EBR-II Test and Operating Experience

Prepared for the US Nuclear Regulatory Commission
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Executive summary

EBR-II operated for 30 years as a very successful test and demonstration sodium-cooled fast-reactor power plant. As a complete power plant, the reliability of the system was demonstrated and sodium operating and maintenance technology was established. As an irradiation test facility, Oxide, Metal, Carbide and Nitride fuels were developed. Oxide fuel for the FFTF and CRBRP was qualified and Metal fuel was extensively developed for EBR-II. As an operational-safety test facility, the self-protecting response of a metal-fueled reactor was demonstrated for Anticipated Transients without Scram and the benefits to safety were quantified in a PRA. The safety of operation with breached fuel was also demonstrated. As the Integral Fast Reactor (IFR) prototype, proliferation-resistant reprocessing and recycle of fuel was demonstrated and fuel containing minor actinides was fabricated and irradiated. When decommissioned, draining and reaction of the sodium to produce an acceptable form for disposal was accomplished, including passivation of residual sodium. Waste forms for geologic storage of waste from fuel reprocessing were developed and qualified. The EBR-II experience and test program has established the viability of sodium-cooled fast reactor power plants.
Introduction

There is an important partnership between fast and thermal reactors because fast-spectrum reactors can burn as fuel the waste that thermal reactors produce (primarily long-lived minor actinides). Studies have indicated that anywhere from 10% to 20% of the fleet should be fast reactors to effectively manage this waste depending on the rate of growth of nuclear deployment. Further, fast reactors can greatly extend the fuel supply (approaching a factor of 100). Extending fuel supply was the promise of fast-reactor
development at the dawn of the nuclear age. EBR-I, a fast-reactor, was the first reactor in the world to produce electricity (December of 1951). EBR-II then followed, producing power in 1964 and operating for 30 years as a complete power plant. Based on this and extensive international experience, the technology has been shown to be successful.

International Experience

Fast reactor experience is extensive. Fast Reactors have been operated in the US, France, UK, Germany, Japan, India and Russia. In each of these countries, small reactors of similar size to EBR-II were operated to develop and test the technology. These early test reactors were, EBR-II (US), Rapsodie, (France), DFR (UK), KNK (Germany), JOYO (Japan), and BOR-60 (Russia). Of these, EBR-II, KNK, DFR were complete power plants.

In the US and Russia, small, specialized fast-spectrum test reactors were operated to address questions of physics, SEFOR and EBR-I (US), and BR-2, BR-5/BR-10 (Russia).

The next generation of fast reactors was made up primarily of complete power plants that incrementally increased power levels over the test reactors that preceded them. These reactors were Fermi-1 (US), PHENIX (France), PFR (UK), SNR-300 (Germany), MONJU (Japan) and BN-350 (Russia).

France and Russia operated larger commercial plants, Super-PHENIX (France) and BN-600 (Russia). In addition the US constructed and operated a second research reactor FFTF, (but without an electricity generating system). The US also pursued design of the CRBRP, which was cancelled before construction was completed. A similar fate befell the German fast reactor, SNR-300.

All of these reactors were/are cooled with sodium. Sodium supports a fast-neutron spectrum because of low neutron moderation and absorption. It has excellent thermal conductivity and high heat capacity, which allows for high power density in the core. Its relatively low density reduces pumping power requirements and its large margin to boiling allows for operation at atmospheric pressure. The coolant is also chemically compatible with structural materials, which minimizes corrosion in plant cooling systems. However, an inert atmosphere covering the sodium is needed because it is reactive with air. Sodium at temperature will burn if exposed to air and special fire-suppression systems are an important part of design.
## International Fast Reactor Experience

<table>
<thead>
<tr>
<th>Reactor</th>
<th>Country</th>
<th>Dates of Operation</th>
<th>Power (MWt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EBR-I</td>
<td>US</td>
<td>1951-1963</td>
<td>1.0</td>
</tr>
<tr>
<td>EBR-II</td>
<td>US</td>
<td>1964-1994</td>
<td>62.5</td>
</tr>
<tr>
<td>Fermi-1</td>
<td>US</td>
<td>1963-1972</td>
<td>200</td>
</tr>
<tr>
<td>FFTF</td>
<td>US</td>
<td>1980-1992</td>
<td>400</td>
</tr>
<tr>
<td>CRBRP</td>
<td>US</td>
<td>Cancelled (1983)</td>
<td>975</td>
</tr>
<tr>
<td>Rapsodie</td>
<td>France</td>
<td>1967-1983</td>
<td>40</td>
</tr>
<tr>
<td>Phenix</td>
<td>France</td>
<td>1973-</td>
<td>563</td>
</tr>
<tr>
<td>Superphenix</td>
<td>France</td>
<td>1985-1997</td>
<td>3000</td>
</tr>
<tr>
<td>BR-5/BR/10</td>
<td>Russia</td>
<td>1958-2002</td>
<td>8</td>
</tr>
<tr>
<td>BOR-60</td>
<td>Russia</td>
<td>1968-</td>
<td>60</td>
</tr>
<tr>
<td>BN-350</td>
<td>Russia</td>
<td>1972-1999</td>
<td>1000</td>
</tr>
<tr>
<td>BN-600</td>
<td>Russia</td>
<td>1980-</td>
<td>1470</td>
</tr>
<tr>
<td>JOYO</td>
<td>Japan</td>
<td>1982-</td>
<td>140</td>
</tr>
<tr>
<td>MONJU</td>
<td>Japan</td>
<td>1980-1992</td>
<td>714</td>
</tr>
<tr>
<td>DFR</td>
<td>UK</td>
<td>1959-1977</td>
<td>72</td>
</tr>
<tr>
<td>PFR</td>
<td>UK</td>
<td>1974-1994</td>
<td>600</td>
</tr>
<tr>
<td>KNK-II</td>
<td>Germany</td>
<td>1972-1991</td>
<td>58</td>
</tr>
<tr>
<td>FBTR</td>
<td>India</td>
<td>1985-</td>
<td>42.5</td>
</tr>
</tbody>
</table>

Sodium-cooled reactor operating experience is extensive and has resulted in the following major conclusions:

**Positives:**

Fast reactor fuel is reliable and safe, whether metal or oxide. Cladding failure does not lead to progressive fuel failure during normal or off-normal reactor operation.

High burnup of fast reactor fuel is achievable, whether metal or oxide. Acceptable conversion ratios (either as breeders or burners) are also achievable with either fuel type.

Sodium is not corrosive to stainless steel or components immersed within it.

Leakage in steam generating system with resultant sodium-water reactors does not lead to serious safety problems. Such reactions are not catastrophic, as previously believed, and can be detected, contained and isolated.

Leakage of high-temperature sodium coolant, leading to a sodium fire, is not catastrophic and can be contained, suppressed and extinguished. There have been no injuries from
sodium leakage and fire (operation at near atmospheric pressure is an advantage to safety).

Fast-Reactors can be self-protecting against Anticipated Transients without Scram when fueled with metal fuel. Load-following is also straightforward.

Passive transition to natural convective core-cooling and passive rejection of decay heat has been demonstrated.

Reliable control and safety-system response has been demonstrated.

Effective systems for purity control of sodium and cleanup have been demonstrated.

Efficient reprocessing of metal fuel, including remote fabrication, has been demonstrated.

Low radiation exposures are the norm for operating and plant maintenance personnel, less than 10% of that typical for LWRs.

Emissions are quite low, in part because sodium reacts chemically with many fission products if fuel cladding is breached.

Maintenance and repair techniques are well developed and straightforward.

Electromagnetic pumps operate reliably.

Negatives:

Steam generators have not been reliable and are expensive to design and fabricate.

Sodium heat-transport systems have experienced a significant number of leaks because of poor quality control and difficulty with welds. Also, because of sodium’s high thermal conductivity, many designs did not adequately anticipate the potential for high thermal stress on transients.

Many problems with handling fuel in sodium systems have occurred, primarily because of the inability to visually monitor operations.

Failure of in-sodium components without adequate means for removal and repair has resulted in costly and time-consuming recovery.

Sodium-cooled fast reactors have been more expensive than water-cooled-reactor systems.
Reactivity anomalies have occurred in a number of fast reactors, requiring careful attention to core restraint systems and potential for gas entrainment in sodium flowing through the core.

Operational problems have been encountered at the sodium/cover-gas interface, resulting from formation of sodium-oxide that can lead to binding of rotating machinery, control-rod drives and contamination of the sodium coolant.

**EBR-II Design Description: keys for success**

EBR-II suffered few of the negatives and was able to develop technology that led to success of plants to follow. The reason for this success was based on design choices, attention to details of construction, disciplined operation and maintenance, and an aggressive test program that developed a deeper understanding of the technology.

EBR-II was a complete power plant, producing 20 MWe with a conventional steam-turbine (with superheat). The reactor produced 62.5 MWt.

**EBR-II Operating Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Power Output, thermal</td>
<td>62.5MWt</td>
</tr>
<tr>
<td>Power Output, electric</td>
<td>20 MWe</td>
</tr>
<tr>
<td>Reactor Inlet Temperature</td>
<td>700 F</td>
</tr>
<tr>
<td>Reactor Outlet Temperature</td>
<td>883 F</td>
</tr>
<tr>
<td>Flow-rate Through Core</td>
<td>9,000 gpm</td>
</tr>
<tr>
<td>Volume of Primary Sodium</td>
<td>89,000 gal</td>
</tr>
<tr>
<td>Sodium Temperature to Superheaters</td>
<td>866 F</td>
</tr>
<tr>
<td>Sodium Temperature from evaporators</td>
<td>588 F</td>
</tr>
<tr>
<td>Steam Temperature</td>
<td>820 F</td>
</tr>
<tr>
<td>Steam Pressure</td>
<td>1,250 psig</td>
</tr>
<tr>
<td>Feedwater Temperature</td>
<td>550 F</td>
</tr>
<tr>
<td>Fuel</td>
<td>Metal 63% enriched</td>
</tr>
<tr>
<td>Primary System Configuration</td>
<td>Piped Pool</td>
</tr>
<tr>
<td>Steam Generator Design</td>
<td>Duplex Tube</td>
</tr>
</tbody>
</table>
EBR-II was a sodium-cooled reactor with a piped-pool configuration. That is, the coolant was drawn from a tank of sodium by two centrifugal pumps and then piped to a plenum at the bottom of the core. The sodium, after flowing through the core, was then piped to an intermediate heat exchanger where heat was transferred to the secondary sodium system. This configuration allowed for leakage at the connections at the outlet of the pumps and at the intermediate heat exchanger, since primary sodium would simply leak back to the tank from which it was drawn. This also allowed for “ball and socket” connections at the pumps which facilitated their removal and replacement. The tank, which was a right circular cylinder, was maintained at a nearly uniform and constant temperature (700F), which limited thermal stress. Another important feature was that the tank included no penetrations through the wall; all penetrations were through the top. This also limited the risk for thermal stress, weld failure and sodium leakage.

A guard tank surrounded the primary tank with an annulus between them which allowed for detection of sodium leakage. The guard tank was in turn surrounded by concrete shielding which acted as a final containment vessel. Were leakage to occur in both the primary and guard tank, the core would not be uncovered and would be adequately cooled.
Cutaway of the EBR-II Primary Tank
An inert gas (argon) filled the space between the tanks and their cover. Since there were penetrations through the cover for rotating machinery (pump shafts, fuel handling systems) and control rods, much attention was paid to seals to prevent ingress of oxygen which would result in formation of sodium-oxide. Sodium oxide as a deposit on this equipment would cause binding of the machinery and contamination of the sodium coolant with particulate. Much attention was paid to instrumentation for detection of oxygen ingress and remained a priority through the life of EBR-II operation.

Heat was removed from the primary sodium by three systems, 1) the secondary sodium loop which transfers heat to the steam generators, 2) thimbles immersed in the primary sodium and filled with sodium-potassium, which removed decay heat by natural convection, and 3) forced flow of air through the annulus between the primary tank and its guard tank, which also removed decay heat. Because decay heat removal did not depend on the secondary sodium loop, sodium in that loop could be drained to a storage tank for maintenance or in the event of a sodium leak. The secondary sodium loop was designed such that a severe reaction between sodium and steam would not endanger the reactor. The steam generators themselves were double-wall (a tube in a tube) to minimize the potential for leakage. The tube sheets were configured such that there was a plenum between the two tube sheets at each end which provided a path for sodium or steam to travel if one of the tubes were to fail, facilitating detection.
The EBR-II containment building was a domed cylinder designed to withstand a pressure of 24 psig. The design pressure was determined from analysis of a massive sodium fire, assuming that primary sodium was somehow sprayed as aerosol to containment (such an event is hypothetical). Interestingly, the extent of the fire is limited by available oxygen so a smaller containment is better, but its size must be great enough to allow for fuel handling, removal of major primary system components and other activities. The result was a rather large containment building. It was a welded steel structure lined with concrete to provide the ability to withstand high temperatures associated with a sodium fire in the building. The building was pressurized slightly to ensure cleanliness of the atmosphere in the building and all exhaust was through HEPA filters. Periodic pressure tests were conducted to verify leak-tightness.

One of the more unique aspects of the EBR-II containment was a fuel transfer tunnel that attached the building to an adjacent Fuel Cycle Facility. Spent fuel from EBR-II was transferred from the holding basket in the primary tank to a shielded cask which was then lowered through a hatch to the tunnel. The cask was then moved through this tunnel on rails where it was then mated with a transfer hatch at the Fuel Cycle Facility. Many thousands of transfers of fuel were made in this manner and during the first five years of operation, ~35,000 reprocessed fuel pins were returned to the reactor.

To facilitate fuel handling, a fuel storage basket was placed in the primary tank, capable of storing a large fraction of the core. Because the containment building and the primary tank of sodium were accessible during reactor operation, the storage basket would be pre-loaded with fresh fuel and when the reactor was shut down for refueling, fresh fuel would
be exchanged for spent fuel in the storage basket. This greatly facilitated core unloading/loading, which typically took 3 days. Spent fuel could then be transferred on a schedule determined by cooling requirements for decay heat generation.

The fuel handling system was one of the more complicated features of EBR-II design. Because fuel handling is done in the blind (sodium is opaque), the equipment had to be precise with many checks and interlocks to ensure that transfers were being made properly. The main fuel assembly gripper was a straight pull through a penetration in a rotating plug in the top of the primary tank cover. This plug was one of two, placed within a larger plug at an eccentric position which allowed positioning of the gripper over any core location. The control-rods also penetrated this smaller rotating plug which required that they be disconnected and withdrawn before rotation of the plugs. When a fuel assembly was withdrawn by the gripper, it was captured by a transfer arm which positioned the assembly above a desired location in the fuel-storage basket. The basket could be rotated, and then raised to accept the assembly, which was then detached from the transfer arm. The systems worked well, with a few exceptions as discussed in later in this report.

Sealing of penetrations to the atmosphere above the primary tank was given special attention in the EBR-II design. The large rotating plug, in particular represented a special challenge. To provide a seal while the plug was rotated, a dip ring was immersed in an alloy of tin-bismuth, which was heated until molten for rotation of the plug. When the plug was secured, the alloy was cooled, sealing the interface. This arrangement created many problems for operation and maintenance. Frequent manual cleaning of this trough was necessary to avoid sticking the rotating plug, which would have created serious problems for recovery.

The intermediate heat exchanger (sodium to sodium) was a conventional shell and tube design, with primary sodium flowing to the shell at the top and exiting at the bottom while the secondary sodium flowed in tubes from the bottom. An electromagnetic pump was immersed in the primary sodium, providing forced flow for a smooth transition from forced to convective primary flow in event of a loss of power to the primary pumps (a feature later determined to be unnecessary).

Purification of the sodium was accomplished by on-line cold traps which cooled sodium to the point that sodium-oxide would solidify and collect on stainless-steel wire mesh. Later, special graphite traps were added to clean the sodium of Cesium, a fission product associated with extensive run-beyond-cladding breach testing in EBR-II. Both systems worked well.

Sodium leak detectors were installed throughout the plant and were of two main types, smoke detectors and “spark-plug” type detectors that would sense the presence of liquid sodium. In the steam generator building, acoustic monitors and hydrogen detectors were installed to detect a sodium-water reaction. In the event of a sodium-water reaction, blow-out diaphragms and panels were installed to relieve pressure away from the reactor building, and fast actuating valves would dump the secondary sodium to a storage tank.
Control of the reactor required two operators, one controlling sodium-flow in the secondary system (to maintain a constant reactor inlet temperature) and the second operator controlling reactor power through control-rod movement. Primary coolant flow was held constant. (More on this later; it was found that the reactor would load follow easily, responding through reactivity feedback as inlet coolant temperature changed in response to changes in power demand. No operator action is required in such a case.)

**EBR-II Operating history**

EBR-II was extremely successful as a test reactor; arguably the most successful ever as measured by the scope of what was accomplished. The test programs successfully addressed issues of safety, operability, maintainability, security and sustainability. Although EBR-II operation was not without problems, major problems which occurred in other fast reactor systems were successfully addressed or avoided at EBR-II.

**Early EBR-II Milestones**

- Site Preparation Begins 5/1957
- All Construction and Component Installation Complete 12/1962
- Primary System Filled with Sodium 2/1963
- Approach to Power Begins 7/1964
- Reactor Operated at 30 MWe, T-G Synchronized with Site Loop 8/1964
- First Spent Fuel Reprocessed in FCF 9/1964
- Completed Demonstration of Fuel Cycle Closure Approximately 9/1969

35,000 Fuel Pins Recycled Back into EBR-II

- Reactor Power Increased to 62.5 MWt 9/1969

EBR-II was constructed and operated at the ANL-W site in Idaho. An important feature of this site was that all of the nuclear facilities needed for fast reactor development were co-located there, which created a synergism between testing programs and expertise that greatly benefited all. Besides the EBR-II reactor, there was the Fuel Cycle Facility which reprocessed EBR-II fuel, the Transient Reactor Test (TREAT), which subjected fuel to severe overpower transients as part of an extensive safety testing program, the Zero Power Physics Reactor (ZPPR), a large critical facility to mock-up fast reactor cores and conduct important physic measurements, the Hot Fuel Examination Facility (HFEF) for post-irradiation examination of fuel and materials, the Fuel Manufacturing Facility.
The mission of EBR-II went through four distinct phases. The first was as a complete power plant with co-located fuel reprocessing. The second was as an irradiation facility, testing fuels for following fast reactors, primarily oxide fuel for the Fast Flux Test Facility (FFTF) and the Clinch River Breeder Reactor Project (CRBRP). The third was as an operational safety testing facility, subjecting fuel and the plant to off normal conditions such as operation of fuel with breached cladding and ultimately, the reactor inherent-safety demonstration tests which subjected the reactor to anticipated transients without scram. The fourth was as the Integral Fast Reactor prototype, including demonstration of new reprocessing and recycle technology. There was actually a fifth phase, decommissioning, that yielded important information about the technology of sodium processing for disposal.
The power plant operated reliably for 30 years. Capacity factors approached 80% even with an aggressive testing program. Maintenance techniques were proven, with exposure to personnel less than 10% of that for a comparable Light Water Cooled Reactor (LWR). Effective sodium management was demonstrated, including successful suppression of a fire from a major sodium leak early in EBR-II’s operation. The steam generators operated quite well, with no failures or leaks in the systems, a testament to the duplex-tube design.
• High plant capacity factors were achieved
  – Capacity factors approached 80% even with an aggressive testing program

• Maintenance techniques were proven
  – Very low exposure to personnel, excellent safety record

• Sodium management demonstrated
  – Sodium leaks well managed

• Fuel reprocessing was demonstrated
  – 35,000 fuel pins reprocessed

Fuel reprocessing was also very successful, with over 35,000 fuel pins reprocessed and recycled to the reactor in the first five years of operation. This demonstrated the viability of remote casting of metallic fuel elements and non-aqueous reprocessing of spent fuel, using a simple melt refining process.

Several key features of design and characteristics of the system contributed to the excellent performance of EBR-II as a power plant. The first was the sodium coolant. Sodium is compatible with the reactor materials in the primary circuit, with no corrosion found after 35 years at temperature. Sodium also has a high boiling point (>1640°F at atmospheric pressure) that allows the primary and secondary systems to be low-pressure. Consequently, there was no potential for high-pressure ejection of coolant. This feature is important for maintenance activities and is a major reason that there were no injuries from sodium leakage over the course of EBR-II operation. Already mentioned was the low exposure to maintenance personnel.

The pool-type primary system also provided distinct advantages. Its large thermal capacity limited the severity of thermal transients and therefore stress on the primary tank and components submerged within it. The piped pool configuration allowed for the majority of the primary sodium to be at reactor inlet temperature, further increasing the capacity of the sodium to absorb heat in the event of an upset. All primary system components were submerged in this relatively cold pool of sodium, which proved to be beneficial for their operating reliability and ease of removal for maintenance or repair. It also minimized the potential for leakage of primary sodium, since all penetrations were through the top of the vessel. The only leakage encountered was in smaller systems, such as sodium sampling and purification, which were external to the primary tank and which contained small inventories of sodium.
Melt Refining Process

Major incidents in EBR-II operation

Early in operation of EBR-II (1968), a major sodium leak was experienced in the secondary sodium system. Nearly 100 gallons of hot sodium were spilled to the floor in the secondary sodium “control” room where sodium was sampled and purified. Repairs were taking place on a bellows-seal isolation valve in the secondary-sodium plugging loop, freezing the sodium in the line, cutting out a section and then re-welding the section into the original line. Unfortunately, the frozen sodium plug did not extend far enough beyond the removed section and when it was welded into the pipe, the sodium melted and spilled to the floor. A major fire erupted but was contained and extinguished by application of Metalex (a mixture of salts which cover the burning sodium and starve the fire of oxygen). Cleanup was accomplished in 13 days and there were no injuries. Fire-
fighting techniques were found to be effective. Maintenance procedures were changed and no further incidents of this type occurred. (Freezing sodium in a line, cutting out a section for repair and re-welding it was a common practice through the life of EBR-II. Such operations were conducted on small piping associated with sampling and purification systems. Large pipes, such as for the secondary sodium systems, were drained before work maintenance was conducted.)

The second major incident was damage to a fuel assembly during fuel handling in April of 1978, bending it so that it could not be removed from the fuel storage basket. Fuel handling in sodium must be done without visual reference and all operations are done remotely. When an attempt was made to engage the assembly upper adaptor with the fuel handling arm as part of the procedure to remove it from the storage basket, it was found that the upper adaptor was out of position and could not be engaged. A technique was developed for profiling the assembly by mechanical means, using the fuel handling equipment to characterize its position and configuration. Following this work, a mock-up of the storage basket, the deformed assembly and the fuel transfer system was constructed to develop the tools and procedures for removal of the assembly. Removal was accomplished in May of 1979 using a specially designed shaft and gripper that penetrated one of the nozzles in the cover of the primary tank. Reactor operation was not impacted and fuel handling from the storage tank proceeded normally for other assemblies located within it. The techniques developed and experience gained have proven valuable for fuel-handling system design and proved to be beneficial for the second incident associated with fuel handling at EBR-II. It was found that the damage occurred because the assembly had not been fully seated in the storage basket and when the storage basket was raised, the assembly contacted the lower shield plug of the primary tank cover.

On November 29, 1982 a fuel assembly was dropped over the EBR-II core as it was being transferred from the fuel-storage tank. The incident was discovered when no assembly was present for the exchange between the transfer arm and the core fuel assembly gripper. Extensive checks were made to verify that the assembly was not located in the storage basket or the transfer arm and then a search began to determine its location. The assembly had been dropped somewhere between the storage basket and the intended location in the core.

Care had been taken in design to provide extensive interlocks to ensure that movement of fuel handling equipment did not begin until assemblies were securely gripped, and manual operation of the transfer operation was such that checks could be made manually. However, in this instance the assembly had become disengaged from the transfer arm and fallen. It was found that the transfer arm and storage basket were misaligned, preventing the assembly upper adapter to be fully seated and locked before transfer.

Mechanical probes were used to locate the assembly and precisely identify its position. As before, a full-scale mockup was constructed and tools and procedures were developed to retrieve the assembly. The major retrieval tool was a stainless-steel cable extending as a loop beyond a stainless-steel tube which penetrated the top cover. (A number of spare nozzles had been provided through the cover in the original design, a decision which
proved to be very valuable). The loop was maneuvered into position manually and the noose pulled tight, snagging the assembly upper adaptor so it could be retrieved. (This process was aided not only by the ability of the operator to feel resistance but also by acoustic monitors installed in the tank which detected the sound from contact with equipment). The assembly was then moved to a position where it hung from the noose and could be engaged by the transfer arm; it was handled normally from that point. The total operation took less than a month and in this case, did require the reactor to be shut down. However, advantage was taken of the down time to conduct preventative maintenance normally scheduled for the spring shutdown, so the overall impact on reactor operation was minimized.

Over 40,000 fuel assembly transfers were made without incident in the 30 years of operation of EBR-II, so these incidents were certainly rare. However, mishaps during fuel handling can have a significant impact on reactor operation and every reasonable precaution needs to be taken to prevent them. Besides robust fuel handling systems and extensive interlocks, the EBR-II experience demonstrated the importance of operator tactile feel and acoustic monitoring for operation of the equipment. Much of the success for the EBR-II fuel handling experience, for example, was due to the fact that motion of the rotating transfer arm was manual, allowing the operator to verify through a “wiggle” test that the arm had successfully engaged the assembly before it was released by the core gripper. Under-sodium viewing technology is now available as another guard against fuel handling errors.

Another lesson learned from EBR-II operation was the importance of anticipating problems and providing design features to accommodate them. For example, in anticipation of an assembly falling from the transfer arm after it had cleared the core, a catch basket was provided that would funnel the assembly to a position where it could be easily retrieved. Spare nozzles had also been provided to support special operations in the primary tank. Of note, each of the primary pumps was removed for maintenance twice during the course of EBR-II operation, facilitated by designs and equipment that anticipated the need.

Mission II: Fast Reactor fuel Development

After the initial demonstration of EBR-II as a complete power plant, the reactor core was reconfigured to enhance its capability as an irradiation test facility for fuels development. The inner blanket surrounding the core was replaced with a stainless-steel reflector which increased the flux levels and provided a smaller flux gradient across the core. The irradiation testing mission was directed primarily at development of oxide fuel for FFTF and CRBR, but also important was improvement of the performance of EBR-II metal fuel. In addition, nitride and carbide fuels were tested, but not to the degree that oxide fuels were developed.
EBR-II metal driver fuel was significantly improved over the course of the 30 year operating life of the reactor. Early in the development of metal fuel, failures in the cladding were seen at burnups as low as 1%. The reason was that the fuel would swell against the cladding, exerting enough force to cause it to fail. The solution was quite simple; the gap was increased between the fuel pin and the cladding which allowed the fuel to swell until the fission gas was released from the pin, stopping the swelling. Fission gas was released at about 2 atom % burnup when the gas bubbles in the fuel would interconnect, creating a porous fuel structure that allowed the fission gas to be released. This interconnected porosity would then backfill with sodium further enhancing the thermal conductivity of the fuel and resulting in very low fuel-centerline temperatures. The second modification to the fuel pin design was to increase the gas-plenum volume to accommodate the fission gas that was released. With these design changes, burnups of in excess of 20 atom % were achieved. In fact the limit was not reached but it is likely to be related to filling of the fuel porosity with solid fission products sufficient to again initiate fuel swelling.

**EBR-II Metallic Fuel**

- EBR-II used a sodium bonded metallic fuel.
  - Highly enriched uranium in driver fuel (63-75% U-235).
  - Fuel rod immersed in sodium encased in a stainless-steel tube
  - Large plenum collected fission gas

Perhaps one of the most important aspects of metal fuel was its ease of fabrication. Metal fuel pins were produced in 100 pin lots by simple injection casting. Glass molds were lowered into molten fuel and then the system was pressurized, forcing fuel into the molds. The molds were removed, allowed to cool, the molds removed and then the pins were cut to length. They were then placed into the cladding tubes which contained a small amount of molten sodium as a thermal bond and a cap was then welded to close the
tube. This process produced ~150,000 fuel pins and was carried out both at the EBR-II Fuel Manufacturing Facility (FMF) and by commercial vendors. It was also accomplished remotely and because of its simplicity was done without difficulty.
Metal Fuel after Casting

In addition to metal fuel development for EBR-II, eight full-sized assemblies (1800 pins) of metal fuel were irradiated to high burn-up in FFTF without failure. This work was done as part of a plan to convert the FFTF core from oxide fuel to metal, but the reactor was shut down before the conversion could be accomplished. Those assemblies have been returned to the HFEF at the INL where they are available for examination.

Minor Actinide Fuel Has Been Fabricated and Irradiated

- Three full length pins containing minor actinides were successfully fabricated and irradiated to 6% burnup.
- As-fabricated composition was: 68.2%U, 20.2%Pu, 9.1%Zr, 1.2%Am, and 1.3%Np.
- Approximately 40% of the initial Am was lost during casting due primarily to volatile impurities of Pu-Am feedstock (3 at% Ca and 2,000 ppm Mg).
- Judicious selection of the cover gas pressure during the melt preparation and the mold vacuum level during casting is expected reduce the Am loss by ~200 times.

A full range of metal fuel compositions was tested, including uranium-zirconium and uranium-zirconium plutonium mixtures, with and without additions of minor actinides. Peak cladding temperatures reached 620 degrees C with maximum in-reactor exposures to 5 years. An important conclusion is the metal is a versatile and “forgiving” fuel design, able to accommodate a wide range of compositions.

Excellent Steady-State Irradiation Performance

- Over 40,000 EBR-II Mark-II (75% smear density U-Fs) driver fuel pins have been successfully irradiated through early 1980’s.
- When IFR Program was initiated in 1984, 10% Zr replaced 5% fissium, and a total of 16,800 U-Zr and 660 U-Pu-Zr fuel pins have been irradiated in the next 10 years. U-Pu-Zr fuel reached peak burnup of ~20%.
- In addition, 8 full metal fuel assemblies have been irradiated in FFTF. Lead test achieved peak burnup of 16%. One assembly contained U-Pu-Zr, which achieved peak burnup of 10%.
As noted earlier, oxide fuel was also demonstrated to be viable, operating to high burnup and achieving the smear densities and power ratings desired. (Details of oxide fuel development and experience will be given by other authors). The major difference is approach to reactor safety. Metal fuel provides a large degree of self-protection in response to off normal events; oxide fuel does not as explained in the following discussion.

When the FFTF began operation, taking on a major role in irradiation-testing of fuels and materials, EBR-II was able to conduct more aggressive operational-safety tests. These involved integral plant-safety tests as well as fuel-safety tests. The interest for fuel was its performance with breached cladding under both steady state and transient over-power conditions. A particular concern for oxide fuel is formation of sodium-oxide as a reaction product with the sodium once fuel is exposed to the coolant. Sodium-oxide is less dense than the fuel and can tend to split the cladding, causing progressive failure. The EBR-II program of run-beyond-clad breach testing supported the safety case for oxide fuel for both the MONJU reactor in Japan and the CRBRP reactor in the US. The testing was extensive and included operational transients in EBR-II as well as more aggressive tests in TREAT. The result of this work was data which demonstrated the safety of continued operation of oxide fuel with breached cladding, forming the safety basis for MONJU.

The question also arose about the performance of metal fuel with breached cladding, since testing of oxide fuel in the reactor would mask failure of cladding for metal fuel. The EBR-II driver fuel had to be qualified to operate safely for extended periods with breached cladding. Metal fuel has an advantage in that it is chemically compatible with the sodium. (Sodium is used in the fuel pin to enhance thermal conductivity between the metal fuel and the cladding). Extensive tests, including both steady state and transient over-power conditions, demonstrated that metal fuel was completely compatible with the sodium coolant and a breach in cladding would not “grow”. The safety case was made that breached cladding in metal fuel could be safely accommodated; no fuel loss would be expected.

A modification made to EBR-II to accommodate fission-gas release was installation of the cover-gas cleanup system which captured the noble gases, Xe and Kr. (Chemically active fission products, like Cs and I were captured in the sodium and subsequently cleaned by the sodium-cleanup systems). The cover-gas cleanup system used cryogenic cooling to capture these gases in an activated charcoal bed, working very well over the remaining life of the plant.

The most dramatic of the safety tests were those involving the whole plant, leading to the inherent safety demonstration tests conducted in April of 1986. The EBR-II plant was subjected to all of the Anticipated Transients without Scram (ATWS) events without damage, demonstrating the self protecting characteristics of a metal-fueled fast reactor.

The first of these was loss of all pumping power with failure to scram, simulating a station blackout with failure to scram. The reactor was brought to 100 % power and the pumps were turned off, allowing them to coast-down and coolant flow to transition from forced to natural-convective flow. Testing and analysis over the previous 4 years had been conducted to accurately model the reactor for this event, and the system responded as expected. Special in-core temperature monitoring had been provided as a safety system to scram the reactor if temperatures rose to unexpectedly high levels, but they did not.
Temperatures initially rose rapidly as the cooling flow decayed, but the increase in temperature introduced sufficient negative reactivity feedback that the power was also reduced rapidly, resulting in peak core coolant temperatures that were higher than for normal operation (~1300 degrees F vs. 890 degrees F at normal operation) but not high enough to damage the fuel. There was also significant margin to sodium boiling temperature, which would occur at ~1640 degrees F. The system power came down rapidly, reducing peak core temperature until they equilibrated at an average temperature very close to that at normal operation.

A point to be emphasized is that there was no fuel or core damage with this event, unlike what would occur in a conventional reactor system. In fact, this was the 45th test of ATWS events on this core and the reactor was restarted for a subsequent test that same afternoon.

**Key Contributors to Inherent Passive Safety**

- Large margin to sodium boiling temperature.
- Pool design provides thermal inertia.
- Low stored Doppler reactivity due to high thermal conductivity (hence, low temperature) of metal fuel.
- Hence, the inherent passive safety characteristics are achieved only in the IFR-type fast reactors.
TEST 45, Loss of Flow without Scram from 100% Power

Key Steps in Test:

• Establish 100% power
• Insert special SCRAM protection for the test
• Bypass loss-of-flow SCRAMs
• Turn off the pumps
The second test subjected the reactor to loss-of-heat-sink without scram. The reactor was brought to 100 % power and flow was stopped in the secondary heat transfer system, blocking the transfer of heat to the steam generators. As the reactor inlet temperature rose, negative reactivity feedback reduced power such that the temperature difference across the core was reduced; peak coolant temperature never increased. The reactor temperatures equilibrated at an average temperature very close to that at normal operation.

Loss of Heat Sink without Scram from 100% Power

Key Steps in the Test:

• Establish 100% power
• Stop all flow in the intermediate sodium loop

Monitor the passive power reduction and the leveling of tank temperature
This behavior results because of the very strong negative feedback associated with neutron leakage as the coolant temperature increases and the lack of a strong positive reactivity feedback from Doppler as fuel centerline temperature falls. Metal fuel operates with a very low centerline temperature and therefore little Doppler feedback reactivity. For loss of cooling or loss of heat sink events, coolant temperature rises, power falls and if one has a high Doppler coefficient of reactivity in the system (such as for oxide fuel), the positive reactivity feedback will delay power reduction with the result that the sodium will boil. Boiling sodium will insert significant positive reactivity, likely leading to a severe overpower transient. For this reason, a metal fuel core is self-protecting against undercooling events while an oxide-fuel core is not.

![Diagram of Oxide Core vs. Metal Core](image)

It was earlier thought that a high Doppler coefficient of reactivity was important to protect against severe overpower events, so tests were done in TREAT with metal fuel to determine its performance under such conditions. Many metal fuel pins from EBR-II were subjected to severe over-power events which took the pins to failure. It was found that the relatively low melting temperature of the fuel was important, since it softened and then flowed like toothpaste in a tube before breaching the cladding. This flow of fuel occurred rapidly and would be effective in introducing large negative feedback on severe transients, acting as an effective self-protecting mechanism. Also, metal fuel cladding failures typically occurred at 4 times nominal power, higher power than typical for oxide fuel which typically fails at 3 times nominal power.
Further tests were conducted to determine the load-following characteristics of the reactor, which are very good. Metal fuel is not adversely affected by cyclic changes in power and temperature, which coupled with its strong tendency to maintain a constant average core temperature, greatly facilitates its ability to load follow. EBR-II could be easily controlled by fixing control-rod position and controlling power demand at the steam turbine. A full range of safety and load following tests were conducted, including for example, rapid run-up of the primary pumps to their maximum capacity which would cool the core, insert positive reactivity and raise power level. No damage occurred to the fuel or core through all of these tests.

A level-1 Probabilistic Risk Assessment (PRA) was completed to quantify these results. It was shown that risks associated with EBR-II operation were substantially lower than typical LWR plants, an order of magnitude less. The EBR-II risks would have been lower still except for its seismic response. (Subsequent plants employ seismic isolation to mitigate even this risk). An important result from this work was that acts of commission (purposely disconnecting a pump, etc) would not lead to core damage.

**Transient Overpower Tests to Failure in TREAT**

![Graph showing power normalized to nominal peak over time](image)
Axial Movement of Metal Fuel before Pin Breach

Mission IV: the Integral Fast Reactor (IFR)

With all that was learned through mission III of EBR-II operation, the results were integrated into an approach to fast-reactor design termed the Integral Fast Reactor (IFR). A new feature of the approach was a reprocessing technology that accommodated fuel containing actinides and that offered proliferation resistance. The Fuel Cycle Facility (FCF) was refurbished and equipment was installed to conduct the work. The heart of the process is an electro-refiner into which the chopped EBR-II spent fuel was placed. The potassium/lithium chloride salt in the electro-refiner was maintained at 500 °C, into which the fuel dissolved leaving the cladding hulls behind. The anode for the electro-refiner was the fuel basket from which the fuel was dissolved and two types of cathodes were employed, a solid cathode upon which uranium was deposited and a liquid-cadmium cathode within which a mixture of uranium and transuranics were deposited. The reason that the system offers proliferation resistance is that it is virtually impossible to cleanly separate Pu. Through a quirk of nature, the free energies of Pu and the minor actinides in
the salt are so closely aligned that it is virtually impossible to adjust electro-refiner voltages to distinguish between them for transport of material.

The Electro-refiner for reprocessing EBR-II Spent Fuel
Uranium Collected on the Electro-refiner Cathode

Spent fuel was first chopped and then loaded into the anode basket. Uranium was then electro-transported to a solid cathode. Subsequently, Pu and a mixture of minor actinides were transported to a liquid-cadmium cathode. From there, material was taken to a cathode processor where clinging salt was distilled from the product, to be returned to the electro-refiner. The fuel product was then consolidated into an ingot for subsequent casting into fuel.
An important aspect of the fuel cycle was the production of waste forms suitable for geologic storage. One was ceramic and the other metallic. To produce the ceramic waste form the electro-refiner, salt was cleaned of active fission products by flowing it over a zeolite bed, which was then consolidated into a ceramic waste-form after the addition of glass frit. To form the metallic waste-form, the cladding hulls and noble metals were recovered from the anode basket and the bottom of the electro-refiner and cast into a metal ingot. Extensive leach tests were conducted on these waste-forms which were qualified for long-term geologic disposal. Because the waste could be free of actinides, required storage times are on the order of hundreds, not thousands of years.

This work was overseen by a special committee of the National Academy of Sciences which issued a final report supportive of the technology.

<table>
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<th>Elements that remain in salt (very stable chlorides)</th>
<th>Elements that can be electrotransported efficiently</th>
<th>Elements that remain as metals (less stable chlorides)</th>
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EBR-II Spent Fuel Treatment Flowsheet

Element Chopper

Electrorefiner

Cathode Processor

Casting Furnace

Depleted Uranium

Uranium Product

Cladding + Noble Metal + Fission Products

Salt with TRU + Fission Products + NaCl

Zeolite + Glass

Salt/Zeolite Blending

Zirconium

Metal Waste Furnace

Ceramic Waste

Ceramic Waste Form

Metal Waste Form
Relative Storage times of Nuclear Waste with and without Actinides
Decommissioning of EBR-II

The first phase of decommissioning involved the removal of all fuel and blanket assemblies, 637 in all. This involved cleaning each assembly of sodium and transfer to a hot-cell facility for disassembly and repackaging, then transfer to interim storage. As a final step, EBR-II fuel is being reprocessed for recovery of uranium and production of waste forms suitable for geologic storage, as described previously. Defueling was accomplished over 14 months without difficulty.

The next phase concentrated on the technology for dealing with sodium coolant to produce a waste-form suitable for land-fill disposal. It was also important that residual sodium left in the coolant systems after draining be fully reacted so as not to pose a long-term hazard. The 89,000 gallons of primary sodium was thoroughly cleaned of fission products (especially Cs137) and sodium oxide. It was then transferred to a sodium process facility where it was reacted with water to produce sodium hydroxide at a concentration of 73% by weight. The sodium hydroxide at this concentration is a solid product that could be stored in drums at a DOE land-fill. In addition to the EBR-II sodium, sodium drained from the Fermi-1 reactor was reacted and disposed of in this manner.

One of the more interesting challenges was passivating the residual sodium that remained in the primary system in order to place the system in a radiologically and industrially safe condition. After a number of laboratory tests, a solution was found. Moist CO2 was introduced to the primary system at a controlled rate, monitoring the reaction rate through the evolution of hydrogen. A question for this process was that since pools of sodium form a “scab” at the surface, whether the reaction would continue. It was found that over time, the CO2 would permeate this surface layer and the reaction would continue to completion, although the process could take several years. The volume of residual sodium has now been reduced to a point that it would be safe to flood the primary tank with water.

An important observation after the sodium was drained from the primary tank was that the condition of the tank and the components submerged in sodium was pristine. There was absolutely no corrosion of the stainless steel after 35 years in contact with hot sodium.

Lessons Learned

The extensive program of operation and testing at EBR-II has established sodium-cooled fast reactors as a viable technology to support a nuclear renaissance. The ability of fast-reactors to manage nuclear materials for waste and fuel has been demonstrated, along with advantages for safety, operability and reliability. Cost remains the major issue but
there are opportunities for significant cost reductions by taking advantage of the self protecting nature of the reactor system to simplify design. The major conclusions are that

- A pool-type, metal-fueled LMR nuclear generating station can be reliably operated and maintained with large margins of safety to workers and the public.
- Sodium system maintenance is straightforward and safe, facilitated by low pressure in operating systems.
- Sodium-spills and fires are manageable, principally because of lack of high pressure driving fluid; no personnel injuries have been associated with leaking sodium systems.
- Sodium is highly compatible with reactor materials, facilitating long life.
- Attention must be given to maintaining purity of the inert gas covering sodium systems to avoid sodium-oxide buildup on systems penetrating the interface.
- Personnel radiation exposure levels are very low, typically <10% of those for LWR systems.
- A metal-fueled LMR nuclear generating station can be passively safe, offering self protection against anticipated transients even without safety-system action.
- Safety benefits have been quantified by PRA, which demonstrates very low levels of risks.
- Metal-fuel offers exceptional benefits for reprocessing and recycle, conversion, load following, passive safety and benign behavior in degraded condition.
- Fuel handling systems require much design, operating and maintenance attention to ensure reliability.

References

8. “Extending the Operating Lifetime of EBR-II to 30 Years and Beyond”, R. W. King, et.al., ANL/EBR-127, Feb. 1985