Safety / Criticality Issues During Reprocessing

NATIONAL NUCLEAR LABORATORY

Caveat

- Use and interpretation of this material should be used with great caution. The information presented is only used to give a simple introduction to Criticality Safety.
- Values, data and statements should NOT be used as a basis of establishing safety without due consideration by Nuclear Criticality Safety Specialists.

Session Structure

In this session we will look at:

- Fundamentals and factors
  - What is criticality safety?
  - What parameters affect criticality safety?
- Findings from the SACSESS Safety Work Package

Different Safety Disciplines

Nuclear industry needs to handle and process nuclear materials safely.

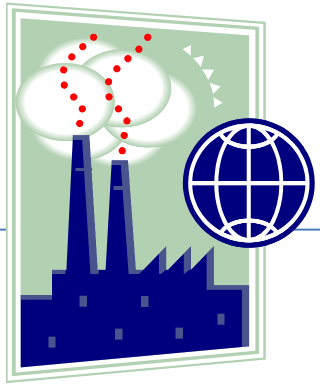
Perhaps more familiar with radiological safety…

- Radiation hazards: External, Internal (ingestion, inhalation), Contamination

… and other safety aspects?

- Chemotoxic, Explosion, Conventional, Environmental

But what is Criticality Safety?



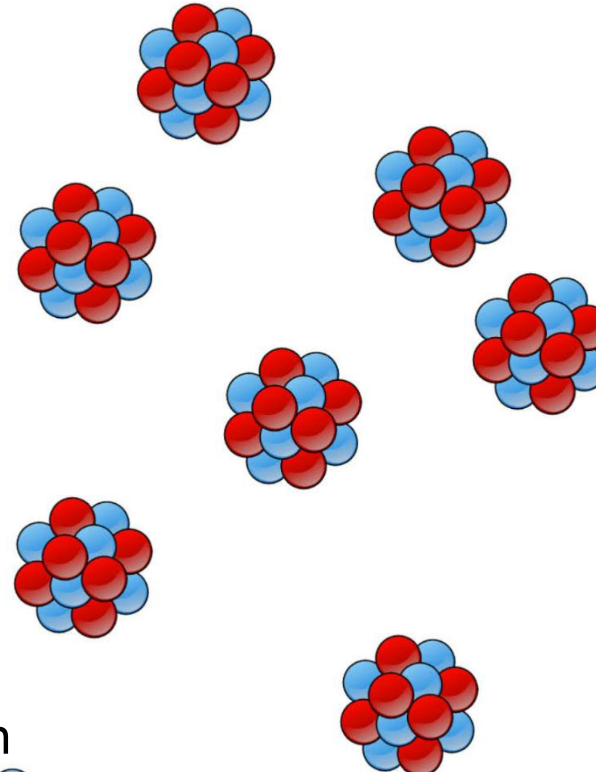
What is Criticality?

A self sustaining or diverging chain reaction of fission processes.

Criticality Safety is:

- Protection against the consequences of an inadvertent nuclear chain reaction, preferably by prevention of the reaction – *ANSI/ANS 8.1-1998*
- The art and science of **NOT** building a nuclear reactor **without** shielding, coolant and control – *Francis Alcorn*

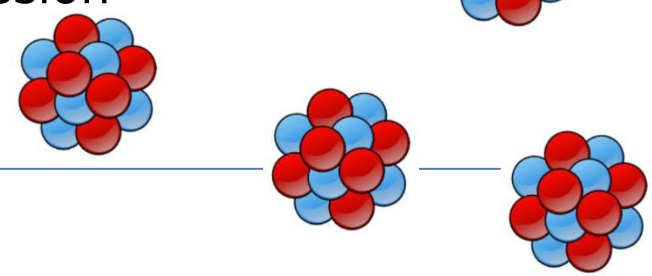
Neutron Interactions



Neutrons can be absorbed

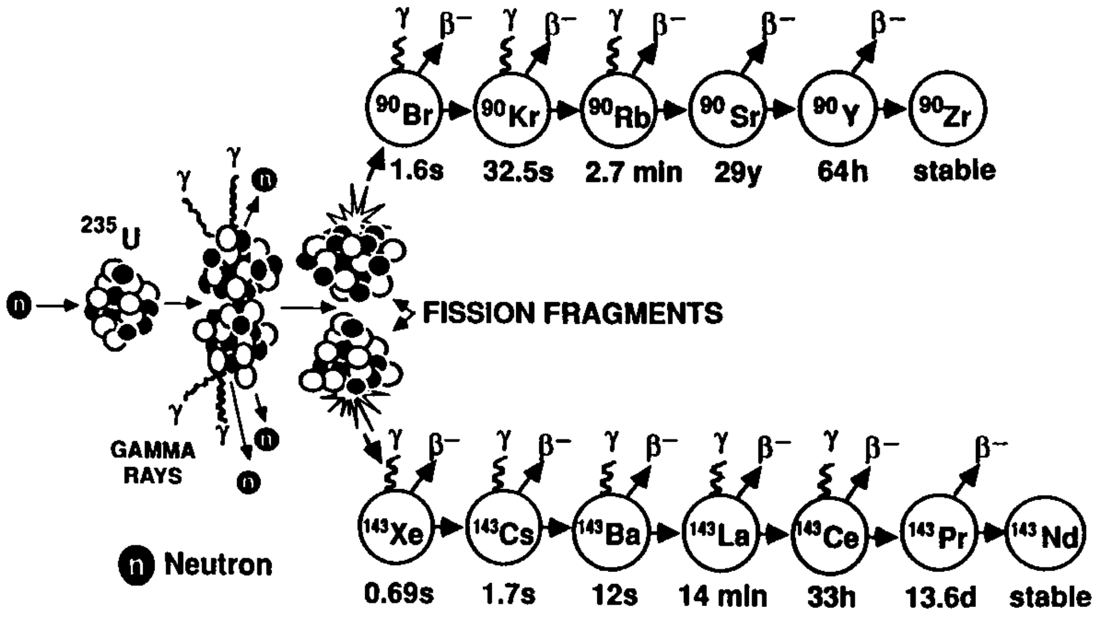
Scattered

Or can cause the nucleus to break apart : fission



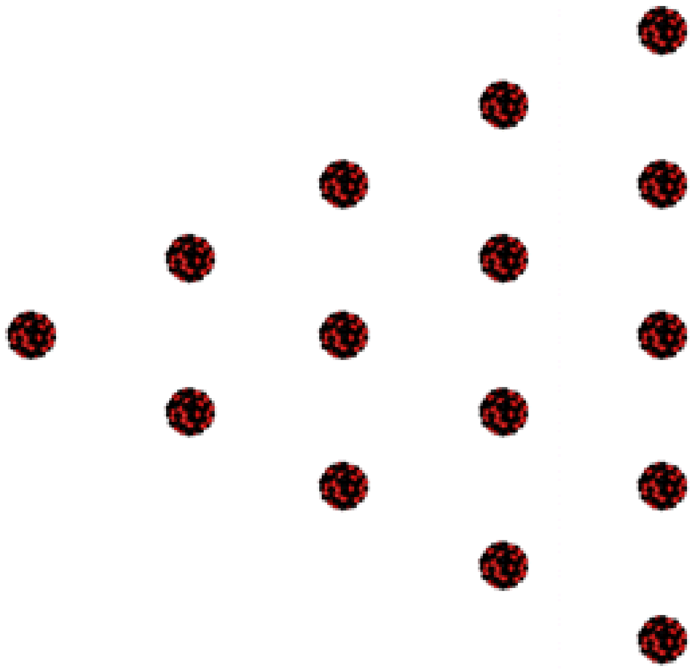
…. a little more on nuclear fission

- Energy
- Fission Fragments
- Neutrons
- Radiation



The chain reaction

Neutrons produce fission produce neutrons produce fission produce neutrons produce fission produce neutrons produce fission produce neutrons produce fission produce neutrons produce fission produce neutrons produce fission produce neutrons produce fission produce neutrons produce fission produce neutrons produce fission produce neutrons produce fission produce neutrons produce fission produce neutrons produce fission produce neutrons produce fission produce neutrons produce fission produce neutrons produce fission............................



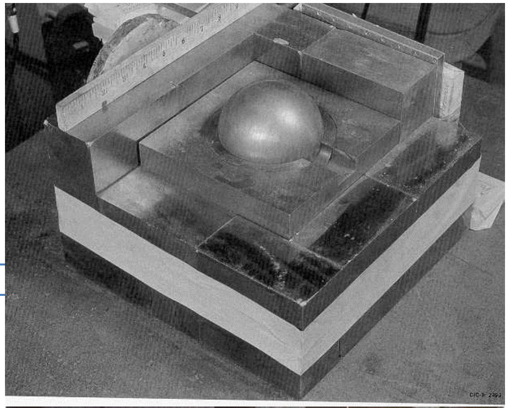
What are the effects of criticality?

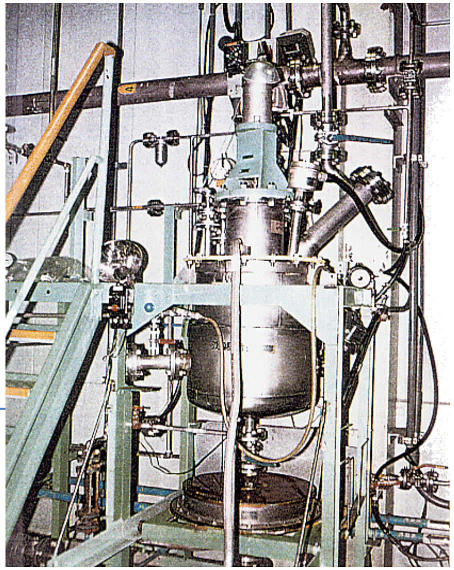
- Release of large amounts of radiation
- Can taken form of:
  - Single spike/burst
  - Multiple burst settling on steady state
  - Slow increase/ramping up
  - → Unpredictable, particularly for solution systems

- Large doses possible
- Can be fatal if within a few metres
- Usually only (local) worker effects
- Usually no plant damage

A bit of history

- 1st criticality accident – 1945
- Most recent criticality accident – 1999
- 60 in total (known)
- Predominantly in USA and former Soviet Union
- 22 chemical process accidents
    - All but one associated with liquid processes
    - Majority were to do with waste and rework processing
- Many fatalities





k_{eff}

k_{eff} = Effective Multiplication Factor

$$= \frac{\text{Production}}{\text{Absorption + Leakage}}$$

$k_{eff} > 1$ neutron level increasing (supercritical)

$k_{eff} = 1$ neutron level steady (critical)

$k_{eff} < 1$ neutron level decreasing (subcritical)

Criticality Control Parameters

Mass

Absorption

Geometry

Interaction/ Spacing

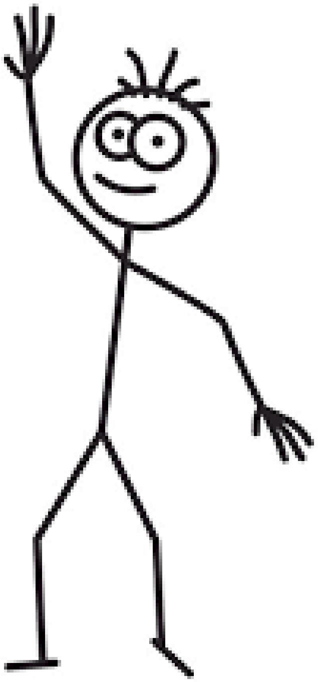
Concentration

Moderation

Enrichment

Reflection

Volume



Criticality Control Parameters

Mass

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Volume

Mass

Not too hard a concept:

40kgU : sub-critical

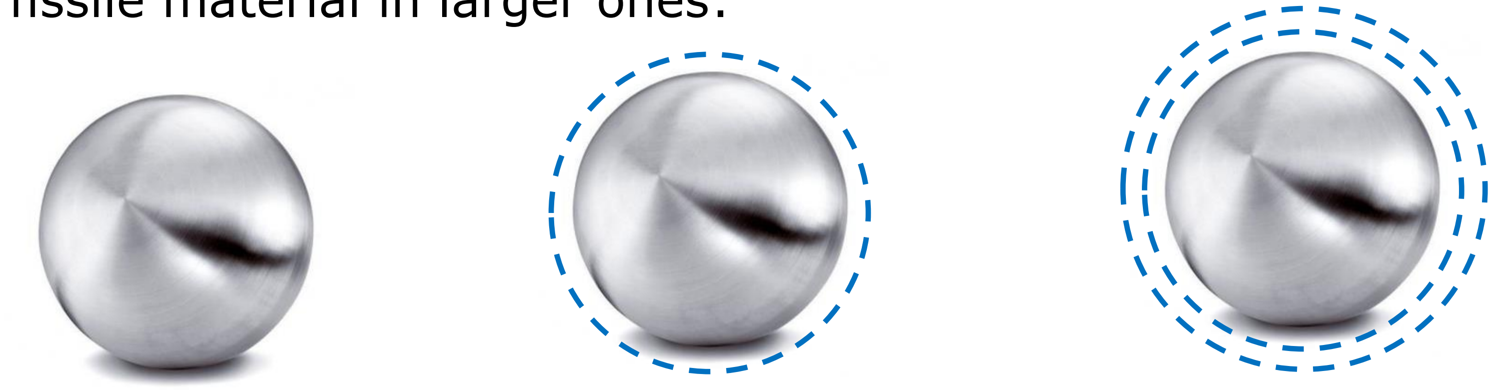
53kgU : critical

60kgU : super-critical

Values for high enriched uranium metal, spherical, unreflected

Mass – but what is actually going on?

Neutrons leaving the surface of the small sphere now encounter more fissile material in larger ones:



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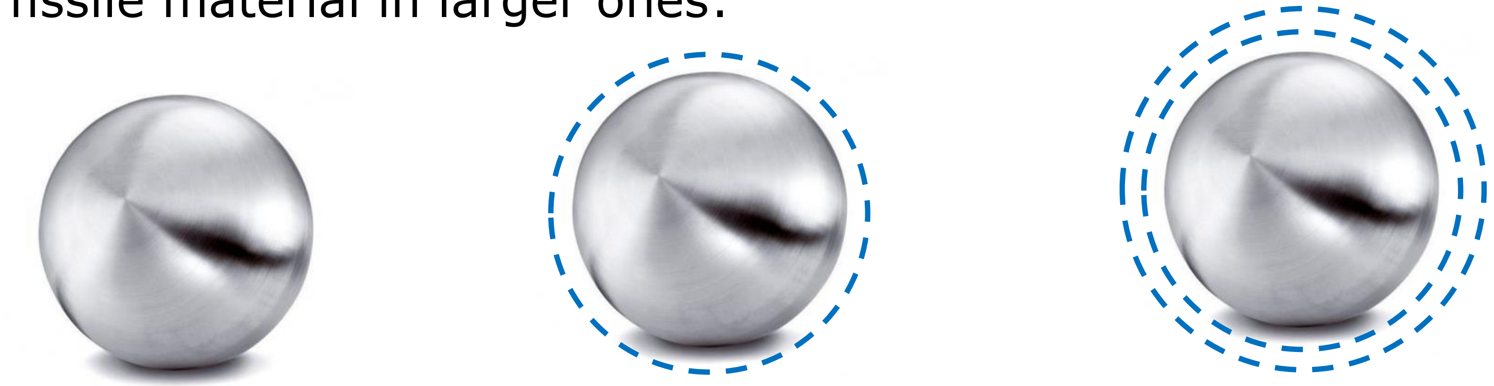

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Increasing reactivity

Values for high enriched uranium metal, spherical, unreflected

Criticality Control Parameters

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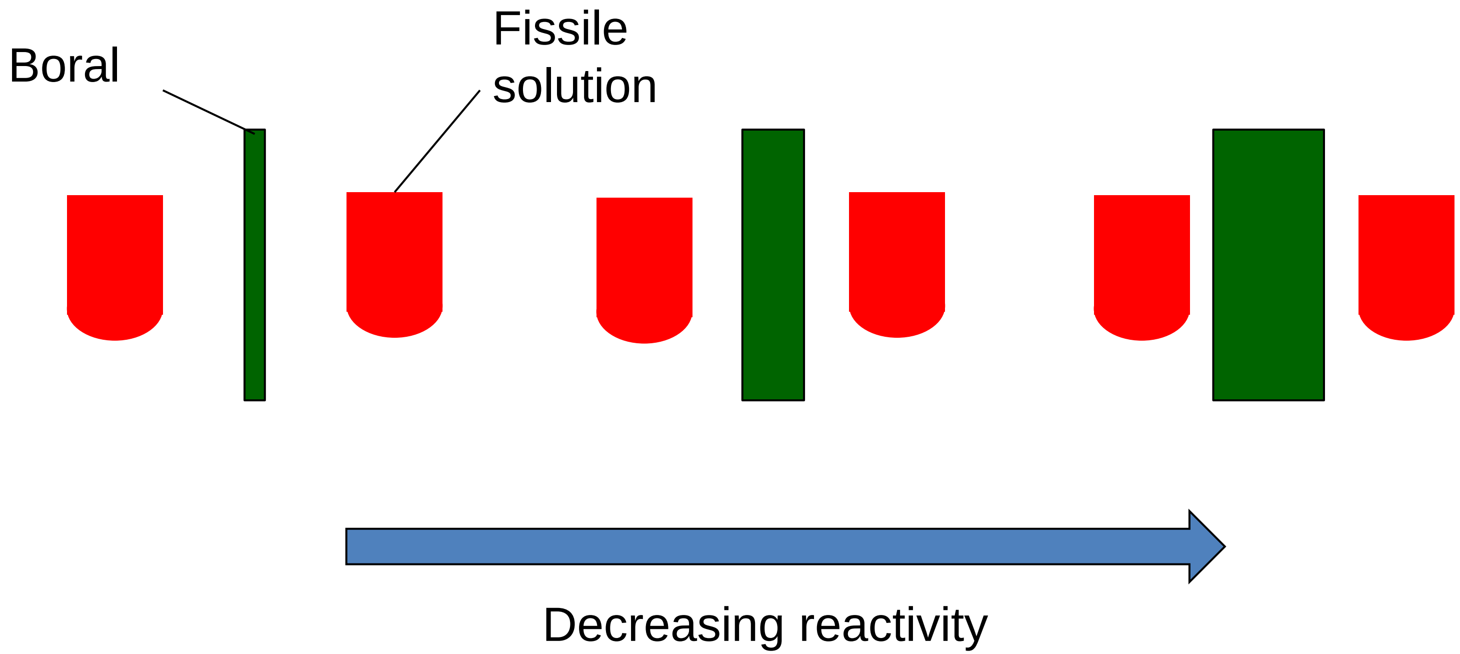
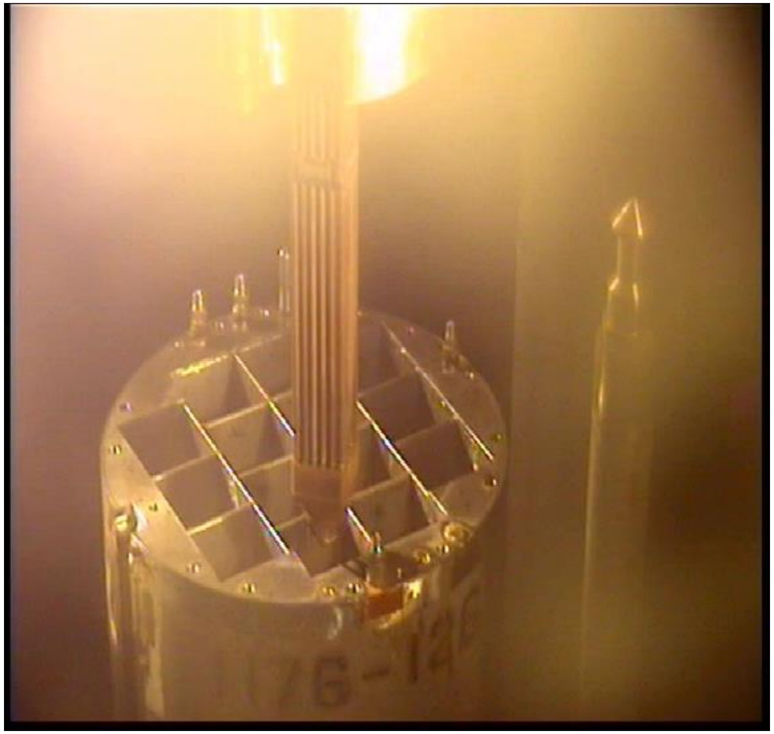
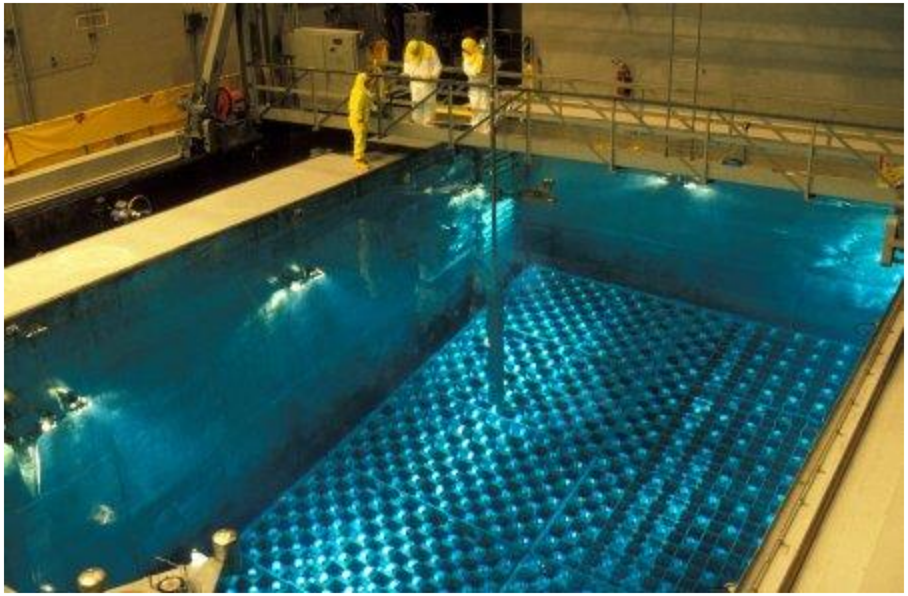
Absorption – but what is actually going on?



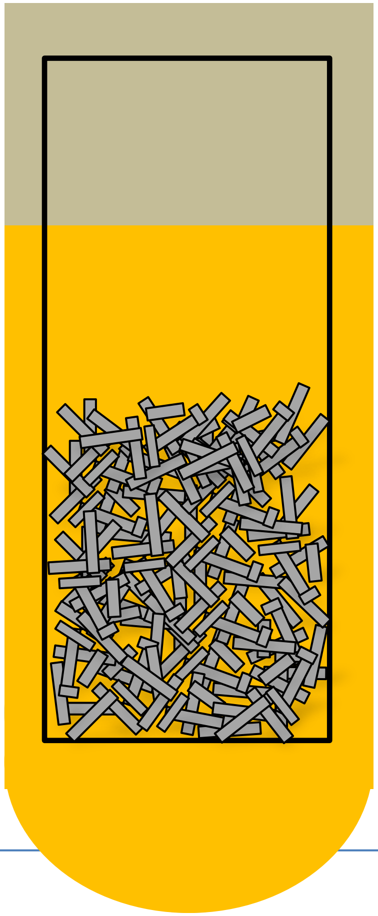
Absorption – Solid Examples



Absorption – Solution Examples



Fuel Storage Pool



THORP Dissolver

Criticality Control Parameters

Mass

Absorption

Geometry

Interaction/ Spacing

Concentration

Moderation

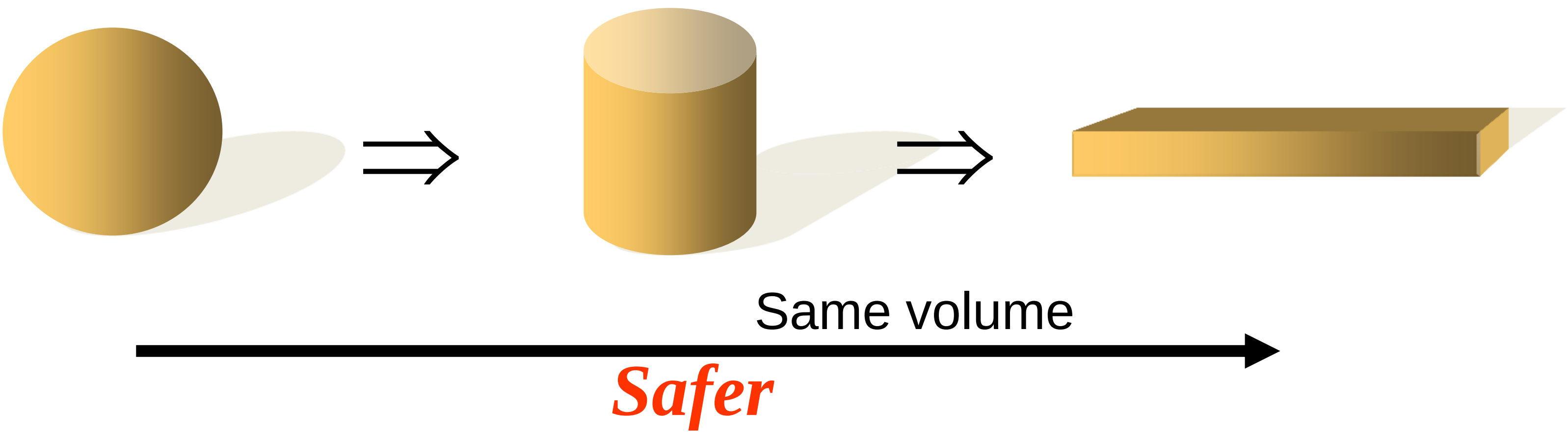
Enrichment

Reflection

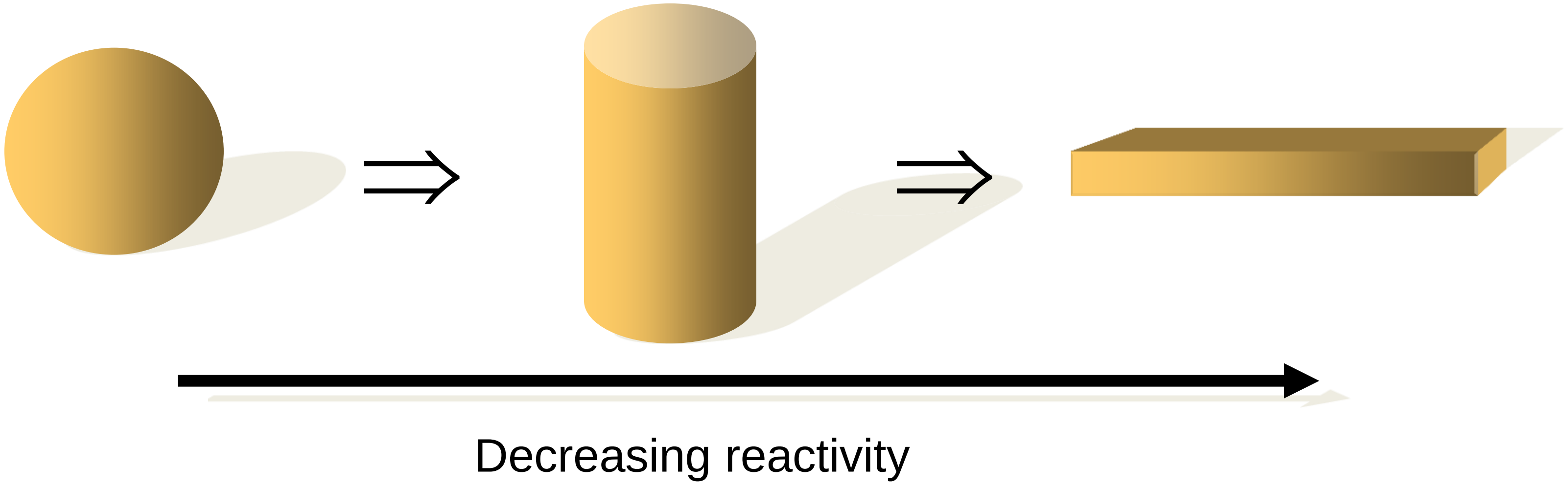
Volume

Geometry

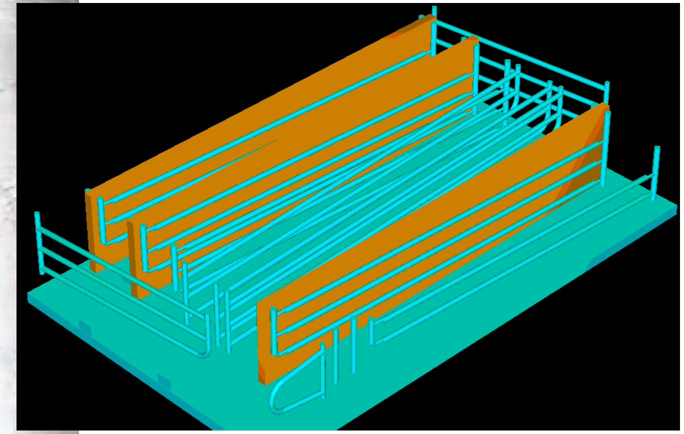
Larger surface area/volume ratio is most safe



Geometry : What's really going on?



Geometry Examples



Criticality Control Parameters

Mass

Absorption

Geometry

Interaction/ Spacing

Concentration

Moderation

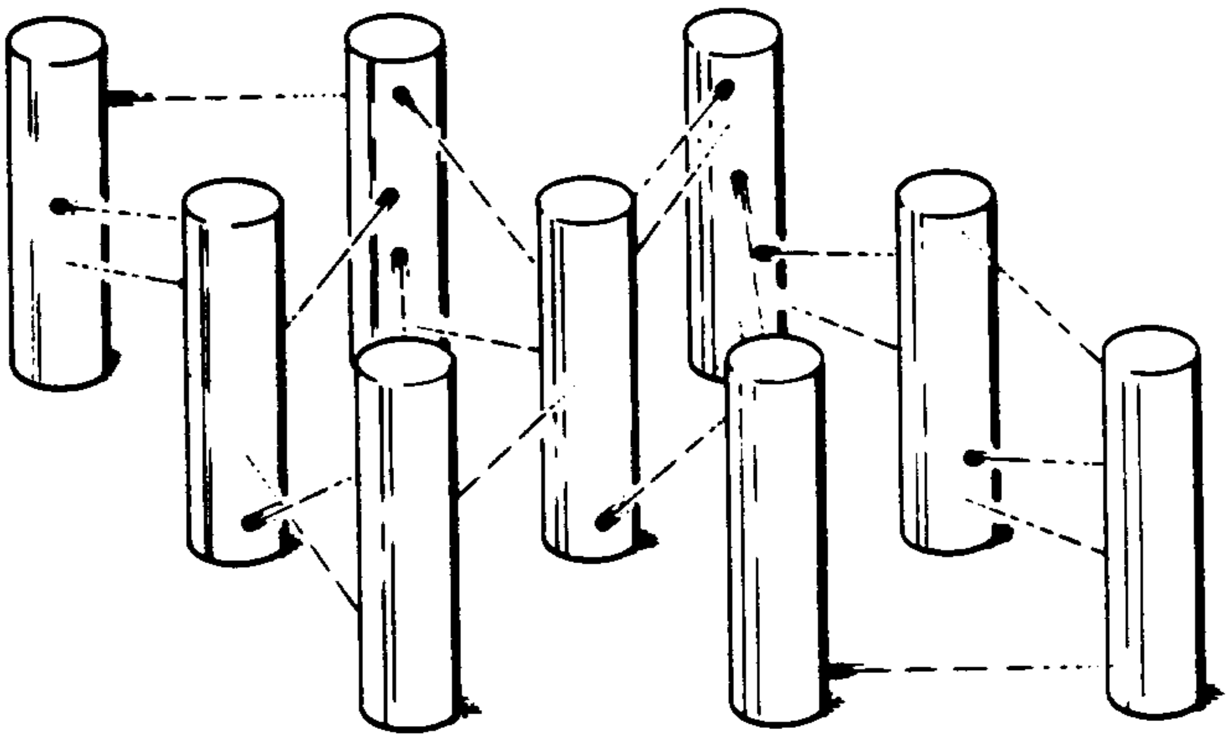
Enrichment

Reflection

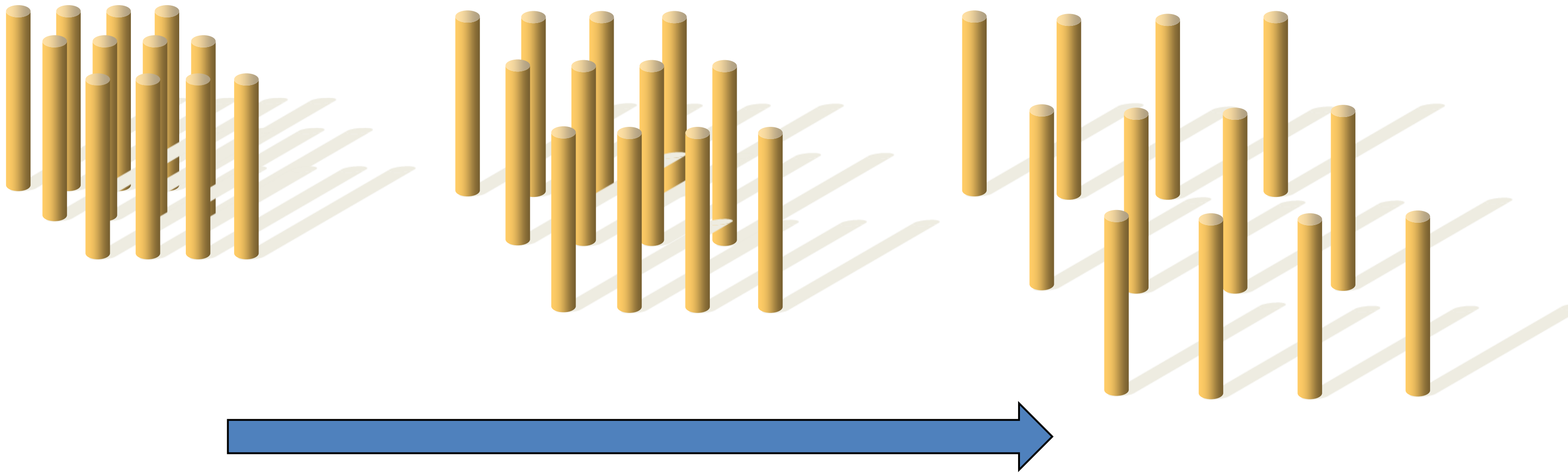
Volume

Interaction

Arrays of fissile materials – can interact in a big way

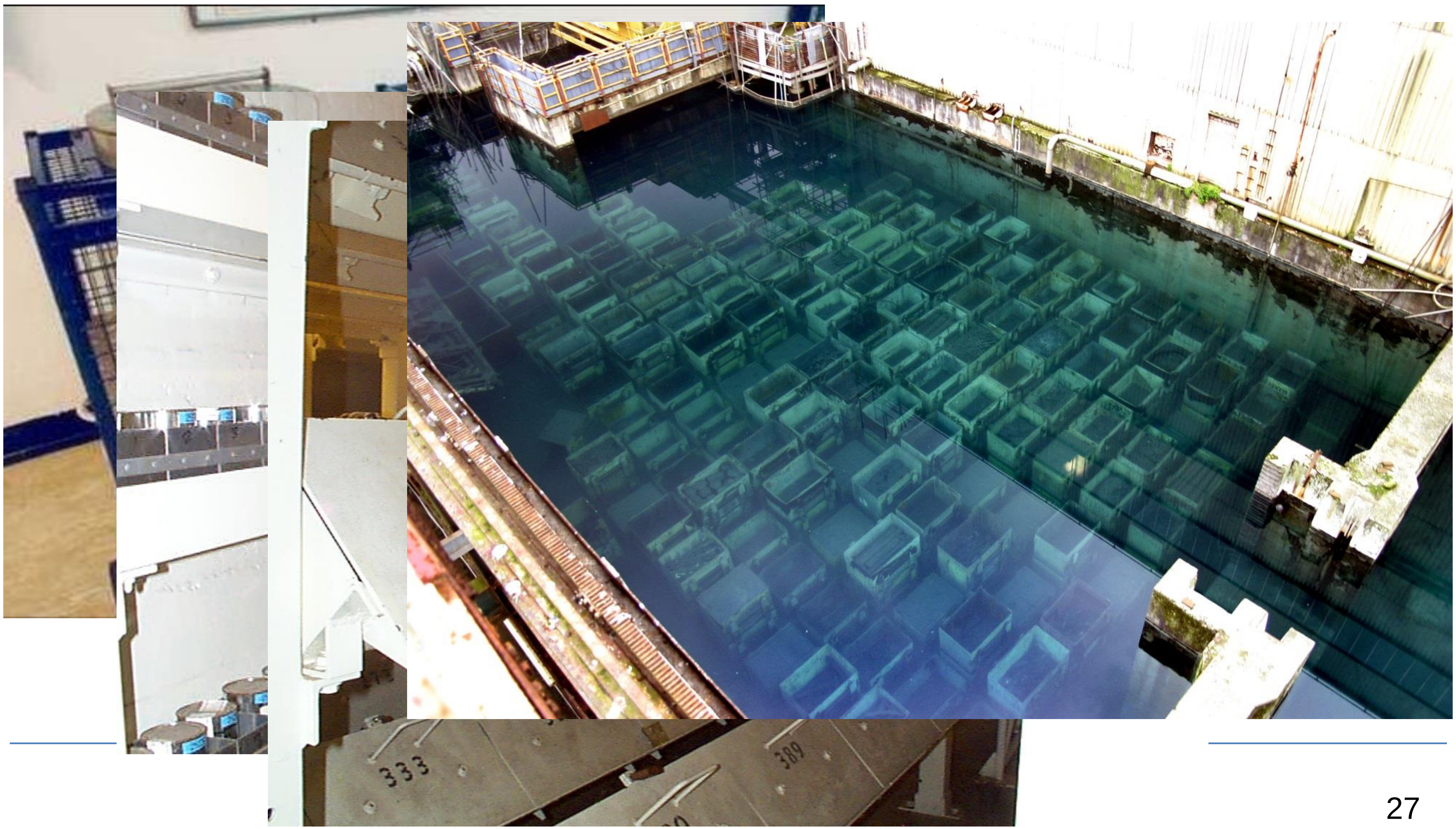


Interaction: What's really going on?



Reactivity decreasing

Interaction - Examples



Criticality Control Parameters

Mass

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Enrichment

Reflection

Volume

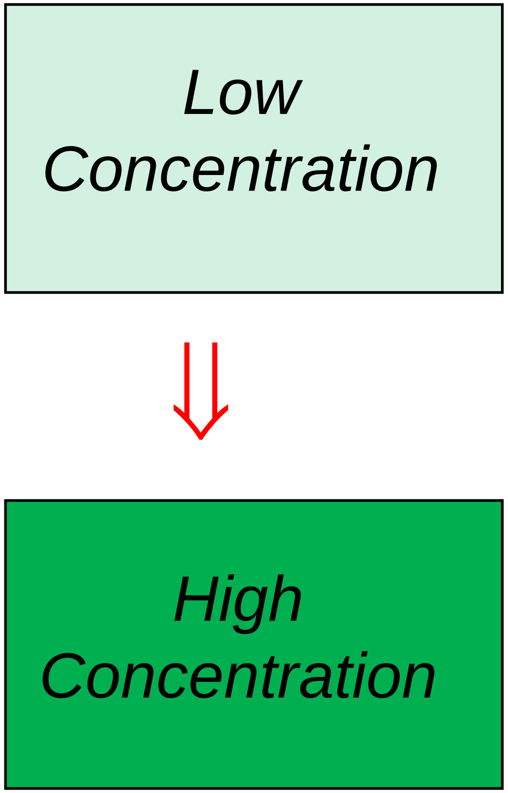
Concentration

Increasing concentration *tends* to a less safe situation

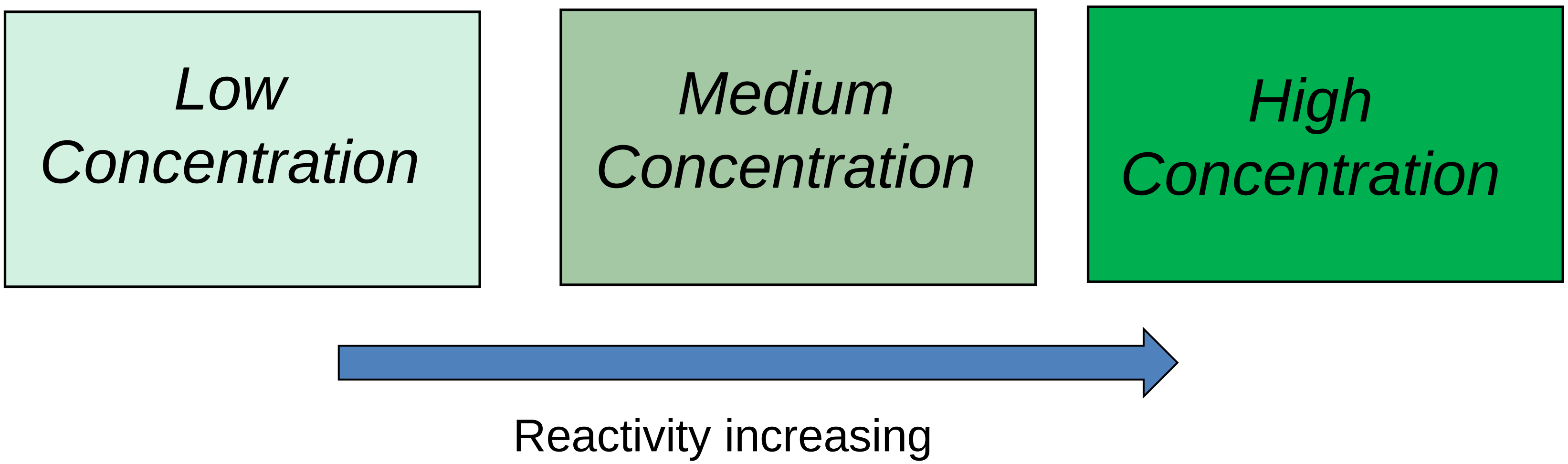
Reason:

Neutrons more likely to encounter another fissile atom.

But see "moderation" later for a little added complexity

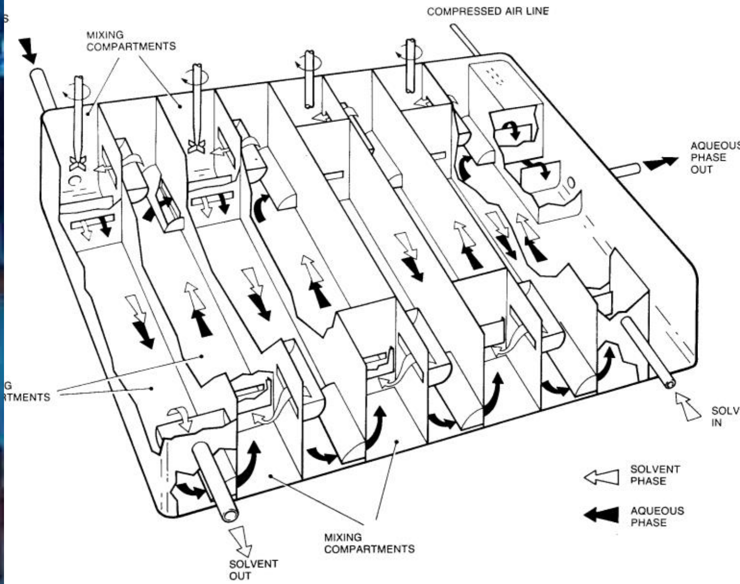


Concentration: What's really going on?



But watch out when concentration gets higher:
There is more to it – need to consider adsorption and *Moderation*!

Concentration - Example



Criticality Control Parameters

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Moderation Process

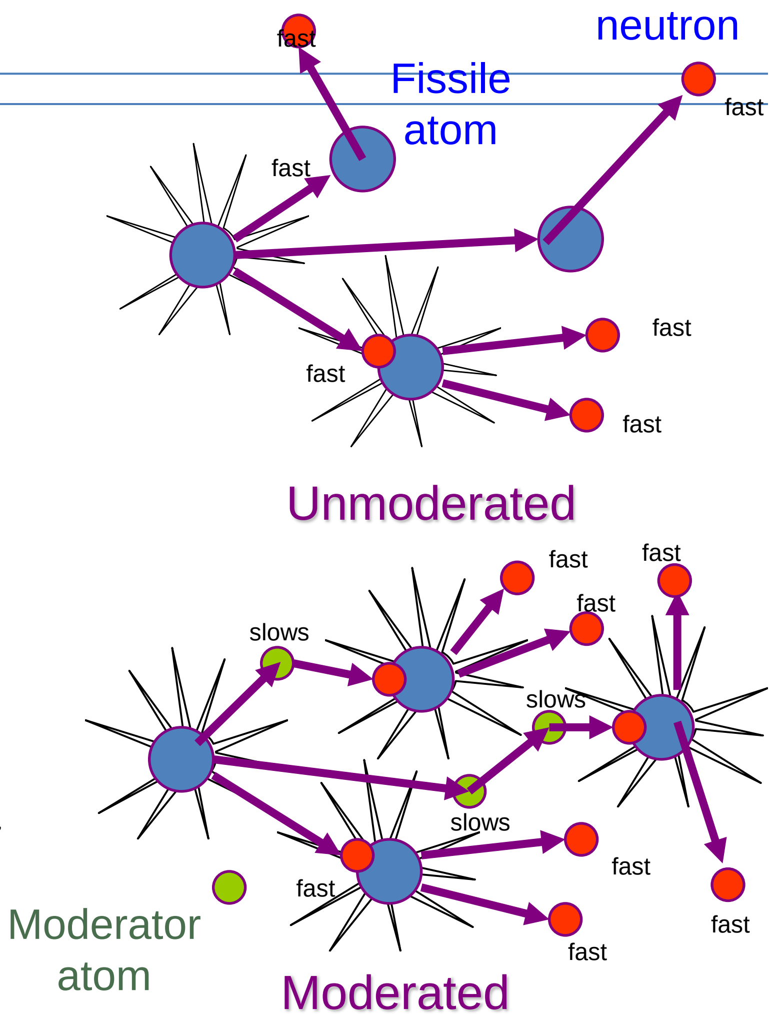
Presence of moderators _can_ increase reactivity for a system with _fissile_ material

Reason:

neutrons more likely to produce fission at low energies

Low atomic weight elements best to "moderate"

But note: absorption can become dominant at low fissile concentrations – can reduce reactivity



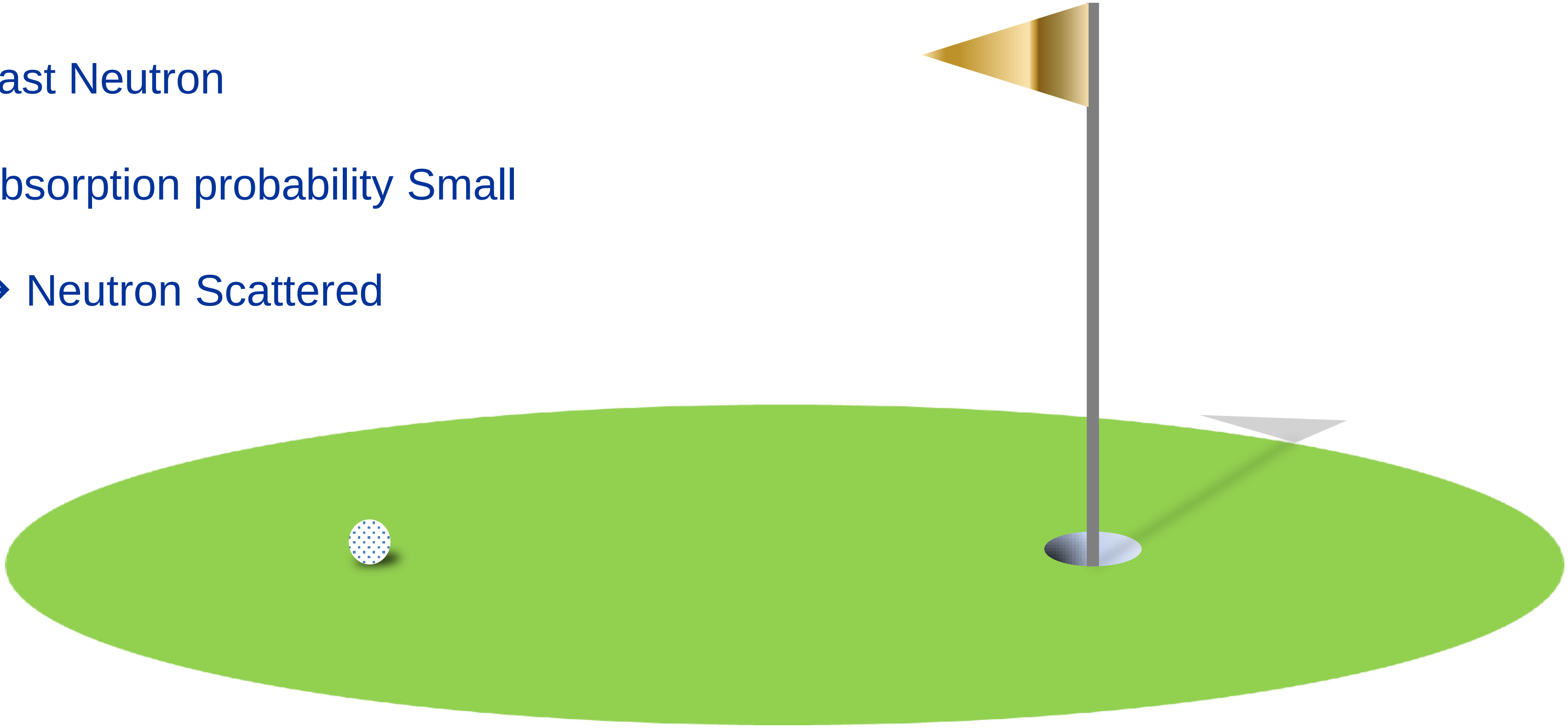
Moderation

Unmoderated

Fast Neutron

Absorption probability Small

→ Neutron Scattered



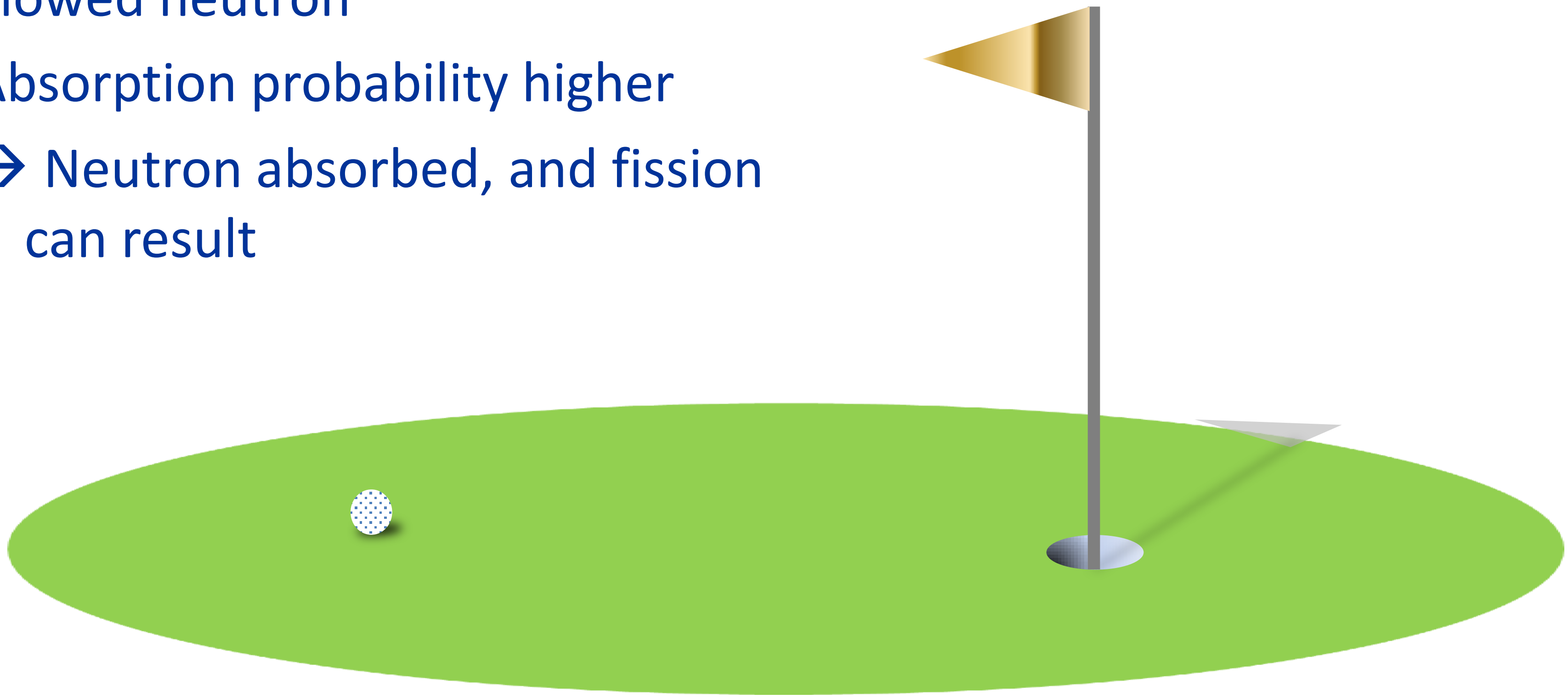
Moderation

<u>Moderated</u>

Slowed neutron

Absorption probability higher

→ Neutron absorbed, and fission can result

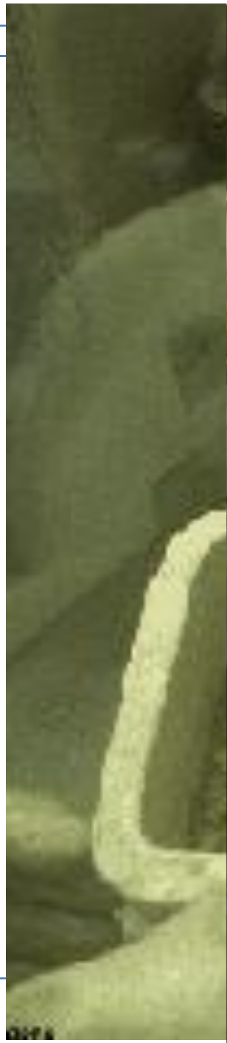


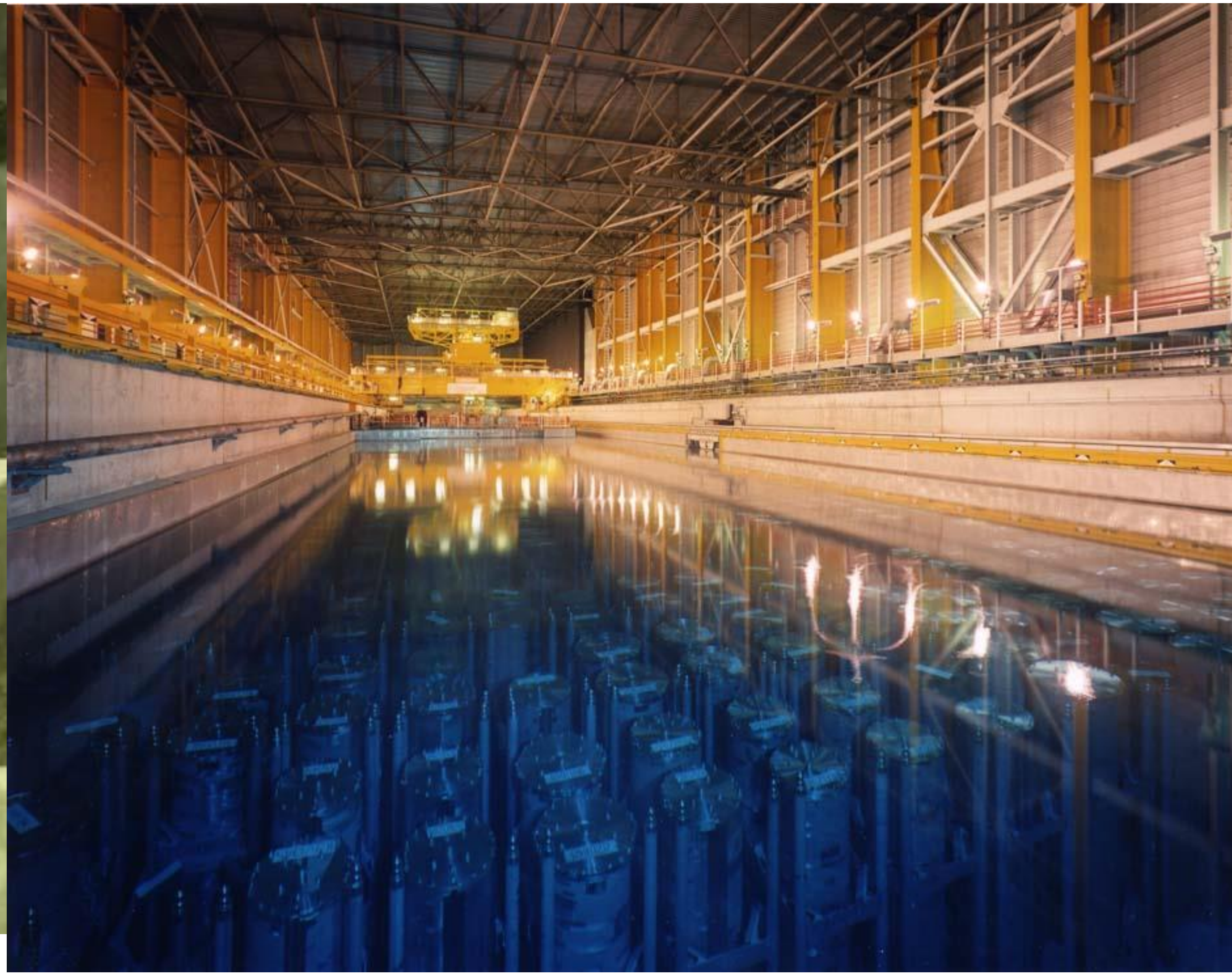
Good Moderators

Water, and a few other materials (oils, plastics, things with lots of hydrogen in them usually, graphite) are special when they are mixed with fissile material.

Any neutrons bouncing around collide with the hydrogen (or carbon) atoms and this slows them down from their normal high speeds.

Moderation - Examples





Criticality Control Parameters

Mass

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Enrichment

By enrichment we mean the amount of “active” (fissile) material present compared to that which is effectively “passive” (non-fissile). E.g. Uranium-235 and Uranium-238.

Lets compare critical masses:

High Enriched Uranium (93% U235) 53kgU

50% U235 165kg

30% U235 320kgU

Approx. values for uranium metal: spherical, unreflected

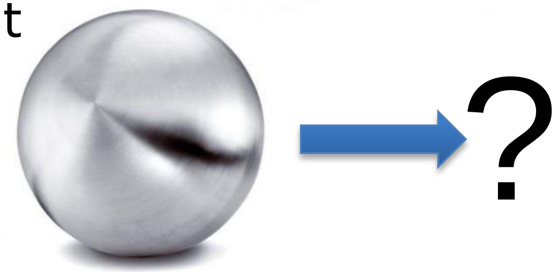
Enrichment

A quick question:

- ➢ What happens for lower enrichments?
- 15w/o U235? ~1400kg
- 10w/o U235? ~3500kg
- 4w/o U235? Infinite, 5% is about the limit

High Enriched Uranium
(93% U235)
53kgU

50% U235
165kg



30% U235
320kgU

Approx. values for uranium metal: spherical, unreflected

Enrichment – What's really going on?

Proportion of material made up of the fissile isotope.

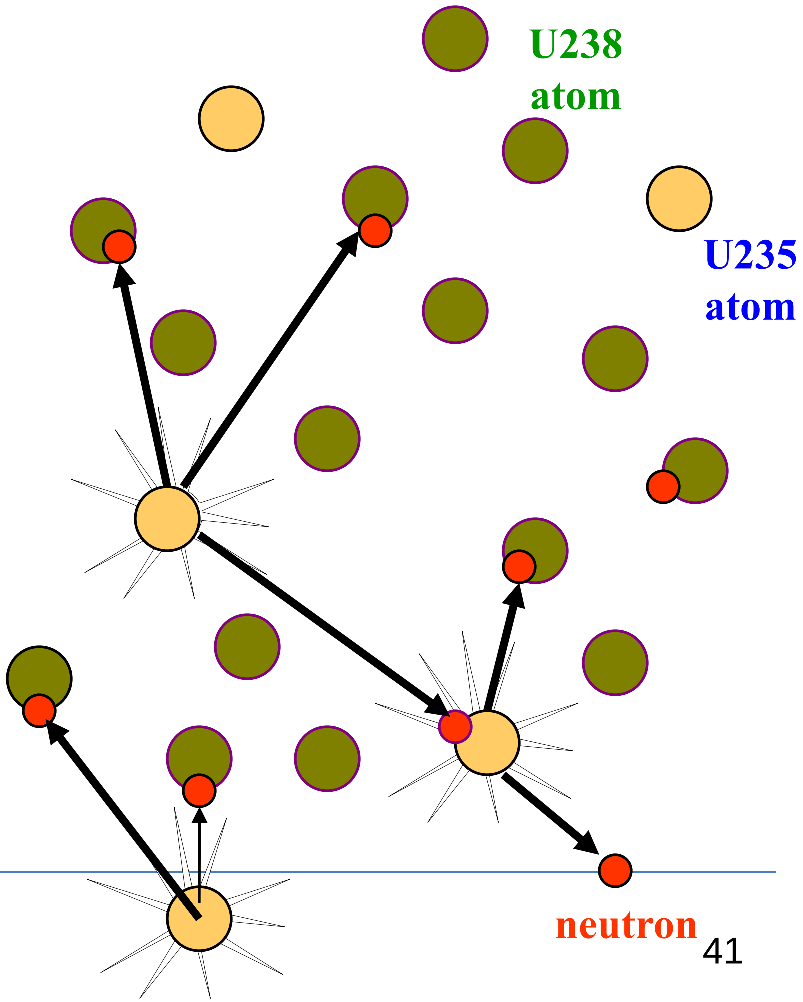
Increasing enrichment **increases** reactivity

Reason:

- *Increased proportion of fissile isotope present promotes likelihood of further fissions*
- *I.e. increases production relative to absorption*

Typical examples:

- U235 in Uranium
- Pu 239 in Pu
- Pu in MOX



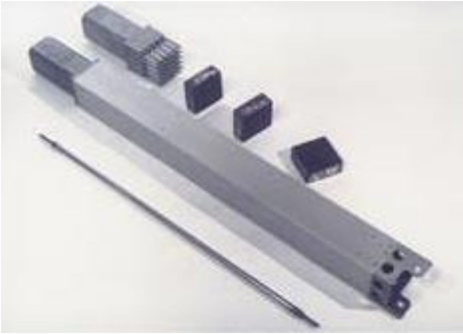
Enrichment - examples

Magnox
0.72w/o U235

AGR
3.5w/o U235

PWR
~4w/o U235

TRIGA
~20-30w/o U235



Criticality Control Parameters

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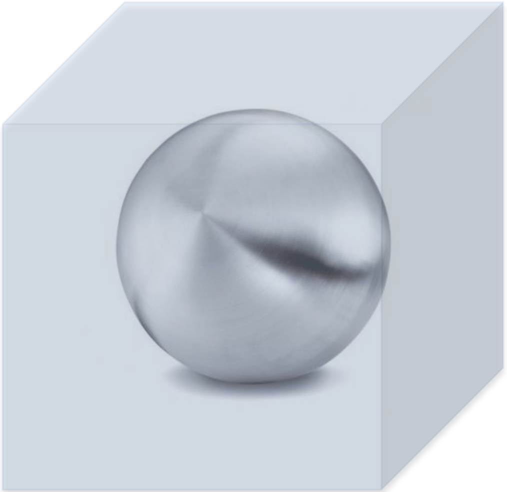
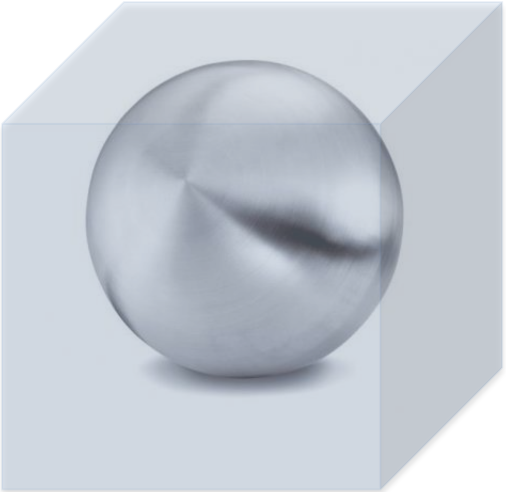
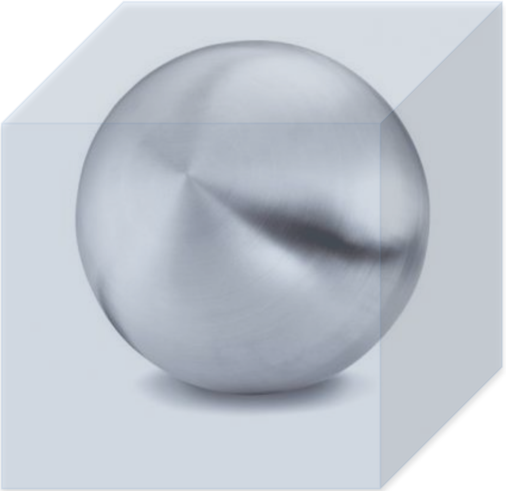
Reflection



40kgU : super-critical



53kgU : super-critical



60kgU : super-critical

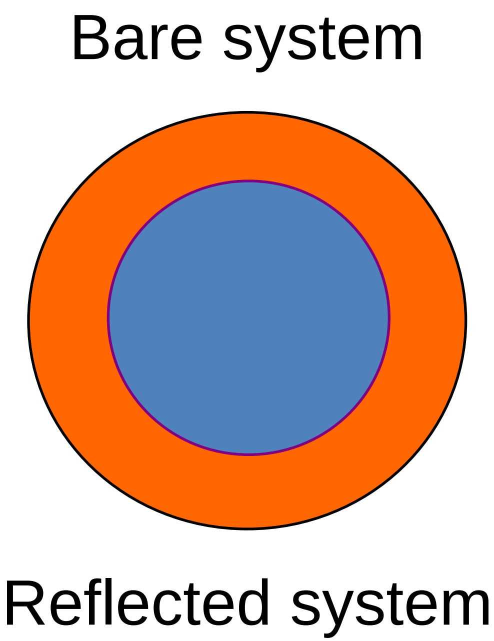
Reflection

Presence of reflectors *typically increases* reactivity

Reason:

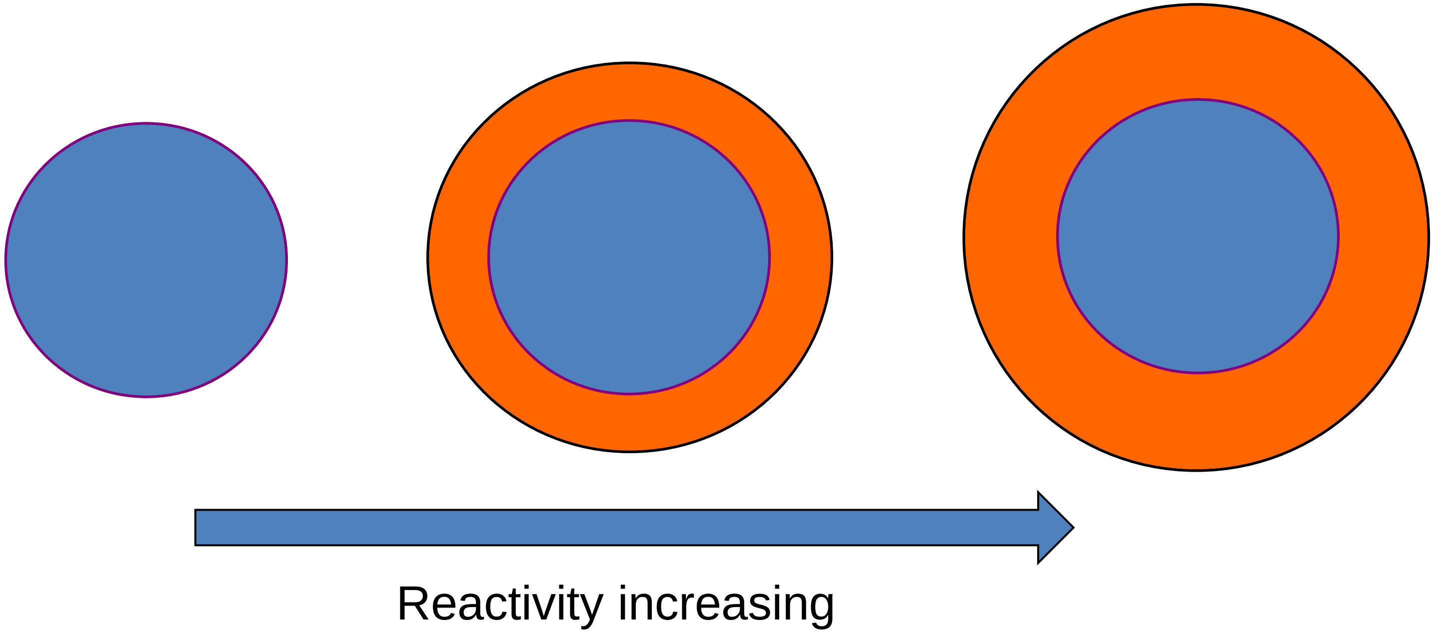
neutrons more likely to be scattered & returned to fissile system

Most effective are high atomic number, dense materials: Uranium, lead, steel, concrete, water etc…



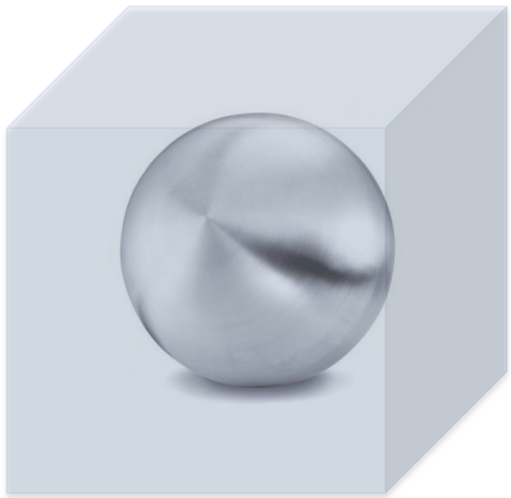
Note: can have the benefits of isolating fissile material in arrays

Reflection – What's really going on?

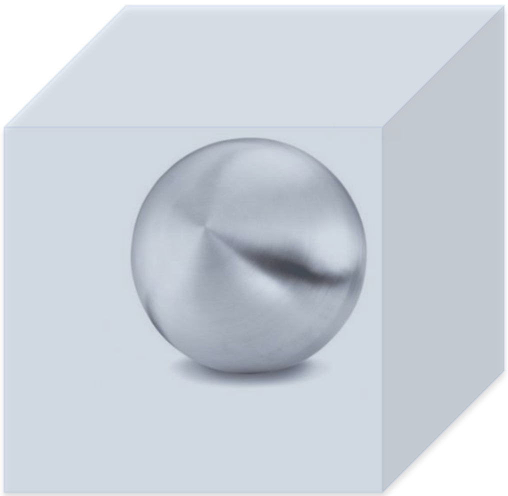


Reflection

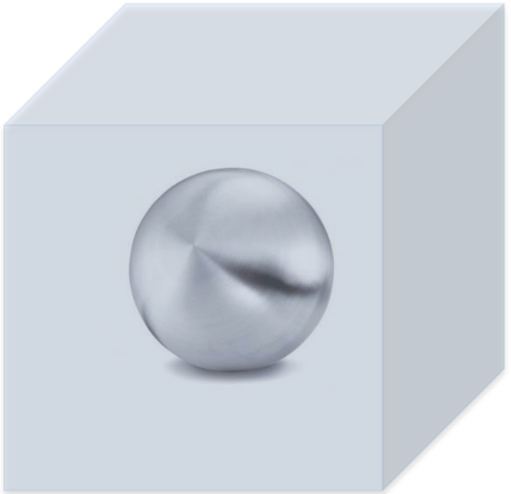
Need to reduce the mass of the HEU sphere:



40kgU : super-critical



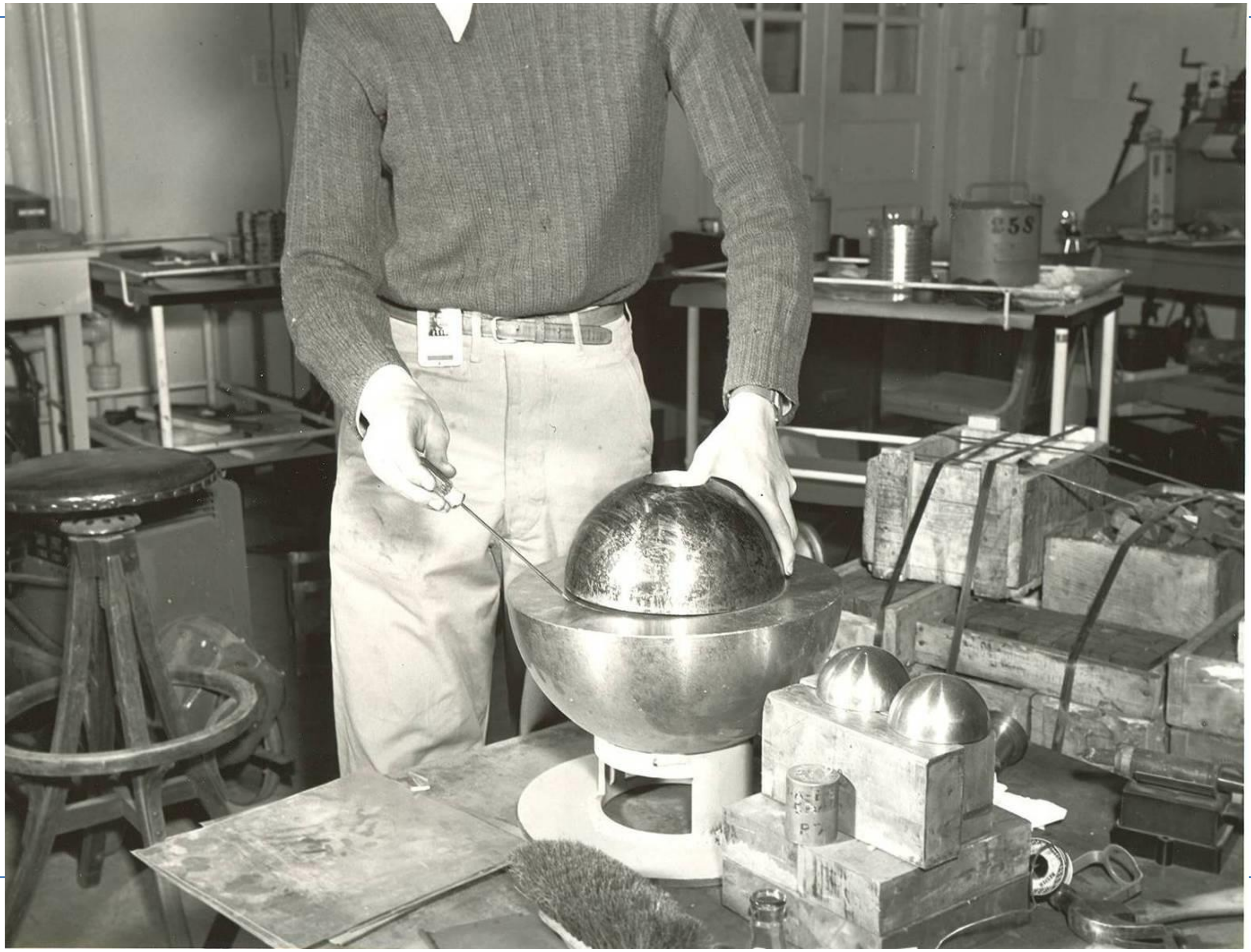
23kgU : critical



17kgU : sub-critical

Values for high enriched uranium metal
spherical, full water reflection

Reflection - example



Summary

Mass

Absorption

Geometry

Interaction/ Spacing

Concentration

Moderation

Enrichment

Reflection

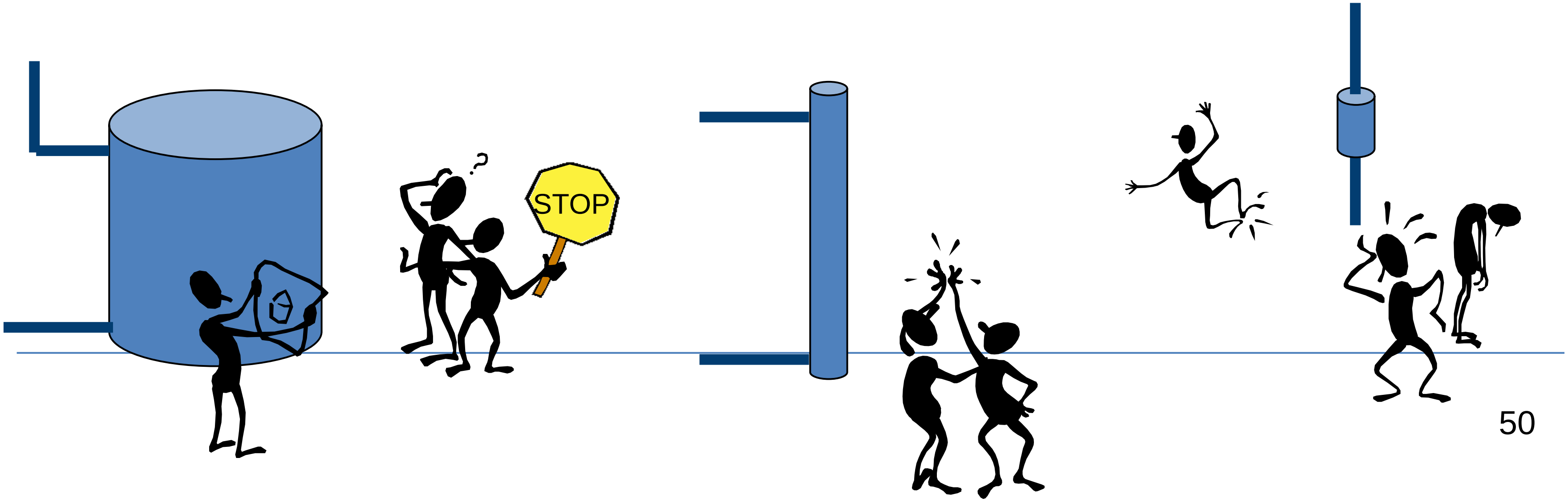
Volume

Reality is that rarely can we consider these in isolation. Combinations and competing effects need to be taken into account.

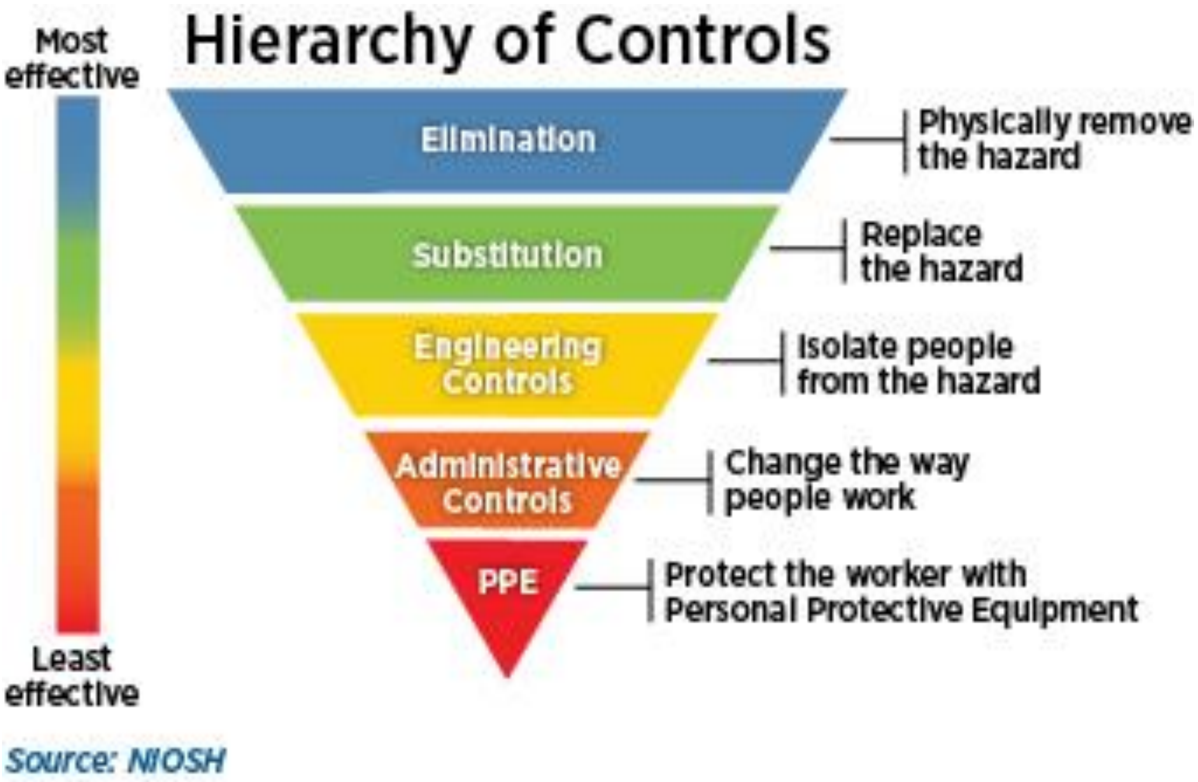
Arrays / real life applications can be complicated with many competing effects.

Design Optimisation Aspects

- Large fissile quantities vs. small
- Big vessels vs. small vessels
- Squat cylindrical vessels vs. thin “pencil” tanks
- Vessels close or separated?
- Fissile concentration requirements



Safety Hierarchy



Future research areas from SACSESS

What is "reference fissile medium"

Understand overall / individual chemical behaviour, process performance and limits

What are the monitoring requirements?

What is solvent life span?
Need a solvent wash design

Industrialisation practicalities?

What is the end goal?

What is head end process?

Potential for explosion and "red oil" reactions?

Potential for solids precipitates?

Process model aspects?

Toxicity? Environmental impact?

Questions?