FAST BREEDER REACTORS

4/6/2017

INTRODUCTION

Energy production by fast breeding remains the main goal of the Liquid Metal Fast Reactor (LMFR) to ensure a sustainable long term fissile fuel supply. In addition, the use of LMFRs allows the recycling of the Minor Actinides content of nuclear waste burning them to produce energy and reduce the amounts of disposed waste. Another advantage of the LMFR is its higher thermal efficiency compared with water-cooled reactors.

The sustainable, environmentally clean long term use of nuclear power can be achieved with fast reactors, since thermal reactors are capable of burning less than 1 percent of the uranium fuel. It is surmised that the known reserves of uranium will fuel thermal reactors for only a few decades. Fast reactors burn most of the uranium fuel extending the power producing capability of the uranium reserves into the hundreds of years, making the recoverable energy resource from uranium larger than from coal.

Figure 1. The Experimental Breeder Reactor I, EBR-I, in the Idaho desert turned into a museum. It used a Na-K eutectic alloy that was liquid at room temperature as a coolant.

The fast reactor first transforms the 99.3 percent in the original ore abundant fertile isotope U^{238} into fissile Pu^{239}, then burning it to produce to produce 50 to 60 times as much energy per metric tonne of uranium ore as a thermal reactor. Recycling becomes an essential part of the fast reactor system since the fuel is recycled through the reactor several times.

The first nuclear electricity was produced on December 20, 1951 in the Experimental Breeder Reactor I or EBR-I at Idaho. It was turned into a museum after an accident, and was superseded by the Experimental Breeder Reactor II, or EBR-II which successfully produced electricity for more than 25 years before being retired.

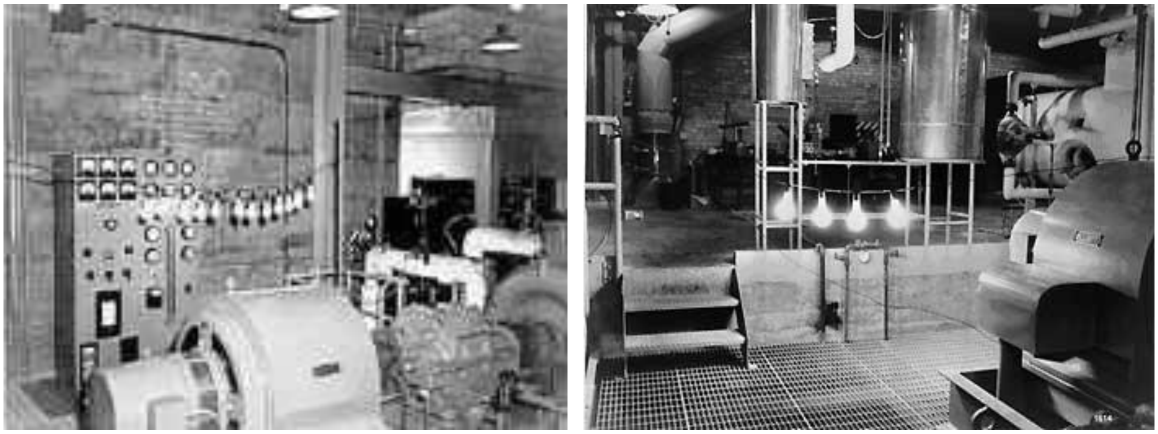

Figure 2. The Experimental Breeder Reactor I, EBR-I, lighted up strings of light bulbs with the first produced nuclear electricity on December 20, 1951.

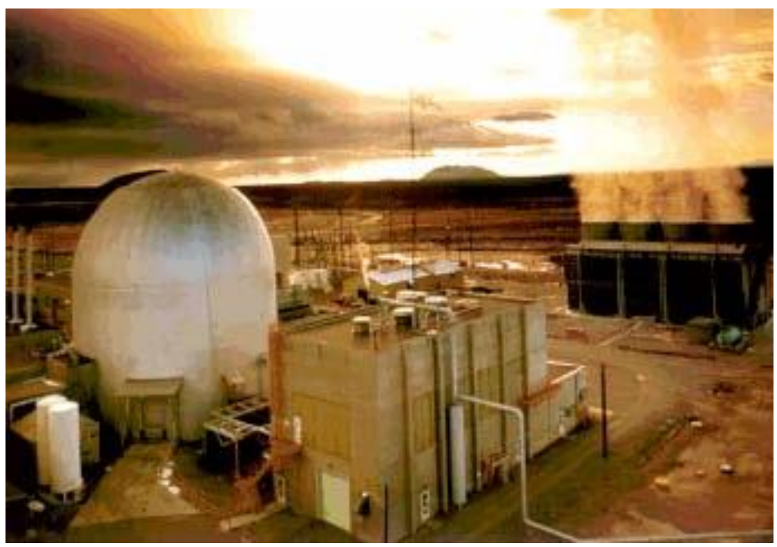

Figure 3. The Experimental Breeder Reactor II, EBR-II, at Idaho used a sodium coolant and operated for 25 years.

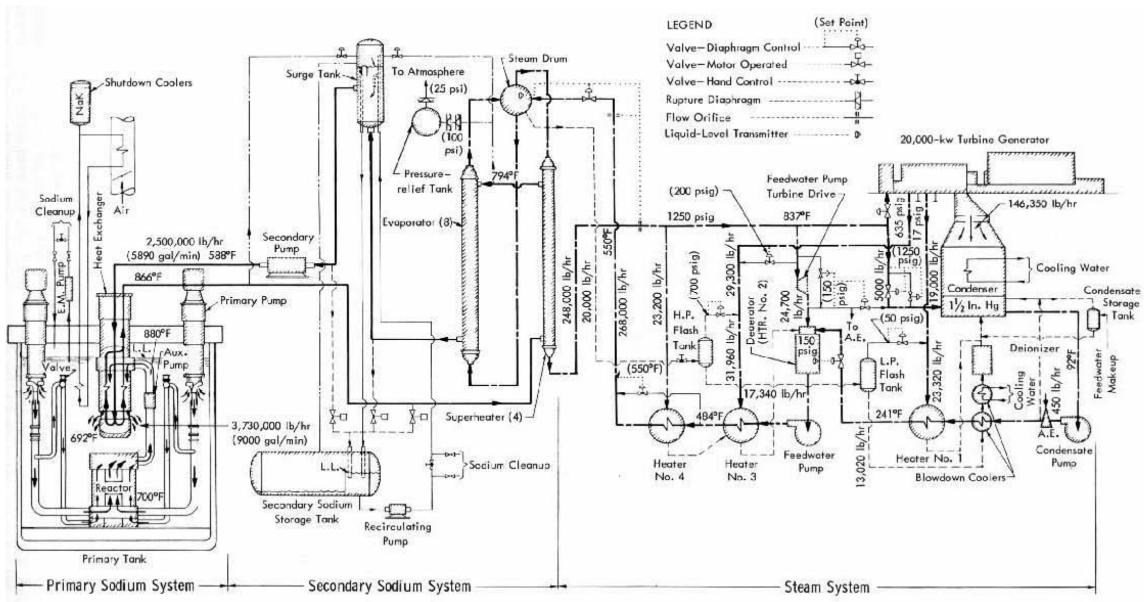

Figure 4. EBR-II Flow diagram.

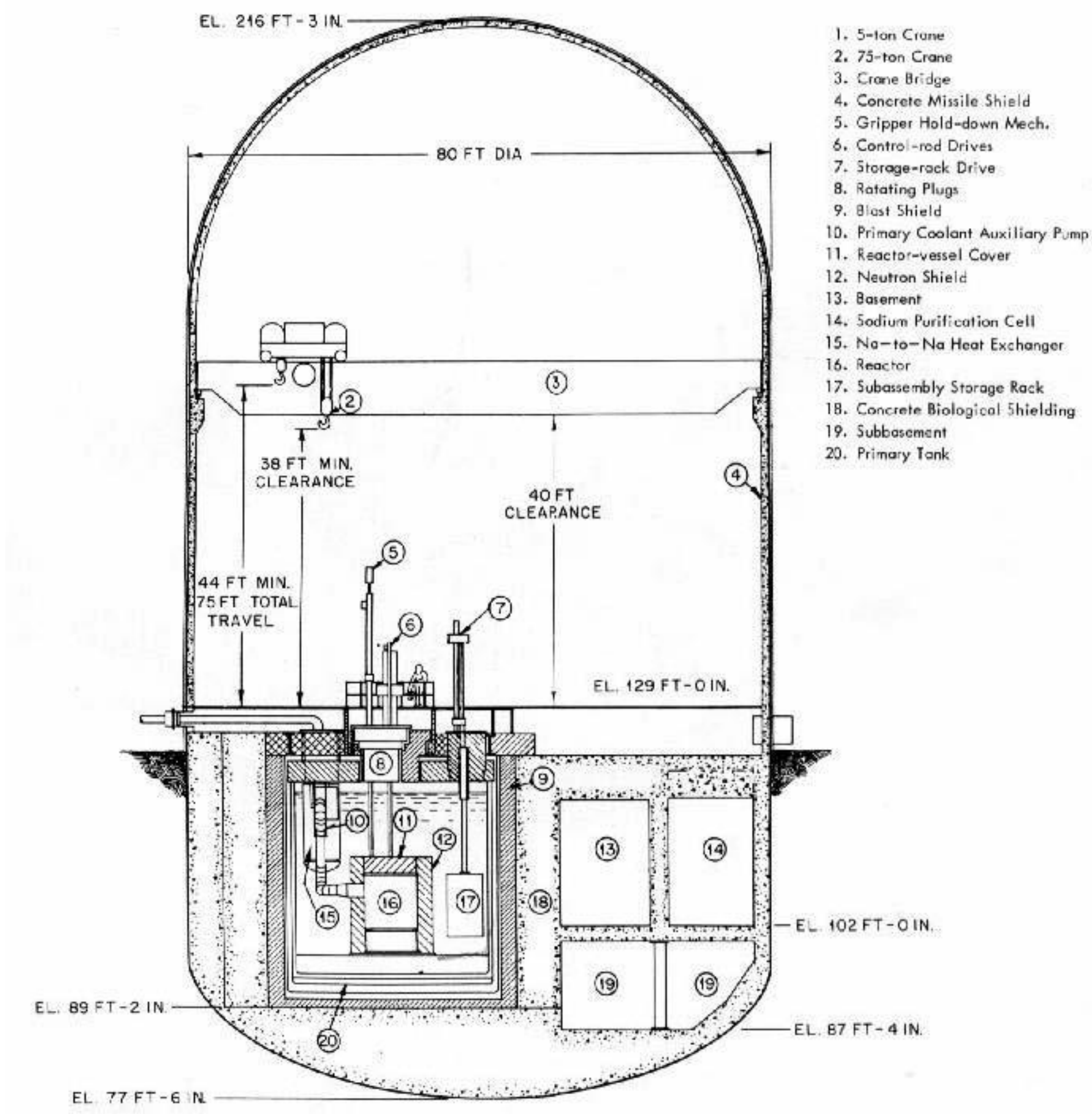

Figure 5. EBR-II Reactor building.

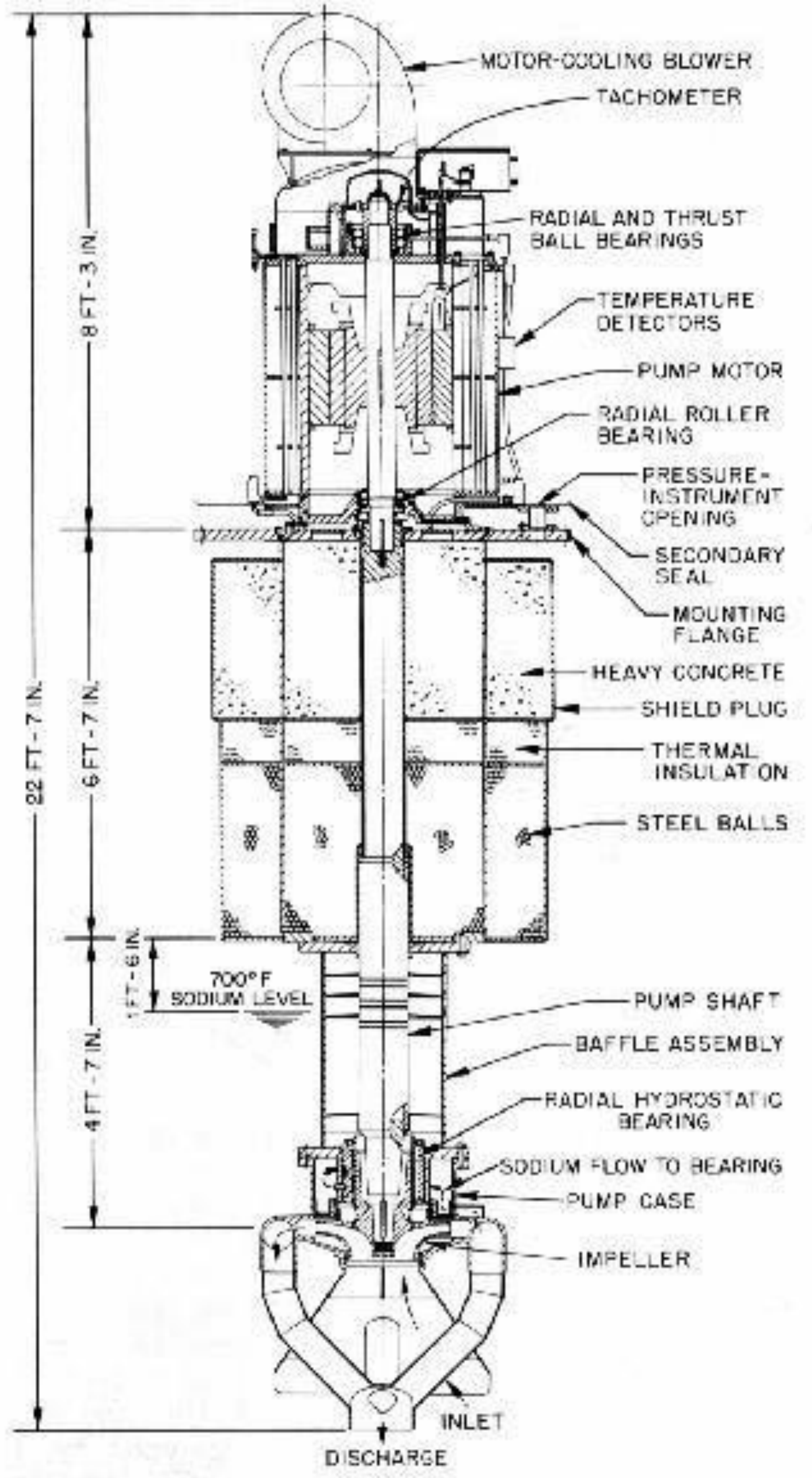

Figure 6. EBR-II sodium pump.

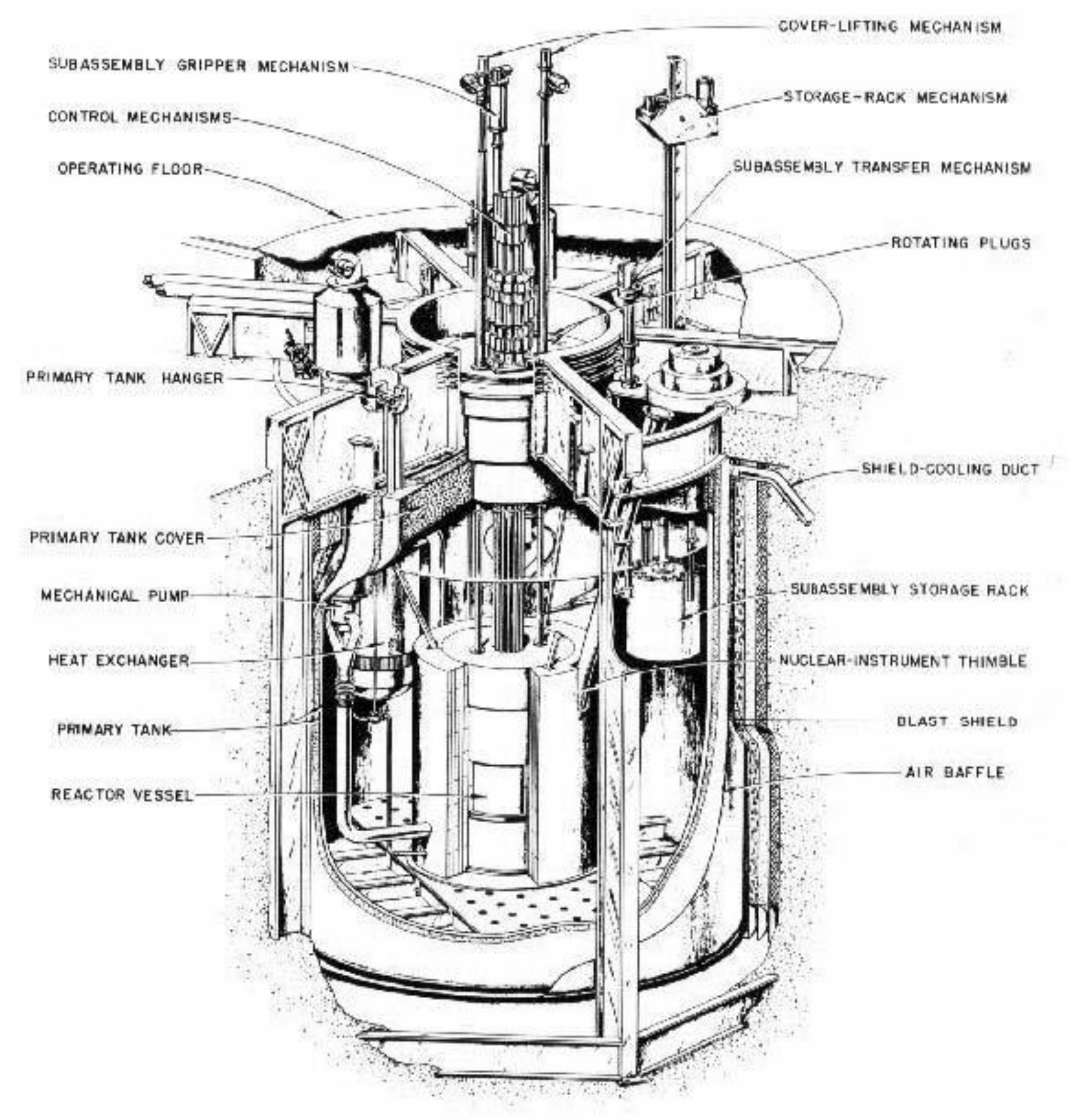

Figure 7. EBR-II pressure vessel configuration.

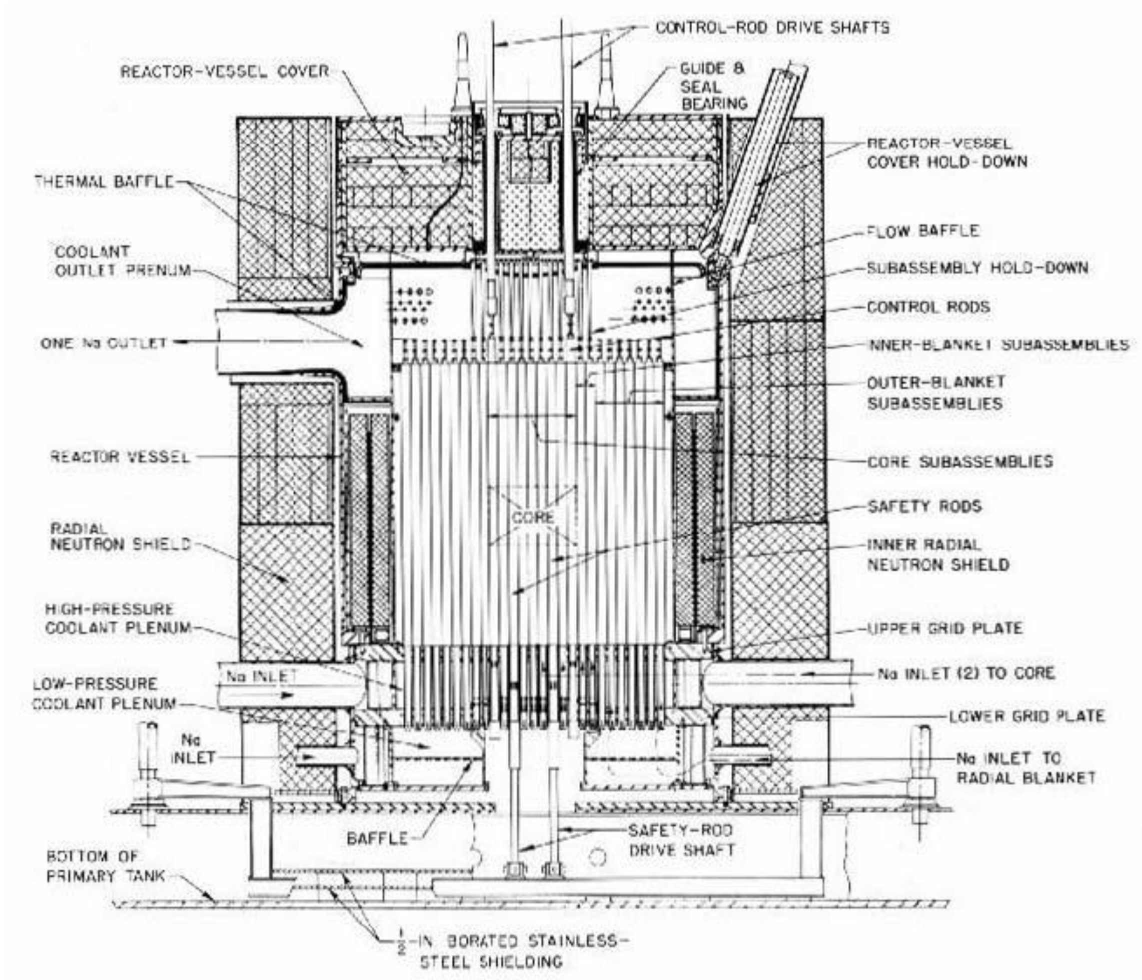

Figure 8. EBR-II core and blanket assembly.

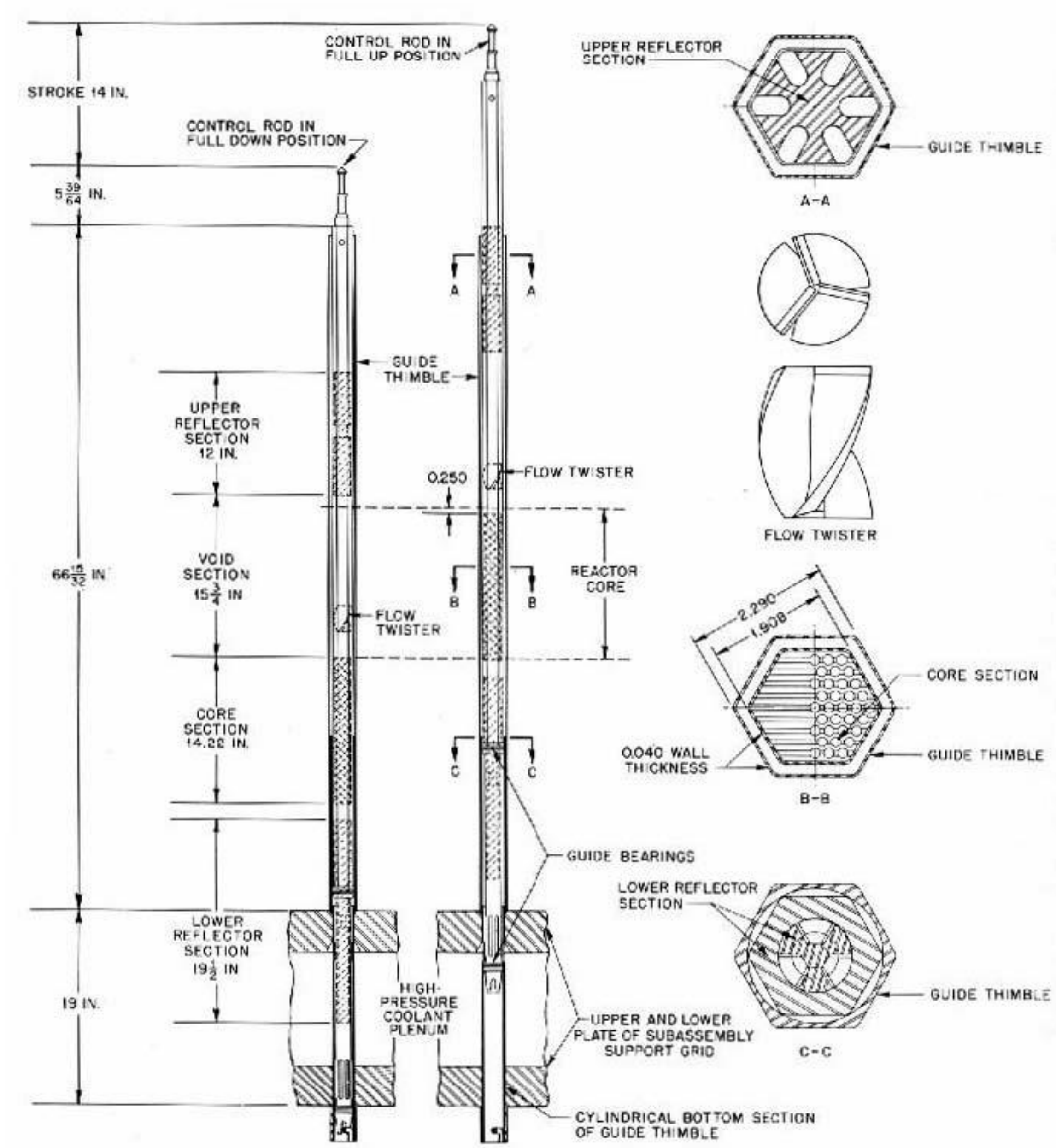

Figure 9. EBR-II control rod assembly.

In the earliest days emphasis was placed on the breeding of fissile material. The increasing availability of cheap fossil fuels in the 1960s shifted the emphasis to include other uses for fast reactors, particularly for the control of plutonium stocks by burning them, and the treatment of radioactive wastes. In spite of these additional functions the main long term importance of fast reactors as breeders, essential to world energy supplies, remains unchanged.

Another advantage of the LMFBR concept is its operation at high temperature offering a high thermal efficiency. In addition it operates at low pressure so that a pressurization system is not required, and the loss of cooling through depressurization is not a safety consideration. This makes the fast reactor an attractive inherently safe system.

HISTORY

In the 1940s it was realized that fast reactors would have potential advantages over thermal reactors because the excess neutrons available. These could be used for breeding fissile material from the fertile isotopes. This is the key to utilizing the enormous world-wide energy reserve represented by U^{238}.

The development of civilian fast reactors in the late 1940s involved test reactors such as Clementine and the Experimental Breeder Reactor I (EBR-I) in the USA and BR-2 in the USSR. There were also low-power experimental assemblies such as Zephyr and Zeus in the UK.

Demonstration reactors followed such as the EBR-II in the USA, BOR-60 in the USSR, Rapsodie in France and DFR in the UK were constructed in the 1950s and 1960s. This eventually led to prototype power reactors such as Phénix in France, PFR in the UK and BN-350 in Kazakhstan, and finally full scale power plants like the Super Phénix or SPX in France and BN-600 in Russia.

FAST REACTOR POWER PLANTS

Prototype fast reactors have been built with a power level of 250 MWe such as Phénix in France and the Prototype Fast Reactor (PFR) in Dounreay, UK. The KNK2 reactor produced 20 MWe and the 300 MWe Schneller Naturiumgekülter Reaktor (SNR300) in Germany.

A full power commercial plant is the 1,200 MWe Super Phénix-1 (SPX1) plant in France. It was built as a collaborative effort between Germany, Belgium, the Netherlands, Italy and the UK. It is owned and operated by three utilities: Electricité de France (EDF), Schnell-Brüter-Kernkraftwerks-Gesellschaft (GSF) and ENEL.

The Mixed Oxide Fuel (MOX) a mixture of PuO_2 and UO_2 is the preferred fuel with sodium as a coolant.

Two design concepts: the pool type and the loop type configurations have been considered, with the pool type gaining a preference. Both approaches use a primary and a secondary heat transport systems followed by a steam generation loop to the turbine plant.

SAFETY CONSIDERATIONS

The reactor core, primary coolant pump and the intermediate heat exchanger are contained in the main reactor tank in the pool design. The liquid sodium metal is contained in a simple double walled tank without penetrations below the sodium surface level and operating at atmospheric pressure. The loss of primary coolant becomes so unlikely as to be incredible.

The primary sodium has such a large thermal heat capacity that it can survive the loss of decay heat cooling after the reactor has been shut down for about 10 hours. There exist substantial margins between normal operating temperatures and the coolant boiling temperature.

Figure 10. Super Phénix fast reactor, France.

Figure 11. The Phénix mythological bird gets reborn out of its own ashes.

The concept possesses a strong negative power coefficient of reactivity associated with the fuel: when the temperature of the fuel rises, the power goes down in the absence of any control action. There exist no significant positive coefficients below the sodium boiling point. This implies that such a reactor is completely stable under normal operation. It can survive some hypothetical fault conditions for which the design intent of fast automatic shutdown is assumed not to take place. For instance, after a hypothesized loss of all pumping power to the coolant flow in the secondary circuits, there would be a reduction of power following the negative reactivity effects arising from thermal expansion, to a degree that can be removed by the emergency decay heat removal loops.

As engineered safety features, highly reliable shutdown and decay heat removal systems are provided. In the prototypes used reliable shutdown systems never experienced any failures.

Two separate systems are used to remove the decay heat following shutdown. The first system uses the conventional steam system associated with the turbine. The second uses dedicated heat exchangers immersed in the primary coolant transferring heat to a Na or a Na-K alloy that is liquid at room temperature, from which heat is removed to the atmosphere. The plant temperatures can be maintained at safe levels by natural air flow in needed.

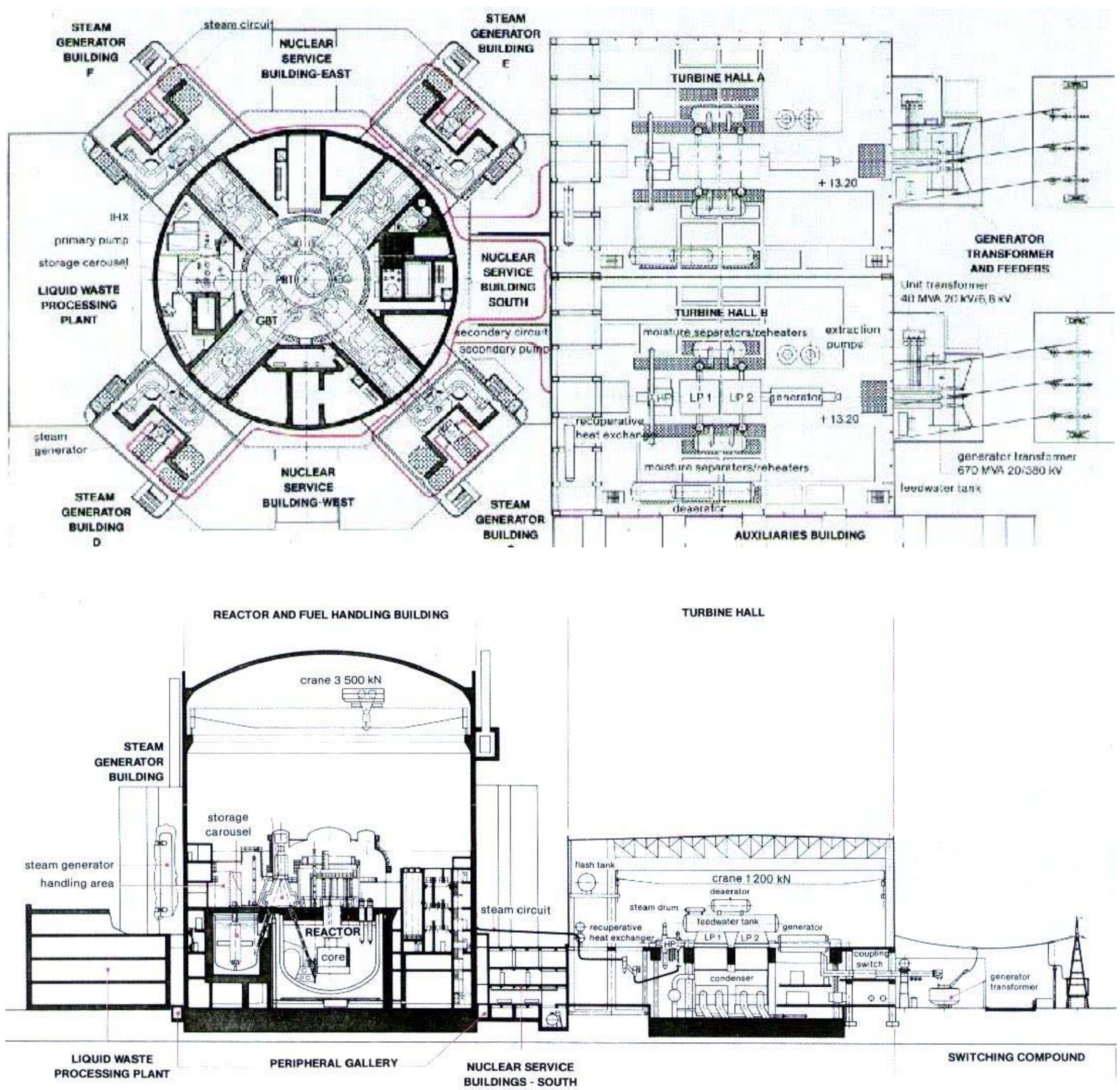

Figure 12. Super Phénix plant configuration.

The double walled reactor tank and its roof provide a strong primary containment structure that can deal with a wide range of hypothetical accidents. A secondary containment is provided around the primary circuit with the ability to deal with an internal pressure with a low leak rate.

With the loss of coolant made incredible, a highly reliable shutdown and decay heat removal systems, the reactor design has practically no faults within the design basis down to 1 in a million, which produces a possibility for any active release from the fuel.

The low operating pressure of the sodium and the enormous affinity of liquid sodium for fission products such as I^{131} provide a second barrier.

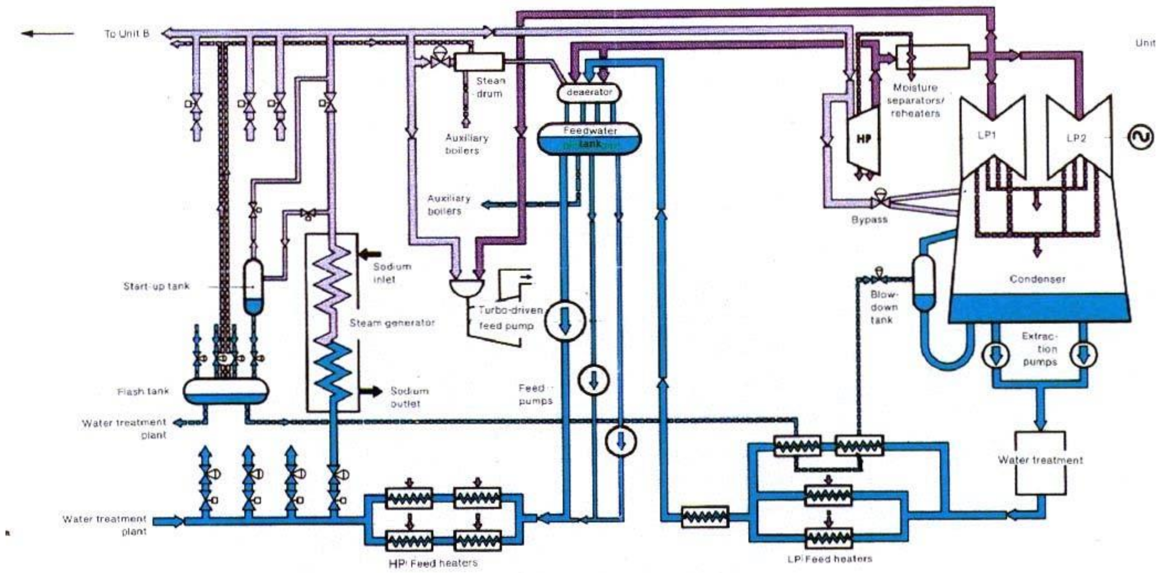

Figure 13. Super Phénix coolant circuit.

COMPONENTS DESIGN

Since the sodium circuit operates at virtually atmospheric pressure, the main stresses on the components are due to the temperature gradients with creep and fatigue being the main considerations.

The steam generators receive particular attention because the leaks of water or steam into the sodium could produce secondary damage and shorten the components lifetimes. Once through units with helically wound tubes have been used and ferritic materials such as 9Cr-1Mo alloys have been adopted.

Inservice inspection methods using ultrasound to monitor the components immersed in sodium are meant to extend the life of the structures.

FUEL AND CLADDING COMPOSITION

The choice fuel is the Mixed Oxide fuel (MOX) which is a mixture of PuO_2 and UO_2. Burnup is the design parameter of most significance for the fuel cycle cost. Higher levels of burnup imply more favorable fuel costs and are achievable at a level of 10-20 percent. The fuel burnup is defined as:

$$\text{Fuel burnup} = \frac{\text{U and Pu nuclei fissioned}}{\text{Total U and Pu nuclei}} \times 100$$

A 10 percent fuel burnup corresponds to 95,000 MWth.days / metric tonne of fuel of energy release.

It is expected that the fuel cycle costs would be lower than for thermal reactors compensating for a higher capital cost component for fast reactors.

Potential new cladding and wrapper materials can increase the fuel burnup such as 10Cr-25Ni, Inconel 706, Nimonic PE16 alloys, dispersion strengthened ferritic steels for the cladding, and martensitic materials for the wrappers.

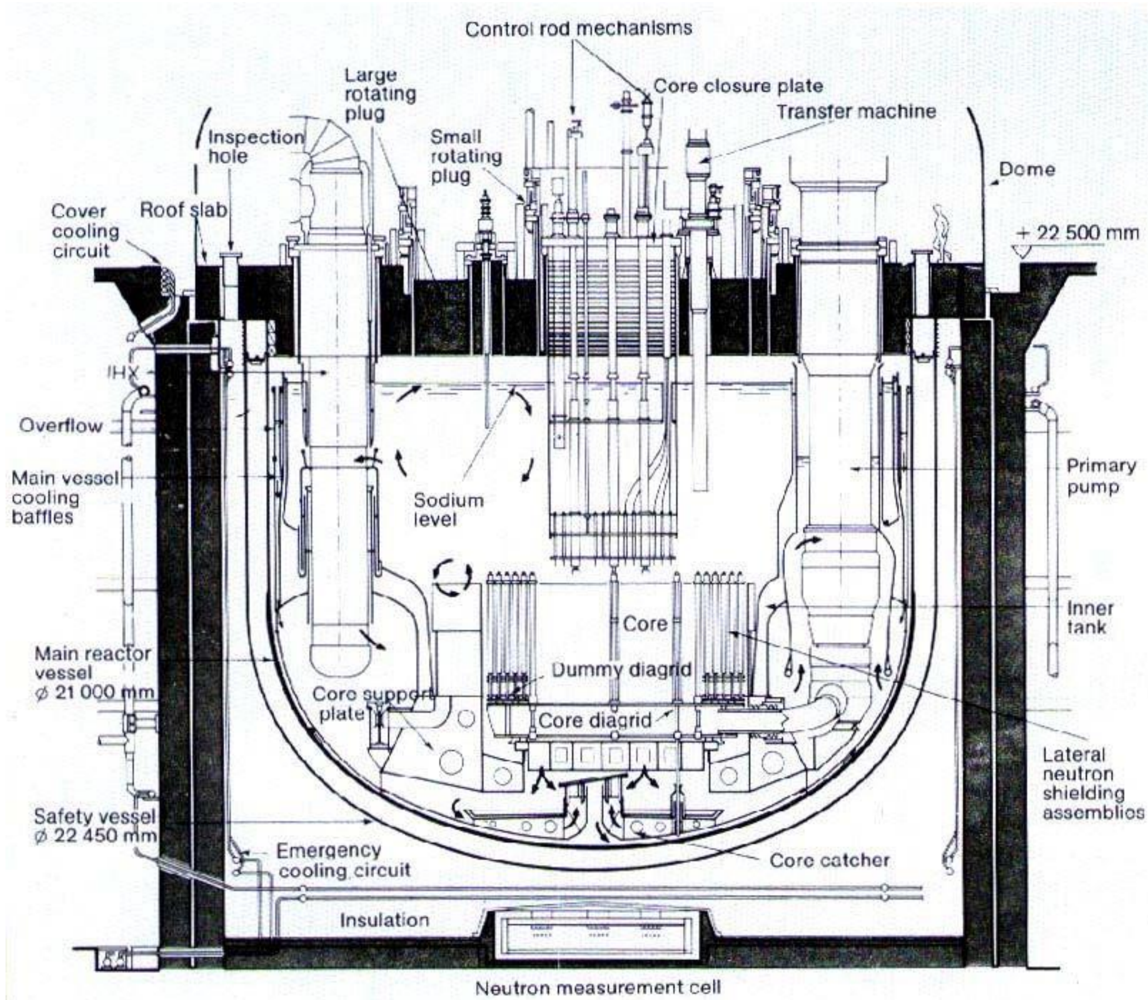

Figure 14. Super Phénix reactor vessel.

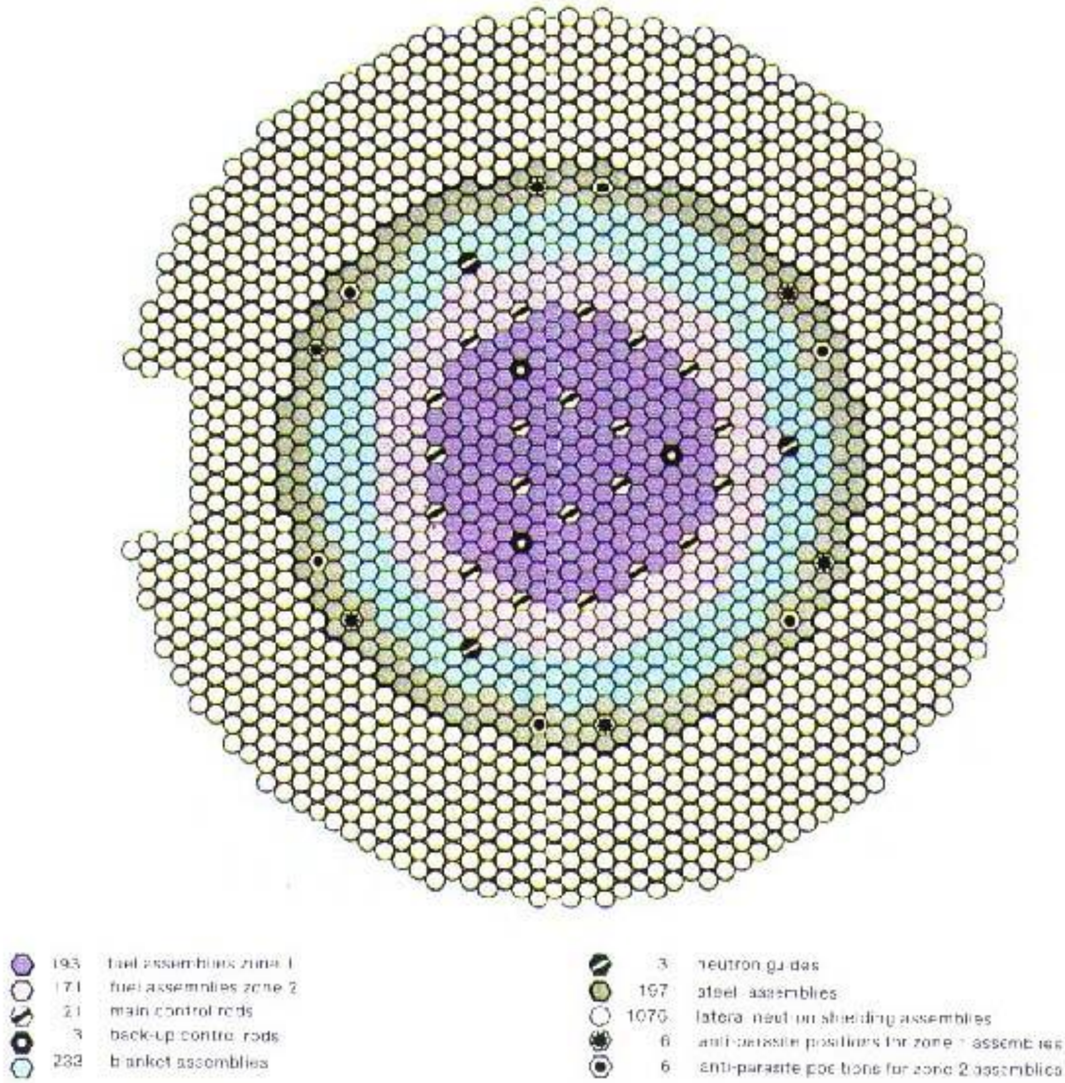

Figure 15. Super Phénix core configuration.

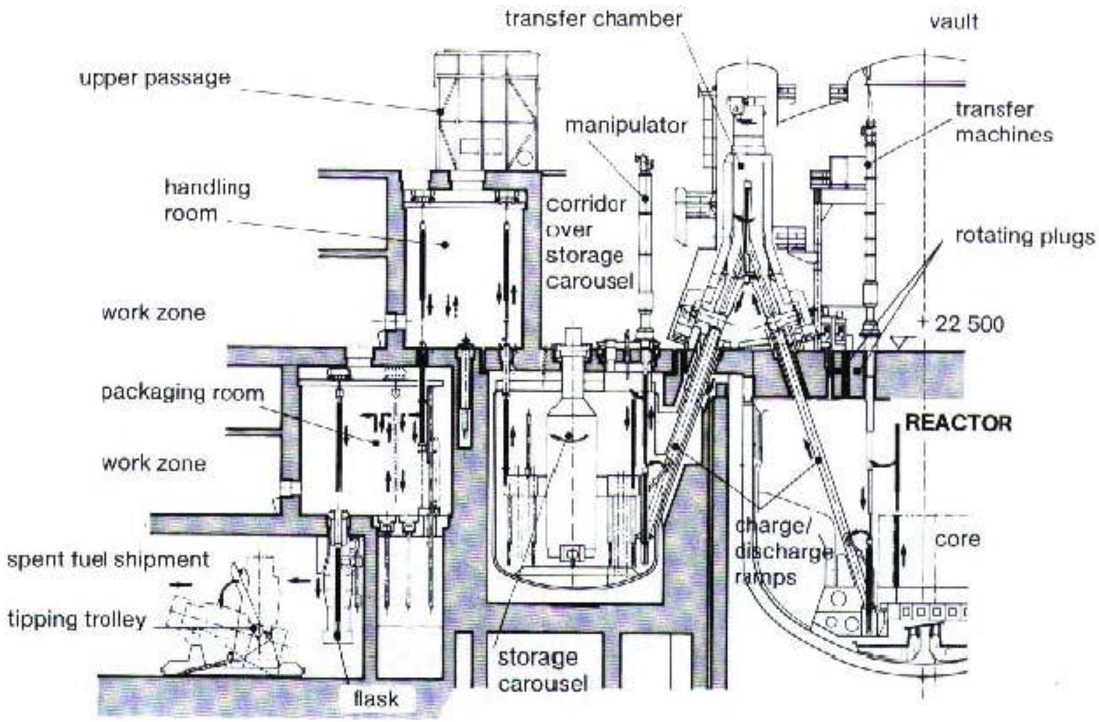

Figure 16. Super Phénix fuel handling system.

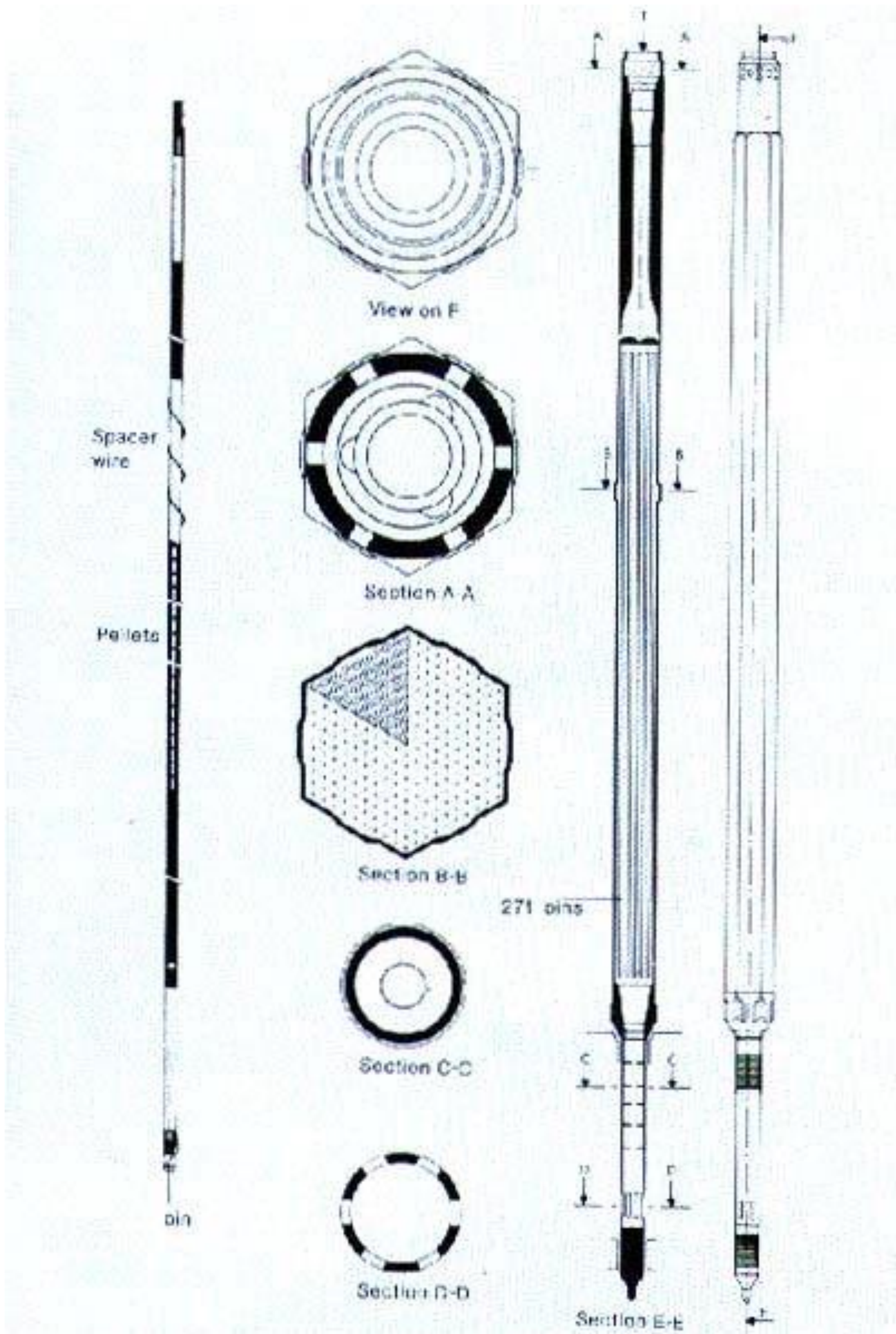

Figure 167. Super Phénix fuel assembly.

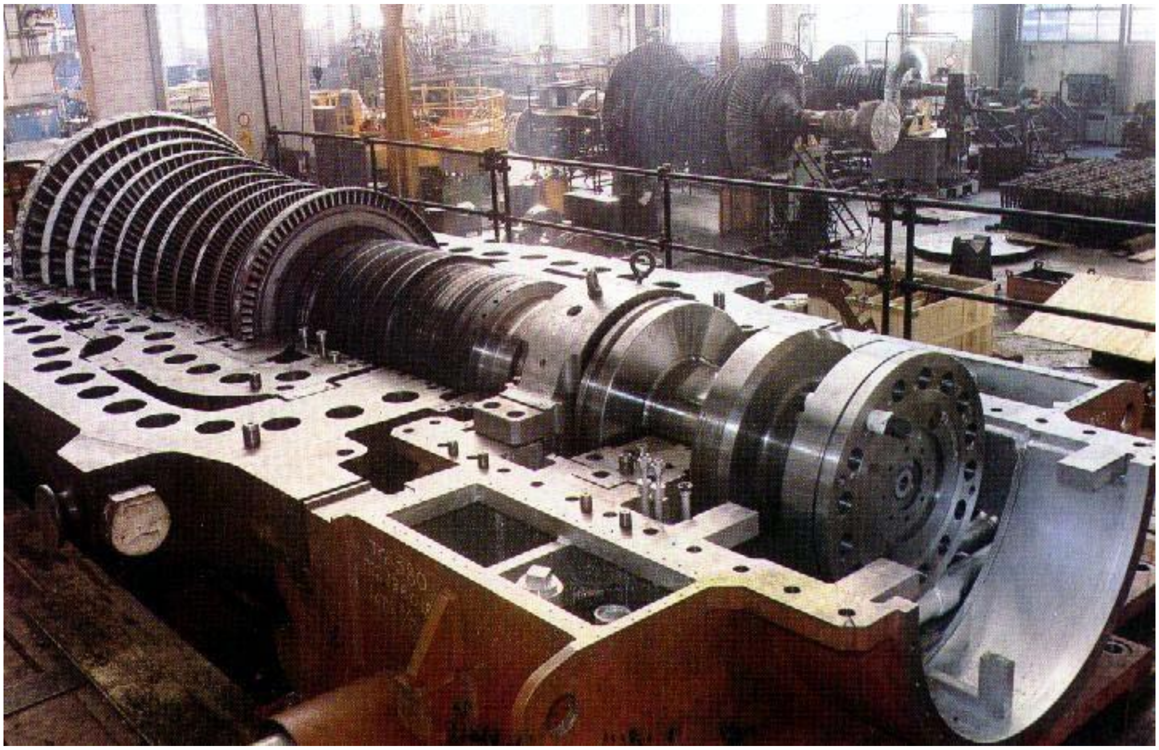

Figure 18. Internals of the Super Phénix steam turbine.

DISARMAMENT BN-800 FAST REACTOR, PLUTONIUM MANAGEMENT AND DISPOSITION TREATY

A treaty was signed between the USA and the Russian Federation on July 13, 2011, known as the "Plutonium Management and Disposition Treaty." This treaty commits the two parties to the treaty to dispose each of 34 metric tonnes of weapons-grade plutonium for a total of 68 metric tonnes. At 4 kgs per device, this suggests the dismantlement of the equivalent of 68,000 / 4 = 17,000 nuclear devices. For reference, the critical mass of an unreflected (bare) core of Pu^{239} is about 10 kgs, and the International Atomic Energy Agency (IAEA) considers 6 kgs or 13 lbs as sufficient for a viable implosion device. President Barack Obama hailed the treaty as an important step in making a "safer and more secure" world. About 1,000 metric tons of reactor-grade Pu exist in the spent fuel of nuclear power plants and 250 metric tonnes of weapon-grade Pu exist worldwide. Reactor grade Pu is unsuitable for weapons manufacture due to the presence of unsuitable isotopes such as the spontaneous fission and alpha-emitting Pu^{240} leading to heating and early detonation and fizzle if used in a weapon manufacture context.

The treaty is a follow-up to the 1993 "Megatons to Meagawatts" treaty, expiring in 2013 that diluted Russian weapons Highly Enriched Uranium (HEU) to the 3-5 percent enrichment level usable in light water reactors used by USA utilities. The USA purchased 500 metric tonnes of HEU from the Russian Federation contributing to about ten percent of electrical energy generation in the USA. The new treaty stipulates the mixing of 20 percent Pu with uranium in the Mixed Oxide (MOX) form.

Russia's approach to burning its 34 metric tonnes share of Pu is to build an 800

MWe “Fast Reactor” designated as the BN-800 be added as a fourth unit at its reactor site at Byelorask. The designation “Fast Reactor” differentiates it from a “Fast Breeder Reactor’ by the absence of a Pu breeding blanket, essentially making it a Pu actinide burner. The Beloyarsk site has already three operational reactor units, the third of which is the 600 MWe BN-600, which is itself a fast sodium cooled reactor, providing 32 years of valuable operational experience and is the only commercial fast reactor operational unit in the world. The BN-800 unit is intended to demonstrate the use of Mixed Oxide (MOX) fuel at an industrial scale, including both reactor-grade and weapons-grade plutonium, and the closed fuel cycle technology. The Byelorask site is located by the town of Zarechny with a population of 30 miles or 50 kms east of the city of Yekaterinburg.

Figure 19. Fast reactor BN-800 under construction at Beloyarsk [6].

The USA approach is two-fold. First, with a deeper pocket and larger purse, it contributes $300 million or €240 million to the cost of the Russian BN-800 “Disarmament Reactor,” according to a section “123 agreement.” Second, it considers burning its 34 metric tonnes share of weapons-grade Pu in its conventional light water reactors in the form of MOX fuel.

Section 123 of the USA Atomic Energy Act requires the conclusion of a specific agreement for significant transfers of nuclear material, equipment, or components from the USA to another nation. Such Agreements are important tools in advancing USA nonproliferation principles. These Agreements act in conjunction with other nonproliferation tools, particularly the Nuclear Nonproliferation Treaty (NPT), to establish the legal framework for significant nuclear cooperation with other countries. The Agreements allow for cooperation in other areas, such as technical exchanges, scientific research, and safeguards discussions. In order for a country to enter into such an Agreement with the USA, that country must commit itself to adhering to usa- mandated nuclear nonproliferation norms.

The project had a startup date of 2014. However, political pressure from the USA, and commercial pressure from the Russian Federation, have added the proverbial fly to the ointment by trying to expedite the project to a starting date in 2013. The USA political pressure aims at showing how the fall of fissile material into the hands of real or imagined non-national groups, is prevented. The commercial pressure originates from Russia by Rosatom, its state nuclear holding company, which reasons that a speedy startup would give it an edge that would translate into an advantage in the global reactors market. In fact, Rosatom is negotiating with China for the construction of two fast reactor units similar to the BN-800.

Along this speedup action, the MOX fuel as well as the Na coolant are apparently being delivered to the BN-800 site in November 2012, without adequate storage being available and the coolant circuits not fully assembled. With a retiring experienced generation of technicians and engineers being replaced by a younger one, this creates a concern, since a speedup of the project can cause quality control issues in the welds and seams of the Na-Na-H_2O coolant circuits. It should be recognized that the use of Na as a coolant is not as straightforward as the use of H_2O coolant circuits and requires special quality control considerations pertaining to the occurrence of Na fires.

Experience with similar Na cooled systems deserve to be invoked. The BN-350 sodium cooled fast reactor was constructed near the city of Aktau, formerly Shevchenko on the Caspian Sea in Kazakhstan, and was placed in operation in 1972. BN-350 was designed as a dual purpose plant of producing 130 MWe of electricity and 150 MWth for desalting water and the production of 120,000 m^3 of fresh water/day, which corresponds to a total power generation of 750 MWth. The BN-350 reactor system has also been utilized for a wide range of experimental work supporting fast reactor development; and several design improvements were developed for the next generation larger power sodium cooled fast reactor BN-600 plant.

Through 1974, two major leaks and three smaller leaks occurred at the BN-350 plant. They were initiated from the end cap welds and caused by micro cracks in the end cap weld seam zone. They were attributed to mechanical deformations introduced during the end cap manufacture process. A decision was taken to replace the tubes in all the evaporators except loop number 4 which did not experience any leaks. After 7 days of operation, one of the evaporators in the recently re-tubed loop number 5 failed leading to a significant leak. In that event 120 tubes failed with 800 kg of water leaking, possibly interacting with the sodium causing a fire. This steam generator was dismantled and was replaced by steam generator manufactured in Czechoslovakia.

It was reported that the safety systems including the rupture disc and the blowdown system prevented the destruction of the evaporator vessels for the three large leaks, resulting in no sodium leaks. It is thought that the reaction products stayed within the vessel shell, aggravating the tube failure propagation.

After the re-tubing process, some leaks continued to occur. However emphasis on sodium and feed-water quality control, early leak detection and remediation through failed tubes plugging, eventually resulted in a stable plant operating at design power levels. The problems with leakage in the steam generators at the BN-350 plant posed a problem because of the possible interaction of water with the sodium coolant. The leaks were reportedly confined to water leaking into the sodium. No sodium leaks were reported, which itself would react with oxygen in the air, also causing a fire. Improved steam generator component manufacturing techniques were developed, particularly in tube drawing, forging and welding.

This suggests a need for designing such systems for failure prevention, sodium and feed-water quality control as well as the necessity of including design provisions for tube failure detection with quick recognition and action to prevent failure propagation, and methods for the remediation and plugging of mleaking tubes. Design provisions should also be included for containment and blow-down relief to control the intermediate sodium system pressure.

Meanwhile, the government of the Sverdlovsk region of Russia has already approved the construction of the country's first BN-1200 1,200 MWe fast reactor as the fifth unit at the Beloyarsk nuclear power plant site. The unit will be built to replace the existing smaller BN-600 reactor at the plant, which is scheduled to be shut down by 2020. The technical design of the BN-1200 is scheduled for completion by 2013, while the manufacture of equipment will start in 2014. Construction is set to begin in 2015.

The BN-1200 reactor is meant to replace the existing smaller BN-600 reactor at unit 3 of the Beloyarsk plant. That unit, which began operating in 1981, is scheduled to be decommissioned by 2020. As the speedup of the BN-800 proceeds, one hopes that the lessons learned from the BN-350 and BN-600 are fully learned and that testing and quality control are well heeded to assure the realization of the expected benefits from the “Disarmament Fast Reactor.

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