## 4.8 Liquid metal fast breeder reactors

Since their power density is significantly higher than LWRs, the FBRs that have been constructed have been cooled by liquid metal since the moderator effect of water is unwanted and liquid metals have a low moderating effect. Moreover, liquid metals have the advantage that they have a high thermal conductivity and can be operated at low pressures. This avoids the dangers that are associated with the high pressures in water-cooled reactors. Despite this there are substantial safety issues associated with FBRs that are addressed in section 7.7 and that have limited their deployment to date. Nevertheless there are some 20 LMFBRs in the world that are currently producing electricity and many more proposals have been put forward (see section 4.9.2).

Sodium has been the universal choice for the primary coolant in LMFBRs for several reasons (lithium is another possibility though, as yet, unused). First, sodium has high thermal conductivity making it a good coolant even though its heat capacity is about one third that of water. Typically the primary coolant loop or pool functions at elevated temperatures of $395 - 545^{\circ}C$ in order to achieve high thermal efficiency, but the pressure this requires is low (order of $0.1\ MPa$) since these temperatures are well below the boiling point of sodium at normal pressures ($883^{\circ}C$). Thus most LMFBRs have a primary coolant loop or pool pressure just slightly above atmospheric and this feature has significant safety advantages. Of course, the violent reactions of sodium with air and water require a very tight coolant loop system and some well-designed safety systems. Also with a low atomic weight of 23, the scattering cross-section for sodium is small and therefore the neutron loss due to slowing is limited. Sodium also becomes radioactive when bombarded with neutrons and so the primary coolant loop must be confined within a containment system and the heat removed by means of a heat exchanger and a secondary coolant loop. This secondary loop also uses liquid sodium, but does not have the radioactivity of the primary coolant.

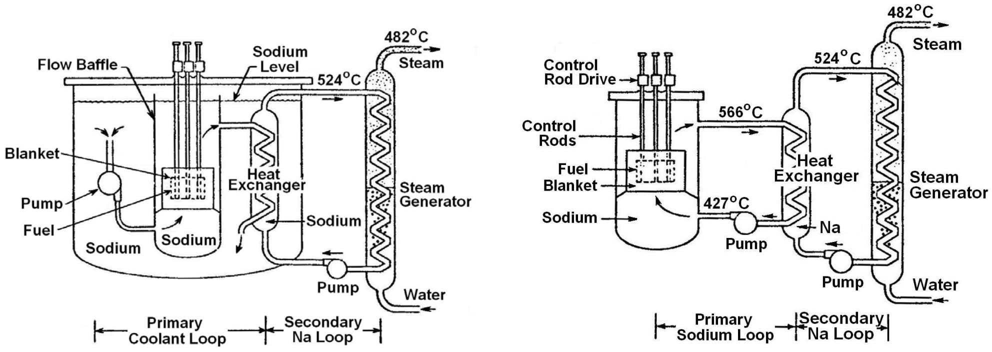

Figure 1: Schematics of a pool-type and a loop-type liquid metal fast breeder reactor. Argonne National Laboratory, adapted from Wilson (1977).

Two types of LMFBRs have been designed and constructed, the distinction being the configuration of the primary coolant loop. The so-called loop-type and pool-type LMFBRs are sketched diagrammatically in figure 1. In the loop-type the primary coolant is circulated through the core by a primary coolant pump in the conventional way. Because of the high radioactivity all these components require substantial shielding. These shielding requirements are significantly simplified in the other pool-type reactor in which the core is submerged in a pool of sodium that is part of the primary coolant loop and this pool as well as the heat exchanger to the secondary coolant loop are all enclosed in a large containment vessel. The Russian BN-600 reactor (figure 2) and the French Phenix reactors (figure 3) are both examples of pool-type LMFBRs.

In most LMFBRs the fuel rods consist of stainless steel tubes about 0.6 *cm* in diameter containing the fuel pellets of oxides of uranium and plutonium. The rods are held apart by spacers and packed in fuel assemblies contained in stainless steel cans about 7.6 *cm* across and 4.3 *m* long. There are typically 217 fuel rods in each assembly and 394 assemblies in a reactor core. In order to achieve higher packing densities for the fuel rods, fast reactor fuel assemblies are always hexagonal with the fuel rods in a triangular array, unlike the square arrangements in LWRs.

Arranged around the periphery of the core are the *blanket* fuel rods, that contain only uranium dioxide. Such a design creates a central *driver* section in the core surrounded on all sides by the blanket whose primary purpose is the breeding of new plutonium fuel (see section 4.7). The core is quite small compared to a LWR core, measuring about 90 *cm* high and 220 *cm* in diameter for a core volume of 6.3 $m^3$. It therefore has an *equivalent* cylindrical diameter and height of about 2.0 *m* (these reactor dimensions will be commented on in section 5.4). The flow pattern is similar to that of a PWR core in that the coolant flows upward though the core assembly and exits through the top of the core.

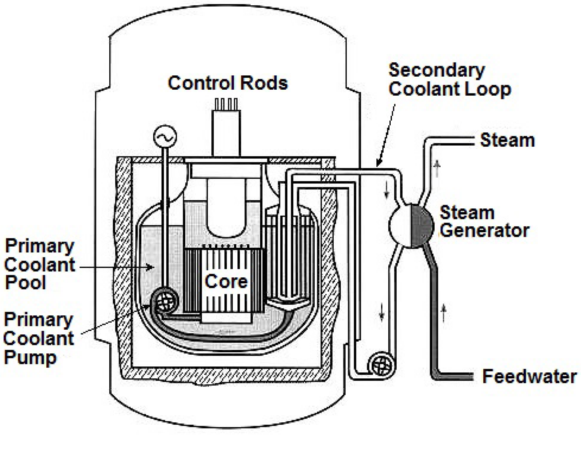

Figure 2: Schematic of Russian BN-600 pool-type LMFBR.

The BN-600 (figure 2) is a Russian, pool-type, liquid sodium cooled LMFBR that has been generating 600 $MW$ of electricity since 1980 and is currently (2013) the largest operating fast breeder reactor in the world. The core (about 1 $m$ tall with a diameter of about 2 $m$) has 369, vertically mounted fuel assemblies each containing 127 fuel rods with uranium enriched to $17-26\%$. The control and shutdown system utilizes a variety of control rods and the entire primary coolant vessel with its emergency cooling system is contained in a heavily reinforced concrete containment building. The primary sodium cooling loop proceeds through a heat exchanger transferring the heat to a secondary sodium loop that, in turn, transfers the heat to a tertiary water and steam cooling loop that drives the steam turbines. The world of nuclear power generation watches this reactor (and a sister reactor under construction, the BN-800) with much interest as a part of their assessment of safety issues with fast breeder reactors and therefore with their future potential. Though there have been a number of incidents involving sodium/water interactions and a couple of sodium fires, the reactor has been repaired and resumed operation.

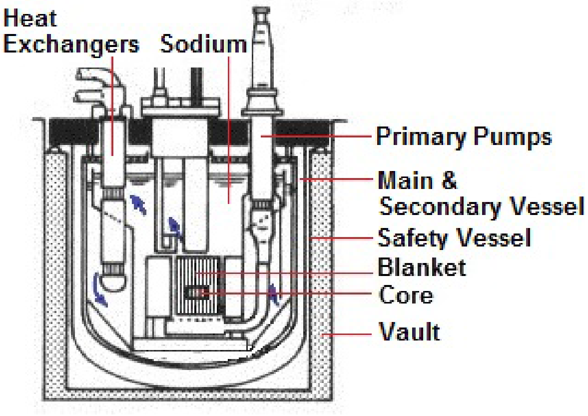

Figure 3: Schematic of the Phenix reactor in Marcoule, France. Adapted from WNA (2015b).

The Phenix was a small prototype 233 $MW$ LMFBR constructed by the French government. Shown diagrammatically in figure 3 it was a pool-type, liquid sodium cooled reactor that began supplying electricity to the grid in 1973. This led to the construction of the larger Superphenix that began producing electricity in 1986 though it was notoriously attacked by terrorists in 1982. Despite this and other public protests it was connected to the grid in 1994. As a result of public opposition and some technical problems, power production by the Superphenix was halted in 1996. The Phenix continued to produce power until it, too, was closed in 2009. It was the last fast breeder reactor operating in Europe.

The Clinch River Breeder Reactor was an experimental reactor designed by the US government as part of an effort to examine the feasibility of the LMFBR

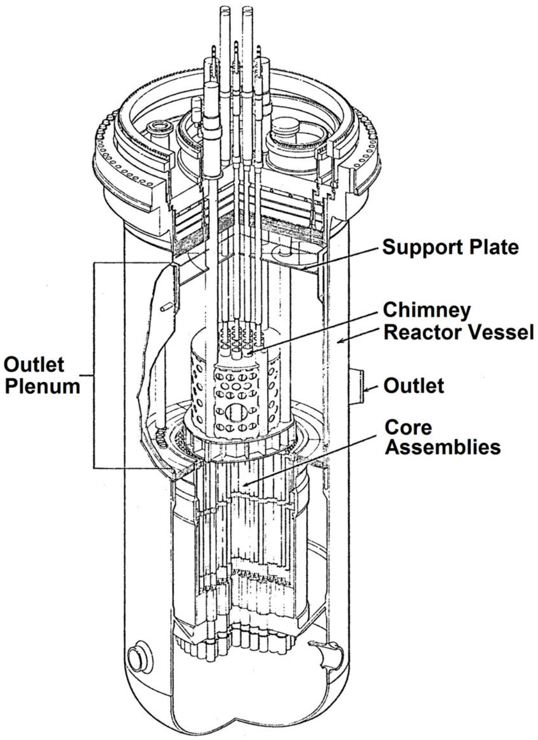

Figure 4: Clinch River breeder reactor. Adapted from CRBRP (1976).

design for commercial power generation. It was a 350 $MW$ electric, sodium-cooled, fast breeder reactor (see figure 4) whose construction was first authorized in 1970. Funding of the project was terminated in 1983, in part because of massive cost overruns. The project demonstrated the potentially high costs of constructing and operating a commercial LMFBR reactor. Moreover, in 1979 as these problems were emerging, the Three Mile Island accident (see section 7.5.1) occurred. This clearly demonstrated that more attention needed to be paid to the safety of existing LWR plants and highlighted the potentially more serious safety issues associated with LMFBRs (see section 7.6.3). Despite these issues, the potential technical advantages of the breeder reactor cycle mean that this design will merit further study in the years ahead.

Although virtually all present day LMFBRs operate with uranium-plutonium oxide fuel, there is considerable interest in the future use of fuel composed of uranium-plutonium carbide, since large breeding ratios are possible with this kind of fuel. This, in turn, is due to the fact that while there are two atoms of oxygen per atom of uranium in the oxide, there is only one atom of carbon per uranium atom in the carbide. Light atoms such as carbon and oxygen tend to moderate fission neutrons, and since there are fewer of the atoms in the carbide than in the oxide, it follows that the energy distribution of neutrons in a carbide-fueled LMFBR is shifted to energies higher than in a comparable oxide-fueled reactor.