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THE INTEGRAL FAST REACTOR

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SUMMARY

On April 3rd, 1986, two dramatic demonstrations of the inherent capability of sodium-cooled fast reactors to survive unprotected loss of cooling accidents were carried out on the experimental sodium-cooled power reactor, EBR-II, on the Idaho site of Argonne National Laboratory. Transients potentially of the most serious kind, one an unprotected loss of flow, the other an unprotected loss of heat sink, both initiated from full power. In both cases the reactor quietly shut itself down, without damage of any kind. The contrast between the consequences of these events in EBR-II and the Chernobyl events just twenty-three days later thrust EBR-II, and the underlying Integral Fast Reactor development program at Argonne, into the national news.

These tests were a part of the on-going development program at Argonne to develop an advanced reactor with significant new inherent safety characteristics. Called the Integral Fast Reactor, or IFR, the basic thrust is to develop everything that is needed for a complete nuclear power system — reactor, closed fuel cycle, and waste processing — as a single optimized entity, and, for simplicity in concept, as an integral part of a single plant. The particular selection of reactor materials emphasizes inherent safety characteristics also makes possible a simplified closed fuel cycle and waste process improvements.

Inherent safety comes down to reactor transient behavior, caused by imbalances between power and cooling capability, in the absence of control actions. Temperatures must stay below critical levels in the initial self-limiting transient, and also below a (lower) long-term limit set by core component life, both in the absence of scrams. In developing a concept, reactor size is likely to be set by economics and the requirements of the specific application, and indifference to reactor size in the inherent safety characteristics will be a useful trait.

As is likely to be true for any reactor type, the particular choice of materials for just a few elements of the IFR system — the two most important are the materials selected for the fuel and for the coolant — largely determines the characteristics that are possible. The question then becomes one of degree: The extent to which the potentially beneficial properties are explicitly recognized and exploited. Much can be done with the IFR selection. The materials are all metals, compatible with each other. The fuel is a metallic alloy, the coolant liquid metallic sodium. Liquid sodium allows a primary system that operates at atmospheric pressure. Without the need to contain high pressures, the reactor vessel can be sized to allow a pool configuration. The pool provides significant thermal inertia. In turn, the metallic fuel provides high thermal conductivity with only a shallow temperature profile across the fuel element and allows power to drop sharply when negative reactivity is introduced by core thermal expansion. This combination is the fundamental basis of the invulnerability of the IFR to unprotected loss-of-cooling events.

Going further, the metallic fuel form in turn allows radically new and simple metallurgical processes for reconstituting spent fuel. And it allows very simple fuel fabrication. Waste volumes are also reduced and can be put in final form in-plant.

The paper describes the IFR concept, the inherent safety tests, and status of IFR development today.

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BASIS OF THE IFR CONCEPT

The Integral Fast Reactor (IFR) is an innovative liquid metal reactor concept being developed at Argonne National Laboratory. It seeks to specifically exploit the inherent properties of liquid metal cooling and metallic fuel in a way that leads to substantial improvements in the characteristics of the complete reactor system. The IFR concept consists of four technical features: (1) liquid sodium cooling, (2) pool-type reactor configuration, (3) metallic fuel, and (4) an integral fuel cycle, based on pyrometallurgical processing and injection-cast fuel fabrication, with the fuel cycle facility collocated with the reactor, if so desired.

The single most significant property of liquid metal cooling is that it allows an atmospheric-pressure primary system. There is ample margin between the boiling temperature of sodium (~900°C) and the coolant operating temperatures (typically 350°C inlet and 510°C outlet). The thick-walled pressure vessels that are needed to contain the high pressures in water cooled systems are unnecessary here. This in turn allows a pool configuration with its accompanying large thermal inertia. To fully capitalize on the potential advantage offered by these properties requires complementary selection of fuel material.

Metallic fuel is the choice. It provides the critically important property of high thermal conductivity. This gives a low-temperature fuel, and one which has negligible positive reactivity feedback on power reduction. This latter property is the essential element in the ability to survive certain classes of potentially very serious accidents. It is the combination of large coolant thermal inertia and negligible positive feedback on power reduction that gives the concept a range of very important inherent safety characteristics. Accumulating evidence from relatively recent theoretical and experimental investigations indicate that the safety characteristics of liquid metal cooled reactors with metallic fuel are in all cases equal or superior to those with oxide fuel.[1-2]

Once the decision is made to adopt metallic fuel, few-step compact metallurgical processing and few-step simple casting fabrication become possible. These radical changes also provide potential for real economic breakthroughs in the fuel cycle. Superior neutronics follow automatically and can also be utilized in a number of ways to improve the system. Excellent breeding characteristics are axiomatic with this fuel type, and can be exploited whenever it is felt desirable to do so, now or in the future.

Much of the technology for the IFR is based on EBR-II experience. EBR-II was the first pool-type liquid metal reactor. Metallic fuel was developed as the driver fuel in EBR-II. During 1964-1969, about 35,000 fuel pins were reprocessed and refabricated in the EBR-II Fuel Cycle Facility, which was based on an *early* pyroprocess with some characteristics similar to that *now proposed* for the IFR. A schematic of EBR-II Reactor and Fuel Cycle Facility is shown in Fig. 1.

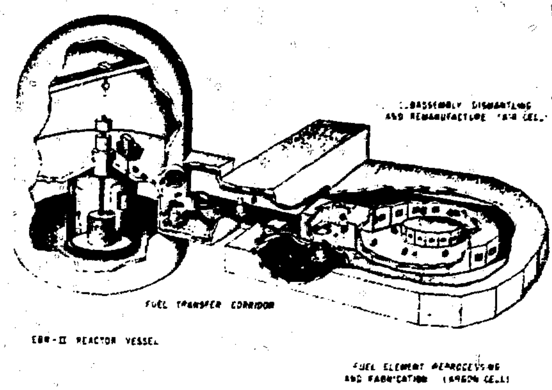

Fig. 1. EBR-II Reactor and Fuel Cycle Facility.

Only in recent years have developments in metallic fuel taken place that now make the metallic fuel-based IFR a promising development choice.[3-5] Even with its potential fuel cycle advantages, metallic fuel was thought to be unacceptable for many years because of its poor irradiation behavior in the 1950's and early 1960's. Discoveries at EBR-II in the late 1960's and design developments and irradiation experience in the 1970's have totally changed this picture. Generic metallic fuel can be designed now for very superior irradiation performance. Over twenty thousand older-design EBR-II fuel pins achieved their 80,000 MWd/T design burnup without any failures. With simple design changes the new EBR-II fuel has a design burnup of 140,000 MWd/T. The evolution of burnup limit for the EBR-II driver fuel is shown in Fig. 2. This figure actually gives the operating limits on the fuel allowed at various times in the past, not what was possible to end-of-life. In fact over 2,500 pins actually achieved burnups greater than 100,000 MWd/T, and one full assembly of 30 pins achieved 185,000 MWd/T. (See Fig. 3.)

Further, very recent metallurgical processing discoveries and developments have radically altered both the pyroprocess itself and the outlook for major breakthroughs in both fuel and blanket processing.[6-8] Pyroprocessing was not promising enough for scale-up in the early EBR-II melt-refining pyroprocess. Losses were several percent, the product fuel still contained all the noble metal fission products,

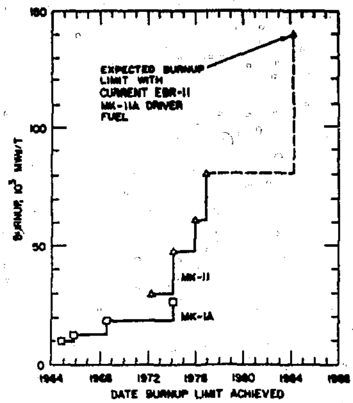

Fig. 2. Evolution of EBR-II Driver Fuel Burnup Capability.

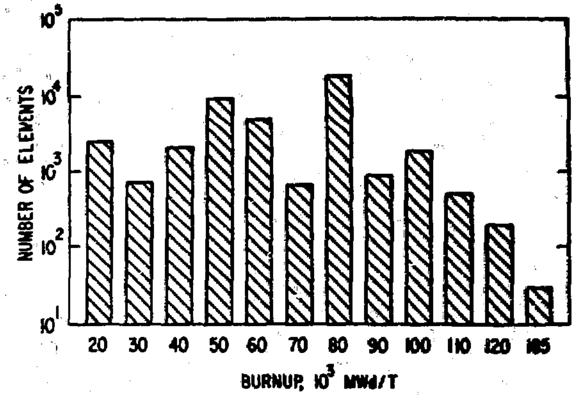

Fig. 3. EBR-II Mark-II Driver Fuel Burnup History.

and blanket material was not processed. The new IFR process replaces melt-refining with a new electrorefining process. Electrorefining, using a liquid cadmium anode and a fused chloride salt, extracts the fuel uranium-plutonium mixture from the dissolved mixture of fuel, steel, and fission products. This is done at temperatures around 500°C with low losses in the single step.

Finally, very recent fabrication developments have simplified metallic fuel fabrication even further. EBR-II fabricates its own fuel. Until recently an alloy preparation step was required in addition to the casting step (which produces about 100 pins at a time). IFR-related developments now allow both to be done in a single step.

PASSIVE OR INHERENT SAFETY

The TMI-2 accident gave impetus to thought about the desirability of reactor characteristics that in-and-of-themselves could make reactors more invulnerable to events that would normally initiate serious accidents. The term "inherent safety" has come into use as an encapsulation of these general ideas. It is also a controversial term. It can be taken to imply both an unwarranted absoluteness and an unwarranted exclusiveness. Clearly, however, a given reactor can possess inherently safe characteristics that unarguably are very important, without implying an absoluteness that covers all possible situations and also without implying that these characteristics are necessarily limited to one reactor type. The IFR reactor concept possesses inherent characteristics that enable it to respond benignly to specific accident-initiating events without control or safety system intervention. And these specific accident-initiating events are a very important class of such events. They are the failures of major mechanical systems that under normal conditions cool the reactor and keep it within safe temperature limits.

In the public mind, the TMI-2 accident called into question the fundamental safety of nuclear power to an unprecedented degree. The consequences of failure of mechanical systems and less-than-optimal operator actions were dramatically played out on national television for many days, and continued to be news for months and years afterward. Chernobyl, even more, has intensified and solidified public concern. At bottom, the public knows instinctively that sooner or later mechanical systems fail, and operators make mistakes. Reactors must be demonstrably able to survive these events. Their nuclear safety should not hinge completely on proper operation of mechanical systems or even on reliable judgments of plant operators.

To the maximum extent then, they should be foolproof. In the end, no such absolute, philosophically at least, is possible. But as a direction that advanced reactor development must take, if nuclear power is to supply a large fraction of world energy needs, this goal is undoubtedly correct.

Metallic fuel promises a higher degree of inherent safety than the conventional oxide fuel, and, as has been mentioned, better or equal safety characteristics across the entire spectrum from normal behavior to postulated severe accidents.

Although the metallic fuel melting temperature is much lower than that of oxide fuel, it is also much more difficult to raise the fuel temperature because of the high thermal conductivity (~20 w/m°C for metal vs. ~2 w/m°C for oxide). As a result, operating margins in terms of power can in fact be greater for metal than for oxide cores. Typical metal core design parameters are presented in Table I. The TREAT experiments performed to date[9] indicate that the margin to fuel pin failure during transient overpower conditions is greater for metal than oxide fuel. However, it is in the inherent safety characteristics under the generic anticipated-transient-without scram (ATWS) events, such as loss-of-flow without scram (LOFWS), loss-of-heat-sink without scram (LOHSWS), and transient overpower without scram (TOPWS), that the metallic fuel shows its greatest advantages over oxide fuel.

Table I. Typical Metal Core Design Parameters

Fuel Materials	U-Pu-10% Zr, U-10% Zr
Fuel Smear Density	75%
Pin Diameter	0.3 in. (7.6 mm)
Cladding Thickness	0.018 in. (0.46 mm)
Peak Linear Power	15 kW/ft (490 w/cm)
Peak Discharge Burnup	150 MWd/kg

In an LOFWS event, the coolant temperatures increase as flow reduces rapidly. The increased coolant temperature results in the thermal expansion of core assemblies, which provides a negative reactivity feedback and starts a power rundown. During this initial period, it is important to maintain a reasonable flow coastdown in order to avoid immediate sodium boiling. This requirement can be met with normal mechanical pump inertia, characterized by a flow halving time of the order of 5 seconds.

The characteristics of the negative reactivity feedback caused by the coolant temperature increase determines the reactor response. The most important factor differentiating the LOFWS and LOHSWS responses in metal and oxide fuels is the difference in stored Doppler reactivity between the two fuels. As the power is reduced, the stored Doppler reactivity comes back as a positive contribution tending to cancel the negative feedback due to the coolant temperature rise. The high thermal conductivity of the metallic fuel and consequent low fuel operating temperatures give a stored Doppler reactivity that is only a small fraction of overall negative reactivity feedback. As a result, the power is reduced rapidly. In contrast, oxide fuel has a much greater stored Doppler reactivity (primarily due to the higher fuel temperatures rather than the difference in the Doppler coefficient itself), and the power does not decrease rapidly during the unprotected LOF or LOHS. And when the power has been reduced to decay power levels, in order to counter the stored Doppler reactivity, the coolant temperature maintains a much higher value in an oxide core. A typical comparison of LOFWS between the metal and oxide is illustrated in Fig. 4. Both the LOFWS and LOHSWS accidents are perfectly benign in a properly designed IFR.

The superior neutronics performance characteristics of metallic fuel allows core designs with minimum burnup reactivity swing even for small modular core designs. Advantage can be taken of this in reducing the TOPWS initiator caused by an unprotected control rod

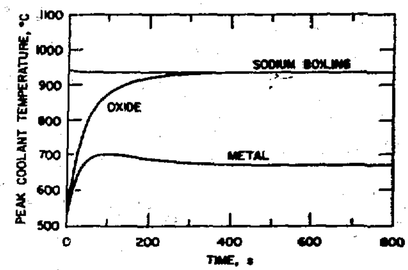

Fig. 4. Loss-of-Flow Without Scram for Large Reactors (1350 MWe).

runout. In addition, TREAT tests performed to date have demonstrated, first, a larger margin to cladding failure threshold for the metallic fuel, and second, that fission gas driven axial expansion of fuel within the clad before failure provides an intrinsic and favorable negative reactivity feedback in the metal fuel that has no parallel in oxide. Thus there are a number of factors that suggest that metallic cores can be designed for benign TOP responses.

It is worth stressing again that the sharply improved performance characteristics of the metallic cores for the unprotected LOF, LOHS, and TOP events are directly traceable to the basic properties of the fuel, and not to engineered features of any kind. Designs must simply take advantage of these properties.

On April 3rd, two safety tests of historic importance were conducted on EBR-II. Their purpose was to show that reactors of the IFR type are extraordinarily and inherently safe. Within hours of each other, two potentially very severe accident situations were initiated while the reactor was operating at full power. In both events the plant simply shut itself down, harmlessly, without any action on the part of the plant operators or any action by the normal plant protection systems. And after each event, the reactor was left ready to be restored to full power operation in normal fashion. The possibility of reaching this level of invulnerability was undreamed-of even a few years ago.

These accident simulations dramatically demonstrated the powerful safety attributes provided by the IFR combination of liquid sodium cooling, pool reactor configuration, and metallic reactor fuel. The EBR-II behavior is completely prototypical of IFRs in general. That is really the central point: The tests demonstrated not only that EBR-II is unharmed by such accidents, but more than that, they demonstrated that no properly designed IFR of any size would be either.

The first accident sequence, conducted in the morning of April 3rd, was a direct simulation of the classical postulated loss-of-flow without scram accident. With the plant operating at full power and with the plant protection system disabled, power to the primary, secondary and auxiliary pumps was turned off, just as though all off-site power had been lost ("station backout"). In effect the reactor continued to run in the absence of all forced cooling. Core coolant temperatures rose, generating negative reactivity which drove the power level close to zero without the assistance of any engineered safety features or operator action. After a brief rise, the coolant temperature returned to normal values, stabilized, and the reactor would have remained in this stable safe condition essentially forever. In fact the test was terminated after the stable condition had been established to prepare for the second accident simulation that afternoon.

The afternoon test was also a direct simulation of a classical postulated serious accident, this one of total loss-of-heat-sink without scram. In this test the reactor was returned to full power (five hours after the first test), the plant protection system again was disabled, and power to the secondary pumping system was turned off. (In some respects this test simulates the sequence of events that led to the TMI accident.) Since heat rejection capability no longer existed, inlet core coolant temperatures rose and again self-generated negative reactivity feedback drove the power to zero. The result was almost a non-event; the outlet coolant temperature actually decreased continuously to a stable value less than the original operating temperature. Again, a safe stable condition was reached in a few minutes. At no time in either event did the coolant come close to boiling, nor did any fuel approach the point of failure.

These tests were witnessed by about 60 representatives of the nuclear industry, electric utilities, and U.S. and foreign governments. The tests were spectacular demonstrations, or confirmations, of the invulnerability of the IFR to the two most plausible serious mechanical failures that could be postulated to happen in a nuclear power plant. In the simplest terms these accidents were forced to occur, and the result was completely harmless. The coolant temperature responses during these two tests are presented in Figs. 5 and 6. More detailed data can be found in a collection of papers prepared for these tests.[10-17]

The overall objective of the IFR safety program is to provide the data to validate the unique inherent safety features of the IFR and to fully characterize the totality of safety features associated with metallic fuel. This involves detailed analysis, calculational modeling, TREAT in-pile tests, out-of-pile experiments, and full-plant tests in EBR-II.

Rapid progress has been made in the metallic fuel transient behavior modeling, experiments and analyses aimed at quantifying the sharply improved inherent safety characteristics of the IFR under the generic anticipated-transient-without-scram (ATWS) events. The analytical predictions are currently being validated through the series of EBR-II tests demonstrating inherent passive shutdown capability, the most spectacular of which were described above.

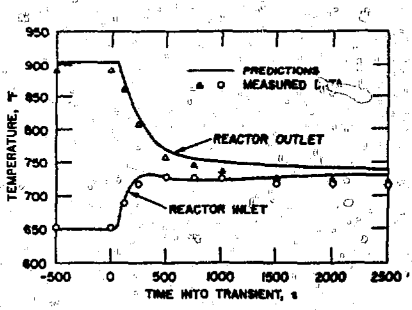

Fig. 5. Loss-of-Flow Without Scram Test in EBR-II.

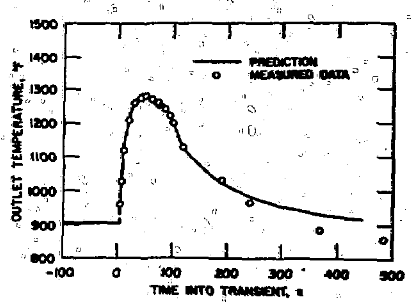

Fig. 6. Loss-of-Heat-Sink Without Scram Test in EBR-II.

The metal fuel characteristic of fission gases entrapped *within the fuel alloy* matrix itself providing a self-dispersive mechanism in the termination of transient overpower accidents has been experimentally established. TREAT tests have demonstrated, first, a large margin to cladding failure threshold, second, that the fission-gas driven axial expansion of fuel within the clad does take place that provides intrinsic negative reactivity feedback before the fuel clad itself fails, and third, that this latter effect is large enough to give a substantial reduction in reactivity in over-power accidents before fuel failure.

Metallic fuel inherent safety characteristics under generic ATWS events therefore reduces the core disruption probability to an exceptionally low value. But furthermore, metallic fuel disruption characteristics are *also* superior to those of oxide fuel. Initial out-of-pile experiments indicate that no fuel-coolant-interaction (FCI) events occurred when molten fuel contacted flowing sodium. These results, along with physical arguments ruling out extremely high molten fuel temperatures, support the case for the exclusion of significant fuel coolant interactions. The absence of FCI events when molten fuel contacted sodium is in contrast to typical results with oxide fuel where FCI events are observed and, while not *energetic*, can void the channel of sodium. Also, out-of-pile tests showed that metallic fuel debris beds were characteristically in the form of large *filaments* and sheets, and thus are more coolable than comparable oxide beds.

FUEL CYCLE DEVELOPMENT STATUS

In addition to the inherent safety characteristics, several aspects of the IFR concept require further proof, and development programs on each are underway at Argonne. Demonstration of the performance of the IFR U-Pu-Zr ternary alloy metallic fuel and development of the new pyroprocesses of electrorefining and halide slagging, are the most important. Development in both areas, initiated in the latter part of FY 1984, is proceeding rapidly. Results from experimental, analytical, design and hardware programs are accumulating daily.

Fuel Performance Demonstration

The basic physical properties of the IFR fuel and the fuel/cladding interactions over a range of conditions, compositions, and temperatures have to be better established. This work is proceeding across the board. Out-of-reactor experiments to establish the compatibility of the IFR fuel with advanced cladding materials, to characterize the distribution of the alloy elements within the fuel, to measure the thermal and physical *properties of the fuel*, and to *validate* calculational methods of modeling the fuel behavior, are all underway.

A major objective is to expand the IFR U-Pu-Zr fuel irradiation data base to provide a technical bridge between this alloy and the extensive data base already in hand for the similar, but not identical, EBR-II metallic fuel. Lead irradiation test assemblies in EBR-II with U-Pu-Zr fuel have reached burnups in excess *of* 100,000 MWd/T as of January 1987, and are continuing their irradiation to cladding breach, which is expected at burnups higher than 140,000 MWd/T. (The burnup limit is expected to be set by fission gas pressure buildup, and therefore by the particular plenum volume selected for this first fuel.) Interim postirradiation examinations have been performed at various burnup levels. No failures have been seen, nor has any reason been seen to expect other than goal performance.

Fabrication technology is also progressing, largely as a result of the need to cast pins for irradiation experiments. Fuel *pins over a wide* range of dimensions and compositions have been successfully cast. Confirmation of solidus/liquidus temperatures, density, and linear thermal-expansion calculations is one of the side benefits from the experimental casting program. Effects of superheat temperatures on metal fluidity have shown that larger fuel-pin *diameters are* in *fact easier to* cast and require less energy input. Internal porosity and solidification defects have been reduced, and in some alloy compositions eliminated, by using the proper *solidification-control techniques*. Several problems of process-material compatibility have been solved with inexpensive plasma-arc-sprayed refactory coatings that are relatively inert to molten U-Pu-Zr. Further study is continuing in this area with the possibility of using state-of-the-art ceramics as melt crucibles and reusable mold materials.

Pyroprocess Development

The objective of this task is to establish the chemical feasibility of the processes for recycle of discharged core and blanket materials and for disposal of the fission product waste. The major process steps are electrorefining for the core material and halide slagging for the blanket. The work is to establish that product yields will be adequate, fission product removal will be sufficient, container materials and process reagents specified will perform as expected, and to develop the processes such that they are adaptable to remote operations.

Over the past year a series of electrorefining experiments with uranium was completed. Uranium metal was transported from a liquid cadmium anode, through various electrolytic salt media, and deposited on molybdenum or steel cathode rods. The deposit is dendritic, but in a subsequent melting operation the uranium coalesces nicely into a product button. Noble metals remained in the anode pool. Zirconium, which is both an alloying metal and a fission product, was found not to electrotransport. Rare earth elements were extracted into the electrolyte as chlorides, and were not reduced to metals at the cathode.

In a subsequent series, plutonium was successfully electrorefined in small-scale (approximately 10 g) experiments, using the cadmium anode pool, a molten $BaCl_2$-$CaCl_2$-LiCl-NaCl-$PuCl_3$ electrolyte, and a molybdenum or steel cathode. Plutonium metal and entrained salt were deposited on the cathode rod. Electrorefining experiments in a pilot-scale furnace (100-300 g) are in progress. Preliminary halide-slagging experiments show that this step works well for selective extraction of plutonium from the blanket alloy. A plant-scale electrorefiner which will utilize multiple 10 kg heavy-metal cathodes is under construction.

Following successful completion of the feasibility demonstrations, the next step is to demonstrate the practicality of the entire fuel cycle using the EBR-II reactor and a refurbished EBR-II Fuel Cycle Facility. The EBR-II Fuel Cycle Facility, now called HFEF/S, has been decontaminated and is ready for the new equipment. As the necessary facilities are already in place, the total cost will be modest.

Modifications to the EBR-II complex will take IFR demonstration through the pilot plant stage. The crucial facilities are EBR-II (for tests and demonstration), TREAT (for transient, accident-simulation fuel tests), ZPPR (for the new metallic core neutronic properties), HFEF/N (for destructive fuel examinations), and HFEF/S (for fuel cycle demonstration). EBR-II is the natural prototype of the IFR. It was the first prototype of the pool concept. Gradual substitution of IFR fuel in EBR-II will lead to whole-core IFR-fueled operation. Modifications to the HFEF/S facility will equip the system with plant-scale metallic processing and fabrication modules. In this way, a complete prototype IFR can be operational in three years. EBR-II will then be in full operation as a complete prototype, with fuel at target burnup levels and fuel being processed, fabricated, and returned to the reactor.

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