Is There a Future for Nuclear Power After Fukushima?

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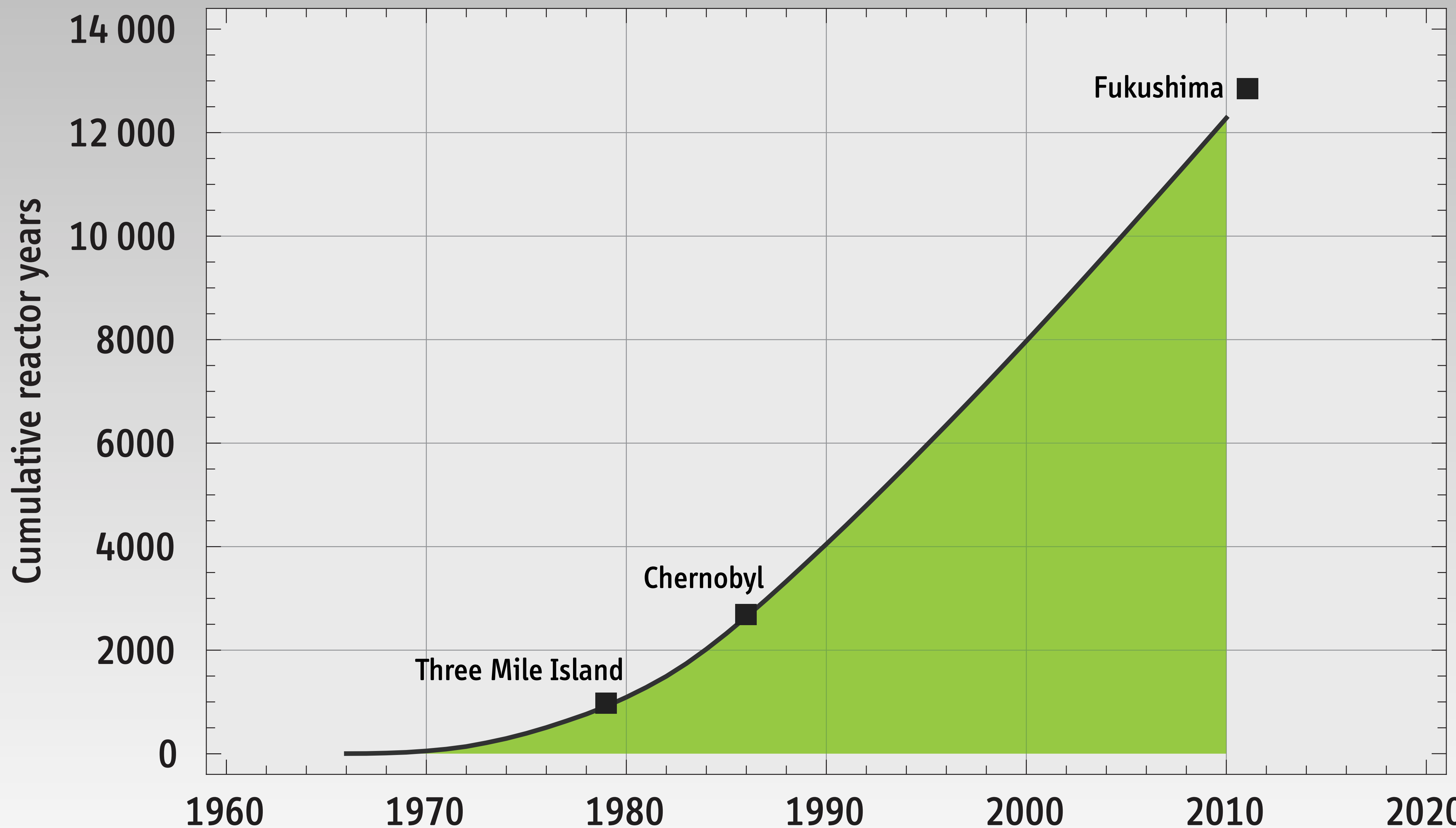
Princeton Plasma Physics Laboratory, January 21, 2012

Revision 6

Nuclear Power: Years of Boredom Interrupted by Moments of Sheer Terror?

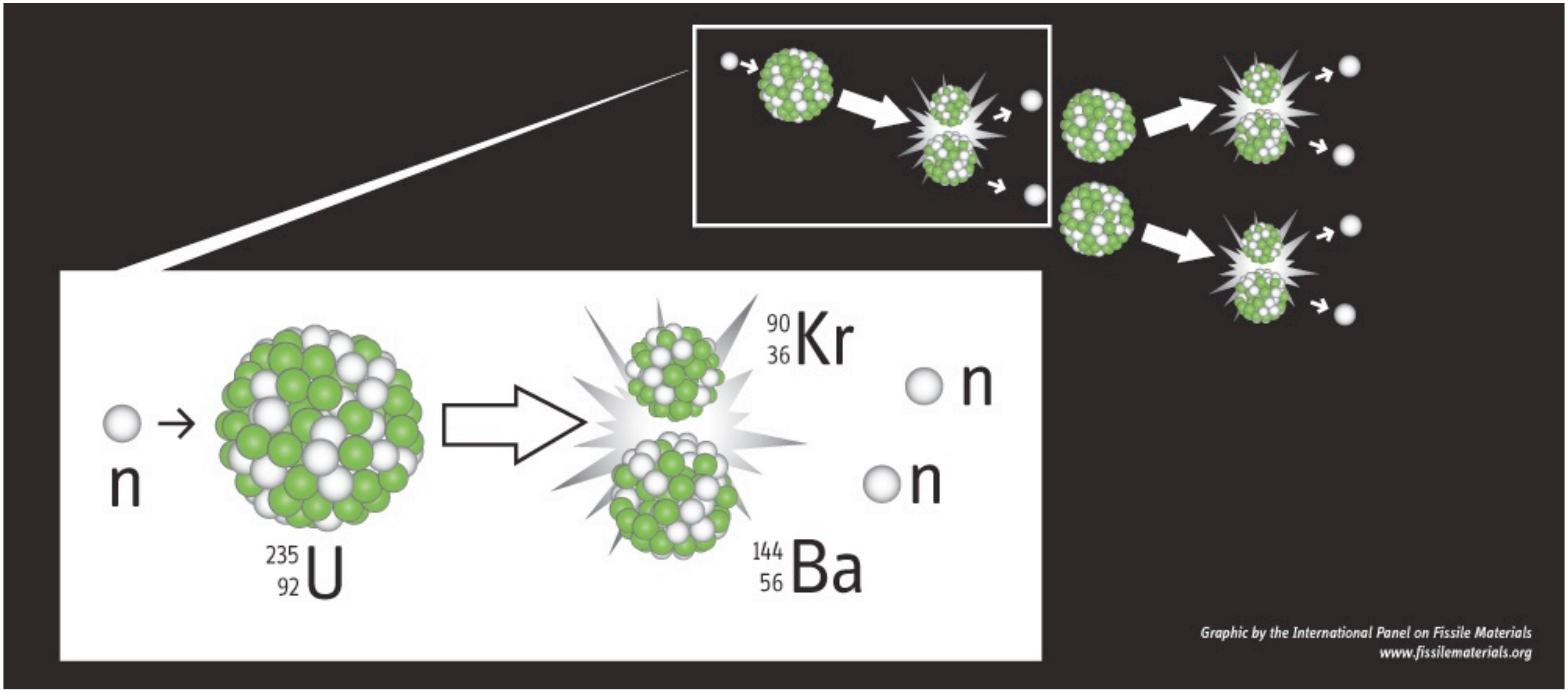


Low estimate based on the age of reactors operating today, IAEA Power Reactor Information System
(actual value for 2010 closer to 14,000 reactor years)

What is Nuclear Power?

Nuclear Fission

(discovered by L. Meitner, O. Hahn, F. Strassmann, 1938)

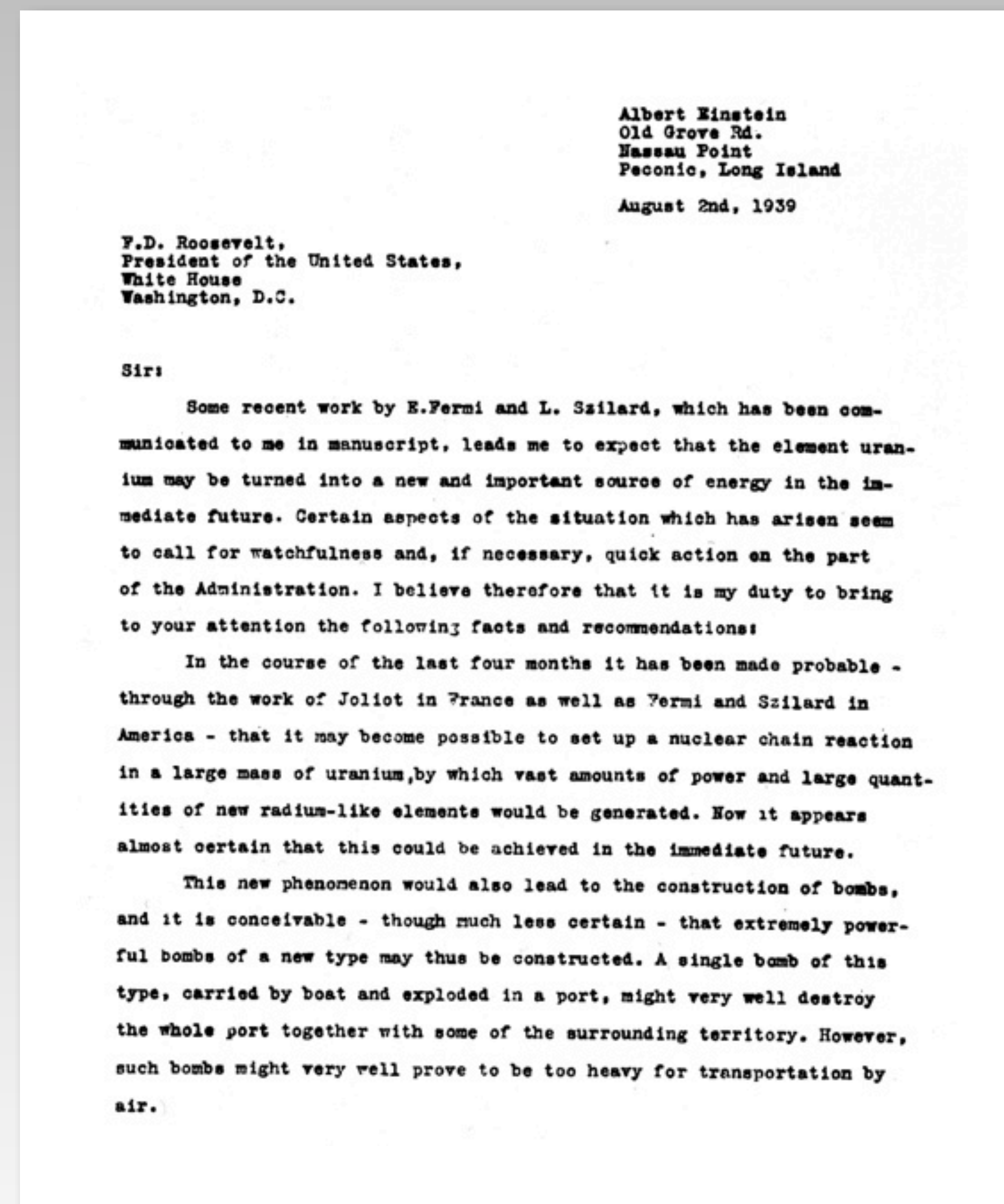


Uranium-235 (0.7% in natural uranium, rest is U-238)

Fission fragments are positively charged and repel each other

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:

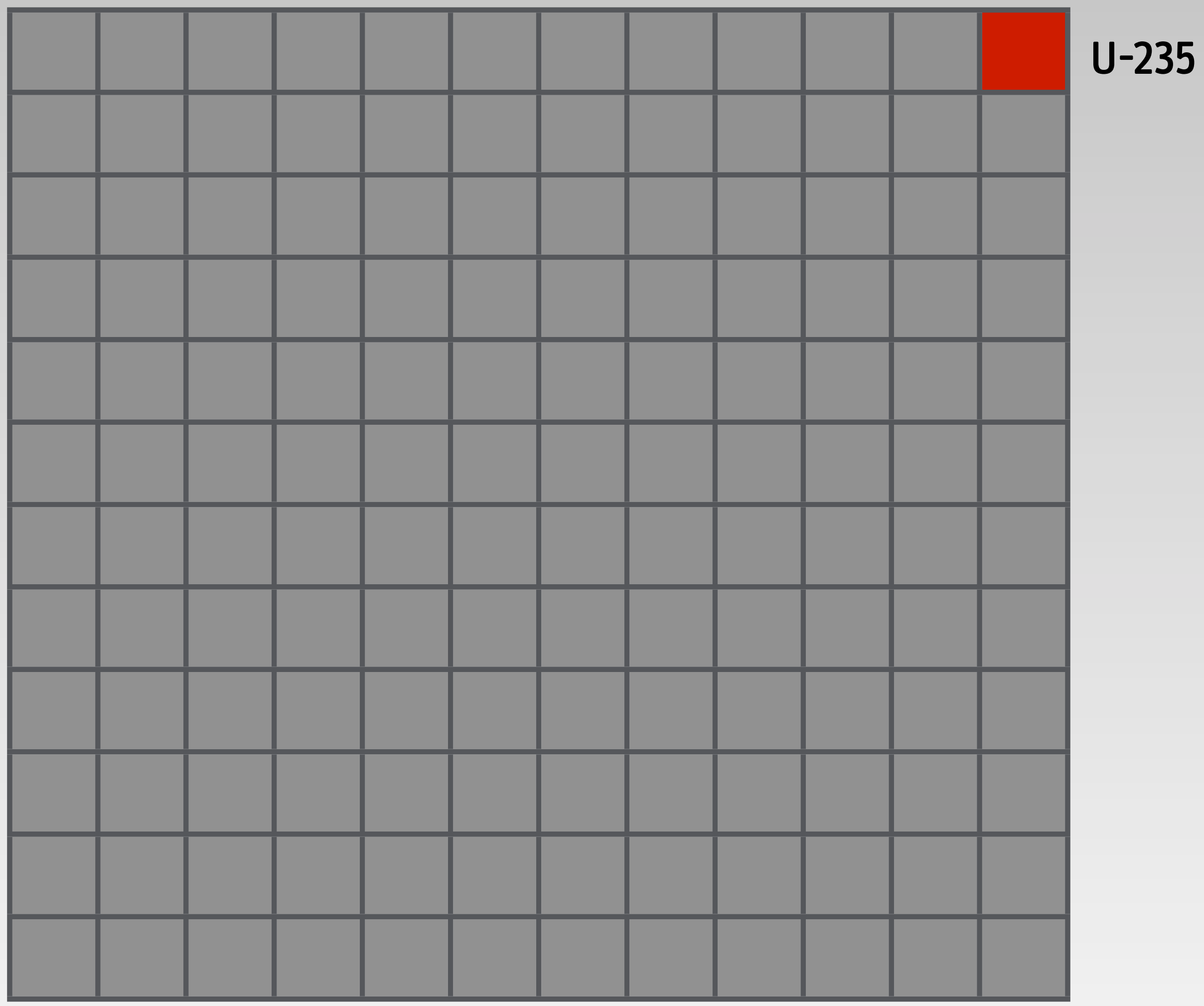
Some recent work by E.Fermi and L. Szilard, which has been communicated to me in manuscript, leads me to expect that the element uranium may be turned into a new and important source of energy in the immediate future. Certain aspects of the situation which has arisen seem to call for watchfulness and, 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.

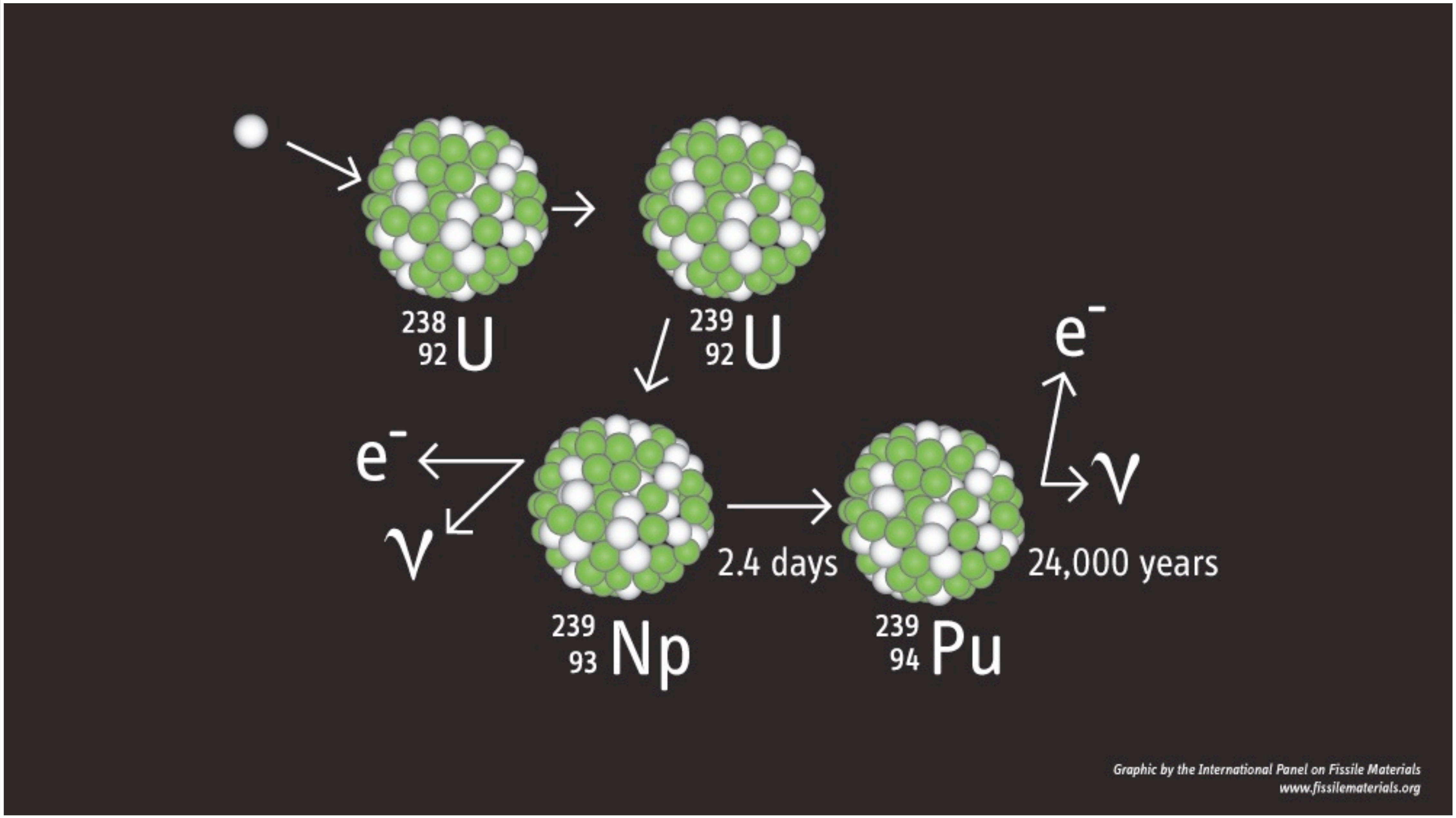
This new phenomenon would also lead to the construction of bombs, and it is conceivable - though much less certain - that extremely powerful bombs of a new type may thus be constructed. A single bomb of this type, carried by boat and exploded in a port, might very well destroy the whole port together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

Two Isotopes in Natural Uranium

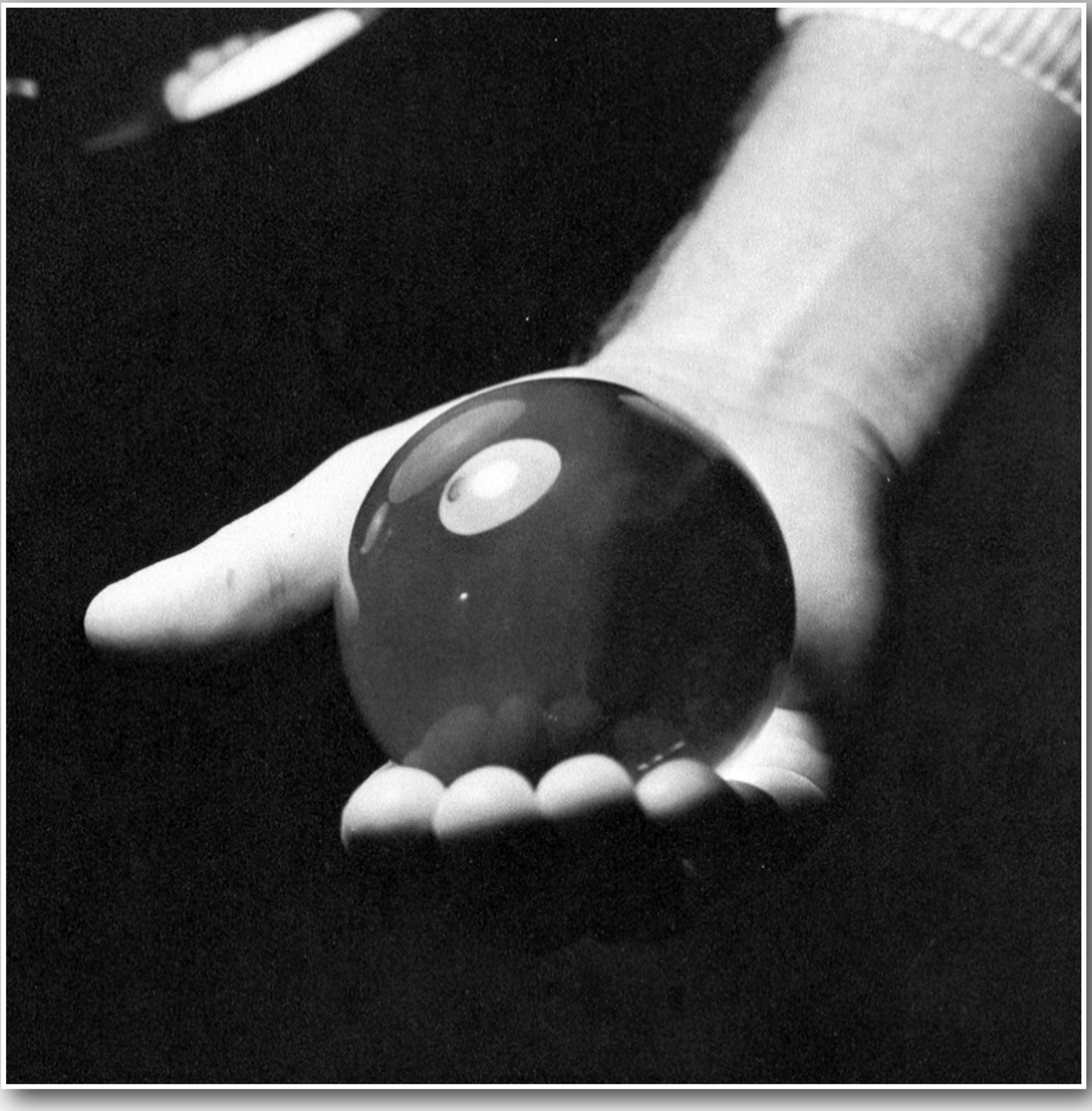
(Only about 0.7% is U-235, virtually all the rest is U-238)



Plutonium Production

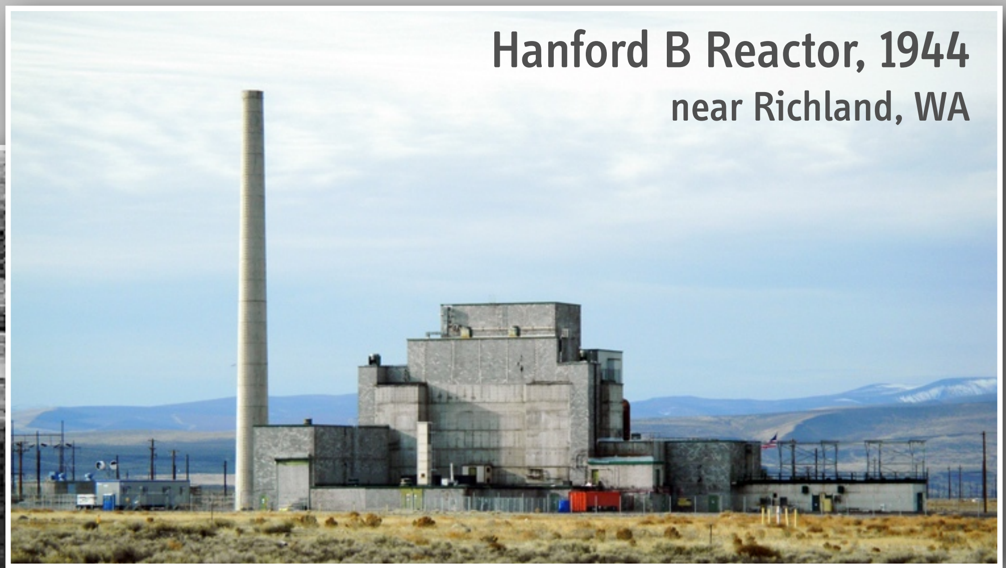


It Takes Only a Few Kilograms of Fissile Material to Make a Nuclear Weapon

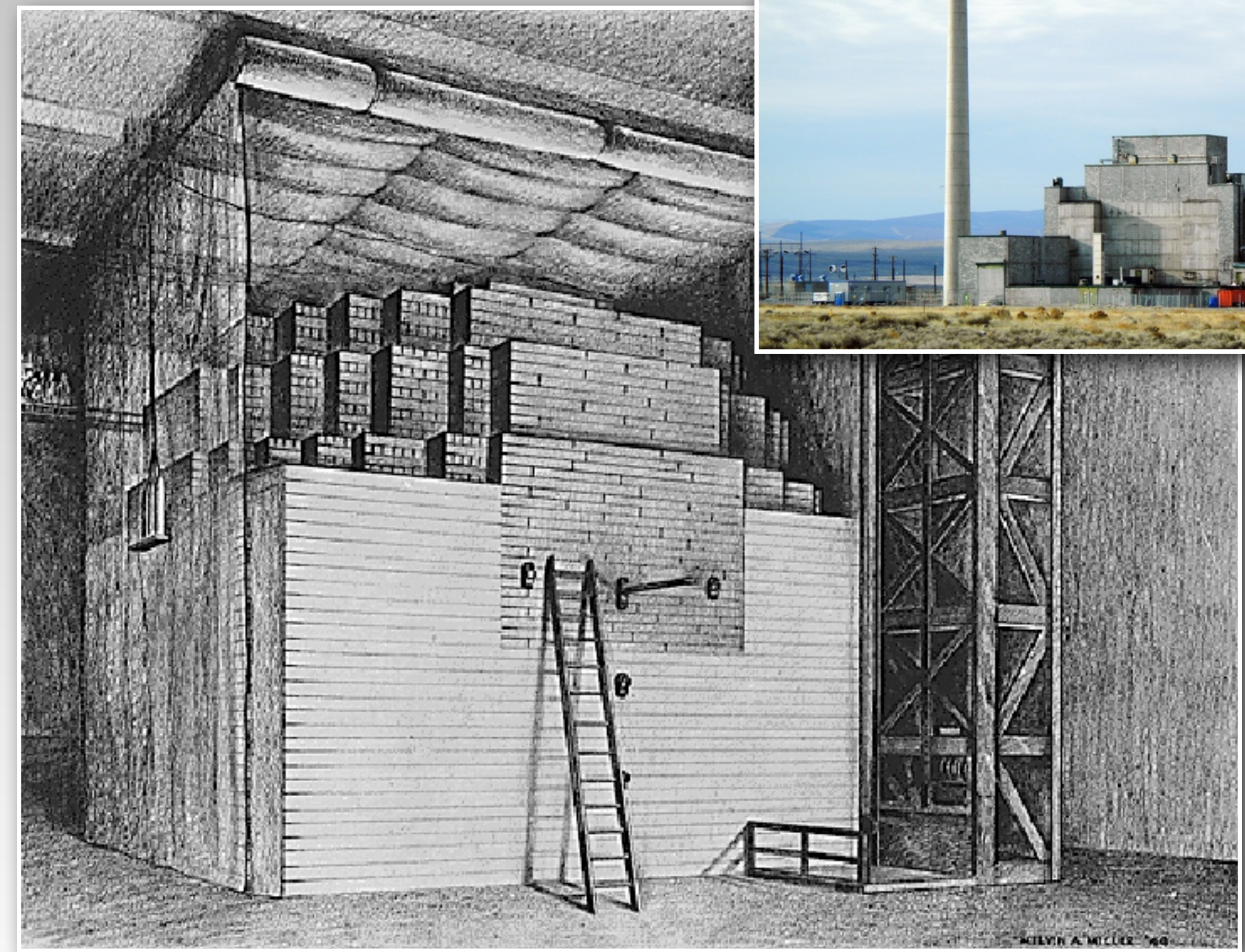


Size of the plutonium sphere used in the Nagasaki Bomb (about 6 kg of plutonium)

The First Nuclear Reactors Were Used To Make Plutonium for Weapons



Hanford B Reactor, 1944
near Richland, WA

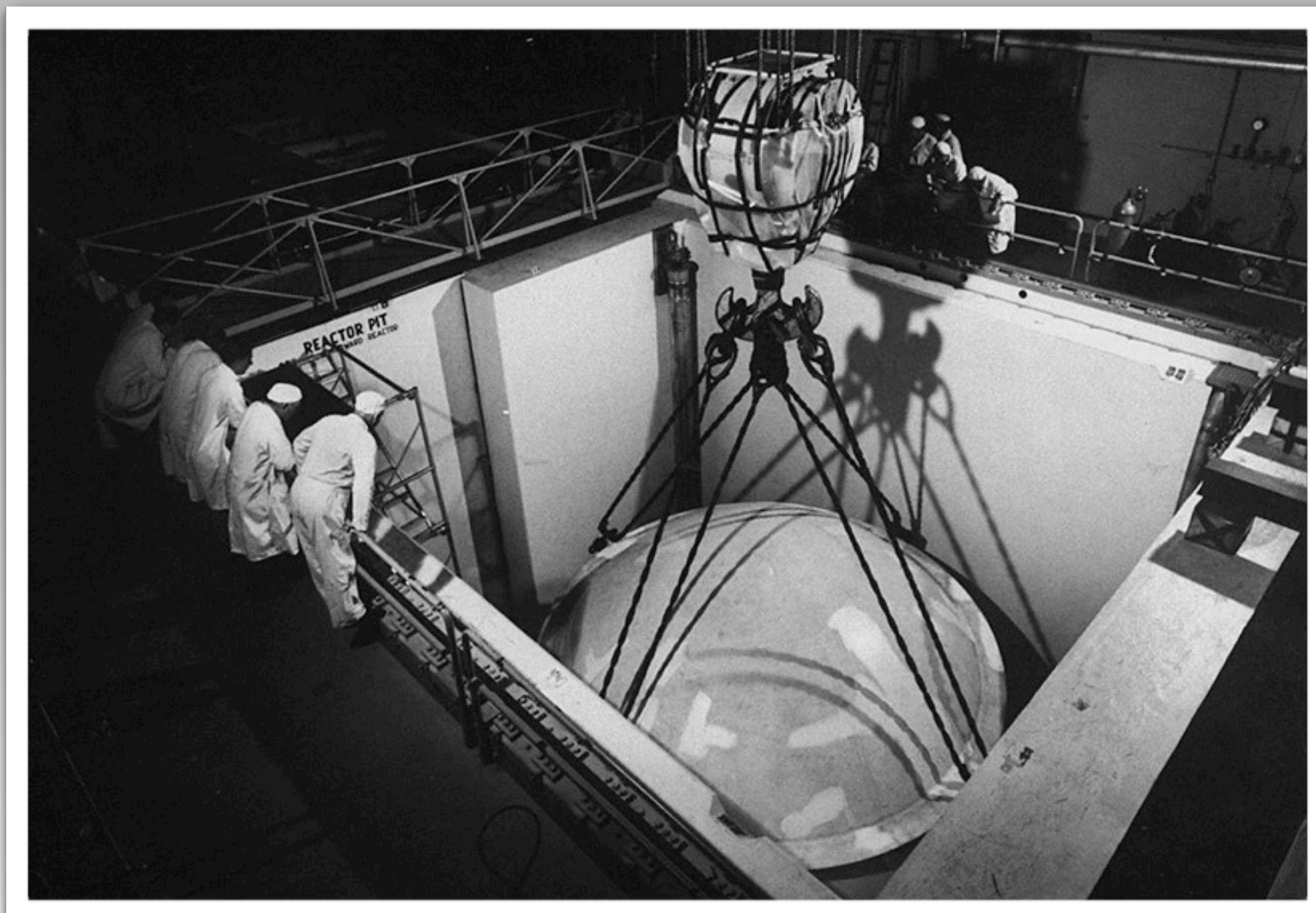


Chicago Pile-1 (CP-1), December 2, 1942

Nuclear-Powered Submarines Came Next

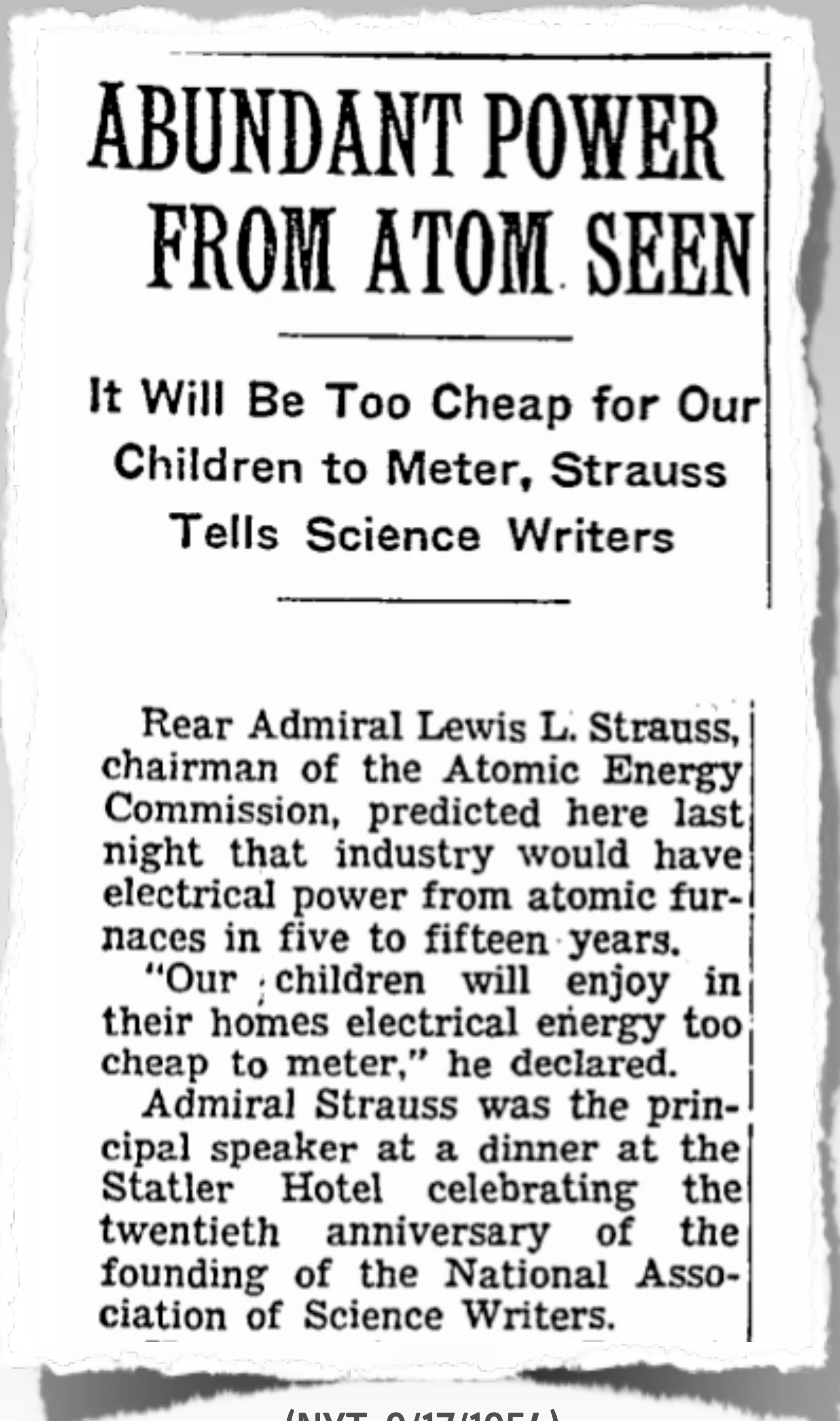
USS Nautilus (SSN-571), launched in 1954, here entering New York Harbor, 1958

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.

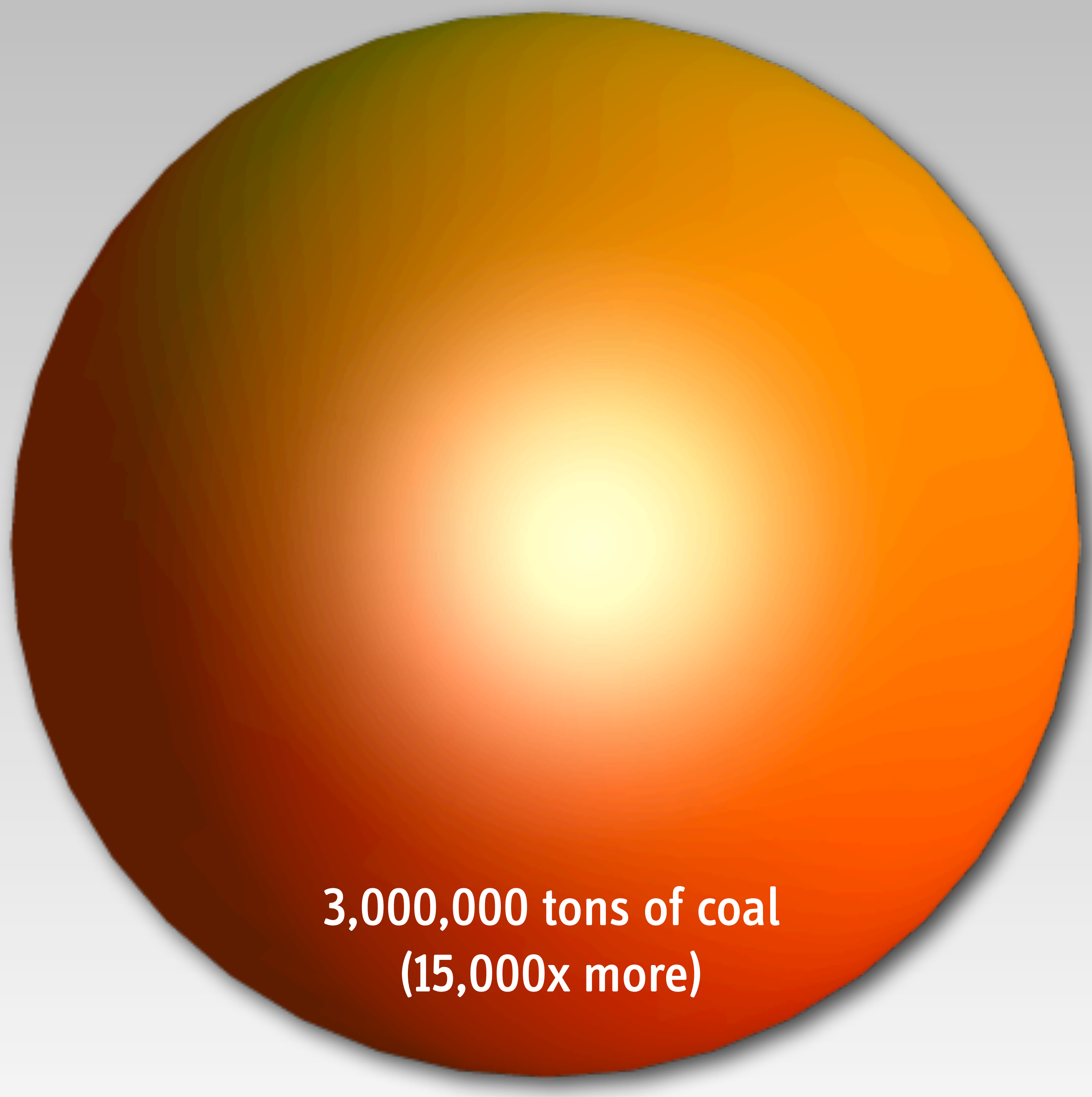
(NYT, 9/17/1954)

"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

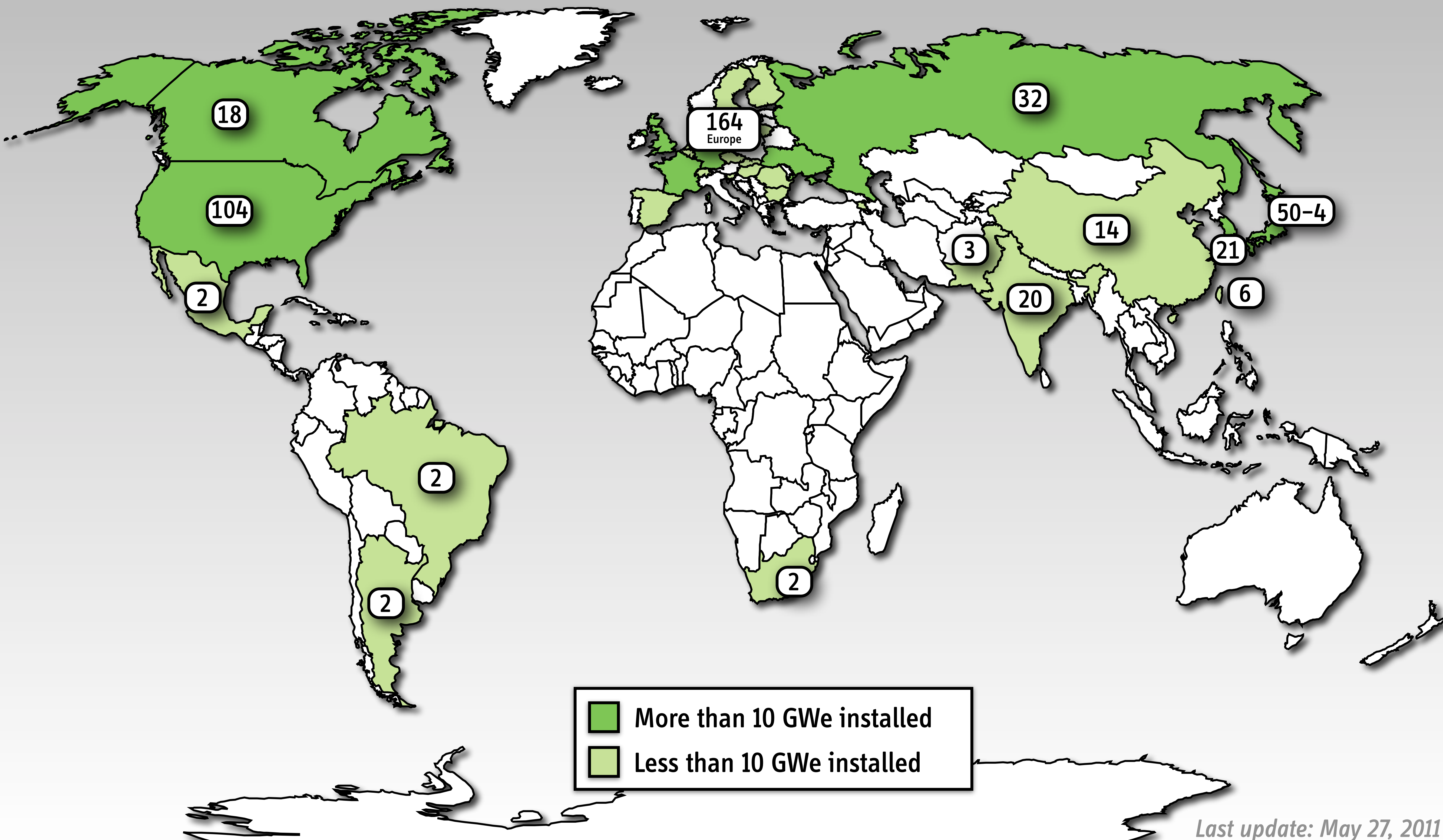
200 tons of uranium have to be mined
to produce 20 tons of nuclear fuel
(only 1 ton is ultimately fissioned)



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

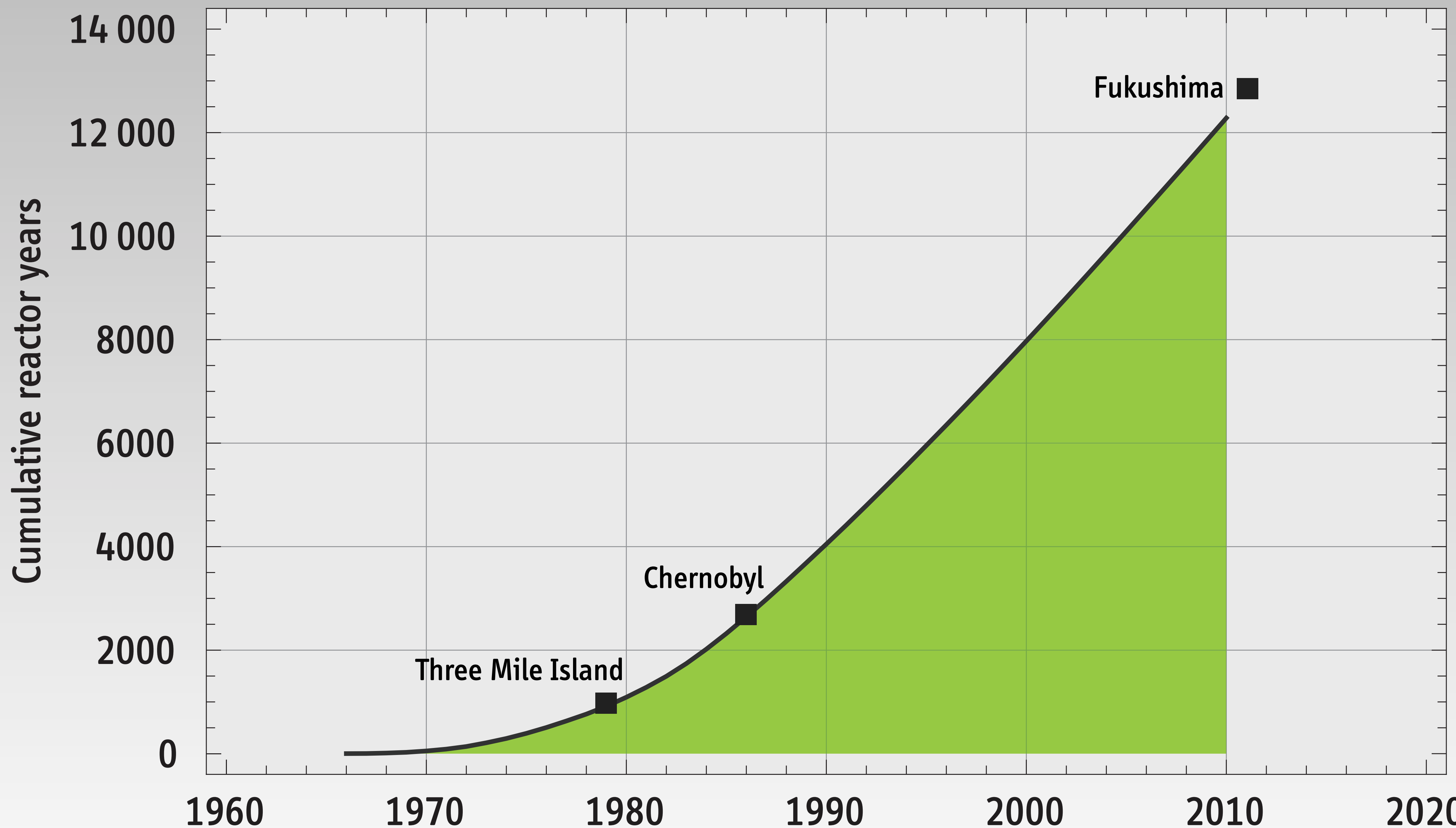
Nuclear Power Reactors in the World, 2011

(444 minus 4 reactors in 30 countries, providing about 14% of global electricity; still counting 17 reactors in Germany)



Last update: May 27, 2011

Nuclear Power: Years of Boredom Interrupted by Moments of Sheer Terror?

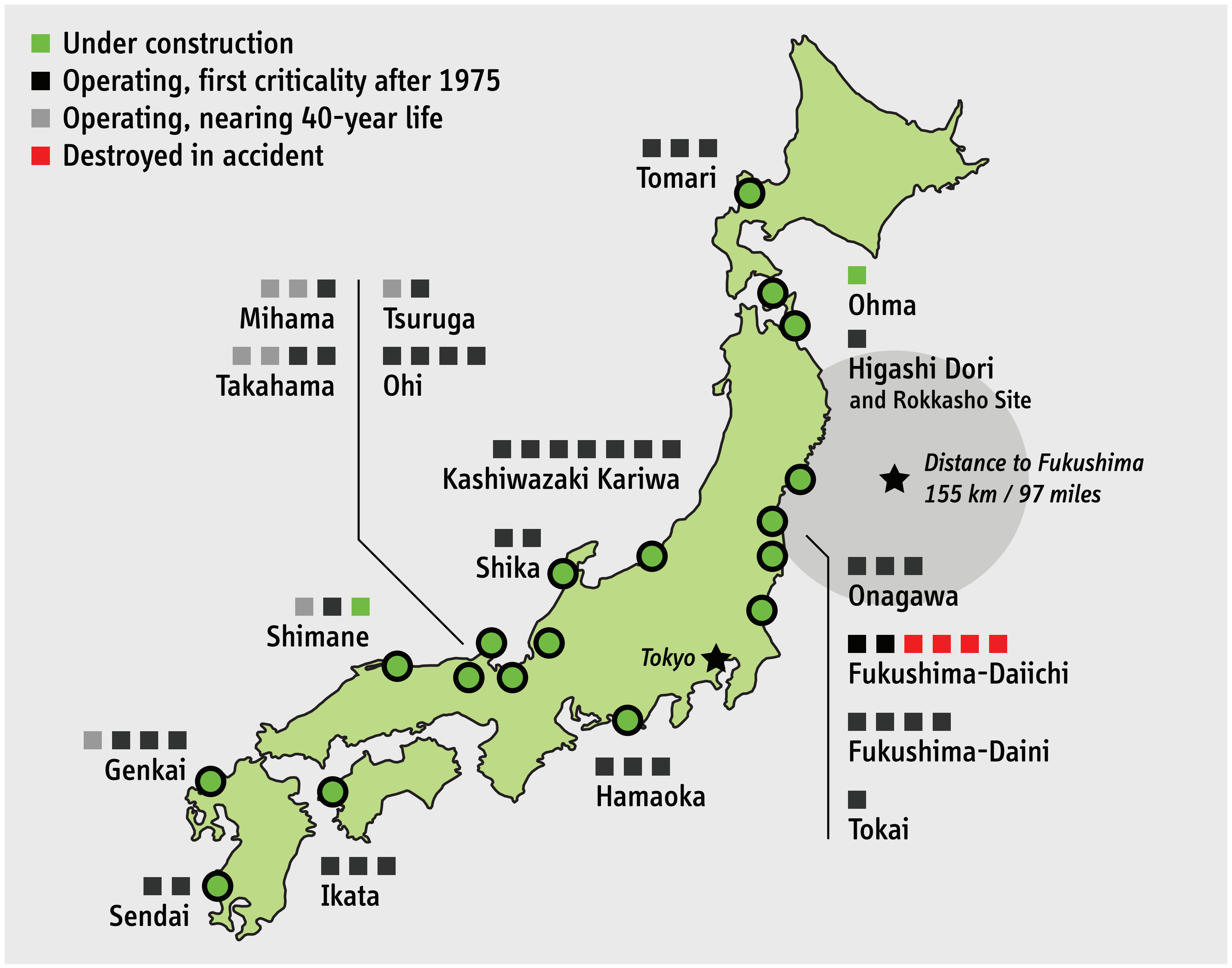


Low estimate based on the age of reactors operating today, IAEA Power Reactor Information System
(actual value for 2010 closer to 14,000 reactor years)

The March 2011 Fukushima Accidents

(Quick Review)

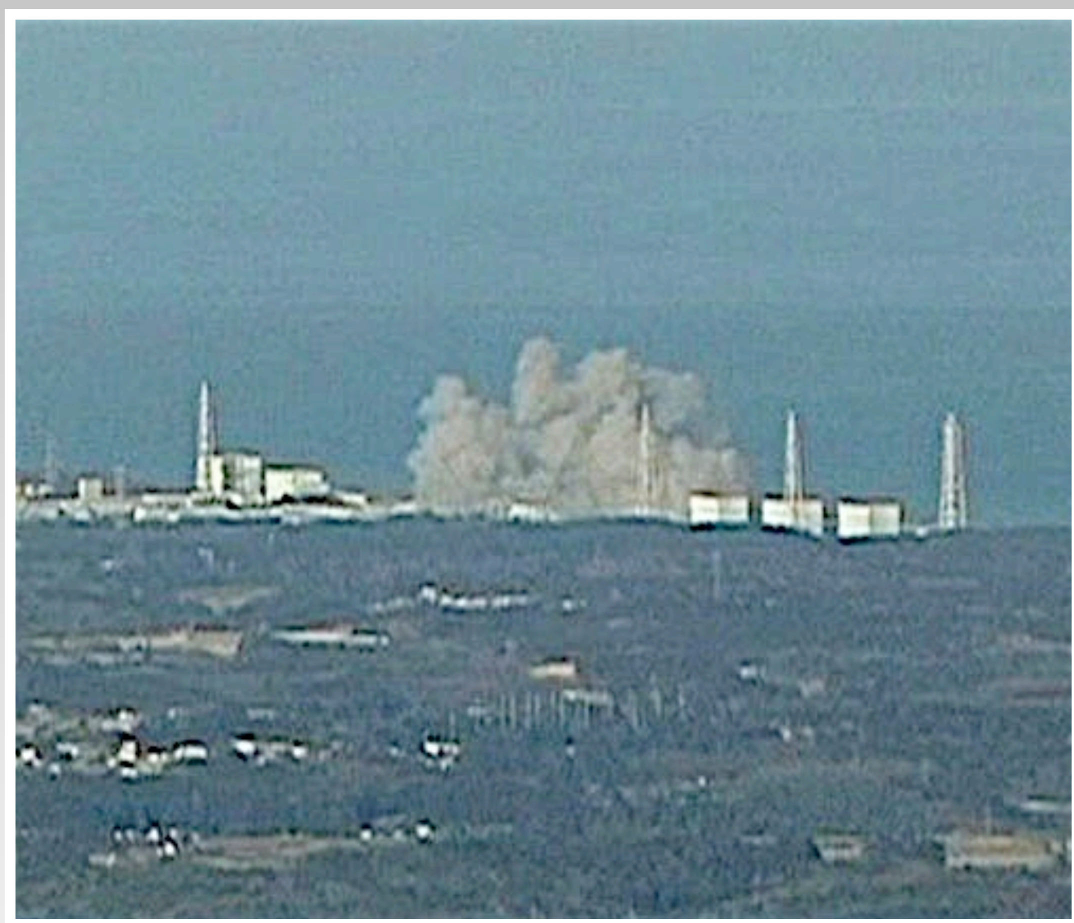
Nuclear Power Plants in Japan, 2011



Fukushima-Daiichi Plant

Source: TEPCO, undated

Explosions of Secondary Containment Buildings of Units 1 and 3



Unit 1, March 12, 2011, 3:36 p.m.

Unit 3, March 14, 2011, 11:01 a.m.


March 14, 2011 - DigitalGlobe

The Future of Nuclear Power?

Compared to Other Sources of Energy:

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 baseload electricity generation)

Centralized production (→ adequate for today's electric grid)

Attractive if projections for future electricity demand are high

Compared to Other Sources of Energy:

What Factors Tend to Put Nuclear Power at a Disadvantage?

- Safety concerns (→ risk of catastrophic accidents)
- Requirement for disposal of radioactive nuclear waste
- Weapons connection (→ nuclear proliferation)
- Possibility of radiological and nuclear terrorism
- Public opinion
- Can go either way: Economics
- Can go either way: Energy security (→ reliable access to fuel resources)

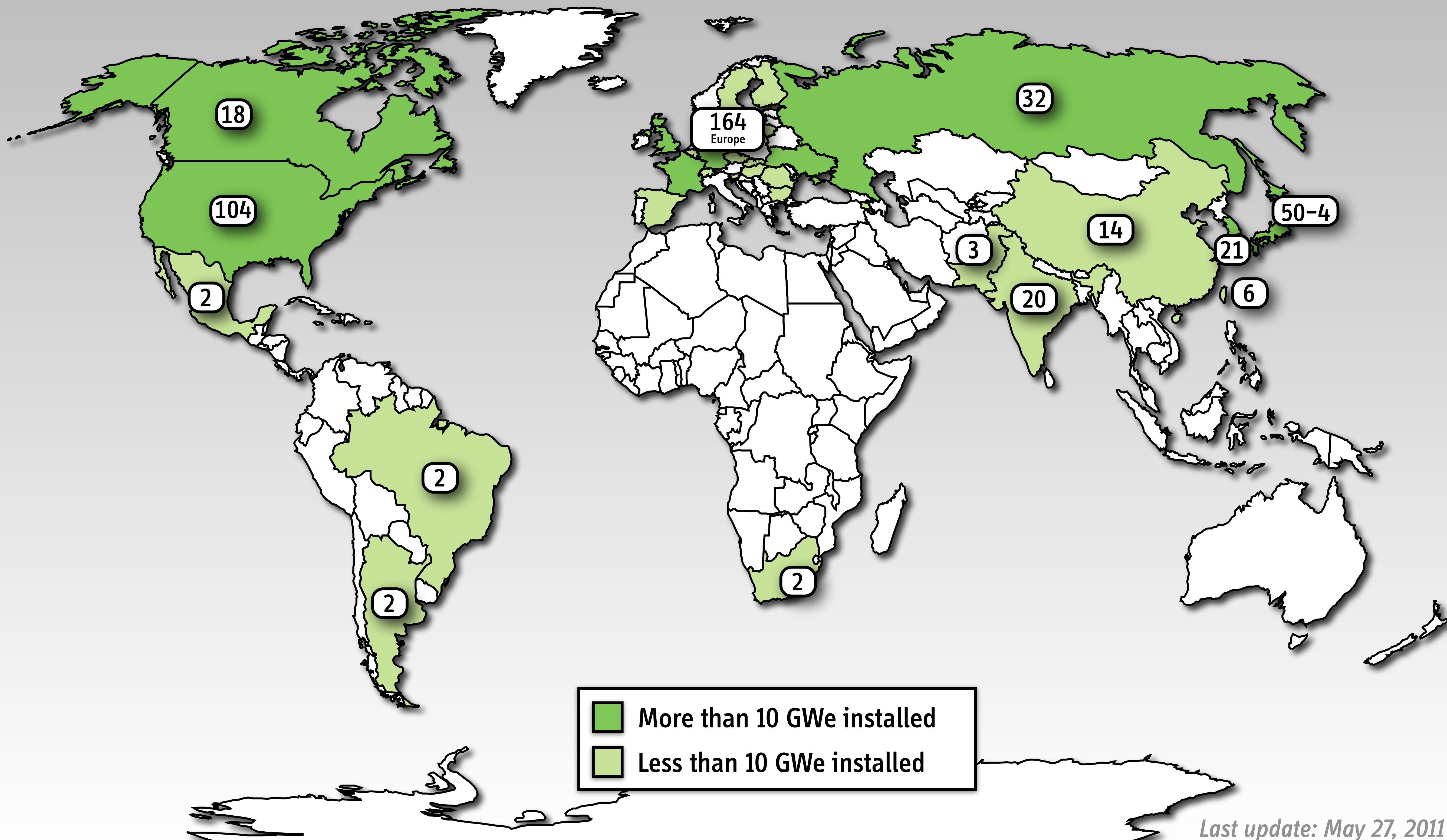
Challenges After Fukushima

(Old and New)

What To Do With the Existing Fleet?

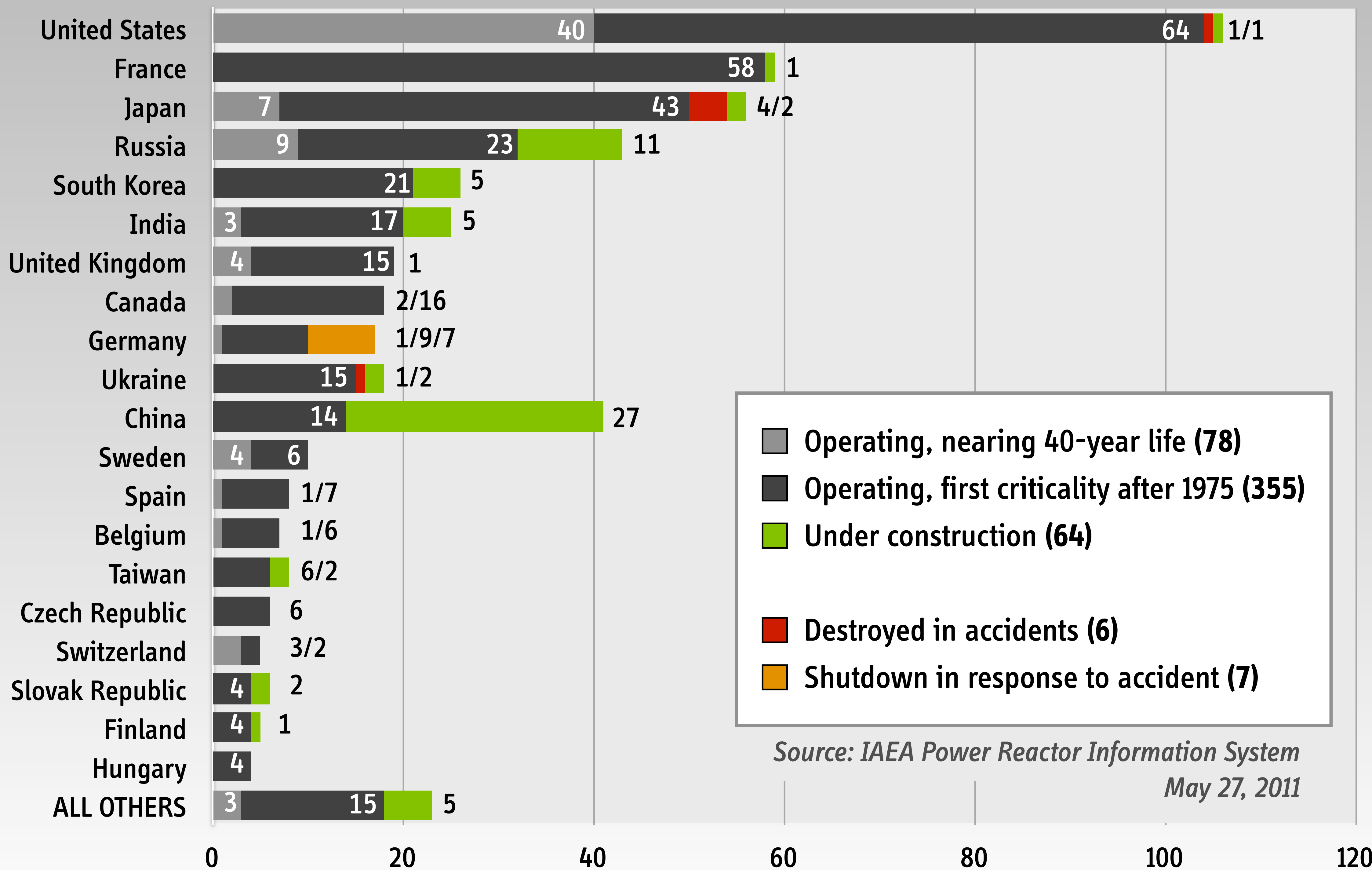
Nuclear Power Reactors in the World, 2011

(444 minus 4 reactors in 30 countries, providing about 14% of global electricity; still counting 17 reactors in Germany)



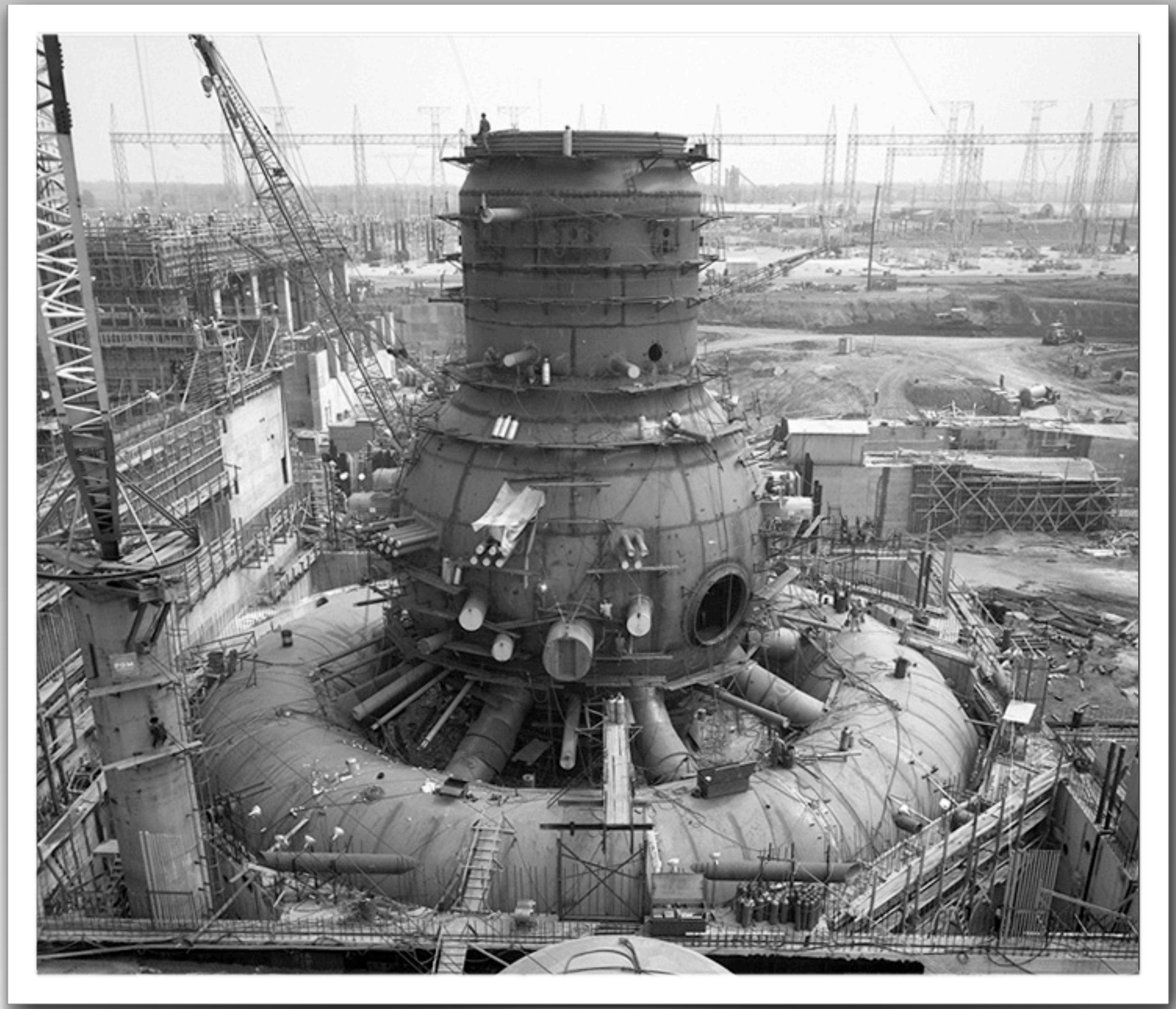
Last update: May 27, 2011

The Existing Fleet of Power Reactors is Aging

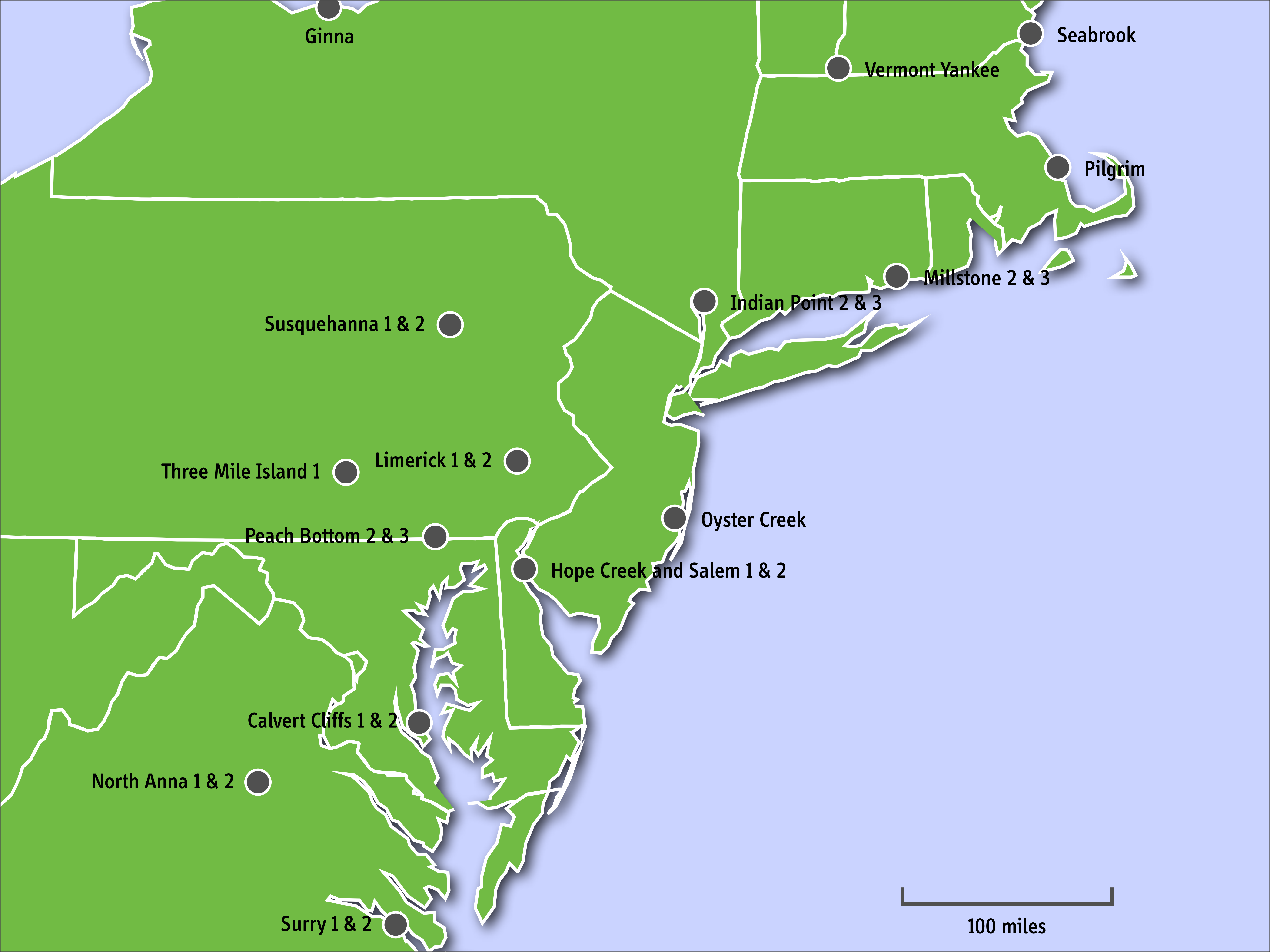


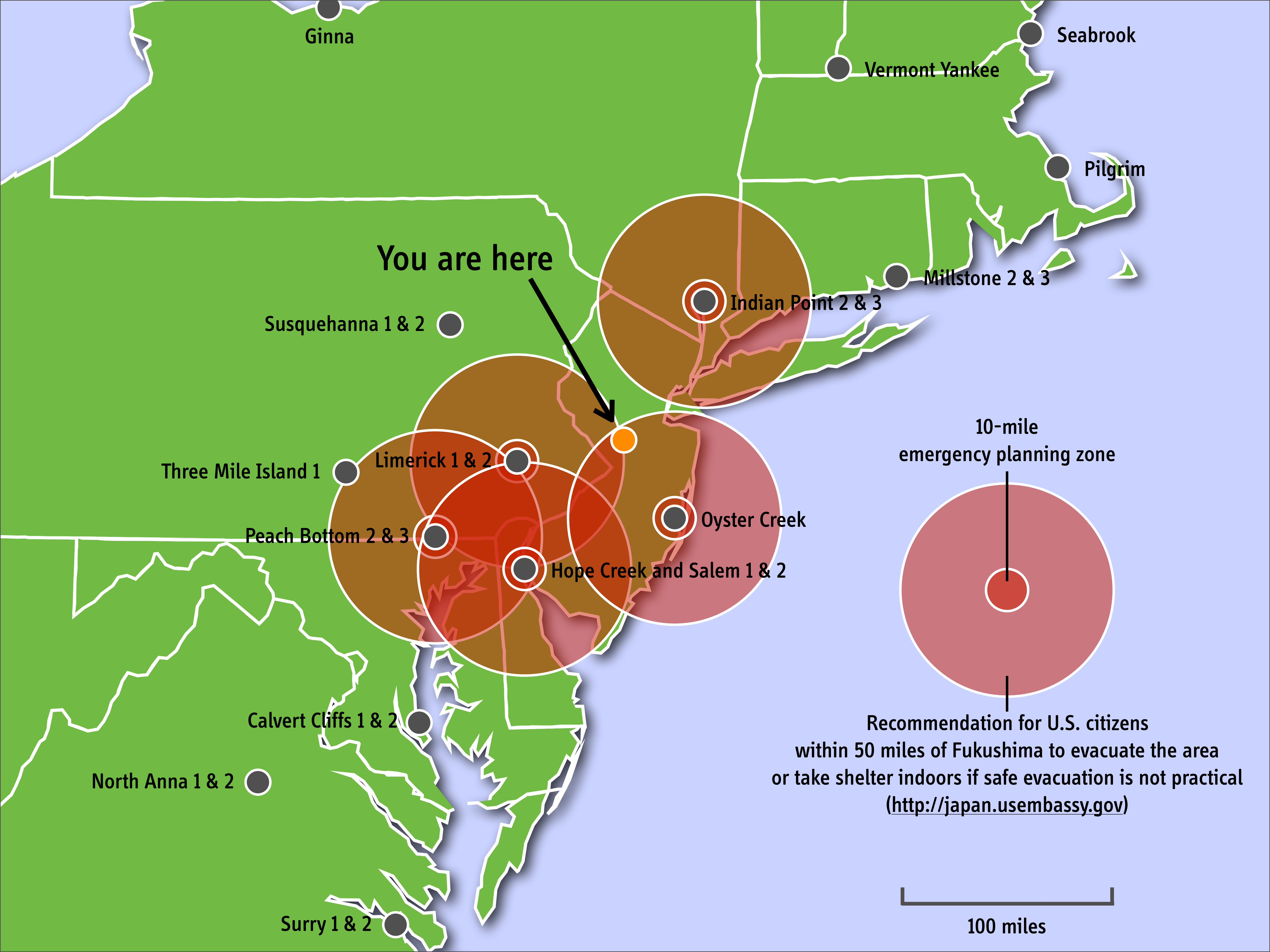
23 Operating Reactors in the United States Are of the Fukushima-Type

(Boiling Water Reactors with MK-I Containment, built in the 1960s)



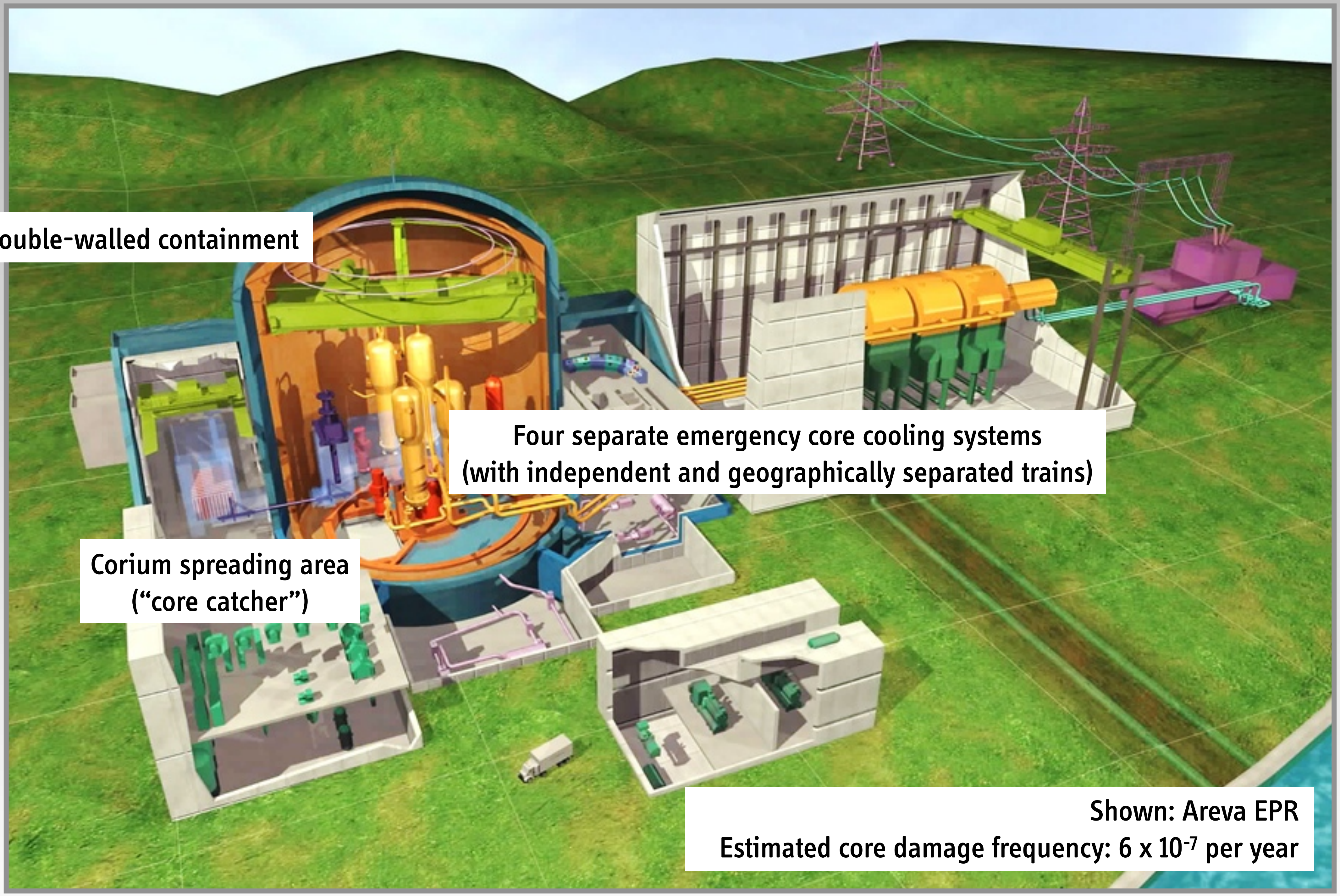
Browns Ferry Unit I near Athens, AL, under construction


Ginna
Seabrook
Vermont Yankee
Pilgrim
Millstone 2 & 3
Indian Point 2 & 3
Susquehanna 1 & 2
Limerick 1 & 2
Three Mile Island 1
Oyster Creek
Peach Bottom 2 & 3
Hope Creek and Salem 1 & 2
Calvert Cliffs 1 & 2
North Anna 1 & 2
Surry 1 & 2
100 miles


Ginna
Seabrook
Vermont Yankee
Pilgrim
You are here
Millstone 2 & 3
Indian Point 2 & 3
Susquehanna 1 & 2
Limerick 1 & 2
Three Mile Island 1
Oyster Creek
Peach Bottom 2 & 3
Hope Creek and Salem 1 & 2
10-mile
emergency planning zone
Recommendation for U.S. citizens
within 50 miles of Fukushima to evacuate the area
or take shelter indoors if safe evacuation is not practical
(http://japan.usembassy.gov)
Calvert Cliffs 1 & 2
North Anna 1 & 2
Surry 1 & 2
100 miles

What About Advanced Reactor Designs?

Advanced Reactors Promise Enhanced Safety



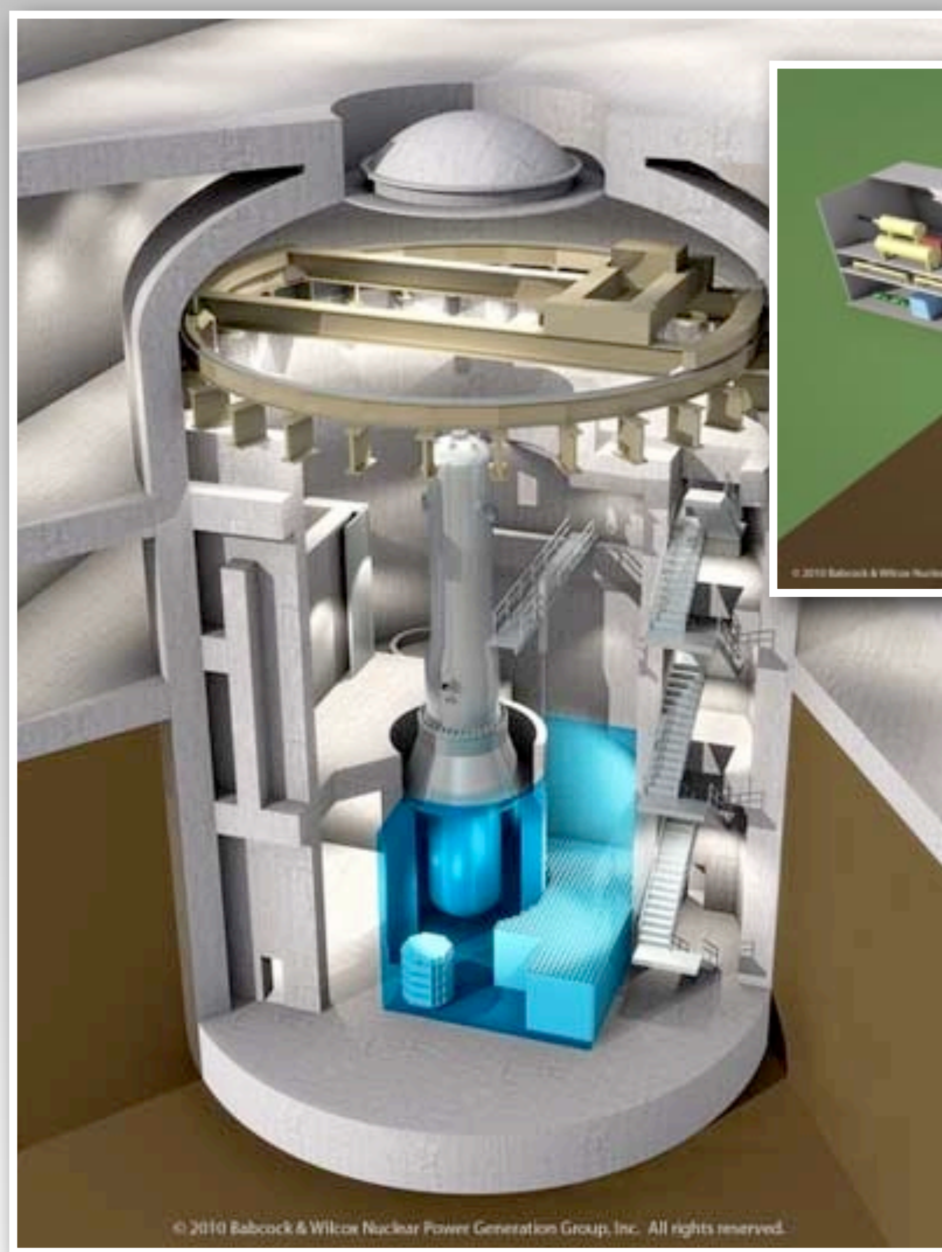
Advanced Reactors Are Also Expensive

Olkiluoto 3 (Finland, Areva): Four years behind schedule (2013 vs 2009)
Turnkey agreement ($4.3 billion), currently estimated loss for Areva: $3.8 billion

Source: Francois de Beaupuy, "Areva's Overruns at Finnish Nuclear Plant Approach Initial Cost," *Bloomberg Businessweek*, June 24, 2010

Could Small Nuclear Reactors Play a Role?

Some concepts are based on proven reactor technology



Babock & Wilcox mPower Concept

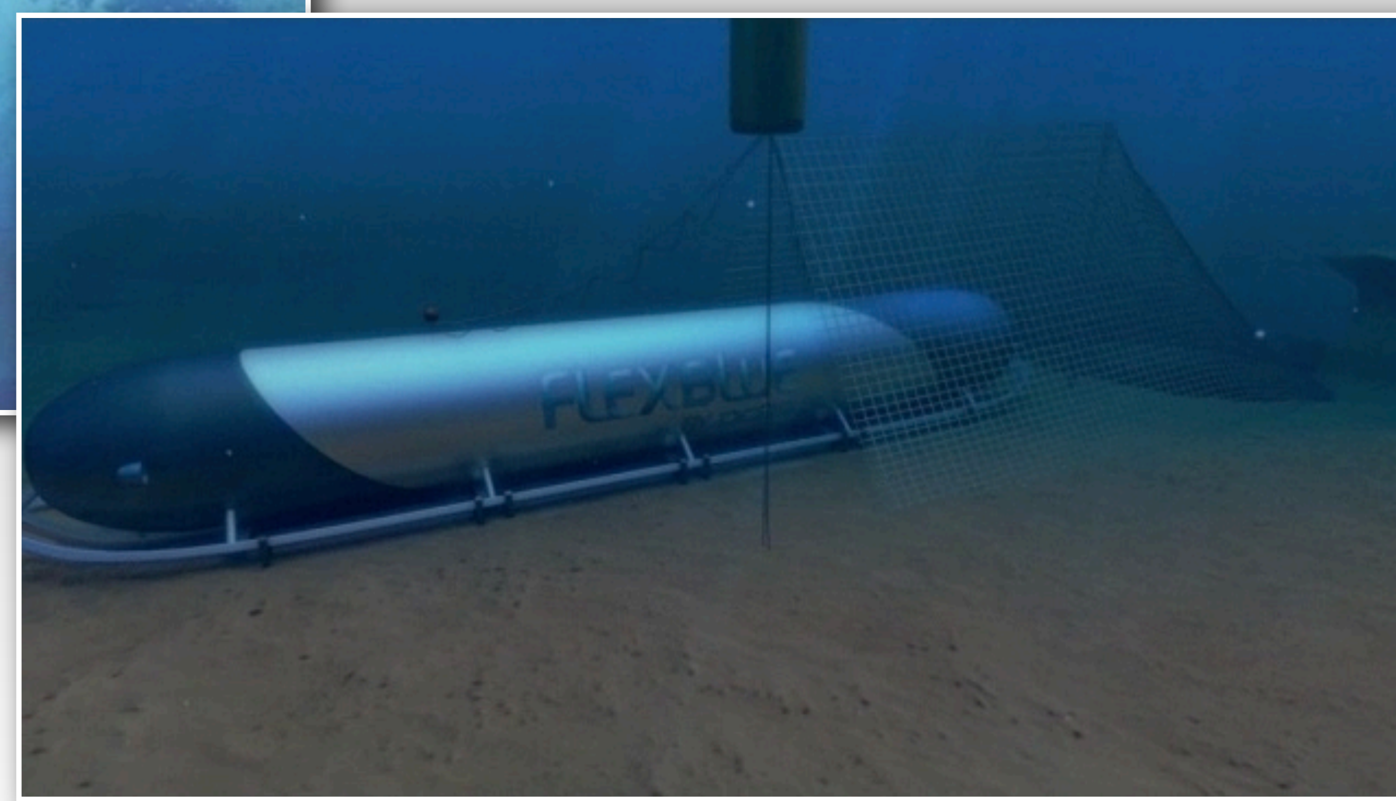
- Light-water cooled
- 125-750 MWe
- Underground construction
- 60-year spent fuel storage onsite
- Quasi-standard LWR fuel

Source: www.babcock.com/products/modular_nuclear/

Could Small Nuclear Reactors Play a Role?

Some concepts are based on proven reactor technology

FlexBlue
DCNS (formerly Direction des Constructions Navales, DCN)
jointly with Areva, CEA, and EDF

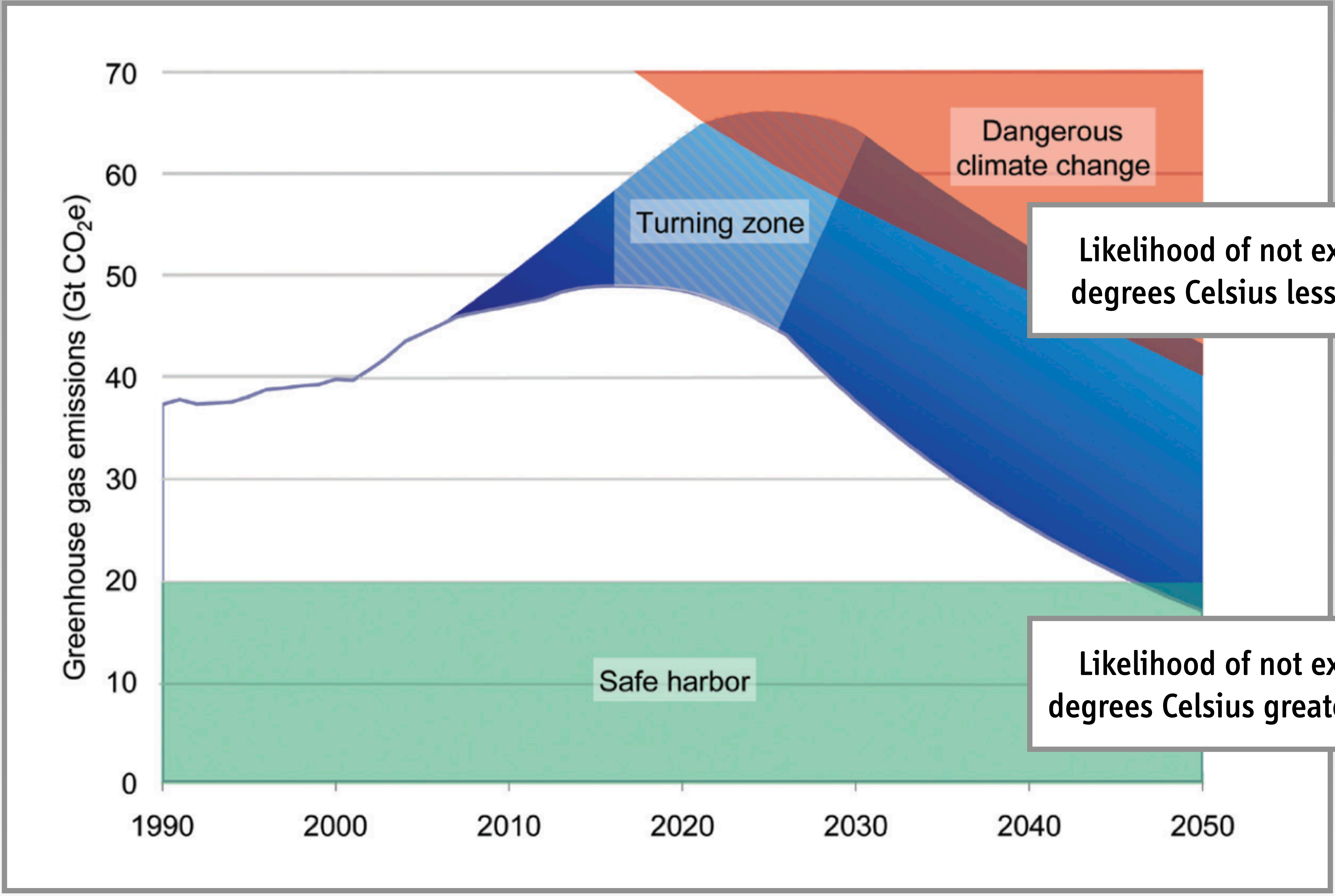


Length: about 100 m
Diameter: 12–15 m
Power: 50–250 MWe
Siting: Seafloor mooring at a depth of 60 to 100 m
a few km off coast

http://en.dcnsgroup.com/energie/civil-nuclear-engineering/flexblue/

What Scale of a Nuclear Expansion Would Make a Difference?

Global Annual CO_2(eq) Emissions



Likelihood of not exceeding 2 degrees Celsius less than 50%

Likelihood of not exceeding 2 degrees Celsius greater than 80%

Courtesy: Michael Oppenheimer (Princeton, EDF)

Computer Models Can be Used to Examine Possible Energy Futures

and understand the impact of technologies and policies related to GHG emissions

Global Change Assessment Model (GCAM)

www.globalchange.umd.edu/models/gcam

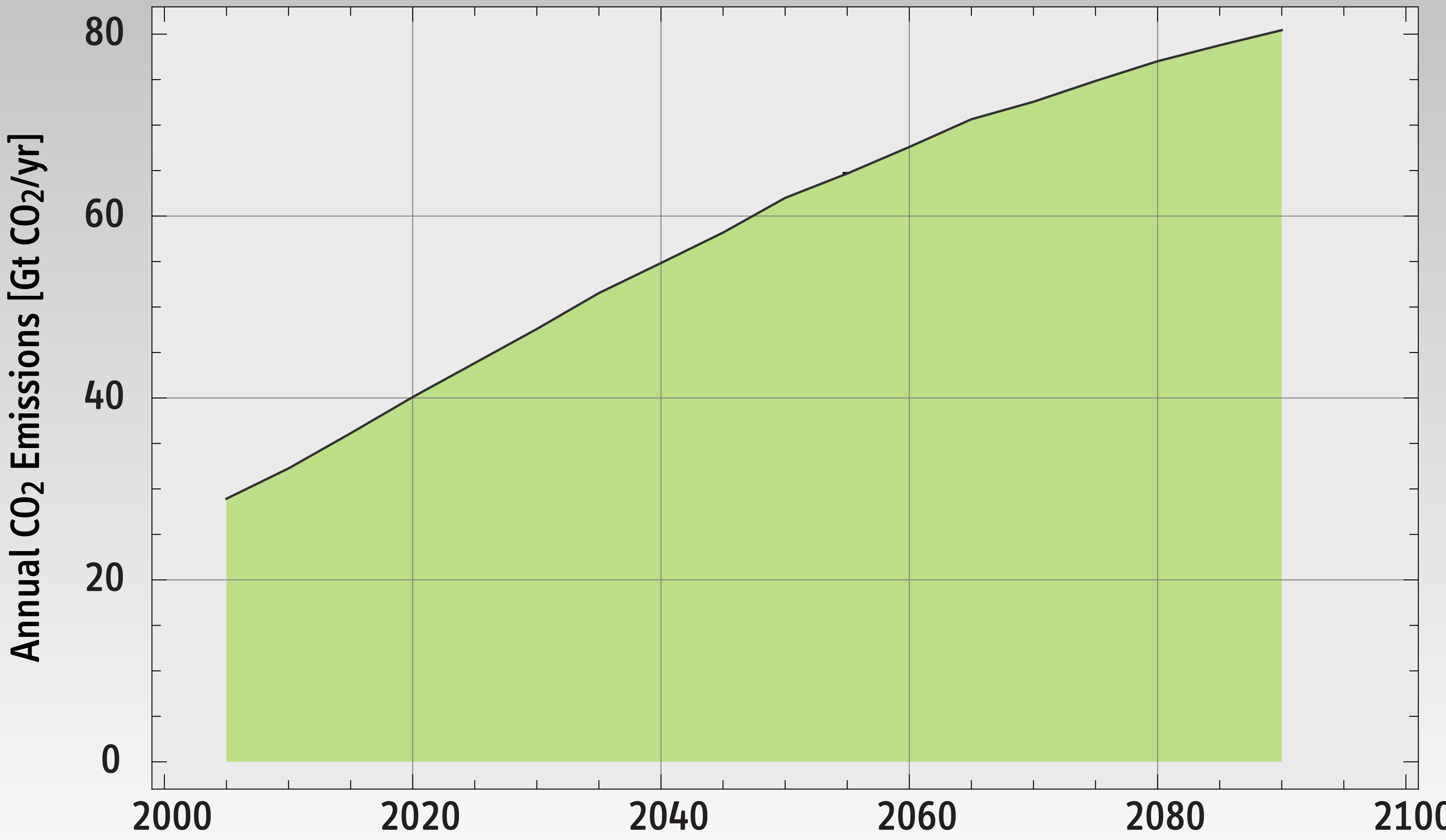
Developed and maintained by the Joint Global Change Research Institute (JGCRI) at University of Maryland (UMD) and U.S. DOE Pacific Northwest National Laboratory (PNNL)

Numerous energy supply technologies
Sixteen types of GHG emissions, global coverage with 14 regions

But always remember: GIGO!

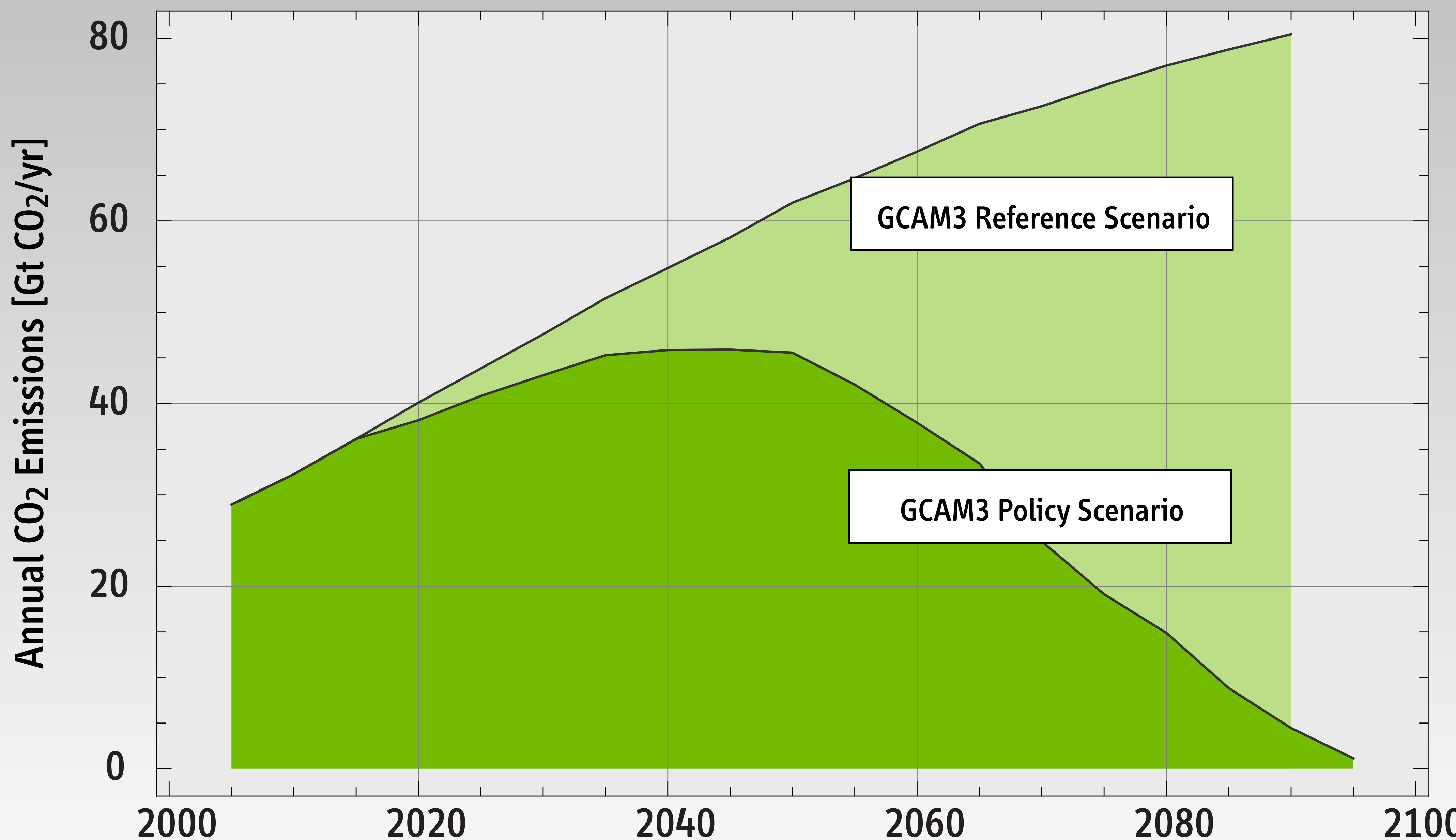
Global CO_2 Emissions

under the GCAM3 Reference Scenario



Global CO_2 Emissions

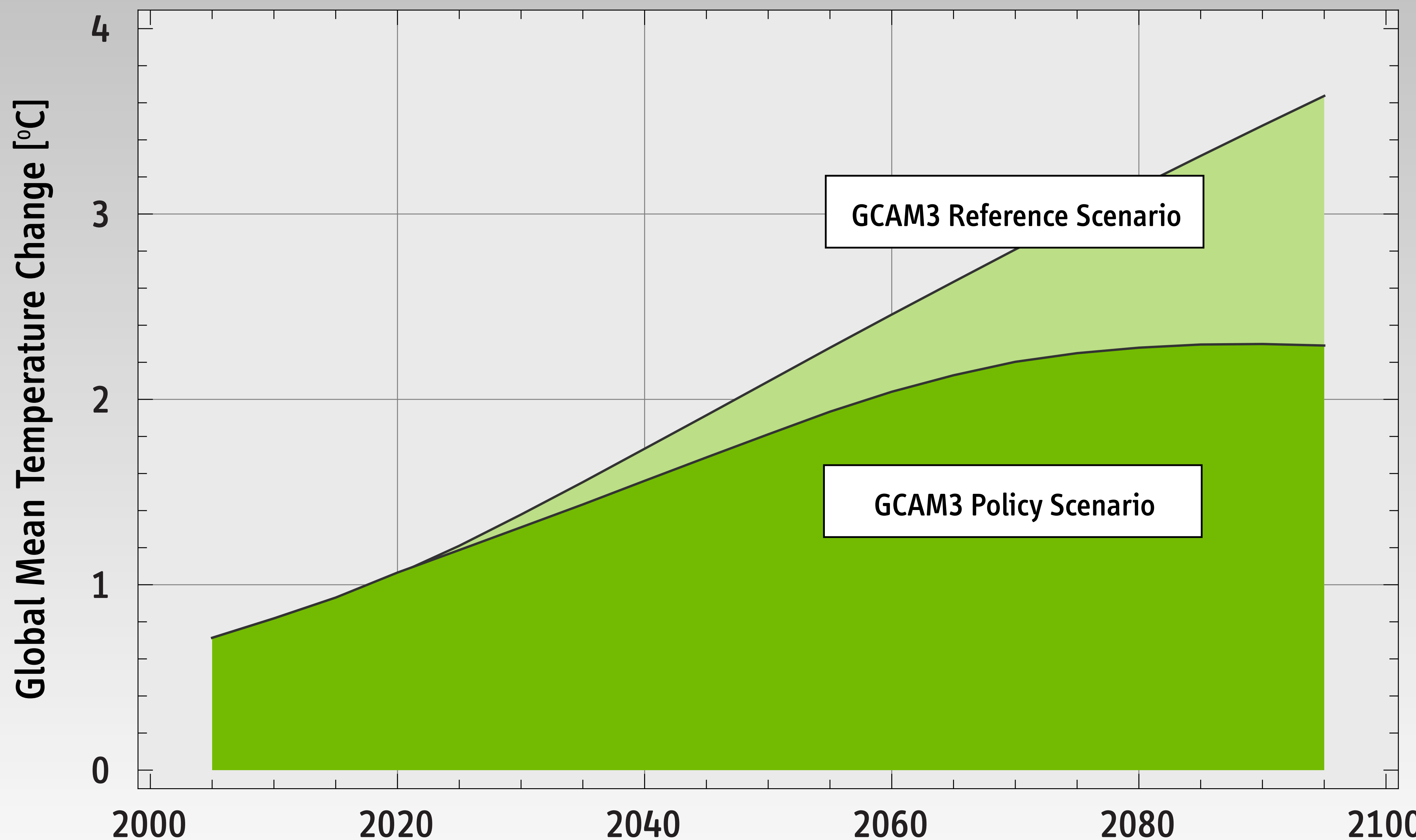
under the GCAM3 Reference and Policy Scenarios



(shown GCAM3 Policy Scenario assumes escalating price of carbon beginning with $20/tC in 2020)

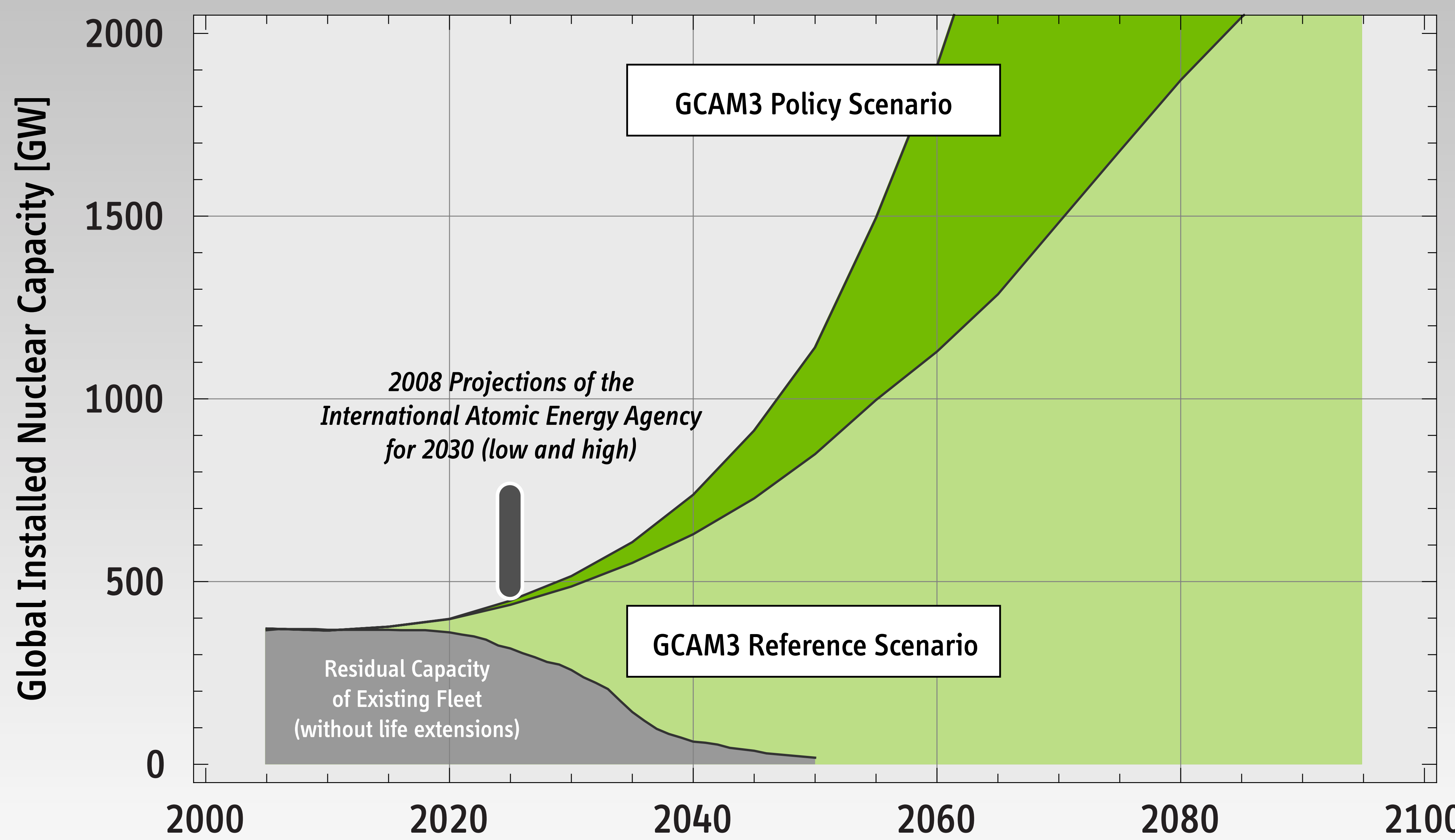
Global Mean Temperature Change

under the GCAM3 Reference and Policy Scenarios



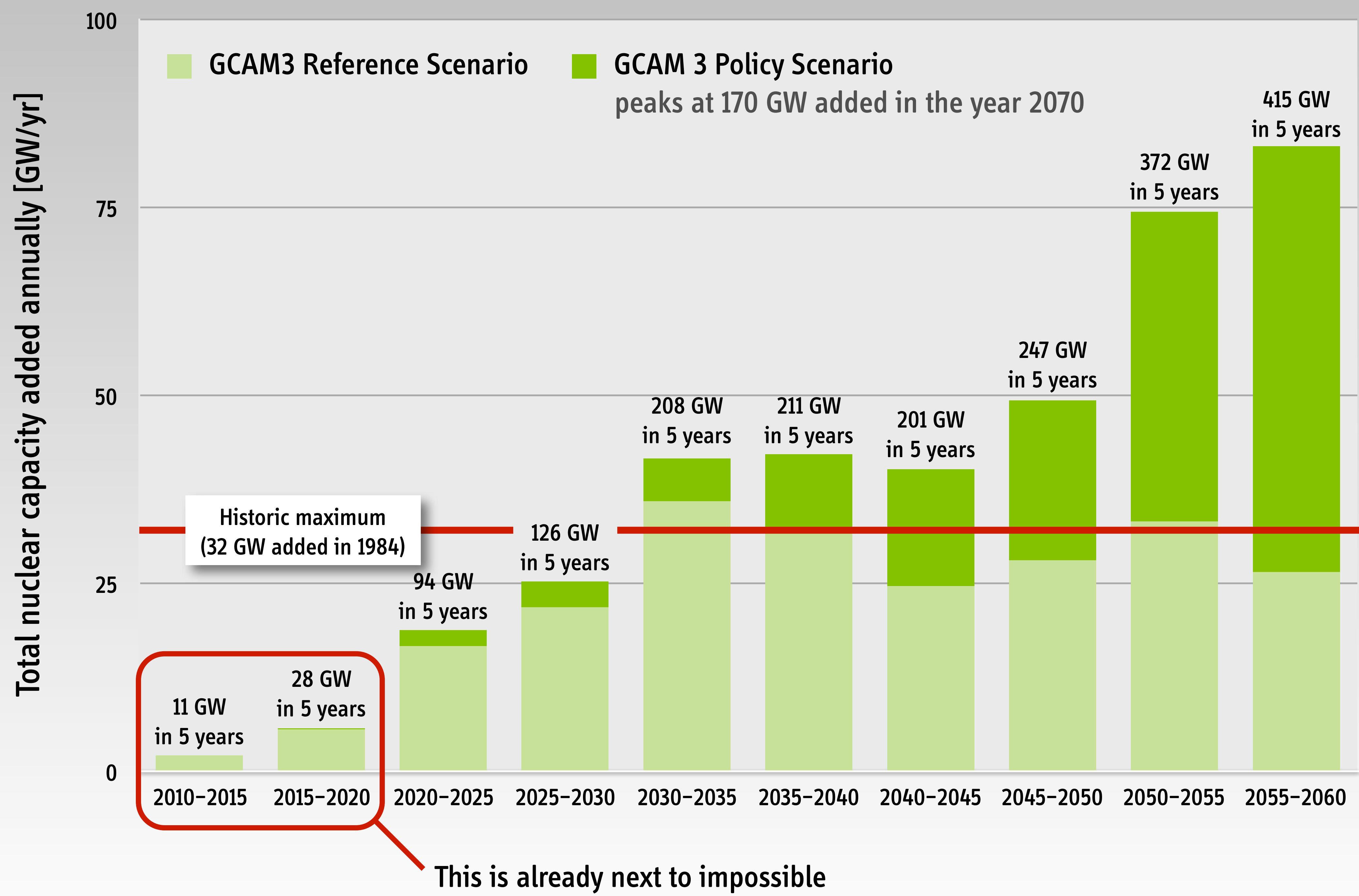
Global Installed Nuclear Capacity

under the GCAM3 Reference and Policy Scenarios (pre-Fukushima)



Global nuclear electricity under Policy Scenario: 1910 GWe in 2060 (23% of total) and 5190 GWe in 2095 (34% of total)

Achieving These Targets Would Require Unprecedented Construction Rates



If an early large-scale global buildup of nuclear power is unrealistic:

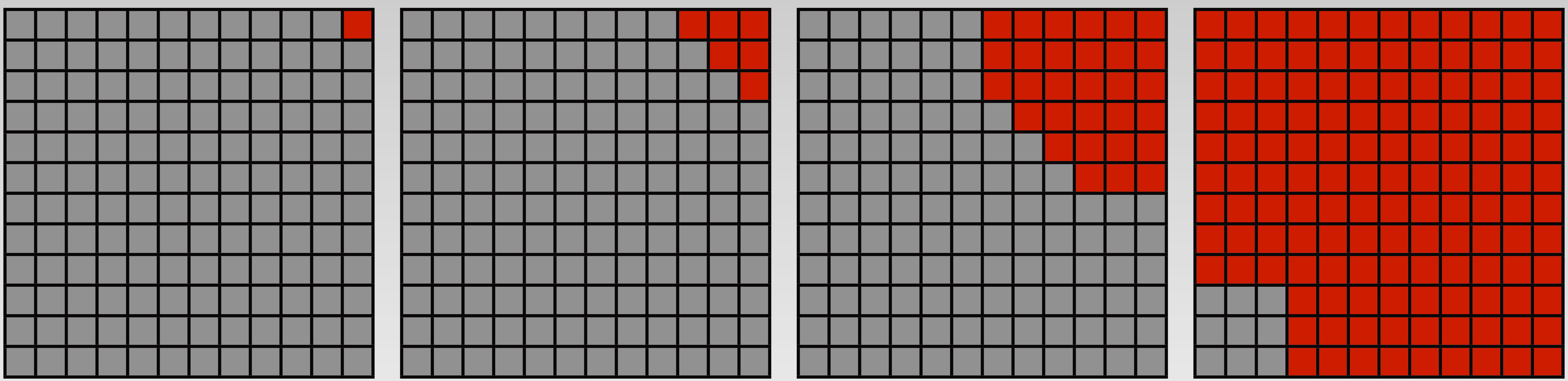
What Should Be Done Instead?

Strengthening The Barriers Against Military Use of Nuclear Power

Enriched Uranium

(visually)

HEU
(weapon-usable)



Natural uranium
0.7% U-235

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

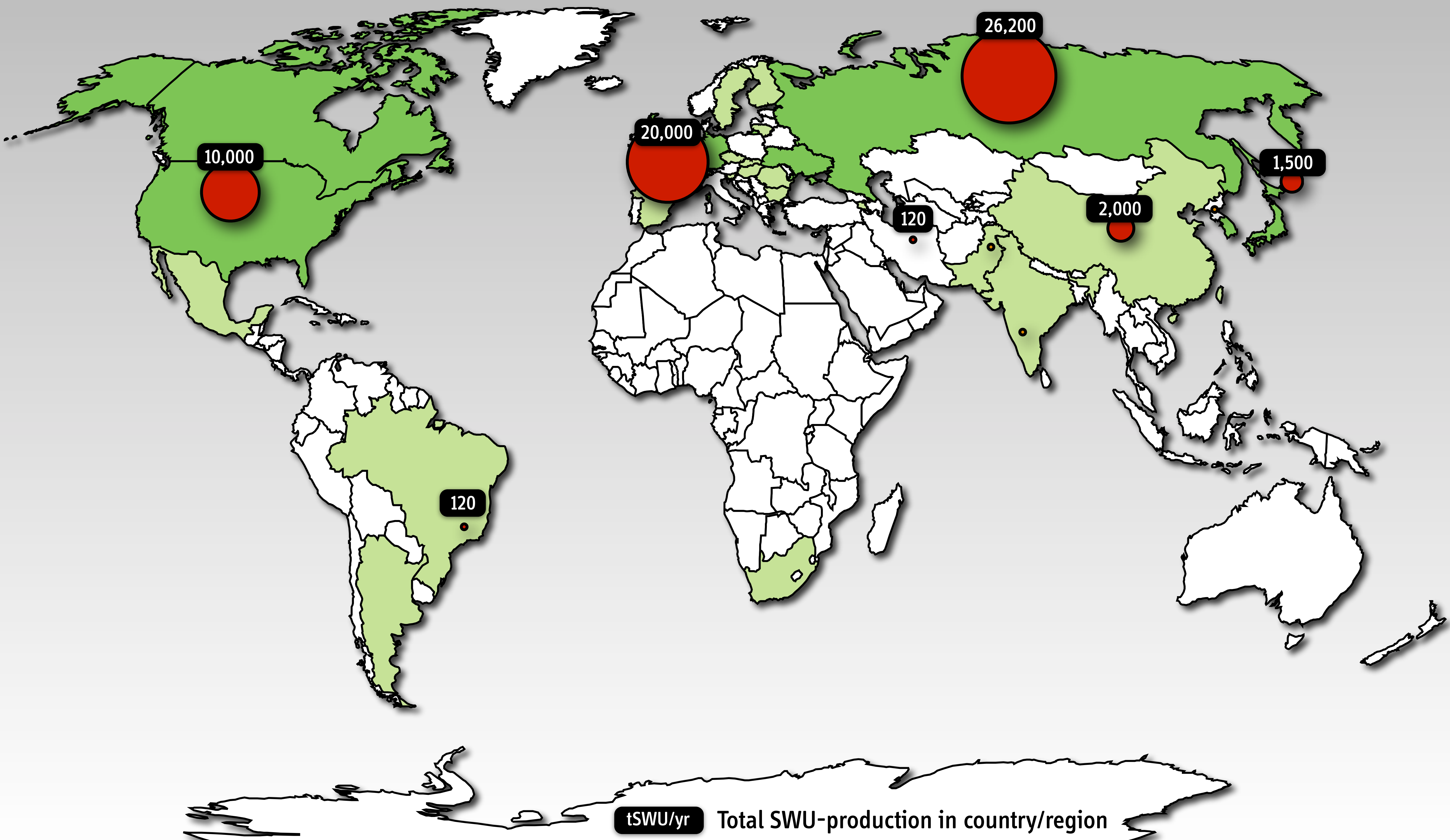
Highly enriched uranium
20% U-235 and above

Weapon-grade uranium
more than 90% U-235

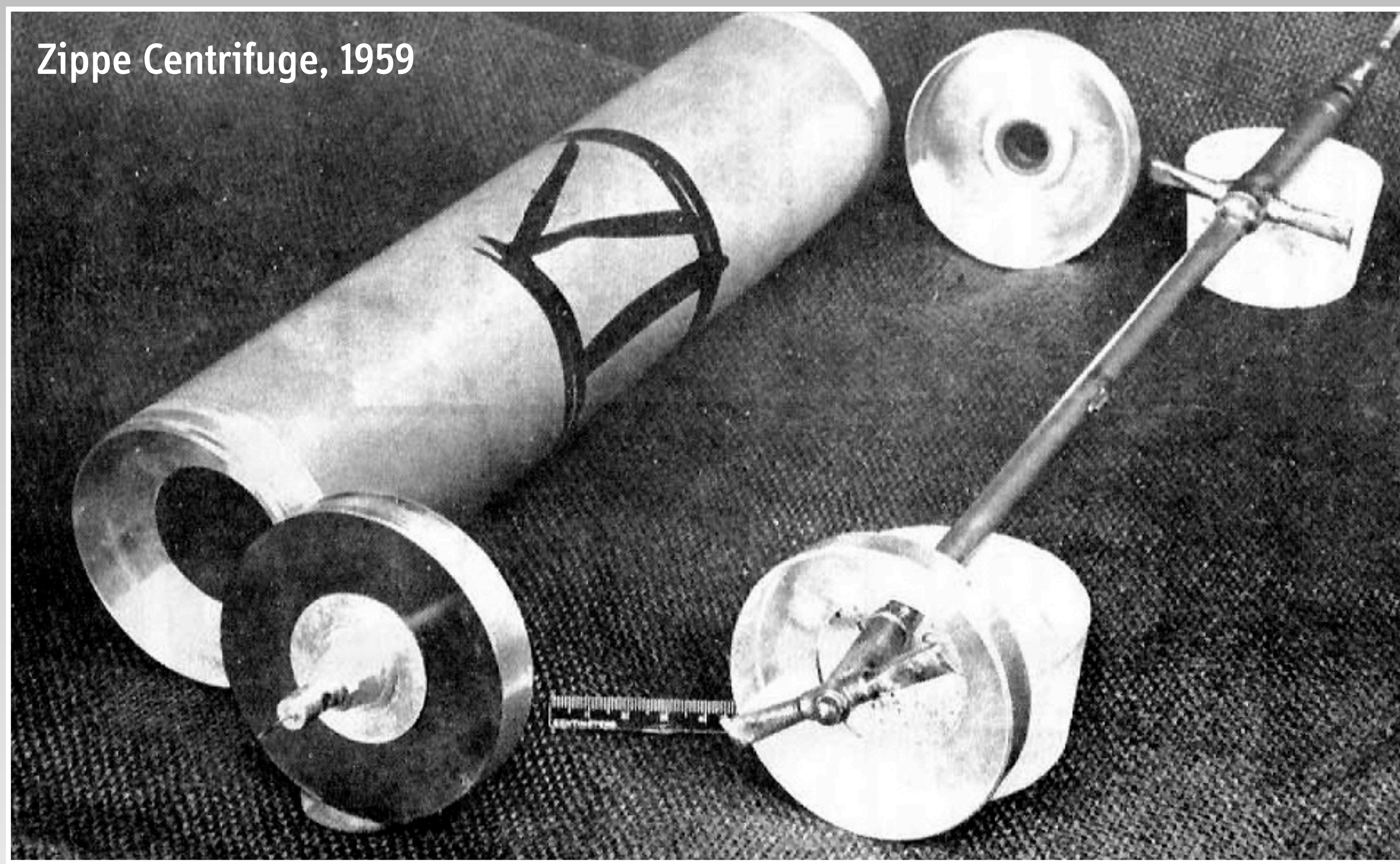
Uranium
U-235
U-238

Global Uranium Enrichment Capacities, 2010

(14 operational plants in 10 countries, not including 3+ military plants)



Why Centrifuges Are Different



Characteristics of centrifuge technology relevant to nuclear proliferation

Rapid Breakout and Clandestine Option

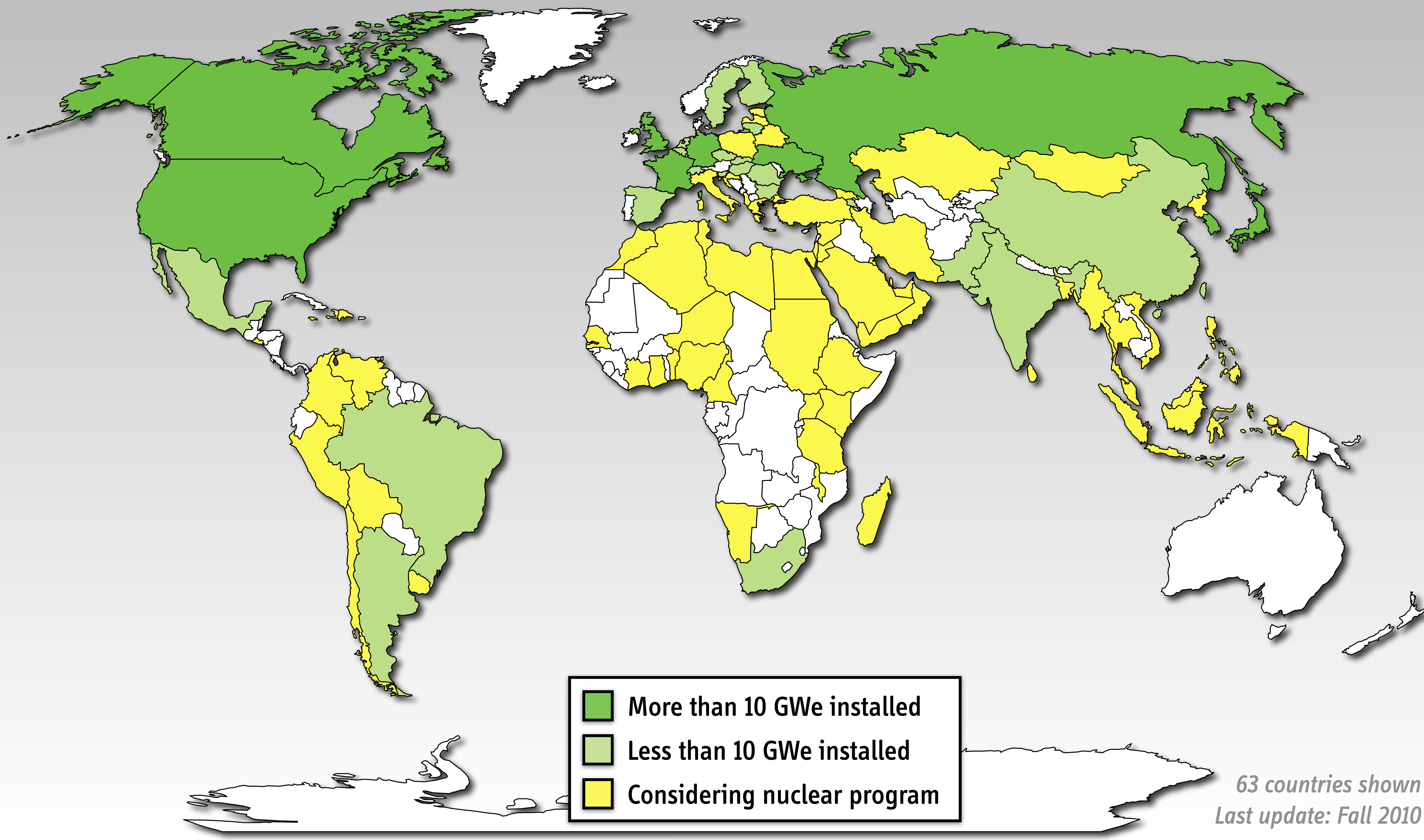

16
17
16
17
18
www.President.ir

Iran’s Second Enrichment Site, near Qom

(Fordow Plant, revealed in September 2009 at 34.885 N, 50.996 E)

Newcomer Countries

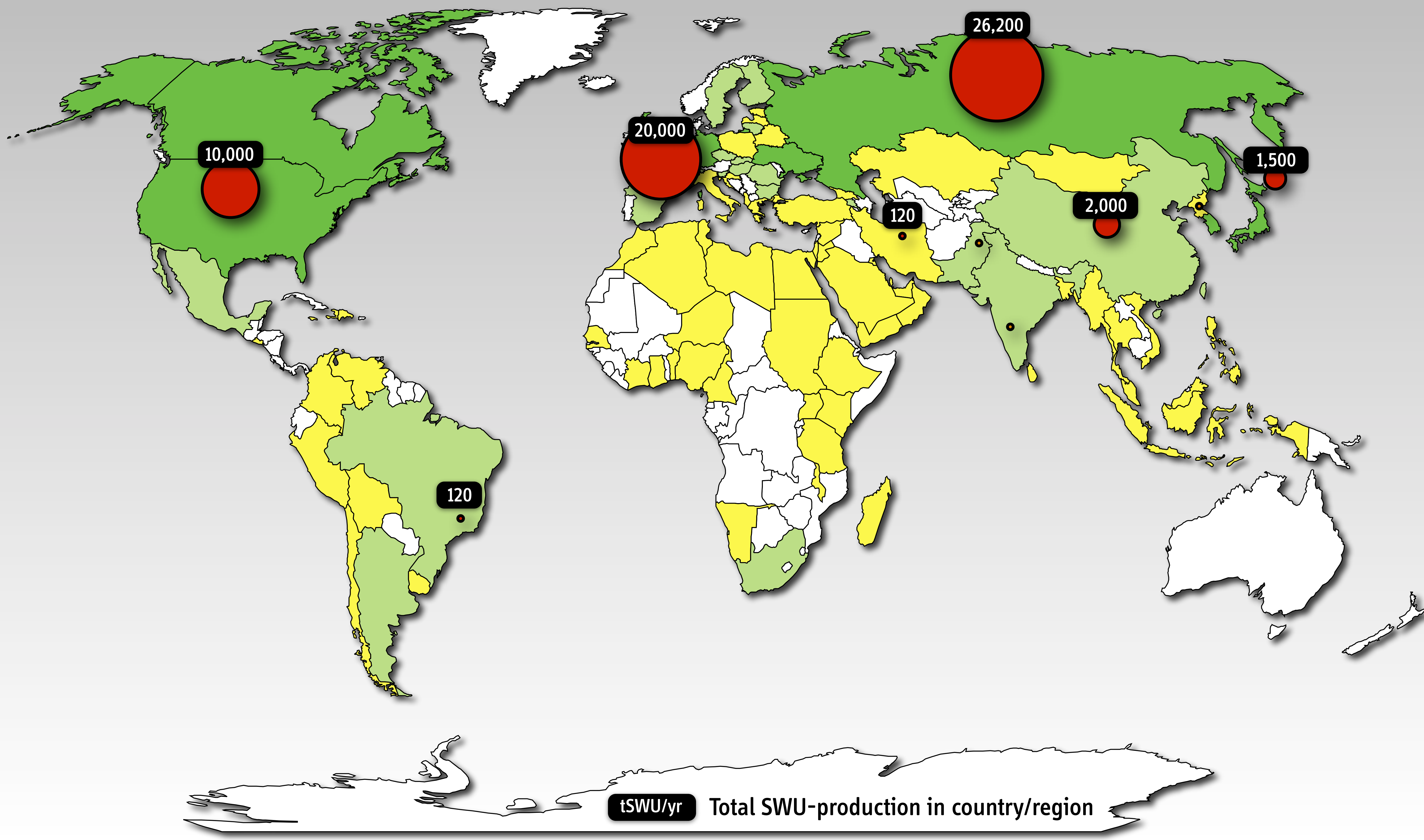
According to the IAEA, 60+ countries were considering nuclear programs in 2010



63 countries shown
Last update: Fall 2010

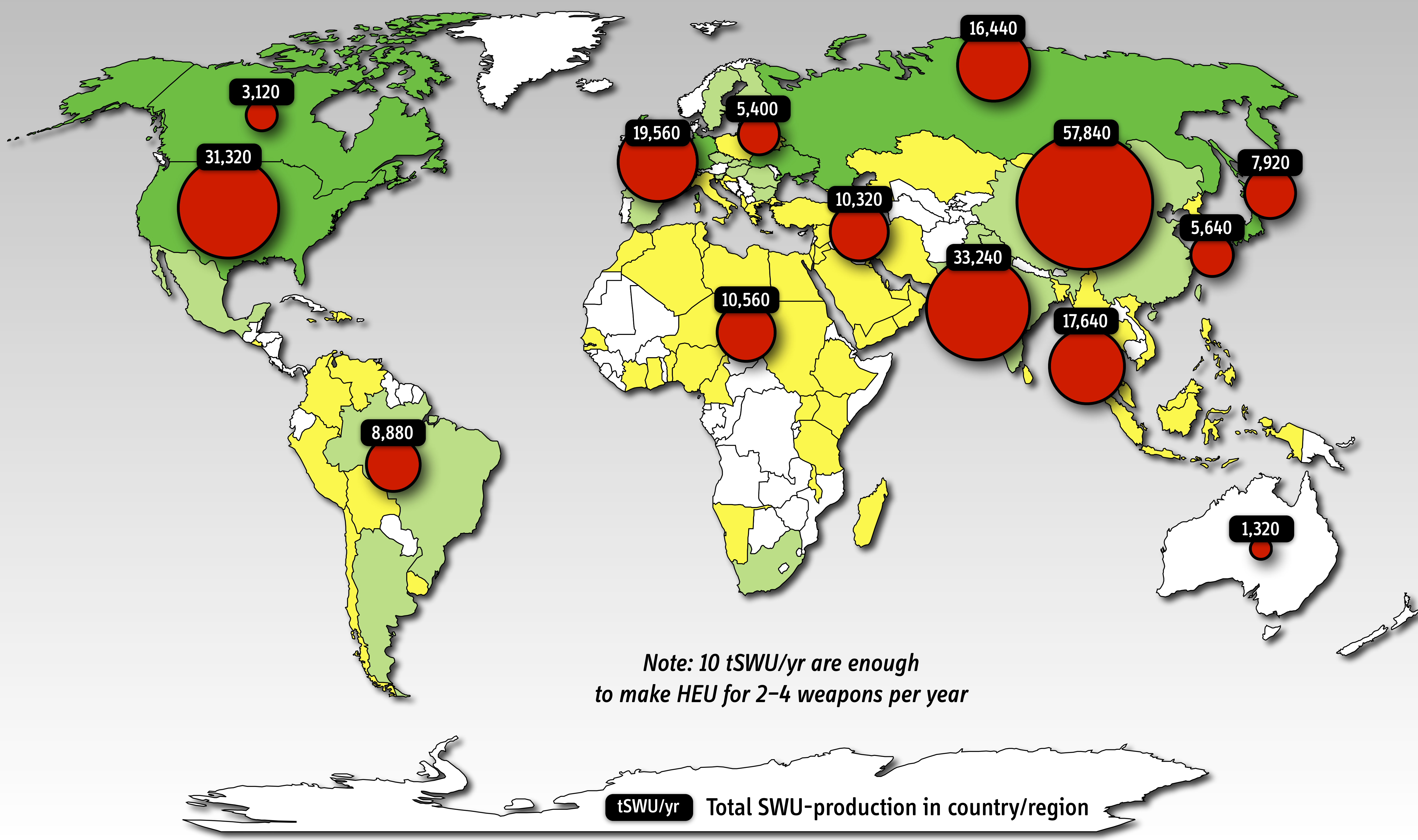
Global Uranium Enrichment Capacities, 2010

(14 operational plants in 10 countries, not including two military plants)



Global Uranium Enrichment Capacities, 2060

Based on the requirements for GCAM3 Policy Scenario in 14 World Regions



Concluding Remarks

The Fukushima accidents have reminded us that we continue to rely on a reactor technology that is not “state-of-the-art”

Critical debate needed about life-extensions and safety objectives for future reactors

The economics of nuclear power are highly uncertain

Advanced reactors promise enhanced safety but are also more expensive

Small modular reactors would have to be “mass-produced” to overcome “economy-of-scale” penalty

This decade is critical

Not much new nuclear capacity will be added in the United States and Europe

Time to establish adequate technologies and new norms of governance