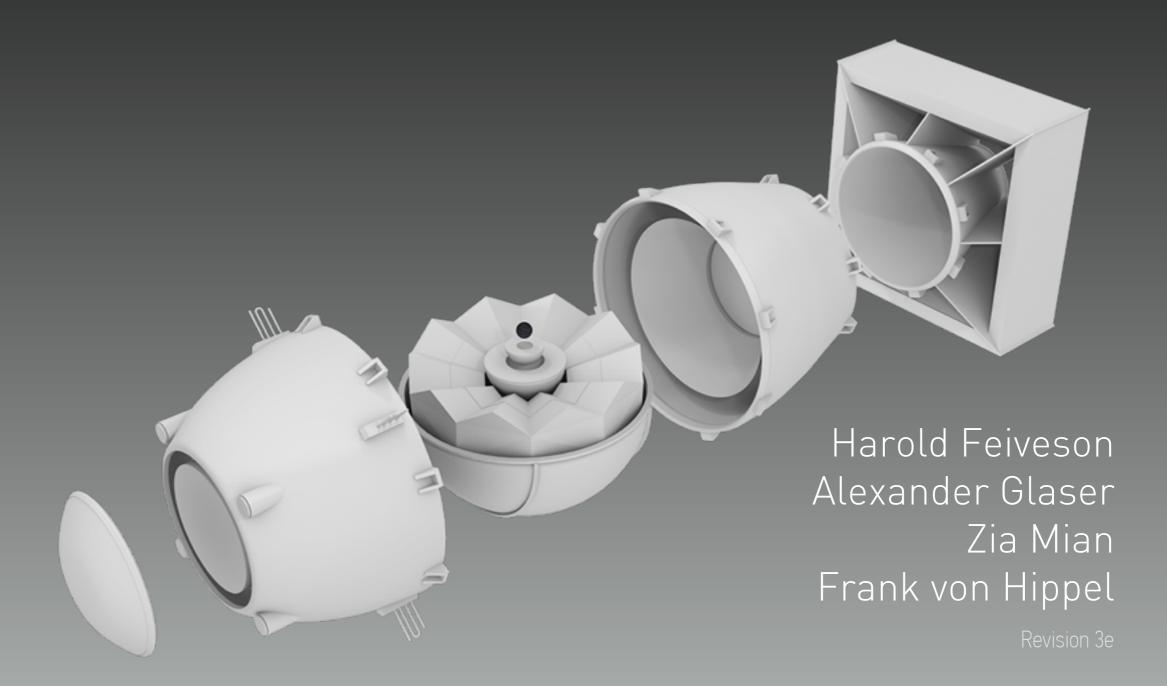
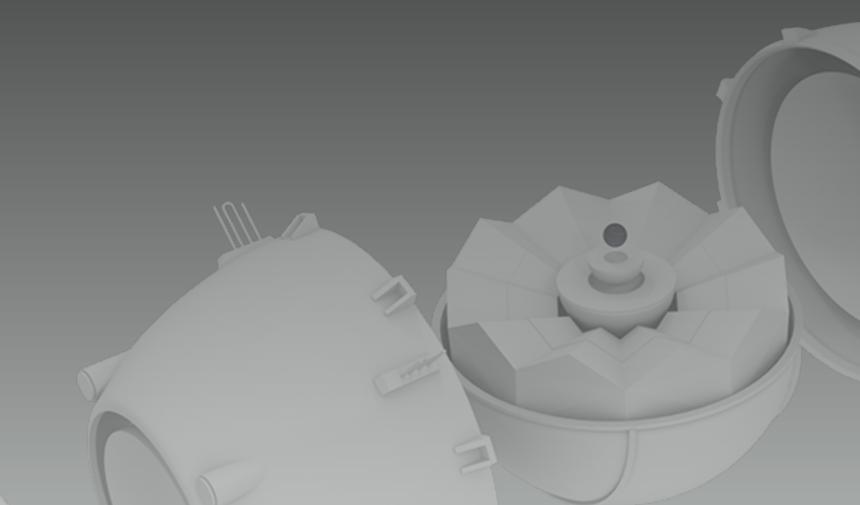
# UNMAKING THE BOMB

A FISSILE MATERIAL APPROACH TO NUCLEAR DISARMAMENT AND NONPROLIFERATION



# PART 1 HOW THE NUCLEAR WORLD EMERGED



# EVERYTHING BEGINS WITH URANIUM



Open pit uranium mine, Namibia *Source: www.wikipedia.org, Ikiwaner* 



Uranium ore (carnotite)
Source: www.mikalac.com

### MAKING FISSILE MATERIALS

### A TALE OF TWO URANIUM ISOTOPES



#### **HIGHLY ENRICHED URANIUM** (TYPICALLY: 90% U-235)

Made by isotope separation using, for example, gas centrifuges

Used in a simple gun-type assembly in Hiroshima bomb (50–60 kg)

A special concern for nuclear terrorism ("improvised nuclear device")



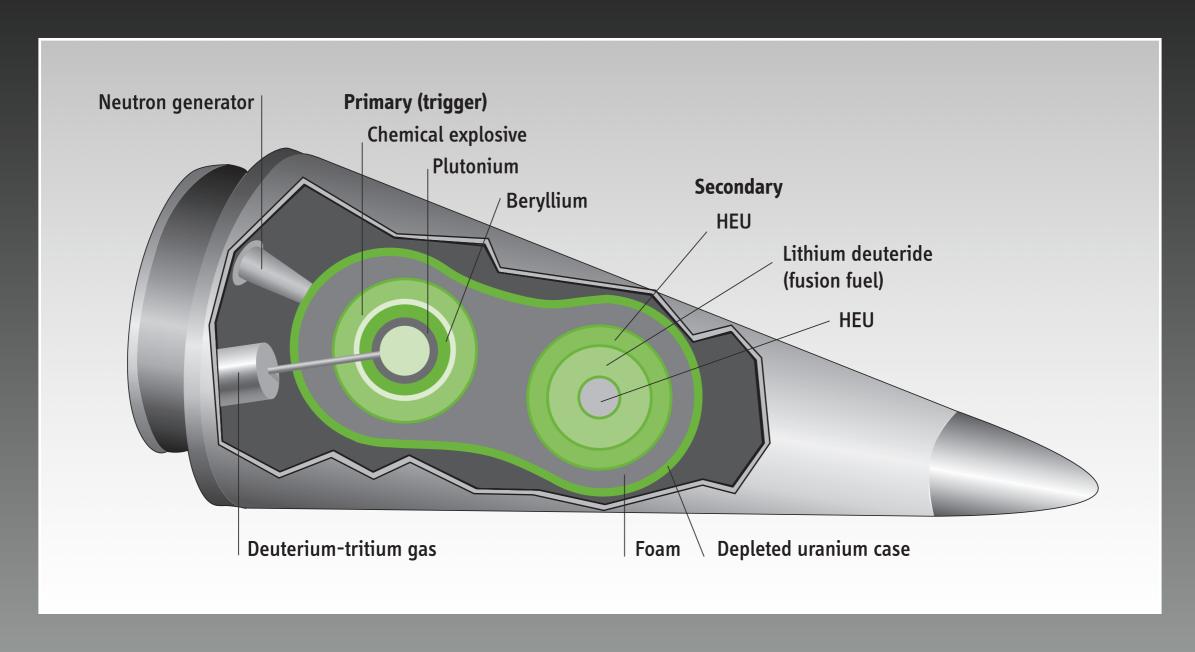
#### PLUTONIUM (ALMOST ANY COMPOSITION, MADE FROM U-238)

Made from U-238 in a nuclear reactor and separated from spent fuel Used in implosion assembly in Nagasaki bomb (6 kg)
Small critical mass, preferred in modern fission primaries

Sources: <u>www.usec.com</u>, www.centrusenergy.com (top) and <u>commons.wikimedia.org</u>, user: Nanking2012 (bottom)

### MODERN THERMONUCLEAR WARHEAD

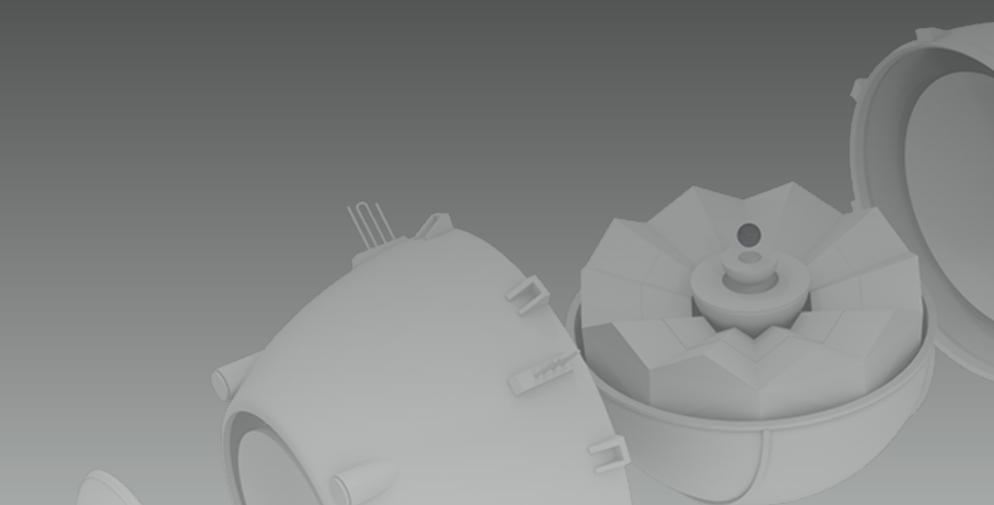
Typically contains an average 3-4 kg of plutonium and 15-25 kg highly enriched uranium



Adapted from Final Report of the Select Committee on U.S. National Security and Military/Commercial Concerns with the Peoples Republic of China ("Cox Report"), U.S. House of Representatives, 3 January 1999

# FRANCE

AMBIGUITY BY DESIGN



## HIDING IN PLAIN SIGHT

### EARLY PLUTONIUM PRODUCTION FOR "PEACEFUL PURPOSES"



Le bubbour de chargement une 1.327 renneur, et deux meer de ditant et place gespelle delette, filoso de deviatione places, our distingue le support instrieur d'une raribusche d'arrangement.

#### DANS SIX MOSS

L'enzembre des untratations de Macrocule et encient lois d'étre autherné : des septement out été que les finces nucléaires données de couvent électrique. Pour l'antient, seul fonctionne les réacheur, le deşs fameux, de 1, qui, pour après pour, auspineurs au puissance. Mais ovite puissance na se maniforte entrore par renn. sixon les vibrations quasivinantes d'aisquilles sur les cadrans des appareils qui manuent los fixs de neutrons par

celle-ci, où tout se fait dans le allesse et l'in visibilité.

En 1958

La plugari des pourseux ont presente Macoule comme uine « ceittale abersigar » Certes, cele s'est par faux. Mais l'essentie s'est pas loi dans la production d'electrica Le titre déficiel dit ben de quoi il s'agil « Castra de Production de Platonium de Marçoules.

Le probleme économique de la production du plutonium a beaucoup évolué depuis quelques années. En 1950, on prevent encore

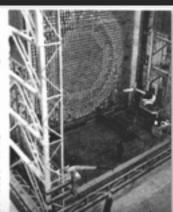
#### Marcoule produira 100 kg de plutonium

de l'atome se divinsit en deux diresanes ben définors:

 d'une part, le donnine militaire, tributaire de la profuntion de plutoritaire ou d'U 235 pur, pour le résiliantion des bombes;
 d'autre part, le donnine énergétique

son come plus deve pror pervenir a con currencer les sources classiques d'énirque con poéciasit qu'une commission de desse tement pouveit axer son programme su l'interdiction de séparer les isotopes de l'un classe d'élocier le alektronium, con mentante au

L'ernie du sort est vesue doublement de-



"Based on the premise of refraining from any military applications in the field of atomic energy, France therefore had to embark on a vast program of plutonium production."



anufflactor assurant la corculation de Taff retholiciament, exigues 5000 NM, alore qu'elle ne distine au réseau de IE.D.F. que 5000 NM. Frécisione tout de saise que cette estivation paradoxale, due la température peu elevise aténiane au sein de C1 (100 degrés) et se tree lable rendement thurmique qui en réteribane trouveau nonversée des que C2 et C3 antirecont enservise. Alora, visaiment, Marcoule aggerters son appoint d'énergie se réseau.

Poerquei de sole de Provence a+d ét chole?... Parce que le site des futures installa tione exigosit certaines conditions qui se se trouvées trutes remplies dans cette garrigu du Clard.

Pour evilue les danquez de contenination à fallair évilonguez de troute applicamésaria importante et se places dans un androit troute applicament dans un androit troute de la contenination de contenination pour evilon participa de la contenination del contenination de la contenination del contenination de la contenination de la contenination

129

Sciences et Avenir, March 1956

icise. Aucune echappatoire, sucune de diversion de la part des inter-

## FRANCE

#### HOW MUCH FISSILE MATERIAL IS ENOUGH?



#### FRANCE HAS FEWER THAN 300 NUCLEAR WEAPONS TODAY

The amount of fissile material in this weapons stockpile is on the order of 1–1.5 tons of plutonium and 3–5 tons of HEU



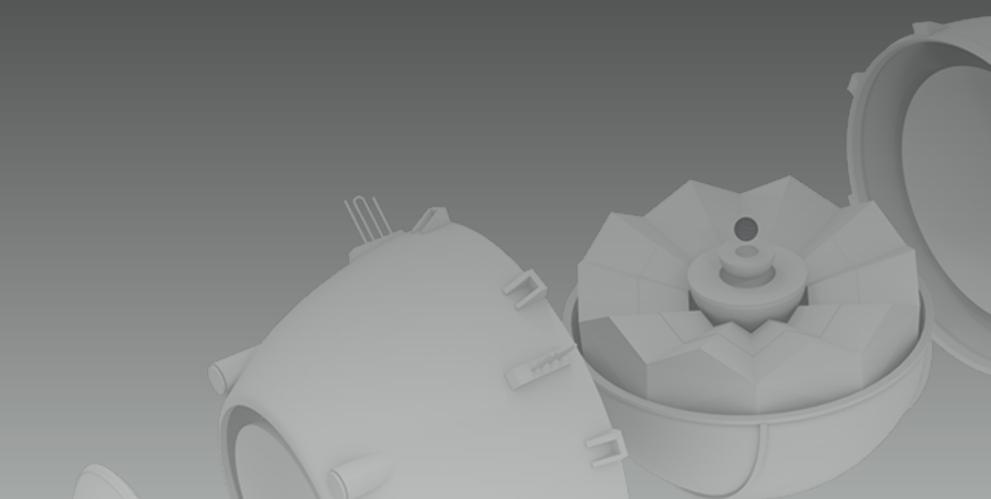
#### FRANCE HAS MATERIAL FOR 1000+ NUCLEAR WEAPONS

Based on our estimates, on the order of 70–80% of the military plutonium and HEU are outside the weapons stockpile (and without apparent military use)

Sources: www.defense.gouv.fr (top) and www.francetnp.fr (bottom)

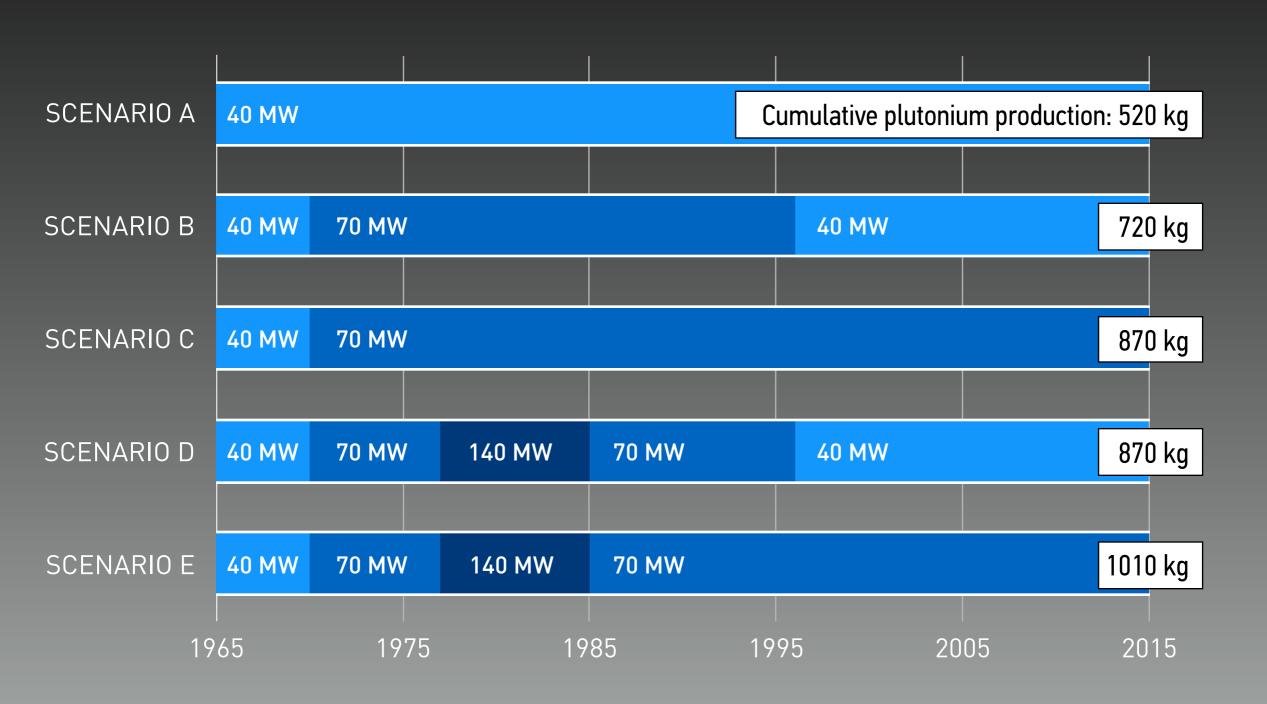
# ISRAEL

A TURNKEY FISSILE MATERIAL PRODUCTION COMPLEX



# DIMONA REACTOR, 1964-2014

#### POSSIBLE OPERATIONAL HISTORIES AND CUMULATIVE PLUTONIUM PRODUCTION



## MORE THAN EVER EXPECTED?

### 50 YEARS OF PLUTONIUM PRODUCTION AT DIMONA, 1964–2014



#### ISRAEL HAS AVAILABLE A LARGE PLUTONIUM STOCKPILE

Estimated inventory on the order of 850 kg  $\pm$  130 kg with a current production rate of 10–18 kg/year, depending on power level of Dimona (40–70 MW thermal)

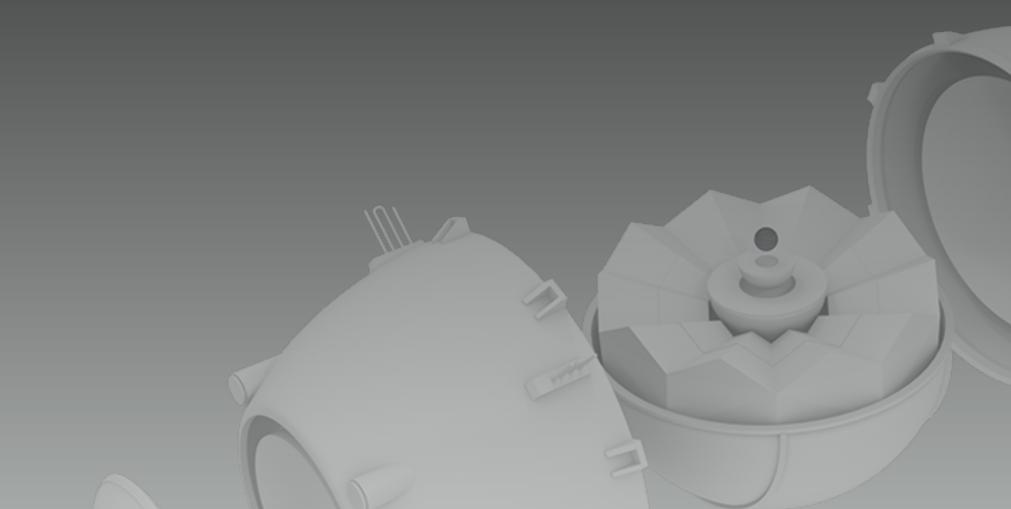


#### PLUTONIUM MOST LIKELY A "BYPRODUCT" TODAY

Israel's arsenal is believed to include 100–150 warheads; if our estimates are correct, Israel has plutonium for 2–3 times as many warheads (and could cease fissile material production)

Sources: authors' archives (top) and Channel 10 (bottom)

# SO, WHERE ARE WE NOW?



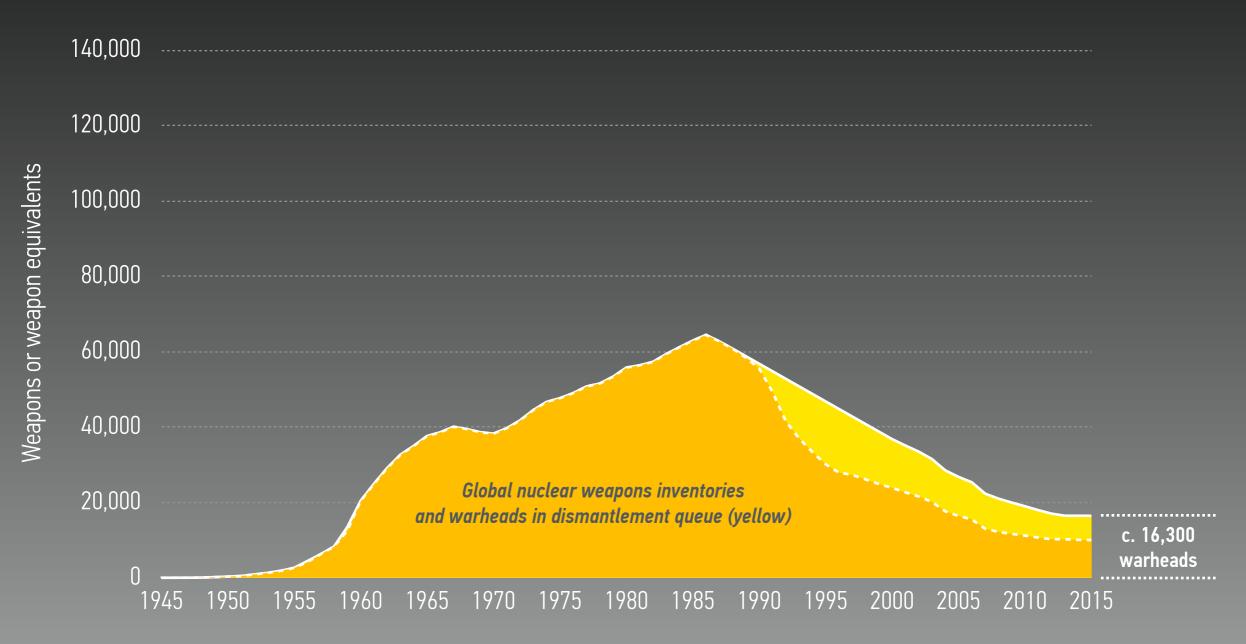
### WHO CAN MAKE FISSILE MATERIAL TODAY

### ENRICHMENT AND REPROCESSING FACILITIES WORLDWIDE



### NUCLEAR WEAPONS AND FISSILE MATERIALS

### GLOBAL INVENTORIES, 1945-2014

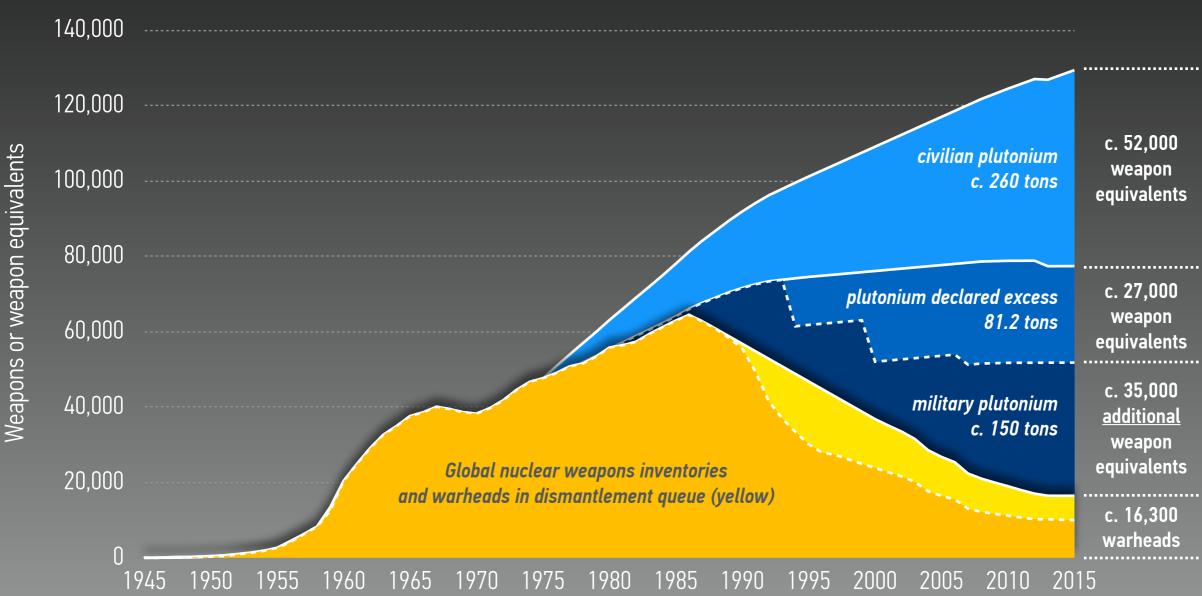


Hans M. Kristensen and Robert S. Norris, "Global Nuclear Weapons Inventories, 1945–2013," Bulletin of the Atomic Scientists, 69 (5), 2013, 75–81

### NUCLEAR WEAPONS AND FISSILE MATERIALS

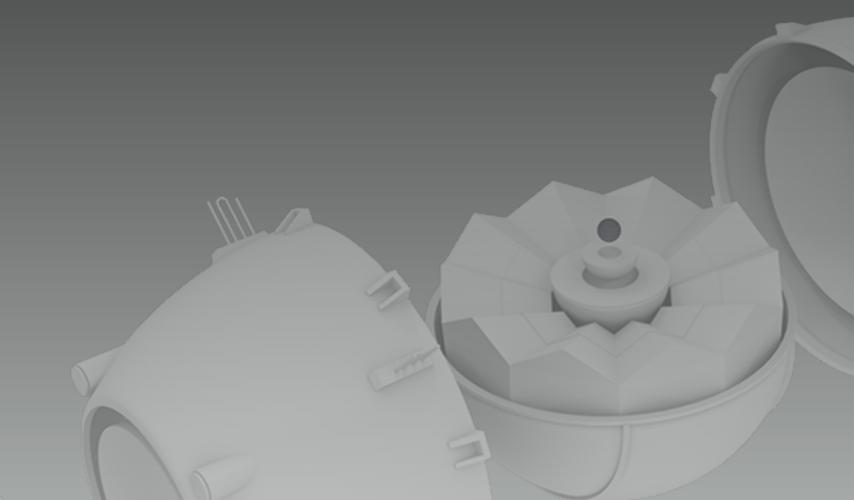
### GLOBAL INVENTORIES, 1945-2014





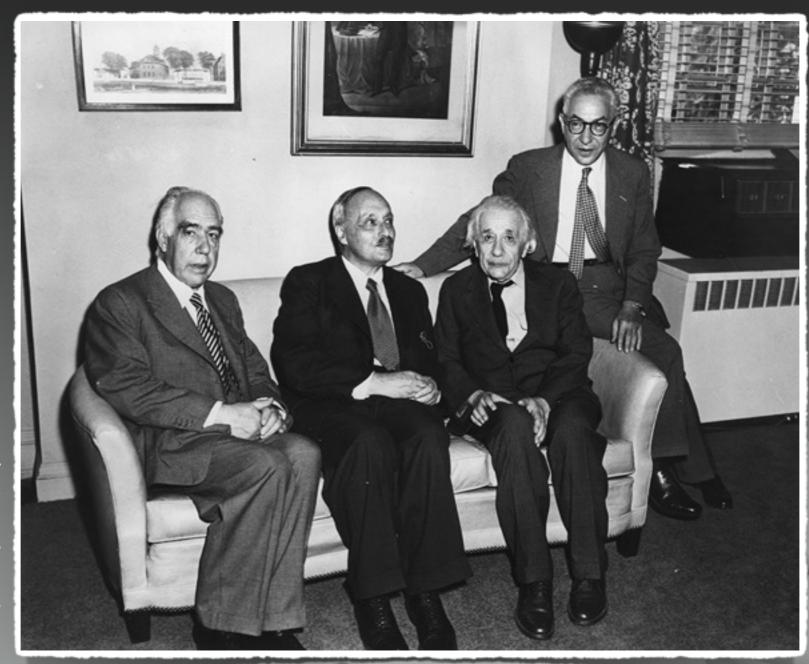
Hans M. Kristensen and Robert S. Norris, "Global Nuclear Weapons Inventories, 1945–2013," *Bulletin of the Atomic Scientists*, 69 (5), 2013, 75–81 Fissile material estimates and weapon-equivalents are authors' estimates; assuming an average of 3 kg for weapon-grade and 5 kg for reactor-grade plutonium per weapon

# PART 2 WHAT IS TO BE DONE



# "A PERPETUAL MENACE TO HUMANKIND"

### FOR 70 YEARS SCIENTISTS HAVE WARNED OF THE FISSILE MATERIAL DANGER



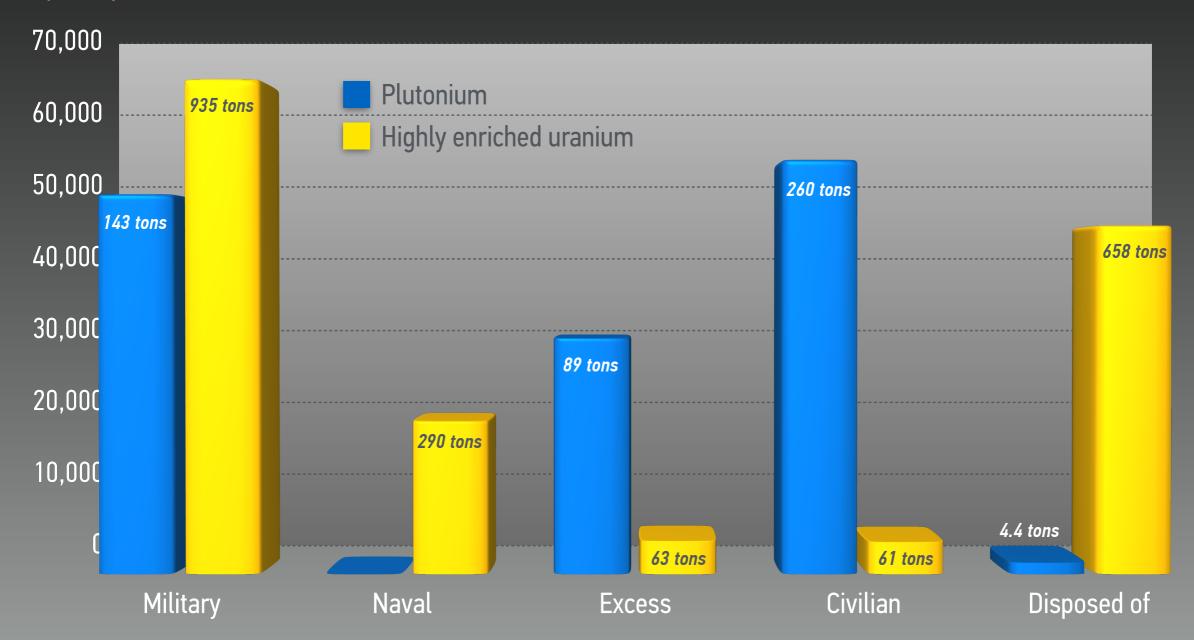
Niels Bohr James Franck Albert Einstein Isidor Rabi

Princeton, NJ October 1954

### FISSILE MATERIALS BY CATEGORY

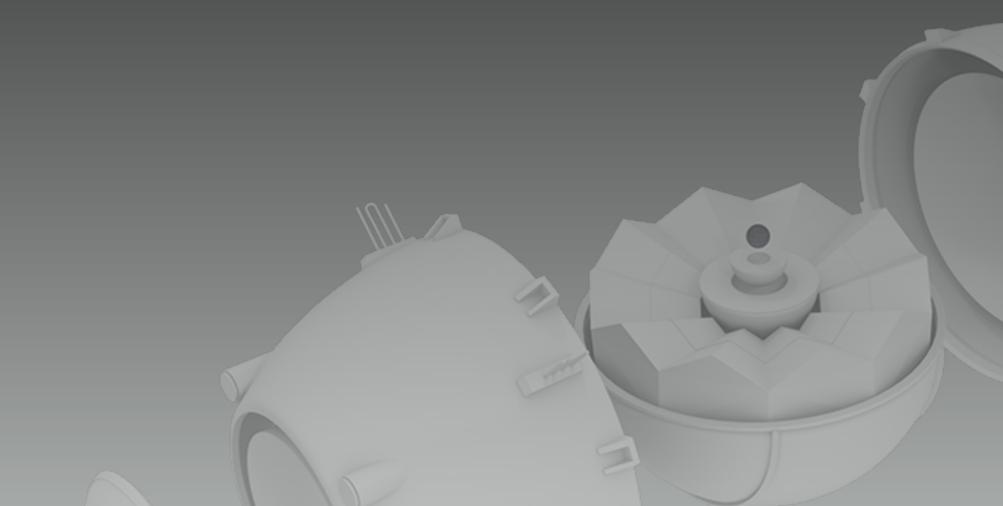
### GLOBAL STOCKPILE OF PLUTONIUM AND HIGHLY ENRICHED URANIUM, 2014

#### Weapon equivalents



Assumptions for weapon equivalents: 3 kg of weapon-grade plutonium, 5 kg of reactor-grade plutonium, 15 kg of highly enriched uranium

# ENDING PRODUCTION AND USE



# FISSILE MATERIAL PRODUCTION FOR WEAPONS HAS LARGELY ENDED

(NPT WEAPON STATES STOPPED DECADES AGO)



Shutdown of the last Russian plutonium production reactor ADE-2 in Zheleznogorsk, 2010 Source: U.S. Department of Energy



Demolition of the K-25 uranium enrichment plant began in December 2008 and has been completed in 2012

Source: Bechtel Jacobs

# ENDING PRODUCTION

### FOR MILITARY AND CIVILIAN PURPOSES



#### **CONTINUING PRODUCTION OF HEU**

For military use: Pakistan, India, and possibly North Korea

For civilian use: Russia, reportedly restarted in 2012 (for export)



#### CONTINUING PRODUCTION (AND SEPARATION) OF PLUTONIUM

For military use: Israel, India, Pakistan, and North Korea

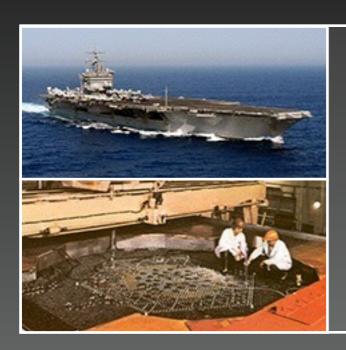
For civilian use: France, Russia, India, (China, Japan)

United Kingdom will end reprocessing around 2020

Sources: U.S. DOE (top) and Getty Images (bottom)

# ENDING USE

### FOR MILITARY AND CIVILIAN PURPOSES



#### **HEU REACTOR FUEL**

US, UK, Russia, India; US has over half of all HEU naval reactors; Russia has over half of all HEU research reactors; over 125 HEU research reactors already retired (twice the number converted to LEU)

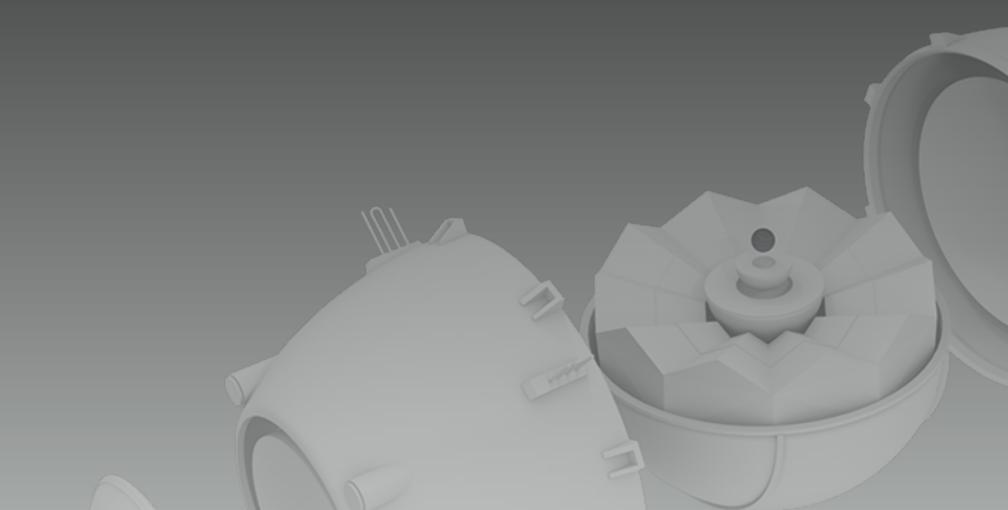


#### **PLUTONIUM FUEL**

France, Germany, the Netherlands, India, (and Japan) use MOX fuel for power reactors; Russia and China plan to do so; most countries store their nuclear spent fuel pending final disposal

Sources: U.S. Navy (top) and UK Decommissioning Authority (bottom)

# ELIMINATING STOCKPILES



# VULNERABILITY OF STORAGE

### A MATTER OF TIME



#### **STORING UP TROUBLE**

About 100 tons of HEU at U.S. HEUMF, Y-12, Oak Ridge, Tennessee About 245 tons of civilian plutonium stored at four sites in Europe and Russia (Sellafield, La Hague, Marcoule, Mayak)



#### **JULY 2012 Y-12 BREAK-IN**

U.S. DOE finding: "ineptitude in responding to alarms, failures to maintain critical security equipment, over reliance on compensatory measures, misunderstanding of security protocols, poor communications"

Sources: U.S. DOE (top) and oakridgetoday.com (bottom)

# DISPOSAL STRATEGIES

### IRREVERSIBILITY, SECURITY, COST, INTERNATIONAL VERIFIABILITY



#### DRY CASK STORAGE OF SPENT FUEL

Most countries with nuclear power store their spent fuel pending final disposal in geological repository;

HEU reactor spent fuel also can be stored for such disposal

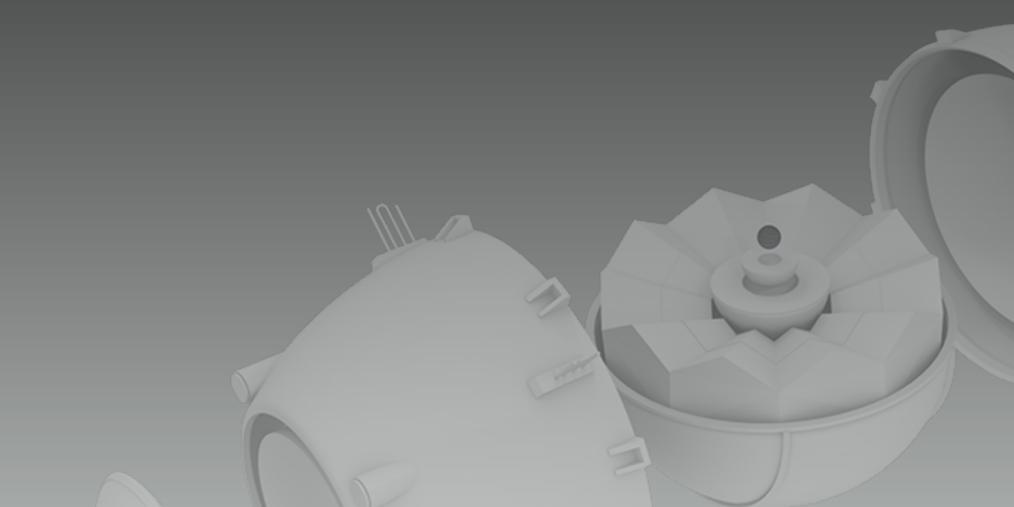


#### DEEP BOREHOLE DISPOSAL OF PLUTONIUM

Excess plutonium could be irreversibly emplaced in several kilometerdeep boreholes; holes are then backfilled and sealed; several tons of plutonium could be disposed in a single borehole

Sources: gns.de (top) and <u>panoramio.com</u>, user: loisiko (bottom)

# TRANSPARENCY AND VERIFICATION



# TRANSPARENCY SCORECARD, 2014

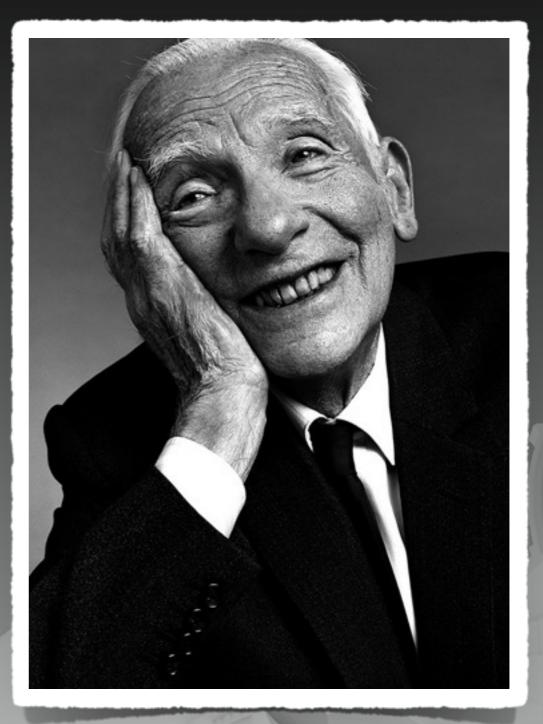
#### INFORMATION ON NUCLEAR WARHEAD AND FISSILE MATERIAL INVENTORIES AND STATUS

	United States	Russia	Britain	France	China
Number of total warheads	Approximate	No	Yes (upper limit)	Yes (upper limit)	Relative (out of date)
Number of deployed warheads	Yes (strategic only)	Yes (strategic only)	Yes (planned)	Yes	No
Dismantlements	Yes	No	Yes (no details)	Yes (no details)	No
Verification	Partial	Partial	No	No	No
Fissile material stockpiles	Yes	No	Yes (no details)	No	No
Production histories	Yes	No	No	No	No
Excess/Disposal	Yes (nothing new)	Yes (nothing new)	Yes (nothing new)	No	No
Verification	Partial	Partial (but no longer)	Partial (some plutonium)	No	No

### DISARMAMENT, TRANSPARENCY, VERIFICATION



Leo Szilard, 1898–1964 Credit: AIP Archives



Joseph Rotblat, 1908–2005 Credit: Petter Hönnemann