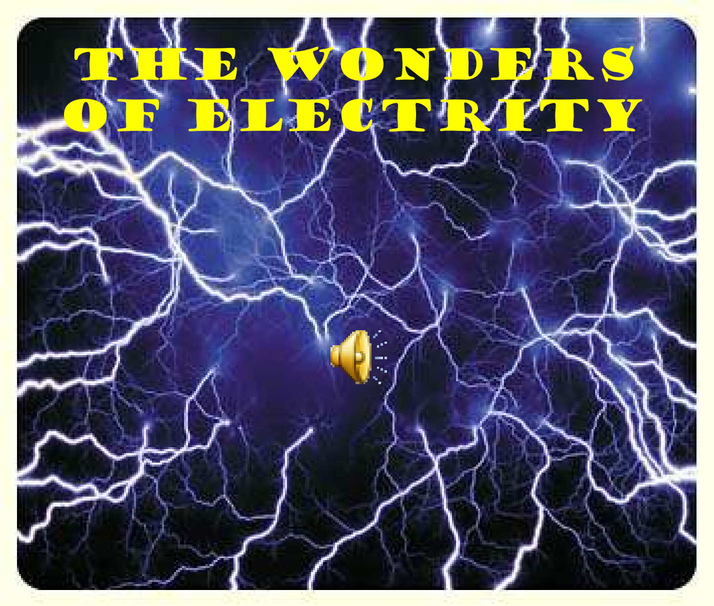
Electricity Generation in Nuclear and Fossil Power Plants



Prof. Jacopo Buongiorno
Nuclear Science and Engineering Dept., MIT
Jacopo@mit.edu, tel. 617-253-7316

CENTER FOR ADVANCED NUCLEAR ENERGY SYSTEMS

Why electricity is important

- Electric lights

Why electricity is important (2)

- Home appliances run on electricity

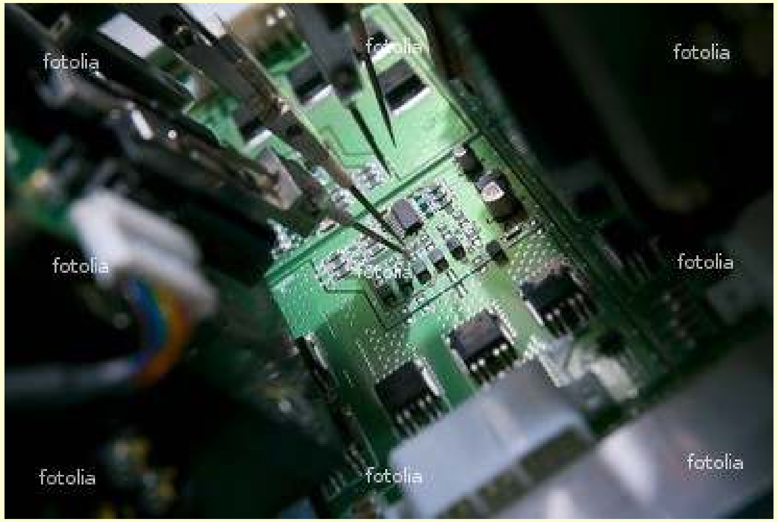
Why electricity is important (3)

- Some means of transportation run on electricity

↑ The fastest trains in the World are electric

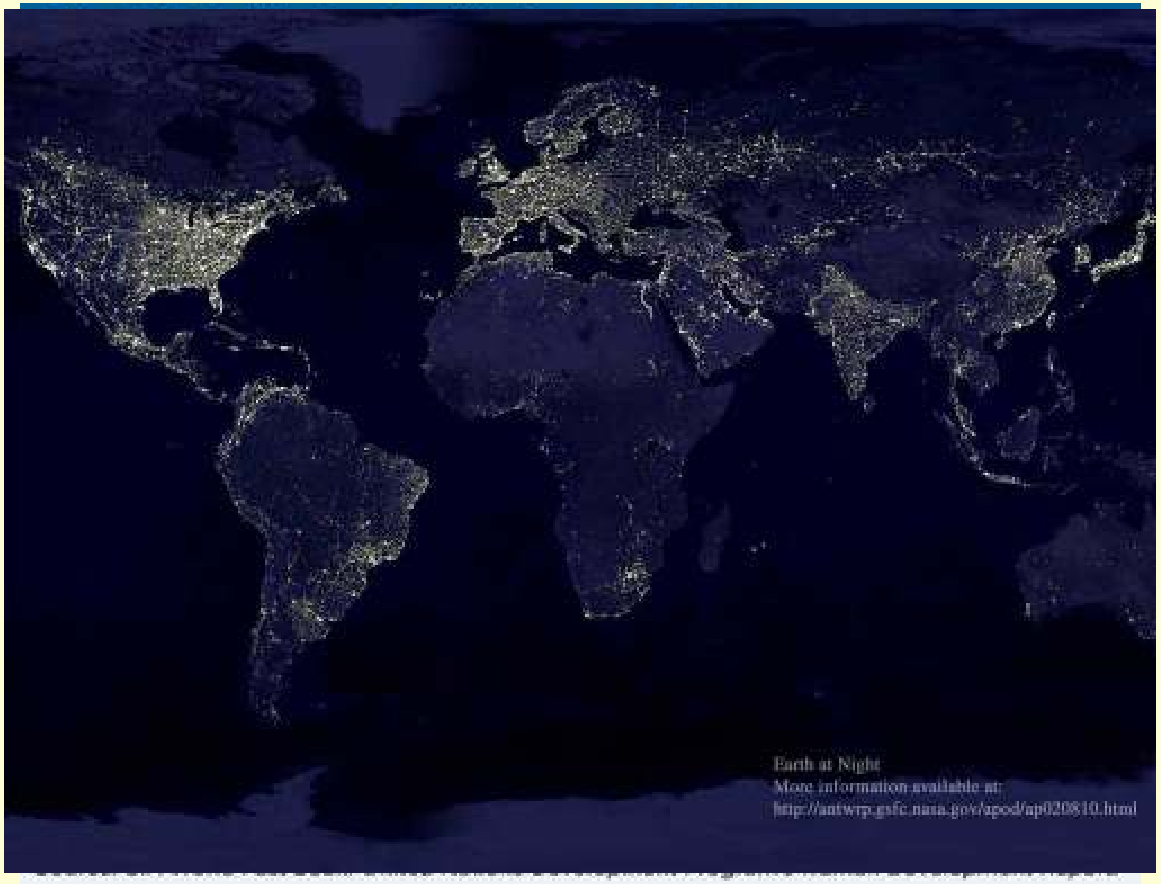
Why electricity is important (4)

- Factories run on electricity



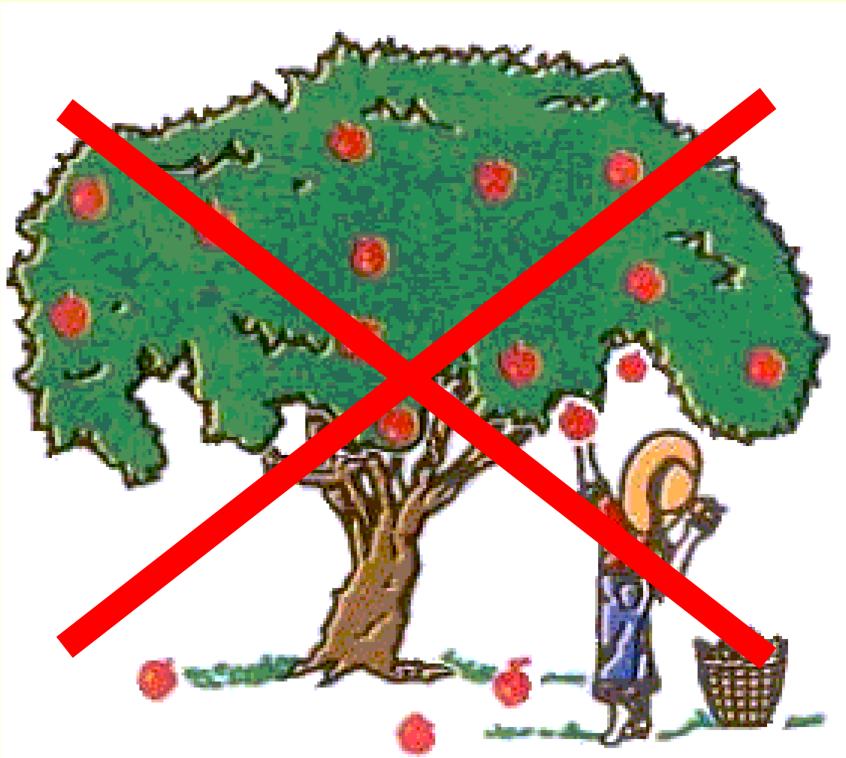
Why electricity is important (5)

- Strong correlation between reliable access to electricity and quality of life



Where do we get electricity from?

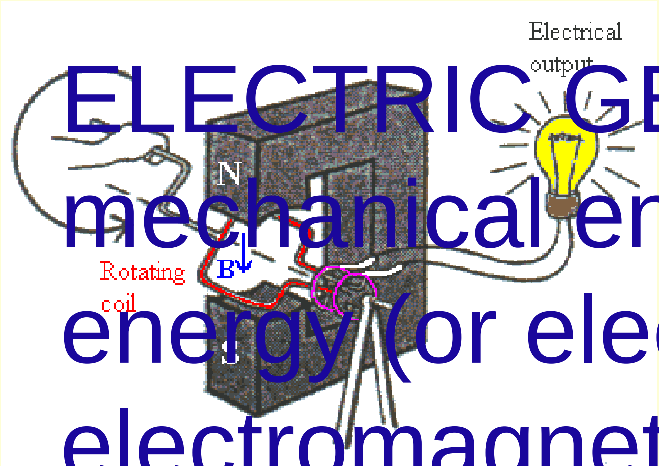
We don't mine it

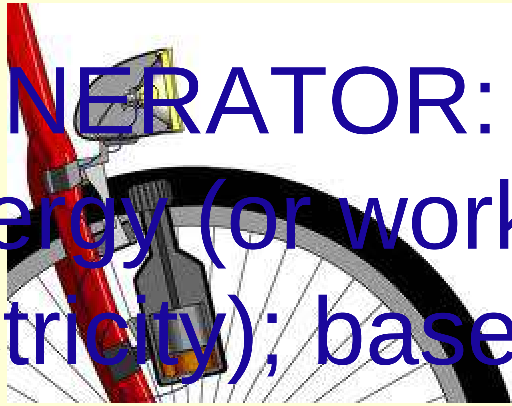


We don't harvest it

Where do we get electricity from? (2)

- We need to generate it from other primary energy sources…





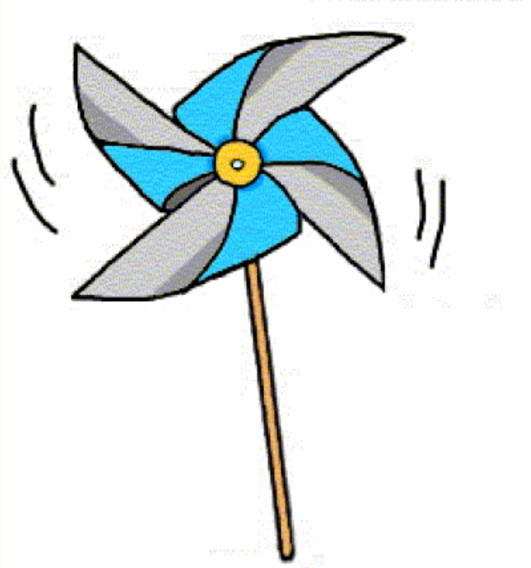
ELECTRIC GENERATOR: turns mechanical energy (or work) into electric energy (or electricity); based on electromagnetic induction

So, to generate electricity, I need to spin an electric generator

Where do we get electricity from? (3)

- To spin an electric generator, I can use:

Wind



Needs a place that is windy most of the time

Where do we get electricity from? (4)

- To spin an electric generator, I can use:

Water

Needs a dam to collect a lot of water

Where do we get electricity from? (5)

- To spin an electric generator, I can use:

Steam

How do I get steam? Boil water, which requires *heat*

Where do we get electricity from? (6)

- To get heat, I can burn:

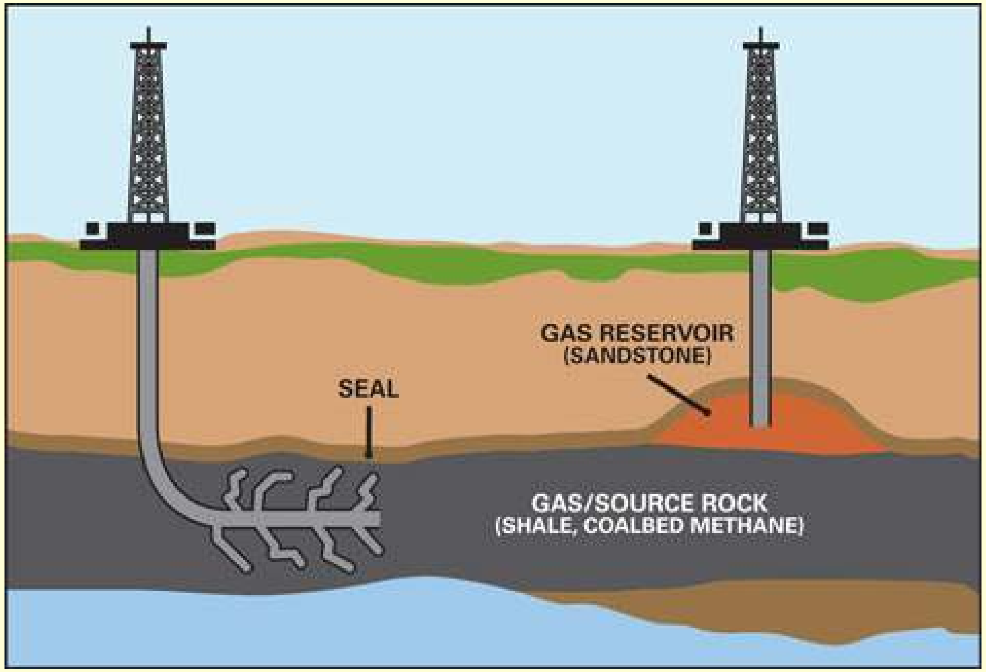
Coal

Coal is mined from the ground

Where do we get electricity from? (7)

- To get heat, I can burn:

Natural Gas



We drill deep underground and undersea to extract natural gas

Where do we get electricity from? (8)

- To get heat, I can use:

Sunlight

Needs a place that is sunny most of the time

Where do we get electricity from? (9)

- To get heat, I can use:

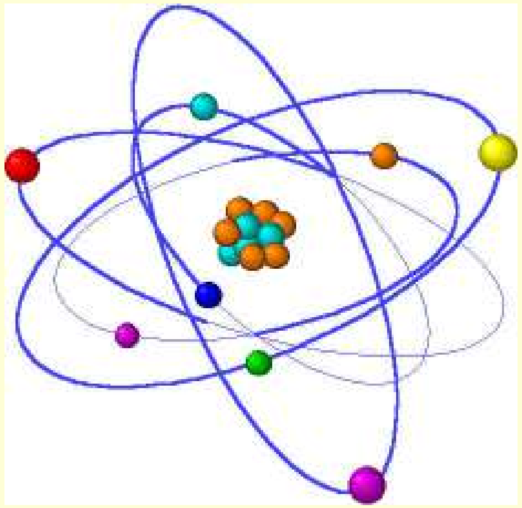
Geothermal

Limited number of locations where Earth’s internal energy rises to the surface

Where do we get electricity from? (10)

- To get heat, I can use:

Nuclear Energy



Nuclear fuel is uranium, mined from underground

Where do we get electricity from? (11)

	US	World
1)Coal	37%	41%
2)Natural Gas	30%	22%
3)Nuclear Energy	19%	12%
4)Water (hydro)	7%	16%
5)Wind	<4%	<2%
6)Geothermal	<1%	<1%
7)Sunlight (solar)	<1%	<1%
8)Other (oil, biomass, …)	~2%	~6%

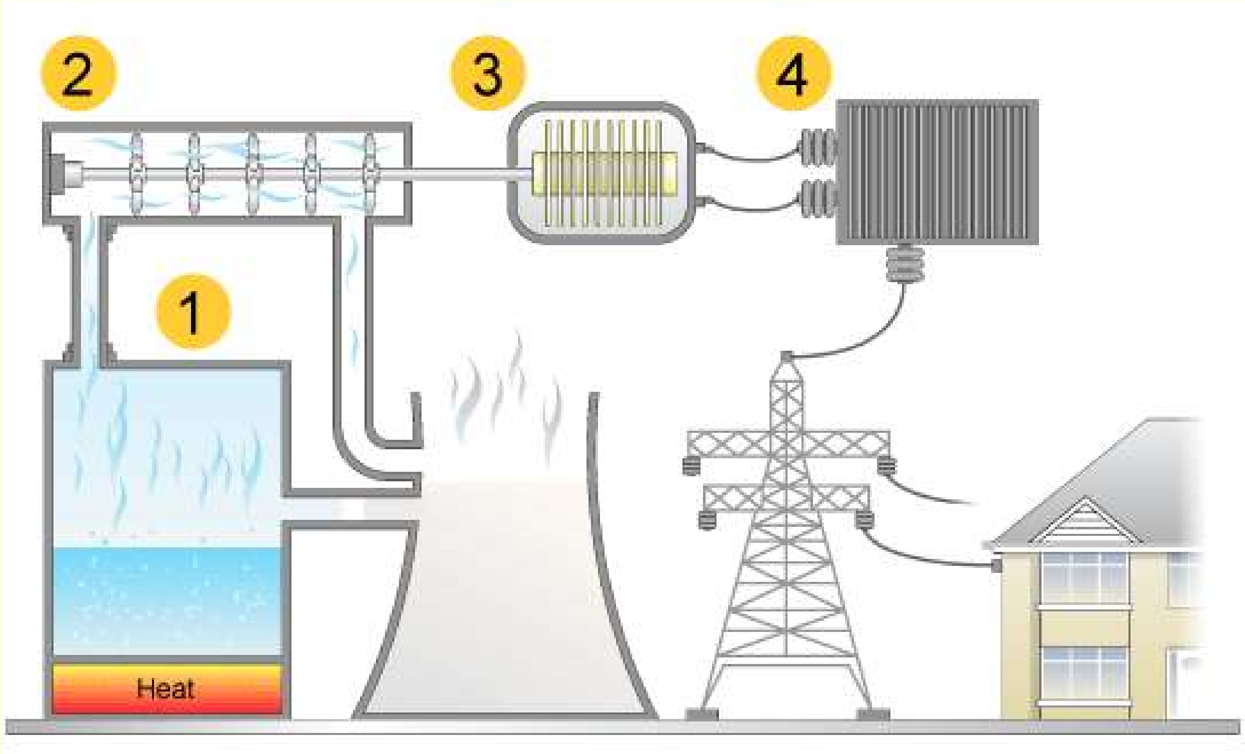
Focus here is on nuclear, coal and natural gas

Things to watch about primary energy sources for electricity generation

- Fuel availability (how much fuel there is) and reliability of fuel supply
- Land use (how much land is used)
- Pollution (what is released into the environment)
- Continuity of generation (can electricity be generated all the time)
- Cost (how expensive it is)

Fossil Fuels
(coal and natural gas)

Electricity Generation from Fossil Fuels

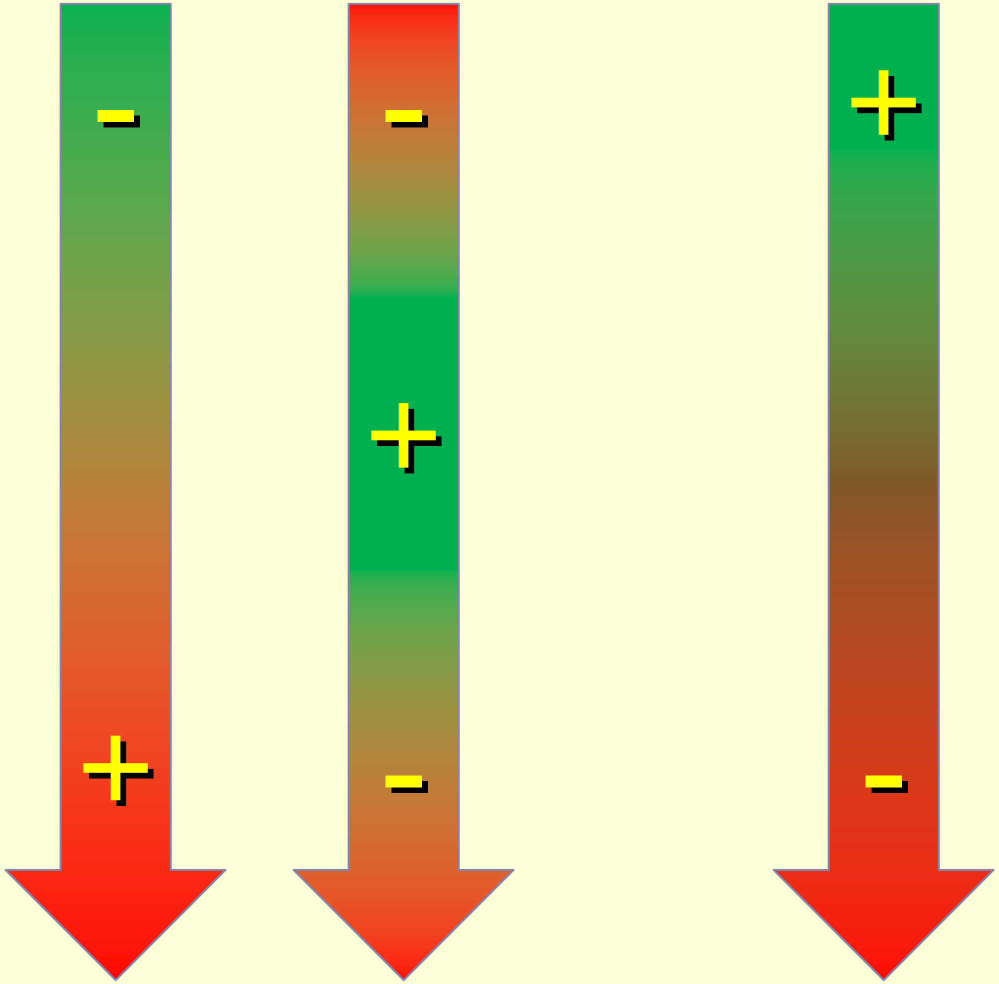


1. Heat is released from combustion of fuel (**coal, gas, oil**) and boils the water to make steam
2. The steam turns the turbine
3. The turbine turns a generator and electricity is produced
4. The electricity goes to the transformers to produce the correct voltage

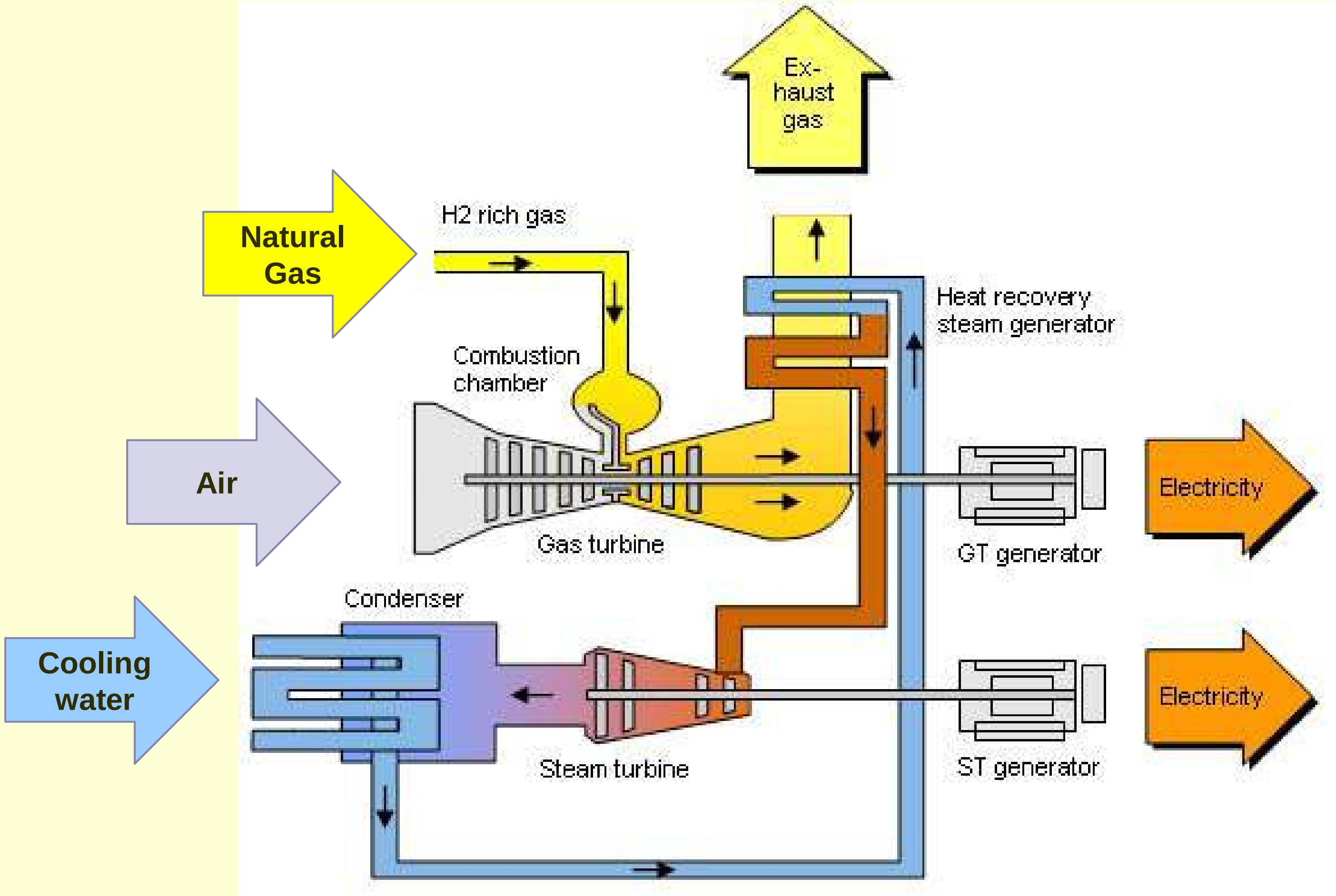
Coal-based Electricity Generation

Technologies | **Costs** | **Efficiency** | **Commercialization & Diffusion**

1. **Subcritical Pulverized Coal**
2. **Supercritical Pulverized Coal**
3. **Ultra-Supercritical Pulverized Coal**
4. **Integrated Gasification Combined Cycle**
5. **Oxygen-Blown Coal Based**

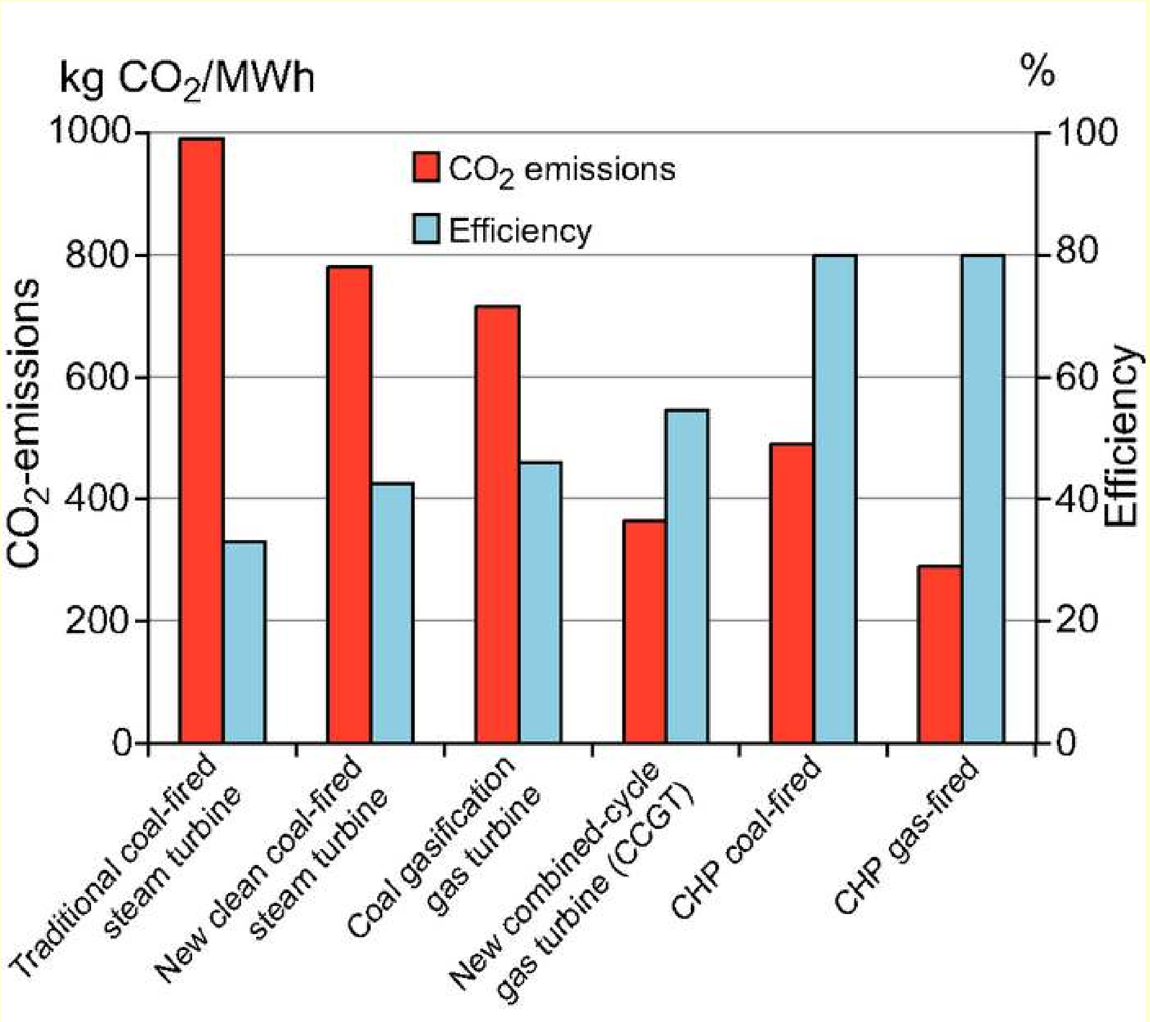


Natural Gas : Combined Cycle Gas Turbine (CCGT)

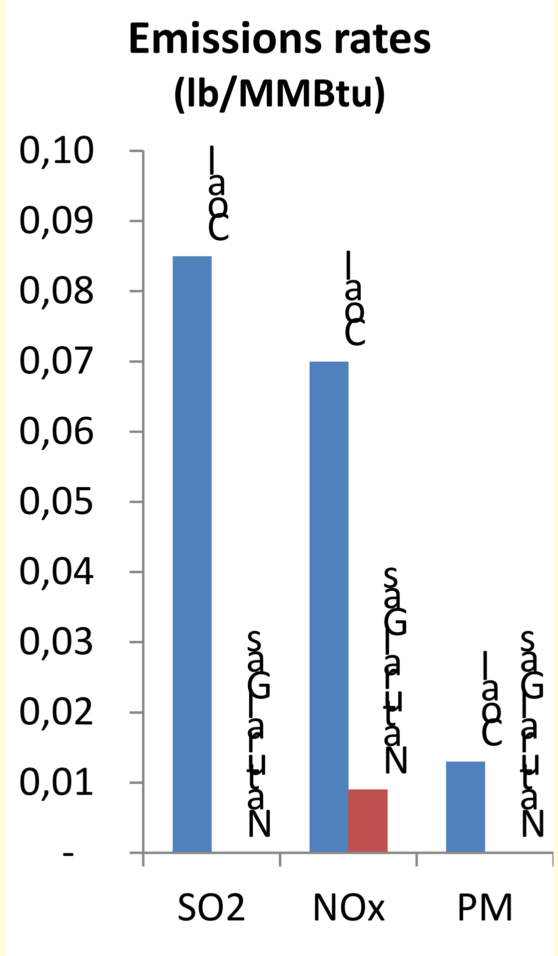


The comparative advantages of CCGT: Low investment cost, Flexibility, Low emissions (compared to coal), High efficiency

Environmental Performance of Coal and Natural Gas Power Plants



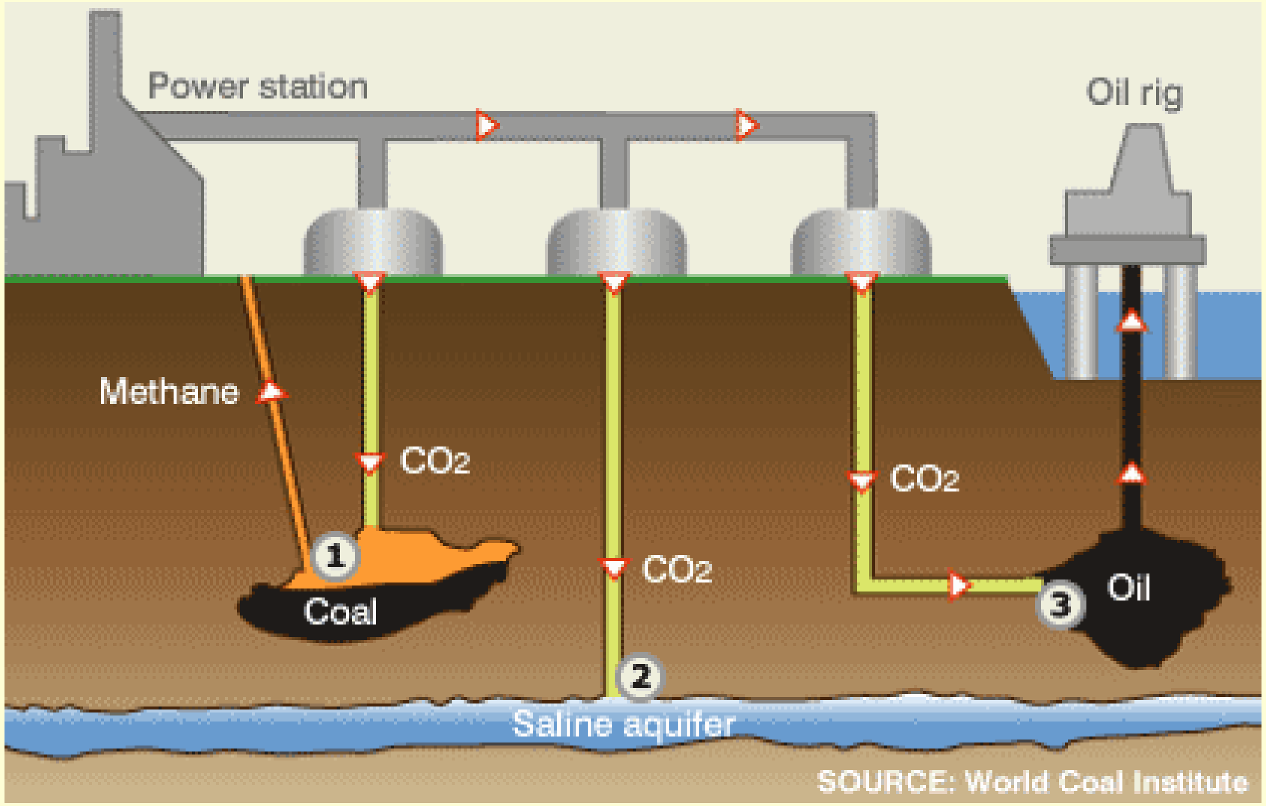
Source: IPCC Fourth Assessment Report



Coal: supercritical PC
Natural gas : CCGT
Source: US DOE/NETL, 2010-1397

Is Carbon Capture and Storage a viable solution?

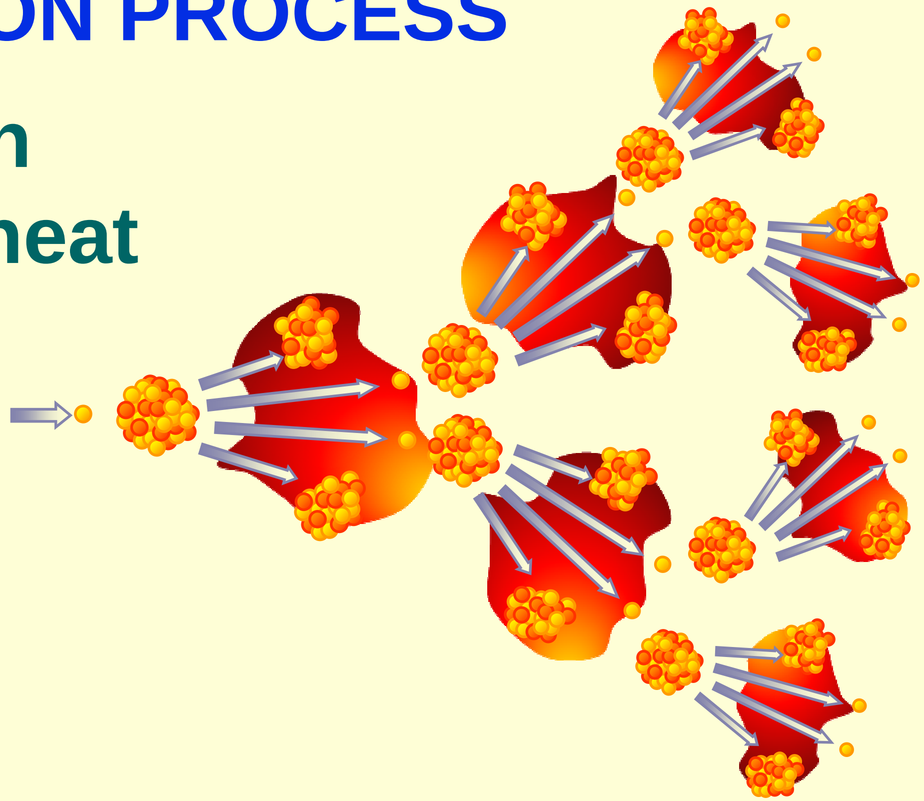
- **Carbon capture and storage** (**CCS**) is the process of capturing CO_2 from fossil fuel power plants, transporting it to a storage site, and depositing it where it will not enter the atmosphere, normally an underground geological formation
- It is a **potential** (CCS on large scale is a relatively new concept) but **expensive** means of mitigating the contribution of fossil fuel emissions to global warming and ocean acidification.



Nuclear Energy

THE NUCLEAR FISSION PROCESS

Neutron-driven chain reaction producing heat



- The isotope 235 of Uranium (U-235) is the fuel: 2.5 million times more energy per kg than coal
- Only 37 tons of fuel (3%-enriched uranium) per year needed for 1000 MWe reactor

- Nuclear fission provides an emission-free heat source that can be converted into electricity

Nuclear compared to fossil fuels

Fuel energy content

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

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

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

Fuel Consumption, 1000 MWe Power Plant (~740,000 homes)

Coal (40% efficiency):

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

Natural Gas (50% efficiency):

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

Nuclear (33% efficiency):

$10^9/(0.33 \times 200 \times 1.6 \times 10^{-13}) \approx 1.0 \times 10^{20}$ ^{235}U/sec (=3 kg/day)

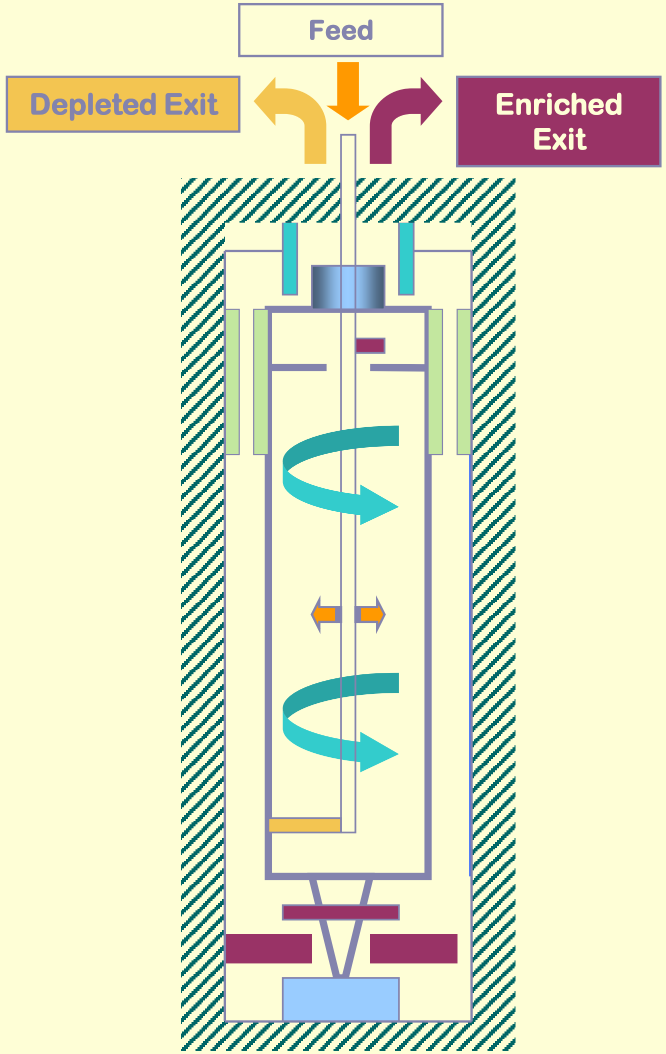
1 eV = 1.6×10^{-19} J

Uranium Milling & Mining Process

- 1 ton ore = 2-3 lb (1-2 kg) uranium
- End product is U_3O_8 powder (“yellowcake”)
- Major suppliers:
  - Canada
  - Australia
  - Kazakhstan
  - Africa
  - Former Soviet Union [FSU]

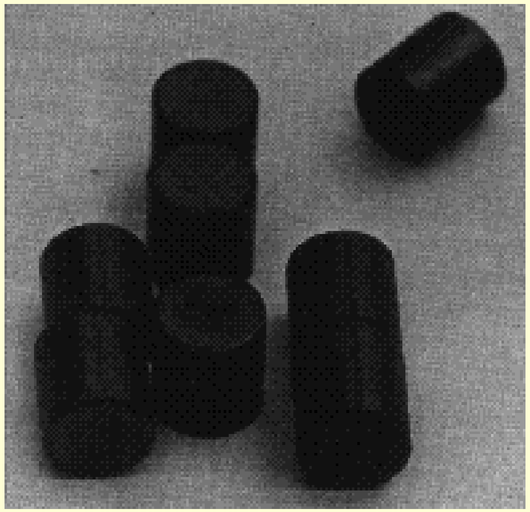
Uranium Enrichment

- Natural uranium is only 0.7% U-235 and 99.3% U-238
- Nuclear reactors need uranium with U-235 concentration in 3-5% range
- Thus the uranium fuel has to be “enriched” in U-235
- U_3O_8 is converted to UF_6 (a gas) and then centrifuged to separate U-235 from U-238



Fabrication of Fuel Assemblies

- Once UF_6 has been enriched, it is converted to UO_2 and formed into cylindrical pellets
- UO_2 pellets are inserted into sealed tubes, called "fuel pins"
- Fuel pins are bundled into a fuel assembly



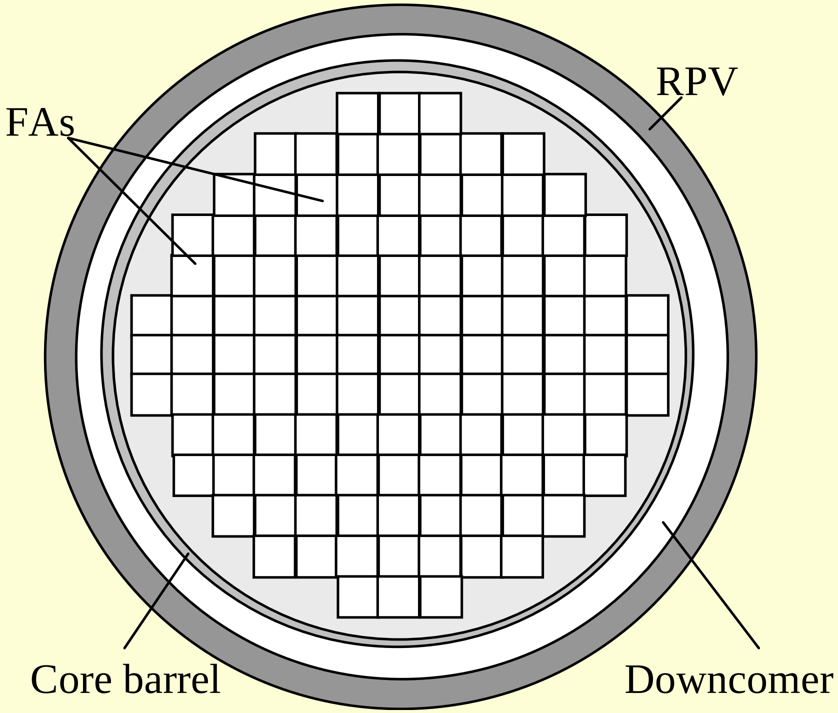
UO_2 pellets

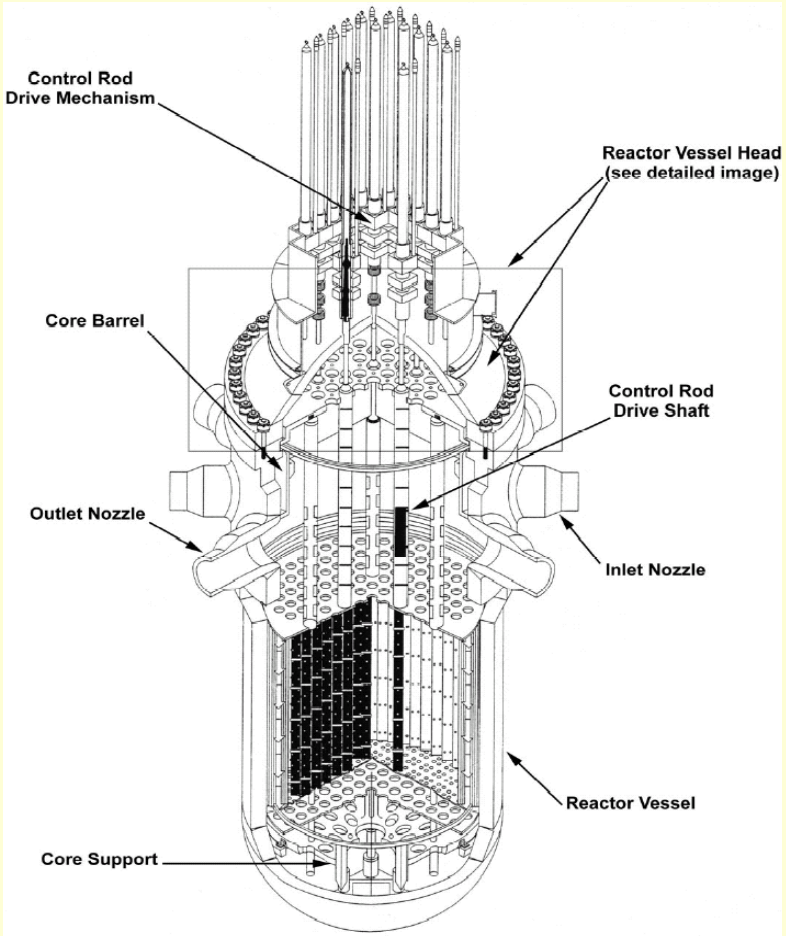
Fuel pin

Fuel assembly

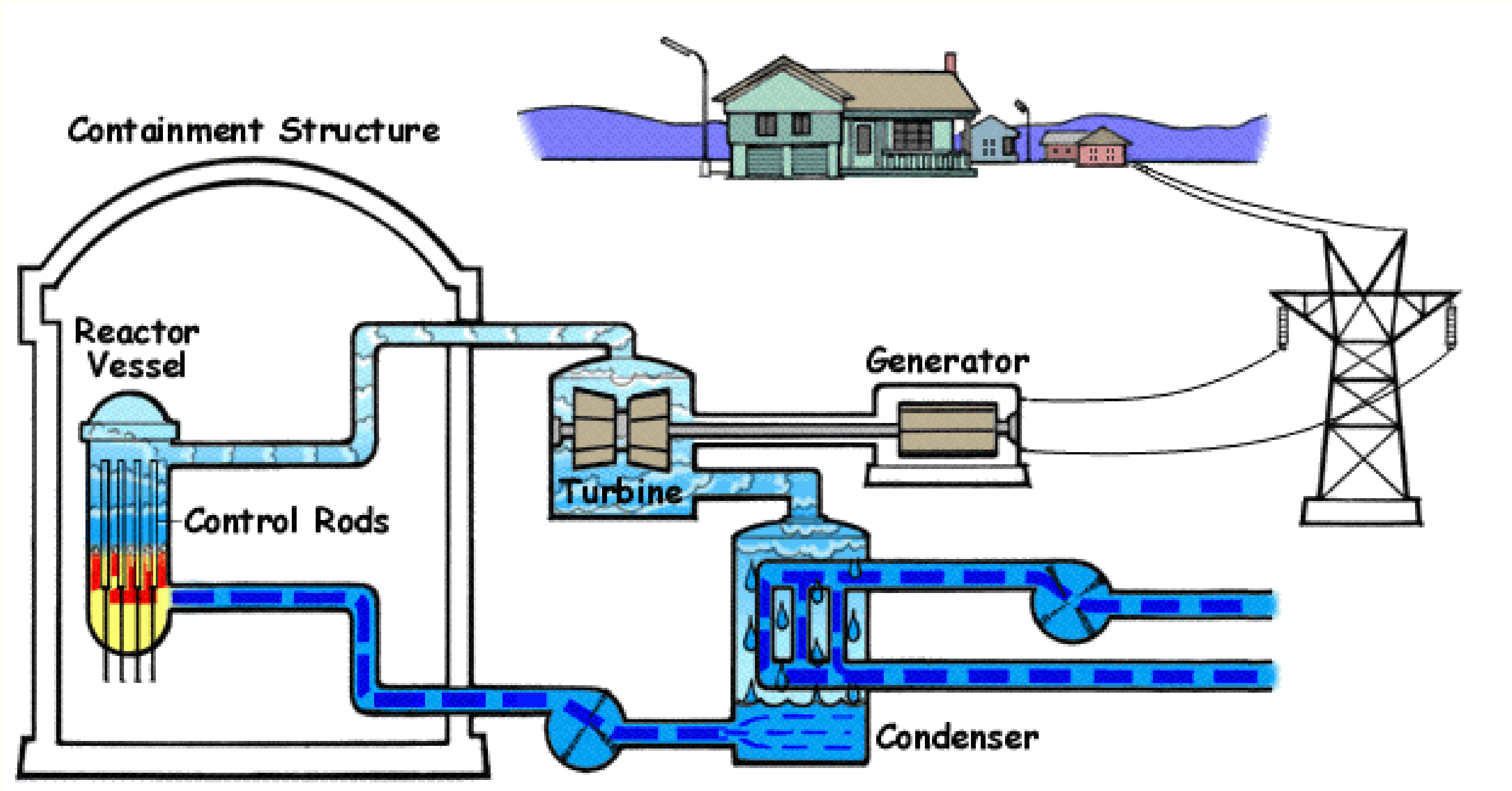
The Nuclear Reactor Core

- Hundreds of fuel assemblies are arranged in a regular lattice to form the reactor core
- The reactor core is housed within a Reactor Pressure Vessel (RPV) made of steel

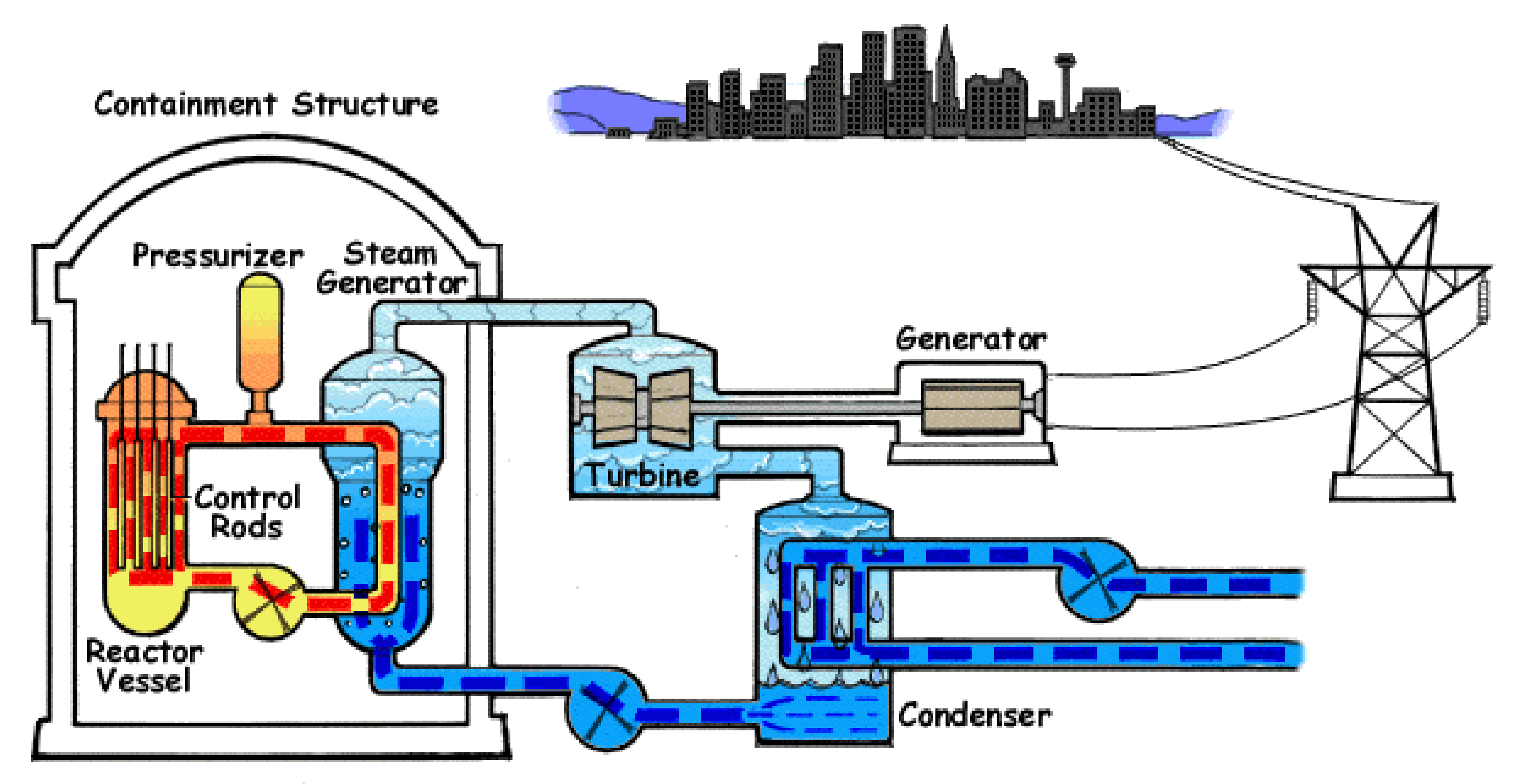




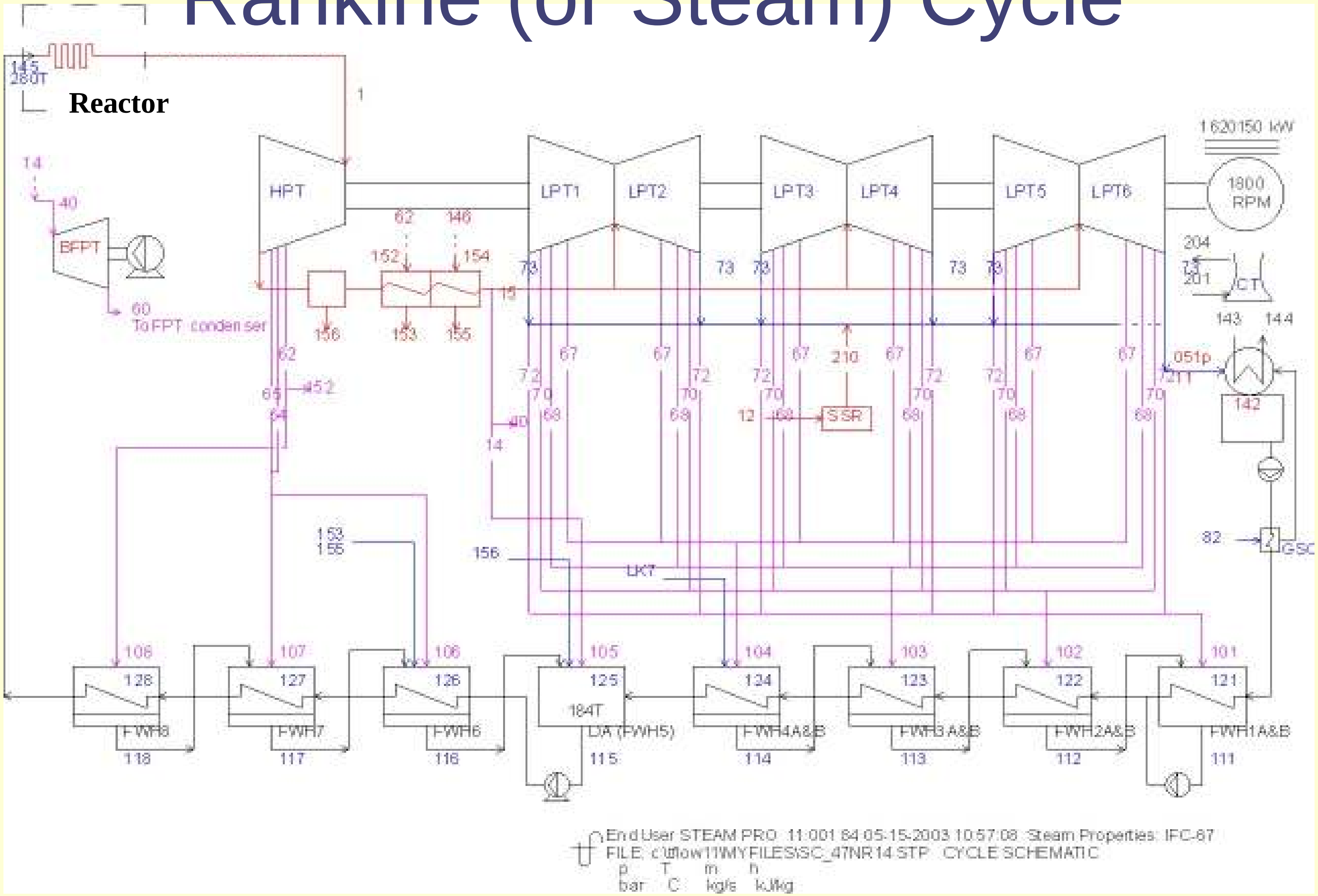
Boiling Water Reactor (BWR)

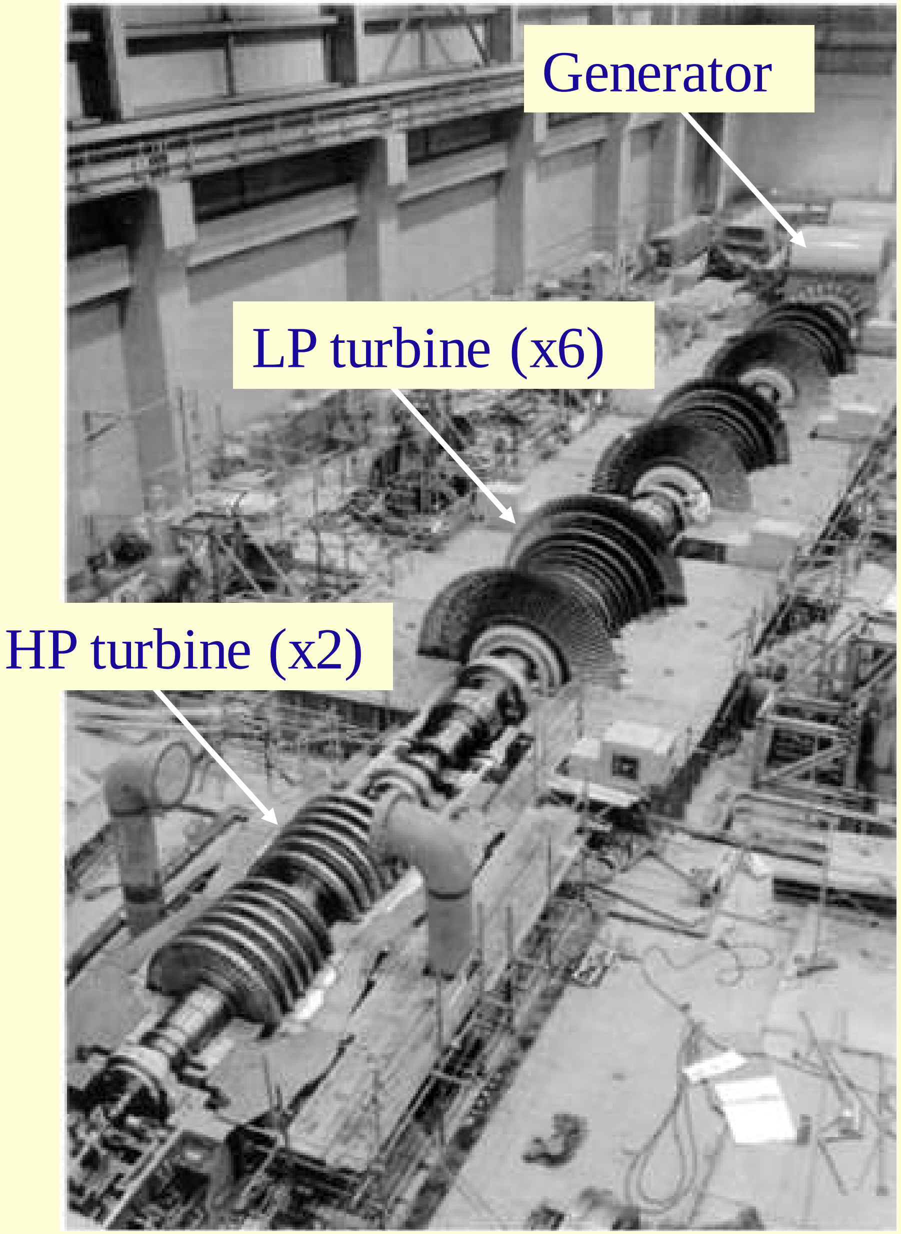


Pressurized Water Reactor (PWR)



Rankine (or Steam) Cycle





Turbine-generator

turns internal energy of steam into work, then electricity

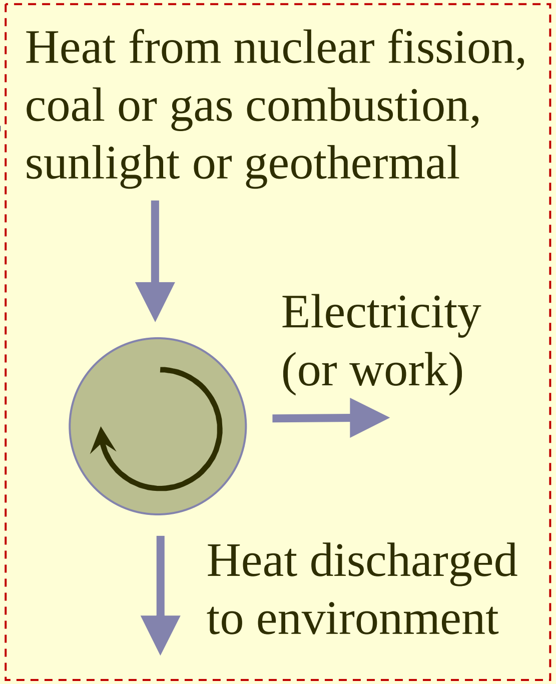
Heat Discharge in Power Plants

2nd law of thermodynamics: not all heat input can be converted to electric energy

$$\eta \ \textit{(efficiency)} \equiv \frac{\text{Net Electric Output}}{\text{Heat Input}}$$

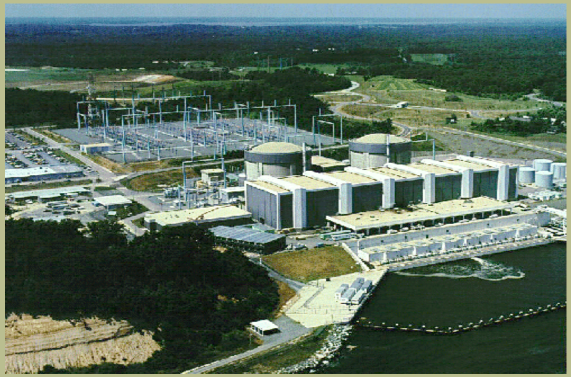
Depends on steam temperature (280-600°C) and ambient temperature: 33-35% (nuclear), 38-45% (coal), 50-60% (CCGT)

Power Plant

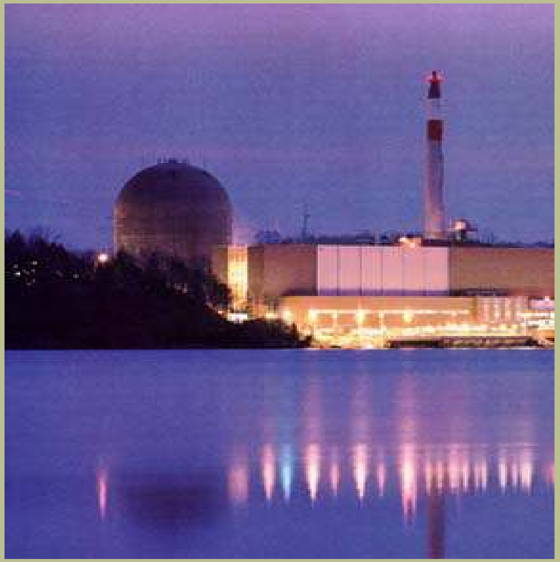


Nuclear Energy in the US, today

- **100 US reactors, 100 GWe is 13% of US installed capacity but provides about 19% of total electricity.**
- **In 2010 nuclear energy production in the US was the highest ever.**
- **US plants have run at 86.4% capacity in 2012, up from 56% in 1980.**
- **3.1 GWe of uprates were permitted in the last decade. 1.5 GWe are expected by 2017.**
- **73 reactor licenses extended, from 40 years to 60 years of operation, 27 more reactors in process.**
- **Electricity production costs of nuclear are the lowest in US (1.9-2.9 ¢/kWh), but natural gas costs have come down**

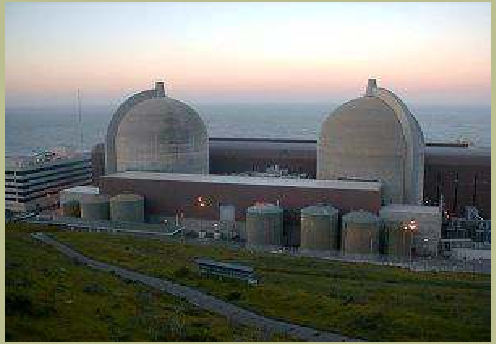


Calvert Cliffs - MD



Indian Point - NY

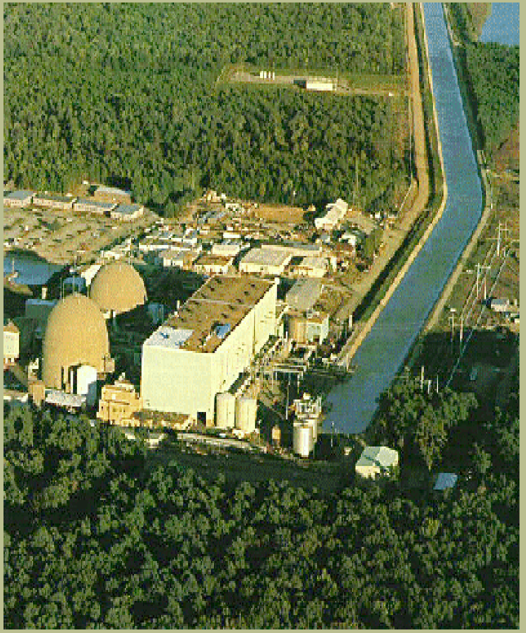
Robinson - SC



Diablo Canyon - CA

Seabrook - NH

Prairie Island site - MN

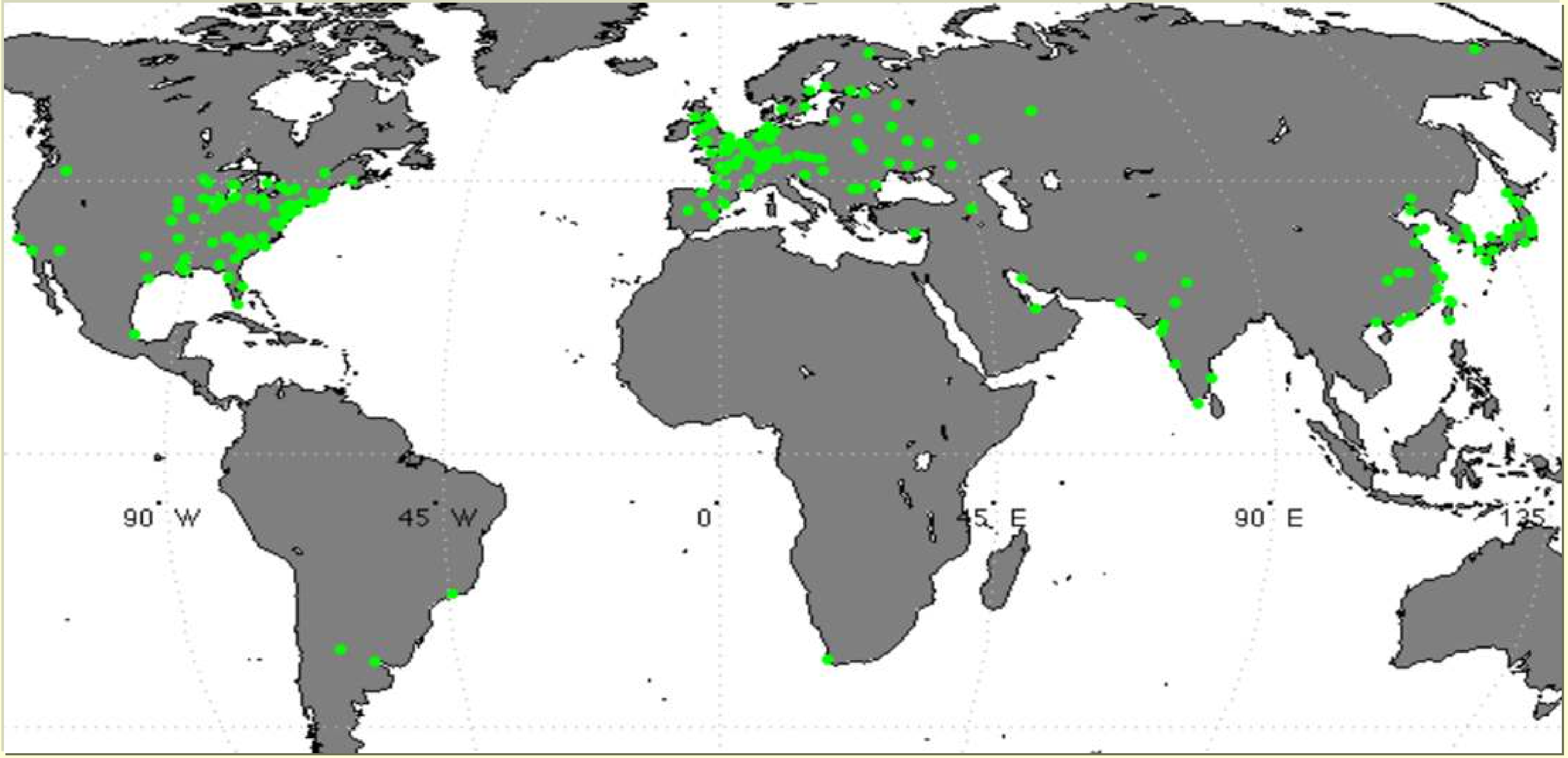


Surry - VA

The MIT Research Nuclear Reactor

- 6 MW power
- Located on MIT campus
- Operated by MIT students
- In service for 50+ years!

Nuclear Energy in the World Today



Courtesy of MIT graduate student Mark Reed

About 440 World reactors in 30 countries, 12% 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

Taishan – China

3 project ongoing in the US

Vogtle, Georgia

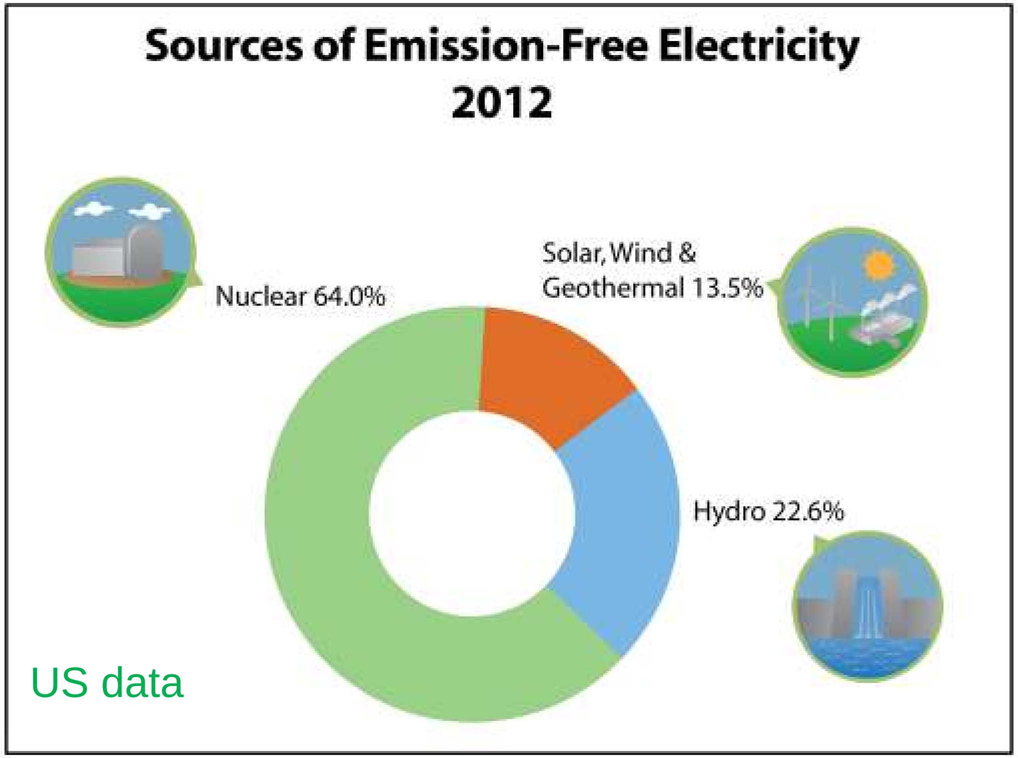
Summer, South Carolina

Watts Bar, Tennessee

The Case for New Nuclear Plants

Concerns for ***climate change…***

Athabasca Glacier, Jasper National Park, Alberta, Canada
Photo provided by the National Snow and Ice Data Center

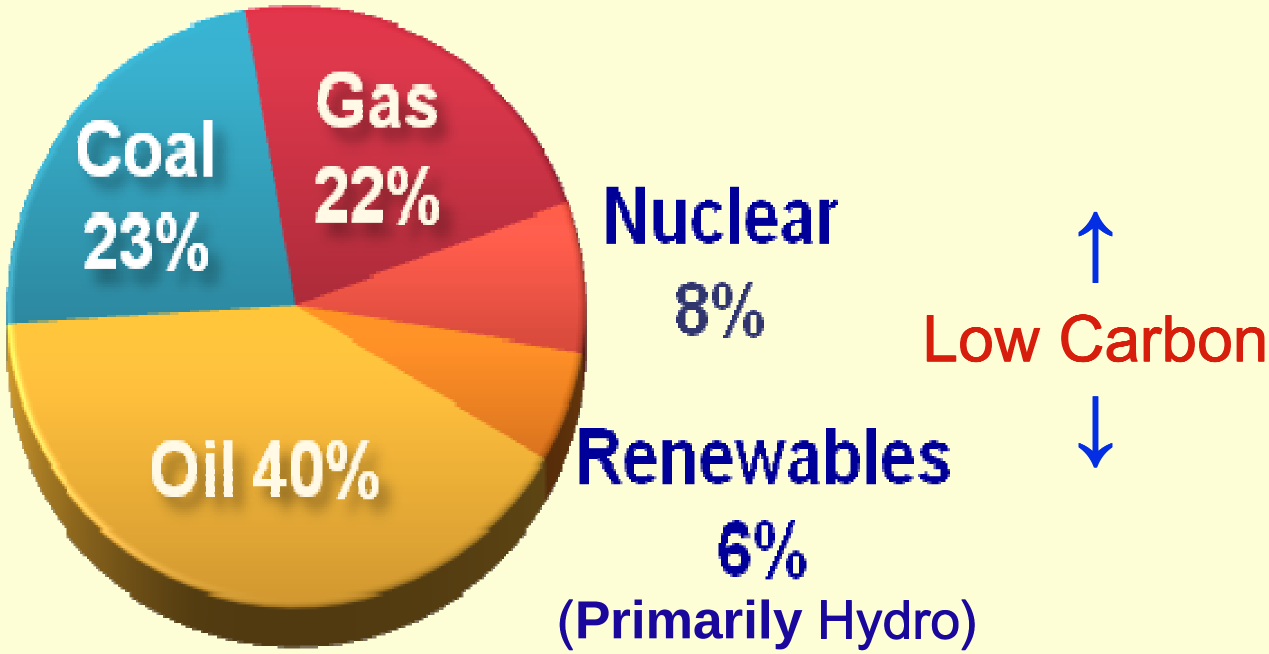


~570,000,000 ton of CO_2 emissions avoided in the US in 2012

The Case for New Nuclear Plants (2)

…and ***growing fossil fuel imports and consumption***

Total U.S. Energy Consumption



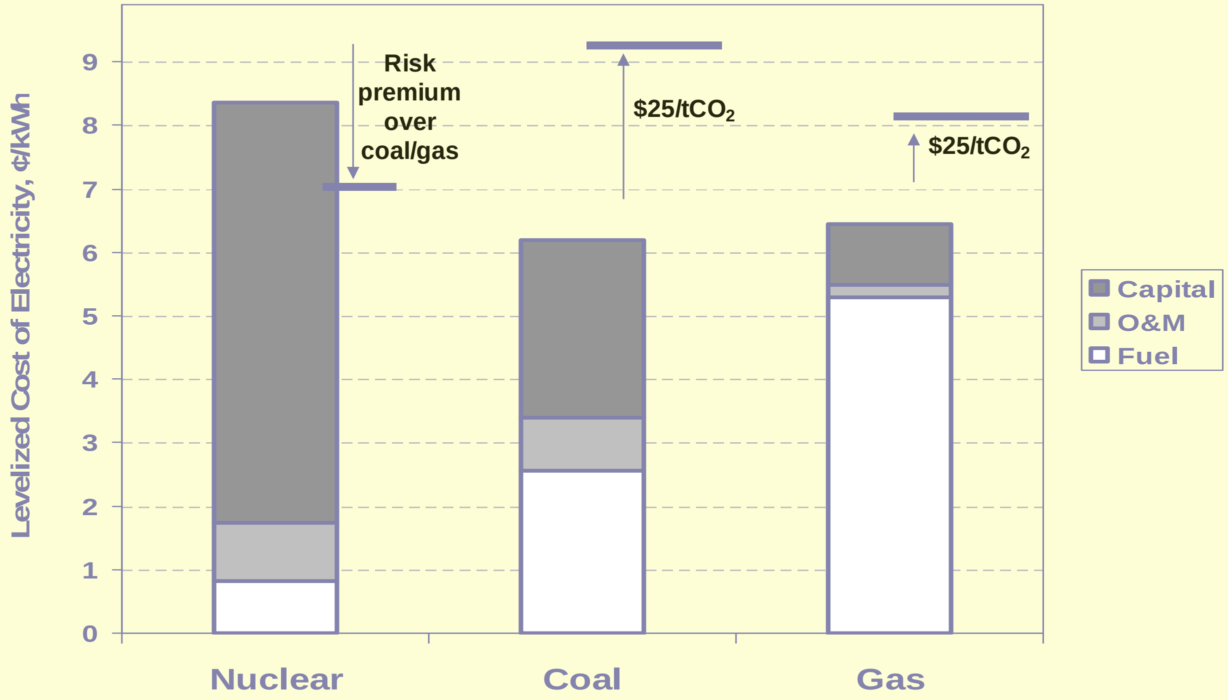
Oil is the Challenge

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

Challenge # 1:
Economics

Nuclear Energy Economics

- Financial risk for new plants is high
  - Initial investment is large (~\$3,500/kW ⇒ G\$/unit)
  - Nuclear production costs (fuel + O&M) are lowest of all energy sources

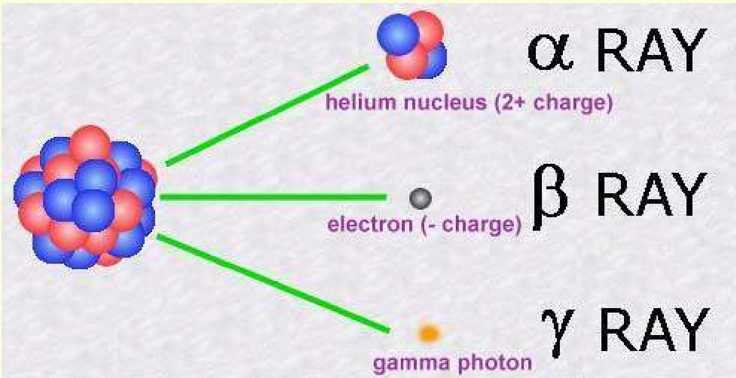


  - Plant decomissioning and nuclear fuel disposal costs are included

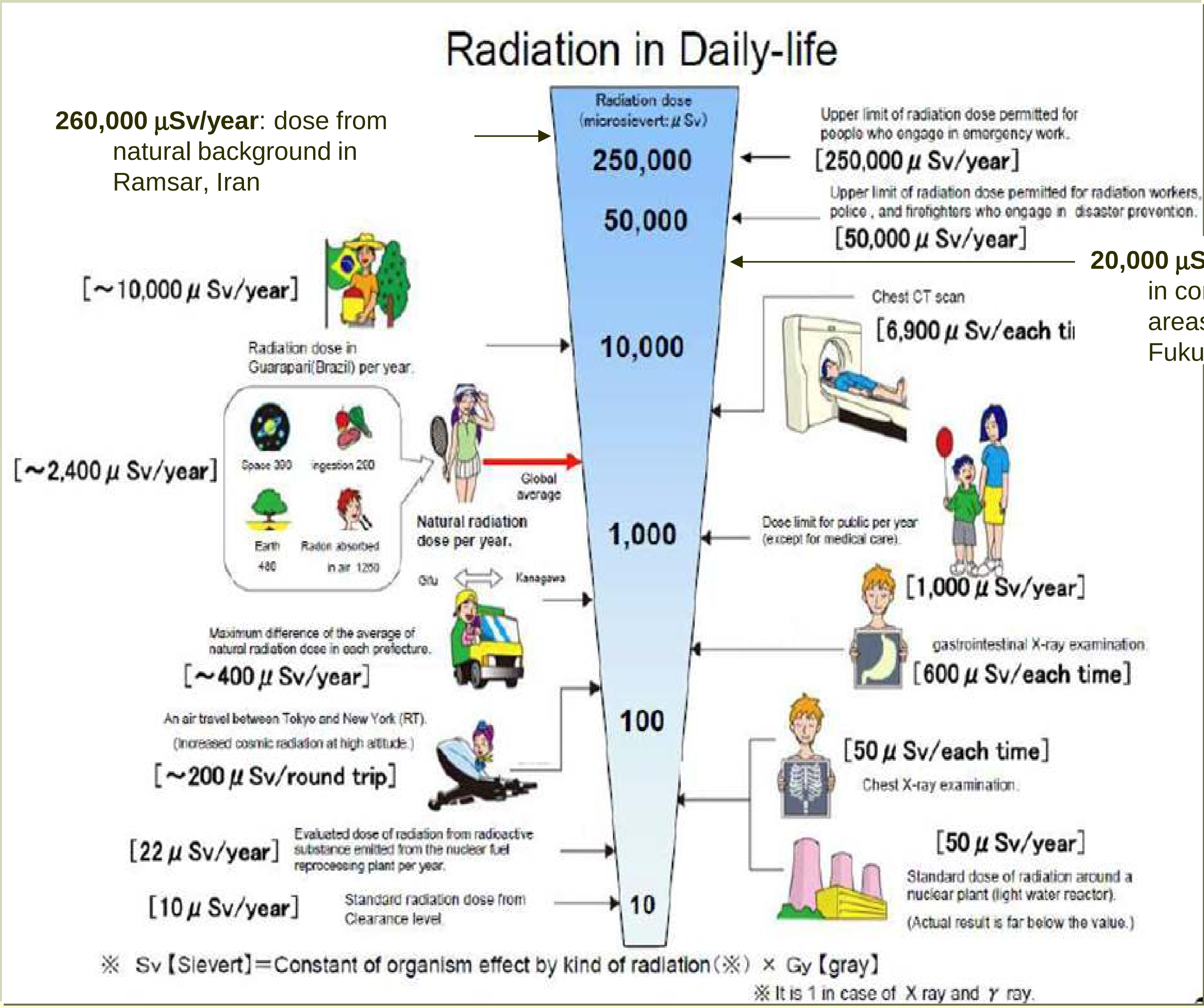
Challenge # 2:
Public Perception of Nuclear Safety

What is nuclear radiation?

- High energy particles emitted by nuclei as a result of a nuclear decay (e.g. α, β, γ) or reaction (e.g. neutrons from fission)
- Nuclear radiation is a natural phenomenon… the Earth, its plants and animals (including humans) are naturally radioactive!
- Radiation damage to humans depends on the "dose", i.e. amount of radiation per unit body mass (the SI unit is the Sievert or Sv)



260,000 μSv/year: dose from natural background in Ramsar, Iran



20,000 μSv/year: dose in contaminated areas around Fukushima plant

Nuclear power plants produce

very large amounts of radioactive nuclides (fission products), some with long half-life (>years)

Radionuclide content of representative LWR spent fuel at discharge and 180 days of representative LMFBR fuel at discharge and 30 days‡

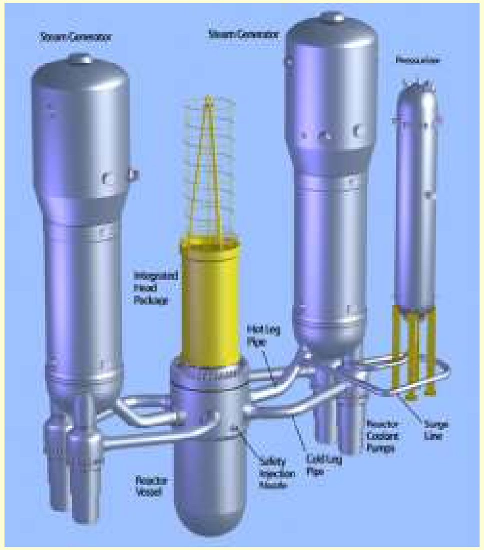
			Activity, Ci/t metal			
			LWR fuel		LMFBR fuel	
Nuclide	Half-life $T_{1/2}$	Radiations‡	Discharge	180 d	Discharge	30 d
^{3}H	12.3 y	β	5.744×10^{2}	5.587×10^{2}	1.648×10^{3}	1.640×10^{3}
^{85}Kr	10.73 y	β, γ	1.108×10^{4}	1.074×10^{4}	1.473×10^{4}	1.466×10^{4}
^{89}Sr	50.5 d	β, γ	1.058×10^{6}	9.603×10^{4}	1.333×10^{6}	8.939×10^{5}
^{90}Sr	20.9 y	β, γ	8.425×10^{4}	8.323×10^{4}	9.591×10^{4}	9.572×10^{4}
^{90}Y	64.0 h	β, γ	8.850×10^{4}	8.325×10^{4}	1.214×10^{5}	9.572×10^{4}
^{91}Y	59.0 d	β, γ	1.263×10^{6}	1.525×10^{5}	1.794×10^{6}	1.269×10^{6}
^{95}Zr	64.0 d	β, γ	1.637×10^{6}	2.437×10^{5}	3.215×10^{6}	2.340×10^{6}
^{95}Nb	3.50 d	β, γ	1.557×10^{6}	4.689×10^{5}	3.149×10^{6}	2.954×10^{6}
^{99}Mo	66.0 h	β, γ	1.875×10^{6}	3.780×10^{-14}	4.040×10^{6}	2.108×10^{3}
^{99m}Tc	6.0 h	γ	1.618×10^{6}	3.589×10^{-14}	3.487×10^{6}	2.002×10^{3}
^{99}Tc	2.1×10^{5} y	β, γ	1.435×10^{1}	1.442×10^{1}	3.278×10^{1}	3.293×10^{1}

Nuclear Safety Primer

- Hazard: fission products are highly radioactive
- Objective: protect environment/staff/public by preventing uncontrolled release of radioactivity
- Safety Principle #1: Defense in Depth - There exist multiple physical barriers between the source of radioactivity (the fission products) and the environment.

Fuel pellet and cladding

>



Reactor coolant system

>

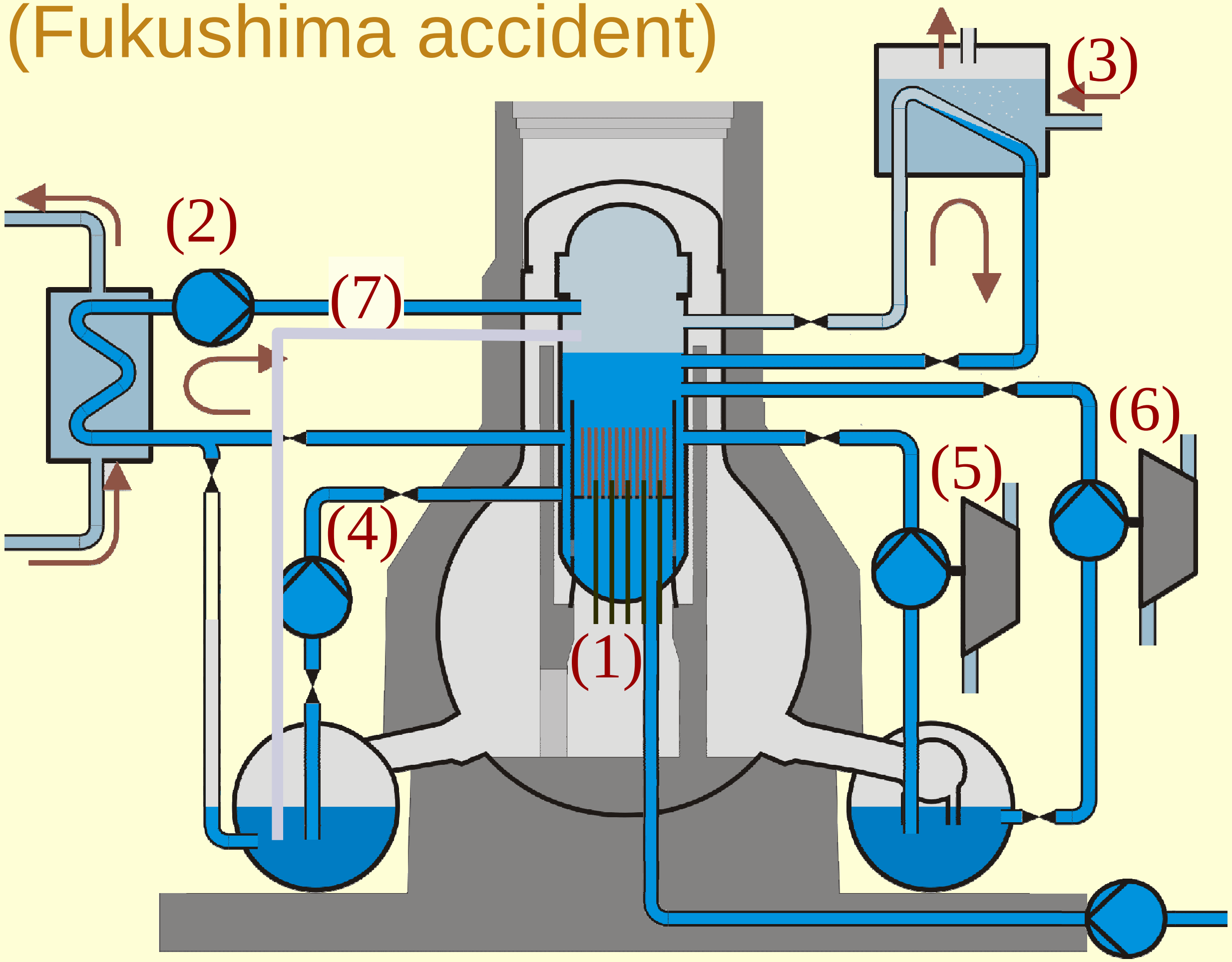
Containment

Nuclear Safety Primer (2)

- Safety Principle #2: prevent fuel overheating at all time. There are Engineered Safety Systems to:
- Shut down reactor: stop chain reaction and terminate fission heat
- Remove decay heat: lingers long after reactor shutdown
- Maintain (or replenish) reactor coolant inventory: keep fuel covered
- Relieve pressure: prevent component failure

Safety Systems in Traditional Plants

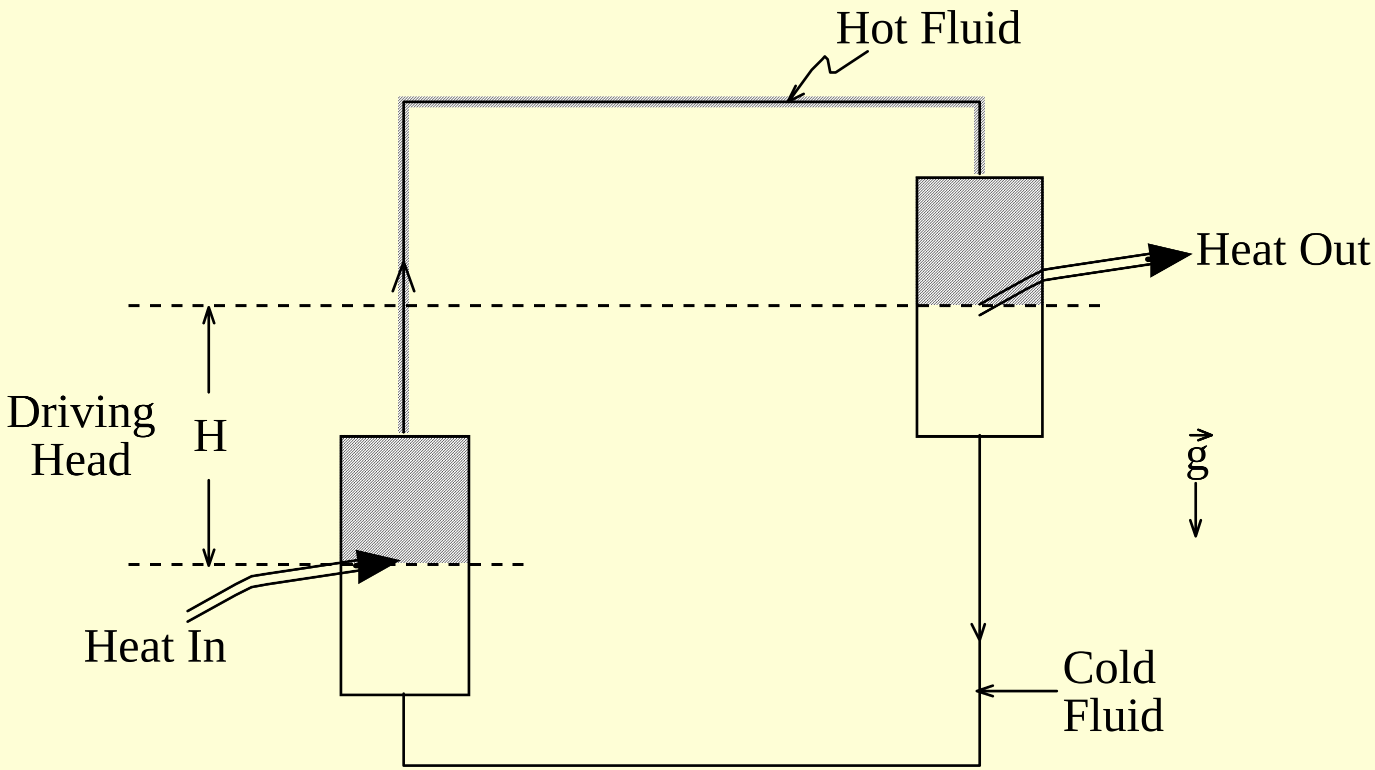
Require offsite AC power and/or diesel generators to operate pumps. Can be defeated by a station blackout (Fukushima accident)



- (1) Shut down the reactor
- (2,3) Remove decay heat
- (4,5,6) Maintain coolant inventory
- (7) Relieve pressure

Fundamentals of Natural Circulation

Natural circulation = fluid flow in the absence of a pump

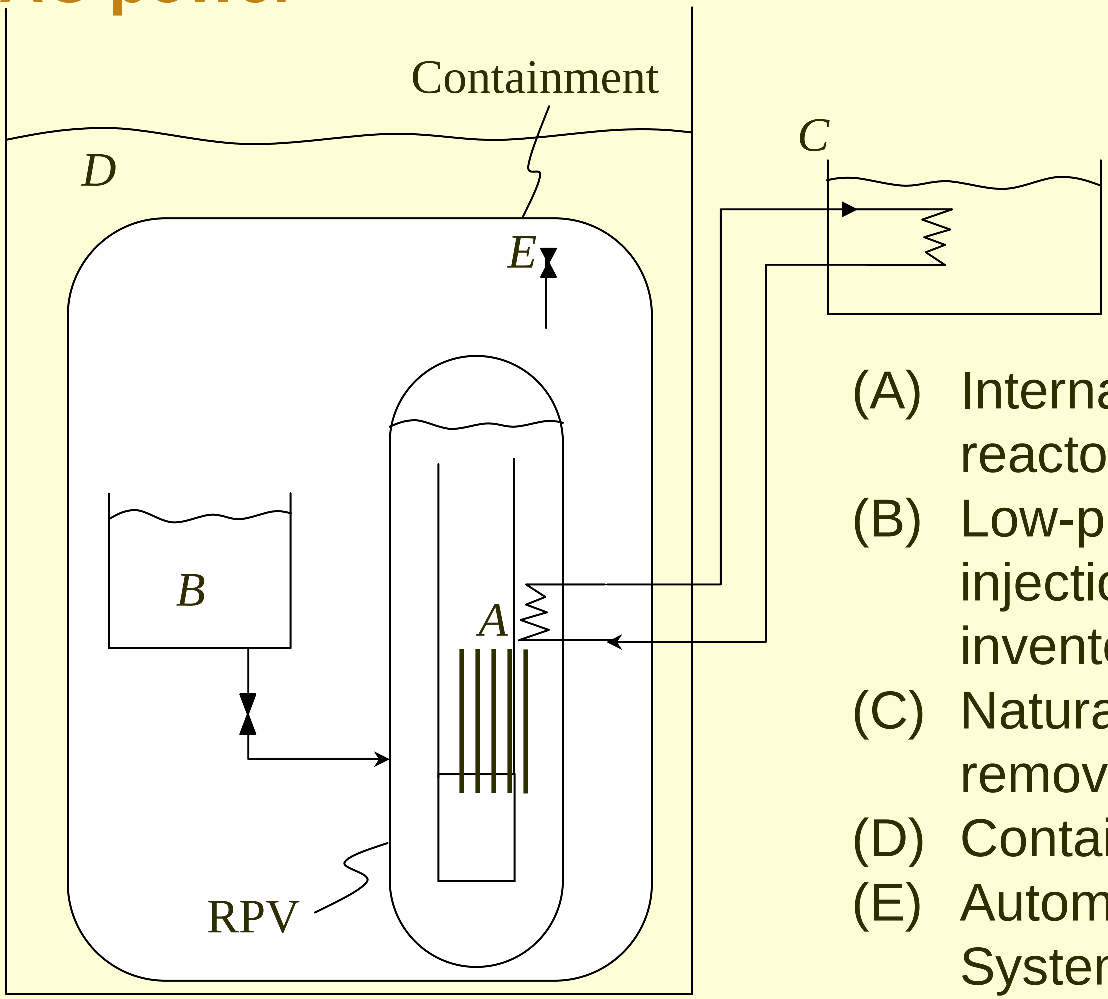


$$\Delta p_{Buoyance} = (\rho_{cold} - \rho_{hot})\, H\vec{g}$$

Hot fluid is light and wants to rise (buoyancy), cold fluid is heavy and wants to sink

Safety Systems in Advanced Plants

Use natural circulation and gravity, no need for pumps and AC power

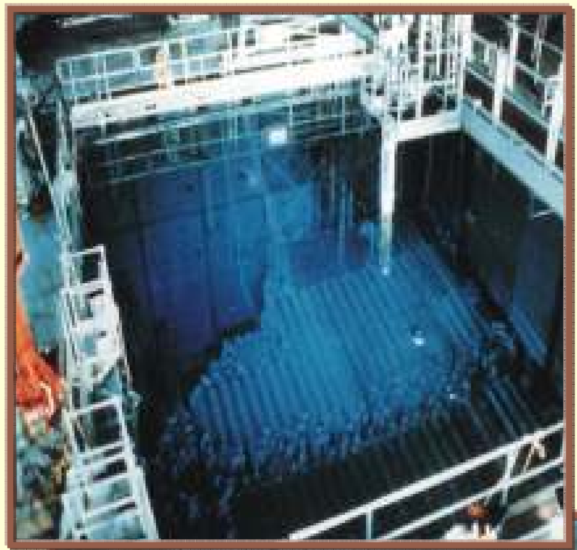


(A) Internal control rods (shut down reactor)
(B) Low-pressure gravity-driven injection (maintain coolant inventory)
(C) Natural-circulation decay heat removal
(D) Containment heat removal
(E) Automatic Depressurization System (relieve pressure)

Challenge # 3: Nuclear Waste Disposal

Spent Fuel Management (waste disposal)

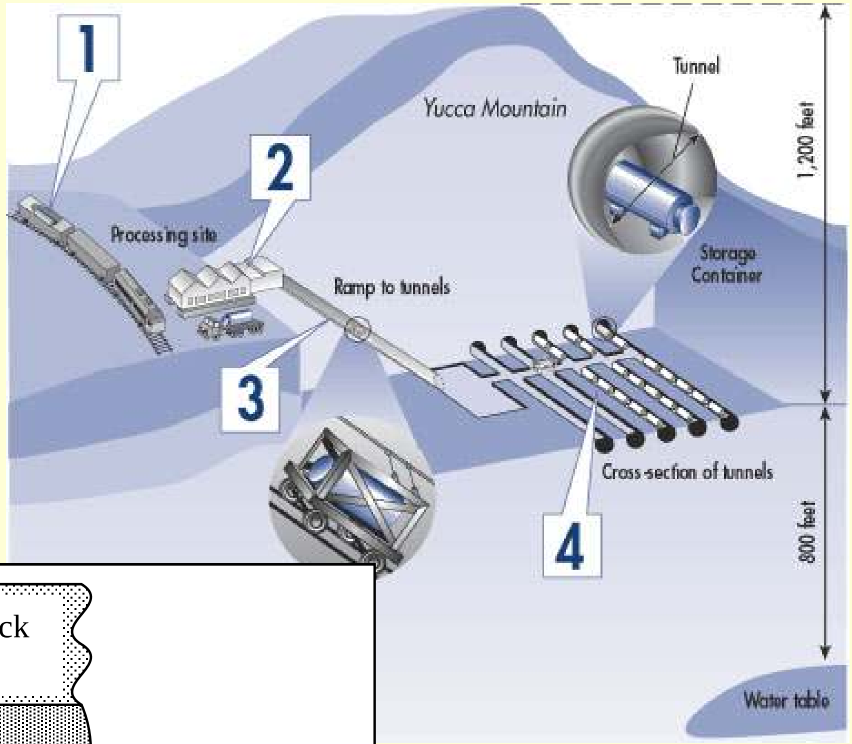
In the US all spent fuel is currently stored at the plants

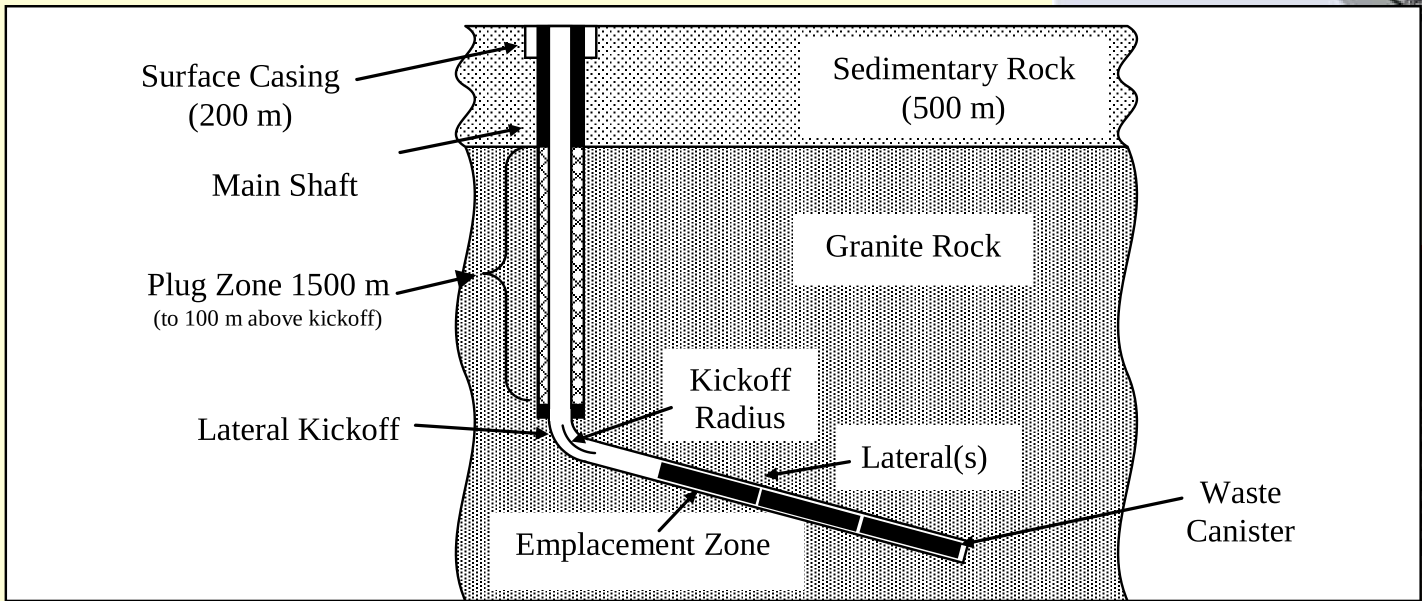


- In the spent fuel storage pools for about 10 years …
  - … then transferred to sealed dry casks; cooled by air; heavily shielded; internal temperature and pressure monitored; can last for decades with minimal maintenance and cost.
  - A 1000-MW reactor requires about 80 dry casks for all the spent fuel it produces in 60 years of 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 geological repositories, either "shallow" (300-400 m) or deep (>2000 m)

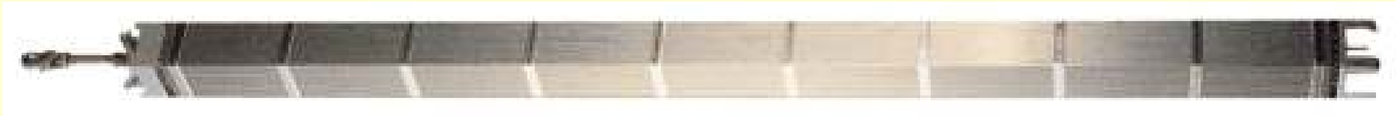




Spent Fuel Management (recycling)

- **Composition of spent nuclear 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 %)	Pu 5 kg (1 %)	FP 15 to 20 kg (3 to 5 %)
RECYCLING	RECYCLING	FINAL WASTE

96% of a spent fuel assembly is still valuable, so could be recycled and reused in reactors!

Conclusions

- Electricity is generated from primary energy sources: coal, natural gas, nuclear, hydro, wind, solar, geothermal etc.
- Fossil fuels (coal and gas) account for >60% of the World's electricity production
- Nuclear fuel (uranium) has the highest energy intensity of all primary energy sources
- Nuclear produces ~19% of US electricity and ~12% worldwide today
- Nuclear does not emit greenhouse gases
- Challenges facing nuclear are capital cost of new plants, perception of safety and waste disposal