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Radiochemistry Webinars
Nuclear Fission/Nuclear Devices

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Meet the Presenter…

Dr. John McClory

Dr. McClory earned his PhD in nuclear engineering from the Air Force Institute of Technology (AFIT), where he has been a professor of nuclear engineering since 2008 and currently serves as the director of the Nuclear Weapons Effects, Policy, and Proliferation Graduate Certificate Program. Dr. McClory has an MS degree in physics from Texas A&M University and a BS degree in physics from Rensselaer Polytechnic Institute. His research interests include nuclear weapon effects, the effects of radiation on military equipment and electronics, nuclear forensics techniques, and nuclear physics. He has published 56 journal articles during his time on the AFIT faculty. He was awarded the MOAA AFIT Outstanding Military Professor Award in 2010; the Dr. Leslie M. Thornton Teaching Excellence Award in 2011; the Military Legion of Merit in 2012; and the AETC Nuclear Deterrence Operations Professional Team of the Year Award in 2013. Prior to joining the AFIT faculty, Dr. McClory served in the U.S. Army, first as an armor officer and then as a nuclear and counter-proliferation operations officer. He served in various assignments in the U.S., Europe, and the Middle East, including service during Operation Iraqi Freedom in 2005 and 2006, and was an assistant professor of physics at the United States Military Academy from 1993 to 1996.

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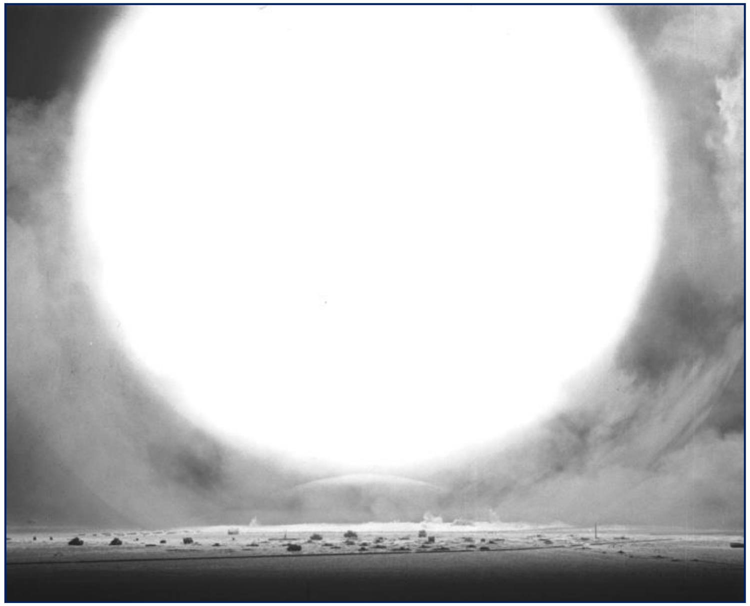
Nuclear Fission/Nuclear Devices

John McClory
US Air Force Institute of Technology

**National Analytical Management Program
(NAMP)**

TRAINING AND EDUCATION SUBCOMMITTEE

Overview



- Nuclear Physics Concepts
- Nuclear Fission and Fusion
- Nuclear Chain Reactions
- Nuclear Explosions and Devices
- Nuclear Weapon Radiation Output

Fundamental Definitions

- Units of Energy
  - Joules, electron-volts, calories, kilotons
    - 1 eV = 1.602×10^{-19} J
    - 1 cal = 4.186 J
    - 1 kT = 1×10^{12} cal
- Mass
  - Atomic mass units or amu [u]
    - 1 Carbon atom ≡ 12.0 u
    - 1 u = 1.7×10^{-27} kg
- Time
  - Shakes ➔ 1 shake = 1×10^{-8} sec

- Nucleons – generic name for protons and neutrons
- Nuclides $^{A}_{Z}\textit{Chemical Symbol}_{N}$
  - Z – atomic or proton number
  - N – neutron number
  - A – mass number
- Isotopes – same Z, different A

<u>Example</u>: Hydrogen has 3 isotopes:

$^{1}_{1}H_{0}$  **Basic Hydrogen (H)**

$^{2}_{1}H_{1}$  **Deuterium (D)**

$^{3}_{1}H_{2}$  **Tritium (T)** ☢

Isotopes are chemically the same

Nuclear Reactions

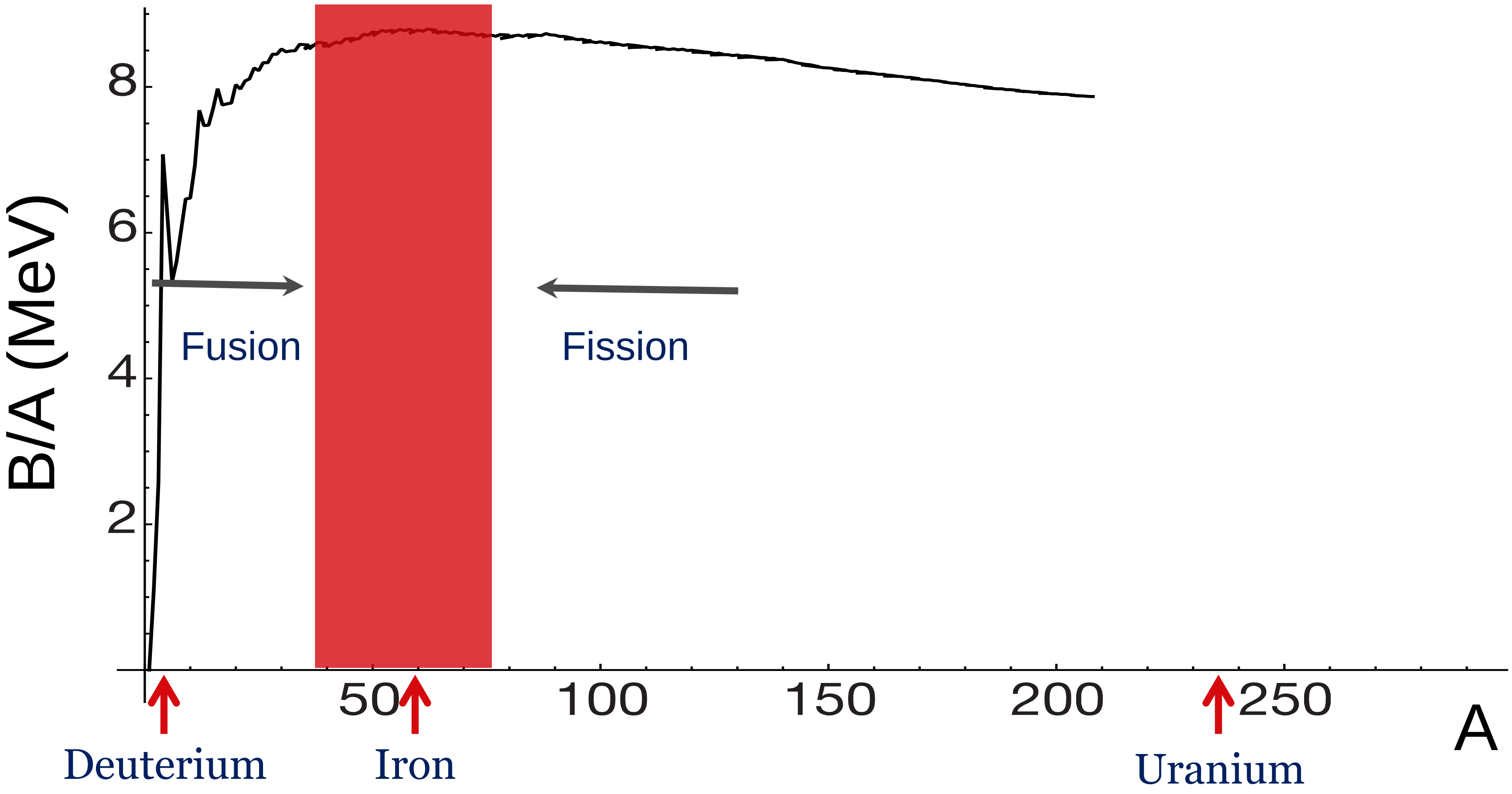
- A collision between nuclei in which the nuclear constituents are rearranged

$$a + A \rightarrow b + B \qquad \text{or} \qquad A(a,b)B$$

$$ {}^{4}_{2}He + {}^{14}_{7}N \rightarrow {}^{1}_{1}H + {}^{17}_{8}O \qquad {}^{14}_{7}N(\alpha, p){}^{17}_{8}O$$

- Principles of Balanced Equations
  - Conservation of charge
  - Conservation of Z (# protons)
  - Conservation of N (# neutrons)
  - Conservation of energy and linear momentum

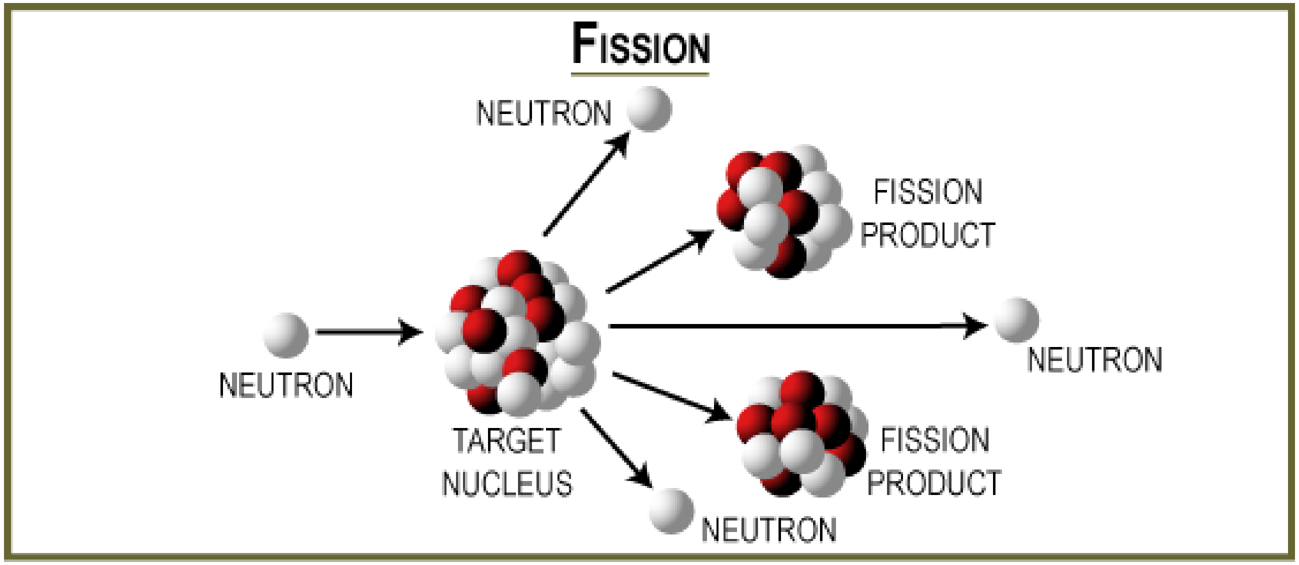
The Binding Energy Curve



Nuclear Fission and Fusion

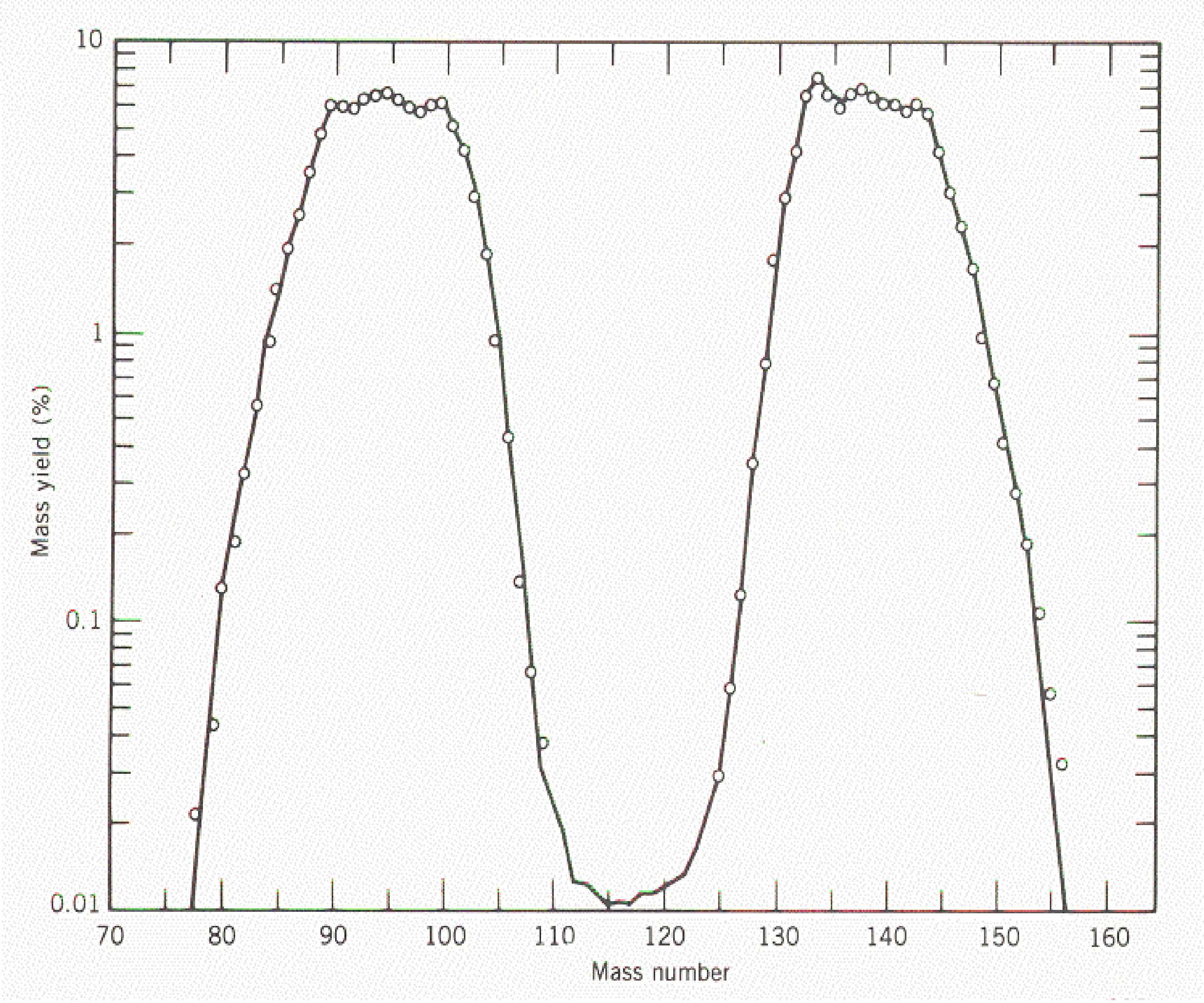
Neutron-Induced Nuclear Fission

- The activation barrier to fission can be overcome by a neutron-induced nuclear reaction
  - Fissile: fission can be initiated by a thermal neutron
  - Fissionable: fission can be initiated by a high energy neutron



$$^{235}U + n_{slow} \rightarrow \left(^{236}U\right)^{*} \rightarrow X + Y + \nu n_{fast}$$

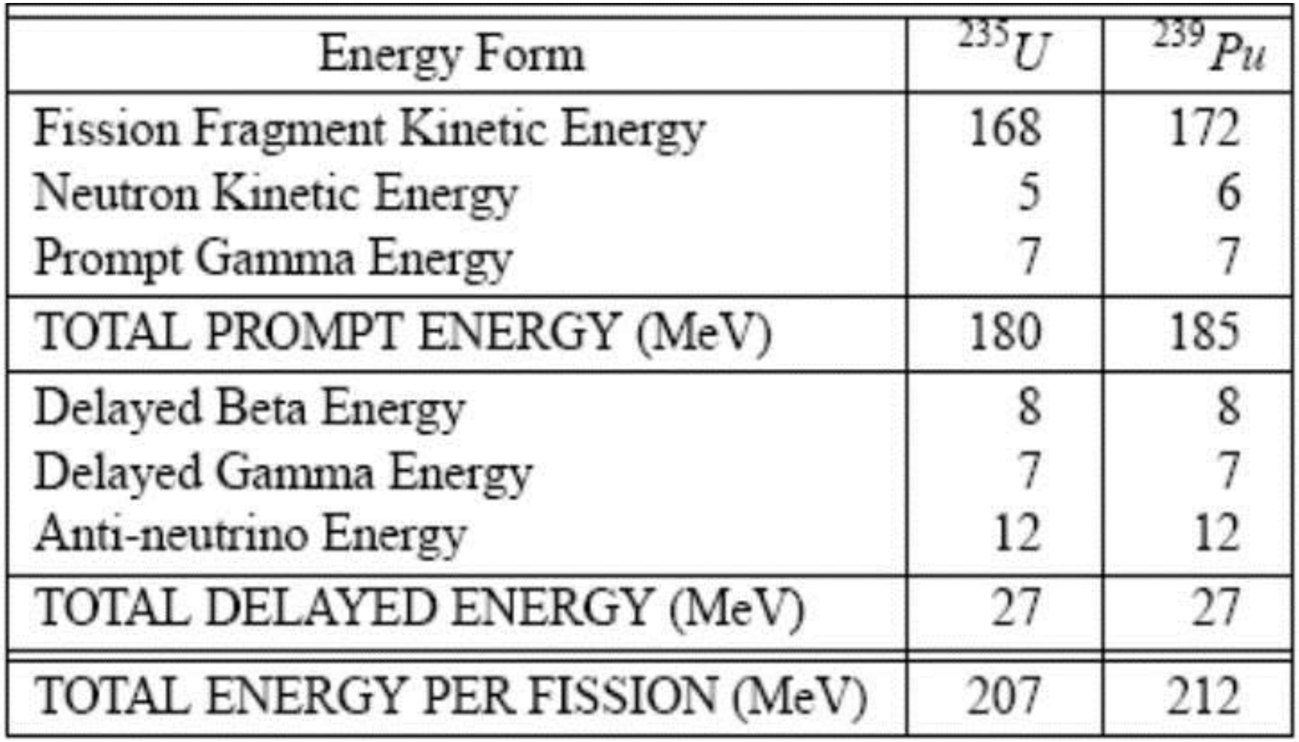
Fission Fragment Mass Distribution



[1]Thermal neutron fission of ${}^{235}U$

Fission Energy Production

Thermal Neutron-Induced Fission Energy Output



Energy Form	^{235}U	^{239}Pu
Fission Fragment Kinetic Energy	168	172
Neutron Kinetic Energy	5	6
Prompt Gamma Energy	7	7
TOTAL PROMPT ENERGY (MeV)	180	185
Delayed Beta Energy	8	8
Delayed Gamma Energy	7	7
Anti-neutrino Energy	12	12
TOTAL DELAYED ENERGY (MeV)	27	27
TOTAL ENERGY PER FISSION (MeV)	207	212

Energy Calculation

- Recall
  - 1 MeV = 1.6×10^{-13} J
  - 1 cal = 4.186 J
  - 1 kT = 10^{12} cal
  - 207 MeV per fission ^{235}U (on average)

- And.... there are 6.02×10^{23} nuclei in 235 g of ^{235}U

- How much energy could be released in a weapon using 25 kg (assuming all the atoms fission)?

Energy Calculation

- Recall
  - 1 MeV = 1.6×10^{-13} J
  - 1 cal = 4.186 J
  - 1 kT = 10^{12} cal
  - 207 MeV per fission ^{235}U (on average)
- And…. there are 6.02×10^{23} nuclei in 235 g of ^{235}U
- How much energy could be released in a weapon using 25 kg (assuming all the atoms fission)?

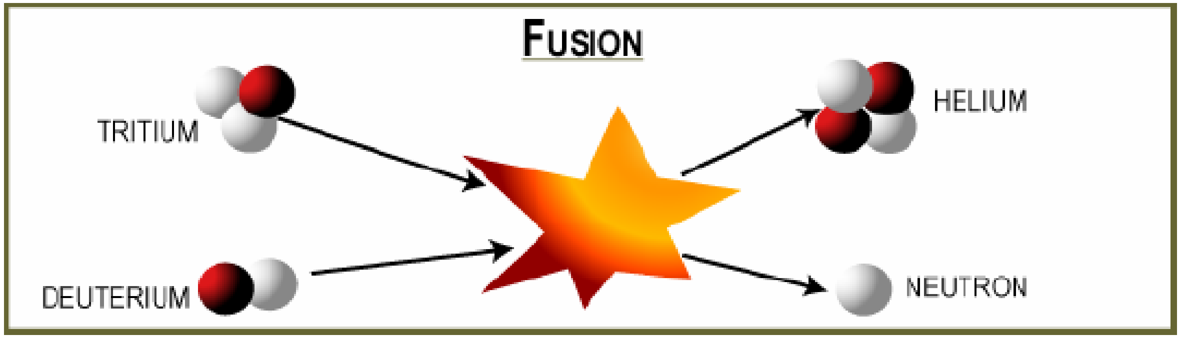
$$E_{kT} = \left(207\frac{MeV}{fission}\right)\left(\frac{6.022\times10^{23}\ fissions}{235g}\right)\left(25000g\right)$$

$$\left(1.602\times10^{-13}\frac{J}{MeV}\right)\left(1\frac{cal}{4.186J}\right)\left(1\frac{kT}{1\times10^{12}\ cal}\right)$$

$\underline{E_{kT} = 508\ kT!!!}$

Nuclear Fusion

- Same concept as fission, in that we emit energy by changing the mass deficit
- Now we cause two “light” nuclei to combine

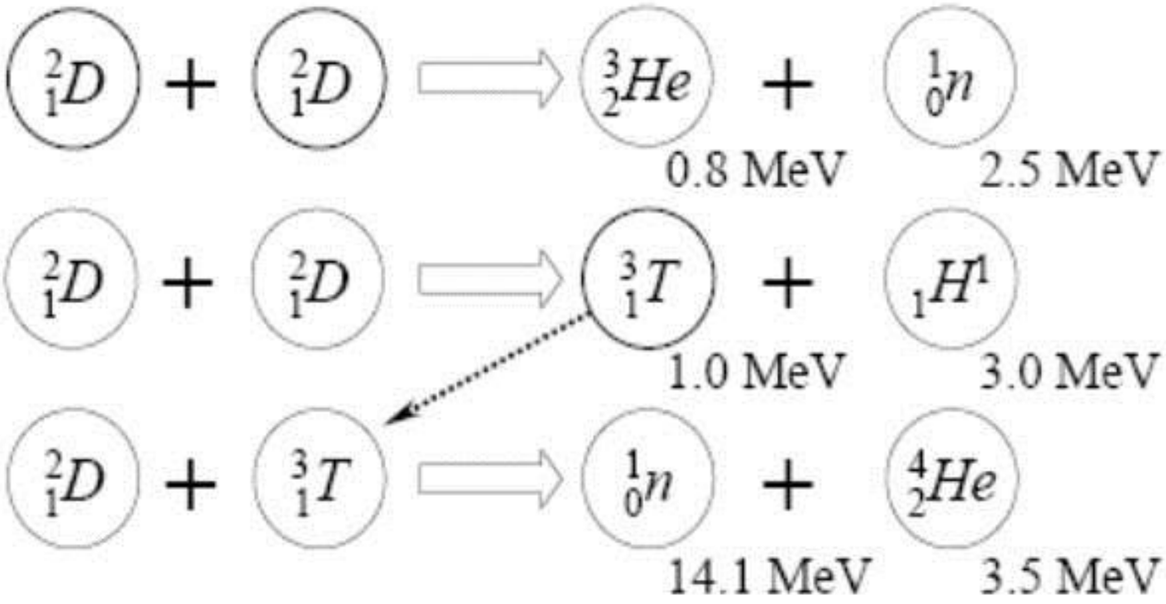


- We again want to maintain or gain neutrons in the process

Fusion Reactions

- Unlike fission, we must spend a LOT of energy getting the D and T to interact (large activation barrier)
- We typically use HEAT at 10^6 to 10^7 K (How?…we use a fission weapon to do so!)
- …thus a thermo-nuclear weapon
- Pure fusion weapon not possible with current technology

Sustained Fusion Burn



$${}^2_1D + {}^2_1D \Rightarrow {}^3_2He + {}^1_0n$$

$${}^2_1D + {}^2_1D \Rightarrow {}^3_1T + {}_1H^1$$

$${}^2_1D + {}^3_1T \Rightarrow {}^1_0n + {}^4_2He$$

$$5\ {}^2_1D = \underbrace{({}^1_1H + {}^3_2He + {}^4_2He)}_{\text{Total Charged Particle Energy} = 8.3\ \text{MeV}} + \underbrace{2\ {}^1_0n}_{\text{Total Neutron Energy} = 16.6\ \text{MeV}}$$

The yield per deuteron consumed = 24.9/5 = 4.98 MeV, but the local (charged particle) yield per deuteron reaction = (8.3)/2 = 4.15 MeV.

Fusion Energy Release

- From all D and T fuel interactions we get 24.9 MeV
- However, per unit mass…

$$\text{fusion E} \approx \frac{24.9\ \text{MeV}}{10\ \text{nucleons}} \cong 2.49 \frac{MeV}{nucleon}$$

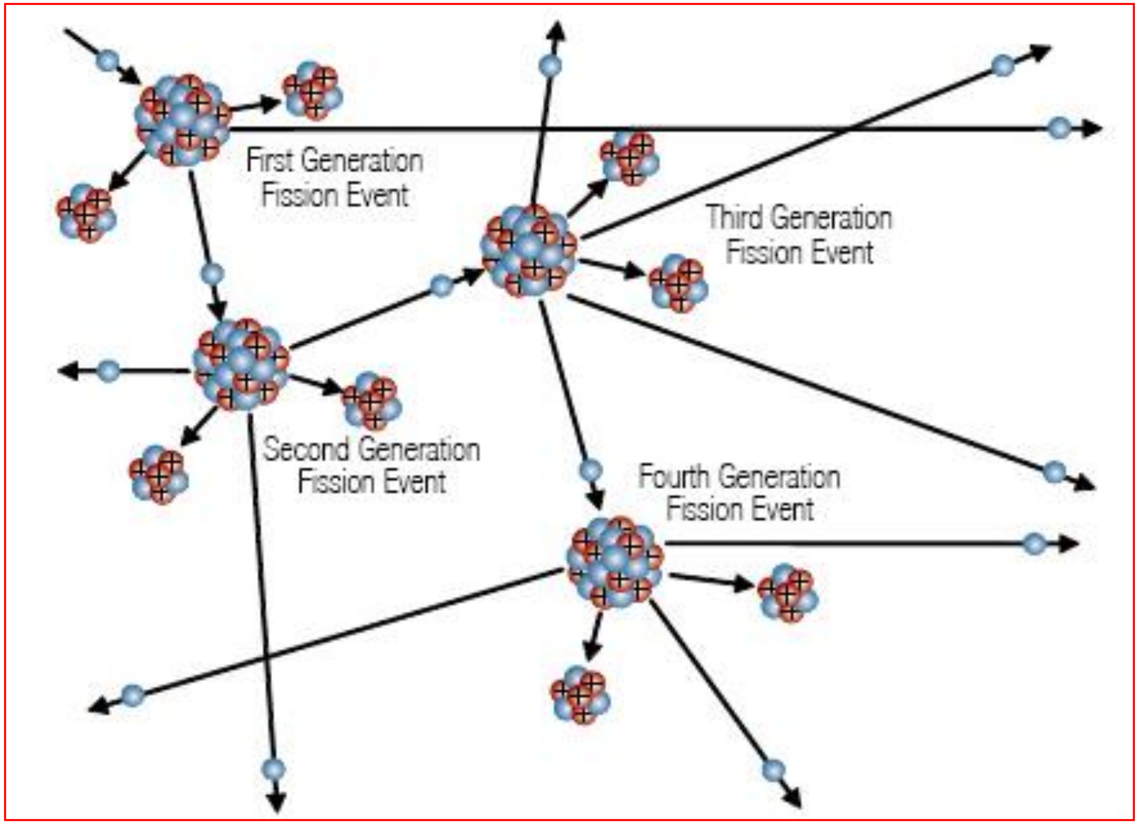
$$\text{fission E} \approx \frac{180\ \text{MeV}}{235\ \text{nucleons}} \cong 0.766 \frac{MeV}{nucleon}$$

$$1\ \text{kg of}\ {}^{235}\text{U} = 17.6\ kT$$

$$1\ \text{kg of D\&T} = 80.6\ kT$$

Nuclear Chain Reactions

Fission Chain Reaction



$$N_{n+1} = N_n(f - l)$$

- N_n is the number of neutrons in generation n
- f is the number of neutrons released per fission
- l is the number of neutrons lost

$$\Delta N = N_{n+1} - N_n = N_n\left(f - l\right) - N_n = N_n\left(f - l - 1\right)$$

Fission Chain Reaction

$$\Delta N = N_{n+1} - N_n = N_n\left(f - l)\right) - N_n = N_n\left(f - l - 1\right)$$

- ΔN is the change in number of neutrons in a generation
- Then the change over time with $x = f - l - 1$ and g as the time of one generation is:

$$\frac{\Delta N}{\Delta t} = \frac{dN}{dt} = N\frac{x}{g}$$

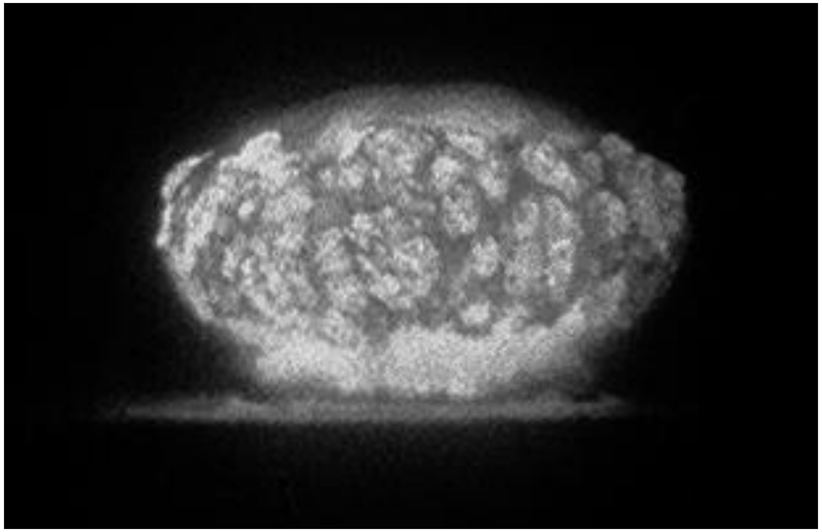
- *The solution to this differential equation is:*

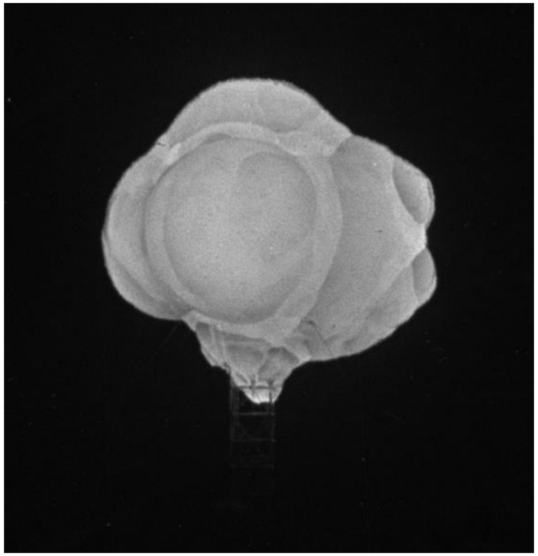
$$\mathbf{N = N_o e^{xt/g} = N_o e^{\alpha t}}$$

- $\boldsymbol{\alpha = x/g}$ is a measure of the neutron multiplication

Values of Alpha

α	***l*** for f = 3	**criticality**
< 0	> 2	sub critical
0	2	critical
> 0	< 2	super critical





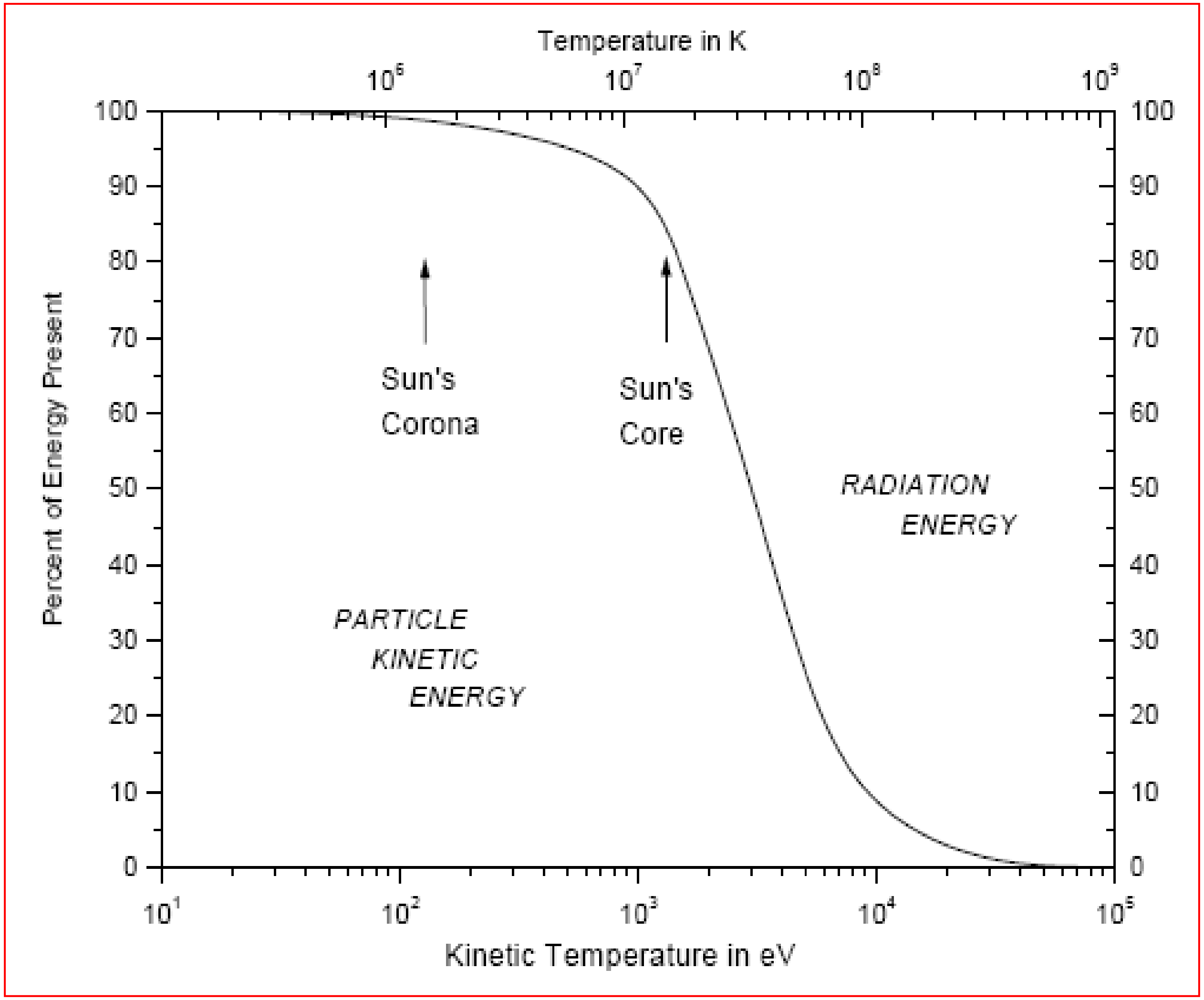
Nuclear Explosions and Devices

Explosive Yield

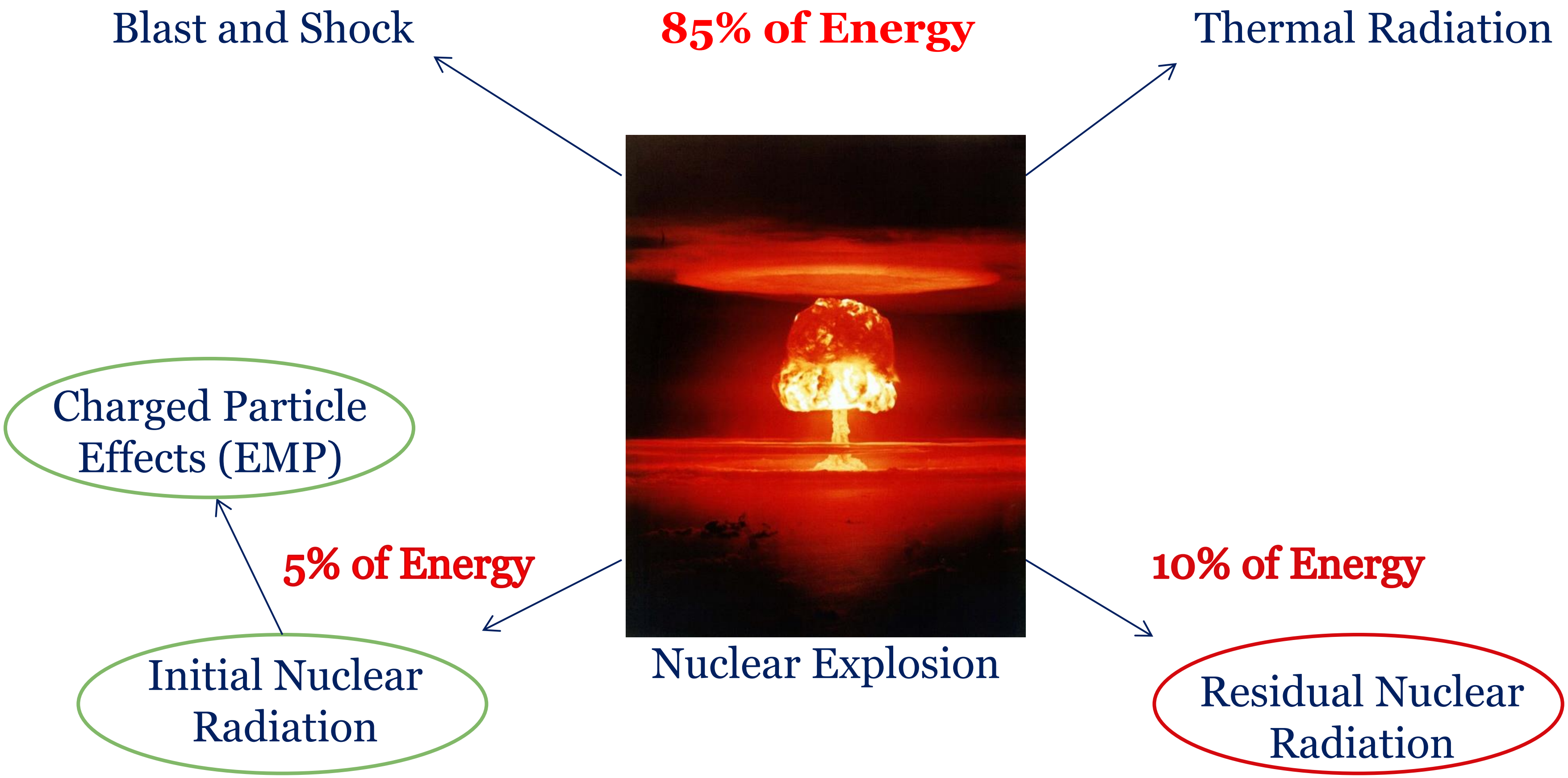
- Complete nuclear burn of 1 kg of U-235 yields:
  - ~18 kilotons (kT) of energy
  - 18 kT = ***36,000,000 lbs*** TNT
  - 1 kT = 2,000,000 lbs TNT
  - Oklahoma City bombing ~5,000 lbs
  - 18 kT = 7,200 Oklahoma City truck bombs

- A kiloton is quite a large amount of energy! The first bomb dropped on Hiroshima on August 6, 1945, exploded with the energy of about 20 kilotons of TNT

Radiative Nature of Nuclear Explosions [2]



Components of a Nuclear Explosion



Blast and Shock

85% of Energy

Thermal Radiation

Charged Particle Effects (EMP)

5% of Energy

10% of Energy

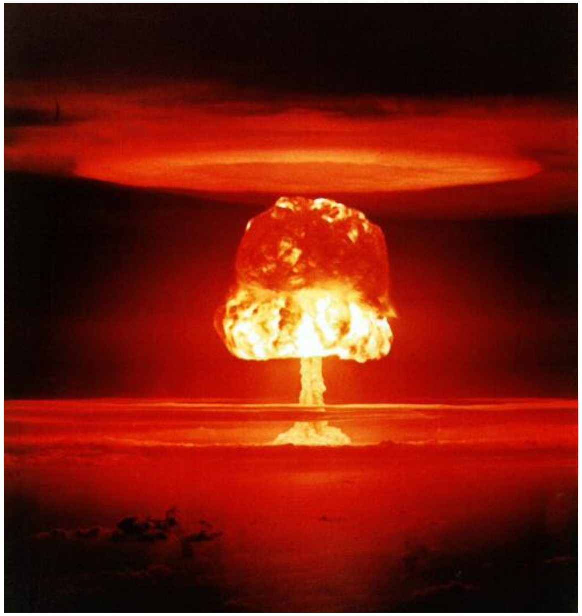
Initial Nuclear Radiation

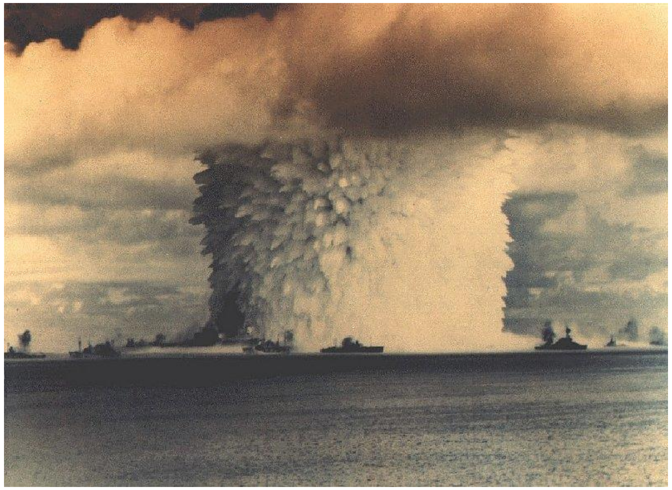
Nuclear Explosion

Residual Nuclear Radiation

Environment Dependencies

- Air burst
- High-altitude burst
- Underwater burst
- Underground burst
- Surface burst





Environment Dependencies

- High Altitude (>20km)
  - EM radiation travels far
  - Little interaction with the ground
  - No direct interaction with population

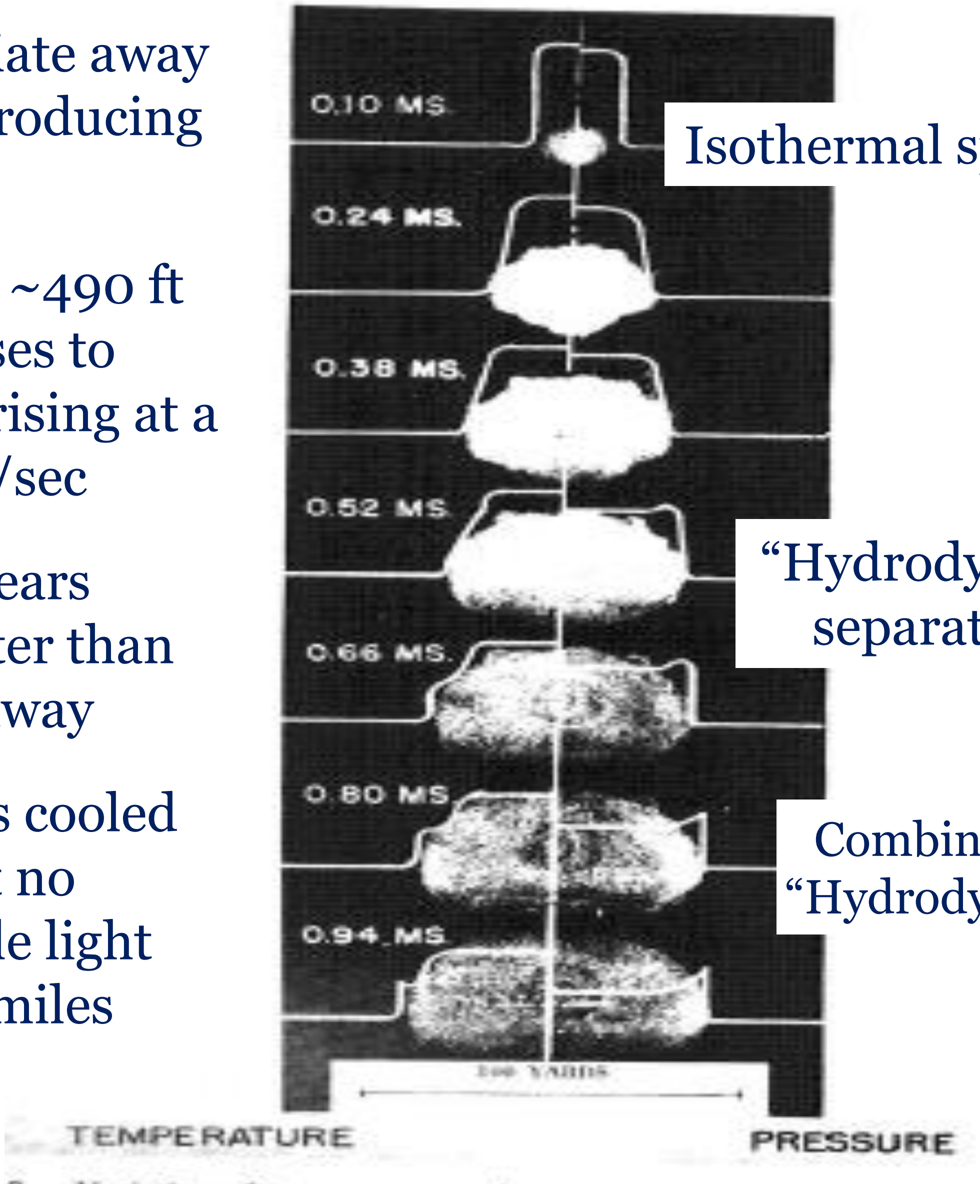
- Air Burst (<20km)
  - Some ground interaction
  - Reflections

- Surface
  - Ground plane

- Sub surface
  - Contained vs. non-contained

Evolution of a 1 MT Explosion[2]

- < 1 μs: X-rays radiate away (few feet in air), producing the fireball
- 0.7 ms: Fireball is ~490 ft across and increases to 5700 ft in 10 sec, rising at a rate of 250-350 ft/sec
- 1 ms: Fireball appears many times brighter than the sun 50 miles away
- 1 min: Fireball has cooled to a point where it no longer emits visible light and has risen 4.5 miles



Isothermal sphere

“Hydrodynamic separation”

Combined shockwave “Hydrodynamic growth”

Very Simple Model

The basic sequence of events for a nuclear explosion as follows:

1. Explosives change the geometry to achieve a supercritical geometry
2. Neutrons are produced to build a large population quickly before the device mechanically disassembles
3. Once a large population of neutrons is produced, yield production begins in earnest
4. Material kinetic energy shuts down yield production

Two Basic Weapon Types

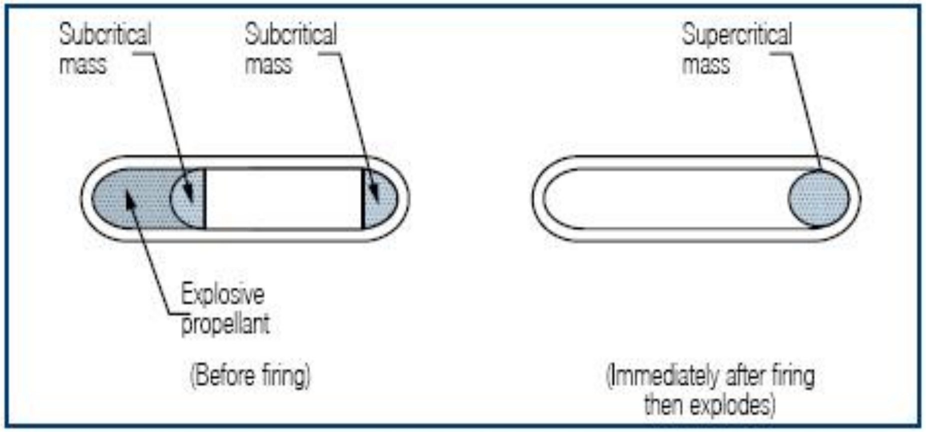
Gun-Assembled

- Simple, virtually foolproof design (U.S. never tested before first use)
- Requires a large quantity of material
- Uranium only
- Little Boy

Implosion

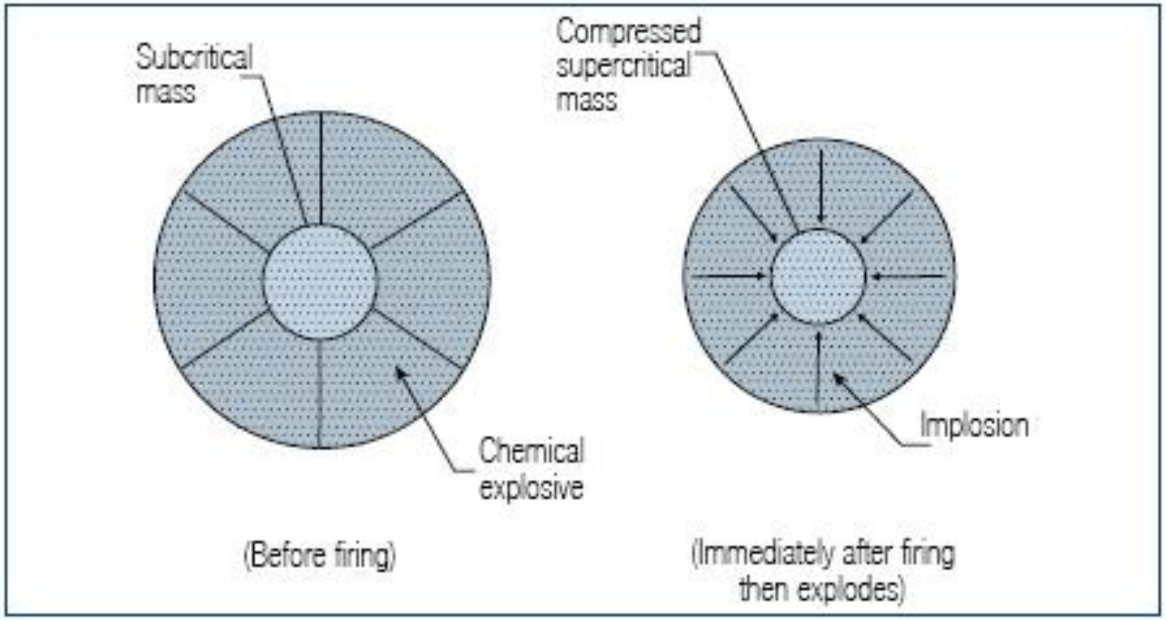
- More complex
- Requires less material because of higher density
- Can use either uranium (U) or Pu
- Fat Man

Critical Assemblies

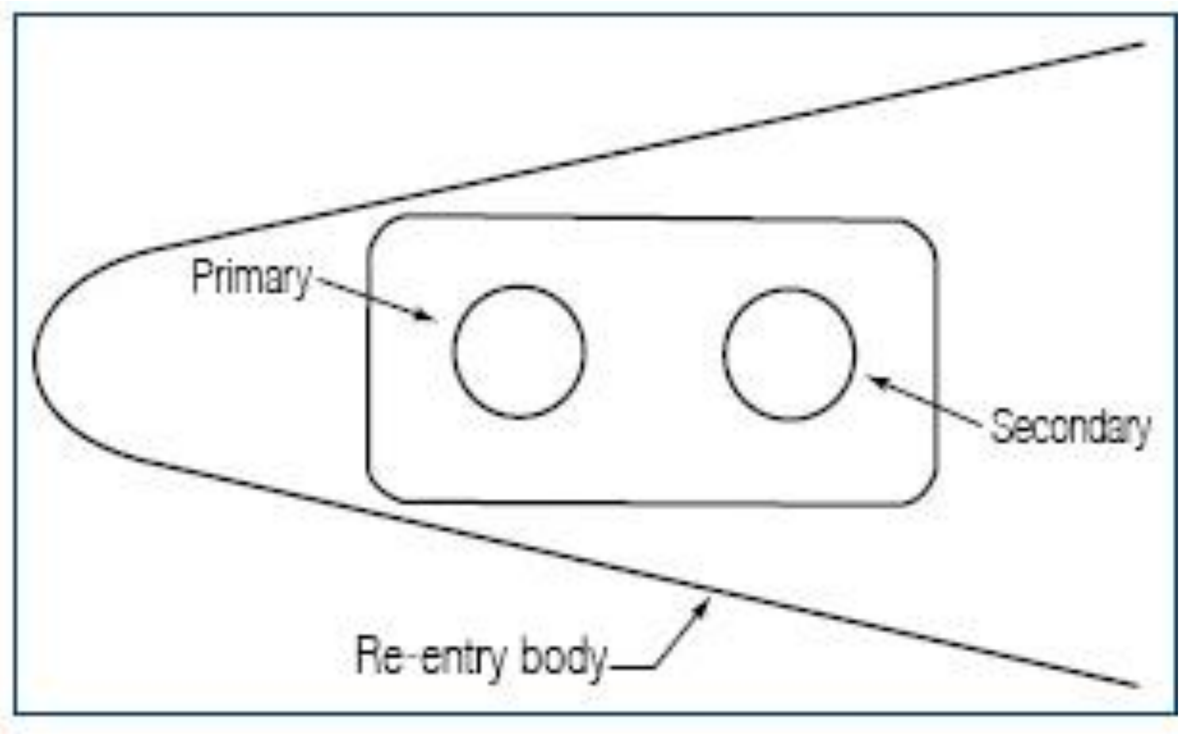


Gun Type Device (Little Boy)

Implosion Device (Fat Man)



Thermonuclear Weapons



Unclassified image of
a two-stage
thermonuclear weapon

Nuclear Myths & Misconceptions

- A nuclear weapon will generate vast quantities of radioactive material
  - About 55 grams of fission products/KT of yield is produced
  - A few hundred kilograms of activation products from casing
  - 0.3 tons to 0.8 tons of activated dirt per ton of yield
- A nuclear reactor can explode like a nuclear bomb
  - The fuel in a nuclear does not have the appropriate geometry to sustain a chain reaction in order to produce the required energy density
  - Reactors are designed to work with thermal neutrons—bombs are designed to work with fast neutrons
- Nuclear bombs are difficult to build
  - A basic weapon is easy to construct
  - A viable weapon system is difficult
  - The real challenge is in obtaining the material

Nuclear Weapon Radiation Output

Nuclear Radiation

- Alpha
- Beta
- Neutron
- Gamma
- However, owing to small fraction and short range, we will not address α and β

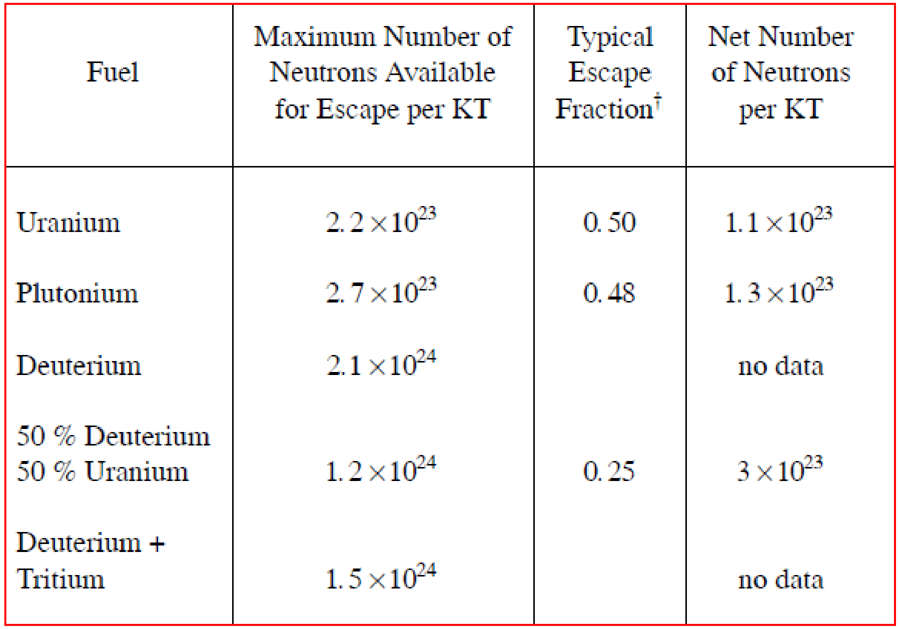
Neutron Source

Fission:

$$S_n^{\max} = \left(2.62\times10^{25}\,\frac{MeV}{kT}\right)\left(\frac{1}{Q\,\frac{MeV}{fission}}\right)(\upsilon-1)\qquad\left[\frac{\text{neutrons}}{\text{kT}}\right]$$

Fusion:

$$S_n^{\max} = \left(2.62\times10^{25}\,\frac{MeV}{kT}\right)/\left(25\,\frac{\text{MeV}}{\text{2 neutrons}}\right) = 2.1\times10^{24}\qquad\left[\frac{\text{neutrons}}{\text{kT of D+D}}\right]$$

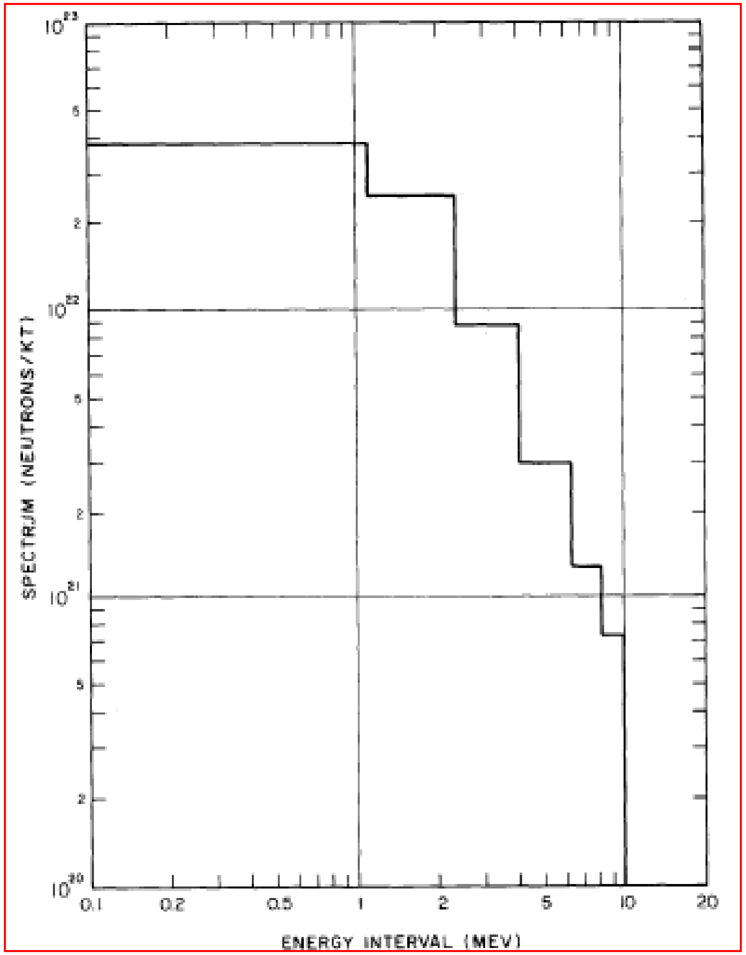


Fuel	Maximum Number of Neutrons Available for Escape per KT	Typical Escape Fraction†	Net Number of Neutrons per KT
Uranium	2.2×10^{23}	0.50	1.1×10^{23}
Plutonium	2.7×10^{23}	0.48	1.3×10^{23}
Deuterium	2.1×10^{24}		no data
50 % Deuterium 50 % Uranium	1.2×10^{24}	0.25	3×10^{23}
Deuterium + Tritium	1.5×10^{24}		no data

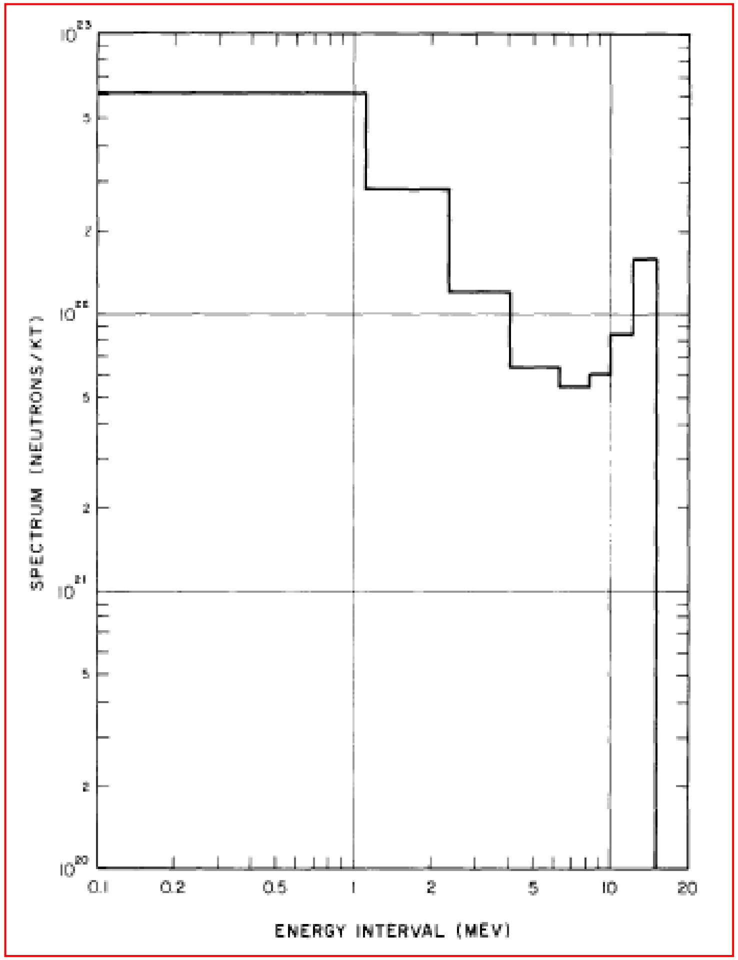
Neutrons per kiloton of yield

Neutron Spectra[2]

Uranium Fission Output



Thermonuclear Output



Gamma Ray Sources

- Prompt γ
  - Produced during weapon fission process
  - Produced in less than a microsecond
  - Many absorbed by weapon debris
    - Initial gammas are 4% of energy
    - Only 1% escape

- Delayed γ
  - Produced after weapon material vaporized
  - Neutron capture (radiative capture)

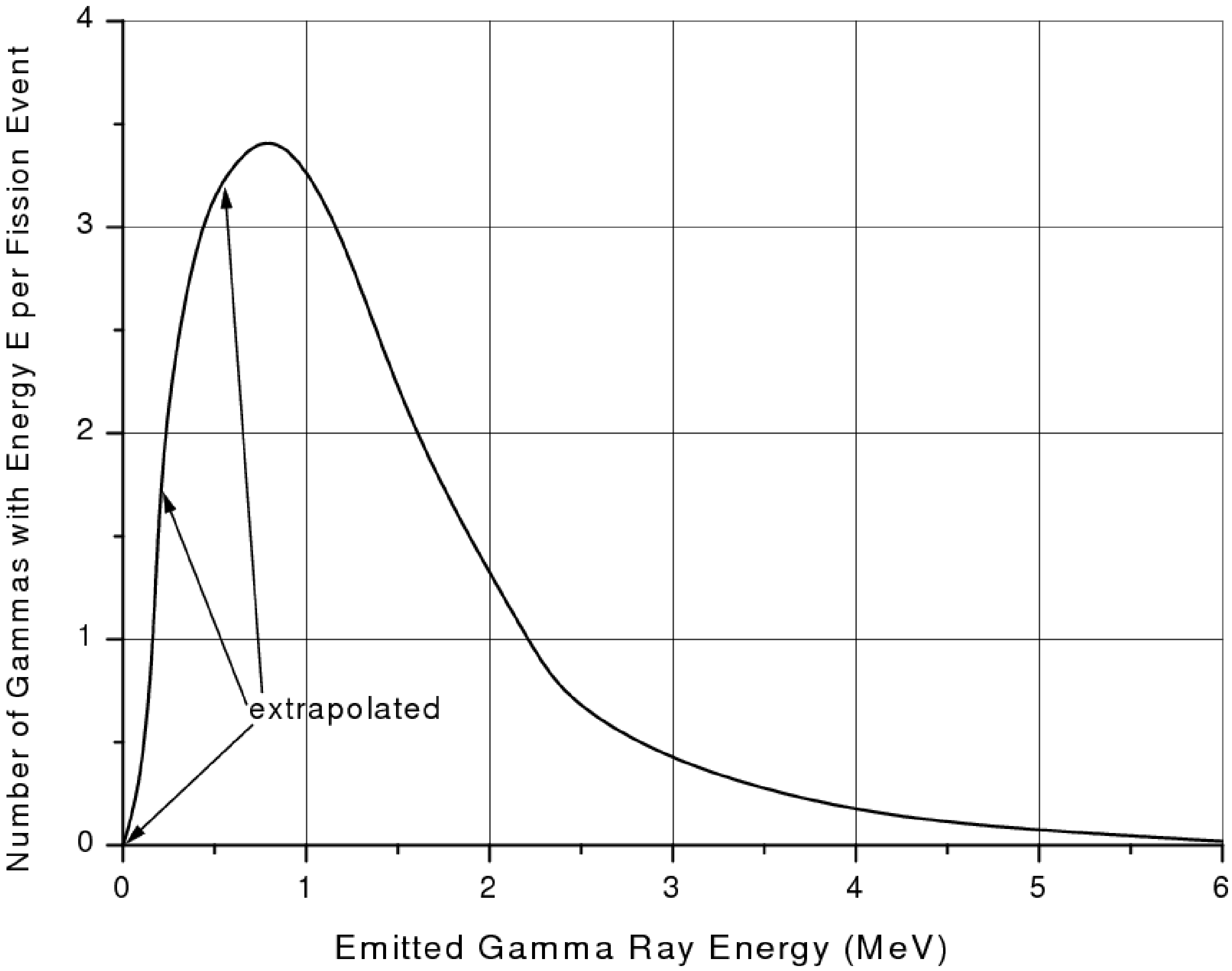
$$ {}_{0}^{1}n + {}_{Z}^{A}X \rightarrow {}_{Z}^{A+1}X + \gamma $$

  - Inelastic scattering

$$ {}_{0}^{1}n + {}_{Z}^{A}X \rightarrow {}_{Z}^{A}X^{*} + {}_{0}^{1}n' \text{ then } {}_{Z}^{A}X^{*} \rightarrow {}_{Z}^{A}X + \gamma $$

  - Decay of fission products

Fission Gamma Source



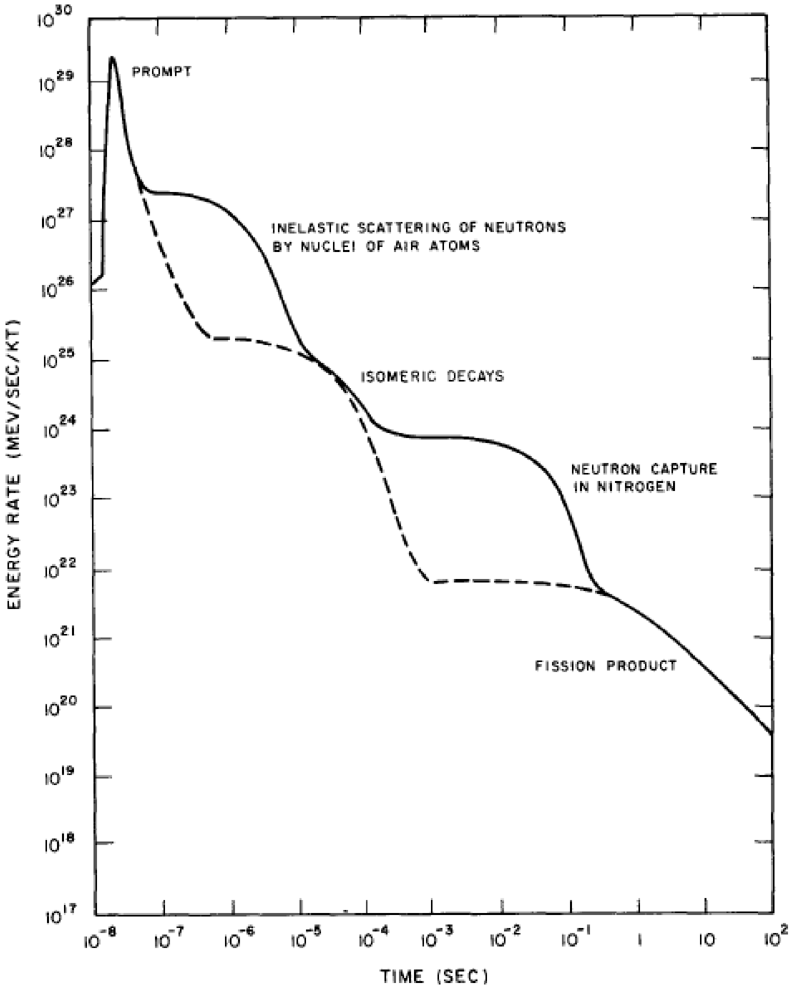
Gamma Ray Sources

- Secondary gamma
  - Primarily from neutron capture in the atmosphere
  - Most important is:

$$ {}^{1}_{0}n + {}^{14}_{7}N \rightarrow {}^{15}_{7}N^{*} \rightarrow {}^{15}_{7}N + \gamma $$

- Delayed + secondary gamma = 100 x prompt

Time Dependence of Gamma Energy [2]



Gamma ray output as a function of time on a logarithmic scale

Questions?

Footnotes

1. G. J. Dilorio, *Direct Physical Measurements of Mass Yields in Thermal Fission of Uranium 235* (New York: Garland, 1979)

2. Samuel Glasstone and Philip J. Dolan, The Effects of Nuclear Weapons, 3rd Edition (Department of Defense, 1977)

Upcoming Webinars

- Uranium Resources
- Chronometry
- Sample Matrices and Collection, Sample Preparation

NAMP website: www.wipp.energy.gov/namp