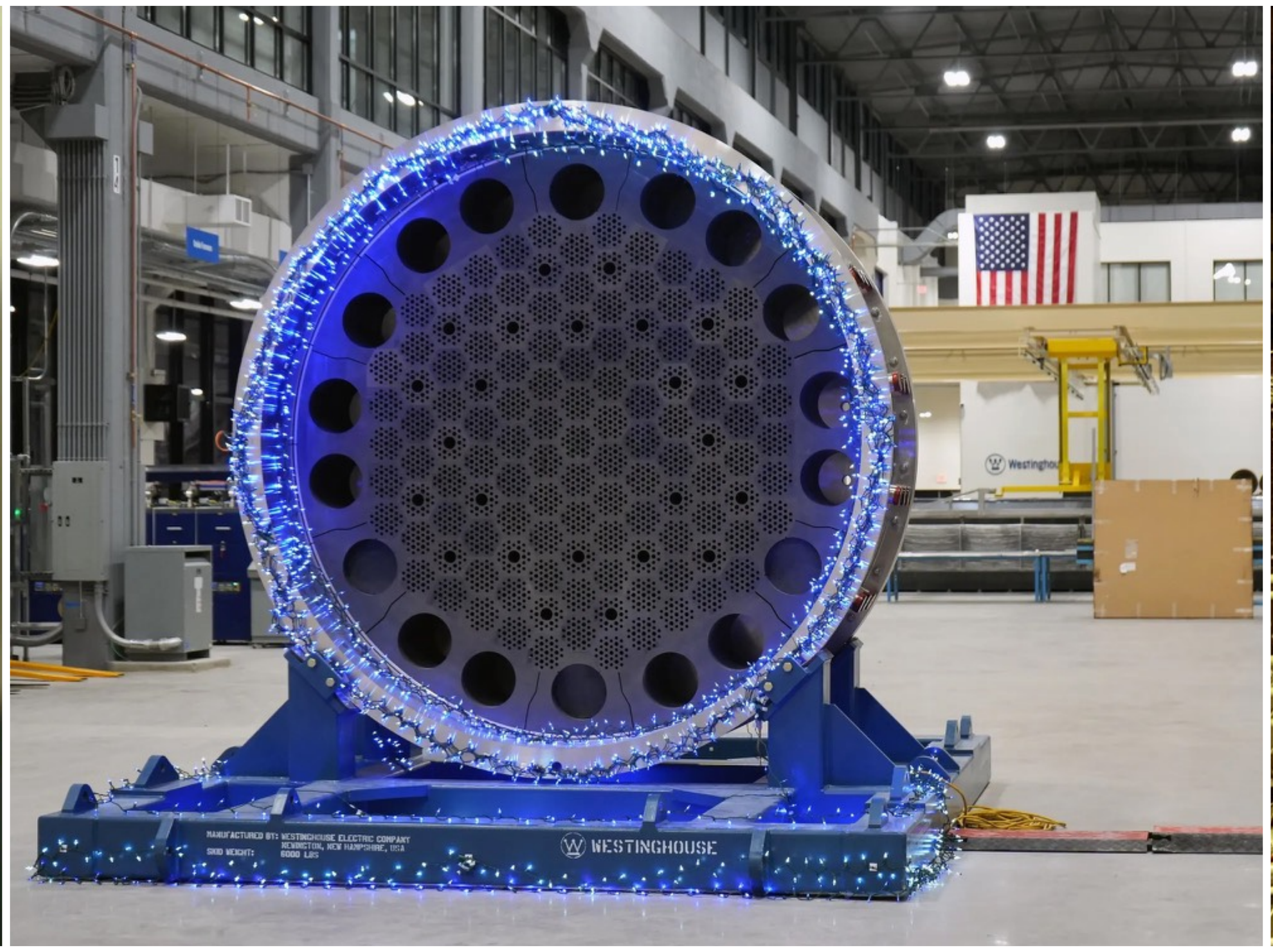


NUCLEAR POWER

STATE OF PLAY 2025

Alex Glaser

Columbia University, April 21, 2025

Revision 0.0

Overview & Historical Context

(very briefly)

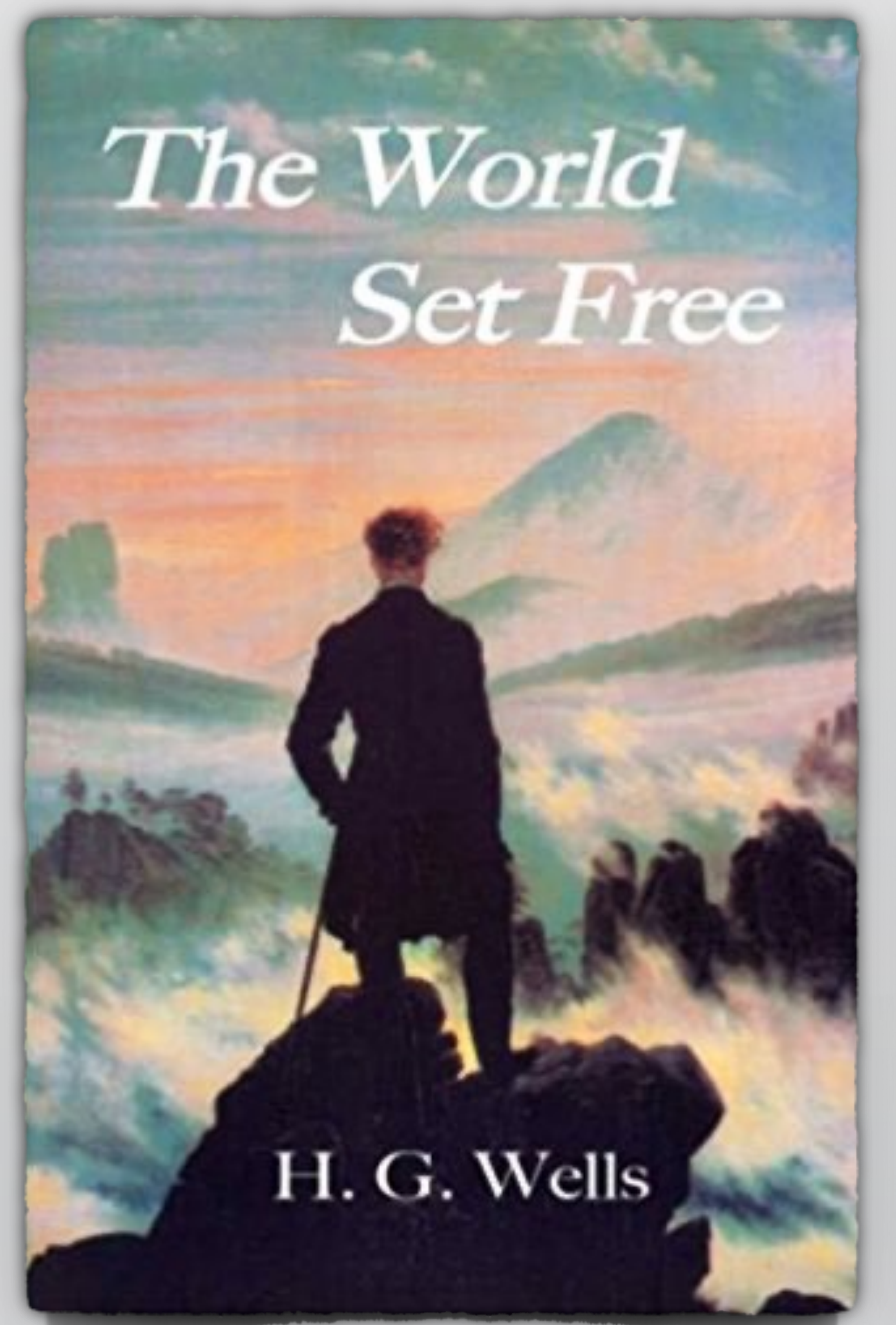
EARLY “SPECULATIVE” ENTHUSIASM

FREDERICK SODDY (1908) AND H. G. WELLS (1913/1914)

As we have seen, we cannot yet artificially accelerate or influence the rate of disintegration of an element, and therefore the energy of uranium […] is practically useless.” (p. 237)

A race which could transmute matter would have little need to earn its bread by the sweat of its brow. If we can judge from what our engineers accomplish with their comparatively restricted supplies of energy, such a race could transform a desert continent, thaw the frozen poles, and make the whole world one smiling Garden of Eden.” (p. 251)

Frederick Soddy, The Interpretation of Radium
Third Edition, G. P. Putnam's Sons, New York, 1912,
books.google.com



Chapter 2

The New Source of Energy

1.

The problem which was already being mooted by such scientific men as Ramsay, Rutherford, and Soddy, in the very beginning of the twentieth century, the problem of inducing radio-activity in the heavier elements and so tapping the internal energy of atoms, was solved by a wonderful combination of induction, intuition, and luck by Holsten so soon as the year 1933. From the first detection of radio-activity to its first subjugation to human purpose measured little more than a quarter of a century. For twenty years after that, indeed, minor difficulties prevented any striking practical application of his success, but the essential thing was done, this new boundary in the march of human progress was crossed, in that year. He set up atomic disintegration in a minute particle of bismuth; it exploded with great violence into a heavy gas of extreme radio-activity, which disintegrated in its turn in the course of seven days, and it was only after another year's work that he was able to show practically that the last result of this rapid release of energy was gold. But the thing was done—at the cost of a blistered chest and an injured finger, and from the moment when the invisible speck of bismuth flashed into riving and rending energy, Holsten knew that he had opened a way for mankind, however narrow and dark it might still be, to worlds of limitless power. He recorded as much in the strange diary biography he left the world, a diary that was up to that particular moment a mass of speculations and calculations, and which suddenly became for a space an amazingly minute and human record of sensations and emotions that all humanity might understand.

Written/published in 1913/1914, onlinebooks.library.upenn.edu/webbin/gutbook/lookup?num=1059

DISCOVERY OF NUCLEAR FISSION

(LISE MEITNER, OTTO HAHN, FRITZ STRASSMANN, 1938)

Lise Meitner and Otto Hahn, Berlin, ca. 1925

Letters to the Editor

The Editor does not hold himself responsible for opinions expressed by his correspondents. He cannot undertake to return, or to correspond with the writers of, rejected manuscripts intended for this or any other part of NATURE. *No notice is taken of anonymous communications.*

NOTES ON POINTS IN SOME OF THIS WEEK'S LETTERS APPEAR ON P. 247.

CORRESPONDENTS ARE INVITED TO ATTACH SIMILAR SUMMARIES TO THEIR COMMUNICATIONS.

Disintegration of Uranium by Neutrons: a New Type of Nuclear Reaction

ON bombarding uranium with neutrons, Fermi and collaborators[1] found that at least four radioactive substances were produced, to two of which atomic numbers larger than 92 were ascribed. Further investigations[2] demonstrated the existence of at least nine radioactive periods, six of which were assigned to elements beyond uranium, and nuclear isomerism had to be assumed in order to account for their chemical behaviour together with their genetic relations.

In making chemical assignments, it was always assumed that these radioactive bodies had atomic numbers near that of the element bombarded, since only particles with one or two charges were known to be emitted from nuclei. A body, for example, with similar properties to those of osmium was assumed to be eka-osmium ($Z = 94$) rather than osmium ($Z = 76$) or ruthenium ($Z = 44$).

Following up an observation of Curie and Savitch[3], Hahn and Strassmann[4] found that a group of at least three radioactive bodies, formed from uranium under neutron bombardment, were chemically similar to barium and, therefore, presumably isotopic with radium. Further investigation[5], however, showed that it was impossible to separate these bodies from barium (although mesothorium, an isotope of radium, was readily separated in the same experiment), so that Hahn and Strassmann were forced to conclude that *isotopes of barium* ($Z = 56$) *are formed as a consequence of the bombardment of uranium* ($Z = 92$) *with neutrons.*

At first sight, this result seems very hard to understand. The formation of elements much below uranium has been considered before, but was always rejected for physical reasons, so long as the chemical evidence was not entirely clear cut. The ...

within a short ...

that the surface tension of a charged droplet is diminished by its charge, and a rough estimate shows that the surface tension of nuclei, decreasing with increasing nuclear charge, may become zero for atomic numbers of the order of 100.

It seems therefore possible that the uranium nucleus has only small stability of form, and may, after neutron capture, divide itself into two nuclei of roughly equal size (the precise ratio of sizes depending on finer structural features and perhaps partly on chance). These two nuclei will repel each other and should gain a total kinetic energy of *c.* 200 Mev., as calculated from nuclear radius and charge. This amount of energy may actually be expected to be available from the difference in packing fraction between uranium and the elements in the middle of the periodic system. The whole 'fission' process can thus be described in an essentially classical way, without having to consider quantum-mechanical 'tunnel effects', which would actually be extremely small, on account of the large masses involved.

After division, the high neutron/proton ratio of uranium will tend to readjust itself by beta decay to the lower value suitable for lighter elements. Probably each part will thus give rise to a chain of disintegrations. If one of the parts is an isotope of barium[5], the other will be krypton ($Z = 92 - 56$), which might decay through rubidium, strontium and yttrium to zirconium. Perhaps one or two of the supposed barium-lanthanum-cerium chains are then actually strontium-yttrium-zirconium chains.

It is possible[5], and seems to us rather probable, that the periods which have been ascribed to elements beyond uranium are also due to light elements. From the chemical evidence, the two short ...

(10 sec. and 40 sec.) ...

...ioned that the body with half- ... was chemically identified with ... really ^{239}U, and goes over into ...ich appears inactive but may ...ably with emission of alpha ...nspection of the natural radio- ...U cannot be expected to give ...wo beta decays; the long chain ...s has always puzzled us.) The ...dy is a typical resonance process[9]; ...e must have a life-time a million ... the time it would take the ...self. Perhaps this state corresponds ...nmetrical type of motion of nuclear ... not favour 'fission' of the nucleus.

LISE MEITNER.

...stitute,
...Sciences,
...olm.

O. R. FRISCH.

...retical Physics,
...sity,
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... 16.

... F., d'Agostino, O., Rasetti, F., and Segrè, E. ... A, **146**, 483 (1934).
...hn, O., and Strassmann, F., *Z. Phys.*, **106**, 249 ...
...tch, P., *C.R.*, **208**, 906, 1643 (1938).
...ssmann, F., *Naturwiss.*, **26**, 756 (1938).
...assmann, F., *Naturwiss.*, **27**, 11 (1939).
..., **137**, 344, 351 (1936).
...ckar, F., *Kgl. Danske Vid. Selskab, Math. Phys.* ... 10 (1937).
...trassmann, F., and Hahn, O., *Z. Phys.*, **109**, 538 ...
... Placzek, G., *Phys. Rev.*, **51**, 450 (1937).

A Novel Thermostat

...necessary to maintain an apparatus at ...emperature. This may be done by ...in a circulating liquid maintained at a ...perature by a thermostat, or by jacketing ...

control of the temperature to within a narrow range requires some complication in the whole system, and it is difficult to prevent 'hunting'.

In a measurement which we are making of the electronic charge, it is necessary to maintain the temperature of the air, in which an oil drop moves, uniform and constant so that it has no motion due to convection. As a convenient solution of this problem has been found which seems capable of many applications, it is described here.

A resistance thermometer is formed by winding a single layer coil of copper wire around and in good thermal contact with the microscope condenser which forms part of the apparatus the temperature of which is under control. (In the accompanying illustration the condenser tube is on the right.) This coil forms one arm of a Wheatstone bridge, the other arms being of manganin resistances. Any change in temperature of the apparatus deflects the light spot of the galvanometer connected to this bridge, and for one direction of deflection the spot falls on a photo-electric cell, which operates a polarized relay, which in turn puts off two 30-watt lamps placed on opposite sides of the apparatus. The amplification of the galvanometer current by the photo-electric cell is 10^6, and including the relay about 10^7.

The bridge is adjusted to be balanced at a temperature a few degrees above the maximum temperature to which the room rises during a day. The lamps flash on and off every few seconds and maintain the temperature of the external surface of the apparatus constant to about 0·002° C. After the thermostat has been in operation for an hour, we have not been able to detect, by means of a thermo-couple, any change of temperature inside the apparatus.

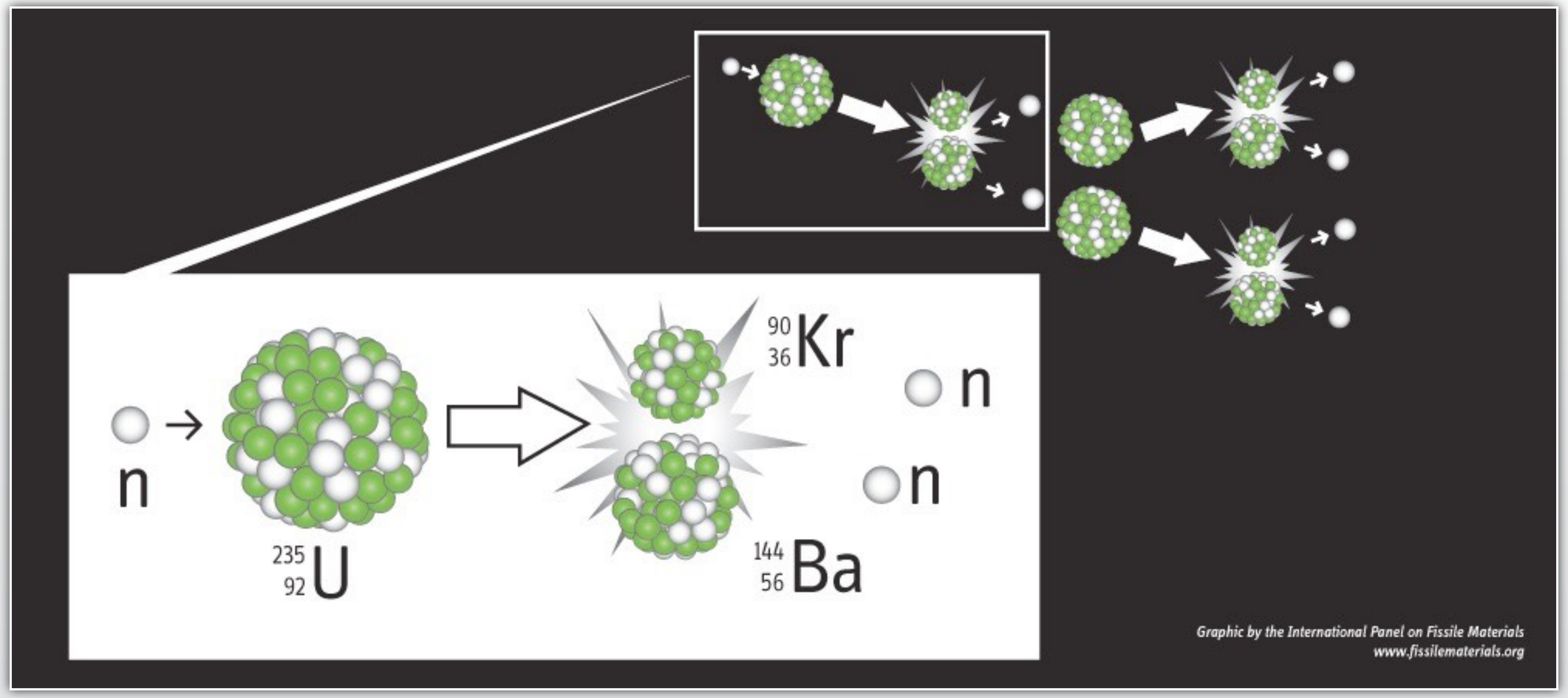
T. H. LABY.
V. D. HOPPER.

Natural Philosophy Laboratory,
University of Melbourne.
Dec. 9.

Limitations on the Modern Tensor Scheme of ...

NUCLEAR FISSION

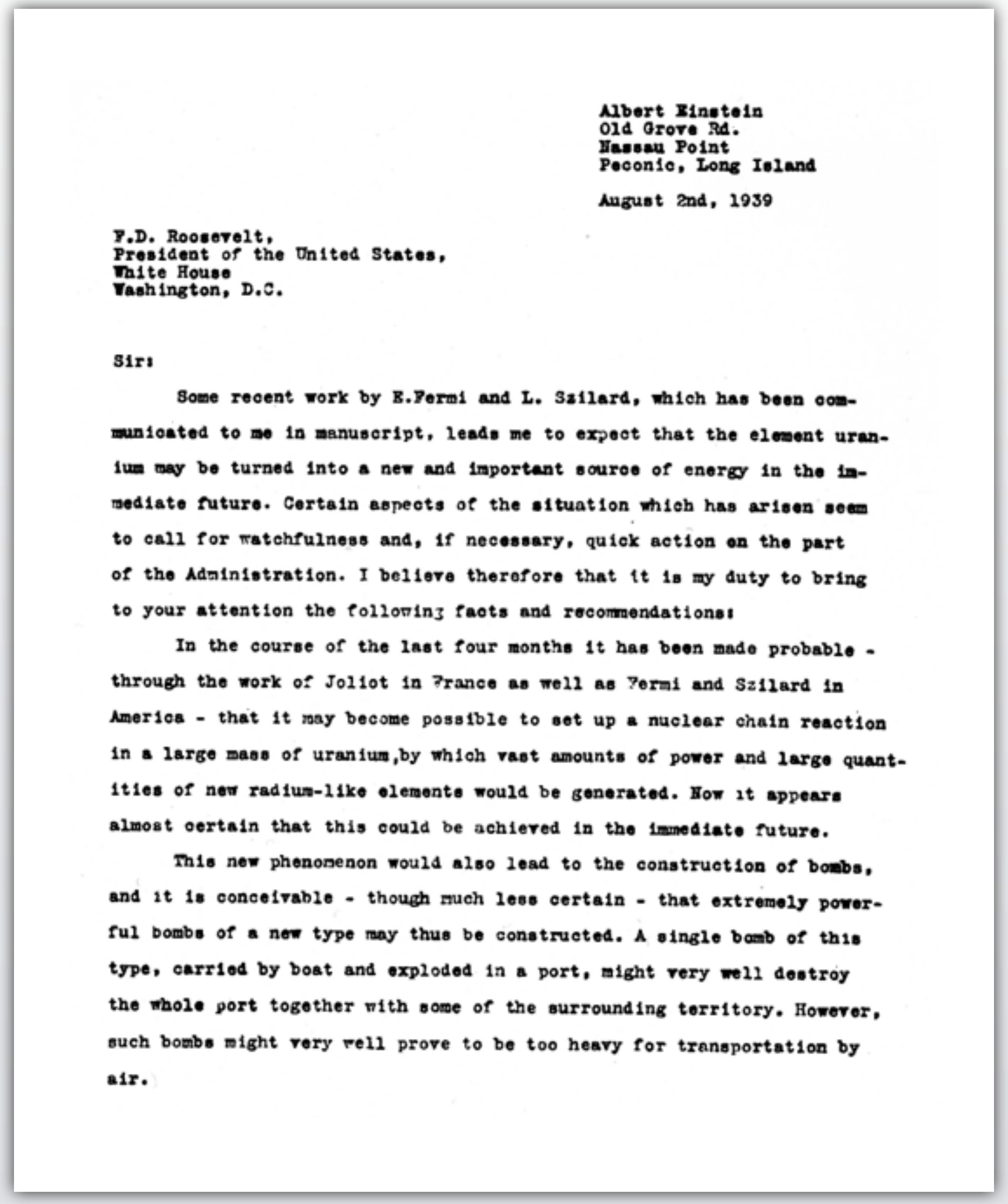
AND THE FISSION CHAIN REACTION SUSTAINED BY NEUTRONS (FROM FISSION EVENTS)



Cillian Murphy as J. Robert Oppenheimer
Universal Pictures, 2023

THE 1939 EINSTEIN LETTER TO PRESIDENT ROOSEVELT

"It may become possible to set up a nuclear chain reaction in a large mass of uranium, by which vast amounts of power … would be generated. Now it appears almost certain that this could be achieved in the immediate future. This new phenomenon would also lead to the construction of bombs, …"



Albert Einstein
Old Grove Rd.
Nassau Point
Peconic, Long Island

August 2nd, 1939

F.D. Roosevelt,
President of the United States,
White House
Washington, D.C.

Sir:

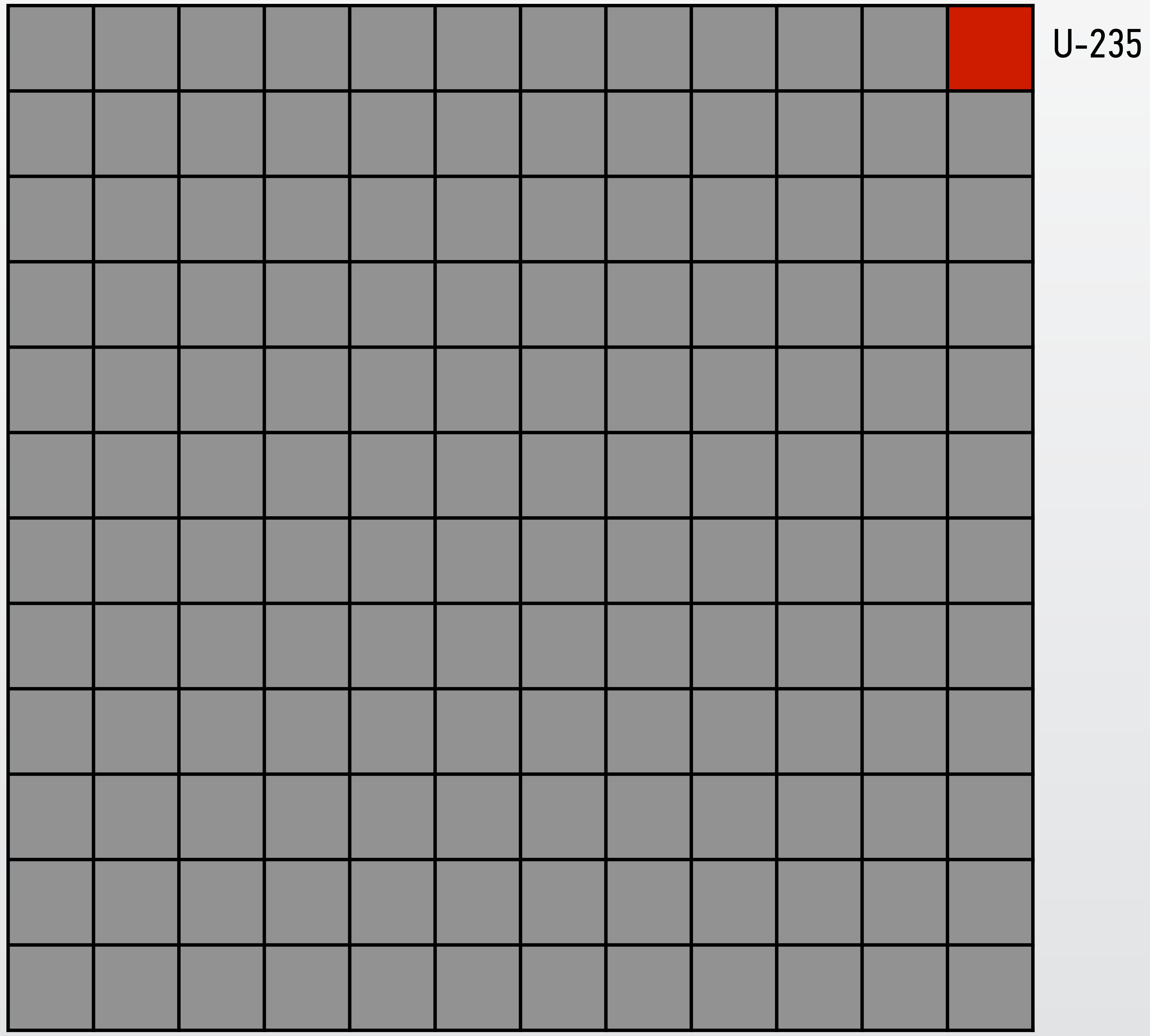
Some recent work by E.Fermi and L. Szilard, which has been communicated to me in manuscript, leads me to expect that the element uranium may be turned into a new and important source of energy in the immediate future. Certain aspects of the situation which has arisen seem to call for watchfulness and, if necessary, quick action on the part of the Administration. I believe therefore that it is my duty to bring to your attention the following facts and recommendations:

In the course of the last four months it has been made probable - through the work of Joliot in France as well as Fermi and Szilard in America - that it may become possible to set up a nuclear chain reaction in a large mass of uranium,by which vast amounts of power and large quantities of new radium-like elements would be generated. Now it appears almost certain that this could be achieved in the immediate future.

This new phenomenon would also lead to the construction of bombs, and it is conceivable - though much less certain - that extremely powerful bombs of a new type may thus be constructed. A single bomb of this type, carried by boat and exploded in a port, might very well destroy the whole port together with some of the surrounding territory. However, such bombs might very well prove to be too heavy for transportation by air.

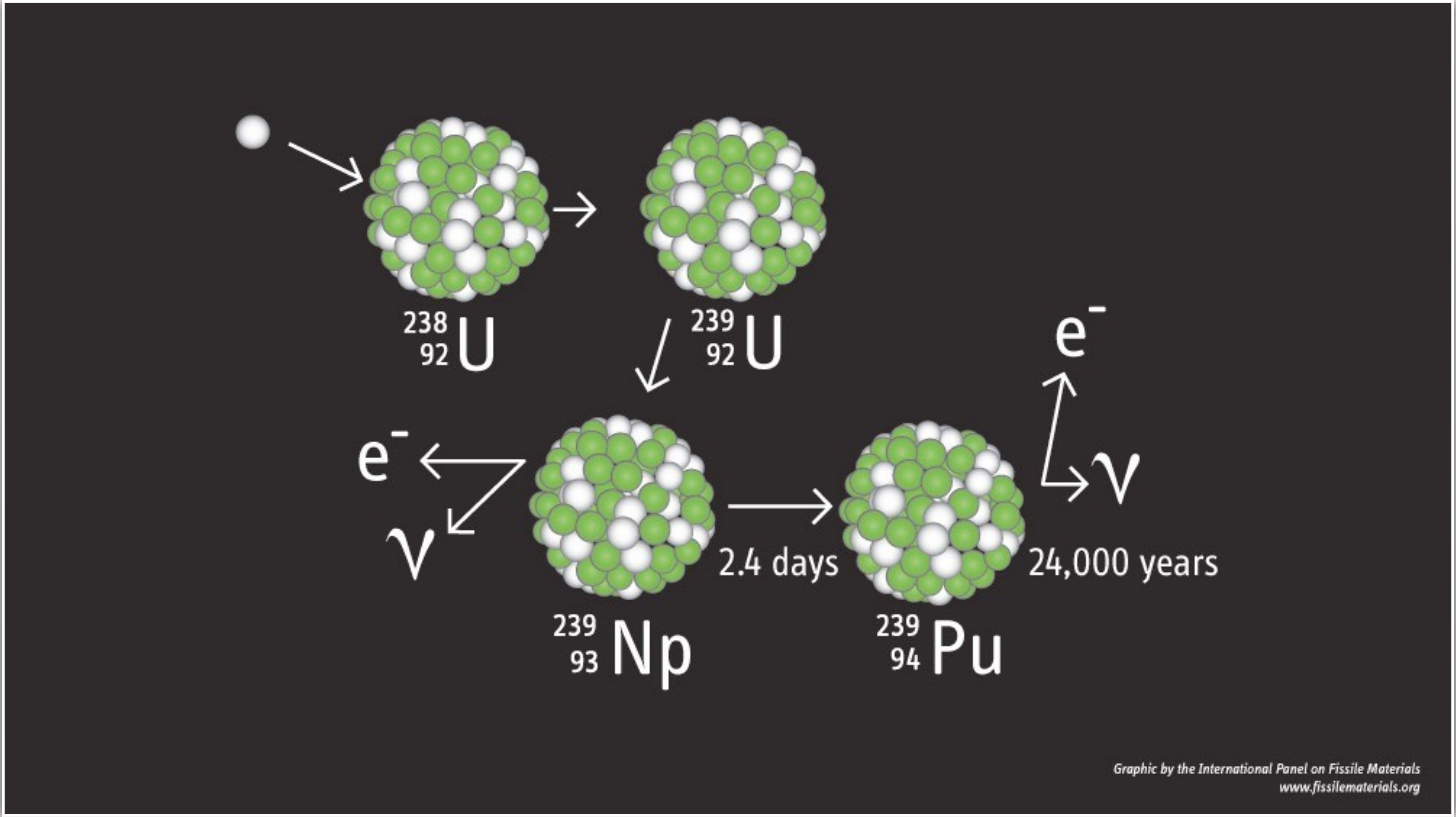
TWO ISOTOPES OF NATURAL URANIUM

ONLY ABOUT 0.7% IS U-235, VIRTUALLY ALL THE REST IS U-238)



(About 2 billion years ago, there remained about 3% U-235; the “Oklo reactor” in Gabon released nuclear energy for several 100,000 years)

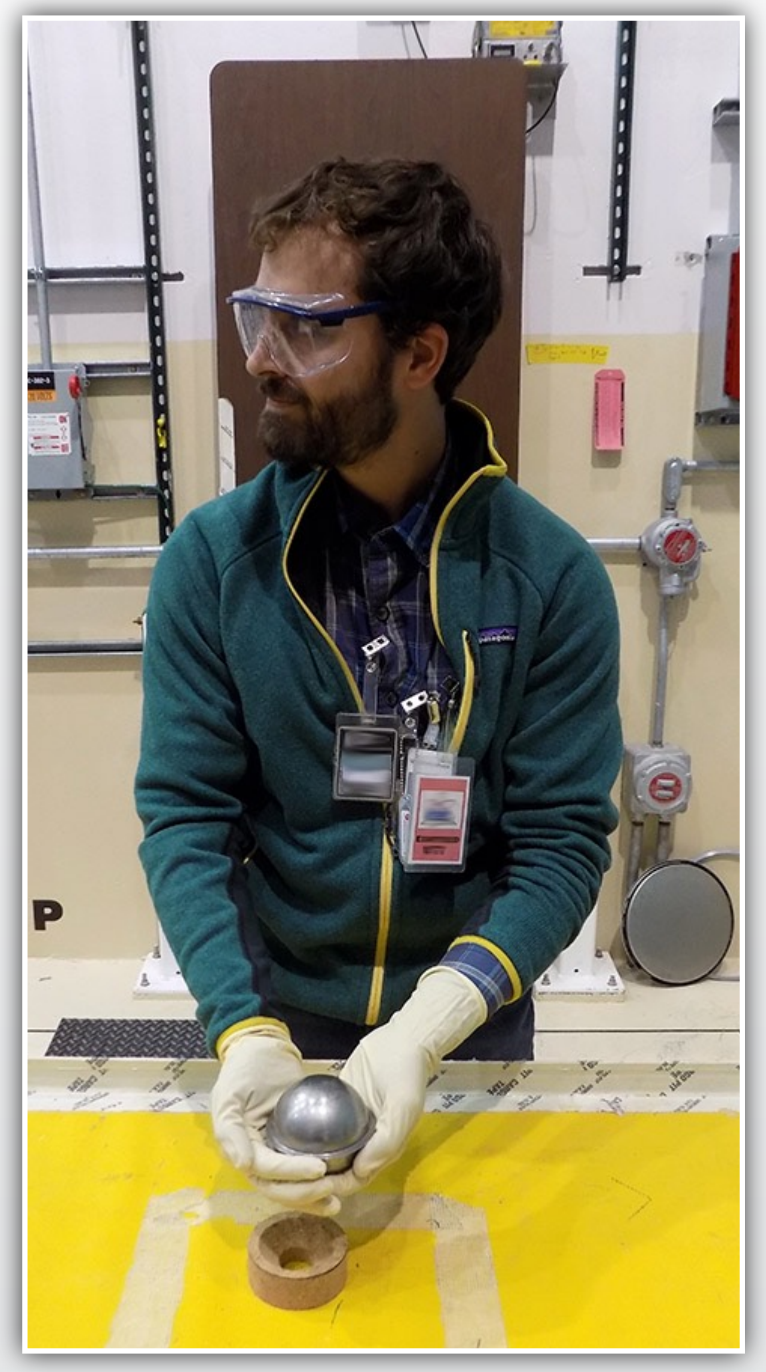
PLUTONIUM PRODUCTION



IT TAKES ONLY A FEW KILOGRAMS OF PLUTONIUM TO MAKE A NUCLEAR WEAPON

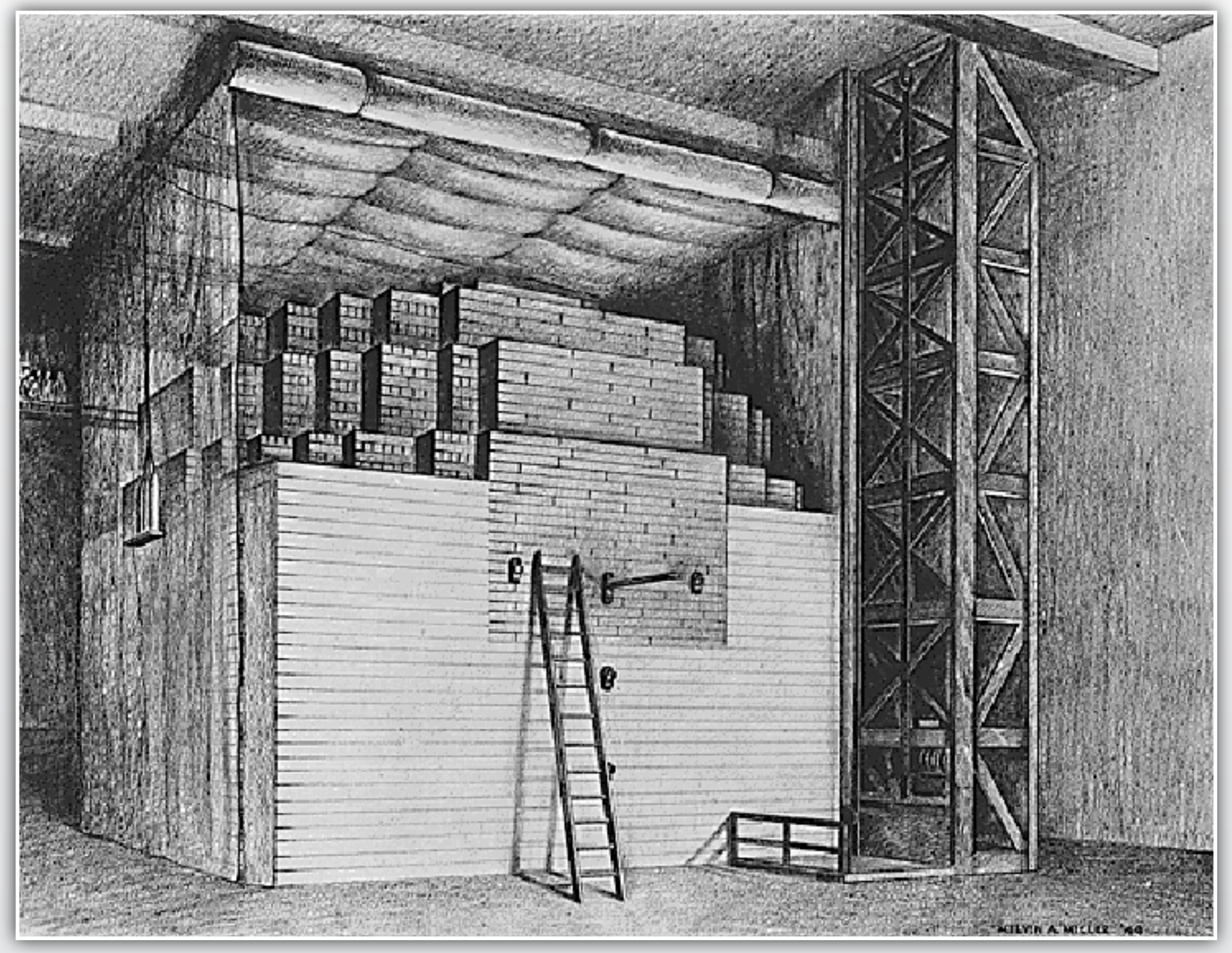
Delivery of the plutonium core at the Trinity Site
July 12, 1945

Holding the plutonium core of the Nagasaki bomb
Tinian Island, August 1945



Fissioning 1 kg of nuclear material (e.g. uranium-235 or plutonium) releases an amount of energy that is equivalent to the explosion of 18,000 tons of high-explosive (TNT)

THE FIRST NUCLEAR REACTORS WERE USED TO MAKE PLUTONIUM FOR WEAPONS



Chicago Pile-1 (CP-1), December 2, 1942

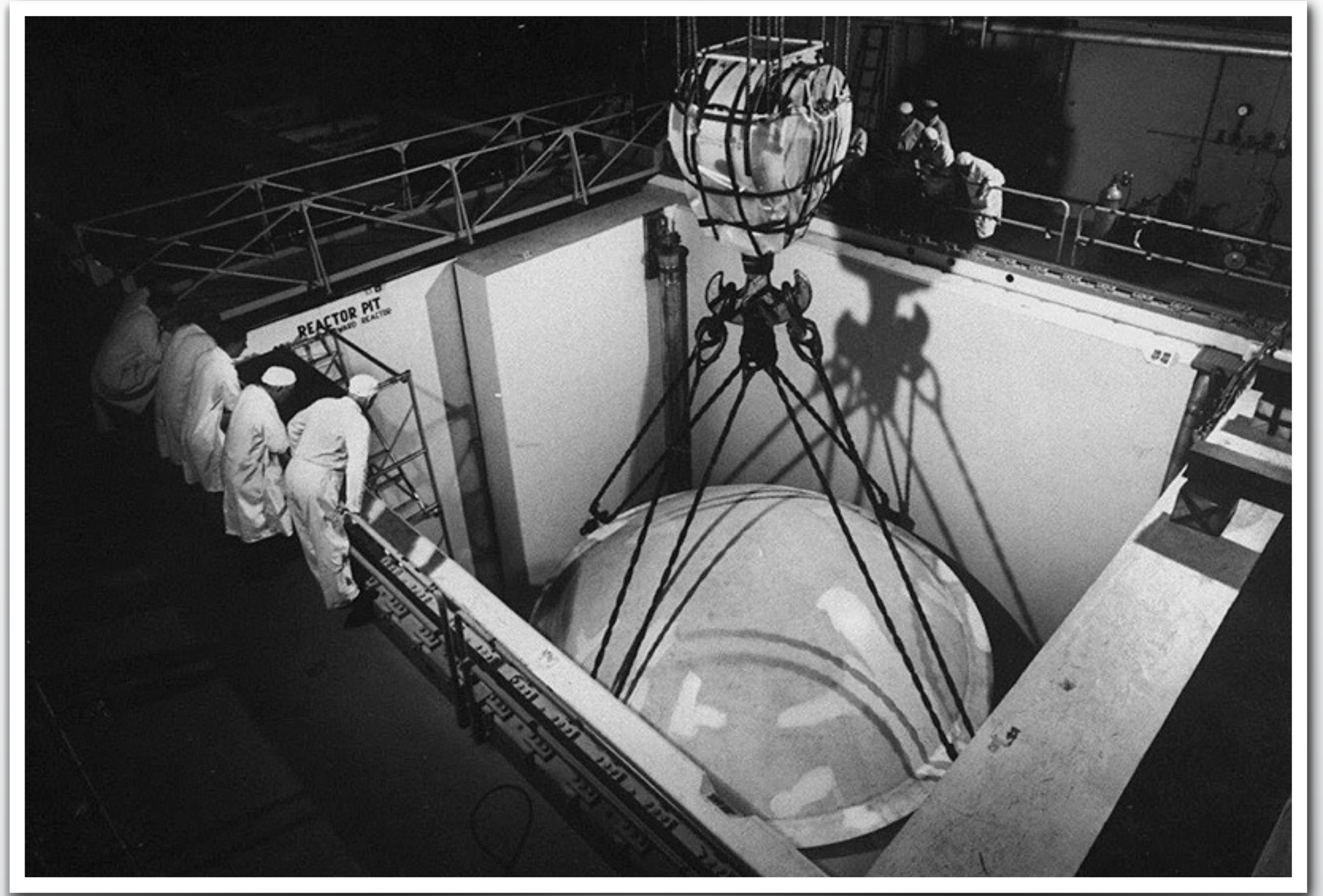
Hanford B Reactor, 1944
near Richland, WA

Ralph Vartabedian, A Poisonous Cold War Legacy That Defies a Solution, *New York Times,* May 31, 2023

NUCLEAR-POWERED SUBMARINES CAME NEXT

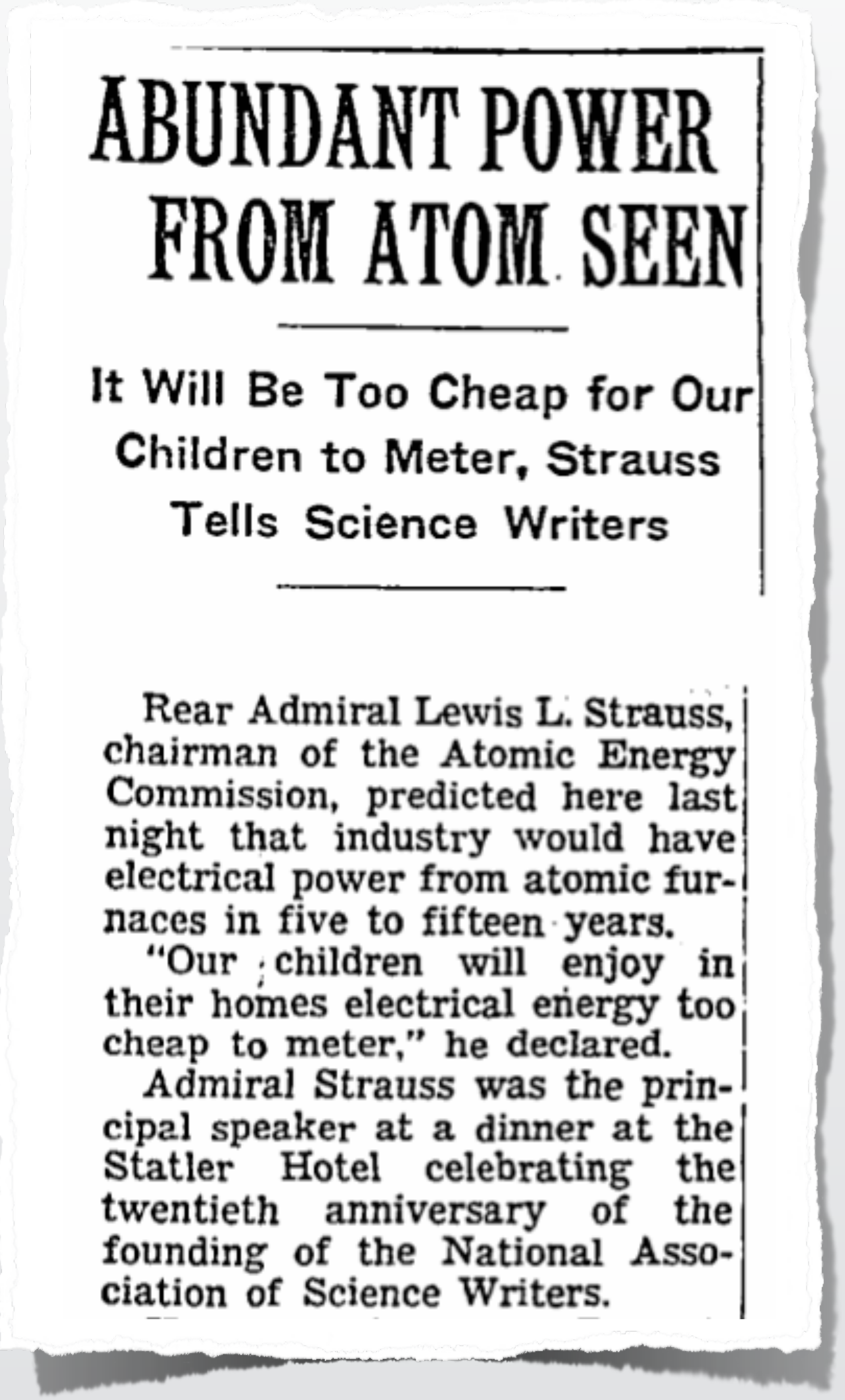
USS Nautilus (SSN-571), launched in 1954, here entering New York Harbor, 1958

THE FIRST CIVILIAN POWER REACTOR, 1957



Shippingport Atomic Power Station, Pennsylvania (Source: LIFE Magazine/Google)

LEWIS STRAUSS, 1954/1955



ABUNDANT POWER FROM ATOM SEEN

It Will Be Too Cheap for Our Children to Meter, Strauss Tells Science Writers

Rear Admiral Lewis L. Strauss, chairman of the Atomic Energy Commission, predicted here last night that industry would have electrical power from atomic furnaces in five to fifteen years.

"Our children will enjoy in their homes electrical energy too cheap to meter," he declared.

Admiral Strauss was the principal speaker at a dinner at the Statler Hotel celebrating the twentieth anniversary of the founding of the National Association of Science Writers.

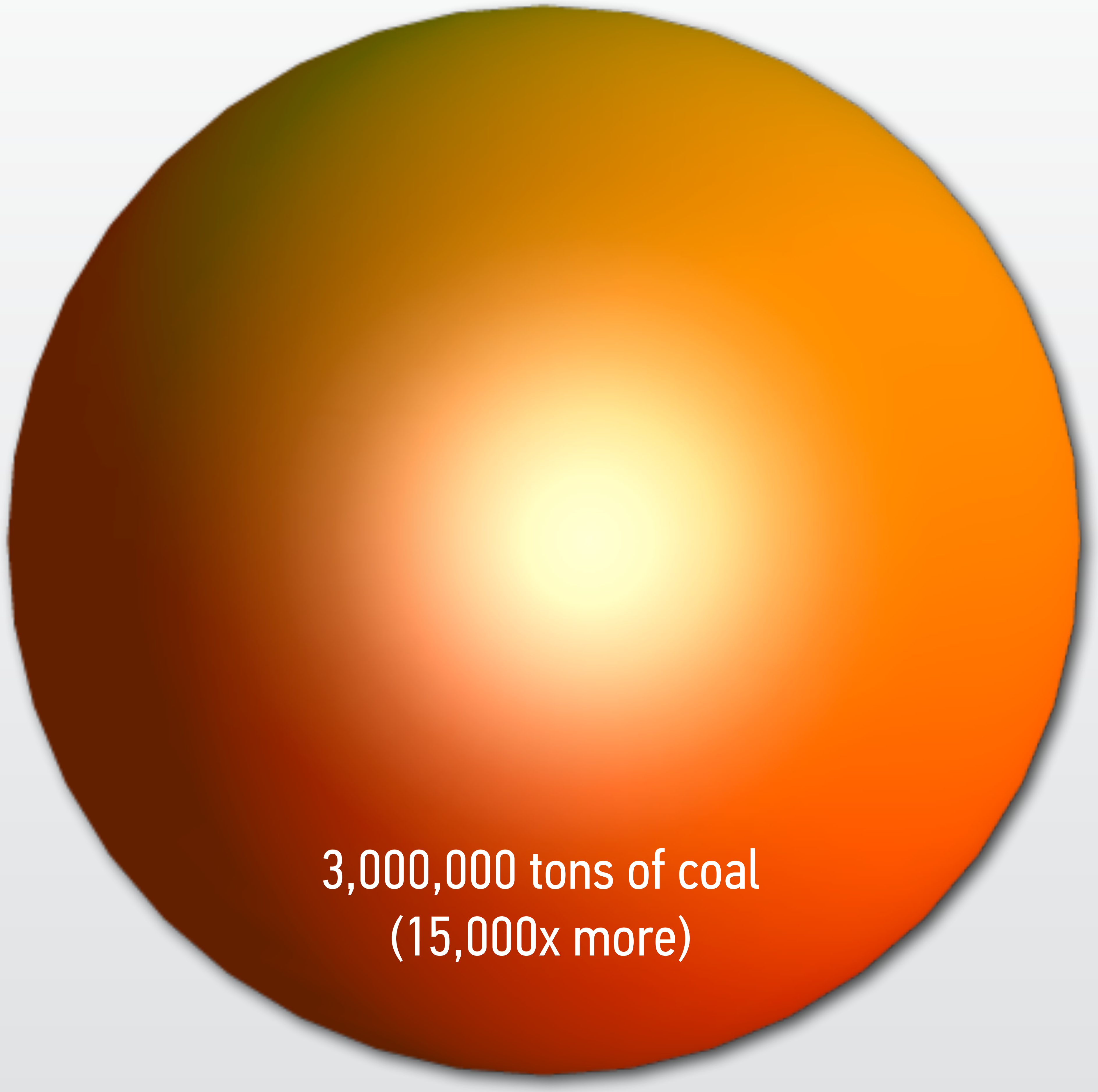
(NYT, 9/17/1954)

"It is not too much to expect that our children will enjoy in their homes electrical energy too cheap to meter; will know of great periodic regional famines in the world only as matters of history; will travel effortlessly over the seas and under them and through the air with a minimum of danger and at great speed, and will experience a lifespan far longer than ours, as disease yields and man comes to understand what causes him to age. This is the forecast of an age of peace."

Lewis L. Strauss quoted in the New York Times, August 7, 1955

ELECTRICITY FOR 800,000 U.S. HOUSEHOLDS

200 tons of uranium have to be mined
to produce 20 tons of nuclear fuel
(only 1 ton is ultimately fissioned)



Shown is annual fuel demand for 1000 MWe plant; average U.S. household consumption: 1.2 kW or about 30 kWh per day

Microreactors and small modular reactors (SMR) — often designed for high-assay low-enriched uranium (HALEU) fuel

Source: Westinghouse Electric Company

Think, Pair, Share

(Pros & Cons of Nuclear Power)

WHAT FACTORS TEND TO PUT NUCLEAR POWER AT AN ADVANTAGE?

Time-tested
Small life-cycle CO_2 Emissions
In principle: scalable (→ few “physical” constraints)
In principle: inexhaustible (→ few resource constraints)
High availability (→ good for “firm” electricity generation)
Centralized production (→ adequate for today’s electric grid)
Attractive if projections for future electricity demand are high

WHAT FACTORS TEND TO PUT NUCLEAR POWER AT A DISADVANTAGE?

Safety concerns (→ risk of catastrophic accidents)

Requirement for disposal of long-lived radioactive nuclear waste

Weapons connection (→ nuclear proliferation)

Concerns about radiological and nuclear terrorism (sabotage)

Public opinion

Economics

Can go either way: Energy security (→ reliable access to fuel resources)

“FOUR CONVICTIONS”

(SOCOLOW & GLASER, 2009)

First, nuclear power could make a significant contribution to climate change mitigation. *To do so, however, nuclear power would have to be deployed extensively, including in the developing world. A “one-tier” world will be required—that is, a world with an agreed set of rules to govern nuclear power that are the same in all countries. ...*

Second, the world is not now safe for a rapid global expansion of nuclear energy. *Nuclear-energy use today relies on technologies and a system of national governance of the nuclear fuel cycle that carry substantial risks of nuclear weapons proliferation. [...] Nuclear war is a terrible trade for slowing the pace of climate change.*

Third, a world considerably safer for nuclear power could emerge as a co-benefit of the nuclear disarmament process. *The national-security community is currently engaged, to an unprecedented degree, in seeking progress toward nuclear disarmament. ...*

Finally, the next decade is critical. *While several approaches to climate change mitigation are available for immediate, rapid scale-up, nuclear power could be so in maybe 10 years, provided the coming decade is used to establish adequate technologies and new norms of governance. Nuclear power ought to be deployed seriously as a mitigation strategy only when and if it can provide a sustainable contribution.*

Controlled Nuclear Power

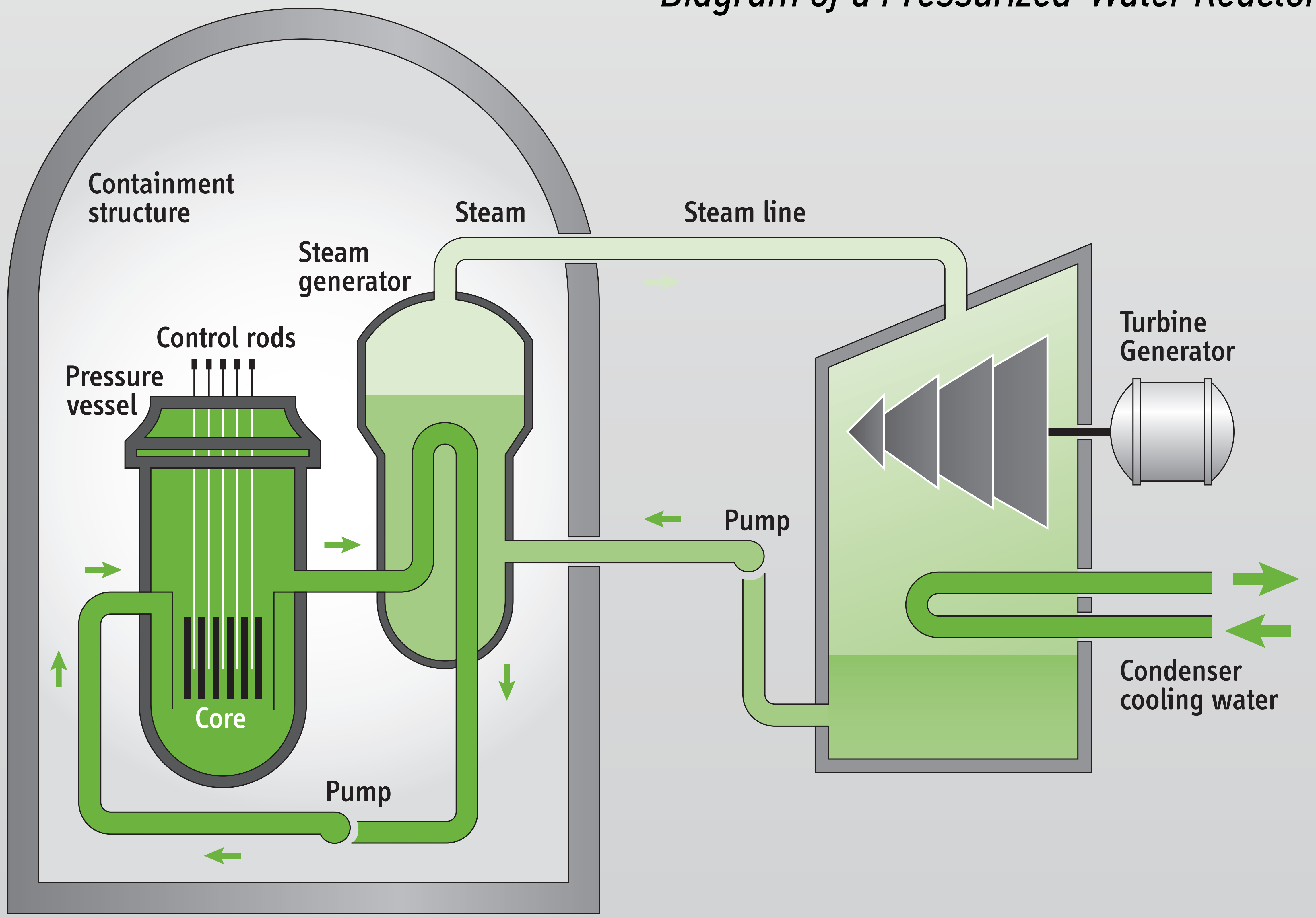
(Nuclear Fuels & Reactor Types)

ELEMENTS OF A NUCLEAR REACTOR

- Fuel
  (containing fissile and fertile materials)
- Coolant
  (to remove the heat from the core)
- Control System
  (to maintain criticality at all times)
- Moderator
  (may or may not be present depending on the type of reactor)

- Containment vessel
  (to prevent escape of radioactive materials)
- Reflector
  (to reduce critical size of reactor)
- Shielding
  (to absorb penetrating radiation and protect operating personnel)
- Emergency Systems
  (to prevent runaway operation in the event of a failure)

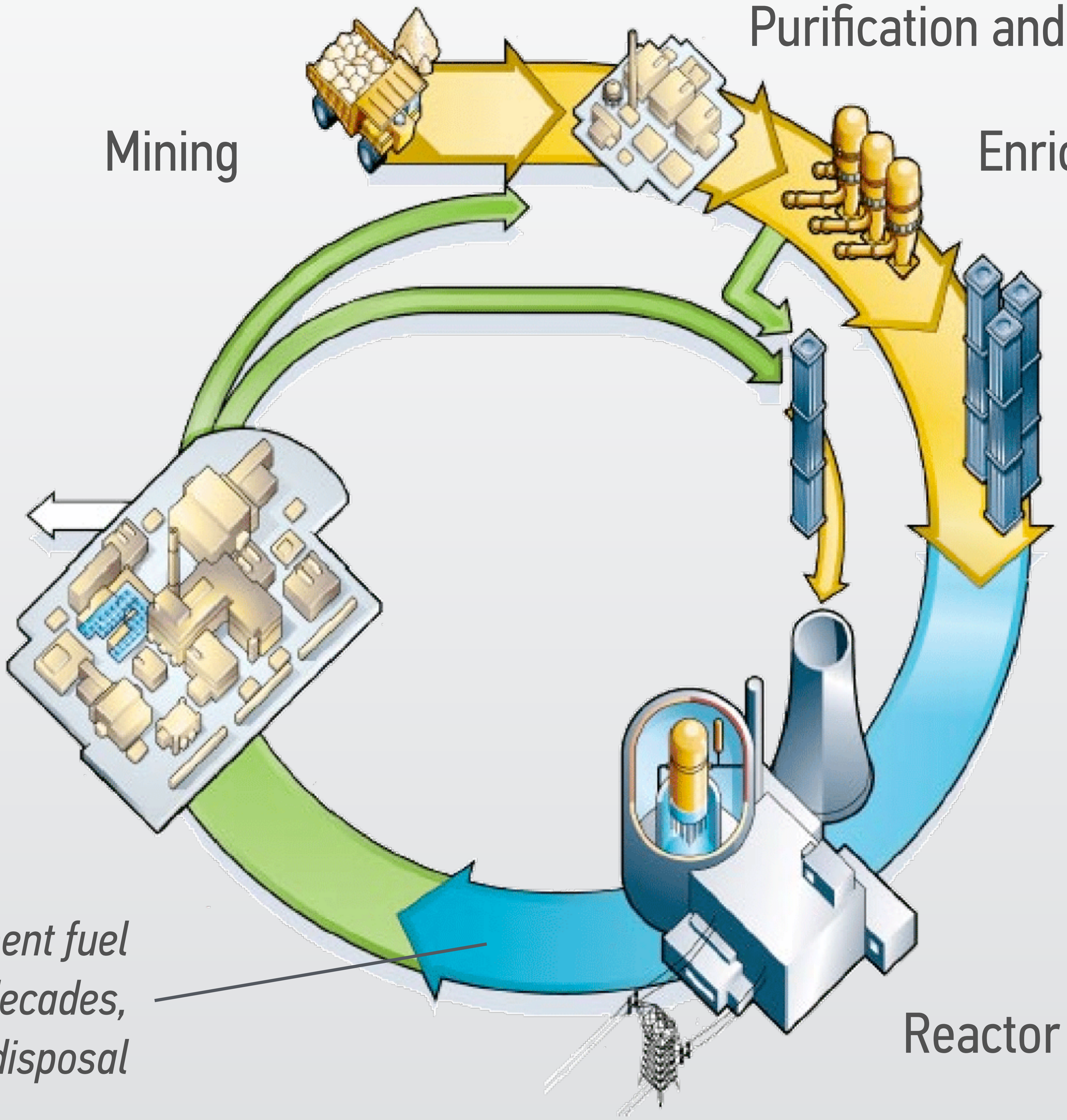
Diagram of a Pressurized-Water Reactor



Source: fissilematerials.org

THE NUCLEAR FUEL CYCLE

(ACCORDING TO AREVA/ORANO)



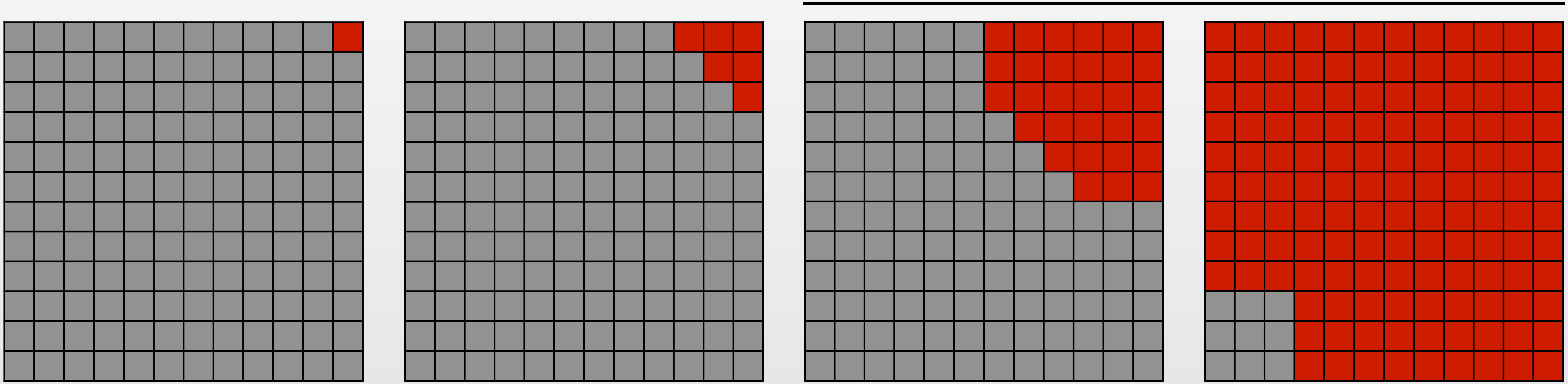
In reality, there are strong arguments to consider spent fuel nuclear waste and store it aboveground for years/decades, pending final geological disposal

Uranium Enrichment

ENRICHED URANIUM

VISUALLY

HEU
(weapon-usable)

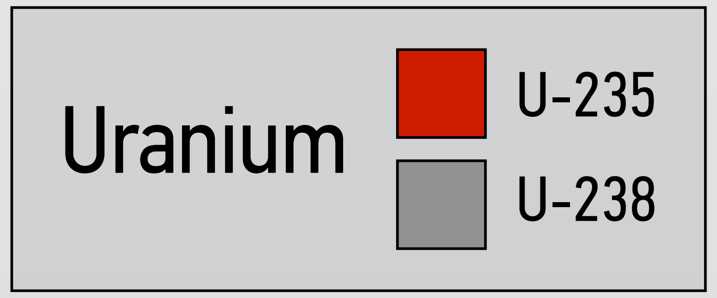


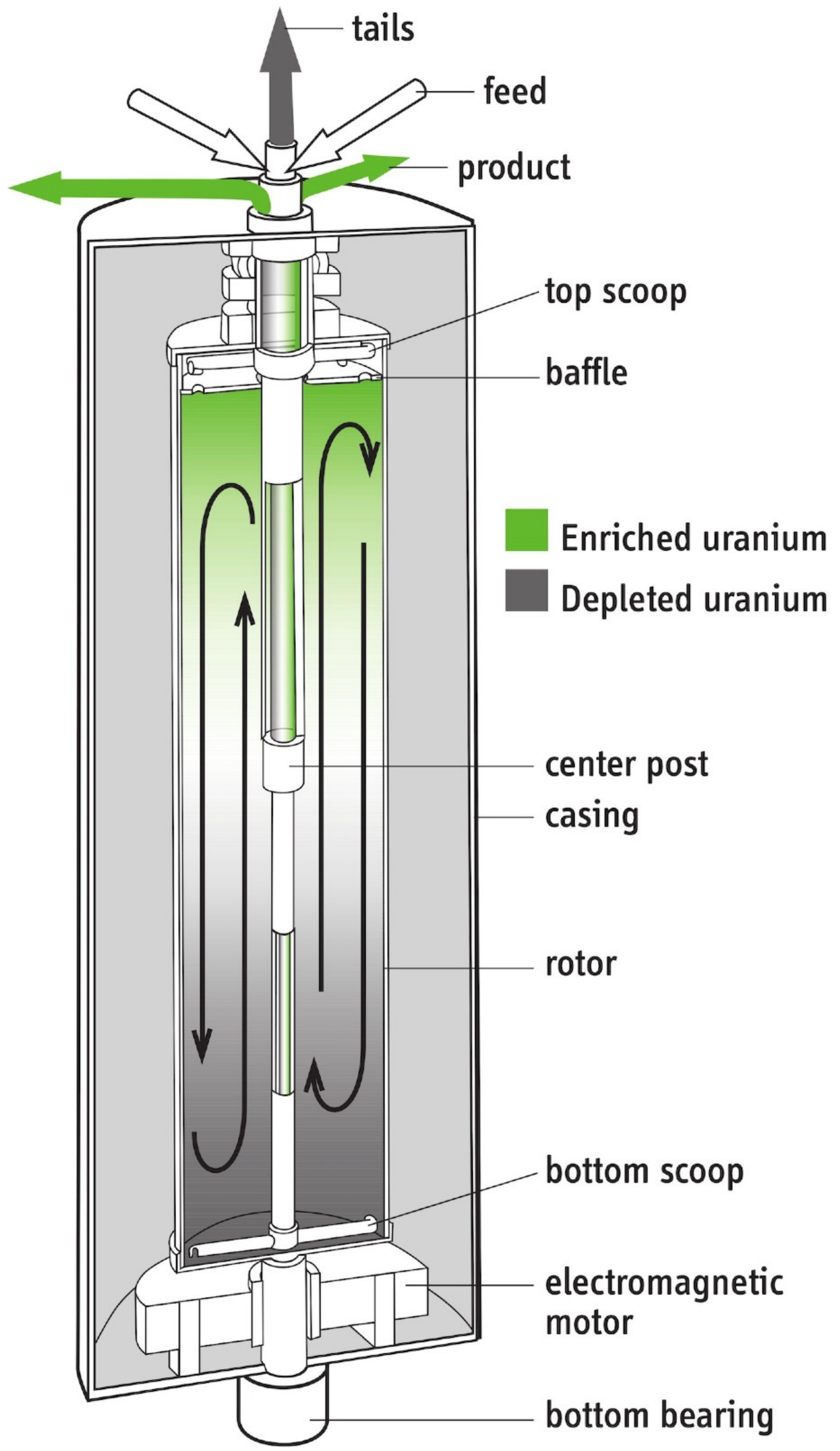
Natural uranium
0.7% U-235

Low-enriched uranium
typically 3-5%,
but less than 20% U-235

Highly enriched uranium
20% U-235 and above

Weapon-grade uranium
more than 90% U-235





Source: fissilematerials.org

Source: urenco.com

WHY CENTRIFUGES ARE DIFFERENT

CLANDESTINE OPTION

Centrifuge enrichment plants can, unlike most other nuclear facilities, be built underground
This was largely a hypothetical, until Iran's first enrichment plant was discovered in 2002

They also don't need much electricity and do not have distinctive features

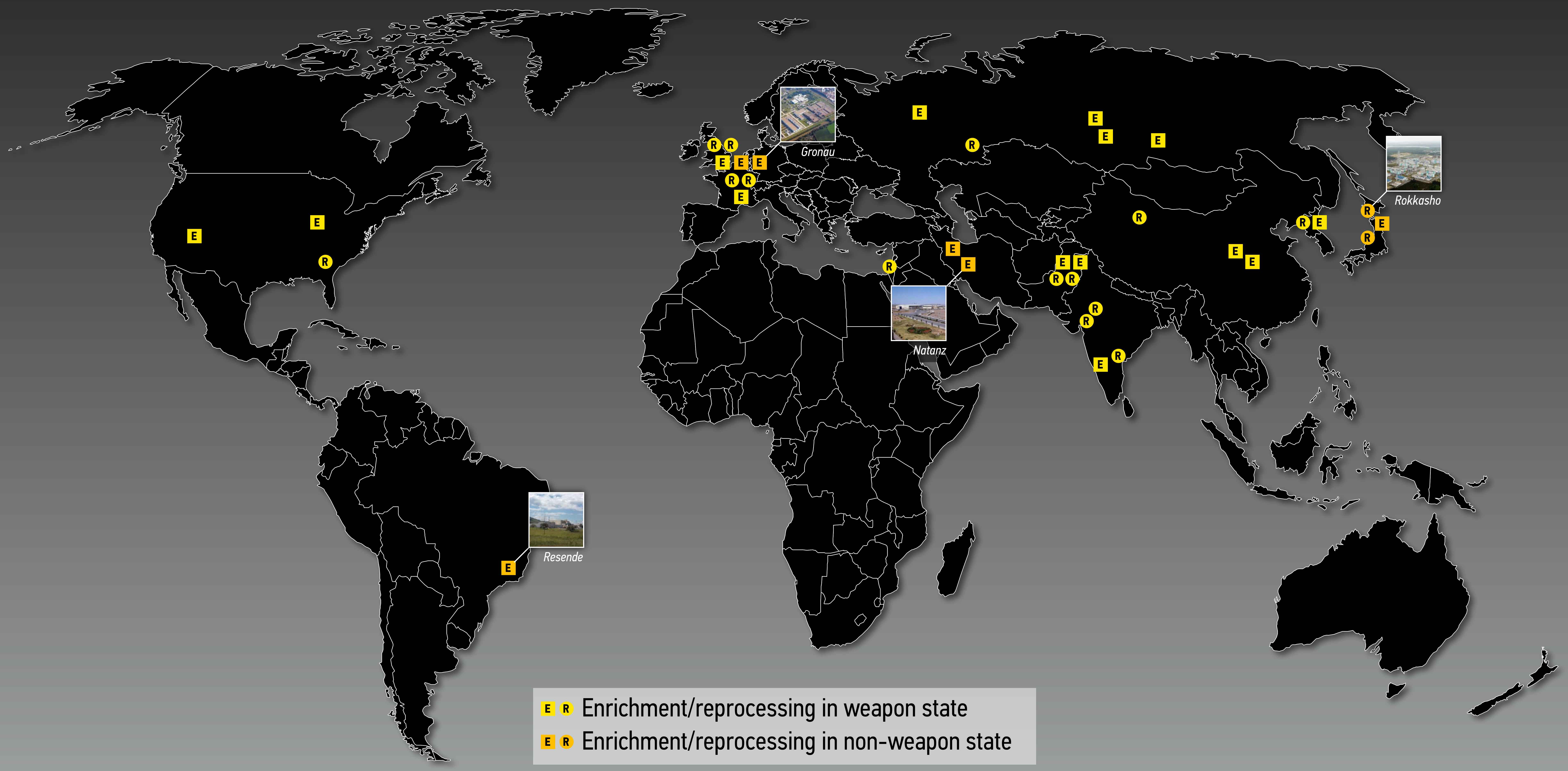
RAPID BREAKOUT

Centrifuge enrichment plants can be quickly reconfigured from the production of low-enriched uranium (for peaceful purposes) to the production of highly enriched uranium (for weapons purposes); this shortens breakout times from months/years to weeks/days

Source: Maxar (top) and president.ir (bottom)

WHO CAN MAKE FISSILE MATERIAL TODAY

ENRICHMENT AND REPROCESSING FACILITIES WORLDWIDE

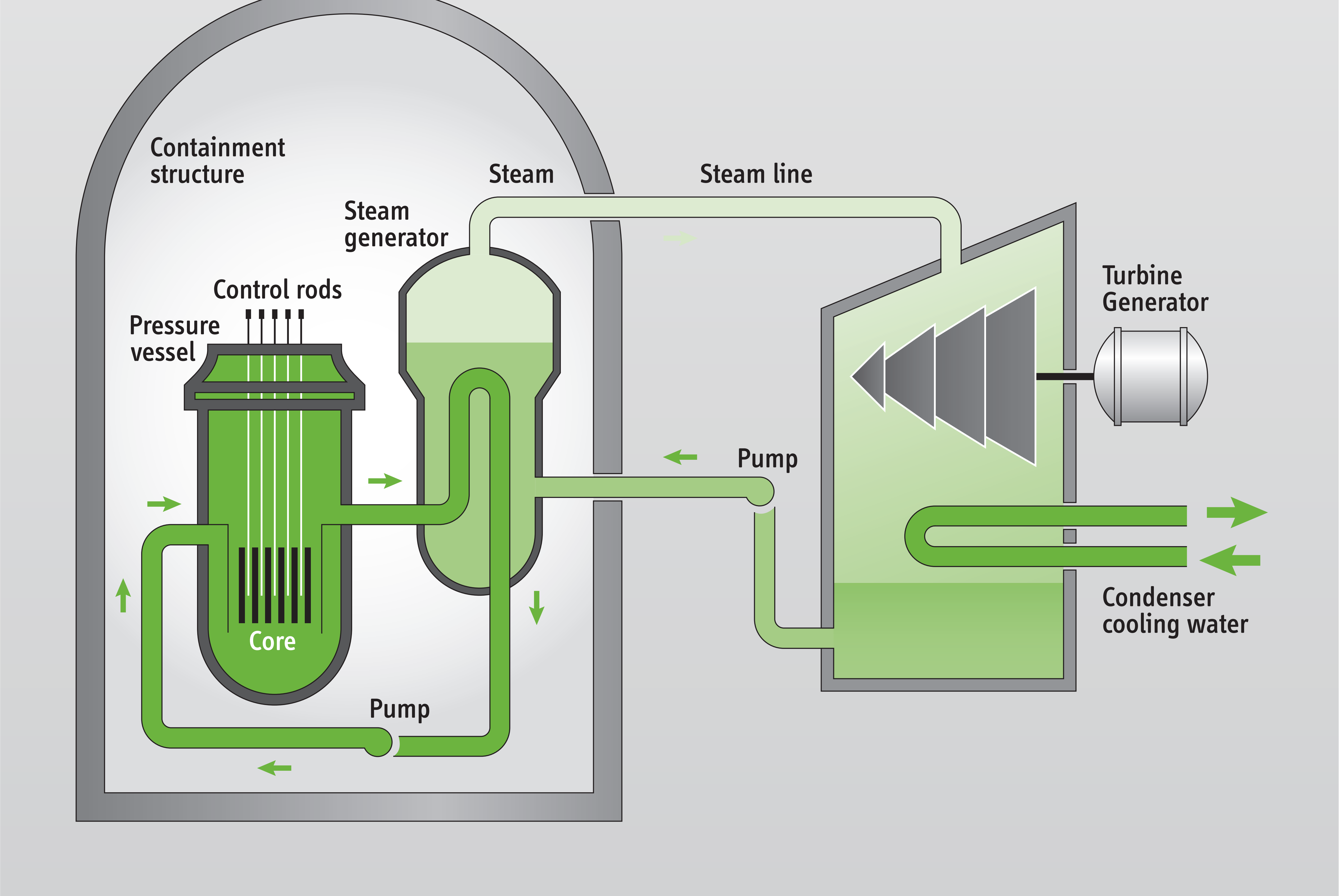


Example

Resource requirements of a light-water reactor

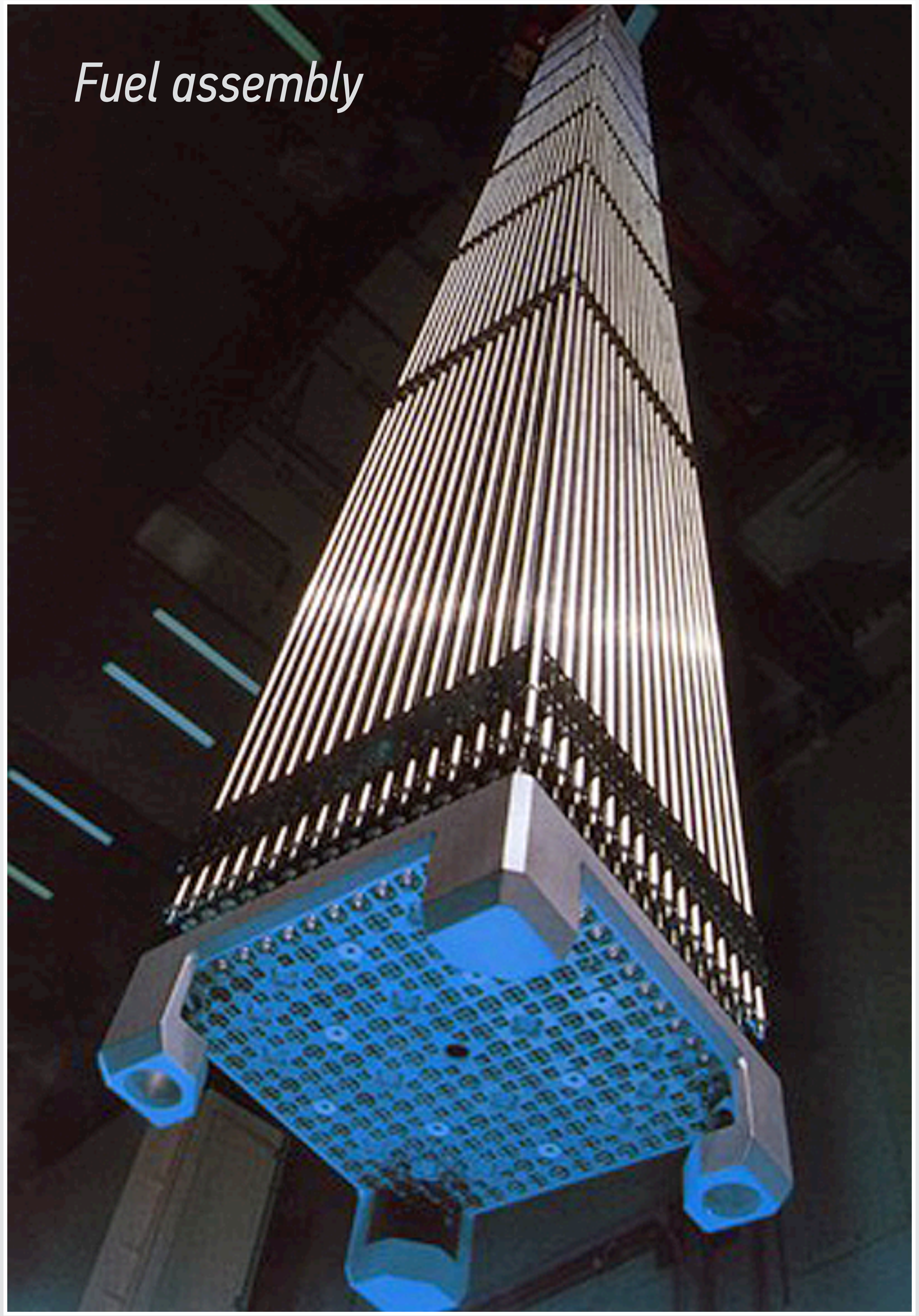
ELEMENTS OF A NUCLEAR REACTOR

Diagram of a Pressurized-Water Reactor



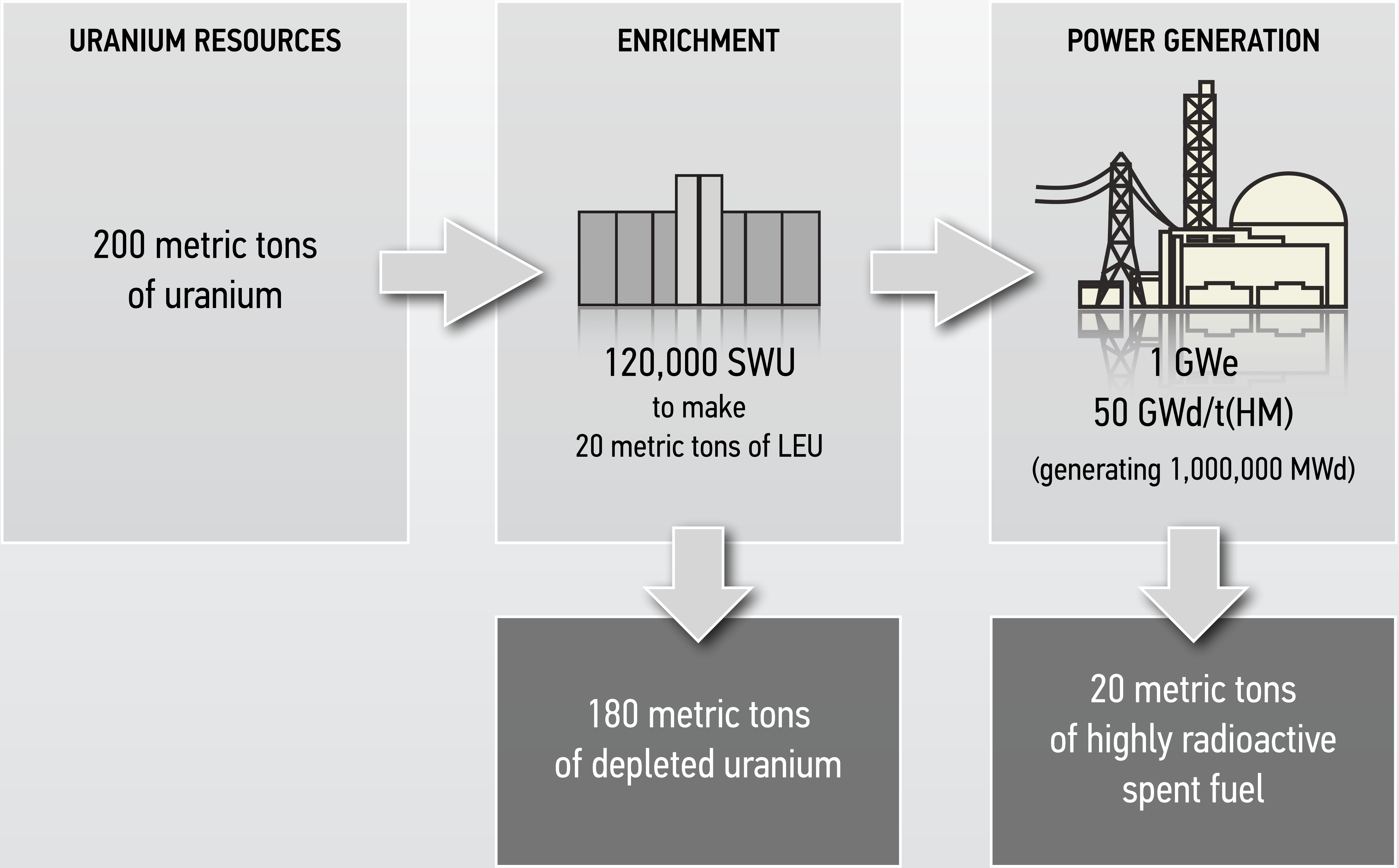
Source: fissilematerials.org

Fuel assembly



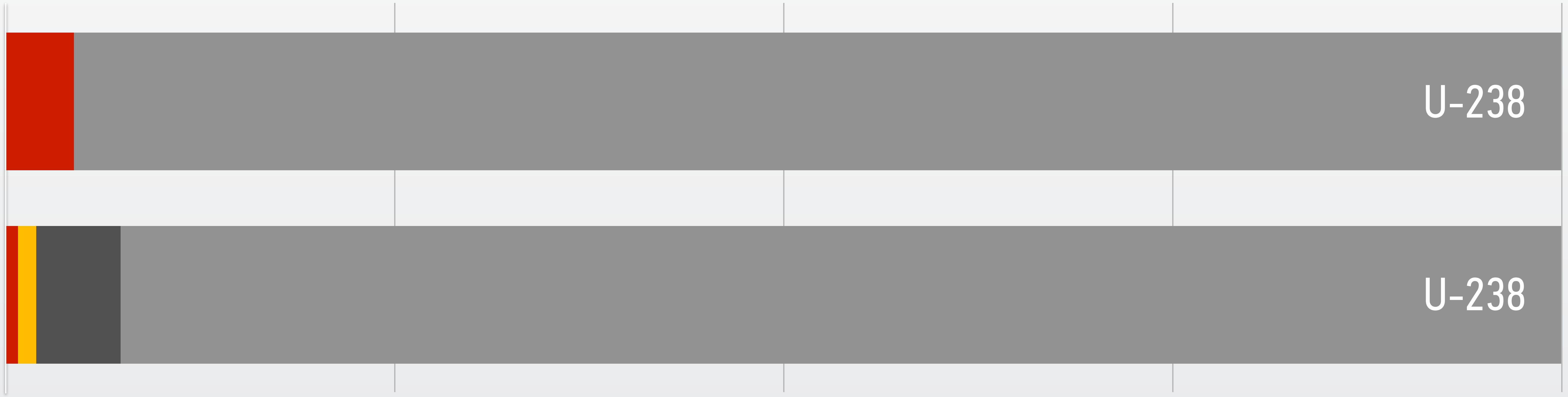
ONCE-THROUGH NUCLEAR FUEL CYCLE

ANNUAL FUEL CYCLE REQUIREMENTS FOR 1 GWe (SIMPLIFIED)



What About the Spent Fuel?

MAKEUP OF FRESH AND IRRADIATED LIGHT-WATER REACTOR FUEL

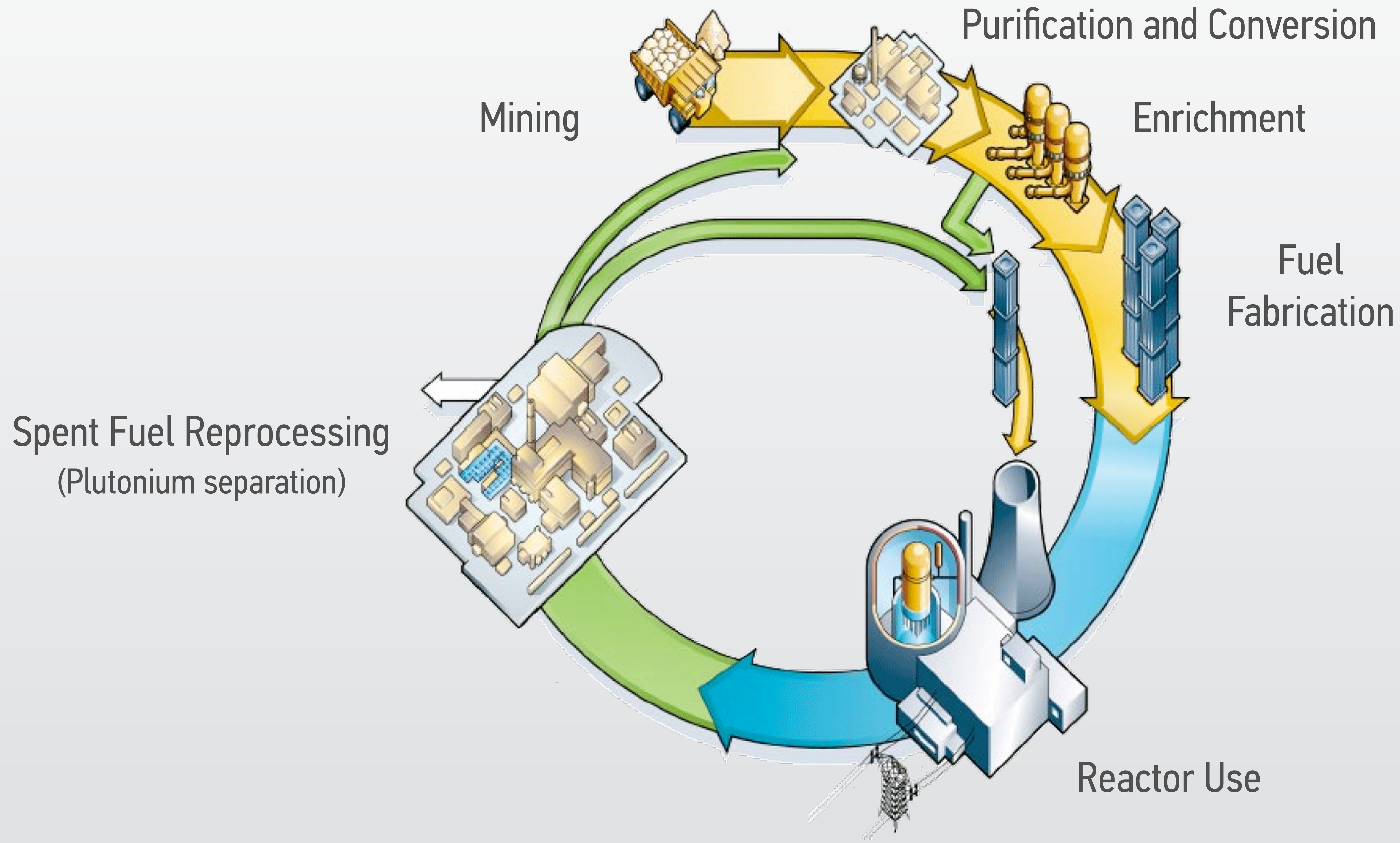


Composition of irradiated fuel

- U-238
- U-235 (0.8–0.9%)
- Plutonium and other actinides (1.0–1.2%)
- Fission products (about 5%)

THE NUCLEAR FUEL CYCLE

(ACCORDING TO AREVA/ORANO)



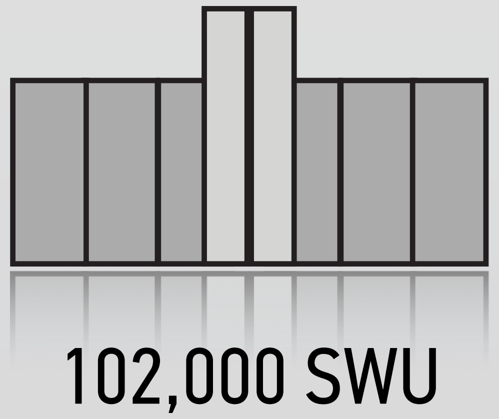
SINGLE-PASS PLUTONIUM RECYCLING

ANNUAL FUEL CYCLE REQUIREMENTS FOR 1 GWe (SIMPLIFIED)

URANIUM RESOURCES

170 metric tons
of uranium

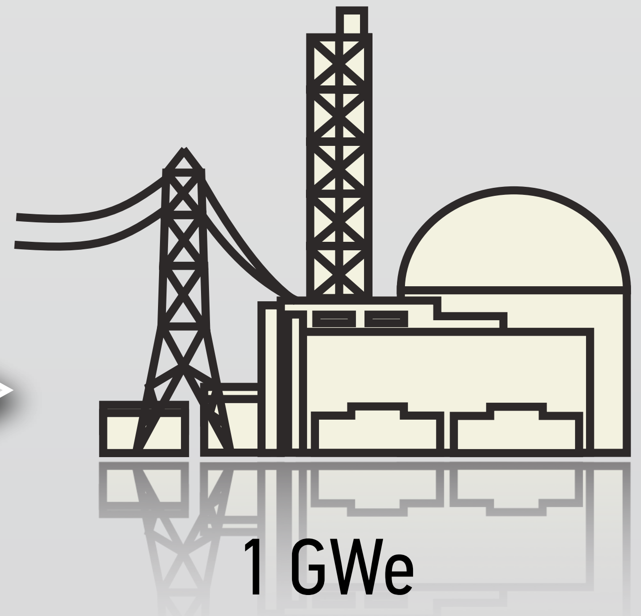
ENRICHMENT



102,000 SWU
to make
17 metric tons of LEU

153 metric tons
of depleted uranium

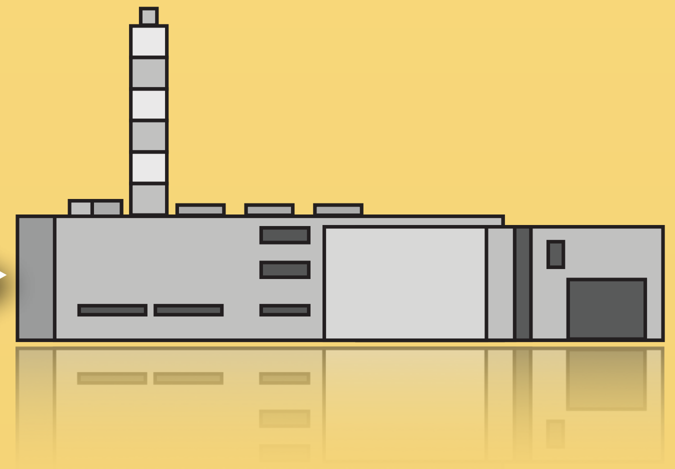
POWER GENERATION



1 GWe
50 GWd/t(HM)
(85% LEU + 15% MOX)

3 metric tons
of highly radioactive
spent MOX fuel

**REPROCESSING
AND MOX FABRICATION**

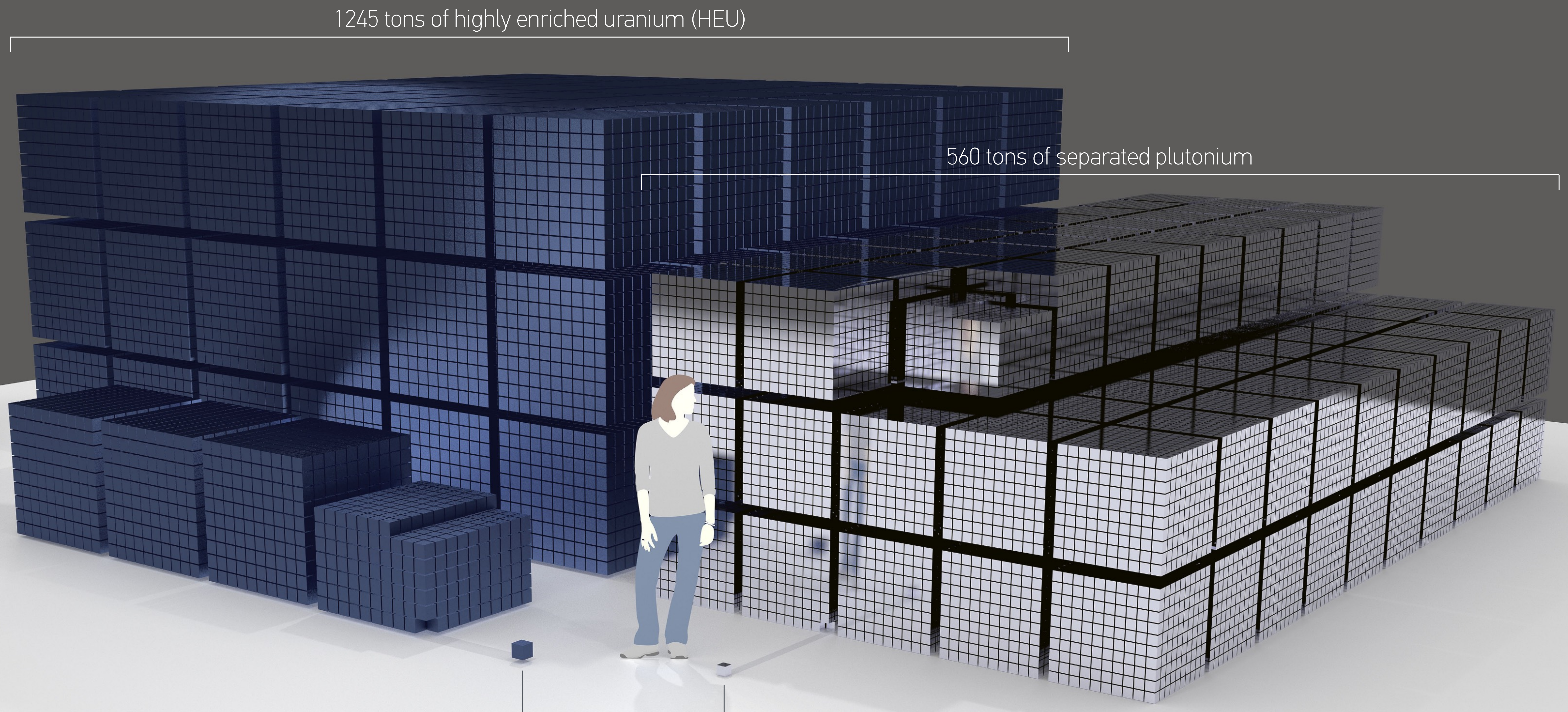


Separation of 205 kg of
plutonium to make 3 metric
tons of “mixed-oxide fuel”

Large amounts of process
waste containing 0.85 metric
tons of fission products

Graphic/concept by Alex Wellerstein and Tamara Patton
Inventory estimates from fissilematerials.org
Status as of end of 2023

There is enough nuclear explosive material in the world to make over 200,000 nuclear weapons

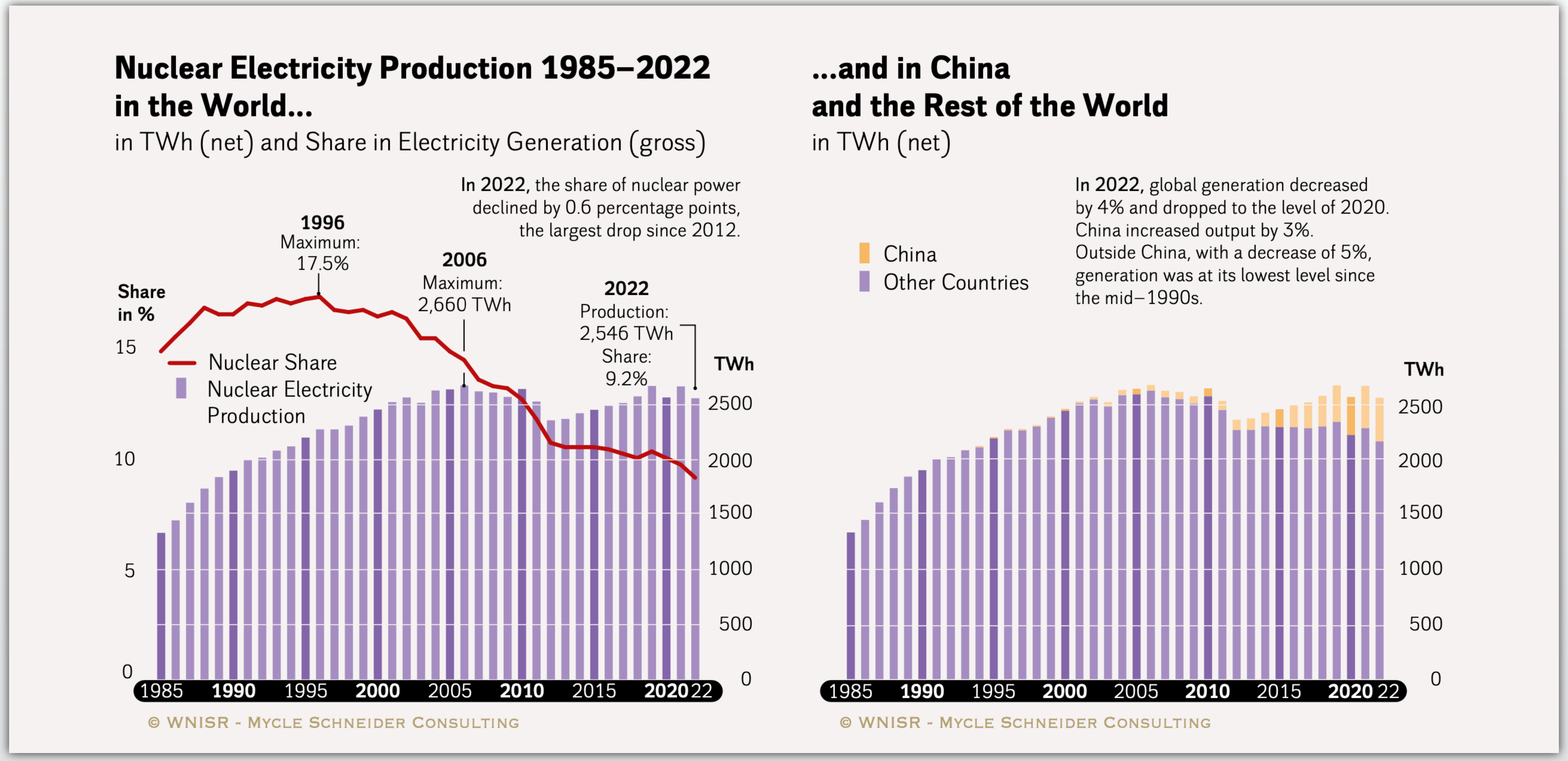


Each block corresponds to 12 kg of HEU, the amount necessary to make a fission bomb; about 100,000 bombs-worth total

Each block corresponds to 4 kg of plutonium, the amount necessary to make a fission bomb; about 140,000 bombs-worth total

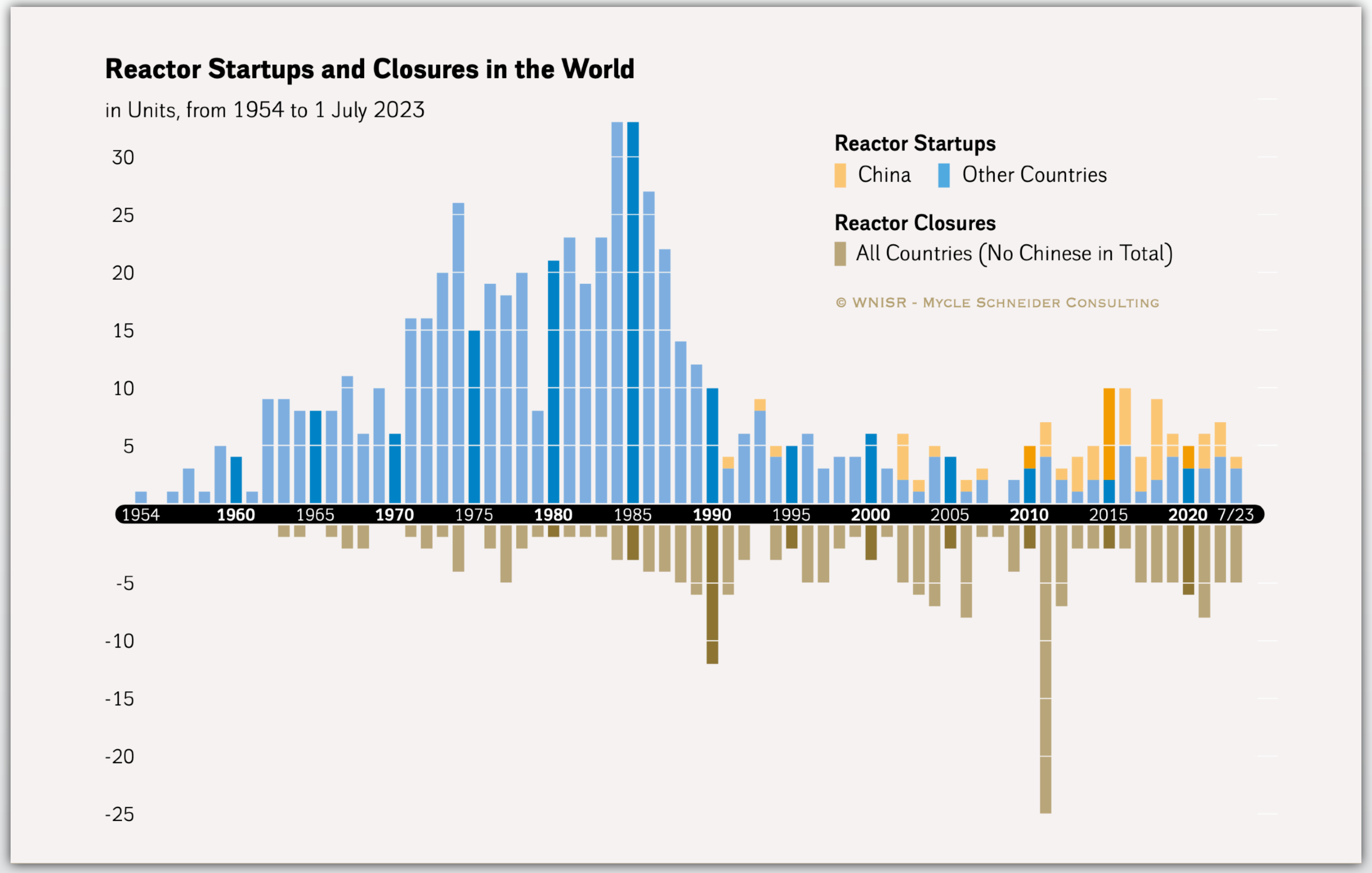
Looking Ahead

GLOBAL NUCLEAR OPERATING CAPACITY



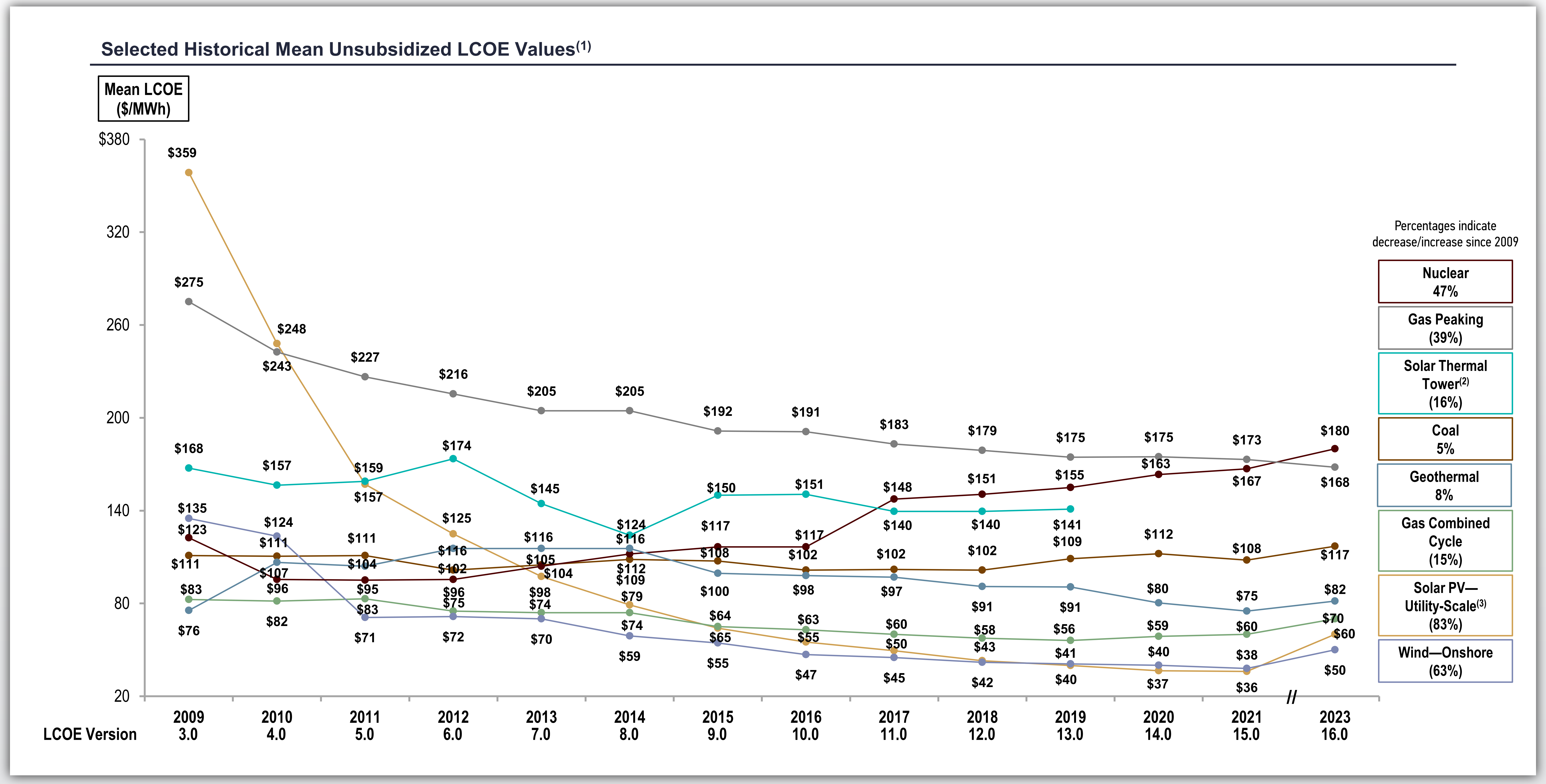
M. Schneider, A.Froggatt, et al., World Nuclear Industry Status Report 2023, Paris, April 2024

REACTOR STARTUPS & CLOSURES



M. Schneider, A.Froggatt, et al., World Nuclear Industry Status Report 2023, Paris, April 2024

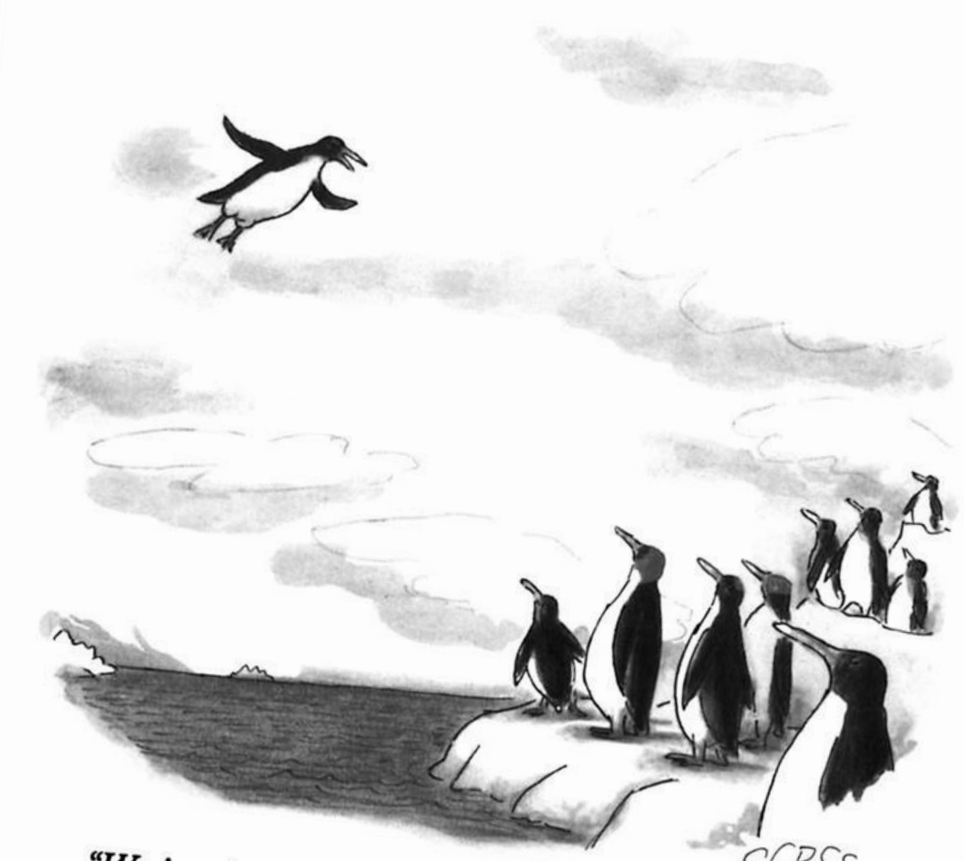
EVOLUTION OF LCOE'S OVER TIME



Lazard, *Levelized Cost of Energy*, Version 16.0, April 2023, www.lazard.com/research-insights/2023-levelized-cost-of-energyplus

Are We Missing Something?

(I really don't think so)



"We just haven't been flapping them hard enough."

WHEN THINGS ARE TOO GOOD TO BE TRUE

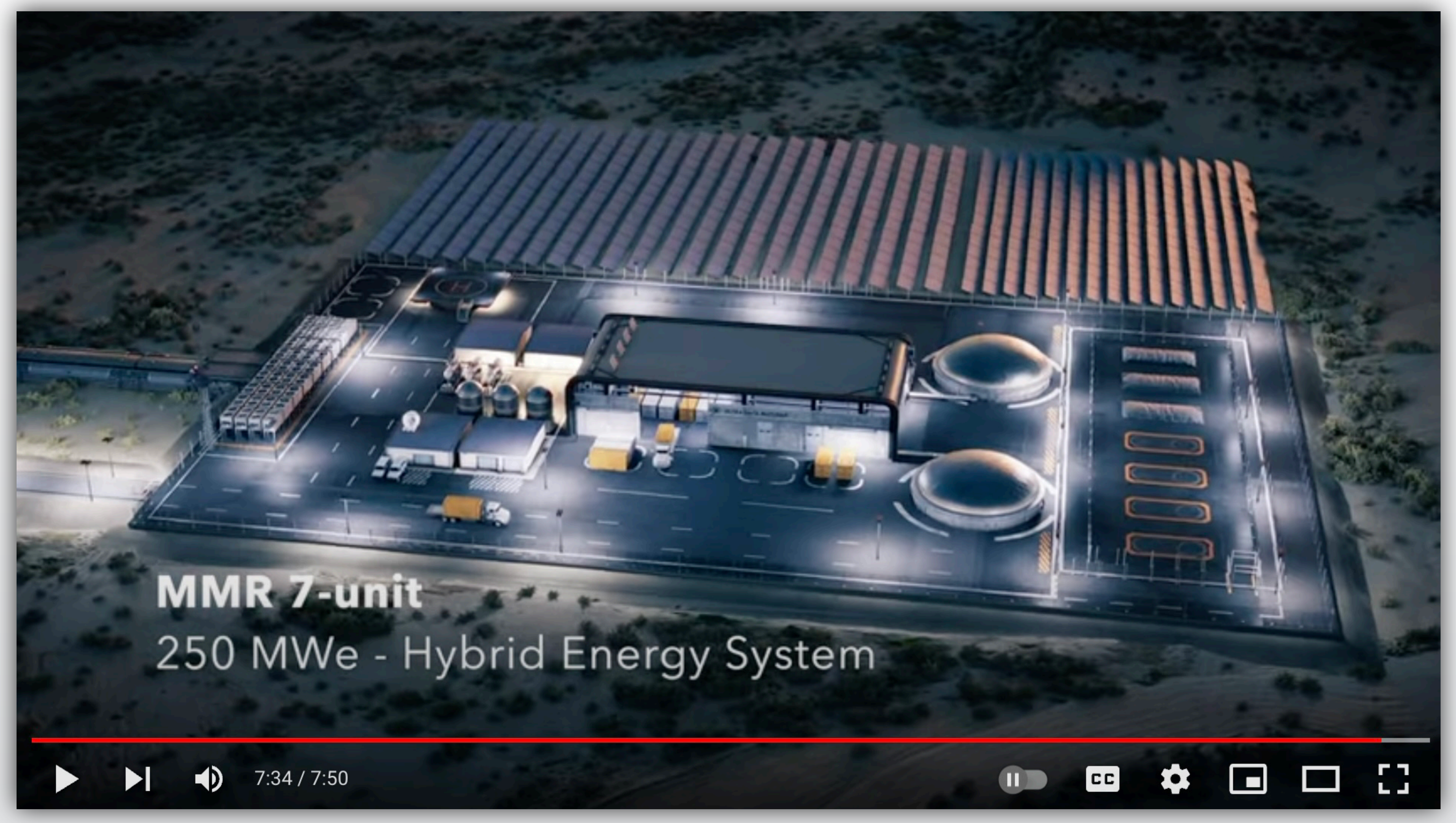
Source: Marius Bugge

TEDxNewEngland, Nov. 2011, www.youtube.com/watch?v=bHJuz5pNQL8&t=721s

www.transatomicpower.com
www.technologyreview.com/2017/02/24/68882/nuclear-energy-startup-transatomic-backtracks-on-key-promises

"THE MICRO MODULAR REACTOR"

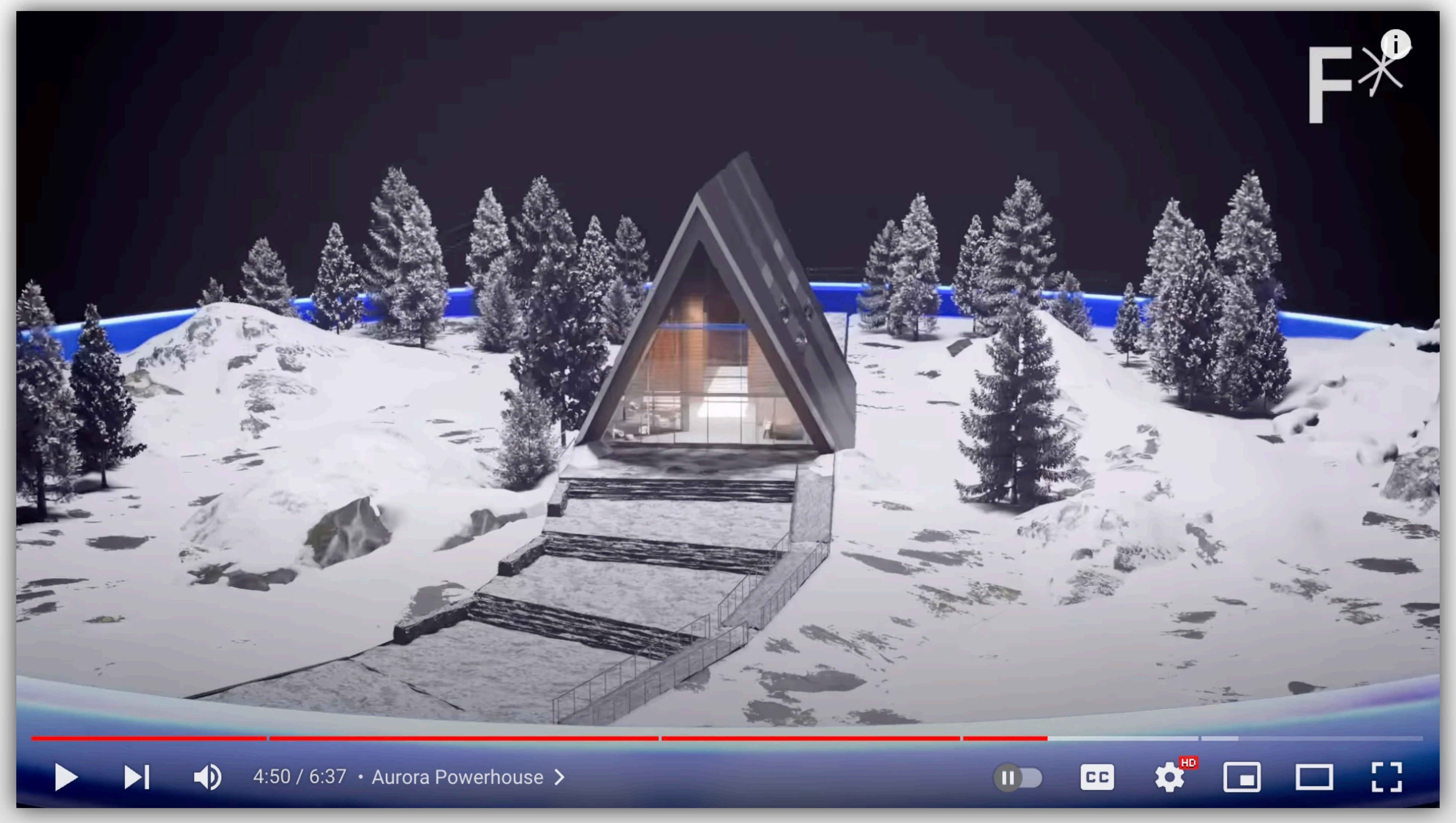
(ULTRA SAFE NUCLEAR FILED FOR CHAPTER 11 BANKRUPTCY IN OCTOBER 2024)



www.youtube.com/watch?v=6PB1OM2yy8I&t=127s

“THE AURORA POWERHOUSE”

(THE U.S. NRC DENIED THE LICENSE “WITHOUT PREJUDICE” IN JANUARY 2022)



www.youtube.com/watch?v=MEfkW9IyYfI and www.nrc.gov

NUCLEAR POWER IN THE AGE OF “AI” AND LARGE LANGUAGE MODELS

HOME > NEWS > THE CRITICAL POWER CHANNEL

Sam Altman-backed nuclear reactor firm Oklo hiring data center lead as it looks to power "AI and cloud computing"

Fission company looks to b
amid power crunch

FORBES > INNOVATION > AI

Microsoft And OpenAI Partner On $100 Billion U.S. Data Center, Report Says

Cindy Gordon Contributor

CEO, Innovation Leader Passionate about Modernizing via AI

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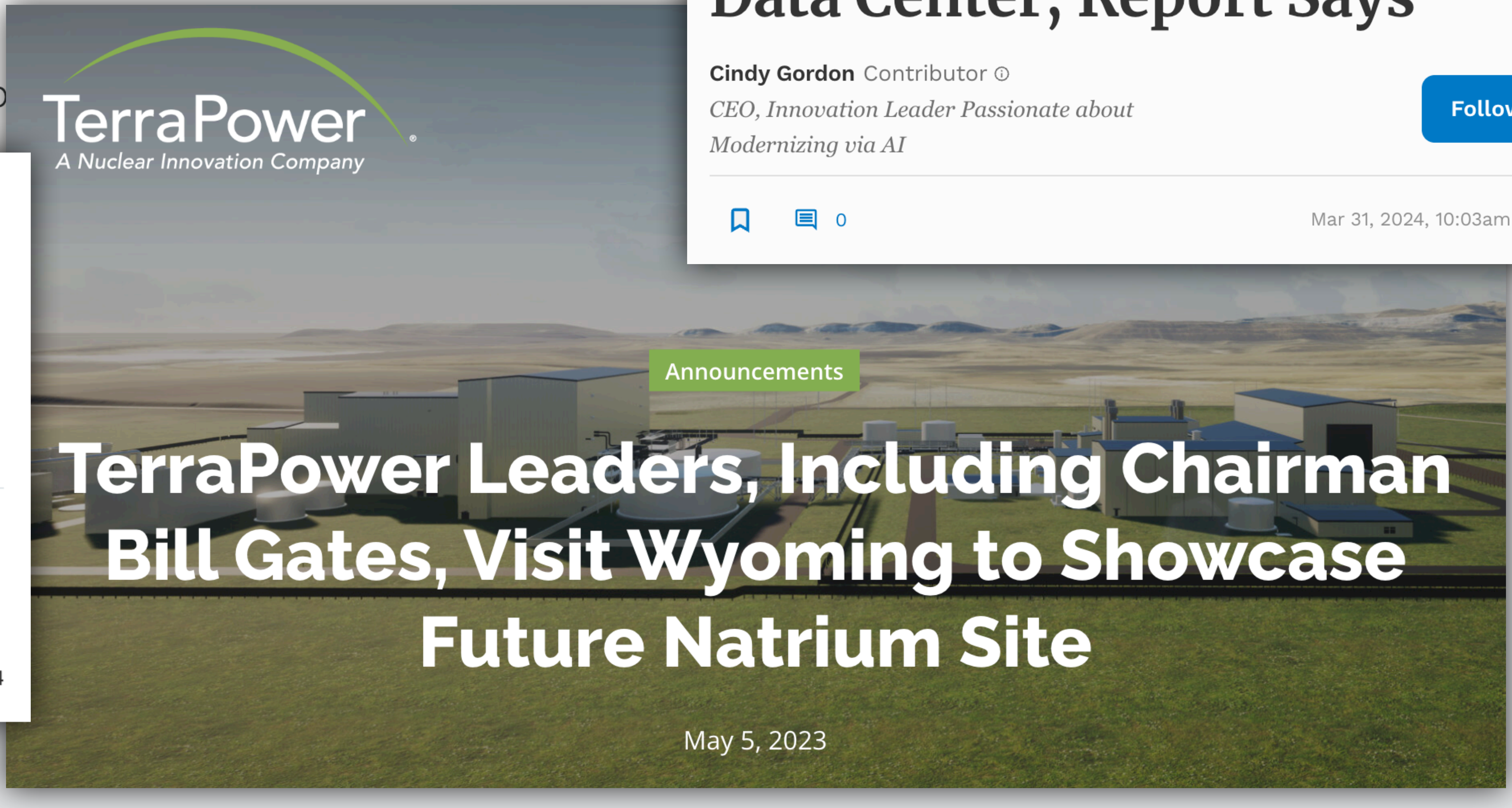
Amazon, Google and Microsoft signal growing interest in nuclear, geothermal power

Rising demand from artificial intelligence is forcing big technology companies to look beyond wind and solar for clean energy.

By **Heather Clancy**

March 25, 2024




Source: Ed Hawkins