Nuclear Reactors & Systems

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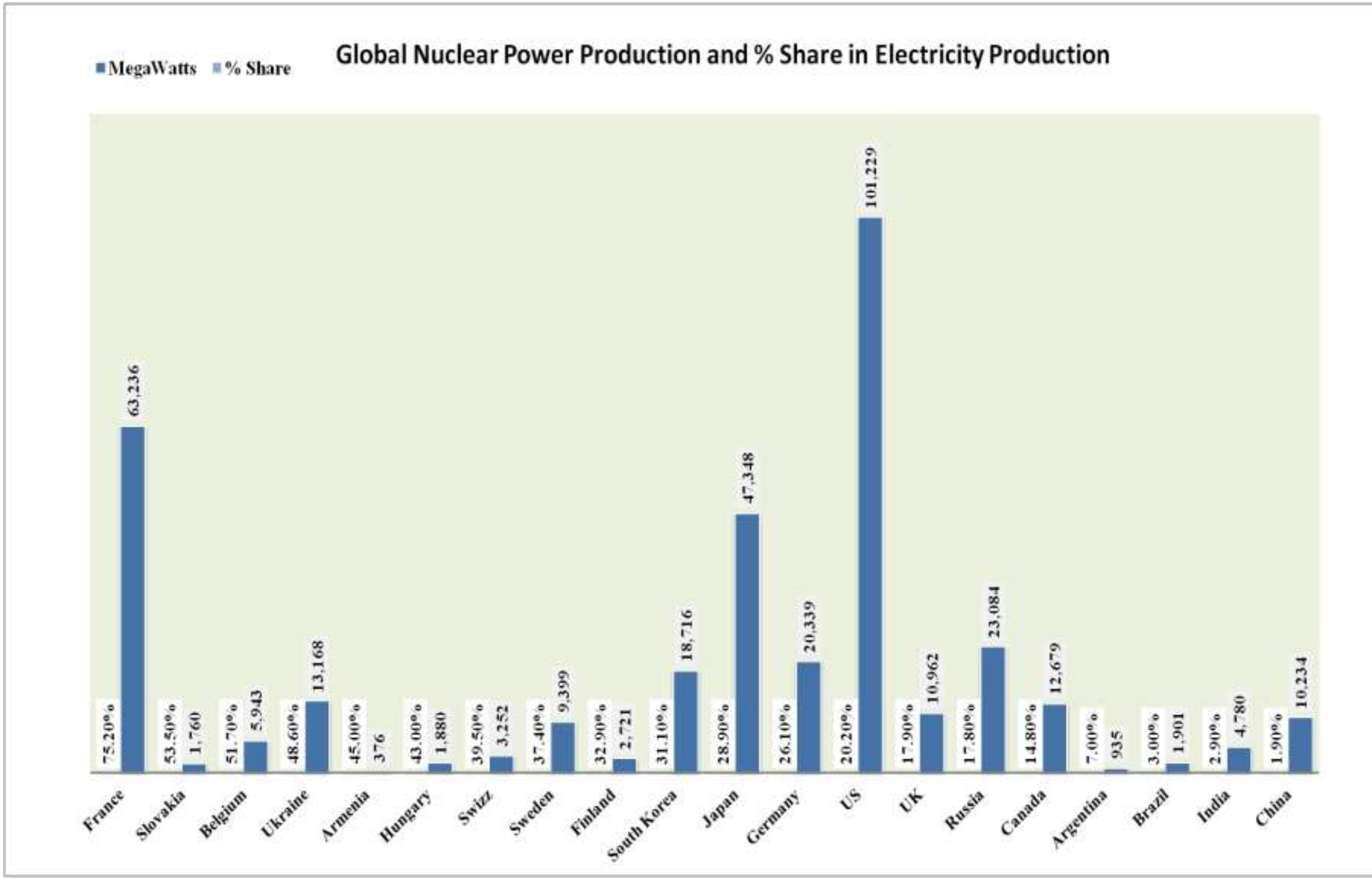
Overview

- Overview of Nuclear Power on a Global Scale
- Overview of Nuclear Power in the US
- Nuclear Reactors – Historic Overview
- Nuclear Reactors and Systems
- Nuclear Fuel
- Questions

Overview of Nuclear Power on a Global Scale

- Roughly 7% of the total world’s energy is from nuclear fission based power plants
- 15% of the global electricity production
- France, US and Japan are leading users of nuclear power
- 435 nuclear reactors around the world as of 2011 (Source : IAEA)
- 5 under shutdown (including Fukushima)
- 63 new nuclear power plants under construction mainly in Asia.

World's Share of Nuclear Power



Recent Global Trends

- Opposition still strong in European countries
  - Germany – Shut down of 8 Nuclear Power Plants in 2011. 9 more to be shut down by 2022. Complete phase out of nuclear power.
  - France – traditionally anti-nuclear socialist party promises to reduce dependence if elected to power

- The Americas and Far East were going steady up until Fukushima
  - Japan – rethinking nuclear power after Fukushima accident
  - Canada – Going ahead with the ACR-1000 design
  - US – Still dilly-dallying on the new additions (COL recently approved for plant Vogtle in Georgia, 2 more unit under construction in S. Carolina)

- Good news from South & Central Asia
  - India and China are going ahead building nuclear power plants (~20 and 50 respectively)

Nuclear Energy in the US

- Roughly 20% of the total electricity produced comes from nuclear power plants
- A total of 104 nuclear reactors currently operating with roughly 1/3rd BWRs and the rest PWRs.
- Pre-Fukushima plans of 30 new reactors – only 4 have withstood Fukushima propaganda, 3 under construction (TVA's Watts Bar Unit -2, TN, 2 VC Summers, SC)
- USDOE continuing research on new generation reactors (Gen IV technology) for both increased electricity production and hydrogen generation

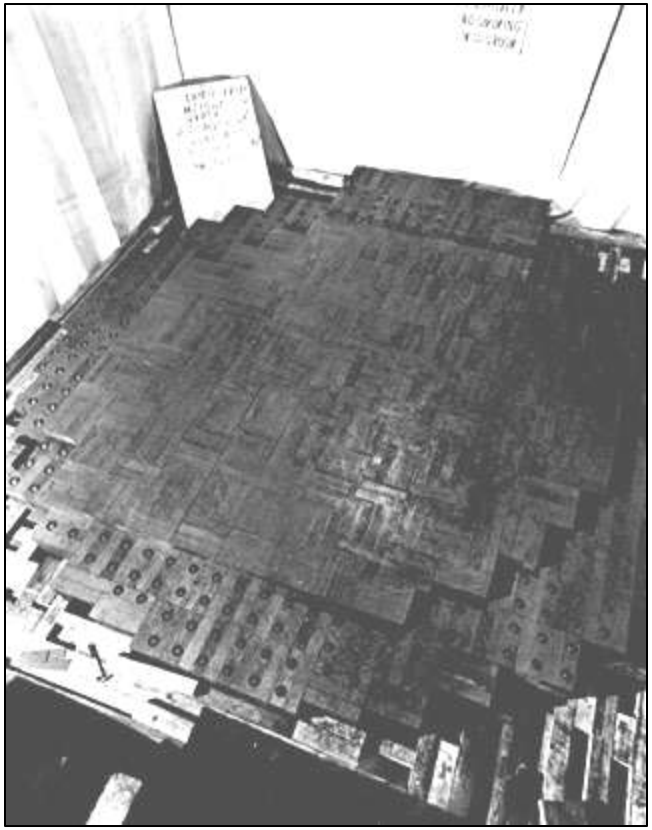
Nuclear Reactors – A Historic Overview

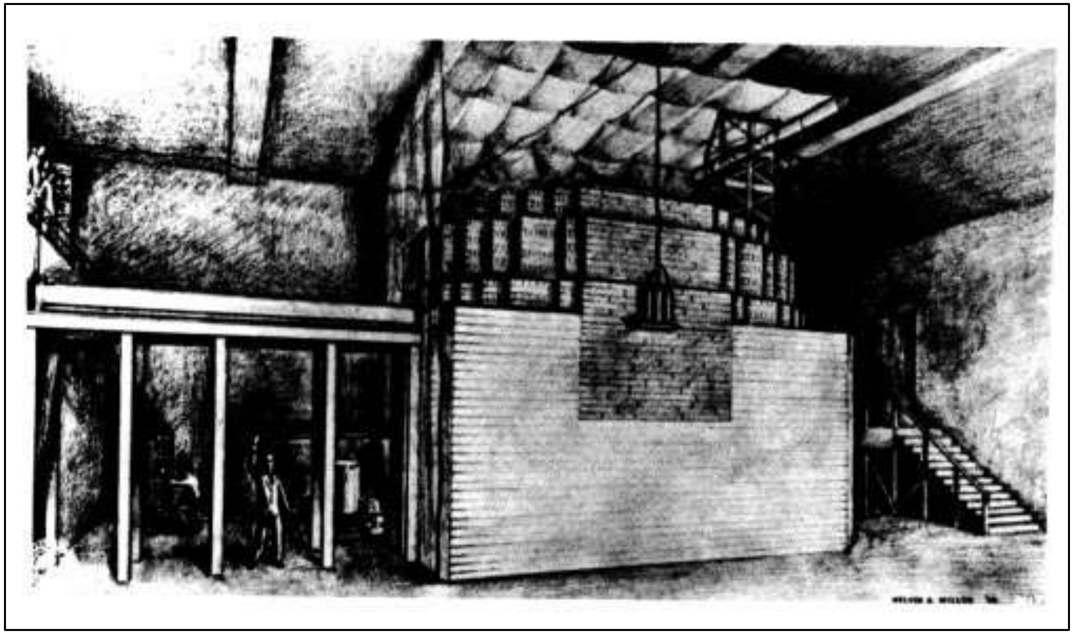
First Reactor – The Fermi Pile - 1

- First artificial reactor to demonstrate controlled, sustained chain reaction – A pile of uranium metal (~12500 lbs), uranium oxide (~80,000 lbs) and graphite (~ 770,000 lbs) blocks
- Cost of ~2M$, 25' wide and 20' high pile
- Principal Investigator – Enrico Fermi
- Venue – University of Chicago – Alonzo Staff Field, Rackets court
- Part of the Manhattan Project - Critical on December 2nd 1942

Nuclear Reactors – A Historic Overview

First Reactor – The Fermi Pile





Courtesy: www.ornl.gov

The X-10 Graphite Reactor – Oak Ridge

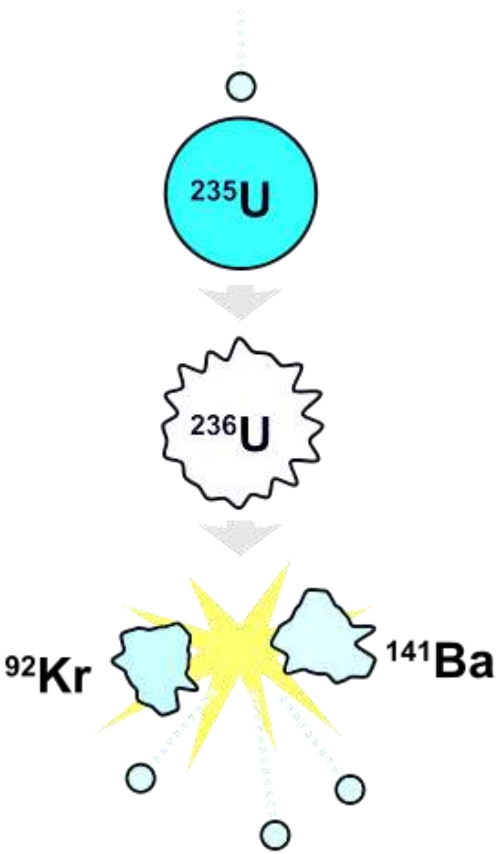
- Second reactor (critical on Nov 2nd 1943) to be built, first reactor to be designed for continuous critical operation.
- Built and operated by Clinton Laboratories and Du Pont.
- Not for power generation, main function was to make Pu-239 from U-238 for weapons research.
- 24' high graphite blocks, 30 tons of Uranium fuel enclosed in aluminum jacket(Metallic fuel). Air cooled core. Operated at a maximum of 4MW.
- 7' thick concrete biological shield.
- Fuel was in the form of slugs (~60,000) which were inserted into some 1248 channels in stages, flux and activity measured at each stage of insertion. Flux profiles were plotted by hand.
- Unlike the popular belief, the X-10 reactor did not produce the plutonium for the atomic weapons but acted more as a research reactor. It produced only 237g of Plutonium.

- Workers loading the uranium slugs into the graphite reactor (courtesy : www.ornl.gov)

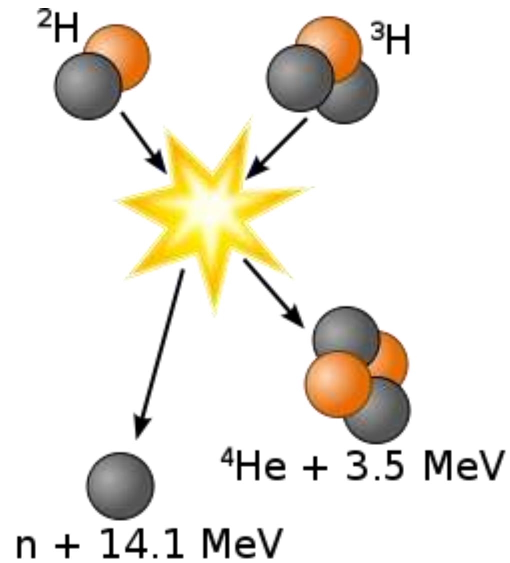
Nuclear Reactions

- In the atomic world, a particular atom splits into two components or combines with another atom of similar species releasing the binding energy
- The process of splitting is sometimes referred to as neutron assisted energetic transmutation (of the parent atom) aka nuclear fission.
- The resultant species are normally two similar or dissimilar nuclei and one or several neutrons. The two nuclei are referred to as fission products or fission daughters
- Nuclear fusion on the other hand does not need neutrons to initiate but a lot of energy to overcome the electrostatic forces. This energy can be supplied by absorbing energetic fission products or subatomic particles resulting from a fission source in a systematic manner.

Overview of Atomic Reactions



NUCLEAR FISSION



NUCLEAR FUSION

Courtesy: Wikipedia

Reactor Characterization by Neutron Spectrum

- Reactors are also classified based on the energy of the neutrons that are the prime source for (and also products of) the fission reaction
  - Fast Reactors (GFR, LMFBR, FBR etc)
    - Fast Neutrons (speeds range from 3000 m/s to 15000 km/s, speed is based on the neutron's energy : 1 eV to 1 MeV)
    - Fast reactors can operate with fissile (U-233, U-235, Pu-239, Pu-241 etc), fissionable (U-238) or fertile materials (U-238, Th-232) in the core
    - Breeder reactors are mostly fast reactors
  - Thermal Reactors (LWR, PHWR etc)
    - Neutrons are generally moderated (slowed down) to speed ranges of ~2200 m/s or 0.025 eV)
    - Neutrons slow down by the process of in-elastic scattering after interacting with moderator atoms.
    - Thermal reactors have to have a certain degree of enrichment of fissile material to keep the fission chain reaction going

Nuclear Reactors & Systems

- Reactors can be classified in many ways but more commonly based on coolant
  - ➢ Water Cooled Reactors (Water)
    - o Pressurized water reactors
    - o Boiling water reactors
  - ➢ Gas Cooled Reactors (Helium, CO_2 etc)
  - ➢ Liquid Metal Cooled Reactors (Sodium, Potassium, Lead, Lead-Bismuth, Mercury ???)
  - ➢ Molten Salt Reactor (LiBeF)
- Based on neutron spectrum
  - ➢ Fast or Thermal
- Based on Type of Fuel
  - ➢ Solid, Liquid, Gas

Nuclear Reactors & Systems

- Reactor Generations (USDOE Classification)

(Classification based mainly on efficiency, multi-purpose, proliferation resistance, waste reduction and safety features)

  - Generation 1 Reactors : X-10 Reactor, Hanford B reactor, Shippingport Reactor, Magnox, etc {Gen 1 reactors were not well suited for power production, mostly for weapons research and isotope production }
  - Generation 2 Reactors: Currently operating reactors including LWRs, CANDU, RBMK/VVERs
  - Generation 3 Reactors: ABWR, AP600, EPR, AP1000 (Gen 3+)
  - Generation 4 Reactors: VHTR, MSR, LMR, LMFBR,

- Fuel types based on Generation
  - Gen 1 reactors used mostly metallic fuel
  - Gen 2, 3 and 4 use and propose to use high temperature ceramic fuel

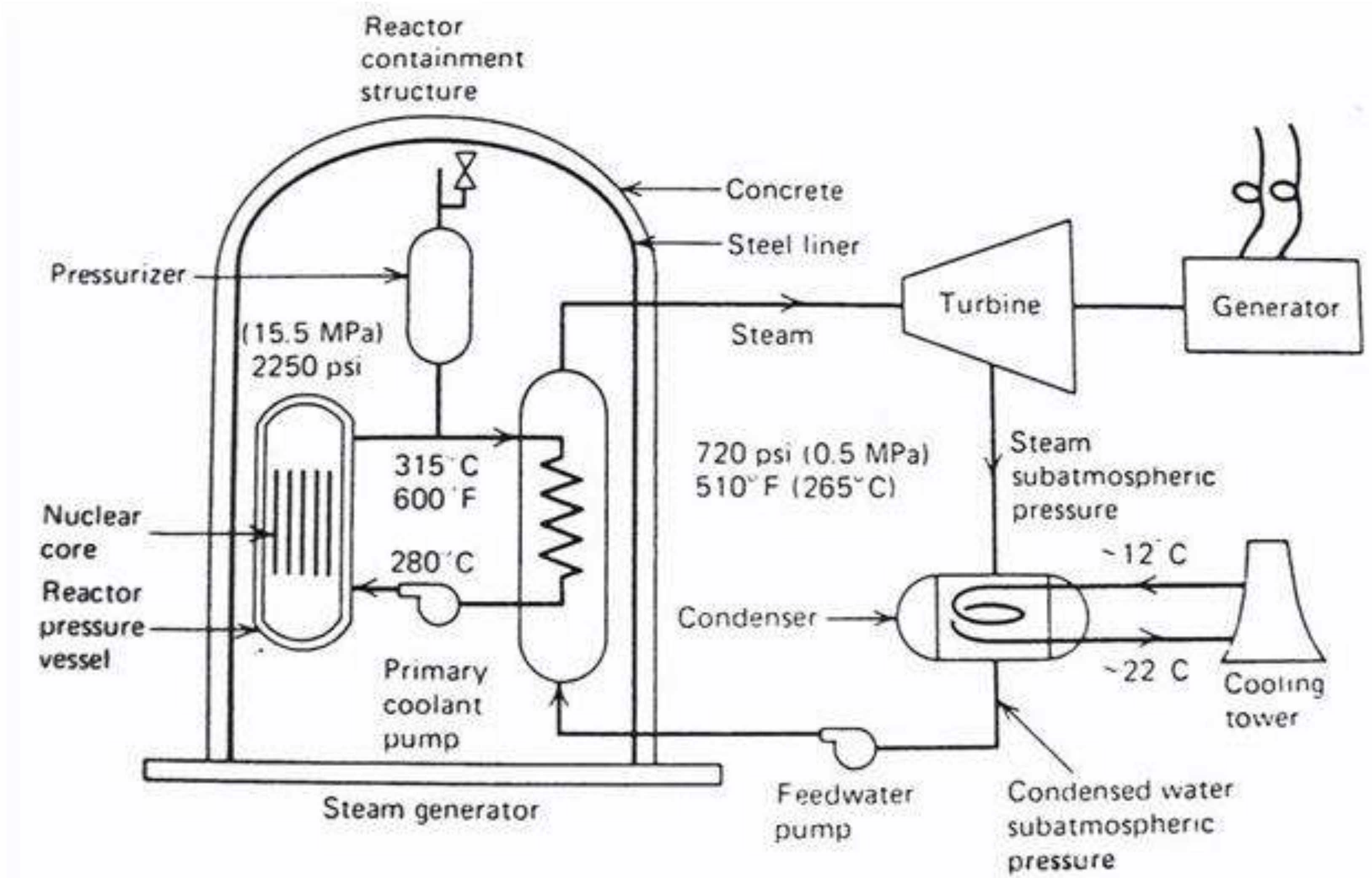
Light Water Reactors (LWRs)

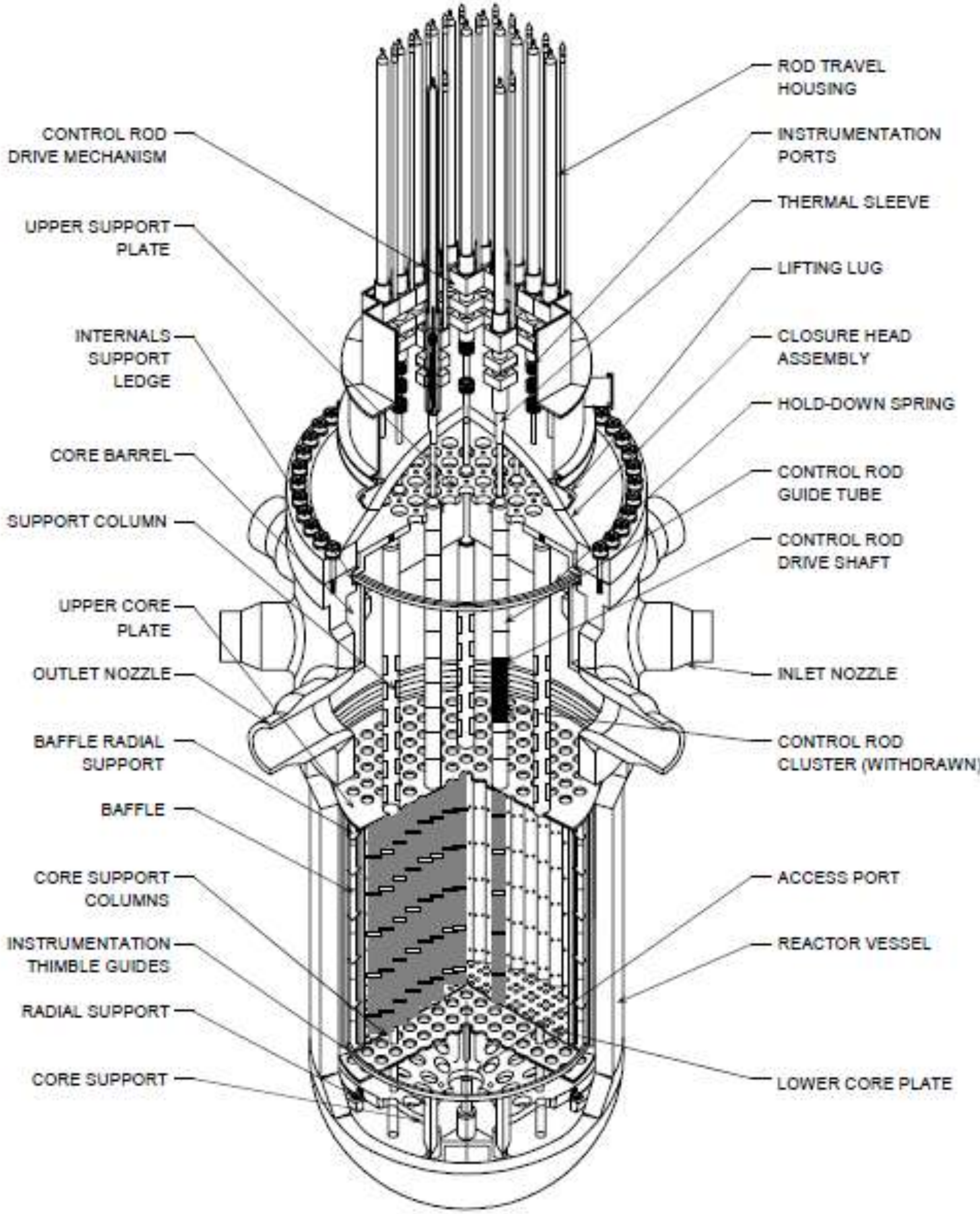
- First conceptualized by Eugene Wigner during the X-10 experiment.
- Design put to work at Hanford B.
- Most extensively employed for power production and largest number currently existing
- Mainly two types
  - Pressurized Water Reactor (PWR)
  - Boiling Water Reactor (BWR)

Pressurized Water Reactor

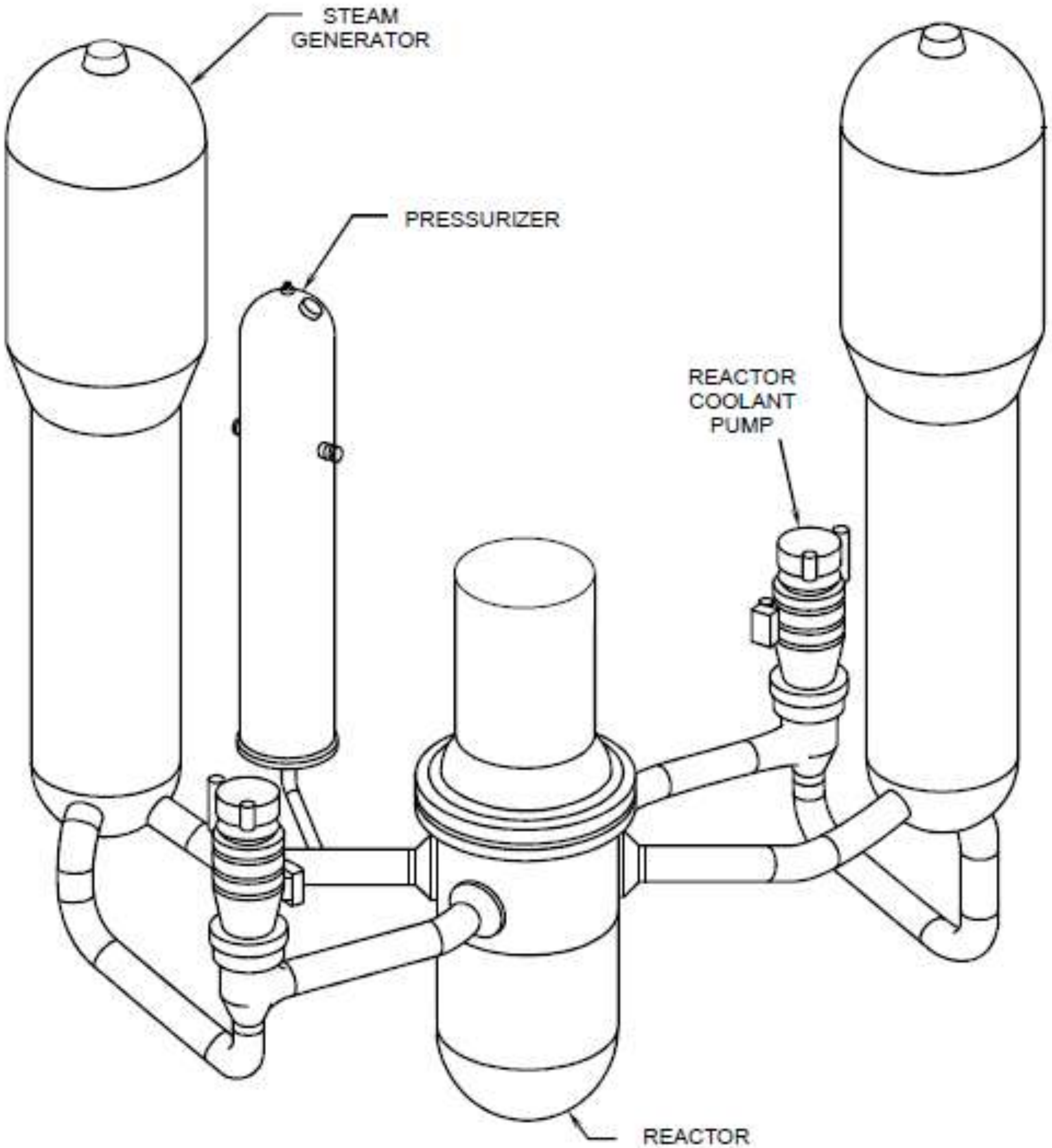
- Pressurized Water Reactor
  - Light water moderated
  - Two loop system : Primary and Secondary
  - Primary pressure is ~15 MPa maintained by a dedicated pressurizer
  - Secondary pressure is ~5.7 MPa.
  - Water does not boil within the reactor
  - Uranium di-oxide ceramic fuel with 3-4% enrichment
  - Primary coolant inlet temperature : 275 - 280ºC
  - Primary coolant outlet temperature : 310 - 315ºC
  - Primary coolant flow rate ~20000 kg/s
  - Secondary coolant inlet temperature: ~238ºC
  - Secondary coolant outlet temperature: ~289ºC
  - Reactor core height ~3.6 m
  - Reactor core diameter ~3.8 m'
  - Total fuel mass ~ 100-110 tons
  - Core volume : 40 cubic meters

PWR Schematic



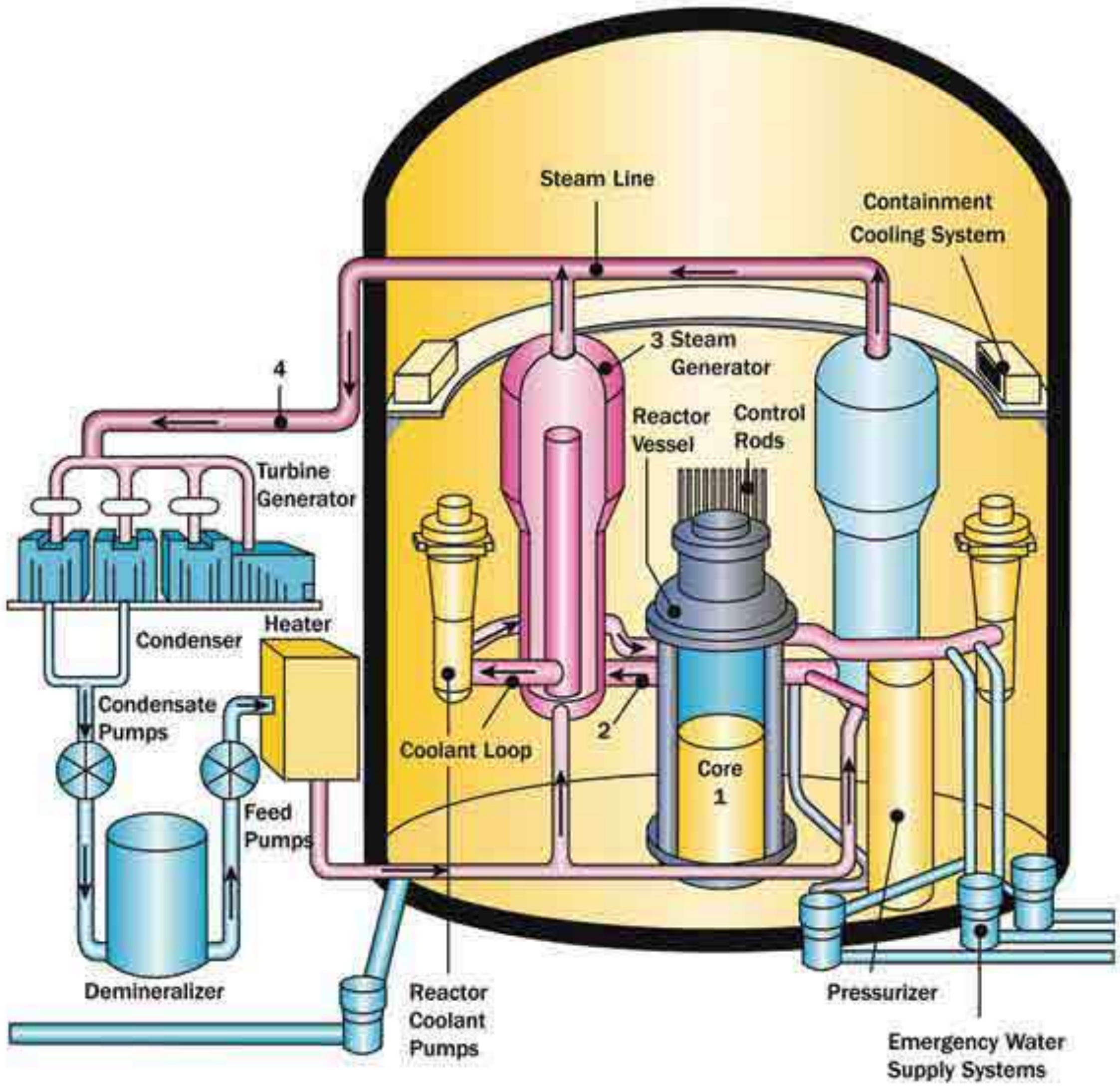


Cutaway View of Reactor Vessel



Pressurized Water Reactor

Typical Pressurized-Water Reactor



Courtesy: www.nrc.gov

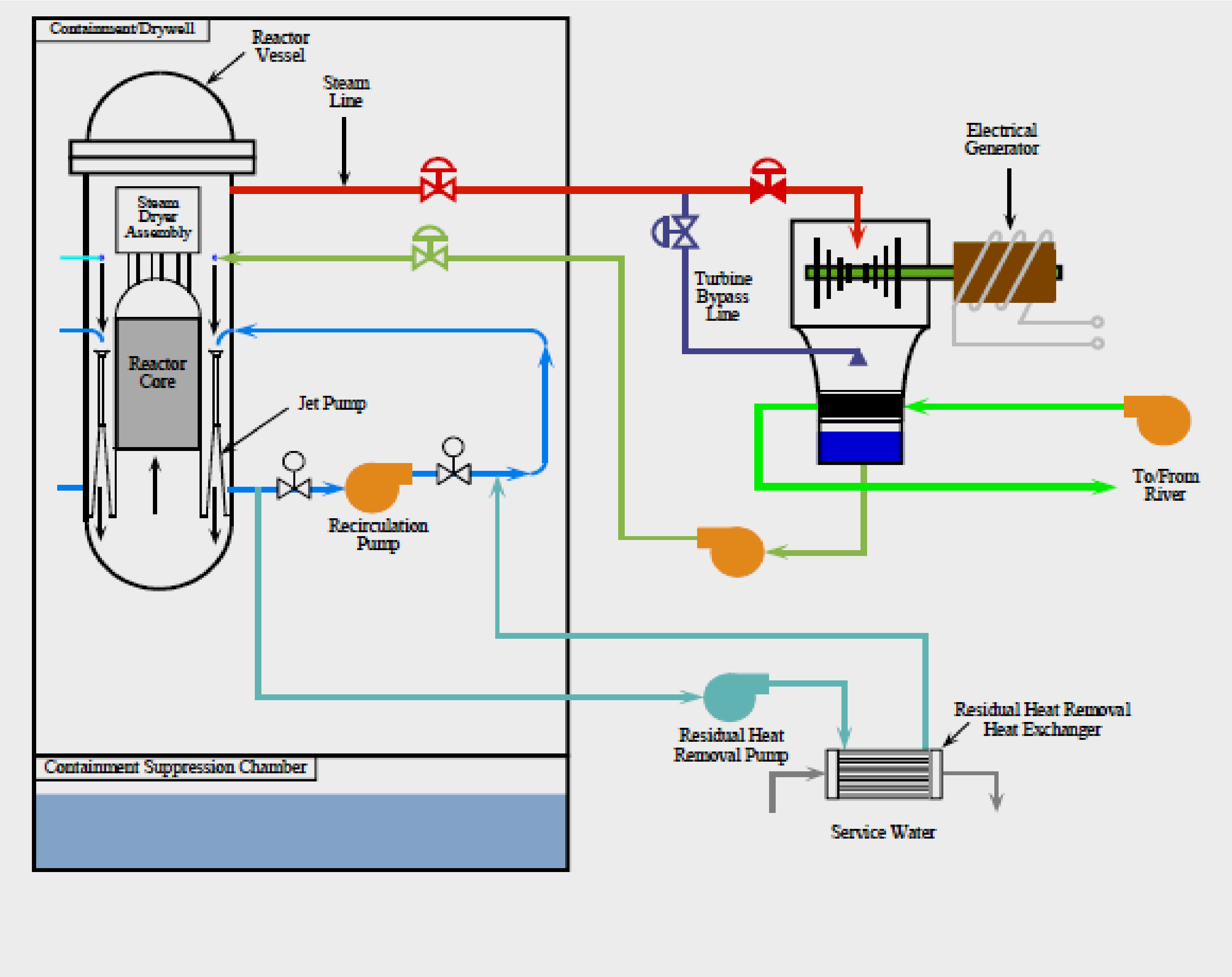
PWR System Components

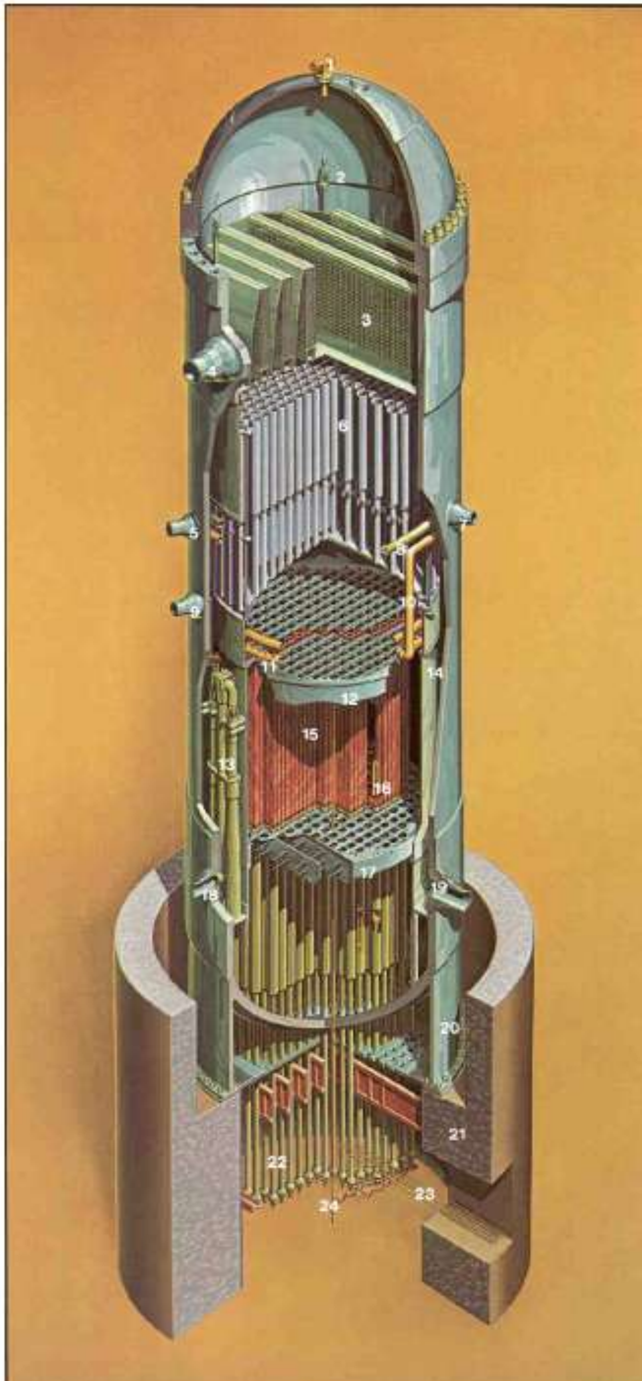
- Containment – protection and safety
- Pressure vessel – houses the reactor core, acts as the primary containment
- Nuclear Steam Generator - heat exchanger between primary and secondary loops.
- Pressurizer – Maintains system pressure
- Reactor Feed Water Pumps (Primary and Secondary) –supply coolant to the respective loops.
- Reactor core – produces the required heat to generate electricity
- Condensation Systems (Condenser, Condensate Feed Pumps, Condensate Cooling Pumps, Demineralization Systems etc)
- Primary Coolant Cleanup System
- Coolant Injection Systems
- Emergency Core Cooling System (ECCS)
- Decay Heat Removal Systems (DHRS)

Boiling Water Reactor

- Boiling Water Reactor Features
  - Light water moderated
  - Single loop system (no secondary) with dual recirculation,
  - Water boils within the reactor vessel
  - Coolant pressure ~ 7.2 MPa
  - Uranium-oxide ceramic fuel with close to 3% enrichment
  - Inlet coolant temperature : 275ºC
  - Outlet coolant temperature : 285ºC (steam at 7.2MPa)
  - Coolant flow rate : 13000 kg/s
  - Core height : ~4 m
  - Core diameter : ~3.6m
  - Vessel wall thickness : ~15 cm
  - Total fuel weight: 140-150 Tons

Boiling Water Reactor





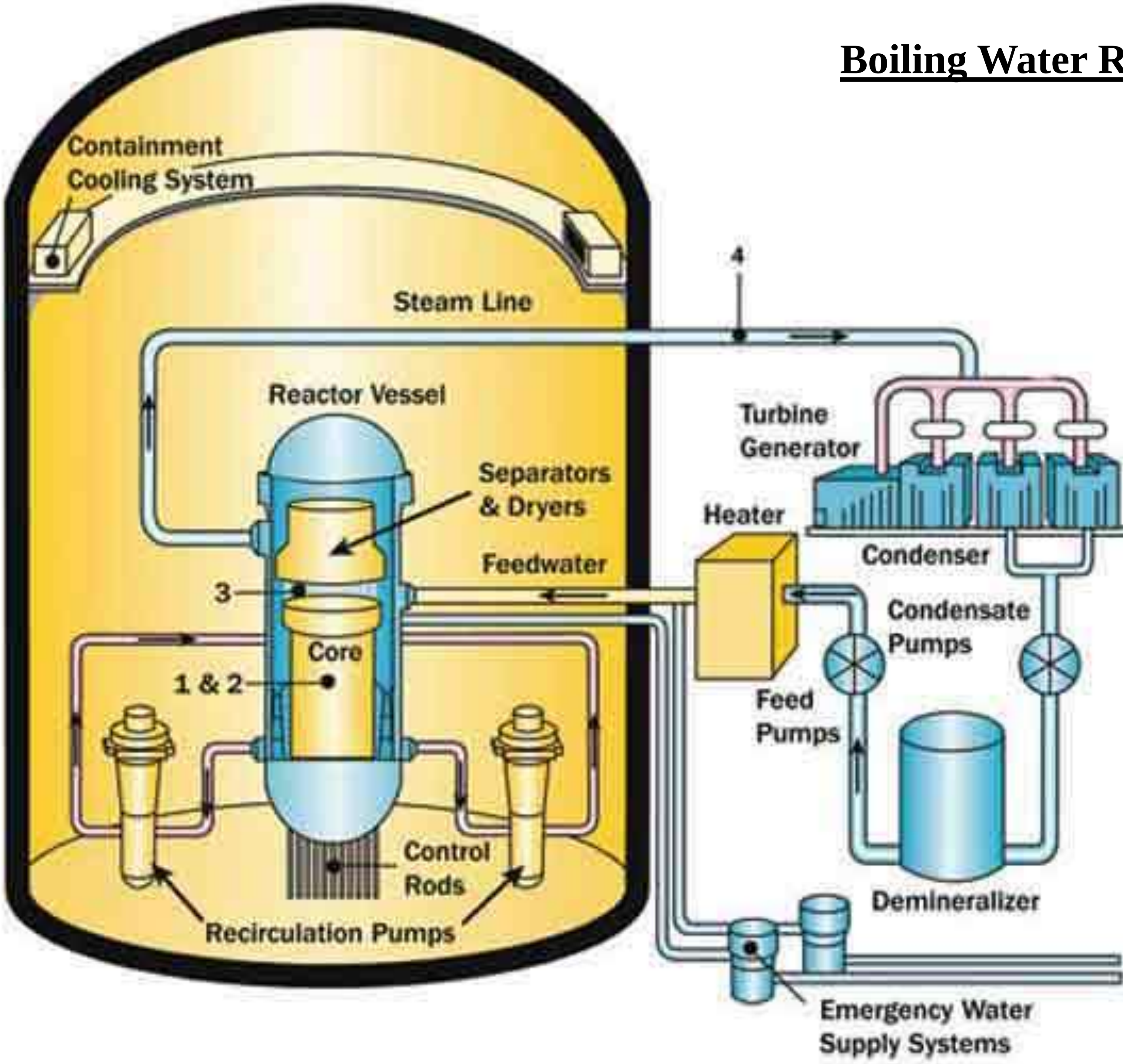
BWR/6

REACTOR ASSEMBLY

1. VENT AND HEAD SPRAY
2. STEAM DRYER LIFTING LUG
3. STEAM DRYER ASSEMBLY
4. STEAM OUTLET
5. CORE SPRAY INLET
6. STEAM SEPARATOR ASSEMBLY
7. FEEDWATER INLET
8. FEEDWATER SPARGER
9. LOW PRESSURE COOLANT INJECTION INLET
10. CORE SPRAY LINE
11. CORE SPRAY SPARGER
12. TOP GUIDE
13. JET PUMP ASSEMBLY
14. CORE SHROUD
15. FUEL ASSEMBLIES
16. CONTROL BLADE
17. CORE PLATE
18. JET PUMP / RECIRCULATION WATER INLET
19. RECIRCULATION WATER OUTLET
20. VESSEL SUPPORT SKIRT
21. SHIELD WALL
22. CONTROL ROD DRIVES
23. CONTROL ROD DRIVE HYDRAULIC LINES
24. IN-CORE FLUX MONITOR

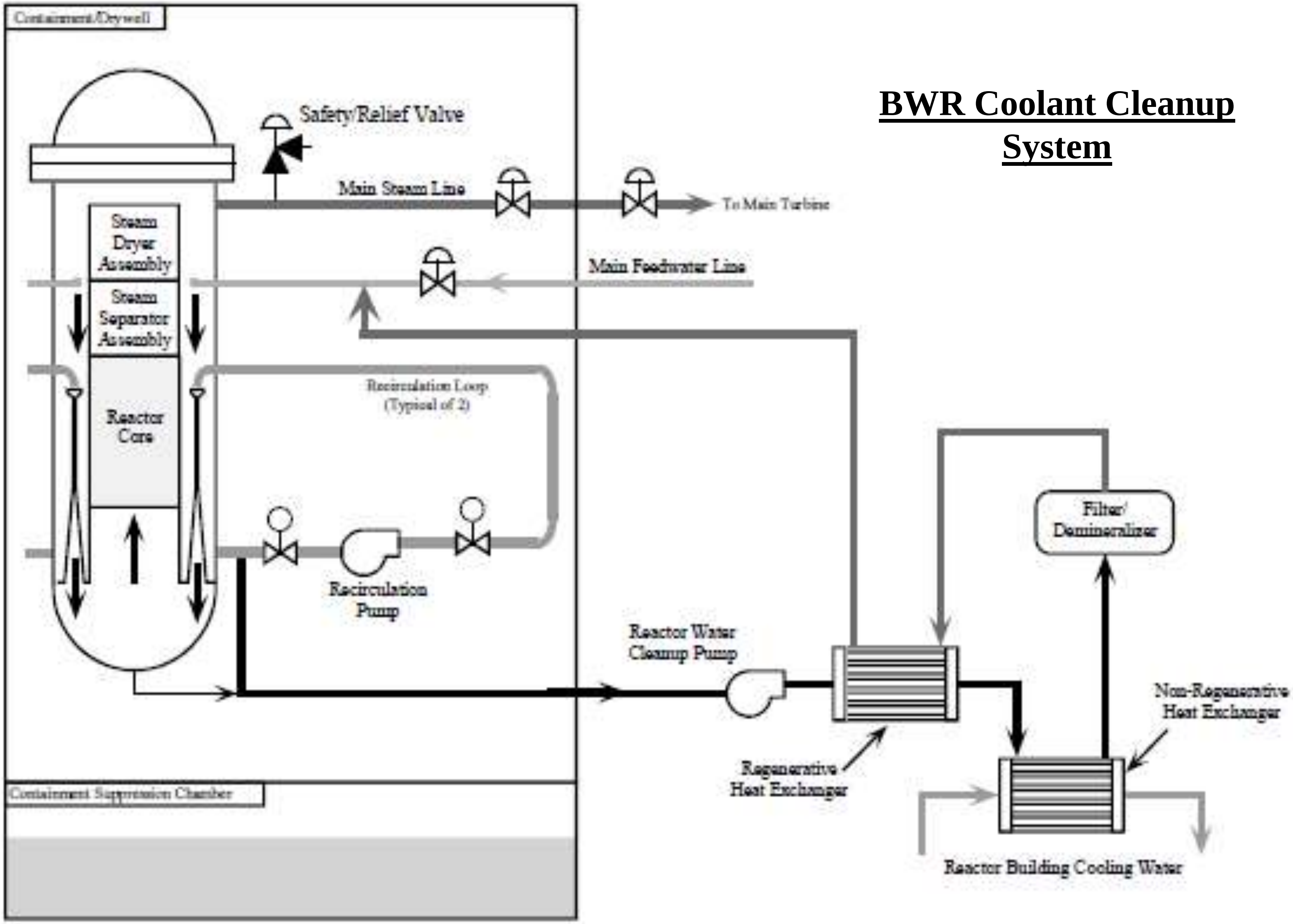
GENERAL ELECTRIC

Boiling Water Reactor

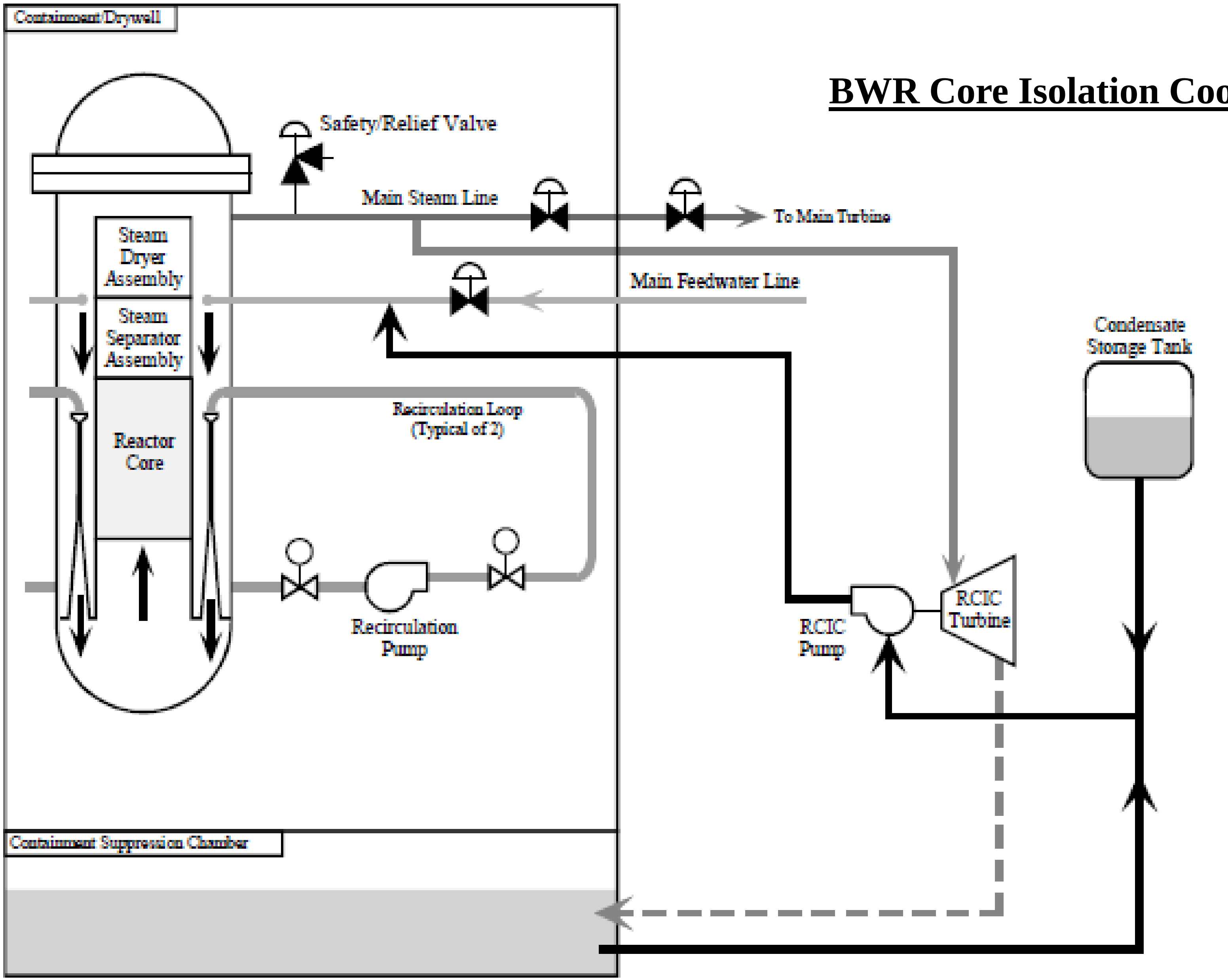


- Primary Systems
  - Containment (Reinforced Concrete)
  - Reactor Pressure Vessel – Primary Containment
  - Reactor Core – Where the ‘action’ takes place
  - Reactor Feed Water Pumps – which pump water back into the reactor
  - Reactor Water Cleanup System – remove fission products from feed water
  - Jet pumps –control flow and turbulent mixing
  - Steam Turbine
  - Electric Generator
  - Condensation System – Condenser, Condenser Feed Water Pump, Steam Water Analysis Systems
  - Emergency Core Cooling Systems (ECCS)
  - Containment Suppression Pool
  - Containment Cooling Systems
  - Low Pressure Injection Systems
  - Control Rod Systems

BWR Coolant Cleanup System



BWR Core Isolation Cooling



The CANadian Deuterium –Uranium Reactor

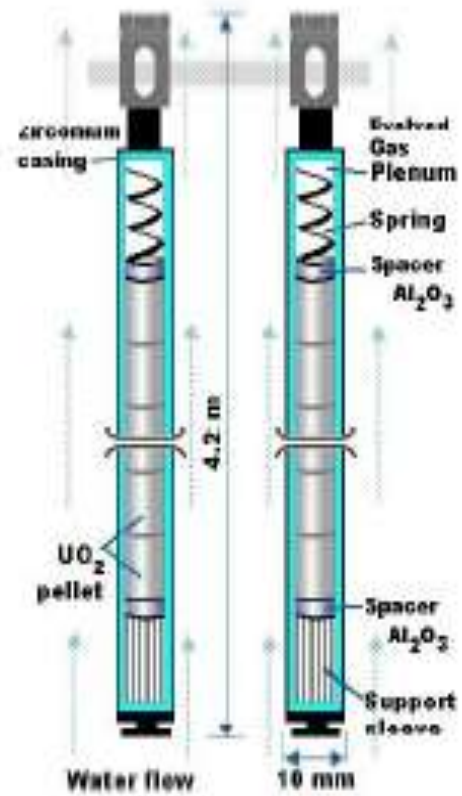
- Developed from the Canadian NRX reactor
- Referred to as a pressurized heavy water reactor (PHWR)
- Dual loop heat extraction similar to PWR.
- Heavy water cooled and moderated primary loop.
- Natural uranium or recovered uranium fuel rather than enriched uranium (~0.7 -0.9 % U-235 content)
- Primary coolant pressure ~10 MPa. Secondary coolant pressure ~4.7 MPa.

Courtesy: www.inl.gov

Nuclear Fuel Types

- Nuclear fuel can exist in all three phases
  - Solid
  - Liquid
  - Gaseous
- Solid Fuel (Current water and gas cooled reactors)
  - Metallic (U-Al, U-Al-Zr alloy, Mixed)
  - Ceramic (U-oxide, U-Carbide, U-oxy-Carbide, Mixed)
- Liquid Fuel – Fluoride salts of Uranium and Thorium (MSRE experiment at ORNL, AHR)
- Gaseous Fuel (hexafluoride gas fuel, RAM reactor)

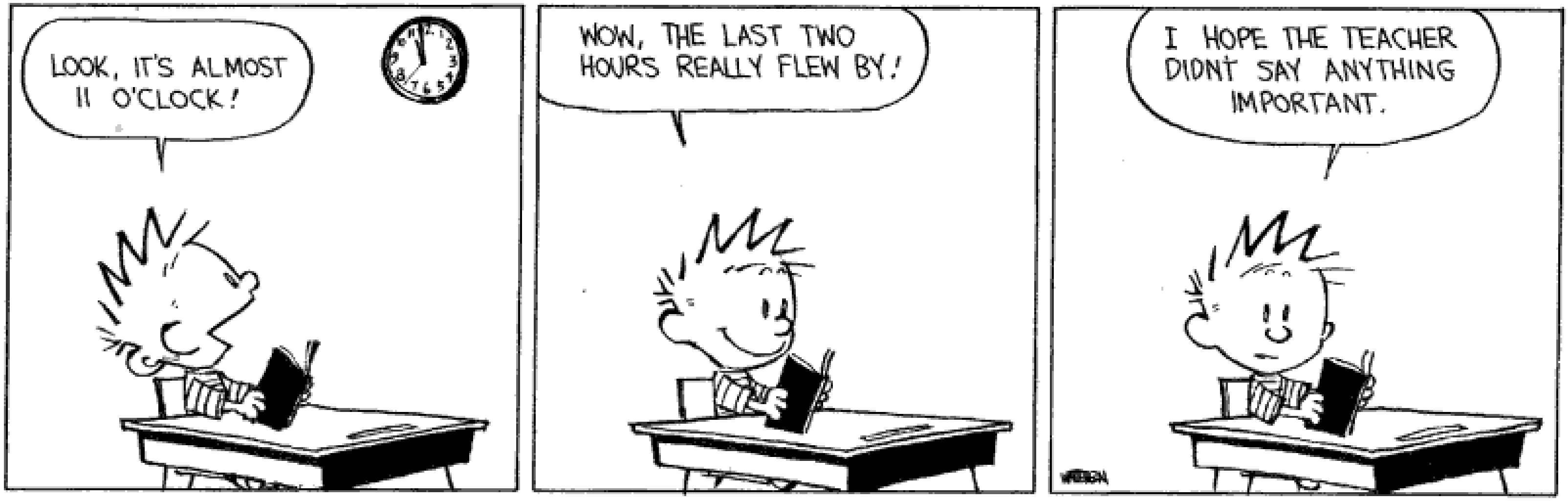
Nuclear Fuel



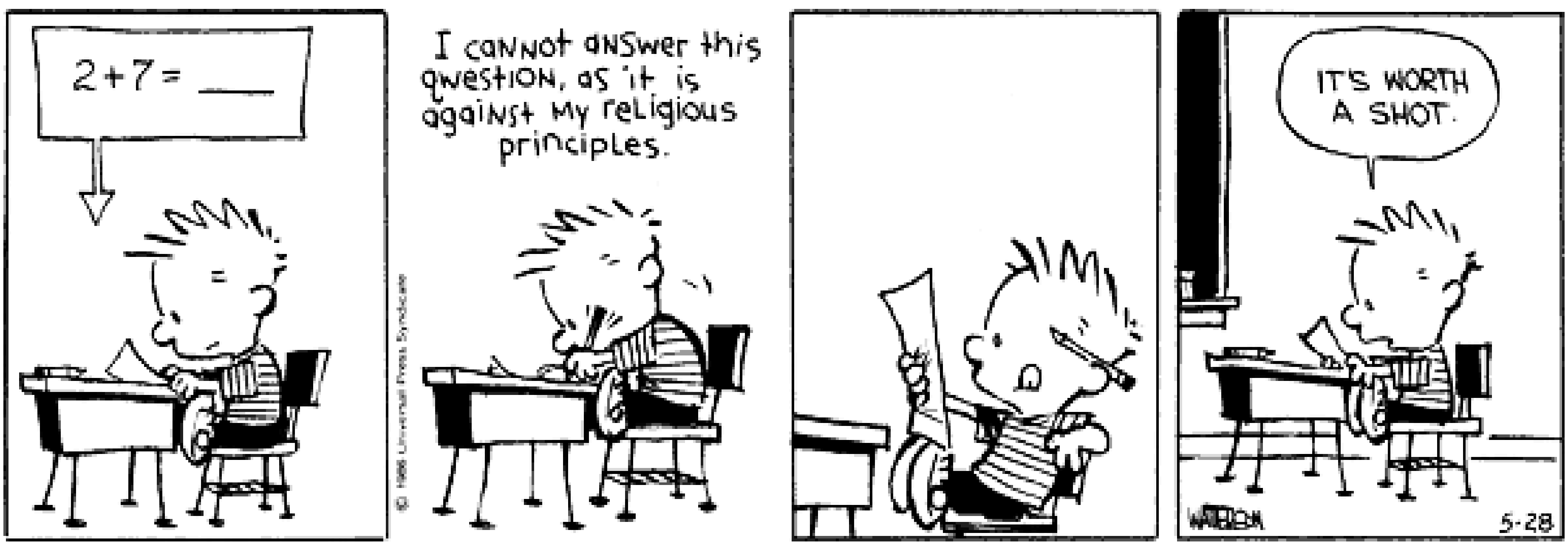
In terms of the energy released by fission 1gm of U-235 is same as burning ~3000 tons of coal or 13000 barrels of oil

Nuclear Fuel Assembly

Source: wikipedia.org


LOOK, IT'S ALMOST 11 O'CLOCK!
WOW, THE LAST TWO HOURS REALLY FLEW BY!
I HOPE THE TEACHER DIDN'T SAY ANYTHING IMPORTANT.

QUESTIONS ?


2+7 = ____
I cannot answer this qwestion, as it is against my religious principles.
IT'S WORTH A SHOT.
5-28