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EVOLUTION OF THE LIQUID METAL REACTOR: THE INTEGRAL FAST REACTOR (IFR) CONCEPT *

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TECHNICAL PROGRESS

The Integral Fast Reactor (IFR) concept(1,2) has been under development at Argonne National Laboratory since 1984. A key feature of the IFR concept is the metallic fuel. Metallic fuel was the original choice in early liquid metal reactor development. In particular, metallic fuel was successfully developed as the driver fuel in EBR-II. During 1964-1969, about 35,000 metallic fuel pins were reprocessed and refabricated in the EBR-II Fuel Cycle Facility, based on an early pyrometallurgical process with some characteristics similar to that now proposed for the IFR.

Except for the continuing development of metallic fuel as the driver fuel for the EBR-II, the national fuel development program in the late 1960's began to concentrate on the development of oxide fuel. At that time, it was perceived that metallic fuel could not achieve high burnup or the high temperature performance essential for economical operation.

Discoveries at EBR-II in the late 1960's along with design developments and irradiation experience in the 1970's have changed the picture completely. Metallic fuel can now be designed for high burnups and superior irradiation performance.

The extensive EBR-II driver fuel experience is based on the uranium-based alloy, uranium-fissium. For the IFR application, the recycle of plutonium is essential, and the best plutonium-bearing alloy for irradiation performance is U-Pu-Zr. Since the database on U-Pu-Zr metallic fuel is rather sparse, the irradiation performance demonstration of this new metallic fuel has been the focus of recent development efforts at Argonne.

The lead irradiation tests on the new U-Pu-Zr metallic fuel in EBR-II have now surpassed 185,000 MWd/T burnup, far exceeding their design goal burnup of 100,000 MWd/T. This is a major technical accomplishment, and the high burnup capability of the new metallic fuel is now fully demonstrated. Important results were also obtained from in-reactor tests of fuel pins tested beyond cladding breach, showing the benign behavior of breached pins. The initial breach of the fuel pin did not degrade with further irradiation even after 223 days of operation beyond breach. This demonstrated another facet of the superior performance of the metallic fuel.

Another key feature of the IFR concept is pyroprocessing. Pyroprocessing, which utilizes high temperatures and molten salt and molten metal solvents, can be advantageously utilized for processing metal fuels because the product is metal suitable for fabrication into new fuel elements. Direct production of a metal product avoids expensive and cumbersome chemical conversion steps that would result from use of the conventional PUREX solvent extraction process.

The key step in the IFR process is electrorefining, which provides for recovery of the valuable fuel constituents, uranium and plutonium, and for removal of fission products. In the electrorefining operation, uranium and plutonium are selectively transported from an anode to a cathode, leaving impurity elements, mainly fission products, either in the anode compartment or in a molten salt electrolyte. A notable feature of this process is that the actinide elements accompany plutonium through the process.

Over the past few years an extensive series of electrorefining experiments has been completed. Uranium-plutonium metal has been successfully electrorefined in small-scale experiments. Large-scale experiments have continued with uranium metal only because of a security limitation on the amount of plutonium that is allowed on the Argonne-East site where the process development is done. At present, transfers of 10 kg of uranium on a single cathode are being carried out routinely. This is close to plant scale.

Solid technical accomplishments have been accumulating year after year in all aspects of the IFR development program. But as we make technical progress, the ultimate potential offered by the IFR concept as a next generation advanced reactor becomes clearer and clearer. The IFR concept can meet all three fundamental requirements needed in a next generation reactor.

FIRST REQUIREMENT: BREEDING

The next generation reactor should be capable of meeting large energy demands, demands that are a substantial fraction of the total energy needs of the future. Rising concern about the greenhouse effect reinforces the need to reexamine the requirements of a next-generation reactor concept so that it can contribute significantly toward substitution for fossil-based energy generation.

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Even with only the limited nuclear capacity online today, worldwide reasonably assured uranium resources would last for only about 50 years. If nuclear is to make a significant contribution, breeding is a fundamental requirement. Breeding is not needed today, and probably not in a decade or two either. However, it is certain that it will be needed, if nuclear is to contribute significantly toward the future energy demands. The IFR can extend uranium resources by a hundredfold, making nuclear essentially the same as a renewable energy source.

SECOND REQUIREMENT: SAFETY

The next generation reactor should have inherent passive safety characteristics and should also be simple to operate. 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. The TREAT experiments performed to date(3) 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.

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 1. Both the LOFWS and LOHSWS accidents are perfectly benign in a properly designed IFR.

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 2 and 3. More detailed data can be found in a collection of papers prepared for these tests(4). 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.

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

Sodium has another remarkable characteristic. It is noncorrosive to the reactor structural materials. The buildup of corrosion products in the reactor systems and components, which plagued the water cooled reactors, is not an issue for the IFR. Access for maintenance is easy and radiation exposures to plant personnel are very

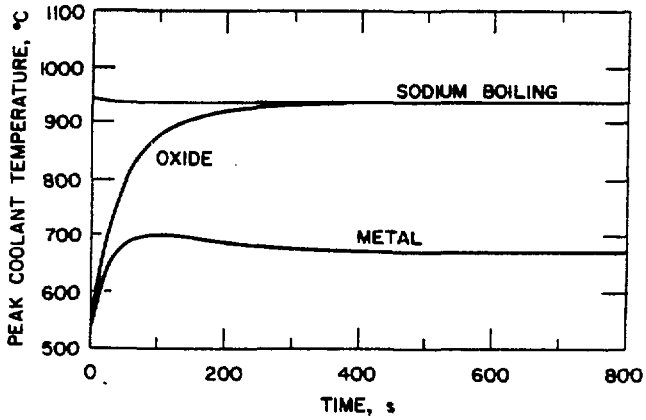

Figure 1--Loss-of-flow without scram for large reactors.

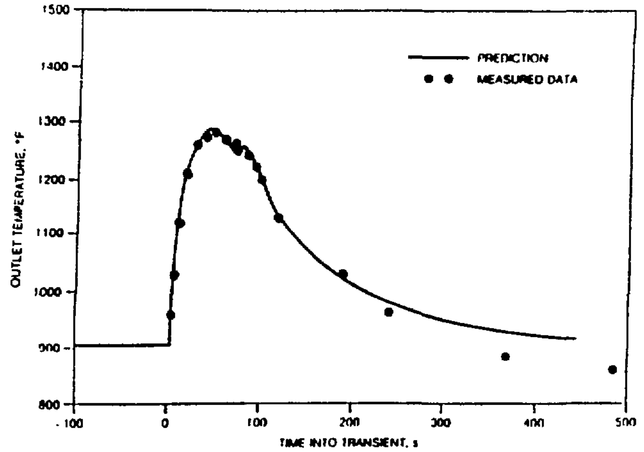

Figure 2--Loss-of-flow without scram test in EBR-II.

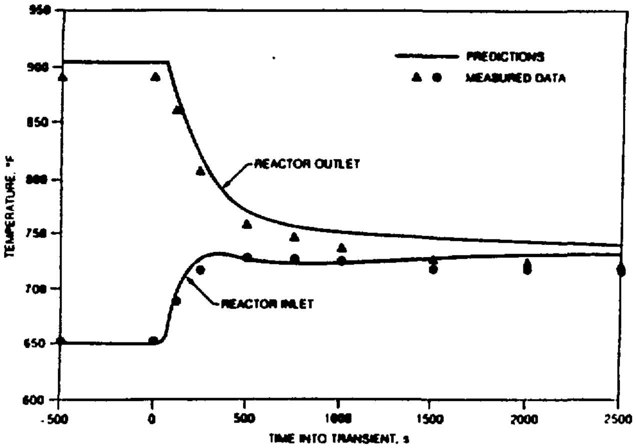

Figure 3--Loss-of-heat-sink without scram test in EBR-II.

low. Noncorrosive coolant also implies reliable sodium components performance and improved plant availability. The original EBR-II steam generators have operated without leaks over 25 years of continuous service. EBR-II achieved 81.3% capacity factor in 1987 and 79.4% in 1988, even with frequent refueling and other outages to accommodate the various irradiation tests. The sodium pool also acts as a buffer between the reactor and the balance-of-plant (BOP), so malfunctions in the BOP systems do not challenge the safety of the reactor system. The plant control system can be simplified by taking advantage of these kinds of reactor system responses. An initial series of tests was successfully conducted in EBR-II during the past year to demonstrate these newly-realized excellent operability characteristics.

THIRD REQUIREMENT: WASTE MANAGEMENT

Nuclear waste is now the factor that probably most influences public acceptance of nuclear power so the next generation reactor should have specific technical solutions to deal with the high level waste disposal. High level nuclear waste is composed of two major constituents: fission products that are produced in the fission process and transuranic elements, or actinides, that are produced as a result of neutron capture. From a radiological risk viewpoint, actinides dominate in the long term. The relative radiological risk factors for fission products and actinides are presented in Figure 4 for LWR spent fuel. In a time span of the order of a few hundred years, the fission products decay to a sufficiently low level that their radiological risk factor drops below the cancer risk level of the original uranium ore. Actinides, on the other hand, typically have very long half-lives and their radiological risk factor remains orders of magnitude higher than that due to fission products for tens or hundreds of thousands of years. Therefore, there is a strong incentive to separate actinides and recycle them back into the reactor for in-situ burning.

IFR pyroprocessing has two distinct advantages for separating actinides from the waste stream. First of all, most of the actinides accompany the uranium/plutonium product stream in the IFR process, and the remaining actinides can then be separated from the waste streams more easily than in the PUREX process. The hardened

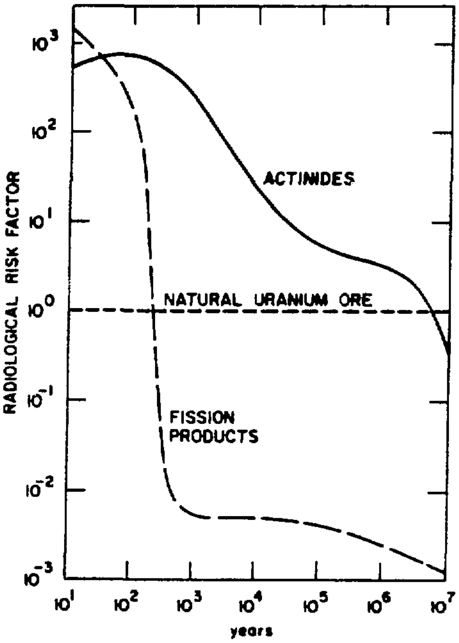

Figure 4--Relative radiological risk factor of fission products and actinides in the LWR spent fuel, normalized to their original uranium ore (data source: Reference 5).

IFR neutron spectrum is better for actinide burning than that of any other reactor type. Thus the potential of the IFR concept to make actinide recycling practical is very promising.

But it should also be realized that even if the actinides are removed and the radiological lifetime of the high-level waste is reduced to a few hundred years, the need will remain for a geologic repository. The everlasting nature of the waste is eliminated, but for decades the activity will still be high and a geologic repository would be still required to store such high-level wastes, regardless of the actinide contents. The benefit of recycling actinides is in the fact that the effective lifetime of the nuclear waste is reduced from millions of years to a few hundred years. This should have enormous impact on assuring the integrity of containment of high-level waste for its lifetime and should also impact ultimately on the public acceptance of nuclear power.

CONCLUSION

We are at a critical juncture in IFR technology development. The breeding principle has long been established. The inherent safety potential has been demonstrated through actual plant tests at EBR-II as well as experiments at TREAT. The key next step is to demonstrate the IFR fuel cycle, including the waste treatment processes. Rapid progress is being made to allow a prototype demonstration of the entire IFR fuel cycle in conjunction with EBR-II to begin in October 1990.

The IFR technology is based on major innovations and radically new processes. The progress to date has been substantial in terms of real and tangible scientific accomplishments. It is easy to cite dramatic improvements or high potential in paper studies. Proving improvements and demonstrating potential through laboratory experiments and plant-scale demonstrations require a real R&D and a prooftesting and experimental infrastructure to support it. The test facilities at ANL-West play a crucial role: EBR-II for irradiation tests and plant testing, TREAT for accident-simulating transient fuel tests, ZPPR for physics tests, HFEF/N for destructive and nondestructive fuel examinations. and HFEF/S for fuel cycle demonstration. These facilities, coupled with the first-rate technological expertise in all reactor-related disciplines that is present at Argonne have given us the IFR technology that promises a real next-generation advanced reactor technology.

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