**Fast Breeder Reactor**

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[](http://en.wikipedia.org/wiki/File:Ebr1core.png)

Assembly of the core of Experimental Breeder Reactor I in Idaho, 1951

A **breeder reactor** is a nuclear reactor capable of generating more fissile material than it consumes because its neutron economy is high enough to breed fissile from fertile material like uranium-238 or thorium-232. Breeders were at first considered superior because of their superior fuel economy compared to light water reactors. Interest in breeders reduced after the 1960s as more uranium reserves were found, and new methods of uranium enrichment reduced fuel costs.

Breeder reactors could in principle extract almost all of the energy contained in uranium or thorium, decreasing fuel requirements by nearly two orders of magnitude compared to traditional once-through light water reactors, which extract less than 1% of the energy. This could greatly damp concern about fuel supply or energy used in mining. In fact, with seawater uranium extraction, there is enough fuel for breeder reactors to satisfy our energy needs for as long as the current relationship between the sun and Earth persists, about 5 billion years (thus making nuclear energy as sustainable in fuel availability terms as solar or wind renewable energy).

Nuclear waste became a greater concern by the 1990s. Breeding fuel cycles became interesting again because they can reduce actinide wastes, particularly plutonium and minor actinides. After the spent nuclear fuel is removed from a light water reactor, after 1000 to 100,000 years, these transuranics would make most of the radioactivity. Eliminating them eliminates much of the long-term radiotoxicity of spent nuclear fuel.

In principle, breeder fuel cycles can recycle and consume all actinides, leaving only fission products. So, after several hundred years, the waste's radioactivity drops to the low level of the long-lived fission products. If the fuel reprocessing process used for the fuel cycle leaves actinides in its final waste stream, this advantage is reduced.

There are two well-known breeding cycles that reduce wastes' radiotoxicity from actinides:

* The fast breeder reactor's fast neutrons can fission even actinides with even neutron numbers. Even numbered actinides usually lack the low-speed "thermal neutron" resonances of fissile fuels used in LWRs.
* The thorium fuel cycle simply produces lower levels of heavy actinides. The fuel starts with few isotopic impurities (i.e. there's nothing like U238 in the reactor), and the reactor gets two chances to fission the fuel: First as U233, and as it absorbs neutrons, again as U235.

A reactor whose main purpose is to destroy actinides, rather than increasing fissile fuel stocks, is sometimes known as a burner reactor. Both breeding and burning depend on good neutron economy, and many designs can do either. Breeding designs surround the core by a breeding blanket of fertile material. Waste burners surround the core with non-fertile wastes to be destroyed. Some designs add neutron reflectors or absorbers.

Today's LWRs do breed some plutonium. They do not make enough to replace the uranium-235 consumed. Only about 1/3 of fissions over a fuel element's life cycle are from bred plutonium. However, LWRs are not able to consume all the plutonium and minor actinides they produce. Non-fissile isotopes of plutonium build up. Even with reprocessing, reactor-grade plutonium can be recycled only once in LWRs as mixed oxide fuel. This reduces long term waste radioactivity somewhat, but not as much as purpose-designed breeding cycles.

**Breeding ratio**

One measure of a reactor's performance is the "breeding ratio" (the average number of fissile atoms created per fission event). Historically, attention has focused on reactors with low breeding ratios, from 1.01 for the Shipping port Reactor running on thorium fuel and cooled by conventional light water to over 1.2 for the Russian BN-350 liquid-metal-cooled reactor. Theoretical models of breeders with liquid sodium coolant flowing through tubes inside fuel elements ("tube-in-shell" construction) show breeding ratios of at least 1.8 are possible. The breeding ratios of ordinary commercial non-breeders are lower than 1; however, industry trends are pushing breeding ratios steadily higher, blurring the distinction

**Breeding versus burnup**

All commercial reactors breed fuel, but they have low (though still significant) breeding ratios compared to machines traditionally considered "breeders." In recent years, the commercial power industry has been emphasizing high-burnup fuels, which last longer in the reactor core. As burnup increases, a higher percentage of the total power is due to the fuel bred in the reactor. At a burnup of 30 gigawatt-days per metric ton of uranium (GWd/MTU), about thirty percent of the total energy comes from bred plutonium. At 40 GWd/MTU, that increases to about forty percent. This corresponds to a breeding ratio of about 0.4 to 0.65. Correspondingly, this effect extends the cycle life for such fuels to sometimes nearly twice what it would be otherwise. MOX fuel has a smaller breeding effect than U-235 fuel and is thus more challenging and slightly less economic to use due to a quicker drop off in reactivity through cycle life.

This is of interest largely because next-generation reactors such as the European Pressurized Reactor, AP1000 and ESBWR are designed to achieve very high burnup. This directly translates to higher breeding ratios. Current commercial power reactors have achieved breeding ratios of roughly 0.55, and next-generation designs like the AP1000 and EPR should have breeding ratios of 0.7 to 0.8, meaning that they produce 70 to 80 percent as much fuel as they consume, improving their fuel economy by roughly 15 percent points compared to current high-burnup reactors.

Breeding of fissile fuel is a common feature in reactors, but in commercial reactors not optimized for this feature it is referred to as "enhanced burnup". Up to a third of all electricity produced in the current US reactor fleet comes from bred fuel, and the industry is working steadily to increase that percentage as time goes on.

**Types of breeder reactors**

Two types of traditional breeder reactor have been proposed:

* **fast breeder reactor** or FBR — The superior neutron economy of a fast neutron reactor makes it possible to build a reactor that, after its initial fuel charge of plutonium, requires only natural (or even depleted) uranium feedstock as input to its fuel cycle. This fuel cycle has been termed the plutonium economy.
* **thermal breeder reactor** — The excellent neutron capture characteristics of fissile uranium-233 make it possible to build a moderated reactor that, after its initial fuel charge of enriched uranium, plutonium or MOX, requires only thorium as input to its fuel cycle. Thorium-232 produces uranium-233 after neutron capture and beta decay.

In addition to this, there is some interest in so-called "reduced moderation reactors", which are derived from conventional reactors and use conventional fuels and coolants, but are designed to be reasonably efficient as breeders. Such designs typically achieve breeding ratios of 0.7 to 1.01 or even higher.

**Reprocessing**

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Actinides** | | | | **Half-life** | **Fission products** | | | |
| 244Cm | **241Pu f** | 250Cf | **243Cmf** | **10–30 y** | 137Cs | 90Sr | 85Kr |  |
| **232U f** |  | 238Pu | **f** is for fissile | **69–90 y** |  |  | 151Sm nc➔ | |
| **4n** | **249Cf f** | **242Amf** | **141–351** | No fission product has half-life 102 to 2×105 years | | | |
| 241Am |  | **251Cf f** | **431–898** |
| 240Pu | 229Th | 246Cm | 243Am | **5–7 ky** |
| **4n** | **245Cmf** | 250Cm | **239Pu f** | **8–24 ky** |
| **233U f** | 230Th | 231Pa | **32–160** |
| **4n+1** | 234U | **4n+3** | **211–290** | 99Tc |  | 126Sn | 79Se |
| 248Cm | 242Pu | **340–373** | Long-lived fission products | | | |
|  | 237Np | **4n+2** | **1–2 My** | 93Zr | 135Cs nc➔ | |  |
| 236U | **4n+1** | **247Cmf** | **6–23 My** |  | 107Pd | 129I |  |
| 244Pu |  | **80 My** | >7% | >5% | >1% | >.1% |
| 232Th | 238U | **235U f** | **0.7–12 Gy** | fission product yield | | | |

Fission of the nuclear fuel in any reactor produces neutron-absorbing fission products, and because of this it is necessary to reprocess the fuel and breeder blanket from a breeder reactor if one is to fully utilize its ability to breed more fuel than it consumes. The most common reprocessing technique, PUREX, is generally considered a large proliferation concern because such reprocessing technologies can be used to extract weapons grade plutonium from a reactor operated on a short refueling cycle. For this reason, the FBR closed fuel cycle is often seen as a greater proliferation concern than a once-through thermal fuel cycle.

However, to date all known weapons programs have used far more easily built thermal reactors to produce plutonium, and there are some designs such as the SSTAR which avoid proliferation risks by both producing low amounts of plutonium at any given time from the U-238, and by producing three different isotopes of plutonium (Pu-239, Pu-240, and Pu-242) making the plutonium used infeasible for atomic bomb use.

Furthermore, several countries are developing more proliferation resistant reprocessing methods that don't separate the plutonium from the other actinides. For instance, the pyrometallurgical process when used to reprocess fuel from the Integral Fast Reactor leaves large amounts of radioactive actinides in the reactor fuel. Removing these transuranics in a conventional reprocessing plant would be extremely difficult as many of the actinides emit strong neutron radiation, requiring all handling of the material to be done remotely, thus preventing the plutonium from being used for bombs while still being usable as reactor fuel.

Thorium fueled reactors may pose a slightly higher proliferation risk than uranium based reactors because, while Pu-239 will fairly often fail to undergo fission after neutron capture and produce Pu-240, the corresponding process in the thorium cycle is relatively rare. Thorium-232 converts to U-233, which will almost always undergo fission successfully, meaning that there will be very little U-234 produced in the reactor's thorium/U-233 breeder blanket, and the resulting pure U-233 will be comparatively easy to extract and use for weapons. However, the *opposite* process (neutron knock-off) happens as a matter of course, producing U-232, which has the strong gamma emitter Tl-208 in its decay chain. These gamma rays complicate the safe handling of a weapon and the design of its electronics; this explains why U-233 has never been pursued for weapons beyond proof-of-concept demonstrations.

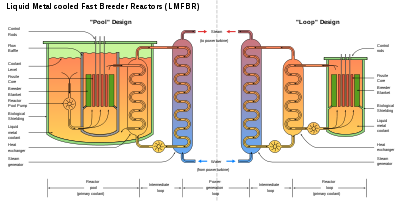
**Associated reactor types**

One design of fast neutron reactor, specifically designed to address the waste disposal and plutonium issues, was the *Integral Fast Reactor* (also known as an *Integral Fast Breeder Reactor*, although the original reactor was designed to not breed a net surplus of fissile material).

To solve the waste disposal problem, the IFR had an on-site electrowinning fuel reprocessing unit that recycled the uranium and all the transuranics (not just plutonium) via electroplating, leaving just short half-life fission products in the waste. Some of these fission products could later be separated for industrial or medical uses and the rest sent to a waste repository (where they would not have to be stored for anywhere near as long as wastes containing long half-life transuranics). It is thought that it would not be possible to divert fuel from this reactor to make bombs, as several of the transuranics spontaneously undergo fission so rapidly that any assembly would melt before it could be completed. The project was canceled in 1994, at the behest of then-United States Secretary of Energy Hazel O'Leary. Use of a breeder reactor assumes nuclear reprocessing of the breeder blanket at least, without which the concept is meaningless. In practice, all proposed breeder reactor programs involve reprocessing of the fuel elements as well. This is important due to nuclear weapons proliferation concerns, as any nation conducting reprocessing using the traditional aqueous-based PUREX family of reprocessing techniques could potentially divert plutonium towards weapons building. In practice, commercial plutonium from reactors with significant burnup would require sophisticated weapon designs, but the possibility must be considered. To address this concern, modified aqueous reprocessing systems, which add extra reagents, forcing minor actinide "impurities" such as curium and neptunium to commingle with the plutonium, have been proposed. Such impurities matter little in a fast spectrum reactor, but make weaponizing the plutonium extraordinarily difficult, such that even very sophisticated weapon designs are likely to fail to fire properly. Such systems as the TRUEX and SANEX are meant to address this.

Even more comprehensive are systems such as the Integral Fast Reactor (IFR) pyroprocessing system, which uses pools of molten cadmium and electro refiners to reprocess metallic fuel directly on-site at the reactor. Such systems not only commingle all the minor actinides with both uranium and plutonium, they are compact and self-contained, so that no plutonium-containing material ever needs to be transported away from the site of the breeder reactor. Breeder reactors incorporating such technology would most likely be designed with breeding ratios very close to 1.00, so that after an initial loading of enriched uranium and/or plutonium fuel, the reactor would then be refueled only with small deliveries of natural uranium metal. A quantity of natural uranium metal equivalent to a block about the size of a milk crate delivered once per month would be all the fuel such a 1 gigawatt reactor would need. Such self-contained breeders are currently envisioned as the final self-contained and self-supporting ultimate goal of nuclear reactor designers.

**The fast breeder reactor**

[](http://en.wikipedia.org/wiki/File:LMFBR_schematics2.svg)

Schematic diagram showing the difference between the Loop and Pool types of LMFBR.

As of 2006, all large-scale FBR power stations have been liquid metal fast breeder reactors(LMFBR) cooled by liquid sodium. These have been of one of two designs:

* *Loop* type, in which the primary coolant is circulated through primary heat exchangers outside the reactor tank (but inside the biological shield due to radioactive sodium-24 in the primary coolant)
* *Pool* type, in which the primary heat exchangers and pumps are immersed in the reactor tank

All current fast reactor designs use liquid metal as the primary coolant, to transfer heat from the core to steam used to power the electricity generating turbines. FBRs have been built cooled by liquid metals other than sodium—some early FBRs used mercury, other experimental reactors have used a sodium-potassium alloy. Both have the advantage that they are liquids at room temperature, which is convenient for experimental rigs but less important for pilot or full scale power stations. Lead and lead-bismuth alloy have also been used. The relative merits of lead vs sodium are discussed here. Looking further ahead, three of the proposed generation IV reactor types are FBRs:

* Gas-Cooled Fast Reactor (GFR) cooled by helium.
* Sodium-Cooled Fast Reactor (SFR) based on the existing Liquid Metal FBR (LMFBR) and Integral Fast Reactor designs.
* Lead-Cooled Fast Reactor (LFR) based on Soviet naval propulsion units.

FBRs usually use a mixed oxide fuel core of up to 20% plutonium dioxide (PuO2) and at least 80% uranium dioxide (UO2). Another fuel option is metal alloys, typically a blend of uranium, plutonium, and zirconium (used because it is "transparent" to neutrons). Enriched uranium can also be used on its own.

In many designs, the core is surrounded in a blanket of tubes containing non-fissile uranium-238 which, by capturing fast neutrons from the reaction in the core, is converted to fissile plutonium-239 (as is some of the uranium in the core), which is then reprocessed and used as nuclear fuel. Other FBR designs rely on the geometry of the fuel itself (which also contains uranium-238), arranged to attain sufficient fast neutron capture. The plutonium-239 (or the fissile uranium-235) fission cross-section is much smaller in a fast spectrum than in a thermal spectrum, as is the ratio between the 239Pu/235U fission cross-section and the 238U absorption cross-section. This increases the concentration of 239Pu/235U needed to sustain a chain reaction, as well as the ratio of breeding to fission.

On the other hand, a fast reactor needs no moderator to slow down the neutrons at all, taking advantage of the fast neutrons producing a greater number of neutrons per fission than slow neutrons. For this reason ordinary liquid water, being a moderator as well as a neutron absorber, is an undesirable primary coolant for fast reactors. Because large amounts of water in the core are required to cool the reactor, the yield of neutrons and therefore breeding of 239Pu are strongly affected. Theoretical work has been done on reduced moderation water reactors, which may have a sufficiently fast spectrum to provide a breeding ratio slightly over 1. This would likely result in an unacceptable power derating and high costs in an liquid-water-cooled reactor, but the supercritical water coolant of the SCWR has sufficient heat capacity to allow adequate cooling with less water, making a fast-spectrum water-cooled reactor a practical possibility. In addition, a heavy water moderated thermal breeder reactor, using thorium to produce uranium-233, is also possible (see Advanced Heavy Water Reactor).

Several prototype FBRs have been built, ranging in electrical output from a few light bulbs' equivalent (EBR-I, 1951) to over 1000 MWe. As of 2006, the technology is not economically competitive to thermal reactor technology—but India, Japan, China, Koreaand Russia are all committing substantial research funds to further development of Fast Breeder reactors, anticipating that rising uranium prices will change this in the long term. Germany, in contrast, abandoned the technology due to political and safety concerns. The SNR-300 fast breeder reactor was finished after 19 years despite cost overruns summing up to a total of 3.6 billion Euros, only to then be abandoned.

As well as their thermal breeder program, India is also developing FBR technology, using both uranium and thorium feedstocks.

**Traveling wave reactor**

Main article: Traveling wave reactor

The traveling wave reactor proposed in a patent by Intellectual Ventures is a fast breeder reactor designed to not need fuel reprocessing during the decades-long lifetime of the reactor, leaving the spent fuel in place. Over the years, a wave of fission starting at one end of the fuel cylinder would drive a wave of breeding ahead of it.

**The thermal breeder reactor**

"The Advanced Heavy Water Reactor is one of the few proposed large-scale uses of thorium. As of 2006 only India is developing this technology. Indian interest is motivated by their substantial thorium reserves; almost a third of the world's thorium reserves are in India, which in contrast has less than 1% of the world's uranium. Their stated intention is to use both fast and thermal breeder reactors to supply both their own fuel and a surplus for non-breeding thermal power reactors. Total worldwide resources of thorium are roughly three times those of uranium, so in the extreme long term this technology may become of more general interest.

"The Liquid fluoride thorium reactor (LFTR) was also developed as a thermal breeder. Liquid-fluoride reactors have many attractive features, such as deep inherent safety (due to their strong negative temperature coefficient of reactivity and their ability to drain their liquid fuel into a passively cooled and non-critical configuration) and ease of operation. They are particularly attractive as thermal breeders because they can isolate protactinium-233 (the intermediate breeding product of thorium) from neutron flux and allow it to decay to uranium-233, which can then be returned to the reactor. Typical solid-fueled reactors are not capable of accomplishing this step and thus U-234 is formed upon further neutron irradiation."

**Breeder reactor development and notable breeder reactors**

FBRs have been built and operated in the USA, the UK, France, the former USSR, India and Japan. An experimental FBR in Germany was built but never operated. There are very few breeder reactors actually used for power generation, there are a few planned, and quite a few are being used for research related to the Generation IV reactor initiative. In many countries, nuclear power has been opposed politically and thus many breeder reactors have been shut down, or are planned to be shut down, with various justifications.

**France**

[](http://en.wikipedia.org/wiki/File:Superph%C3%A9nix.jpg)

Superphénix, the biggest fast breeder reactor

France's first fast reactor, Rapsodie first achieved criticality in 1967. Built at Cadarache near Aix-en-Provence, Rapsodie was a loop-type reactor with a thermal output of 40MW and no electrical generation facilities, and closed in 1983. The plant was also a focus point of anti-nuclear political activity by the Green party and other groups. Right wing groups claim the plant was shut down for political reasons and not lack of power generation.

This was followed by the 233 MWe *Phénix*, grid connected since 1973, both as a power reactor and more importantly as the center of work on reprocessing of nuclear waste by transmutation. It was definitely shut down in 2009. The life-time load factor was just below 40 per cent, according to the IAEA data base PRIS.

*Superphénix*, 1200 MWe, entered service in 1984 and as of 2006 remains the largest FBR yet built. It was shut down in 1998 due to political commitment of the left-wing government to competitive market forces. The power plant had not produced electricity for most of the preceding ten years. The life time load factor was 7.79 percent according to IAEA.

**Germany**

Germany has built two FBRs.

**KNK-II** as a Research reactor was converted from a thermal reactor, KNK-I, which had been used to study sodium cooling. KNK-II first achieved criticality as a fast reactor in 1977, and produced 20MWe. It was shut down in 1991 and is being dismantled

Construction of the 300MWe SNR-300 at Kalkar in North Rhine-Westphalia was completed in 1985 but never operated. The price had exploded from 0.5 billion DM to 7.1 billion DM, the Three Mile Island accident had heightened public opposition to nuclear power, and the expected increase in electricity consumption had not occurred. The plant was maintained and staffed until a decision to close it was finally made in 1991, and has since been decommissioned. Today it houses an amusement park (Wunderland Kalkar).

**India**

India has an active development program featuring both fast and thermal breeder reactors.

India’s first 40 MWt Fast Breeder Test Reactor (FBTR) attained criticality on 18 October 1985. Thus, India became the sixth nation to have the technology to build and operate an FBTR after US, UK, France, Japan and the former USSR. India has developed the technology to produce the plutonium rich U-Pu mixed carbide fuel. This can be used in the Fast Breeder Reactor.

At present the scientists of the Indira Gandhi Centre for Atomic Research (IGCAR), one of the nuclear R & D institutions of India, are engaged in the construction (already in its final stages) of another FBR — the 500 MWe prototype fast breeder reactor - at Kalpakkam, near Chennai, with plans to build more as part of its three stage nuclear power program.

India has the capability to use thorium cycle based processes to extract nuclear fuel. This is of special significance to the Indian nuclear power generation strategy as India has among the world largest reserves of thorium, which could fuel nuclear projects for an estimated 2,500 years. The higher construction expense of the Fast Breeder Reactor in comparison with the Pressurized Heavy Water Reactors (PHWR) in use is one of the main reasons why India is looking at the cheaper option — uranium fuel.

**Japan**

Japan has built one demonstration FBR, Monju, in Tsuruga, Fukui Prefecture, adding on to the research base developed by its older research FBR, the Joyo reactor. Monju is a sodium-cooled, MOX-fueled loop type reactor with 3 primary coolant loops, producing 714 MWt / 280 MWe.

Monju began construction in 1985 and was completed in 1991. It first achieved criticality on 5 April 1994. It was closed in December 1995 following a sodium leak and fire in a secondary cooling circuit, and was expected to restart in 2008. The reactor was restarted for tests in May 2010, for the goal to production usage in 2013. However, on August 26, 2010, a 3.3-tonne "In‐Vessel Transfer Machine" fell into the reactor vessel when being removed after a scheduled fuel replacement operation. The fallen device was not retrieved from the reactor vessel until June 23, 2011.

In April 2007, the Japanese Government selected Mitsubishi Heavy Industries as the "core company in FBR development in Japan". Shortly thereafter, MHI started a new company, Mitsubishi FBR Systems (MFBR), with the explicit purpose of developing and eventually selling FBR technology.

**UK**

Main article: Dounreay

The UK fast reactor program was conducted at Dounreay, Scotland, from 1957 until the program was cancelled in 1994. Three reactors were constructed, two of them fast neutron power reactors, and the third, DMTR, being a heavy water moderated research reactor used to test materials for the program. Fabrication and reprocessing facilities for fuel for the two fast reactors and for the test rigs for DMTR were also constructed onsite. Dounreay Fast Reactor (DFR) achieved its first criticality in 1959. It used NaK coolant and produced 14MW of electricity. This was followed by the sodium-cooled 250 MWe Prototype Fast Reactor (PFR) in the 1970s. PFR was closed down in 1994 as the British government withdrew major financial support for nuclear energy development, DFR and DMTR both having previously been closed.

**USA**

On December 20, 1951, the fast reactor EBR-I (Experimental Breeder Reactor-1) at the Idaho National Laboratory in Idaho Falls, Idaho produced enough electricity to power four light bulbs, and the next day produced enough power to run the entire EBR-I building. This was a milestone in the development of nuclear power reactors. The reactor was decommissioned in 1964.

The next generation experimental breeder was EBR-II (Experimental Breeder Reactor-2), which went into service at the INEEL in 1964 and operated until 1994. It was designed to be an "integral" nuclear plant, equipped to handle fuel recycling onsite. It typically operated at 20 megawatts out of its 62.5 megawatt maximum design power, and provided the bulk of heat and electricity to the surrounding facilities.

The world's first commercial LMFBR, and the only one yet built in the USA, was the 94 MWe Unit 1 at Enrico Fermi Nuclear Generating Station. Designed in a joint effort between Dow Chemical and Detroit Edison as part of the Atomic Power Development Associates consortium, groundbreaking in Lagoona Beach, Michigan (near Monroe, Michigan) took place in 1956. The plant went into operation in 1963. It shut down on October 5, 1966 due to high temperatures caused by a loose piece of zirconium which was blocking the molten sodium coolant nozzles. Partial melting damage to six subassemblies within the core was eventually found. (This incident was the basis for a controversial book by investigative reporter John G. Fuller titled *We Almost Lost Detroit.*) The zirconium blockage was removed in April 1968, and the plant was ready to resume operation by May 1970, but a sodium coolant fire delayed its restart until July. It subsequently ran until August 1972 when its operating license renewal was denied.

The Clinch River Breeder Reactor Project was announced in January, 1972. A government/business cooperative effort, construction proceeded fitfully and abandoned in 1982 because the US has since halted its spent-fuel reprocessing program and thus made breeders pointless. Funding for this project was halted by Congress on October 26, 1983.

The Fast Flux Test Facility, first critical in 1980, is not a breeder but is a sodium-cooled fast reactor. It is in cold standby.

**USSR**

The Soviet Union constructed a series of fast reactors, the first being mercury cooled and fueled with plutonium metal, and the later plants sodium cooled and fueled with plutonium oxide.

**BR-1** (1955) was 100W (thermal) was followed by BR-2 at 100 kW and then the 5MW BR-5.

**BOR-60** (first criticality 1969) was 60 MW, with construction started in 1965.

BN-350 (1973) was the first full-scale Soviet FBR. Constructed on the Mangyshlak Peninsula in Kazakhstan and on the shore of the Caspian Sea, it supplied 130MW of electricity plus 80,000 tons per day of desalinated fresh water to the city of Aktau. Its total output was regarded as the equivalent of 350MWe, hence the designation.

BN-600 (1986, end of life 2020) is 1470MWth / 600MWe.

There are plans for the construction of two larger plants, BN-800 (800 MWe) at Beloyarsk, expected to be completed in Q1/2013, and BN-1200 (1200 MWe), expected to be completed in 2018.

**Future plants**

As of 2003 one indigenous FBR was planned for India, which is due to be completed by 2010. The FBR program of India includes the concept of using fertile thorium-232 to breed fissile uranium-233. India is also pursuing the thermal breeder reactor, again using thorium. A thermal breeder is not possible with purely uranium/plutonium based technology. Thorium fuel is the strategic direction of the power program of India, owing to their large reserves of thorium, but worldwide known reserves of thorium are also some four times those of uranium. India's Department of Atomic Energy (DAE) says that it will simultaneously construct four more breeder reactors of 500 MWe each including two at Kalpakkam.

The China Experimental Fast Reactor (CEFR), scheduled for completion in 2008, is a 25 MW(e) prototype for the planned China Prototype Fast Reactor (CFRP). It started generating power on July 21, 2011.

The People’s Republic of China has also initiated a research and development project in thorium molten-salt thermal breeder reactor technology (Liquid fluoride thorium reactor). It was formally announced at the Chinese Academy of Sciences (CAS) annual conference in January 2011. Its ultimate target is to investigate and develop a thorium based molten salt nuclear system in about 20 years.

Kirk Sorensen, former NASA scientist and Chief Nuclear Technologist at Teledyne Brown Engineering, has been a long time promoter of thorium fuel cycle and particularly liquid fluoride thorium reactors. In 2011, Sorensen founded Flibe Energy, a company aimed to develop 20-50 MW LFTR reactor designs to power military bases.

South Korea is developing a design for a standardized modular FBR for export, to complement the standardized PWR (Pressurized Water Reactor) and CANDU designs they have already developed and built, but has not yet committed to building a prototype.

The BN-600 (Beloyarsk NNP in the town of Zarechny, Sverdlovsk Oblast) is still operational. A second reactor (BN-800) is scheduled to be constructed before 2015.

On 16 February 2006 the U.S., France and Japan signed an "arrangement" to research and develop sodium-cooled fast reactors in support of the Global Nuclear Energy Partnership.