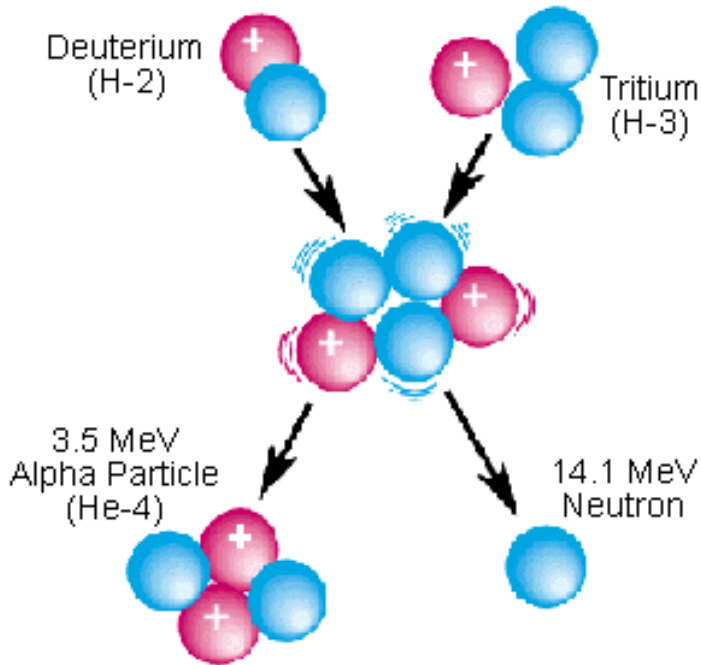


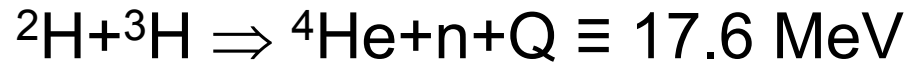
The Hydrogen Bomb



The fusion process

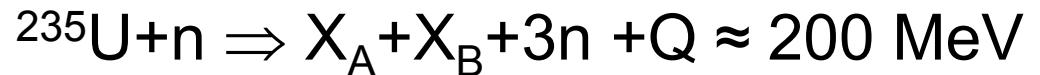
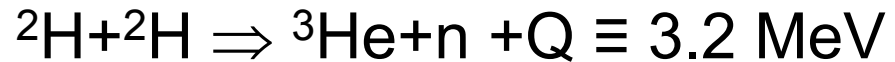


Deuterium-Tritium Fusion Reaction



Energy release $\text{Q} = 17.6 \text{ MeV}$

In comparison



Fusionable Material, deuterium ${}^2\text{H}$ (D) and tritium ${}^3\text{H}$ (t):

Deuterium: natural occurrence (heavy water) (0.015%).

Tritium: natural occurrence in atmosphere through cosmic ray bombardment; radioactive with $T_{1/2} = 12.3 \text{ y}$.

“Advantages” of hydrogen bomb

$$\text{Fusion of } ^2\text{H} + ^3\text{H}: \quad \frac{Q}{A} = \frac{17.6 \text{ MeV}}{(3+2) \text{ amu}} = 3.5 \frac{\text{MeV}}{\text{amu}}$$

$$\text{Fission of } ^{235}\text{U}: \quad \frac{Q}{A} = \frac{200 \text{ MeV}}{236 \text{ amu}} = 0.85 \frac{\text{MeV}}{\text{amu}}$$

Fusion is 4 times more powerful than fission
and generates 24 times more neutrons!

$$\text{Neutron production:} \quad ^2\text{H} + ^3\text{H}: \quad \frac{n}{A} = \frac{1}{5} = 0.2$$

$$^{235}\text{U} + n: \quad \frac{n}{A} = \frac{2}{236} = 0.0085$$

Fuel Considerations

Successful operation of hydrogen bomb requires light fusionable fuel.

- deuterium for d+d based bombs
- tritium & deuterium for d+t based bombs
- tritium needs to be replaced regularly
- on-line produced tritium through ${}^6\text{Li}(n,t)$

Industrial production facilities are necessary.

Deuterium Fuel Production

Deuterium separation takes place by electrolysis or chemical catalysts based methods with subsequent distillation.

Electrolysis separates water in oxygen and hydrogen. The hydrogen and deuterium mix can then be liquefied and distilled to separate the two species.

Chemistry based methods include distillation of liquid hydrogen and various chemical exchange processes which exploit the differing affinities of deuterium and hydrogen for various compounds. These include the ammonia-hydrogen system, which uses potassium amide as the catalyst, and the hydrogen sulfide-water system (Girdler Sulfide process). Process enriches to ~15% deuterium.

Distillation process of deuterium enriched water leads to 99% enrichment – boiling points of heavy water (101.4 °C) and normal water (100 °C).

Known producers are Argentina, Canada, India, Norway, plus all five declared Nuclear Powers. Recent newcomers are Pakistan and Iran.

Heavy Water Plants



Newly-Identified
Heavy Water Plant
Khushab, Pakistan

The estimated production
capacity is 50-100 tons
of heavy water per year.



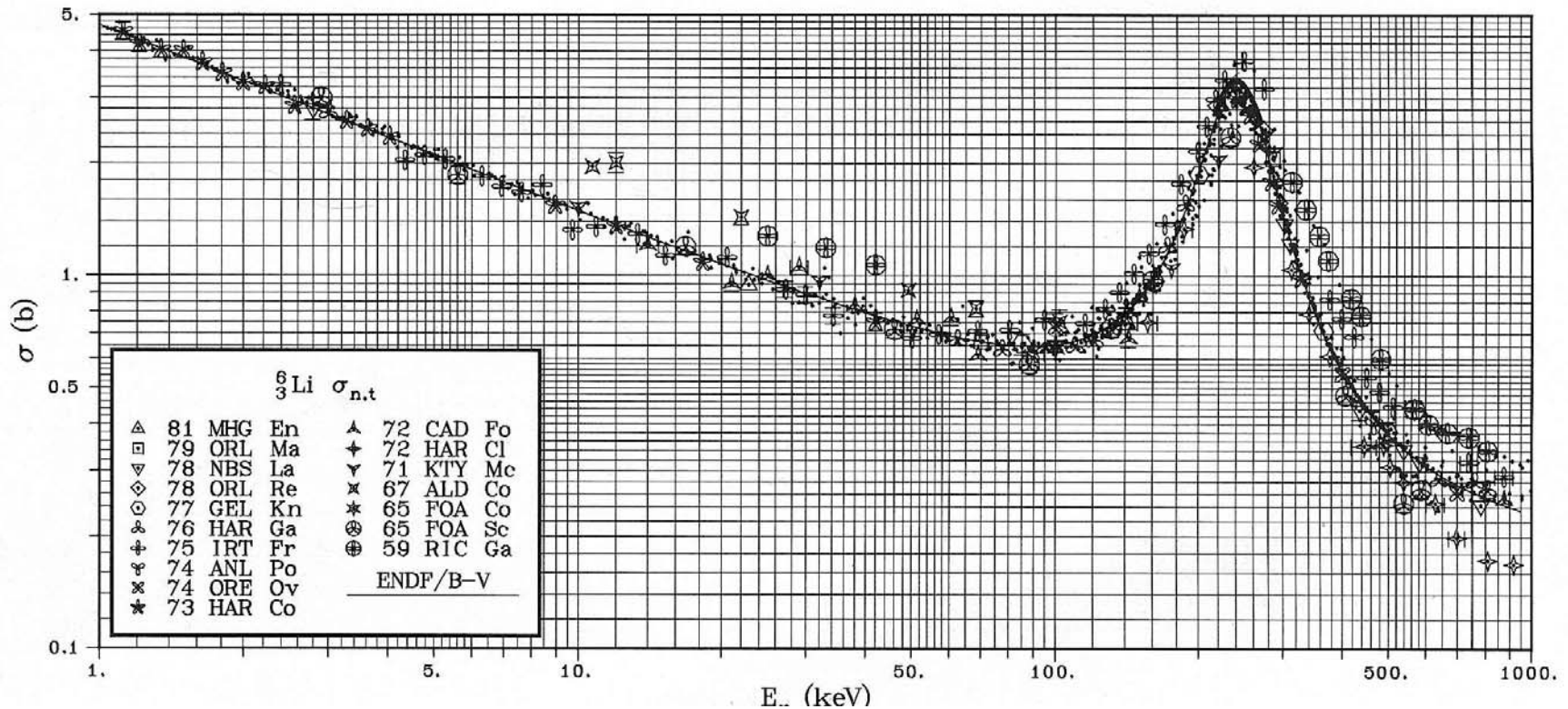
Kota, India



Comparison of the Khushab heavy water plant and the Kota plant in India.

Tritium fuel production

Tritium occurs naturally but low abundance can be enhanced by accelerator or reactor based Tritium breeding through neutron capture on ${}^6\text{Li}(n,t){}^4\text{He}$.

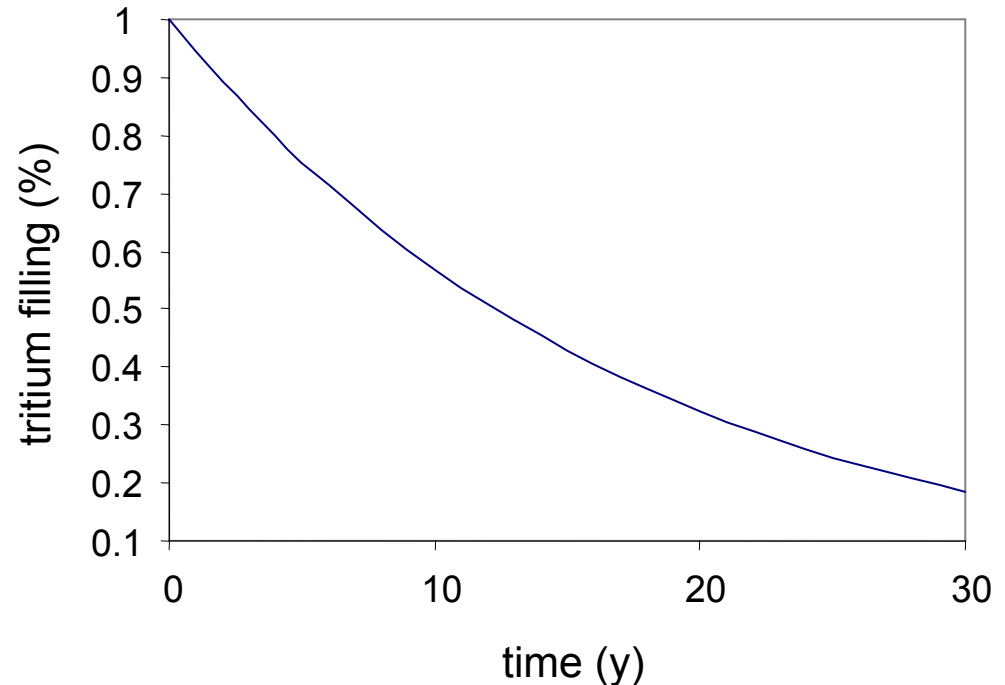


The United States has not produced tritium since 1988, when the Department of Energy Closed it's production facility site in South Carolina closed. Immediate tritium needs are being met by recycling tritium from dismantled U.S. nuclear weapons. New plans?

Maintaining weapon stock-pile

Loss of tritium fuel
in nuclear warheads
by natural decay
~5% per year!

$$N_{3H}(t) = N_{3H}(t_0) \cdot e^{-\frac{\ln 2}{t_{1/2}} \cdot t}$$



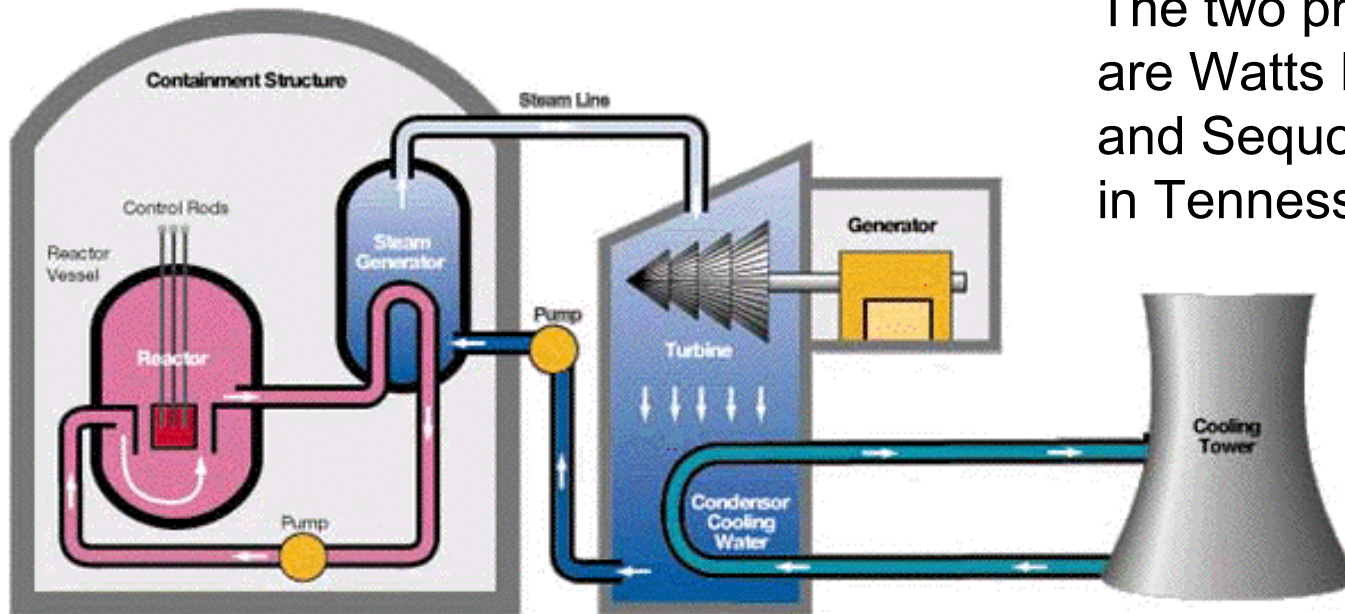
To keep nuclear weapons stockpiles at the level prescribed by the START I (Strategic Arms Reduction Treaty), however, the United States will require a tritium supply capable of producing three kilograms of tritium each year, to go online no later than 2007.

New US tritium production plans

On May 22, 1996, DOE and NRC agreed on the use of commercial reactors for the production of tritium. Lithium containing control rods instead of boron rods will be used in pressurized water reactors for absorbing neutrons. Neutron capture on lithium in control rods will produce tritium. The rods are later removed from the fuel assemblies for extracting the tritium.

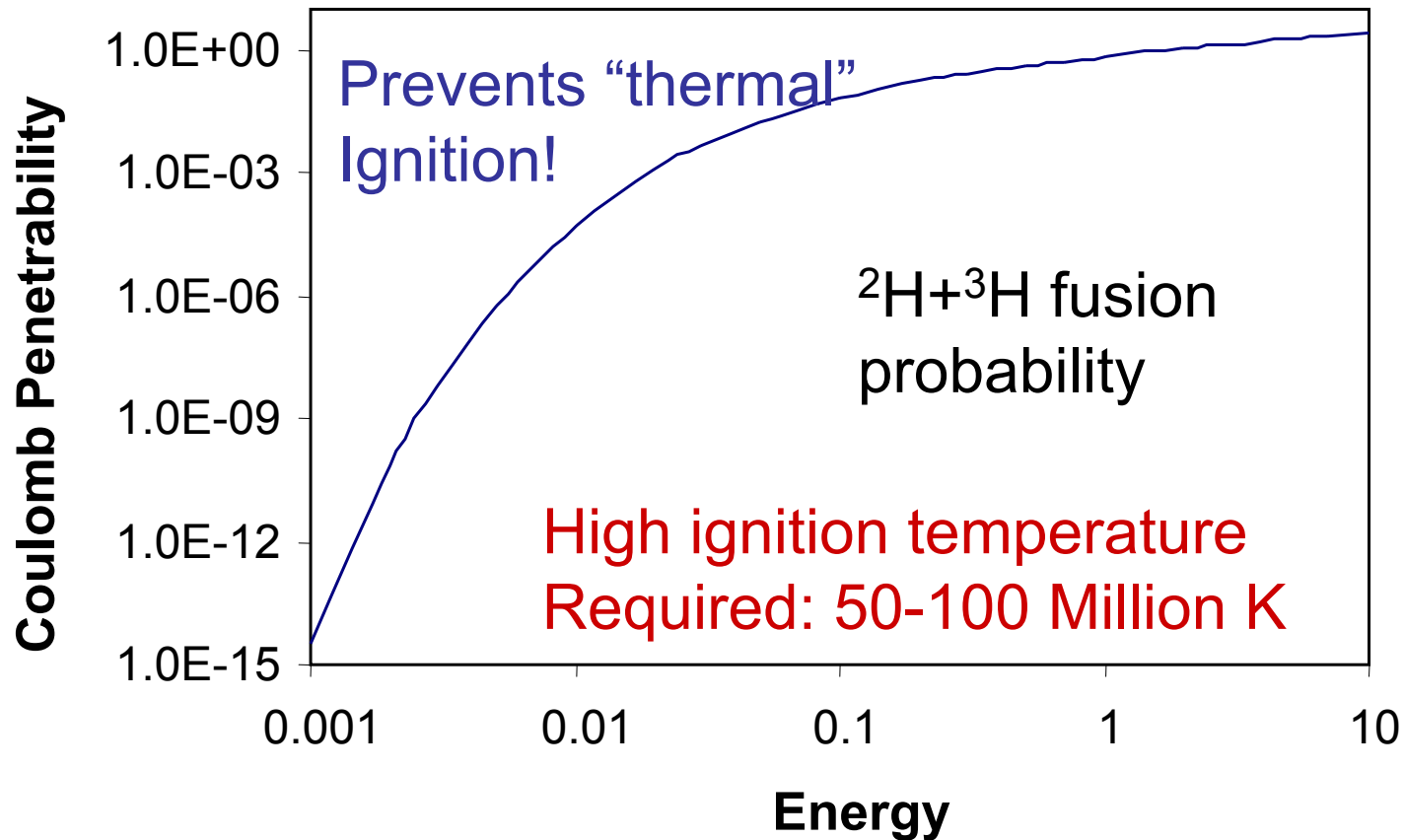


The two production reactors are Watts Bar Nuclear Plant and Sequoyah Nuclear Plant in Tennessee.



Non-proliferation
Concerns!

Disadvantages for hydrogen bomb



Acceleration of positive charged particles towards high energies above Coulomb barrier is necessary!

The Fathers of (US) Hydrogen Bomb

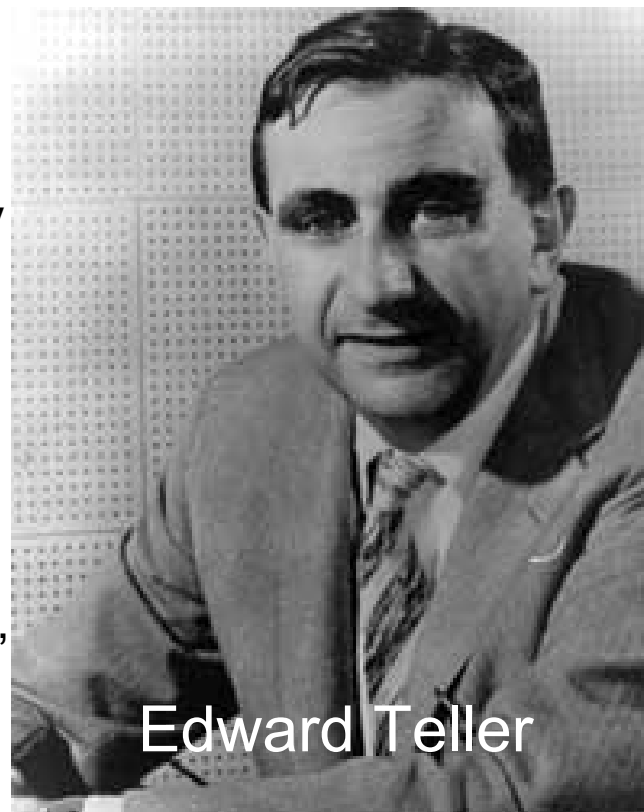
All thermonuclear weapons existing in the world today appear to be based on a scheme usually called the "Teller-Ulam" design (after its inventors Stanislaw Ulan and Edward Teller, two emigrants), or "staged radiation implosion" for a physically descriptive designation.



Stanislaw Ulan

Teller, Hungarian physicist, PhD 1930 Leipzig, Germany with Heisenberg. Emigration to the US 1935. He worked with Oppenheimer in 1943 -1946 on the Manhattan project.

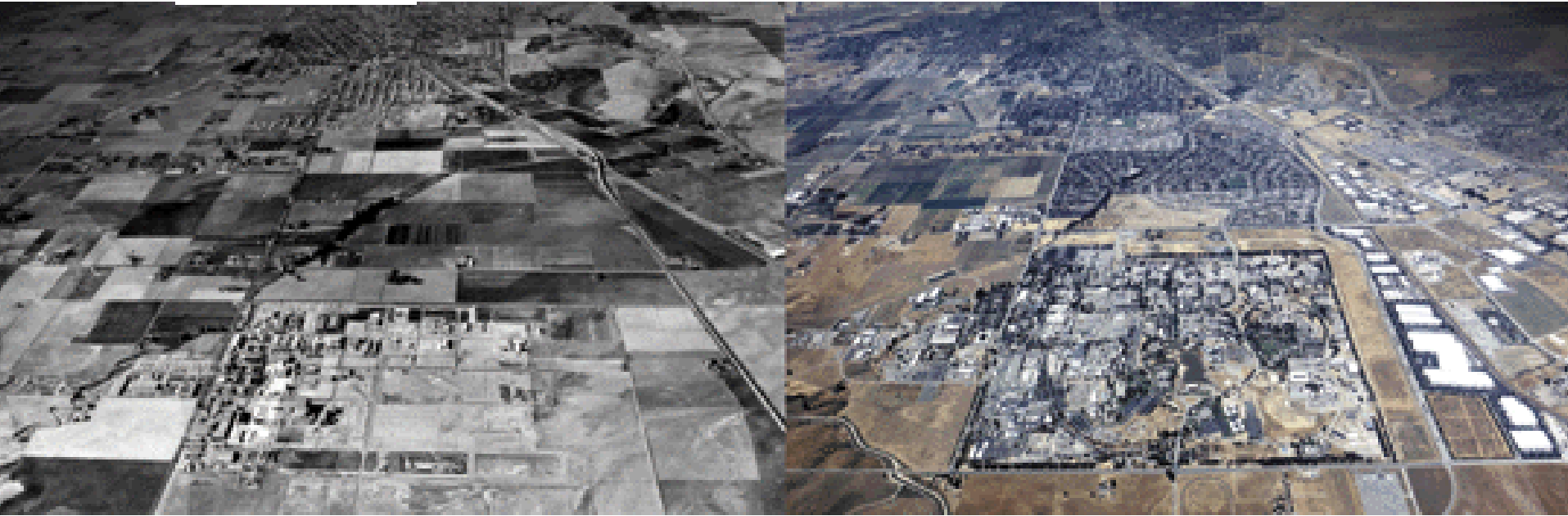
Ulam, Polish mathematician, came 1935 to US (Harvard), joined Manhattan project in 1943;



Edward Teller

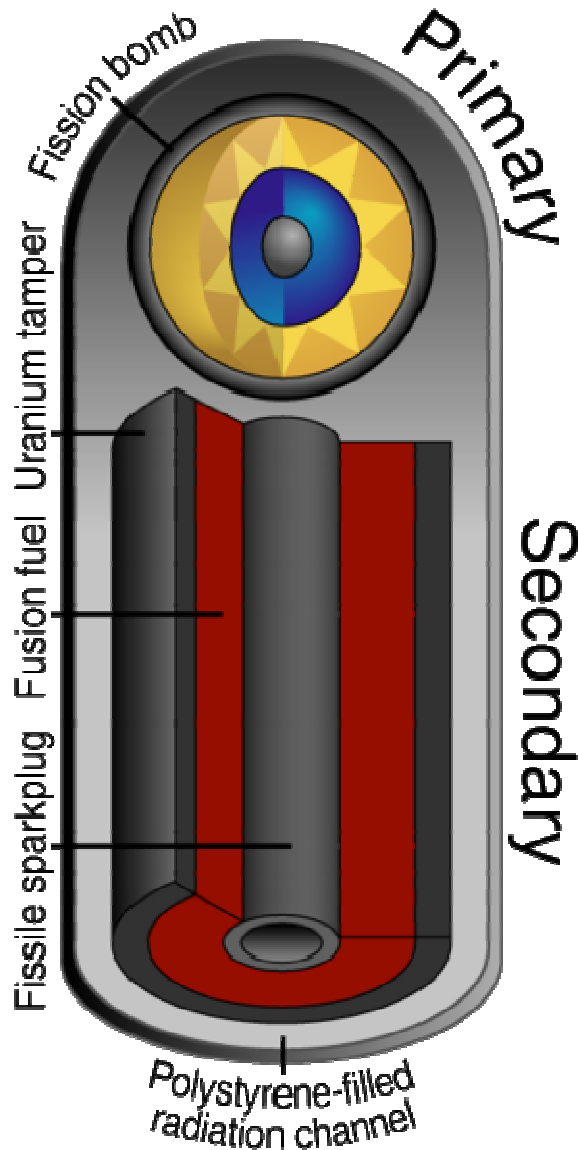
Lawrence Livermore Laboratory

Founded in 1952 in San Francisco bay area as second US weapons National Laboratory for the development and construction of H bomb. H-bomb development and test program progressed through Livermore.

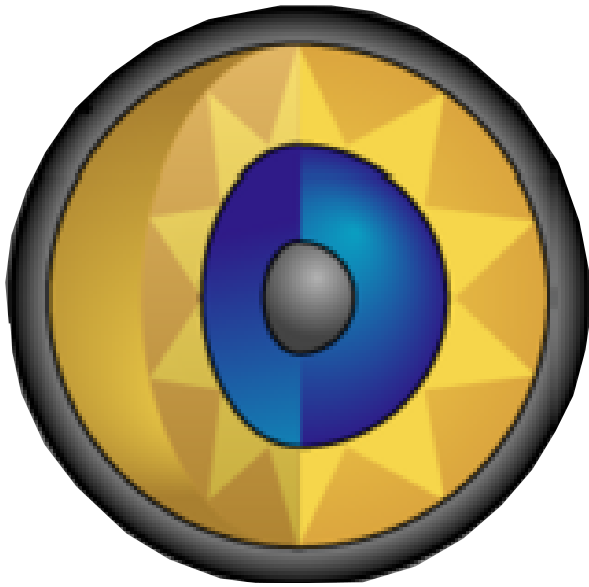


First director Edward Teller, most controversial figure in nuclear weapons history
Fight with Oppenheimer about H-bomb feasibility, accusing Oppenheimer disloyalty (Oppenheimer lost security clearance in 1954). Pushed weapons test program from the early 50s to the 80s, instigated Reagan's star war program

Ulam-Teller Design



Staged explosion of fission (primary) bomb and fusion (secondary) bomb). The fission bomb is based on a regular Pu bomb design (Fat Man). Fusion device is based on d+d & d+t reaction with on-line ${}^6\text{Li}(n,t)$ tritium production and n induced fission. The fusion bomb is triggered by rapid shock driven compression (Ulam) which is enhanced by radiation pressure (Teller) from released X-ray and γ -ray flux.



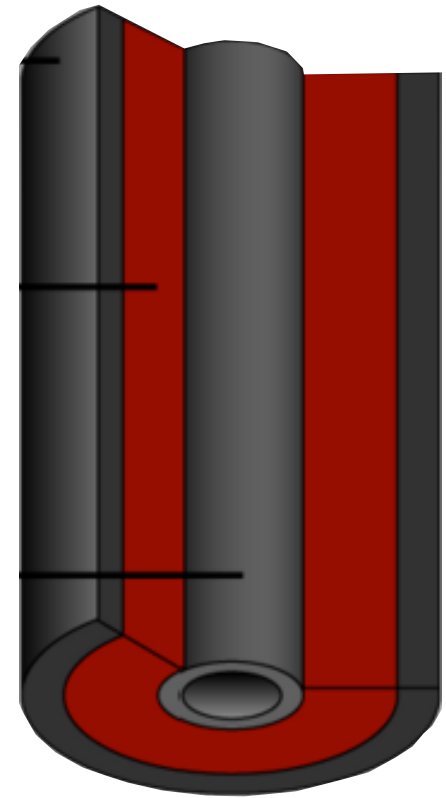
Primary Fission Device

Core: ^{239}Pu , ^{235}U ,
plus $^2\text{H}+^3\text{H}$ booster

Shell: ^{238}U tamper

High explosive lenses

Fuel



Secondary Fusion Device

Radiation channel

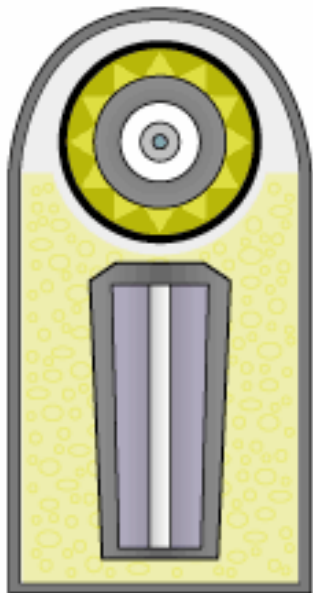
^{239}Pu sparkplug

^6Li , ^2H , ^3H fusion cell

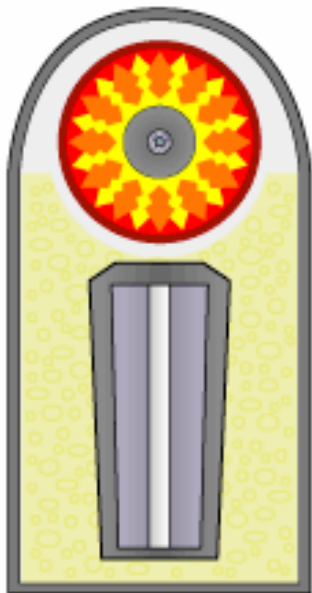
^{238}U tamper

Event Sequence

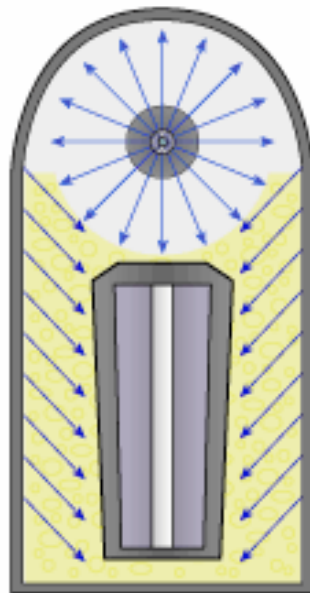
The two devices are surrounded by radiation case to contain (temporarily) the energy released in primary fission driven explosion for efficient conversion into compression shock



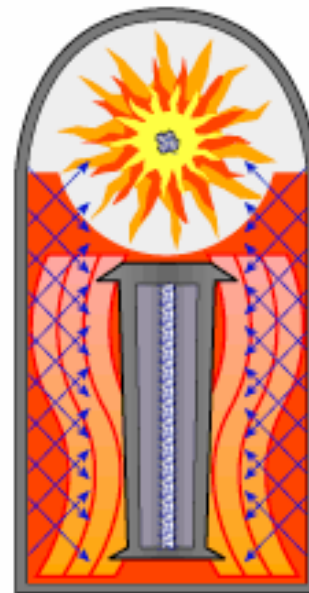
1. Warhead before firing; primary (fission bomb) at top, secondary (fusion fuel) at bottom, all suspended in polystyrene foam.



2. HE fires in primary, compressing plutonium core into supercriticality and beginning a fission reaction.



3. Fissioning primary emits X-rays which reflect along the inside of the casing, irradiating the polystyrene foam.



4. Polystyrene foam becomes plasma, compressing secondary, and plutonium sparkplug begins to fission.



5. Compressed and heated, lithium-6 deuteride fuel begins fusion reaction, neutron flux causes tamper to fission. A fireball is starting to form...

Additional pressure from recoil of exploding shell (ablation)!

Radiation pressure P_{rad}

$$P_{rad} = \frac{F}{A} = \frac{1}{3} \cdot a \cdot T^4$$

F : force

A : Area

a : radiation constant: $a = 7.566 \cdot 10^{-16} \text{ J m}^{-3} \text{ K}^{-4}$

T : temperature in K For $T \approx 10^7 \text{ K}$

$$P_{rad} = \frac{1}{3} \cdot 7.566 \cdot 10^{-16} \cdot (10^7)^4 = 2.52 \cdot 10^{11} \left[\frac{\text{J}}{\text{m}^3} = \text{Pa} = 10^{-5} \text{ bar} \right]$$

$$P_{rad} = 2.52 \text{ [Mbar]}$$

Pressure Conditions in MIKE

Comparing the three mechanisms for generating ignition pressure, we see that:

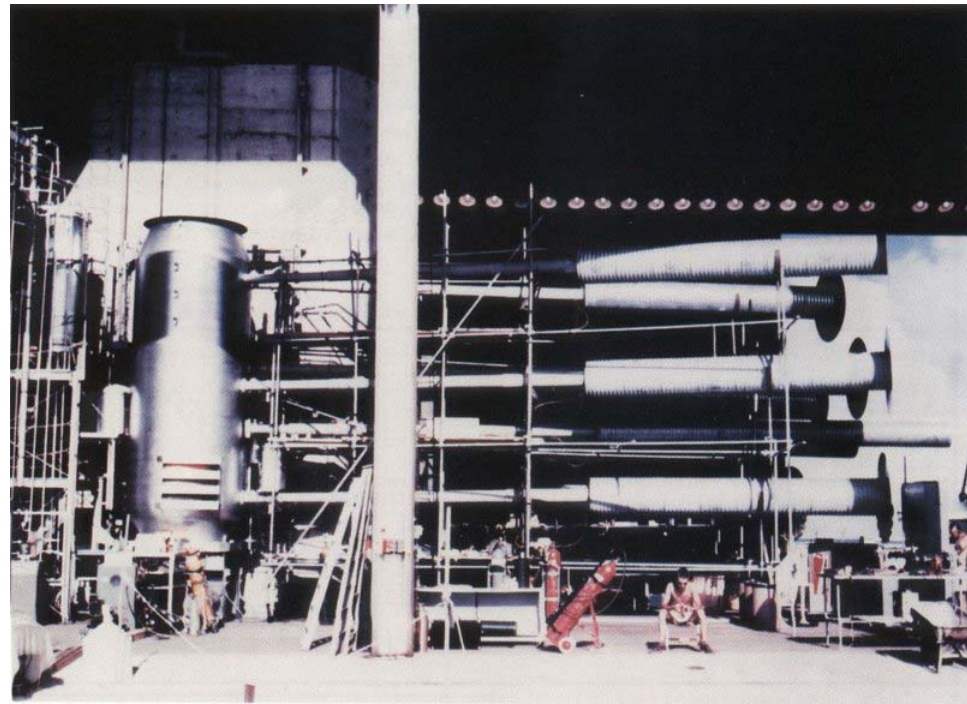
- Radiation pressure:
 - Ivy Mike: 73 million bar (7.3 TPa)
 - W-80: 1.4 billion bar (140 TPa)
- Plasma pressure:
 - Ivy Mike: (est) 350 million bar (35 TPa)
 - W-80: (est) 7.5 billion bar (750 TPa)
- Ablation pressure:
 - Ivy Mike: 5.3 billion bar (530 TPa)
 - W-80: 64 billion bar (6400 TPa)



The calculated ablation pressure is one order of magnitude greater than the higher proposed plasma pressures and nearly two orders of magnitude greater than calculated radiation pressure. No mechanism to avoid the absorption of energy into the radiation case wall and the secondary tamper has been suggested, making ablation apparently unavoidable.

Mike

The "Mike" device was essentially a very large cylindrical thermos flask for holding the cryogenic deuterium fusion fuel, with a regular fission bomb (the "primary") at one end; the latter was used to create the conditions for starting the fusion reaction. The primary was a boosted fission bomb in a separate space atop the assembly.



The "secondary" fusion stage used liquid deuterium because this fuel simplified the experiment, and make the results easier to analyze. Running down the center of the flask which held it was a cylindrical rod of plutonium (the "sparkplug") to ignite the fusion reaction. Surrounding this assembly was a five-ton natural uranium "tamper". The interior of the tamper was lined with sheets of lead and polyethylene foam, which formed a radiation channel to conduct X-rays from the primary to secondary. The outermost layer was a steel casing 10-12 inches thick. The entire "Sausage" (as it was nicknamed) assembly measured 80 inches in diameter and 244 inches in height and weighed about 60 tons.

The entire Mike device (including cryogenic equipment) weighed 82 tons, and was housed in a large corrugated-aluminium building called a "shot cab" which was set up on the Pacific island of Elugelab, part of the Enewetak atoll.

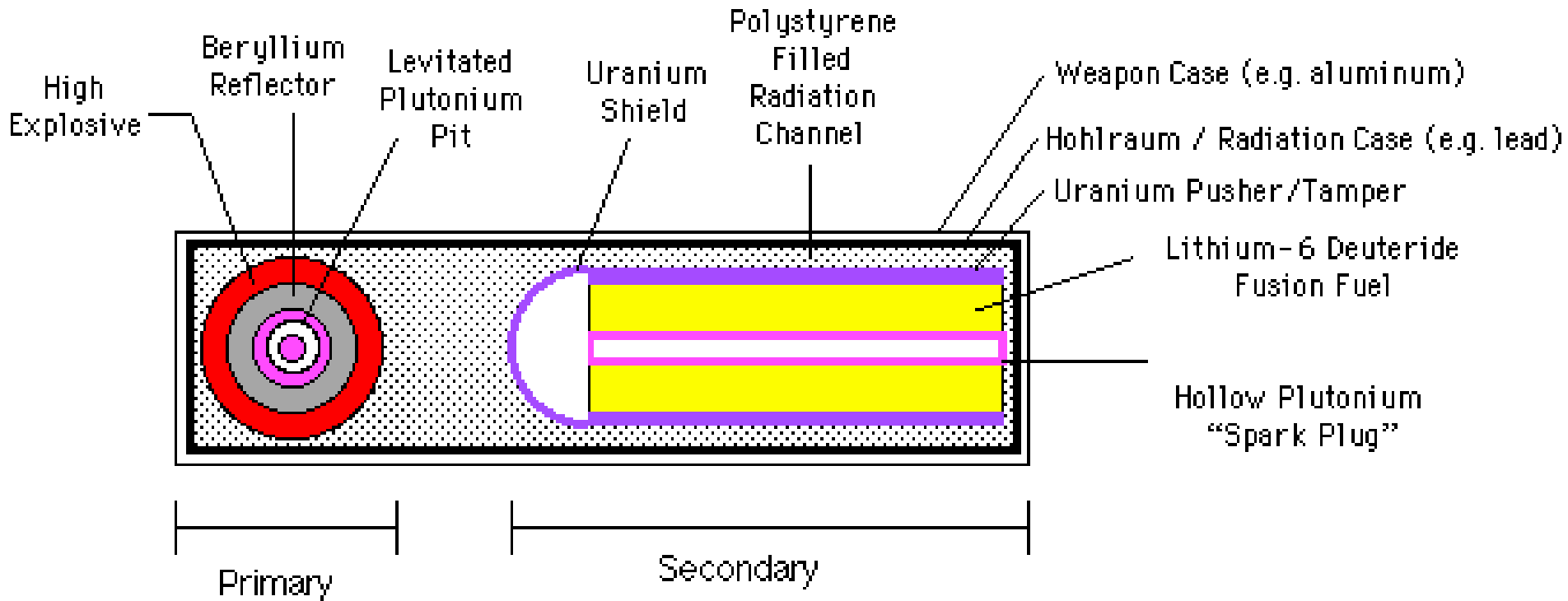
- First staged fusion explosion occurred on Eniwetok Atoll on Oct. 31, 1952.
- Mike used liquid deuterium as a fuel.
- The output of 10.4 megatons of TNT exceeded all of the explosives used in WW II including both atomic bombs.

Mike



Mike consisted of a cylinder about 20 ft high, ~7 ft wide, weighing 164,000 lb; The detonation of Mike left underwater crater 6240 feet wide and 164 ft deep. Mike created a fireball 3 miles wide; the 'mushroom' cloud rose to 57,000 ft in 90 seconds, and topped out in 5 minutes at 135,000 ft , with a stem eight miles across. The cloud eventually spread to 1000 miles wide, with a stem 30 miles across. 80 million tons of soil were lifted into the air by the blast."

Modern Thermonuclear Warhead



The bomb design is based on a bomb casing containing implosion fission bomb and a cylinder casing of ^{238}U (tamper). Within the tamper is the ^6LiD (fuel) and a hollow rod of ^{239}Pu in the center of the cylinder. Separating the cylinder from the implosion bomb is a shield of ^{238}U and plastic foam that fills the remaining space in the bomb casing.

Modern H-bomb design

The detonation of the trigger bomb will cause the following sequence of events:

1. The fission bomb implodes, emitting X-rays.
2. X-rays heat the interior of the bomb and the tamper; which prevents premature detonation of the fuel.
3. The heat causes the tamper to expand and burn away, exerting pressure inward against the lithium deuterate. The lithium deuterate is squeezed by about 30-fold.
4. The compression shock waves initiates fission in the plutonium rod.
5. The fissioning rod gives off radiation, heat and neutrons.
6. The neutrons enter the lithium deuterate, and generate tritium.
7. The combination of high temperature and pressure is sufficient for tritium-deuterium and deuterium-deuterium fusion reactions to occur, producing more heat, radiation and neutrons.
8. The neutrons from the fusion reactions induced fission in the uranium-238 pieces from the tamper and shield.
9. Fission of the tamper and shield pieces produced even more radiation and heat.
10. The bomb explodes.



Multiple stage design possible!

The Castle-Bravo Test



Soviet Response 1955

RDS-37: The First Soviet Superbomb ("True H-Bomb") Test
November 22, 1955; Semipalatinsk Test Site, Kazakhstan



The bomb exploded underneath an inversion layer, which focused the shock back toward the ground unexpectedly. This refracted shock wave did unanticipated collateral damage, killing three people from a building collapse.



The Cold War and Nuclear Arms Race

I remember President Kennedy once stated... that the United States had the nuclear missile capacity to wipe out the Soviet Union two times over, while the Soviet Union had enough atomic weapons to wipe out the United States only once... When journalists asked me to comment... I responded, "Yes, I know what Kennedy claims, and he's quite right. But I'm not complaining... We're satisfied to be able to finish off the United States first time round. Once is quite enough. What good does it do to annihilate a country twice? We're not a bloodthirsty people."

Nikita Khrushchev - 1974

Ridiculous Dimensions



Biggest US bomb:
1MT TNT MARK-17



Biggest Soviet Bomb:
50 MT Tsar Bomb

The big bomb never had any military significance. It was a demonstration of force, part of the superpower game of mutual intimidation. This was the main goal of the unprecedented test. Super-weapons are rejected by contemporary military doctrine, and the proposition that “now we have even more powerful warheads” is simply ridiculous.

Attempts for stopping the race

The Baruch Plan 1946; Bernard Baruch, U.S. representative to the U.N. Atomic Energy Commission, seemed to propose a radical plan to put atomic weapons under strict U.N. control. The United States was at the time the only nuclear power in the world. Under the so-called Baruch Plan, the United States would relinquish its atomic monopoly in favor of the creation of a new U.N. Atomic Development Authority, which would become the sole body in the world that could legally possess nuclear arms. Violators were subject to preemptive measures including a nuclear strike. The Soviet Union opposed the Baruch Plan, and in 1949 the first Soviet atomic bomb was detonated.

UN proposal for nuclear disarmament 1955; Soviet Union accepted the plan, after achieving hydrogen weapon success. In 1956 US rejected the U.N. proposed plan for disarmament and identified nuclear weapons as a “powerful deterrent to war”

Voluntary Test Moratorium: 1958-1961

October 10, 1963; Limited Nuclear Test Ban Treaty

Towards a Test Ban treaty?

The three nuclear powers refrained from testing beginning 1958. This voluntary "moratorium" was marked by several public statements of intent, by the United States, the United Kingdom, and the Soviet Union, in varying degrees of specificity and with various caveats. At the end of December 1959 President Eisenhower announced that the United States would no longer consider itself bound by the "voluntary moratorium" but would give advance notice if it decided to resume testing. The Soviet Government stated on August 28 and Premier Khrushchev repeated on December 30, 1959, that the Soviet Union would not resume testing if the Western powers did not. France conducted its first test on February 13, 1960, two more later in the year, and a fourth on April 25, 1961. On May 15, 1961, the Soviet Government stated that if France continued testing, the Soviet Union might be compelled to test. On August 30, 1961, although neither the United States nor the United Kingdom had resumed testing and France had not continued to test, the Soviet Union announced that it would resume testing. It did so on September 1, thus ending the moratorium. The United States resumed testing two weeks later.

Why?



1960 -- May 2: U-2 INCIDENT A U.S. - U-2 reconnaissance plane is shot down over Sverdlovsk in the Soviet Union. Premier Khrushchev cancels a scheduled four-power Paris summit, and no further progress is made in the test ban negotiations.

1960 -- February 13: FIRST FRENCH NUCLEAR TEST France explodes its first nuclear device at a test site in the Sahara Desert.

1961 -- September 1: RESUMPTION OF SOVIET NUCLEAR TESTING - Arguing that increased international tensions and the French nuclear test program have created a changed security environment, the Soviet Union resumes atmospheric nuclear testing

