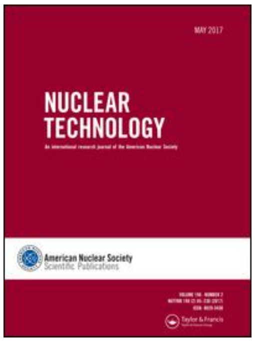

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THE INTEGRAL FAST REACTOR

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The Integral Fast Reactor (IFR) is an innovative liquid-metal reactor concept being developed at Argonne National Laboratory. It seeks to 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 key technical features and potential advantages of the IFR concept, its technology status, and its future research and development requirements are described.

INTRODUCTION AND BACKGROUND

The Integral Fast Reactor (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.

Much of the technology for the IFR is based on Experimental Breeder Reactor II (EBR-II) experience. The EBR-II was the first pool-type liquid-metal reactor (LMR). Metallic fuel was developed as the driver fuel in EBR-II. From 1964 through 1969, ~35 000 fuel pins were reprocessed and refabricated in the EBR-II fuel cycle facility,[1] which was based on an early pyroprocess with some characteristics similar to that now proposed for the IFR.

Only in recent years have developments in metallic fuel taken place that now make the metallic fuel-based IFR a promising development choice. 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 1950s and early 1960s. Discoveries at EBR-II in the late 1960s and design developments and irradiation experience in the 1970s have totally changed this picture.[2-5] Generic metallic fuel can now be designed for very superior irradiation performance. Over 20 000 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.

Furthermore, 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. Pyroprocessing was inadequate 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 electrorefining process.[6-8] 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.

In the development of the next generation of advanced reactors, particular attention must be given to inherent passive safety, fuel cycle closure including waste management, and economics. The basic thrust of IFR development is to exploit the inherent properties of the reactor materials to achieve the desired characteristics of next-generation nuclear power, which is also capable of extending uranium resources to meet large energy demands expected in the future.

POTENTIAL ADVANTAGES

The IFR concept has a number of specific technical advantages that collectively address the design goals of the advanced LMR. These advantages are in the areas of fuel performance, inherent passive safety, economics, waste management, and operability and reliability.

Fuel Performance

Metallic fuel is the key to the IFR concept. Metallic fuel is easy to fabricate. Metallic fuel slugs, typically of 0.5 cm in diameter and 30 to 45 cm in length, are produced by injection casting. One to three fuel slugs are then loaded into an individual cladding jacket and the gap between slugs and cladding is filled with sodium bond. The cross-sectional area of the fuel slug is 75% of the available area inside the cladding. As the fuel is irradiated, the fission gas bubbles grow, inducing fuel swelling. As the fuel swells out to the cladding wall, the fission gas bubbles interconnect and provide a gas release path to the plenum located on top of the fuel column. This interconnected porosity is the key to stopping further fuel swelling and mitigating any significant cladding stresses due to fuel/cladding contact.

Metallic fuel has excellent steady-state and off-normal performance characteristics. High burnup potential has been demonstrated with the EBR-II uranium-fissium driver fuel. The new IFR U-Zr and U-Pu-Zr fuel irradiation experience has been better than expected. The lead tests have achieved 17 at.% burnup (~170 MWd/kg) as of July 1988, and irradiation is continuing to cladding breach.

Metallic fuel has excellent transient capabilities. The metallic fuel itself does not impose any restrictions on transient operations or load-following capabilities. The robustness of metallic fuel is illustrated by the following sample history of a typical EBR-II driver fuel:

40	start-ups and shutdowns
5	15% overpower transients
3	60% overpower transients
45	loss-of-flow (LOF) and loss-of-heat-sink tests including a LOF test from 100% power without scram.

The metallic fuel has benign run beyond cladding breach (RBCB) performance characteristics. A recent RBCB test with metallic fuel operated 223 days beyond cladding breach, including many start-up and shutdown transients. Very little fuel loss was observed and the breach of the fuel pin remained small. Metallic fuel is expected to be very reliable. However, even if fuel failures occur, the RBCB experience indicates that the failed fuel elements could be left in the core until the scheduled shutdown without raising any safety concerns.

The metallic-fueled cores also have a higher breeding potential due to a superior neutron economy associated with a hardened spectrum. As illustrated in Fig. 1, metallic fuel has a much higher breeding ratio than oxide or carbide fuels. The superior neutron economy further allows reactor core design improvements, such as minimizing the reactivity swing over the operating cycle, increased cycle length, etc.

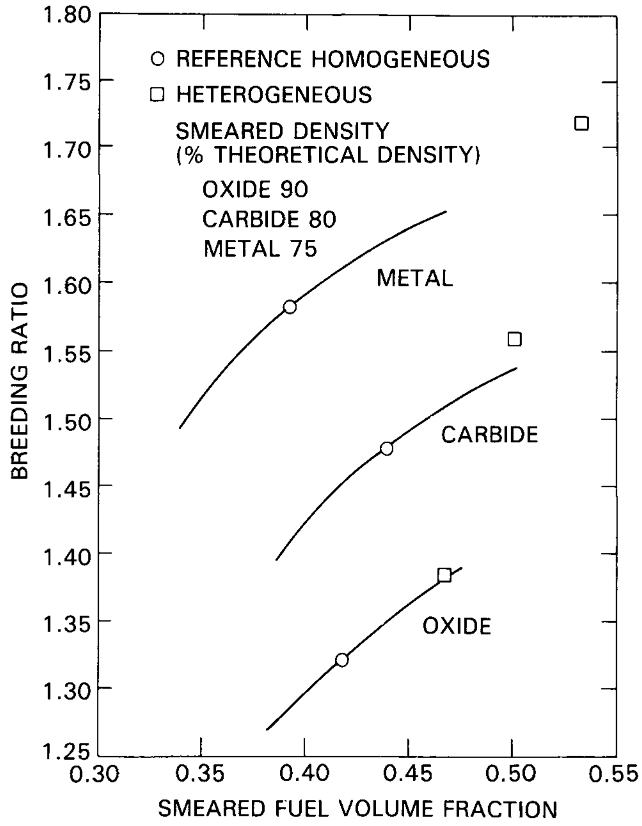

Fig. 1. Comparison of breeding ratio potentials of oxide, carbide, and metal fuels.

Inherent Passive Safety

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 large margin to coolant boiling temperature, large thermal inertia of the pool configuration reactor system, and the metallic fuel properties all combine to provide a unique inherent passive safety potential for the IFR concept.

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 compared to ~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. Metallic fuel provides better or equal safety characteristics across the entire spectrum from normal behavior to postulated severe accidents. 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.[9-12]

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 s.

The characteristics of the negative reactivity feedback caused by the increase in coolant temperature determine 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 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. 2.

The superior neutronics performance characteristics of metallic fuel allows core designs with minimum burnup reactivity swing even for small modular core designs. This can be used in reducing the TOPWS initiator caused by an unprotected control rod runout. In addition, Transient Reactor Test Facility (TREAT) tests performed to date have demonstrated a larger margin to cladding failure threshold for the metallic fuel and 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, a number of factors suggest that metallic cores can be designed for benign TOPWS responses.

It is worth stressing again that the sharply improved performance characteristics of the metallic cores for the unprotected LOFWS, LOHSWS, and TOPWS 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 (Refs. 13 through 20), the test was the LOFWS and LOHSWS tests. 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 the operation of active, engineered components. The coolant temperature responses during these two tests are presented in Figs. 3 and 4. The EBR-II tests demonstrated in a very concrete way what is possible with liquid-metal cooling and metallic fuel in achieving wind-ranging inherently safe characteristics.

Economics

Economic competitiveness with existing reactor systems is a necessary condition for any advanced reactor system to penetrate the commercial nuclear market. The economics of advanced nuclear reactors is dictated by the plant capital cost and the fuel cycle cost.

Light water reactor (LWR) experience indicates that most of the plant capital cost is associated with the

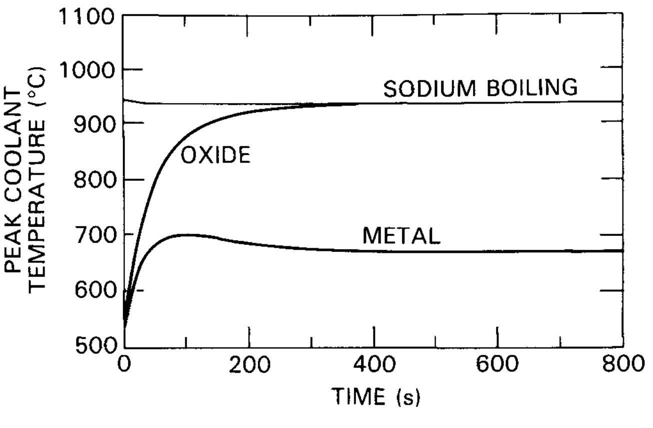

Fig. 2. Comparison of oxide and metal core responses to an LOFWS event for a typical large reactor.

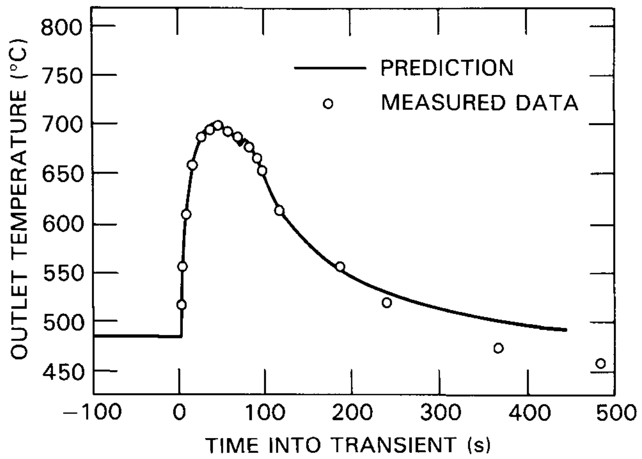

Fig. 3. LOFWS test in EBR-II.

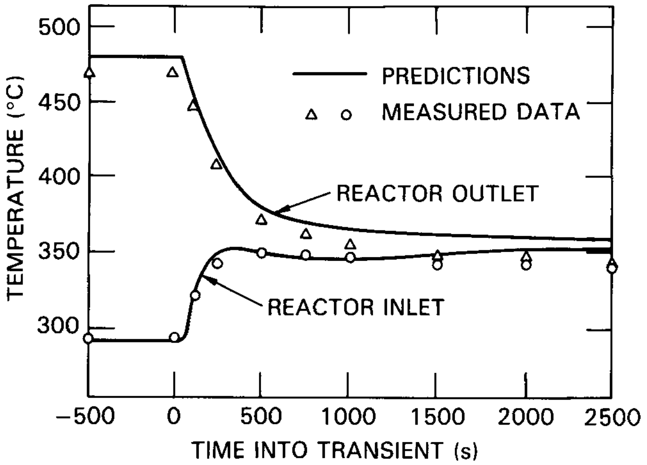

Fig. 4. LOHSWS test in EBR-II.

balance of plant (BOP) and indirect costs such as field engineering and construction services. The nuclear reactor itself constitutes only a small fraction of the capital cost. The IFR concept provides opportunity for a new construction approach for the BOP that would yield substantial cost savings. A large thermal inertia associated with the sodium pool combined with favorable reactivity feedback characteristics of the metallic fuel makes the reactor system immune to various transients originating from the BOP. The plant protection function does not have to rely on the BOP at all, and the BOP construction could be done following a nonnuclear construction approach.

The only area in which the LMR is intrinsically more costly than the LWR is the reactor plant itself. The key question related to the capital cost competitiveness of the LMR, therefore, is whether the increased reactor system cost can be offset by savings in the BOP and indirect costs, or, if not completely offset, to what extent the reactor system cost increase can be minimized.

The capital cost reduction potential has been vigorously pursued in two conceptual design projects for innovative LMR concepts: power reactor inherently safe module (PRISM) designed by General Electric Company[21] and the sodium advanced fast reactor (SAFR) designed by Rockwell International.[22] These conceptual design efforts have made significant progress in simplifying the reactor system designs and maximizing the modular construction approach.

The IFR concept provides a drastic reduction in fuel cycle cost compared to the conventional Purex-based oxide fuel cycle. The IFR fuel cycle is based on pyrometallurgical reprocessing and injection-casting fabrication. There are few steps in this fuel cycle, and all the processes are extraordinarily compact. There is potential for dramatic simplifications and cost reductions in the three areas of reprocessing, fabrication, and waste.

Because the necessary fuel cycle facility is so different from Purex facilities, a detailed conceptual design of a commercial-scale IFR fuel cycle facility has been developed[23] to provide a firm technical basis for quantifying the IFR fuel cycle economics. The throughput capability is for an electrical generating capacity of 1200 to 1400 MW. The conceptual design is illustrated in Fig. 5.

The IFR fuel cycle facility size and process cell volume are very small, less than an equivalent Purex facility by a large factor. Large capital cost reductions can also, therefore, be expected. Preliminary estimates indicate that the capital costs of this IFR fuel cycle facility is about $50 million, as compared to about $250 million for the equivalent oxide fuel cycle facility. These costs include construction of the building, engineering and construction services, and equipment for reprocessing, fabrication, waste packaging, and interim storage. They do not include the costs associated with research and development and equipment development, nor contingencies.

In translating the fuel cycle facility cost 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 distinct contributions to the levelized fuel cycle cost: (a) fuel cycle facility capital fixed charges, (b) fuel cycle facility operating and maintenance (O&M) cost, (c) driver and blanket hardware supplies, (d) fissile inventory carrying charges, and (e) waste disposal fee.

The IFR fuel cycle cost is compared with the fuel cycle cost for an equivalent oxide-fueled LMR in Table I. The fuel cycle cost is calculated on a constant dollar basis (1986 dollars) for a generating capacity of 1350 MW(electric). The IFR fuel cycle cost of ~5 mill/kW·h on a constant dollar basis is very competitive with present LWRs, and it is substantially lower than that for the oxide fuel cycle based on Purex reprocessing and pelletized fuel fabrication. The comparison in Table I indicates that the uranium start-up is also a viable backup option to the plutonium start-up core.

A more important observation from Table I is that the fuel cycle facility capital cost for the IFR 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. It would be particularly important to consider the implications of uncertainties in the facility cost estimates, because the capital cost estimates used for the calculations summarized in Table I might be considered optimistic minimum estimates. It is quite conceivable that the capital costs may be increased by at least a factor of 2 for both metal and oxide cases in actual deployment.

Another key uncertainty deals with the fixed change rate. Traditionally, a higher fixed change rate is used for fuel cycle facilities as compared to reactor

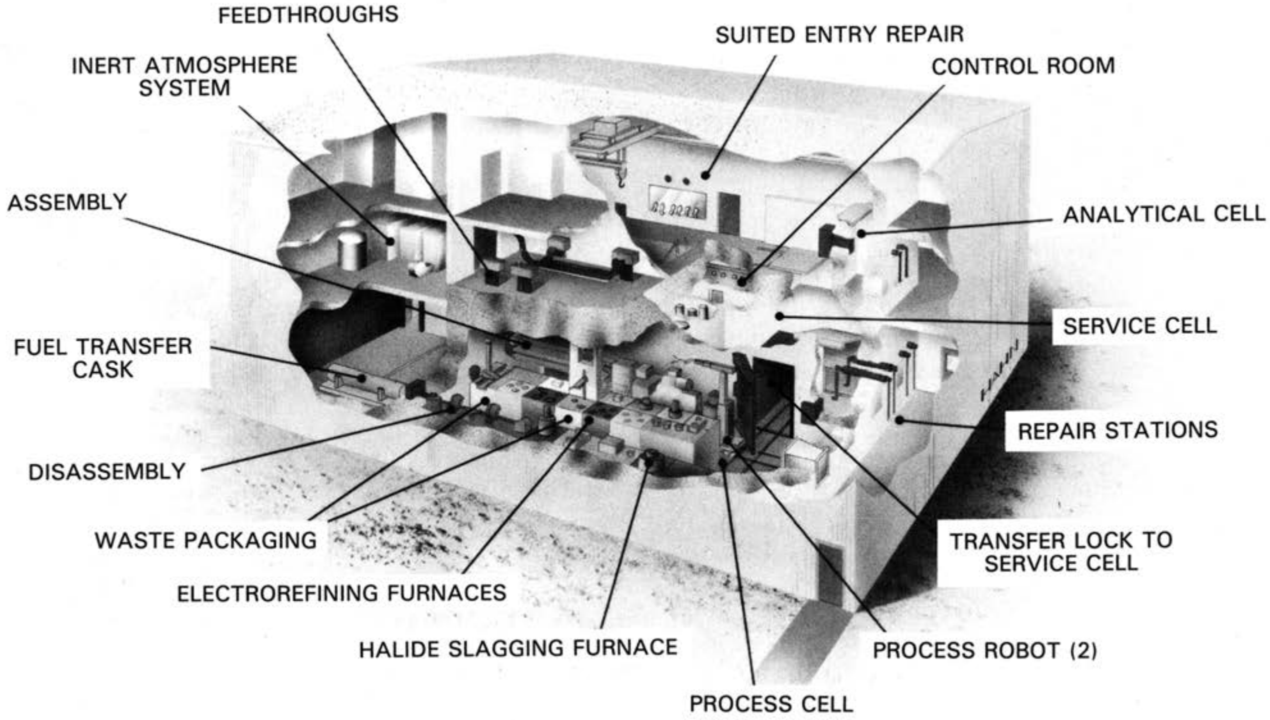

Fig. 5. Commercial-scale IFR fuel cycle facility.

TABLE I

Fuel Cycle Cost Comparison for 1350-MW(electric) Plants

	Metal (mill/kW·h)	Oxide (mill/kW·h)
Fuel cycle facility capital fixed charges	0.68	3.39
Fuel cycle facility O&M cost	1.28	2.31
Hardware components	0.80	0.80
Fissile inventory carrying changes		
Plutonium start-up ($25/g)	0.73	0.88
Uranium start-up ($35/g)	1.66	1.99
Waste disposal fee	1.00	1.00
Total		
Plutonium start-up	4.49	8.38
Uranium start-up	5.42	9.49

TABLE II

Impact of Fuel Cycle Facility Capital Cost Uncertainties on Fuel Cycle Cost

	Metal (mill/kW·h)	Oxide (mill/kW·h)
Reference case with optimistic capital cost	5.4	9.5
Realistic case with capital cost uncertainties	6.9	17.2

plants, reflecting higher market risks and different capital structure of private ownership. However, for the reference case presented in Table I, the fixed change rate used for the fuel cycle facility was the same rate used for the reactor plant, assuming that the dedicated fuel cycle facility for a single reactor can be treated as an integral part of the reactor plant project. A more realistic fixed change rate for the fuel cycle facility could be much higher than that for the reactor plant.

Table II summarizes the effects of these two uncertainties on the fuel cycle cost. The capital costs were increased by a factor of 2, and the fixed charge rate (on a constant dollar basis) was increased from the 9.2% used in Table I to 15%/yr. For the realistic case with uncertainties, the economic advantage of the IFR fuel cycle is particularly noticeable: 6.9 mill/kW·h for the IFR fuel cycle compared to 17.2 mill/kW·h for the oxide fuel cycle. Hence, the cost reduction potential of the IFR fuel cycle far exceeds any conceivable reductions achievable in the plant capital cost.

Note that the comparisons presented here are for a small-scale deployment. It is expected that the 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.

Waste Management

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 as a metal matrix in copper or lead containers.

In the pyroprocess, the actinide elements tend to stay together, and most of the actinides are recycled along with the plutonium. Furthermore, the extraction of the remaining actinides from the waste streams is relatively easy because of a large separation factor between actinides and rare earth fission products. The potential for separating the actinides and recycling them into the reactor for *in situ* burning appears to be very promising for the IFR concept. With the long-lived actinides removed, the fission products in the high-level waste will decay sufficiently in ~300 yr so that their long-term radiological risk drops below the cancer risk level of natural uranium ore.[24,25]

Operability and Reliability

Sodium is noncorrosive to the metals used in the LMR reactor structures and components. Radioactive corrosion products are not formed in any significant amounts. Radioactive corrosion products circulating and depositing around the system make access for maintenance difficult. This is an increasingly important problem in the LWRs. Worldwide experience has now demonstrated that this is not a serious problem in the LMR. Therefore, access for maintenance is easy and radiation exposures to plant personnel are expected to be very low. For example, no exposures are expected during maintenance and inspection of the steam generator, turbine generator, steam and feedwater pumps and equipment, etc. Even after >20 yr of operation, EBR-II and other LMRs are all experiencing <0.2 person-Sv/yr personnel exposure, as compared to some LWRs that now approach 10 person-Sv/yr.

Noncorrosive coolant also implies reliable sodium components performance and improved plant availability. For example, LWR steam generator tube failures are mostly caused by the water chemistry and the accumulating corrosion products in shell-side crevices. In LMR steam generators, noncorrosive sodium flows through the shell side and the corrosion product accumulation in crevices is minimal. Steam flows inside the tube where the simple geometry prevents corrosion product accumulation. The original EBR-II steam generators have operated without leaks over 23 yr of continuous service.

The LMR also has a potential for achieving a higher availability. In EBR-II, even with very frequent refueling (five times per year) and accommodating various irradiation tests, a very high capacity factor is evident after >20 yr of operation. The EBR-II capacity factors in recent years are summarized in Table III.

TECHNOLOGY DEVELOPMENT STATUS

Several aspects of the IFR concept require further proof, and development programs are under way at Argonne National Laboratory (ANL). The major areas are demonstration of the performance of the IFR U-Pu-Zr ternary alloy metallic fuel, development of the new pyroprocess, and demonstration of the inherent safety characteristics.

A major element of the IFR fuels development program is to expand the U-Pu-Zr and U-Zr fuel irradiation data base to provide a technical bridge between these alloys and the extensive data base already in hand for the similar, but not identical, EBR-II uranium-fissium

TABLE III

EBR-II Capacity Factor History

Year	Capacity Factor (%)
1976	76.9
1977	71.5
1978	72.8
1979	71.1
1980	77.1
1981	73.0
1982	62.3
1983	65.5
1984	65.9
1985	75.0
1986	71.9
1987	81.3
Average	72.0

driver fuel. As of August 1988, ~2000 pins of tests or lead driver assemblies are undergoing irradiation in EBR-II and the fast flux test facility. These tests encompass variations in plutonium compositions (0, 3, 8, 19, 22, and 26%), zirconium contents (2, 6, 10, and 14%), and cladding materials (Type 316, D-9, and HT-9 stainless steels), as well as other design parameters and operating conditions. As mentioned earlier, the lead tests in EBR-II have achieved burnup in excess of 170 MWd/kg as of August 1988 and are continuing their irradiation to cladding breach. This is a much higher burnup than ever expected of these early tests and promises a high burnup performance for the metallic fuels.

In addition to the irradiation programs, out-of-reactor experiments are also being performed 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.

The key step in the IFR fuel cycle is electrorefining, which is illustrated in Fig. 6. The objective of the pyroprocess development 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 the processes will be adaptable to remote operations.

Electrorefining experiments have been successfully conducted with uranium and plutonium on a few hundred grams scale. These experiments have demonstrated the chemical feasibility of transporting uranium and plutonium from a liquid cadmium anode, through various electrolytic salt media, to a solid cathode rod or to a liquid cadmium cathode. Noble metals remain in the anode pool, and rare earth elements are extracted into the electrolyte as chlorides. These laboratory-scale experiments also provided a data base to quantitatively verify the flow sheets.

At the present time, engineering-scale electrorefining experiments with depleted uranium are being conducted in a newly established glove-box facility with an argon atmosphere. The engineering-scale electrorefiner, illustrated in Fig. 7, is ~75 cm in diameter and 125 cm deep and can handle up to two cathode deposits of 10 kg each. An initial series of engineering-scale experiments has been successfully conducted. The uranium deposit on the solid cathode is dendritic, as shown in Fig. 8. Electrorefining to a liquid cadmium cathode has been also successful, and the initial deposit is shown in Fig. 9. Work is also progressing in dissolution methods evaluation and cadmium vaporization experiments to optimize consolidation of uranium-plutonium products.

The overall objective of the IFR safety program 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 ATWS events. The analytical predictions are currently being validated through a 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

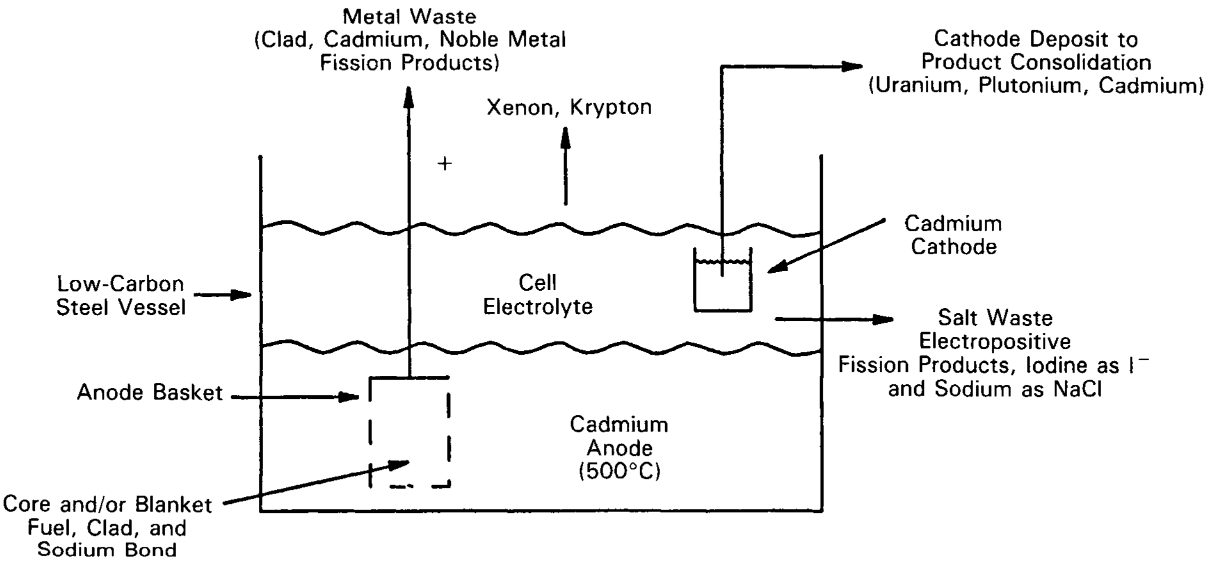

Fig. 6. Schematic representation of electrorefining.

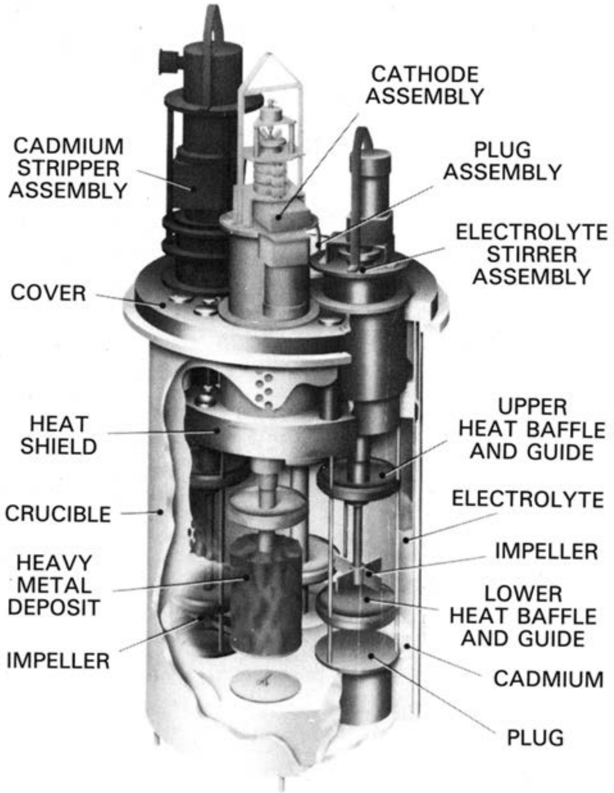

Fig. 7. Engineering-scale electrorefiner.

overpower accidents. Three TREAT tests performed to date demonstrated a large margin to cladding failure threshold and that the fission gas-driven axial expansion of fuel within the clad does take place, which provides intrinsic negative reactivity feedback before the fuel clad itself fails. This latter effect can provide a substantial reduction in reactivity in overpower accidents before fuel failure. The TREAT test results that illustrate the prefailure fuel axial expansion are presented in Fig. 10.

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 the 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 FCIs. 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.

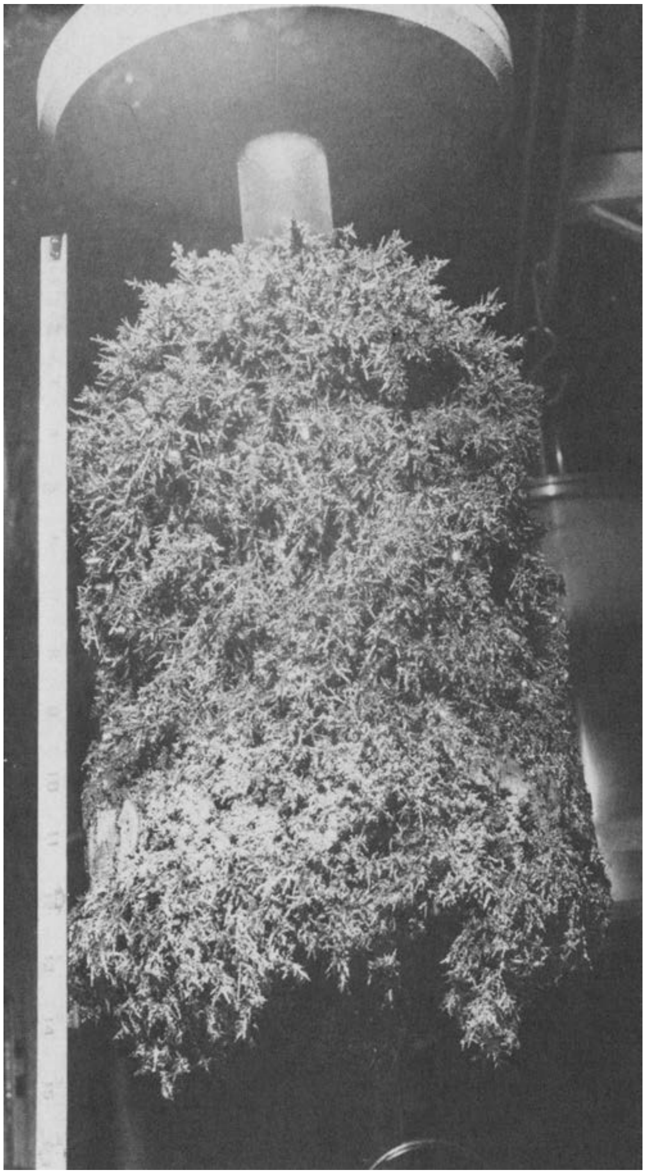

Fig. 8. Engineering-scale uranium deposit on solid cathode.

FUTURE DEVELOPMENT PATH

Following successful completion of the feasibility demonstrations, the next step is to demonstrate the practicality of the entire fuel cycle using the EBR-II and a refurbished EBR-II fuel cycle facility (HFEF/S), which 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), the Zero Power Physics Reactor (for the new metallic core neutronic properties), HFEF/N (for destructive fuel examinations), and HFEF/S (for fuel cycle demonstration). Modifications to the HFEF/S facility will

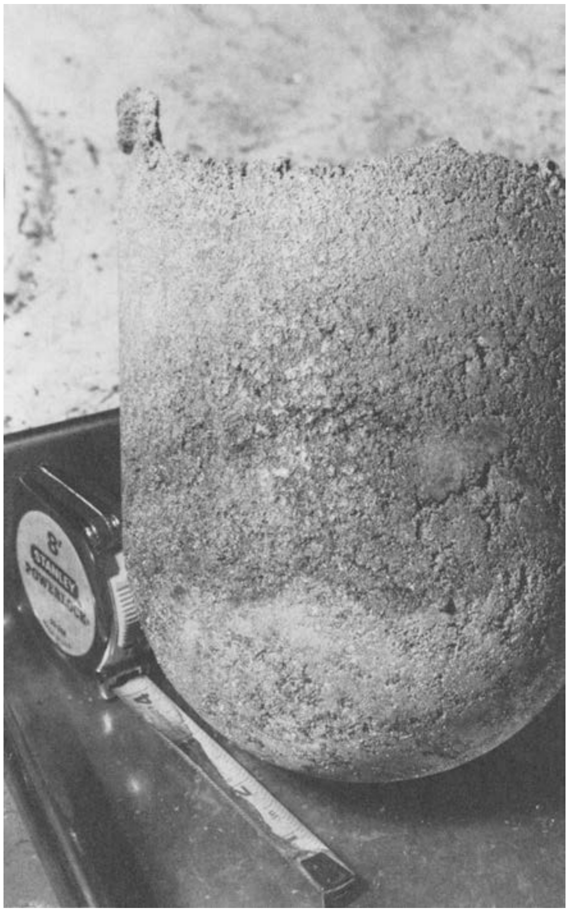

Fig. 9. Engineering-scale uranium deposit on liquid cadmium cathode.

equip the system with plant-scale metallic processing and fabrication modules. In this way, a complete prototype IFR can be operational in the near term. The 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.

The IFR technology development effort also provides ample opportunities for active participation by the academic community. First of all, the IFR is a next-generation advanced reactor concept. Now is the right time to pursue fundamental research and development to advance its technology base. The IFR incorporates many new technologies that are different from conventional nuclear technologies: metallic fuel, pyroprocessing based on electrorefining, new waste forms, etc. As the development programs at ANL will concentrate on the integral performance characterization and the prototype demonstration, there are many gaps and research areas that can be filled by extensive and broad participation of the academic community. Some of the specific research areas include the following:

1. thermophysical property studies on U-Pu-Zr ternary alloy system

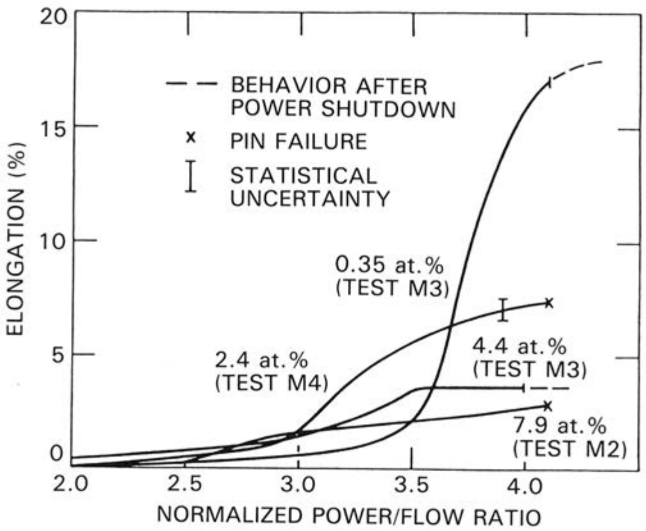

Fig. 10. Fission gas driver axial elongation of metallic fuel under transient overpower conditions simulated in TREAT tests.

2. basic ternary diffusion studies to understand restructuring under irradiation environment
3. modeling of steady-state metallic fuel performance and transient behavior
4. thermodynamic behavior of samarium, gadolinium, europium, etc., in cadmium and activity coefficients of metal chlorides
5. actinide element behavior and partitioning
6. pyroprocessing waste forms and characterization
7. metallic core design optimization and system transient modeling
8. application of artificial intelligence and advanced control technologies
9. application of robotics and automation to the fuel cycle facility.

In addition, new emerging technologies and further innovations in the reactor design and the fuel cycle closure can be used. Most of the research agenda discussed above can be carried out independently within the academic community or in collaboration with the IFR development programs at ANL. Opportunities also exist for research programs that are closely tied with EBR-II and its associated facilities at ANL-West.

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