CONF-8909263--1

FISSION ENERGY: THE INTEGRAL FAST REACTOR

Yoon I. Chang
Argonne National Laboratory
Argonne, IL 60439 USA

CONF-8909263--1

DE90 001760

Background

The Industrial Revolution initiated the era of a large-scale fossil fuel usage, and over the past 200 years we have experienced substitution of energy sources. As illustrated in Fig. 1, wood was the primary source of energy before 1850. Coal became the major source starting around 1850 and it still is a major fossil energy source. Oil and natural gas started contributing as major energy sources at the turn of this century.

The harnessing of nuclear energy especially for electricity generation has been a remarkable technological achievement. The first controlled nuclear chain reaction was achieved by Enrico Fermi on December 2, 1942 in Chicago Pile-1 (CP-1) reactor. The initial nuclear power demonstration plants started operation in the late 1950s through early 1960s. The subsequent commercialization was rapid and at the present time a substantial portion of the electricity generation is contributed by nuclear energy. As summarized in Table I, there are over 400 reactors in operation throughout the world. In many countries, the nuclear power is a major source for electricity generation. For example, in France more than two-thirds of electricity was generated by nuclear in 1988 and in Spain about one-third.

Although the fission energy has potential as a major energy source, it faces a new challenge. Following the 1979 accident at TMI-2 nuclear power plant and the 1986 accident at Chernobyl plant, the public confidence on nuclear energy has declined. Although TMI-2 was a major accident which caused extensive damage to the plant, there is no indication that any member of the public was physically harmed. The Chernobyl accident was linked to features unique to such a design, which could not have been licensed in Western countries. Lessons learned from these accidents have been incorporated into the design, construction and operation of nuclear power plants, and the nuclear power plants are expected to achieve an outstanding record for

protecting the public's health and safety and the environment, while providing needed electricity.

In a global time scale as illustrated in Fig. 1, large-scale energy production based on carbon fuels is ultimately resource-limited. Nuclear power has potential for massive carbon fuel substitution in the long-term. The present hiatus in nuclear deployment provides a time window to develop a new advanced reactor concept for a future generation application.

The Integral Fast Reactor (IFR) is an innovative reactor concept being developed at Argonne National Laboratory as a such next-generation reactor concept.

Technical Features of IFR

The coolant for the IFR is liquid metal sodium, instead of water used in most present-day commercial reactors. The single most significant property of liquid metal cooling is the atmospheric-pressure primary system. There exists an ample margin between the boiling temperature of sodium (~900°C) and the coolant operating temperatures (typically 350°C inlet and 510°C outlet). This means that the primary system can operate near atmospheric pressures, and that the thick pressure vessels that are needed to contain the high pressures in water cooled systems are not needed with liquid metal reactors. This, in turn, allows the pool configuration with a large thermal inertia, which plays a key role in achieving passive safety.

Another key feature of the IFR concept is the metallic fuel. Metallic fuel was the original choice in early liquid metal reactors because it is compatible with the liquid metal sodium coolant. Except for the continued use of metallic fuel in Experimental Breeder Reactor-II (EBR-II), the metallic fuel development as liquid metal reactor fuel was abandoned in the late 1960s in favor of the oxide fuel developed for the commercial water cooled reactors. At that time, it was perceived that metallic fuel could not achieve high burnup because the irradiation induced fuel swelling could not be restrained by the cladding. However, it was discovered at EBR-II that metallic fuel can achieve high burnup by allowing room for fuel to swell rather than trying to constrain the swelling. The fuel swelling is driven

primarily by the internal pressure of fission gas bubbles. Once fuel swells by about 30% in volume, then the fission gas bubbles interconnect and provide passage for fission gases to be released to the plenum located above the fuel rod. By adequately sizing the plenum to contain fission gases released through interconnected porosity, the fuel swelling can be easily constrained by the cladding and a high burnup can be easily achieved.

The successful EBR-II metallic fuel experience is based on uranium-based alloy. For commercial IFR application, the recycle of plutonium is essential, and the best plutonium-bearing alloy for irradiation performance is U-Pu-Zr. The irradiation performance of this new metallic fuel has been the focus of recent development efforts at Argonne National Laboratory.

The first three assemblies containing the new U-Pu-Zr metallic fuel started irradiation in EBR-II in February 1985. These assemblies, which have been examined at several burnup levels, have provided confirmation of adequate steady-state performance. After four years of irradiation in EBR-II, these lead tests have now surpassed 18.5% burnup, far exceeding their design goal burnup of 10%. This is a major technical accomplishment, and the high burnup capability of the new metallic fuel is now fully demonstrated. The typical burnup level for commercial reactors is about 3%. The burnup rate is defined as the percentage of the original fuel consumed by fissioning, and it indicates a facet of efficiency in fuel utilization. A higher burnup means a reduced fuel cycle cost because more energy is derived from given costs of making the nuclear fuel, such as uranium mining, enrichment, fabrication, fuel assembly components, etc.

A third key feature of the IFR concept is pyroprocessing. Pyproprocessing, 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 convetional 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 the 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.

The IFR concept has a number of specific technical advantages that collectively address the potential difficulties facing the expansion of nuclear power deployment. In particular, the IFR concept can meet all three fundamental requirements needed in a next-generation reactor as discussed below.

First 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 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 with 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. 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 Figs. 2 and 3. More detailed data can be found in a collection of papers prepared for these tests. 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 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.

Second 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 Fig. 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 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 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.

Third Requirement: Resource Extension

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.

Natural uranium contains only about 0.7% of U-235 isotope, which is fissionable. The remaining 99.3% is U-238, which is called fertile because it can be converted by neutron capture to fissionable Pu-239. In commercial reactors, the U-235 content is increased by a factor of 4 or 5 through enrichment process. As illustrated in Fig. 5, about 83% of original uranium (mostly U-238) is discarded as tailings in the enrichment process. Of the 17% loaded in the reactor, about 3% is burned up (including some Pu-239). The spent fuel is then stored for ultimate disposal as high-level nuclear waste. Even with Pu recycle, the total uranium utilization is less than 1% in the light-water reactor.

As illustrated in Fig. 6, essentially all uranium can be utilized for energy generation in the IFR through the breeding process. Figure 7 indicates that even with only the limited nuclear capacity on-line today and planned in the near future, worldwide reasonably assured uranium resources would last for only a few decades. 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 esentially the same as a renewable energy source.

IFR Technology Status

There are several aspects of the IFR concept still to be proven, and development programs on each are underway at Argonne National Laboratory. The major areas are demonstration of the performance of the new U-Pu-Zr ternary alloy metallic fuel, development of new electrorefining process and demonstration of the inherent safety characteristics. IFR development, which was initiated in 1985, 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 entire IFR fuel cycle including the waste treatment processes in a prototype scale. The necessary facilities are already in place. EBR-II is the natural prototype of the IFR, and its

core has been converted with the new IFR-type fuels. The original EBR-II Fuel Cycle Facility, which operated during the 1960s, has been decontaminated and is ready for the new equipment. The refurbishment of the Fuel Cycle Facility is expected to be completed by late 1990, so that a prototype scale hot operation can start in early 1991.

Table I. Nuclear Generating Capacity in 1988

	No. of Reactors	Capacity GWe	% of Electricity Generation
U.S.	110	97.2	15
France	54	52.8	70
USSR	47	34.4	11
Japan	38	27.9	28
W. Germany	22	20.8	34
Canada	18	11.8	16
UK	40	10.4	19
Sweden	12	9.7	47
Spain	10	7.4	36
S. Korea	8	6.7	47
Belgium	7	5.5	66
Taiwan	6	4.7	41
Czechoslovakia	8	3.3	27
Switzerland	5	2.9	37
Bulgaria	5	2.6	36
Finland	4	2.3	36
Others	27	9.2	-
Total	421	309.6	

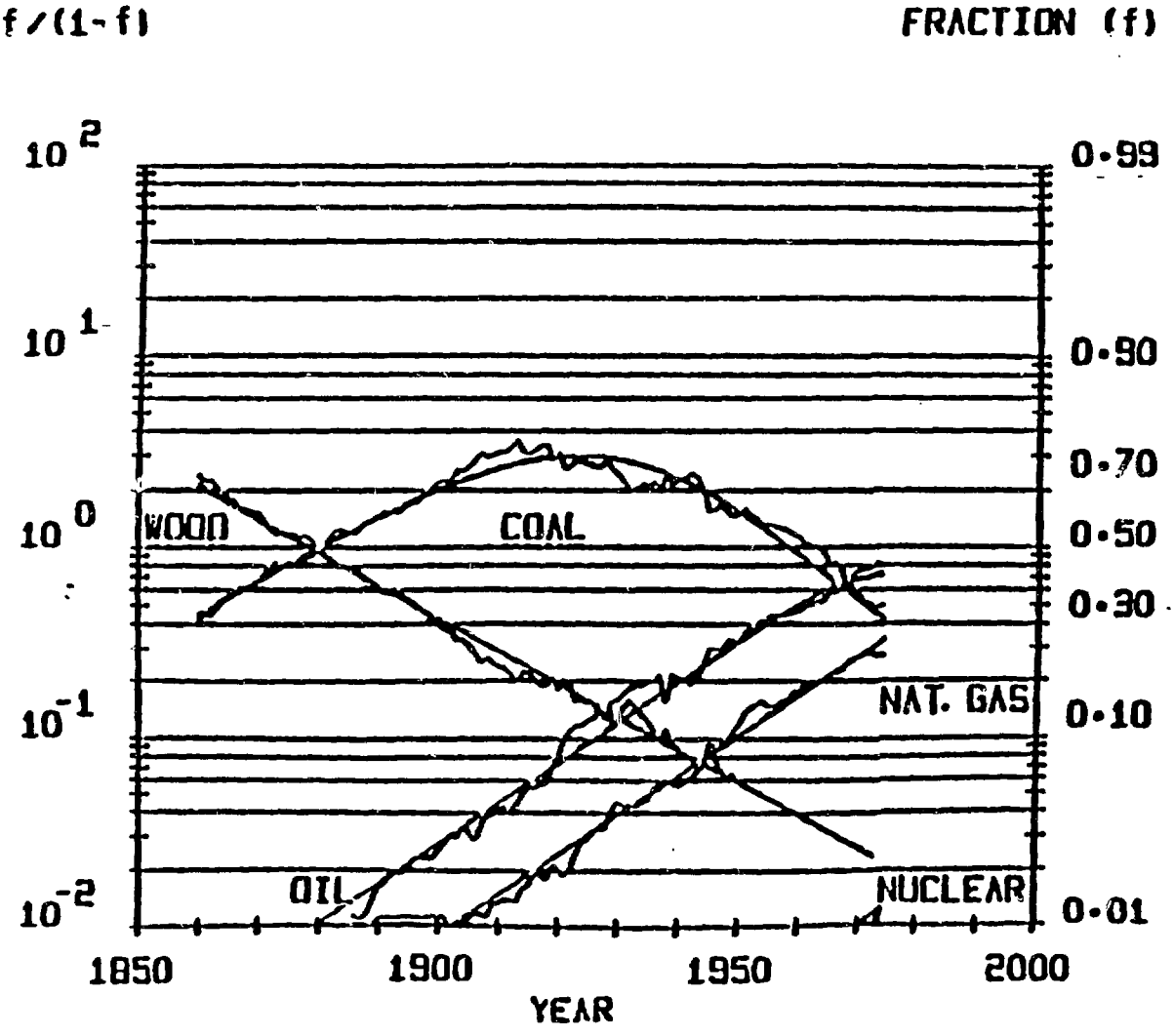

Fig. 1. Evolution of Primary Energy Sources.

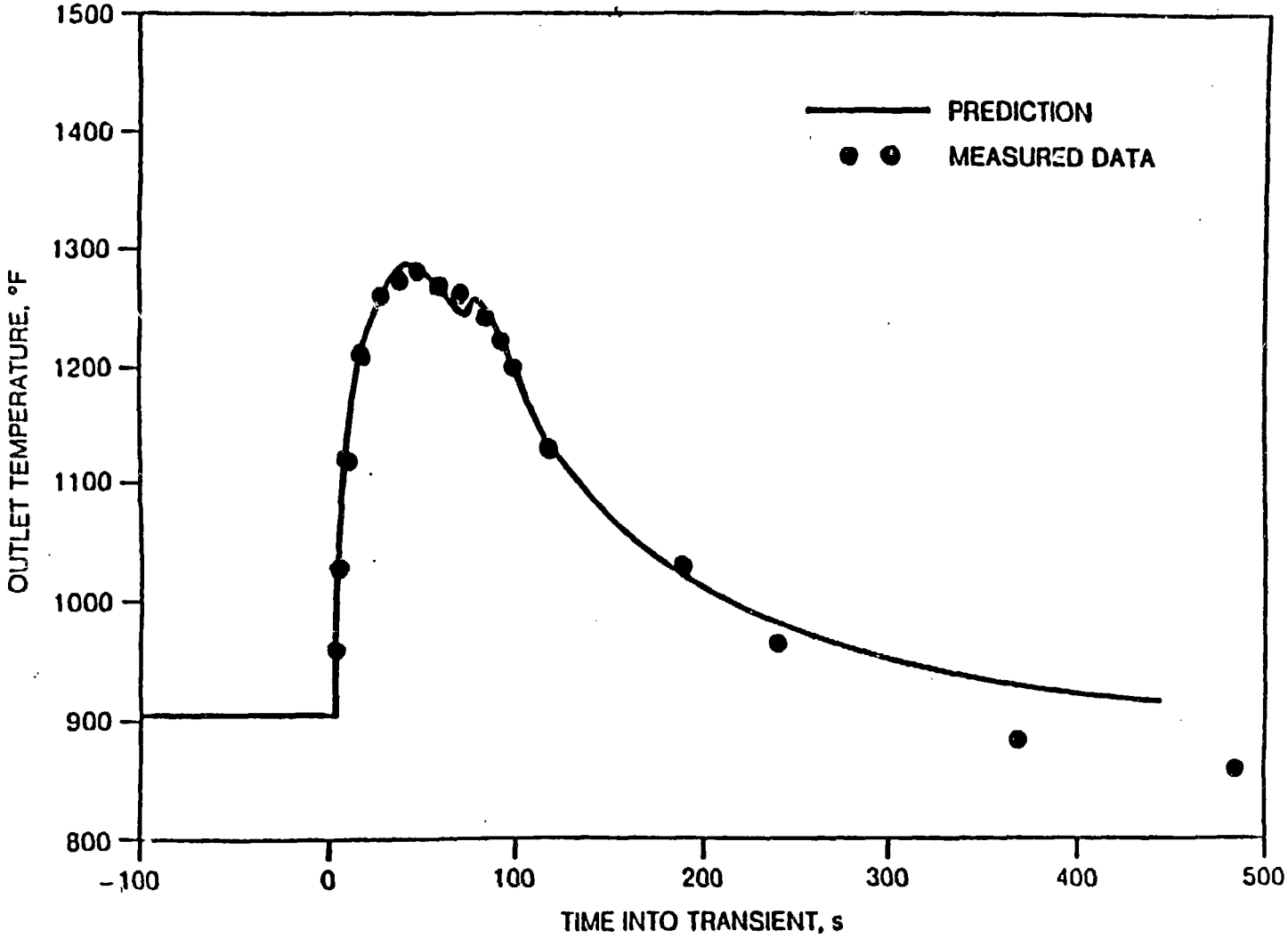

Fig. 2. Loss-of-flow Without Scram Test in EBR-II.

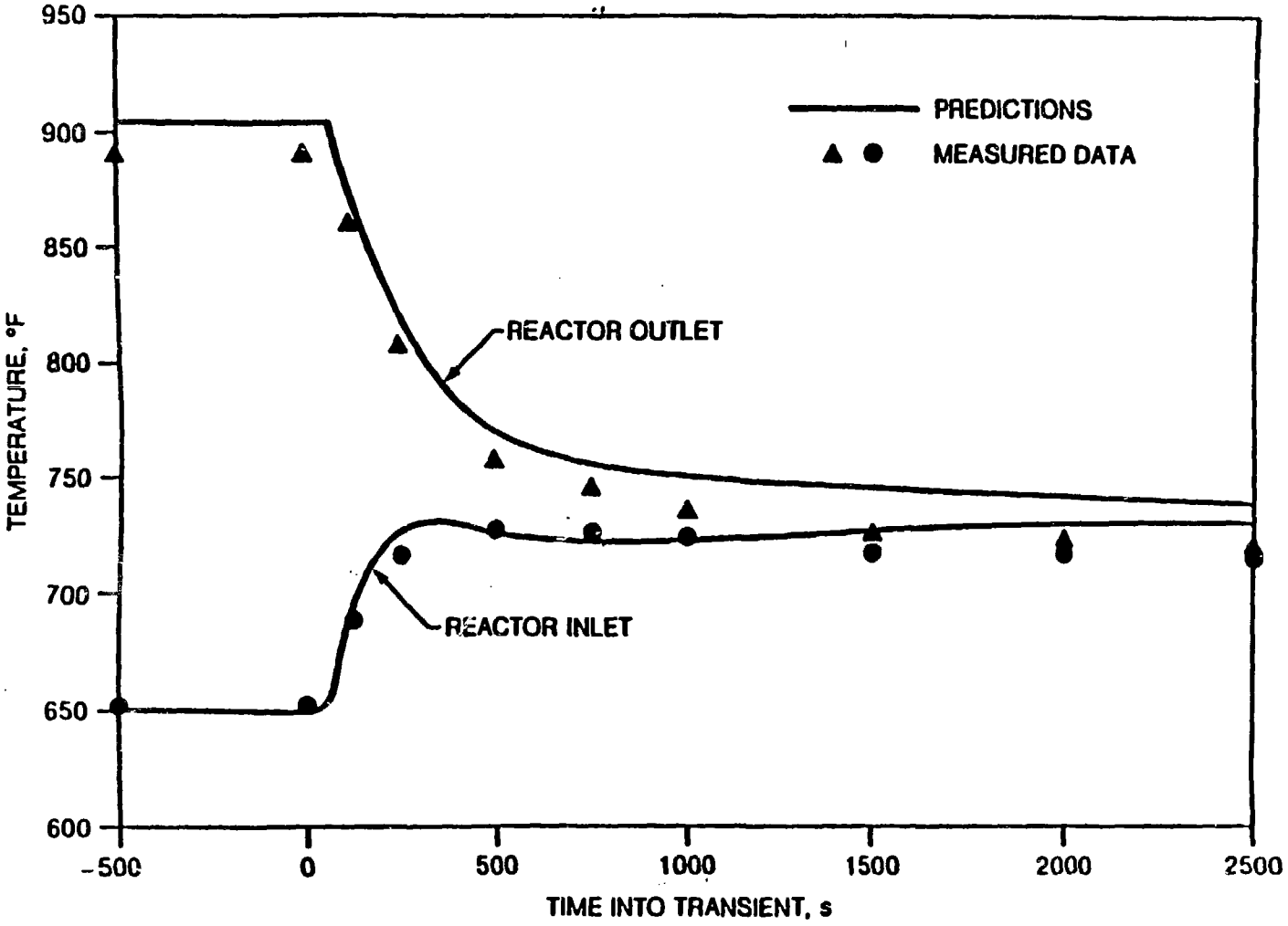

Fig. 3. Loss-of-heat-sink Without Scram Test in EBR-II.

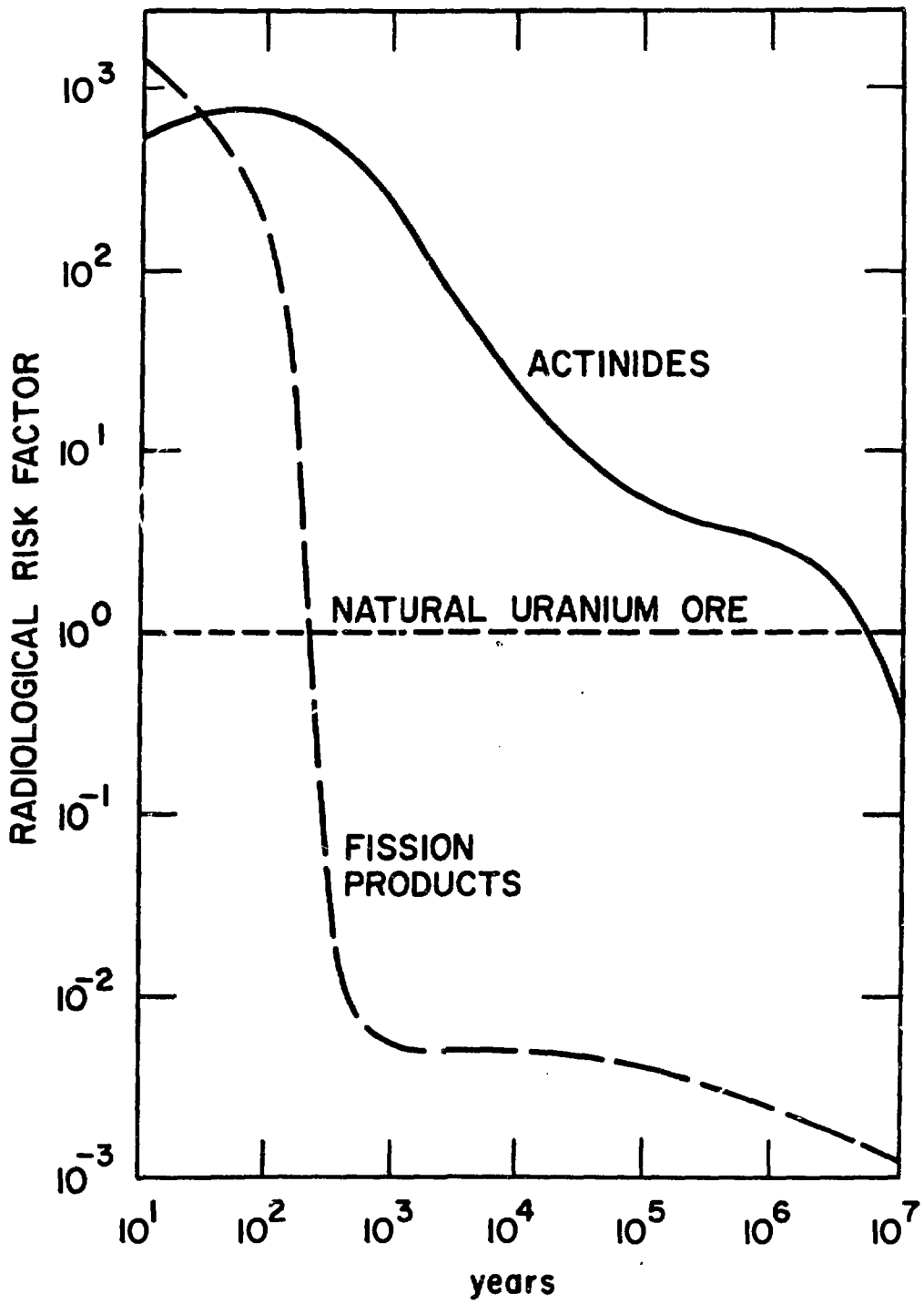

Fig. 4. Relative Radiological Risk Factor of Fission Products and Actinides in the LWR Spent Fuel, Normalized to Their Original Uranium Ore.

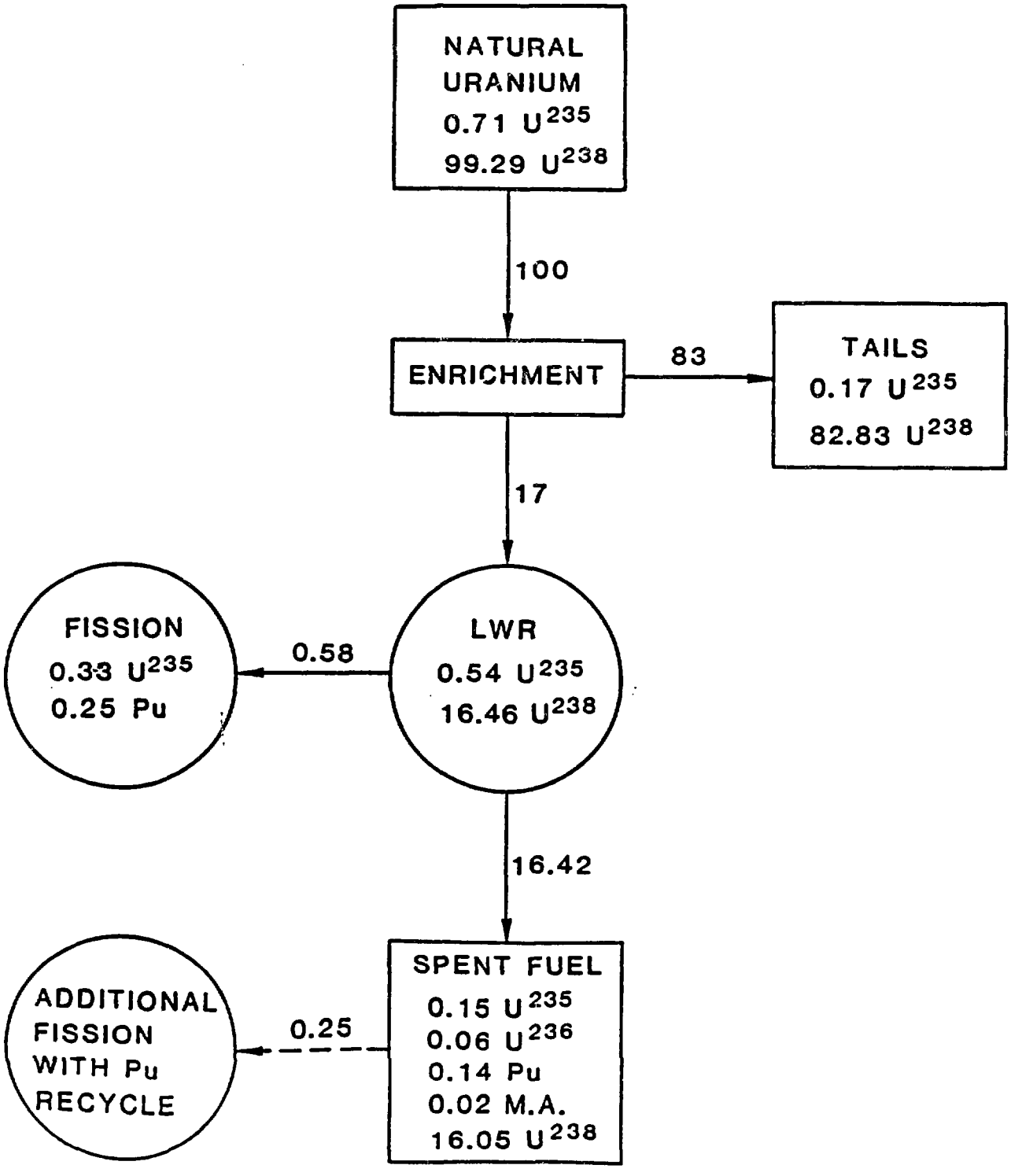

Fig. 5. Uranium Utilization in Light-water Reactors.

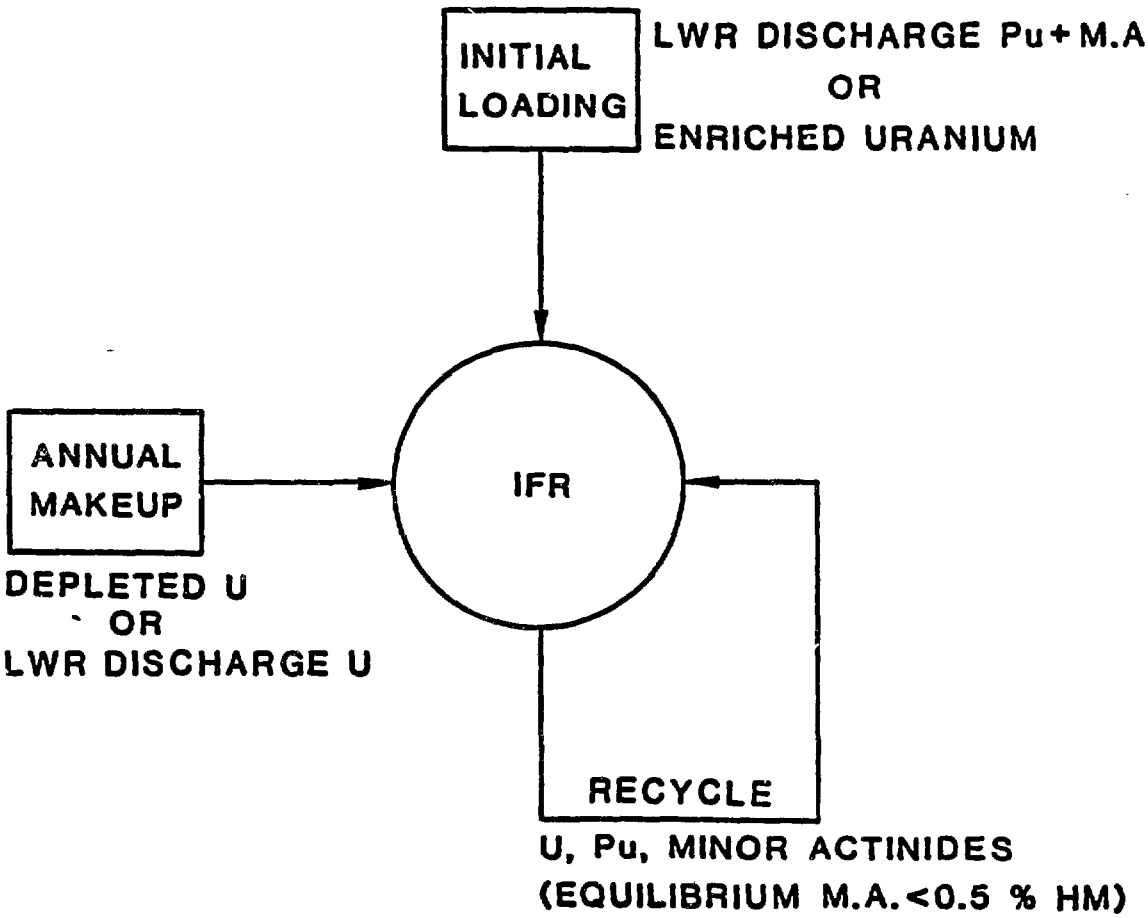

Fig. 6. Complete Resource Utilization in the IFR Fuel Cycle.

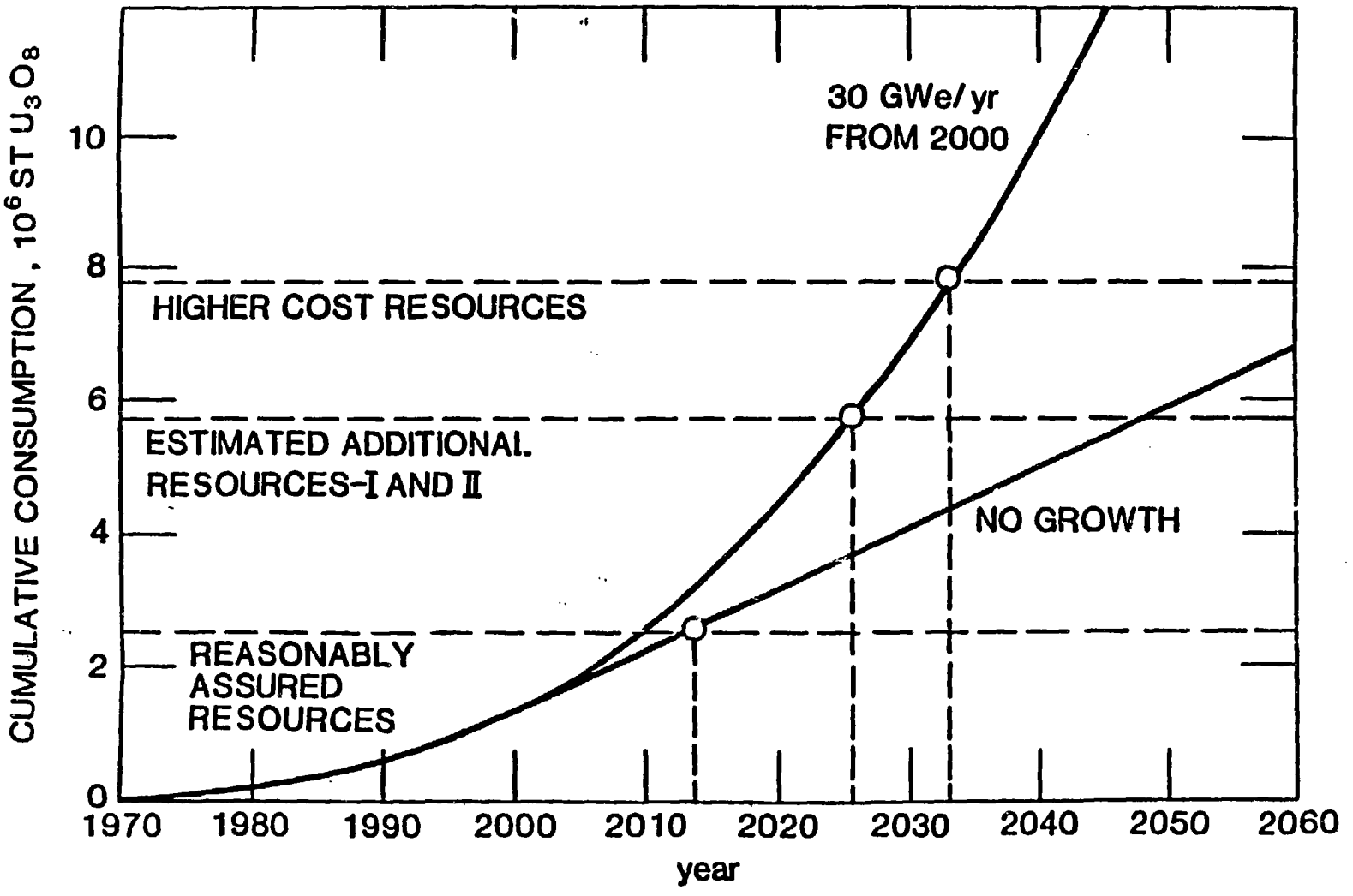

Fig. 7. Uranium Resource Usage with Light-water Reactors.