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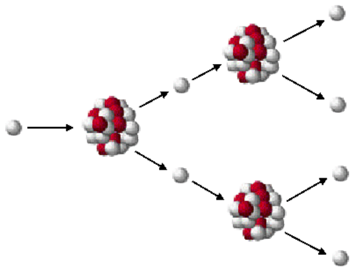
The Evolving National Fuel Cycle

ARPA-E Workshop on Reducing Disposal Impact from Advanced Reactor Fuel Cycles

Idaho National Laboratory

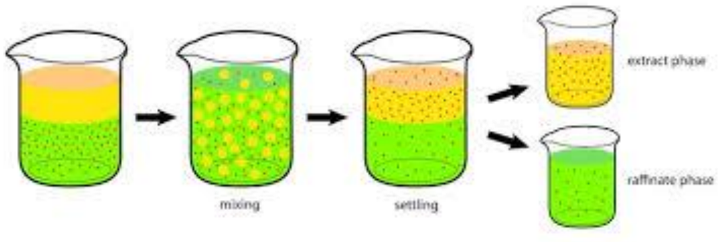
Presentation Outline

- Why process irradiated materials?
- National fuel cycle – historical perspective
  - *Discovery Era*
  - *Weapons Development*
  - *Nuclear Power Development*
- Current domestic fuel cycle
- Future domestic fuel cycle

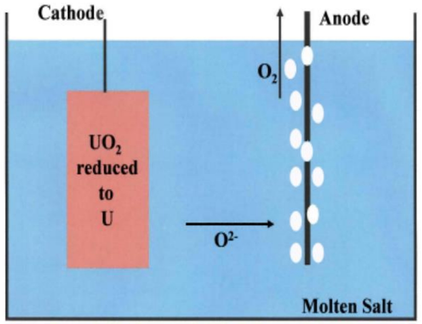


Why Process Irradiated Materials?

- **Recover useful materials**
  - Medical isotopes
  - Industrial applications
  - Actinides for fuel fabrication and, in the old days, for weapons production

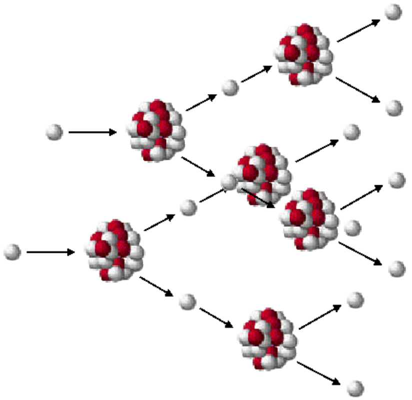


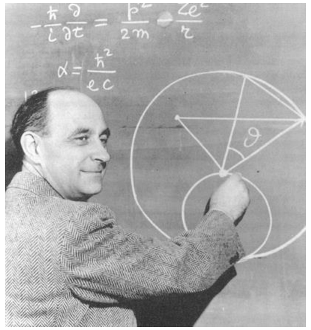
- **Stabilized materials prior to disposal**
  - Tank waste
  - Na-bonded and other types of fuels
  - Damaged materials

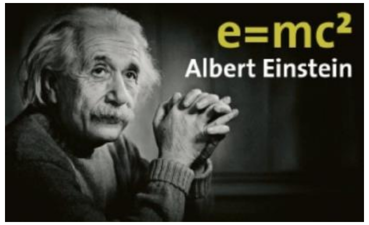


Discovery Era

- The discovery of fission
  - *1934 – Enrico Fermi showed neutrons could split many kinds of atoms*
  - *1938 – Confirmation of Einstein's Theory–uranium neutron bombardment confirmed that the total fission product masses did not equal the uranium's mass, showing that the lost mass had been converted to energy.*
- The first self-sustaining chain reaction
  - *1941 – Fermi and his associates suggested a possible design for a uranium chain reactor. The model consisted of uranium placed in a stack of graphite blocks to make a cube-like frame of fissionable material.*
  - *1942 – The world's first reactor known as Chicago Pile-1 began construction.*



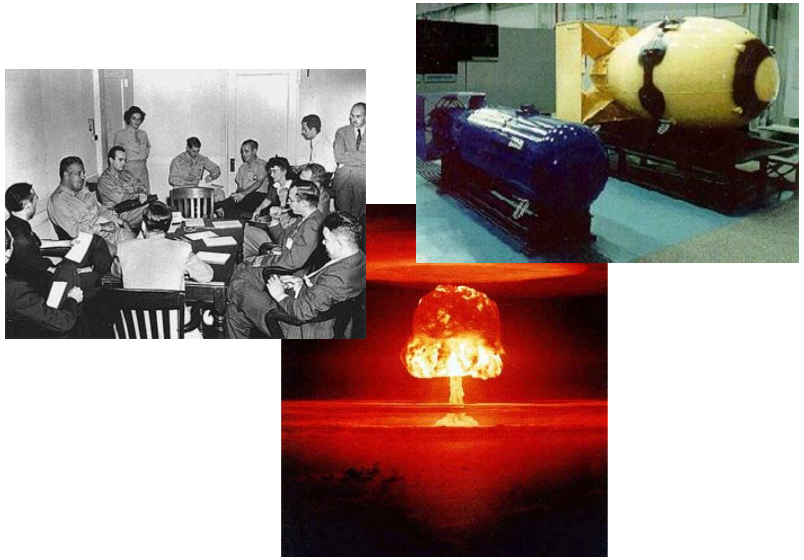


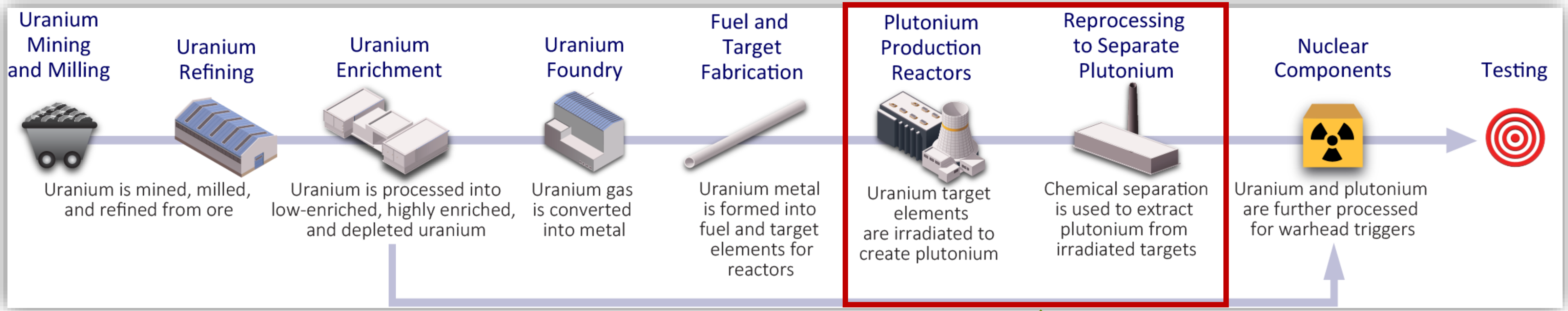


December 2, 1942, CP-1 became self-sustaining, and the world entered the nuclear age

The First Fuel Cycle Was for Weapons Development

- 1943 – CP-1 was dismantled and reassembled at the Argonne Forest site as CP-2
  - *Model for the first Hanford production reactor*
- 1944 – The world's first heavy-water moderated reactor, CP-3 was constructed at Argonne
  - *Model for the Savannah River production reactors*





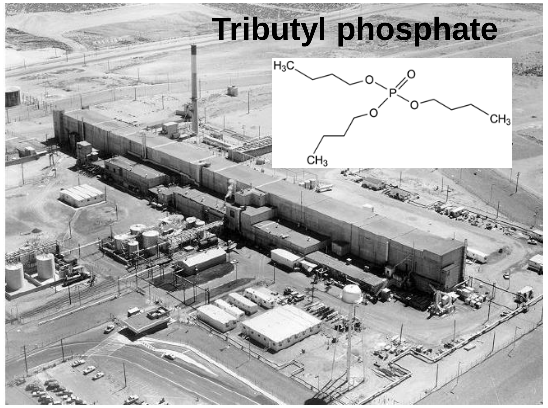
Waste treatment absent for 50 years

Recovery of Pu-239

- Originally by precipitation with lanthanum fluoride and bismuth phosphate
  - *Hanford T-Plant built in1944*
- Japan surrenders August 15, 1945, ending World War II
- REDOX – 1st solvent extraction process used
  - *Developed at ANL, tested at ORNL, plant built in Hanford (1948 –1951)*
- BUTEX – Developed at Chalk River Lab (Canada) utilized dibutyl carbitol, plant built in Sellafield, UK
- PUREX – Developed at ORNL utilized tributyl phosphate, plants built in:
  - *SRS – recover Pu/HEU*
  - *Hanford – recover Pu*

Hanford T-Plant 1944

Hanford REDOX -Plant (1951)



Weapons Development Fuel Cycle Produced Contamination on a Large Scale

Over **700,000 tons of depleted uranium** produced as a by-product of enriching uranium to weapons grade

Former U.S. Nuclear Weapons Complex

Over **5,000 facilities contaminated** as a result of activities such as reactor operations and uranium enrichment (which produce fissile material for nuclear weapons)

Millions of cubic meters of soil and billions of gallons of groundwater contaminated by environmental releases of radioactive and hazardous materials

Over **100 metric tons** of plutonium

plutonium
94
Pu
[244]

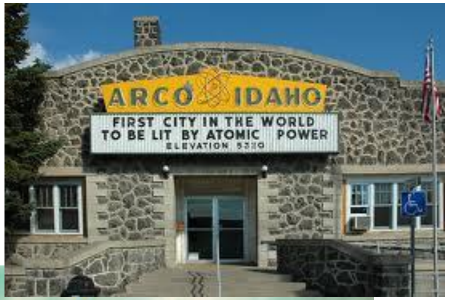
Over **1,000 metric tons** of weapons-grade uranium

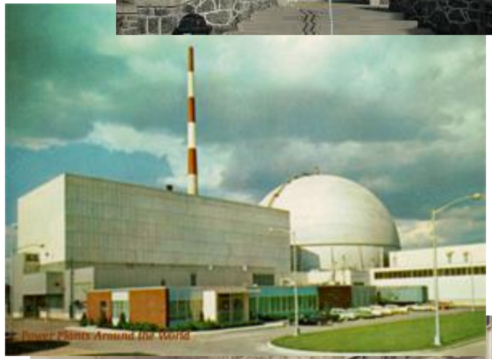
uranium
92
U
238.03

Over **90 million gallons of liquid waste** produced as a by-product of the separation of plutonium and uranium from used nuclear fuel rods

Civilian Nuclear Power Development

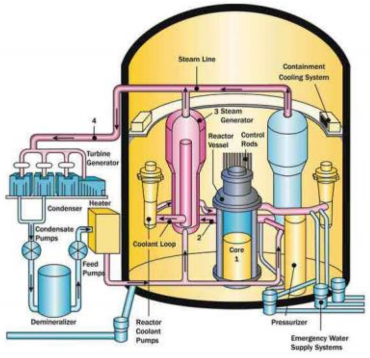
- In the late ‘40s and early ‘50s nuclear power development programs began in many countries
  - *Striving for energy independence*
  - *Exciting new technology at forefront of science*
- Nuclear power development began as an exploration of the possible
  - *Hedge against an energy shortage in the future*
  - *Potentially inexpensive, plentiful energy – “too cheap to meter”*
- Early development of thermal reactors focused on simplicity as the way to early economic viability
  - *Understand their behavior*
  - *Develop low-enrichment fuel*
  - *Design and construction*

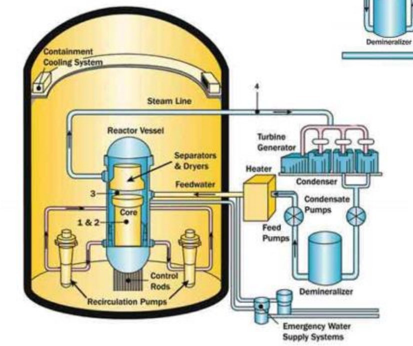




Selection of the Light-water Reactor (LWR)

- The nation selected the LWR – a uranium-oxide-fueled reactor moderated and cooled by ordinary water in two variants
  - *The pressurized-water reactor (PWR) – the choice of Admiral Rickover for submarine propulsion and of Westinghouse for commercialization*
  - *The boiling-water reactor (BWR) – the choice of GE for commercialization*
- Other power reactor types included:
  - *Fast Breeder Reactor: EBR-I*
  - *High-Temperature Gas-Cooled Reactor: Peach Bottom-1*
  - *Molten-Salt Reactor*

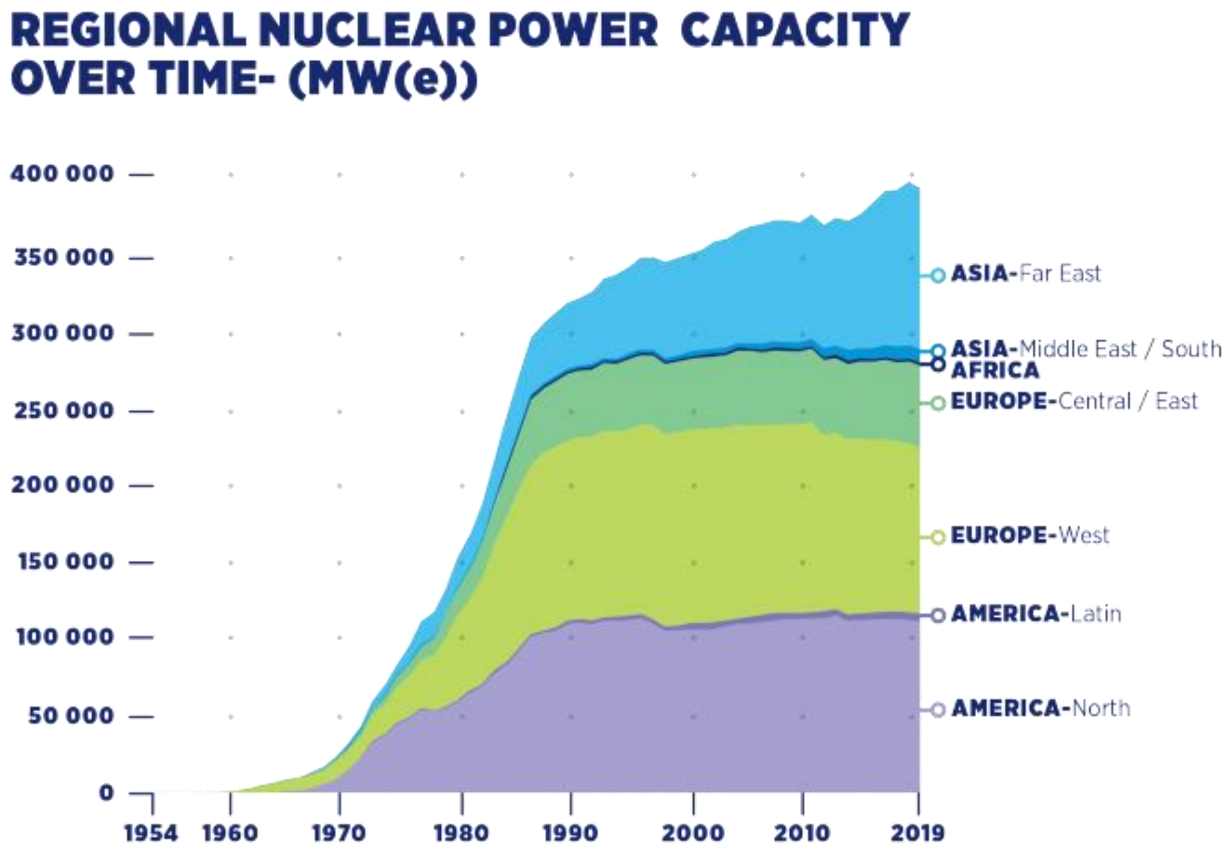




The Period of Rapid Development and Construction

Late 1960s – success had been achieved, plants were technically feasible and economically viable

- *A boom in orders and construction began*
- *Between the late 1960s and mid-1970s, over 100 nuclear plants were built in the U.S.*
- *There were 5 active reactor vendors (Westinghouse, GE, B&W, C-E, and GA), and major oil companies (Exxon, Gulf, etc.) had entered the fuel cycle arena*



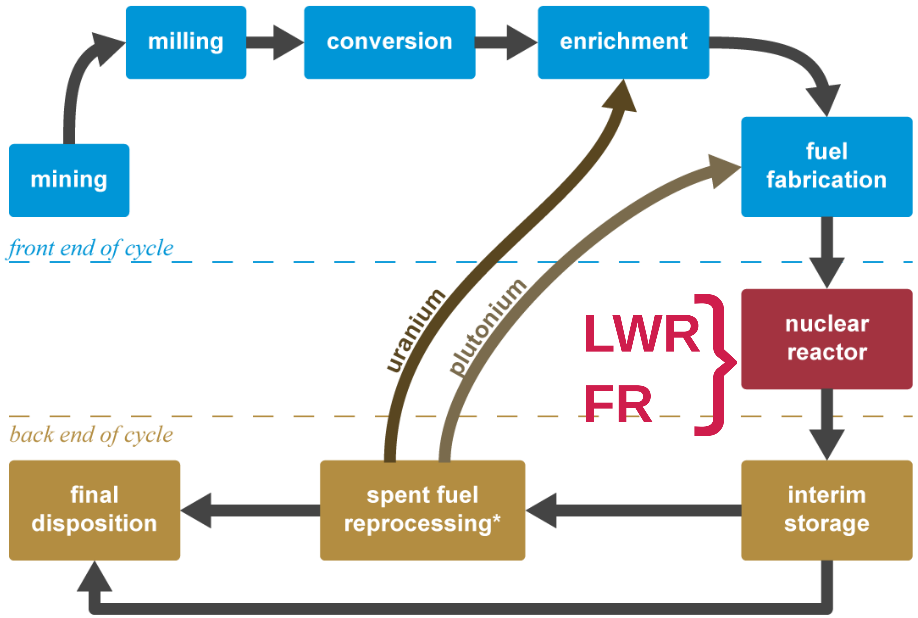
https://www.iaea.org/newscenter/news/iaea-releases-2019-data-on-nuclear-power-plants-operating-experience

‘70s Energy Crisis

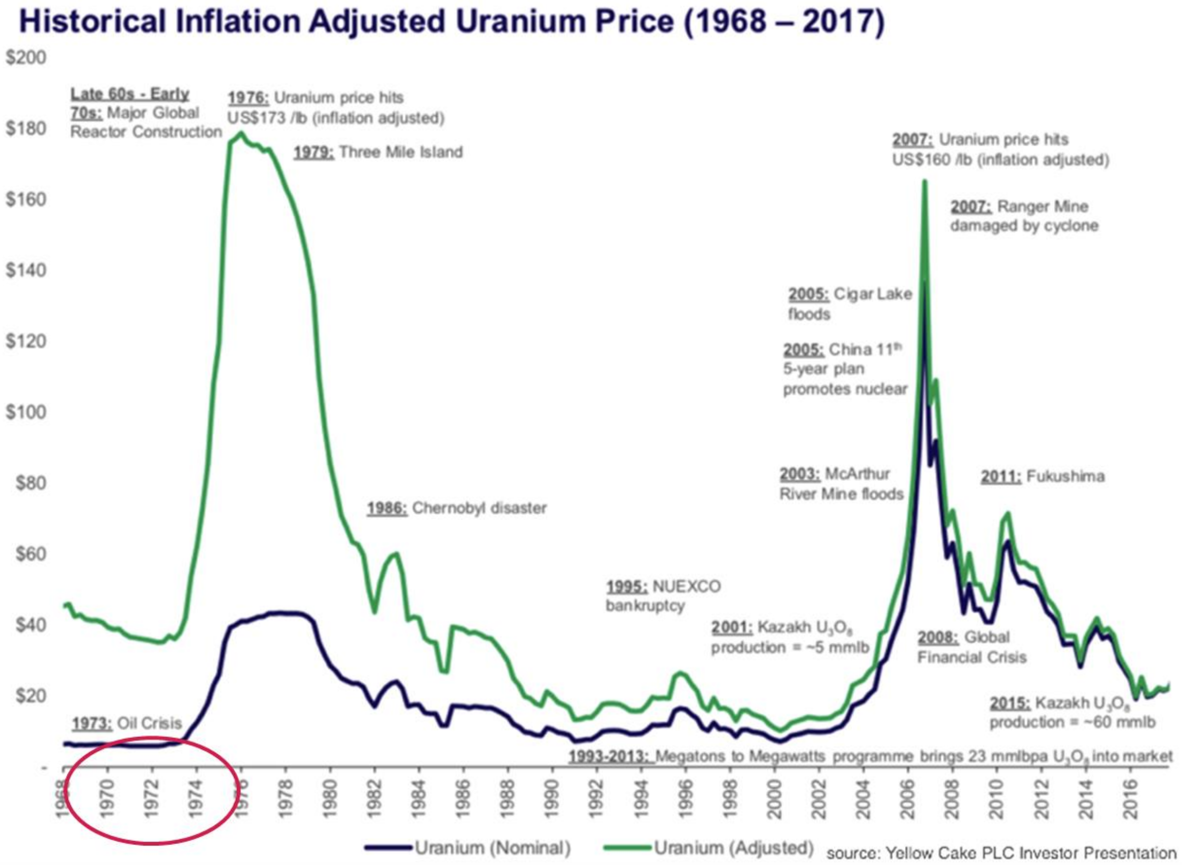
- Uranium resources were thought to be limited, and reprocessing and recycling in high-conversion fast (breeder) reactors was envisioned.
- The oil crisis started, and energy fuels were of great concern

In 1971, President Nixon said, “Our best hope today for meeting the Nation’s growing demand for economical clean energy lies with the fast breeder reactor.”

Domestic Fuel Cycle Envisioned in the early '70s



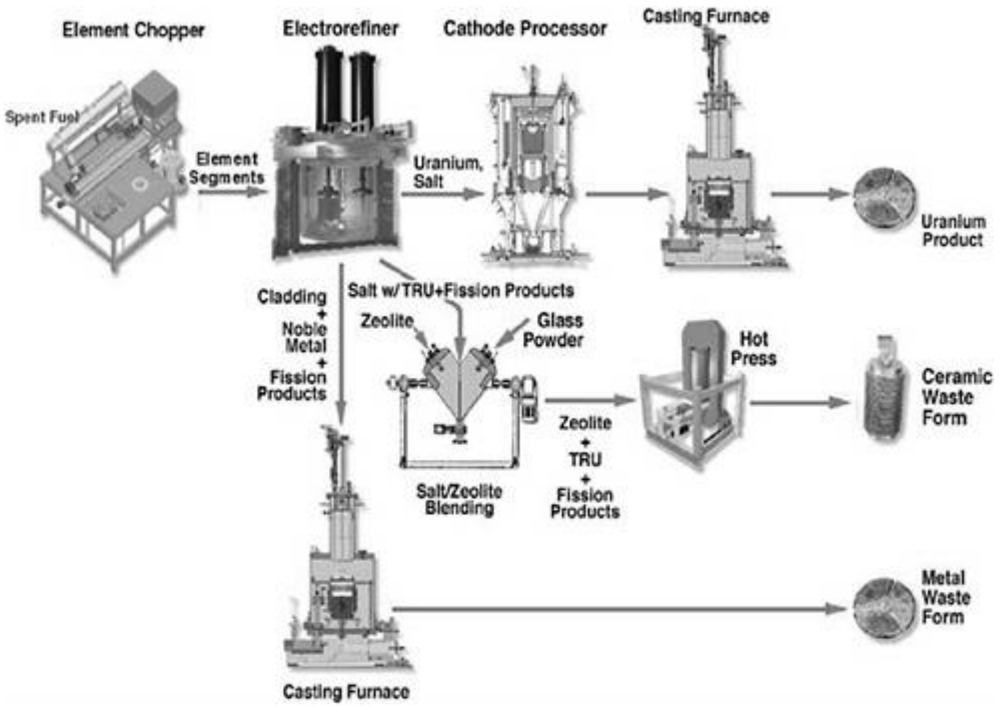
https://www.eia.gov/energyexplained/nuclear/the-nuclear-fuel-cycle.php



Spent Fuel Recycling

Fast Reactors – Metal Fuels

- PYRO or Electrochemical process – developed at ANL (EBR II 1964 – 1994)



LWRs – Oxide Fuels

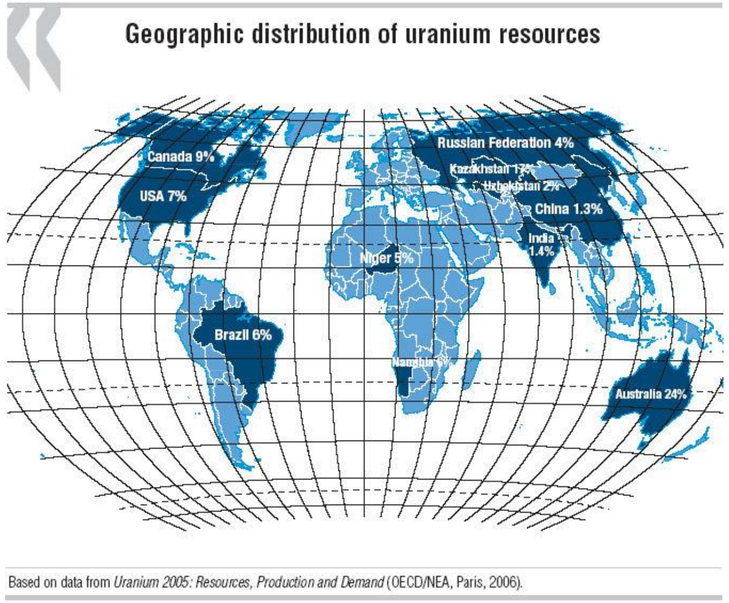
- PUREX Domestic
  - West Valley, NY (1966 – 1972)
  - Morris, IL (construction halted 1972)
  - Barnwell, SC (construction halted 1977)
- PUREX International
  - France
  - United Kingdom
  - Japan
  - Russia
  - China

The Effect of the TMI-2 and Chernobyl Accidents

- Three Mile Island – 1979, partial core meltdown with no radiation release
  - *New regulatory and retrofit requirements caused delays in the licensing process and the escalation of construction costs*
  - *Most plants not under construction were canceled, some under construction were mothballed, and no new orders were placed for several years*
- Chernobyl – 1986, complete core meltdown with radiation release
  - *Public concern about the safety of nuclear facilities*
  - *Cemented public opposition to further expansion of nuclear power for years*

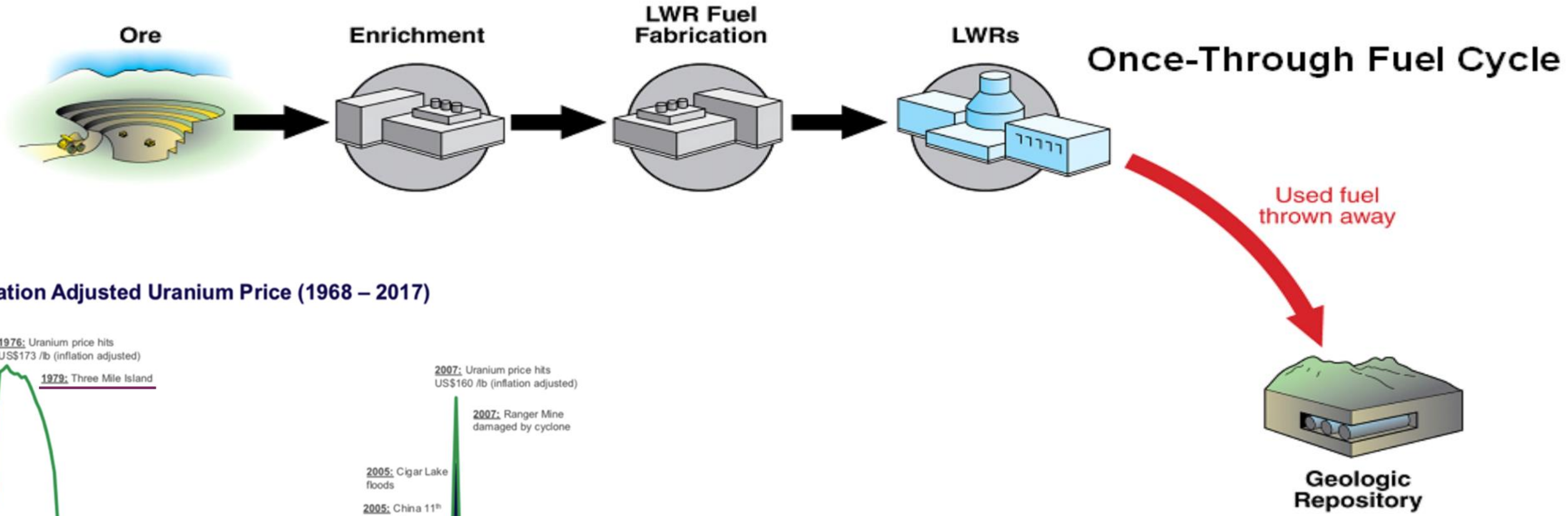
By the Early 1990s

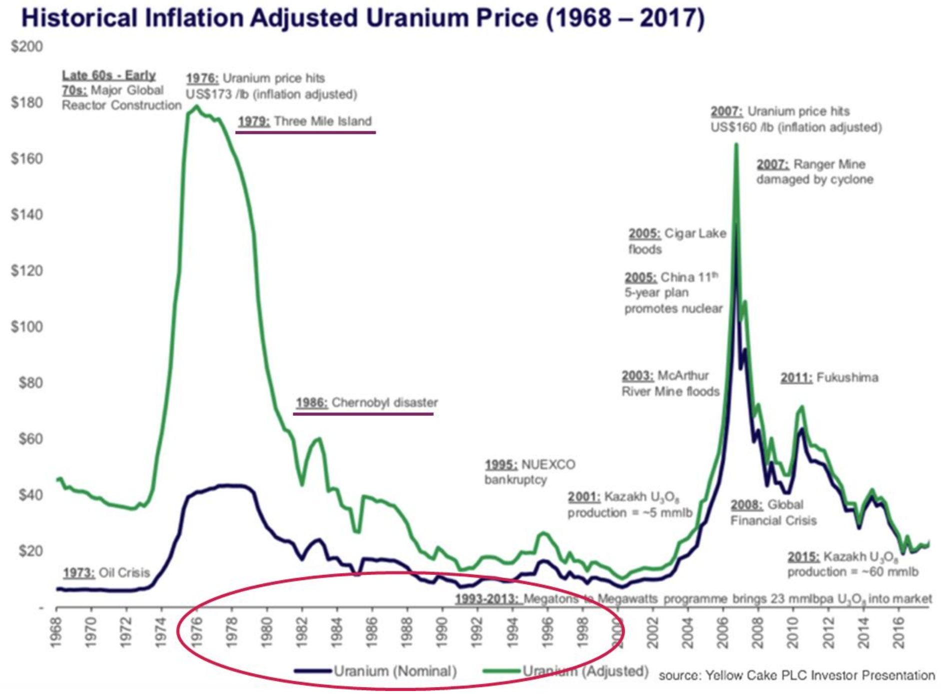
- Uranium resources were proven not to be limiting
- Nonproliferation concerns being addressed
  - *Megatons to megawatts program (Russian warheads)*
  - *Defer indefinitely the U.S. commercial reprocessing and recycling of plutonium*
  - *Defer the introduction of a commercial breeder reactor*
  - *Induce other nations to limit or eliminate plutonium use in their civilian nuclear power programs*



- Bankruptcy of some companies due to cancelation of nuclear power reactors orders
- Reactor pools were filling up, highlighting the need for permanent disposal of spent fuel
  - *NWPA amendment designated Yucca Mountain as the nuclear waste repository*

Domestic Fuel Cycle Envisioned in the Mid – 1990s

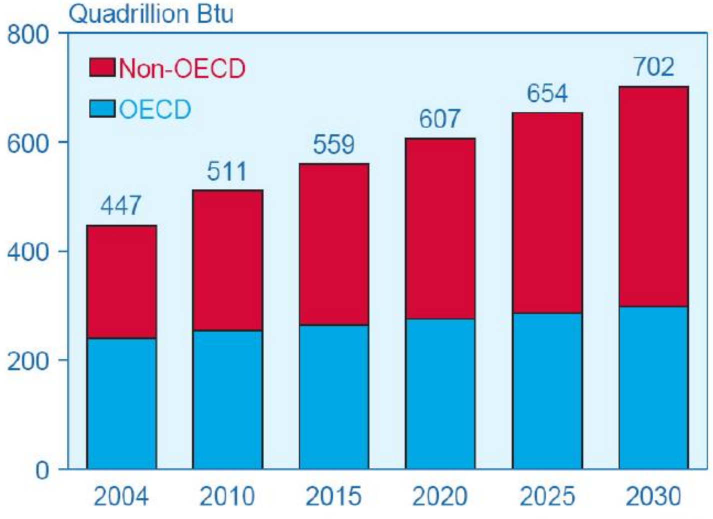




Nuclear Renaissance – 2000s

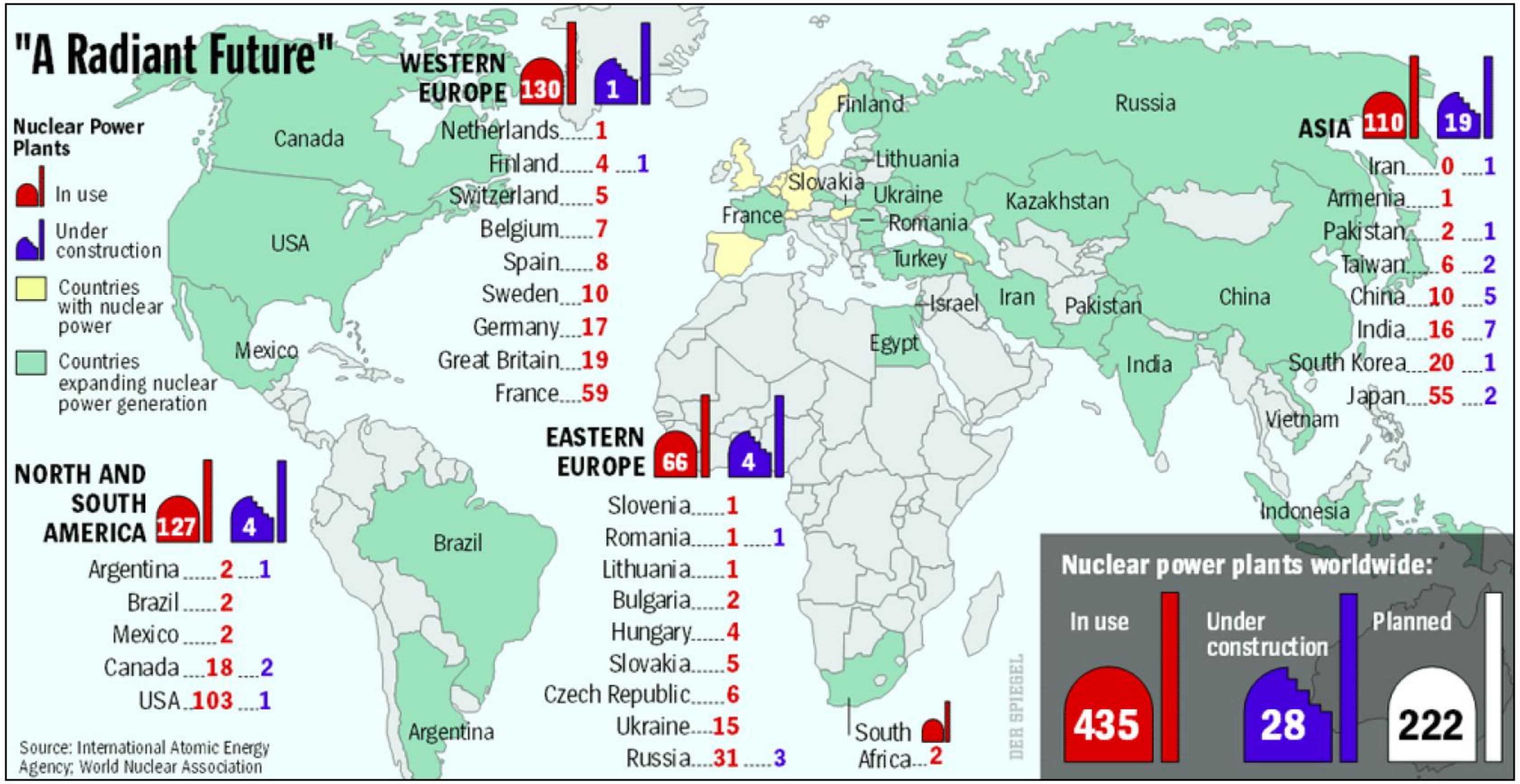
- Economic growth renewed an interest in the expansion of nuclear power in emerging nations to meet energy demands
  - *China, Russia, India, Brazil, and the United Arab Emirates*
- Nuclear growth driven by
  - *Rising fossil fuel prices*
  - *Concerns about meeting greenhouse gas emission limits*

World Marketed Energy Consumption by Region, 2004-2030



Sources: **2004:** Energy Information Administration (EIA), *International Energy Annual 2004* (May-July 2006), web site www.eia.doe.gov/iea. **Projections:** EIA, System for the Analysis of Global Energy Markets (2007).

2007 – Projected Growth for Nuclear Energy by 2050



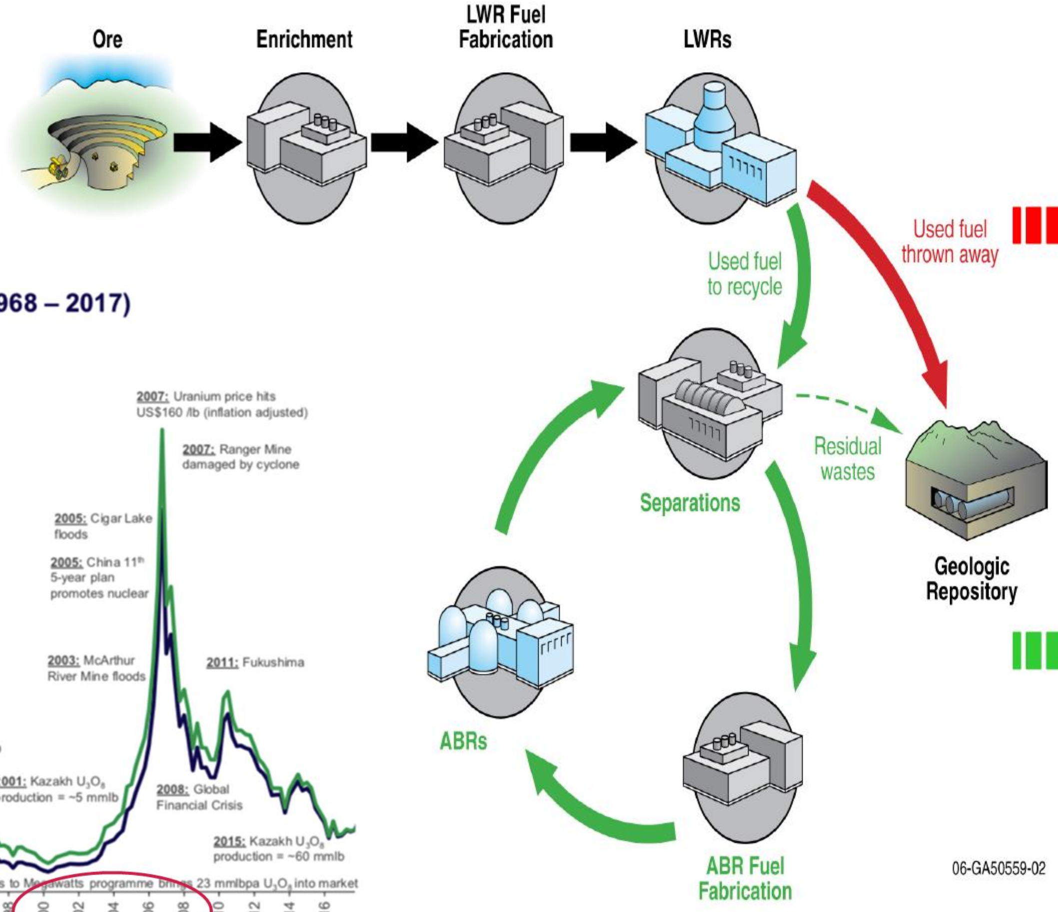
http://www.spiegel.de/international/spiegel/0,1518,460011,00.html

The Global Nuclear Energy Partnership (GNEP)

- Expand use of nuclear power
- Minimize nuclear waste
- Develop and deploy fuel recycling technology
- Develop and deploy advanced recycling reactors
- Establish reliable fuel services
- Support grid-appropriate exportable reactors
- Enhance nuclear safeguards technology

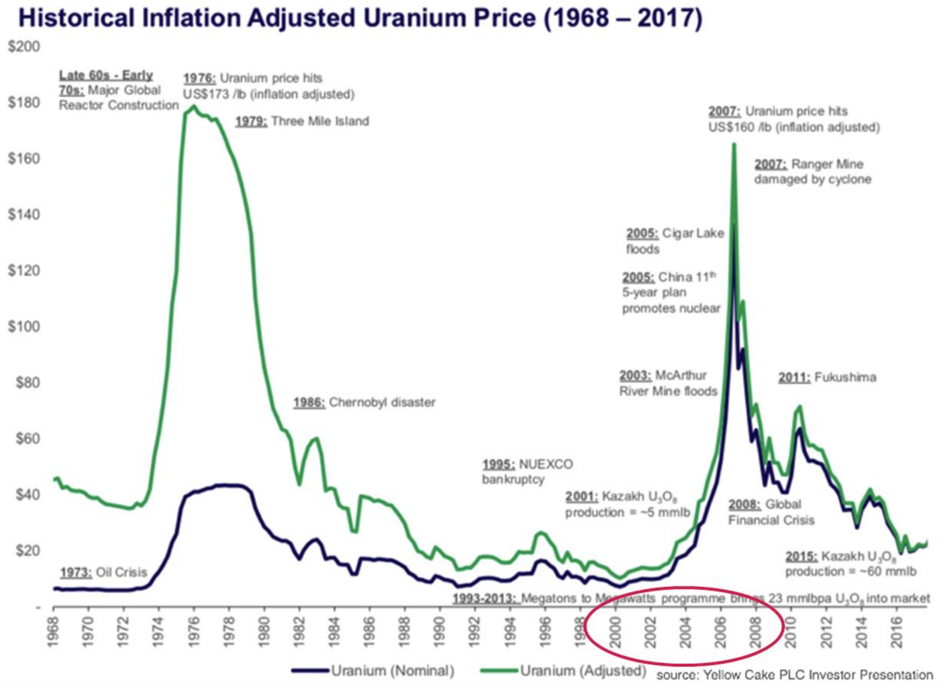
- GNEP aims to establish a worldwide foundation for safe and secure expansion of nuclear energy
- Partner nations provide fuel services programs to developing nations
  - *Benefits of abundant cost completive sources of clean, safe nuclear energy*
  - *In exchange for their commitment to forgo enrichment and reprocessing activities*

GNEP – Envisioned Fuel Cycle (2007)



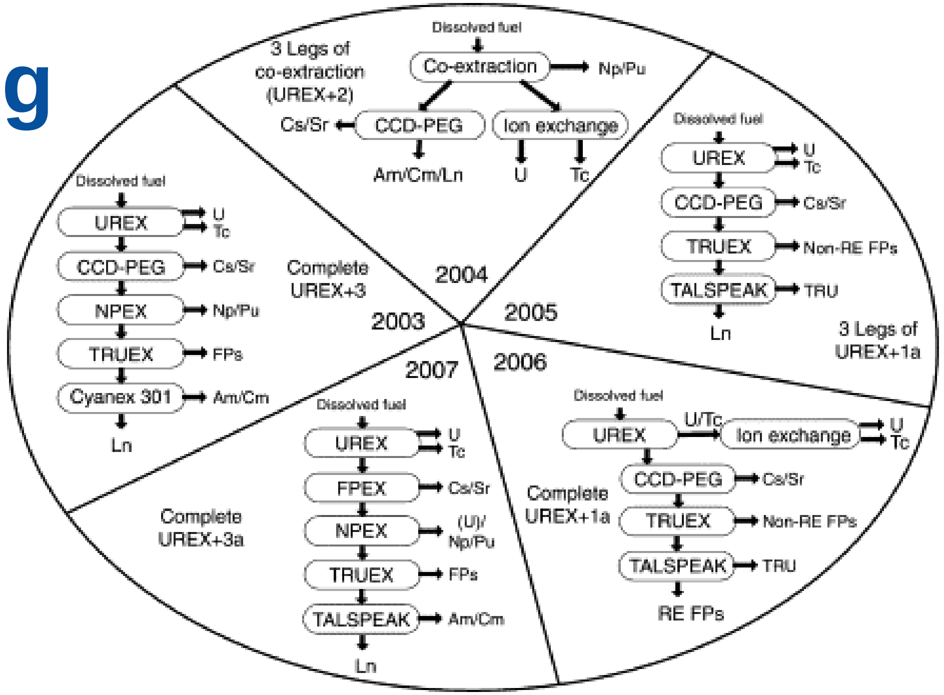
Once-Thru
Requires multiple repositories by 2100

GNEP Recycle
May need only one repository thru 2100



https://www.nrc.gov/docs/ML0717/ML071710438.pdf

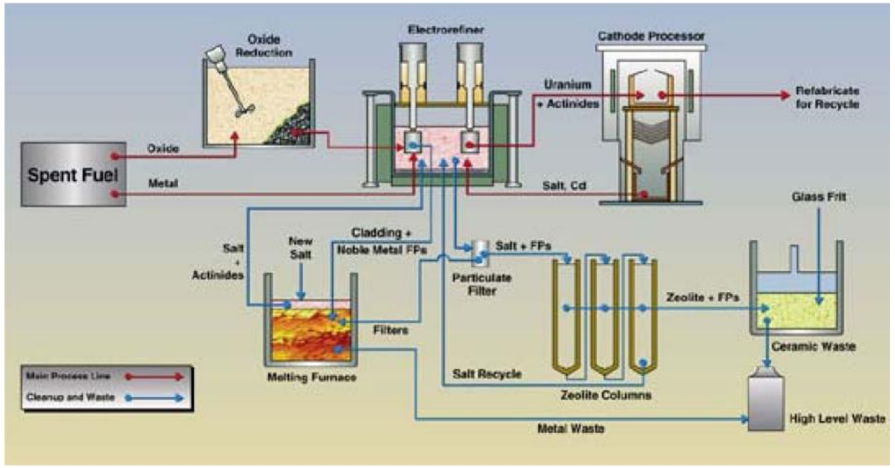
Renewed Interest in SNF recycling



UREX+ Processes

- Couple with LWRs to:
  - *Recover U/Pu stocks for advanced reactor startups*
  - *Recover long-lived actinides and fission products, providing benefits to deep geological disposal systems*

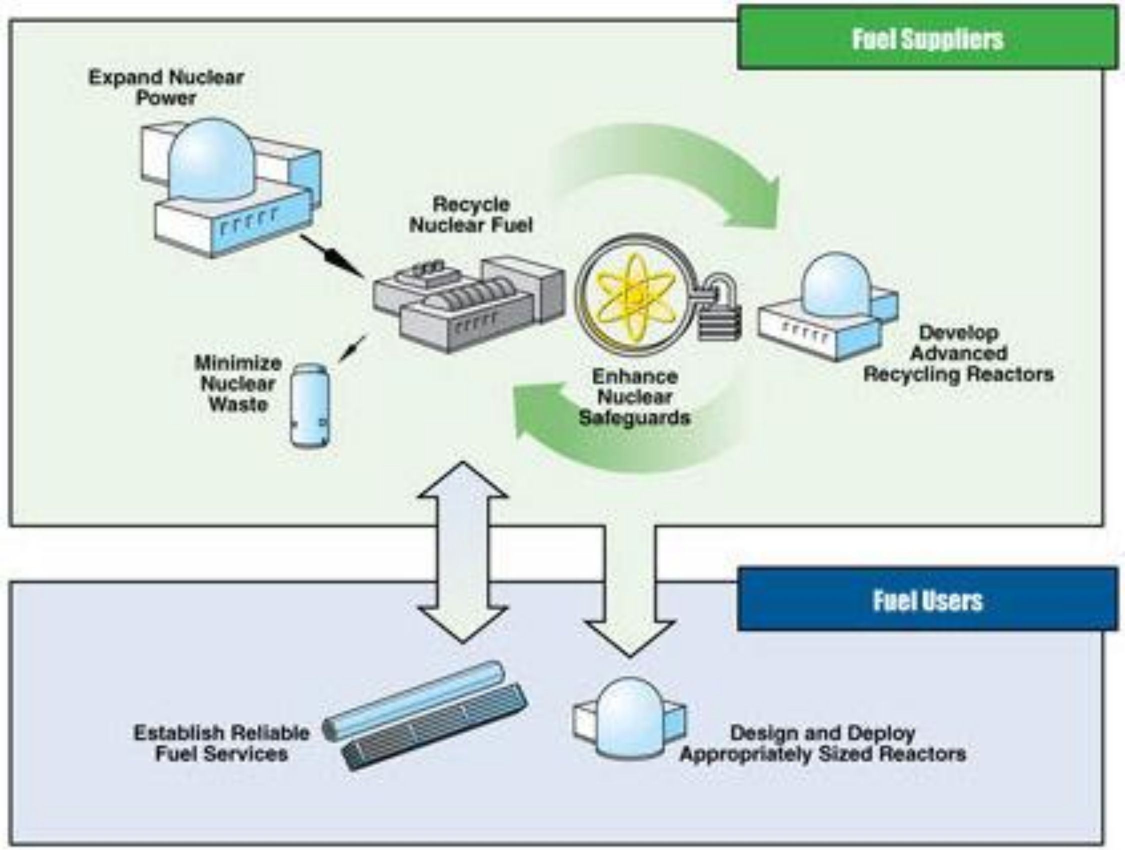
PYRO Metal & Oxide



- Oxide reduction for LWRs
- Metal processes couple with advanced burner reactors
  - *Fully closed fuel cycle*

By 2010

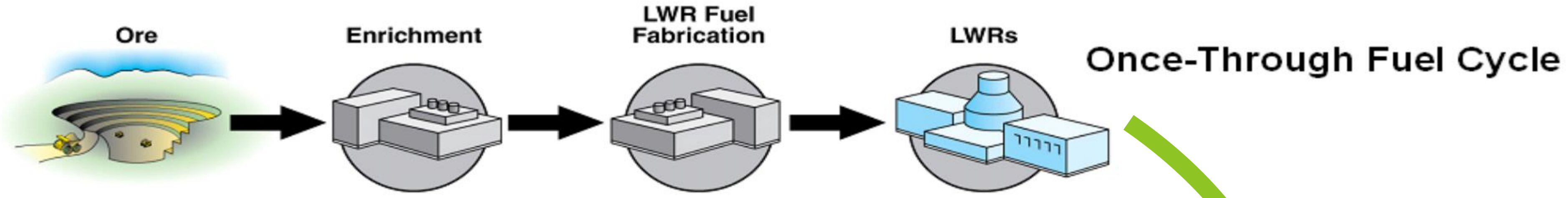
- Proposal to resume reprocessing
  - *Concerns about commercial viability*
  - *Concerns about increasing proliferation risks*
  - *Criticisms of discriminating between countries as nuclear fuel cycle "haves" and "have nots"*
- Economical natural gas generators
- BRC recommended long-term consolidated interim storage

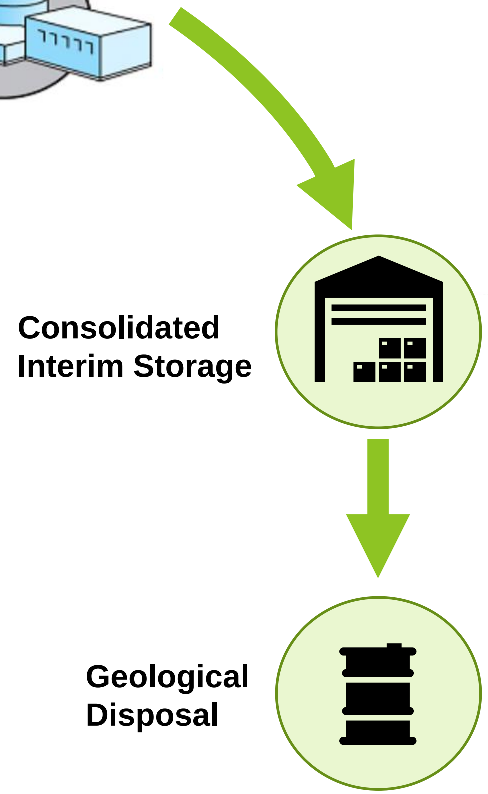


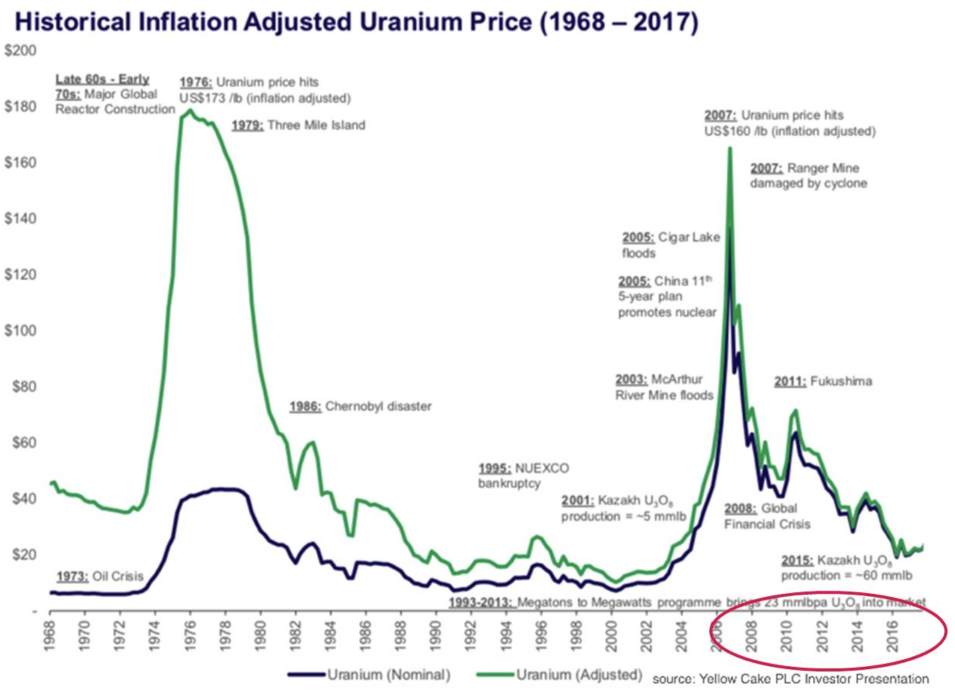
The Effect of the Fukushima Accident

- In March 2011, the Tōhoku earthquake and tsunami caused the nuclear accidents at Japan's Fukushima Daiichi Nuclear Power Plant
  - *Core meltdowns in three units*
- Called for a phase-out of nuclear power in some countries
- Demand for uranium drops

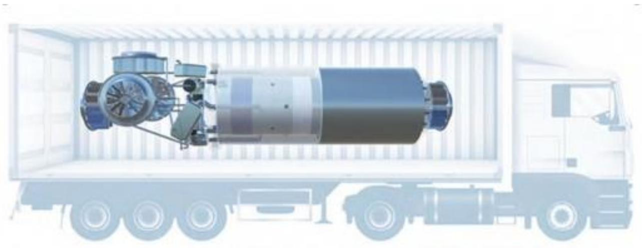
Domestic Fuel Cycle Envisioned by Mid – 2010s



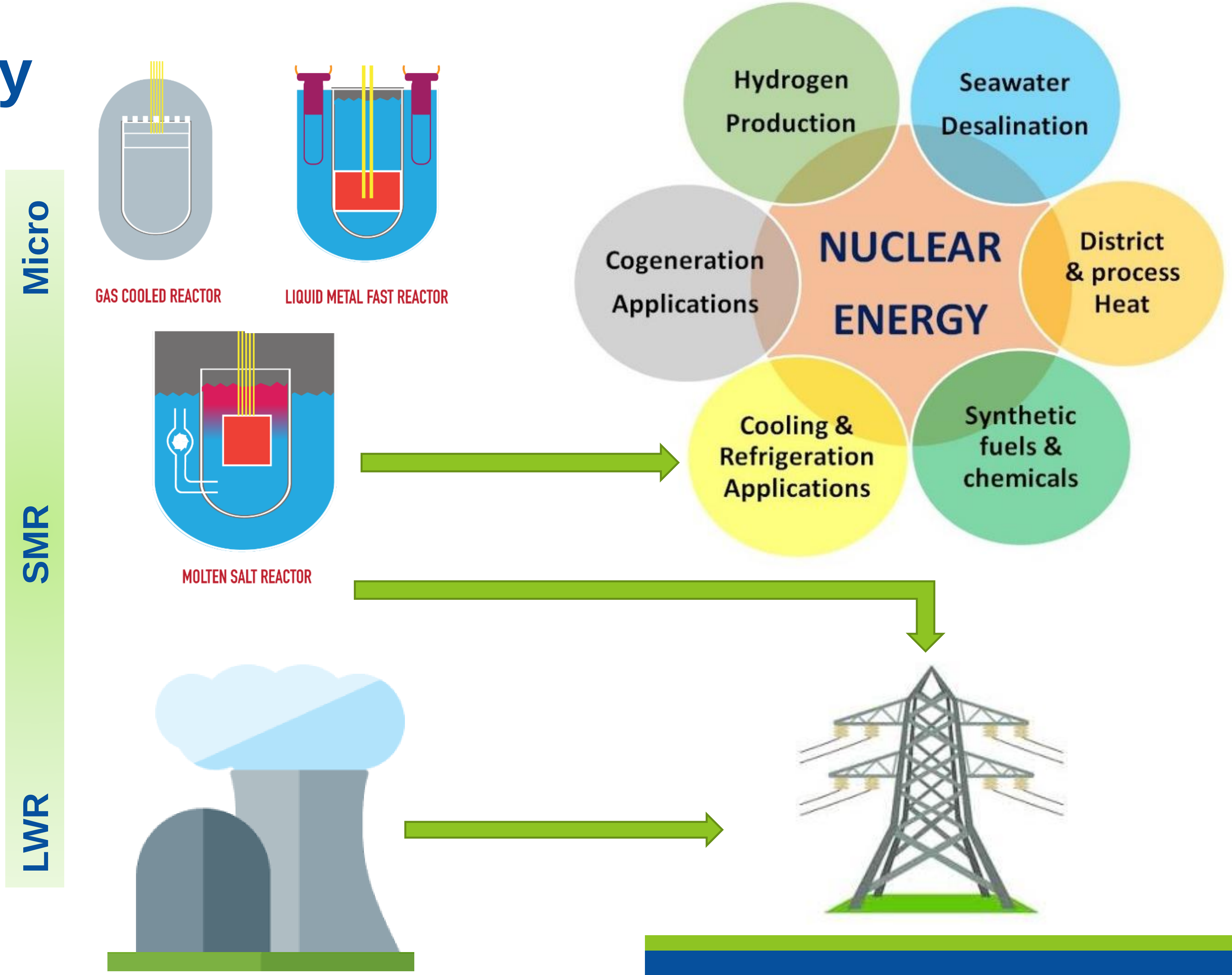




Brings us to Today



- Many emerging applications
- Multiple capacities (sizes)
- Advanced designs
  - *Fast and Thermo*
  - *Variety of coolants*
  - *Variety of fuels*



Fuel Cycle of the Future

We don’t know what it will look like, but we know what attributes are needed

- Cost competitive
- Manage proliferation risk
- Manage of waste
- Address safety and security

Today, attributes are well known and established for LWRs

- Regulatory process
  - *Safety, security and safeguards requirements*
- Cost of construction and operation
- SNF management and disposition understood (but not finalized)

Today’s fuel cycle is bounded by LWRs

How Do We Address Advanced Reactors Fuel Cycles?

Design bounded by LWRs?

No

- **Can materials be tracked in real time?**
  - *What are the intrinsic signals to the process that would allow near-real-time tracking?*
  - *Is new instrumentation needed?*
- **The chemistry and physics well understood to address safety and security?**
  - *What knowledge is missing?*
  - *Are new security requirements needed?*
- **What is the impact of all waste streams to the environment?**
  - *Is direct disposal of spent fuel feasible?*
  - *Are waste components migration patterns to the environment well understood?*
  - *Are new waste forms needed?*
  - *Are new off-gas treatment processes needed?*
- **Are there impacts to storage and transportation?**

Yes

- **Specify how**
- **Address economic impact**
- **Evaluate opportunities for improvement**

Hanford's K East Basin Vacuuming radioactive sludge

It's our responsibility to address the impact of future nuclear fuel cycles today.

Hon. Monica C. Regalbuto
Former Assistant Secretary
DOE Environmental Management

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QUESTIONS