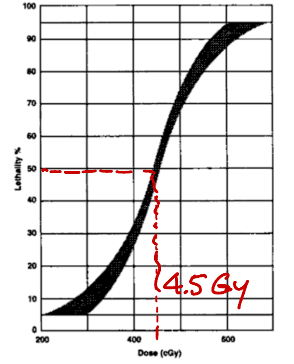
where we were---

radiological effects of radiation

1 rem = 1 rad × Q

Q = 10-20 n
20 α
1 γ, β

1 Gy = 100 rad



fission natural & induced
liquid drop model

typical natural $^{>200}X \longrightarrow {}^{<100}Y + {}^{>100}Z$ + neutrons

energies released ~ 200 MeV / fission
30-40 MeV's to neutrons

^{238}U 99.3% of natural uranium

not useful as target for induced fission

^{235}U ^{239}Pu are ...

Chain Reactions

prompt neutrons

$n + U \rightarrow X + Y + n's$

$Y \rightarrow B, n \rightarrow \beta\gamma \rightarrow \beta\gamma$

$X \rightarrow A, n \rightarrow \beta\gamma \rightarrow \beta\gamma$

delayed neutrons ✓

need to produce >1 neutrons per fission... <u>at least</u>

^{235}U & ^{238}U both absorb neutrons... but fission is not equal

$^{238}U \rightarrow$ 99.3% of natural Uranium

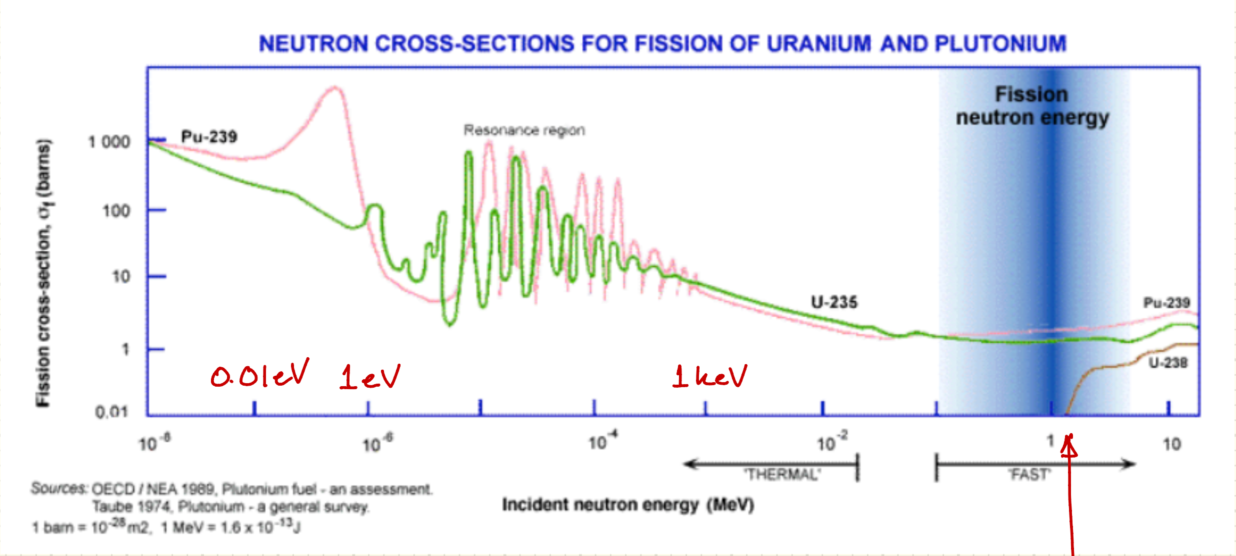
induce fission: $n + {}^{238}U \rightarrow {}^{145}Ba + {}^{94}Kr$

discovery reaction

& generally:

$n + {}^{238}U \rightarrow$ fragments + 2, 3 neutrons

NEUTRON CROSS-SECTIONS FOR FISSION OF URANIUM AND PLUTONIUM



Sources: OECD / NEA 1989, Plutonium fuel - an assessment.
Taube 1974, Plutonium - a general survey.
1 barn = 10^{-28}m2, 1 MeV = 1.6 x 10^{-13}J

minimum required
1.2 MeV

BUT!

$n + {}^{238}U \to$ fragments + $\underbrace{2, 3 \text{ neutrons}}$

↳ quickly slow down and there aren't enough to → threshold

SO: ^{238}U is said to be un-fissionable

More ^{238}U ...

there is a chain – look back at ^{239}Pu --- fissions at all $K(n)$

$$n + {}^{238}_{92}U_{146} \longrightarrow {}^{239}_{92}U_{147} \longrightarrow {}^{239}_{93}Np_{146} + e^- + \nu$$

$$\hookrightarrow {}^{239}_{94}Pu_{145} + e^- + \nu$$

- a mechanism to produce Plutonium
- the "breeder cycle" fn power → only in Europe

Criticality. K (reproduction constant)

$$K = \frac{\#\ \text{neutrons from one generation}}{\#\ \text{neutrons from previous generation}}$$

$K = 1$ ⇒ critical → self-sustaining.

$K < 1$ ⇒ subcritical

$K > 1$ ⇒ supercritical
→ can lead to explosive fission

$\langle k \rangle$ U ~ 2.5

critical mass – mass of fissile material necessary to maintain $k=1$
⇒ neutrons don't leave

^{235}U

17 cm diameter
53 kg

^{239}Pu

9 cm diameter
18 kg

Consider 1 kg ^{235}U & 100% efficiently fission it all.

$N = 3\times10^{24}$ nuclei   assume $k = 2$

$$(k)^G = \#\ \text{fissions} = 3\times10^{24}$$

$$\ln k^G = \ln 3\times10^{24}$$

$$G \ln k = \ln 3\times10^{24}$$

$$G = \frac{\ln 3\times10^{24}}{\ln 2} = \frac{56}{0.69} = 81 \text{ generations.}$$

^{235}U fission for power.

- need neutrons to be slow → "thermal" $K = \frac{3}{2}kT \sim$ eV's

→ moderate them by allowing elastic scattering in "moderator"
water (US reactors), Heavy water (Canadian reactors)
Carbon (original chain by Fermi) . . .

→ don't make too many!

prompt neutrons

$n + U \rightarrow X + Y + n\text{'s}$

$Y \rightarrow B, n \rightarrow \beta\gamma \rightarrow \beta\gamma$

$X \rightarrow A, n \rightarrow \beta\gamma \rightarrow \beta\gamma$

delayed neutrons ✓

prompt neutrons very fast
99%

delayed neutrons . . . slower.

$n + {}^{235}U \rightarrow {}^{93}Rb + {}^{141}Cs + 2n$

$^{141}Cs \xrightarrow{25s} {}^{141}Ba$ & n 0.03%

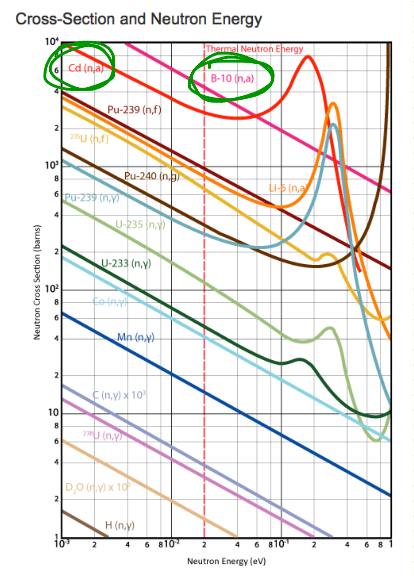
$^{93}Rb \xrightarrow{6s} {}^{93}Sr$ & n 1.4%

Delayed neutrons make power reactors possible

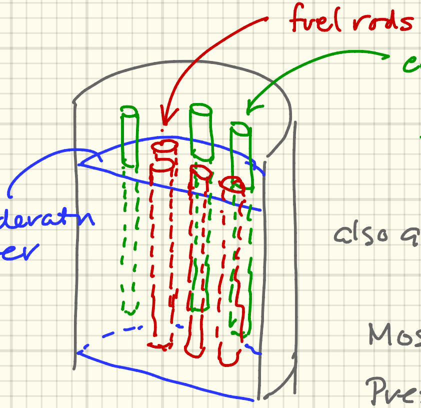
design for some # prompt neutrons

control # delayed neutrons

how? take them out with a "knob" → control rods of high-cross section material



← Cd & B



— moved up and down

→ fully in to stop chain reaction

also graphite probably.

Most U.S. reactors —

Pressurized Water Reactor

PLWR

example –

that 1 kg of ^{235}U ? – if $Q = 208$ MeV ... what energy results ?

$$\# \text{ nuclei} = N = \frac{6.02 \times 10^{23} \text{ molecules}}{235 \text{ g/mol}} \text{/mole } (10^3 \text{ g})$$

$$= 2.56 \times 10^{24} \text{ nuclei}$$

$$E = N\,Q = 5.32 \times 10^{26} \text{ MeV}$$

$1 \text{ MeV} = 4.45 \times 10^{-20}$ kWh

$$E = 2.4 \times 10^{7} \text{ kWh} = 24{,}000 \text{ MWh}$$

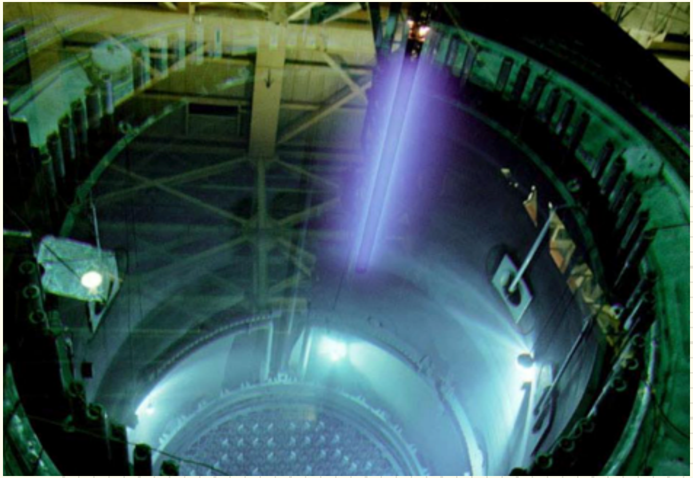
OR

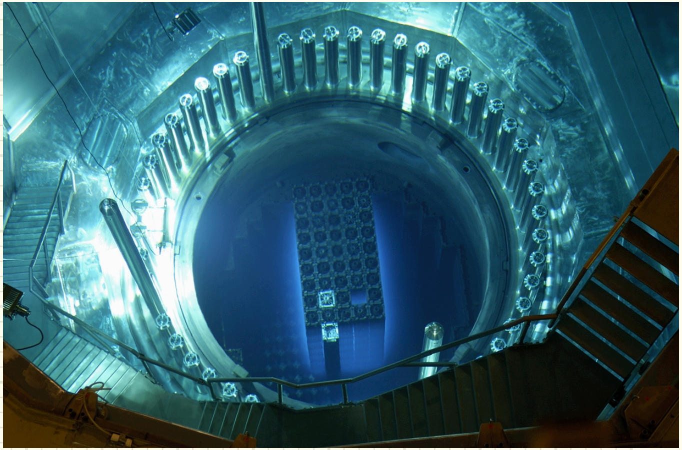
$1 \text{ ton TNT} = 10^9 \text{ cal} = 4.2 \times 10^{7}$ J

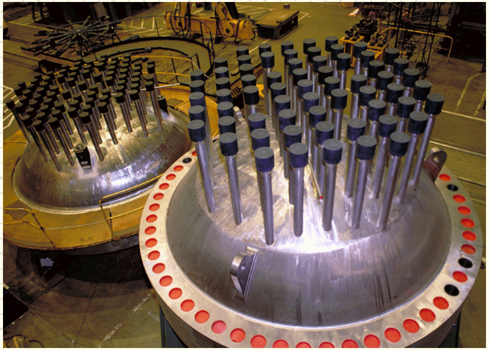
$$E = (5.32 \times 10^{26} \text{ MeV} \times 10^{6} \text{ eV/MeV})(1.6 \times 10^{-19} \text{ J/eV})\left(\frac{1 \text{ ton TNT}}{4.2 \times 10^{7} \text{ J}}\right)$$

$$E = 20{,}000 \text{ tons TNT}$$

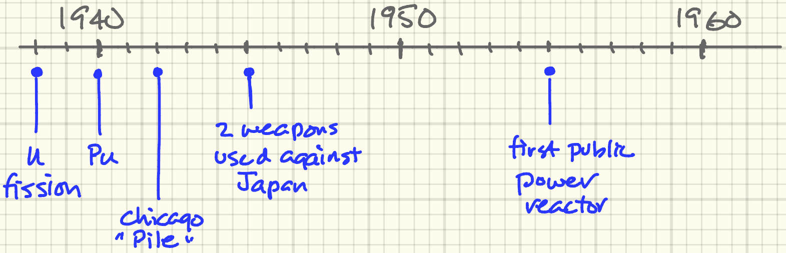
$$E = 20 \text{ kt}$$







Some history



German Program

Technical Choices :

1. Did not try to extract ^{235}U from ^{238}U
2. Did tried to convert $^{238}U \rightarrow {}^{239}Pu$
3. Moderator
   - tried Graphite, decided it would not work wrong
   - chose D_2O, heavy water

clue to Allies when Germany occupied Norw & its ammonia production facility

→ D_2O by product

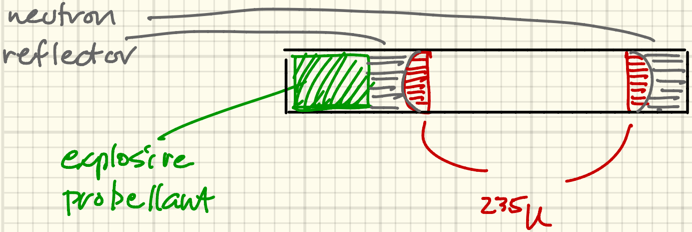
allies, including Norway, destroyed plants repeatedly

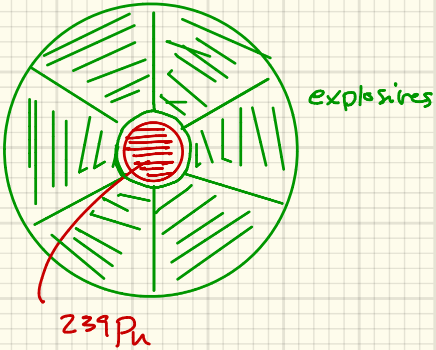
U.S. program

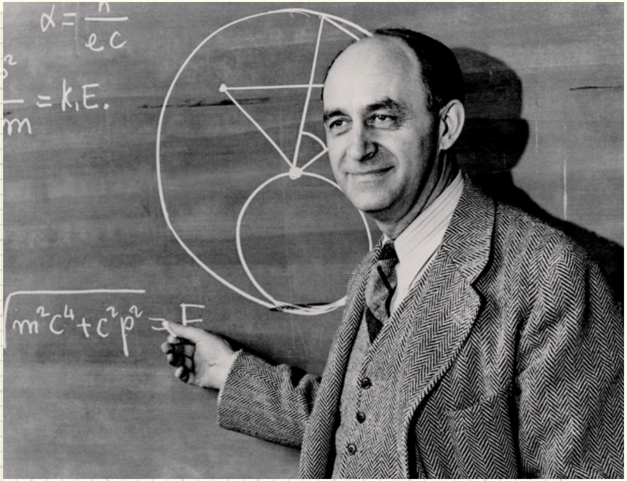
technical choices

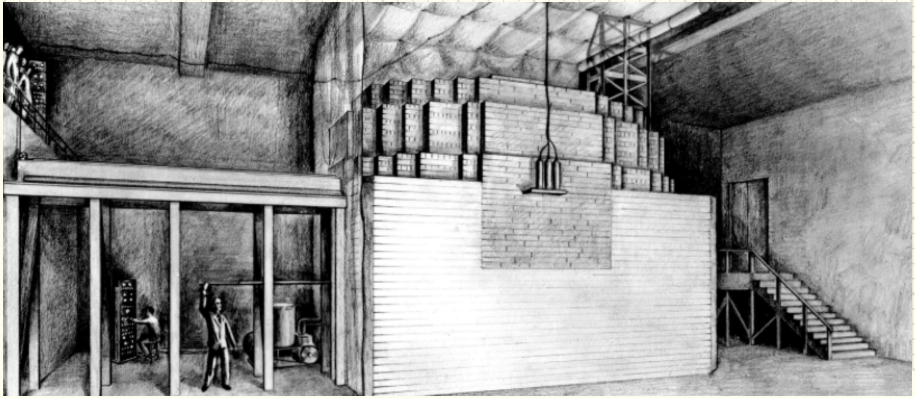
1. chose to try both
   - extract ^{235}U from ^{238}U
   - convert $^{238}U \longrightarrow {}^{239}Pu$
2. moderator
   - Fermi guessed Germans contaminated their graphite
   - he purified graphite and ^{238}U fuel achieved criticality

Manhattan Project @ Los Alamos Nat. Lab


neutron reflector
explosive propellant
^{235}U


explosives
^{239}Pu



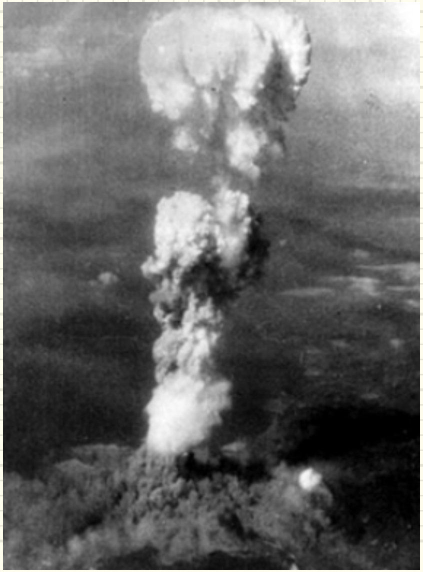


5/8/45 Germany surrendered

7/16/45 "Trinity Test"
Alamogordo, NM

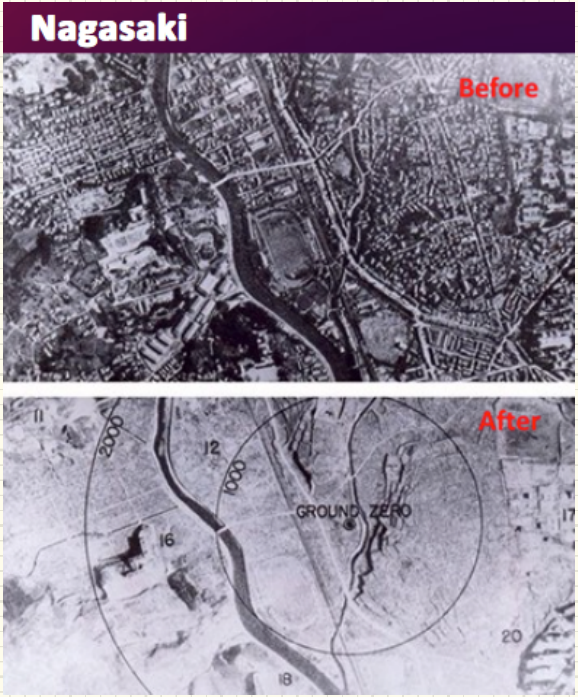
8/6/45 2 weapons
8/9/45 used against
Japan

^{235}U 12.5 kt Hiroshima 8/6/45



^{239}Pu 20 kt Nagasaki 8/9/45

Hiroshima



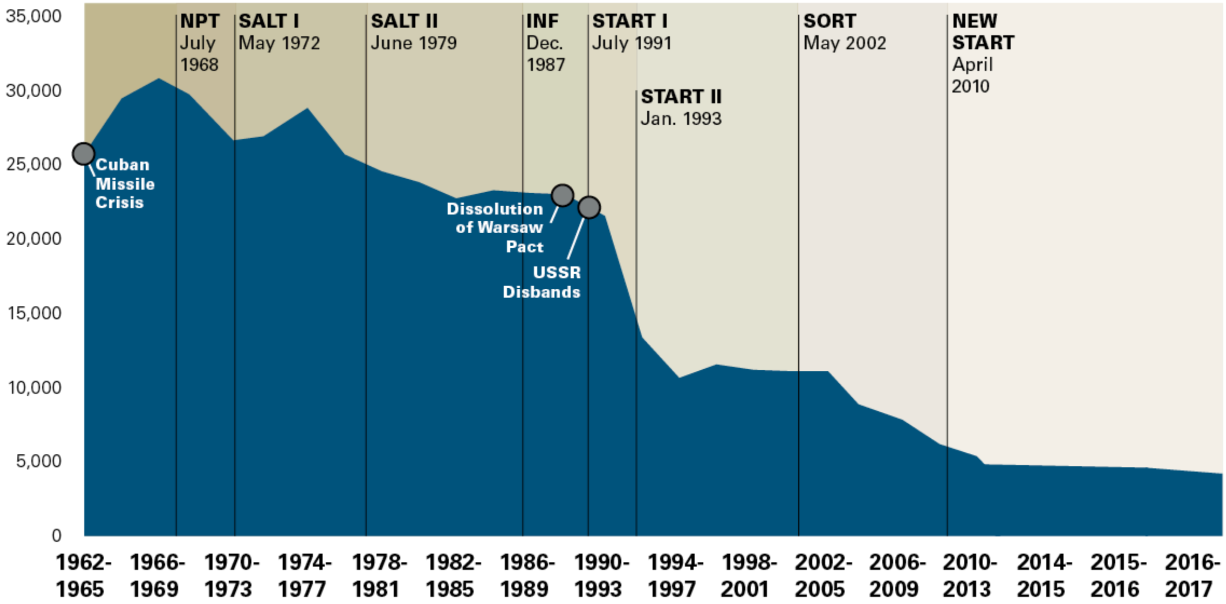
Nagasaki

80,000 civilians killed immediately
10,000's later

40,000 civilians killed immediately

U.S. Nuclear Weapons Stockpile, 1962-2017

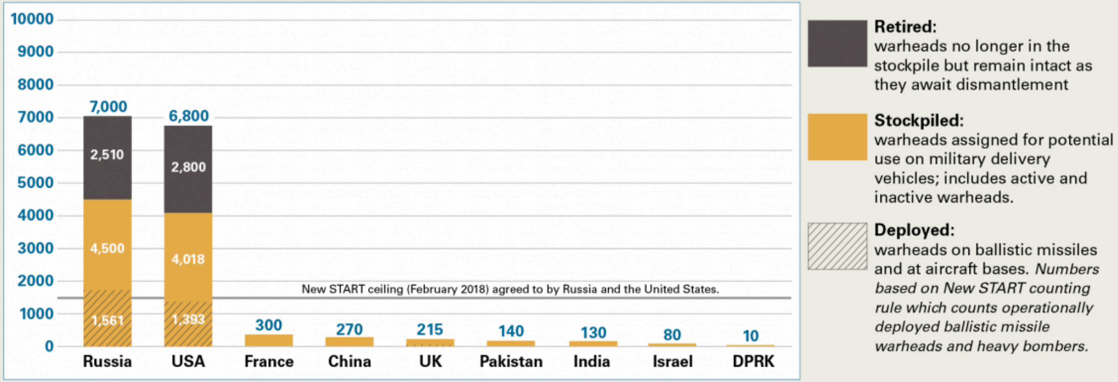
Since the late-1960s, the United States and Russia have signed a series of nuclear arms treaties that have contributed to steep cuts in their active and inactive nuclear warhead stockpiles.



Sources: U.S. Department of State, U.S. Department of Defense, Arms Control Association. Updated: January 19, 2017.

2017 Estimated Global Nuclear Warhead Inventories

The world's nuclear-armed states possess a combined total of roughly 15,000 nuclear warheads; more than 90 percent belong to Russia and the United States. Approximately 9,600 warheads are in military service, with the rest awaiting dismantlement.



■ **Retired:** warheads no longer in the stockpile but remain intact as they await dismantlement

■ **Stockpiled:** warheads assigned for potential use on military delivery vehicles; includes active and inactive warheads.

▨ **Deployed:** warheads on ballistic missiles and at aircraft bases. *Numbers based on New START counting rule which counts operationally deployed ballistic missile warheads and heavy bombers.*

Sources: Hans M. Kristensen and Robert S. Norris; U.S. Department of State. Updated October 3, 2017.

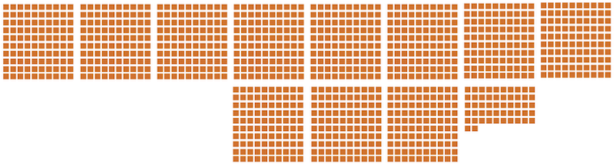
Arms Control Association

Land: Intercontinental ballistic missiles

450
ICBMs

Minuteman III

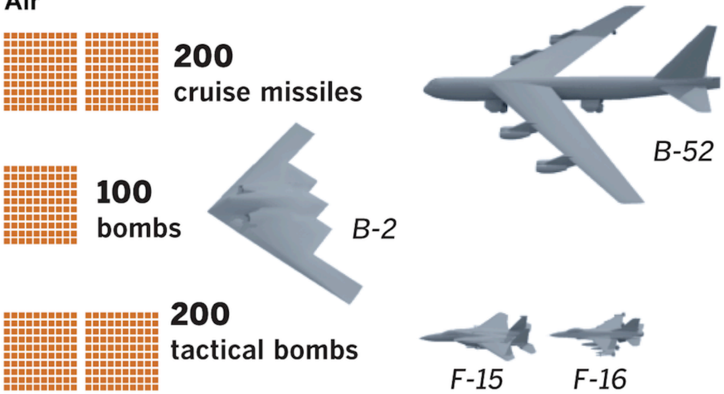
Sea: Submarine ballistic missiles



1,152
warheads

Ohio Class Submarine

Air



200
cruise missiles

B-52

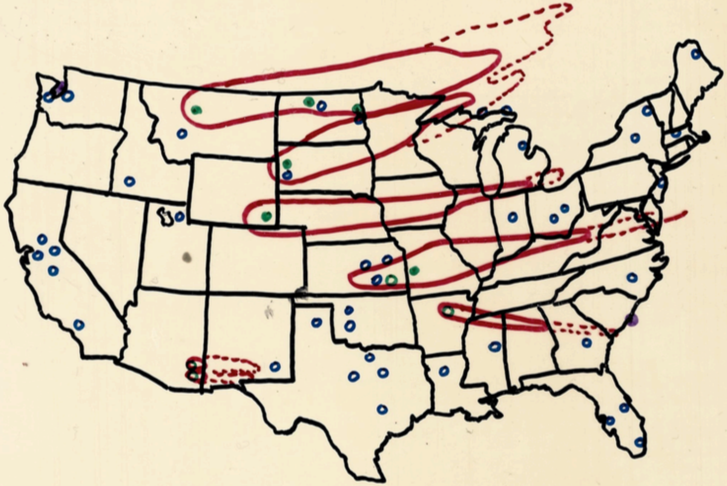
100
bombs

B-2

200
tactical bombs

F-15
F-16

* The U.S. holds an inactive stockpile of 2,548 to 2,700 tactical warheads



○ ICBM (TITAN) FIELDS

● ICBM (MM) FIELDS

○ SAC BASES

● SSBN SUPPORT BASES

COUNTERFORCE ATTACK ON ICBM FIELDS <u>ONLY</u>

2 1 Mt GROUND BURSTS (50% FISSION) / SILO

⬭ 450-rem indoors (50% DEAD)

⬭ 200-rem indoors (50% HOSPITALIZED)

Raw meterial depends on goal. Natural Uranium 99.3% ^{238}U

0.7% ^{235}U

TYPE	MAIN USES
natural ^{238}U	some power reactors militery Pu production reactors
"low enriched" Uranium LEU => 0.7–20% ^{235}U	most operating power reactors → 4-5% ^{235}U some research reactors French naval propulsion reactors
"highly enriched" Uranium HEU => >20% ^{235}U	most research reactors US, British, Russian naval propulsion reactors military Pu and T production reactors
mixed plutonium-uranium oxide "MOX"	some research reactors some power reactors
Pu	reactors

"weapons-grade" uranium > 90% ^{235}U

Enrichment techniques

1. Gaseous diffusion – Manhattan Project @ Oak Ridge Nat. Lab, TN

   diffuses UF_6 gas through semi-permiable membranes
   @ high pressure $\propto \frac{1}{M^2}$ so ^{235}U wins

2. Electromagnetic isotope separation

   like a high-flux mass spectrometer.

3. Gas centrifuge

   UF_6 separated through 100's of stages
   sophisticated metalurgical designs

4. Molecular laser isotope separation

   exploits the molecular energy level differences between
   ^{235}U and ^{238}U in UF_6

Gaseous Diffusion Enrichment

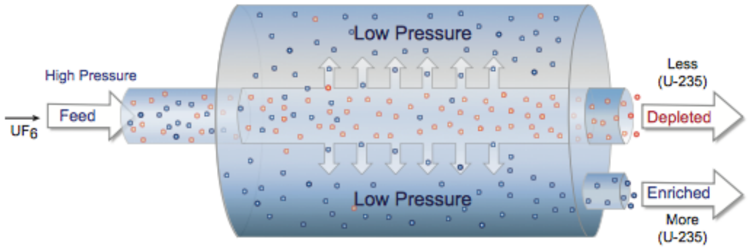
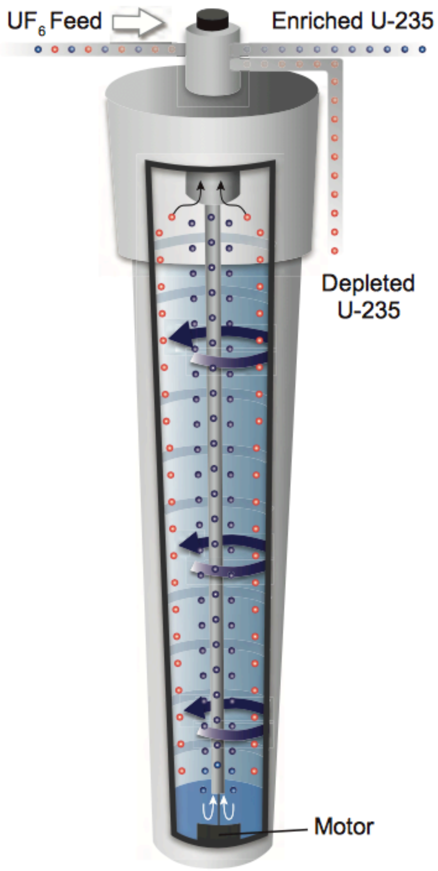
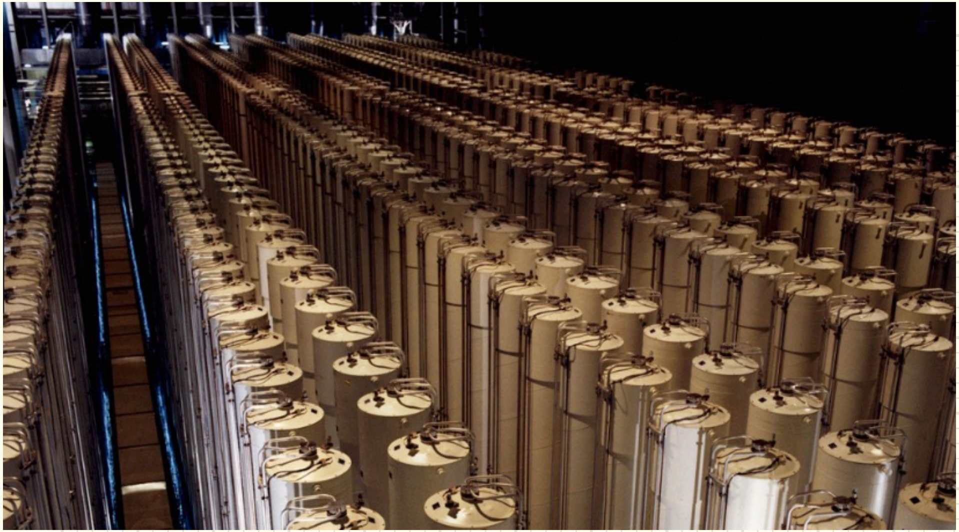
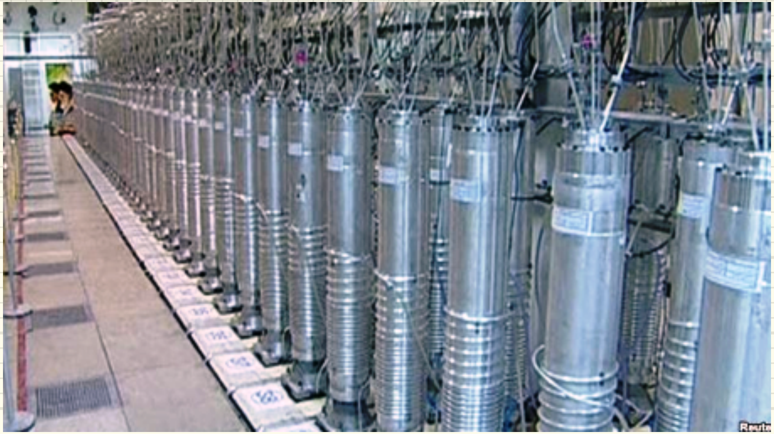


Image Credit: USEC, Inc.

Centrifuge Enrichment






Reute

Proliferation concerns

Technology transfer

Pakistan → Iran, N. Korea, Lybia (1989–1997)

LEU facilities can be → HEU

Breeder reactors

$$n + {}^{238}U \rightarrow {}^{239}U^* \rightarrow {}^{239}U + \gamma$$

$$\hookrightarrow {}^{239}Np + \beta + \nu$$

$$\hookrightarrow {}^{239}Pu + \beta + \nu$$

$$\hookrightarrow \text{fission} + 2.7\, n$$

"breed" Pu fuel

- leave one running for a long time: ${}^{239}Pu + {}^{240}Pu$ ← not fissile
- remove products quickly: ${}^{239}Pu$ + trace ${}^{240}Pu$

  ↑ weapons grade

IRIANIAN "NUCLEAR DEAL" – you know enough now to understand it

"P5+1" July 2015

not political except to note: it's the most intrusive, comprensive, inclusive arms control agreement in history.

My numbering:

1. centrifuge technology. Iran has ~8 generations. Agreement restricts them to only the first 4 generations for a decade. #8 .. 1 cascade only, R&D

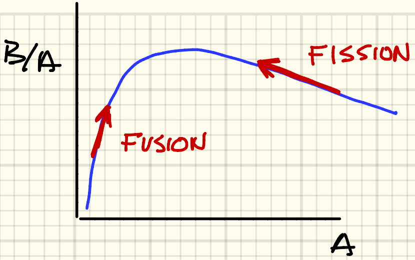
2. number of centrifuges. Previously, 20,000 ... dismantled 15,000

3. uranium enrichment. Restricts them to 3.67% ^{235}U enrichment. → LWPR
15y

4. stockpile. At agreement signing, they had
10,000 kg LEU <20% in oxide and gaseous form ~8,000 kg?
– ready for further enrichment
Agreement restricts them to 300 kg.

8,000 kg + 5,000 centrifuges → few months to make 8 weapons
↓ ↓
300kg 5,000 centrifuges → > year

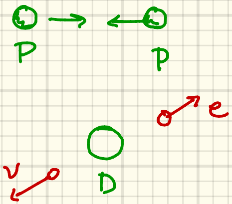
Fusion



About the same time fission weapons were being engineered...

Hans Bethe calculated how the sun works.

→ light elements @ high speeds overcome the Coulomb barrier and fuse



understood by liquid drop model
D has smaller surface volume than 2p → binds

Not enough KE... so tunneling again

Thermonuclear "burning" in solar interior — chains. $T \simeq 1.4 \times 10^7\,K$

PROTON CHAIN

there's a story here

		KE	Reaction Times
${}^1H + {}^1H \rightarrow {}^2H + e^+ + \nu$	$\times 2$	0.41 MeV	$7 \times 10^9\,y$
${}^1H + {}^2H \rightarrow {}^3He + \gamma$	$\times 2$	5.51 MeV	4s
${}^3He + {}^3He \rightarrow {}^4He + {}^1H + {}^1H$		12.98 MeV	$4 \times 10^5\,y$

$\Rightarrow \quad 6\,{}^1H \rightarrow {}^4He + 2\,{}^1H$ net: $4\,{}^1H \rightarrow {}^4He$

CARBON CHAIN

	KE	Reaction Times
${}^1H + {}^{12}C \rightarrow {}^{13}N + \gamma$	1.93 MeV	$10^6\,y$
$\hookrightarrow {}^{13}C + e^+ + \nu$	1.2 MeV	10 min
${}^1H + {}^{13}C \rightarrow {}^{14}N + \gamma$	2.60 MeV	$2 \times 10^3\,y$
${}^1H + {}^{14}N \rightarrow {}^{15}O + \gamma$	2,39 MeV	$3 \times 10^7\,y$
$\hookrightarrow {}^{15}N + e^+ + \nu$	1.71 MeV	2min
${}^1H + {}^{15}N \rightarrow {}^{13}C + {}^4He$	4.99 MeV	$10^4\,y$

on Earth?

Controlled nuclear fusion? seems to be always 10years from any time

$^2H + ^2H \rightarrow n + ^3He$ $Q = 3.3$ MeV

$^2H + ^2H \rightarrow p + ^3H$ $Q = 4$ MeV

$^2H + ^3H \rightarrow n + ^4He$ $Q = 17.6$ MeV ← best shot

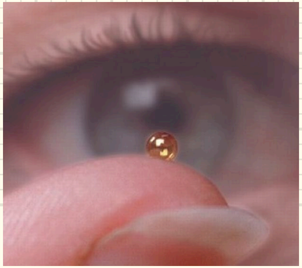
$T \simeq 1.5 \times 10^8$ K

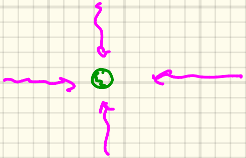
↑ easily made

↑ by product of CANDU reactors

2 main approaches

1. Inerial Confinement





lasers tuned to compress D-T ice pellet

LLNL — close to weapons physics so touchy management.

National Ignition Facility

2. Magnetic confinement → complicated in practice, simple in principle

$$\overset{(D)}{{}^{2}H} + \overset{(T)}{{}^{3}H} \longrightarrow {}^{4}He + n + 17.6\ \text{MeV} \longrightarrow$$ heat to... you guessed it, heat water

$$n + {}^{6}Li \longrightarrow {}^{4}He + {}^{3}H$$

$$n + {}^{7}Li \longrightarrow {}^{4}He + {}^{3}H + n$$

Tritium "breeding"

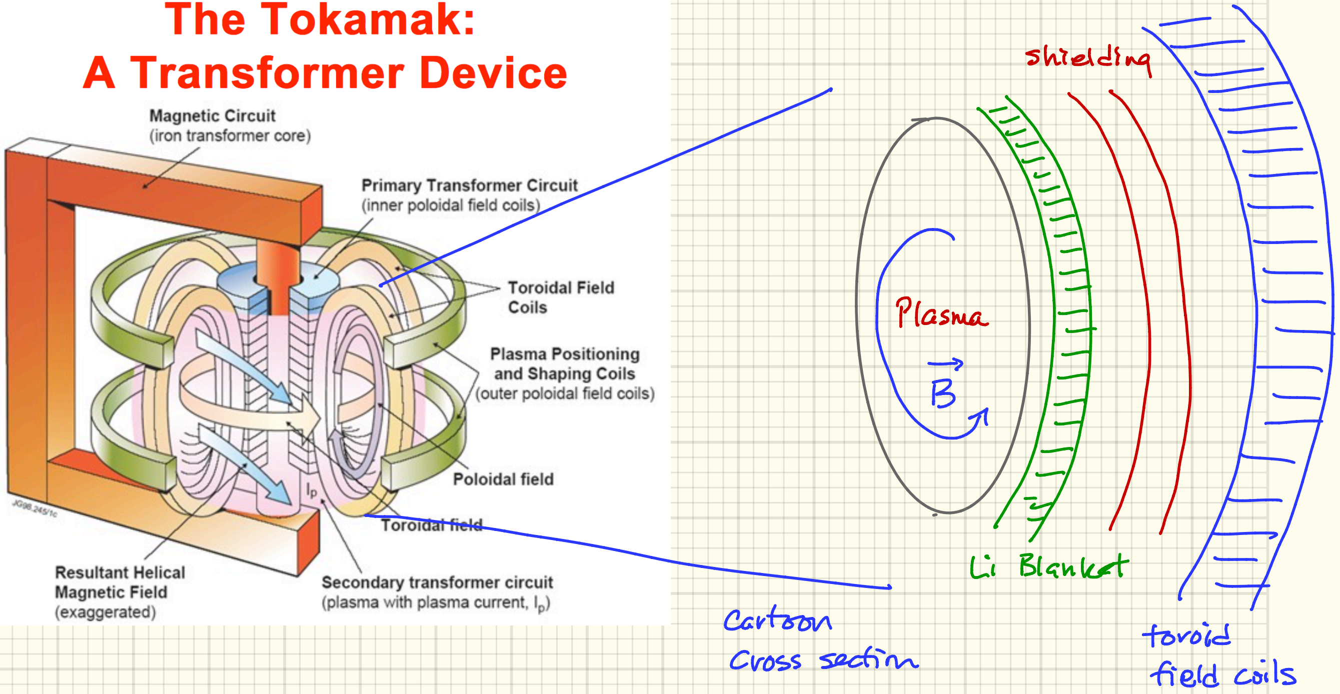
Li? easily acquired and would be built into special "Lithium Blanket"

Need

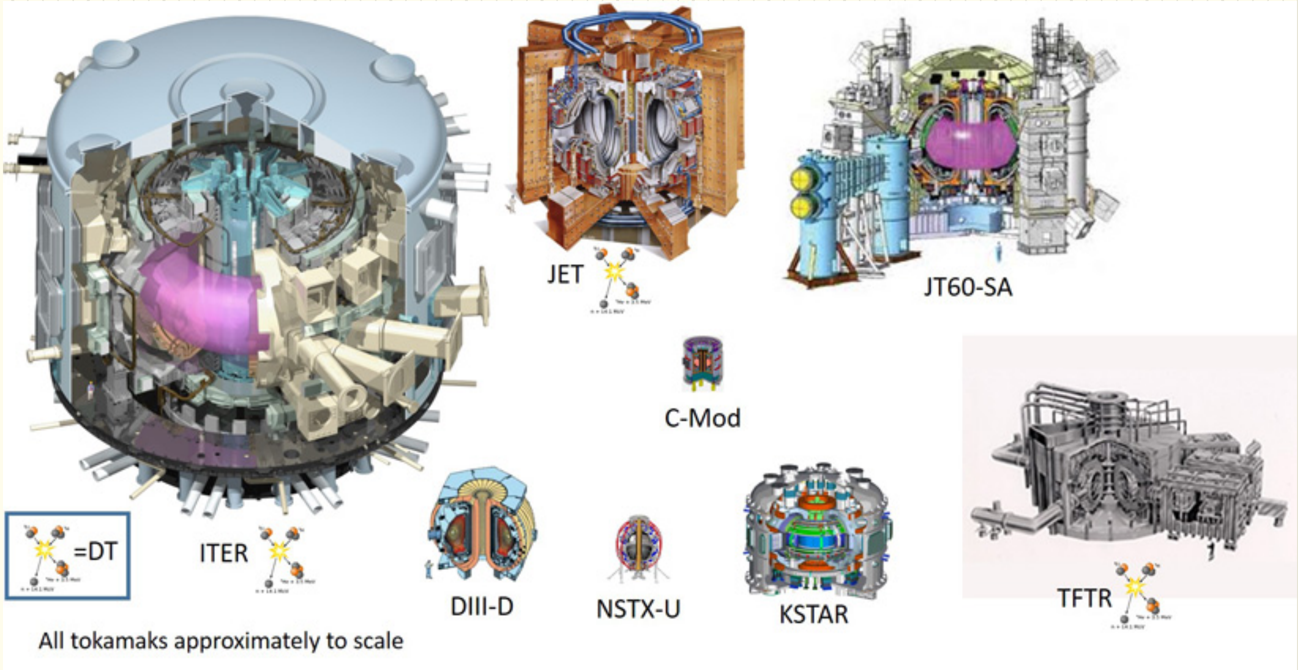
- Hot plasma of D and T
- High $\vec{B}$ to confine plasma
- Enormous material and engineering challenges

many bet on TOKAMAK (Russian for "toroidal magnetic chamber")

The Tokamak:
A Transformer Device



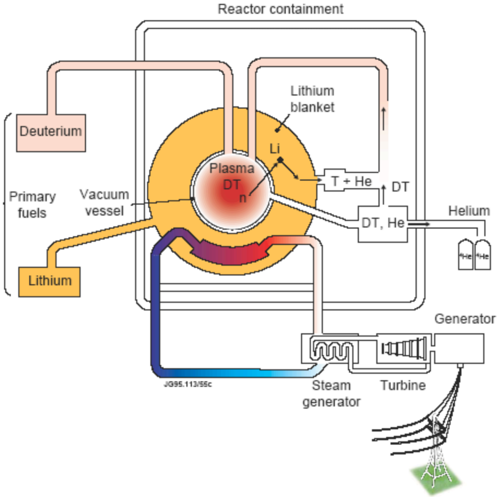
The world: ITER International Thermonuclear Experimental Reactor



All tokamaks approximately to scale

→ "first plasma" ~ 2028-2035 2 scenarios
"DT" operation ~ 2050

WORKING OF ITER



under construction

Cadarache, France China, EU, India, Japan,
Korea, Russia, US

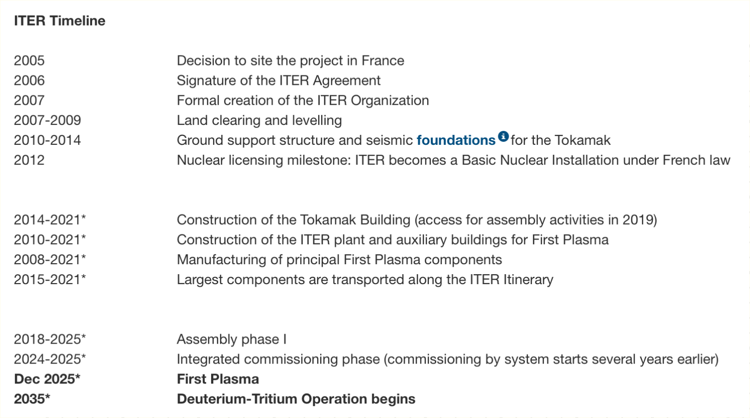
Enormous International
Project

goal: 500MW sustained
at Q = 10 (different "Q")
(current best Q = 0.67)

revised 2016...

EUR 6B construction
EUR 5B operations
(2008 values)

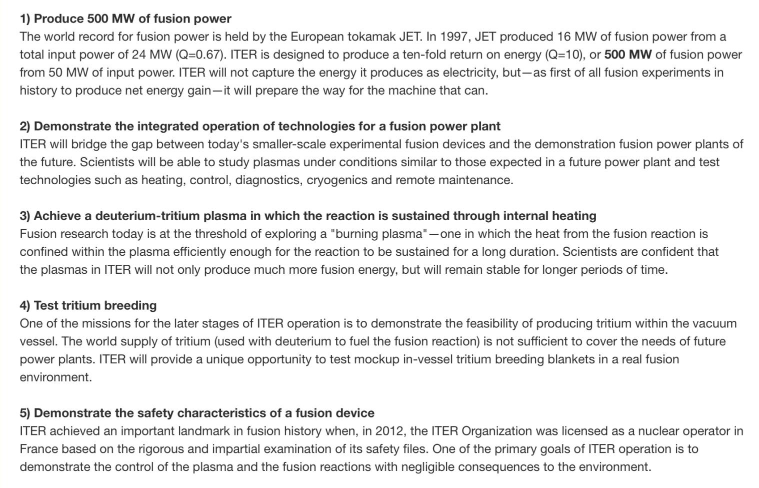
EU 5/11
others ~ 1/11th each.
US Moniz..
largest US year: $250M



ITER Timeline

2005	Decision to site the project in France
2006	Signature of the ITER Agreement
2007	Formal creation of the ITER Organization
2007-2009	Land clearing and levelling
2010-2014	Ground support structure and seismic **foundations** for the Tokamak
2012	Nuclear licensing milestone: ITER becomes a Basic Nuclear Installation under French law
2014-2021*	Construction of the Tokamak Building (access for assembly activities in 2019)
2010-2021*	Construction of the ITER plant and auxiliary buildings for First Plasma
2008-2021*	Manufacturing of principal First Plasma components
2015-2021*	Largest components are transported along the ITER Itinerary
2018-2025*	Assembly phase I
2024-2025*	Integrated commissioning phase (commissioning by system starts several years earlier)
Dec 2025*	**First Plasma**
2035*	**Deuterium-Tritium Operation begins**

from ITER site



1) Produce 500 MW of fusion power

The world record for fusion power is held by the European tokamak JET. In 1997, JET produced 16 MW of fusion power from a total input power of 24 MW (Q=0.67). ITER is designed to produce a ten-fold return on energy (Q=10), or **500 MW** of fusion power from 50 MW of input power. ITER will not capture the energy it produces as electricity, but—as first of all fusion experiments in history to produce net energy gain—it will prepare the way for the machine that can.

2) Demonstrate the integrated operation of technologies for a fusion power plant

ITER will bridge the gap between today's smaller-scale experimental fusion devices and the demonstration fusion power plants of the future. Scientists will be able to study plasmas under conditions similar to those expected in a future power plant and test technologies such as heating, control, diagnostics, cryogenics and remote maintenance.

3) Achieve a deuterium-tritium plasma in which the reaction is sustained through internal heating

Fusion research today is at the threshold of exploring a "burning plasma"—one in which the heat from the fusion reaction is confined within the plasma efficiently enough for the reaction to be sustained for a long duration. Scientists are confident that the plasmas in ITER will not only produce much more fusion energy, but will remain stable for longer periods of time.

4) Test tritium breeding

One of the missions for the later stages of ITER operation is to demonstrate the feasibility of producing tritium within the vacuum vessel. The world supply of tritium (used with deuterium to fuel the fusion reaction) is not sufficient to cover the needs of future power plants. ITER will provide a unique opportunity to test mockup in-vessel tritium breeding blankets in a real fusion environment.

5) Demonstrate the safety characteristics of a fusion device

ITER achieved an important landmark in fusion history when, in 2012, the ITER Organization was licensed as a nuclear operator in France based on the rigorous and impartial examination of its safety files. One of the primary goals of ITER operation is to demonstrate the control of the plasma and the fusion reactions with negligible consequences to the environment.

on Earth?

Controlled nuclear fusion? – none

uncontrolled fusion – hundreds of times

for a weapon $D + T \rightarrow n + {}^4He$ ... hard to assemble T & D in a bomb

rather.. think of ${}^6Li$ as an $\alpha + D$ and make T:

LiD is a solid @ STP

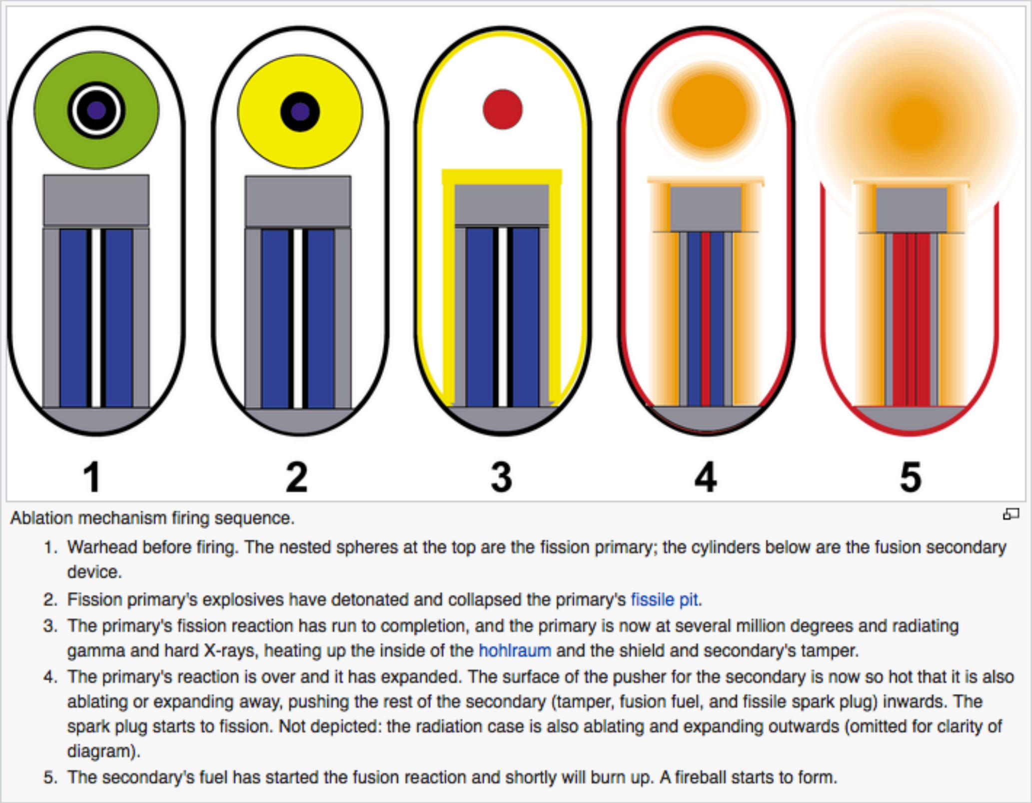
So 2 paths:

Li path $n + {}^6Li \rightarrow {}^4He + {}^3H$ + energy

D path ${}^2H + {}^3H \rightarrow 4He + n$ + energy

$\longrightarrow$ overall ${}^6Li + {}^2H \rightarrow 4He + {}^4He$

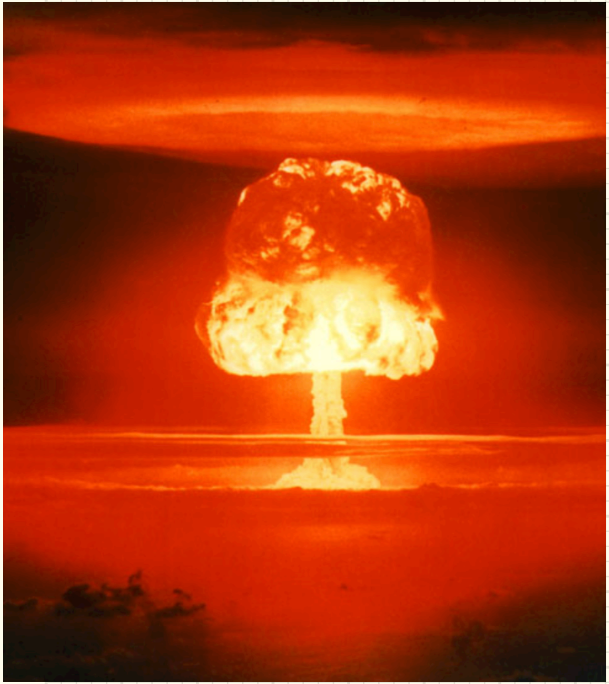
Ignition? Fission bomb



Ablation mechanism firing sequence.

1. Warhead before firing. The nested spheres at the top are the fission primary; the cylinders below are the fusion secondary device.
2. Fission primary's explosives have detonated and collapsed the primary's fissile pit.
3. The primary's fission reaction has run to completion, and the primary is now at several million degrees and radiating gamma and hard X-rays, heating up the inside of the hohlraum and the shield and secondary's tamper.
4. The primary's reaction is over and it has expanded. The surface of the pusher for the secondary is now so hot that it is also ablating or expanding away, pushing the rest of the secondary (tamper, fusion fuel, and fissile spark plug) inwards. The spark plug starts to fission. Not depicted: the radiation case is also ablating and expanding outwards (omitted for clarity of diagram).
5. The secondary's fuel has started the fusion reaction and shortly will burn up. A fireball starts to form.

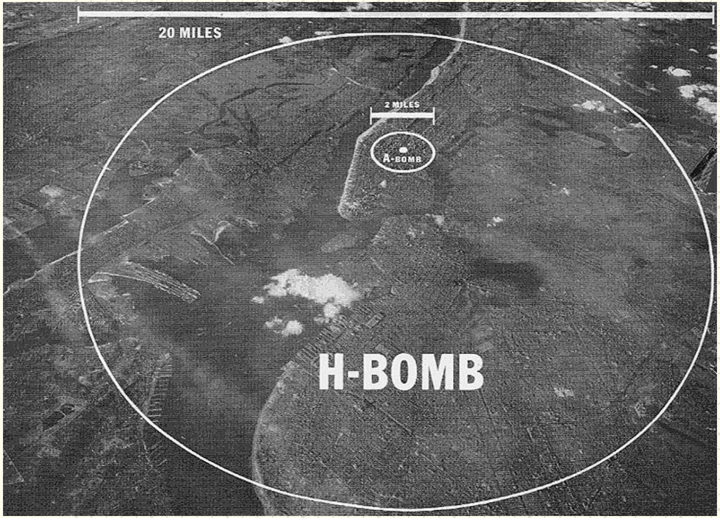
From the merely absurd to the obscene.



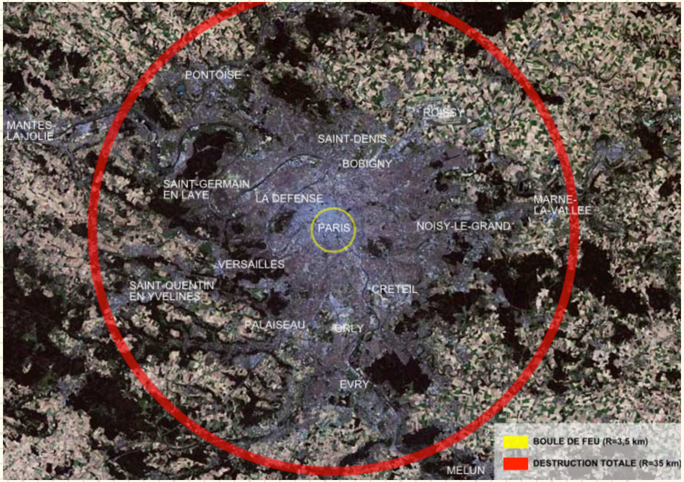
Castle Romeo mushroom cloud, Bikini Atoll, March 27, 1954: 11Mt

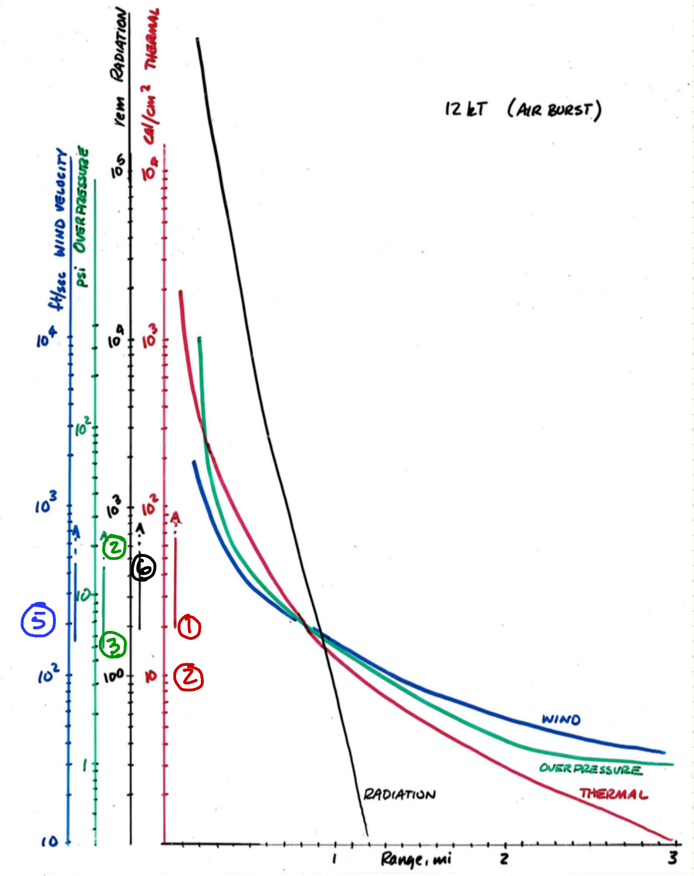
The Tsar Bomba mushroom cloud seen from a 100 mi. The crown of the cloud is 35 mi high at the time of the picture. October 30, 1961: 50 Mt

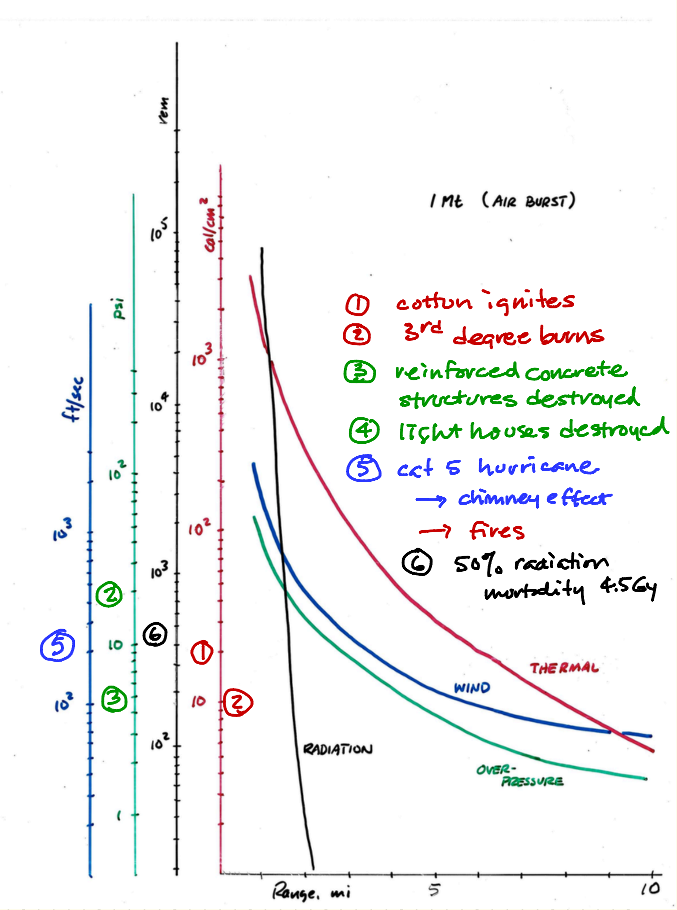
1 Mt total descruction superimposed on NYC

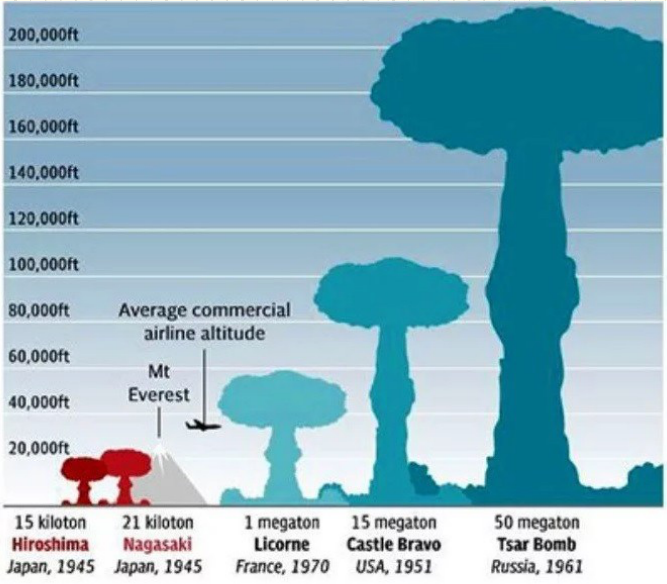


Tsar Bomba's range of total destruction superimposed on Paris.




12 kT (AIR BURST)
ft/sec WIND VELOCITY
psi OVERPRESSURE
rem RADIATION
cal/cm² THERMAL
10⁴
10³
10²
10
10²
10
1
10⁵
10⁴
10³
100
10⁴
10³
10²
10
A
⑤
②
③
⑥
①
②
WIND
OVERPRESSURE
THERMAL
RADIATION
1
Range, mi
2
3


1 Mt (AIR BURST)
ft/sec
psi
rem
cal/cm²
10³
10²
10²
10
1
10⁵
10⁴
10³
10²
10³
10²
10
⑤
②
③
⑥
①
②
① cotton ignites
② 3rd degree burns
③ reinforced concrete structures destroyed
④ light houses destroyed
⑤ cat 5 hurricane
→ chimney effect
→ fires
⑥ 50% radiation mortality 4.5Gy
THERMAL
WIND
RADIATION
OVER-PRESSURE
Range, mi
5
10


200,000ft
180,000ft
160,000ft
140,000ft
120,000ft
100,000ft
80,000ft
60,000ft
40,000ft
20,000ft
Average commercial airline altitude
Mt Everest
15 kiloton
Hiroshima
Japan, 1945
21 kiloton
Nagasaki
Japan, 1945
1 megaton
Licorne
France, 1970
15 megaton
Castle Bravo
USA, 1951
50 megaton
Tsar Bomb
Russia, 1961