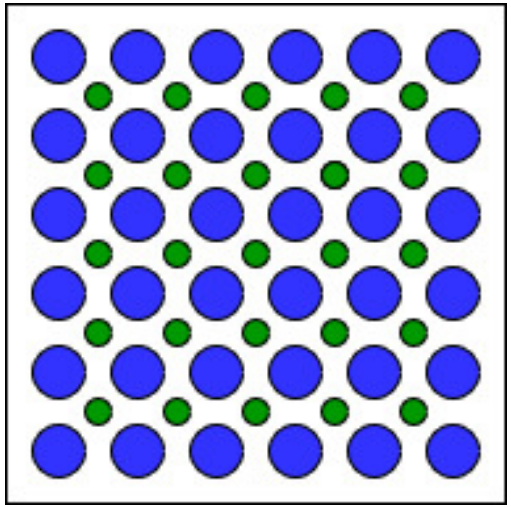
Concentration





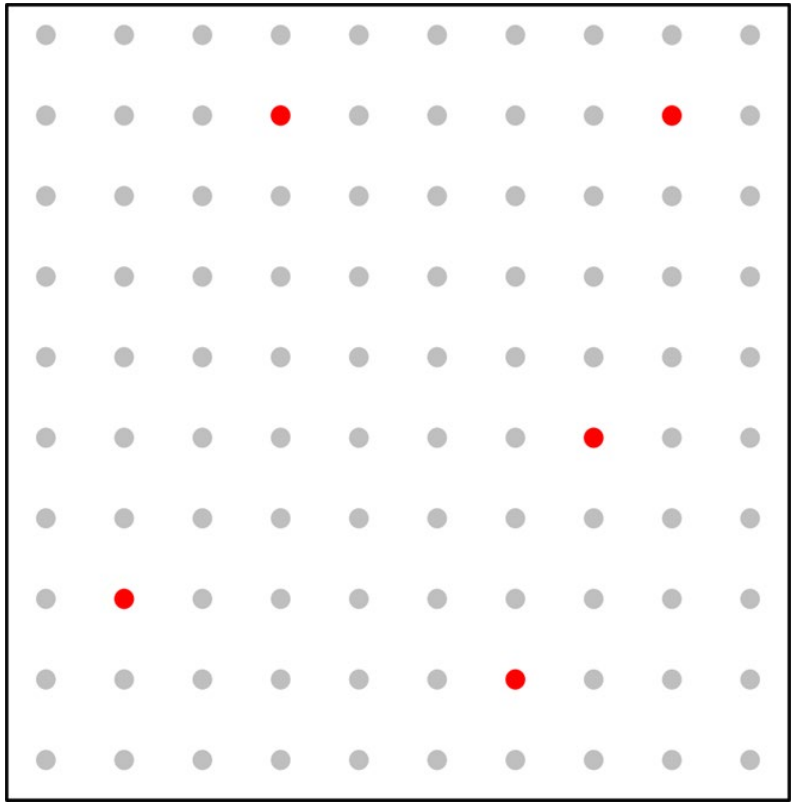
Moderation



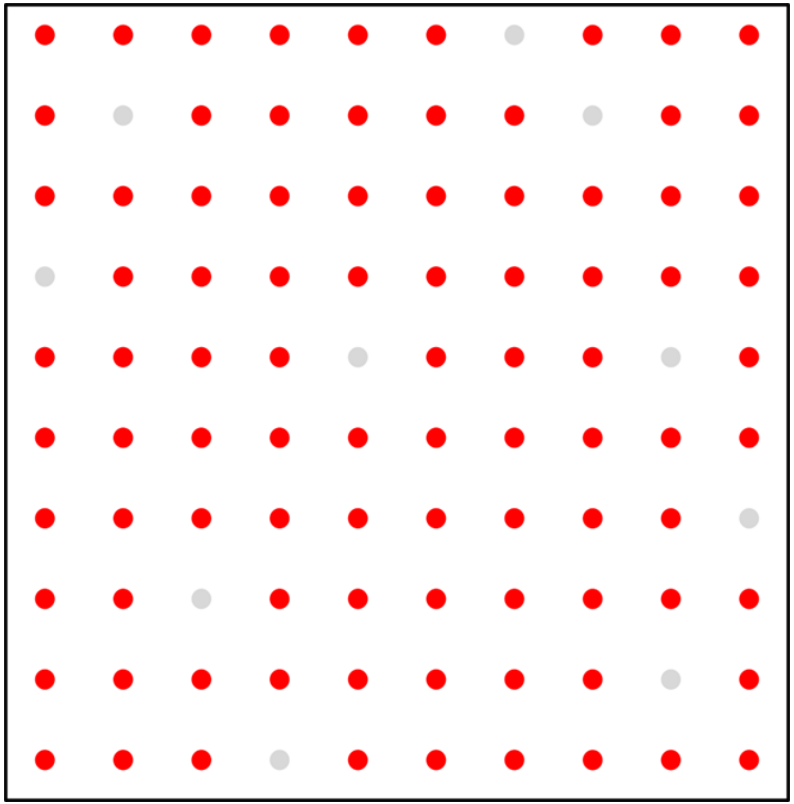


Enrichment

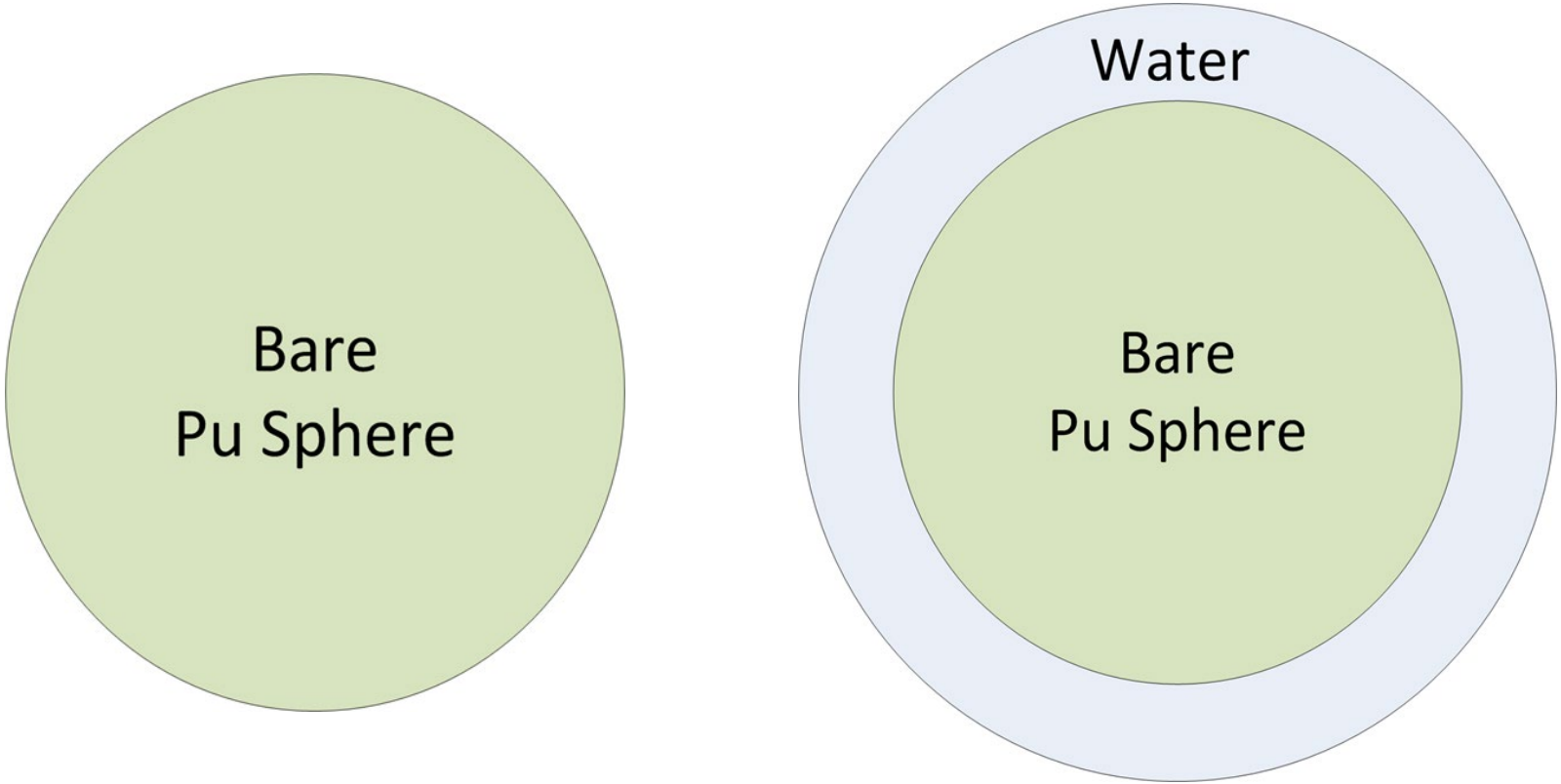
5% U-235



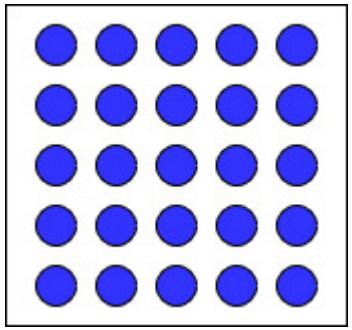
90% U-235

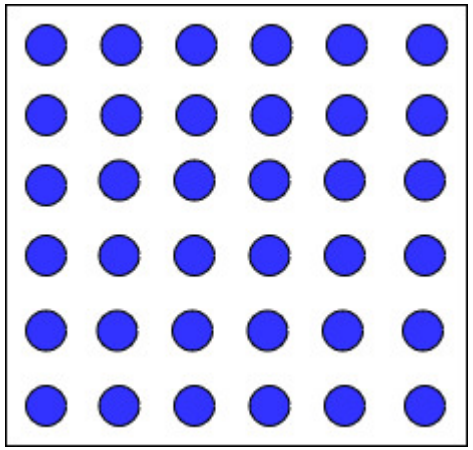


Reflection



Volume





Combining All Parameters

- **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

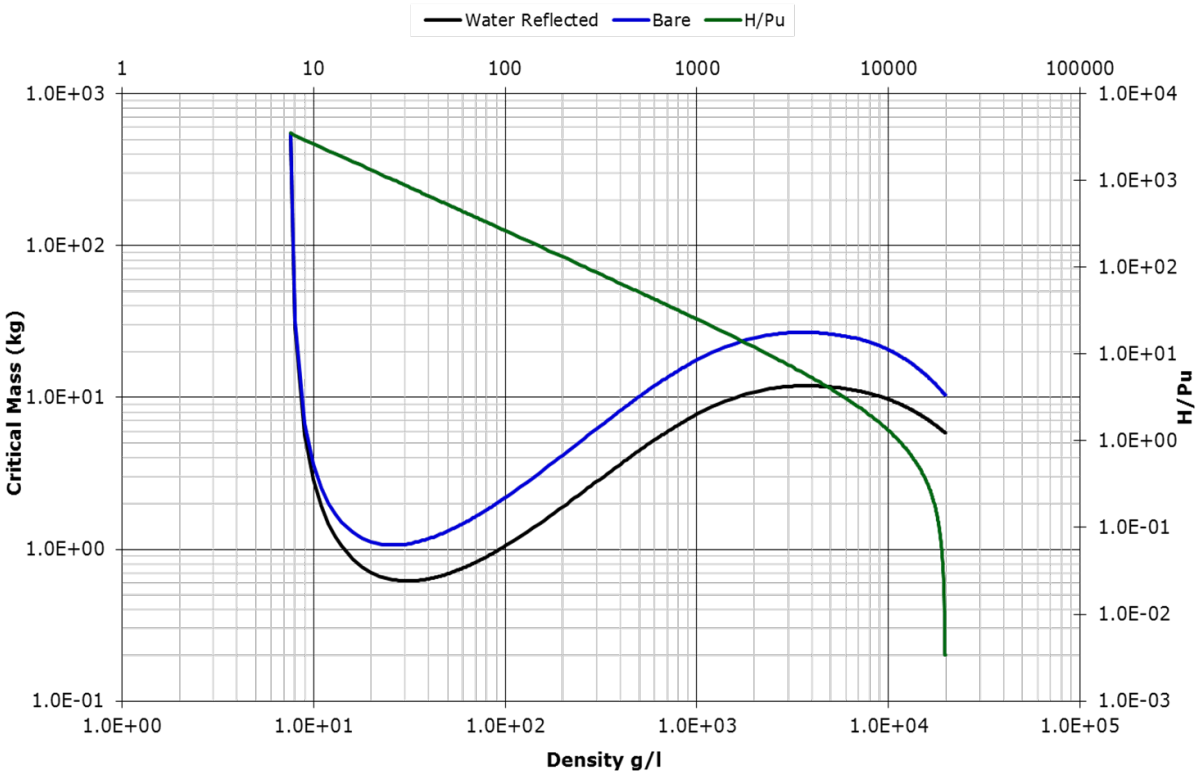
As fissionable material is handled the parameters change

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

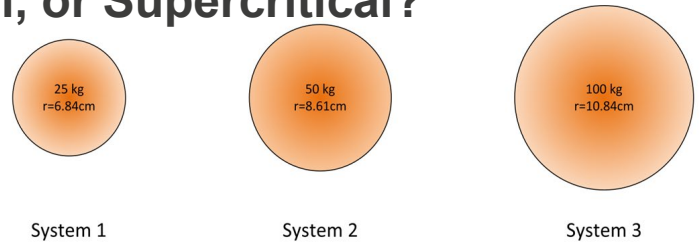
- **The critical mass of a**
  - water reflected system is about ½ that of a bare system
  - moderated systems require less fissionable material
    - ~10 times less for optimally moderated systems
- **21 of the 22 process accidents have occurred with solution**
  - Why?

^{239}Pu(5) Metal-Water Critical Mass Curves



Parameters and Chain Reactions

- **Consider three different metal systems**
  - Bare (no reflector)
  - U(100) metal
  - Spherical geometry
- **Subcritical, Critical, or Supercritical?**



- **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 Effects of the Parameters

- **What would happen to that bare metal critical system 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?, A Gel Block?, Foam?, High Explosive?
  - It was placed on the ground?
  - 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
  - A Cf-252 source was placed a foot from the sphere?

In Metals, Ceramics, Oxides

- **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

In Solutions, Plastics, Oils

- **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 mixed with
    - Plastic, oil, water, Be, C

Nuclear Reactor Kinetics (Words you may hear us say)

- Terminology/Definitions
  - k-effective
  - Neutron multiplication

K-Effective – Effective Multiplication Factor

- **k_{eff} is the multiplication factor**
- **k_{eff} is a measure of the number of fission neutrons in one generation compared to the previous generation**

$$k_{eff} = \frac{\text{Fission Neutrons in eneration}}{\text{Fission Neutrons in Preceeding eneration}}$$

- **Three possible values for k_{eff}:**
  - $k_{eff}<1$, system is **subcritical**, neutron population **drops** from generation to generation
  - $k_{eff}=1$, system is **critical**, neutron population is **constant**
  - $k_{eff}>1$, system is **supercritical**, neutron population **grows** with each generation

Neutron Multiplication

- **Neutron Multiplication (M) is not the same as the multiplication factor (k_{eff})!**
- **Neutron Multiplication is the total number of neutrons that would be generated through fission from a single starter neutron**
  - How is the original starter neutron "amplified" through the fission process?
- **Neutron Multiplication is only meaningful for subcritical reactors (ie, $k_{eff} < 1$)**
  - $1 \leq M < \infty$
  - If the system is critical or supercritical, the number of neutrons generated for a single starter neutron will be infinity, so M has no meaning in that case
- **Simple formula relates Multiplication to multiplication factor:**

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

What Can You Do?

- **Take criticality safety training**
- **Consider Criticality Safety before taking action**
- **Have a questioning attitude**
- **Participate in operational planning**
  - There is always a way to accomplish our goals
  - May just not be the first idea
- **Ask questions of the science staff**
  - We are here for your benefit

What Can You Do As a Team Lead?

- Ensure data reaches Diagnostician and Home Team quickly
- Consider criticality safety when creating operational plan to make execution of the safe job easy
- Important instructions must be repeated

Take Aways

- Criticality safety can be complicated and non-intuitive
- Cannot stop an accident once it has started - best to avoid an accident from starting
- Follow the rules and your procedures (see above - any issues with procedures (etc), please bring them up!)
- Important criticality safety parameters: MAGIC MERV

- Mass
- Absorption
- Geometry
- Interaction/Spacing
- Concentration

- Moderation
- Enrichment
- Reflection
- Volume

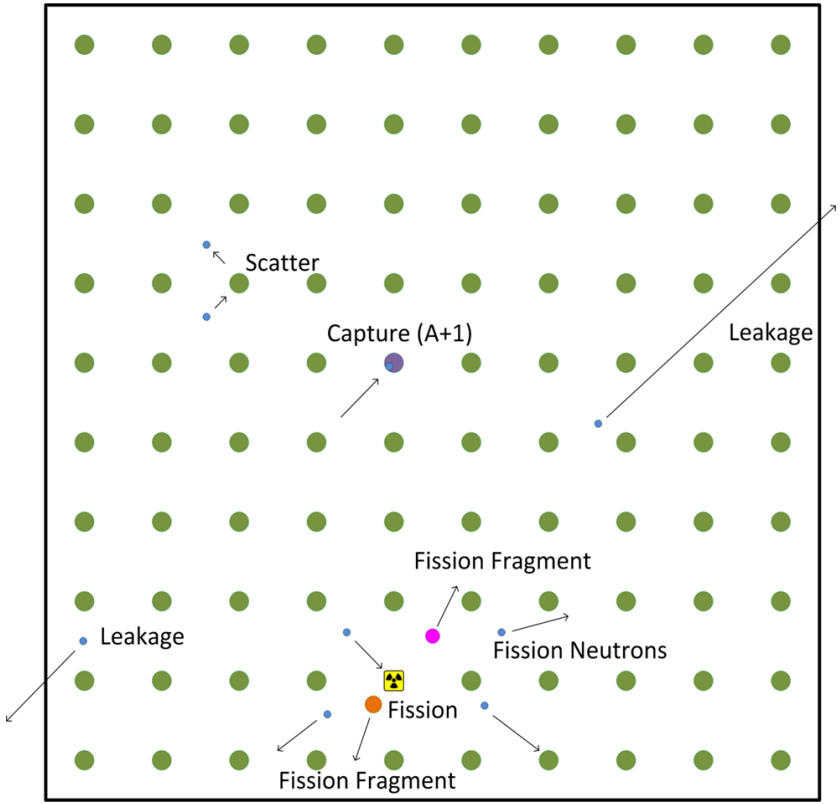
Questions?

Extra Slides

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 (properties of a given system or IPC)
      - size (volume, mass), shape (geometry), density, enrichment, etc.
    - micro-properties of individual nuclei (properties of every single atom)
      - what things can happen
      - the size of the nucleus (cross section)
    - shorthand way of saying this is *everything*
- **Micro and macro properties combine such that the overall system behavior is very predictable**

Possible Fates



Nuclear Microscopic Cross Section

- **When a neutron is near a nucleus whether it interacts or not is affected by the size of the nucleus**
  - Known as the microscopic **cross section**
    - Size of one nucleus
    - Units of area, cm^2 or barns (1 barn = 10^{-24} cm^2)
    - Physically the nucleus is small compared to the atom
      - Matter is mostly empty space, punctuated by regions of incredible density
    - If this view of nature was true on the nuclear scale
      - Neutrons would rarely interact
      - Fission chains would not be possible
- **In subatomic reality**
  - The size of the nucleus appears to grow or shrink, varying in a complex manner with how fast (energy) the neutron is moving

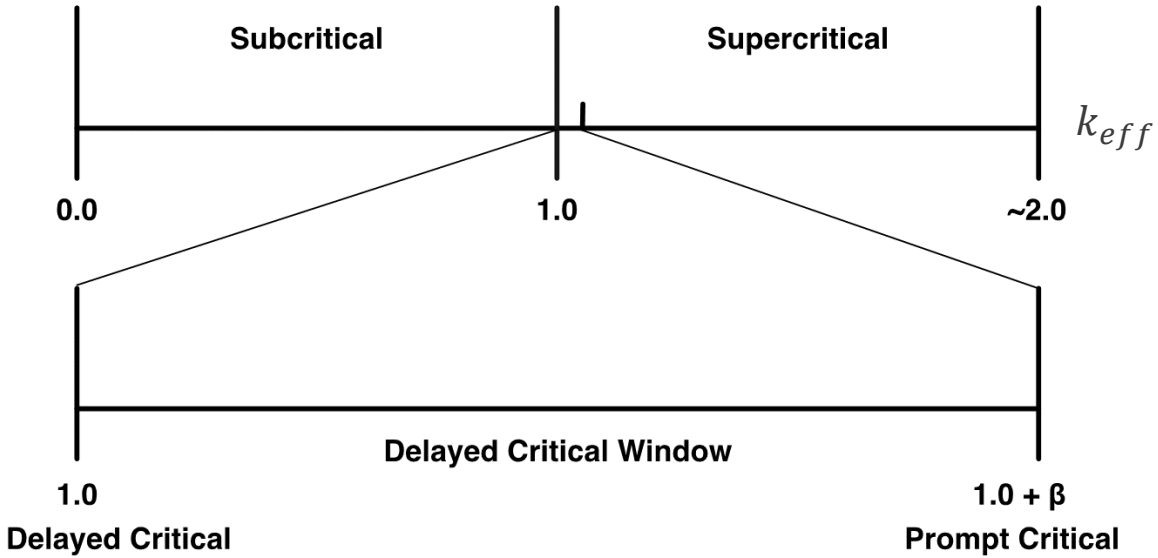
Microscopic Cross Section Notables

- **Any one neutron as it approaches a nucleus will have only a single speed (energy)**
  - The nuclear cross section will have a one set value
- **The microscopic total cross section is larger (~100 times or more) for slow as opposed to fast moving neutrons**
  - Fission neutrons are all born moving fast
- **The total microscopic cross section can be divided into two parts**
  - Absorption
  - Scattering

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 nuclear criticality safety purpose
    - “Fissionable” is used generically to refer to SNM that that contribute to criticality safety concerns

Regions of Criticality

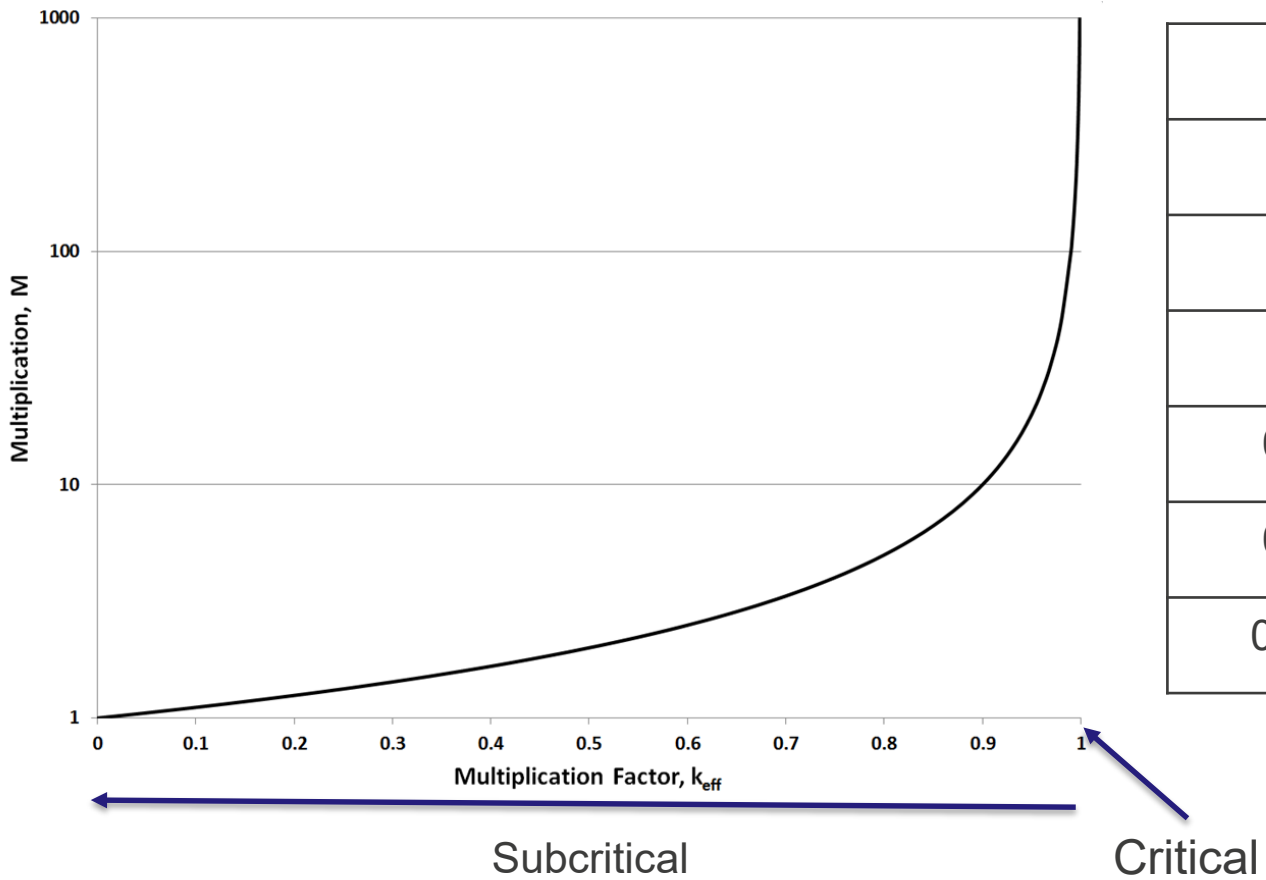


- **β and the Delayed Critical Window**
  - β is the delayed neutron fraction (β < 1%)
  - Delayed Critical Window is where delayed neutrons are required to maintain a critical (or slightly supercritical) system
    - $1.0 \leq k_{eff} < 1.0 + \beta$

Delayed Critical versus Prompt Critical

- **Delayed Critical: Reactor needs both prompt and delayed neutrons to be critical**
  - increase in neutron population (power) dominated by time for delayed neutrons to appear
    - long time for power increase allows for control mechanisms
- **Prompt Critical: Reactor only needs prompt neutrons to be critical**
  - increase in neutron population (power) dominated by time for prompt neutrons to appear
    - short time for power increase does not allow for control mechanisms
  - Criticality accidents are always in this prompt region

Neutron Multiplication



k_{eff}	M
0	1
0.5	2
0.9	10
0.95	20
0.99	100
0.999	1000

Moderation in Detail

- **As light nuclei are added to fissionable material, three effects occur simultaneously**
  1. fissionable material is diluted, its density is lowered
     - fission rate decreases
  2. neutrons slow down
     - fission rate increases
  3. light nuclei absorb neutrons competing with fissionable material
     - fission rate decrease
- **One affect will dominate the system depending on how much moderator is present and the cross section of the nuclei**
- **Result is a critical mass curve**
  - Critical mass is a function of the fissionable material density in the moderator