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THE INTEGRAL FAST REACTOR*

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Abstract

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. This paper describes the key features and potential advantages of the IFR concept, with emphasis on its safety characteristics.

The Integral Fast Reactor (IFR) is a generic reactor concept based on 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 EBR-II. EBR-II was the first pool-type liquid metal reactor. Metallic fuel was successfully 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.

The IFR concept has a number of specific technical advantages that collectively satisfy all fundamental requirements demanded on the next generation reactor. Recent debates on the greenhouse effect reinforce the need to develop an advanced next generation reactor concept that can contribute significantly toward substituting the fossil-based energy generation. If nuclear is to make a significant contribution, breeding is a fundamental requirement, so that the uranium resources can be extended by two orders of magnitude, making nuclear essentially a renewable energy source. In addition to breeding, there are two other fundamental requirements that the next generation reactor should address. Safety and waste are two key factors that influence the public acceptance of nuclear power and, hence, determine the extent to which nuclear power contributes to meet the long-term energy substitution as well as future demand growth.

For the discussion of high-level waste management, it is convenient to categorize the nuclear waste constituents into two parts: fission products comprised of hundreds of various isotopes, and actinides comprised of uranium and the transuranic elements--neptunium, plutonium, americium, curium, etc. Fission products are produced by fissioning of heavy atoms, and transuranics are produced as a result of neutron capture reactions.

Most of fission products decay in relatively much shorter time periods than actinides. In the order of 200 years, the fission products decay to a sufficiently low level so that their radiological risk factor drops below the cancer risk level due to their original uranium ore. Actinides, on the other hand, have longer half-lifes and their radiological risk factor remains orders of magnitude higher than that due to fission products for millions of years. The relative radiological risk factors for fission products and actinides are presented in Figure 1 for the LWR spent fuel[1].

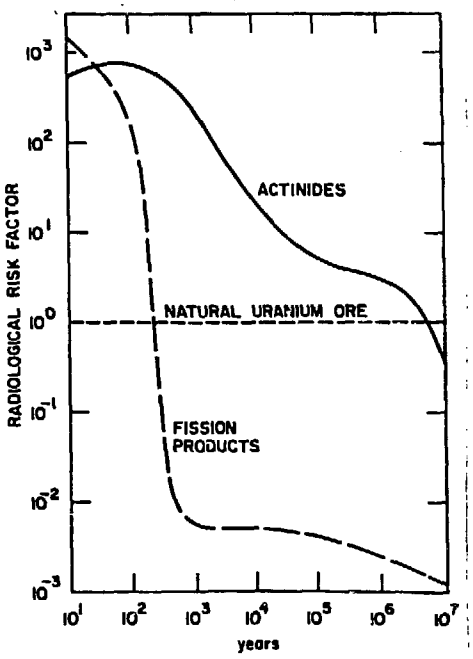

Figure 1. Relative Radiological Risk Factor of Fission Products and Actinides in the LWR Spent Fuel, Normalized to Their Original Uranium Ore (Data Source: Ref. 1).

There is a strong incentive to separate actinides and recycle them back into the reactor for in-situ burning. The benefit of the actinide recycling is in the fact that the effective lifetime of the nuclear waste is reduced from millions of years to a few hundred years. This would have an enormous impact on assuring the integrity of high-level waste over its lifetime and should ultimately be helpful in public acceptance of the nuclear power. However, even if the actinides are removed and the lifetime of the high-level waste is reduced to hundreds of years, this does not mean that actinide recycling could vitiate the need for a geological repository. A geological repository would still be necessary to store high-level wastes regardless of the actinide contents.

The IFR pyroprocessing has unique technical features that make the actinide separation more practical than it is in conventional PUREX processing. In the IFR process, most of the actinide elements accompany the plutonium product stream, and furthermore, the ability of pyrochemical process to separate rare earths from actinides, which is very difficult in the PUREX processing, is remarkable. The hard IFR neutron spectrum is better for actinide burning than that of any other reactor type. The prospects of the IFR concept for actinide recycling are excellent. Further research and development is needed to fully establish feasibility, but the main lines of the necessary development are easily defined and should be straightforward to carry out.

The IFR metallic fuel promises a higher degree of inherent safety than the conventional oxide fuel, and 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[2] 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 2. Both the LOFWS and LOHSWS accidents are perfectly benign in a properly designed IFR.

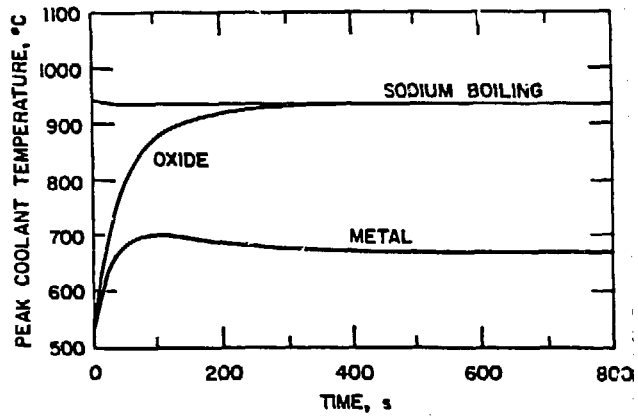

Figure 2. Loss-of-Flow Without Scram for Large Reactors (1350 MWe).

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 3 and 4. More detailed data can be found in a collection of papers prepared for these tests[3]. 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.

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

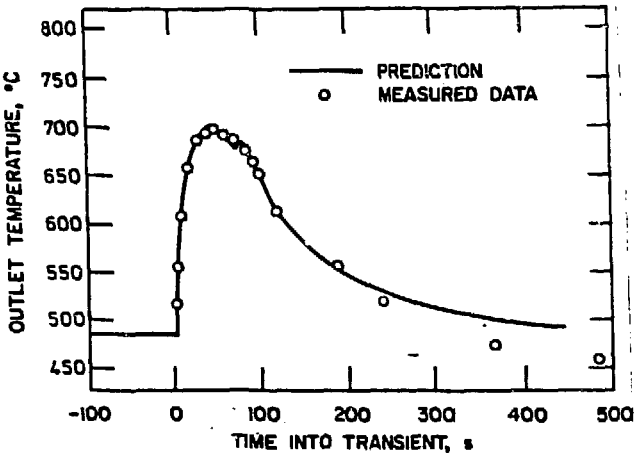

Figure 3. Loss-of-Flow Without Scram Test in EBR-II.

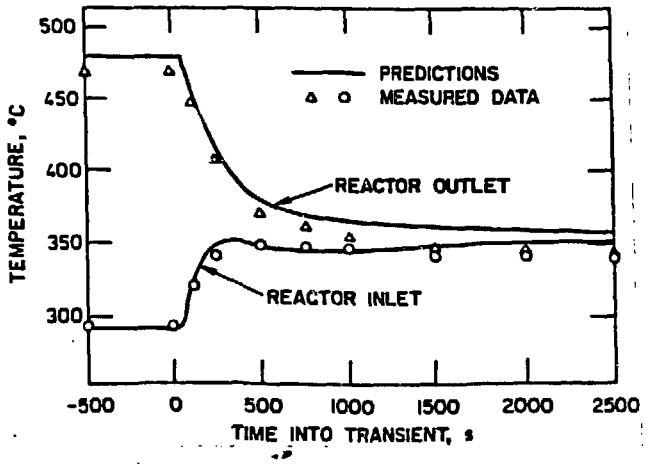

Figure 4. Loss-of-Heat-Sink Without Scram Test in EBR-II.

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.

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.

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.

As discussed above, the IFR concept has a potential of satisfying all fundamental requirements for the next generation reactor--breeding, waste treatment and safety. 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 development of the new pyroprocesses based on electrorefining, 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.

The key 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.

References

1. L. Koch, "Minor Actinide Transmutation - A Waste Management Option," J. of the Less-Common Metals, 122, 371-382 (1986); L. Koch, "Formation and Recycling of Minor Actinides in Nuclear Power Stations," Chapter 9 in Handbook on the Physics and Chemistry of the Actinides, edited by A. J. Freeman and C. N. Kelber (1986).

2. J. F. Marchaterre, J. E. Cahalan, R. H. Sevy, and A. E. Wright, "Safety Characteristics of the Integral Fast Reactor Concept," Proc. ASME Winter Meeting, 85-WA/NE-14, Miami Beach, FL (November 1985).

3. S.H. Fistedis, ed., "The Experimental Breeder Reactor-II Inherent Safety Demonstration," Vol. 101, No. 1 (1987).