McMASTER SCIENCE FOR PEACE
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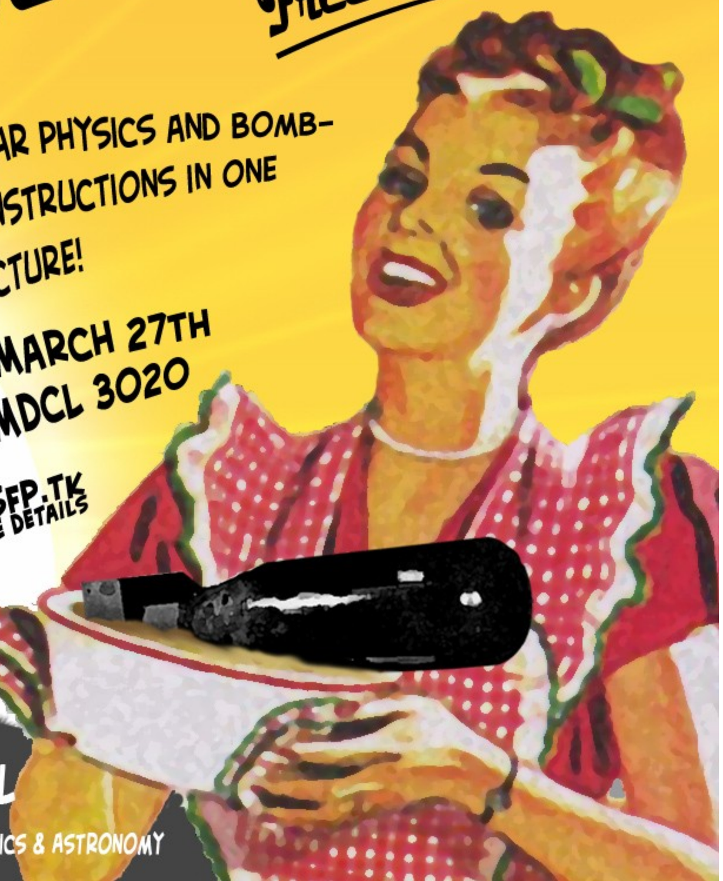
MSU

FROM THE MINDS THAT BROUGHT YOU "THE NUKES OF HAZZARD"...

# HOW TO BUILD A NUCLEAR BOMB

*Free Admission!*



EASY NUCLEAR PHYSICS AND BOMB-BUILDING INSTRUCTIONS IN ONE SHORT LECTURE!

**TUESDAY, MARCH 27TH**
**7:30PM, MDCL 3020**

VISIT WWW.MSFP.TK FOR MORE DETAILS

PRESENTED BY:
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GRADUATE STUDENT
DEPARTMENT OF PHYSICS & ASTRONOMY

# How to Build a Nuclear Bomb

Hosted by McMaster Science for Peace

David Kahl

27 March 2007

# Overview

- Motivation
- Principles of Nuclear Energy
- Uranium acquisition and refinement
- Nuclear Reactors
- Bomb Physics

# Motivation

- Distinguish Between Good and Bad
- Undergrad Course Project
- *The Los Alamos Primer*
  - *"Those who worry that it is all too easy to find bomb-building instructions in the library or on the Web should rest assured: these lectures were tough for the greatest theoretical physicists of the time to follow"* ~Amazon.com official book review
- Support Nuclear Disarmament

# Manhattan Project

- Fission: New Science in the 1940s
  - **Today we are standing on the shoulders of giants**
  - **Texts also widely available now**
- This talk will explain *Little Boy*
  - **Uranium shotgun design**
  - **This design is much simpler than a plutonium bomb**
  - **Untested prior to detonation at Hiroshima**
  - **Do not scoff at 'elementary' bomb design**
- Weapons are more advanced now
  - **Higher Efficiency Output**
  - **Signifcantly more sophisitcated engineering and physics**
  - **ICMB technology yield unlimited target range**

# Nuclear Basics

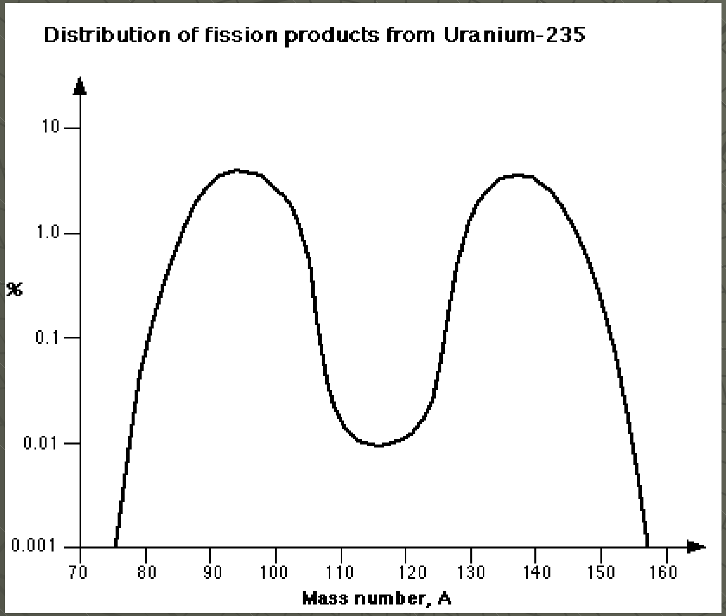
- Nuclei and Elements
- Big Bang and Stellar Nucleosynthesis
- $E = mc^2$
- Fusion and Fission
- Rubber Band Model

# Radioactivity

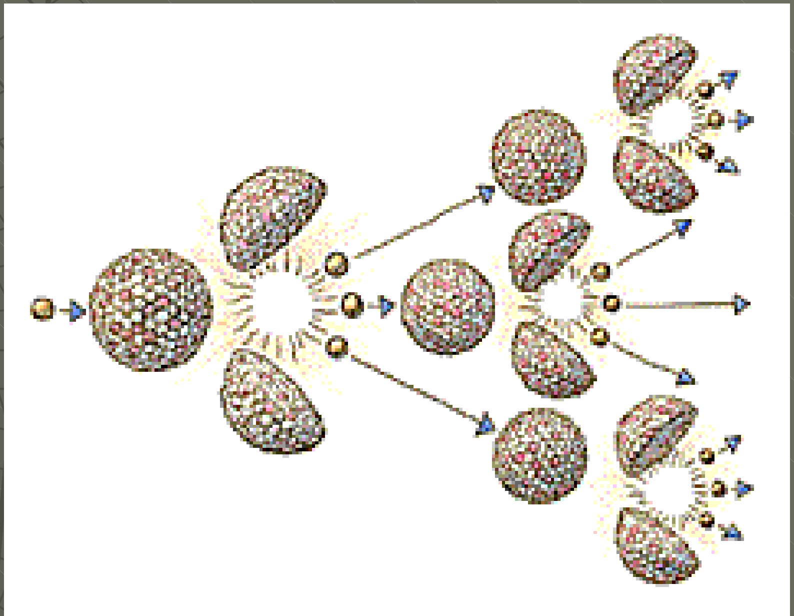
- Release of Energy
  - Adjusts Proton/Neutron Number
- Alpha, beta, gamma
- Varying Lifetimes
  - Shade of Grey, not black and white
- Radioactivity is everywhere
- Earth's magnetic field, temperature

# Uranium Fission in Detail

- Spontaneous vs. Induced
- Splits into uneven nuclei and neutrons
  - Average of 2.5 neutrons each with 2 MeV

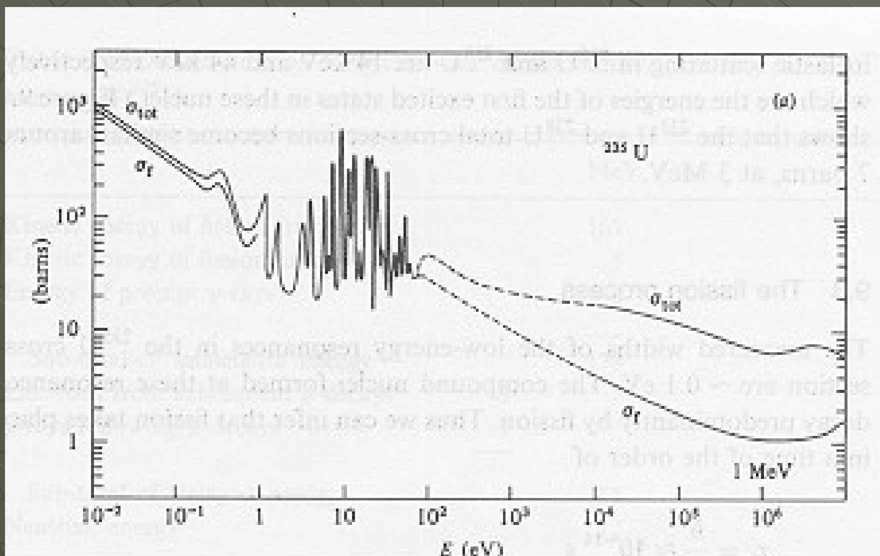


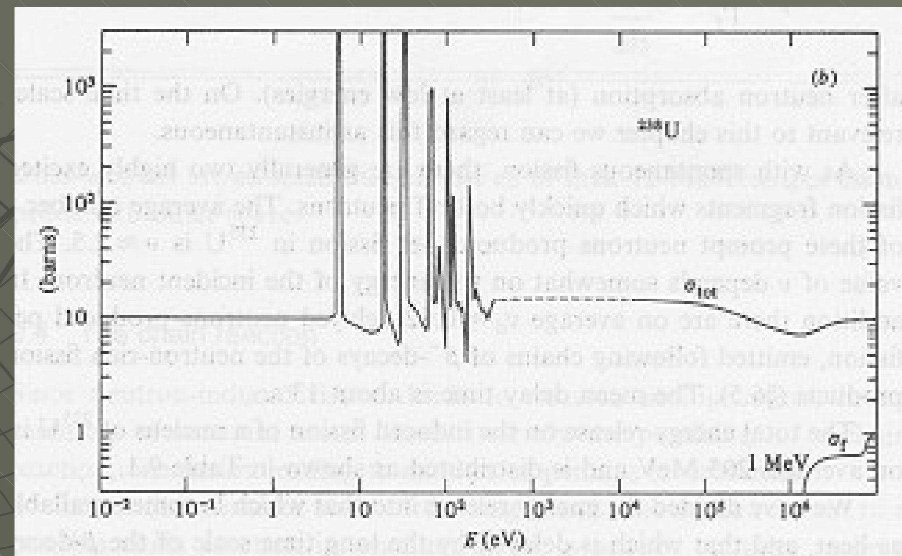

Fission Products
www.uic.com.au/graphics/fissU235.gif



Chain Reaction of Fission

# Uranium Fission Cross-section




**U-235**

High cross section at low energies

Will fission fairly easily

**U-238**

No cross section below 1.4MeV

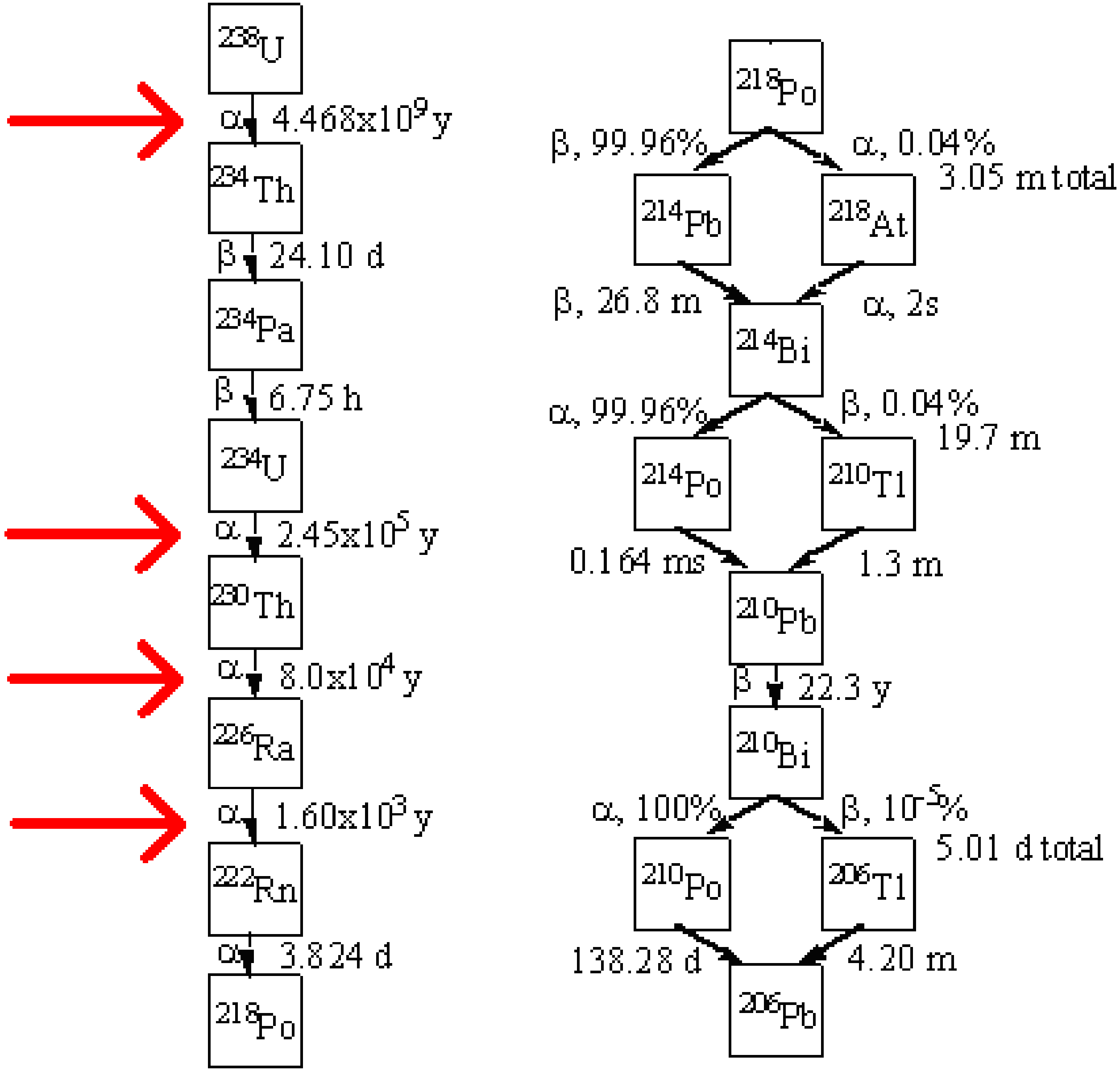
Will only fission with high energy neutrons, and even then, cross section of n-capture is high, leading to plutonium.

Cottingham, W. N., Greenwood, D. A. *An Introduction to Nuclear Physics, 2nd Edition.* Cambridge University Press, 2001.

# Natural Uranium

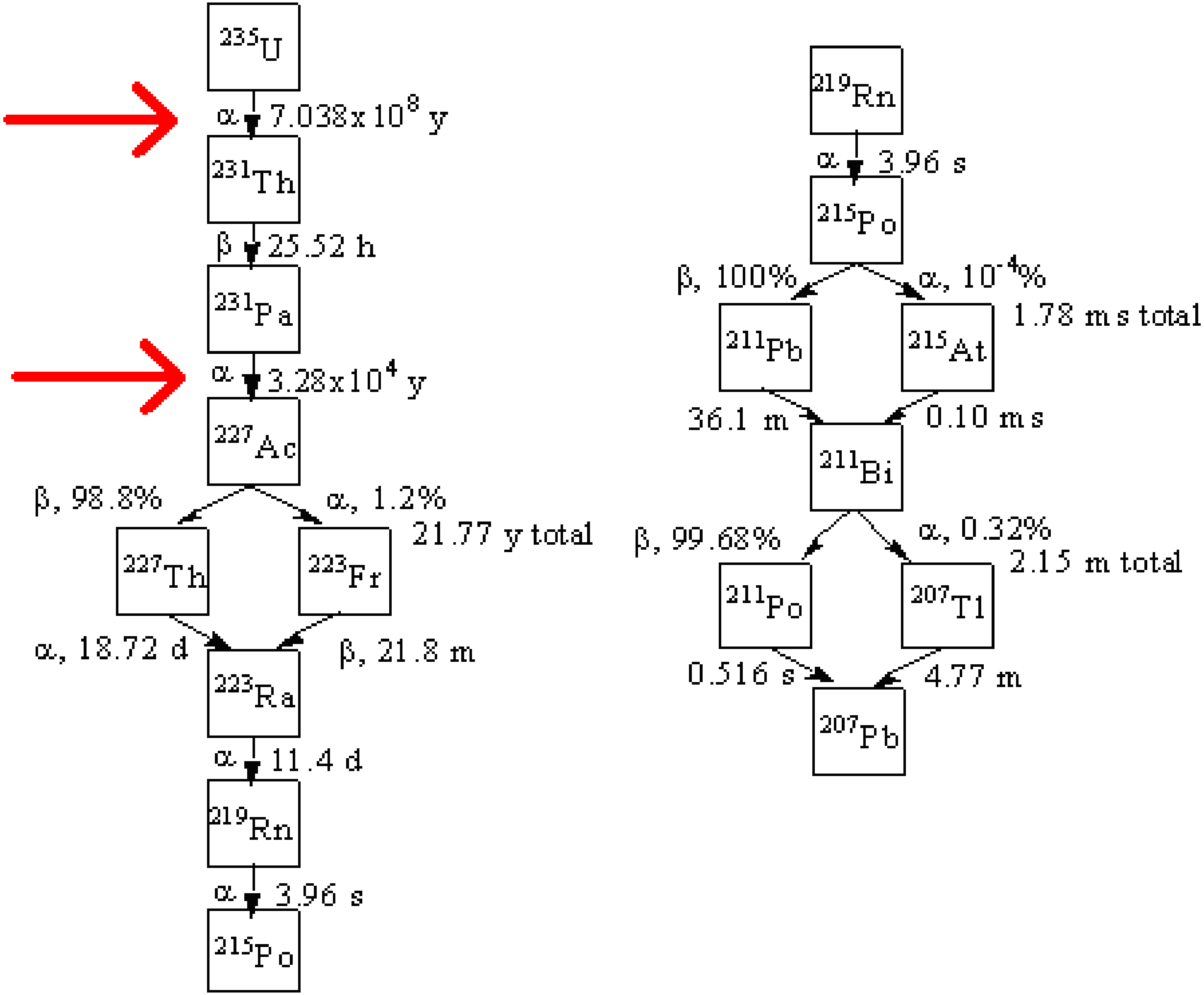
- Ore Must be Mined
  - **Pitchblende and Uranite**
    - **$UO_2$ , $UO_3$ , $U_3O_8$**
  - **Saskatchewan produces 30% of the world's uranium**
  - **Ore can be bought for ~$20/kg**
- Machinery for Processing
- Isotopic Composition
  - 99.3% $^{238}U$, 0.7% $^{235}U$
- Decay series
  - **Explains the isotope disparity**
  - **$^{238}U$ has a longer lifetime than all elements in $^{235}U$ decay chain**
    - **Roughly 4 billion year difference**

# Uranium 238 Decay Series




Adapted from Greenwood, N.N. *Chemistry of the Elements*. Pergamon Press Ltd., U.S.A., 1984.

# Uranium 235 Decay Series



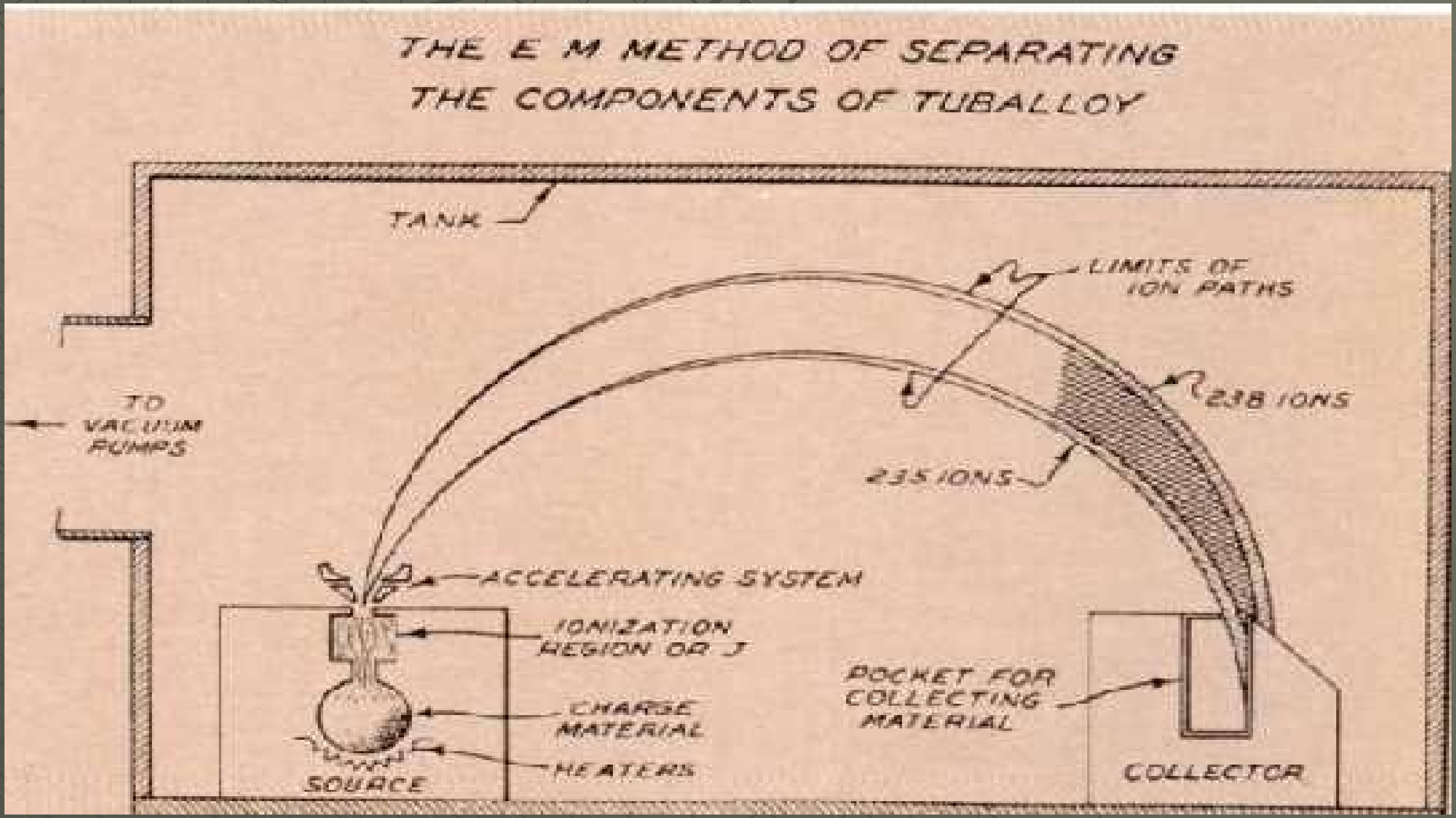

Adapted from Greenwood, N.N. *Chemistry of the Elements*. Pergamon Press Ltd., U.S.A., 1984.

# Uranium Enrichment

- A weapon requires mainly $^{235}U$
- Compare enrichment with depletion
- Largest Single Limiting Factor
  - **Getting $^{235}U$ in highly purified form**
  - **For our purposes, over 11,000 kg will need to be refined!**
- Initial Refinement Most Time Consuming
  - Range: .7% to ~15%
  - Target value: 80% to 99%
- Refinement methods use mass difference
  - **1.26% mass difference makes this difficult**
  - **Electromagnetic**
    - **Method used for the Manhattan Project**
  - **Gas Centrifuge**
    - **Primary Method Employed since 1946 due to lower cost**
  - **Aerodynamic**
  - **Thermal Diffusion**
  - **Laser Process**

# Electromagnetic Separation

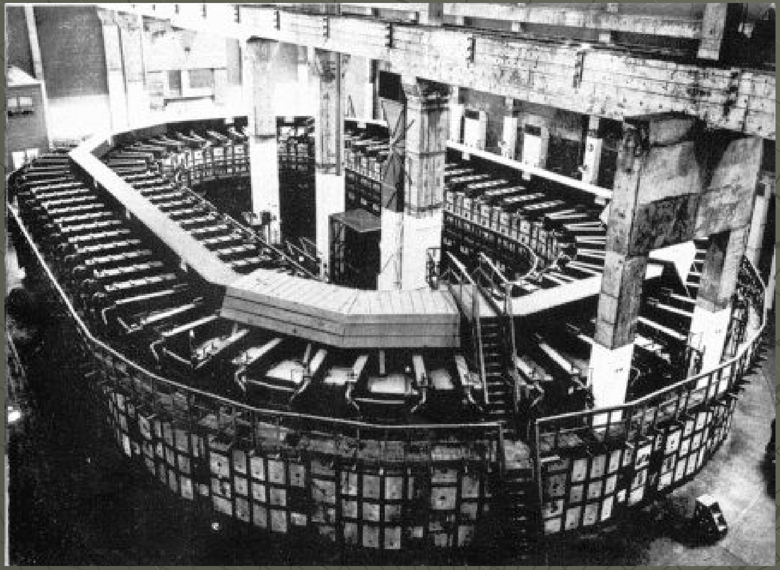
- Ionize and accelerate $UCl_4$ into B-field
- Imperfect ionization / collection

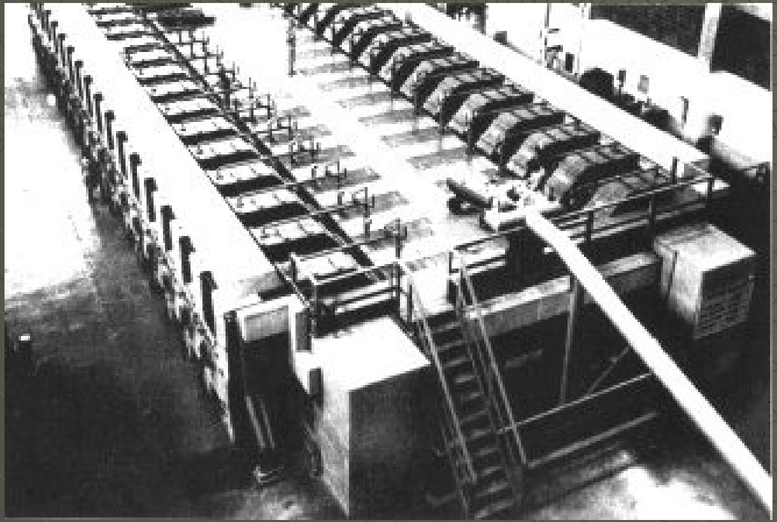



http://www.chemcases.com/2003version/nuclear/nc-07.htm

# Refinement Facility

**Oak Ridge, TN**





- Sample Alpha Track at Y-12
  - Refines natural to 12-20%
- Sample Beta Track at Y-12
  - Refines Alpha Track to 80-90%



http://www.hcc.mnscu.edu/programs/dept/chem/abomb/age_id_33232.html

# Y-12 Refinement Facility

**40 – 240 grams/day of $^{235}U$**

http:/nuclearweaponarchive.org/Usa/Med/Med.html

# Gas Centrifuge

- Inject $UF_6$ gas into rotor
  - Gas is very corrosive
- Separates like a merry-go-round
- Only causes slight enrichment
  - Must use a series of centrifuges
- 2500 Centrifuges for 1 year
  - This would process ~11 metric tons of uranium ore

# Nuclear Power

- Controlled reactions make heat
- No greenhouse gases
- Natural reactors in West Africa
- Ontario: 50% power from nuclear
- Worldwide: 550 reactors, 450 active
- Chernobyl
  - By-passed safeguards to increase output
- Three Mile Island
  - Contained all radiation

# Type of Reactors

- Slow vs. Fast Neutrons
  - Recall cross section for uranium isotopes
  - $^{238}U$ can capture a fast neutron and decay to $^{239}Pu$
  - Breeder reactors fabricate $^{239}Pu$ in excess
- Light water vs. Heavy water (CANDU)
  - Light water reactors require ~3-20% enriched uranium
    - Compare to >80% enrichment for weapons
  - Heavy water reactors may operate with natural uranium
  - CANDU reactors can burn plutonium

# Spent Fuel

- May be stored underground
  - This is where uranium originally came from!
- Reprocessing 'waste'
  - Spent fuel contains many valuable materials
  - Over 90% of waste is uranium
  - Conserve world's uranium supplies
  - 1 ton of reprocessed material = ~100,000 barrels of oil
  - Does contain ~1% plutonium
- Oil and coal also make nuclear waste
  - Much less controlled or accounted for

# Molecular and Nuclear Reactions

- Conventional explosives
  - Rely on breaking chemical bonds for energy
  - Energy release on the order of 10eV/molecule
- Nuclear weapons
  - Break apart the nucleus for energy
  - Immediate energy released: 178MeV/nucleus (determined experimentally)
- Comparison
  - Nuclear explosives are around 10,000,000 times more powerful than conventional explosives

# So you want to design a bomb…

Considerations:

- We need a fast chain reaction of fissions
  - Mean free path
  - Critical mass
- Trigger design
  - How the bomb is detonated
- Output and efficiency
  - Energy ouput of explosion
  - How much uranium underwent fission

# Neutron Mean Free Path

- Mean distance a neutron travels before collision with U
  - Think of this like a pinball machine

- Mean free path for any interaction ($\ell$), with cross-section ($\sigma$) and density ($\rho$=4.8 x $10^{28}$ nuclei $m^{-3}$):

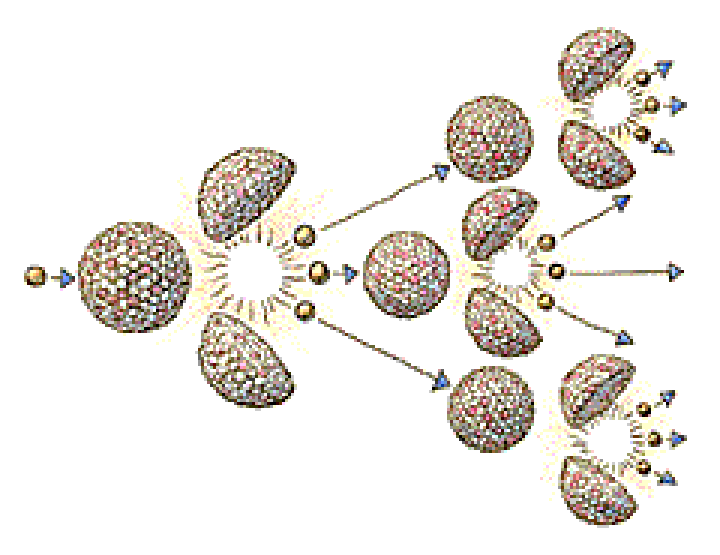
$$\ell = \frac{1}{\sigma_t \rho_{235U}} = 0.029\,m = 2.9\,cm$$

- 1 in 6 collisions is a fission with a neutron energy of 2 MeV. Assume 'random walk.' Then the fission mean free path (s) is:

$$s = \sqrt{6} \cdot \ell = .07\,m = 7\,cm$$

- The time ($\tau$) for this to occur with neutron velocity ($v$) is:

$$\tau = \frac{s}{v} = \frac{.07\,m}{1.7 \text{x}\, 10^{7}\, m \cdot s^{-1}} = 8.1 \text{x}\, 10^{-9}\, s$$



Chain reaction of fission

# Critical Mass Calculation

- Minimum uranium mass to sustain chain reaction
  - Number of neutrons (N), with neutrons per fission ($\upsilon$), variable neutron current (j), computed fission time-scale ($\tau$), as a function of time (t) and radius (r):

$$\frac{dN}{dt} = \frac{(\upsilon - 1)}{\tau} N - \frac{dj}{dr}$$

  - The neutron current (j) and its radial derivative, with the mean free path ($\ell$) and neutron velocity ($v$) as before:

$$j = -\frac{\ell v}{3} \frac{dN}{dr} \qquad \frac{dj}{dr} = -\frac{\ell v}{3} \frac{d^2 N}{dr^2}$$

  - We may easily combine these two equations which yields:

$$\frac{dN}{dt} = \frac{(\upsilon - 1)}{\tau} N + \frac{\ell v}{3} \frac{d^2 N}{dr^2}$$

# Critical Mass Calculation

- We only need to consider the time-independent part of the equation to find the critical radius, so we can set it to zero:

$$\frac{(\upsilon-1)}{\tau}N+\frac{\ell v}{3}\frac{d^2N}{dr^2}=0$$

- This is an easily solvable 2nd order homogenous ordinary differential equation. The solution is simply dependent on unknown constants $C_1$ and $C_2$:

$$N=C_1 cos\left(\sqrt{\frac{3(\upsilon-1)}{\tau\cdot\ell\cdot v}}r\right)+C_2 i\,sin\left(\sqrt{\frac{3(\upsilon-1)}{\tau\cdot\ell\cdot v}}r\right)$$

- This is a sinusoidal wave function, and if we apply the boundry condition N=0 at the centre (r=0), then we have:

$$0=C_1 cos(0)-C_2 i\,sin(0)$$

# Critical Mass Calculation

- So this means that $C_1=0$ and we are left with a single constant $C=C_2 i$, which gives us the following equation:

$$N = C \sin\left(\sqrt{\frac{3(v-1)}{\tau \cdot \ell \cdot v}}\, r\right)$$

- We set r as one half of the critical radius ($R_c$), because this is where we expect the neutron density to be the highest because of elastic and inelastic scattering of neutrons. The sine function has its first maxium at $\pi/2$. Thus:

$$\sqrt{\frac{3(v-1)}{\tau \cdot \ell \cdot v}}\, R_c = \pi$$

# Critical Mass Value

- Solving for the critical radius $R_c$, we get:

$$R_c = \sqrt{\frac{\pi^2 \tau \cdot \ell \cdot v}{3(\upsilon - 1)}}$$

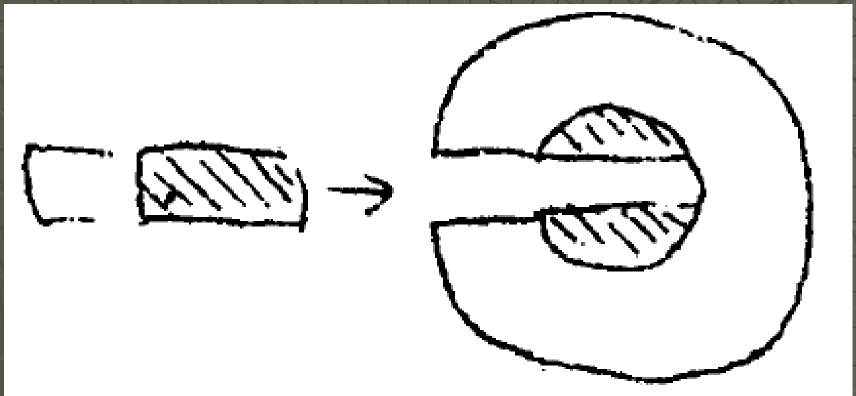
- Recalling that we have the following values for our variables:

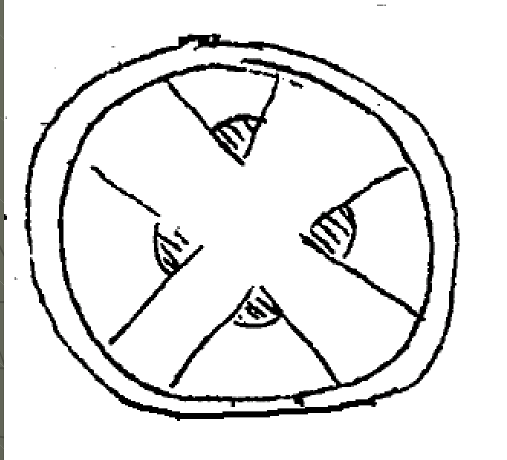
$$\ell = 0.029\,m \qquad \tau = 8.1 \times 10^{-9}\,s$$
$$\upsilon = 2.5 \qquad v = 1.7 \times 10^{7}\,m/s$$

- If we plug in these values, we find that $R_c$=9.35 cm. Using $\rho_{235U}$, we find that a sphere with this radius is 64.9 kg
- A mass of this size is precisely large enough to sustain a chain reaction despite neutrons lost through the surface of the sphere of uranium.

# Trigger design

- Assemble the critical mass at high speed
  - Speed of assembly for $^{235}U$ is 600 m/s to avoid pre-detonation
  - This calculation is tough, but the values are known
  - $^{239}Pu$ requires a much faster assembly speed
- Include a source of neutrons





- $^{235}U$ can be detonated with a simple shotgun design
- $^{239}Pu$ requires a more sophisticated concentric shell explosion

Serber, R. *The Los Alamos Primer*. University of California Press, 1992.

# Trigger Neutron Source

- Once the critical mass is assembled, any free neutron that interacts with it will be sufficient to trigger detonation
- $^{210}Po$ is an α-emitter
- $^{9}Be + \alpha \rightarrow {}^{12}C + n$
- The neutron released in this reaction has enough kinetic energy to induce fission in a $^{235}U$ nucleus
- Put half the neutron source on the bullet, and half on the target

# Efficiency

- *Little Boy* had an explosive output of 20kT of TNT
- A 20kT output is equal to 24 TeraJoules
- There are $2.85 \times 10^{-11}$J/fission
- This means that $8.4 \times 10^{23}$ atoms must fission for a 20kT yield
- This number of atoms will fission in 80 generations of fission
- The time this will take is .648 microseconds
- This is equivalent to .327 kg of uranium
- This means the bomb must have an efficiency of slightly over 0.5%

# Tampers

- A tamper is a material which surrounds the critical mass
- To increase efficiency the critical mass you can add a tamper of highly dense material like $^{238}U$ or gold

- The tamper serves two purposes
  - It reflects neutrons back into the mass, decreasing surface loss of neutrons
  - It increases the density around the mass, holding it together longer so more fissions can occur before density drops too far to sustain the reaction
  - Given that expected efficiency is less than half of one percent any minor increase that the tamper provides will greatly increase the magnitude of the explosion

# Aerial of Hiroshima Before


http://newsimg.bbc.co.uk/media/images/41357000/gif/_41357959_hiroshima_1_629.gif

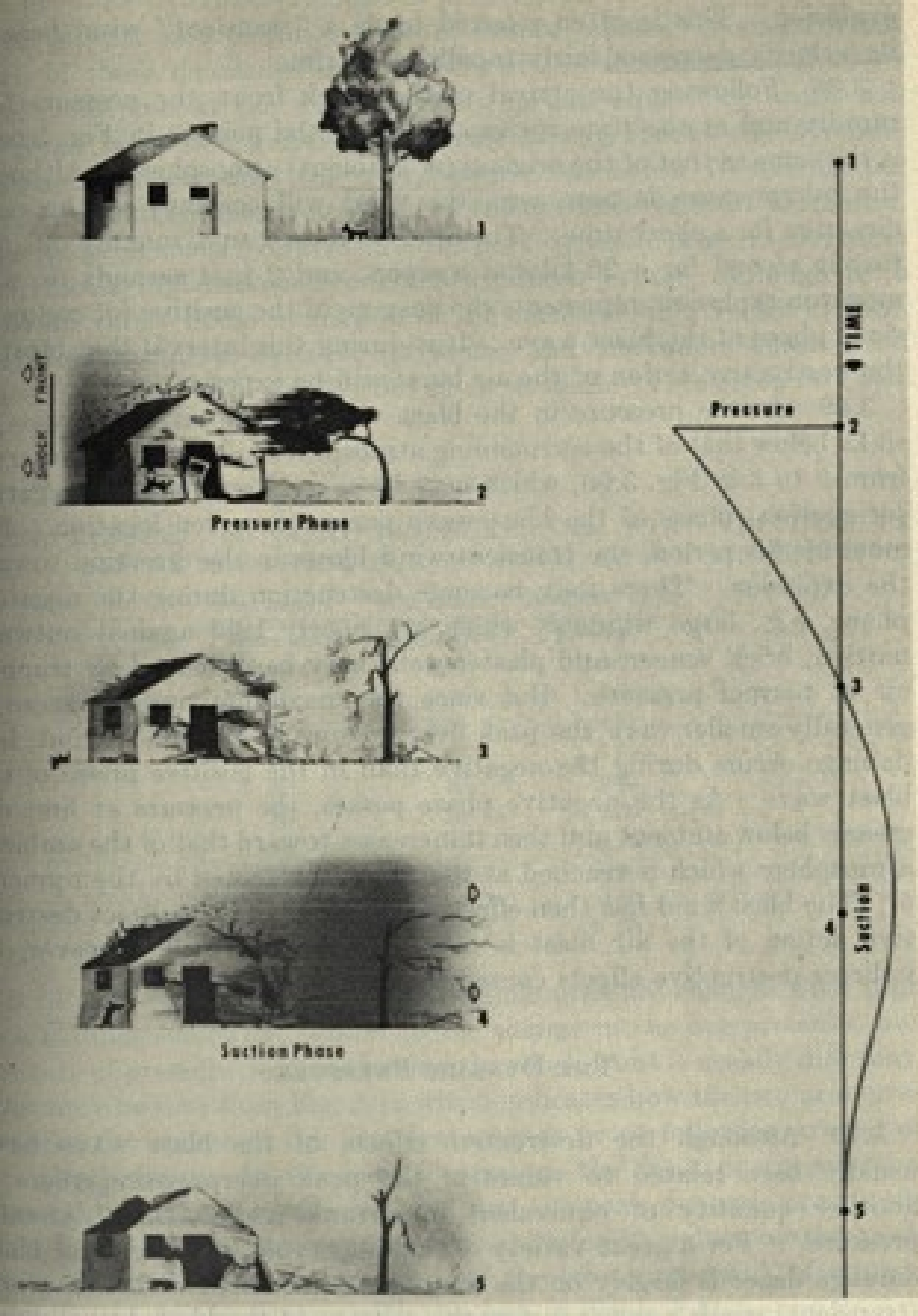
# Aerial of Hiroshima After


http://newsimg.bbc.co.uk/media/images/41357000/gif/_41357965_hiroshima_2_629.gif

# Former Prefectoral Office

- This was the only building in Hiroshima to survive the nuclear bombing by the US in 1945.  Now *A-Bomb Building.*

http://upload.wikimedia.org/wikpedia/en/5/5d/HiroshimaPrefectualPromotionHall.JPG




# Pressure Effects

# Conclusion

- Covered Enrichment
  - **This is where uranium originally came from!**
- Explained *Little Boy*
  - **Showed most of the calcuations that the book omits**
  - **Such a basic nuclear bomb is not conceptually difficult**
  - **Did not show how to calculate minimum detontation velocity**
  - **Critical mass explains why there are not small nuclear weapons**
- Even a low efficiency is deadly
  - **Did not do advanced yield calculations**

# Final Statement

- Understanding basic nuclear physics is useful for effective opposition to nuclear arms proliferation
- Limiting factor for building a bomb is acquiring the fissile materials
    - Must protect existing fissile material
- The physics involved isn't prohibitively difficult
    - I went through most the details in under an hour
- Many reactor designs do not use or produce bomb grade material
    - Reactors are safe and do not emit greenhouse gases
- Please don't go out and build a bomb now

# Acknowledgements

**Chad Huibregtse**, Steve Abbott, Elizabeth Boatman, Elon Candea, Sarah Johns, Jason Marmon, *Dr. Patrick Polley*, **Jared Nance**, Eric Stall, John Stierna, Loren Warmington

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