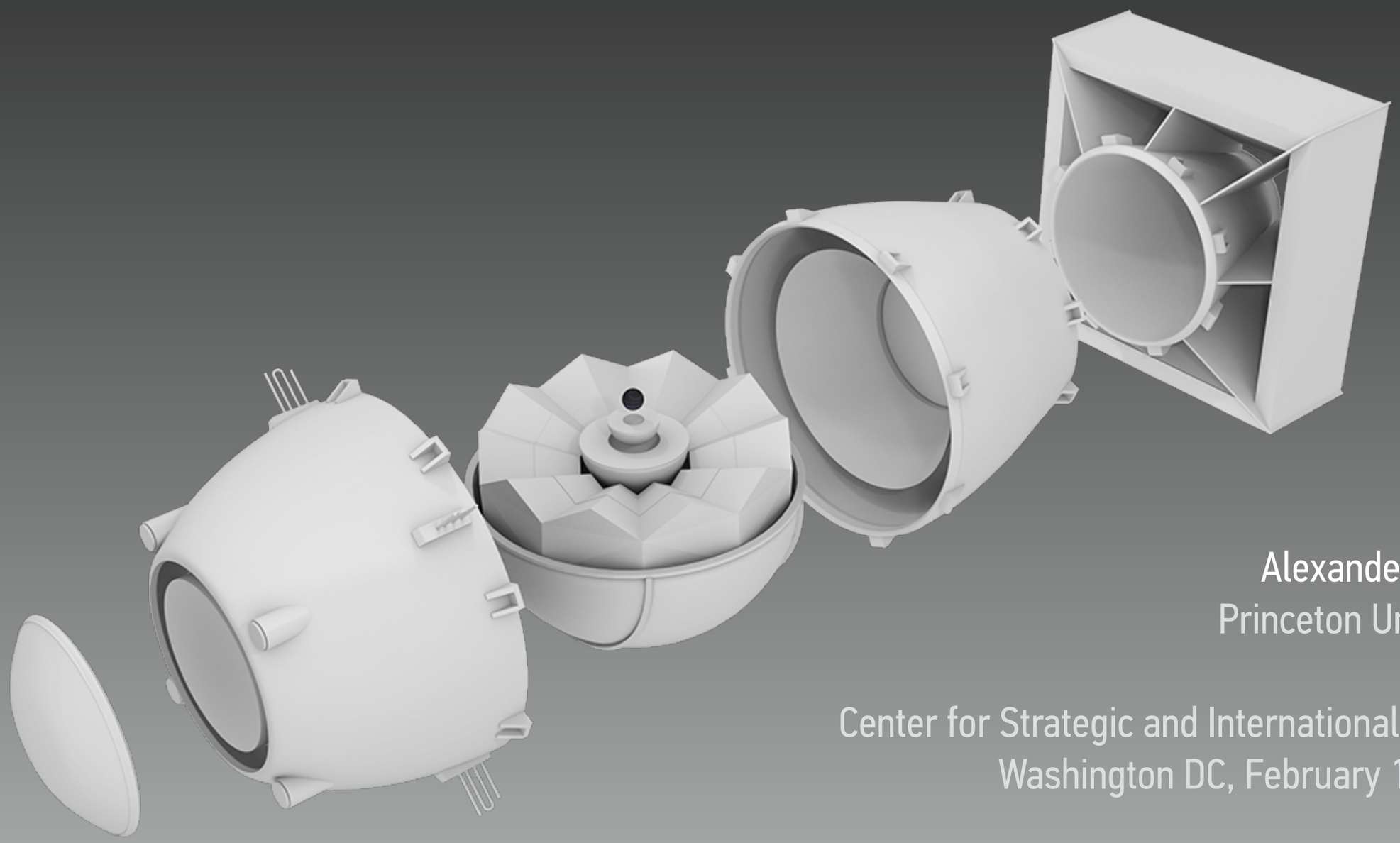
# ESTIMATING FISSILE MATERIAL PRODUCTION

## TRANSPARENCY WORKSHOP: NUCLEAR WEAPONS AND FISSILE MATERIAL



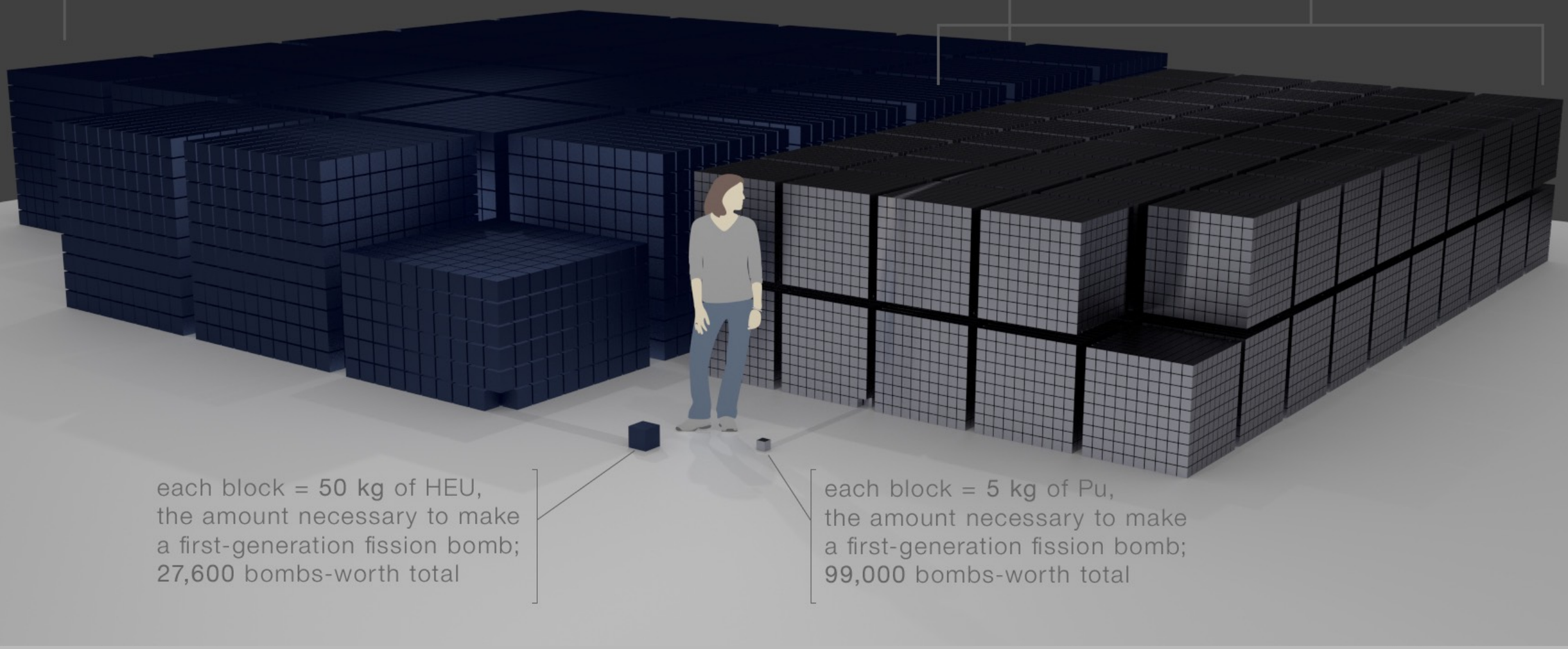
Alexander Glaser
Princeton University

Center for Strategic and International Studies
Washington DC, February 13, 2017

# World Stockpiles of Fissile Materials

1370 ~~1380~~ tons of highly-enriched uranium

505 ~~495~~ tons of separated plutonium



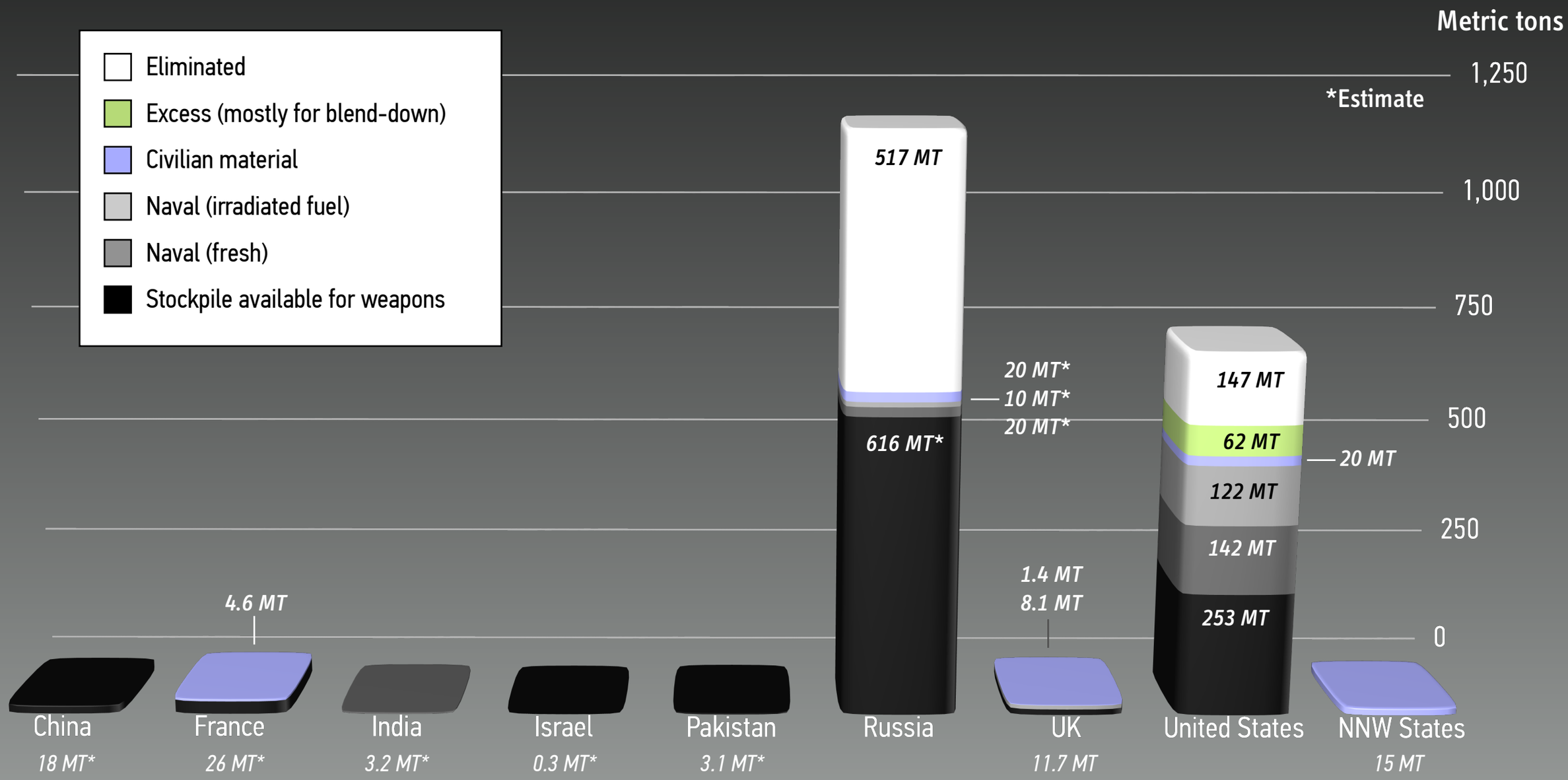
each block = **50 kg** of HEU,
the amount necessary to make
a first-generation fission bomb;
**27,600** bombs-worth total

each block = **5 kg** of Pu,
the amount necessary to make
a first-generation fission bomb;
**99,000** bombs-worth total

*Graphic by Alex Wellerstein, nuclearsecrecy.com*

# HIGHLY ENRICHED URANIUM, 2015

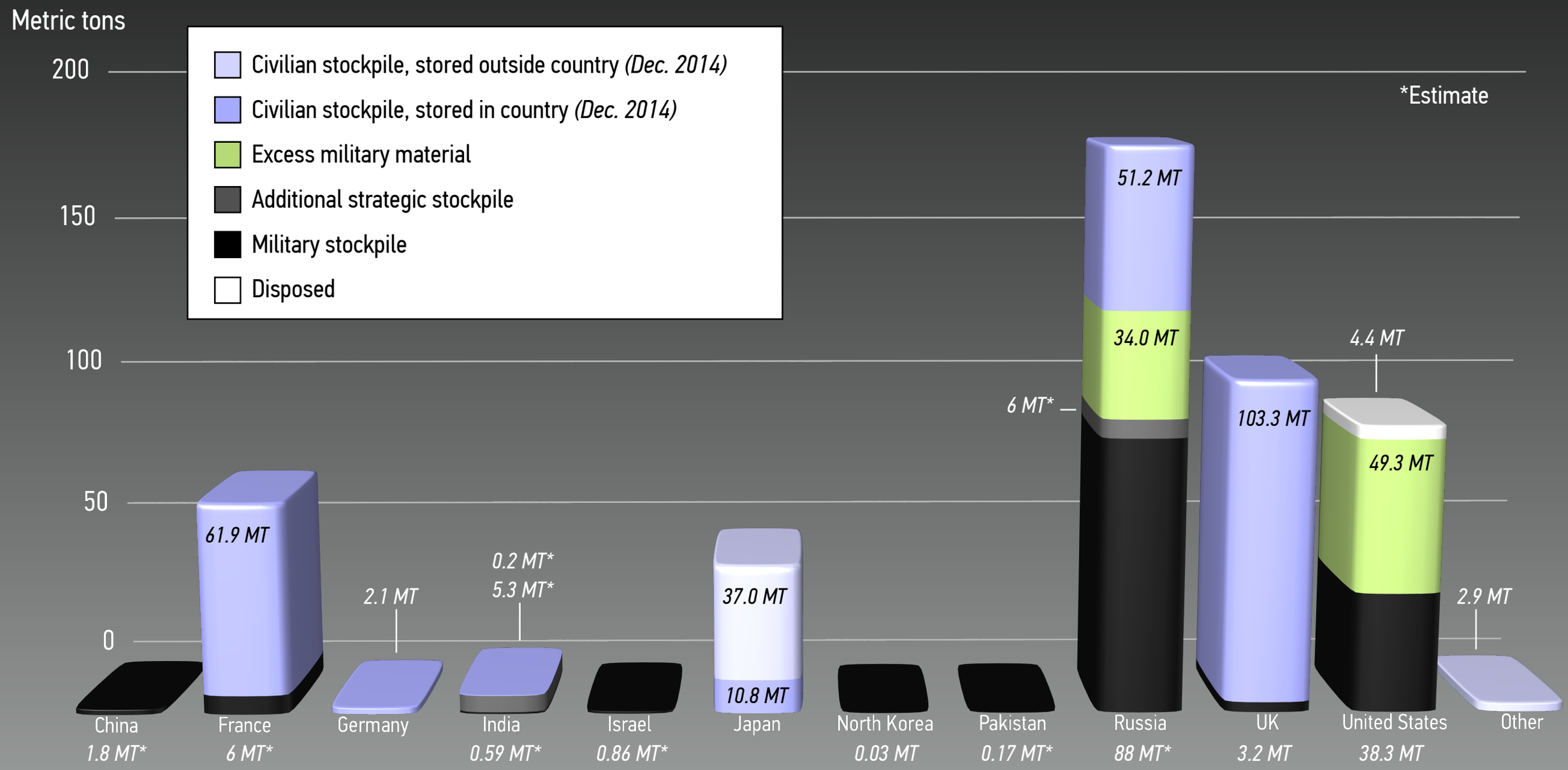
## GLOBAL STOCKPILE IS ABOUT 1357 TONS, ALMOST 99% IS IN WEAPON STATES




*Global Fissile Material Report 2015,* International Panel of Fissile Materials, Princeton, December 2015, www.ipfmlibrary.org/gfmr15.pdf

# SEPARATED PLUTONIUM, 2015

## GLOBAL STOCKPILE IS ABOUT 503 TONS, MORE THAN HALF IS CIVILIAN AND THIS STOCK IS GROWING



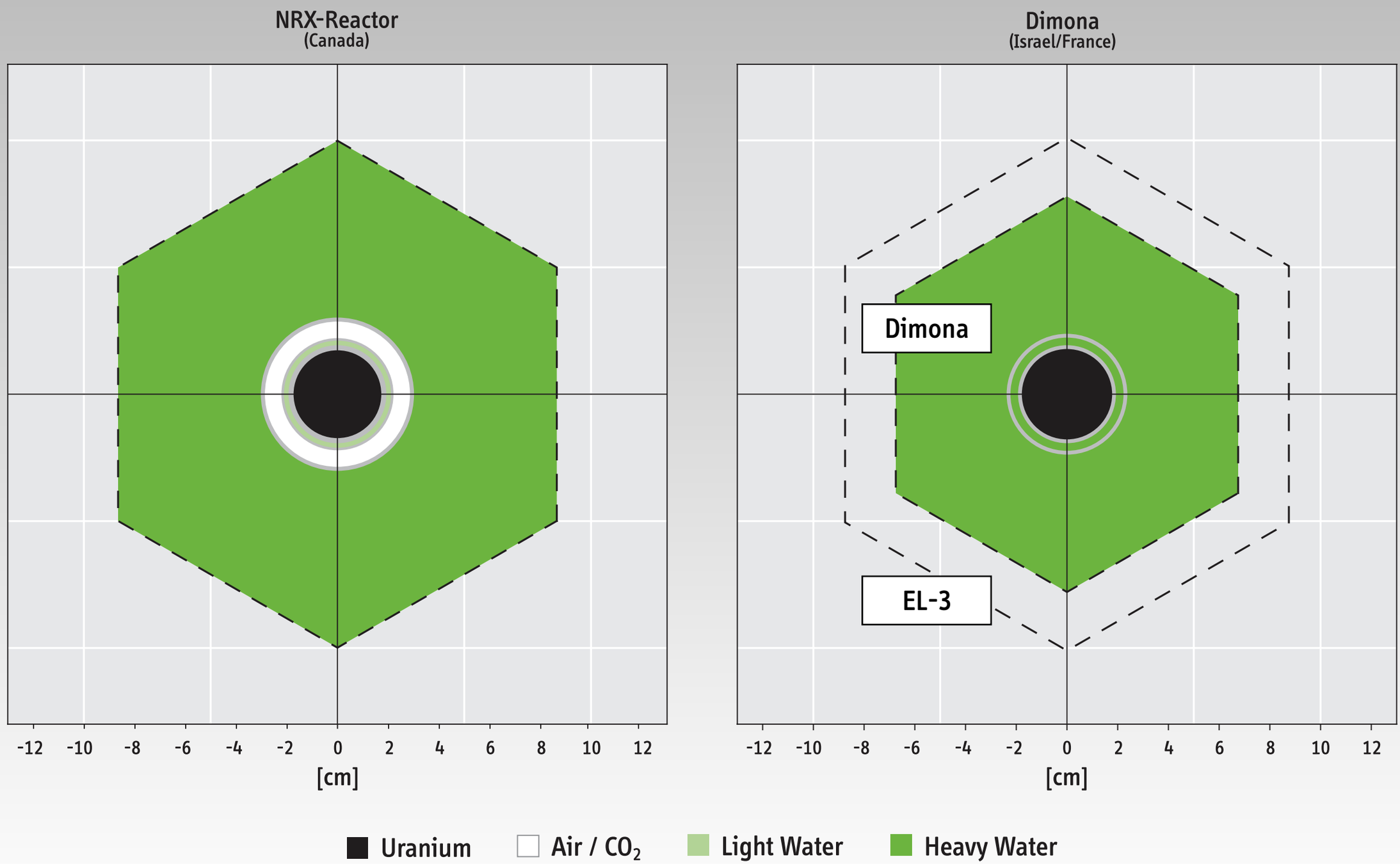

*Global Fissile Material Report 2015,* International Panel of Fissile Materials, Princeton, December 2015, www.ipfmlibrary.org/gfmr15.pdf

# MAKING FISSILE MATERIAL ESTIMATES

## THE CASE OF PLUTONIUM

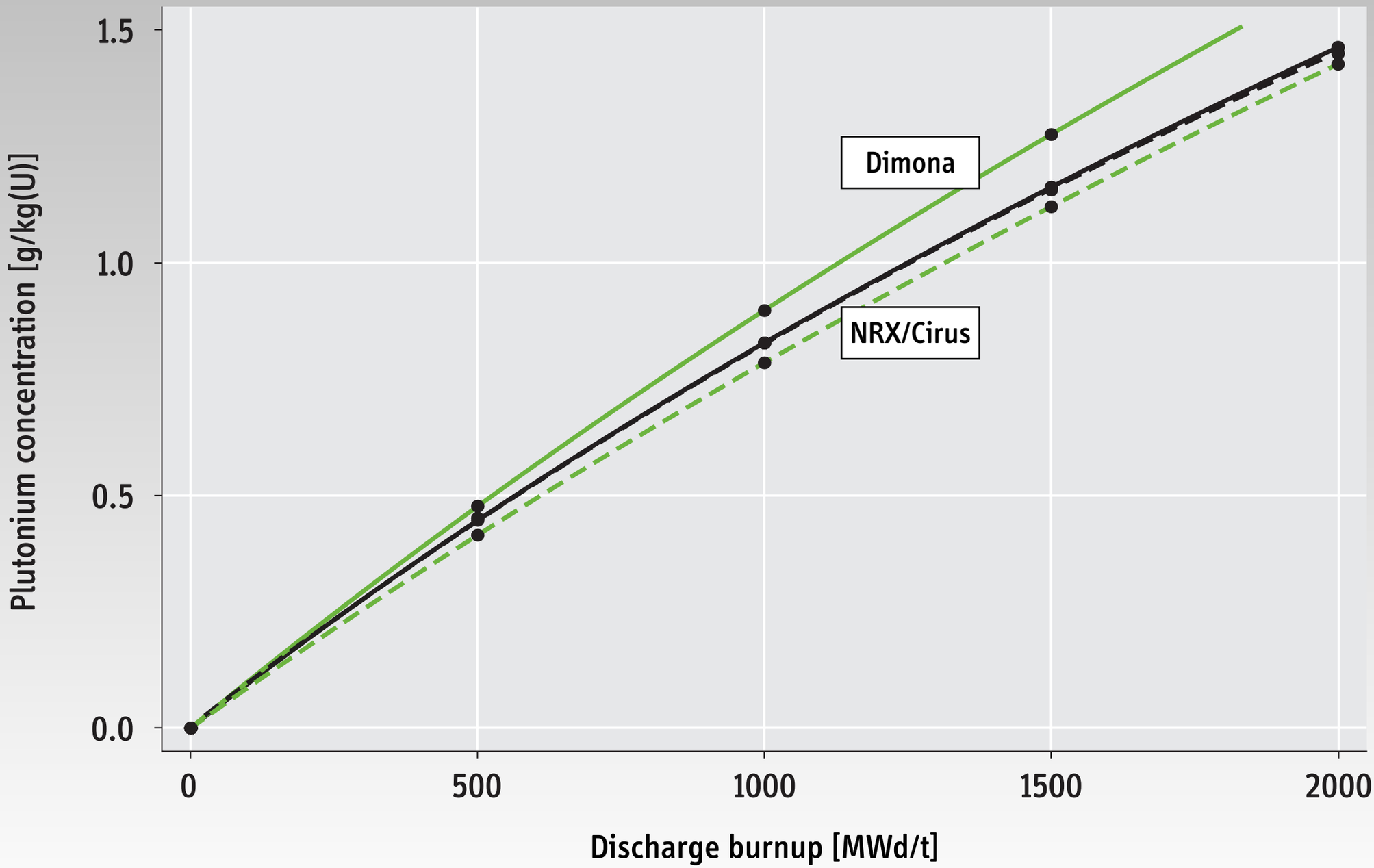

Global Fissile Material
Report 2009
A Path to Nuclear Disarmament
Fourth annual report of the International Pane
IPFM
INTERNATIONAL PANEL
ON FISSILE MATERIALS
Global Fissile Material
Report 2010
Balancing the Books: Production and Stocks
Fifth annual report of the International Panel on Fissile Materials

# UNIT CELLS OF HEAVY WATER REACTORS



# PLUTONIUM CONCENTRATION IN URANIUM

## FOR VARIOUS NATURAL-URANIUM FUELED REACTOR TYPES



# ISRAEL

## A TURNKEY FISSILE MATERIAL PRODUCTION COMPLEX


Image © 2011 DigitalGlobe
©2010 Google

# Dimona, Israel

Coordinates: 31.00 N, 35.14 E

1. Dimona reactor
2. Plutonium separation plant (Machon 2)
   According to Vanunu, Machon 2 has two floors above ground and six floors below ground; besides plutonium separation, lithium-6 production, tritium extraction, plutonium pit production, and fabrication of other weapon components are carried out in Machon 2.
3. Uranium metal production
4. Fuel fabrication
5. Pilot-scale enrichment plants




N
W
E
S

250 m

1000 ft

CONF - DEF

Summary of Reactor Design

| | |
|---|---|
| Power | 26 MW Thermal |
| Moderator | $D_2O$ |
| Coolant | $D_2O$ |
| Coolant flow | 1800 cubic meters per hour |
| Inlet temperature | 40.8°C |
| Outlet temperature | 51.7°C |
| Velocity | About 4.2 meters/second |

Inconel tubes and lining in primary heat exchanger. Standard equipment in secondary heat exchanger system.

| | |
|---|---|
| Number of coolant loops | 3 |
| Design capacity | 13 MW each loop - (on spare) |

Primary coolant inlet and outlet at bottom of reactor.

Physical dimensions

| | |
|---|---|
| Lattice spacing | 13.5 cm hexagonal |
| Calandria diameter | 2.57 meters |
| Graphite reflector | 80 cm thick |
| Iron thermal shield | 20 cm thick |
| Concrete shield | 3.80 meters thick |
| Containment vessel - diameter | 36 meters |

NOTES ON VISIT TO ISRAEL — DRAFT 5/23/61 CONF-DEF

U. M. Steebler - J. W. Croach, Jr.

We arrived at Tel Aviv at about 8:15 p.m. on Wednesday, , 1961. We were contacted immediately on deplaning and taken ivate room where we met Mr. Katchalski, Head of the Department ysics of the Weizmann Institute of Science and Mr. M. Gilboa ublic Relations Department of the Ministry of Defence. halski said that the Prime Minister had asked him to greet s one of the scientific advisors to the Prime Minister. Mr. Gilboa r guide and accompanied us everywhere we went. We stayed at the otel - a resort remote from Tel Aviv. The rooms were in 's name.

d on the second day if we were to meet Professor Bergman ised that he is a public political figure and that such a refore seemed undesirable but might be arranged if we really The fact that the Atomic Energy Commission is only an p was also emphasized on a number of occasions in response ions.

edule was suggested which we agreed should be satisfactory. of the following:

ay, May 18, 1961 (A.M.) Visit to Swimming Pool Reactor at Nahal Shorek

(P.M.) Visit to Weizmann Institute of Science at Rehovoth.

Mr. Katchalski entertained in the evening.

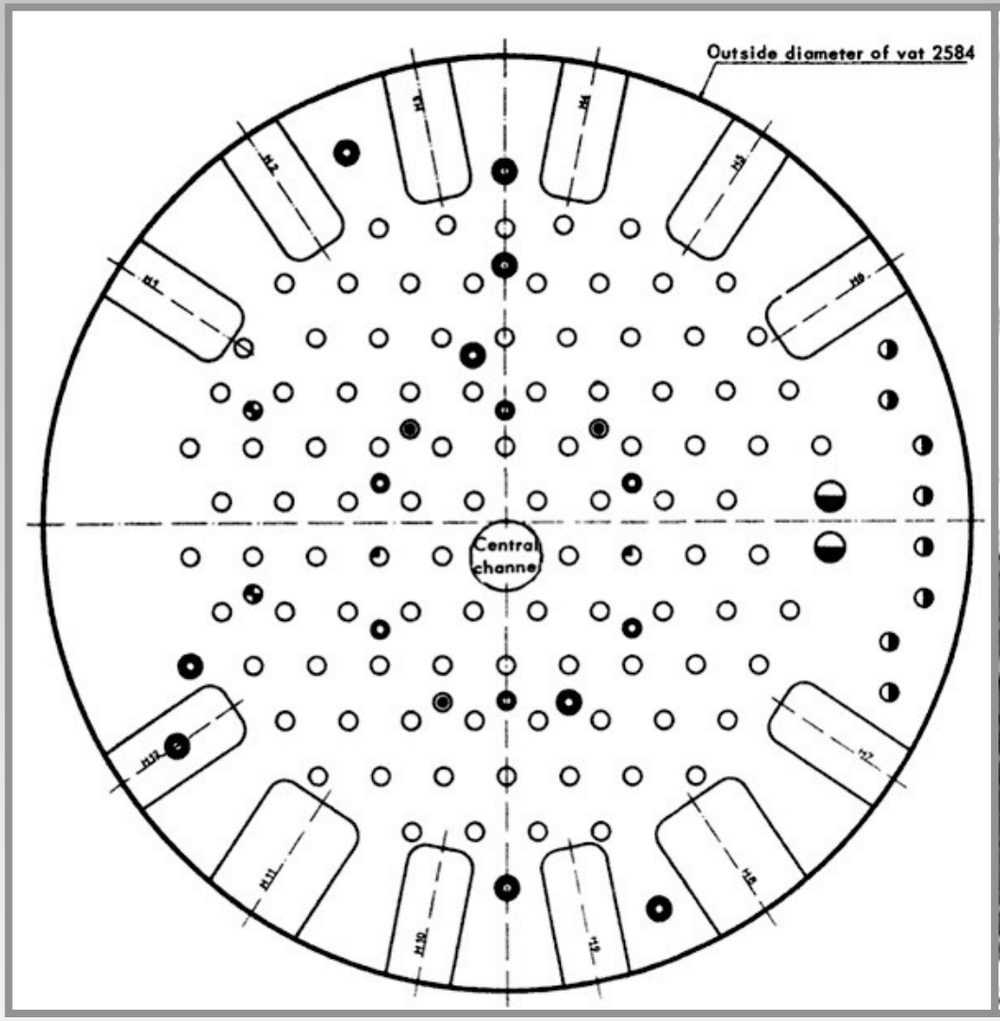
XXXXXXXX
y 19, 1961

CONFIDENTIAL - DEFENSE INFORMATION

U. M. Staebler and J. W. Crouch, Jr., *Notes on Visit to Israel,* Draft, 23 May 1961
Available at www.gwu.edu/~nsarchiv/israel/documents/first, mirrored at www.ipfmlibrary.org/sta61.pdf

# TECHNICAL SPECIFICATIONS OF “EL-3”

## SOME DATA CAN BE USED TO COMPLEMENT DATA OTHERWISE UNAVAILABLE FOR DIMONA

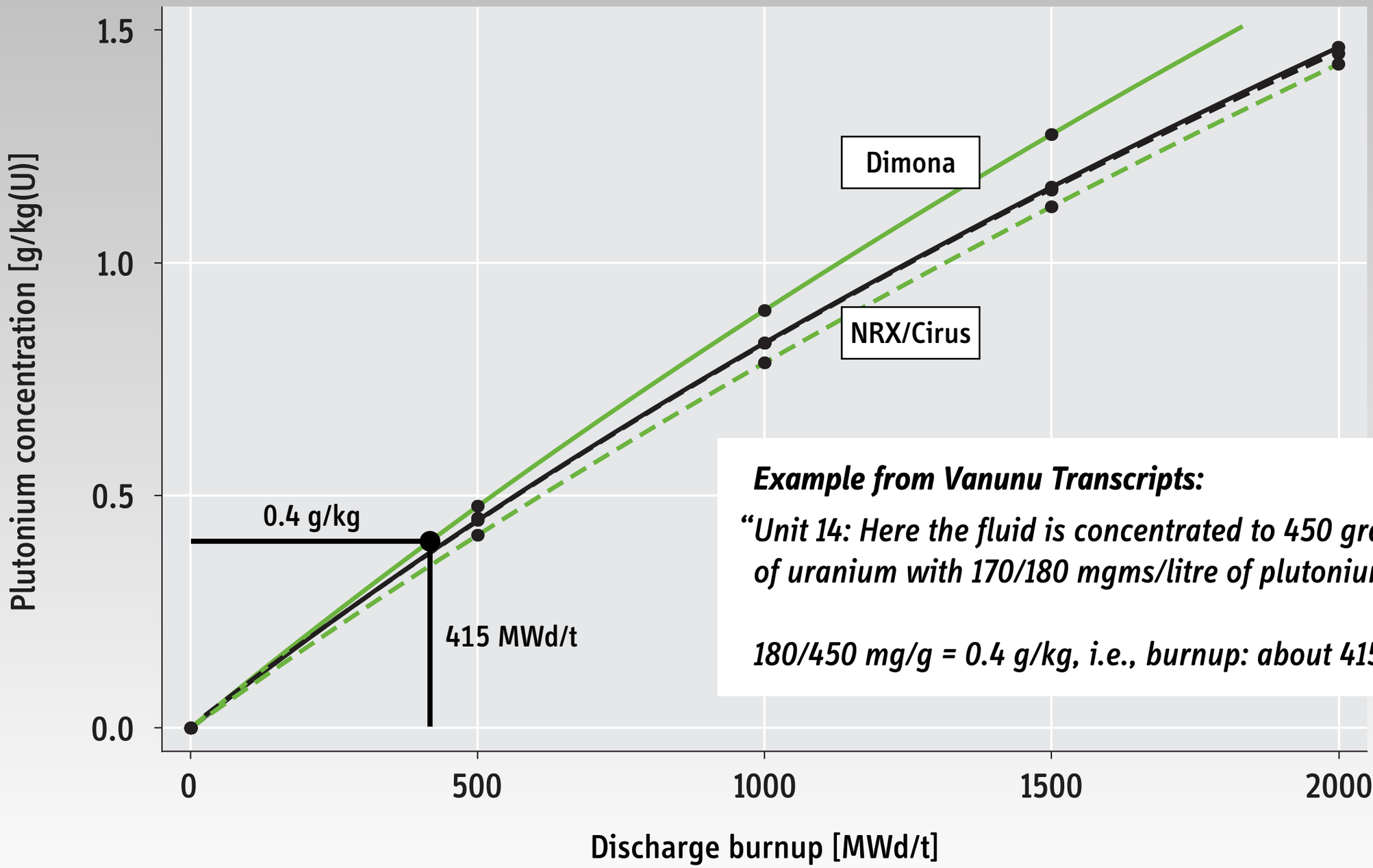



J. Robert, J. Hainzelin, and V. Raievski, “The EL-3 Reactor,” A/CONF. 15/P/335, *Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy,* Geneva, 1958, www.ipfmlibrary.org/rob58.pdf

# 1985 VANUNU PICTURES AND TESTIMONY

# PLUTONIUM CONCENTRATION IN URANIUM

## FOR VARIOUS NATURAL-URANIUM FUELED REACTOR TYPES



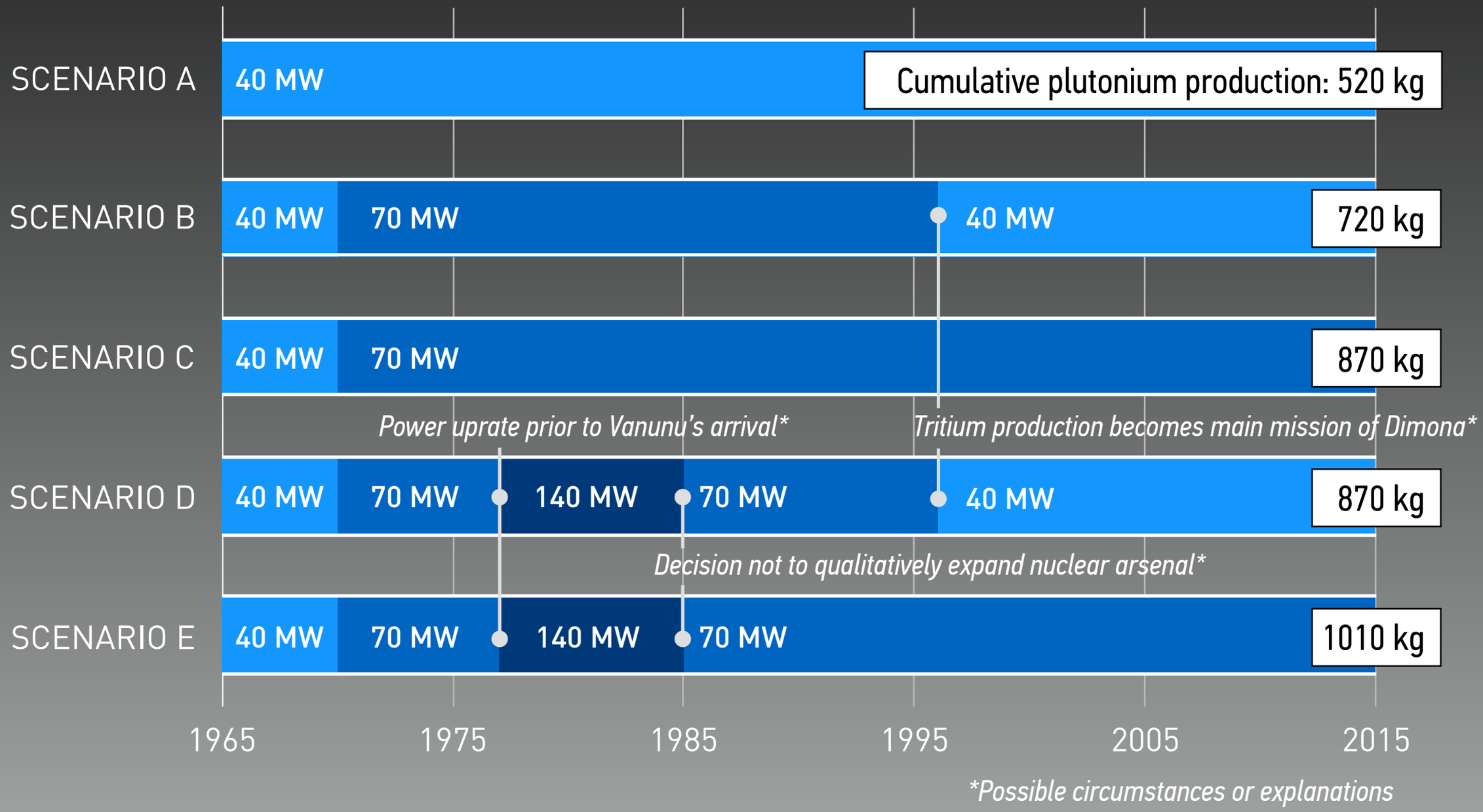

***Example from Vanunu Transcripts:***

*"Unit 14: Here the fluid is concentrated to 450 grams/litre of uranium with 170/180 mgms/litre of plutonium."*

*180/450 mg/g = 0.4 g/kg, i.e., burnup: about 415 MWd/t*

# DIMONA REACTOR, 1965–2015

## POSSIBLE OPERATIONAL HISTORIES AND CUMULATIVE PLUTONIUM PRODUCTION



# MORE THAN EVER EXPECTED?

## 50+ YEARS OF PLUTONIUM PRODUCTION AT DIMONA, 1964–2017

### ISRAEL HAS AVAILABLE A LARGE PLUTONIUM STOCKPILE

Estimated inventory on the order of 850 kg ± 130 kg

with a current production rate of 10–18 kg/year, depending on power level of Dimona (40–70 MW thermal)

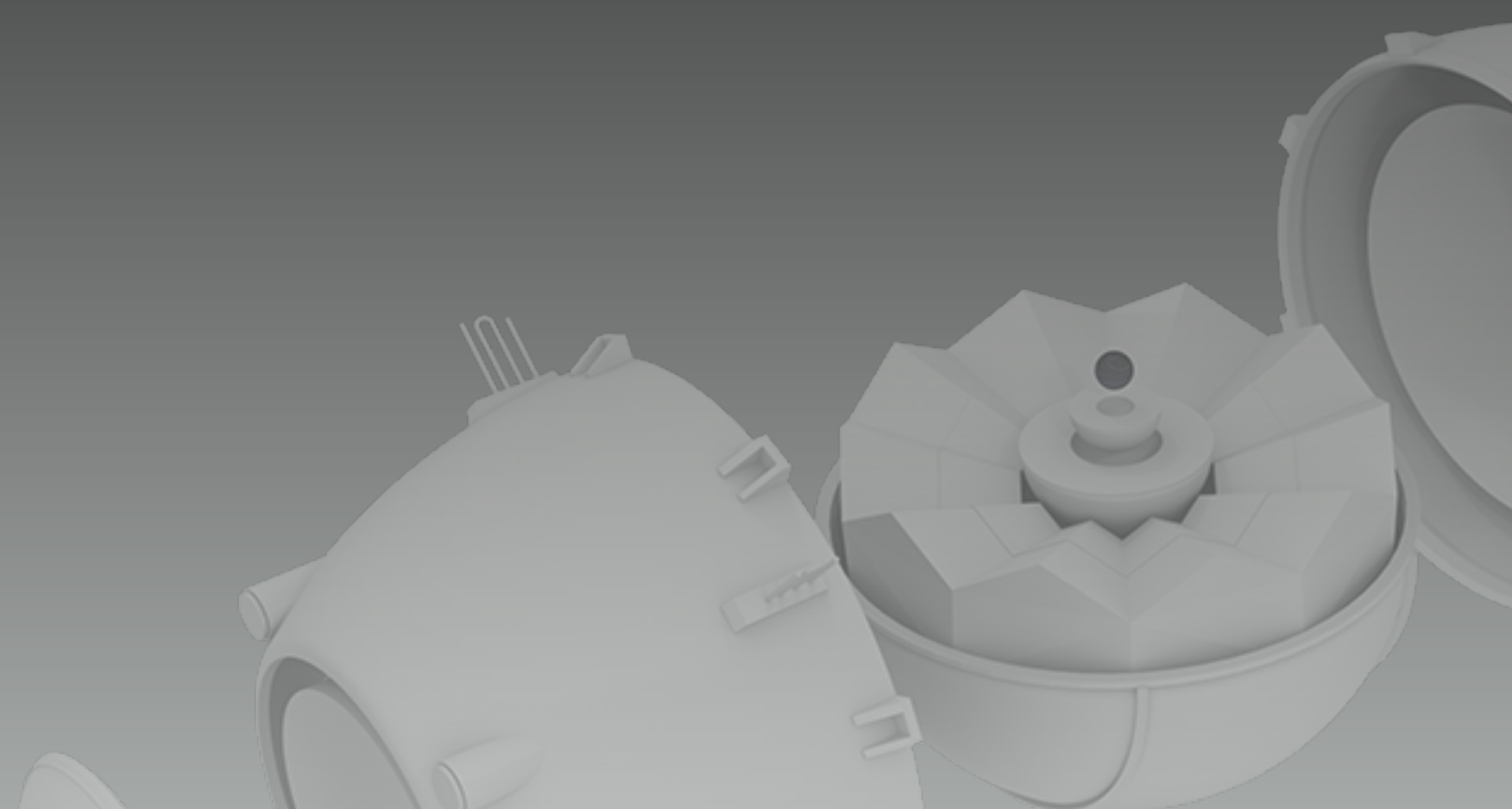
### PLUTONIUM MOST LIKELY A "BYPRODUCT" TODAY

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

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

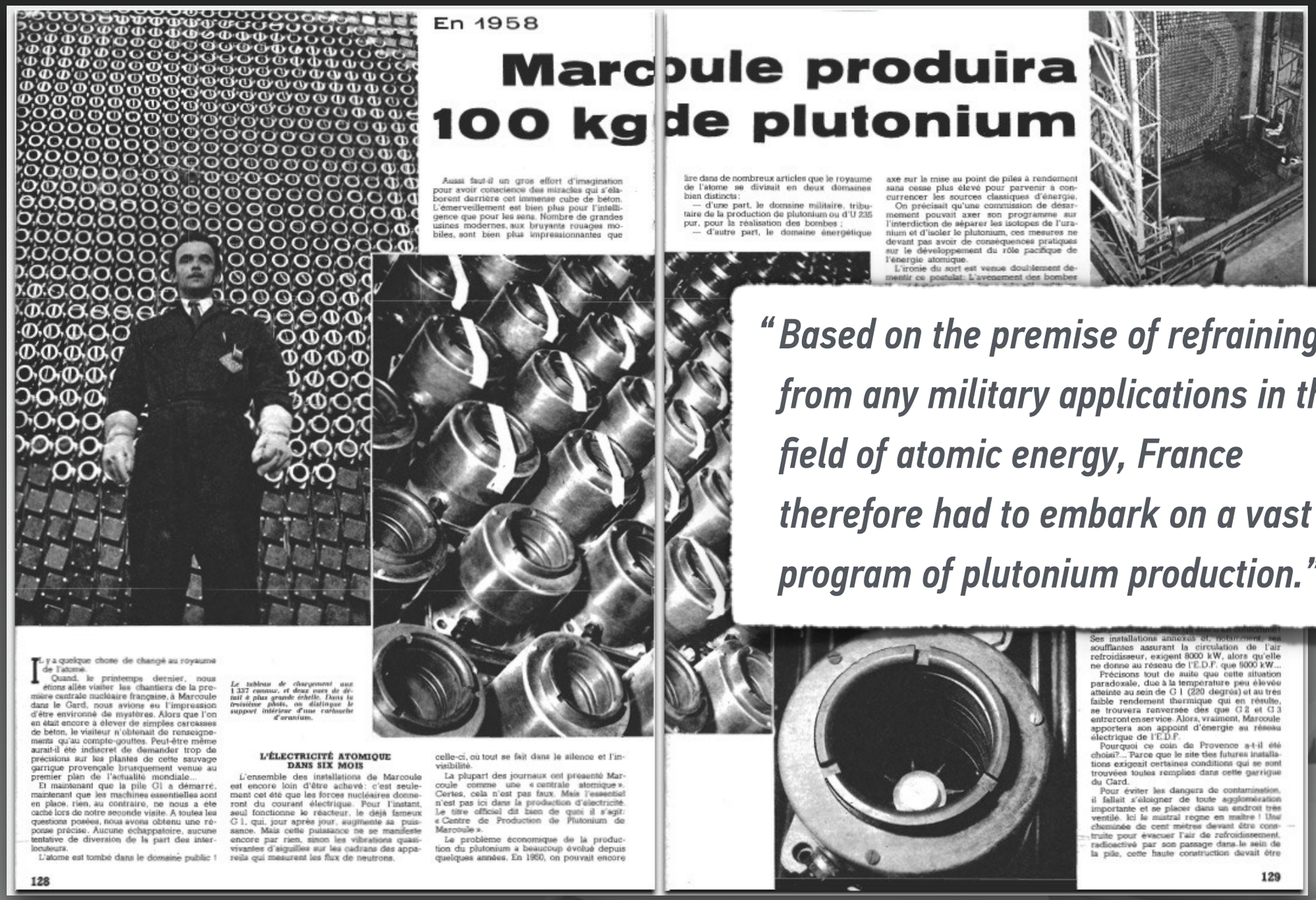
# FRANCE

## AMBIGUITY BY DESIGN



# HIDING IN PLAIN SIGHT

## EARLY PLUTONIUM PRODUCTION FOR "PEACEFUL PURPOSES"



En 1958

**Marcoule produira 100 kg de plutonium**

Aussi faut-il un gros effort d'imagination pour avoir conscience des miracles qui s'élaborent derrière cet immense cube de béton. L'émerveillement est bien plus pour l'intelligence que pour les sens. Nombre de grandes usines modernes, aux bruyants rouages mobiles, sont bien plus impressionnantes que

lire dans de nombreux articles que le royaume de l'atome se divisait en deux domaines bien distincts :

— d'une part, le domaine militaire, tributaire de la production de plutonium ou d'U 235 pur, pour la réalisation des bombes ;

— d'autre part, le domaine énergétique

axé sur la mise au point de piles à rendement sans cesse plus élevé pour parvenir à concurrencer les sources classiques d'énergie.

On précisait qu'une commission de désarmement pouvait axer son programme sur l'interdiction de séparer les isotopes de l'uranium et d'isoler le plutonium, ces mesures ne devant pas avoir de conséquences pratiques sur le développement du rôle pacifique de l'énergie atomique.

L'ironie du sort est venue douloureusement démentir ce postulat: L'avènement des bombes

*"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."*

Il y a quelque chose de changé au royaume de l'atome.

Quand, le printemps dernier, nous étions allés visiter les chantiers de la première centrale nucléaire française, à Marcoule dans le Gard, nous avions eu l'impression d'être environné de mystères. Alors que l'on en était encore à élever de simples carcasses de béton, le visiteur n'obtenait de renseignements qu'au compte-gouttes. Peut-être même aurait-il été indiscret de demander trop de précisions sur les plantes de cette sauvage garrigue provençale brusquement venue au premier plan de l'actualité mondiale...

Et maintenant que la pile G1 a démarré, maintenant que les machines essentielles sont en place, rien, au contraire, ne nous a été caché lors de notre seconde visite. A toutes les questions posées, nous avons obtenu une réponse précise. Aucune échappatoire, aucune tentative de diversion de la part des interlocuteurs.

L'atome est tombé dans le domaine public !

*Le tableau de chargement aux 1 337 canaux, et deux vues de détail à plus grande échelle. Dans la troisième photo, on distingue le support intérieur d'une cartouche d'uranium.*

### L'ÉLECTRICITÉ ATOMIQUE DANS SIX MOIS

L'ensemble des installations de Marcoule est encore loin d'être achevé: c'est seulement cet été que les forces nucléaires donneront du courant électrique. Pour l'instant, seul fonctionne le réacteur, le déjà fameux G 1, qui, jour après jour, augmente sa puissance. Mais cette puissance ne se manifeste encore par rien, sinon les vibrations quasi-vivantes d'aiguilles sur les cadrans des appareils qui mesurent les flux de neutrons.

celle-ci, où tout se fait dans le silence et l'invisibilité.

La plupart des journaux ont présenté Marcoule comme une « centrale atomique ». Certes, cela n'est pas faux. Mais l'essentiel n'est pas ici dans la production d'électricité. Le titre officiel dit bien de quoi il s'agit: « Centre de Production de Plutonium de Marcoule ».

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

Ses installations annexes et, notamment, ses soufflantes assurant la circulation de l'air refroidisseur, exigent 8000 kW, alors qu'elle ne donne au réseau de l'E.D.F. que 6000 kW...

Précisons tout de suite que cette situation paradoxale, due à la température peu élevée atteinte au sein de G 1 (220 degrés) et au très faible rendement thermique qui en résulte, se trouvera renversée dès que G 2 et G 3 entreront en service. Alors, vraiment, Marcoule apportera son appoint d'énergie au réseau électrique de l'E.D.F.

Pourquoi ce coin de Provence a-t-il été choisi?... Parce que le site des futures installations exigeait certaines conditions qui se sont trouvées toutes remplies dans cette garrigue du Gard.

Pour éviter les dangers de contamination, il fallait s'éloigner de toute agglomération importante et se placer dans un endroit très ventilé. Ici le mistral règne en maître ! Une cheminée de cent mètres devant être construite pour évacuer l'air de refroidissement, radioactivé par son passage dans le sein de la pile, cette haute construction devait être

128

129

*Sciences et Avenir, March 1956*

# 2010 CEA FACTSHEET

www.ipfmlibrary.org/cea10c.pdf

(Currently also available at www.francetnp.gouv.fr/IMG/pdf/dossier_de_presse_demantelement_-_2015_v2.pdf)

## Marcoule : G1, G2 and G3 reactors for plutonium production

In the 1950s, the Marcoule site of the French Atomic Energy Commission, in the department of Gard, was selected for the first industrial-scale reactors for producing plutonium.

The techn
graphite a

The G1 (
in 1956.
was also
operated

The desi
initiated
number
notably th
carbon
cooling.
were cylin
in length
diameter.
thick and
pre-stress
exerting
pressure.

The grap

Having 250 megawatts of thermal power per unit, the G2 and G3 reactors operated from 1958 to 1980 and from 1959 to 1984, respectively. During this period, they produced plutonium for national defence purposes and also supplied the electricity grid with 11 billion kWh.

# PUBLIC HISTORIC DOCUMENTS CAN OFTEN HELP RECONSTRUCT PRODUCTION HISTORIES

## (MUCH BETTER WOULD BE FORMAL DATA EXCHANGES OF HISTORIC PRODUCTION RECORDS)

Hague et de la Cogema a été de minimiser les faits et leurs conséquences possibles, afin de rassurer l'opinion publique française et la clientèle étrangère, faisant prendre ainsi

chaque année en séparant le combustible venant de G3 (taux de combustion compris entre 700 et 1200 MWJ/t) et le combustible EDF (taux de combustion atteignant 5000 MWJ/t.)

| | 1959 | 1960 | 1961 | 1962 | 1963 | 1964 | 1965 | 1966 | 1967 | 1968 | 1969 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Tonnage G2, G3 . . . . | 190 | 130 | 320 | 620 | 640 | 760 | 850 | 820 | 960 | 730 | 890 |
| Tx de combustion . . . | 100 | 100 | 100 | 200 | 200 | 300 | 300 | 300 | 400 | 400 | 450 |
| Tonnage EDF . . . . . | – | – | – | – | – | – | – | – | – | – | – |
| | **1970** | **1971** | **1972** | **1973** | **1974** | **1975** | **1976** | **1977** | **1978** | **1979** | **1980** |
| Tonnage G2 G3 . . . . | 530 | 570 | 460 | 480 | 240 | 280 | 260 | 170 | non connu | non connu | 190 |
| Tx de combustion . . . | 450 | 450 | 500 | 600 | 700 | 800 | 1000 | 1200 | | | 1200 |
| Tonnage EDF . . . . . | | | | | 113 | 8 | 25 | 120 | 245 | 280 | 310 |

Si jusqu'aux années 1972-73 les tonnages retraités sont très élevés, une des raisons essentielles en est le faible taux de combustion des combustibles.

Le tonnage retraité diminue ensuite sensiblement en

ne. Il est également inférieur aux prévisions faites par la Cogéma au début de l'année 1980 puisque 310 tonnes ont été retraitées alors que les prévisions étaient 365 tonnes.

Le retraitement des combustibles irradiés: La situation de la Hague et Marcoule, Analyses et positions de la CFDT *Rayonnement,* Syndicat National du Personnel de l'Energie Atomique, No. 92, Février 1981

# 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

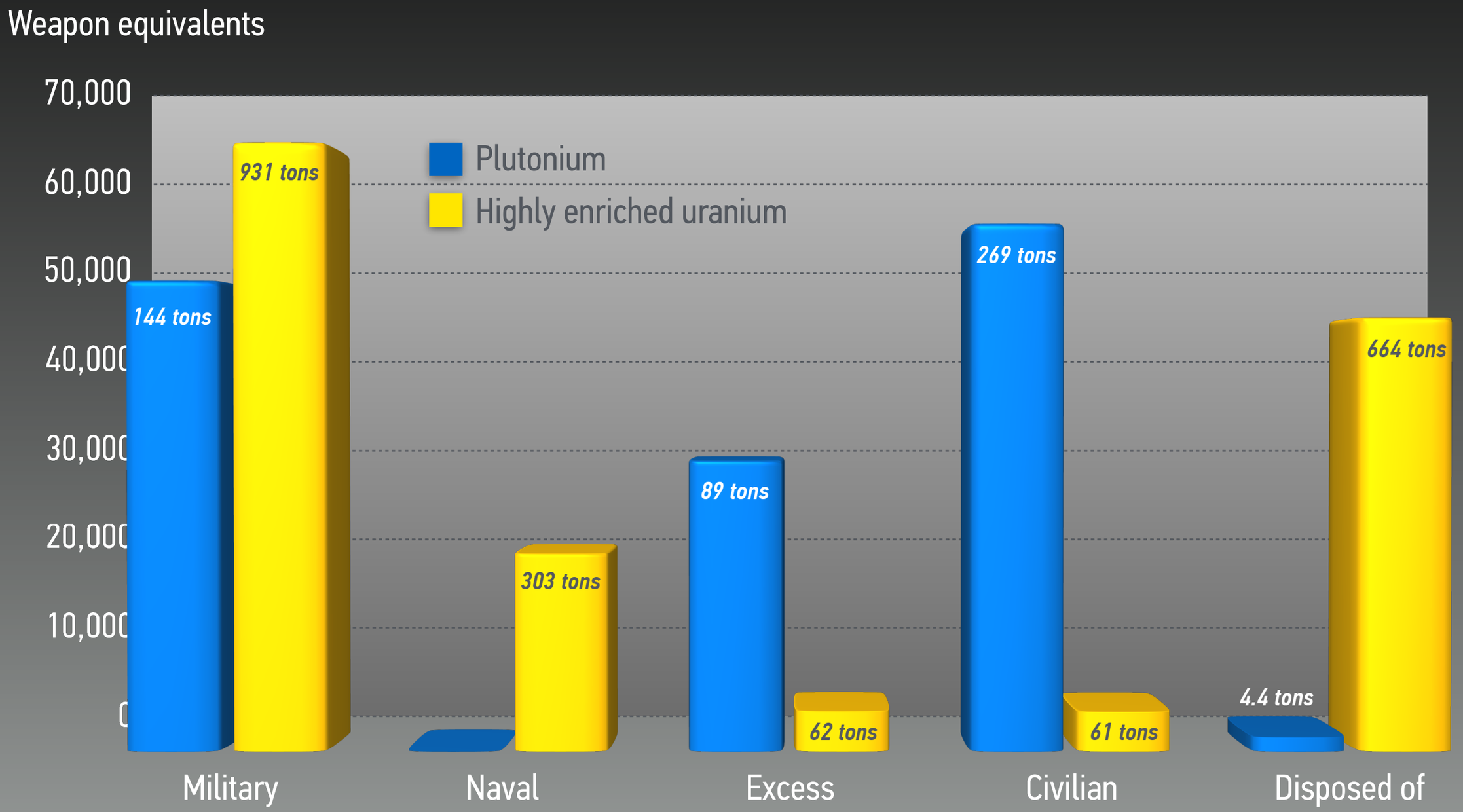
Based on our estimates, on the order of 70–80% of the military plutonium and HEU are outside the weapons stockpile (and without apparent military use)

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

# WHAT'S NEXT?

# FISSILE MATERIALS BY CATEGORY

## GLOBAL STOCKPILE OF PLUTONIUM AND HIGHLY ENRICHED URANIUM, 2015




Assumptions for weapon equivalents: 3 kg of weapon-grade plutonium, 5 kg of reactor-grade plutonium, 15 kg of highly enriched uranium
(As of 2015, more than 220,000 weapon-equivalents in the global stockpile of fissile material)
Source: *Global Fissile Material Report 2015,* International Panel on Fissile Materials, Princeton, NJ, www.ipfmlibrary.org/gfmr15.pdf

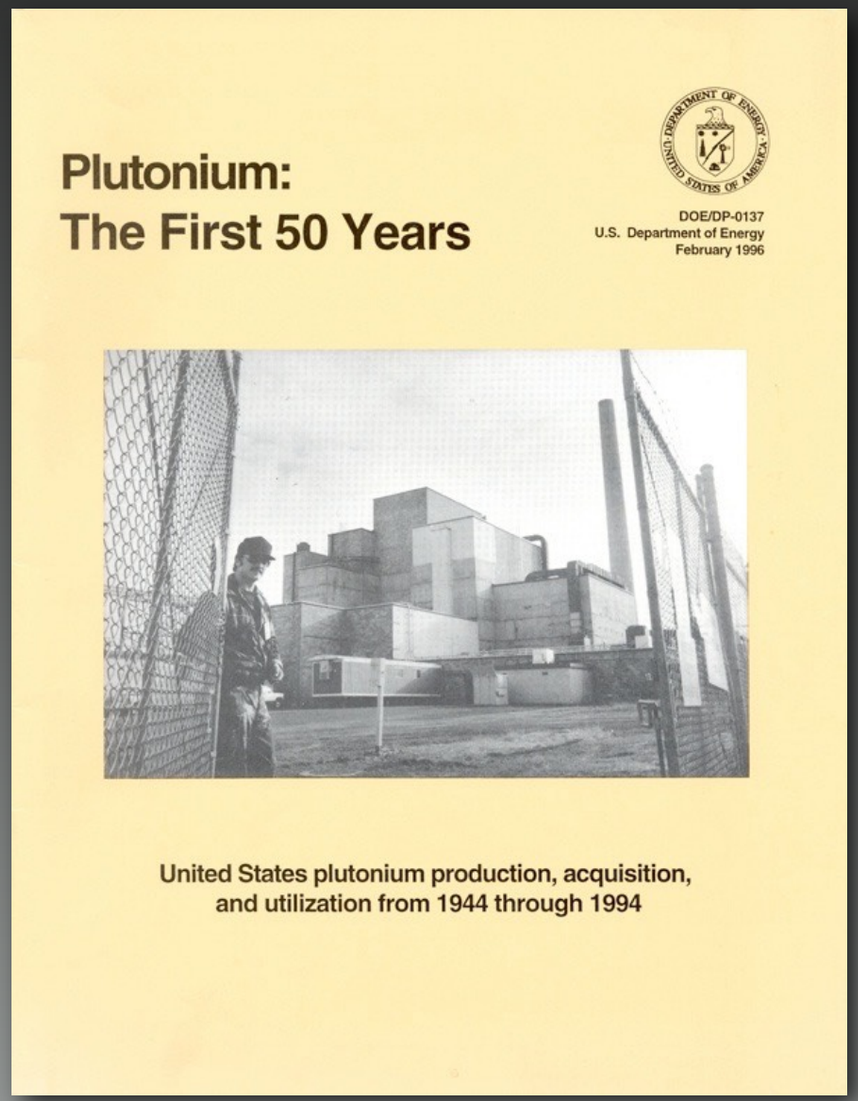
# TRANSPARENCY SCORECARD, 2017

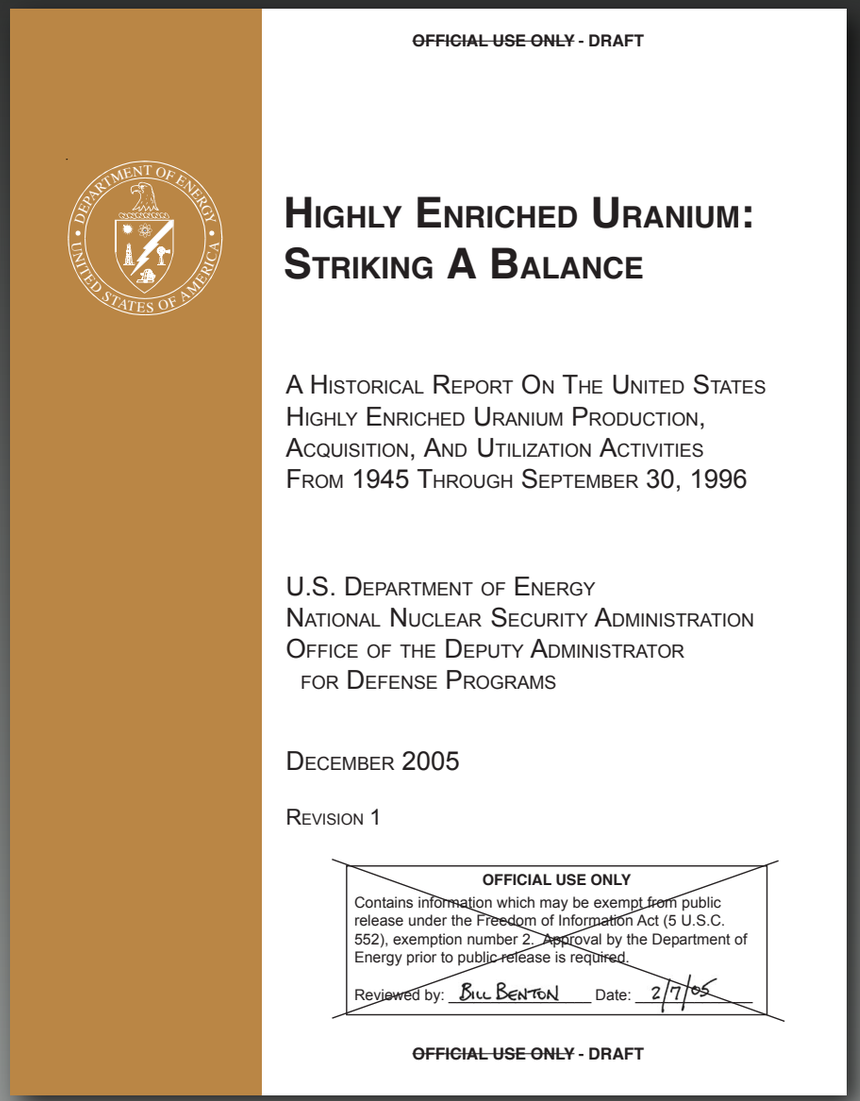
## INFORMATION ON NUCLEAR WARHEAD AND FISSILE MATERIAL INVENTORIES AND STATUS

| | 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 |

# THE UNITED STATES HAS ALREADY MADE BASELINE DECLARATIONS

## (BUT COULD UPDATE THEM MORE FREQUENTLY)




1996 and 2001 U.S. Declarations on Plutonium and HEU

# POSSIBLE REPORTING FORM

## FOR A FISSILE MATERIAL (BASELINE) DECLARATION

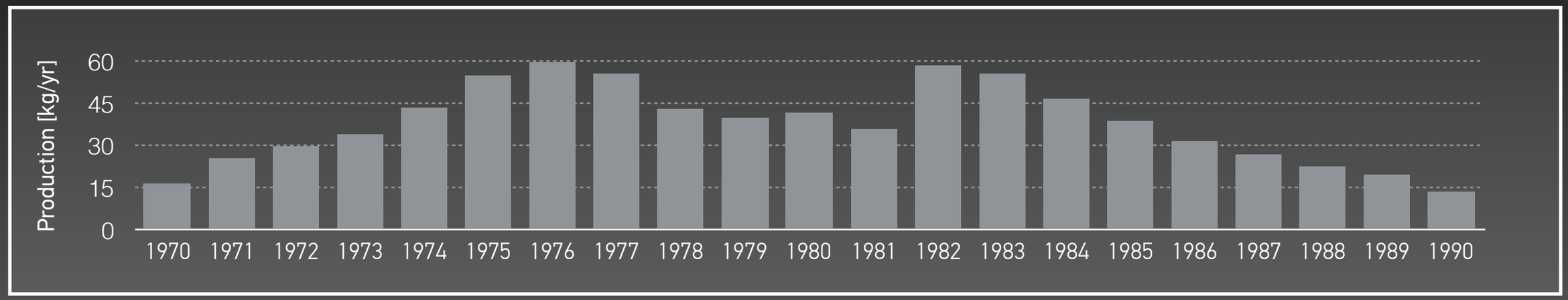
| | HEU | Plutonium |
|---|---|---|
| **Inventory as of (DATE)** | ---------- | ---------- |
| Military, available for weapons | ---------- | ---------- |
| Military, reserved for non-weapon purposes | ---------- | ---------- |
| Military, in irradiated fuel | ---------- | ---------- |
| Excess military, not available for IAEA safeguards | ---------- | ---------- |
| Civilian, not available for IAEA safeguards | ---------- | ---------- |
| Civilian, available for IAEA safeguards | ---------- | ---------- |
| Excess military, available for IAEA safeguards | ---------- | ---------- |

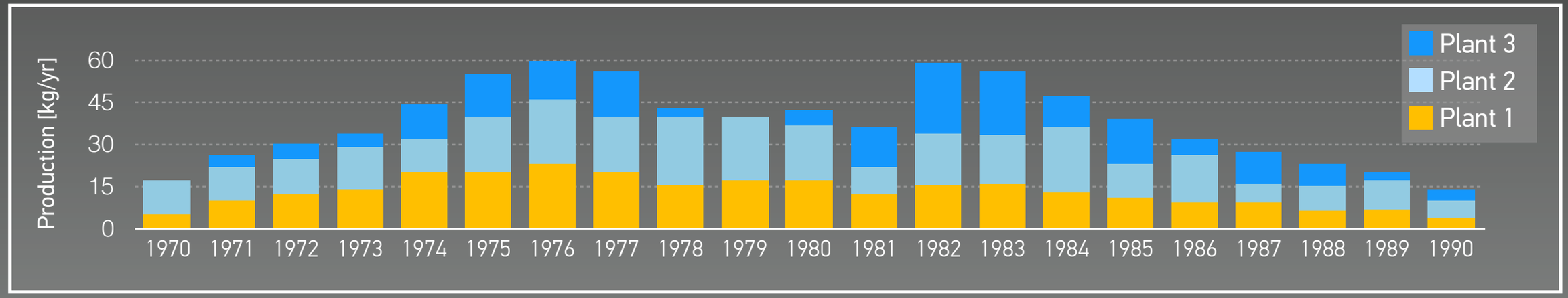
Specifying average isotopics (uranium-235 content in HEU and plutonium-239 in plutonium) would enable further consistency checks of the declarations

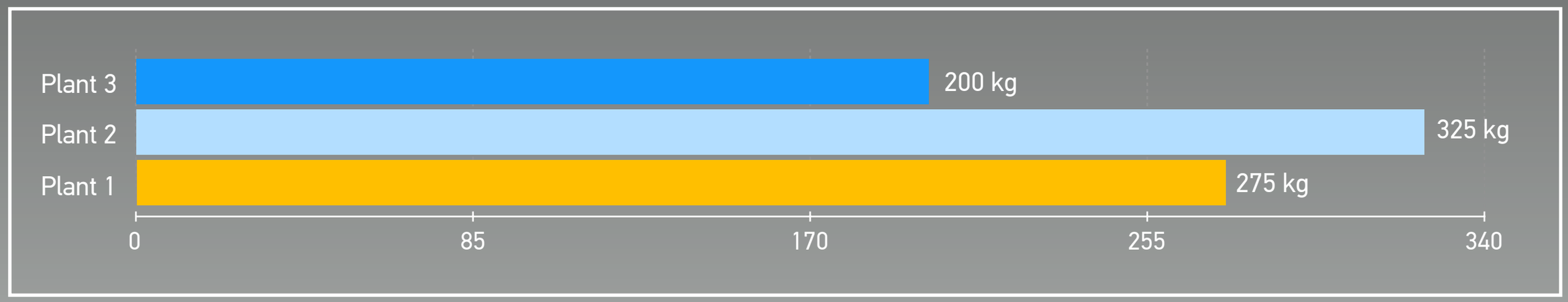
*Global Fissile Material Report 2013,* International Panel on Fissile Materials, Princeton, October 2013, www.ipfmlibrary.org/gfmr13.pdf

# NOTIONAL PRODUCTION SCENARIO

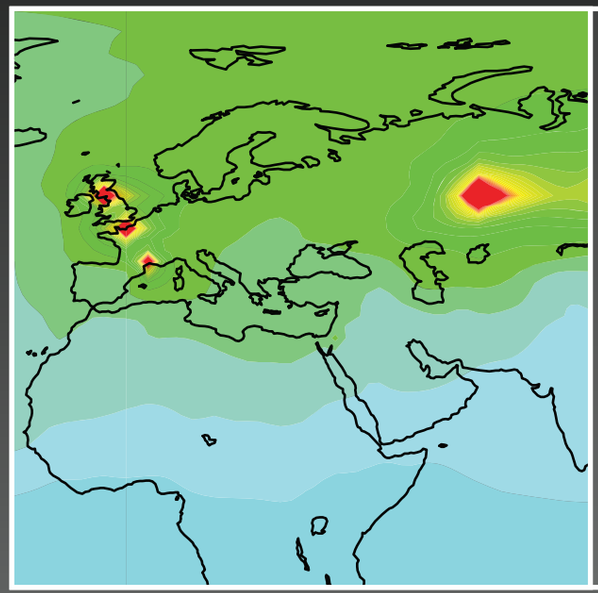
## (AND ALTERNATIVE WAYS OF DECLARING HISTORIC FISSILE MATERIAL PRODUCTION)



# WILL WE EVER KNOW HOW MUCH FISSILE MATERIAL EXISTS WORLDWIDE?



## RECONSTRUCTING HISTORIC FISSILE MATERIAL PRODUCTION

Many aspects of declared production histories can be reviewed for consistency even without dedicated verification efforts

(for example, by comparison with historic krypton emissions)

## DATA EXCHANGE AND NUCLEAR ARCHAEOLOGY

Verification could begin with data exchanges (e.g. sharing of available operating records) and, eventually, envision onsite inspections

Nuclear archaeology is based on nuclear forensic analysis of samples taken at former production facilities

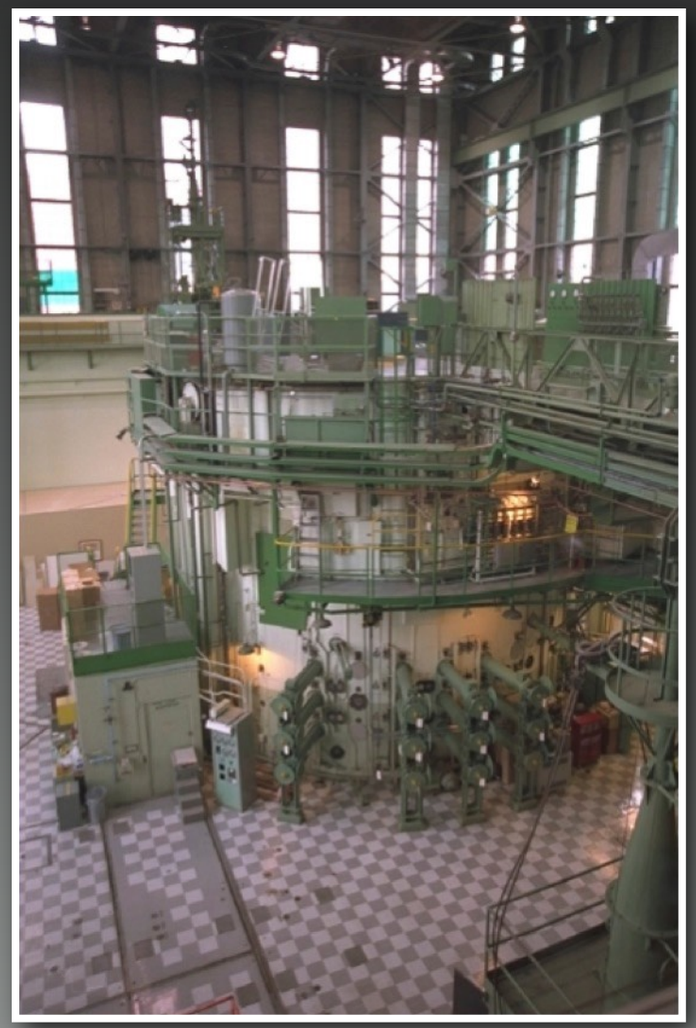
*Source: Ole Ross and www.francetnp2010.fr*

# TEST BEDS FOR NUCLEAR ARCHAEOLOGY

To begin countries could offer single sites or facilities as test beds and invite partners with similar production facilities to engage in “site-to-site exercises” to jointly demonstrate verification approaches and measurement techniques

*Left: Windscale Piles, www.sellafieldsites.com*
*Right: G2/G3, Marcoule, www.francetnp.fr*

# MANY NON-NUCLEAR WEAPON STATES HAVE CANDIDATE FACILITIES THAT COULD BE USED TO DEMONSTRATE METHODS REQUIRED FOR NUCLEAR ARCHAEOLOGY



*NRX, Canada*

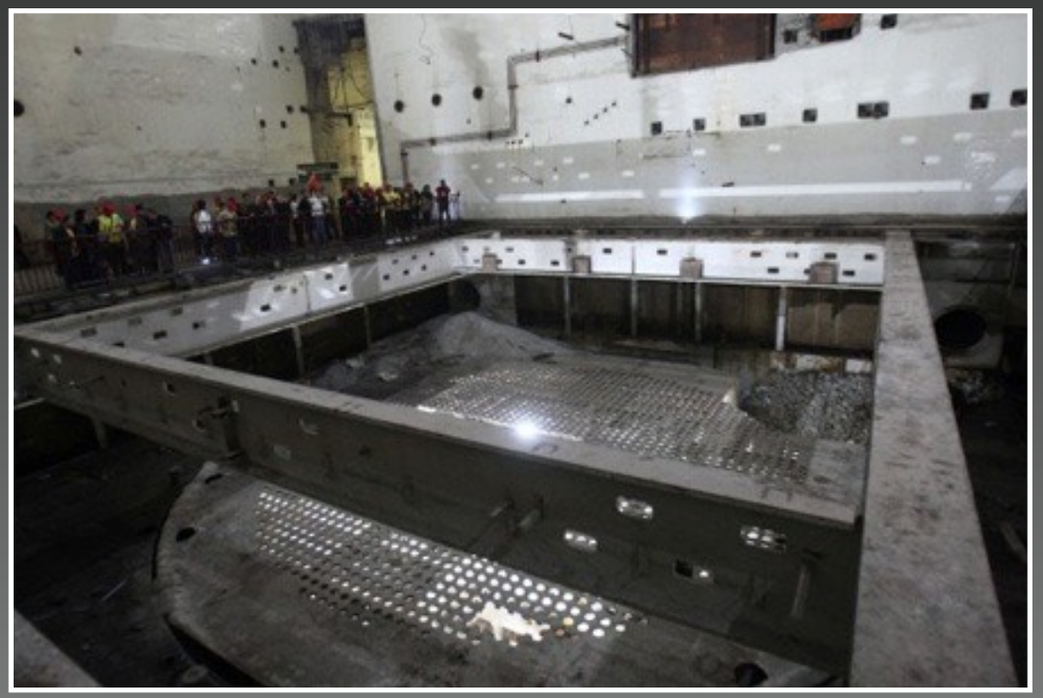
*Ågesta Reactor (105 MWt), near Stockholm, Sweden*

# “THE CLOCK IS TICKING”

## SHUTDOWN ENRICHMENT PLANTS AND PRODUCTION REACTORS ARE BEING DECOMMISSIONED OR DEMOLISHED

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

*Source: Bechtel Jacobs*



China’s unfinished underground plutonium production complex (Project 816), near Chongqing

*Source: CQTV*

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