SURVEY OF WEAPONS DEVELOPMENT AND TECHNOLOGY

WR708

~~SECRET~~

UNCLASSIFIED

SESSION II

- REVIEW OF WEAPONS PHYSICS
- THEORY OF NUCLEAR EXPLOSIONS

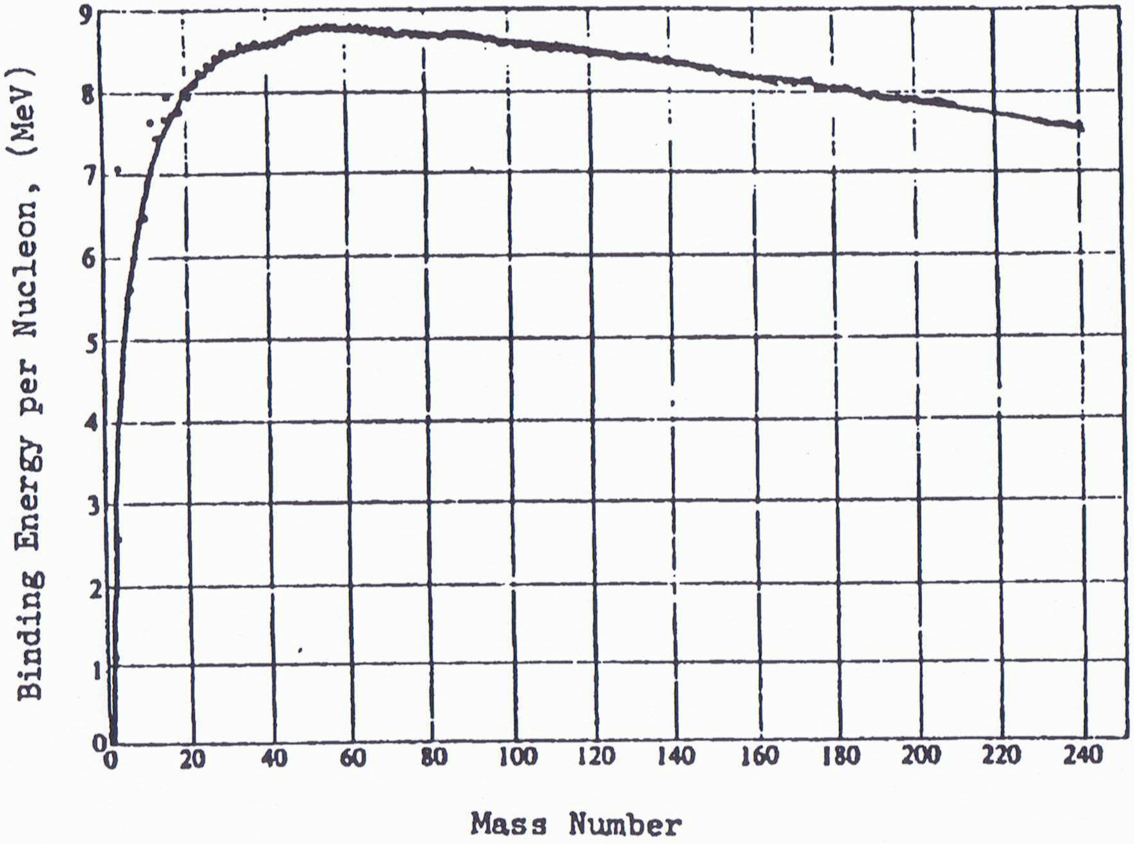
~~SECRET~~

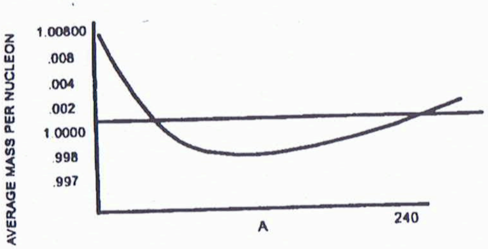
UNCLASSIFIED

Weapons Physics and Nuclear Material

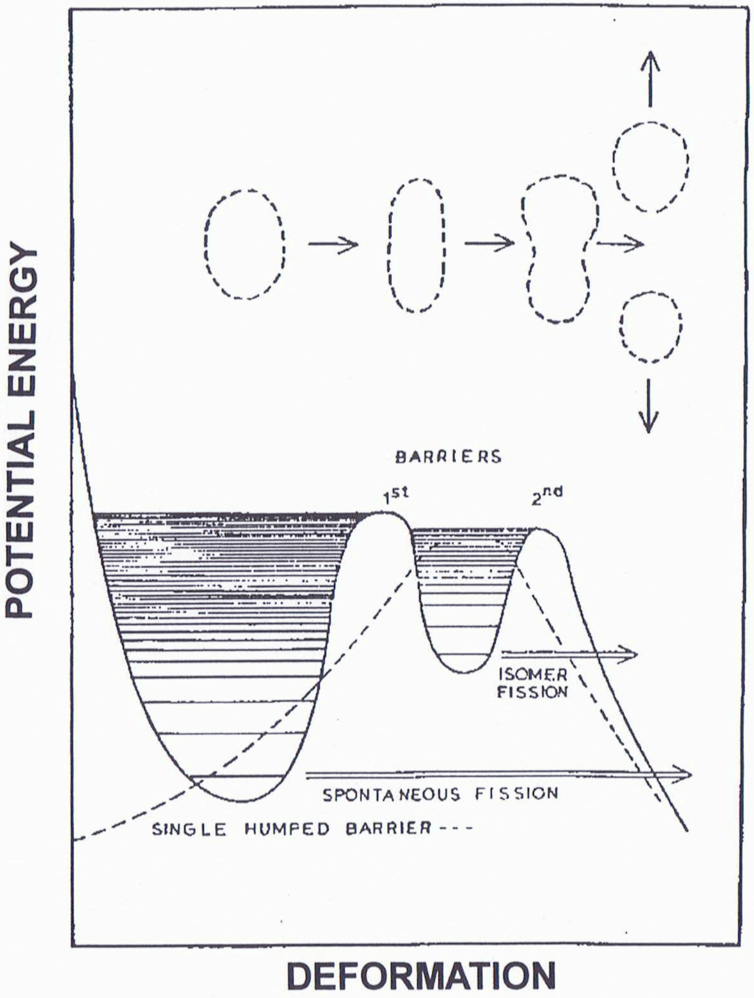
- Several basic nuclear physics concepts and the properties of the nuclear fissile material are very important to the understanding of weaponization
- The physics of fission
- Nuclear properties
- Availability of material
- How the fissile material is obtained
- Energy available and energy trades

NUCLEAR BINDING ENERGY

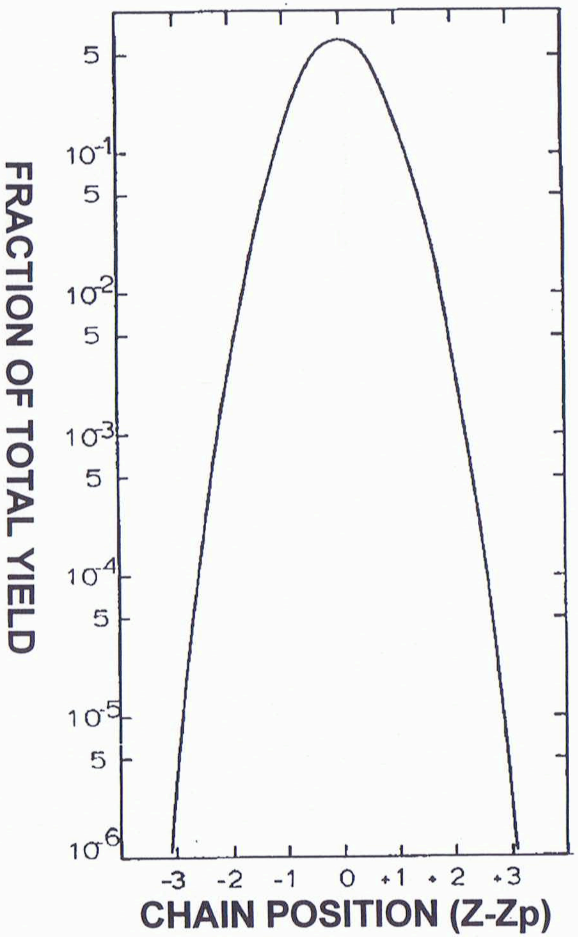




LIQUID DROP MODEL APPLIED TO POTENTIAL BARRIERS



CHARGE DISTRIBUTION CURVE



~~SECRET~~

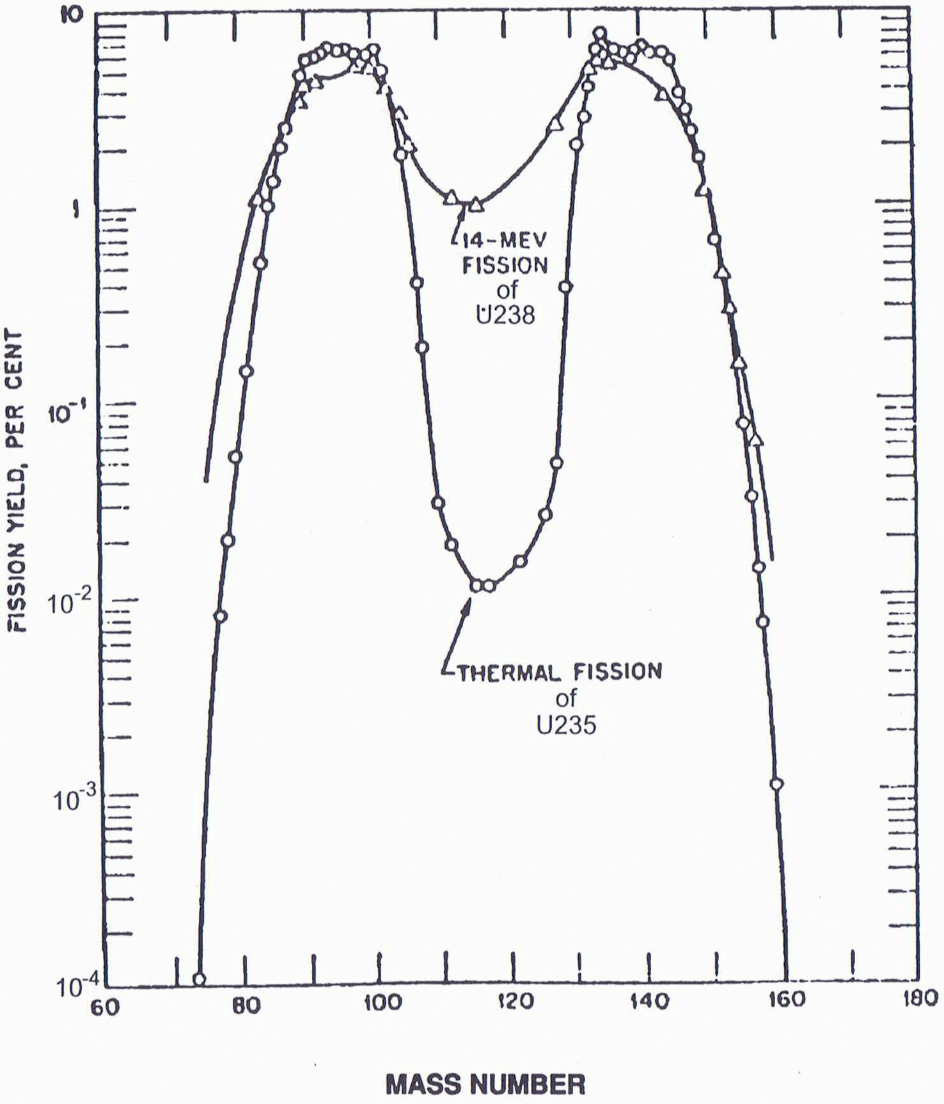
UNCLASSIFIED

UNCLASSIFIED

~~SECRET~~

~~SECRET~~

UNCLASSIFIED



LIKELIHOOD FOR FISSION FRAGMENT

UNCLASSIFIED

~~SECRET~~

~~SECRET~~

UNCLASSIFIED

[redacted]

b(3)

DOE
b(3)

UNCLASSIFIED

~~SECRET~~

Terminology

Asymmetric fission	-	division of excited nucleus into two unequal fragments with masses about 100 & 140 ama.
Binary	-	division at scission point into two parts.
Cross-Section	-	probability that a certain reaction between a nucleus and an incident particle or photon will occur, as in a neutron and U^{235} (measured in "barns")
Fission Fragment	-	fragment after scission but before prompt neutron emission
Fission Product	-	fragment after prompt neutron emission

~~SECRET~~

UNCLASSIFIED

[redacted]

DOE

b(3)

b(3)

~~SECRET~~

UNCLASSIFIED

~~SECRET~~

UNCLASSIFIED

DOE
b(3)

[redacted]

b(3)

~~SECRET~~

UNCLASSIFIED

b (3)

[redacted]

~~SECRET~~

UNCLASSIFIED

~~SECRET~~

UNCLASSIFIED

The Gang of Four

$^{238}U_{92}$ % in nature - 99.27 When the $^{238}U_{92}$ is extracted, it is called depleted ^{238}U or TUBALLOY or D38 (from UK WWII effort - TUBE ALLOY) Will fission but not fissile Physically separated	^{239}Pu % in nature - essentially zero (mine in South Africa) Made in reactor: $n + {}^{238}U = {}^{239}Pu$
^{235}U % in nature - 00.73 Concentrated to 93.5% Called ORALLOY for Oak Ridge Alloy	^{240}Pu % in nature - essentially zero Made by reactor If you leave the ^{239}Pu in "too long," it will absorb a n ➡ ^{240}Pu Spontaneously fissions (originally a problem for pre-ignition)

~~SECRET~~

UNCLASSIFIED

~~SECRET~~

UNCLASSIFIED

CALCULATION OF ENERGY RELEASE

$${}_{92}U^{235} \quad + \quad {}_{0}n^{1} \longrightarrow {}_{42}Mo^{95} \quad + \quad {}_{57}La^{139} \qquad 7\,{}_{-1}e^{0} \quad + \quad 2\,{}_{0}n^{1}$$

$$\begin{array}{r} 235.0439 \\ 1.0087 \\ \hline 236.0526 \text{ amu} \end{array} \quad \xrightarrow{\qquad\qquad} \quad \begin{array}{r} 94.905837 \\ 138.906400 \\ .003850 \\ 2.017340 \\ \hline 235.8334 \text{ amu} \end{array} \quad \text{atomic mass unit}$$

MASS DEFECT OF .219 amu

n = 1.00867 amu
p = 1.00728 amu
e = .00055 amu

$$(.219 \text{ amu}) \quad \left(931.4 \ \frac{\text{MeV}}{\text{amu}}\right) \quad \doteqdot \quad 204 \ \text{MeV}$$

THE EXAMPLE STARTED WITH

$${}_{54}Xe^{139} \xrightarrow{3\,\beta} {}_{57}La^{139} \qquad \text{AND} \qquad {}_{38}SR^{95} \xrightarrow{4\,\beta} {}_{42}Mo^{95}$$

FISSION CHAIN

~~SECRET~~
UNCLASSIFIED

THEORETICAL FISSION ENERGY

- THERE ARE $\frac{6.025X10^{23}}{235.0439}$ ATOMS PER GRAM OF $_{92}U^{235}$
- THEREFORE, 1 kg OF $_{92}U^{235}$ HAS $2.5634X10^{24}$ ATOMS
- HENCE, @ 180 MeV PER FISSION 1 kg OF $_{92}U^{235}$ WOULD PRODUCE $4.6141x10^{26}$ MeV IF EACH ATOM WERE FISSIONED.
- CONVERTING TO KILOTONS
- $(4.6141X10^{26}\ \text{MeV})\ (3.824X10^{-26}\ \frac{\text{kT}}{\text{MeV}}) \simeq 18\ \text{kT}$

FACTORS AFFECTING CRITICAL MASS

- GEOMETRY
- AMOUNT OF MATERIAL
- TYPE OF MATERIAL
- PURITY OF MATERIAL
- SURROUNDING MATERIAL
- DENSITY

B-3

UNCLASSIFIED

~~SECRET~~

UNCLASSIFIED

~~SECRET~~

B-3

DOE

[illegible]

~~SECRET~~ UNCLASSIFIED

~~SECRET~~ UNCLASSIFIED

UNCLASSIFIED

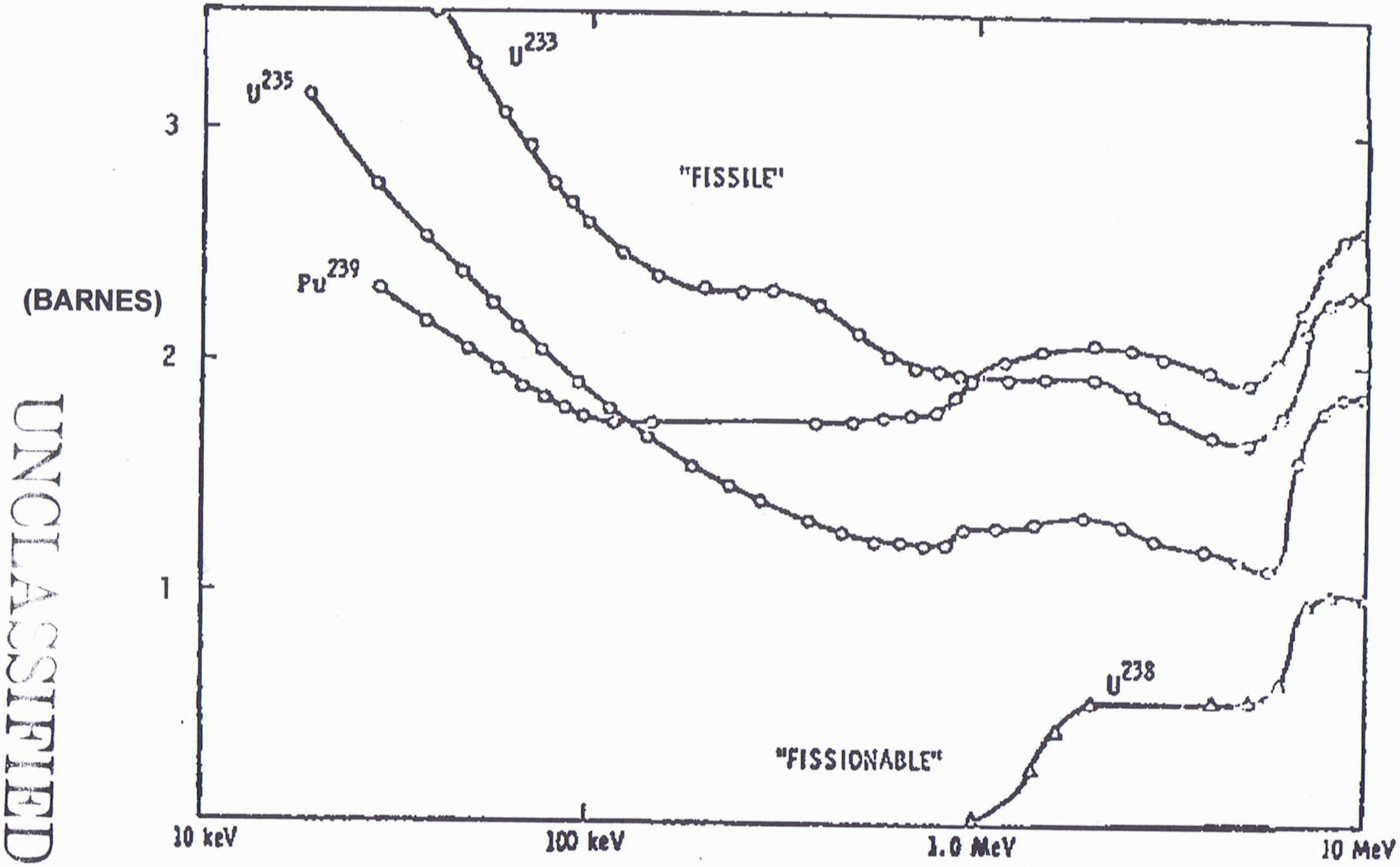
~~SECRET~~

B-3

~~SECRET~~

UNCLASSIFIED

FISSION CROSS SECTIONS



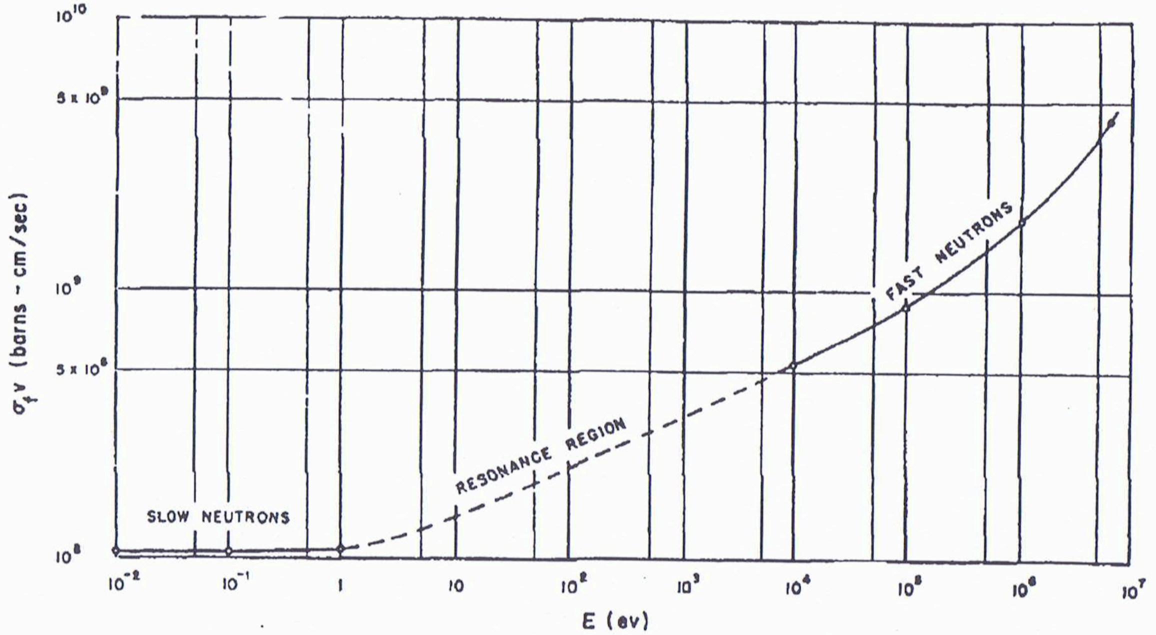
INCIDENT NEUTRON ENERGY

NOTE: The thermal neutron energy is not on the chart

~~SECRET~~ UNCLASSIFIED

UNCLASSIFIED ~~SECRET~~

Variation of Cross Section x Ave. # Neutrons for ^{235}U



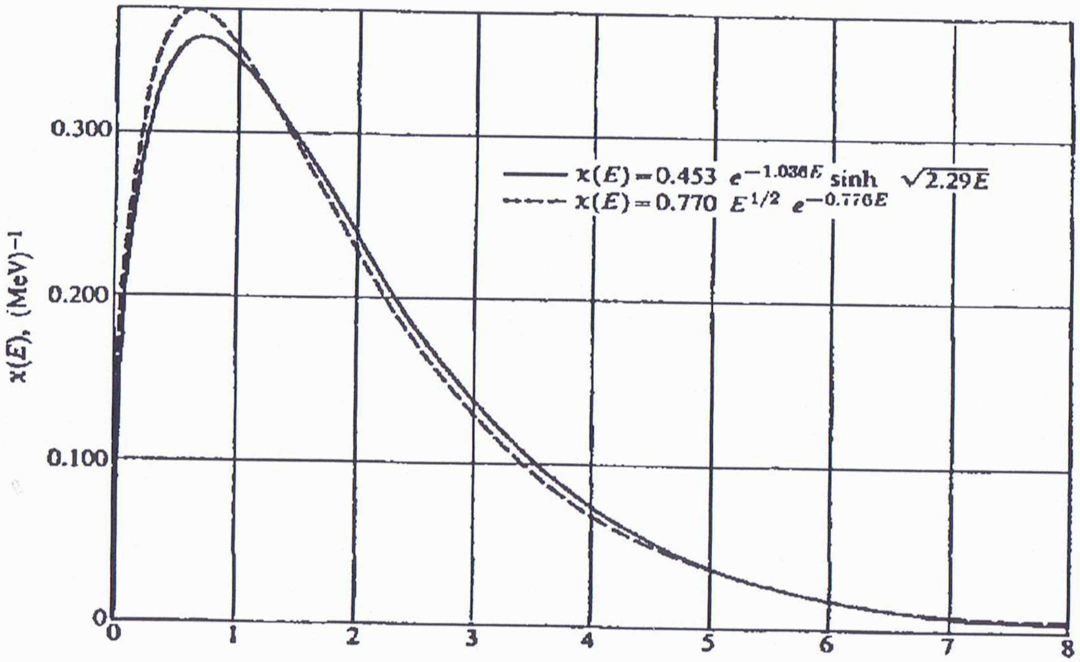
Neutron Energy

Fission is more effective at higher energies N

Smallest fission generation time at high energies ($T = 1/N\sigma_f \cdot v$)

Neutron Energy (MeV)
U_{235} Fission Neutron Energy Spectrum

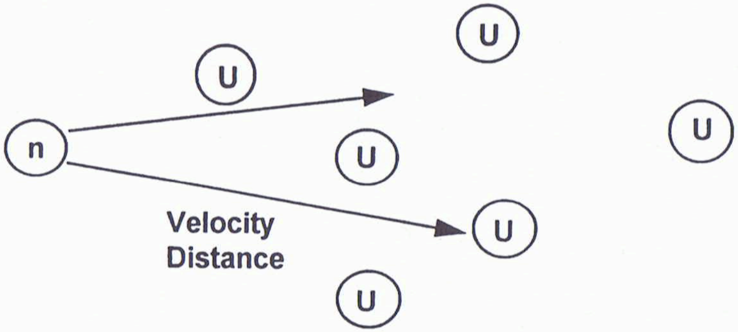
~~SECRET~~ UNCLASSIFIED



UNCLASSIFIED ~~SECRET~~

(Reference, Lamarsh, 1966)

"A Shake"



- Fission mean free path - how long before it clobbers an atom like URANIUM
- Average velocity - how fast it is going

- $$\tau = \frac{\textit{fission mean free path}}{\textit{average velocity of neutron}}$$

These values are derived experimentally and are related to the fission cross section and velocity of the neutron.

- $\tau = 10^{-8}$ Seconds or 1 shake
  (real fast like the shake of a lamb's tail)

~~SECRET~~ UNCLASSIFIED

UNCLASSIFIED ~~SECRET~~

We Care About Neutrons

- An efficient way to fission U^{235} or Pu^{239} is with neutrons.
- The fission of one atom of U^{235} or Pu^{239} releases approximately 200 MeV.
- To create an explosion by fission, a bunch of neutrons are required.
- The more neutrons--the more fission, i.e., We Care About Neutrons!
- Remember that each fission gives off integral numbers of neutrons--about 2-4, but over a bunch of fissions, we measure an average (i.e., 2.54 etc.) and this varies with input neutron energy.

  υ = average number of neutrons
- The whole idea of sustaining the fission process is to get these fission neutrons to go fission more U^{235} or Pu^{239}.
  - If all the neutrons escape without fissioning anything, then the reaction fizzles! (The population becomes extinct.)
  - If at least one of the 2 to 4 neutrons fission something every generation, then we have a steady state condition--a reactor.
  - If most of the neutrons fission another atom etc., etc., we have a run-away condition--a nuclear explosion.

We Care About the Neutrons that Escape

- We call the escapees "lost neutrons," and the abbreviation is *l* (the letter after k).

- So the number of neutrons available for population growth is the average number per fission (u), i.e., 2.54 minus the lost ones.

- Someone called this k.

- Therefore: $k = u - l$
  - for every neutron causing fission in one generation k will cause it in the next generation.

We Care About the Multiplication

- Now let's look at a bunch of fissions and bunch of neutrons.
- If we start with some number of neutrons (one or more), let that number equal n.

n = number of neutrons at beginning of a generation

- Remember, k= number of neutrons available for Round 2...
- And k times n equals number of neutrons at the next generation.
- Don't forget we've used up the original neutrons (n) in the first fission process..
- The gain of neutrons is thus:

$$n \cdot k - n$$

(number of neutrons we started with)•(average number in a fission of Round 2 (etc.)) minus the ones we used up in the previous round.

Determine Growth Rate

- We still care about neutrons, but we really care about the rate (speed) that they are produced.
- The rate is the $\dfrac{\text{change in the number of neutrons}}{\text{change in time}}$
- Mathematically this is represented

$$\frac{Dn}{Dt} \longrightarrow \frac{dn}{dt}$$

- To get the rate change, we divide the actual gain in neutrons by time (t)

$$\frac{nk - n}{t}$$

- Therefore $\dfrac{dn}{dt} = \dfrac{nk - n}{t}$

Apply Basic Calculus

- $\dfrac{dn}{dt} = \dfrac{nk - n}{\tau} = \dfrac{n(k-1)}{\tau}$

- *Let* α *"alpha"* $= \dfrac{k-1}{\tau}$ *substitution gives*

- $\dfrac{dn}{dt} = n\alpha;$ *Rearrange (cross multiply and divide)*

- $\dfrac{dn}{n} = \alpha\, dt$ *Integrate from zero neutrons (N_o) to N neutrons.*

- $N = N_o\, e^{\alpha t}$

  If α is known, one can calculate the number of neutrons at any time (t).

The Energy Released is Proportional to the Number of Fissions

$\alpha \approx \frac{\mu - \iota - 1}{\tau} \approx \frac{3 - 1 - 1}{\tau} \approx \frac{1}{\tau}$ 1 gen / shake for 1 MeV neutron

where: μ = ave# Neutrons
ρ = Post Neutons

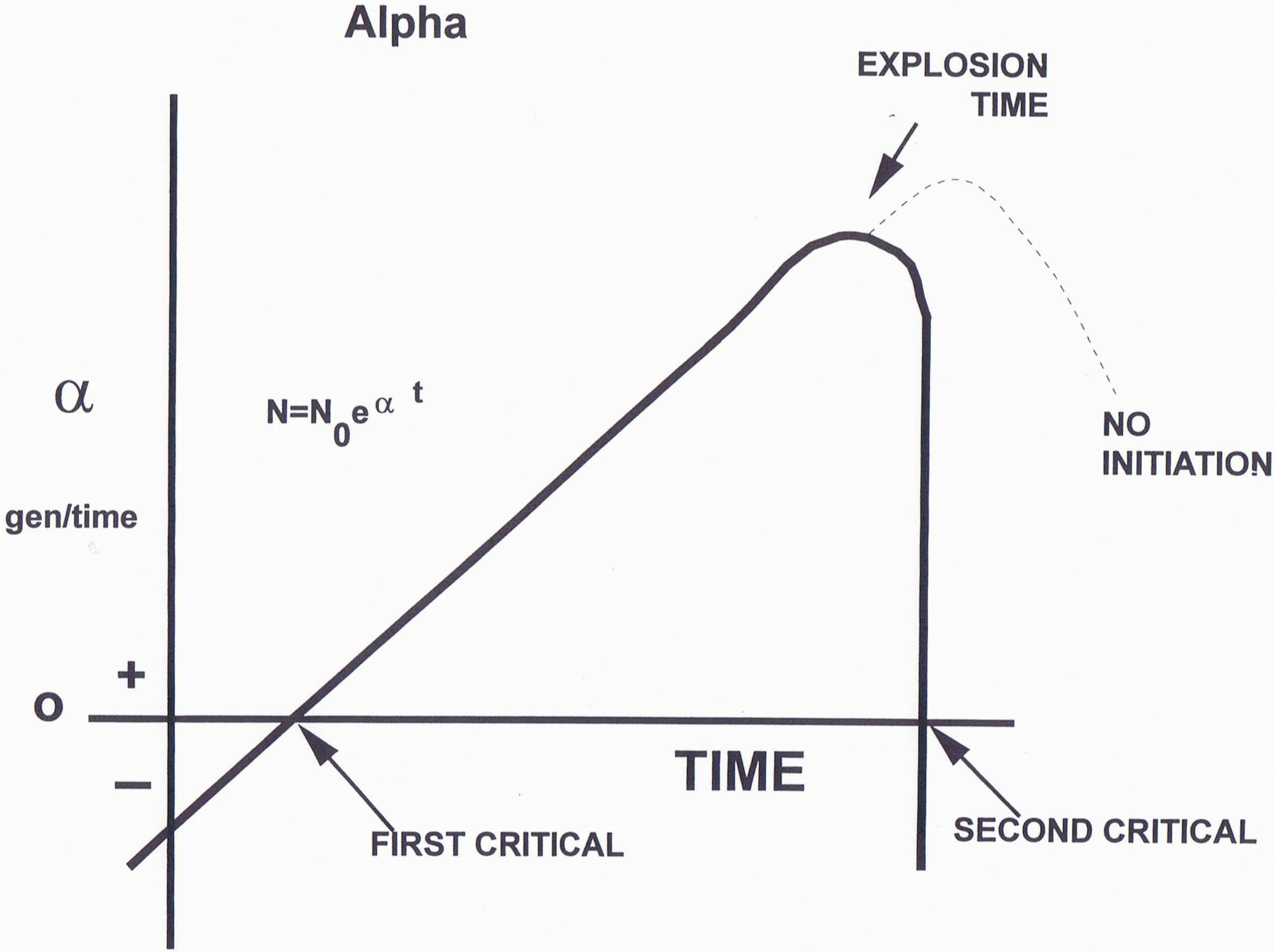
$$N = N_o e^{dt} \cong N_o e^{\frac{t}{\gamma}} = e^{g}$$ where g = Number of generations

The energy released is proportional to the number of fissions
The numer of fissions is proportional to the number of neutrons
1 fission $\cong$ 7 x 10^{-21} tons of TNT
At g = 48 we would have ≈ 9800 lbs.

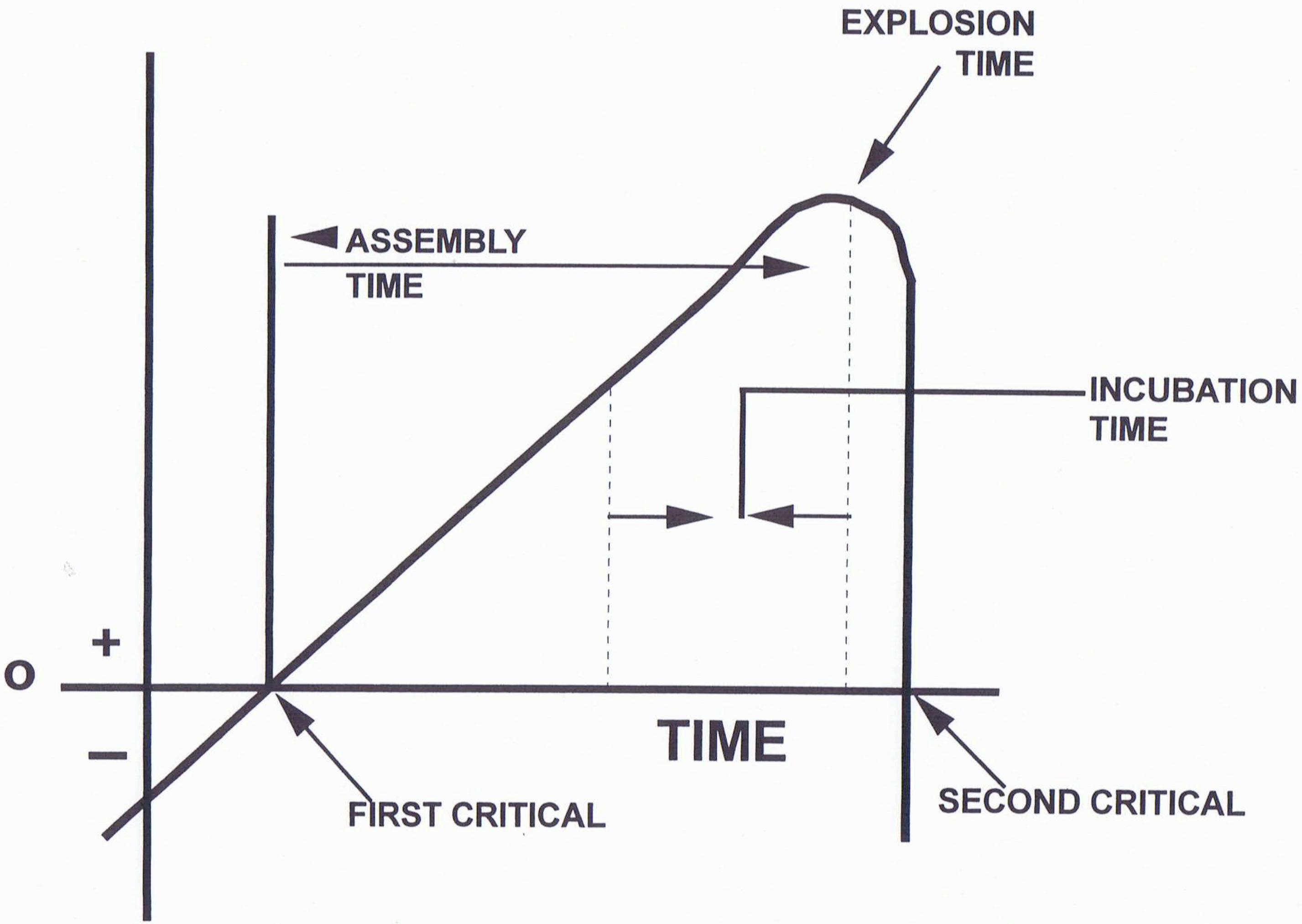
b(3)

[redacted]

α - Curve


Alpha
α
gen/time
$N=N_0e^{\alpha t}$
EXPLOSION TIME
NO INITIATION
+
o
−
TIME
FIRST CRITICAL
SECOND CRITICAL

α - Curve


EXPLOSION TIME
ASSEMBLY TIME
INCUBATION TIME
+
O
−
TIME
FIRST CRITICAL
SECOND CRITICAL

α - Curve

~~SECRET~~
UNCLASSIFIED

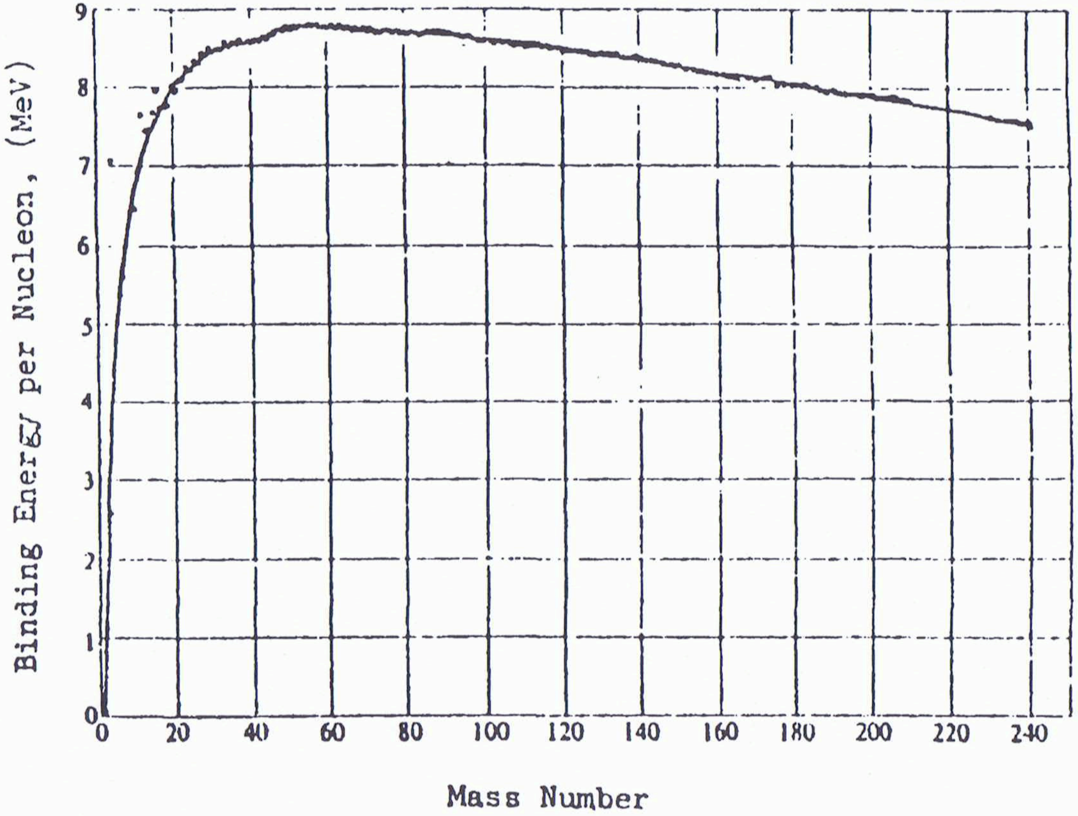
DOE
b(3)

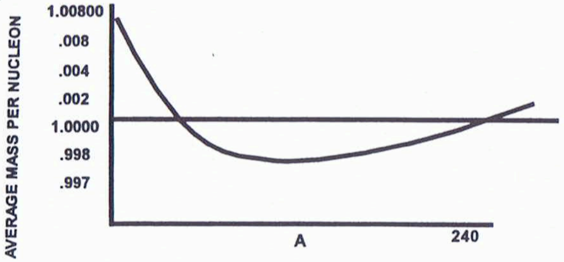
~~SECRET~~
UNCLASSIFIED

~~SECRET~~

UNCLASSIFIED

NUCLEAR BINDING ENERGY





UNCLASSIFIED

~~SECRET~~

~~SECRET~~ UNCLASSIFIED

Potential Fusion Reactions

$$\begin{tikzcd}
 & {}_2\mathrm{He}^3 + {}_0n^1 + 3.27\ \mathrm{MeV} \\
{}_1D^2 + {}_1D^2 \arrow[ur] \arrow[dr] & \\
 & {}_1T^3 + {}_1H^1 + 4.03\ \mathrm{MeV}
\end{tikzcd}$$

$${}_1D^2 + {}_1T^3 \longrightarrow {}_2\mathrm{He}^4 + {}_0n^1 + 17.6\ \mathrm{MeV}$$

$${}_1D^2 + {}_2\mathrm{He}^3 \longrightarrow {}_2\mathrm{He}^4 + {}_1H^1 + 18.3\ \mathrm{MeV}$$

$${}_1T^3 + {}_1T^3 \longrightarrow {}_2\mathrm{He}^4 + 2\,{}_0n^1 + 11.3\ \mathrm{MeV}$$

$${}_3\mathrm{Li}^6 + n \longrightarrow {}_2\mathrm{He}^4 + {}_1T^3 + 4.6\ \mathrm{MeV}$$

UNCLASSIFIED ~~SECRET~~

Theoretical Fusion Energy in Equal Atom Mixture of Li^6D

$$1 \text{ kg of } Li^6 \text{ has } \frac{6.025\text{x}10^{26}}{6.0151} = 1.00165\text{x}10^{26} \text{ Atoms}$$

$$1 \text{ kg of D has } \frac{6.025\text{x}10^{26}}{2.0141} = 2.99141\text{x}10^{26} \text{ Atoms}$$

Hence,

$$.25084 \text{ kg of D has } \left(\frac{2.01410}{6.01512 + 2.0141}\right)\left(2.99141\text{x}10^{26}\right) \cong .75038410^{26} \text{ Atoms}$$

$$.7491 \text{ kg of } Li^6 \text{ has } \left(\frac{6.01512}{6.01512 + 2.0141}\right)\left(1.00165\text{x}10^{26}\right) \cong .750390\text{x}10^{26} \text{ Atoms}$$

$$Li^6 + {}_0n^1 \Rightarrow \left(.75039\text{x}10^{26}\right)(4.6)\text{MeV} \cong 13.2\text{kT}$$

$$D + T\ (.75039\text{x}10)(17.6\text{MeV}) \cong 50.5\text{kT}$$

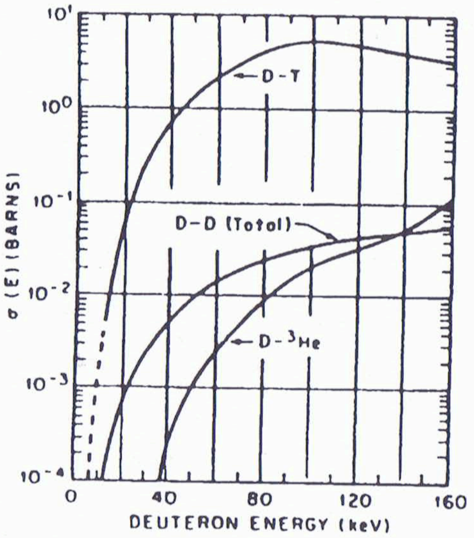
TEMPERATURE EXPRESSED IN kT (ENERGY)

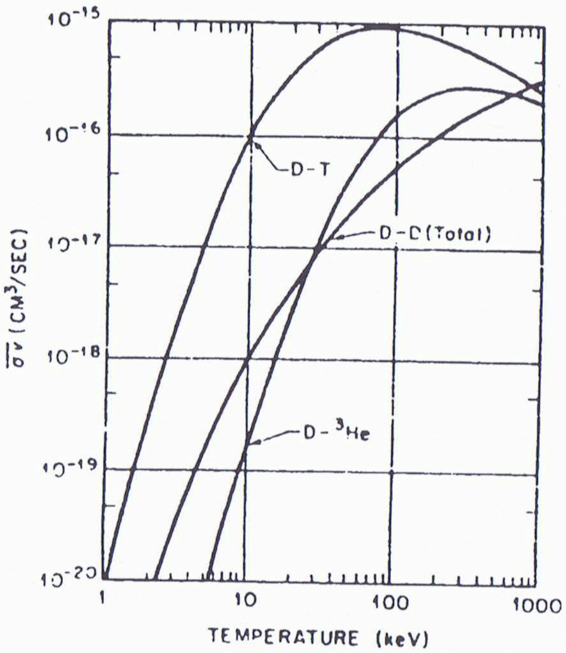
where K is Boltzmann Constant $\left\{ \begin{array}{l} 1.38\text{X}10^{-16}\ \text{erg}/\,^{\circ}\text{K} \\ 8.62\text{X}10^{-8}\ \text{keV}/\,^{\circ}\text{K} \end{array} \right.$

$$T\ (\text{in keV}) = 8.62\text{X}10^{-8}\ T\ (\text{in }^{\circ}\text{Kelvin})$$

Temperature of 1 keV = $1.16\text{x}10^{7}$ degrees Kelvin

Rational for Choice of Fusion Reaction





UNCLASSIFIED
~~SECRET~~

UNCLASSIFIED
~~SECRET~~

FUEL

- ^{6}LiD (95% ^{6}Li, 5% ^{7}Li)

- Tritium

$$^{6}\mathrm{Li} + \mathrm{n} \rightarrow {}^{4}\mathrm{He} + {}^{3}\mathrm{T} + 4.6\ \mathrm{McV}$$

- Fusion

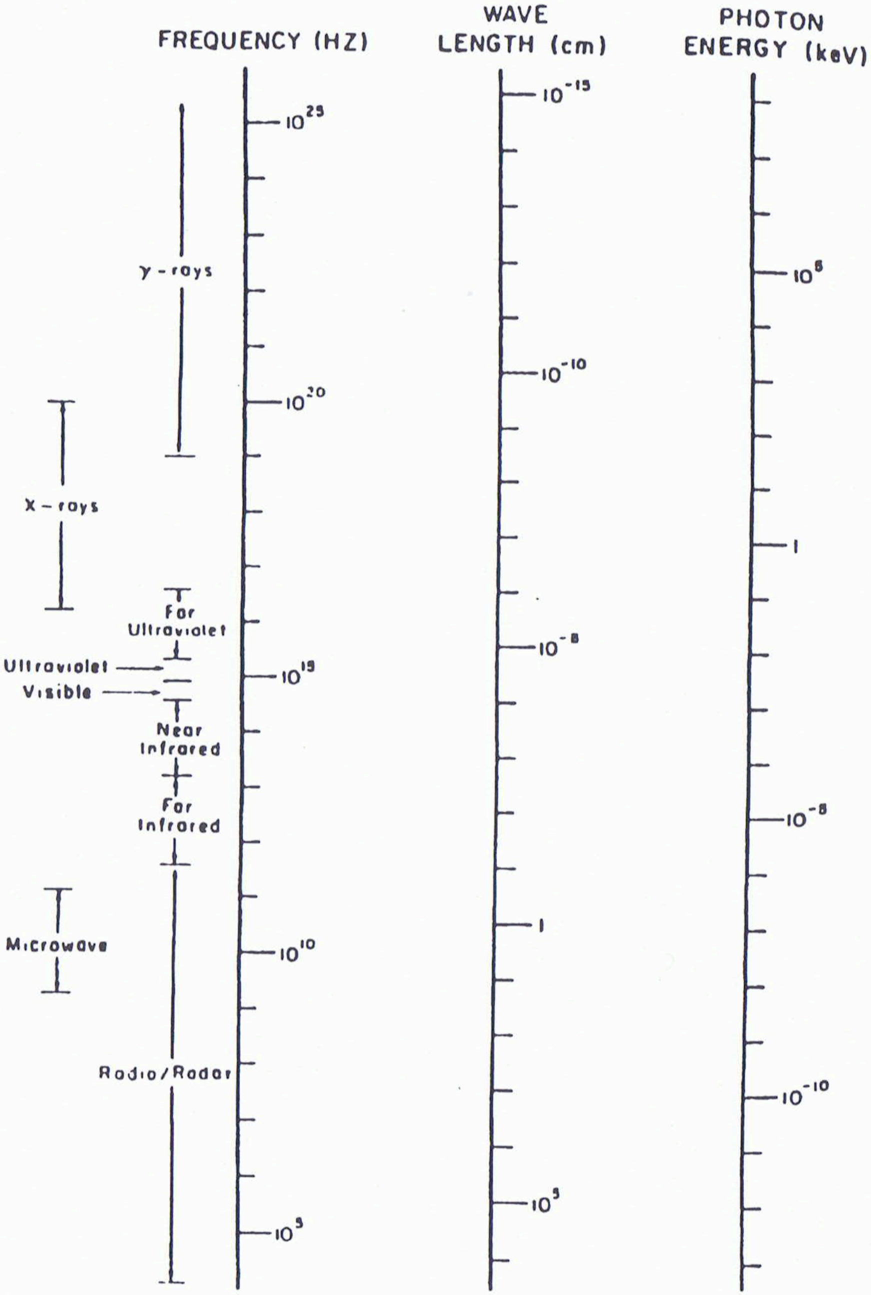
$$^{3}\mathrm{T} + {}^{2}\mathrm{D} \rightarrow {}^{4}\mathrm{He} + \mathrm{n} + 17.6\ \mathrm{McV}$$

$$^{2}\mathrm{D} + \mathrm{n} \rightarrow \mathrm{H} + {}^{2}\mathrm{n}$$

- Net Reaction

$$^{6}\mathrm{Li} + \mathrm{D} \rightarrow 2\ {}^{4}\mathrm{He} + 22.3\ \mathrm{McV}$$

Net Energy = 22.3 McV per Event


FREQUENCY (HZ)
WAVE LENGTH (cm)
PHOTON ENERGY (keV)
10^{25}
10^{20}
10^{15}
10^{10}
10^{5}
10^{-15}
10^{-10}
10^{-5}
1
10^{5}
10^{5}
1
10^{-5}
10^{-10}
γ - rays
X - rays
Far Ultraviolet
Ultraviolet
Visible
Near Infrared
Far Infrared
Microwave
Radio/Radar

Thermal Nuclear Plasma

AT FUSION TEMPERATURES, WE HAVE A PLASMA OF IONS (NUCLEI AND ELECTRONS).

$$\text{ENERGY} = aT_{\text{(ion)}} + bT_{\text{(electron)}} + cT^4_{\text{(radiation)}}$$

IF PLASMA IS IN THERMODYNAMIC EQUILIBRIUM THE THREE TEMPERATURES ARE EQUAL ➡ AT HIGH TEMPERATURES, RADIATION WILL DOMINATE.

REFERENCES

AN INTRODUCTION TO NUCLEAR WEAPONS; WASH 1037 REVISED; SRD (n) SIGMA 1 etc.; GLASSSTONE AND REDMAN.

SOURCE BOOK ON ATOMIC ENERGY; GLASSTONE; UNC 3rd EDITION

BASIC NUCLEAR PHYSICS; INTERSERVICE NUCLEAR WEAPONS SCHOOL

DNA PUBLICATIONS – TECHNOLOGY ANALYSIS REPORT

SANDIA, LLL, LANL TECHNOLOGY REPORTS