PHY4362
Breeder Reactors

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I. INTRODUCTION

When nuclear reactions were discovered, it became apparent that the heat of the reactions could be harnessed as energy sources. Over the course of the twentieth century, many types of nuclear reactors were designed and built to utilize this energy. The fuel of these reactors are fissionable elements; elements like Uranium, Plutonium, and Thorium. Of these elements, there are isotopes that are "fissile", which are isotopes that undergo fission with low-energy neutrons and occur with high probability (like Uranium-235) and isotopes that are simply "fissionable", that is, they undergo fission, but require high-energy neutrons and occur with low probability (like Uranium-238).

Early on it was clear that natural Uranium consisted primarily of non-fissile Uranium-238 and only contained a very minute amount of fissile Uranium-235. Light-water reactors, a reactor design that could generate electricity, required ^{235}U as its fuel. Before more Uranium reserves were found, it was feared that the world would run out of ^{235}U to use as fuel. Thus there was interest in reactions that produced fissile material out of the common ^{238}U isotope, and reactors were designed that produced more fissile material than they consumed. These reactors were called breeder reactors, because they "bred" fissile material.

There are two main types of breeder reactors: those that convert ^{238}U into fissile material, and reactors that convert Thorium-232 (^{232}Th) into fissile material. The ^{238}U reactors are more common and are called 'fast breeder reactors', as they require fast neutrons for the reaction. Thorium-232 breeder reactors can use slow (or 'thermal' neutrons) in the reaction and are called 'slow breeder reactors'.

In addition to producing fissile material, breeder reactors can be used to reduce waste by bombarding heavy elements (actinides) with fast neutrons, thus reducing them to lighter fission products.

Despite the theoretical benefits of breeder reactors, these types of reactors have been criticized as more expensive than light-water reactors, dangerous because of the coolants involved, and unnecessary once more reserves of Uranium (and thus, ^{235}U) were found. Moreoever, since these breeder reactors produce large quantities of fissile material, there have always been fears of proliferation of dangerous material through theft or mismanagement.

This paper will examine the nuclear reactions that are used to breed fissile material, some designs of breeder reactors, and a history of constructed breeder reactors, as well as a discussion of their future, in light of the current state of the technology and its criticisms.

II. NUCLEAR REACTIONS IN BREEDERS

Uranium-238

The most common reaction used in breeder reactors is the conversion of the non-fissile, but abundant, ^{238}U to fissile Plutonium-239 (^{239}Pu). This reaction occurs through the absorption of a fast neutron:

$$\begin{aligned} {}^{238}\mathrm{U} + \mathrm{n} &\longrightarrow {}^{239}\mathrm{U} \\ {}^{239}\mathrm{U} &\longrightarrow {}^{239}\mathrm{Np} + e^- + \bar{\nu}_e \\ {}^{239}\mathrm{Np} &\longrightarrow {}^{239}\mathrm{Pu} + e^- + \bar{\nu}_e \end{aligned}$$

An atom of ^{238}U absorbs a neutron to become ^{239}U. This atom then undergoes beta decay and produces ^{239}Np, which then also undergoes beta decay to form ^{239}Pu. The half-life of ^{239}U is only 23.5 minutes. The half-life of ^{239}Np is about 2 days. The half-life of the the ^{239}Pu is about 24000 years, thus effectively, it is the final product.

The source of neutrons comes from the fission of ^{235}U, thus some fissile material is consumed. On average, the fission of ^{235}U produces 2.4 neutrons. Note that these are generally fast neutrons. This means that you need a larger ratio of ^{235}U (or ^{239}Pu) to sustain a chain reaction, since ^{235}U is less likely to undergo fission with fast neutrons.

Typically, non-fissionable ^{238}U surrounds a core of enriched uranium and absorbs neutrons from the core. No moderator is needed to slow down the neutrons, as this would stop the production of Plutonium. Since water is a typical moderator in reactors, this means that water cannot be used as a coolant in breeder reactors exploiting this reaction.

Thorium-232

Though not used as much in practice, Thorium-232 (^{232}Th) can be used to breed ^{233}U, which can be used as fuel in a reactor. The breeding of Uranium-233 from Thorium-232 is analogous to the case with Uranium-238:

$$
\begin{aligned}
{}^{232}\mathrm{Th} + n &\longrightarrow {}^{233}\mathrm{Th} \\
{}^{233}\mathrm{Th} &\longrightarrow {}^{233}\mathrm{Pa} + e^{-} + \bar{\nu}_e \\
{}^{233}\mathrm{Pa} &\longrightarrow {}^{233}\mathrm{U} + e^{-} + \bar{\nu}_e
\end{aligned}
$$

The half-lives of ^{233}Th, ^{233}Pa, and ^{233}U are 22 minutes, 27 days, and 159,200 years, respectively.

The main drawback with using Thorium-232 is its lack of a fissile isotope in a sample. While Uranium can be enriched until Uranium-235 can drive the reaction, Thorium-232 needs fissile material like ^{235}U or ^{239}Pu to be added for the reaction to sustain itself.

Another drawback is the long lifetime of the intermediate product ^{233}Pa, which is an order of magnitude greater than the ^{239}Np present in the breeding of ^{239}Pu. Because of this long lifetime, large amounts of ^{233}Pa build up during the breeding process, and, since ^{233}Pa is a significant neutron absorber, it slows and can halt the reaction.

III. REACTOR DESIGN

A breeder reactor at its simplest is a reactor that creates more fissile material than it consumes. This necessarily means that these types of reactors are designed to have a very high neutron economy to increase breeding.

Breeder reactors are different from the usual light-water reactors in several ways. Firstly, the core of a breeder reactor usually consists of some fissile material blanketed by the element to be converted. For example, placing a core of Uranium enriched with the fissile ^{235}U and then surrounding –or "blanketing"– it with the non-fissile ^{238}U will breed ^{239}Pu in the blanketing material.

In the case of Uranium-238, which is the usual breeding material, water cannot be used as the primary coolant. As mentioned earlier, Uranium-238 requires fast neutrons to undergo a reaction, and water slows neutrons down. Thus a different way of cooling must be designed.

The central core of a breeder breeding from Uranium-238 must be enriched to a higher proportion of ^{235}U than in light-water reactors because the fission of ^{235}U is less likely to occur with fast neutrons. Increasing the proportion of ^{235}U ensures that the fission of ^{235}U atoms can sustain itself. This is not the case when using Thorium-232 as the breeding material, which requires slow, or thermal, neutrons.

With these general requirements in mind, there are a few varying designs of breeder reactors, including the Liquid Metal Fast Breeder Reactor (LMFBR), the Gas-Cooled Fast Reactor (GFR), and the integral fast reactor.

Liquid Metal Fast Breeder Reactor (LMFBR)

To achieve fast neutrons, liquid water coolant is switched out for liquid metal coolant. Water is a strong moderator of neutrons, and slows them down. A liquid metal coolant will not slow down neutrons.

Fast breeders have a high power density due to the fast neutrons, and a water coolant would boil quickly. The water can be pressurized to not boil, but this complicates the design. Liquid metal has a high heat capacity making it an efficient coolant. Moreover, fast breeders regularly operate safely within the melting and boiling points of a liquid metal, meaning there is little risk of the coolant freezing or boiling away.

Mercury was the first metal to be used as liquid coolant since it was already liquid at room temperature. It quickly fell out of favor because of the toxic fumes it produced and the relatively low boiling temperature.

Liquid lead was considered a good choice because it is highly reflective to neutrons, as well as an effective radiation shield to gamma rays. Its extremely high boiling point means it can cool the reactor efficiently, but at the same time its high melting point (around 327°C) makes the reactor very difficult to service and refuel. Sometimes bismuth is mixed with the lead to lower the melting point, but the alloy is corrosive to the metals used in the surrounding structure.

Liquid sodium has a much lower melting temperature that is easier to manage and is still below the operating temperature of the reactor, so it won't freeze and will effectively cool the reactor. Using sodium as the coolant would also avoid the structural problems that lead poses, since the liquid sodium is not corrosive. There are some concerns with using liquid sodium however. The sodium is highly reactive to air and water so it must be tightly contained. Any leaks could quickly cause a fire or explosion. Moreoever while the reactor is in operation, neutrons will activate the sodium and the coolant will become highly radioactive, thus, it must be contained by some kind of biological shield during operation. Fortunately, the half-life of this activated sodium is only 15 hours, so using liquid sodium as a coolant does not create an additional nuclear waste problem.

Liquid tin, though useless for a functioning or long-term reactor because it forms a crust, is instead quite useful in the case of a coolant accident or disaster. It is an effective coolant and in the case of disaster, if dumped on a reactor, will cool the reactor and at the same time form a crust above the liquid tin beneath. This crust will help contain any dangerous material, contrary to dumping lead which would release dangerous fumes or dumping sodium, which would explode. Water would quickly vaporize and carry away radioactive material.

Most large-scale liquid metal fast breeder reactors use liquid sodium as their coolant. A schematic of an ex-

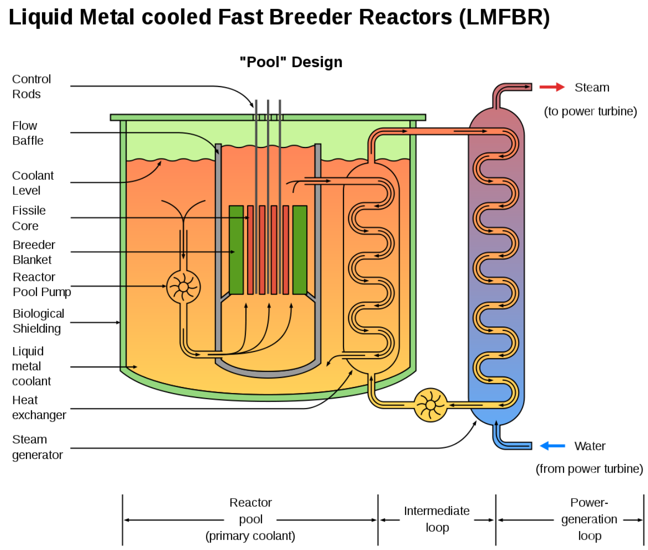

Figure 1. Diagram of an LMFBR Reactor

ample LMFBR using liquid sodium is shown in Figure 1.

In the LMFBR, the fissile core is surrounded by a breeder blanket and is then immersed in liquid coolant. All of this is placed inside a tank with radiation-shielding walls. The core heats the sodium which then flows into a heat exchanger. In the heat exchanger, a pipe carrying heated sodium from the core flows snakelike through a separate tank also filled with liquid sodium. The hot sodium from the core heats the sodium in the heat exchanger. This heat is then used to boil water in the steam generator, which can be used to turn a turbine that generates electricity.

The **gas-cooled fast reactor** is the same idea but uses helium or carbon dioxide gas as the coolant.

Integral Fast Reactor (IFR)

The Integral Fast Reactor is a next generation design that combines a breeder reactor with a waste reprocessing facility nearby. The reactor breeds material which is then quickly reprocessed to extract material that can be used in the inner core (like Uranium-235 and Plutonium-239). The reactor's core is then replenished and the breeding continues. This allows almost the entirety of a Uranium sample to be used to generate electricity, which is a huge increase in energy output compared to just using the Uranium-235 in a sample. Uranium-235 comprises less than 1% of natural Uranium.

The onsite processing of material is what makes the reactor *integral*. It allows for the complete use of a fissionable sample and turns what would normally be considered as waste into a source of energy. IFRs also reduce the risk of nuclear proliferation by consuming fissile material and leaving only decay products lighter than Uranium. Since the processing of material is meant to be done on site, no material containing Plutonium or Uranium need be transported from the site.

The reprocessing of material happens with a pyroprocessing unit at the reactor site.

IV. HISTORY

Since the 1950s many countries have worked to construct commercial fast breeder reactors that lived up to the promises of the designs. The reactors have been plagued with problems and setbacks and many shut down due to high costs and a distrust of the technology.

At the beginning it was expected that a shortage of Uranium fuel would become a problem. This was the stimulating factor in research into breeder reactors. When more Uranium reserves were discovered, light-water reactors became more prevalent and breeder reactors became a sort of unnecessary investment.

Still, interest remained since breeder reactors recycle most of their waste and effectively deal with one of the largest problems of nuclear power.

In 1951 the USA built the Experimental Breeder Reactor-1 (EBR-I) and demonstrated that it could generate electricity by powering the building it was housed in. They decommissioned it in 1964 and replaced it with EBR-II, which was meant to be a prototype of the Integral Fast Reactor, and was cooled with liquid sodium. It was shut down in 1994 when the US Congress withdrew funding for it three years before the completion of the program, despite the very positive results coming out of the project.

France first built an experimental fast breeder reactor in 1967 called *Rapsodie*. It generated 40MW of heat but had not electrical generation facilities, and closed in 1983. France followed this up with a small-scale prototype sodium-cooled reactor called *Phénix* that both generated electricity and reprocessed nuclear waste. It was shut down in 2009. *Phénix* was meant as a demonstration of a larger fast breeder reactor called *Superphénix* (Figure 2), which opened and started producing electricity in 1986. The construction, which started in 1968, heavily overran its budget and provoked public protests. In 1982 five RPG rockets were fired at the building by a group that doubted the safety of such a reactor. Though designed to output 1.20GW of electricity, it almost always operated between 0 and 33% of its max output, only reaching 90% power in December 1996, less than a year before its closure in 1997. During its operation the plant shut down for long periods of repairs to the liquid sodium cooling system, which leaked. In 1997 a newly-elected Prime Minister shut down the reactor due to its excessive costs. It was to date the largest fast breeder reactor in the world.

Figure 2. The *Superphénix* Reactor

India is deeply interested and invested in breeder reactors because they possess the world's largest Thorium reserves. India first activated an experimental fast breeder reactor in 1985, and is currently building the "Prototype Fast Breeder Reactor", a 500MW reactor also using liquid sodium, and is expected to reach criticality in March 2015. India has enough Thorium to power itself for the next 10,000 years, and is planning more reactors to tap into this potential.

V. CONCLUSION

In this paper we have examined an overview of the field of breeder reactors including the nuclear reactions that make it possible, the more important designs of breeder reactors and the types of cooling they utilize, and a brief history of the efforts over the last 60 years of building a commercial breeder reactor. Despite the very significant energy and nuclear waste benefits that breeder reactors offer, their development has been slowed in favor of the more tested light-water reactors, especially with the discovery of more Uranium reserves. The costs of breeder reactors have made them unpopular among governments and the public remains suspicious of the benefits and fearful of the risks that breeder reactors pose.

Nonetheless, there is still active research in the design of next generation reactors, where breeder reactors and integral fast breeders play an almost exclusive role.

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