Chapter 1

Learning from Other Designs

In the process of learning about nuclear engineering one undoubtedly learns a great deal about existing reactor designs. On one hand the designer should start a project with a clean slate, but on the other hand knowledge in memory can greatly accelerate the design process. Trends, heuristics, and limitations are useful as long as the designer does not prematurely eliminate design possibilities.

In this chapter we will discuss types of nuclear reactors that have been built. The strengths and shortcomings will be listed, although not exhaustively. The purpose of this chapter is not to promote one design over another, because different constraints, priorities, and goals will favor different designs.

The following figure is a convenient way to categorize nuclear reactor types. Many other reactor designs have been conceived of (e.g. organic reactors, internal combustion-style reactors, etc.), but only common types used for commercial purposes are displayed. Of course there are other ways to categorize reactors (e.g. breeder vs. burner).

1.1 Light Water Reactors

Light water reactors are by far the most common reactor in the world.

Advantages	Disadvantages
Widely used technology	
Inexpensive coolant	Corrosion issues
	Requires enriched fuel

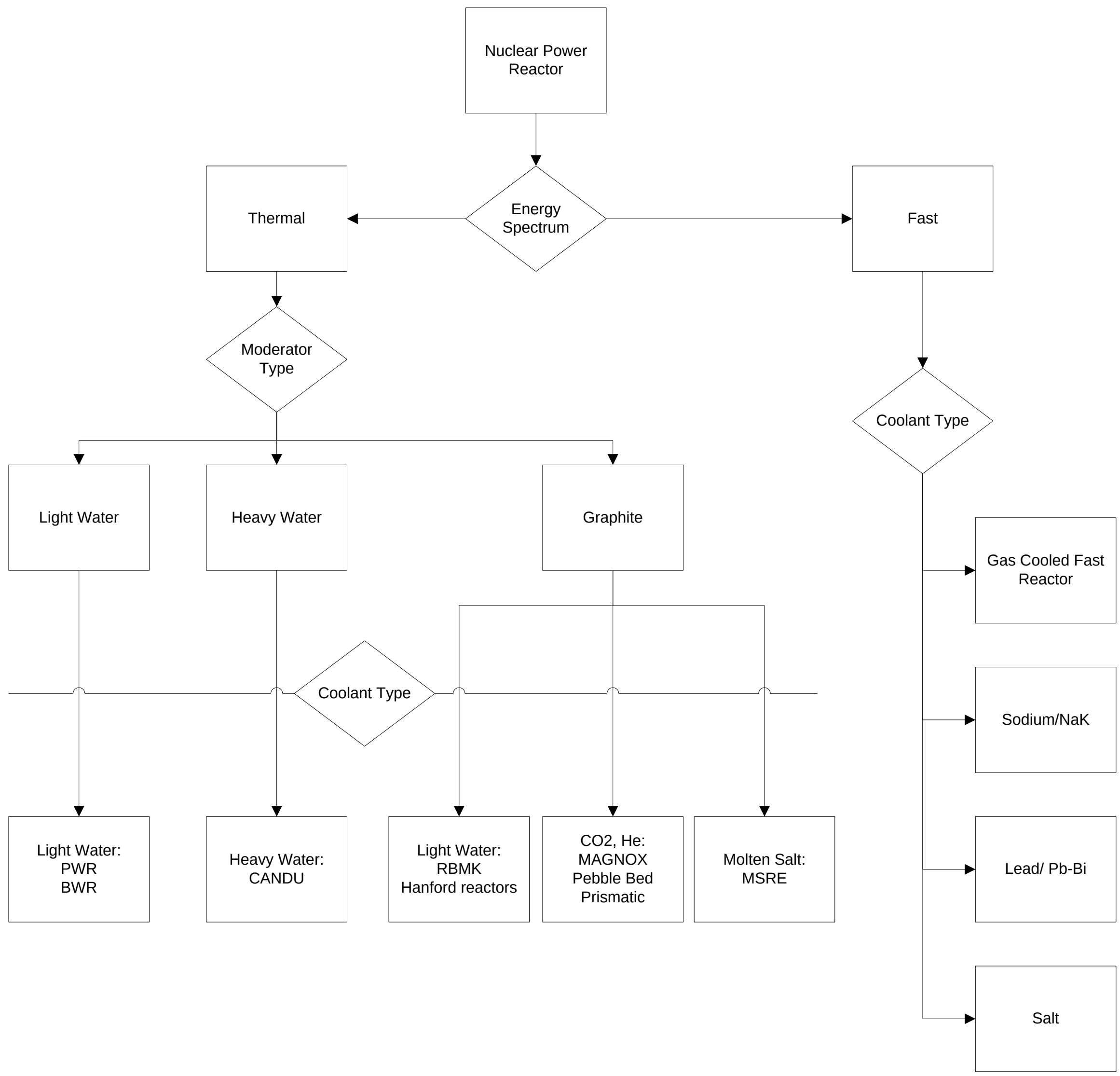

Figure 1.1: Reactor classification by major reactor components.

1.1.1 Pressurized Water Reactors

Pressurized water reactors are the more common type of light water reactor. The water must be kept high pressure to preclude boiling inside the primary coolant loop.

1.1.2 Boiling Water Reactors

Boiling Water Reactors aim for improved efficiency by using a direct power conversion cycle. However, boiling in the reactor core leads to a variety of challenges.

Advantages	Disadvantages
Improved Efficiency	Two-phase flow
Load following	Unstable at low power
	Radioactivity in the steam turbine

1.2 Heavy Water Reactors

This type of reactor was developed in Canada and has since been exported around the world. The use of heavy water allows the use of un-enriched uranium. This appears to be a good feature for proliferation resistance, but the combination of on-line refueling and natural uranium leads to optimal conditions for breeding plutonium for weapons. The excellent neutron economy of this design may lead to extended uses in the future. For example used LWR fuel could be used as fuel in a heavy water reactor.

Advantages	Disadvantages
Natural uranium fuel	Expensive Moderator
On-line refueling	Proliferation Risk
High burnup per ore	Low burnup per fuel element
No pressure vessel	Many pressure tubes

1.3 Graphite-Moderated Water-Cooled Reactors

These reactors are traditionally associated with weapons production. Graphite moderation allows for natural uranium fuel and efficient breeding of plutonium. The RBMK reactor in Chernobyl was not carefully designed to achieve a negative boiling reactivity coefficient, which was part of the cause of that disaster.

Advantages	Disadvantages
Natural uranium fuel	Large size
On-line refueling	Proliferation Risk
	Potential for positive reactivity coefficients

1.4 Gas Cooled Reactors

1.4.1 MAGNOX Reactors

1.4.2 Prismatic Block Reactors

The fuel for these reactors is composed of millimeter-scale TRISO particles. A kernel of UO_2 is surrounded by several layers of graphite and silicon carbide which act as containers for fission products. The TRISO particles are interspersed in a graphite matrix. This fuel block has various holes for coolant flow and fuel handling. Fuel blocks are stacked to compose the reactor core. The large mass of graphite has a very large heat capacity which can absorb the energy of almost any transient.

Graphite reactors do have some safety issues, however. First, dislocations to the graphite atomic matrix build up with neutron fluence. The reactor must be taken to higher temperatures periodically in order to anneal the graphite and release the energy stored in these imperfections. Also, there is still some debate about the flammability of graphite.

Advantages	Disadvantages
High heat capacity	Requires annealing
High temperature ceramic	Flammable?
Low absorption moderator	Large core
Multiple layers around fuel	Complex manufacturing
Allows high output temperature	High pumping power
	Complex/large spent fuel waste

1.4.3 Pebble Bed Reactors

Pebble bed reactors share many features with prismatic block reactors. However, by using many fuel pebbles, better fuel economy can be achieved. Construction of the reactor core is greatly simplified: it is essentially a can with guide tubes and a bottom nozzle.

Advantages	Disadvantages
Increased burnup	Complex fuel manufacturing
Replaceable fuel elements	Greater likelihood of individual failure
	Complex, indeterminate geometry

Table 1.1: See Table 1.4.2 for the pros and cons common to graphite reactors.

1.4.4 Gas-Cooled Fast Reactors

Gas cooled fast reactors share several features with gas-cooled thermal reactors, but the lack of a large mass of graphite moderator greatly reduces the heat capacity of the reactor core. Without out this sink for energy during accidents, passive safety is much harder to attain.

The original motivation for gas cooled-fast reactors was improved neutron economy due to decreased absorption in the coolant.

Advantages	Disadvantages
Single-phase coolant	High pumping power
Direct cycle energy conversion	High pressure
	Coolant leakage
High temperature	Risk of corrosion
Little absorption in coolant	Low heat capacity
High breeding ratio	Low heat transfer coefficient

1.5 Liquid Metal Cooled Reactors

Liquid metal coolants have been considered for fast spectrum reactors since the earliest days of nuclear energy. It was the NaK-cooled Experimental Breeder Reactor (EBR-I) that first produced electricity from nuclear energy. Liquid metals are excellent heat transfer media and also allow for the benefits of a fast-spectrum.

1.5.1 Sodium(-Potassium) Cooled Fast Reactors

Sodium is an excellent heat transfer medium, but its melting temperature is 98°C. Either the coolant loops must be heated continually during shutdown, or potassium must be added to lower the melting temperature. Both metals are highly flammable. Potassium absorbs more neutrons.

Advantages	Disadvantages
Good heat transfer	Incompatible with air and water
Fast neutron spectrum	shorter neutron lifetime
Passive safety demonstrated	Sodium activated by neutrons
Electronic pumping	opaque coolant
	Sodium: solid at room temperature
High temperature	Intermediate coolant loop

1.5.2 Lead(-Bismuth) Fast Reactors

Bismuth is added to lead to decrease the melting point. Lead does not react with water, air, or CO_2, which means intermediate cooling loops are unnecessary. There is less experience with lead-cooled reactors. Some Russian submarines had lead-cooled reactors, but there were eventually decommissioned. Corrosion issues can be managed by controlling the oxygen content of the coolant. The protective oxide layer will remain intact if the coolant flow rate does not exceed about 2m/s.

Advantages	Disadvantages
Good heat transfer	Melting point 327°C
Insignificant moderation	Inelastic scattering
Lead: does not absorb	Bismuth: creates Polonium
Inexpensive material	very heavy
	opaque coolant
High boiling point	Erosion limit on flow rate

1.6 Molten Salt Reactors

Molten salt reactors have received much attention in recent years, but have little operating experience.