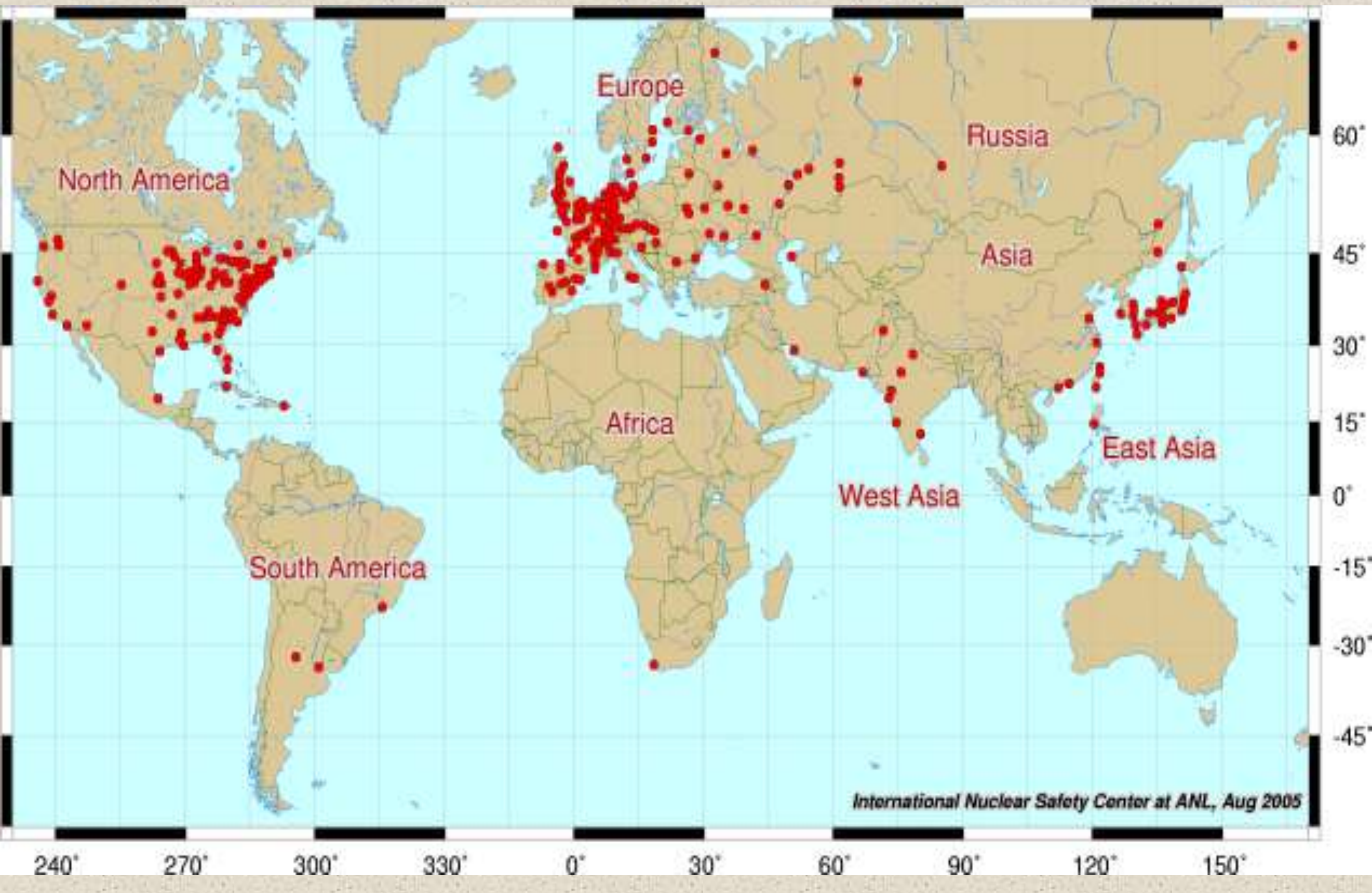
NUCLEAR POWER [PAST HISTORY, FUTURE POTENTIAL]

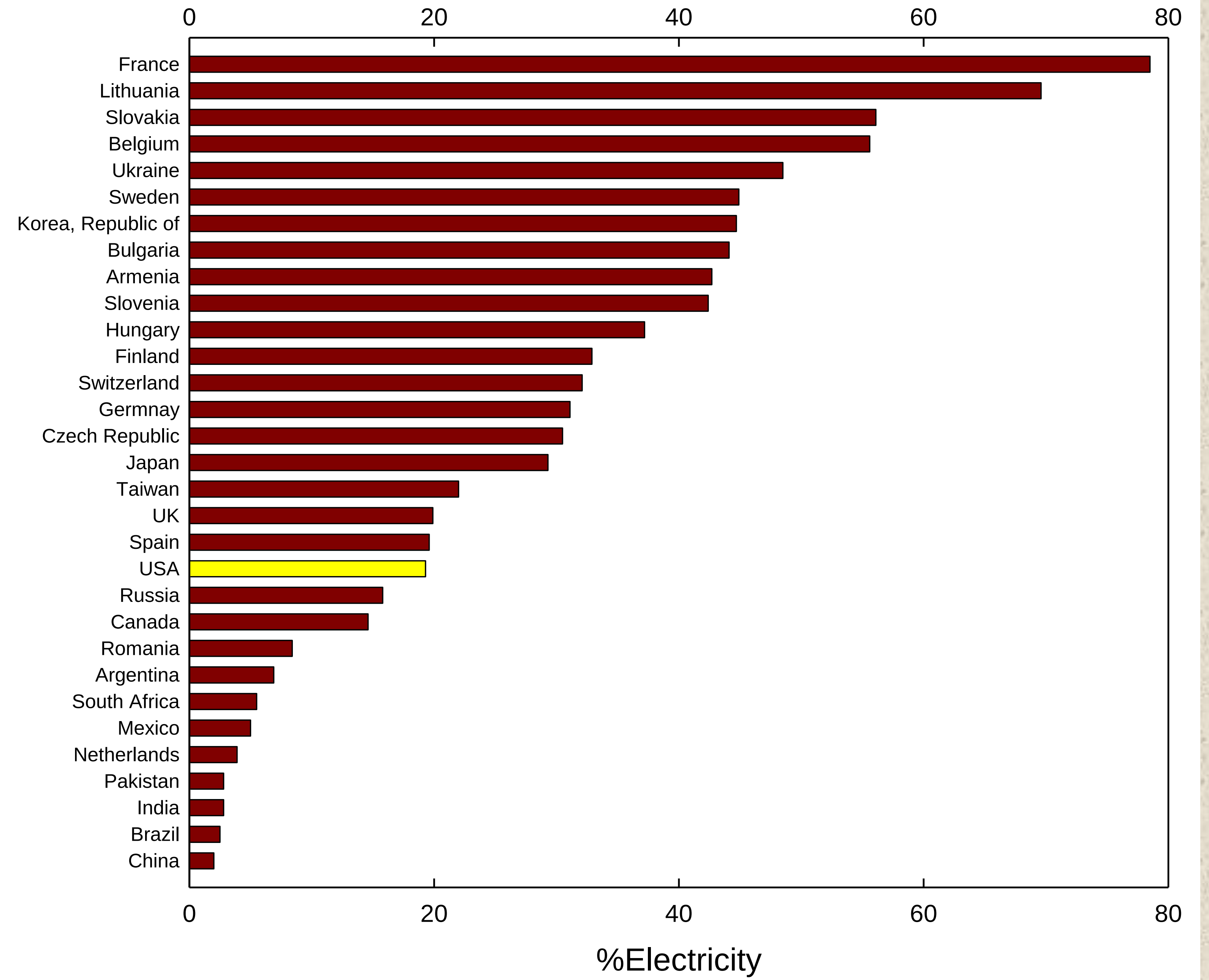
108 Nuclear Power Plants in the U.S.

Accounts for **~19%** of the total net electricity generated in the U.S.; about as much electricity as is used in CA, TX and NY combined.

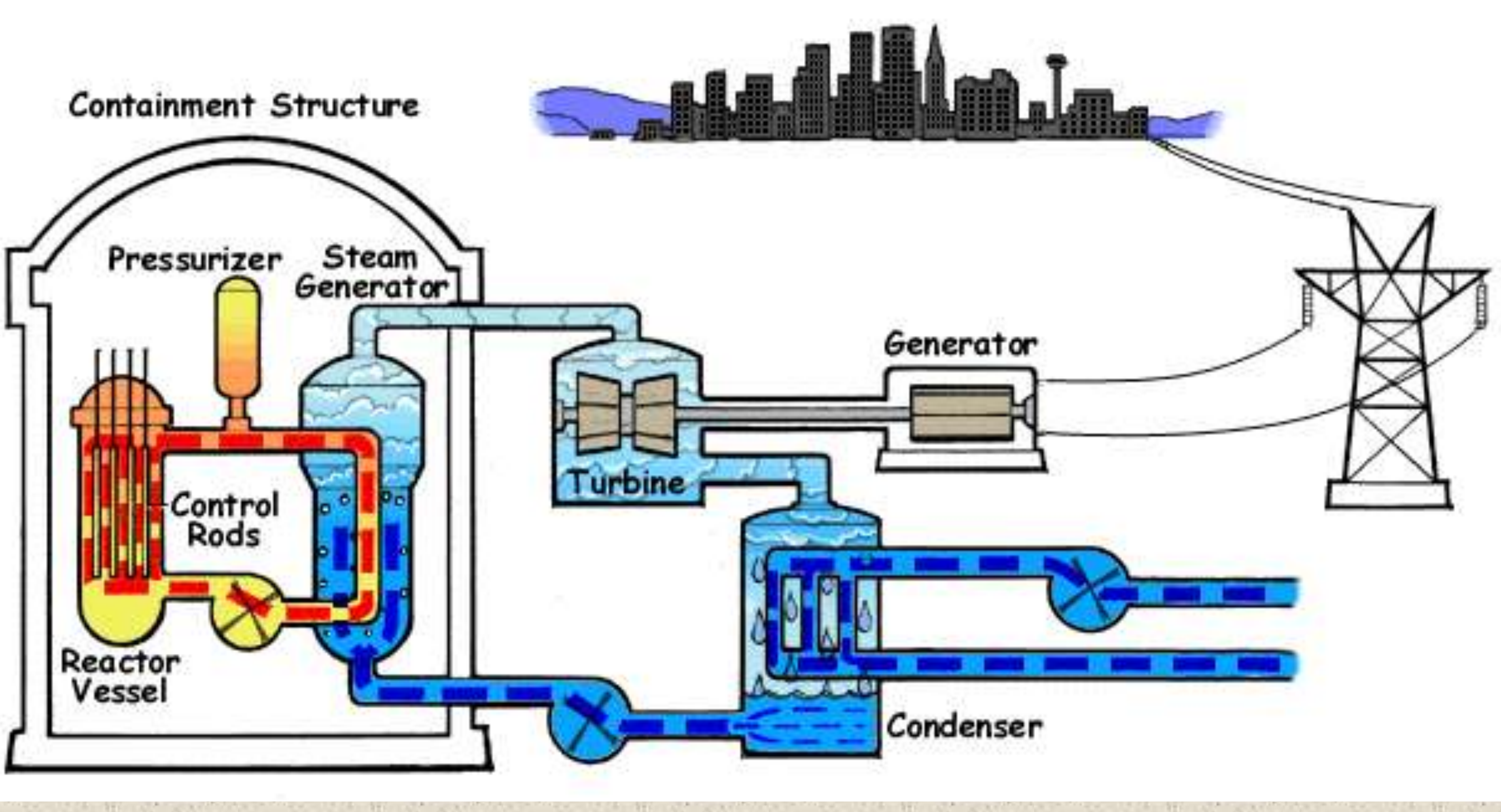
Global Nuclear Energy



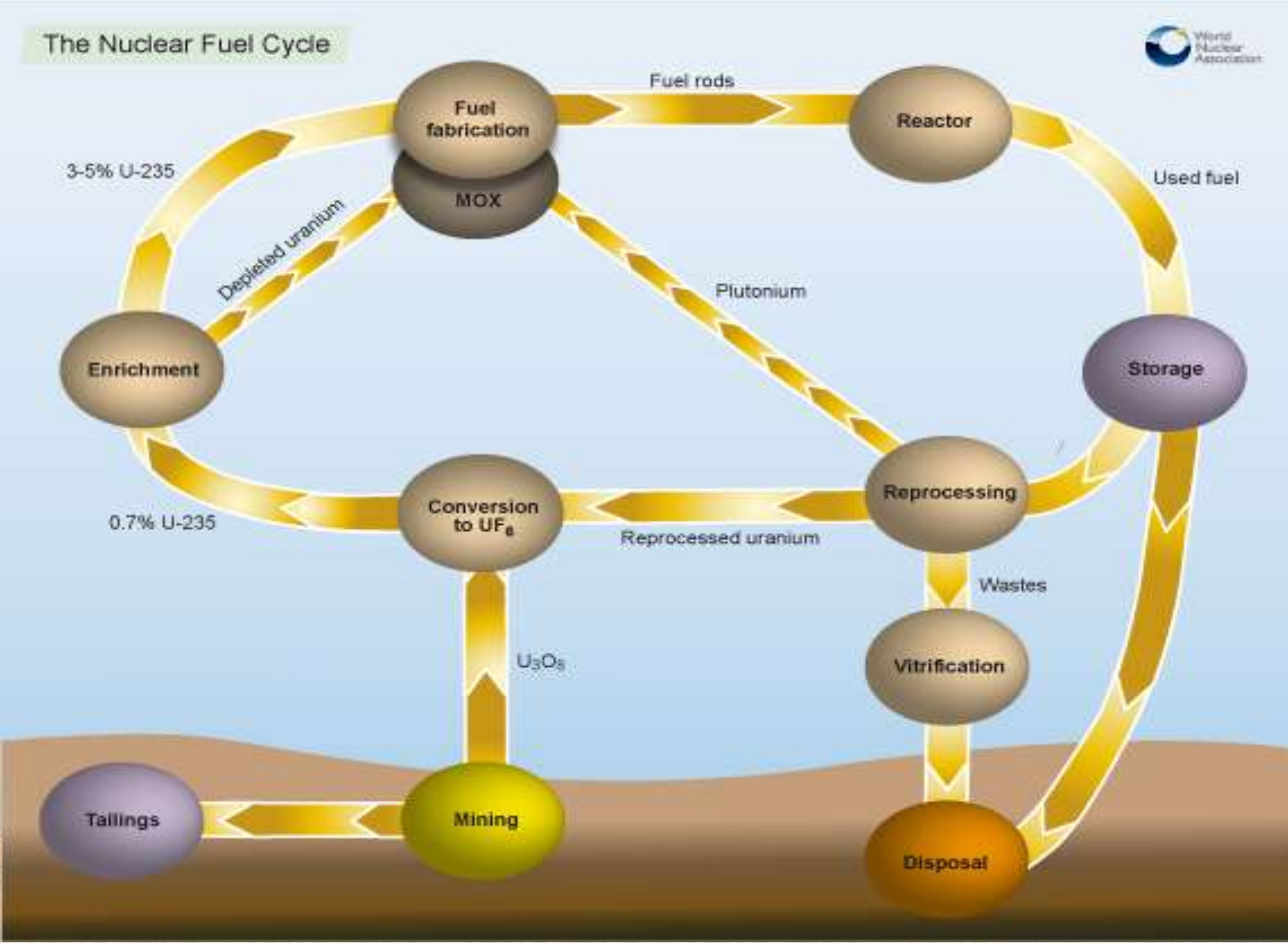
%Electricity Generated from Nuclear Power



Nuclear Power Plant Operations



Animation from the Nuclear Regulatory Commission Students' Corner
http://www.nrc.gov/reading-rm/basic-ref/students.html


The Nuclear Fuel Cycle
World Nuclear Association
Fuel fabrication
MOX
Fuel rods
Reactor
Used fuel
3-5% U-235
Depleted uranium
Plutonium
Enrichment
Storage
Conversion to UF_6
Reprocessing
0.7% U-235
Reprocessed uranium
Wastes
U_3O_8
Vitrification
Tailings
Mining
Disposal

Safety

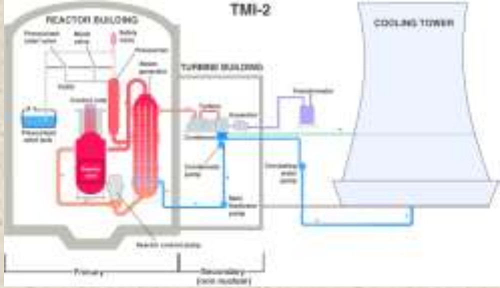
Nuclear Power Plant Accidents

Three Mile Island,
near Middletown, Pennsylvania
March 28, 1979


Photo Credit: Kurchatov Institute

Chernobyl Nuclear Power Plant,
near Pripyat, Ukraine
April 26, 1986

Three Mile Island

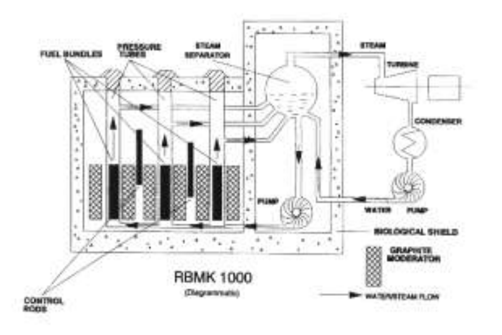


near Middletown, Pennsylvania

- Accident on March 28, 1979
  - Most serious in U.S. commercial nuclear power plant history
  - Equipment malfunction, design-related problems, and worker errors led to partial meltdown of the TMI-2 reactor core and very small off-site releases of radioactivity
  - No deaths or injuries to plant workers or members of nearby community
    - (avg radiation dose from accident: ~1 millirem; full set of chest X-rays ~6 millirem; background natural radiation does of area: ~100-125 millirem)
  - Led to **sweeping** changes in plant operations
  - The TMI-2 reactor is permanently shut down and defueled, with the reactor coolant system drained, the radioactive water decontaminated and evaporated, radioactive waste shipped off-site to an appropriate disposal site, reactor fuel and core debris shipped off-site to a Department of Energy facility, and the remainder of the site being monitored.

Chernobyl Plant

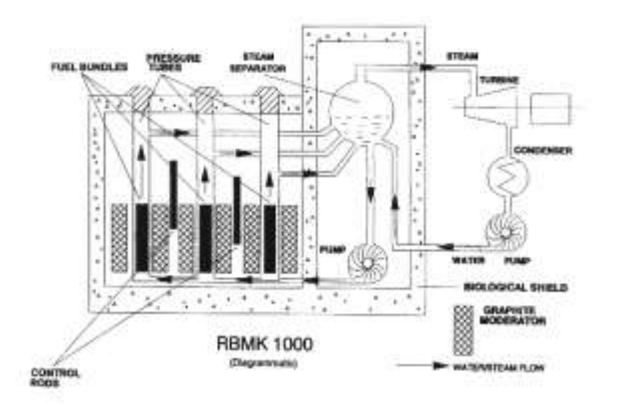
near Pripyat, Ukraine



- Accident on April 26, 1986
  - Most serious in global nuclear power plant history
  - Plant not properly designed & could only be run with very specific instructions;
    - Operators failed to follow instructions
    - Scientists were trying to determine how long turbines would spin and supply power following loss of main electrical power supply – risky experiment b/c reactors were known to be unstable at low power settings (removed safety and cooling equipment for experiment)
    - Fuel elements ruptured, explosive steam pressure blew cover plate from reactor emitting molten uranium, burning graphite, radioactive ash into atmosphere
      - NOT a nuclear explosion but amount of material released was 10 times that caused by US atomic bombing of Hiroshima

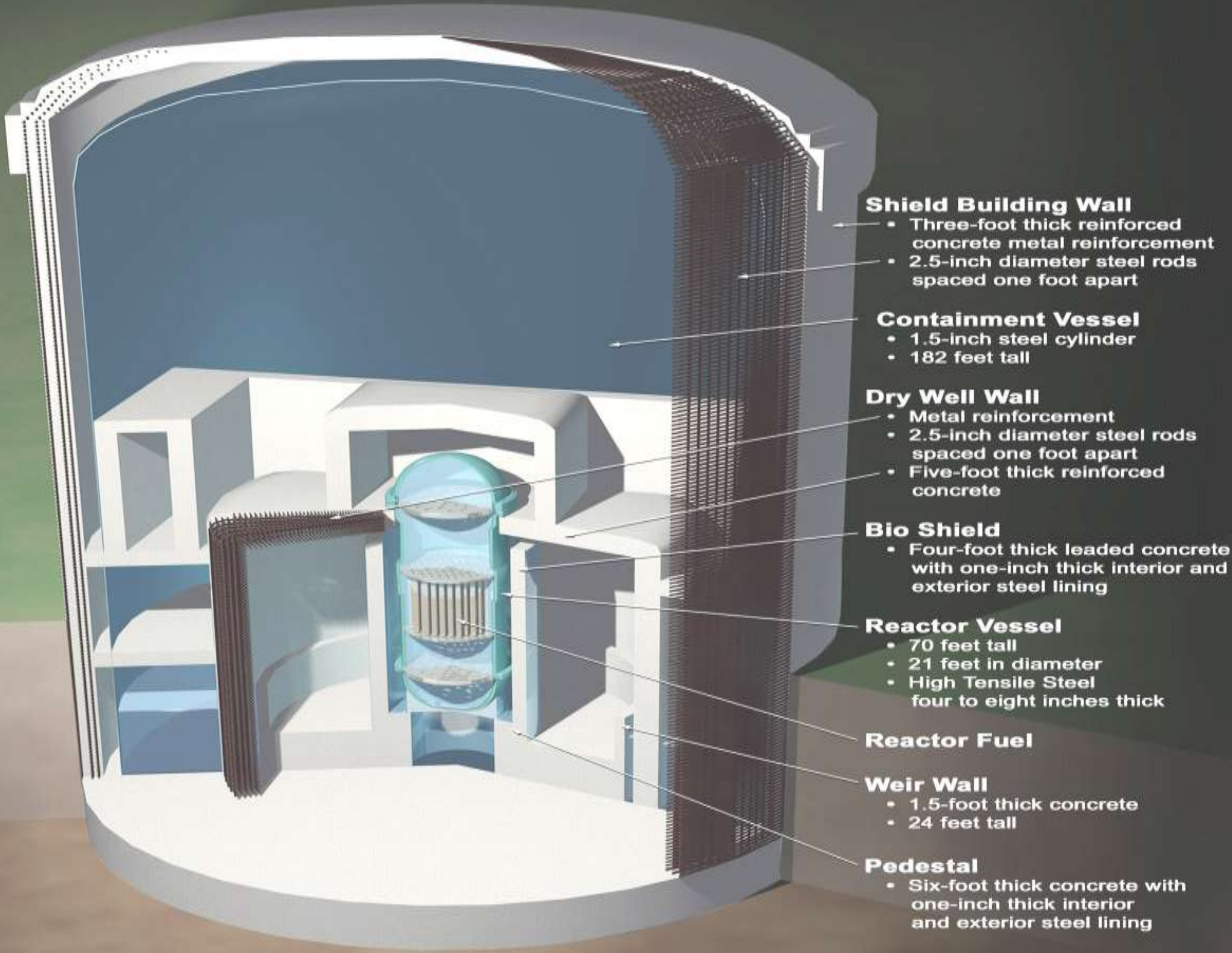
Chernobyl Plant

near Pripyat, Ukraine



- Accident on April 26, 1986
  - 135,000 people evacuated; 30-km exclusion zone created, later extended to cover 4300 km^2
    - 30-31 people died in accident and immediate aftermath from radiation exposure (most in fighting fires); 209 on site and involved in clean up were treated for acute radiation poisoning (19 of these later died from effects)
      - Radiation doses were up to 20,0000 millisieverts
    - Estimates vary on delayed health effects, and published reports range from negligible to extensive
      - At least 9 children died from thyroid cancer related to radiation
  - Reactor type is RBMK: high-power, pressure-tube reactors
    - These reactors are NOT used in the U.S. because of safety concerns

Multiple Layers of Safety at Nuclear Power Plants

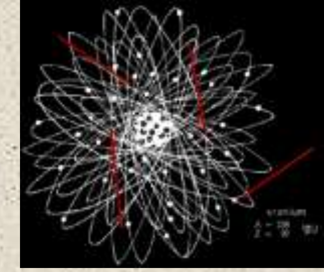


Boiling Water Reactor

Quantities & Cost

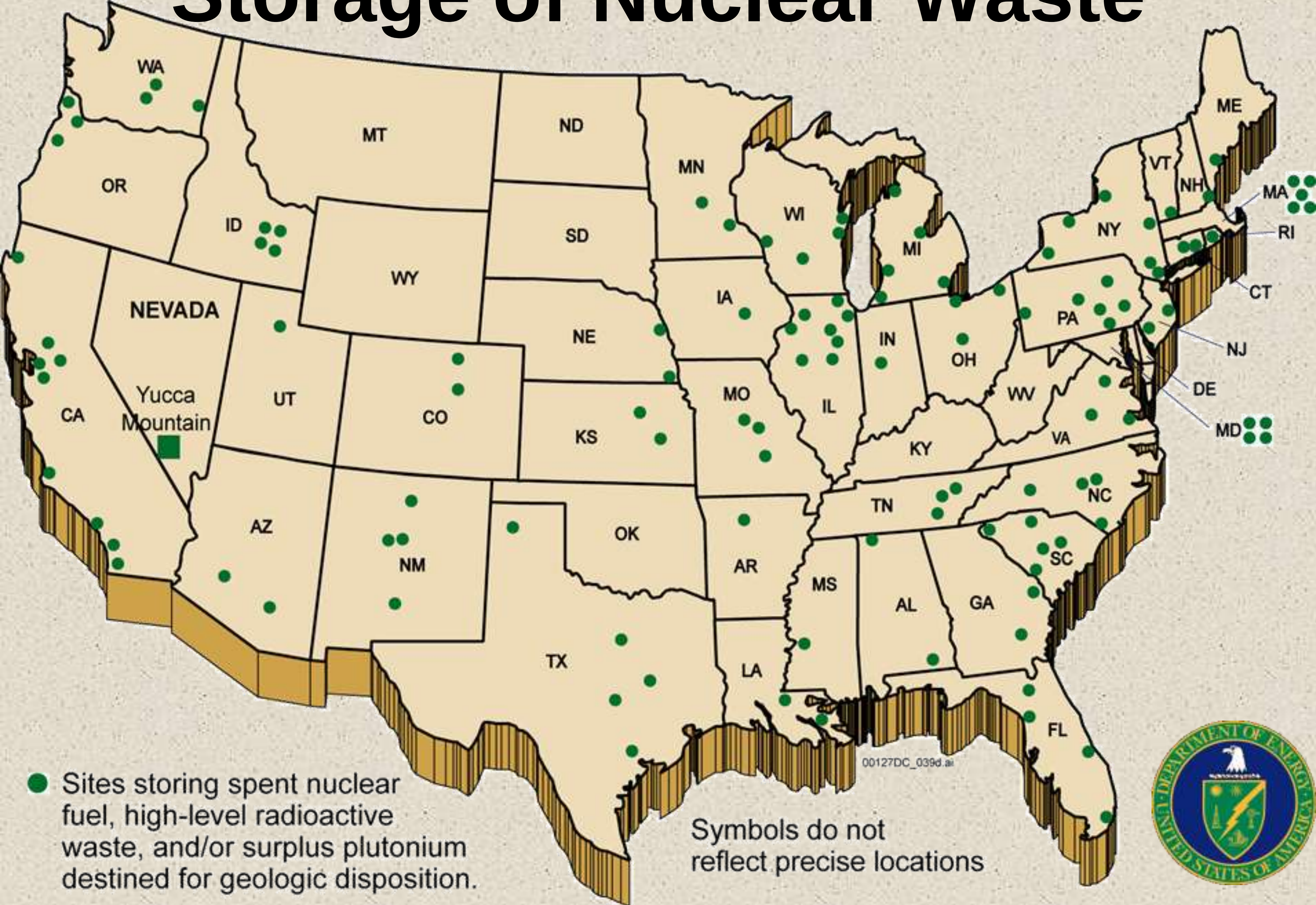
- about 200 tonnes U_3O_8 containing 170 tU gives rise to 24 tonnes of uranium in enriched UO_2 fuel, via conversion and enrichment stages. So, to get 1 kg of enriched uranium in fuel you need about 8 kg of mine product, now @ US$ 90/kg or a bit more, hence US$ 720.
- Total cost is thus about US$ 1393 for 1 kg enriched fuel, plus about $240 for actual fuel fabrication. This will yield about 3900 GJ thermal energy at modern burn-up rates, or about 360,000 kWh of electricity (at 33% thermal efficiency), and does the same job as about 160 tonnes of steaming coal for a total cost of 0.45 cents/kWh (US$) - a bit more at lower burn-up.

Uranium



- Heaviest natural element (92 protons)
- 2 ppm in earth's crust
  - To be mined, must be at least 100 ppm of the rock it is in
  - Wyoming and Four Corners region produce most U.S. uranium
  - DOE estimates that U.S. has proven uranium reserves of at least 300 million lbs; Power plants use over 40 million lbs/year
- *1 lb of uranium has as much energy as 3,000,000 lbs of coal*

Storage of Nuclear Waste

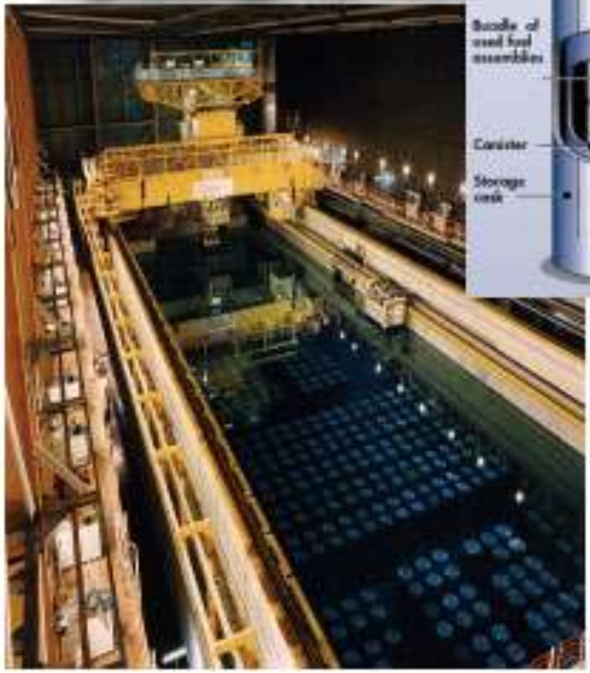


Spent Fuel Storage

Temporary Storage

Fuel Rod storage pools

Dry storage containers



Storage pool for spent fuel at UK reprocessing plant

Loading silos with canisters containing vitrified high-level waste in UK, each disc on the floor covers a silo holding ten canisters

http://www.uow.edu.au/eng/phys/nukeweb/fuel_disposal.html

Permanent Storage

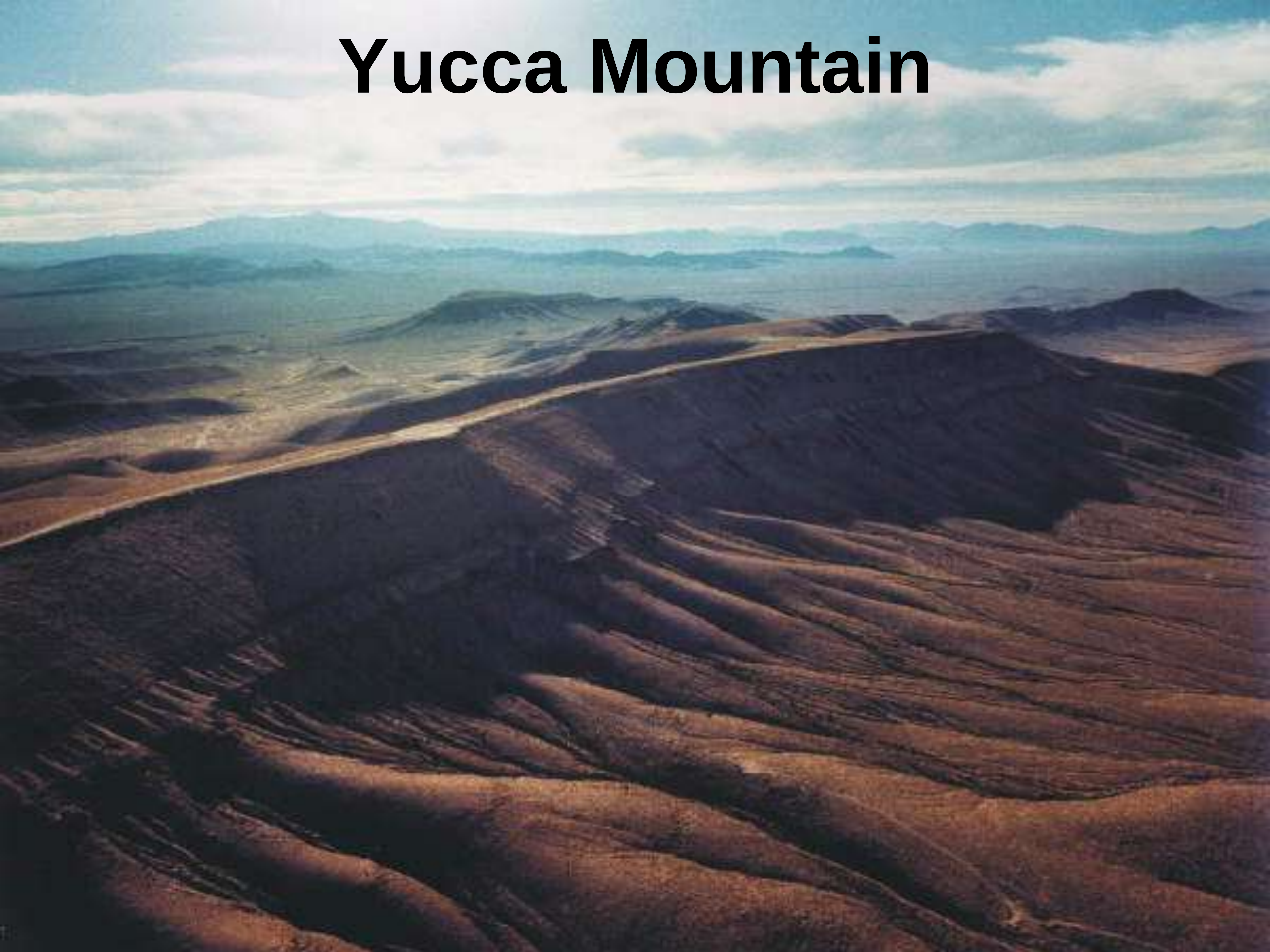
- Radioactive Waste must be dealt with for the next 10,000 to 1,000,000 years
- Long-term storage requires stabilization of waste into a form that will not react or degrade for extended periods of time.
  - Vitrification (high-level waste)
    - Evaporate water and de-nitrate fission products
    - Added to molten glass matrix, poured into stainless steel cylinders and sealed
    - Stored in underground repository
  - Ion exchange (medium active waste - NPP)
    - Concentrate radioactivity into small volume through ion exchange
    - Mix resulting sludge with cement (fly ash, blast furnace slag, or portland cement) in metal drum for storage
  - Synroc
    - Currently being developed for U.S. military waste
    - Synthetic rock is created from waste, developed at Australian National University

New research could spearhead permanent nuclear waste storage

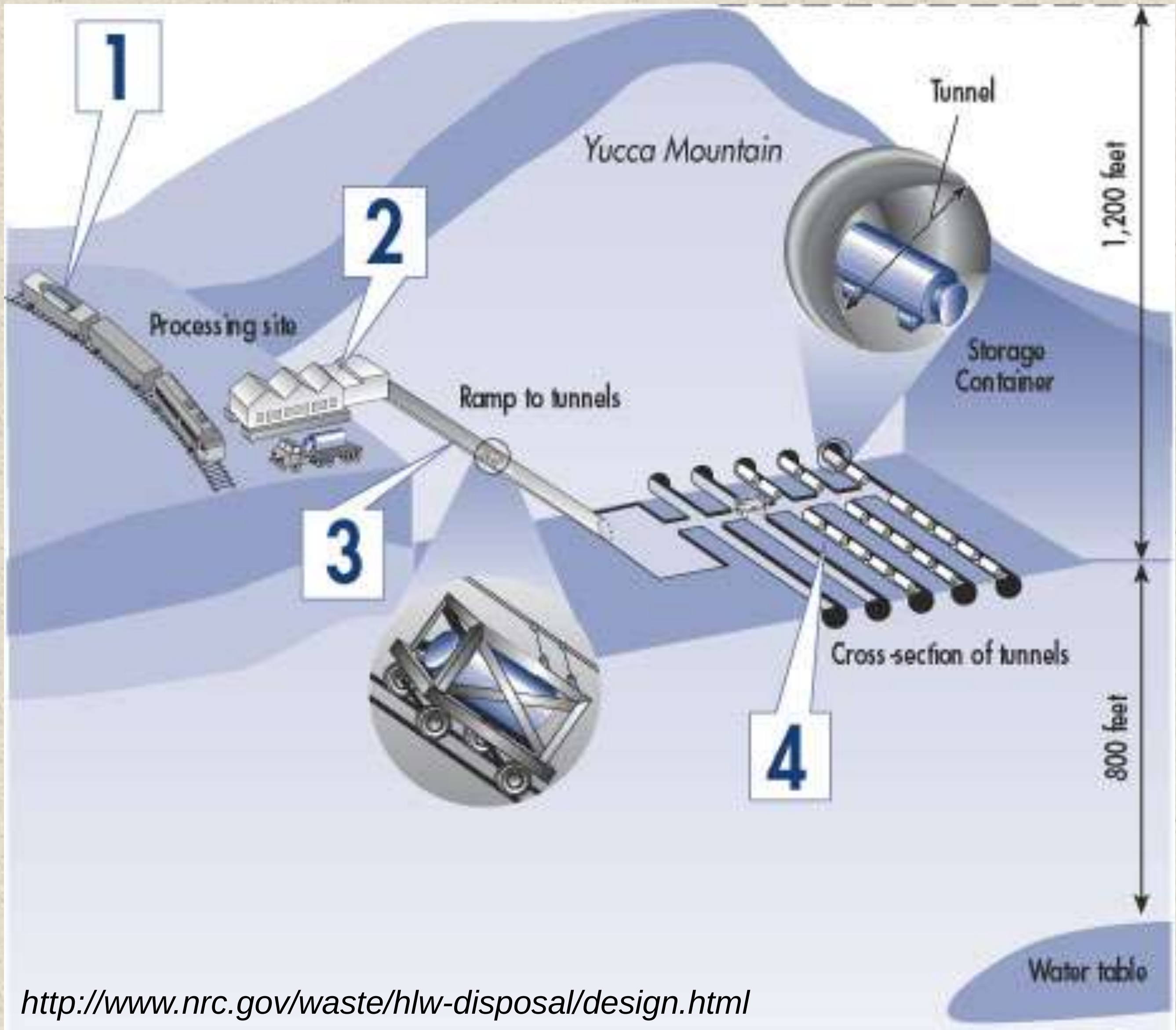
May 6, 2002

- Radioactive waste is primarily a combination of fuel rods and caustic solutions added to storage tanks to break down rods => unknown chemistry
- Need to decrease the waste volume
- Studies underway to better understand the chemistry of the waste and how it reacts in different environments

Yucca Mountain



Conceptual Design of Yucca Mountain Disposal Plan

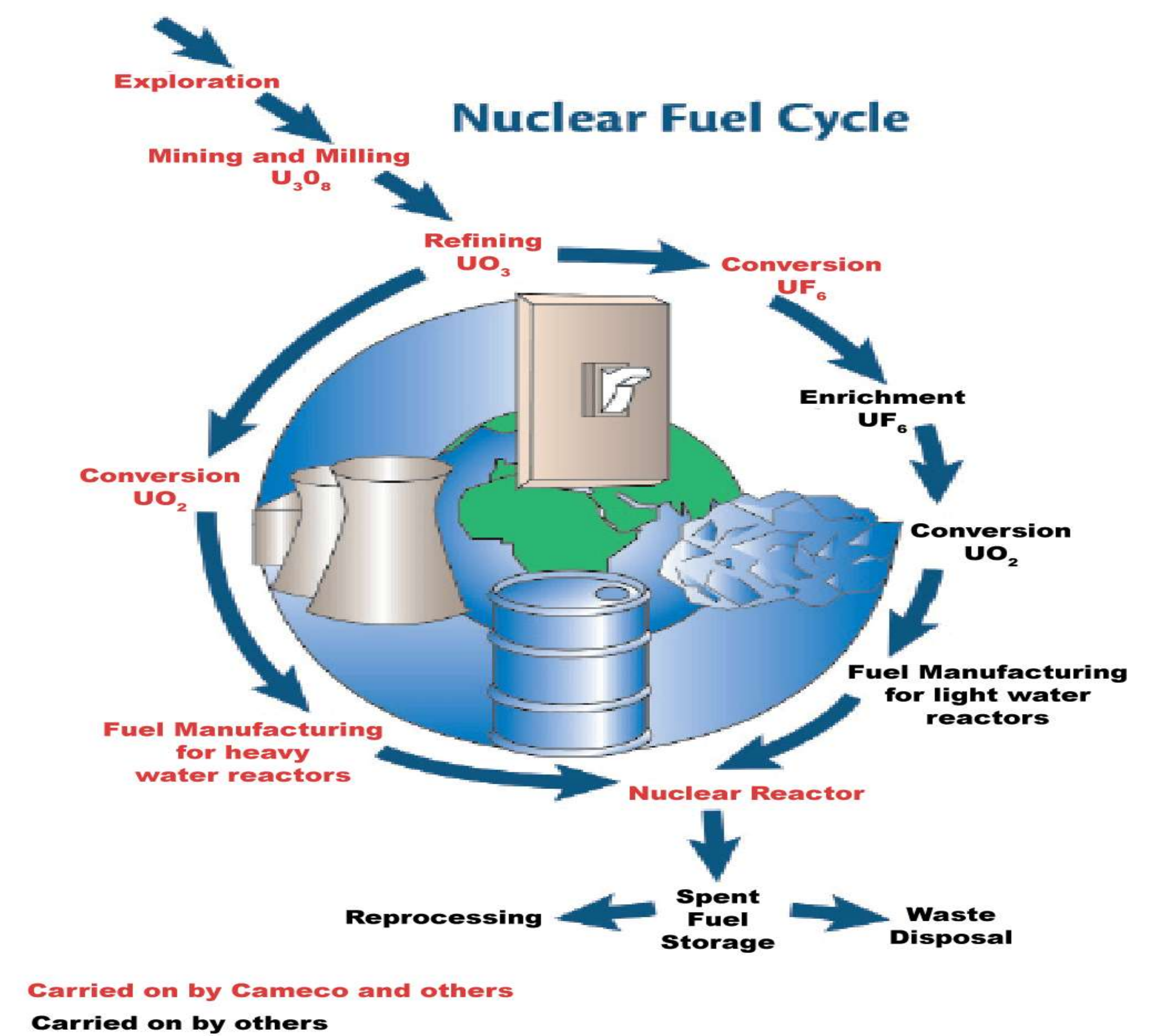


http://www.nrc.gov/waste/hlw-disposal/design.html

1. Canisters of waste, sealed in special casks, are shipped to the site by truck or train.
2. Shipping casks are removed, and the inner tube with the waste is placed in a steel, multilayered storage container.
3. An automated system sends storage containers underground to the tunnels.
4. Containers are stored along the tunnels, on their side.

Yucca Mountain

Nuclear Fuel Recycling



Exploration
Nuclear Fuel Cycle
Mining and Milling
U_3O_8
Refining
UO_3
Conversion
UF_6
Enrichment
UF_6
Conversion
UO_2
Conversion
UO_2
Fuel Manufacturing
for light water
reactors
Fuel Manufacturing
for heavy
water reactors
Nuclear Reactor
Reprocessing
Spent
Fuel
Storage
Waste
Disposal
Carried on by Cameco and others
Carried on by others

Nuclear Fuel Recycling

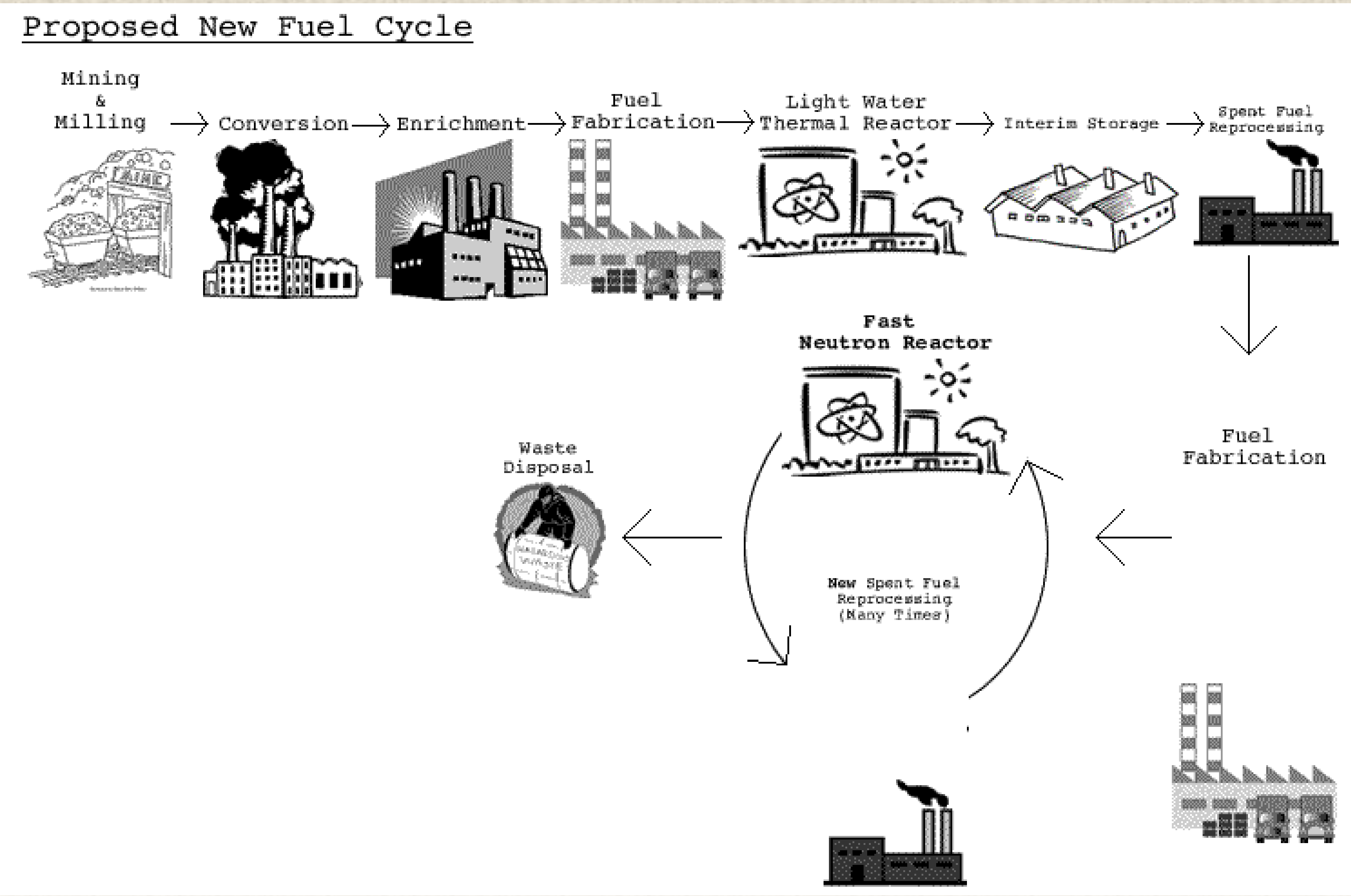
- Fuel rods are neutron emitters that, in close proximity to each other, begin a self-sustaining chain reaction – releasing energy and producing new elements by fission of uranium and producing plutonium (^{239}Pu) by nuclear chain reactions.

Nuclear Fuel Recycling

- Nuclear fuel is uranium oxide is enriched to 3-4%; ^{235}U is fabricated into pellets, and then inserted into fuel rods
- Fuel rods can supply energy for 1-3 years.
- Spent fuel has a considerable amount of ^{235}U but has also generated significant ^{239}Pu.
- After 3 years in a reactor, 1,000 lbs of 3.3-percent-enriched uranium (967 lb of ^{238}U and 33 lbs of ^{235}U) contains
  - 8 lbs of ^{235}U and 8.9 lbs of plutonium
  - Separating these two from the other components greatly reduces the radioactivity of the residue
  - Purified ^{235}U can be used as reactor fuel.

Nuclear Fuel Recycling

- U.S. doesn’t reprocess spent fuel, although it was planned at one time.
- France has been reprocessing power plant spent fuel rods at the COGEMA LaHague site since 1966.
- Problems with fuel recycling: theft of plutonium
- Safety records of current recycling plants are not good



http://www.fas.org/programs/ssp/nukes/nuclear_power_and_fuel_cycle/index.html

Long-Term Availability of Raw Uranium Supply

How much uranium is there?

- Uranium is one of the world's most abundant metals and **can provide fuel for the world's commercial nuclear plants for generations to come**. The price of uranium has increased significantly since 2000, spurring uranium exploration and mining. (http://www.nei.org/howitworks/nuclearpowerplantfuel/)

OR

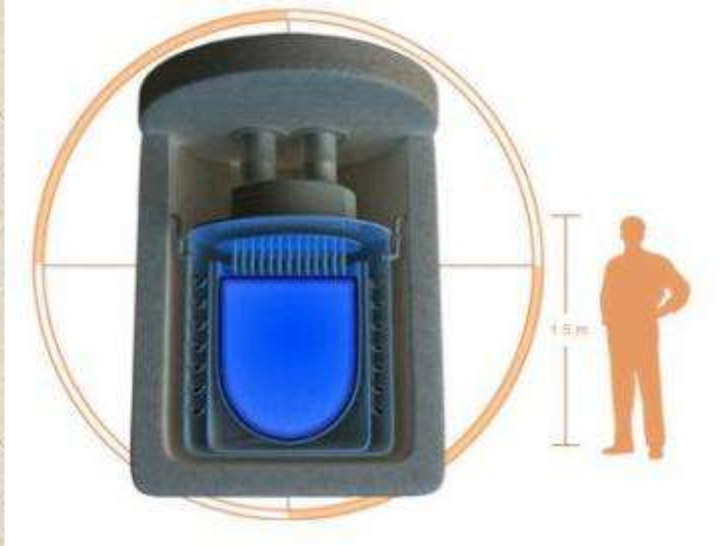
- There is enough uranium to maintain 1000 new reactors for their 40-year lifetime. (MIT, "The Future of Nuclear Power")

Mini Nuclear Power Plants

Mini Nuclear Power Plant

- Each one could Power 20,000 Homes
- Goal: Generate Electricity for 10 cents/Watt
- Cost: $25 million each
- Assembled quickly & transported by truck, rail, ship to remote locations, even if they do not currently have electricity

Mini Nuclear Power Plant



- Never need to be opened on site.
  - Very small amount of enclosed fuel
  - “impossible” to go supercritical or ‘melt down’
  - Buried underground; guarded by security detail
  - Not appropriate for proliferation (can’t enrich)
  - Refuel every 7-10 years
  - Total waste = size of softball & candidate for fuel recycling
- Nuclear Regulatory Commission (NRC) has no plans to review the Hyperion design in the near future
  - Very little testing information available
  - NRC expects it will take significant time to ensure safety requirements
  - Technical reports to support pre-application review will be submitted to NRC in late FY 2009.

Prospects for Nuclear Power Limited

MIT RELEASES INTERDISCIPLINARY STUDY ON "THE FUTURE OF NUCLEAR ENERGY"

Professors John Deutch and Ernest Moniz Chaired Effort to Identify Barriers and Solutions for Nuclear Option in Reducing Greenhouse Gases, July 29, 2003

- High relative costs
- Perceived adverse safety, environmental, and health effects
- Potential security risks stemming from proliferation
- Unresolved challenges in long-term management of nuclear wastes

- a standardized design for each type to expedite licensing, reduce capital cost and reduce construction time,
- a simpler and more rugged design, making them easier to operate and less vulnerable to operational upsets ,
- higher availability and longer operating life - typically 60 years,
- reduced possibility of core melt accidents,
- resistance to serious damage that would allow radiological release from an aircraft impact
- higher burn-up to reduce fuel use and the amount of waste,
- burnable absorbers ("poisons") to extend fuel life

Generation IV Reactors

- 1. **Gas cooled fast reactor**- These reactors are typified as helium cooled high temperature reactors. This would be a closed loop fuel cycle with all actinides being reprocessed on site to minimize waste. An 80 MW experimental demonstration plant developed by Euratom name ALLEGRO is set to come online in 2011.
- 2. **Lead cooled fast reactor**- Is a fast neutron reactor which can operate on enriched uranium or thorium fuel matrices and can burn spent fuel from an LWR plant.
- 3. **Molten salt reactor**- Basically the fuel is different instead of ceramic crucibles or metallic fuel rods the uranium is dissolved in a liquid sodium fluoride coolant. The fission products are removed continuously and actinides are fully recyclable. The MSFR has unique capabilities when it comes to fuel consumption. It has no radiation damage constraint on fuel burnup, no spent nuclear fuel and a homogeneous isotopic composition of reactor fuel.
  4.**Sodium cooled fast reactor**- A sodium cooled fast neutron reactor with a closed fuel cycle and onsite reprocessing.
  5. **Super critical water-cooled reactor**- A variation of the LWR which acts at a higher efficiency range. Can be built as a fast reactor with onsite full actinide fuel reprocessing or as an open cycle traditional LWR.
  6. **Very high temperature gas reactor**- These are graphite moderated, helium cooled reactors based on substantial experience.