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# THE INTEGRAL FAST REACTOR CONCEPT*

by

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## DISCLAIMER



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## 1. INTRODUCTION

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.

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Metallic fuel is the choice. It provides the ritically 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 Figure 1.

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 MWd/kg design burnup without any failures. With simple design changes the new EBR-II fuel has a design burnup of 140 MWd/kg. The evolution of burnup limit for the EBR-II driver

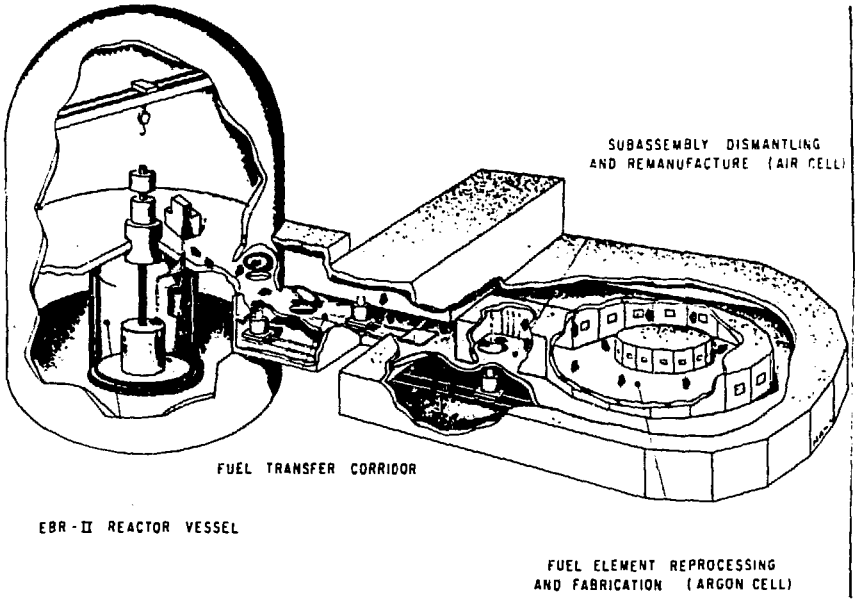


Figure 1. EBR-II Reactor and Fuel Cycle Facility

fuel is shown in Figure 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 MWd/kg, and one full assembly of 30 pins achieved 185 MWd/kg. (See Figure 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, 7, 8*). Pyroprocessing was not adequate 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, and blanket material was not processed. The new IFR process replaces melt-refining with a new electro-refining process. Electrorefining, using a liquid cadmium anode and a fused chloride salt, extracts the fuel uranium-plutonium mixture from the dissolved mixture of fuel and fission products. This is done at temperatures around 500 °C with low losses in the single step.

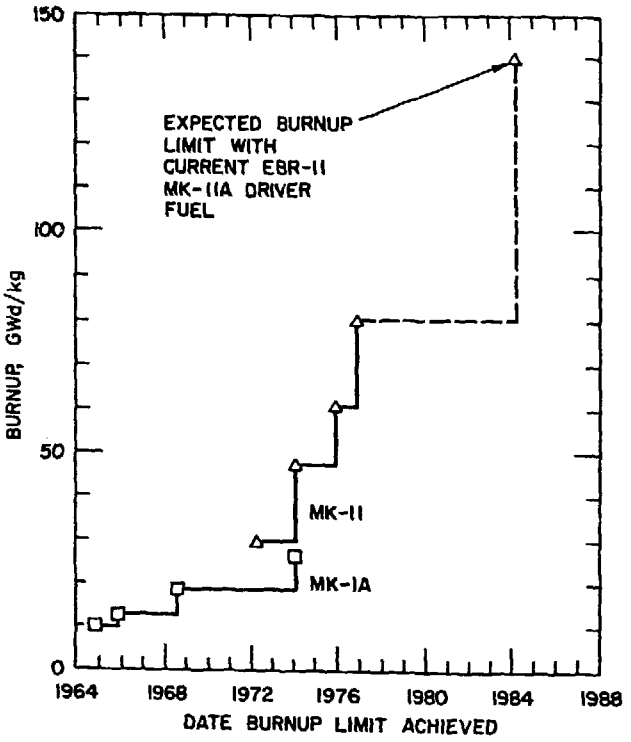


Figure 2. Evolution of EBR-II Driver Fuel Burnup Capability

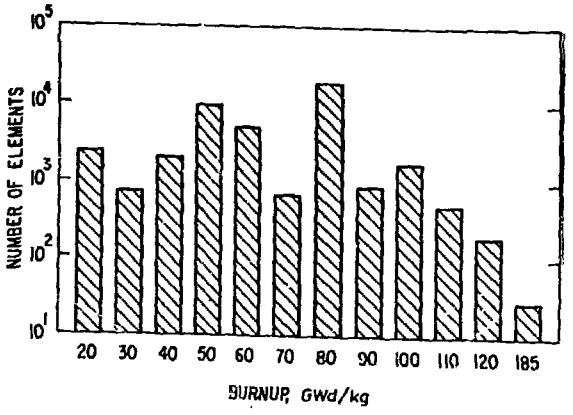


Figure 3. EBR-II Mark-II Driver Fuel Burnup History

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.

## 2. PASSIVE INHERENT SAFETY

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 K for metal vs. ~2 W/m K 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 | 7.6 mm (0.3 in.) |
| Cladding Thickness | 0.46 mm (0.018 in.) |
| Peak Linear Power | 50 kW/m (15 kW/ft) |
| 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 LOFWS or LOHSWS event. 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 Figure 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 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 TOPWS responses.

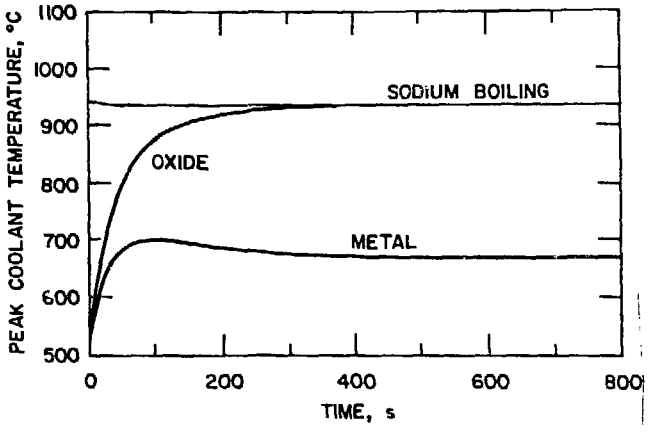


Figure 4. Loss-of-Flow Without Scram for Large Reactors (1350 MWe)

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.

The inherent safety potential of the metallic fuel was demonstrated by two landmark tests conducted in EBR-II on April 3, 1986. The first test was loss-of-flow without scram and the other loss-of-heat-sink without scram. These tests demonstrated that the unique combination of the high heat conductivity of metallic fuel and the thermal inertia of the large sodium pool can shut the reactor down during these potentially very severe accident situations without depending on human intervention or operation of active, engineered components. The coolant temperature responses during these two tests are presented in Figures 5 and 6. More detailed data can be found in a collection of papers prepared for these tests(*10-17*).

The EBR-II tests demonstrated in a very concrete way what is possible with liquid metal cooling and metallic fuel in achieving wide-ranging inherently safe characteristics.

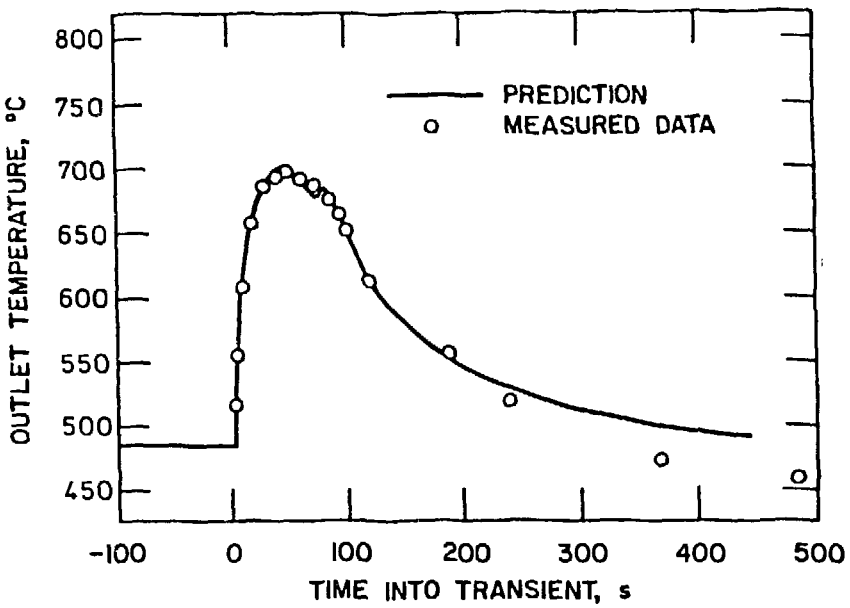


Figure 5. Loss-of-Flow Without Scram Test in EBR-II

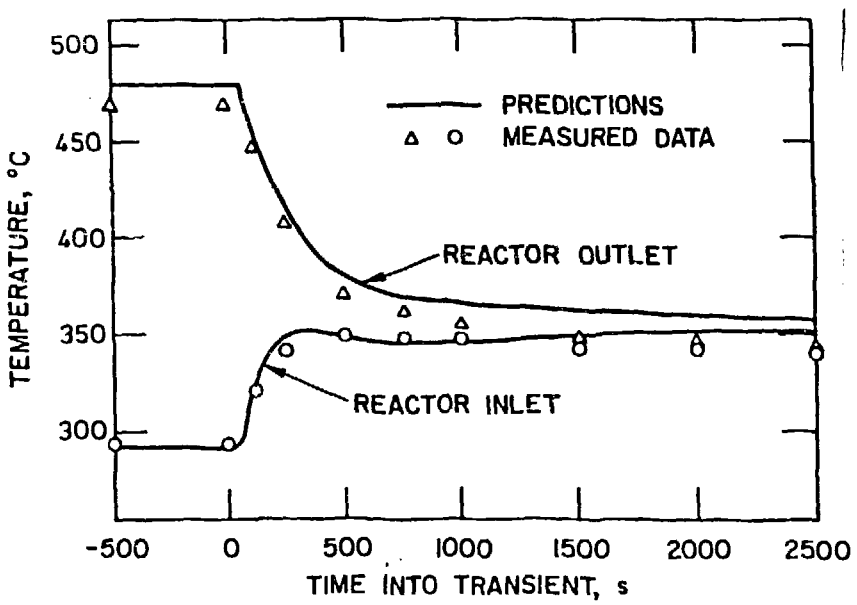


Figure 6. Loss-of-Heat-Sink Without Scram Test in EBR-II

## 3. IFR FUEL CYCLE

The IFR fuel cycle is based on pyrometallurgical reprocessing and injection-casting fabrication. The steps in this fuel cycle are few and all processes are extraordinarily compact. There is potential for dramatic simplifications and cost reductions in all of three areas of reprocessing, fabrication, and waste.

Because the necessary fuel cycle facility is so different from Purex facilities, in order to provide a firm technical basis for quantifying the IFR fuel cycle economics a detailed conceptual design of a commercial-scale IFR fuel cycle facility has been developed. The throughput capability is for an electrical generating capacity of 1200-1400 MW.

As illustrated in Figure 7, the fuel cycle facility can be very compact: 29 m x 32 m, with a height of 13.4 m. The key part of the facility is the inert-atmosphere process cell, which is only 164 $m^2$ in area and 4.3 m in height. Overhead handling systems have been eliminated through the use of both process and repair robots. The process cell rests directly on the seismically qualified basemat. The feed-throughs for the equipment systems come through the cell ceiling, allowing high utilization of the process-cell

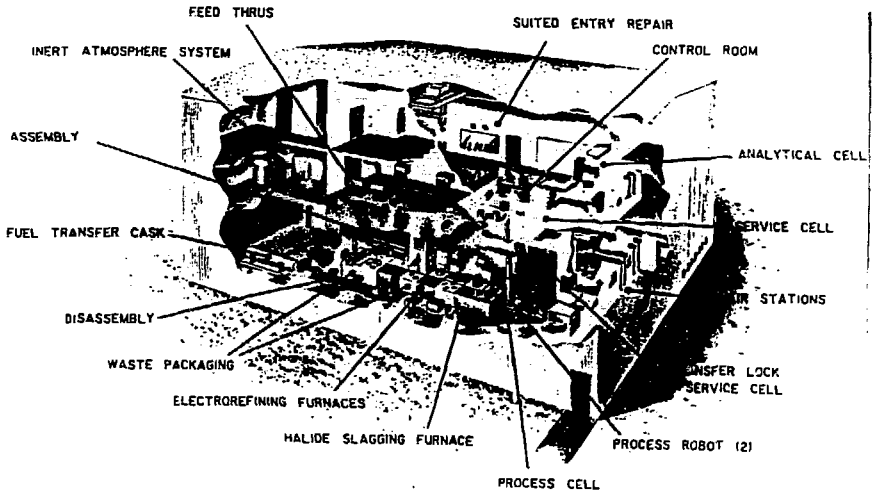


Figure 7. Commercial-Scale IFR Fuel Cycle Facility

floor area. Also, the final fabrication of the fuel and blanket assemblies is sufficiently simple that much of the work can be done out of cell.

The facility size and process cell volume are very small, less than equivalent Purex facility by a large factor. Capital cost reductions also by a large factor can therefore be expected for the IFR fuel cycle facility, compared to a conventional Purex-based fuel cycle facility of the same capacity. Preliminary estimates indicate that the capital costs of this IFR fuel cycle facility would be about $M 48. This includes construction of the building, provision of engineering and construction services, and the procurement and installation of equipment for reprocessing, fabrication, waste packaging, and interim storage. It does not include the costs associated with R&D and equipment development, nor contingencies. The capital cost breakdown is summarized below (in thousands of dollars):

| | |
|---|---|
| Building and Building Systems | 24 604 |
| Process Equipment | 5 515 |
| Engineering and Construction Services | 8 024 |
| Total | $k 48 143 |

In translating this to fuel cycle economics, the conventional breakdown of fuel cycle components adopted for LWRs is not directly applicable. For the IFR fuel cycle, it is appropriate to consider the following five distinct components that contribute to the levelized fuel cycle cost: (1) fuel cycle facility capital fixed charges, (2) fuel cycle facility operating and maintenance (O&M) cost, (3) driver and blanket hardware supplies, (4) fissile inventory carrying charges, and (5) waste disposal fee.

The IFR fuel cycle cost is summarized in Table II. A few important observations can be made from the data in Table II. The IFR fuel cycle cost of about 5 mill/kWh on a constant dollar basis is very competitive with the present LWRs, and it is substantially lower than that for the oxide fuel cycle based on Purex reprocessing and pelletized fuel fabrication. The fuel cycle facility capital cost is only a small fraction of the levelized fuel cycle cost, so that economic competitiveness is not sensitive even to smaller scale or to any possible uncertainties in the facility cost estimates.

Table II. IFR Fuel Cycle Cost
(for a generating capacity of 1350 MW)

| Components | $M/a | mill/kWh |
|---|---|---|
| 1. FCF Capital Fixed Charges | 6.4 | 0.68 |
| 2. FCF O&M Cost | 12.1 | 1.28 |
| 3. Hardware Components | 7.6 | 0.80 |
| 4. Fissile Inventory Carrying Charges | | |
| - Uranium Startup @ $35/g | 15.8 | 1.66 |
| - Plutonium Startup @ $25/g | 6.9 | 0.73 |
| 5. Waste Disposal Fee | 9.5 | 1.00 |
| Total | | |
| - Uranium Startup | 51.4 | 5.42 |
| - Plutonium Startup | 42.5 | 4.49 |

The IFR fuel cycle facility provides wide flexibility in sizing its throughput capacity. The particular size (1200-1400 MW) for the conceptual design was chosen because it represents a likely initial reactor deployment. The co-location of the fuel cycle facility with each reactor plant is not a required feature, of course. It is quite conceivable that a utility company with a large nuclear capacity may choose to build one regional fuel cycle facility servicing several thousands MW generating capacity or even more, within its grid system. It is also conceivable that some utilities may choose not to operate the fuel cycle facilities but have independent engineering companies operate the facilities for them. In other words, the word "integral" as used for the IFR concept should be viewed in the context that the fuel cycle closure is an integral part of the IFR development, and it is convenient to regard the whole system as a single entity. But the actual scheme for deployment will depend on specific institutional arrangements, size and location options, timing, etc.

Although the necessary detailed study has not yet been carried out, a preliminary study indicates that economies of

scale will also apply to the IFR fuel cycle facility. However, it is expected that cost advantages of the IFR fuel cycle, relative to the oxide fuel cycle based on Purex reprocessing, will be reduced as the size of the fuel cycle facility is scaled up by large factors. However, other advantages of the IFR fuel cycle remain, and are independent of size, particularly those in waste treatment and handling and possibly in diversion resistance characteristics.

The pyroprocess lends itself to much simplified waste treatment operations. The volume of radioactive waste is lessened. Long-lived fission products, troublesome in the Purex process, are easily contained and immobilized in the pyroprocess. Tritium is collected as HTO by cell purification systems. Removal of krypton by cryogenic distillation is straightforward. Carbon-14 remains in the salt or metal waste as carbides and iodine is contained in salt waste as CsI or NaI. Ruthenium is contained as metal in the cadmium waste.

Although it is feasible to convert the chloride salt waste from pyroprocesses to glass waste form, a promising and simpler approach is to extract the actinides and convert the salt waste into an intermediate level concrete waste. The high level metal wastes from pyroprocesses can be directly encapsulated in copper or lead containers.

Because the decontamination factor achievable with the electrorefining process is not very high, the fuel is always highly radioactive and this provides a measure of self-protective theft and diversion-resistance.

## 4. TECHNOLOGY DEVELOPMENT STATUS

Several aspects of the IFR concept require further proof, and development programs on each are underway at Argonne. The major areas are demonstration of the performance of the IFR U-Pu-Zr ternary alloy metallic fuel, development of the new pyroprocesses of electrorefining and halide slagging, and demonstration of the inherent safety characteristics. IFR development, which was initiated in the latter part of FY 1984, is proceeding rapidly. Results from experimental, analytical, design and hardware programs in all areas are accumulating daily and substantial progress has been made to date.

A. 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 at the present time. 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 burnup in excess of 100 MWd/kg as of January 1987, and are continuing their irradiation to cladding breach, which is expected at burnups higher than 140 MWd/kg. (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 proven that larger fuel-pin diameters are in fact easier to cast and require less energy. 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 refractory 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.

B. 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 two years 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.

C. Demonstration of Safety Characteristics

The overall objective of this task is to provide the experimental 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.

Another unique characteristic of metallic fuel is that fission gases entrapped within the fuel alloy matrix itself provide a self-dispersive mechanism that plays an important role in the termination of transient overpower accidents. Three TREAT tests performed to date demonstrated, first, a large margin to cladding failure threshold, and 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. This latter effect can provide a substantial reduction in reactivity in over-power accidents before fuel failure.

The inherent safety characteristics of metallic fuel under generic ATWS events reduce the core disruption probability to an exceptionally low value. 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 hence are more coolable than oxide beds.

## 5. FUTURE DEVELOPMENT PATH

Following successful completion of the feasibility demonstrations described in the previous section, 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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