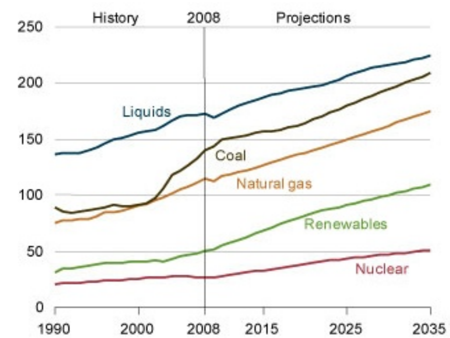
Nuclear Reactors

Physics 6605

2012

Annual World Energy Consumption

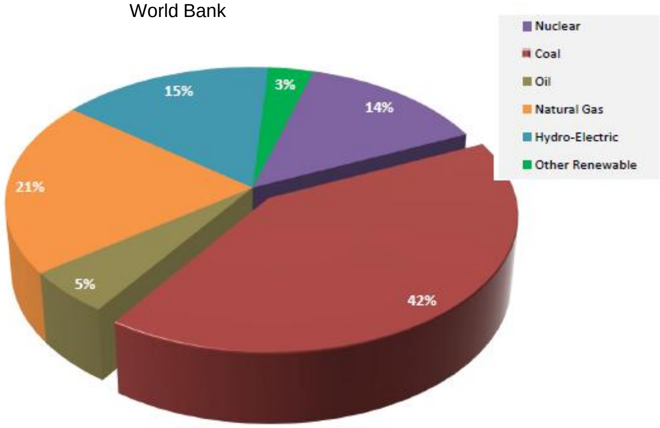
10^{15} BTU



US Energy Information Administration

Electricity Sources

World Bank



3 Unit Nuclear Power Station - Desert

3 Unit Nuclear Power Station - Coastal

2 Unit Nuclear Plant, Byron, Illinois

International Nuclear Energy Statistics

(World Nuclear Association, 2012)

- Worldwide, the number of operable nuclear power plants has been relatively constant:
  - 440 plants in 1996
  - 441 in 1997
  - 435 in 1999
  - 433 in 2000,
  - 440 in 2002
  - 443 in 2005
  - 442 in 2011
  - 434 in 2012
- They operate in 30 countries and supply about 14% of the world's electricity
- There are 61 reactors being built in 2012, up from 43 in 2009 and 34 in 2007
- Countries active in building new plants are
  - China (26)
  - Russia (9)
  - India (6)
  - South Korea (5)
  - Canada (3)
  - Japan, Slovakia and Taiwan (2 each)
  - Argentina, Brazil, Finland, France, and Pakistan USA (1 each)

International Nuclear Energy Statistics

(World Nuclear Association, 2012)

- 15 countries generate more than 20% with nuclear
  - France generates highest percentage, 74%
  - Slovakia is in second place with 52%
- In terms of numbers of reactors for largest users: US (104), France (58), Japan (51), Russia (33), South Korea (21), India (20), UK (18), Canada (17), Ukraine (15), China (15), Sweden (10), and Germany (9)

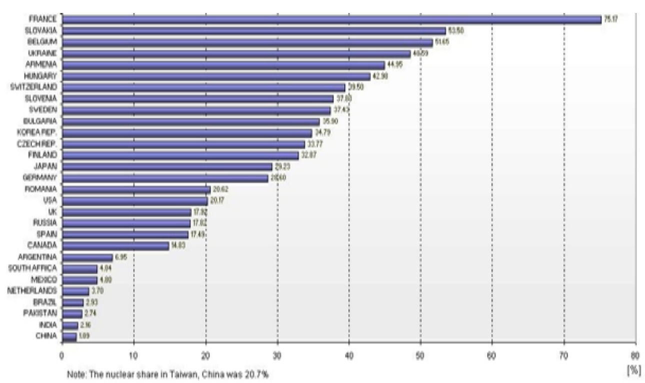
International Nuclear Energy Statistics

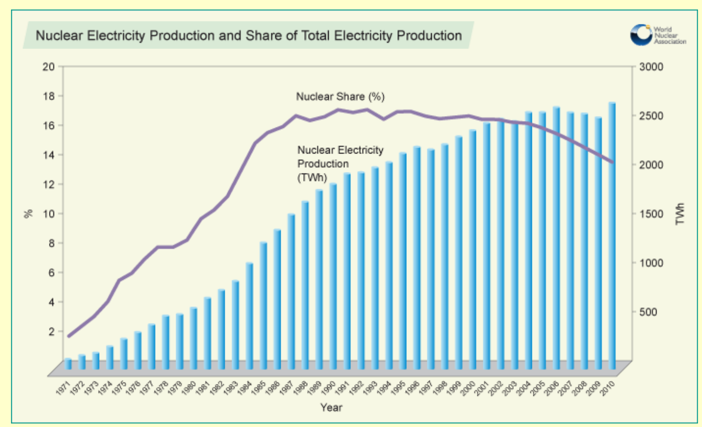
(World Nuclear Association, 2012)

- The 434 nuclear operable power plants have a total net installed capacity of 371 GW(e)
- There are
  - 61 under construction
  - 156 Planned
  - 343 Proposed

Worldwide Power Plant Locations

Approximate Country Shares of Nuclear, IAEA

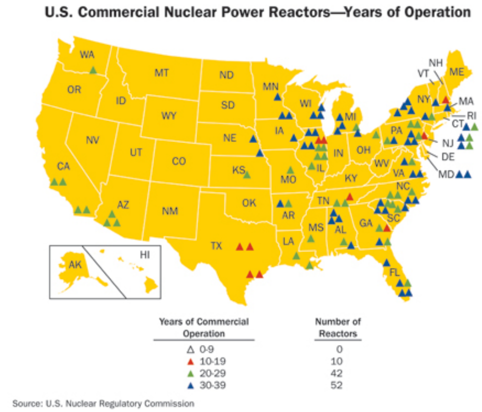




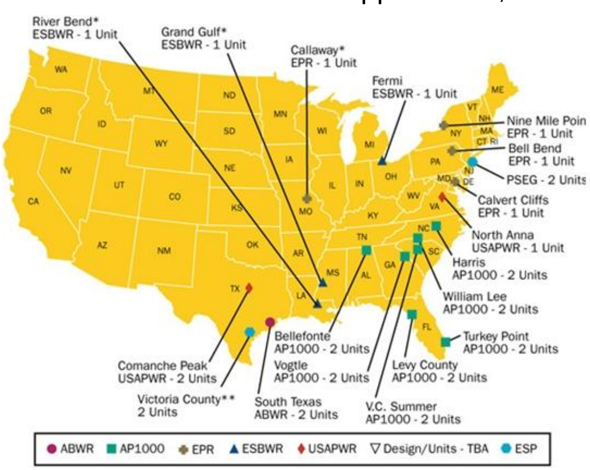
US Nuclear Energy Statistics, 2012

- The US has 104 nuclear power reactors in 31 States operated by 30 power companies
  - 69 pressurized water reactors
  - 35 boiling water reactors
  - produced 807 billion kWh in 2010
    - largest amount for a single country (30%)
    - approximately 20% of total electricity in the US
- Seven new reactors are on order or planned and 27 are proposed (WNA)
- License applications have been received for 28 reactors at 18 sites (US Nuclear Regulatory Commission)

The 104 US Licensed Reactors, 2011

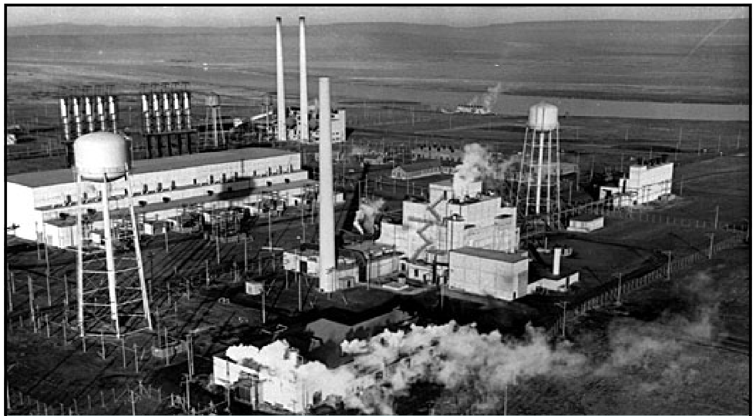


US Nuclear Power License Applications, 2011



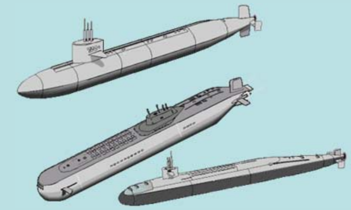
Other Uses of Reactors

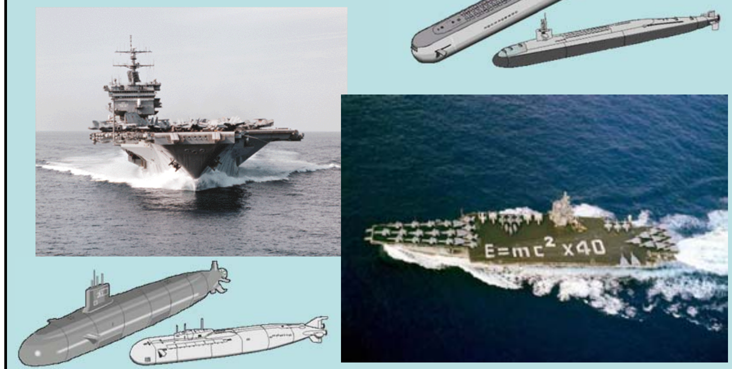
- Weapons materials production
- Propulsion
  - Worldwide there are about 140 ships powered by more than 180 small nuclear reactors
- Research
  - Worldwide there are 230 research reactors operating in 56 countries
  - The US has 31 research and test reactors operating in 21 States

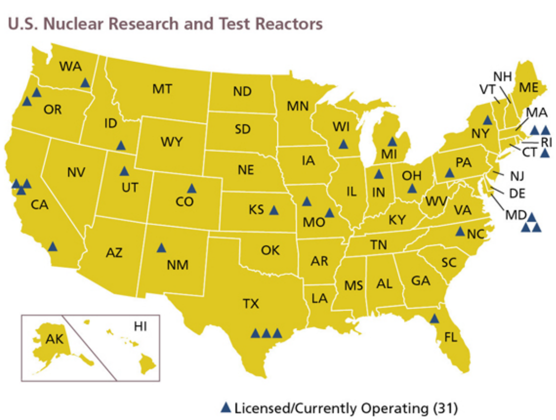


Hanford:Completed in September 1944, the 250,000 kilowatt B Reactor was the world's first large-scale plutonium production reactor. Two hundred tons of aluminum clad uranium slugs the size of rolls of quarters went into tubes. Cooling water from the Columbia River was pumped through tubes around the uranium slugs at 75,000 gallons per minute. This and all other US production reactors are shut down.

US and Russia Have Nuclear-powered Fleets with classified reactor designs







Reactor Design

- Basic purposes of reactors are
  - research
  - production
  - propulsion
  - electrical generation
- Major variations relate to fuel, moderator and coolant

Reactor Design

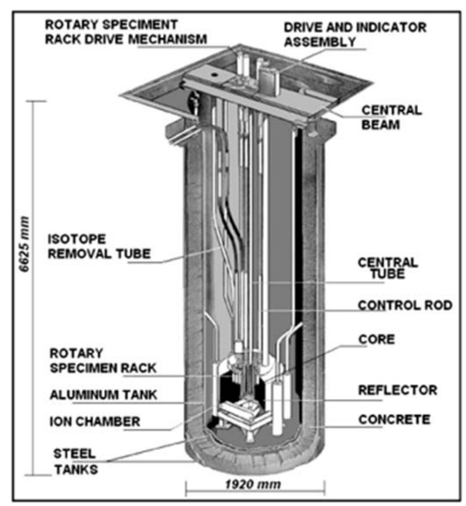
- Many configurations of reactors have been designed and tested
- Neutron Energy
  - thermal or slow neutron
  - fast neutron (breeders)
- Coolant
  - gas cooled
  - liquid cooled
    - boiling water reactors
    - pressurized water reactors

Reactor Design

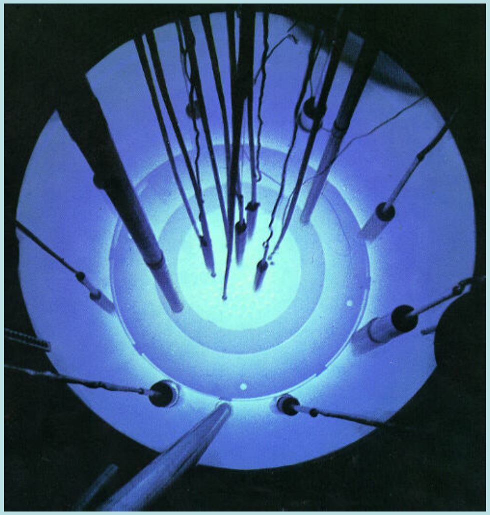
- Moderators
  - light water
  - heavy water
  - graphite
- Fuel enrichment
  - none
  - slight
  - Highly
- Advanced design

TRIGA

- TRIGA is a class of small nuclear reactor designed and manufactured by General Atomics of the USA.
  - acronym for "Training, Research, Isotopes, General Atomics"
- A pool-type reactor
  - can be installed without a containment building
  - used by scientific and academic institutions
  - purposes include
    - graduate education and academic research
    - private commercial research
    - non-destructive testing
    - isotope production.



TRIGA Research Reactor Diagram



TRIGA Research Reactor Core During Operation

Advanced Test Reactor at INL

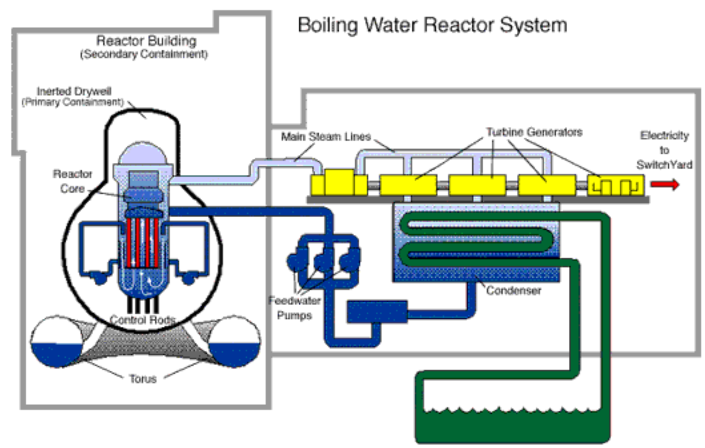
Power Reactors

Nuclear power reactor types: typical characteristics

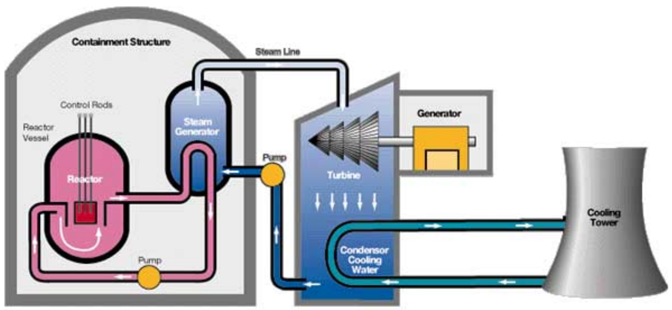
Characteristic	PWR	BWR	GCR	AGR	PHWR (Candu)	LWGR (RBMK)	FBR
Active core height, m	4.2	3.7	7.6	8.3	5.9	7.0	1.0
Active core diameter, m	3.4	4.7	14.0	9.3	6.0	11.8	3.7
Fuel inventory, tonnes	104	134	300	110	90	192	32
Vessel type	Cylinder	Cylinder	Cylinder	Cylinder	Tubes	Tubes	Cylinder
Fuel	UO_2	UO_2	U	UO_2	UO_2	UO_2	PuO_2/UO_2
Form	Enriched	Enriched	Natural	Enriched	Natural	Enriched	-
Coolant	H_2O	H_2O	CO_2	CO_2	D_2O	H_2O	Sodium
Steam generation	Indirect	Direct	Indirect	Indirect	Indirect	Direct	Indirect
Moderator	H_2O	H_2O	Graphite	Graphite	D_2O	Graphite	None
Number in operation*	264	92	4	14	44	16	2

* as of 01.06.09

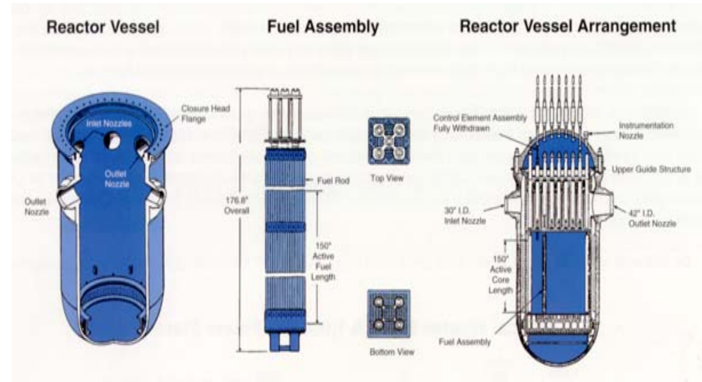
Boiling Water Power Reactor



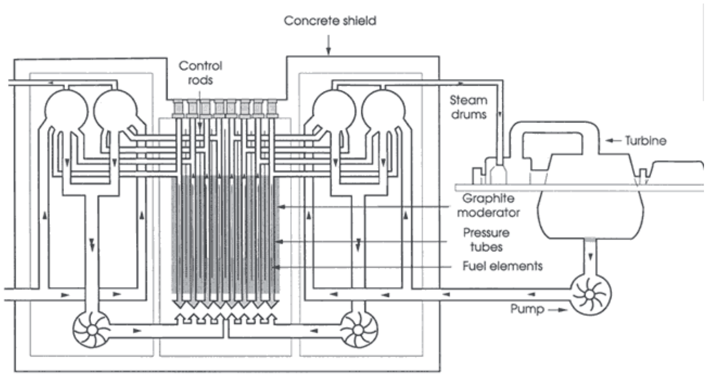
Pressurized Water Power Reactor



Reactor Components

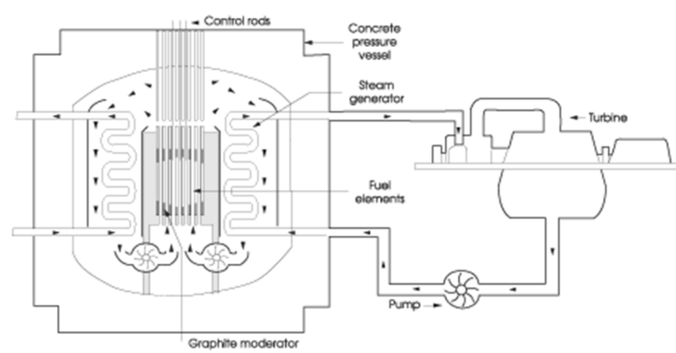


RBMK Reactor (Russian Design with Graphite Moderator)

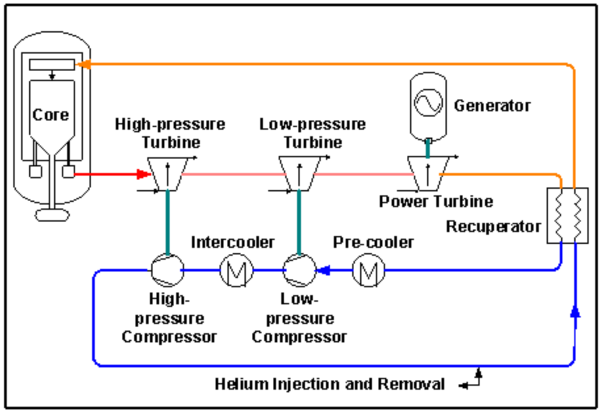


Advanced Gas-cooled Reactor

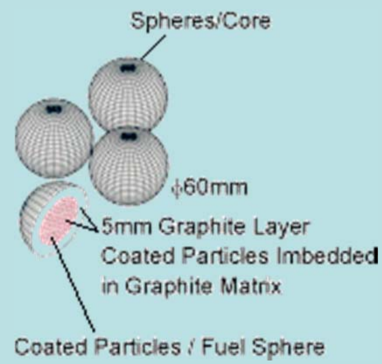
(second generation British design-Helium Coolant)

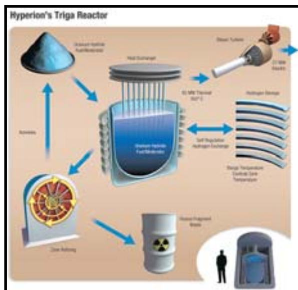


Pebble Bed Reactor



Pebble Bed Reactor Fuel Spheres





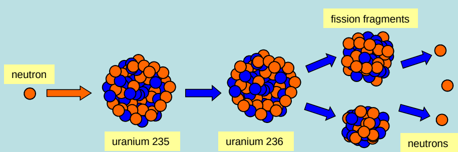
Hyperion is proposing a self-contained 25 MW(e) reactor about the size of a "hot tub" with uranium hydride fuel/moderator

Reactor Design

- Today's most common power reactor is a light water reactor using slightly enriched fuel, but there are exceptions
- Basis for the design was naval propulsion reactors
- Fuel is usually uranium oxide pellets in rods or pins about 1/2 inch in diameter
- Cladding serves as a barrier to fission products
- Space is allowed for build-up of gaseous fission products

Reactor Kinetics

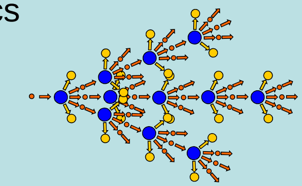
- Basis of fission reactor is that neutrons induce fission and fission produces neutrons
- Reactor is designed to permit this process to occur in a stable, controlled fashion



Reactor Kinetics

- k is the neutron multiplication factor per generation
  - k > 1, reaction rate increases
  - k < 1, reaction rate decreases
- Reactivity is another way to express reactor kinetics

$$\rho = \left(\frac{k-1}{k}\right)$$



Reactor Kinetics

TRIGA control rod and drive

- It is important that reactivity have a negative temperature coefficient
- Reactivity is adjusted by poisons
  - control rods
  - neutron absorbers in coolant
- As fuel ages, fission products act as poisons

Control rod from Russian reactor

Reactor Kinetics

- The rate of change of neutron flux is given by

$$\frac{dn}{dt} = n\left(\frac{k-1}{L}\right)$$

- Where k is neutron multiplication factor and l is the generation time, about 10^{-3} s

$$\frac{1}{n}dn = \left(\frac{k-1}{L}\right)dt \qquad n = n_0 e^{\left(\frac{k-1}{L}\right)t}$$

- On this basis alone, reactors would be uncontrollable

Reactor Kinetics

- Fortunately there are delayed neutrons which effectively increases L
- If beta is the fraction of delayed neutrons, then for the case

$$\rho < \beta$$

- Delayed neutrons control the reaction
- If however,

$$\rho \geq \beta$$

- The reaction is prompt supercritical, a condition to be avoided

What are the Emissions?

- Reactor emissions and waste are mostly fission products
- Fission product inventories: text Figs 8-3 & 8-8 and Table 8-6
- Also activation products & “hot particles”

Fission Product Mass Number Distributions

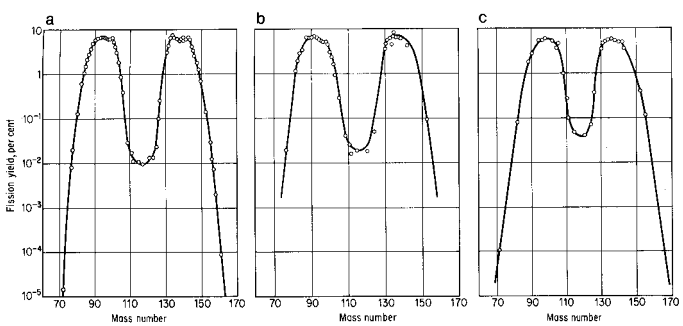
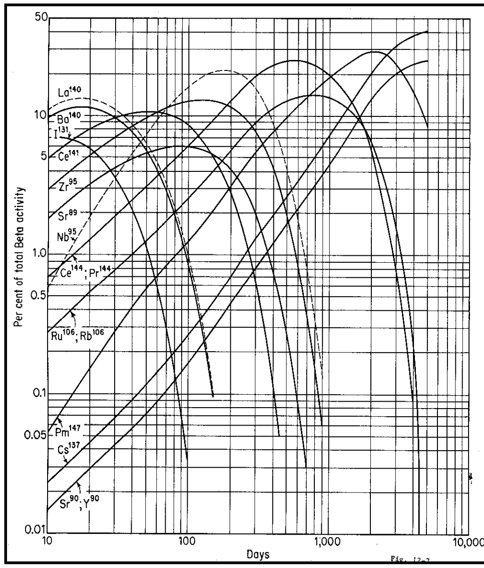


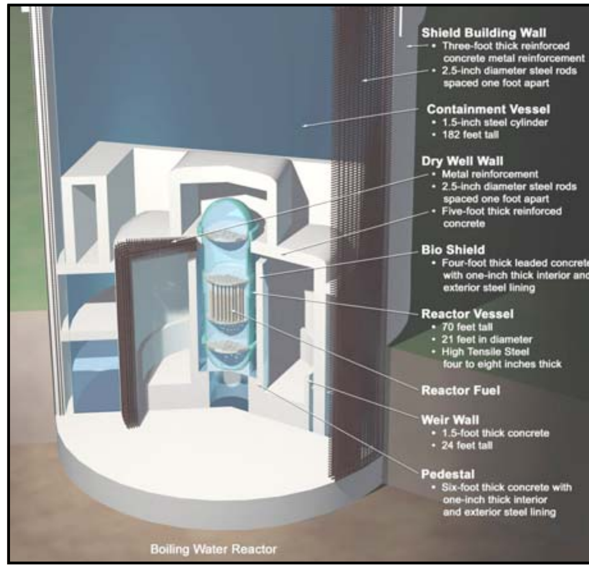
FIGURE 8-8 Mass yields for slow neutron fission of (a) ^{235}U, (b) ^{233}U, and (c) ^{239}Pu. [From Steinberg and Glendenin (1956).]



Percent of Total Beta Activity as a Function of Time After Reactor Shutdown

How Are Emissions Released?

- Emissions from the fuel
  - tramp uranium
  - diffusion and leakage from fuel
  - failed fuel
- Airborne wastes (mostly gas)
  - source is removal of gases from the operating fluids
  - cleanup can include
    - filtration (HEPA)
    - charcoal trapping
    - cryogenic trapping
- Liquid waste
  - leakage
  - Coolant cleanup



Safety and Emission Barriers at Nuclear Power Plants

Other Wastes

- Solid waste
  - resin cores
  - contaminated worn out parts
  - cleaning materials
  - disposable protective clothing

Routine Emissions and Wastes

- Doses from routine reactor operations
  - noble gases typically dominate dose
- Note that air pathway dose limits have been superseded by EPA limits
- http://hps.ne.uiuc.edu/natcenviro/ has power plant environmental reports for a few years.
  - Works only with internet explorer
  - Does not appear to be well maintained
  - Dr. Harris can provide access to environmental data

Emissions from Reactor Accidents

- Three accidents have resulted in large releases of radionuclides
  - Fukushima – 21,000,000*
  - Chernobyl - 48,000,000 curies
  - Windscale - 20,000 curies
  - (TMI - 4 curies)
- Iodines dominate early dose
- Cesium-137 dominates late dose
- U.S. reactor accident probabilities have been calculated to be small
  - even smaller for accidents with serious consequences

*Japan's Nuclear and Industrial Safety Agency, estimate in June 2011