Radiochemistry Webinars
Nuclear Fission/Nuclear Devices

In Cooperation with our University Partners
Meet the Presenter...

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.

Email: John.McClory@afit.edu
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 x 10^{-19} J
    • 1 cal = 4.186 J
    • 1 kT = 1 x 10^{12} cal

• Mass
  – Atomic mass units or amu [u]
    • 1 Carbon atom ≡ 12.0 u
    • 1 u = 1.7 x 10^{-27} kg

• Time
  – Shakes ➔ 1 shake = 1x10^{-8} sec

• Nucleons – generic name for protons and neutrons
• Nuclides $^{A}_{Z} \text{Chemical Symbol}^{N}_r$
  – Z – atomic or proton number
  – N – neutron number
  – A – mass number

• Isotopes – same Z, different A

**Example:** 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

\[ a + A \rightarrow b + B \quad \text{or} \quad A(a, b)B \]

\[ ^4_2He + ^{14}_7N \rightarrow ^1_1H + ^{17}_8O \]

\[ ^{14}_7N(\alpha, p)^{17}_8O \]

• 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

- **Fusion**
  - Deuterium
  - Iron

- **Fission**
  - Uranium
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

\[ ^{235}U + n_{\text{slow}} \rightarrow \left( ^{236}U \right)^* \rightarrow X + Y + \nu n_{\text{fast}} \]
Fission Fragment Mass Distribution

\[ ^1 \text{Thermal neutron fission of } ^{235}\text{U} \]
Fission Energy Production

Thermal Neutron-Induced Fission Energy Output

<table>
<thead>
<tr>
<th>Energy Form</th>
<th>$^{235}U$</th>
<th>$^{239}Pu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fission Fragment Kinetic Energy</td>
<td>168</td>
<td>172</td>
</tr>
<tr>
<td>Neutron Kinetic Energy</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>Prompt Gamma Energy</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>TOTAL PROMPT ENERGY (MeV)</td>
<td>180</td>
<td>185</td>
</tr>
<tr>
<td>Delayed Beta Energy</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Delayed Gamma Energy</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Anti-neutrino Energy</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>TOTAL DELAYED ENERGY (MeV)</td>
<td>27</td>
<td>27</td>
</tr>
<tr>
<td>TOTAL ENERGY PER FISSION (MeV)</td>
<td>207</td>
<td>212</td>
</tr>
</tbody>
</table>
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 $6.02\times10^{23}$ 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
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• And…. there are 6.02×10^{23} nuclei in 235 g of $^{235}\text{U}$

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

$$E_{kT} = \left(207 \frac{\text{MeV}}{\text{fission}}\right) \left(\frac{6.022 \times 10^{23} \text{ fissions}}{235 \text{ g}}\right) \left(25000 \text{ g}\right) \left(1.602 \times 10^{-13} \frac{\text{J}}{\text{MeV}}\right) \left(1 \frac{\text{cal}}{4.186 \text{ J}}\right) \left(1 \frac{\text{kT}}{1 \times 10^{12} \text{cal}}\right)$$

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

\[ \begin{align*}
\text{2}_1^1D + \text{2}_1^1D & \rightarrow \text{3}_2^2He + \text{1}_0^1n, \\
& \quad 0.8 \text{ MeV} + 2.5 \text{ MeV} \\
\text{2}_1^1D + \text{2}_1^1D & \rightarrow \text{3}_1^1T + \text{1}_1^1H, \\
& \quad 1.0 \text{ MeV} + 3.0 \text{ MeV} \\
\text{2}_1^1D + \text{3}_1^1T & \rightarrow \text{1}_0^1n + \text{4}_2^2He, \\
& \quad 14.1 \text{ MeV} + 3.5 \text{ MeV} \\
5 \text{2}_1^1D & = (\text{1}_1^1H + \text{3}_2^2He + \text{4}_2^2He) + 2 \text{1}_0^1n \\
\text{Total Charged Particle Energy} & = 8.3 \text{ MeV} \quad \text{Total Neutron Energy} = 16.6 \text{ MeV}
\end{align*} \]

The yield per deuteron consumed = \( \frac{24.9}{5} = 4.98 \text{ MeV} \), but the local (charged particle) yield per deuteron reaction = \( \frac{8.3}{2} = 4.15 \text{ MeV} \).
Fusion Energy Release

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

\[
\text{fusion } E \approx \frac{24.9 \text{ MeV}}{10 \text{ nucleons}} \approx 2.49 \frac{\text{MeV}}{\text{nucleon}} \\
\text{fission } E \approx \frac{180 \text{ MeV}}{235 \text{ nucleons}} \approx 0.766 \frac{\text{MeV}}{\text{nucleon}}
\]

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

\[ \Delta N = N_{n+1} - N_n = N_n (f - l) - N_n = N_n (f - l - 1) \]
Fission Chain Reaction

\[ \Delta N = N_{n+1} - N_n = N_n(f - l) - N_n = N_n(f - l - 1) \]

- \( \Delta N \) 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:

\[ N = N_0 e^{xt/g} = N_0 e^{\alpha t} \]

- \( \alpha = x/g \) is a measure of the neutron multiplication
Values of Alpha

<table>
<thead>
<tr>
<th>$\alpha$</th>
<th>$l$ for $f = 3$</th>
<th>criticality</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&lt; 0$</td>
<td>$&gt; 2$</td>
<td>sub critical</td>
</tr>
<tr>
<td>$0$</td>
<td>$2$</td>
<td>critical</td>
</tr>
<tr>
<td>$&gt; 0$</td>
<td>$&lt; 2$</td>
<td>super critical</td>
</tr>
</tbody>
</table>
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
- Thermal Radiation
- Charged Particle Effects (EMP)
- Initial Nuclear Radiation
- Residual Nuclear Radiation

85% of Energy
5% of Energy
10% of Energy
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

- < 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
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

<table>
<thead>
<tr>
<th>Gun-Assembled</th>
<th>Implosion</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Simple, virtually foolproof design (U.S. never tested before first use)</td>
<td>• More complex</td>
</tr>
<tr>
<td>• Requires a large quantity of material</td>
<td>• Requires less material because of higher density</td>
</tr>
<tr>
<td>• Uranium only</td>
<td>• Can use either uranium (U) or Pu</td>
</tr>
<tr>
<td>• Little Boy</td>
<td>• Fat Man</td>
</tr>
</tbody>
</table>
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 $\alpha$ and $\beta$
Neutron Source

Fission: \[ S_n^{\text{max}} = \left( \frac{2.62 \times 10^{25} \text{ MeV}}{kT} \right) \left( \frac{1}{Q_{\text{fission}}} \right)(\nu - 1) \left[ \frac{\text{neutrons}}{\text{kT}} \right] \]

Fusion: \[ S_n^{\text{max}} = \left( \frac{2.62 \times 10^{25} \text{ MeV}}{kT} \right) / \left( 25 \frac{\text{MeV}}{2 \text{ neutrons}} \right) = 2.1 \times 10^{24} \left[ \frac{\text{neutrons}}{\text{kT of D+D}} \right] \]

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Maximum Number of Neutrons Available for Escape per KT</th>
<th>Typical Escape Fraction (^\dagger)</th>
<th>Net Number of Neutrons per KT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uranium</td>
<td>(2.2 \times 10^{23})</td>
<td>0.50</td>
<td>(1.1 \times 10^{23})</td>
</tr>
<tr>
<td>Plutonium</td>
<td>(2.7 \times 10^{23})</td>
<td>0.48</td>
<td>(1.3 \times 10^{23})</td>
</tr>
<tr>
<td>Deuterium</td>
<td>(2.1 \times 10^{24})</td>
<td></td>
<td>no data</td>
</tr>
<tr>
<td>50 % Deuterium 50 % Uranium</td>
<td>(1.2 \times 10^{24})</td>
<td>0.25</td>
<td>(3 \times 10^{23})</td>
</tr>
<tr>
<td>Deuterium + Tritium</td>
<td>(1.5 \times 10^{24})</td>
<td></td>
<td>no data</td>
</tr>
</tbody>
</table>

Neutrons per kiloton of yield
Neutron Spectra

Uranium Fission Output

Thermonuclear Output
Gamma Ray Sources

- **Prompt $\gamma$**
  - 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 $\gamma$**
  - Produced after weapon material vaporized
  - Neutron capture (radiative capture)
    \[
    _0^1n + A^Z_X \rightarrow _Z^{A+1}X + \gamma
    \]
  - Inelastic scattering
    \[
    _0^1n + A^Z_X \rightarrow _Z^A X^* + _0^1n' \text{ then } _Z^A X^* \rightarrow _Z^A X + \gamma
    \]
  - Decay of fission products
Fission Gamma Source
Gamma Ray Sources

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

\[
_0^1n + _7^{14}N \rightarrow _7^{15}N^* \rightarrow _7^{15}N + \gamma
\]

- **Delayed + secondary gamma = 100 x prompt**
Time Dependence of Gamma Energy

Gamma ray output as a function of time on a logarithmic scale
Questions?
Footnotes


Upcoming Webinars

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

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