National Analytical Management Program (NAMP)
U.S. Department of Energy Carlsbad Field Office

United States Environmental Protection Agency

Radiochemistry Webinars

Nuclear Fuel Cycle Series

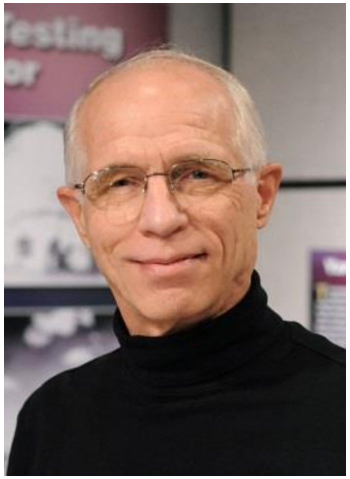
- *Overview of Nuclear Reactors*

NWP Nuclear Waste Partnership LLC
A URS-led partnership with B&W and AREVA
INL Idaho National Laboratory
NEW BRUNSWICK LABORATORY

In Cooperation with our University Partners

OSU Oregon State University
Illinois Institute of Technology
Colorado School of Mines
The University of Iowa
Clemson University
1914 2014 Centennial Celebration The University of Texas at El Paso
UNM
California State University Long Beach
UNLV
University of California · Irvine
NM State University Carlsbad

Meet the Presenter… *Dr. Roger Blomquist*



Dr. Roger Blomquist is a Principal Nuclear Engineer at Argonne National Laboratory. He served in the U.S. Navy for four years as a submarine nuclear propulsion officer, working as a shift supervisor responsible for reactor operations, testing, safety and maintenance of mechanical, electrical and instrumentation and controls systems. He was also responsible for the ship's non-nuclear mechanical systems' operation and maintenance during a major shipyard overhaul, including testing of hydraulic, high pressure air and other systems, and was the ship's QA Officer. After completing his active duty, he served 26 years in the Navy Reserve, commanding four reserve units. Before retiring as a Captain, he was responsible for national leadership training courses for mid-grade Naval Engineers and coordinator of engineering-type reserve units in a six-state area.

Dr. Blomquist earned a B.S. degree in physics at the College of William and Mary in Virginia. Following his active duty, he earned M.S. and Ph.D. degrees in nuclear engineering at Northwestern University. In 1979, he joined Argonne National Laboratory, where he specializes in reactor physics, criticality safety, and Monte Carlo methods. He has served as Chair of the American Nuclear Society Mathematics and Computations Division, and as Chair of the Source Convergence Expert Group, an international working group of the Organization for Economic Cooperation and Development's Nuclear Energy Agency. His technical accomplishments include nuclear design of the Intense Pulsed Neutron Source target at Argonne, collaborative studies of the behavior of Monte Carlo calculations, development of high-performance computing methods for supercomputers, and non-proliferation-related studies. He also manages Argonne's Nuclear Engineering Division information technology program and is very active in Argonne and nuclear energy outreach activities.

Contact Information:
Telephone: 1-630-252-8423
Email: RNBlomquist@anl.gov

Overview of Nuclear Reactors: History, Technology, and Future

Dr. Roger Blomquist

Argonne National Laboratory

National Analytical Management Program (NAMP)
U.S. Department of Energy Carlsbad Field Office

TRAINING AND EDUCATION SUBCOMMITTEE

Outline

- History of nuclear energy – U.S. and world
- How reactors work
- What will future reactors be able to do?

History: Oklo Natural Fission Reactors

- 1.7B years ago, off and on for hundreds of thousands of years
- Cycled many times through 30 minutes of criticality, 2.5h cool-down from hundreds of degrees C
- Several different cm-to-m-sized veins, consumed about 5t U^{235}

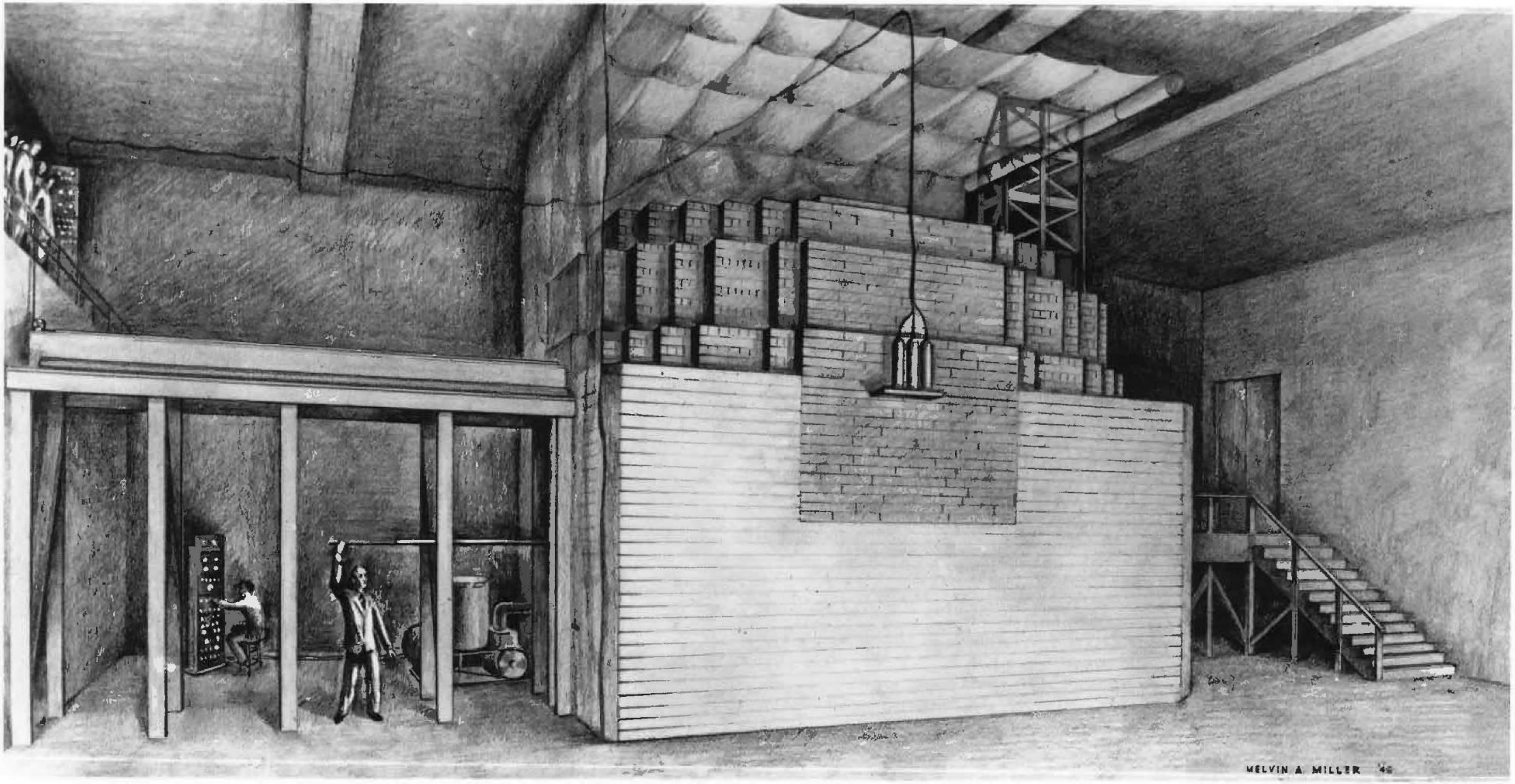
History: Oklo Natural Fission Reactors

Discovered in 1972 in a French enrichment plant.

Evidence:

- Natural U^{235} concentrations as low as 0.440% (vs. 0.71%)
  - U-238 half-life = 4.5By
  - U-235 half-life = 0.7By
- Nd isotopic composition in residues consistent with U^{235} Xe fission products found

December 2, 1942: CP-1 at University of Chicago: < 10 years after discovery of fission!



Early U.S. Development, after WW-II

- Atomic Energy Commission established in 1946
  - Later split into Energy Research and Development Administration (ERDA) and Nuclear Regulatory Commission (NRC) in 1974
  - ERDA merged with other energy-related agencies into Department of Energy in 1977
  - Argonne National Laboratory established, with the mission of “cooperative research in nucleonics” (commercial reactor technology development)

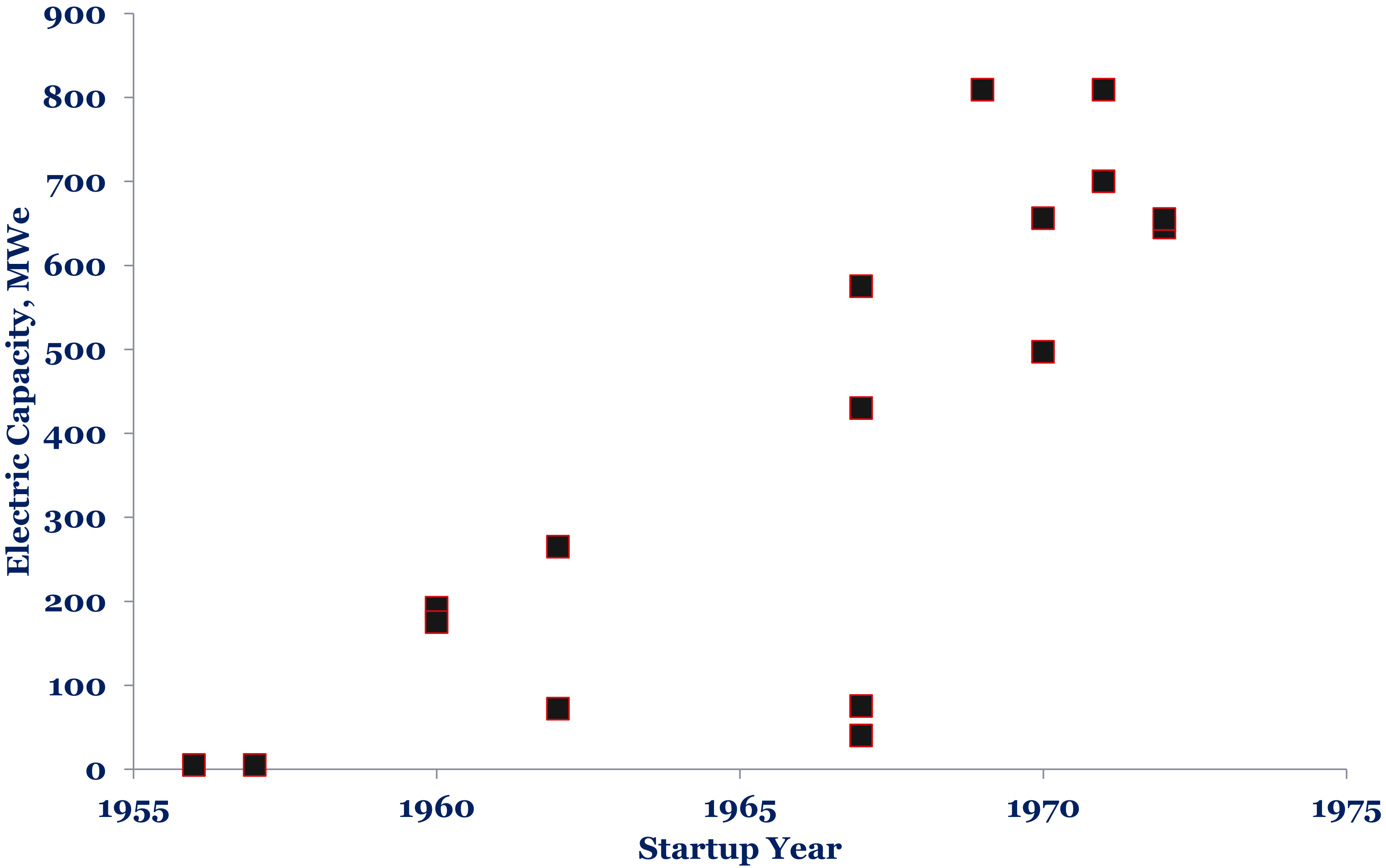
- Several pre-commercial research and test reactors and facilities were constructed at National Reactor Testing Station in Idaho by several companies

- Joint Committee on Atomic Energy oversaw the nuclear related legislations and appropriations in Congress

Atoms for Peace

- President Eisenhower: "Atoms for Peace" speech at UN General Assembly on December 8, 1953
  - Proposed creation of International Atomic Energy Agency
  - "A special purpose would be to provide abundant electrical energy in the power-starved areas of the world"
- U.S. action: U.S. would share technology for peaceful use
- Objective: Discourage development of weapons technology in other countries

Early Technology Scale-up: U.S. Reactor Sizes



1950s: Pressurized Water Reactor - Development Money from Navy

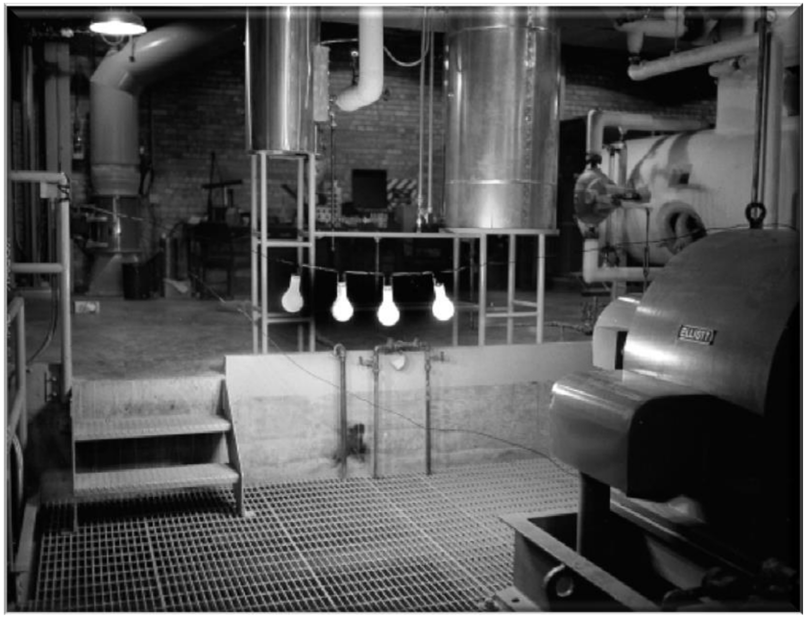
- 1953 – Submarine Thermal Reactor prototype (later renamed S1W) core designed by Argonne, plant by Westinghouse
- 1954 – USS Nautilus
- 1957 – Shippingport Atomic Power Station in Pennsylvania – commercial PWR/thorium breeder
- Navy development determined which civil nuclear technology was pursued in U.S., Europe, Japan, and elsewhere
- PWR commercialized by Westinghouse

1950s: Boiling Water Reactor

- 1953: Argonne's BORAX series of safety experiments started in the NRTS in Idaho. BORAX-III produced electricity for Arco, Idaho.
- 1956: Experimental Boiling Water Reactor (20 MWt/5 MWe initial, later upgraded to 100 MWt) at Argonne
- 1957: GE Vallecitos BWR (5 MWe)
- 1960: Dresden-1 (192 MWe)
- 1962: Big Rock Point (72 MWe)
- GE commercialized BWRs

Other Early US Reactor Types

- Liquid metal-cooled Fast Breeder Reactor
  - 1951: Argonne's EBR-I: the first nuclear electricity
  - 1954: Submarine USS Seawolf; then converted to PWR
  - 1957: Sodium Reactor Experiment (SRE)
  - 1964: Argonne's EBR-II, with fuel cycle closure
  - 1965: Fermi-1 (200 MWt/61 MWe) with private sector funding
- 1967 – High Temperature Gas-Cooled Reactor (HTGR): Peach Bottom-1 (40 MWe)
- 1965-1969: Molten Salt Reactor Experiment
- 1965: Organic Moderated Reactor Experiment



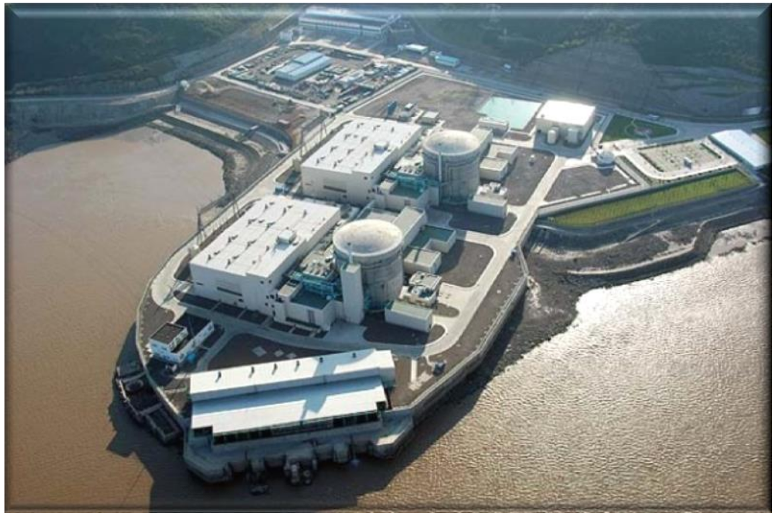
Gearing Up for Industry: 1960s

- Turnkey era – reactor vendors sold ready-to-operate power plants
  - Westinghouse and GE, 1959-1965
  - Dresden-1 (192 MWe GE BWR)
  - Yankee Rowe (175 MWe Westinghouse PWR)
  - Big Rock Point (72 MWe GE BWR)
  - Indian Point-1 (265 MWe WH PWR)

- End of turnkey era – custom-built large power-plants, individually licensed
  - + B&W, CE new vendors
  - 1966 – 20 plants ordered
  - 1967 – 30 plants ordered, 400-600 MWe
  - 1969 -- Dresden-2 (809 MWe, BWR)
  - Very vulnerable to legal challenges by interveners → delays, cost escalations

World Reactor Technology Deployments

- 1950 – 1969: USSR, UK, France, Sweden, Italy, West German, Japan, Spain, Switzerland, Netherlands, Canada, Belgium
  - Some were dual purpose reactors
- 1970s: Pakistan, India, Argentina, Bulgaria, East Germany, Armenia, Finland, Ukraine, Lithuania, Taiwan
- 1980s: South Korea, Hungary, Lithuania, Czechoslovakia, South Africa, Brazil
- 1990s: Romania, Mexico, China



U.S. in Early to Mid 1970s: Optimism

- LWRs:
  - In addition to the reactors already in operation, many reactors in 1,000 MWe class under construction
  - About 50 reactors were ordered each year around 1974-76
  - 5 active reactor vendors (Westinghouse, GE, B&W, C-E, and GA)
- Fuel Cycle:
  - Major oil companies (e.g., Exxon, Gulf) entered fuel cycle business
  - NRC initiated Generic Environmental Impact Statement on Mixed Oxide (GESMO) in 1974 – used fuel recycling
- Breeders:
  - Necessitated by apparently inadequate (for LWRs) uranium resources
  - 1,000 LMFBRs were assumed to be on-line by 2000
  - ERDA initiated Programmatic Environmental Impact Statement for Liquid Metal-cooled Fast Breeder Reactor (LMFBR) in 1974
  - FFTF (400 MWt) fuel test reactor and CRBR (350 MWe) commercial prototype projects initiated

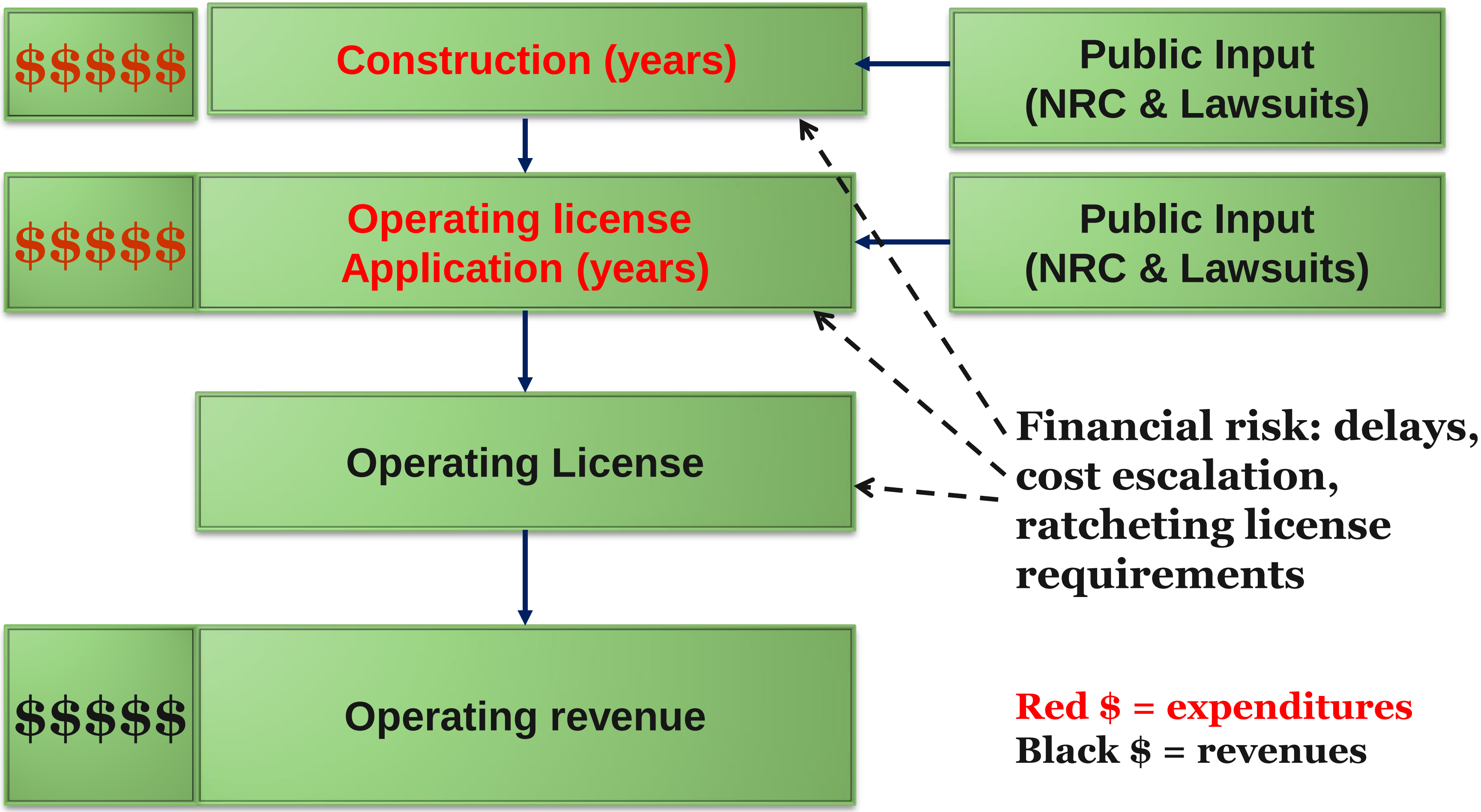
1970s: Emerging Negatives

- Nuclear reactors become conflated with nuclear weapons by many people
- Perceived reactor safety risk becomes a public acceptance issue
- Well-funded anti-nuclear groups use licensing procedures to slow construction
- Construction & licensing delays → huge cost overruns due to <u>very</u> high interest rates → order cancellations
- Some public utilities not very well prepared for the rigor of building and operating nuclear power plants or for the legal difficulties involving anti-nuclear intervenors.

Late 1970s – 1980s

- 1979 – Three Mile Island:
  - Core melt, no radiological consequences
  - Led to Institute for Nuclear Power Operations (INPO)
  - NRC refocus on management, operational safety, operator training, human factors, understanding accident sequences, core damage mitigation measures, emergency planning
- 1986 – Chernobyl RBMK accident: major fuel and fission product release
  - Gross violation of good design methods and operating procedures
  - Led to WANO = international equivalent of INPO
- 1989 – 10 CFR 52 improved licensing procedure: design certification, Early Site Permit, Combined Operating License

Original licensing (<1990) --> delays, cost overruns



$$$$$

Construction (years)

Public Input
(NRC & Lawsuits)

$$$$$

Operating license
Application (years)

Public Input
(NRC & Lawsuits)

Operating License

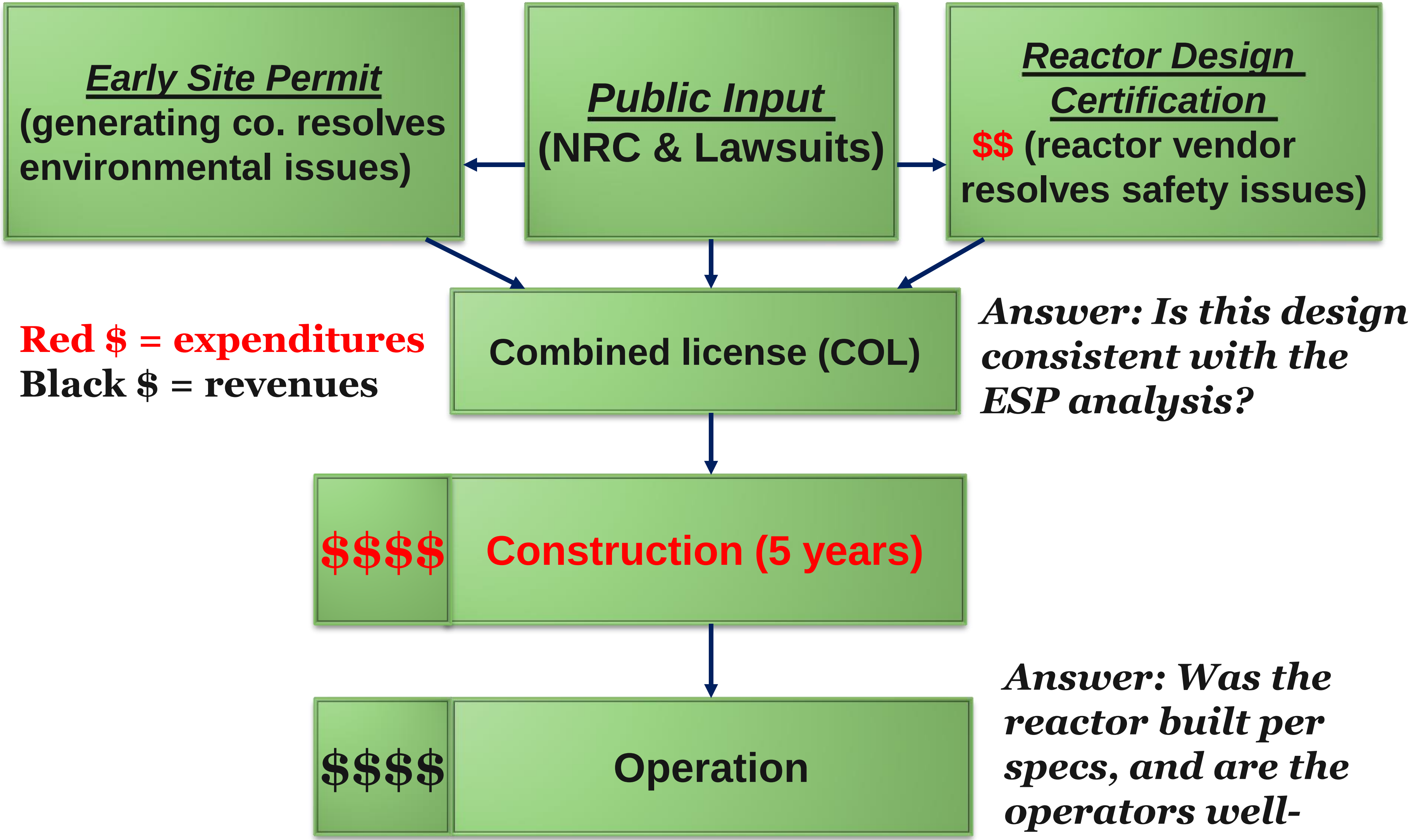
Financial risk: delays, cost escalation, ratcheting license requirements

$$$$$

Operating revenue

Red $ = expenditures
Black $ = revenues

New Licensing Procedure, after 1990



Early Site Permit
(generating co. resolves environmental issues)

Public Input
(NRC & Lawsuits)

Reactor Design Certification
$$ (reactor vendor resolves safety issues)

Red $ = expenditures
Black $ = revenues

Combined license (COL)

Answer: Is this design consistent with the ESP analysis?

$$$$ **Construction (5 years)**

$$$$ **Operation**

Answer: Was the reactor built per specs, and are the operators well-trained?

Commercial Reprocessing Plants in U.S. – Interrupted by Policy Changes

- 1966-1972: West Valley (300 T/yr)
- 1971: Midwest Fuel Recovery Plant (300 T/yr), at Morris, Illinois; not commissioned
- 1977: Barnwell Reprocessing Plant (1500 T/yr), being built when President Carter indefinitely deferred reprocessing/recycling to discourage foreign reprocessing
- Exxon Nuclear was planning another commercial reprocessing plant and had already built a recycled fuel (MOX) fabrication plant
- Reagan lifted the ban, but no reprocessing now

Reprocessing: President Carter’s Nuclear Policy Statement (April 7, 1977)

1. Defer indefinitely U.S. commercial reprocessing and recycling of plutonium.
2. Restructure the U.S. breeder program to give greater priority to alternates to the plutonium breeder and to defer the introduction of a commercial breeder.
3. Redirect the U.S. nuclear R&D program to accelerate research into alternate fuel cycles not involving direct access to materials useful for weapons production.

→ aggravated spent fuel disposition issue

U.S. Nuclear Waste Policy Act of 1982

1. Enacted in 1982 and amended in 1987
2. Funded by a waste disposal fee of 0.1 cent/kwhr, title to spent fuel was to be transferred to Federal Government for long-term storage and permanent disposal
3. "Contracts … shall provide that"
    a) "following commencement of operation of a repository, the Secretary shall ***take title*** to … spent nuclear fuel involved as expeditiously as practical …"
    b) "in return for the payment of fees … , the Secretary, beginning not later than January 31,1998, will dispose of … spent nuclear fuel involved …"

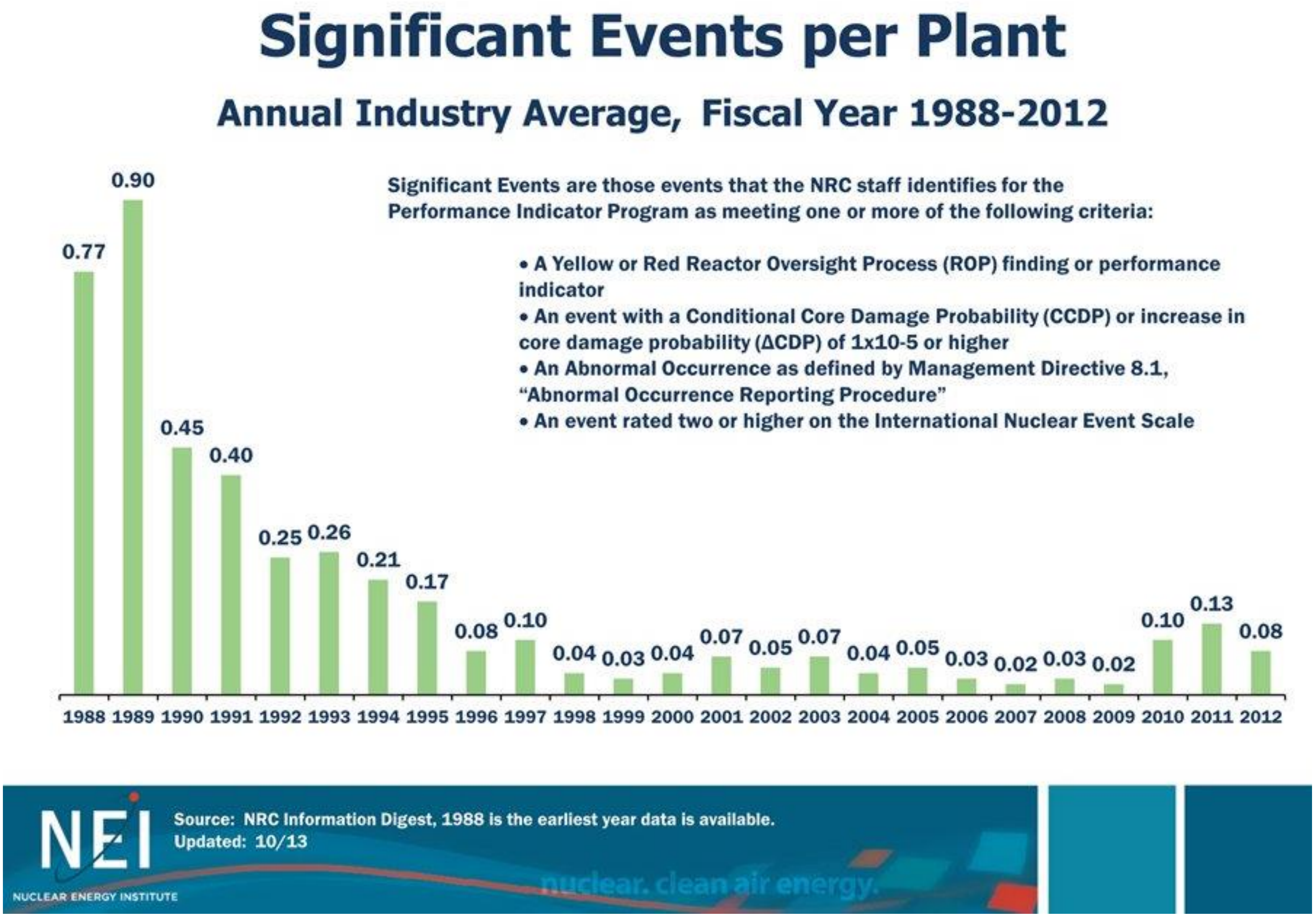
Result: U.S. government now owns the used nuclear fuel problem

Commercial Reprocessing Around the World

- France: major reprocessing started in late 1950s, expanded through 1992
- Mayak, Russia: takes back VVER-440 fuel from other countries
- UK: stalled
  - Magnox fuel reprocessing plant (1500 T/yr) at Sellafield started operation in the 60's
  - THORP (designed at 1200 T/yr but operated at 800 T/yr) started operation in 1993, but has been unproductive
- Japan: stalled
  - Tokai Plant (90 T/yr) started operation in 1981
  - Rokkasho (800 T/yr) waiting to start commercial operation
- U.S.: none

1990 – Present (U.S.): The Quiet Expansion

- Power “uprates” → equivalent of 5 new reactors in 20 years
  - Take advantage of original “over-design,” better analysis, and deeper materials experience
- Better operations from INPO “networking” (Navy-inspired)
- Utility deregulation:
  - Merchant operators (e.g., Exelon) bought up plants from local operators
  - (Incompletely) deregulated wholesale power markets auction electricity to distribution utilities (e.g., Exelon to Com Ed)
  - Existing plants sold for $billions
  - Specializing in nuclear plant operations using U.S. Navy practices
  - New focus on quarterly profits
- License extensions for 20 years past original 40
- 2002 “Screw Nevada Bill” drops MI & TX from list of geologic repository locations



Significant Events per Plant

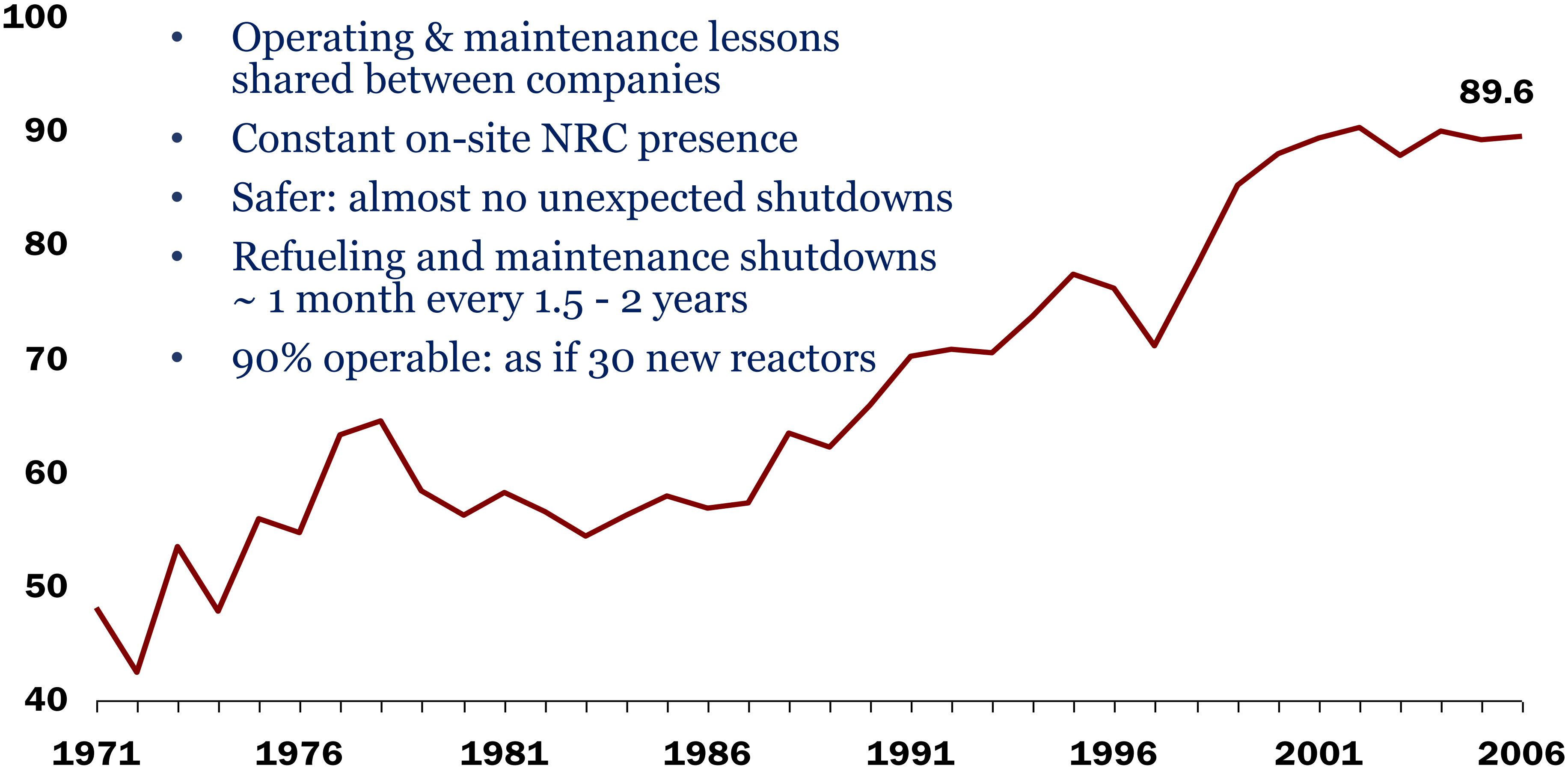
Annual Industry Average, Fiscal Year 1988-2012

Significant Events are those events that the NRC staff identifies for the Performance Indicator Program as meeting one or more of the following criteria:

- A Yellow or Red Reactor Oversight Process (ROP) finding or performance indicator
- An event with a Conditional Core Damage Probability (CCDP) or increase in core damage probability (ΔCDP) of 1x10-5 or higher
- An Abnormal Occurrence as defined by Management Directive 8.1, “Abnormal Occurrence Reporting Procedure”
- An event rated two or higher on the International Nuclear Event Scale

Source: NRC Information Digest, 1988 is the earliest year data is available.
Updated: 10/13

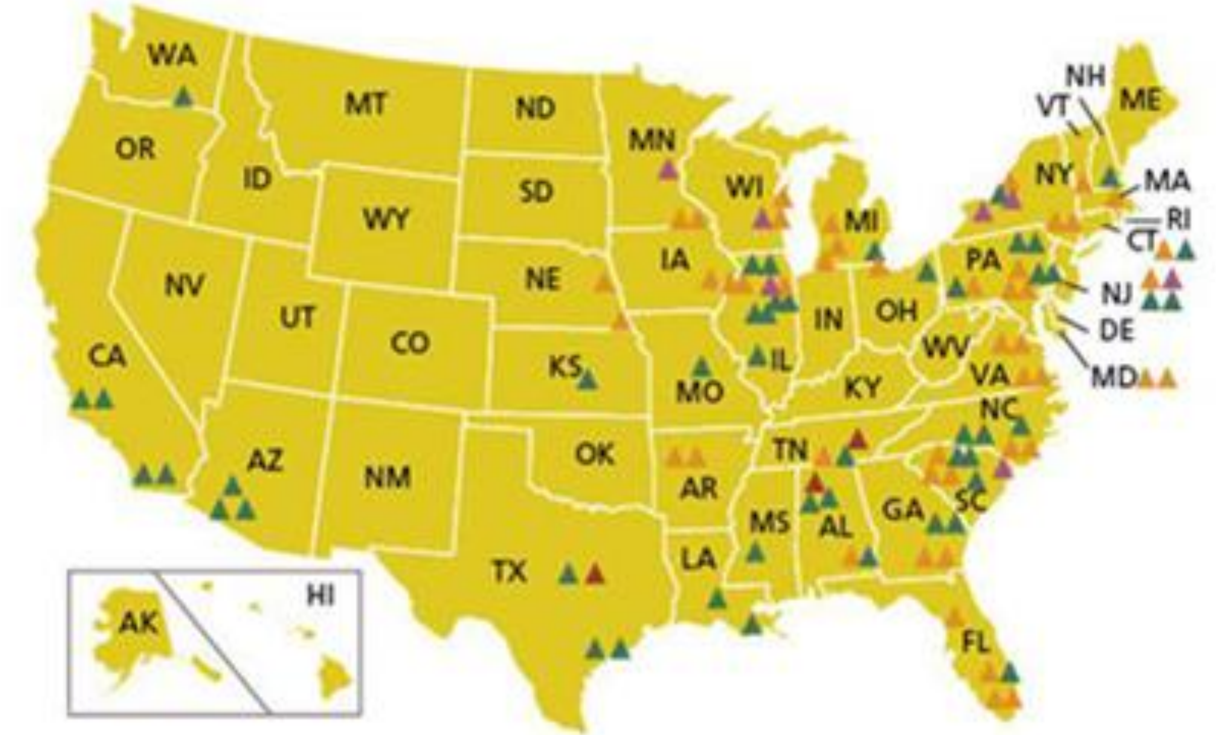
Huge Improvements in Operational Efficiency: U.S. Nuclear Generation Capacity Factors (% operability) 1971 - 2006



- Operating & maintenance lessons shared between companies
- Constant on-site NRC presence
- Safer: almost no unexpected shutdowns
- Refueling and maintenance shutdowns ~ 1 month every 1.5 - 2 years
- 90% operable: as if 30 new reactors

Source: Global Energy Decisions / Energy Information Administration
Updated: 10/07

U.S. Commercial Nuclear Reactors-Years of Operation by the End of 2010



Years of Commercial Operation	Number of Reactors
△ 0 – 9	0
▲ 10 – 19	3
▲ 20 – 29	48
▲ 30 – 39	46
▲ 40 plus	7

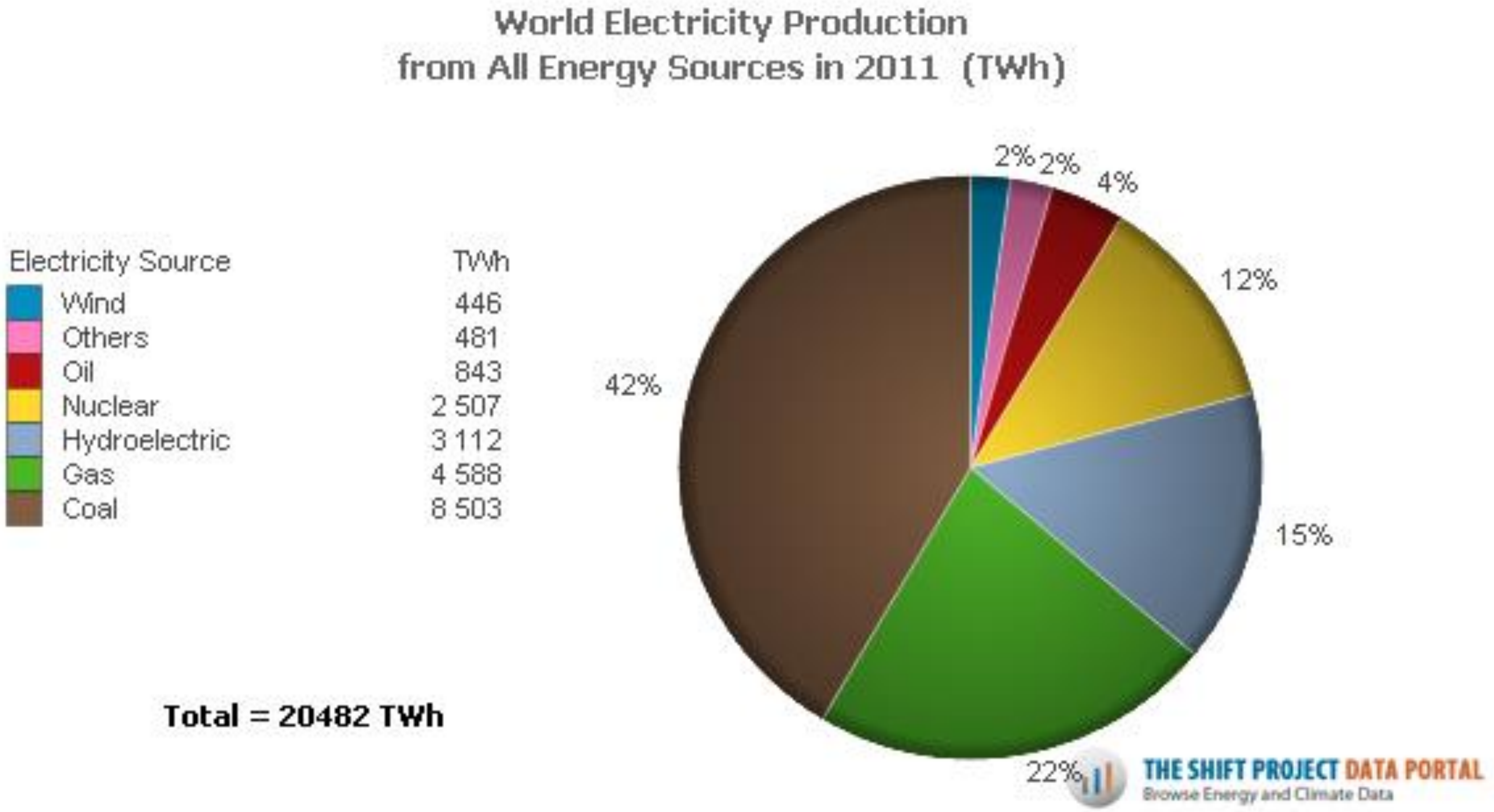
Note: Ages have been rounded up to the end of the year.

Source: Nuclear Regulatory Commission

U.S. New Construction, License Applications, & Shutdowns

- Under construction:
  - 2 AP-1000 PWRs in South Carolina (2018, 2019) – by regulated utility
  - 2 AP-1000 PWRs in Georgia (2017, 2018) – by regulated utility
  - 1 TVA PWR resumed construction, startup in 2015/2016
- License applications at NRC:
  - 12 new reactor licenses under review
  - 9 new reactor license applications suspended
  - 3 withdrawn
- Recent shutdowns: San Onofre-2,3 (CA), Vt Yankee, Crystal River-3 (FL), Kewaunee (WI)

2011 World Electricity Sources

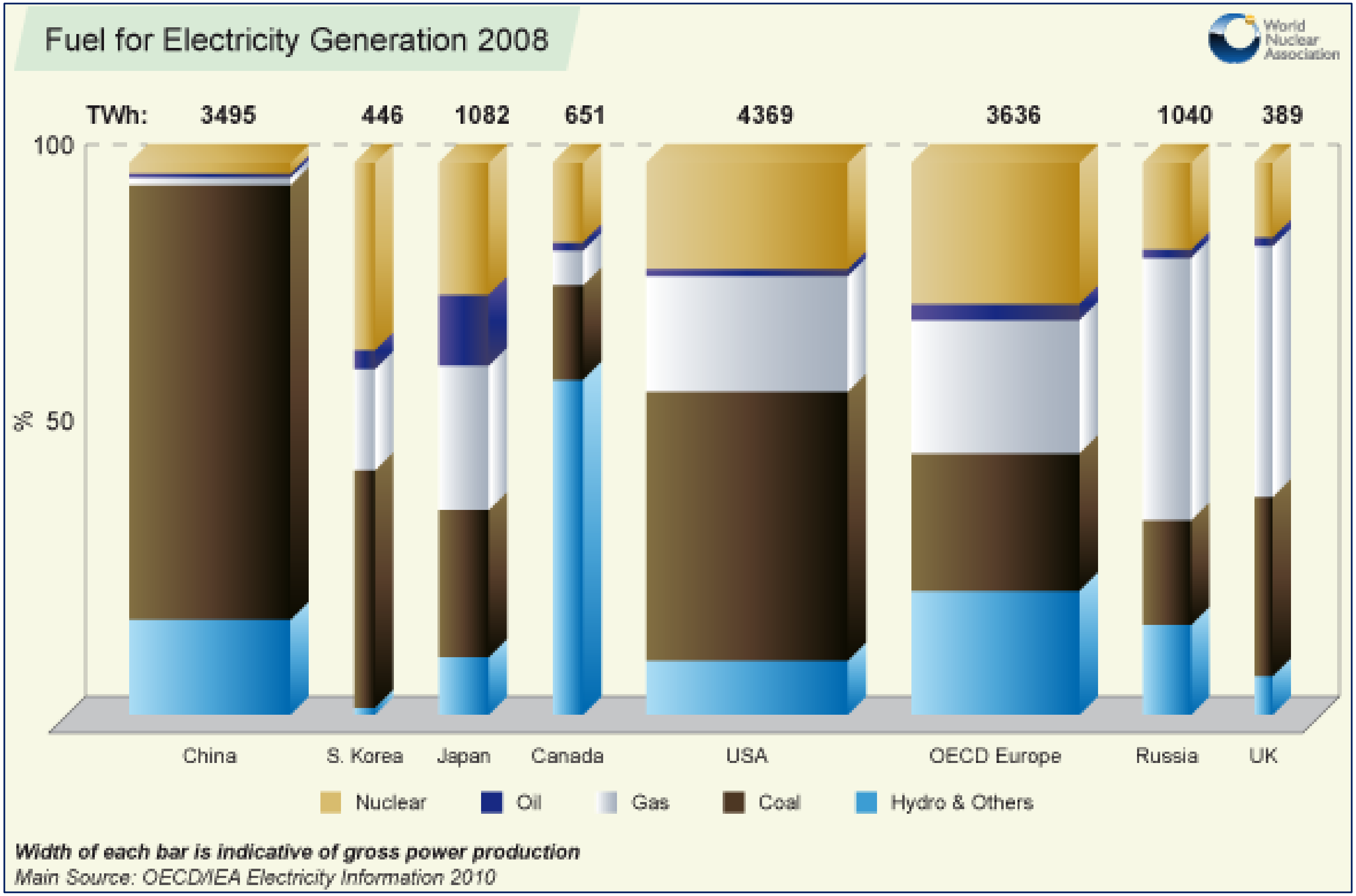


World Electricity Production
from All Energy Sources in 2011 (TWh)

Electricity Source	TWh
Wind	446
Others	481
Oil	843
Nuclear	2 507
Hydroelectric	3 112
Gas	4 588
Coal	8 503

Total = 20482 TWh

Electricity Fuels for Selected Countries: (Width = TWh, Height = %)



Width of each bar is indicative of gross power production

Main Source: OECD/IEA Electricity Information 2010

Where in the world are the NPPs?

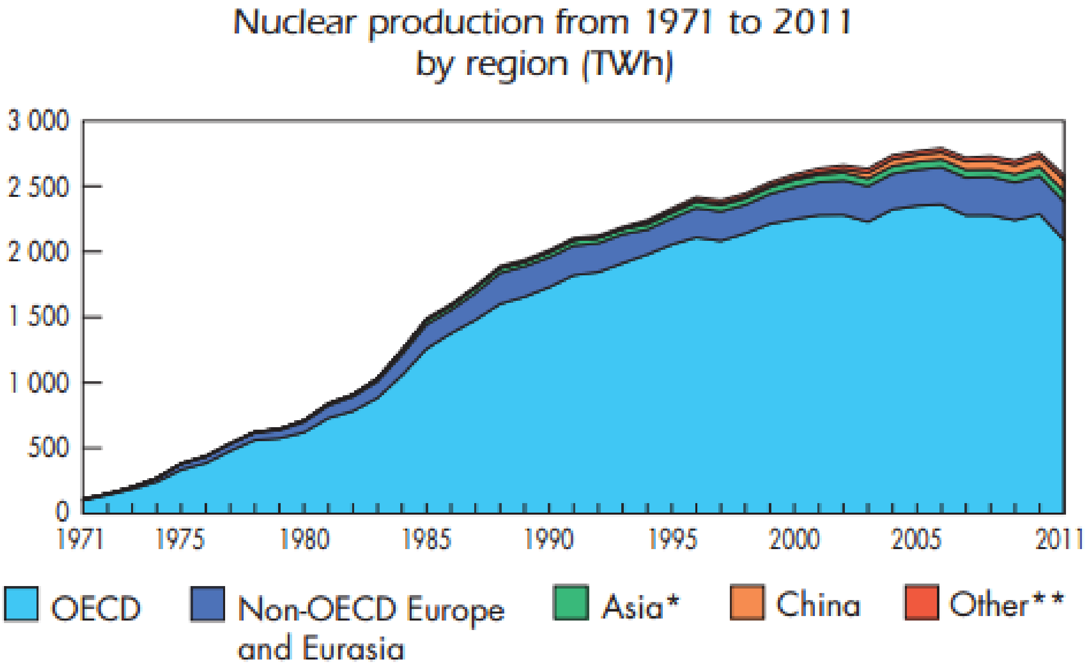
Yellow = under construction
Blue = planned
Orange = not operating
Green = operating
Red = shut down

(50 add'l planned NPPs not shown)

Graphic: The Guradian; data from World Nuclear Association; 2012

2014: World Totals

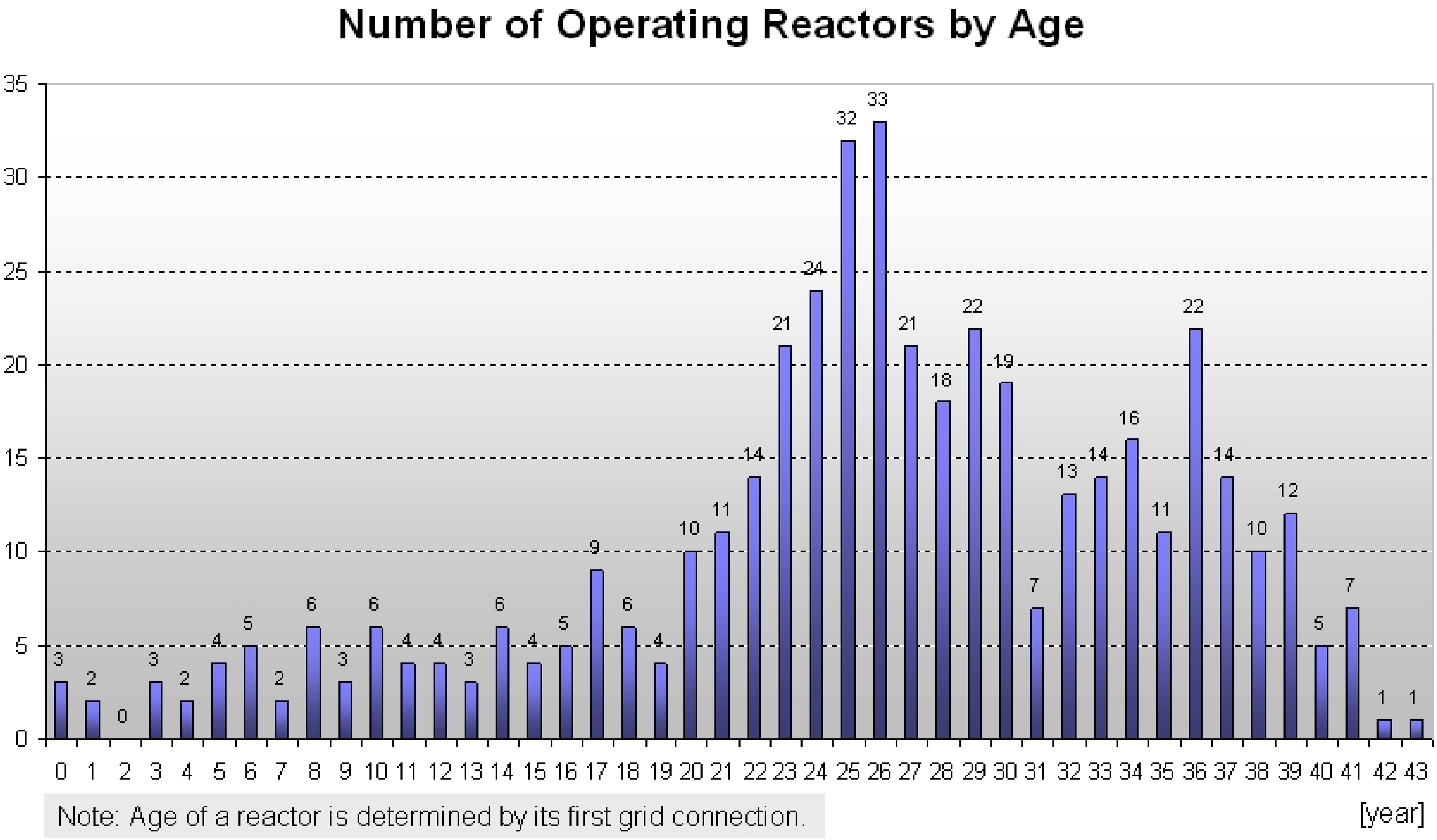
- Nuclear energy produces about 5% of total energy worldwide
- 435 reactors in 32 countries produce 375 Gwe, about 11.7% of electricity worldwide
- Nuclear and hydro are the *only* low-carbon sources presently providing significant amounts of electricity



US Nuclear Renaissance Impediments

- Resource bottlenecks:
  - Large forgings (reactor vessels) -- not in the U.S. anymore
  - Trained operators, experts, etc., but undergrad nuclear engineering enrollments are up
  - Manpower and funding for NRC license application reviews
- Economics
  - Merchant generators vs. regulated monopolies – gas is now cheap
  - Renewable subsidies and state portfolio requirements
  - Rising materials costs, especially metals
  - Shrinking supply of skilled trades people
  - Some cost escalation, but only short delays; low interest rates
  - Some cancellations and 4 recent operating reactor closures
- Legal
  - New licensing not yet tested to the U.S. Supreme Court
  - State legal bans, most based on waste issue; some have been dropped

US Nuclear Plant Replacement Requirements



Note: Age of a reactor is determined by its first grid connection.

NPPs Under Construction Worldwide

Location	#	MWe (net)	type
China	27	26756	PWR
Russia	10	8382	PWR, FBR
India	6	3907	PHWR, PWR, FBR
South Korea	5	6370	PWR
USA	5	5633	PWR
UAE	3	4035	PWR
Japan	2	1325	BWR
Pakistan	2	630	PWR
Slovakia	2	880	PWR
Ukraine	2	1900	PWR
Argentina	1	25	PWR
Belarus	1	1109	PWR
Brazil	1	1245	PWR
Finland	1	1600	PWR
France	1	1630	PWR
Total	71	68027	

IAEA, 2014

Sources

- World Nuclear Association
- *Controlled Nuclear Chain Reaction – the First 50 Years*, American Nuclear Society, 1992
- International Atomic Energy Agency
- *U.S. Capacity Factors: Staying Around 90 Percent*, Nuclear News, American Nuclear Society, May 2011
- U.S. Department of Energy, Office of Nuclear Energy
- U.S. Nuclear Regulatory Commission

How Nuclear Reactors Work

- A reactor is a (well-organized) pile of hot rocks arranged so that the heat generated can be removed and used in an energy conversion system
  - Stationary fuel is heated by the fission breakup of uranium and plutonium nucleii made unstable by absorbing neutrons
  - Neutrons are released during fission – this makes the chain reaction possible
- DEFINITION: A chain reaction is a reaction in which one of the products is also one of the inputs.
- Common examples of chain reactions (product and input):
  - Combustion (heat)
  - Financial system ($)
  - Scholarship (understanding and knowledge)
  - The network effect (connections in social media)
  - Nuclear fission (neutrons)

Why Nuclear? -- Energy Density!

Fuel requirements so small that it operates as a closed system:

Per atom or molecule:

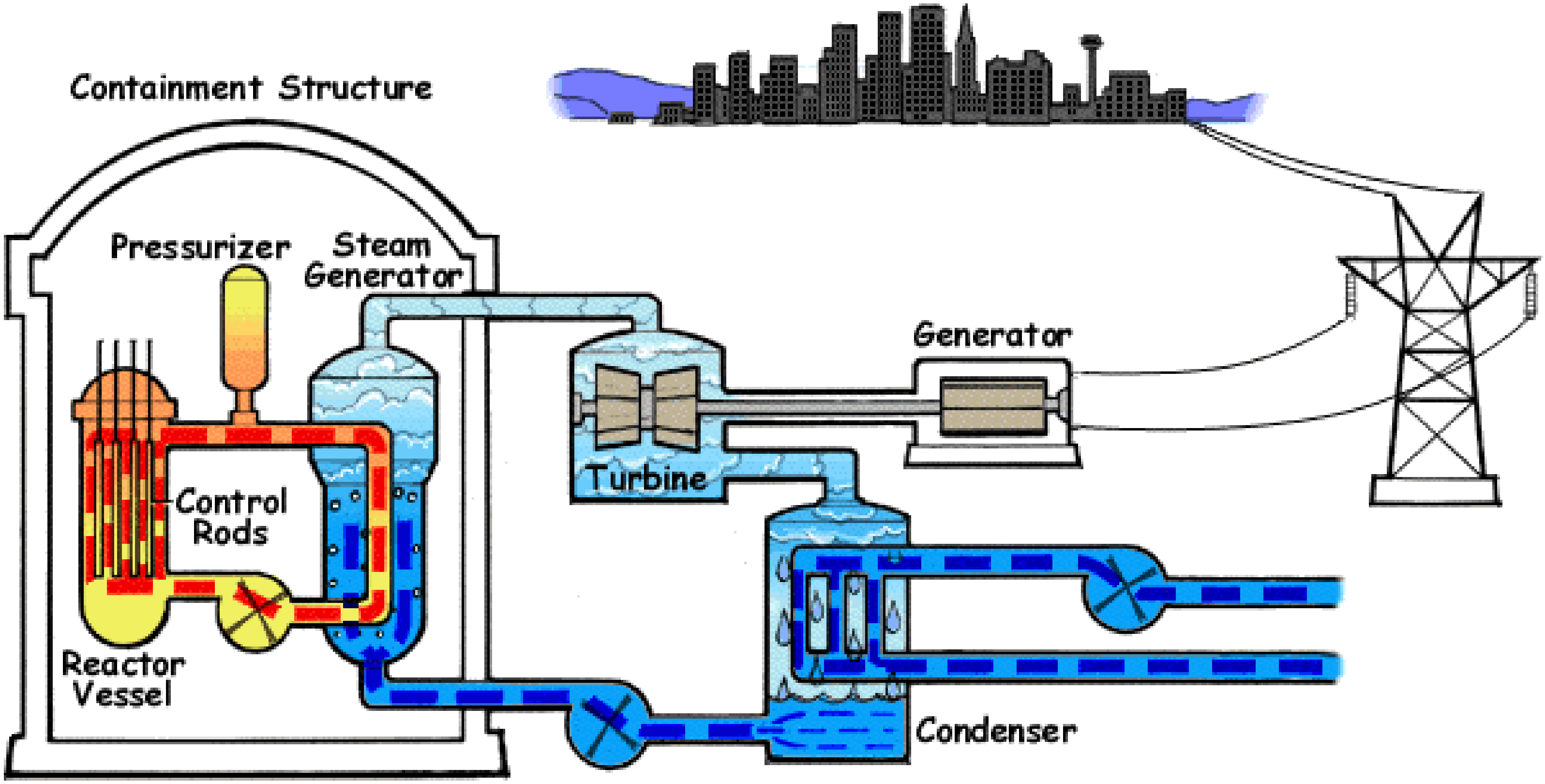
- One uranium fission to one methane (natural gas) molecule oxidation ~70,000,000 ratio

Per unit mass:

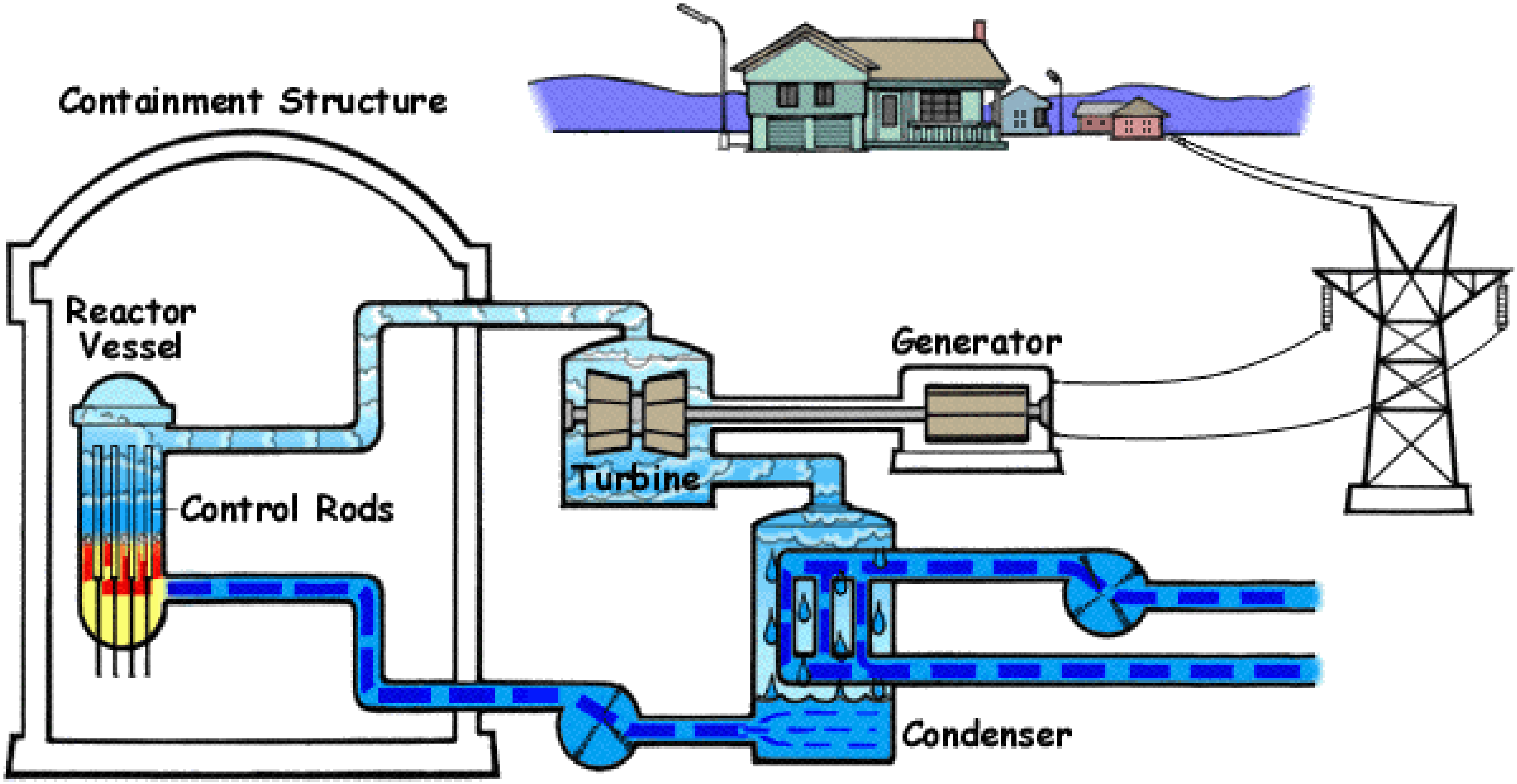
- One kg of uranium fission = 1,500,000 kg methane oxidation
- One kg of uranium fission = 3,800,000 kg wood combustion

Fossil systems must be open.

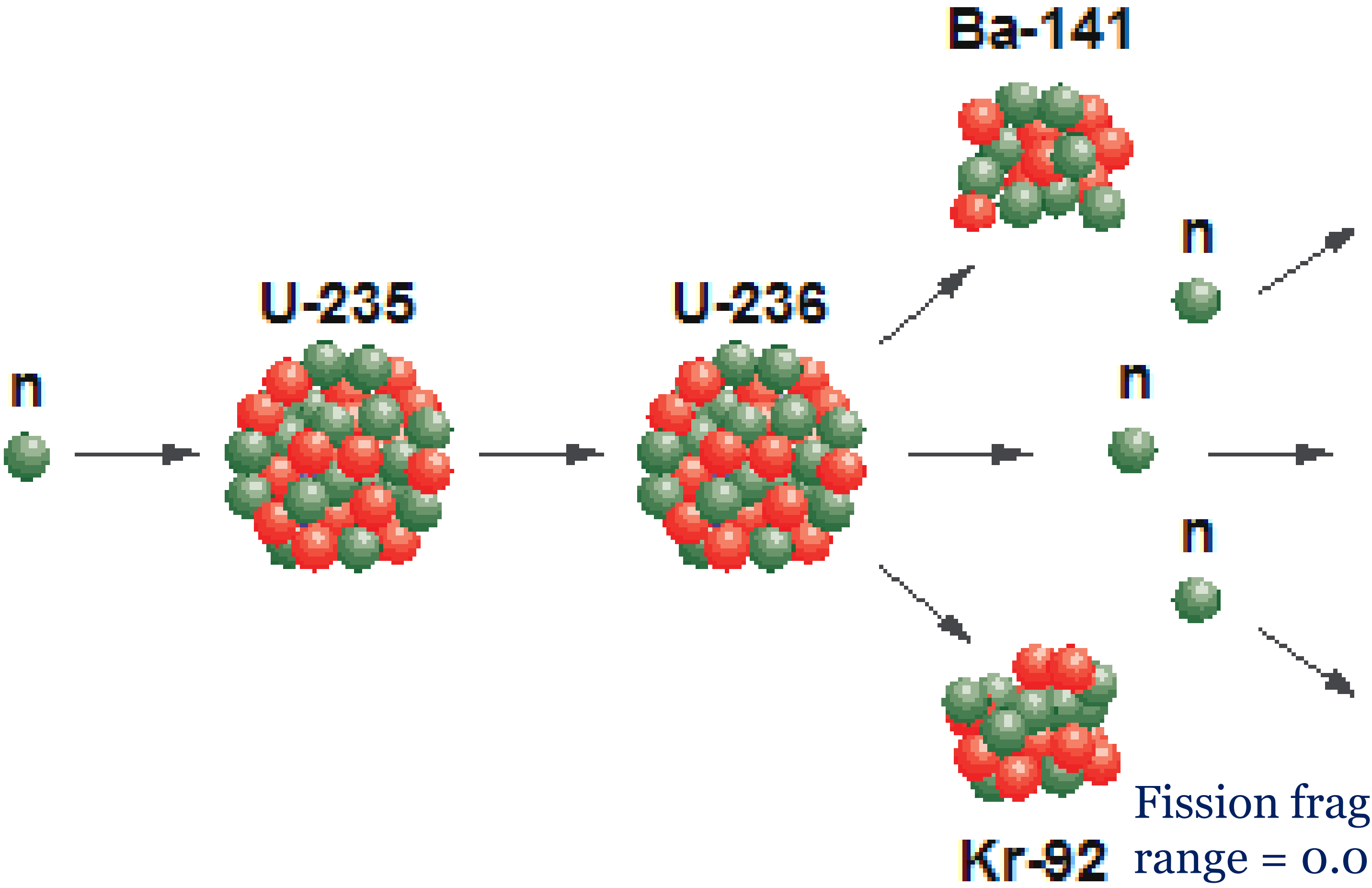
Pressurized Water Reactor (PWR)



Boiling Water Reactor (BWR)

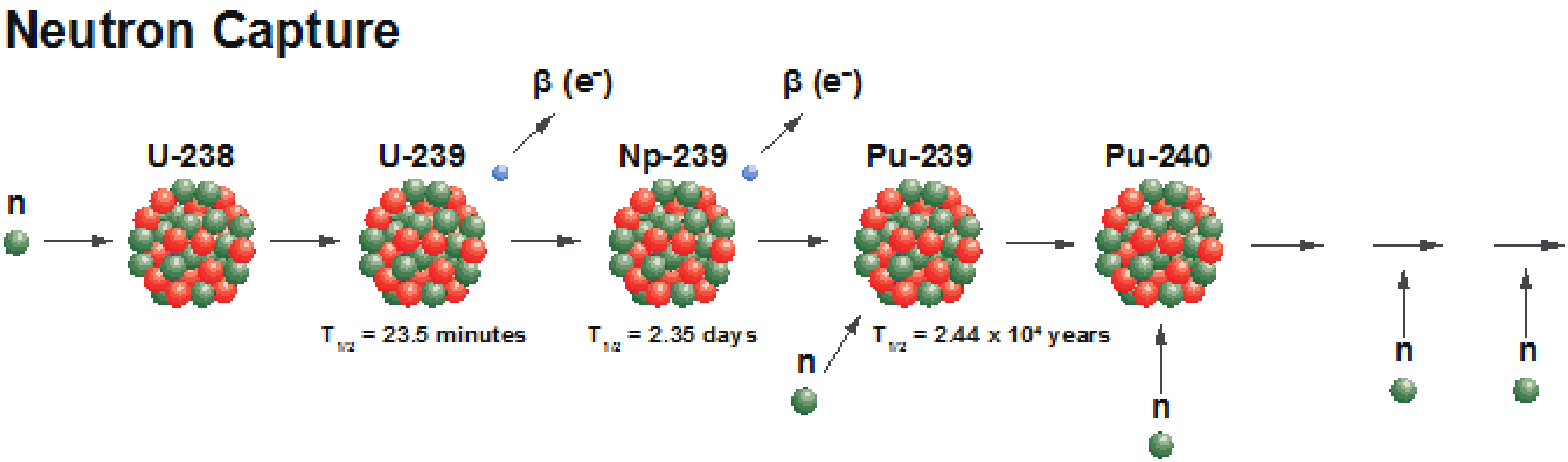


Neutron Physics: A Sample Fission Reaction



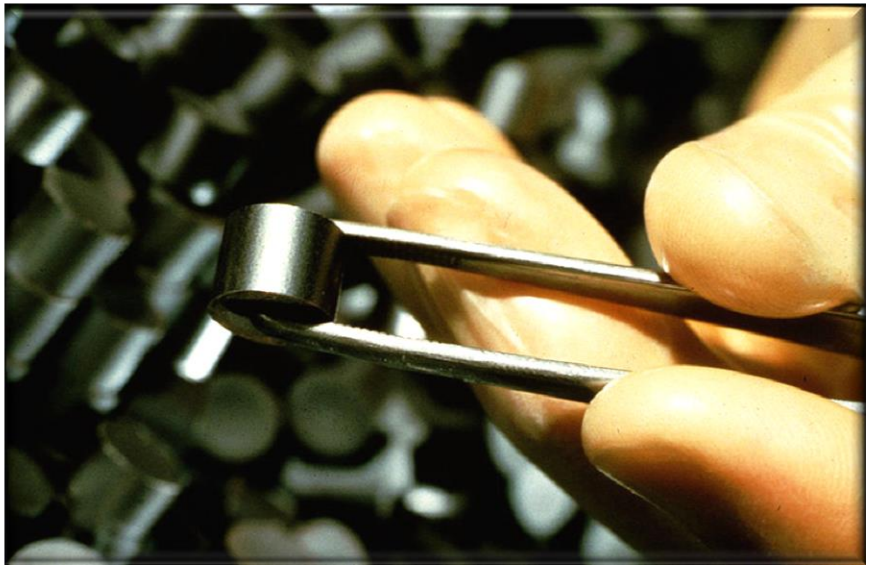
Fission fragment
range = 0.01mm

Pu Production Concurrent with Uranium Fission Chain Reaction



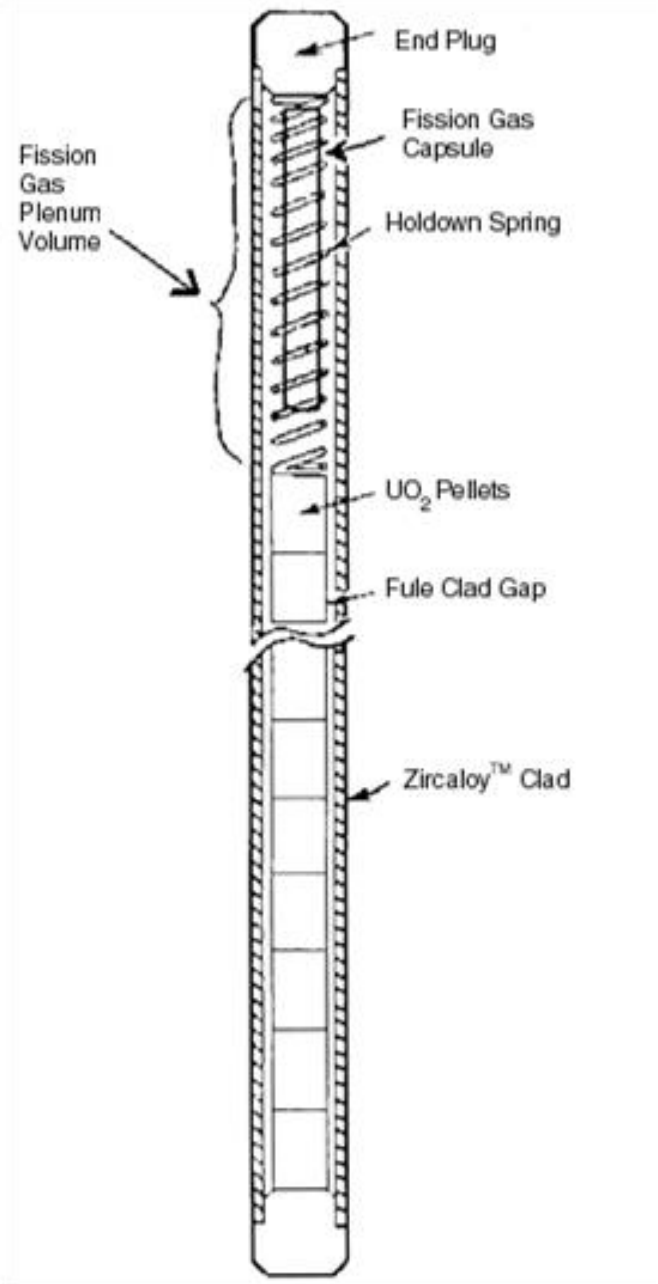
UO2 Nuclear Fuel Pellets

- A nuclear fuel is a material that is used to sustain a controlled nuclear fission reaction, usually by releasing neutrons and energy
- PWR and BWR reactors use a uranium oxide (U-235 and U-238) sintered into ceramic pellets that are placed in tubes, and the tubes are bundled together.
- The uranium is typically enriched to about 4.5% U-235, vs. the 0.71% in nature

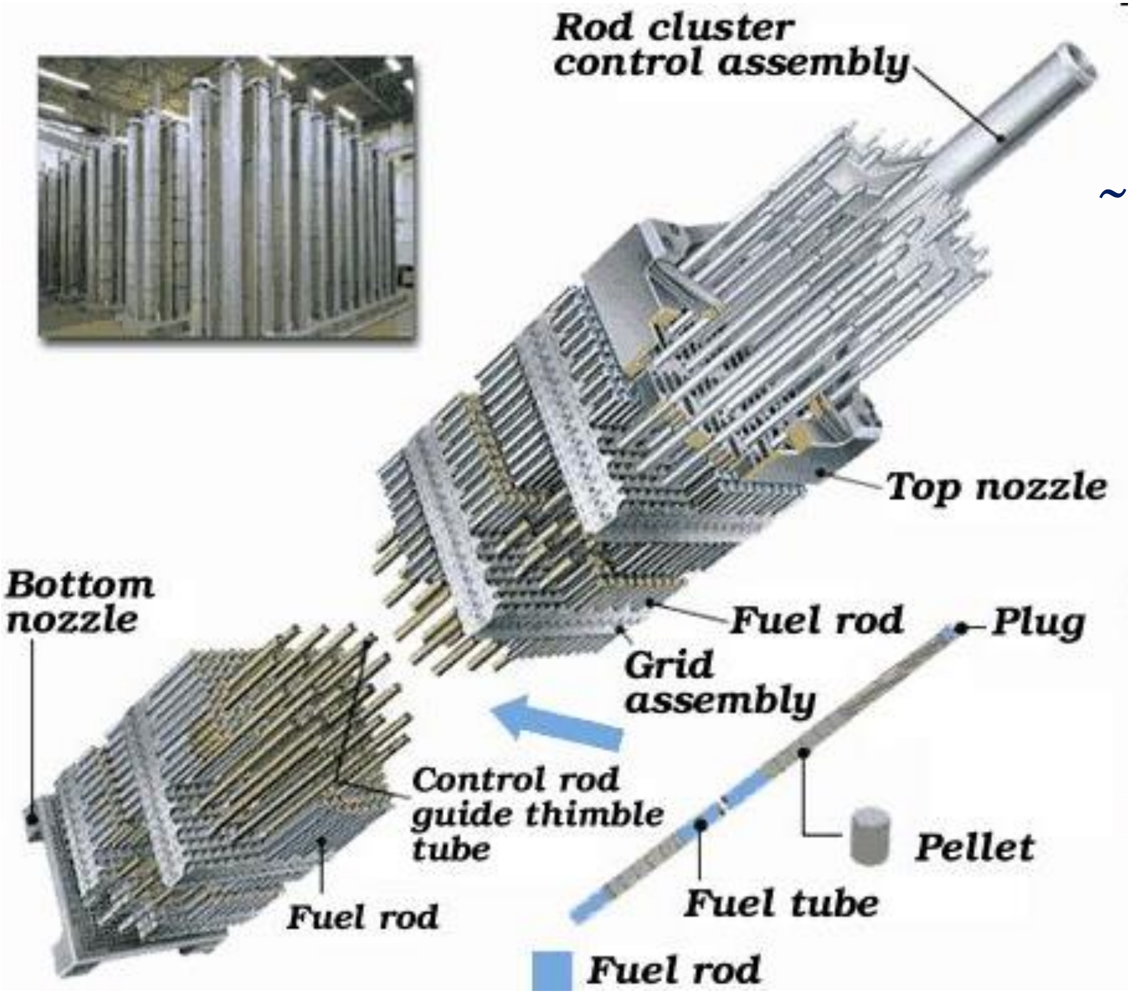


Fuel Rods (or Pins)

- Fuel pellets: Convert fissions to heat to boil water, contain most of the radioactive fission products
- Zircaloy clad: Welded shut, barrier to radioactive fission products; keeps fuel pellets in place
- Helium gas: Improve the heat transfer capability from fuel to cladding
- Spring: Allows fuel pellets to expand and contract vertically with heat-up and cool-down



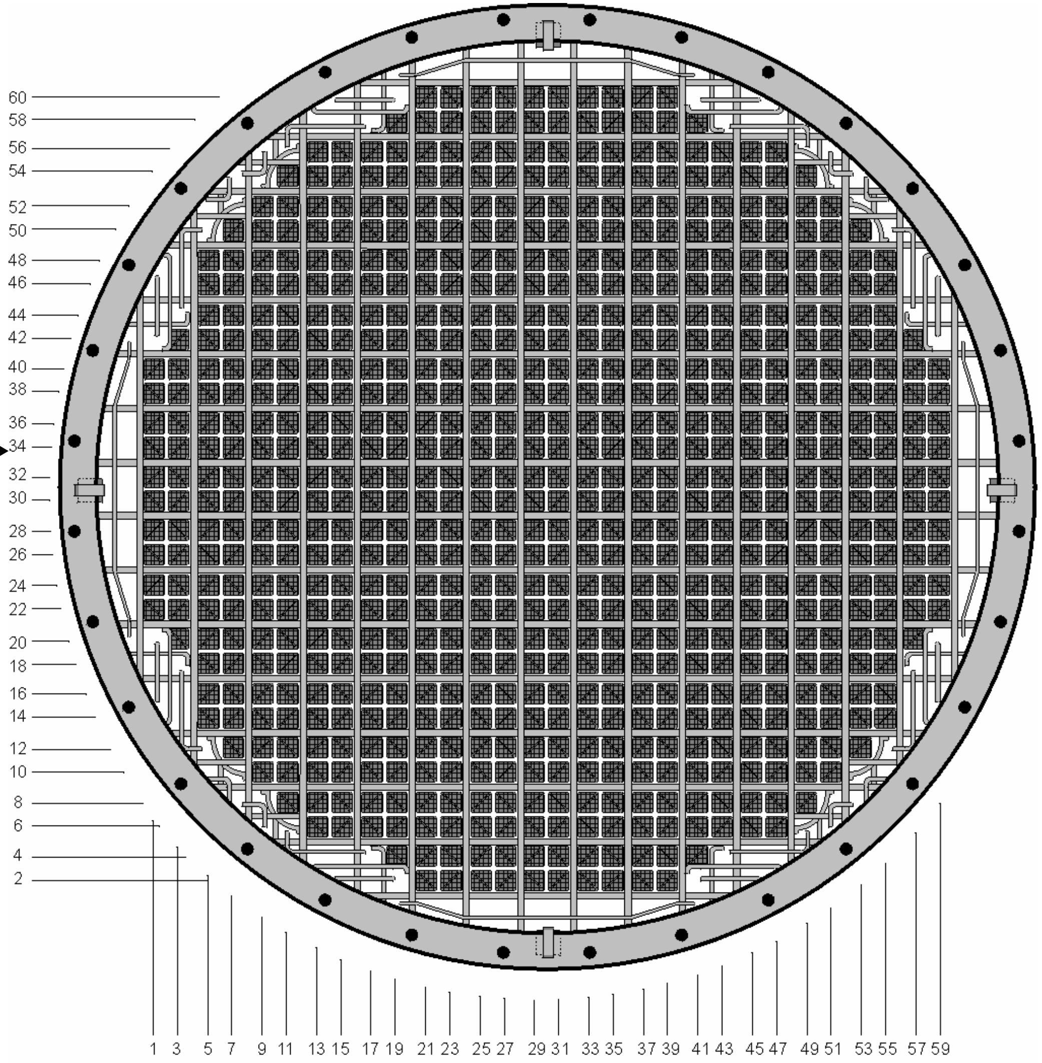
A PWR Nuclear Fuel Assembly (→ "waste")



~ 600 kg

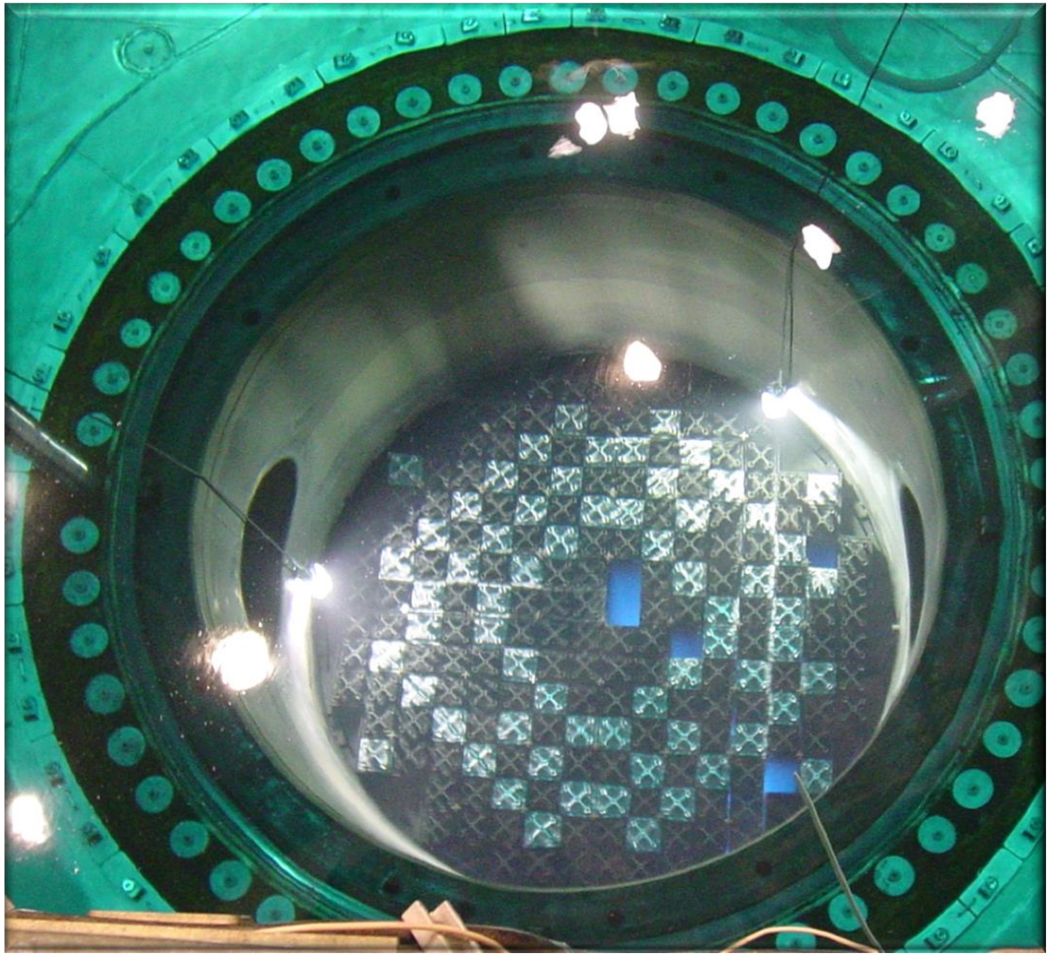
Fuel Assemblies Arranged in Core (top view)

- Hundreds of fuel assemblies are arrayed into specific locations in the core
  - ~200 in PWR
  - ~760 in BWR
- Overall cylindrical shape



Core in Pressure Vessel

- Old irradiated fuel cells are dark grey
- New fuel cells are silver
- Bright blue areas are removed fuel cells and the area is glowing due to Cherenkov radiation

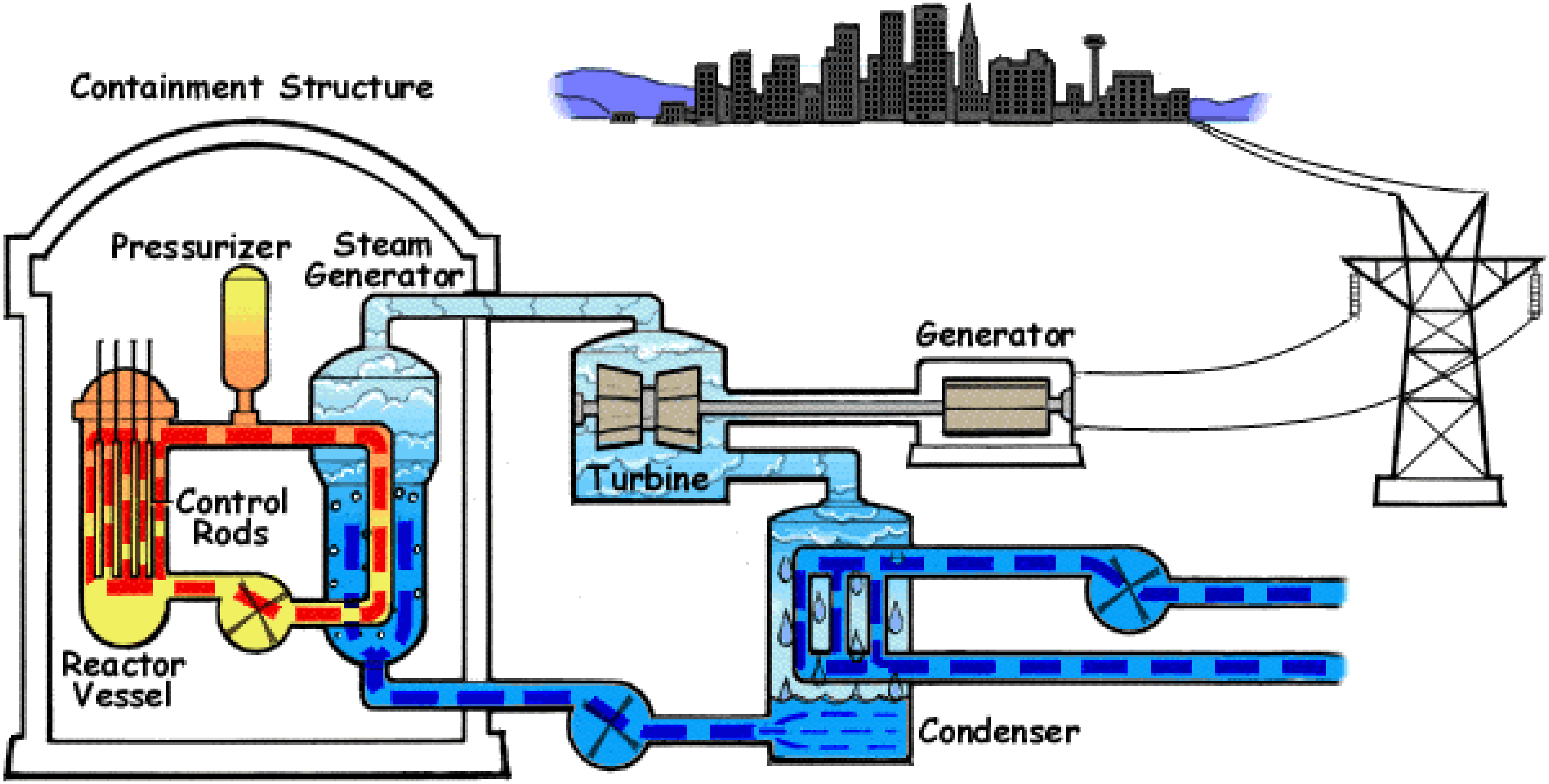


A partly refueled core, submerged in water

Reactor control systems change whether a reactor is subcritical, critical, or supercritical

- Control rods are moved to manage the neutron chain reaction in the core to:
  - Control rods use a material that strongly absorbs neutrons, e.g., B4C, In, Cd, Ag.
  - Control reactor power during startup and shutdown
  - Control reactor temperature during power operations
  - Control or shape the neutron flux of a BWR core
  - Shutdown in an emergency
- Boric acid is added to PWR reactor coolant to control temperature during power operations and to ensure the chain reaction stays terminated during refueling shutdown

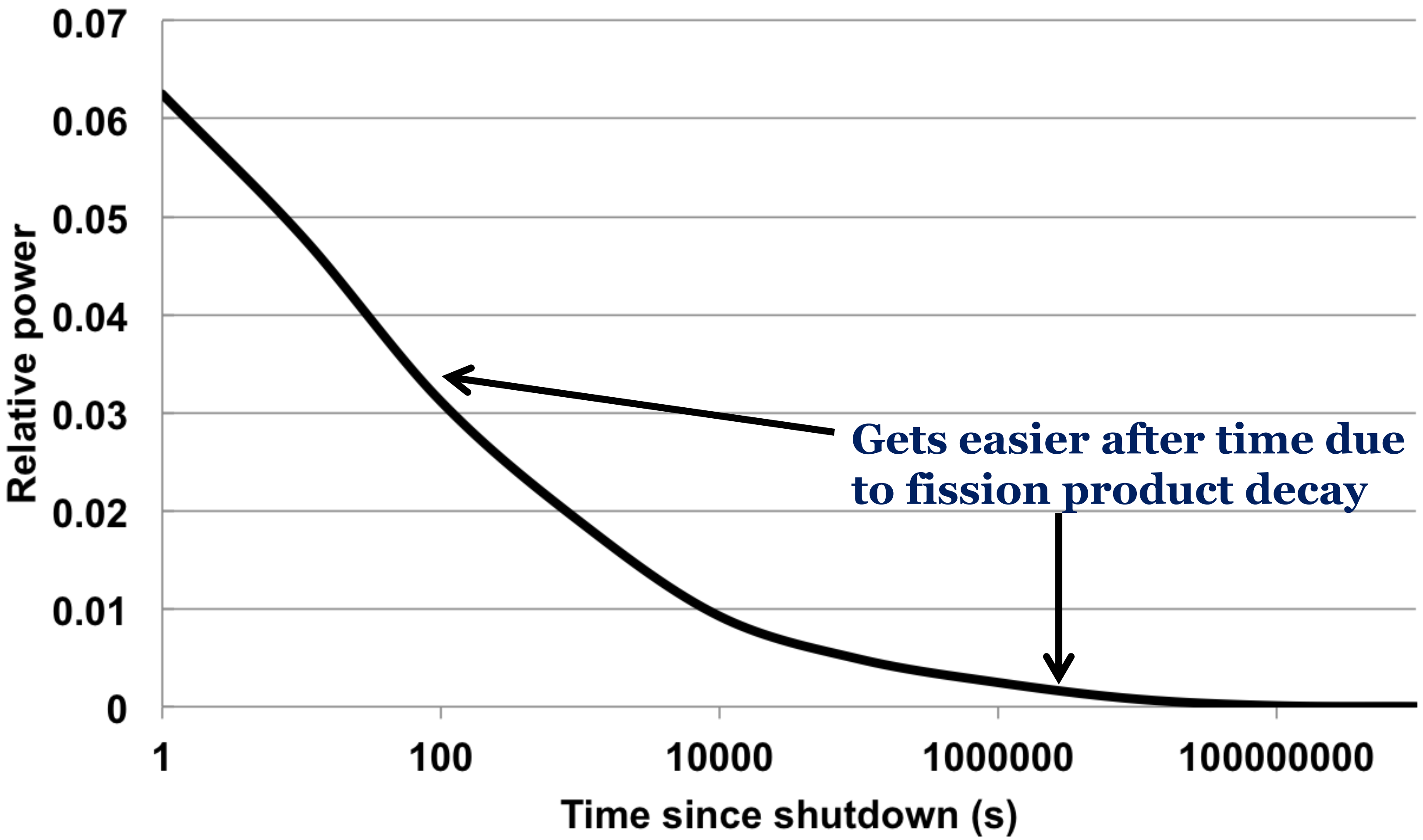
PWR Power Conversion System (heat → electricity)



Ultimate Heat Sink

- Cooling towers
- River
- Ocean
- Lake
- Man-made lake
- Treated sewage

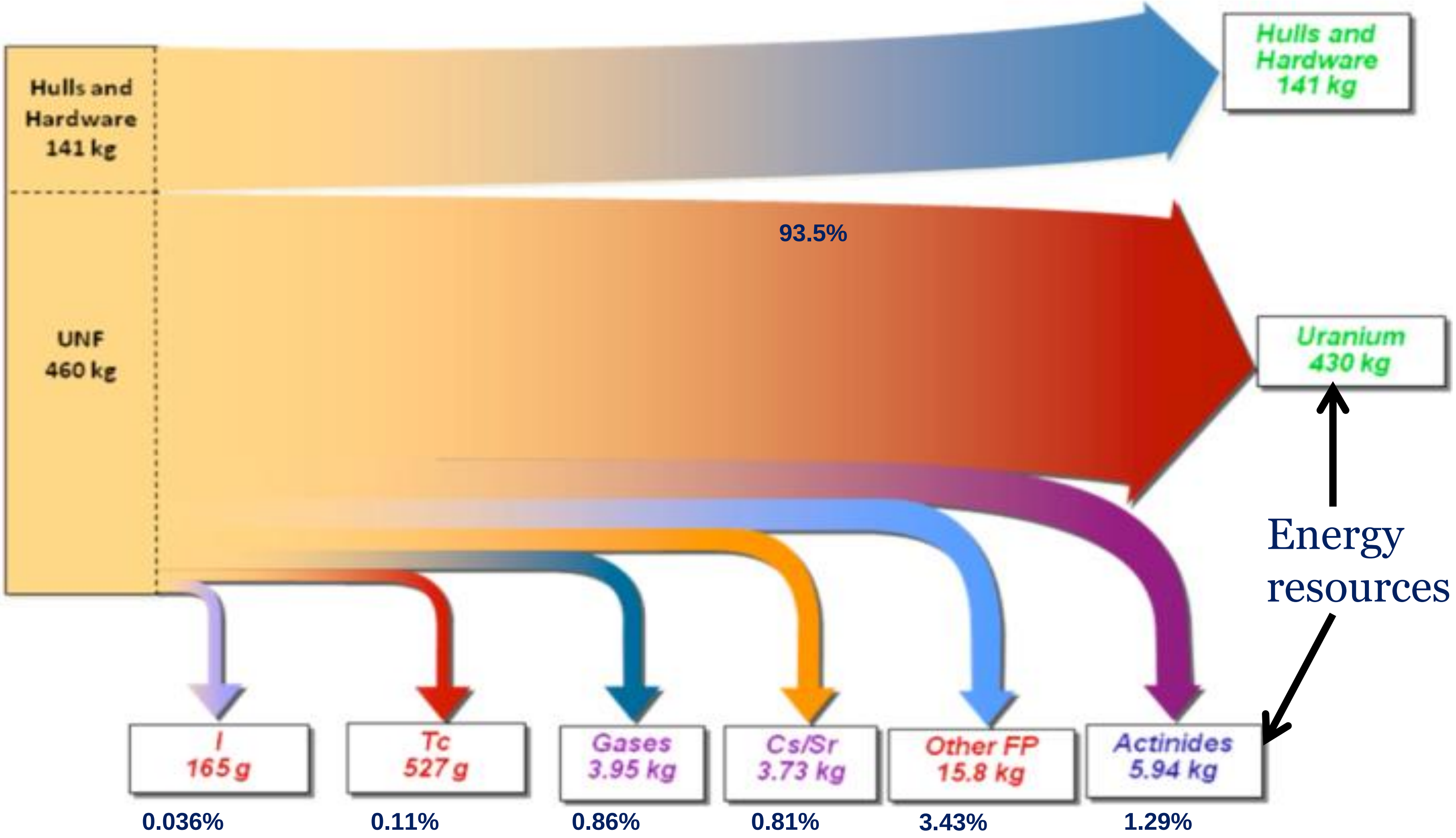
The Main Reactor Safety Challenge: Remove Fission Product Decay Heat



Gets easier after time due to fission product decay

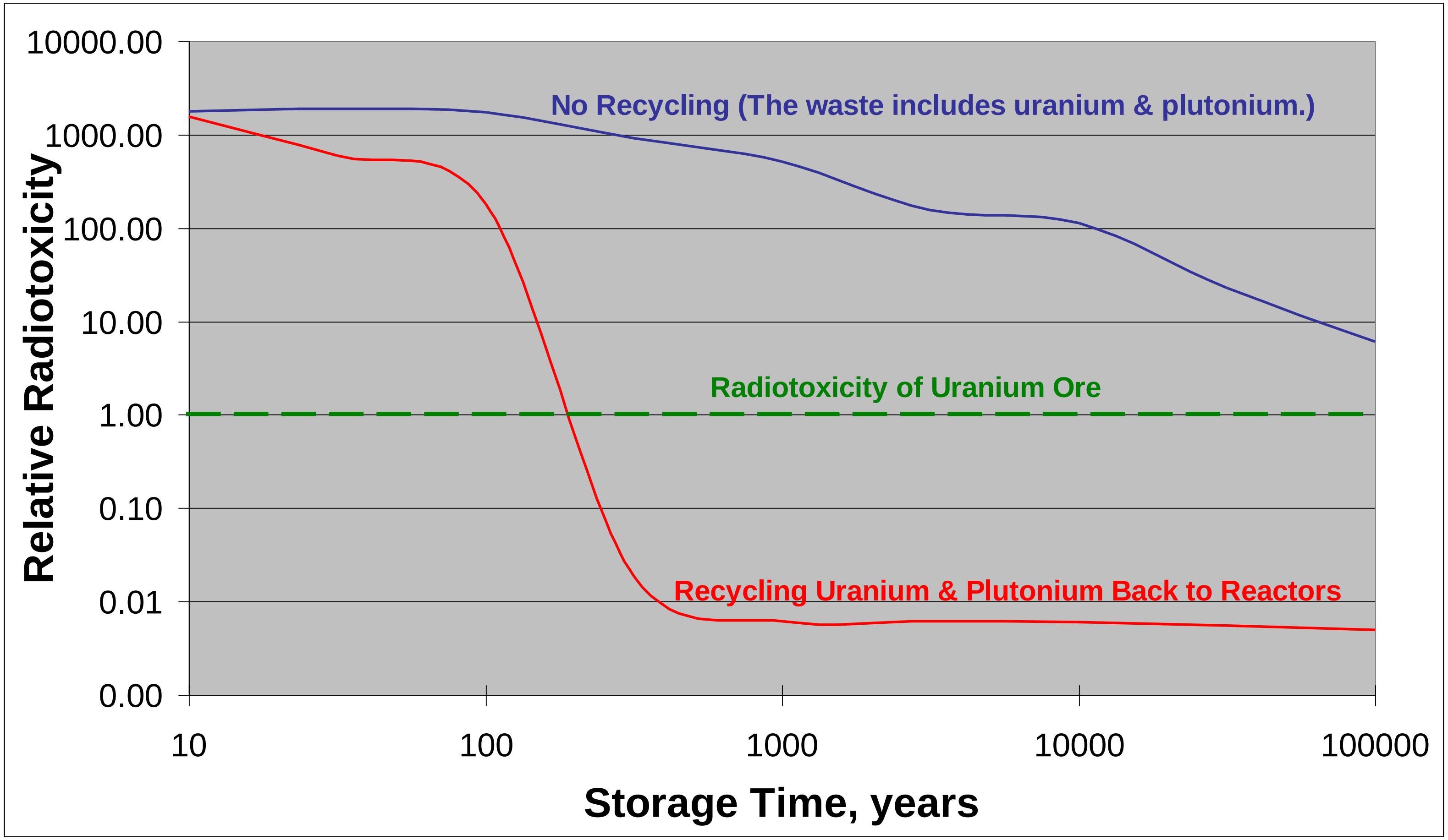
What is “nuclear waste”? -- Used Fuel Characteristic Masses

Constituents (kg) of an LWR fuel assembly following irradiation to ~50 GWd/T burnup (not to scale); due to radioactive decay, these masses are somewhat time-dependent



Used Fuel: Heat & Radiotoxicity

- For the first few decades following discharge from a LWR, fission products dominate toxicity and heat emission -- decay with ~30 year half-life
- In the longer term, actinides dominate heat emission and toxicity

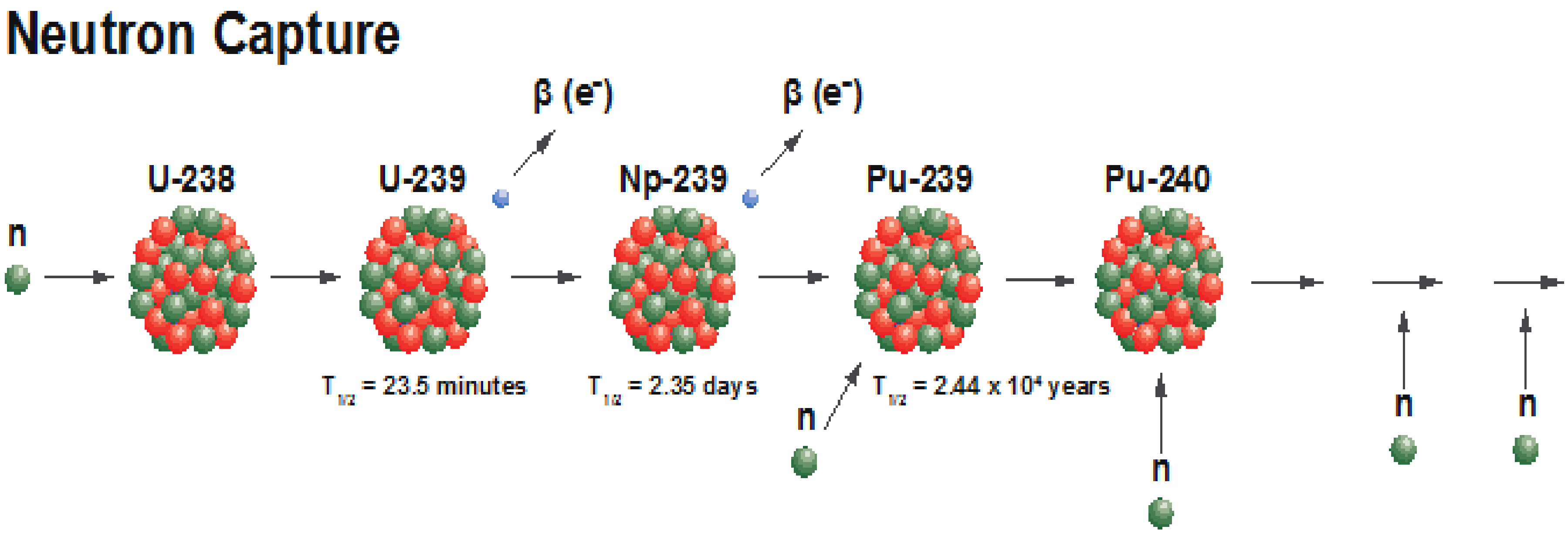


Future Reactors

The Future: Argonne’s Work on Nuclear Energy Challenges

- Make nuclear more economical – lifetime extension of current reactors, and improvements in new designs
- Improve nuclear non-proliferation (mostly unrelated to commercial nuclear energy)
- Extend usable uranium and thorium resources
- Produce technical options to resolve the “waste” issue
- Demonstrate inherent (natural) reactor safety

What should we do about Pu production in uranium reactors?

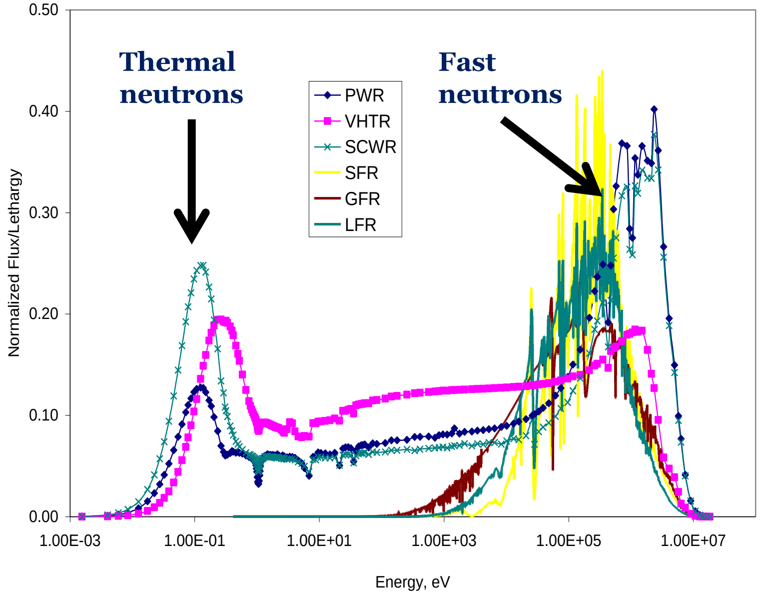


Actinide Management with Fast Reactors

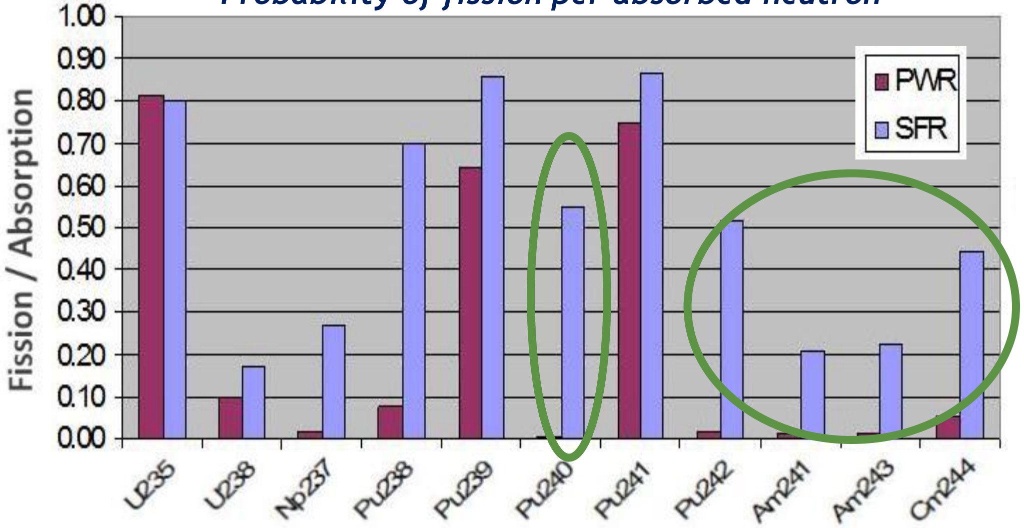
Fast neutron reactors:

- About 4 neutrons released in each fission (vs. 2.43 in LWR)
- Employ heavy or low-density coolant to avoid neutron moderation
- Enhance actinide fission probability
    - Especially significant for ^{240}Pu
- Limit buildup of higher Pu isotopes and minor actinides with irradiation
- Enable multi-recycle for transuranic consumption or fissile conservation/breeding

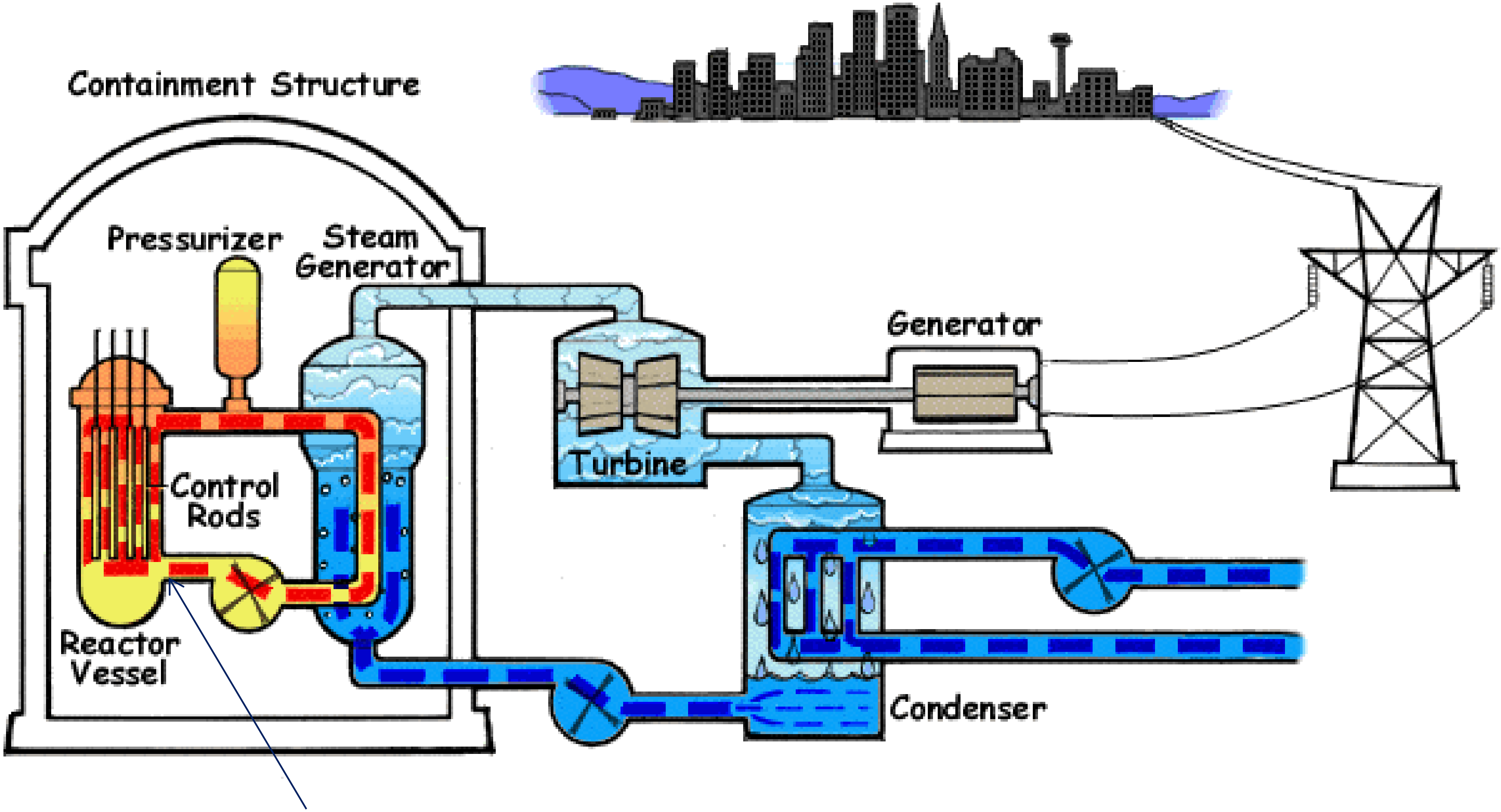
Comparison of neutron energy spectra



Probability of fission per absorbed neutron



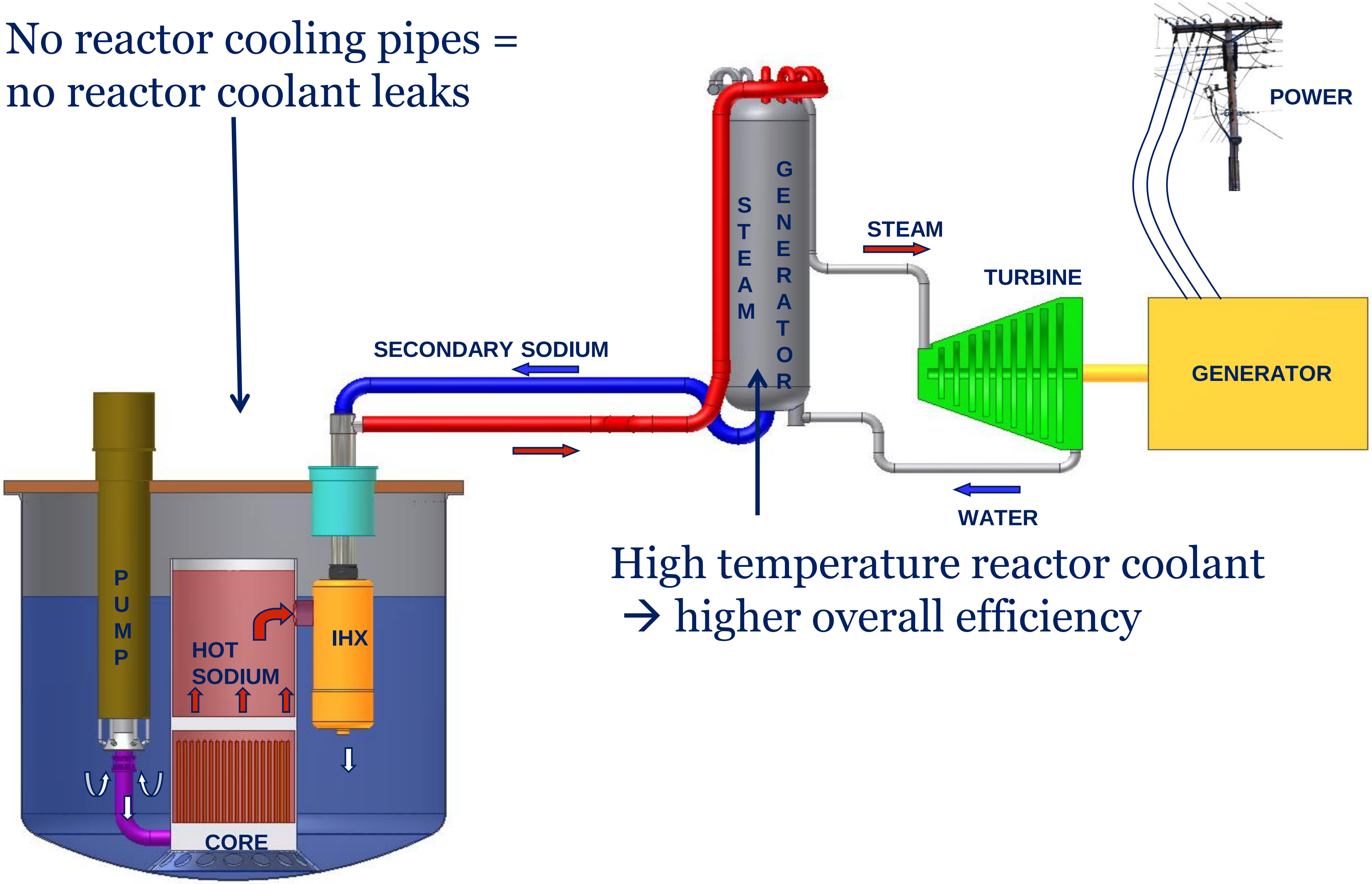
PWR is a Loop System (uses piping)



Piping penetrations in reactor vessel

Pool-type sodium-cooled fast reactor has no reactor cooling system piping

No reactor cooling pipes =
no reactor coolant leaks



High temperature reactor coolant
→ higher overall efficiency

Sodium-cooled Fast Reactors (SFRs)

- Terrific coolant, compared to water:
  - Much higher boiling point (883C) →***low operating pressure***
  - Thermal conductivity = 100 x water's
  - Good specific heat
  - Wets better than water
  - Less corrosive to steels than water; still must control oxygen
  - Good radiation stability (no chemical bonds to be broken)

- Challenges, compared to water:
  - Need to keep primary sodium and steam plant water apart, so use:
    - Intermediate cooling loop
    - Guard pipes for intermediate sodium system
    - Double-walled steam generator tubes to guarantee no sodium-water reactions
    - Zero steam generator leaks at EBR-II for 30 years
  - Must avoid sodium boiling – positive void reactivity coefficient
  - Freezes at 98C

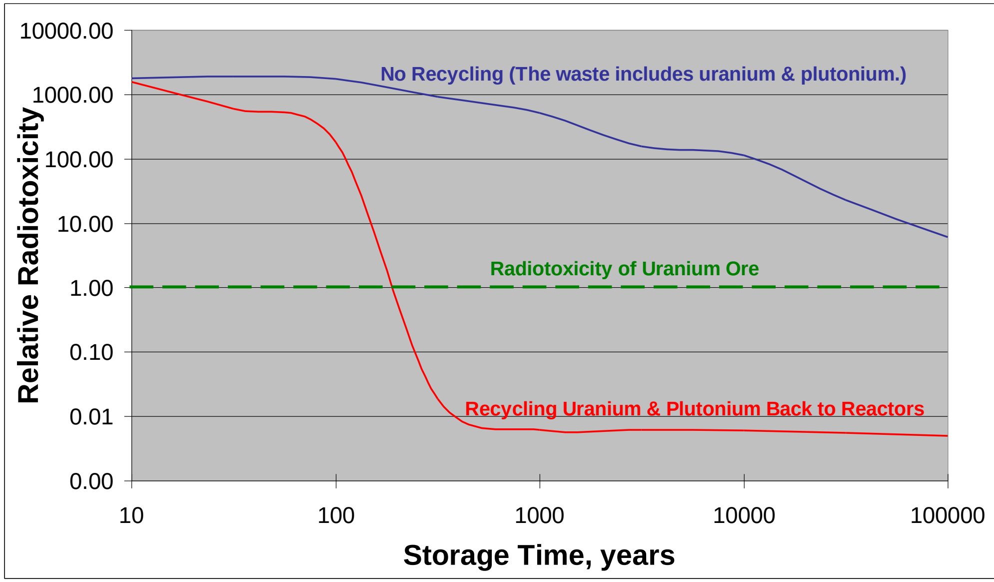
SFR Safety Pros/Cons

- Low operating pressure → affordable large pool plant vessel
- Can immerse entire reactor cooling system in vessel with no penetrations that can leak
- Large vessel provides weeks-long heat sink if power is unavailable
- Inherent feedbacks shut down chain reaction if cooling fails – demonstrated at Argonne using EBR-II
- Can have positive coolant boiling coefficient, but sodium boils at hundreds of degrees above operating temperatures
- Higher temperature = thermodynamic efficiency & process heat, not just electricity

- Bottom line: expected to be x100 safer than LWRs

Nuclear Waste Non-radioactive after 300 Years

- Easier fuel recycling on-site = *Integral* Fast Reactor (IFR)
- IFR can ‘burn’ U-238 & transuranics using fast neutrons
- Turns ‘waste’ into ‘fuel’
- With recycling, residual radiotoxicity of waste declines to original uranium ore radiotoxicity in 300 years → no need for geological repository with 300,000-year design life



No weapons-usable materials exist at any time

- No need to enrich uranium for fission
- Continuous plutonium breeding useful for the IFR reactor, but:
  - No Pu is separated in pyroprocessing – product is wildly unsuited for weapons use – wrong material and far too radioactive
  - Fuel reprocessing done remotely in hot cell – extremely radioactive fissile material is self-protecting
  - Separating bomb-grade Pu would require large PUREX reprocessing – easily detected by inspectors or intelligence

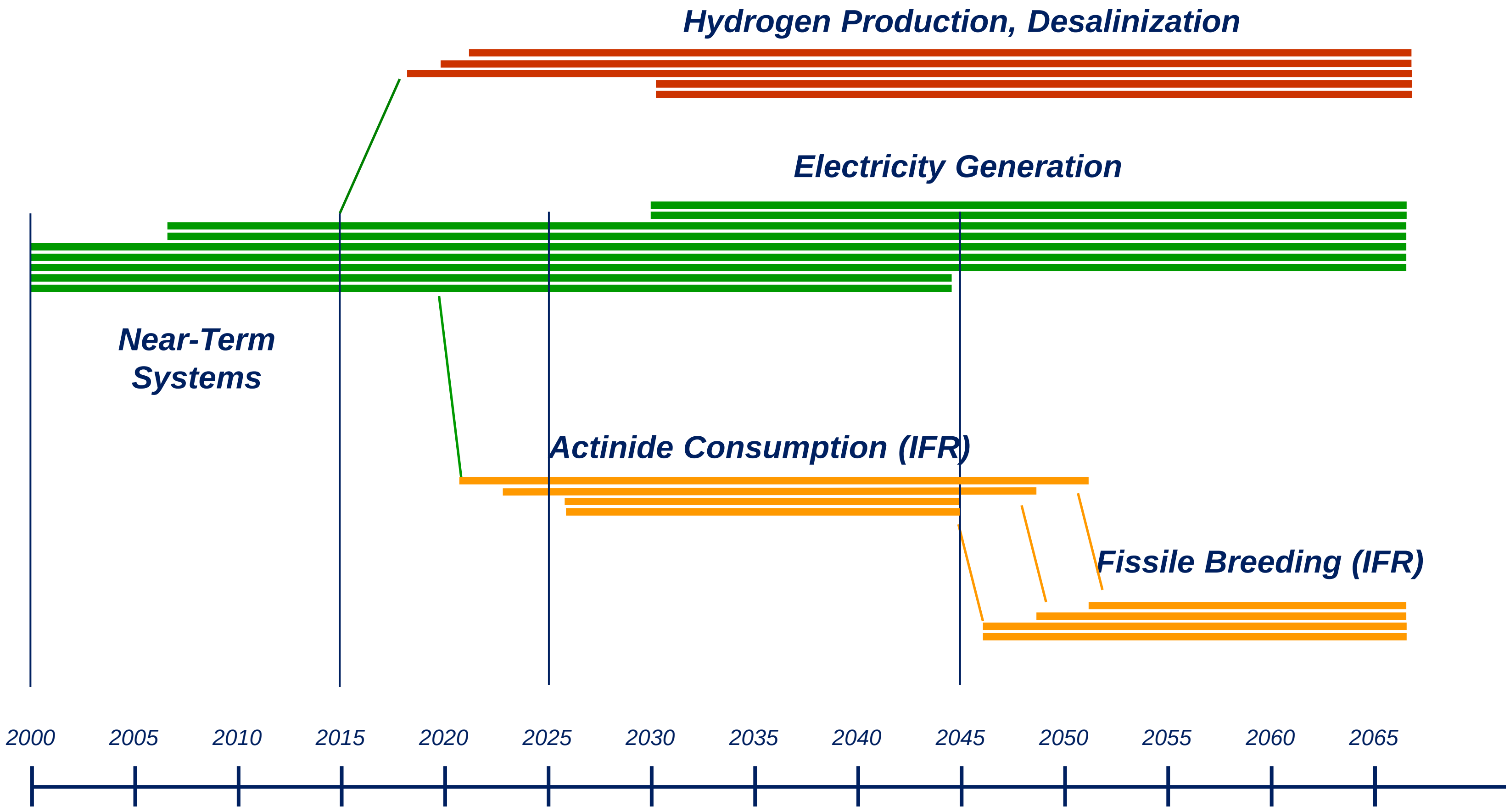
Inexhaustible energy supply

- Current commercial reactors use ~ 1% energy in U
- After initial startup, IFRs have sustainable energy generation
- Already mined resources:
  - U-238 in enrichment tails (currently waste)
  - Pu & U-238 in spent nuclear fuel
  - **1,000 years of total energy production in U.S. (not just electricity)**
- Sea water contains roughly 1,000,000 times more U than ore resources.
  - **Tens of thousands of years total energy supply**
  - Cost is irrelevant if energy extraction

Cost Advantages of IFR

- Small versions (SMRs) can be fully modular, made on factory assembly lines and shipped to sites is feasible
- Costs offset by nuclear waste disposal savings
- Pyroprocessing much cheaper than PUREX
- Can sell high-quality waste heat for industrial processes—hydrogen production, etc.
- GE-Hitachi proposal to UK: plutonium stockpile ‘disposition’ instead of MOX, no upfront costs
- Inherent safety reduces need for expensive actuated safety systems.
- Costs uncertain until 1st plant is completed and operational

Future Applications of Nuclear Energy



The Integral Fast Reactor References

- Truth About Energy by Don Lutz, http://www.truthaboutenergy.com/argonne.html
- Plentiful Energy, The IFR Story, by Charles E. Till and Yoon Il Chang, http://www.google.com/search?client=safari&rls=en&q=plentiful+energy+ifr&ie=UTF-8&oe=UTF-8 , available at amazon.com.
- Articles, papers, and books by James Hansen, http://www.columbia.edu/~jeh1/
- Articles, papers, and books by Tom Blees, http://www.google.com/search?client=safari&rls=en&q=tom+blees+ifr&ie=UTF-8&oe=UTF-8
- Beyond Fossil Fools by Joe Shuster, http://www.beyondfossilfools.com/
- Brave New Climate websites and commentary by Barry Brook, moderator, http://www.google.com/search?client=safari&rls=en&q=brave+new+climate+barry+brook&ie=UTF-8&oe=UTF-8
- Articles by Steve Kirsch, http://www.google.com/search?client=safari&rls=en&q=steve+kirsch+ifr&ie=UTF-8&oe=UTF-8

Upcoming Webinars in the Nuclear Fuel Cycle Series

- Chemistry and Radiochemistry of the Reactor Coolant System
- The PUREX Process
- Advanced Partitioning Technologies in the U.S.

NAMP website http://www.wipp.energy.gov/namp/