Chemical Engineering 412

Introductory Nuclear Engineering

Lecture 20

Nuclear Reactor Theory V

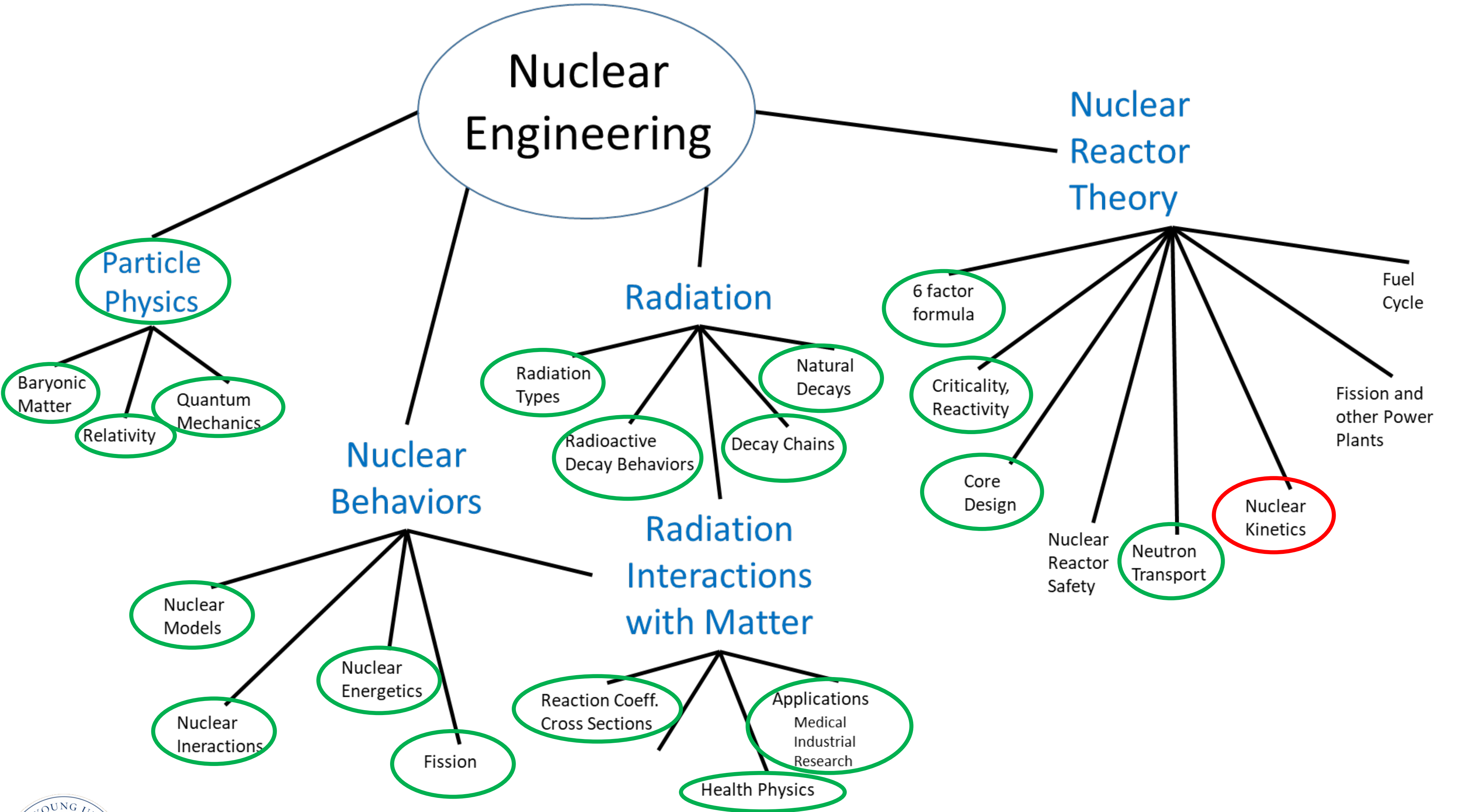
Reactivity Insertions

Spiritual Thought

"In unfair situations, one of our tasks is to trust that all that is unfair about life, can be made right through the atonement of Jesus Christ. Jesus Christ overcame the world and absorbed all unfairness. Because of him, we can have peace in this world and be of good cheer. If we let him, Jesus Christ will consecrate the unfairness for our gain. He will not just console us and restore what was lost; He will use the unfairness for our benefit."

-Dale G. Renlund

Roadmap



Nuclear Engineering
Particle Physics
Baryonic Matter
Relativity
Quantum Mechanics
Nuclear Behaviors
Nuclear Models
Nuclear Ineractions
Nuclear Energetics
Fission
Radiation
Radiation Types
Radioactive Decay Behaviors
Natural Decays
Decay Chains
Radiation Interactions with Matter
Reaction Coeff. Cross Sections
Applications
Medical
Industrial
Research
Health Physics
Nuclear Reactor Theory
6 factor formula
Criticality, Reactivity
Core Design
Nuclear Reactor Safety
Neutron Transport
Nuclear Kinetics
Fission and other Power Plants
Fuel Cycle

Objectives

- Understand, recognize and do calculations relating to feedback coefficients
- Understand reactor “control strategies”
- Understand xenon peak phenomena

Kinetics

- Reactor power is controlled:
  - Control rods add/subtract worth
  - Chemical Shim
  - Burnable Poisons
- The circumstances we've seen so far are not a real, however. Why?
- Nature gets involved:
  - Feedback Mechanisms!

Isotopic Feedbacks (slow)

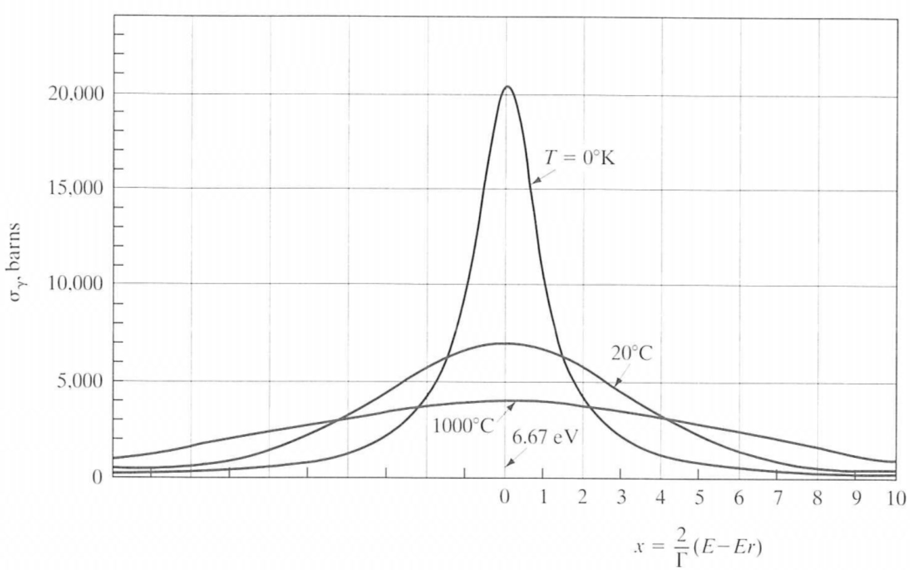
- Fuel Burnup (slow)
  - Decrease in reactivity
- Fuel breeding (slow)
  - Increase in reactivity
- Fission product poisons (moderate–hours)
  - ^{135}Xe and ^{149}Sm
  - Decrease reactivity until decay away
- Burnable Poisons (slow)
  - Decrease reactivity until transmuted away

Temperature Feedbacks (fast)

- Atomic concentration changes
  - Moderator coolant density
  - Void coefficient fuel expansion
- Neutron energy distribution changes
  - “harden” spectrum with increased T
  - TRIGA reactor is extreme example
- Resonance interaction changes
  - Doppler – dominant feedback
- Burnable Poisons
  - Geometry changes

Temperature Dependence

$$\alpha_T = \frac{d\rho}{dT} = \frac{d}{dT}\left(\frac{k-1}{k}\right) = \frac{1}{k^2}\frac{dk}{dT} \cong \frac{1}{k}\frac{dk}{dT}$$



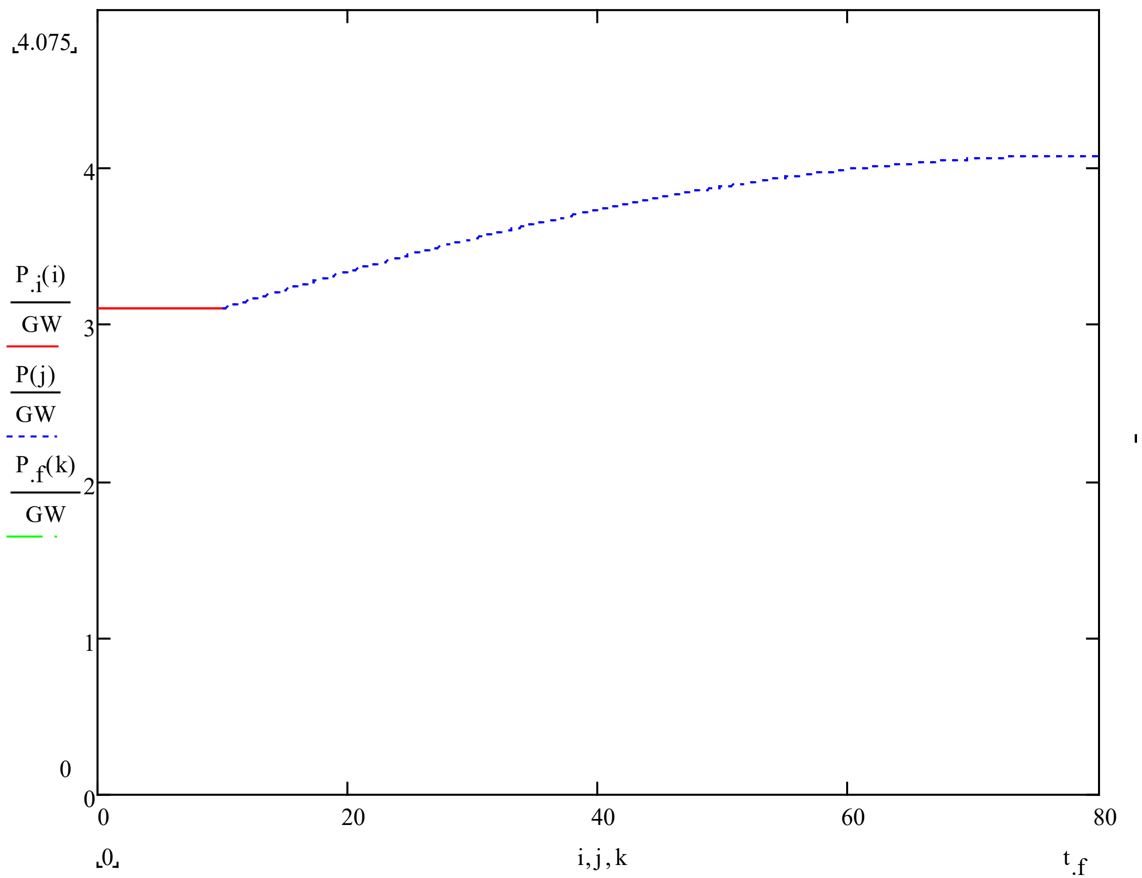
Breit-Wigner describes absorption profile at 0 K but Doppler effect broadens peaks, with little change in area, at higher temperatures.

$$\sigma_\gamma(E) = \frac{\lambda_r^2 g}{4\pi}\frac{\Gamma_n \Gamma_\gamma}{(E - E_r)^2 + \frac{\Gamma^2}{4}}$$

- *α_T = temperature reactivity feedback coefficient*
- *If α_T* > 0,
  - Unstable
  - increases and decreases in temperature run away to meltdown or shutdown without operator response.
- *If α_T* < 0,
  - Stable
  - Increases and decreases in temperature self regulate and the reactor stabilizes.
- Different α's for fuel/moderator
  - Different timescales
    - Fuel is most rapid
    - α_{prompt}
- NRC requires negative α_{prompt} values for licenses

Feedback Effects

- What if we add $0.1 to AP1000 core with temperature feedbacks included?



Example 1

A standard US pressurized water reactor (1000 MWe) experiences a transient in which a control rod bank is ejected from the core. This adds 0.1$ of reactivity. What is the power after 1 minute?

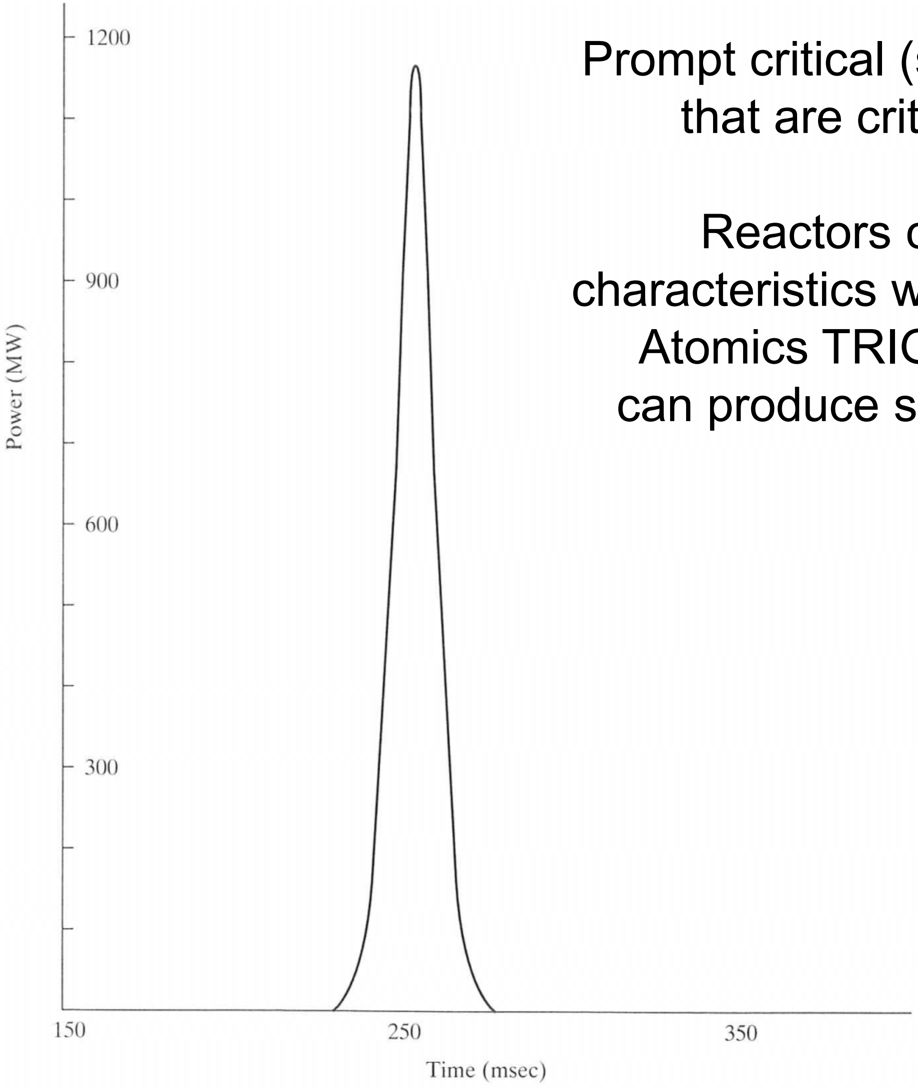
Feedback Types

- Flowering
- Axial Expansion
- Radial Expansion
- Coolant
- Doppler

Example 2

Based on the previous AP1000 example, a rod-ejection accident occurs, but assume now an axial expansion feedback coefficient of -0.00001₵/K, a Doppler feedback of -0.01 ₵/K, and a coolant void coefficient of -0.03 ₵/K. How much of a temperature increase occurs before the power level stops increasing?

Exotic Reactors



Prompt critical (supercritical) behavior refers to reactors that are critical based on prompt neutrons only and hence have very short periods.

Reactors can be designed with inherent shutdown characteristics when they become supercritical. General Atomics TRIGA reactor is an example. Such reactors can produce short but intense pulses of neutrons (see chart at left).

Xenon (Iodine, Tellurium)

Xenon-135 has a high absorption cross section (2.65×10^6 b in thermal region) and is the most significant absorbing poison.

$$\underset{\substack{\uparrow \\ Fission}}{{}^{135}Te} \xrightarrow[11\,\mathrm{sec}]{\beta^-} \underset{\substack{\uparrow \\ Fission}}{{}^{135}I} \xrightarrow[6.7\,hr]{\beta^-} \underset{\substack{\uparrow \\ Fission}}{{}^{135}Xe} \xrightarrow[9.2\,\mathrm{sec}]{\beta^-} {}^{135}Cs \xrightarrow[2.3x10^6\ yr]{\beta^-} {}^{135}Ba\ (stable)$$

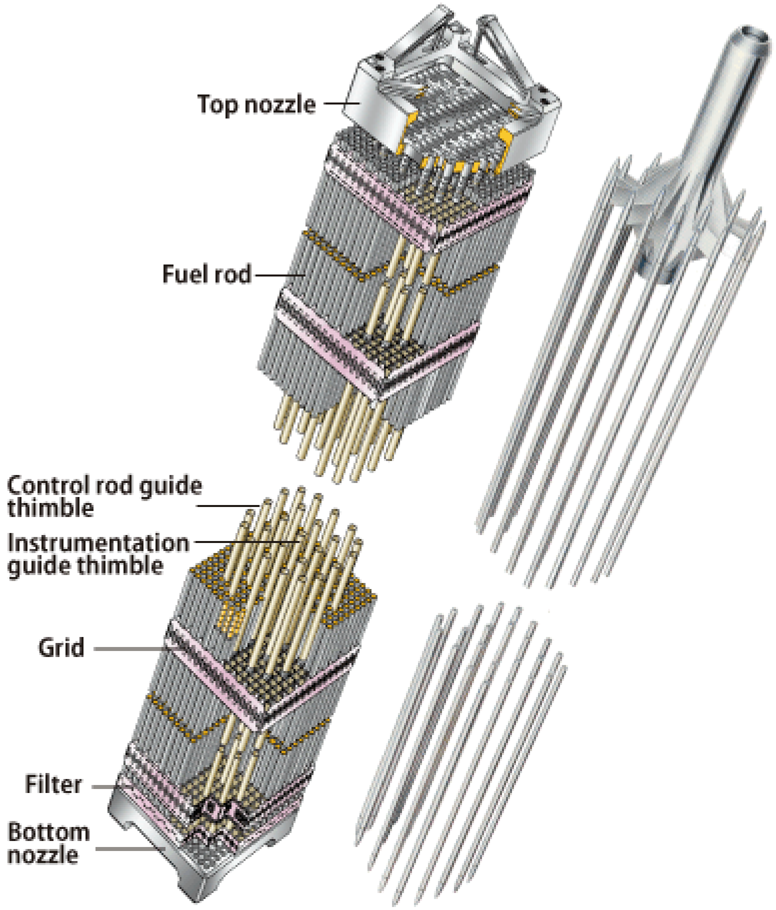
$$\frac{dI}{dt} = \underbrace{\gamma_I \overline{\Sigma}_f \phi_T}_{fission\ yield} - \underbrace{\lambda_I I}_{natural\ decay}$$

$$\frac{dX}{dt} = \underbrace{\lambda_I I}_{Iodine\ decay} + \underbrace{\gamma_X \overline{\Sigma}_f \phi_T}_{fission\ yield} - \underbrace{\lambda_X X}_{natural\ decay} - \underbrace{\overline{\sigma}_{aX} \phi_T X}_{absorption\ decay}$$

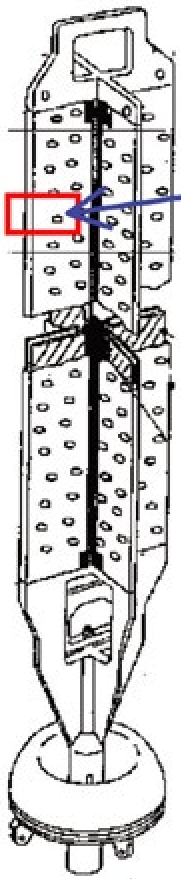
$$= \lambda_I I + \gamma_X \overline{\Sigma}_f(t) \phi_T(t) - \left(\lambda_X + \overline{\sigma}_{aX} \phi_T\right) X$$

$$\left(T_{1/2}\right)_{X,eff} = \frac{0.693}{\lambda_X + \overline{\sigma}_{aX} \phi_T(t)}$$

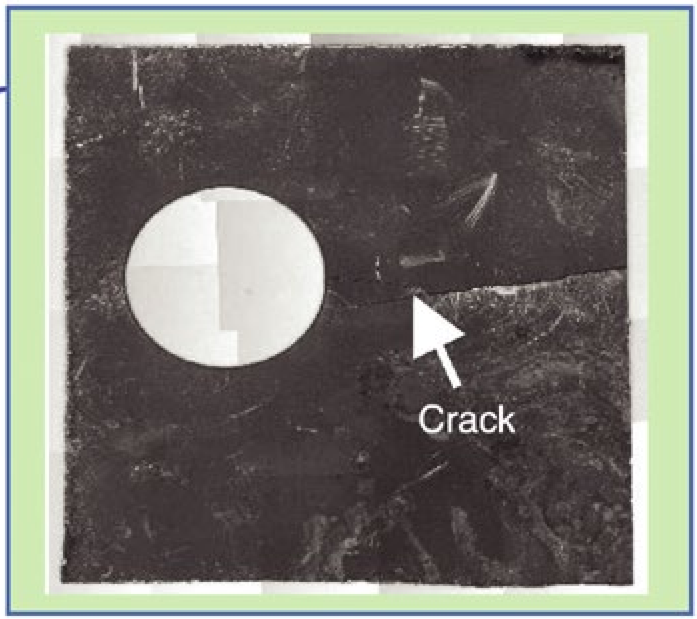
Cluster Control Rods



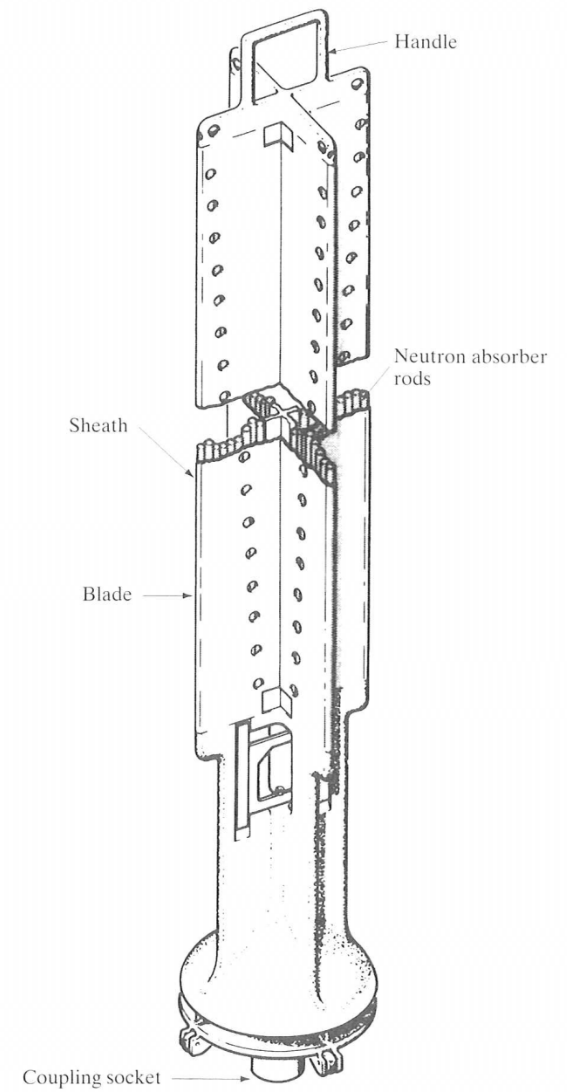
Cruciform Control Rods



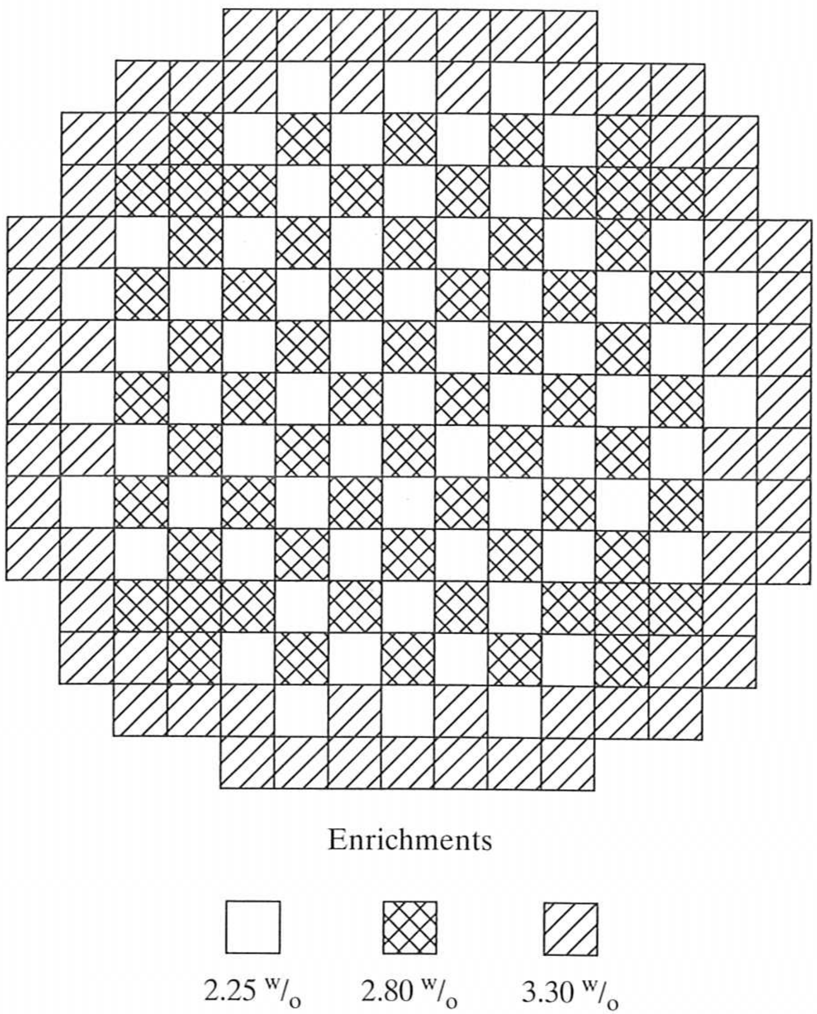
Control rod

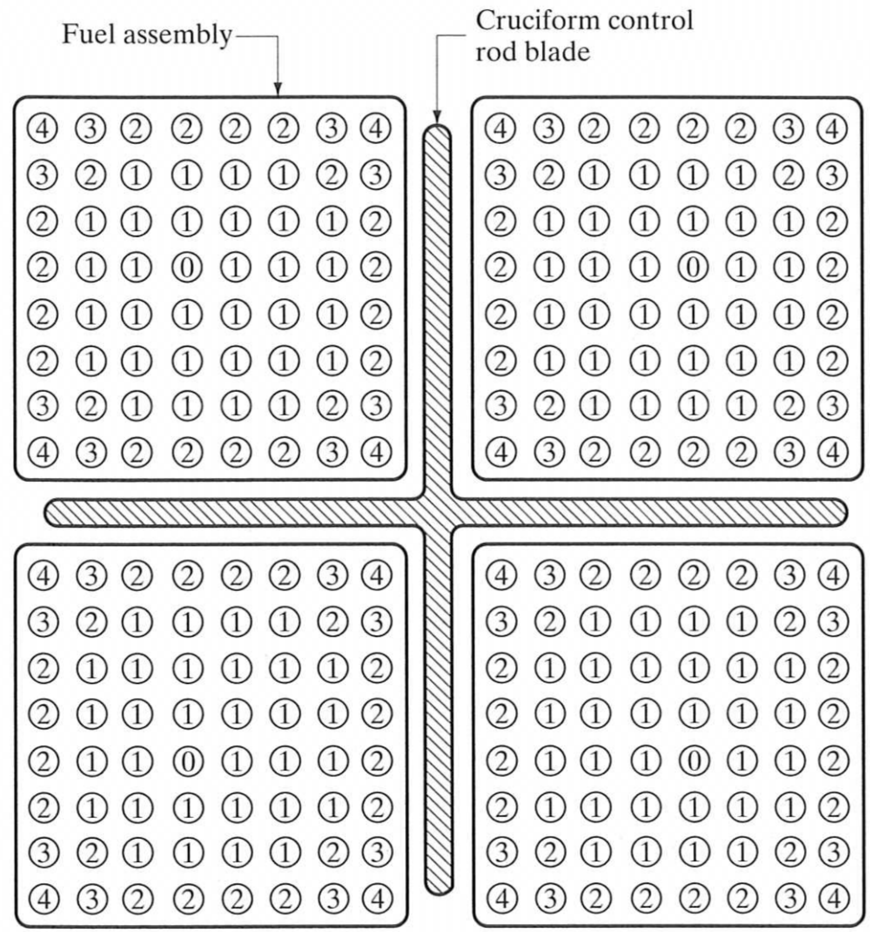


Cracks in the control rod

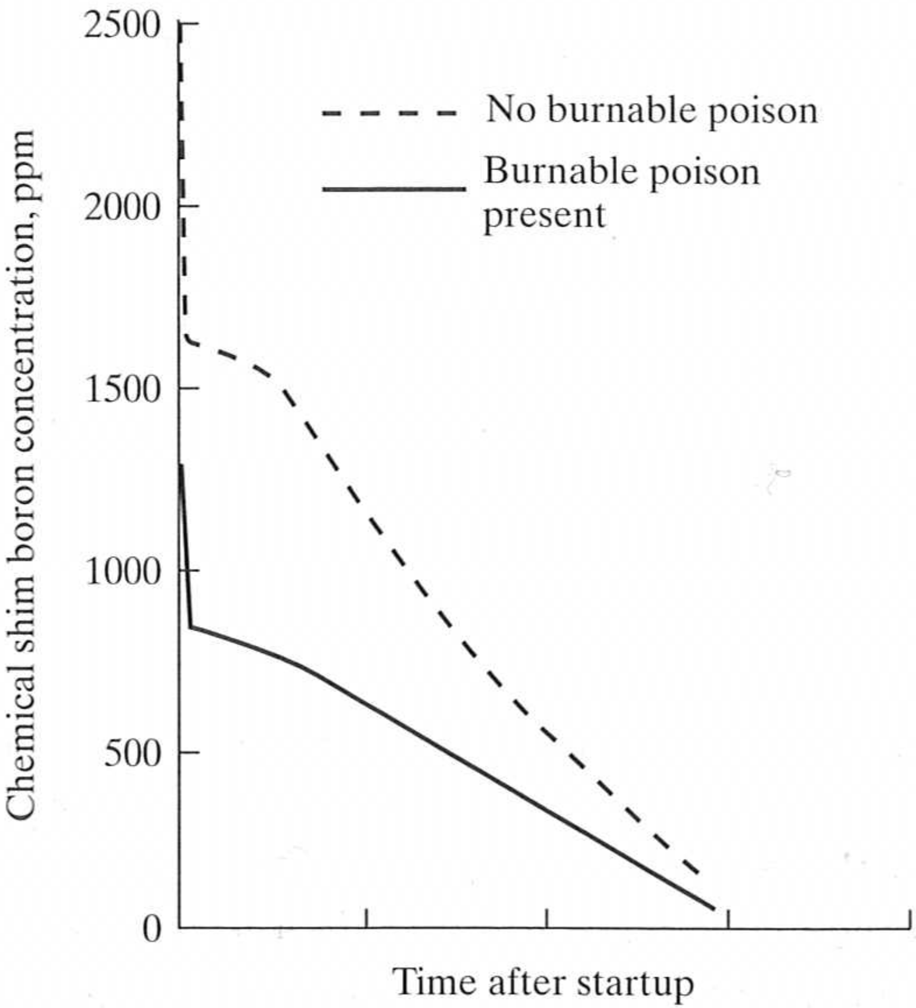


Fuel Loading Patterns





Burnable (absorbing) poisons



Burnable poison forms products with lower adsorption cross sections, compensating for accumulation of other poisons. Boron and gadolinium oxides (gadolina) are examples.

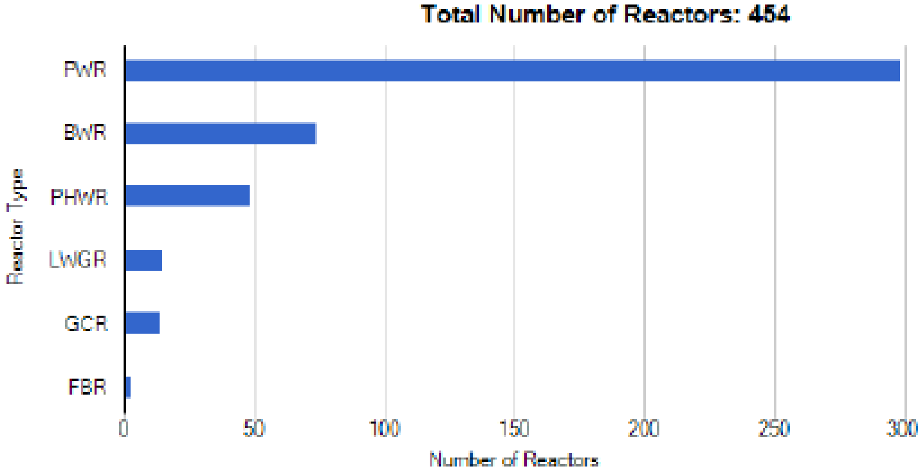
Typical Control Worths

TABLE 7.7 TYPICAL REACTIVITY WORTHS FOR CONTROL ELEMENTS 3,000 MWT LIGHT-WATER REACTOR

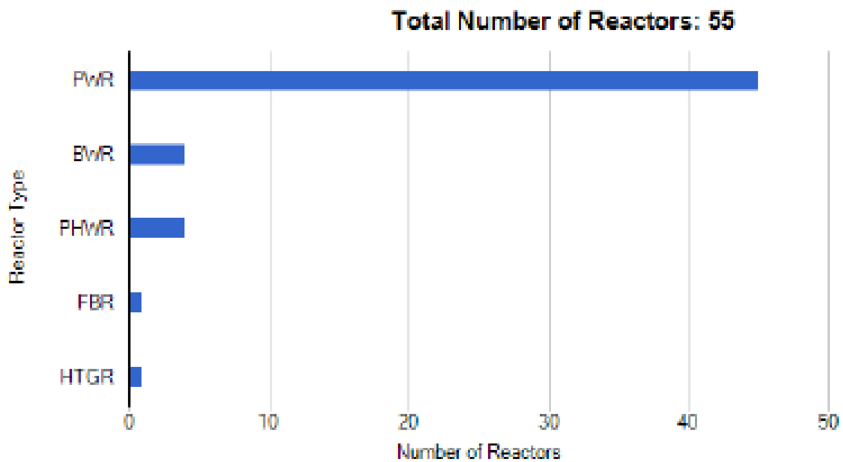
	PWR	BWR
Excess reactivity at 20°C	\$45	\$38
No Xe or Sm	$k = 1.41$	$k = 1.33$
Total control rod worth	\$11	\$26
	~60 clusters	140–185 rods
Fixed burnable poisons	\$13	\$18
Chemical shim worth	\$26	–
Net reactivity	–\$5	–\$6

Worldwide Summary

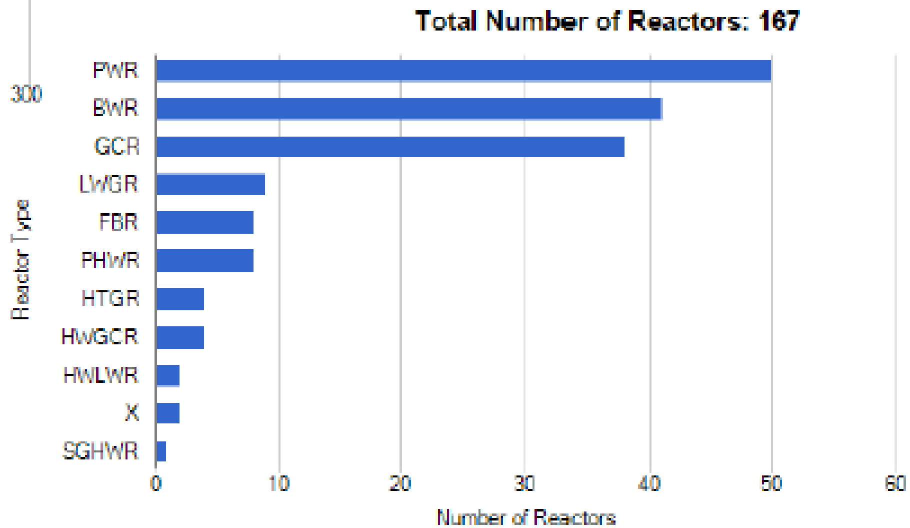
Operating power reactors



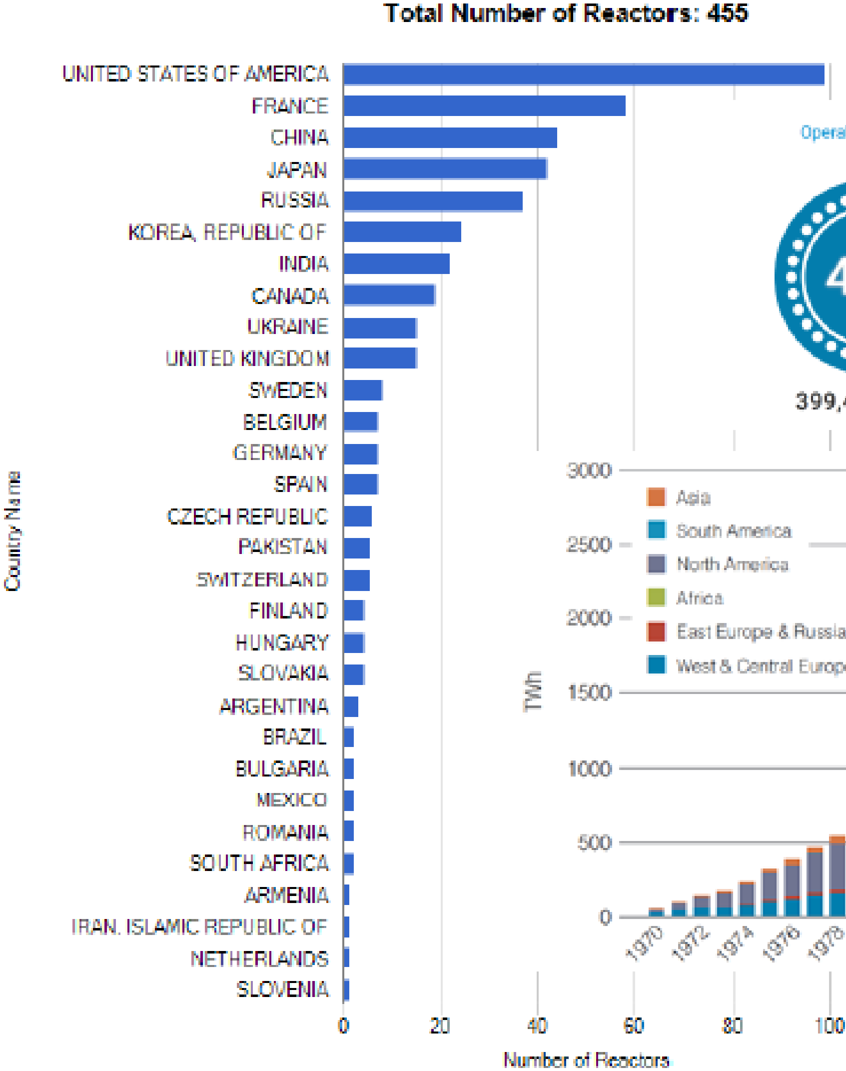
Under construction power reactors

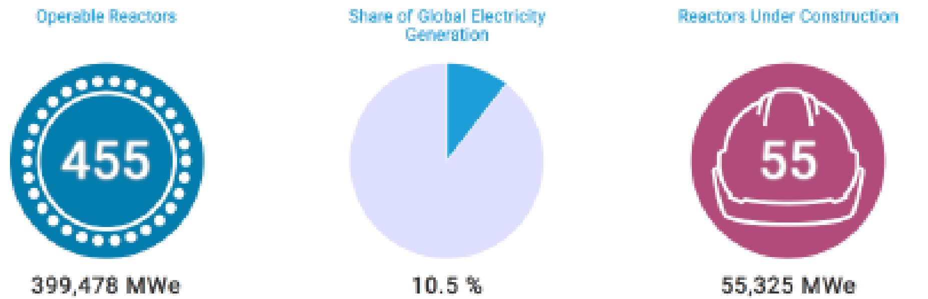


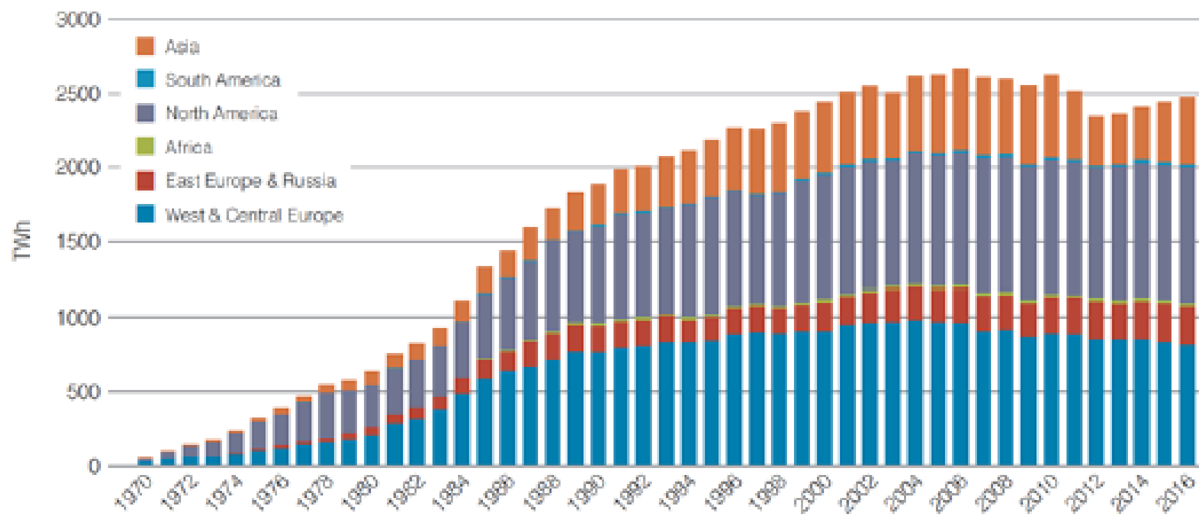
Permanent shutdown power reactors



Current Reactors/Power



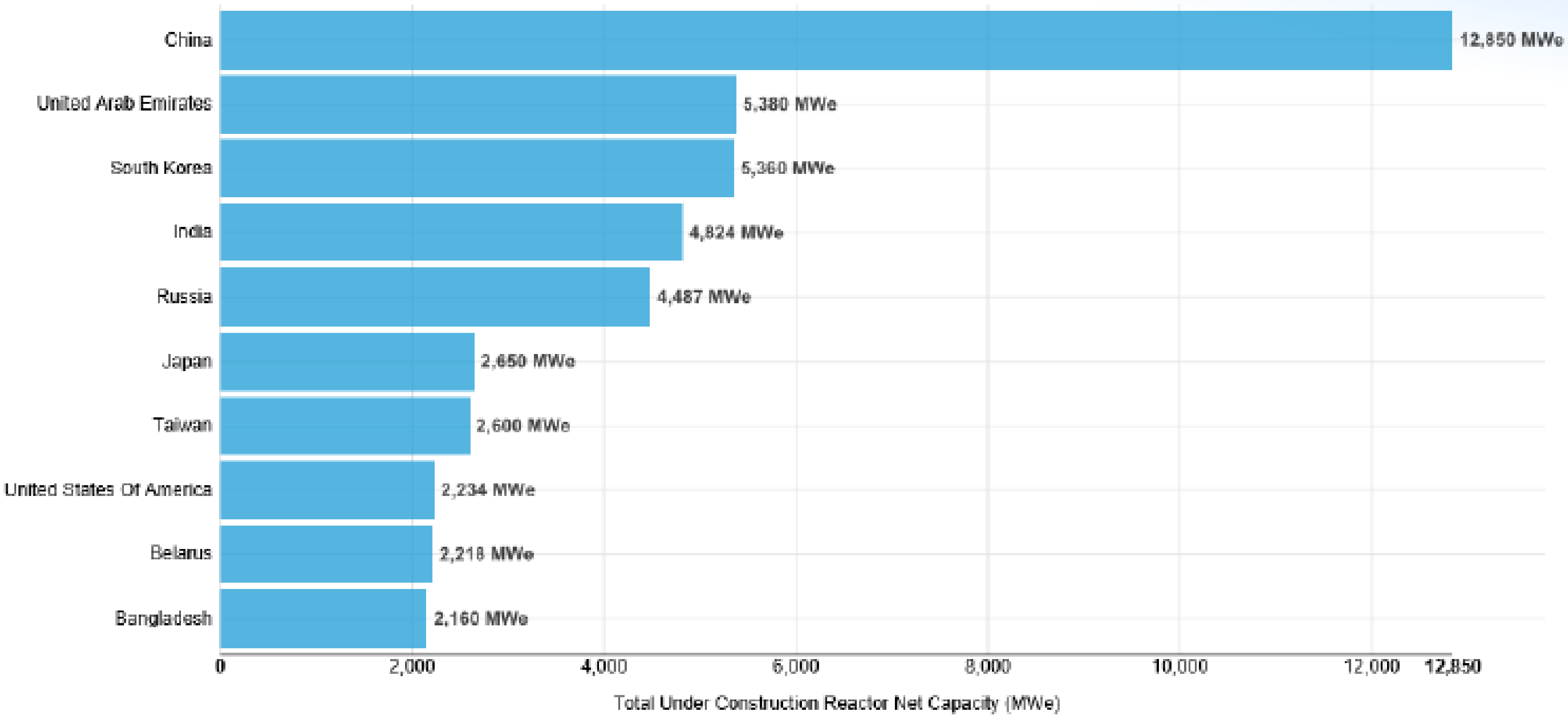




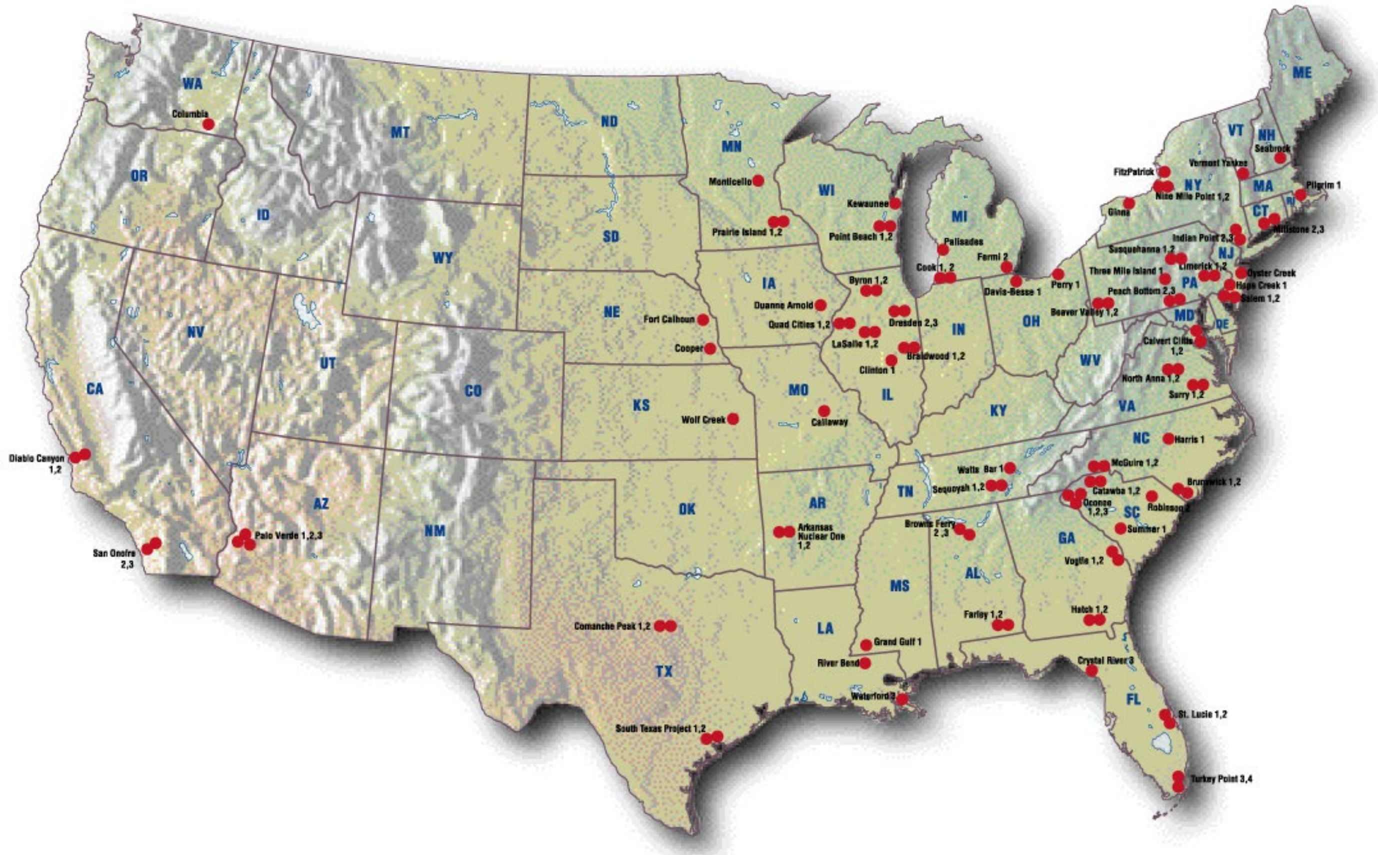
2,506 TWh: global electricity generation from nuclear energy in 2017

Sources: IAEA PRIS Database (update on 2018-09-13) https://www.iaea.org/PRIS/home.aspx
World Nuclear Association http://www.world-nuclear.org/information-library/facts-and-figures/reactor-database.aspx

Worldwide Construction

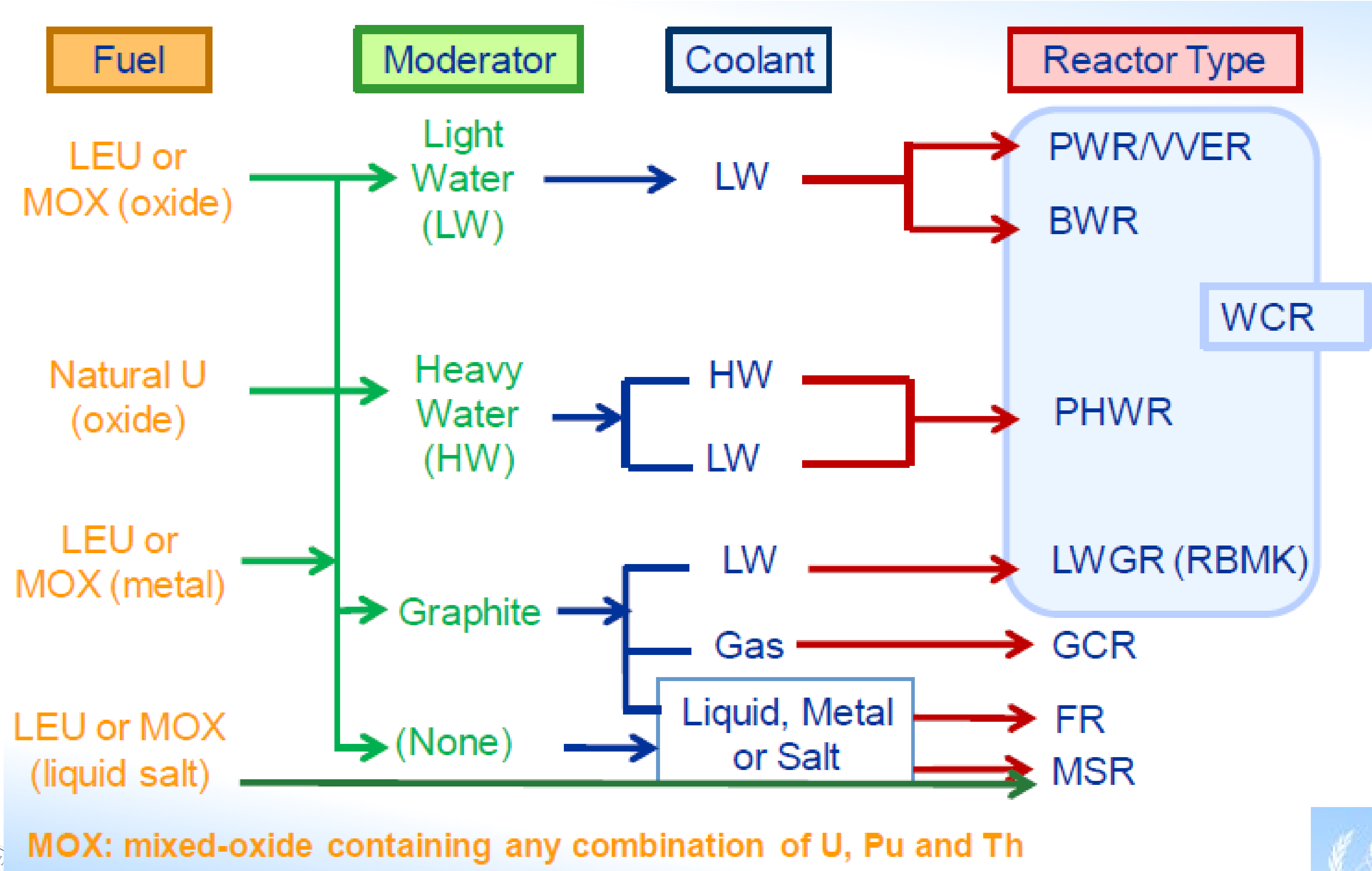


US Power Plants



96 plants in 31 states operated by 30 utilities with combined capacity and generation of 98.6 GW and 800 GWh, respectively, with average capacity factors slightly over 90%. 5 reactors under construction on 3 sites.

Reactor Classifications



All Reactor Summary Data Taken from the IAEA PRIS Database

Reactor Startup

Sandia National Laboratories