Introduction to Nuclear Energy

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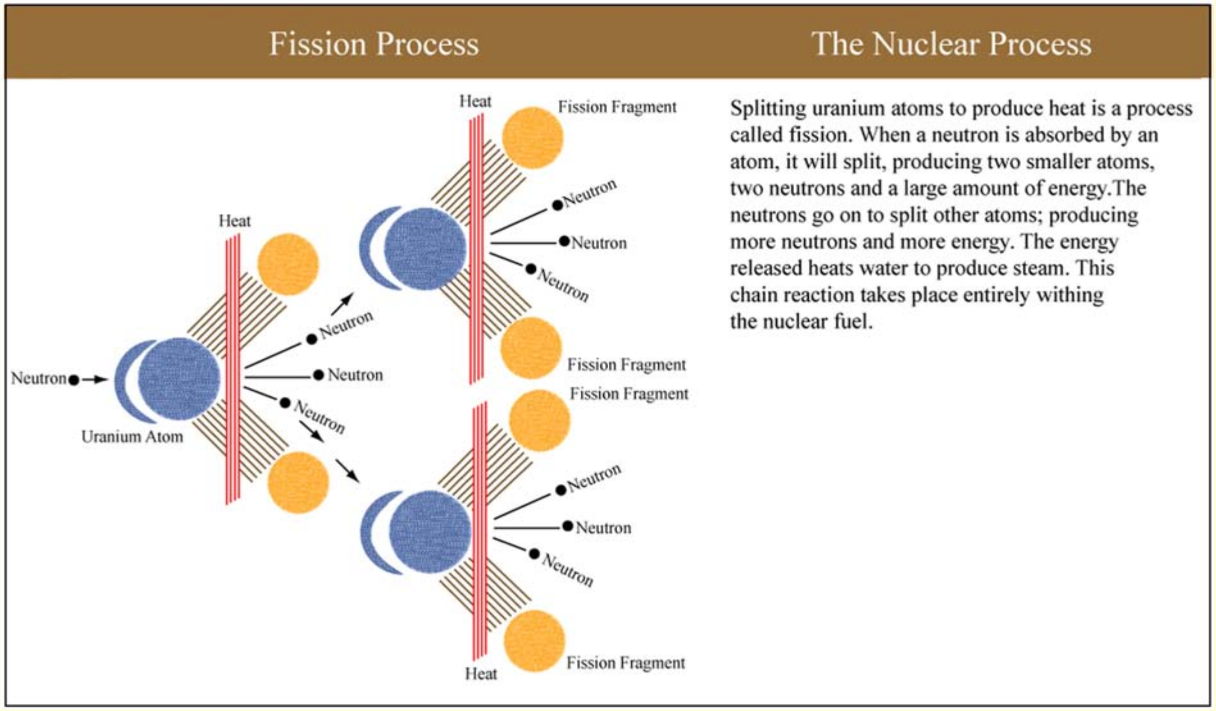
CANES
CENTER FOR
ADVANCED NUCLEAR
ENERGY SYSTEMS



Fission Process

The Nuclear Process

Splitting uranium atoms to produce heat is a process called fission. When a neutron is absorbed by an atom, it will split, producing two smaller atoms, two neutrons and a large amount of energy.The neutrons go on to split other atoms; producing more neutrons and more energy. The energy released heats water to produce steam. This chain reaction takes place entirely withing the nuclear fuel.

Image by MIT OpenCourseWare.

- U-235 has 2.5 million times more energy per pound than coal: 37 tons of fuel (3%-enriched uranium) per 1000 MWe reactor per year
- Nuclear provides an <u>emission-free heat source</u> that can be converted into multiple products
  - Electricity (worldwide)
  - Steam for industry (done in Switzerland, Russia, Japan, not in the U.S.)
  - Hydrogen (future with development of technology)

Nuclear compared to fossil fuels

Fuel energy content

Coal (C): $C + O_2 \rightarrow CO_2 + 4\ \text{eV}$

Natural Gas (CH_4): $CH_4 + O_2 \rightarrow CO_2 + 2H_2O + 8\ \text{eV}$

Nuclear (U): $^{235}U + n \rightarrow {}^{93}Rb + {}^{141}Cs + 2n + 200\ \text{MeV}$

Fuel Consumption, 1000 MWe Power Plant (=10^6 homes)

Coal (40% efficiency):

$10^9/(0.4 \text{x} 4 \text{x} 1.6 \text{x} 10^{-19}) \approx 3.9 \text{x} 10^{27}$ C/sec (=6750 ton/day)

Natural Gas (50% efficiency):

$10^9/(0.5 \text{x} 8 \text{x} 1.6 \text{x} 10^{-19}) \approx 1.6 \text{x} 10^{27}$ CH_4/sec (=64 m^3/sec)

Nuclear (33% efficiency):

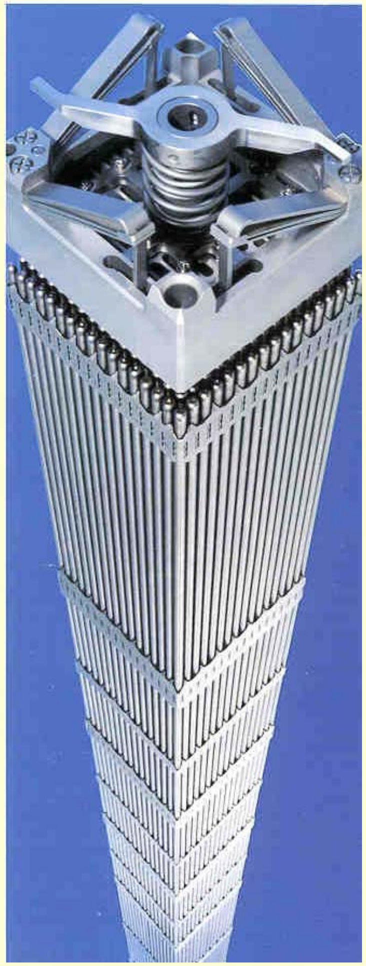
$10^9/(0.33 \text{x} 200 \text{x} 1.6 \text{x} 10^{-13}) \approx 1.0 \text{x} 10^{20}$ U/sec (=3 kg/day)

1 eV = $1.6 \text{x} 10^{-19}$ J

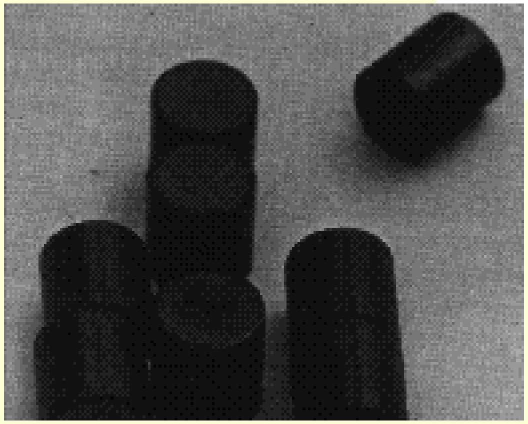
U ore

Yellow cake

Fuel assembly

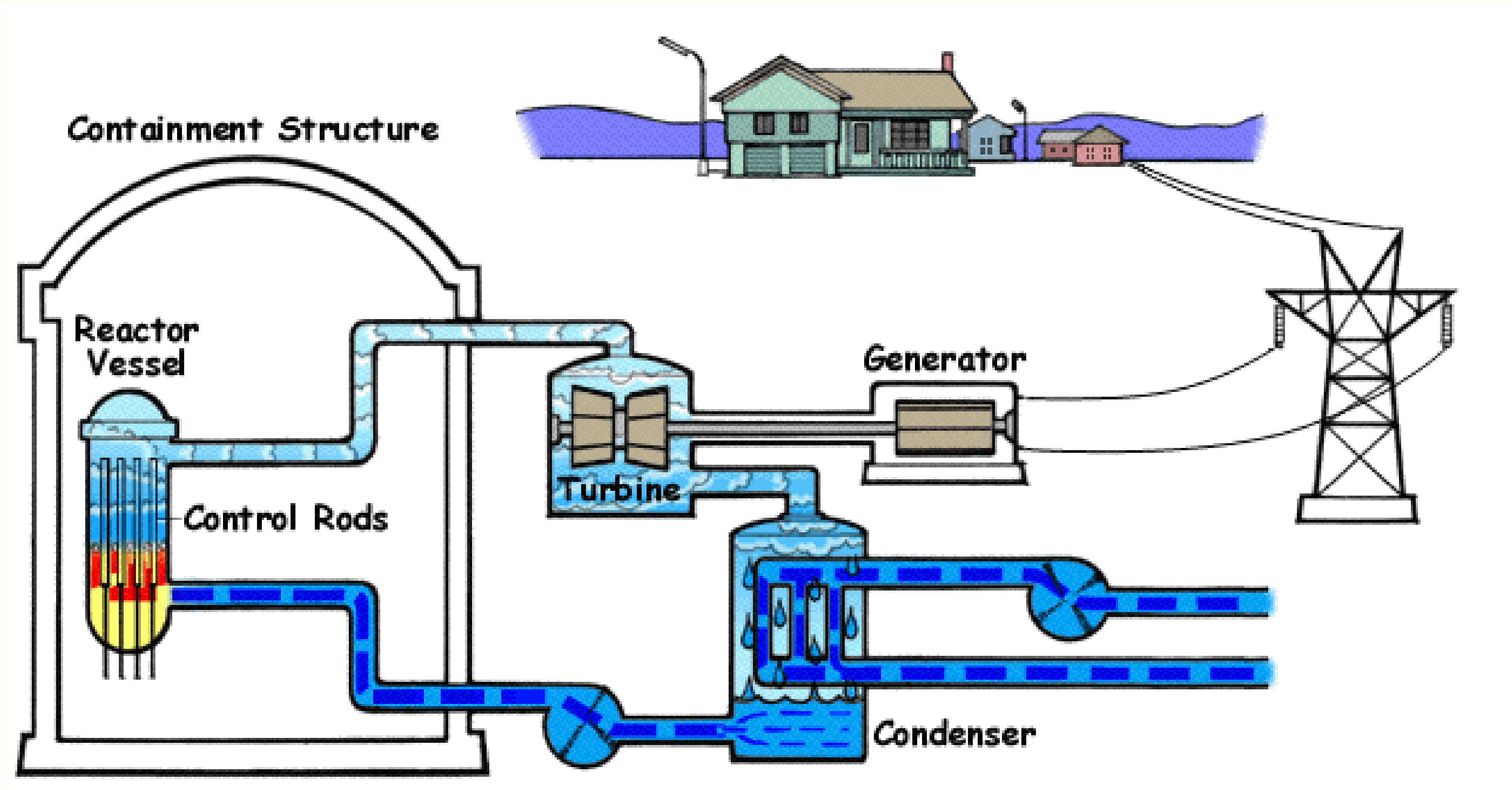


Pellets



Fuel pin

Boiling Water Reactor (BWR)



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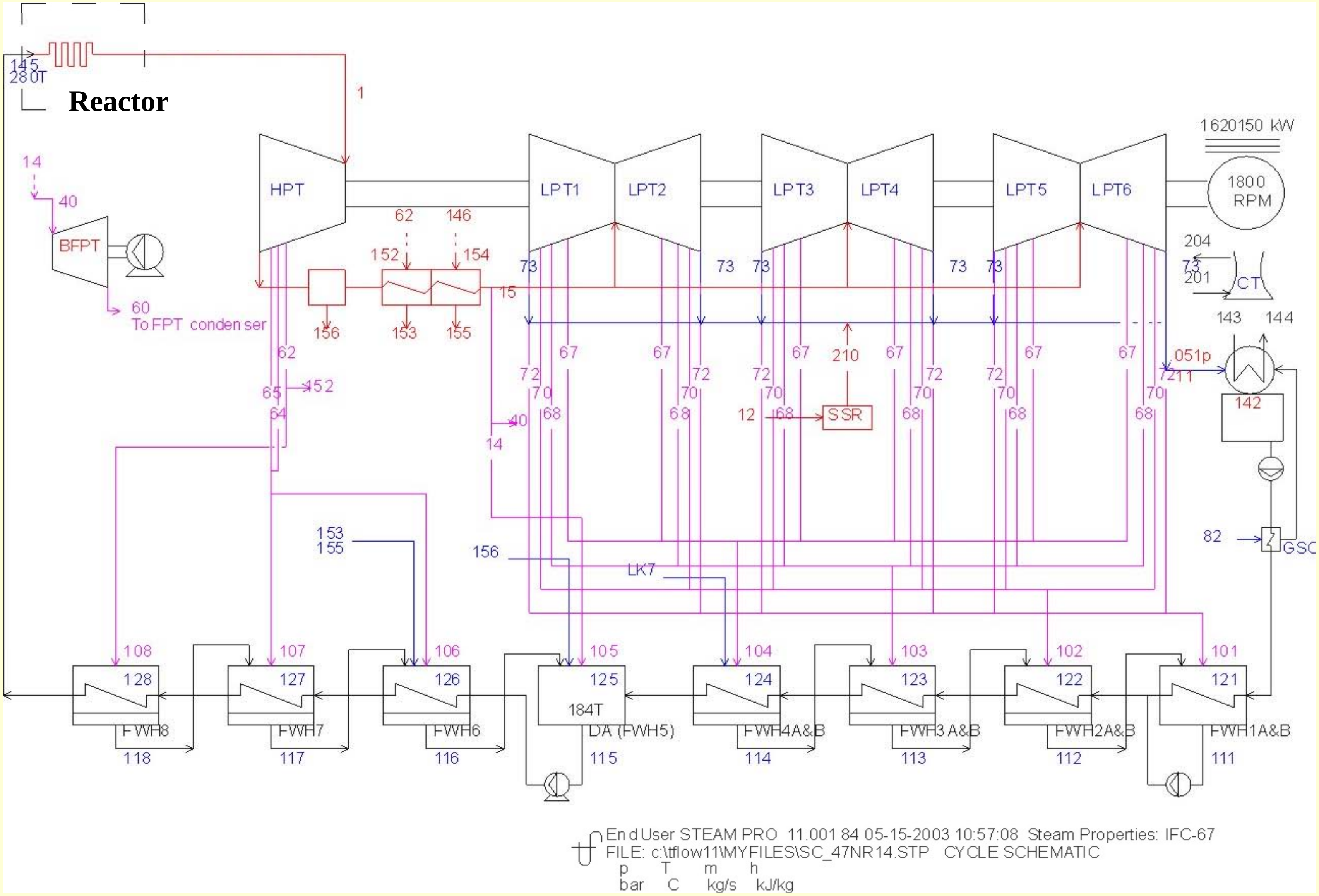
Rankine Cycle



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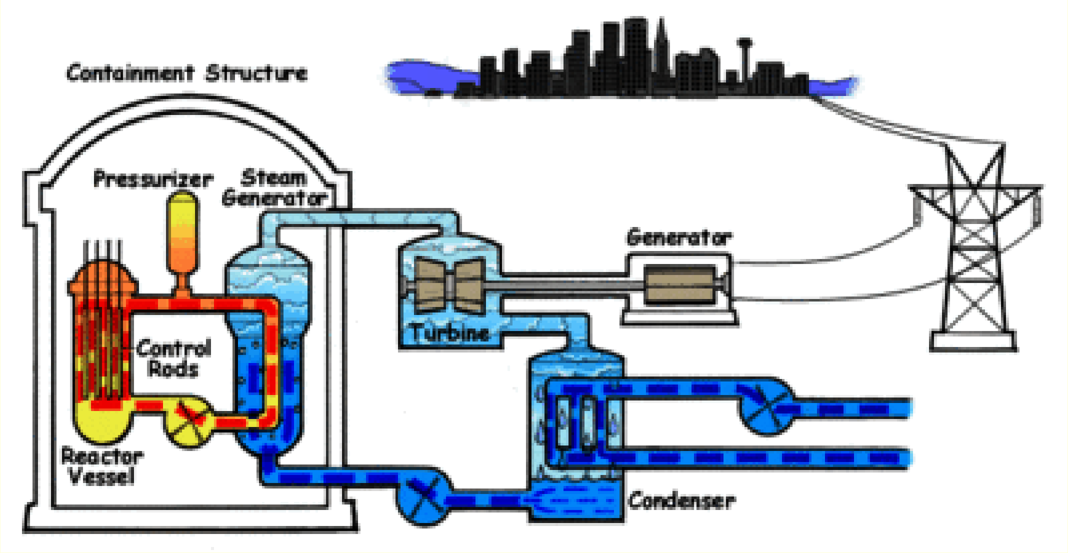
Turbine-generator

turns heat into work, then electricity

Pressurized Water Reactor (PWR)



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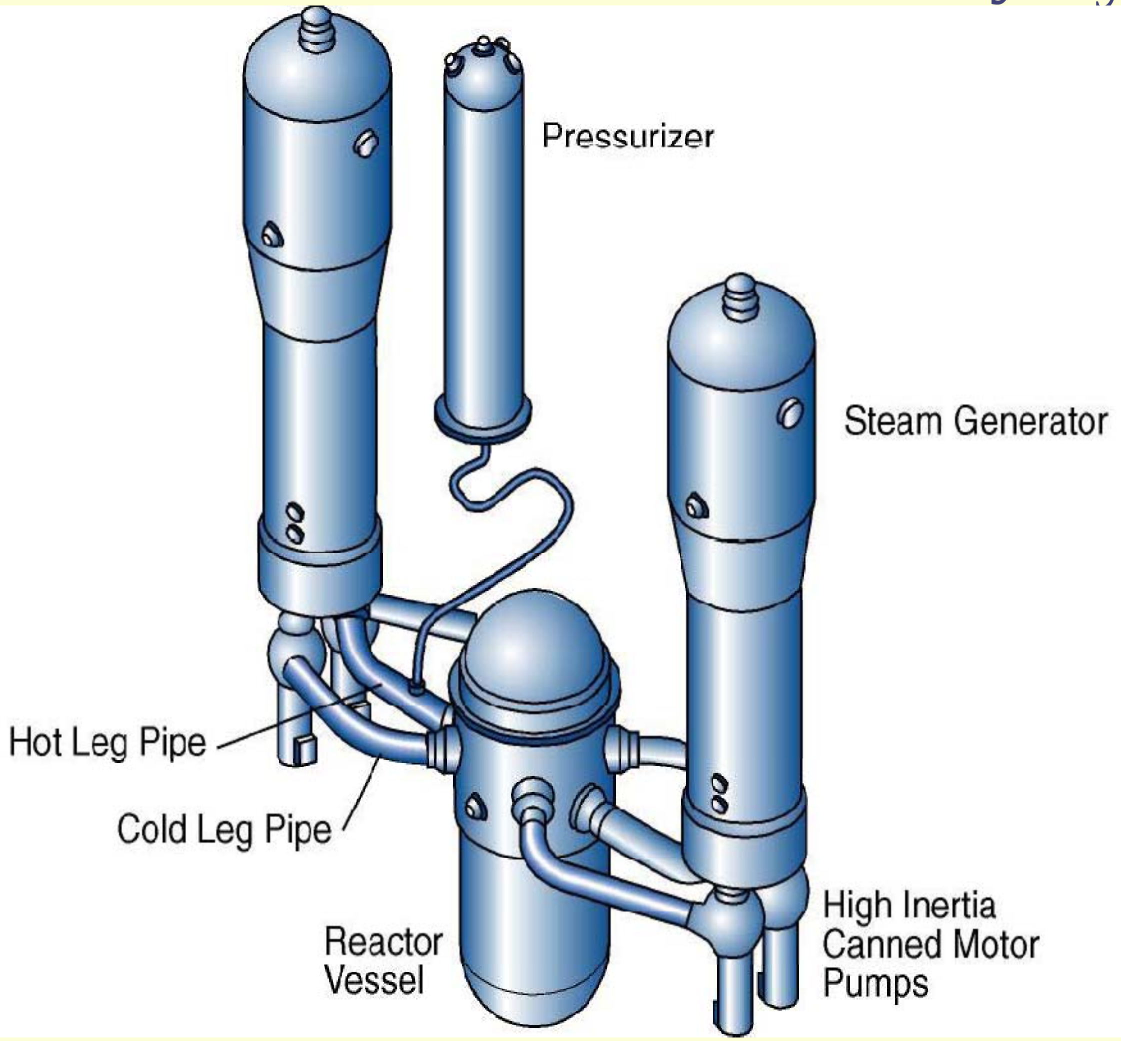
PWR Primary System



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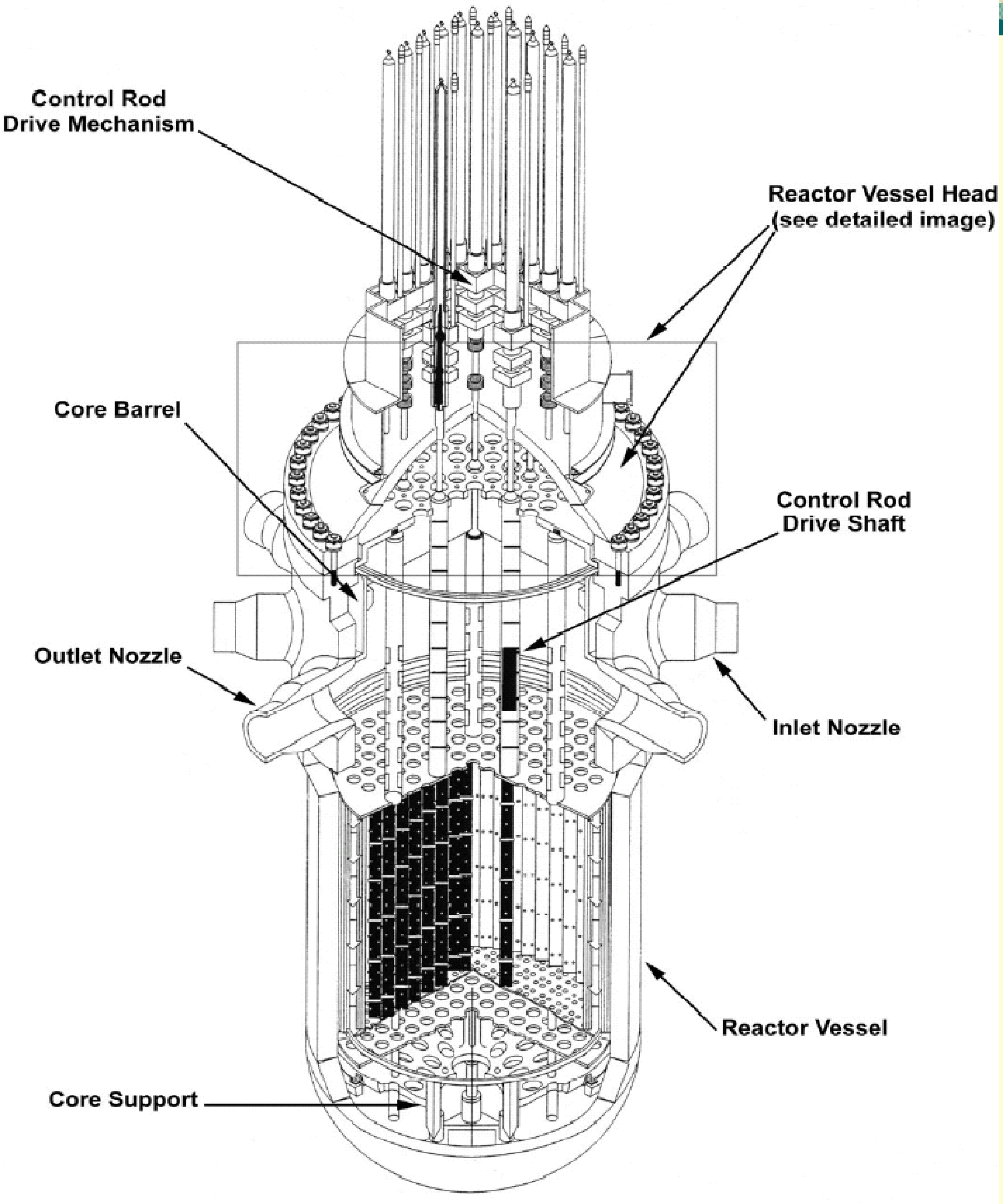
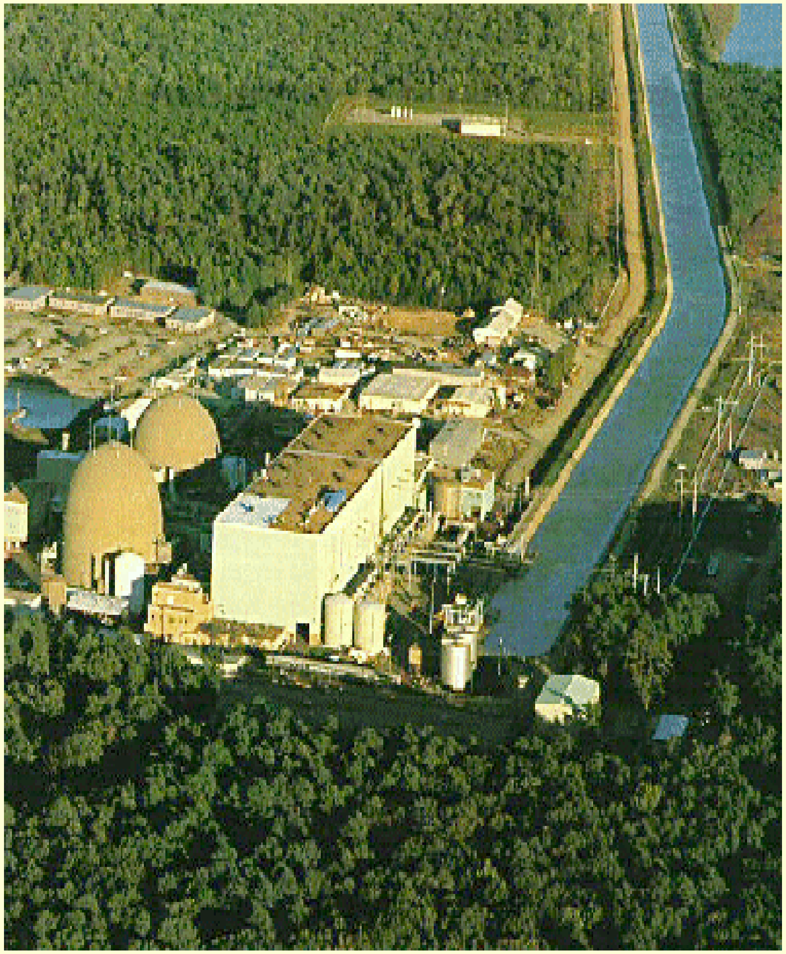


PWR Reactor Vessel Showing internal Structures and Fuel Assemblies

Public domain image from wikipedia.

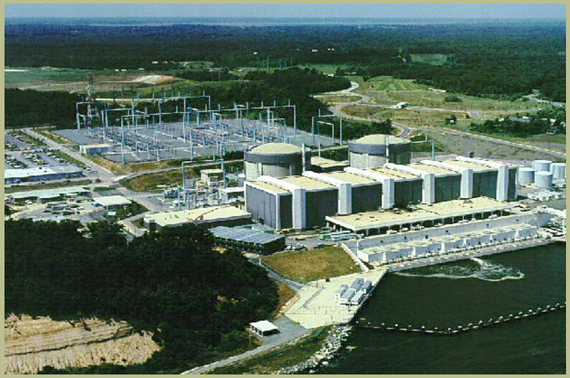
Heat Discharge in Nuclear Plants

(2nd law of thermodynamics)



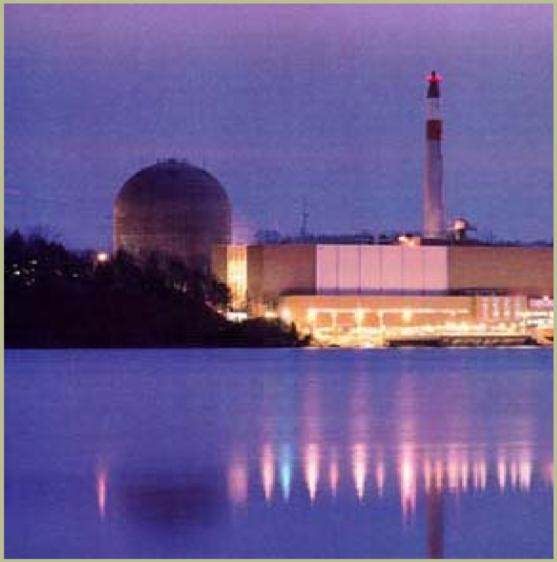
Nuclear Energy in the US ,today

- 104 US reactors, 100 GWe is 13% of US installed capacity but provides about 20% of electricity.
- In 2007 nuclear energy production in the US was the highest ever.
- US plants have run at 90.5% capacity in 2009, up from 56% in 1980.
- 3.5 GWe of uprates were permitted in the last decade. 3.5 GWe are expected by 2014 and more by 2020.
- 59 reactor licenses extended, from 40 years to 60 years of operation, 20 more reactors in process.
- **Electricity production costs of nuclear are the lowest in US (1-2 ¢/kWh)**



Calvert Cliffs - MD

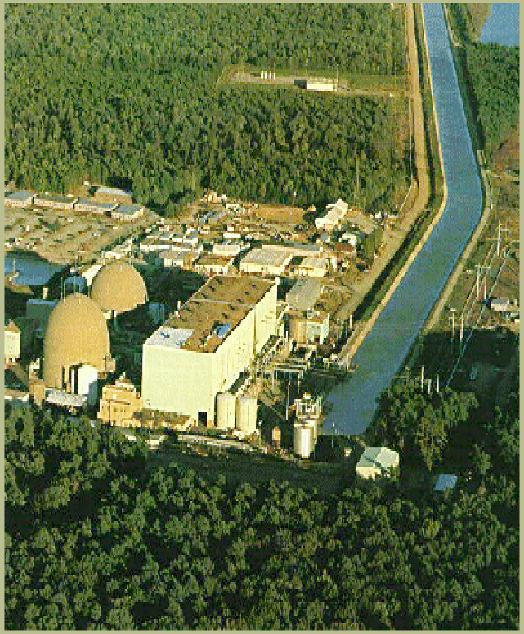
Diablo Canyon - CA



Indian Point - NY

Prairie Island site - MN

Robinson - SC

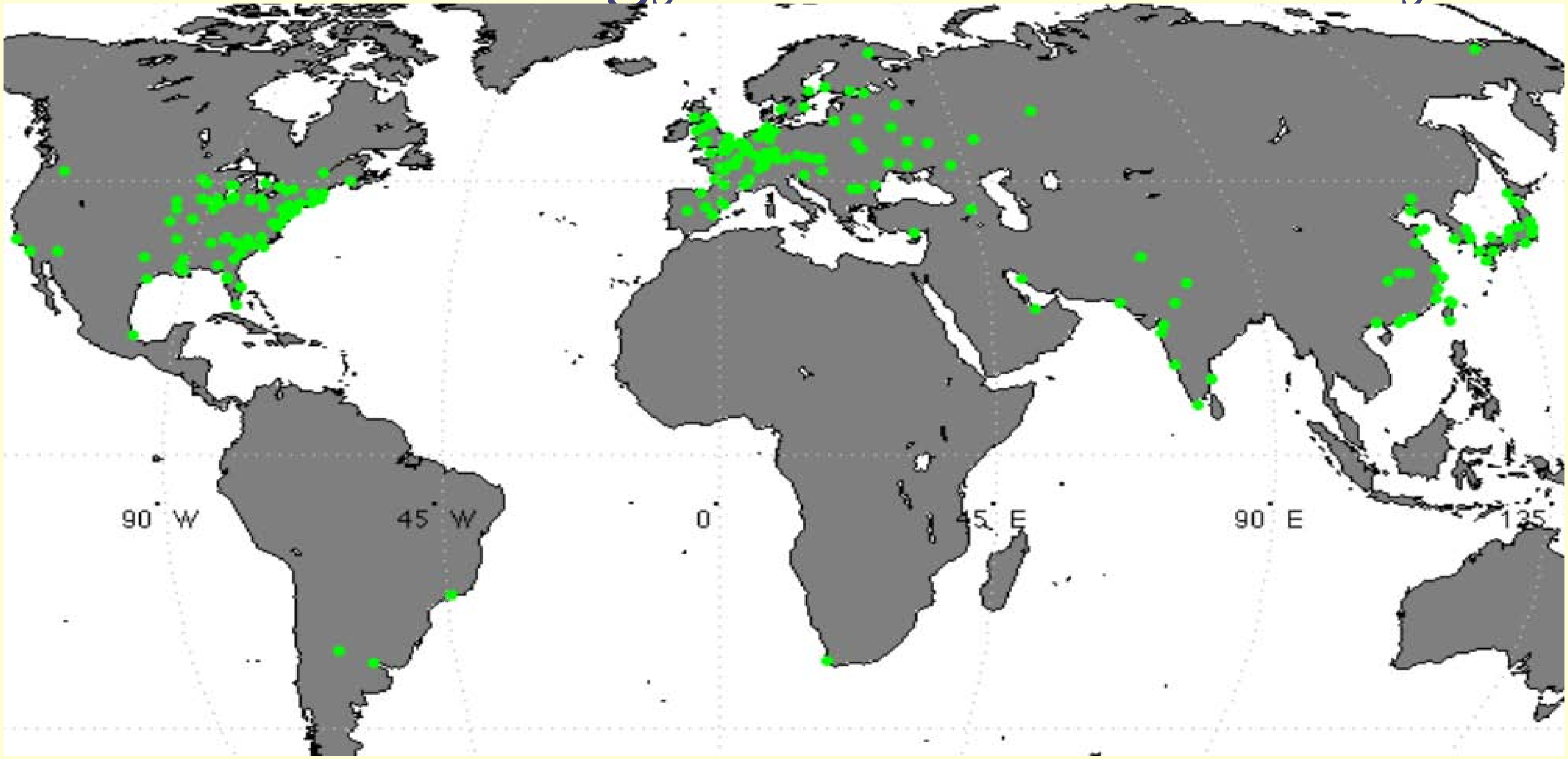


Surry - VA

The MIT Research Reactor

- 5 MW power
- Located near NW12 on Albany St.
- Operated by MIT students
- Just turned 50!

Nuclear Energy in the World Today



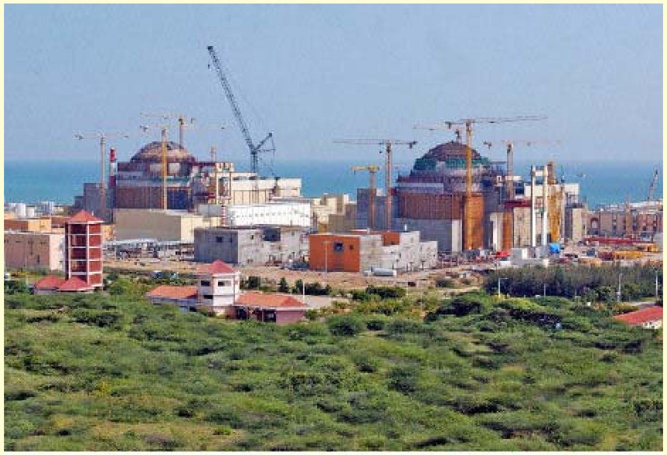
Courtesy of MIT student. Used with permission.

About 440 World reactors in 30 countries, 14% of global electricity produced.

60 new reactors are in various stages of construction


Olkiluoto – Finland


Lungmen – Taiwan


Kudankulam – India


Flamanville – France


Rostov – Russia


Shin kori – S. Korea


Shimane – Japan


Sanmen – China

3 ongoing in the US!

Vogtle, Georgia

Summer, South Carolina

Watts Bar, Tennessee

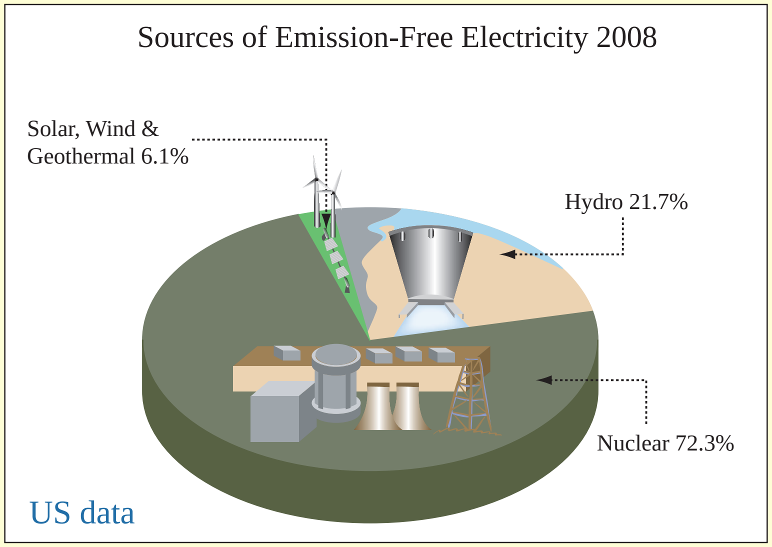
The Case for New Nuclear Plants in the US

Concerns for ***climate change…***

Athabasca Glacier, Jasper National Park, Alberta, Canada

Photo provided by the National Snow and Ice Data Center

Courtesy of National Snow and Ice Data Center. Used with permission.



Sources of Emission-Free Electricity 2008

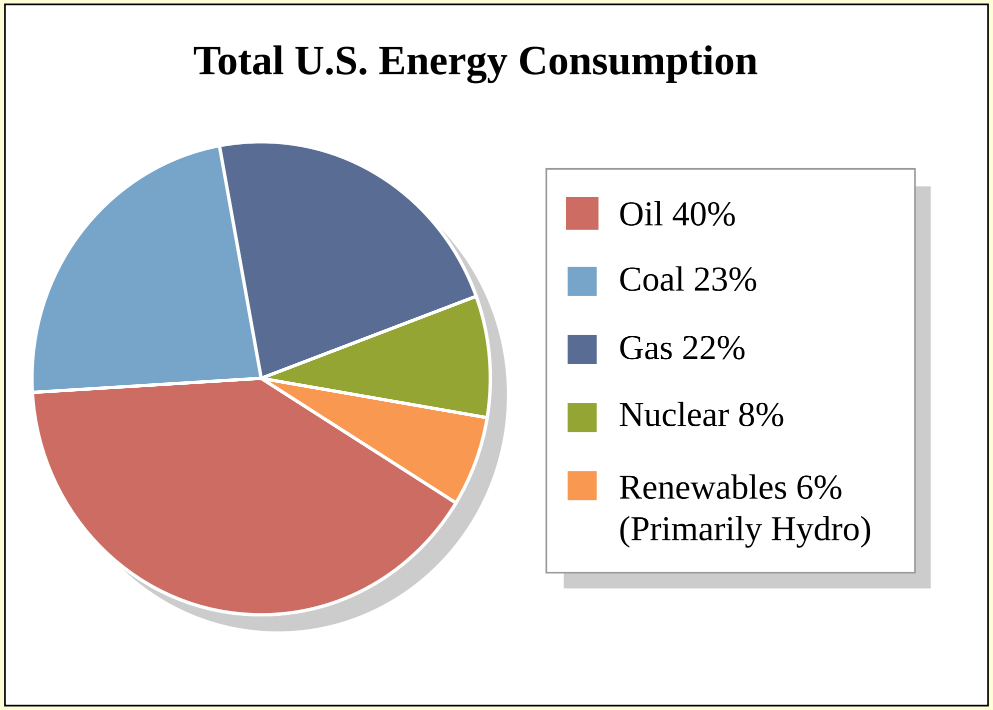
Image by MIT OpenCourseWare.

About 700,000,000 ton of CO2 emissions avoided every year in the US

The Case for New Nuclear Plants in the US (2)

...and *growing fossil fuel imports and consumption*

Total U.S. Energy Consumption



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↑

Low Carbon

↓

Oil is the Challenge

U.S. data from EIA, Annual Energy Outlook 2008 Early Release, years 2006 and 2030; world data from IEA, World Energy Outlook 2007, years 2005 and 2030

Can nuclear displace coal?

Yes, as they are both used for baseload electricity generation.

What about oil?

Oil Is Used for Transportation. What Are the Other Transport Fuel Options?

- **Plug-in hybrid electric vehicles (PHEVs)**
- **Liquid fuels from fossil sources (oil, natural gas and coal)**
- **Liquid fuels from biomass**
- Hydrogen
  - Long term option
  - Depends upon hydrogen on-board-vehicle storage breakthrough

PHEVs: Recharge Batteries from the Electric Grid Plus Use of Gasoline

Images removed due to copyright restrictions.

- Electric car limitations
  - Limited range
  - Recharge time (Gasoline/Diesel refueling rate is ~10 MW)
- Plug-in hybrid electric vehicle
  - Electric drive for short trips
  - Recharge battery overnight to avoid rapid recharge requirement
  - Hybrid engine with gasoline or diesel engine for longer trips
- Connects cars and light trucks to the electrical grid

Courtesy of the Electric Power Research Institute

PHEVs: Annual Gasoline Consumption

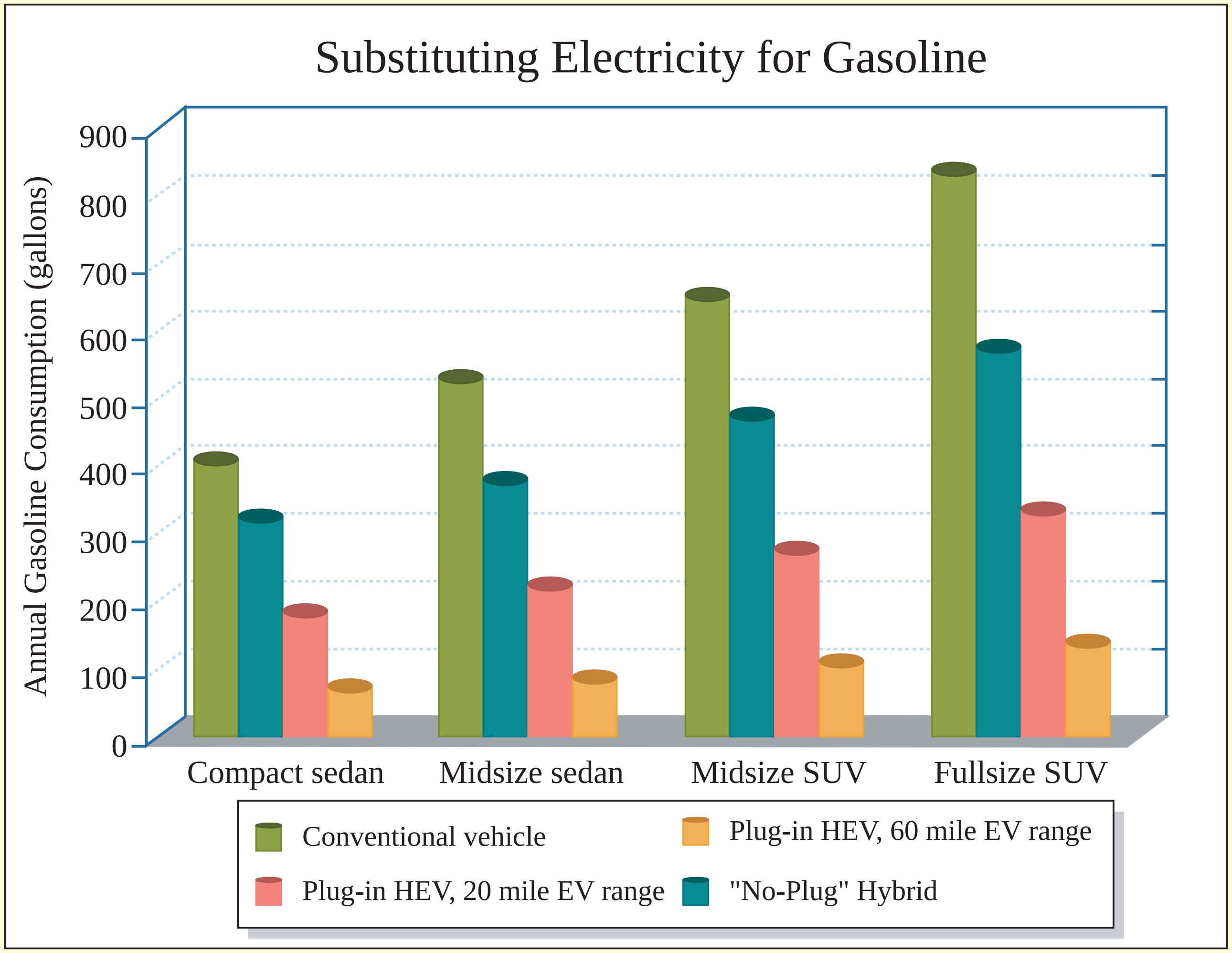


Image by MIT OpenCourseWare.

Need 150 to 200 Nuclear Plants Each Producing 1000 MW(e)

Refineries Consume ~7% of the Total U.S. Energy Demand

Traditional Refining

- Energy inputs
  - Primarily heat at 550 C
  - Some hydrogen
- <u>High-temperature gas reactors could supply heat and hydrogen</u>
  - Market size equals existing nuclear enterprise

Biomass: 1.3 Billion Tons per Year

Available Biomass without Significantly Impacting U.S. Food, Fiber, and Timber

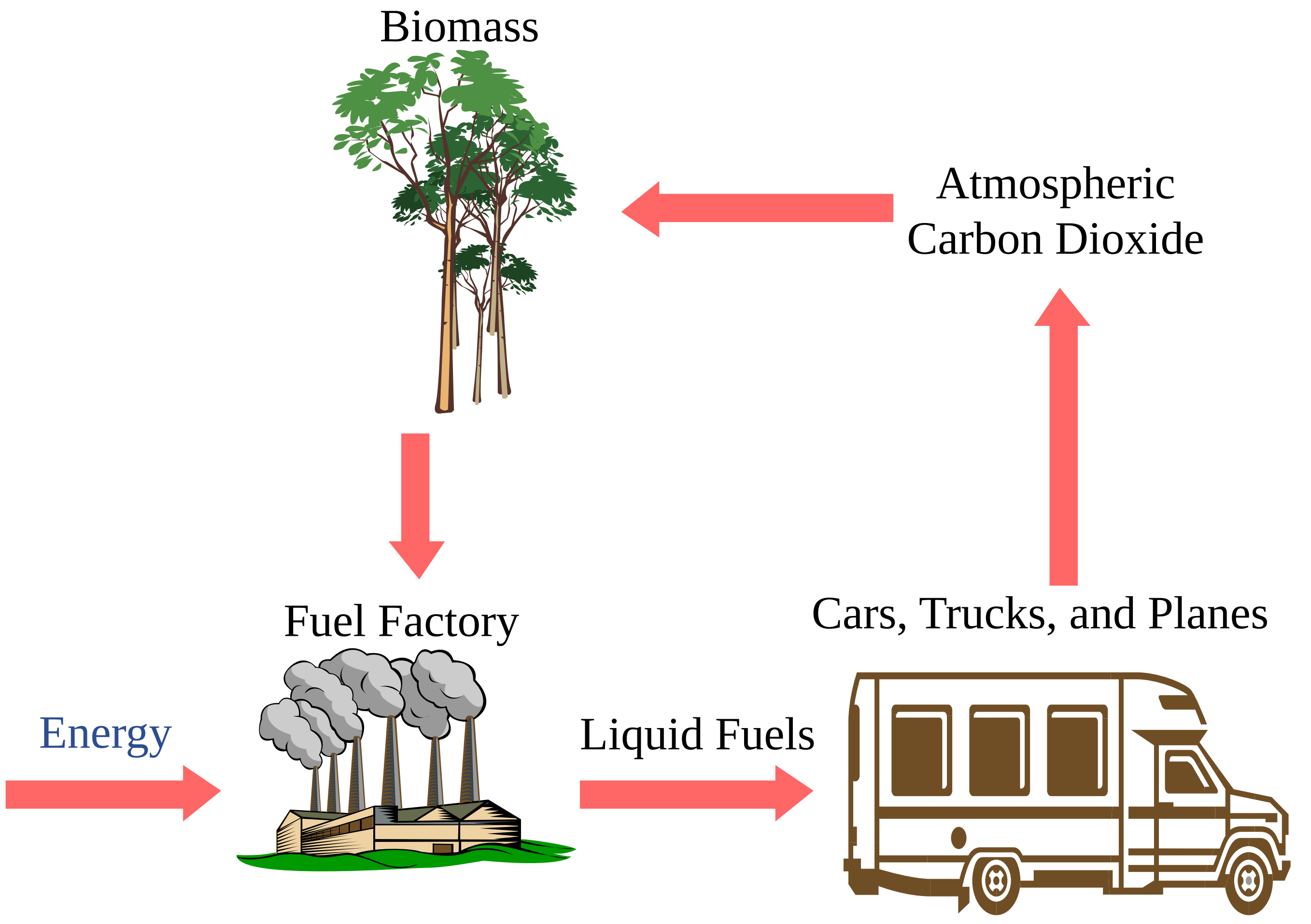

Agricultural Residues


Logging Residues


Urban Residues


Energy Crops

Conversion of Biomass to Liquid Fuels Requires Energy



Biomass

Atmospheric Carbon Dioxide

Fuel Factory

Cars, Trucks, and Planes

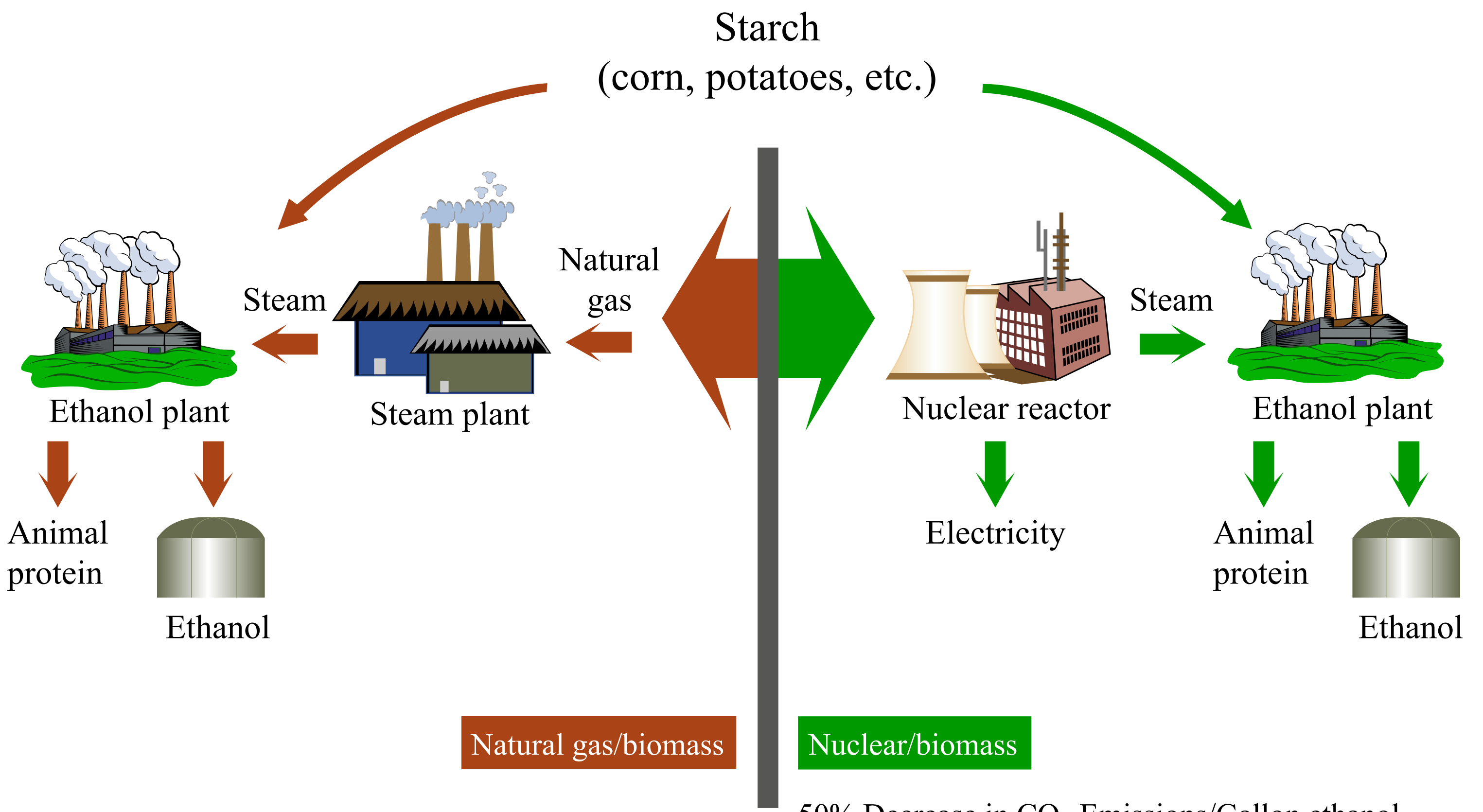
Energy

Liquid Fuels

$$C_xH_y + (X + \frac{Y}{4})O_2 \longrightarrow CO_2 + (\frac{Y}{2})H_2O$$

Image by MIT OpenCourseWare.

Option Today: Steam From Existing Nuclear Plants to Starch-Ethanol Plants



Starch
(corn, potatoes, etc.)

Ethanol plant
Steam
Steam plant
Natural gas
Animal protein
Ethanol

Nuclear reactor
Steam
Ethanol plant
Electricity
Animal protein
Ethanol

Natural gas/biomass

Nuclear/biomass

Fossil energy input 70% of energy content of ethanol

50% Decrease in CO_2 Emissions/Gallon ethanol
50% reduction in steam cost

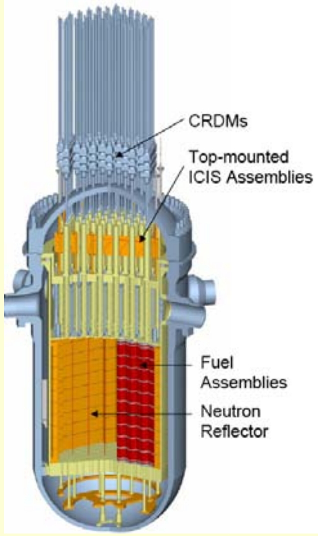
Image by MIT OpenCourseWare.

5 Advanced Reactor Designs Considered for New Construction in the US

Gen III+ Plants: Improved Versions of Existing Plant Designs

ABWR (GE-Hitachi)

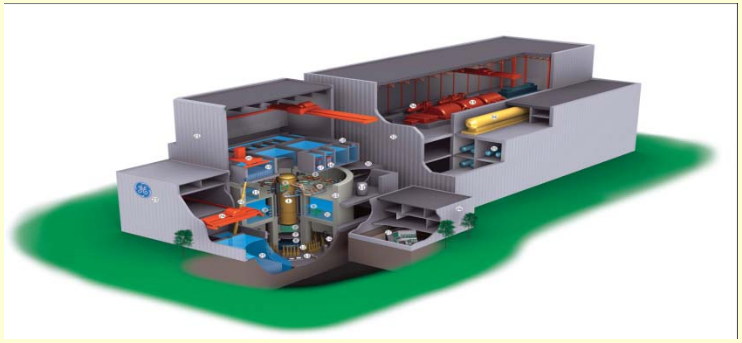
US-APWR (Mitsubishi)



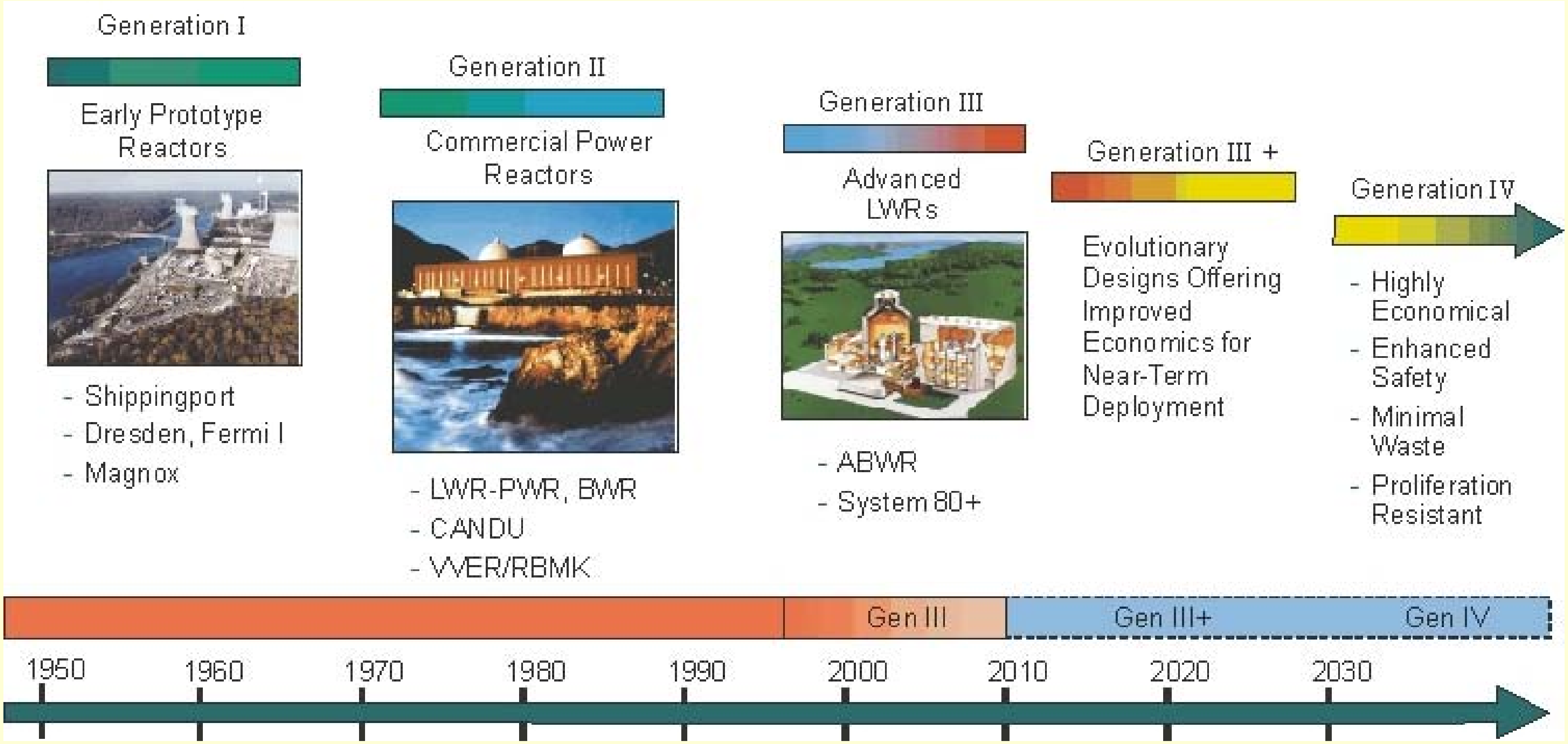
AP1000 (Toshiba: Westinghouse)

US-EPR (AREVA)

ESBWR (GE-Hitachi)



Nuclear Reactor Timeline



Generation I

Early Prototype Reactors

- Shippingport
- Dresden, Fermi I
- Magnox

Generation II

Commercial Power Reactors

- LWR-PWR, BWR
- CANDU
- VVER/RBMK

Generation III

Advanced LWRs

- ABWR
- System 80+

Generation III +

Evolutionary Designs Offering Improved Economics for Near-Term Deployment

Generation IV

- Highly Economical
- Enhanced Safety
- Minimal Waste
- Proliferation Resistant

Advanced Reactors (Gen III+) that initiated design certification process with the NRC

Design	Applicant	Type	Design Certification Status
AP1000	Westinghouse-Toshiba	Advanced Passive PWR 1100 MWe	Certified, Amendment under review
ABWR	GE-Hitachi	Advanced BWR 1350 MWe	Certified, Constructed in Japan/Taiwan
ESBWR	GE-Hitachi	Advanced Passive BWR 1550 MWe	Under review
US-EPR	AREVA	Advanced PWR 1600 MWe	Applied in 2007
US-APWR	Mitsubishi	Advanced PWR 1700 MWe	Applied in 2007

U.S. utilities have submitted 18 licensing applications (total 28 units)

Mission/Goals for Gen III+

- Improved economics. Targets:
  - Increased plant design life (60 years)
  - Shorter construction schedule (36 months*)
  - Low overnight capital cost (~\$1000/kWe** for NOAK plant)
  - Low O&M cost of electricity (~ 1¢/kWh)

* First concrete to fuel loading (does not include site excavation and pre-service testing)

** Unrealistic target set in early 2000s. Current contracts in Europe, China and US have overnight capital costs >\$3000/kWe

- Improved safety and reliability
  - Reduced need for operator action
  - Expected to beat NRC goal of CDF<10^{-4}/yr
  - Reduced large release probability
  - More redundancy <u>or</u> passive safety

Nuclear Safety Primer

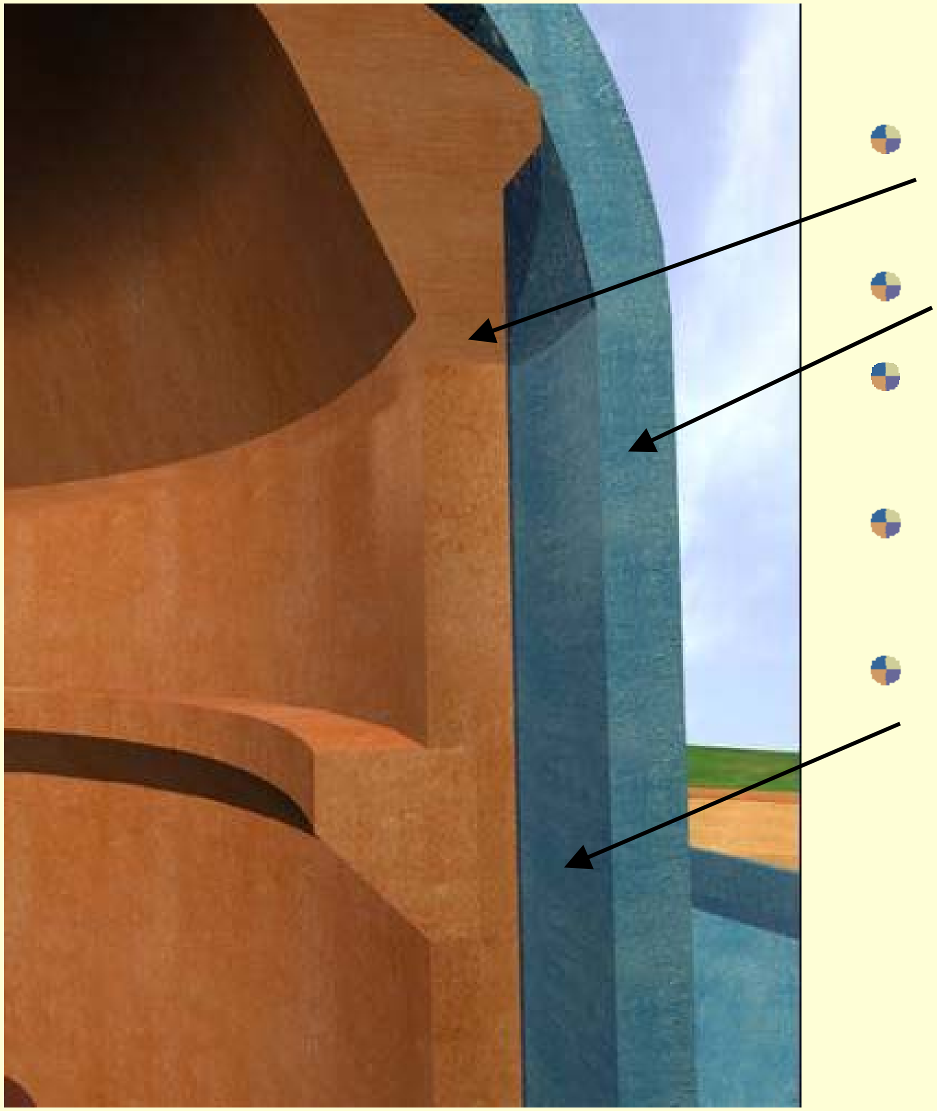
- Hazard: fission products are highly radioactive
- Aggravating factor: nuclear fuel can never be completely shut down (decay heat)
- Objective: prevent release of radioactivity into environment
- Safety Pillars:
  - *Defense-in-depth*: multiple, independent physical barriers (i.e., fuel pin + vessel + containment)
  - *Safety systems*: prevent overheating of the core when normal coolant is lost

Some interesting safety-related features of the Gen III+ reactors…

Higher redundancy (US-EPR ECCS)

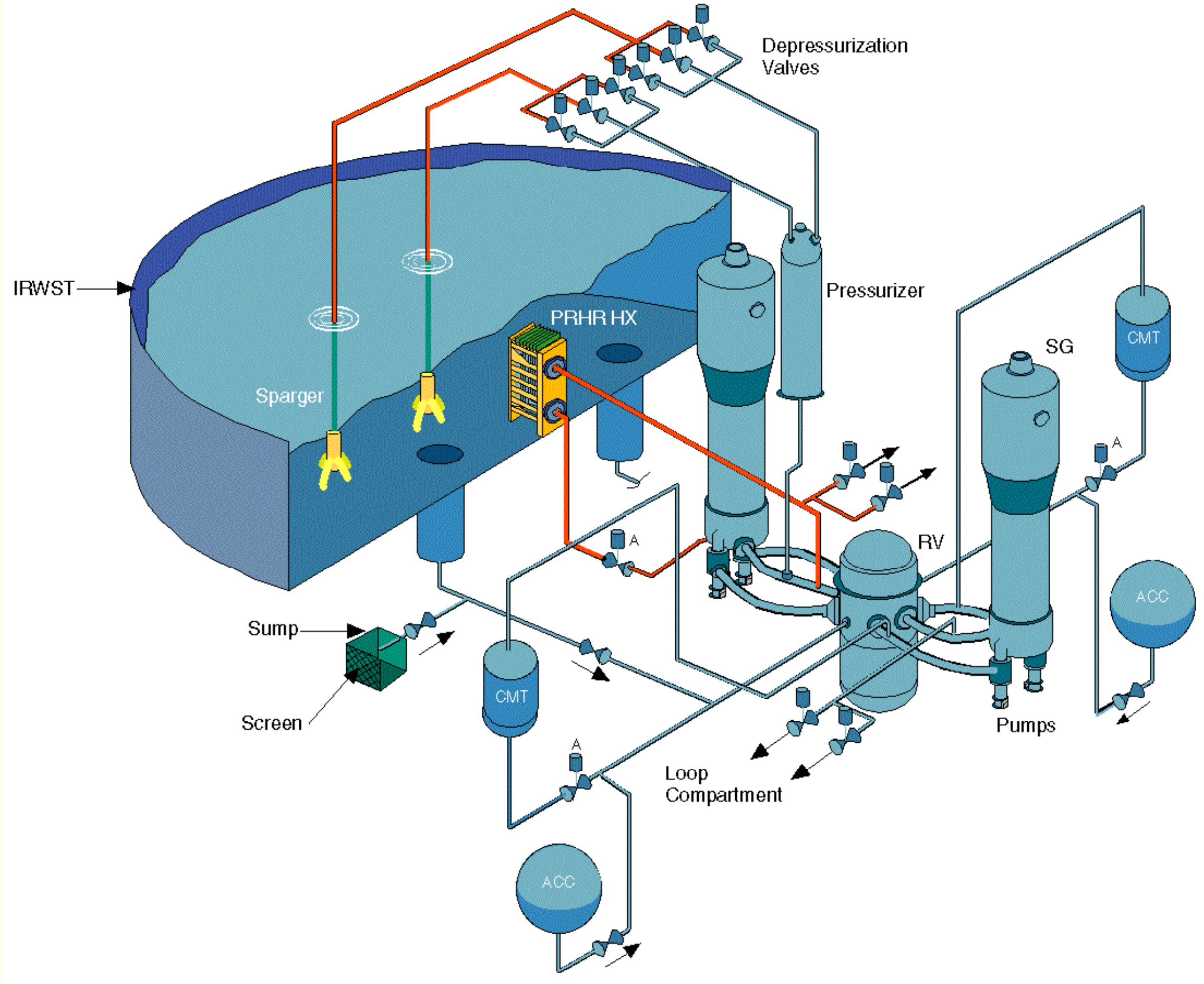
- Four identical diesel-driven trains, each 100%, provide redundancy for maintenance or single-failure criterion (N+2)
- Physical separation against internal hazards (e.g. fire)

Higher redundancy (US-EPR Containment)



- **Inner wall pre-stressed concrete with steel liner**
- **Outer wall reinforced concrete**
- **Protection against airplane crash**
- **Protection against external explosions**
- **Annulus sub-atmospheric and filtered to reduce radioisotope release**

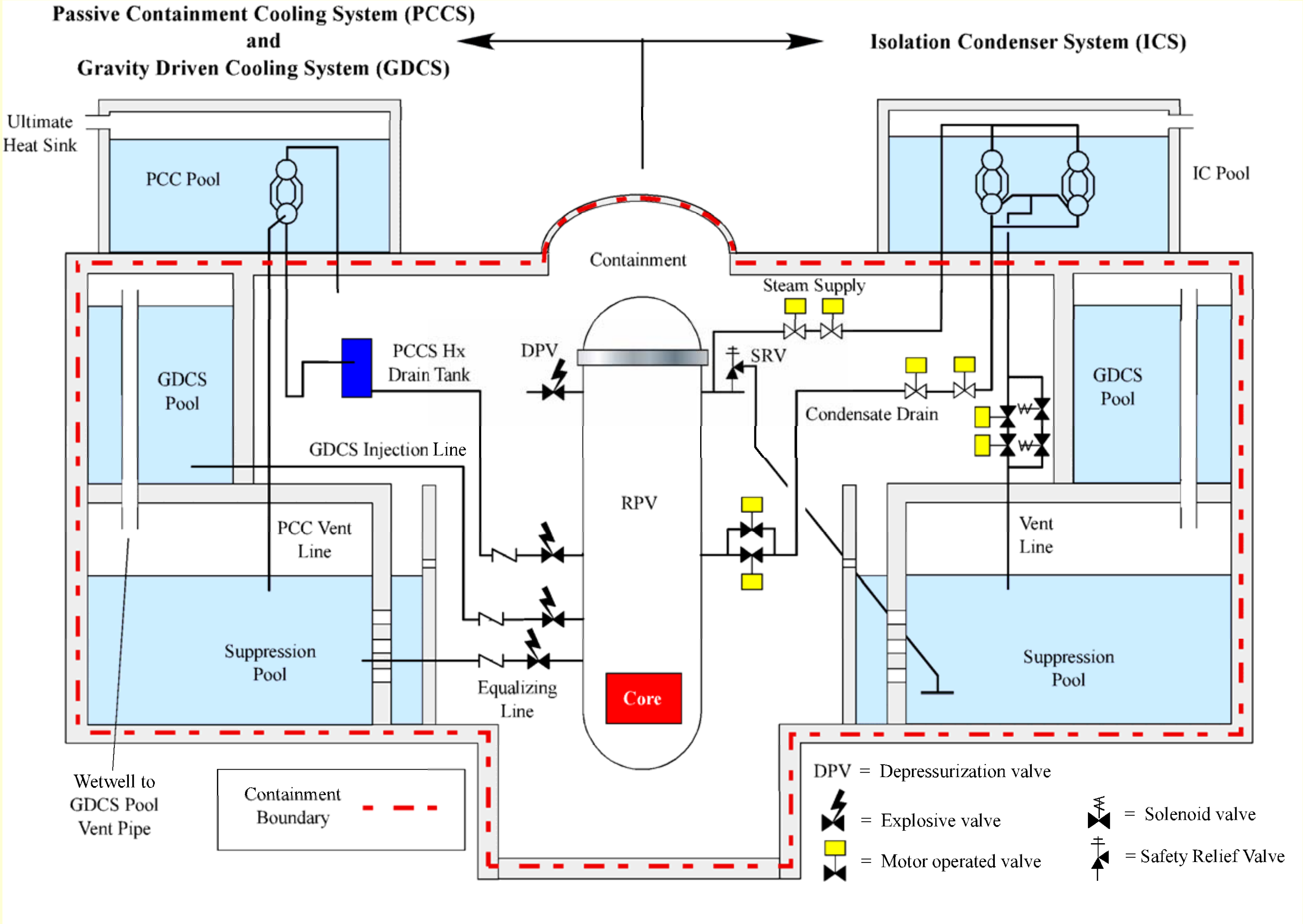
Passive safety systems (AP1000 ECCS)



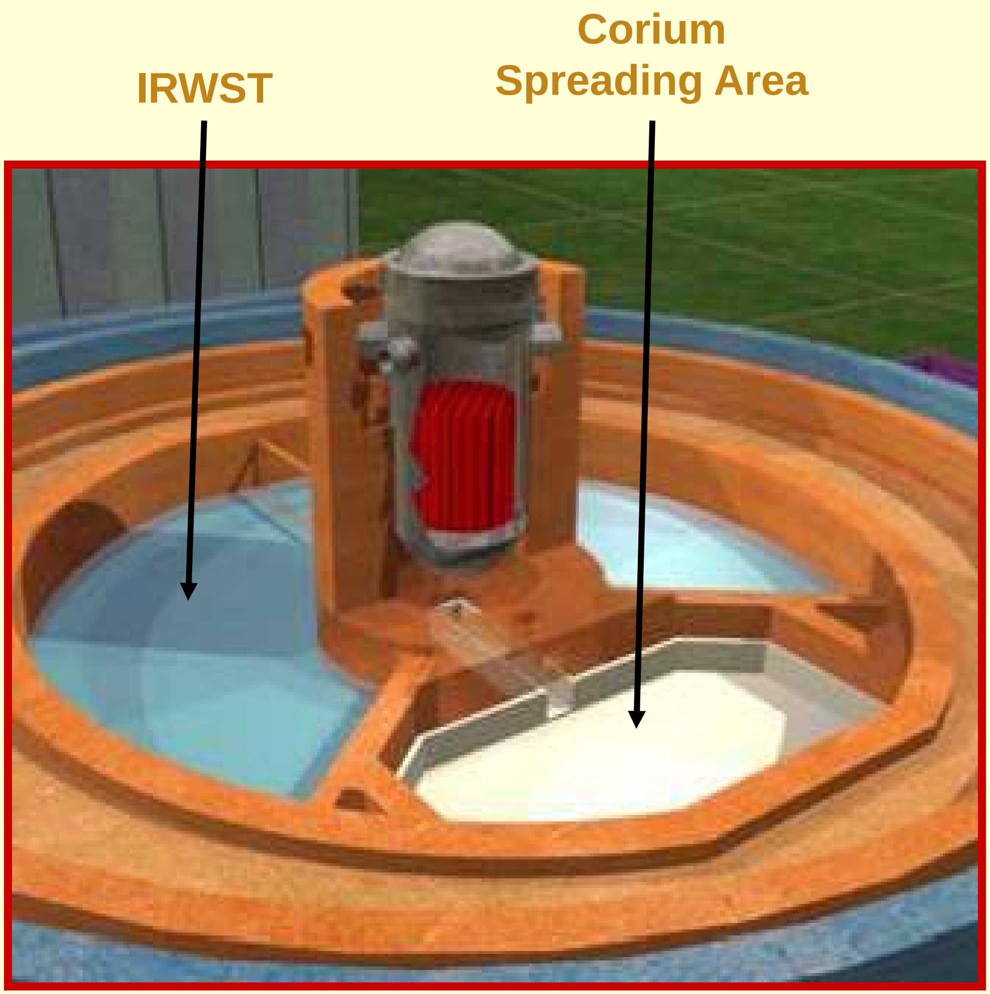
http://www.ap1000.westinghousenuclear.com/ap1000_psrs_pccs.html

Courtesy of Westinghouse. Used with permission.

Passive safety systems (ESBWR ECCS and PCCS)



Severe accidents mitigation (EPR core catcher)



Ex-vessel core catcher concept (passive)

- Molten core is assumed to breach vessel

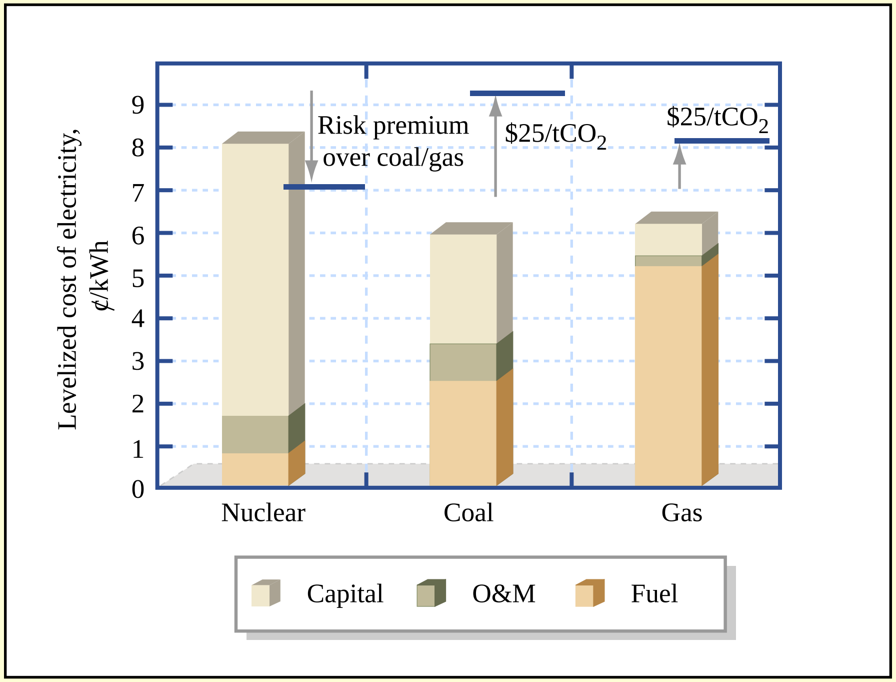
- Molten core flows into spreading area and is cooled by IRWST water

- Hydrogen recombiners ensure no detonation within container

Nuclear energy economics

Nuclear Energy Economics

- **Financial risk for new plants is high**
  - **Initial investement is large** (~$3,480/kW ⇒ G$/unit)
  - **Fear of delays during construction (like in 70s and 80s)**



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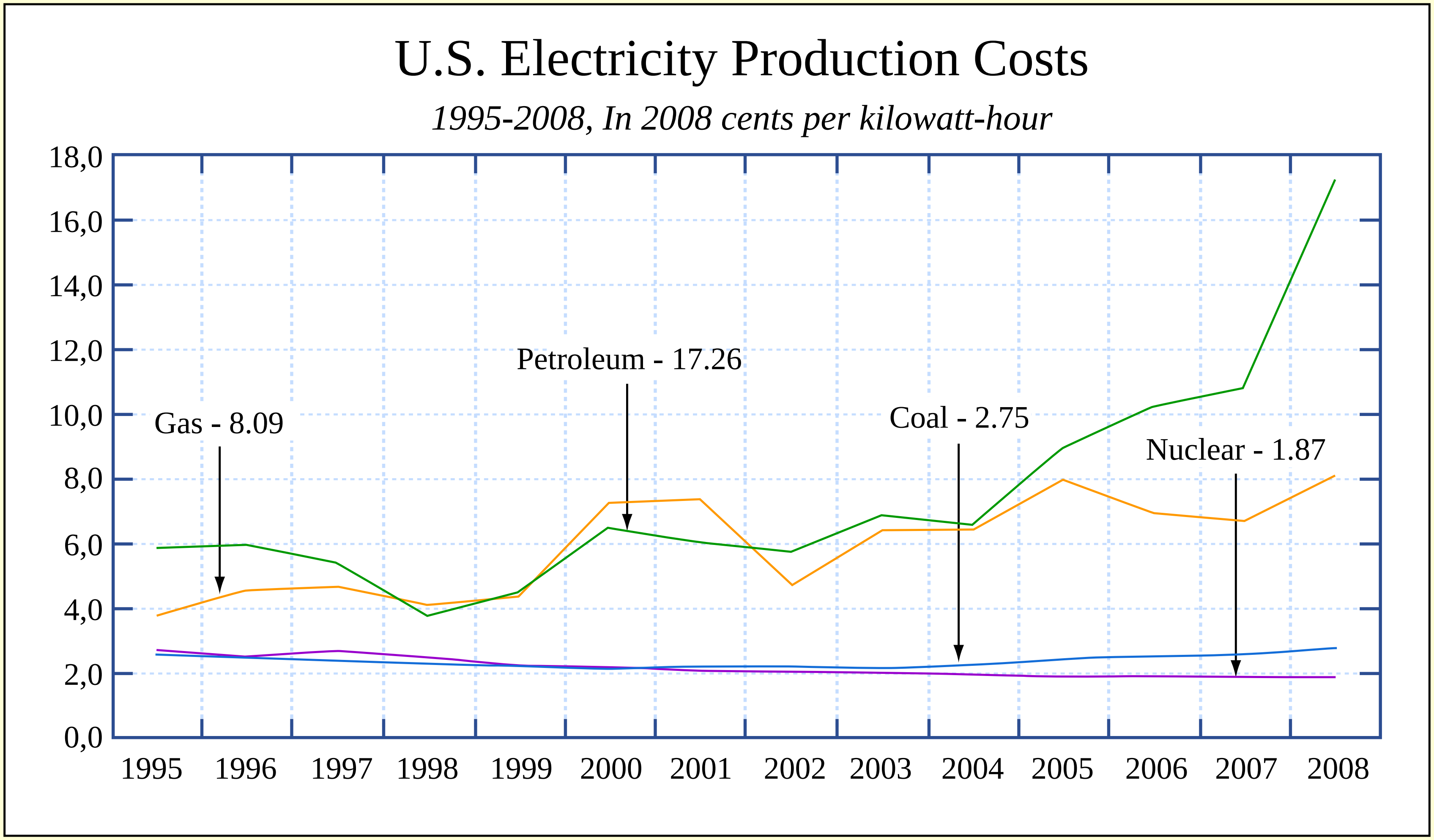
- **Nuclear production costs are lowest of all energy sources**



U.S. Electricity Production Costs

1995-2008, In 2008 cents per kilowatt-hour

Image by MIT OpenCourseWare.

Production Costs = Operations and Maintenance Costs + Fuel Costs. Production costs do not include indirect costs and are based on FERC Form 1 filings submitted by regulated utilities. Production costs are modeled for utilities that are not regulated.

Source: Ventyx Velocity Suite
Updated: 5/09

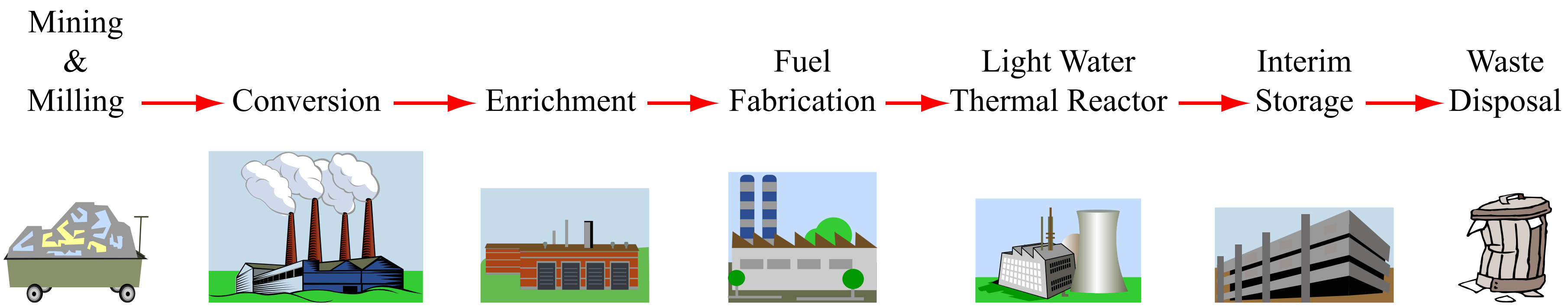
Nuclear Fuel - Compact & Economic

- Nuclear fuel cycle has made up less than 15% of the cost of nuclear electricity. In 2006 that was about 6 $/MWhr, out of a total electricity cost of 50 $/MWhr
- This covers the following steps
  - Uranium ore extraction and conversion to U_3O_8, at $48/kg
  - Enrichment in U235, typically by centrifugal forces spinning gaseous UF_6, to about 4% (Japan Rakashu plant in side pictures)
  - Manufacturing of UO_2 pellets, and placing them in Zr tubes (cladding) thus producing fuel rods. The rods (or pins) are arranged in square lattices called assemblies.
  - Removal of spent fuel assemblies to temporary storage in fuel pools, then to interim dry storage
  - 1 $/MWhr for spent fuel disposal fees

Nuclear fuel cycle

Fuel Cycle Scenarios (1)

Once-through (US current)

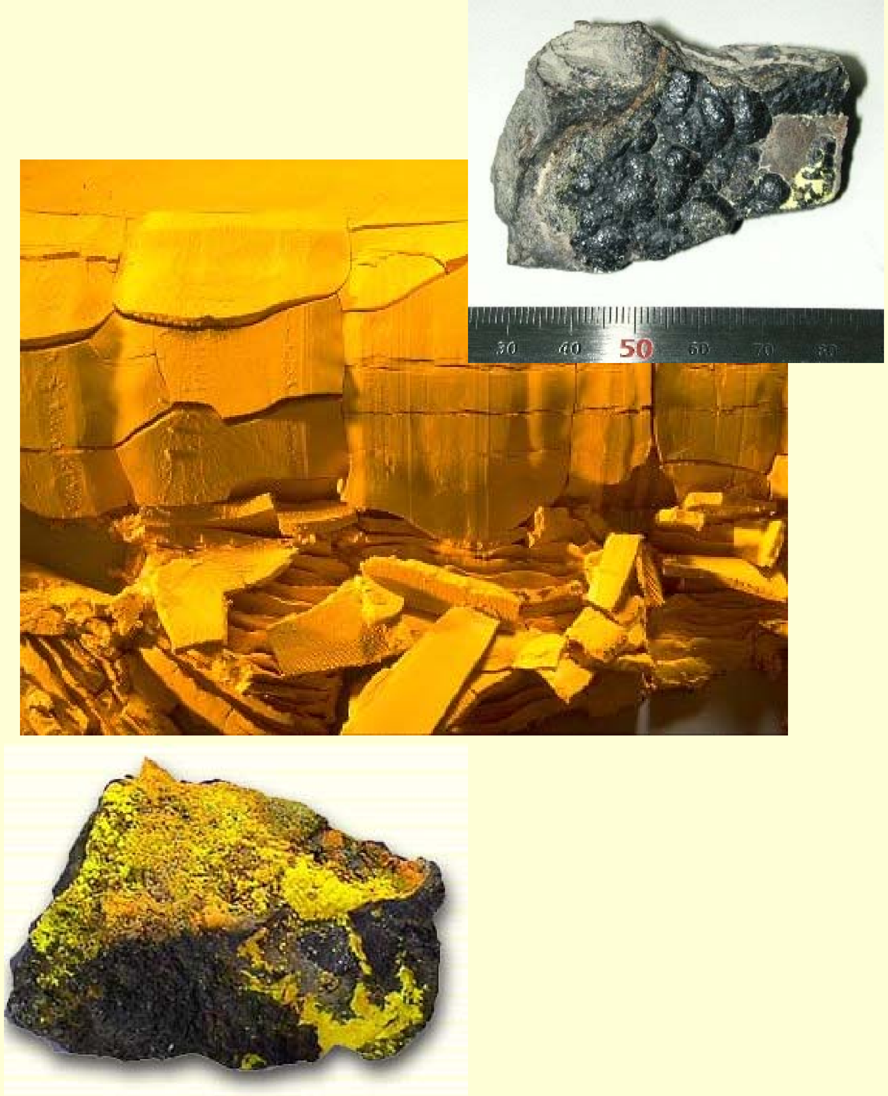


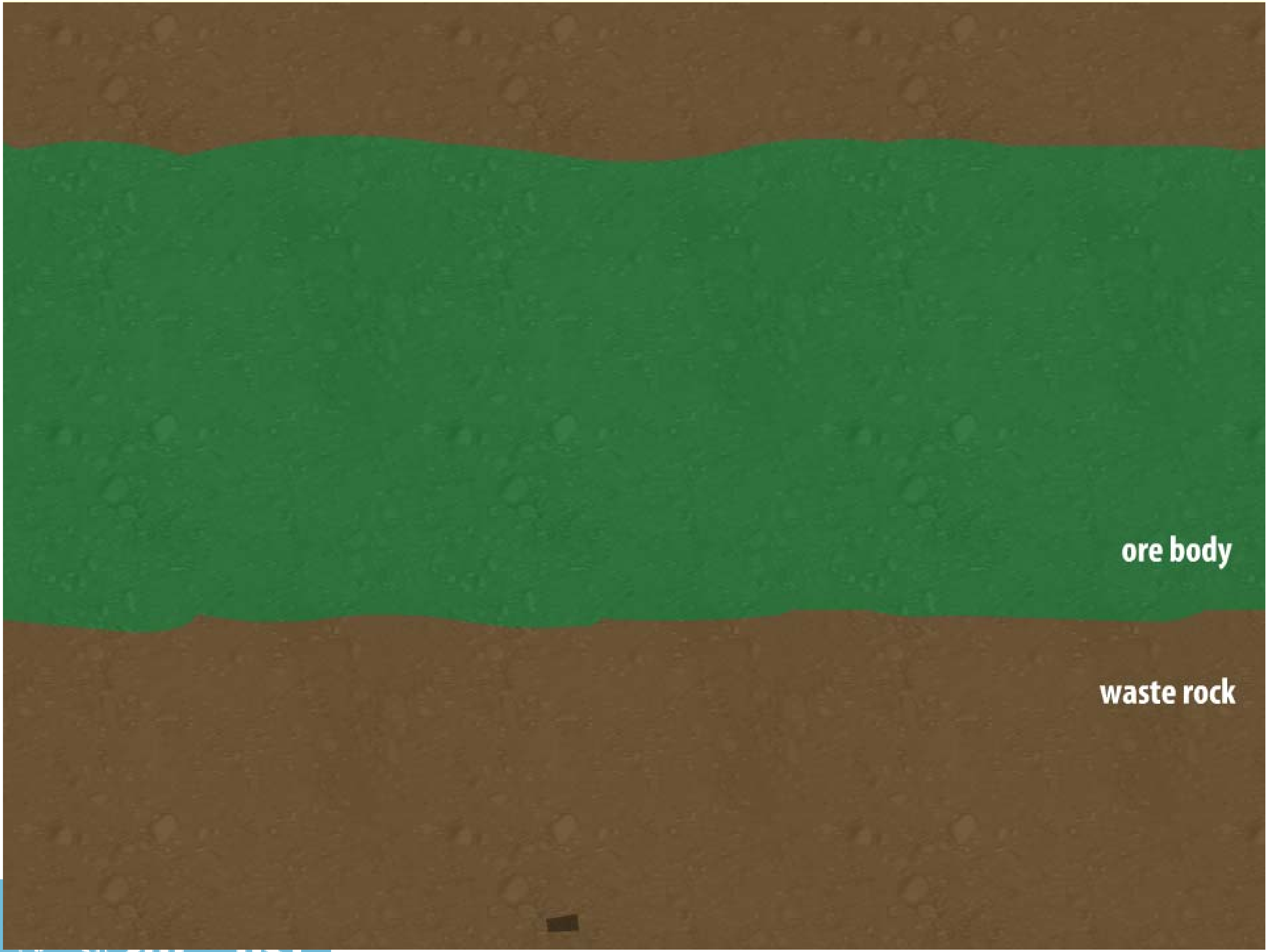
Mining & Milling → Conversion → Enrichment → Fuel Fabrication → Light Water Thermal Reactor → Interim Storage → Waste Disposal

Image by MIT OpenCourseWare.

Milling & Mining Process

- 1MT ore = 2-3 lb uranium
- End product is U_3O_8 powder (“yellowcake”)
- Major suppliers:
  - Canada
  - Australia
  - Kazakhstan
  - Africa
  - Former Soviet Union [FSU]
- Large secondary (“already mined”) market dominates supplies




ore body
waste rock

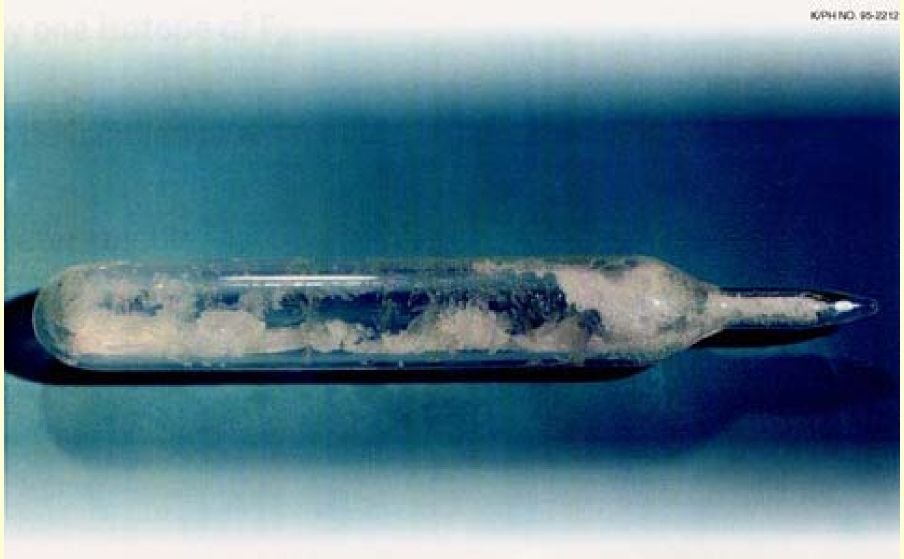
Bellezane, France Site (open pit mine)

Bellezane Site: After Reclamation

Kazakhstan KATCO (In situ leaching)

Conversion Process

- U_3O_8 converted to UF_6 for enrichment process
- UF_6: only form of uranium that is gaseous at “industrial” temperatures
  - Gaseous at 133°F (56.1°C)
  - In solid form at room temperature

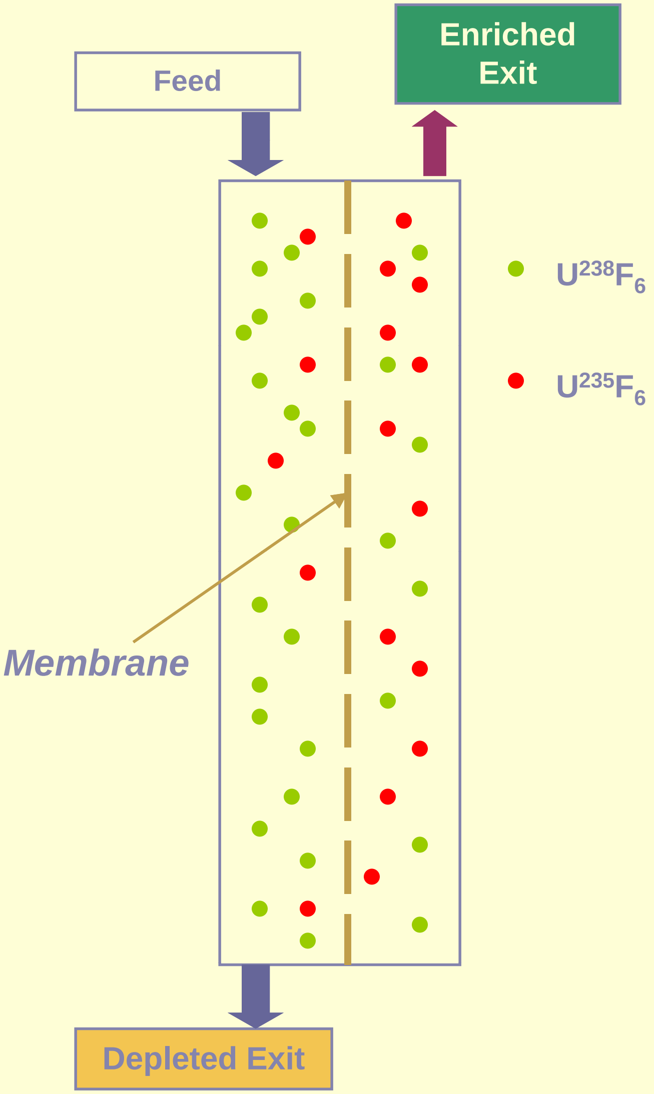


Uranium Enrichment

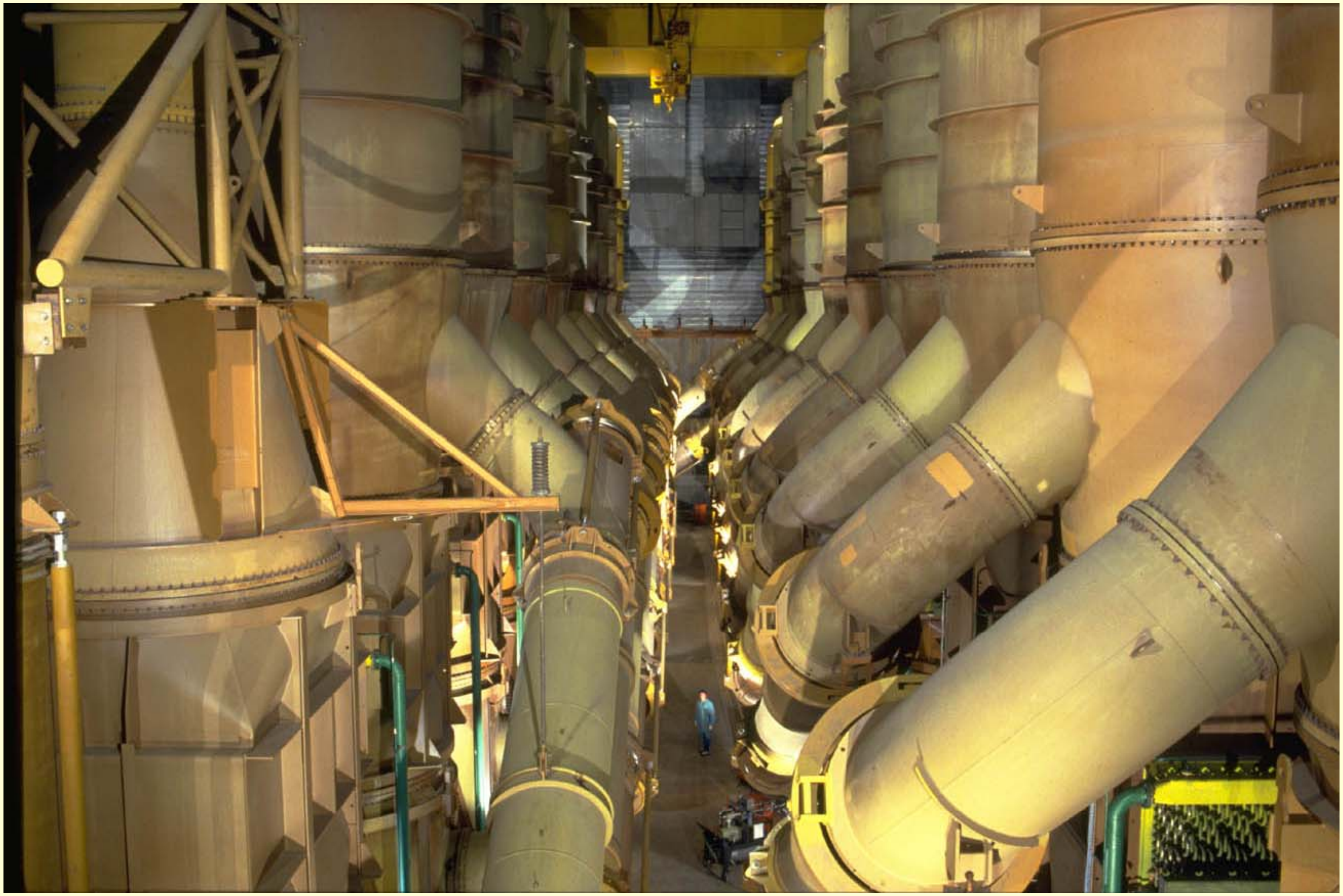
- Two major commercial processes:
  - Gaseous Diffusion
  - Gas Centrifuging
- Can also blend down weapons-grade HEU
  - U.S.-Russian HEU Agreement ("Megatons to Megawatts") - ~50% of U.S. fuel supply
- Upward price pressure driven by demand
- Priced in Separative Work Units (SWU)

Enrichment: Gaseous Diffusion

- The UF_6 gas diffuses across a membrane (filter):
  - $U^{235}F_6$ molecules are smaller, faster: they cross the membrane more often, statistically
    - This gas is enriched in U^{235}
  - $U^{238}F_6$ molecules are bigger, slower: they cross the membrane less often, statistically
    - This gas is depleted in U^{235}



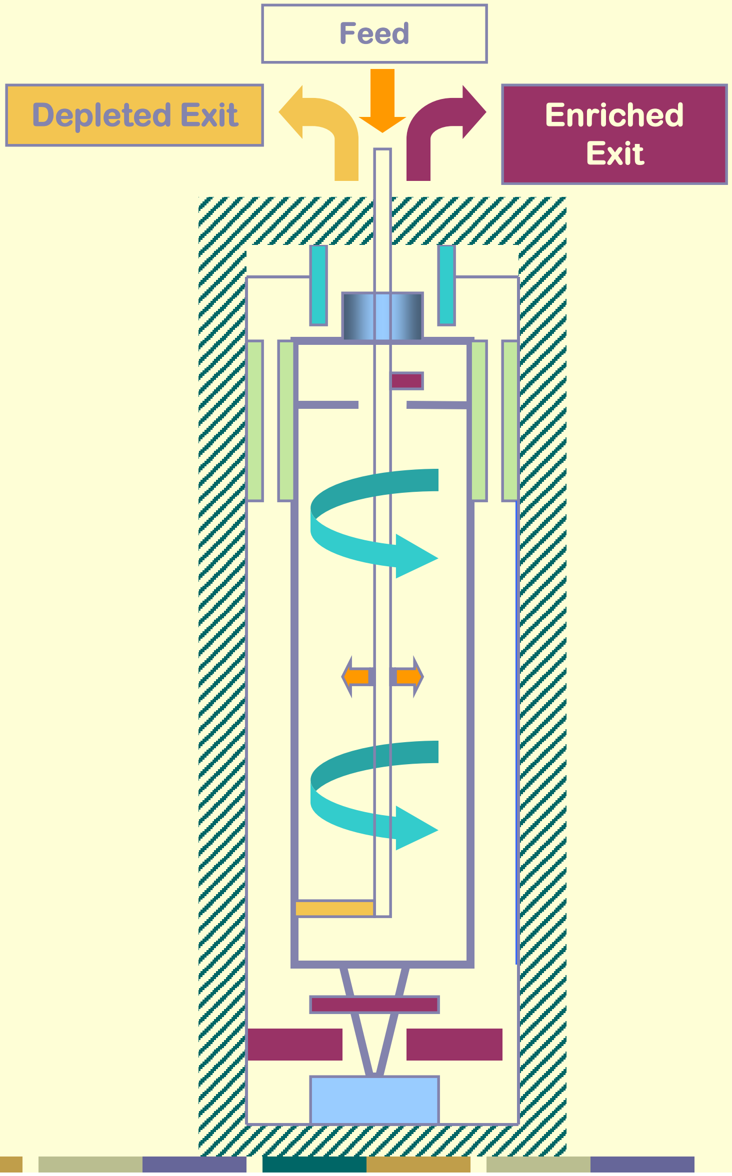
Gaseous Diffusion Enrichment Facility



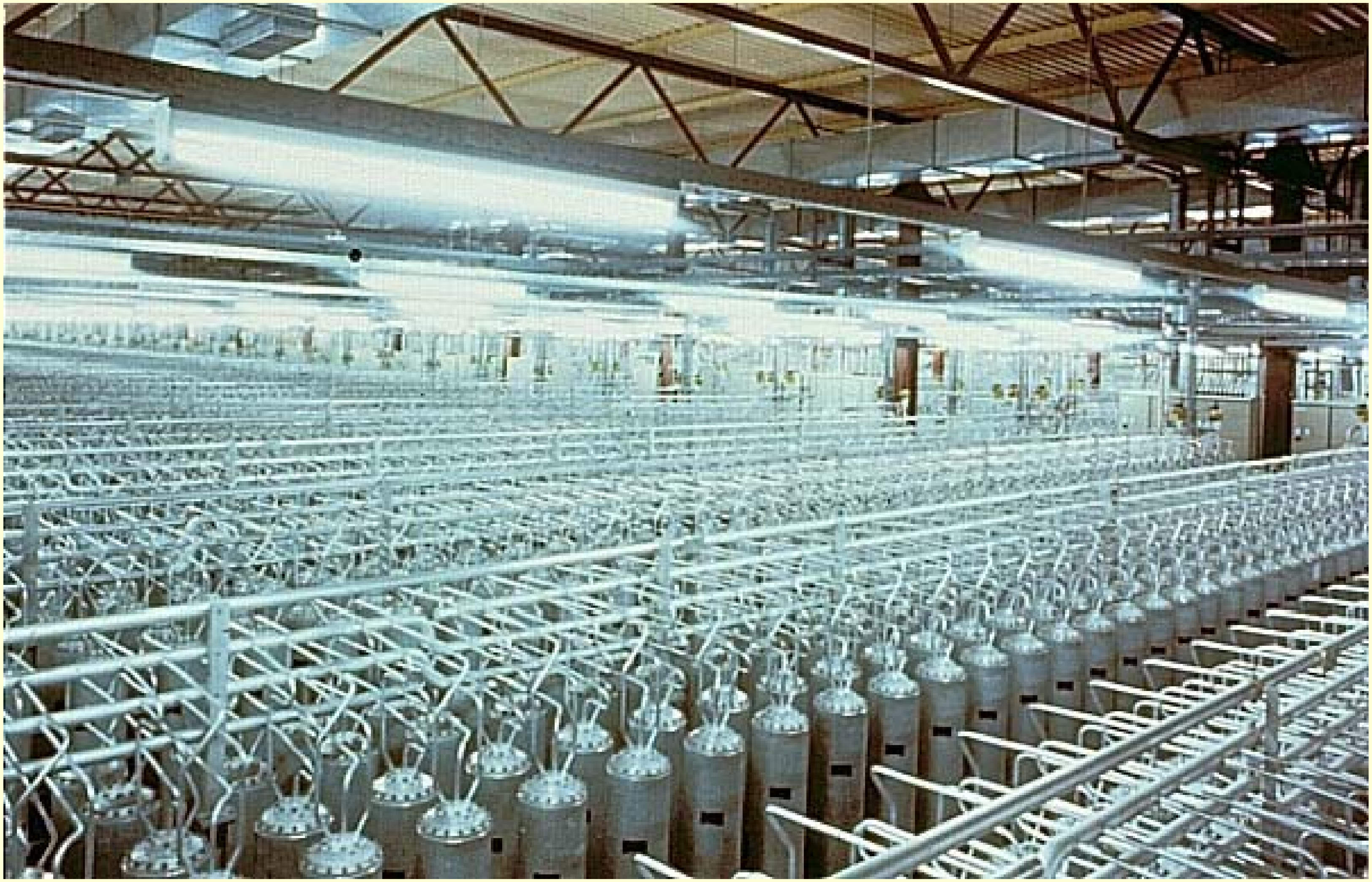
Tricastin Site: EURODIF Gas Diffusion Enrichment Plant

Enrichment: Gas Centrifuging

- The UF_6 gas is centrifuged:
  - $U^{235}F_6$ molecules are lighter and move preferentially toward the center of the rotor
    - Red Bale/Gas enriched in U^{235}
  - $U^{238}F_6$ molecules are heavier and move preferentially toward the periphery of the rotor
    - Yellow Bale/Gas depleted in U^{235}



Gas Centrifuge Enrichment Facility

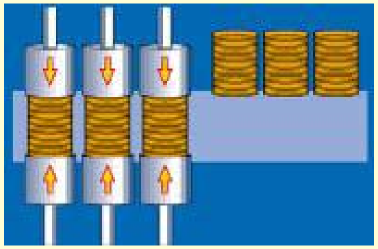


Fuel Fabrication Process

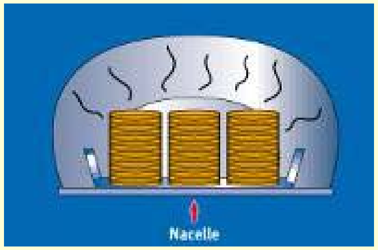
« De-Conversion »

$UF_6 \Rightarrow UO_2$

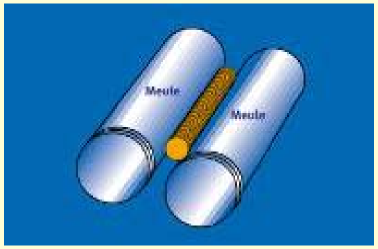
1 *Powder Production*



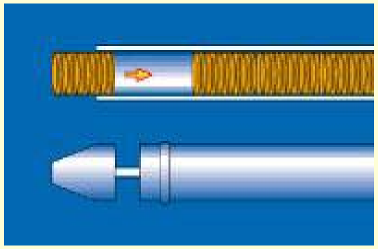
2 *Pressing or pelletizing*



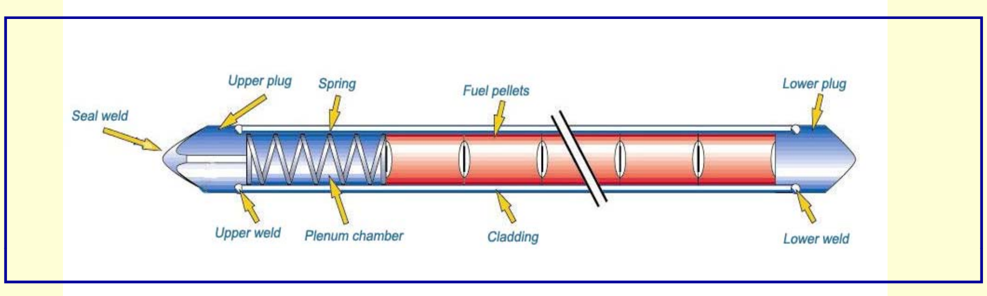
3 *Sintering*



4 *Grinding*



5 *Rod cladding*



Light water reactor fuel rod

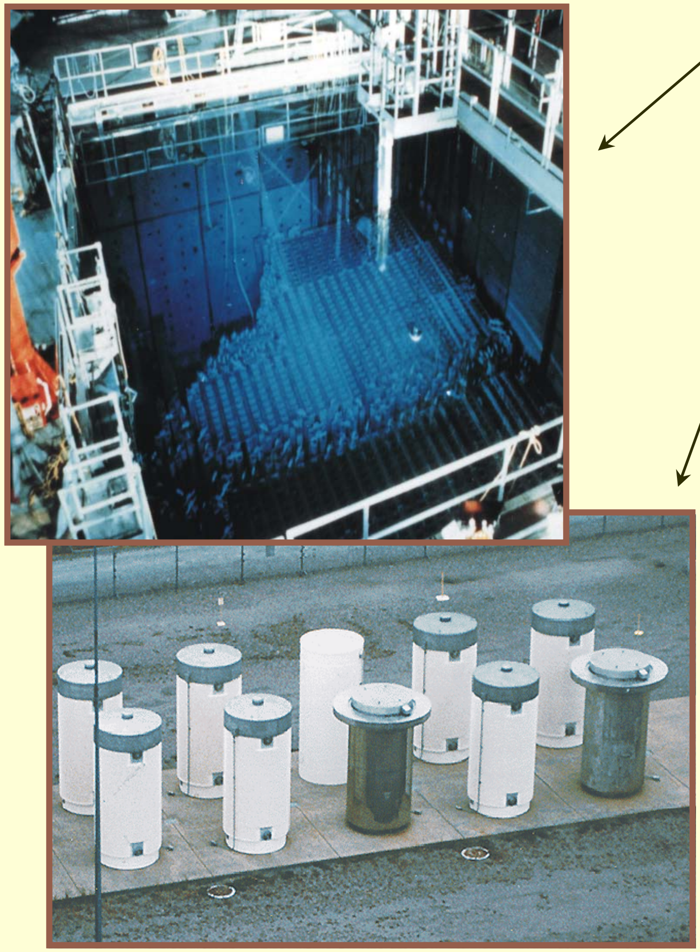
6 *Assembly fabrication*

Fabricator Consolidations

- Toshiba
  - Westinghouse (PWR)
  - ABB-CE (PWR, BWR)
  - Nuclear Fuel Industries, Ltd. (PWR, BWR)
- AREVA NP
  - Framatome Cogema Fuels (PWR)
  - Siemens Nuclear (PWR, BWR)
- GNF (Global Nuclear Fuels)
  - GE Nuclear Fuel (BWR)
  - JNF: Hitachi/Toshiba (BWR)

Spent Fuel Management (waste disposal)

In the US all spent fuel is currently stored at the plants



- In the spent fuel storage pools for about 10 years …
  - … then transferred to sealed dry casks; cooled by air; heavily shielded; internal temp and press monitored; can last for decades with minimal maintenance and cost.
  - A 1000-MW reactor requires about 80 dry casks for all the spent fuel it produces in 60 years fo operation (about 3 acres of land).
  - Dry cask storing of all US nuclear fleet spent fuel would require only 300 acres of land. (The volumes are small !!!)

Spent Fuel Management (waste disposal) (2)

In the long-term the spent fuel can be stored in deep geological repository

- The Yucca Mountain site was selected for the US, authorized by then-President Bush, the license application received by NRC in 2008
- The project is strongly opposed by the State of Nevada

The current administration intends to shut down the Yucca Mountain project and search for alternatives solutions (yet to be defined…)

The Yucca Mountain Spent Nuclear Fuel Repository

Fuel Cycle Scenarios (2)

Thermal Reactor Recycle (France, Germany, Switzerland, Belgium and Japan current, soon in the US)

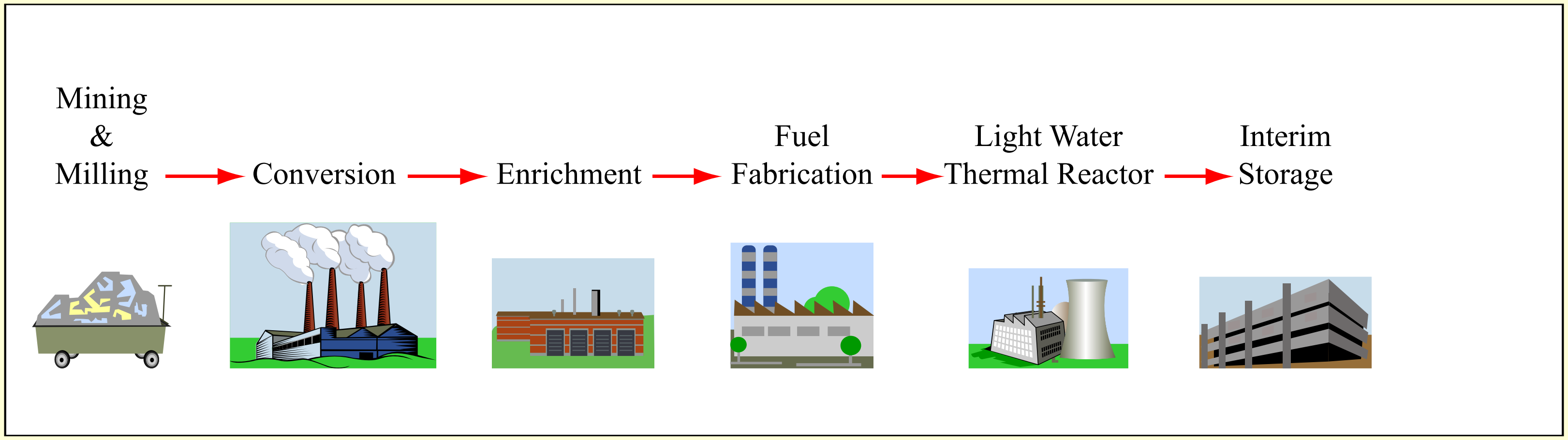
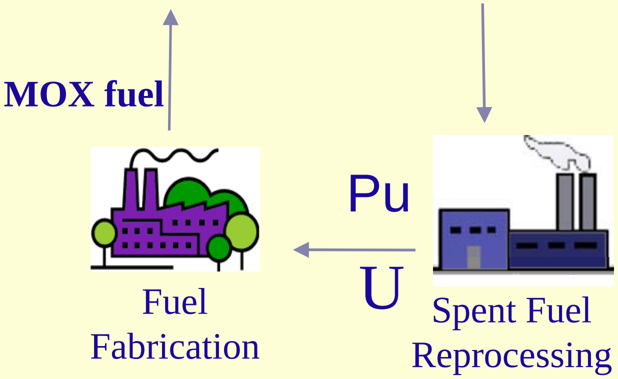


Image by MIT OpenCourseWare.



MOX fuel

Pu

U

Fuel
Fabrication

Spent Fuel
Reprocessing

Fuel Cycle Scenarios

3. Fast Reactor Recycle (demonstration stage in Japan and Russia)

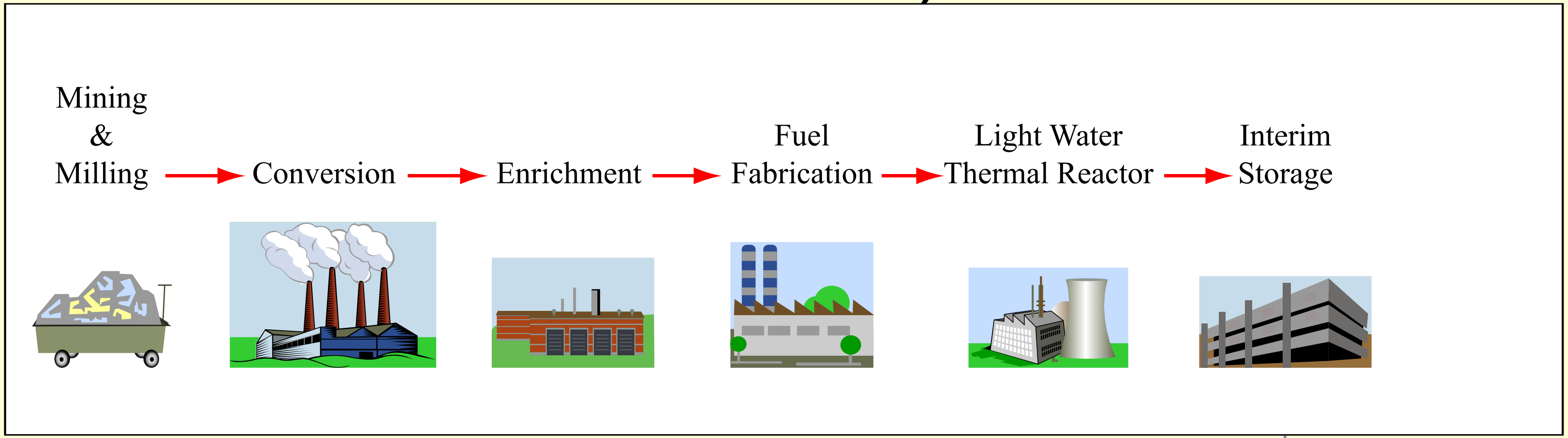
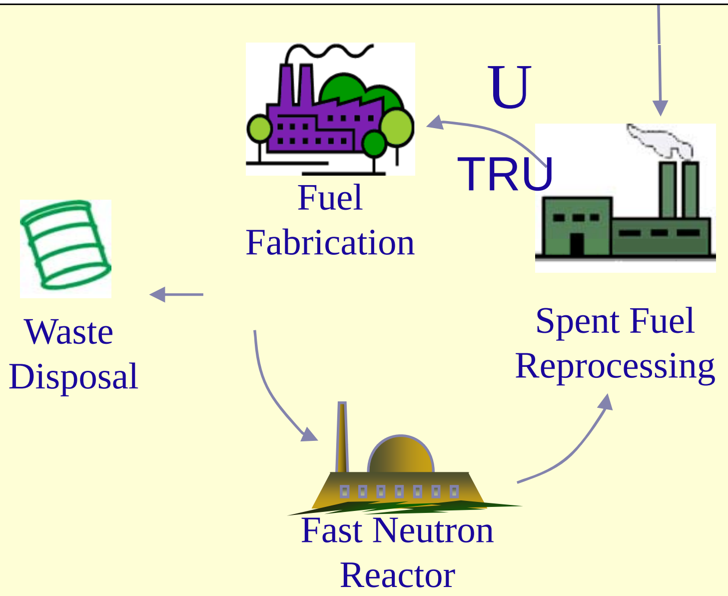


Image by MIT OpenCourseWare.



Fuel Fabrication

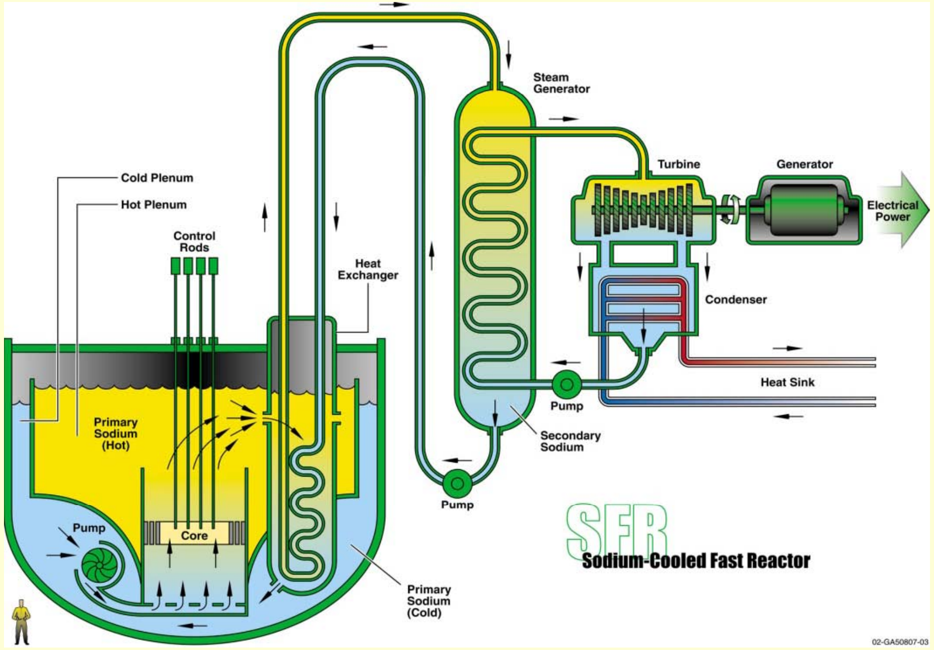
Spent Fuel Reprocessing

Waste Disposal

Fast Neutron Reactor

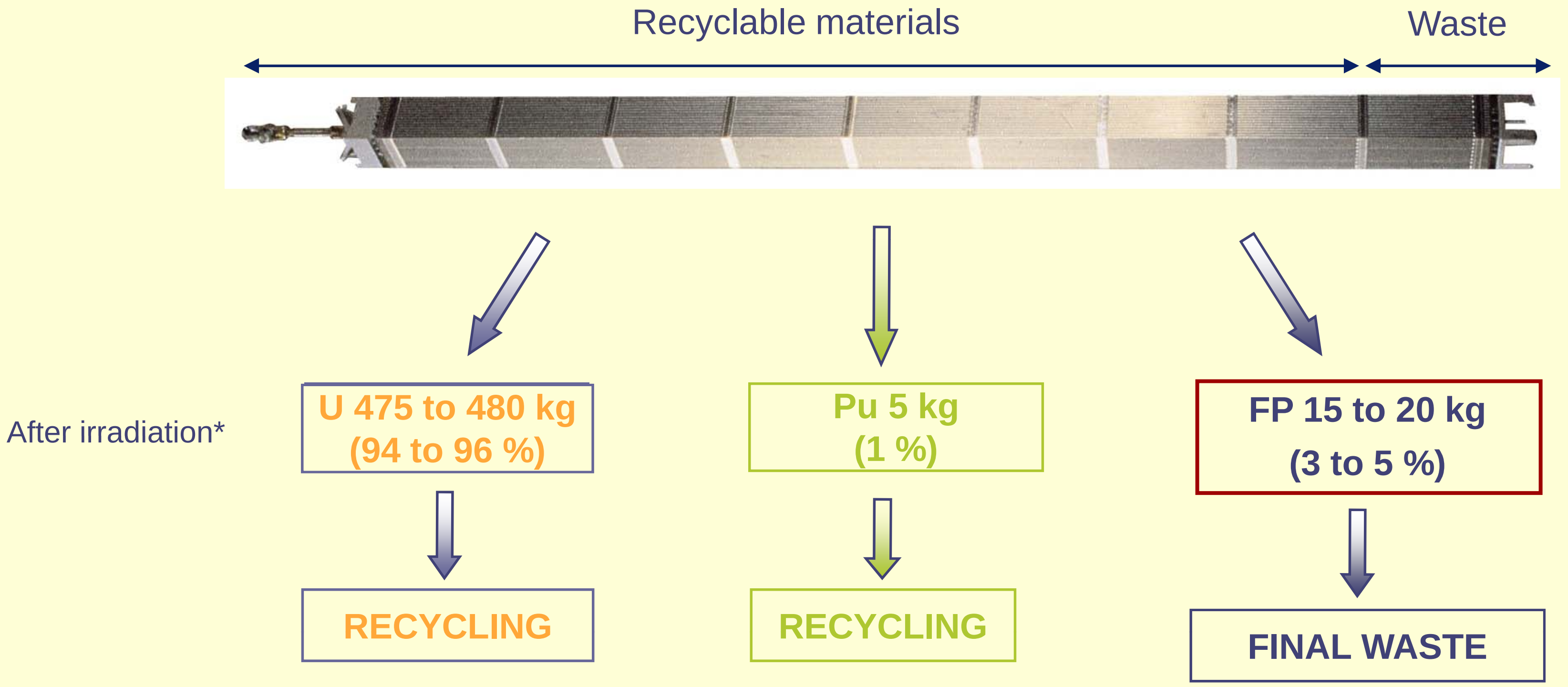
Spent fuel management (recycling)

- Spent fuel from LWRs is reprocessed and:
  - Separated Pu is recycled in LWRs (MOX approach, done in France and Japan)
  - Pu+U recycled in (sodium-cooled) fast reactors (being reconsidered in Russia, Japan, France and US under GNEP umbrella)



96% of a used fuel assembly is recyclable

- **Composition of used light water reactor fuel**
  - 1 LWR fuel assembly = 500 kg uranium before irradiation in the reactor



Recyclable materials

Waste

After irradiation*

U 475 to 480 kg
(94 to 96 %)

RECYCLING

Pu 5 kg
(1 %)

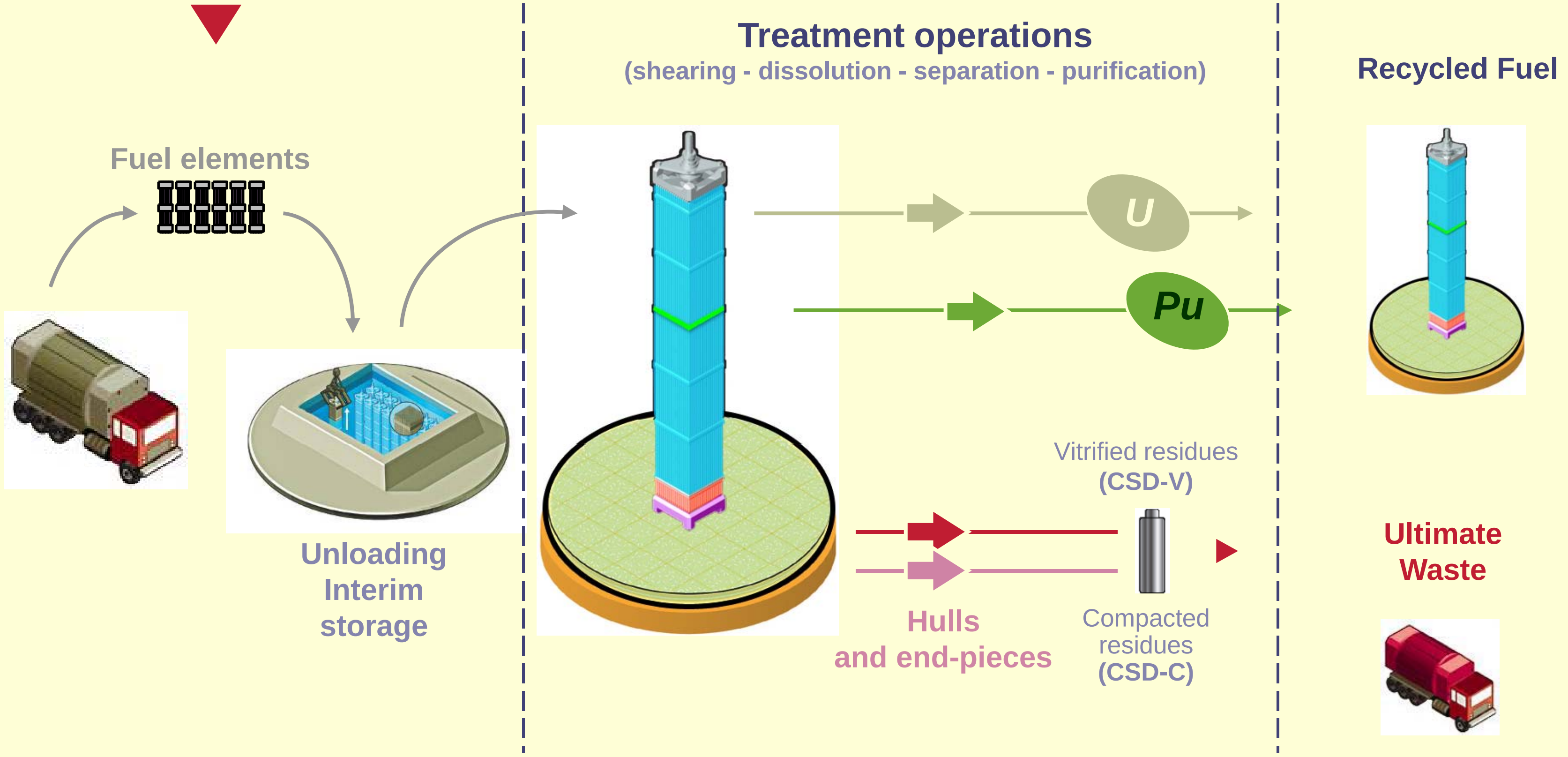
RECYCLING

FP 15 to 20 kg
(3 to 5 %)

FINAL WASTE

* Percentages may vary based on fuel burnup

The Main Stages in Recycling



Fuel elements

Unloading
Interim
storage

Treatment operations

(shearing - dissolution - separation - purification)

Recycled Fuel

U

Pu

Vitrified residues
(CSD-V)

Hulls
and end-pieces

Compacted
residues
(CSD-C)

Ultimate Waste

At each stage, nuclear material accounting under EURATOM and IAEA safeguards

Standard packaging for long-term management

Compacted waste **Vitrified waste**

Proliferation Risk

- **Some technical characteristics of the fuel cycle (high burnup, no Pu separation, use of Th) can alleviate (but not completely eliminate) the proliferation risk**
- **For the US the problem is minimal, as the fuel cycle is well safeguarded**
- **For developing countries it is mostly a political problem, perhaps best handled through multilateral and/or bilateral inspections (successful example: Brazil/Argentina)**

Conclusions

- Nuclear produces 20% of US electricity today
- Renewed interest in nuclear stems from concerns over climate change and fossil fuel imports
- Nuclear can displace coal in electricity sector and a lot of oil in transportation sector
- New reactor technologies offer superior level of safety achieved via increased redundancy and/or passive safety systems
- Various nuclear fuel cycle options are available
- Challenge is capital cost of new plants (not safety… and not waste)

22.06 Engineering of Nuclear Systems
Fall 2010