Is There a Future for Nuclear Power After Fukushima?

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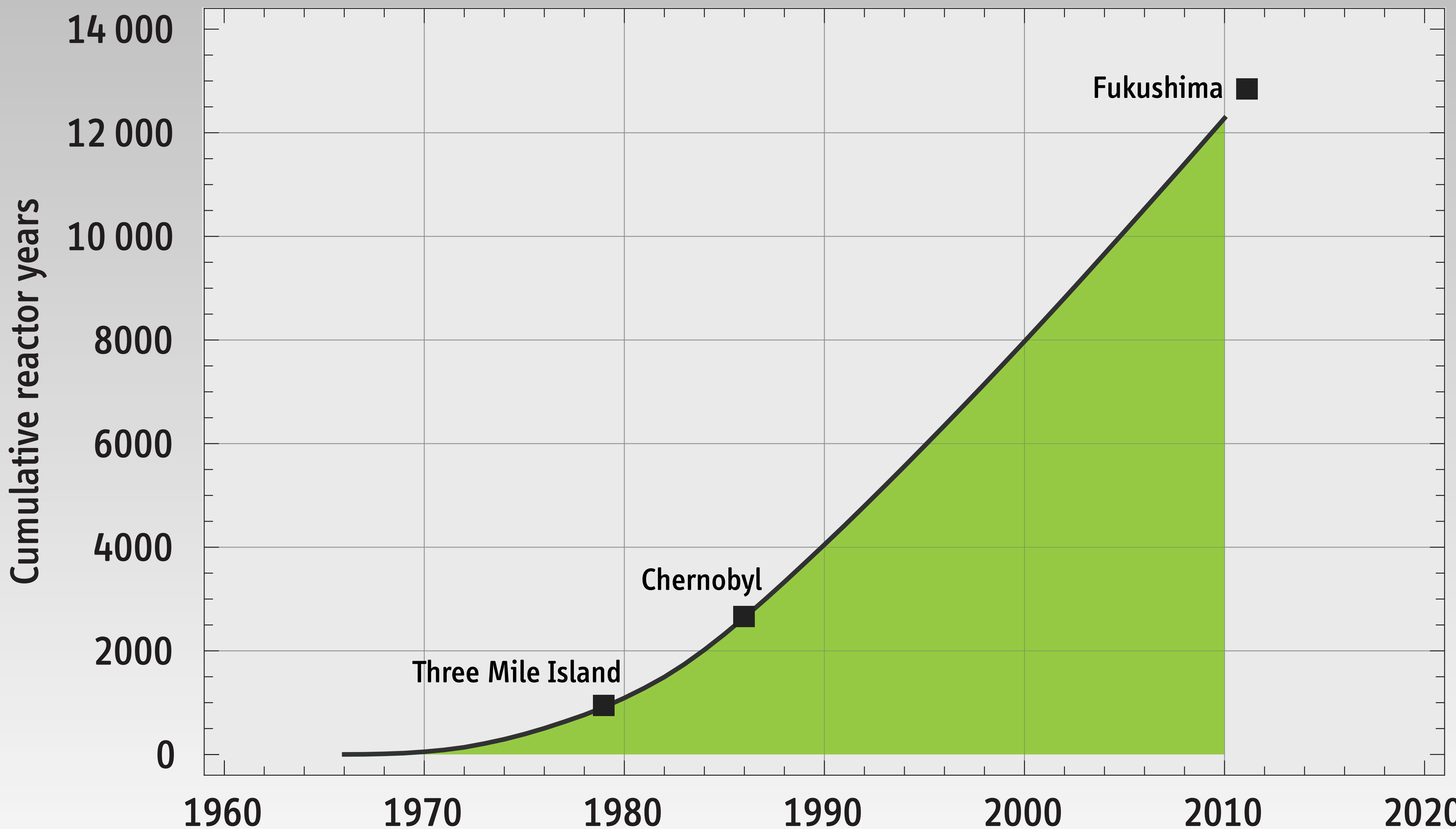
Princeton University

Princeton, May 28, 2011

Revision 4

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)

U.S. President Barack Obama

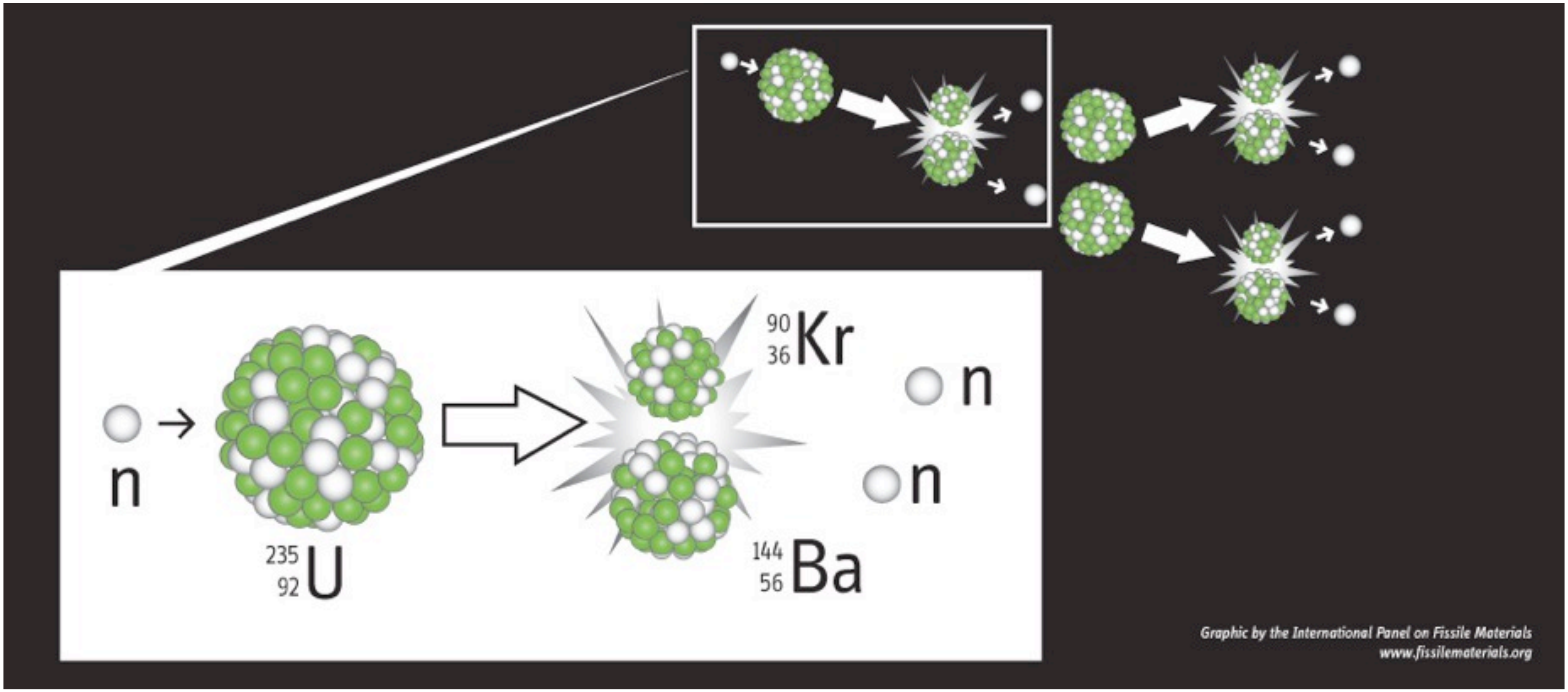
Energy Security Speech, Georgetown University, March 30, 2011

"And that's why, in my State of the Union address back in January, I called for a new Clean Energy Standard for America: By 2035, 80 percent of our electricity needs to come from a wide range of clean energy sources – renewables like wind and solar, efficient natural gas. And, yes, we're going to have to examine how do we make clean coal and nuclear power work.

What is Nuclear Power?

Nuclear Fission

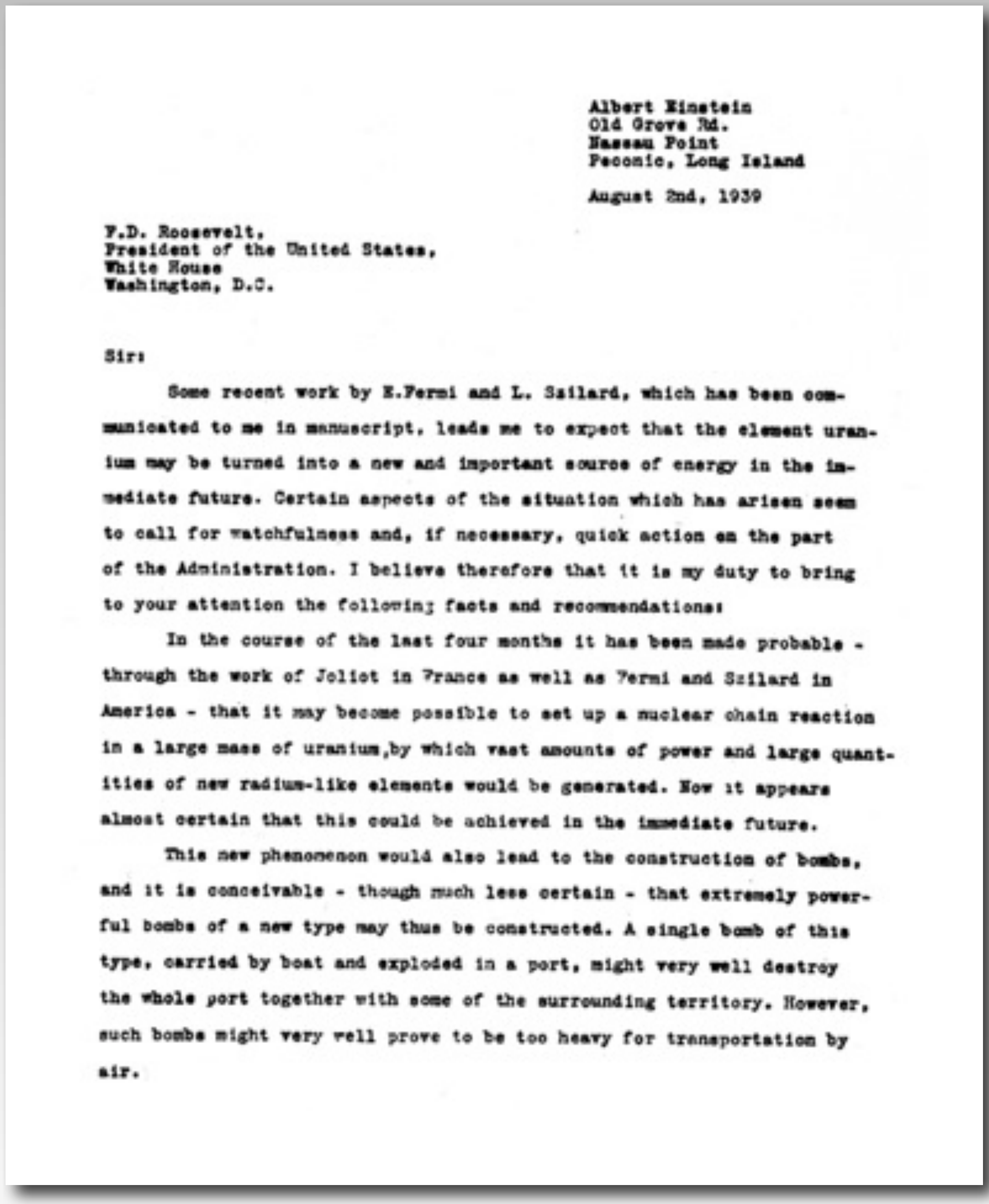
(discovered by L. Meitner, O. Hahn, F. Strassmann, 1938)



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.

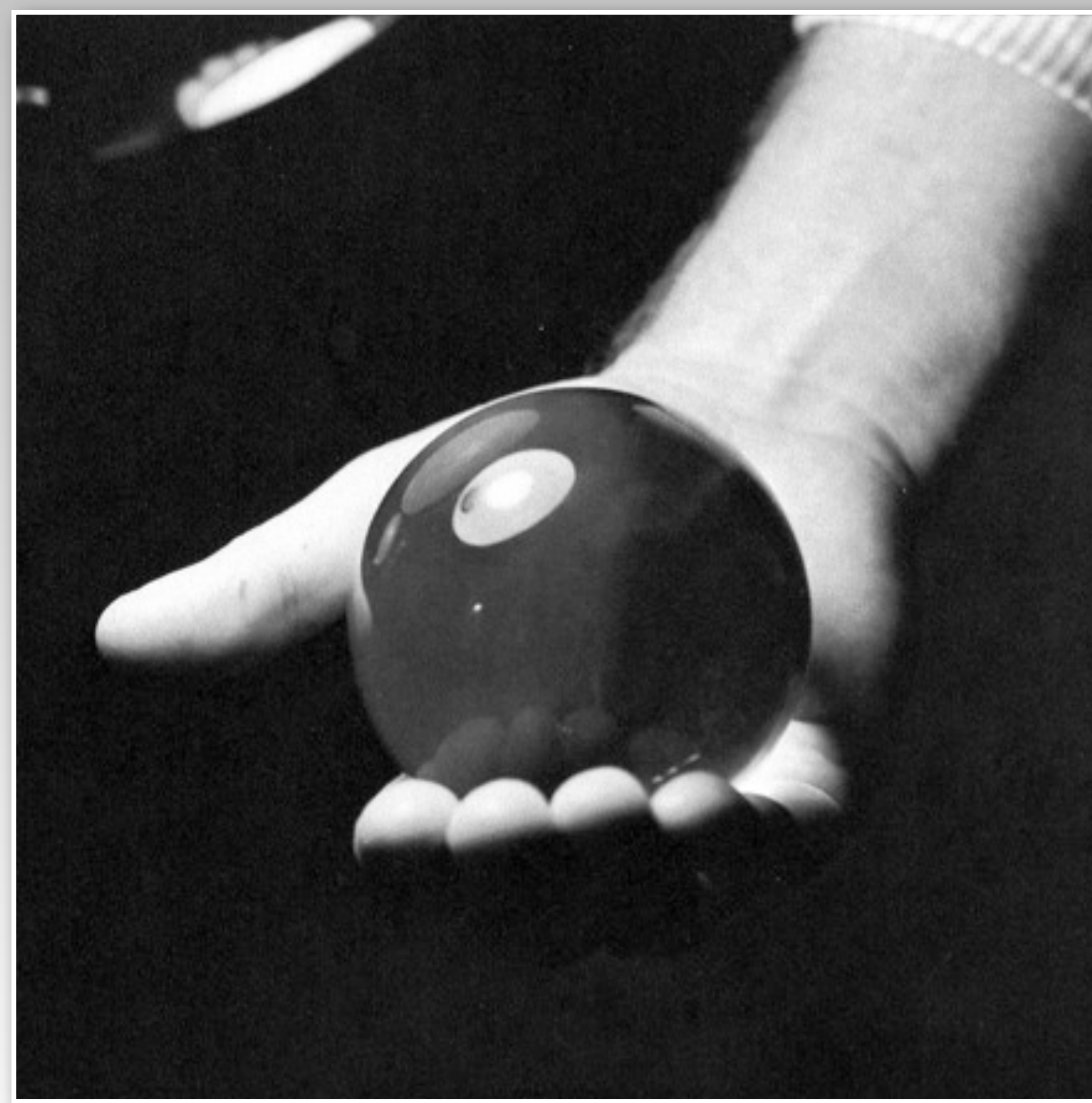
Sir:

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.

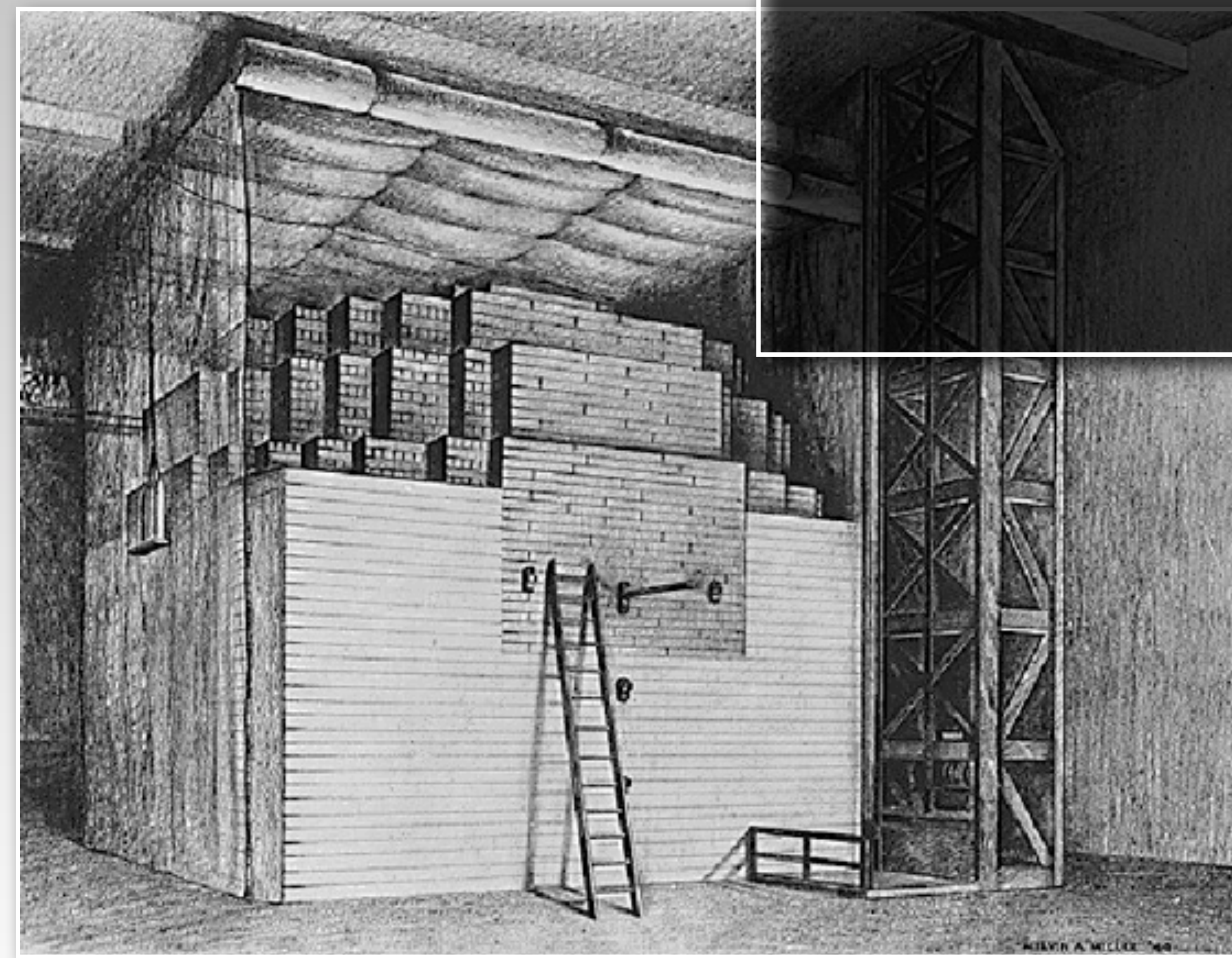
It Takes Only a Few Kilograms of Fissile Material to Make a Nuclear Weapon



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

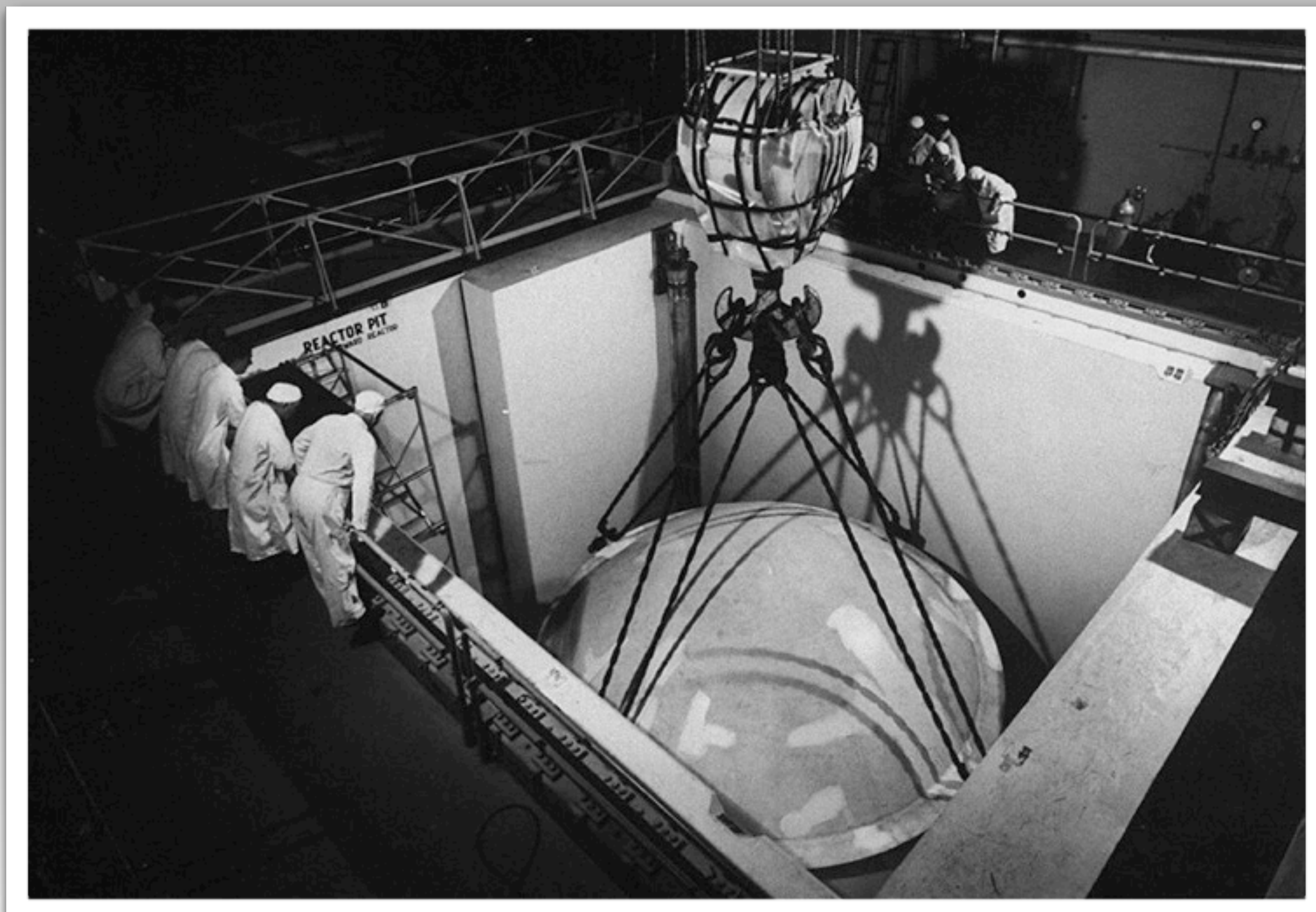


Chicago Pile-1 (CP-1), December 2, 1942

Nuclear-Powered Submarines Came Next

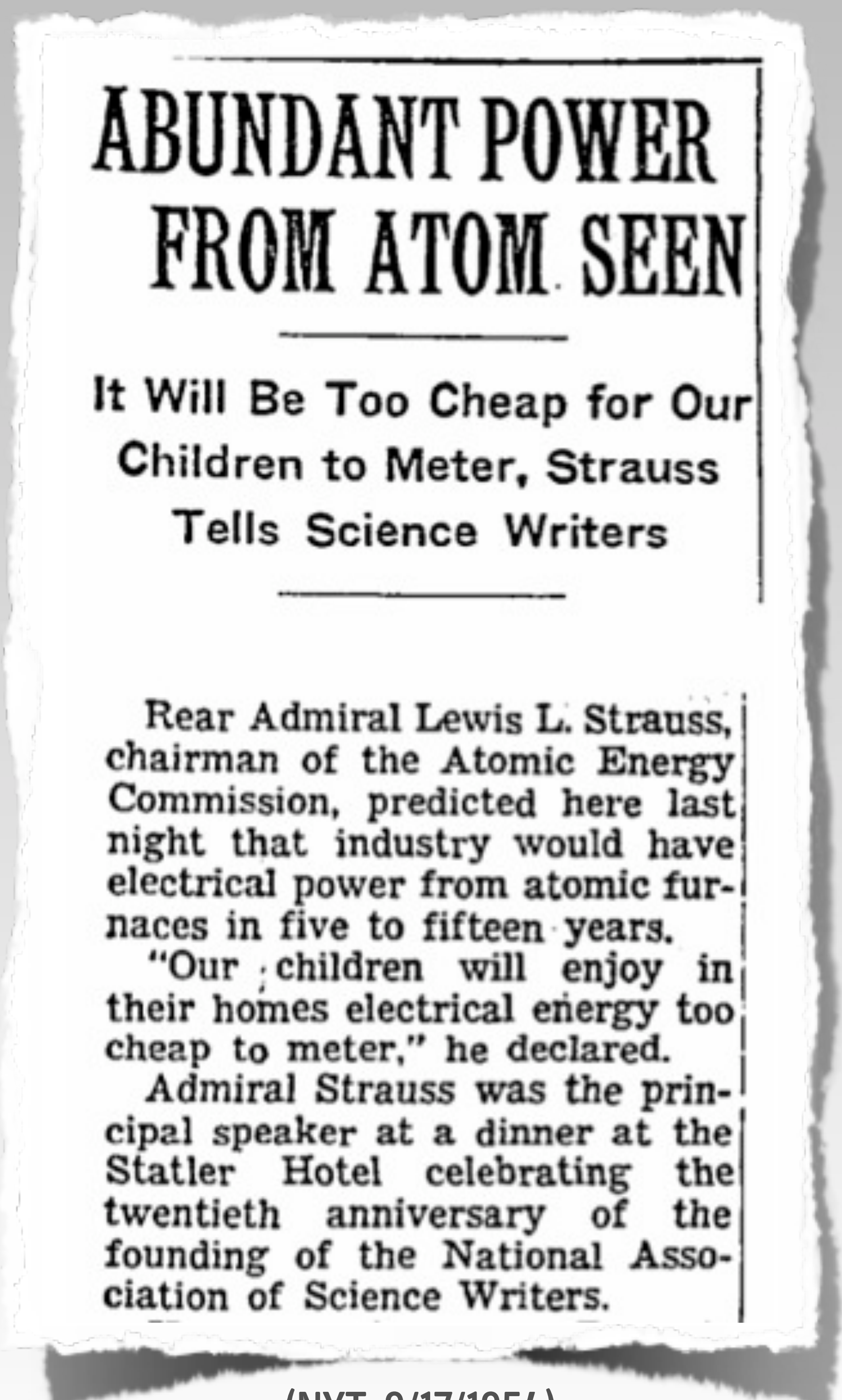
USS Nautilus (SSN-571), launched in 1954, here entering New York Harbor, 1958

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.

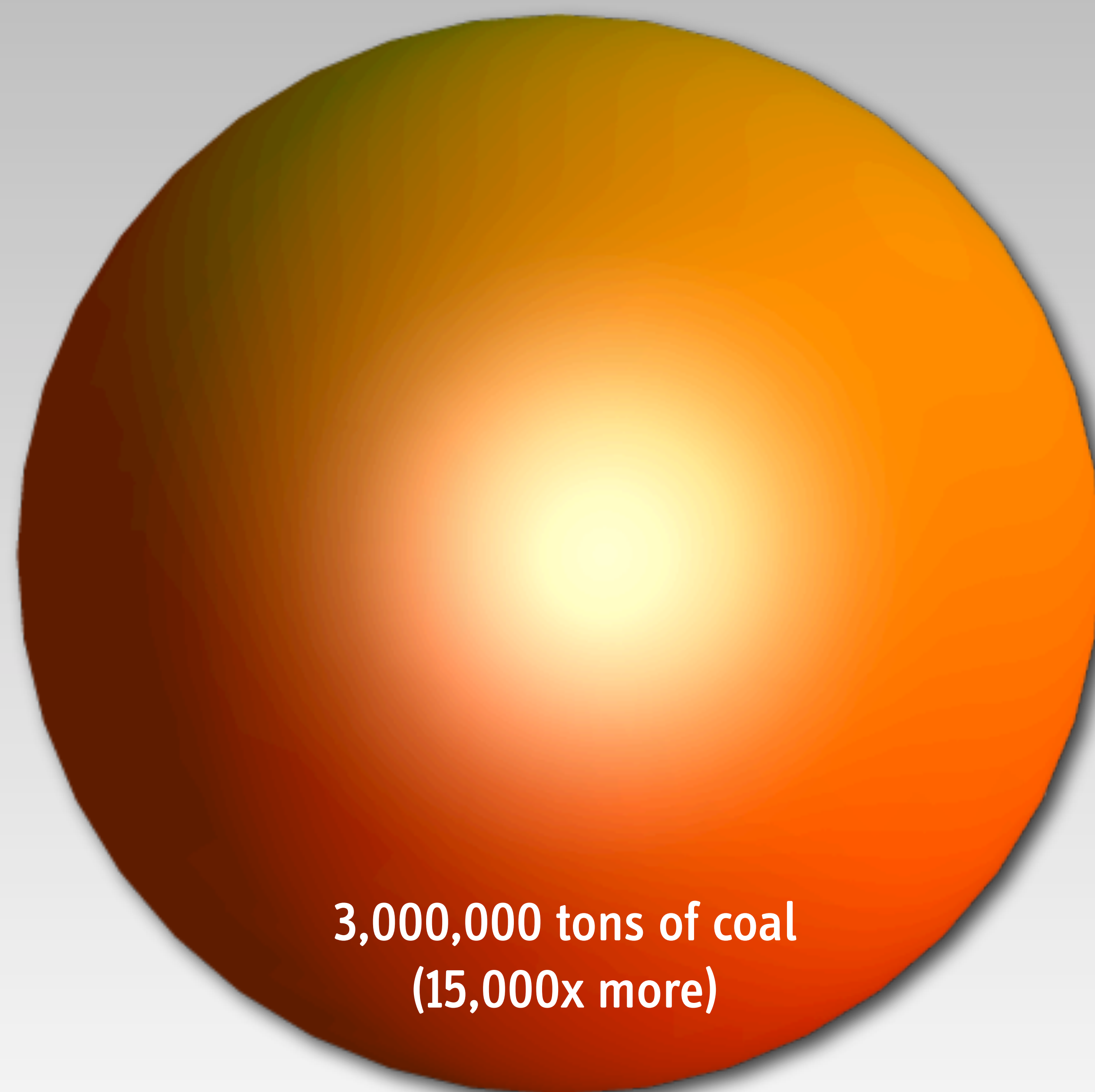
(NYT, 9/17/1954)

"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

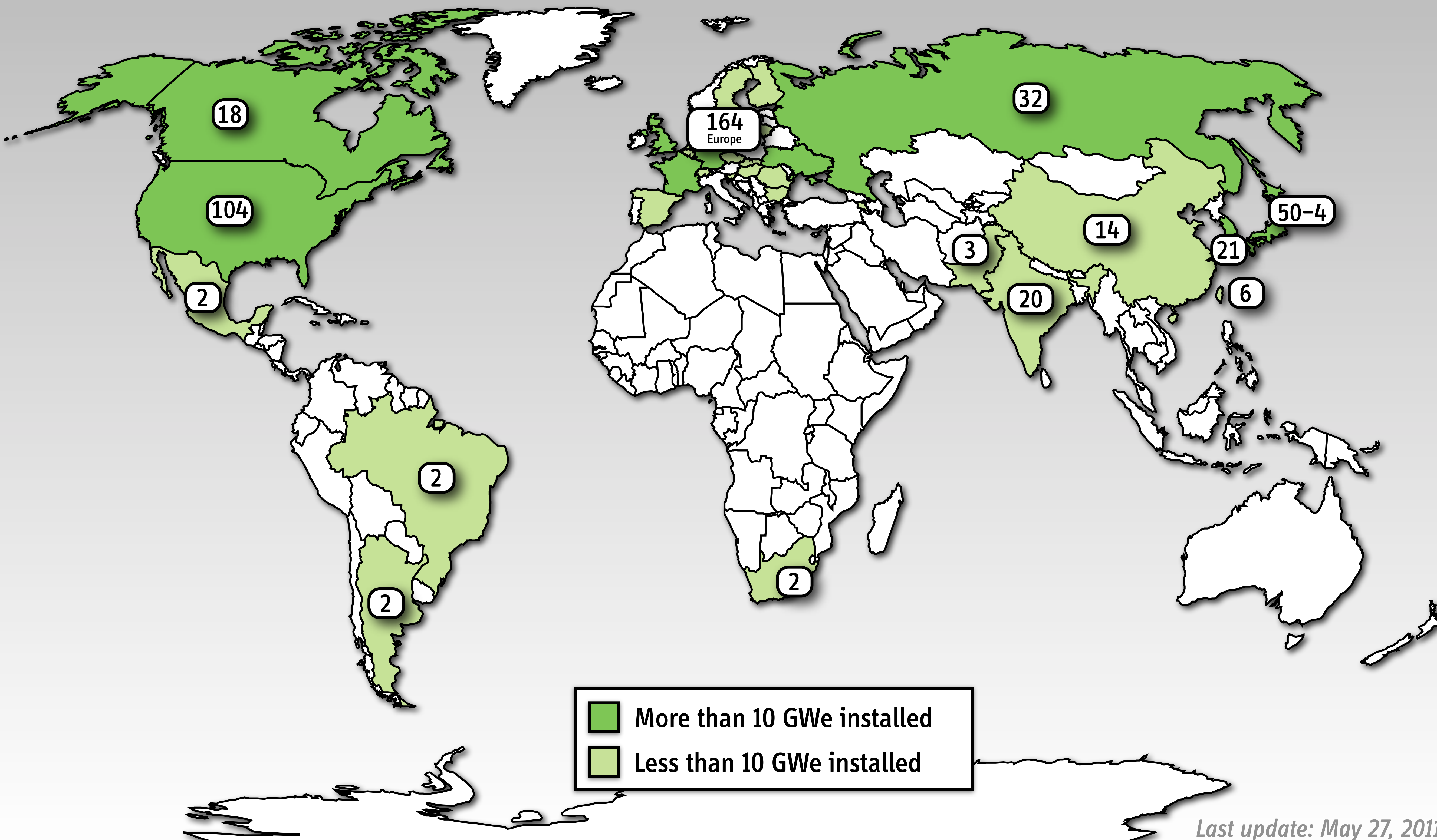
200 tons of uranium have to be mined
to produce 20 tons of nuclear fuel
(only 1 ton is ultimately fissioned)



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

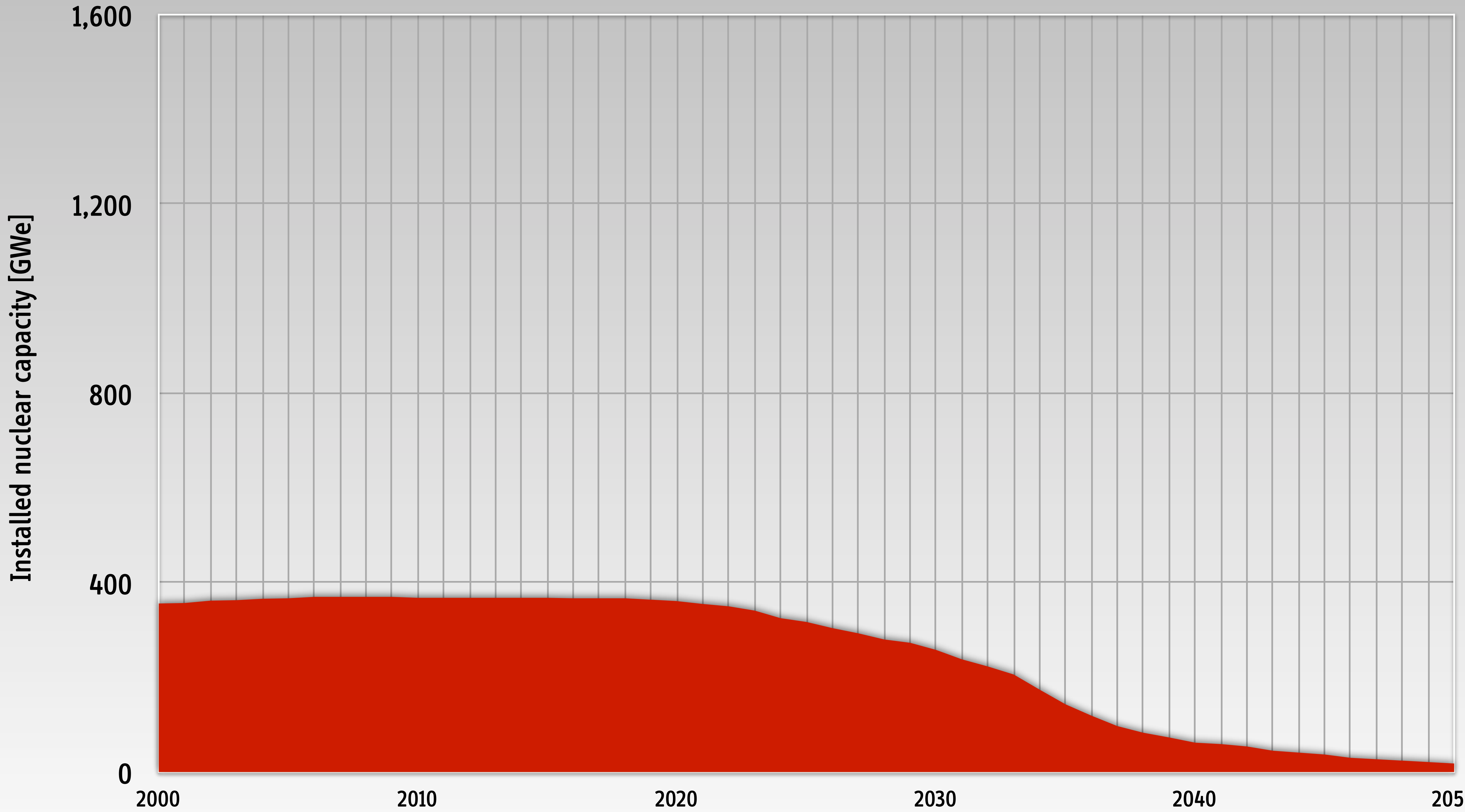
Nuclear Power Reactors in the World, 2011

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



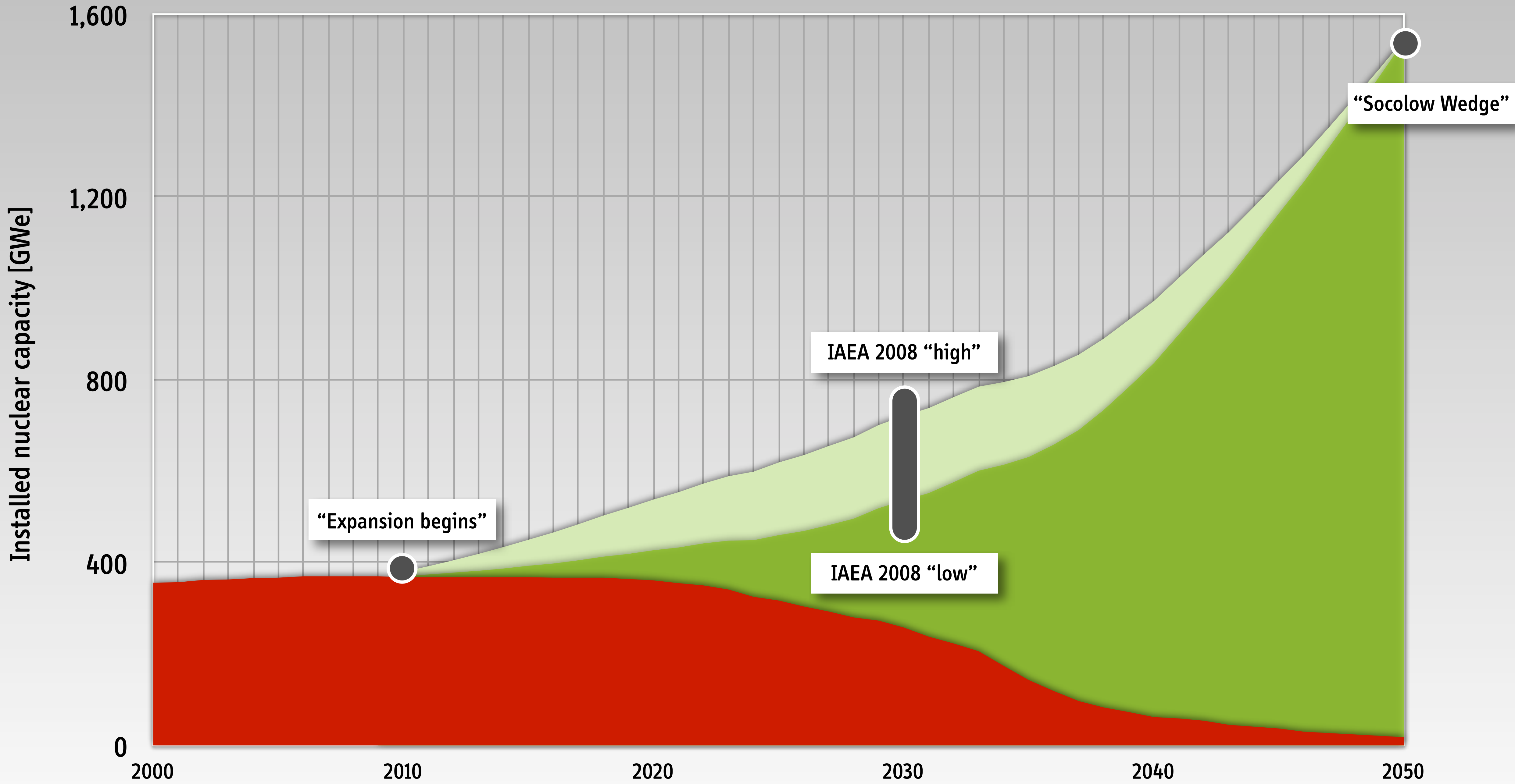
Last update: May 27, 2011

Achieving One “Socolow-Pacala Wedge” By 2050



Achieving One “Socolow-Pacala Wedge” By 2050

Notional Buildup of Nuclear Capacity



Compared to Other Sources of Energy:

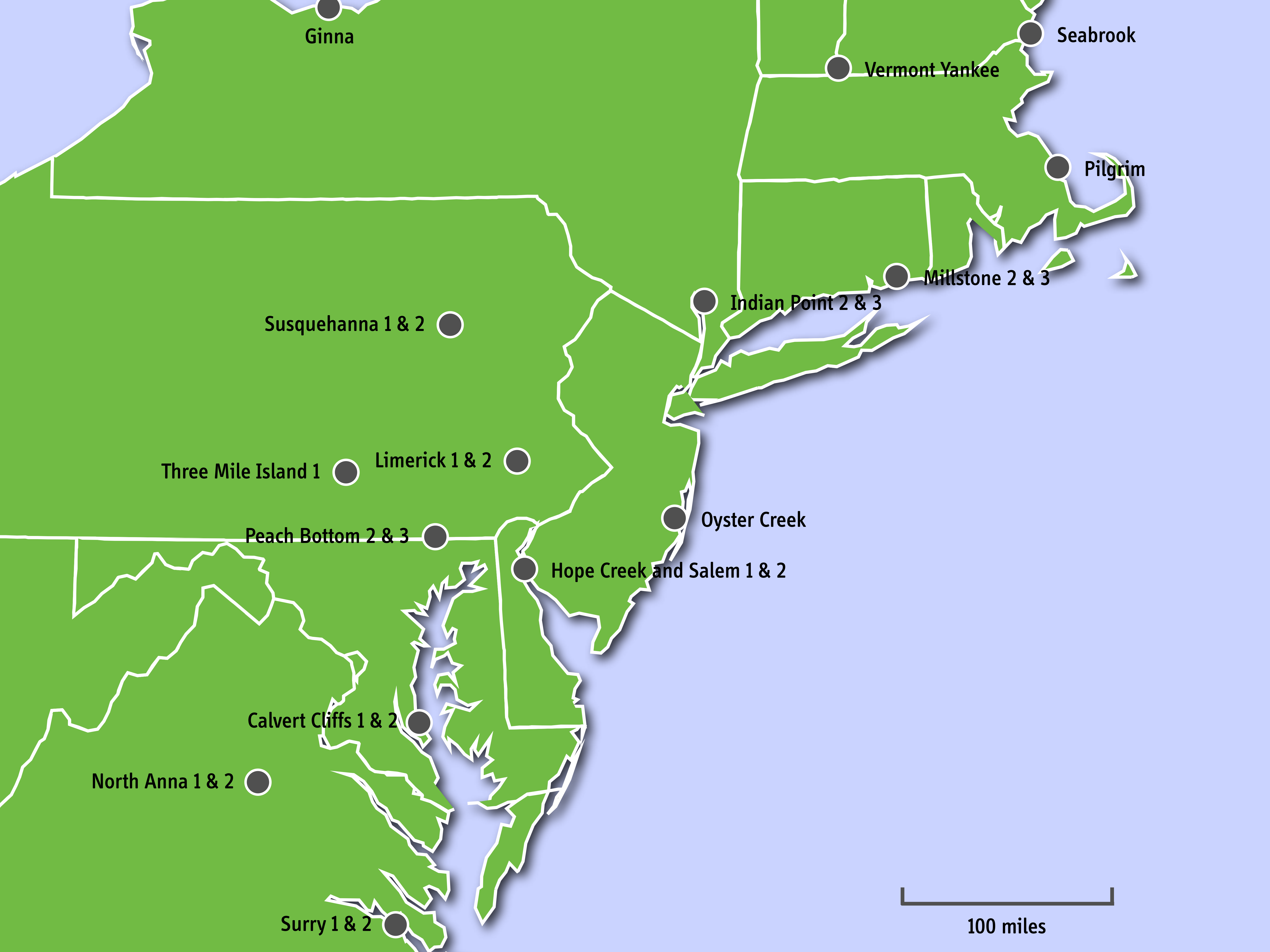
What Factors Tend to Put Nuclear Power at an Advantage?

- 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

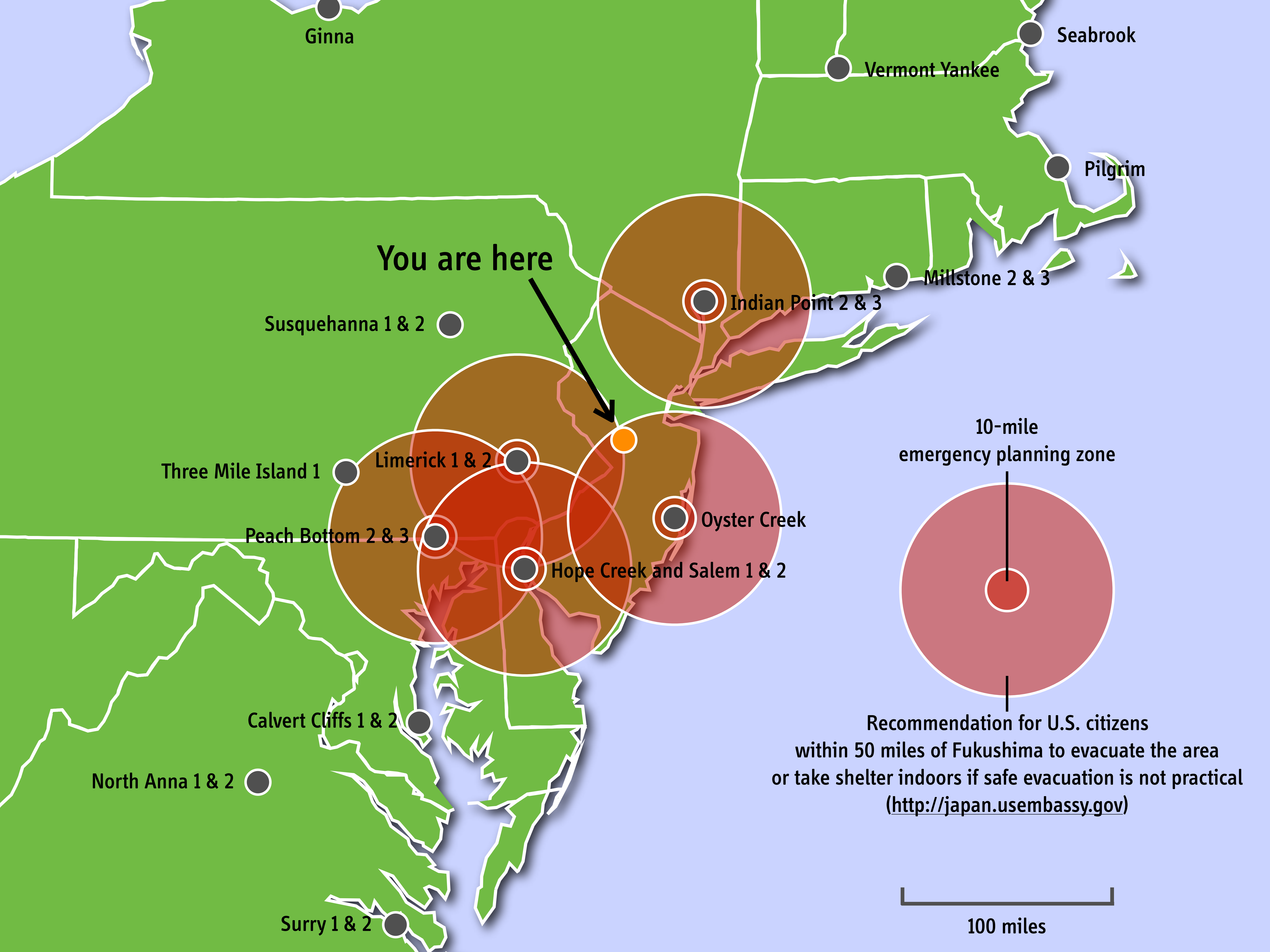
Compared to Other Sources of Energy:

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)



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



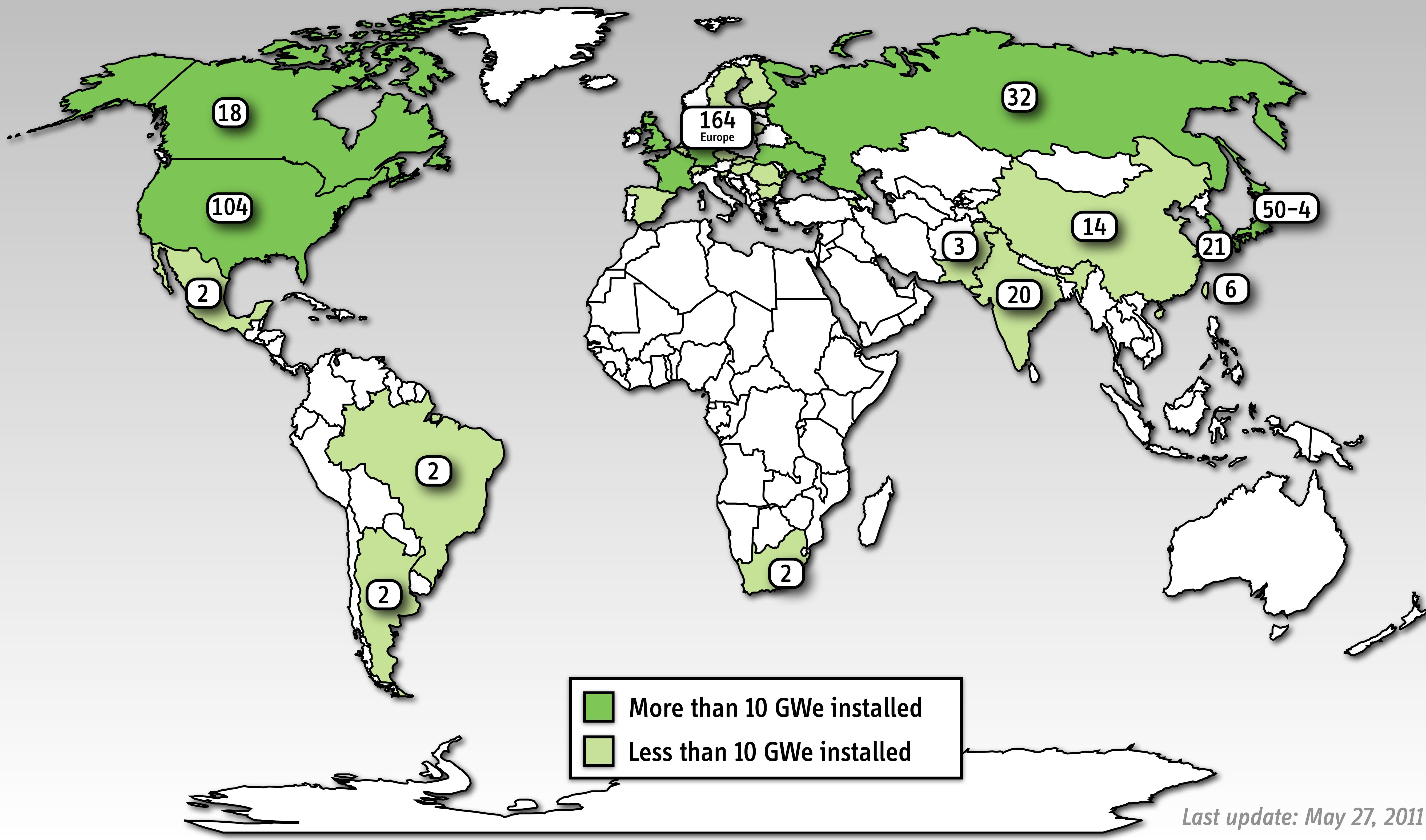
Ginna
Seabrook
Vermont Yankee
Pilgrim
You are here
Millstone 2 & 3
Indian Point 2 & 3
Susquehanna 1 & 2
Limerick 1 & 2
Three Mile Island 1
Oyster Creek
Peach Bottom 2 & 3
Hope Creek and Salem 1 & 2
10-mile
emergency planning zone
Recommendation for U.S. citizens
within 50 miles of Fukushima to evacuate 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

Lessons (to be) Learned

What To Do With the Existing Fleet?

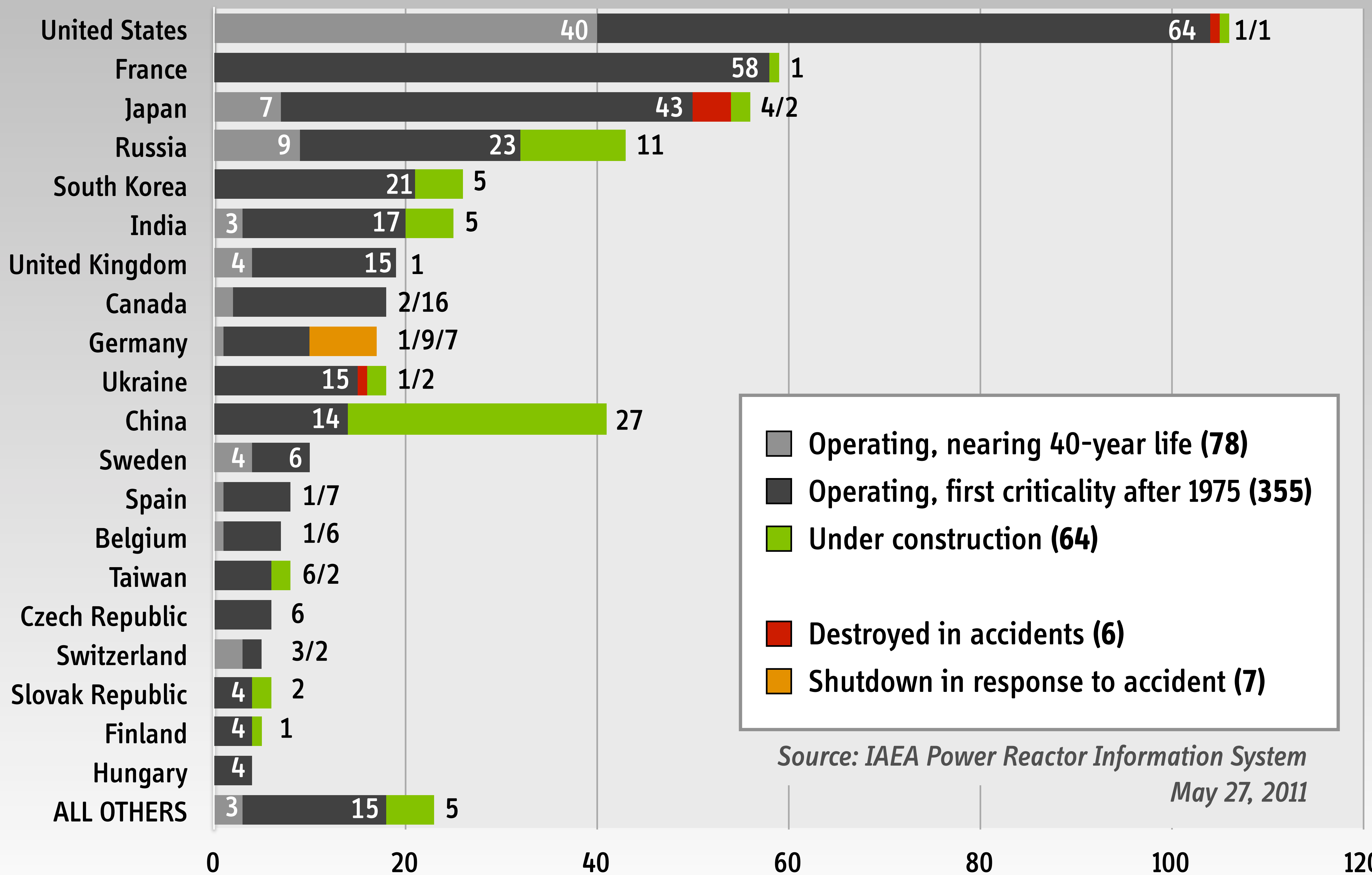
Nuclear Power Reactors in the World, 2011

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



Last update: May 27, 2011

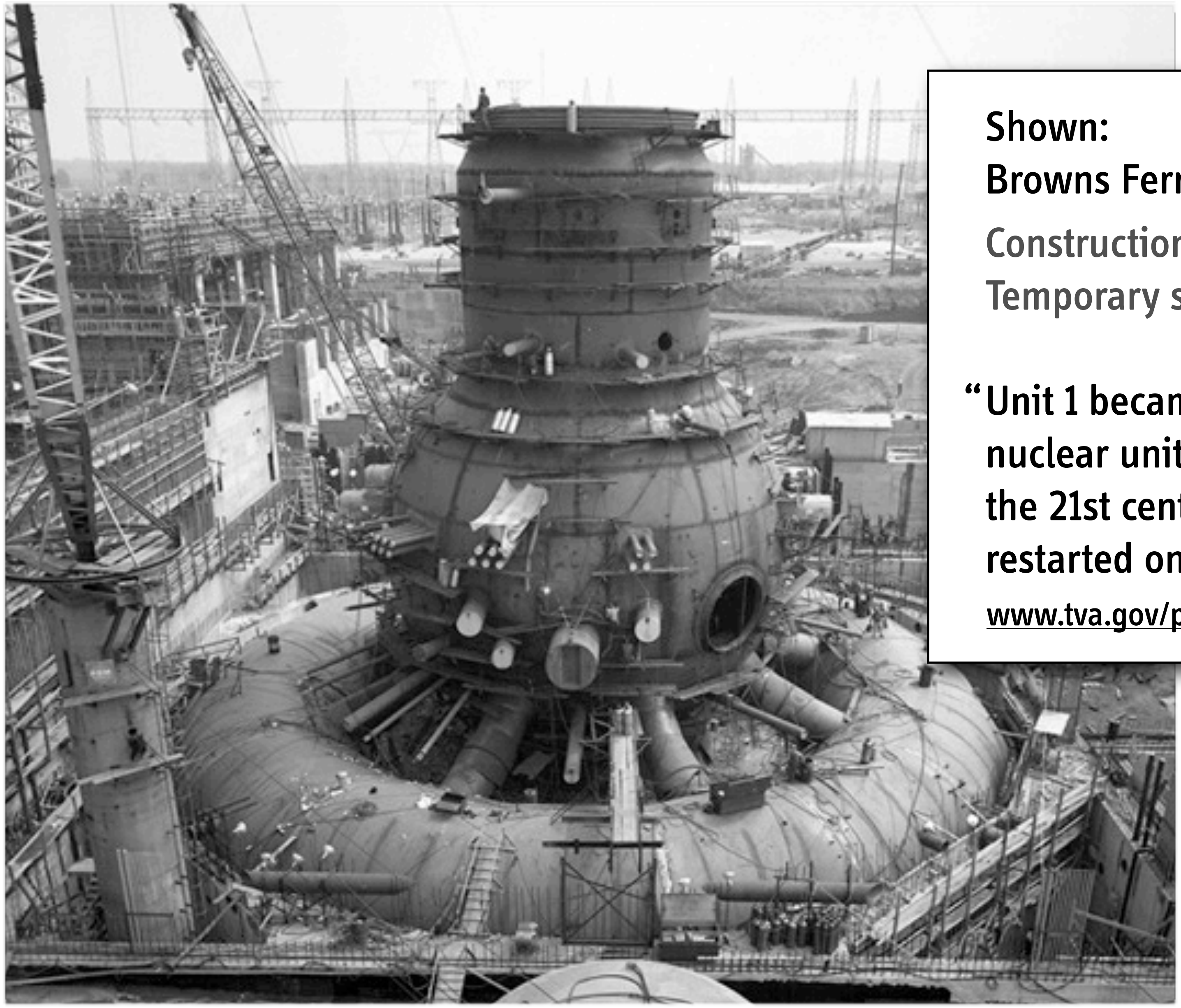
The Existing Fleet of Power Reactors is Aging



Source: IAEA Power Reactor Information System
May 27, 2011

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

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



Shown:
Browns Ferry Unit I near Athens, AL

Construction start: 1966
Temporary shutdown: 1985–2007

"Unit 1 became the nation's first nuclear unit to come online in the 21st century when it was restarted on time in May 2007."

www.tva.gov/power/nuclear/brownsferry.htm

Weaknesses of Old Reactor Designs Have Been Known for Decades

"Steve's idea to ban pressure suppression containment schemes is an attractive one in some ways. ... However, the acceptance of ... [these] containment concepts ... is firmly embedded in the conventional wisdom. Reversal of this hallowed policy ... could well be the end of nuclear power. It would throw into question the operation of licensed plants, would make unlicensable the ... plants now under review, and would generally create more turmoil than I can stand."

Joseph Hendrie, 1972
Then Deputy Director for Technical Review
U.S. Atomic Energy Commission

What About Advanced Reactor Designs?

Advanced Reactors Promise Enhanced Safety

Double-walled containment

Four separate emergency core cooling systems
(with independent and geographically separated trains)

Corium spreading area
("core catcher")

Shown: Areva EPR
Estimated core damage frequency: 6×10^{-7} per year

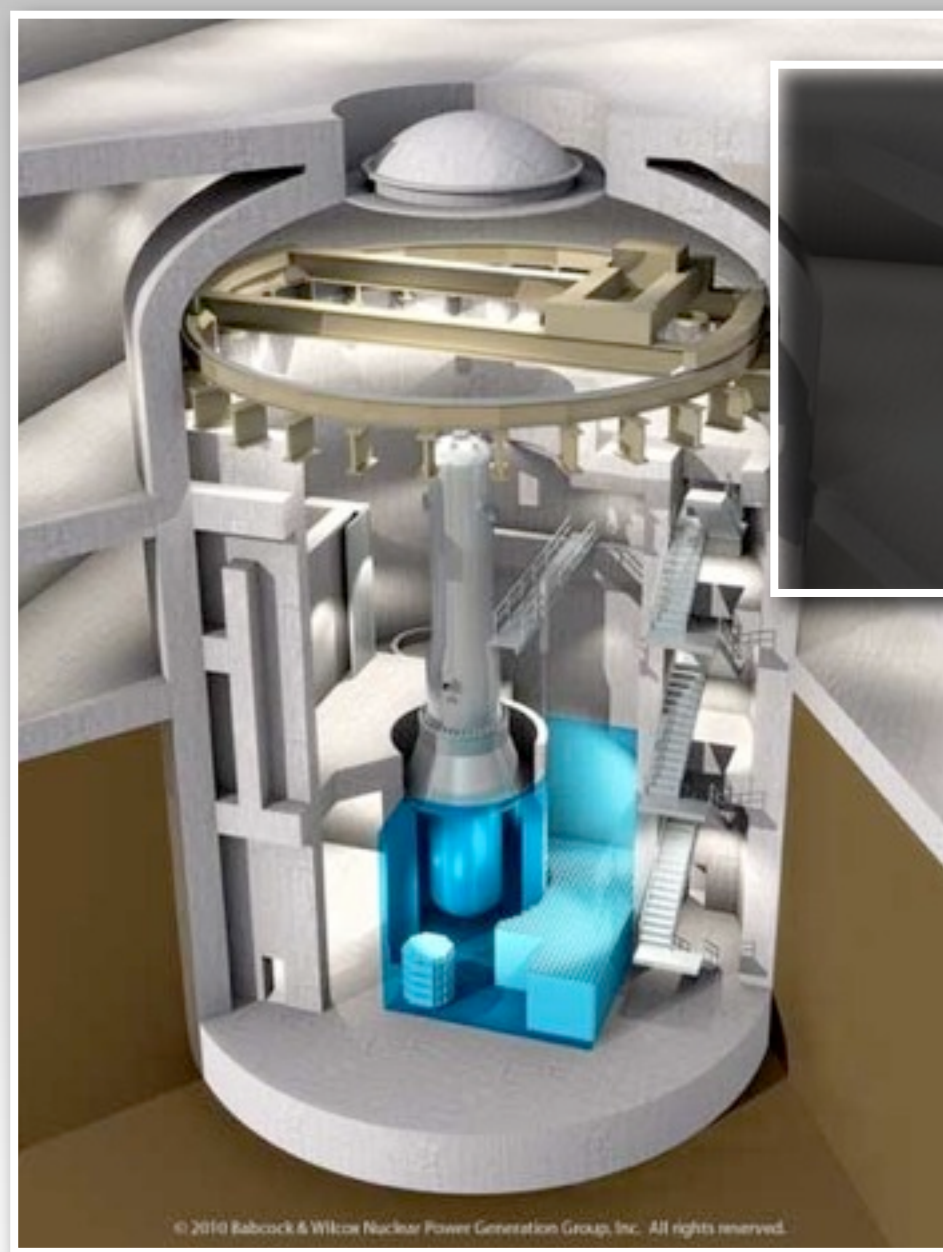
Advanced Reactors Are Also Expensive

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



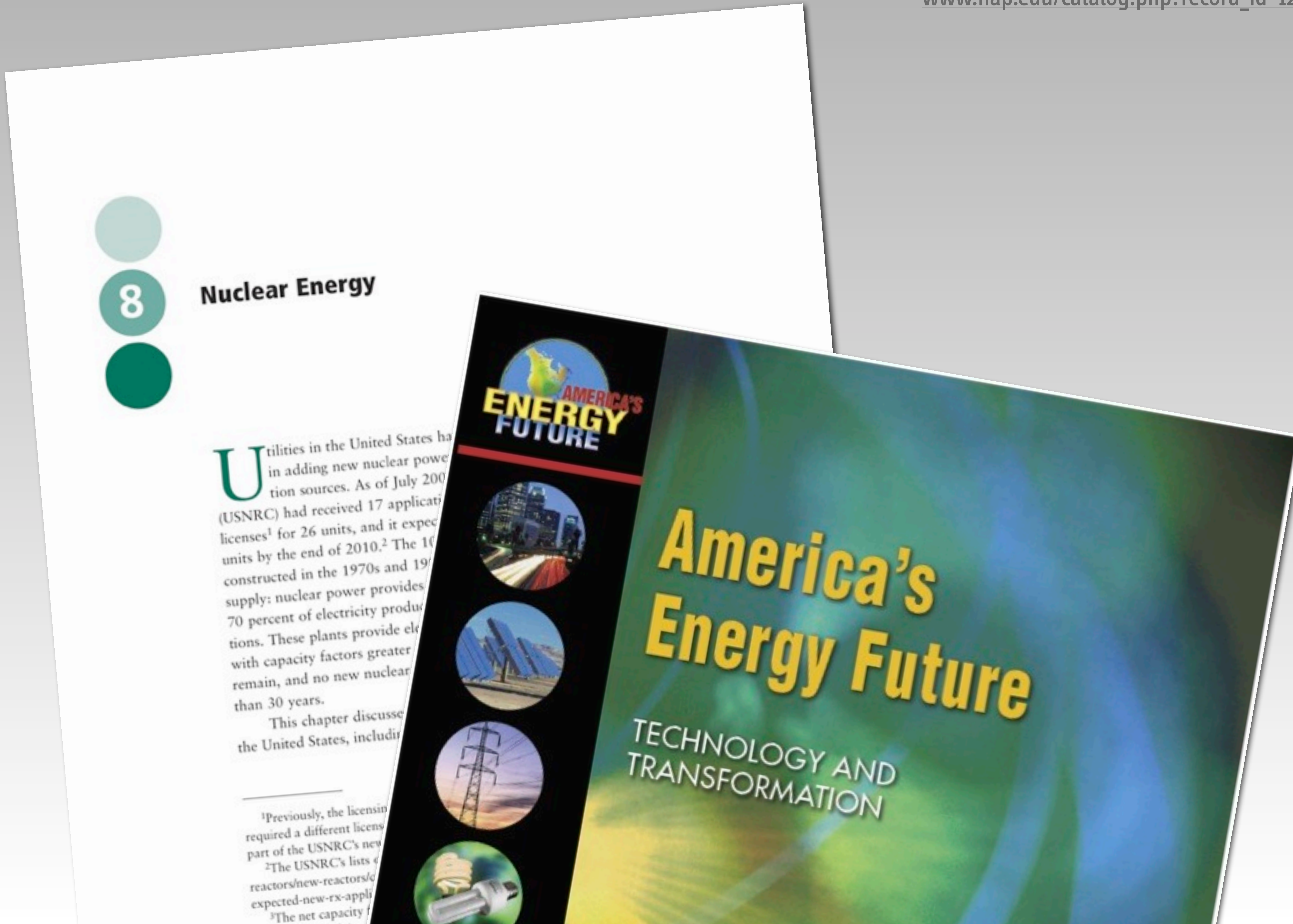
Babock & Wilcox mPower Concept

- 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/

Looking Ahead

America's Energy Future: Technology and Transformation
National Academy of Sciences; National Academy of Engineering; National Research Council
Washington, DC, July 2009
www.nap.edu/catalog.php?record_id=12091



America's Energy Future

National Research Council, July 2009, Executive Summary

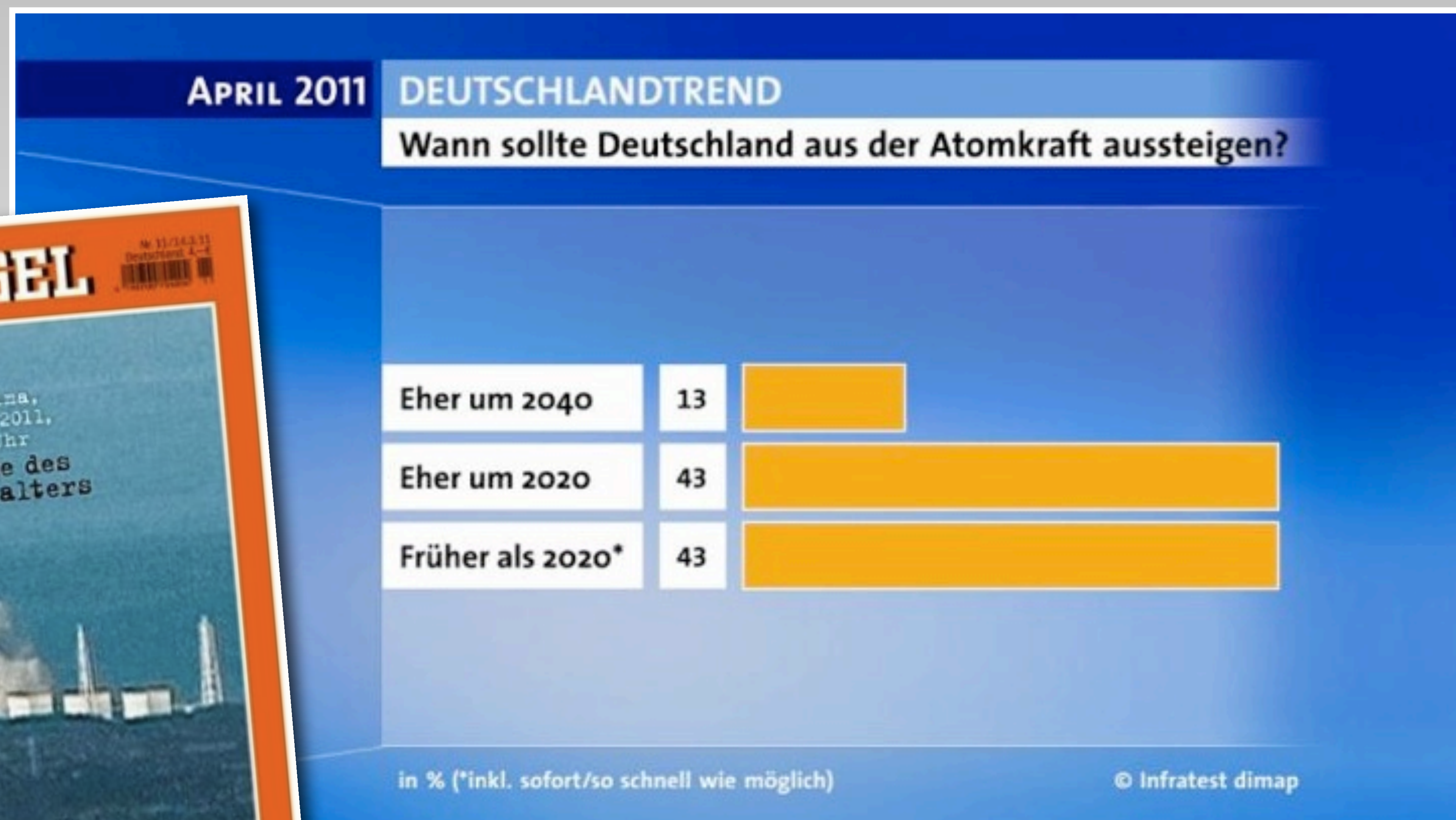
"The viability of two key technologies must be demonstrated during the next decade to allow for their widespread deployment starting around 2020:

- Demonstrate whether CCS technologies ... are technically and commercially viable for application to both existing and new power plants. [...]

- Demonstrate whether evolutionary nuclear plants are commercially viable in the United States by constructing a suite of <u>about five plants</u> during the next decade."

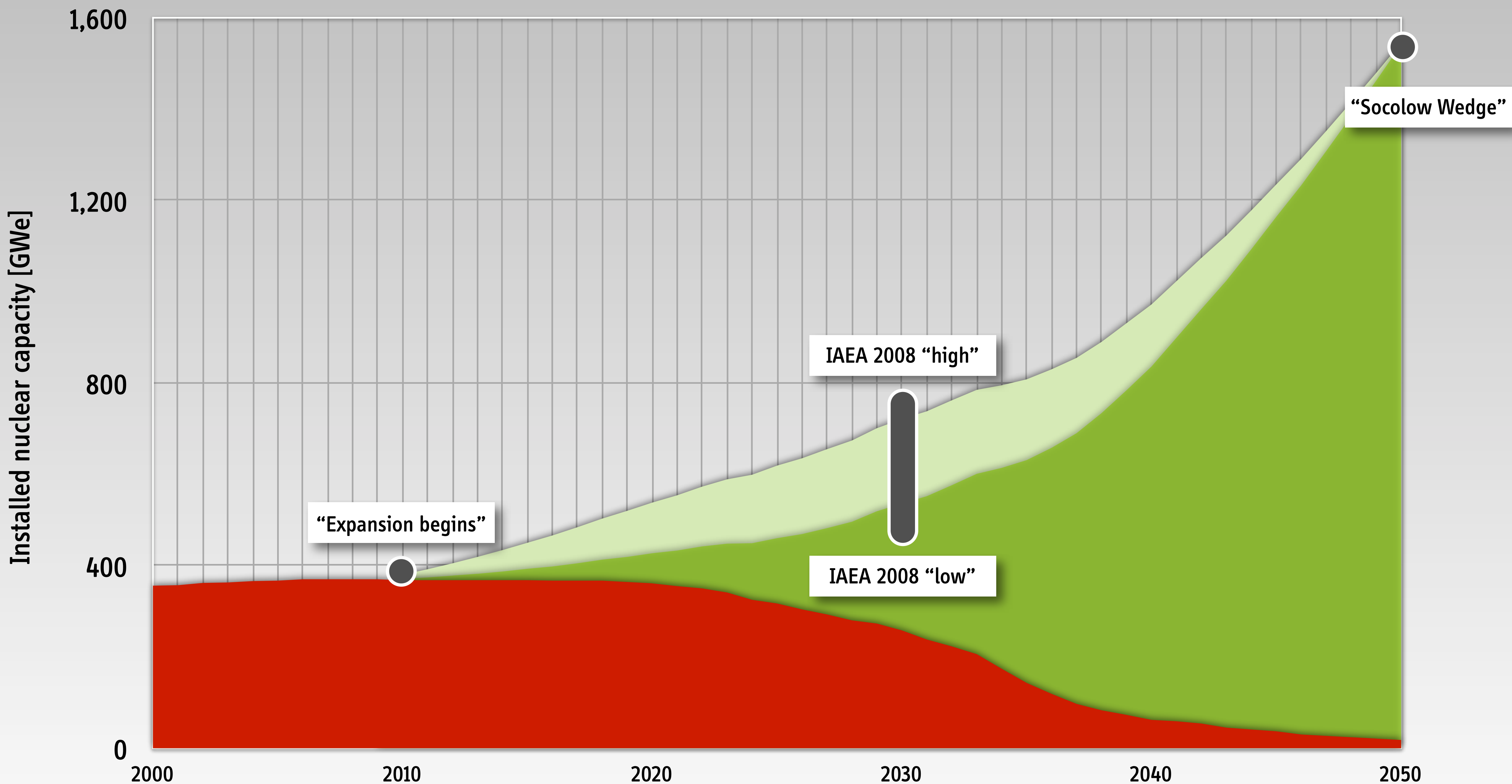
Meanwhile in Germany

86% Support Nuclear Phaseout by 2020 (Polling Data from April 4-5, 2011)

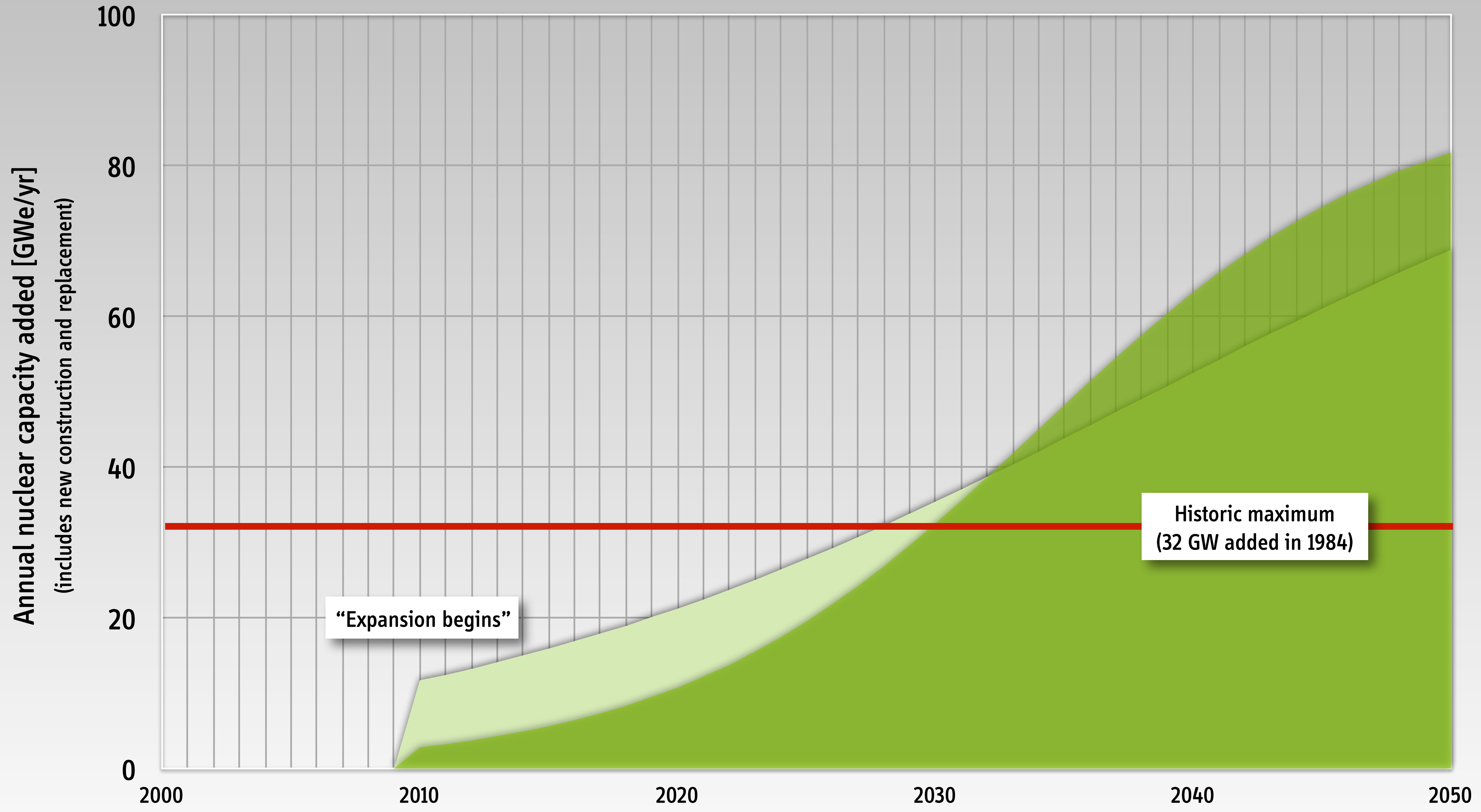


Top: www.presseportal.de/pm/6694/2022635/ard_das_erste
Left: Spiegel Cover from March 14, 2011: The End of the Atomic Era

Trying to Achieve One "Socolow Wedge" By 2050 is an Unrealistic (and Distracting) Objective



Achieving One Socolow-Pacala Wedge By 2050 Would Require Unprecedented Construction Rates

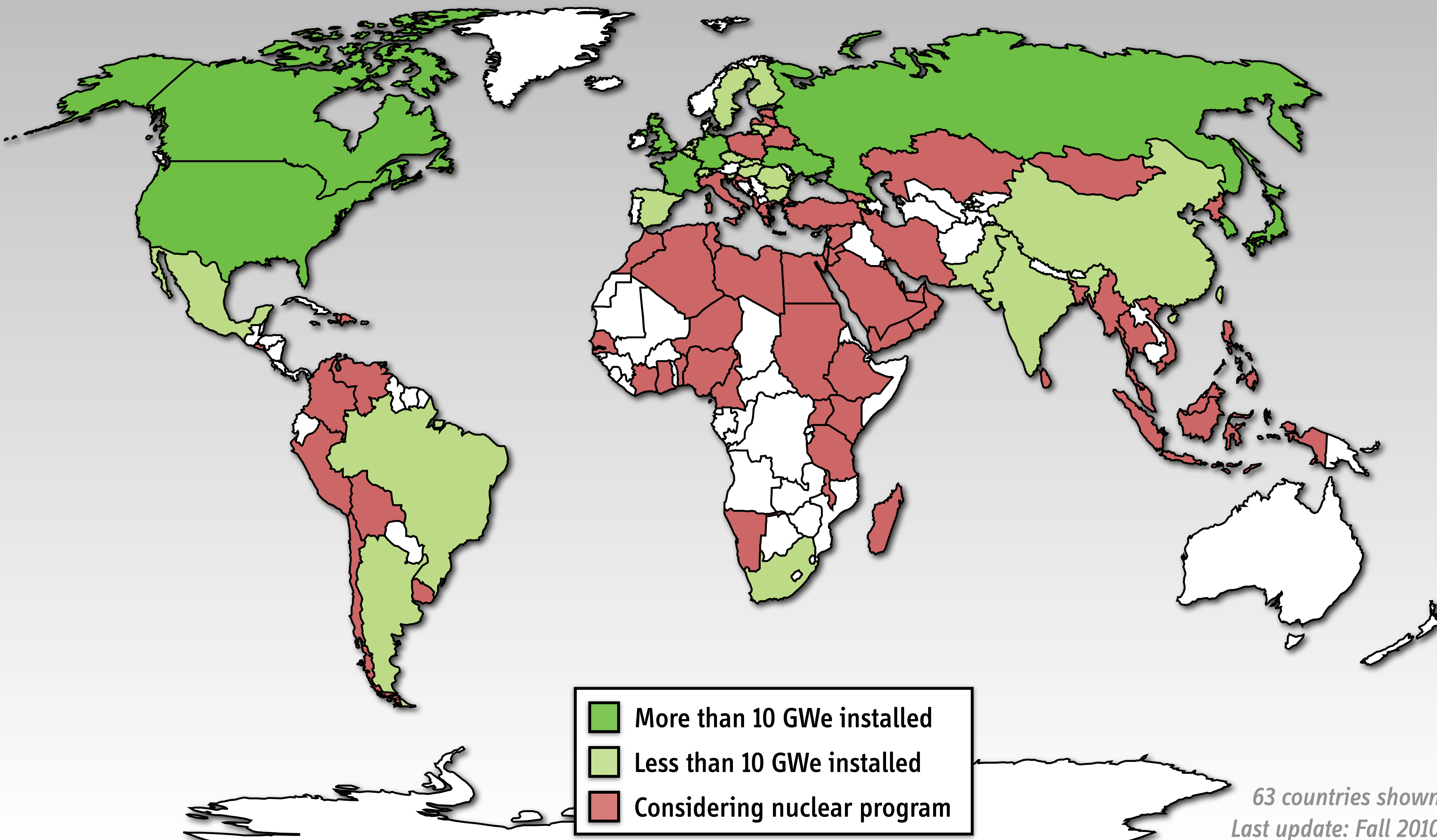


If an early large-scale global buildup of nuclear power is unrealistic:

What Should Be Done Instead?

Newcomer Countries, 2010

According to the IAEA, 60+ countries are currently considering nuclear programs



63 countries shown
Last update: Fall 2010

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 bleak

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

The next decade is critical

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

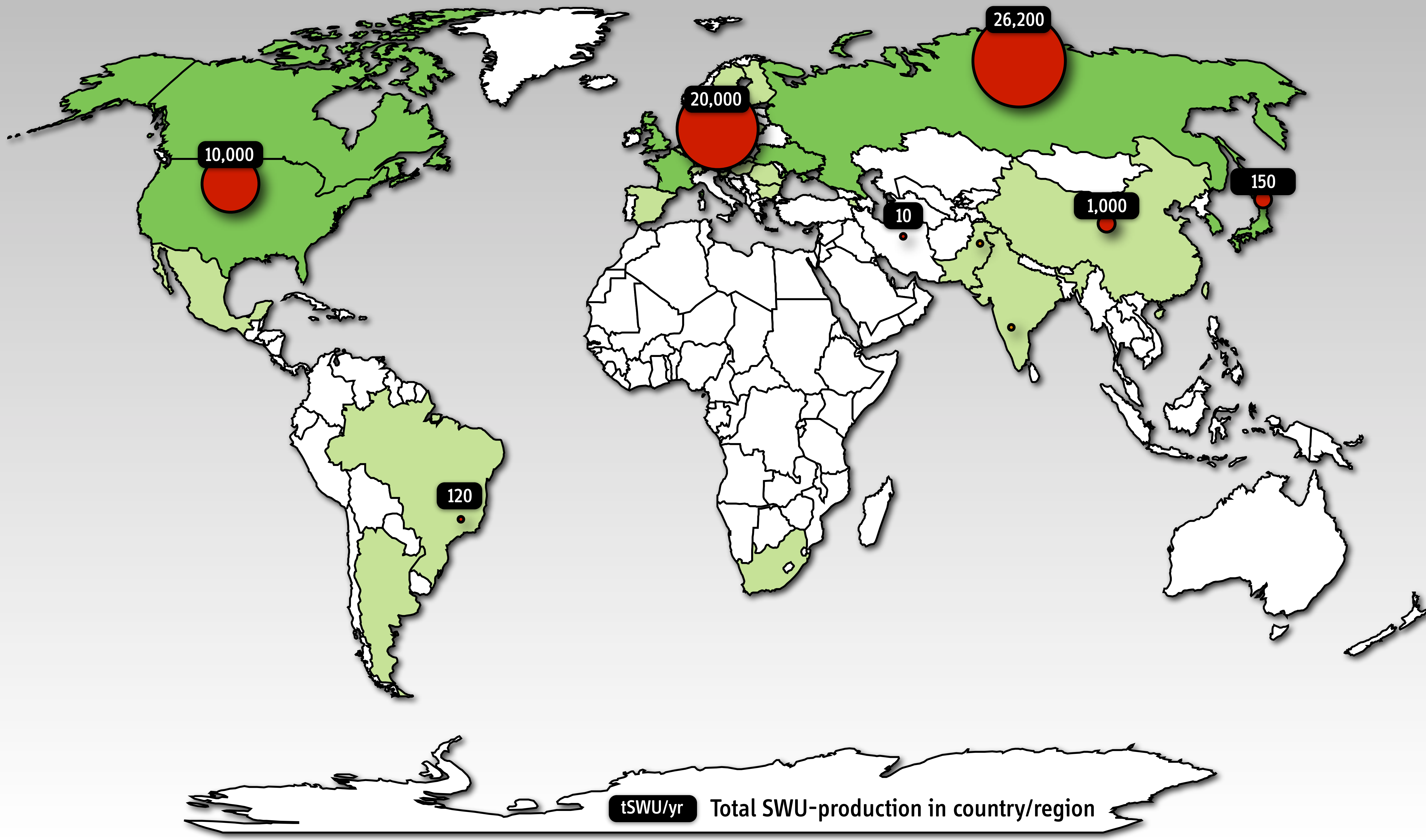
Time to establish adequate technologies and new norms of governance

EXTRA

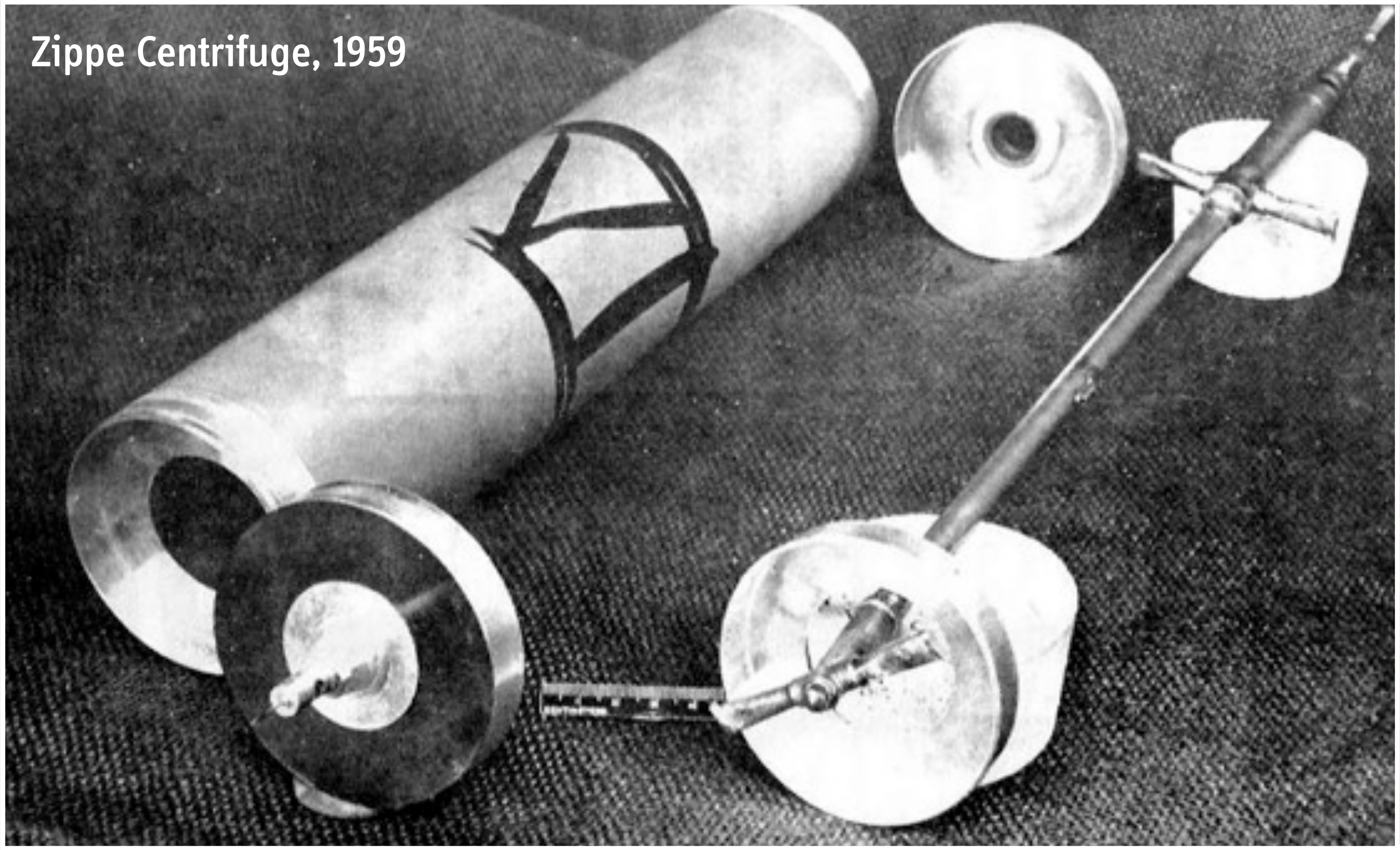
Build a New Framework for the Nuclear Fuel Cycle

Global Uranium Enrichment Capacities, 2010

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



Why Centrifuges Are Different



Characteristics of centrifuge technology relevant to nuclear proliferation

Rapid Breakout and Clandestine Option


www.President.ir

Preventing the Further Spread and Assuring Peaceful Use

Preventing Further Spread	• Tighten export controls (further)
	• Delegitimize enrichment in today's "non-enrichment" states
	• Increase the ability to detect undeclared facilities
	• Encourage multilateral approaches to the nuclear fuel cycle
Assuring Peaceful Use	• Increase the effectiveness of IAEA safeguards
	• Revisit alternative "proliferation-resistant" technologies