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THE INTEGRAL FAST REACTOR

by

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Argonne National Laboratory, since 1984, has been developing the Integral Fast Reactor (IFR). This paper will describe the way in which this new reactor concept came about; the technical, public acceptance, and environmental issues that are addressed by the IFR; the technical progress that has been made; and our expectations for this program in the near term.

The great surge of creative enthusiasm that marked the first decades of nuclear power development has passed. The world has deployed essentially two water reactor types -- the light-water reactor widely, and the heavy-water type less so. Other reactor types have been tried and are now stopped or stalled. Graphite moderated reactors enjoyed a number of orders in the early 1970s in this country, but all were subsequently cancelled. The Liquid Metal Fast Breeder Reactor (LMFBR), the widely accepted hope for the future, saw its prototype in the United States, the Clinch River Breeder Reactor (CRBR), cancelled, and progress elsewhere in the world has been slowed or stalled.

Yet in this period of retrenchment of advanced reactors worldwide, and therefore of an increasing trend to rely more or less completely on the current generation of reactors for the intermediate term, Argonne came forward with a proposal for the IFR, a radically different advanced reactor system. It was a breeder system (even in the face of the cancellation of CRBR). It was accepted, its basic feasibility was proven, and there is now a large, active development program in place, with the goal to put a prototype of the IFR system in full operation just a year or two from now.

Origin of the IFR

The IFR program was shaped by two key events. The first was the accident at Three Mile Island-2 (TMI-2), and the second was the cancellation of the CRBR Project. These events crystallized troubling issues that had been prevalent, but unfocused, even before the events occurred. Following TMI, it seemed clear that a revolution in the ways of thinking about safety was inevitable. As for CRBR, the real meaning of its cancellation had to be that the LMFBR, as represented by CRBR, its demonstration plant, did not meet the conditions of the times. Together these two events pointed to the need for a new advanced reactor, and it was clear that it must have a quite different set of characteristics than those that previously had been seen as important.

Among these characteristics must be breeding capability. A breeder will be needed eventually, and developing a new interim converter reactor does not address the long-term nuclear future. Next, passive or inherent safety characteristics are important, or at least there is a widespread perception that these characteristics are important. Third, the fuel cycle is the essence of the problem; the whole question of the fuel cycle and nuclear wastes and the proliferation issue (and ultimately, economic and public acceptance) are at the core of whether there can ever be widespread nuclear plant deployment, and these issues require resolution.

The key to obtaining new characteristics is the choice of the fuel and the technology of the fuel cycle. The fuel cycle is interpreted here in a broad sense, including the effect of the fuel choice on the reactor behavior itself, particularly in accident situations. It also includes whatever the fuel makes possible in processes for spent fuel and nuclear waste, and also for meeting diversion and proliferation concerns.

At Argonne we had had some rather special experience with metal fuel. Commercially metal fuel had really never been thoroughly investigated. It had been dropped early, in favor of oxide, when it was found not to sustain reasonable burnups (at only one or two percent burnup, early uranium metal alloys would swell and burst the clad). But the Experimental Breeder Reactor-II (EBR-II) because the significant exception. EBR-II was fueled with a metallic uranium alloy from the beginning. Through the 1960s and 1970s, development of metal fuel continued at Argonne, because metal had so many other attractive qualities.

By the late 1970s, the burnup problem was solved. Almost any burnup was achievable insofar as the metal fuel itself influences the lifetime. The solution turned out to be simple and is now well known: Allow sufficient initial clearance radially for the fuel to expand. With an initial 75% or so smear density, the metal is made porous enough by the accumulated fission product gases that when it does swell to the cladding (at 2% burnup or less). its porosity prevents the fuel from causing stresses sufficient to challenge the cladding integrity. By the early 1980s, the standard EBR-II fuel ran routinely to 8½% heavy metal burnup, many experimental assemblies had gone beyond 10%, and an exploratory assembly had gone past 18% burnup.

Meanwhile, the intensive looks at fuel forms and fuel cycle that Argonne had done as part of the International Nuclear Fuel Cycle (INFCE) studies of the late 1970s had raised real possibilities for both reactor safety and fuel cycle improvements with metal fuel.

The foundations for a greatly simplified fuel cycle based on metal fuel had been laid at Argonne in the late 1960s. In the period 1964-69, a crude form of pyrometallurgical reprocessing and injection casting fabrication of metal fuel had been demonstrated at the EBR-II Fuel Cycle Facility.(1) Successful though it was in demonstrating features of what has come to be known as the pyroprocess, the technology of the late 1960s was inadequate in several respects. First, it dealt only with uranium recovery, plutonium being left to an undemonstrated future process. Second, even the uranium process was incomplete in that the noble metal fission products were not separated significantly from the uranium.

Still, what was demonstrated in the late 1960s was that a simple process could be housed in a very compact facility, and remotely operated, to close the metal-fueled breeder reactor fuel cycle. During the 1970s and early 1980s, some thinking continued on methods of addressing the deficiencies of the early pyroprocess. The fabrication of metal fuels continued to be improved because the main EBR-II fuel remained a metal, and there was continuous motivation to make its fabrication as easy (and its burnup as high) as possible. But the reprocessing side of the metal-based pyroprocess became feasible, at least in principle, only with the discovery that electrorefining, useful in other applications, could be adapted to a one-step approach to reprocessing.

So by the early 1980s, the stage was set for a detailed look at what kind of reactor system a metallic fuel, now with high burnup, might make possible. It was clear that, to be seen as viable in the conditions of the day, the entire system would have to be brought along at once; reactor, fuel cycle, and waste technology.

This then was the background Fast Reactor concept, so named because all the elements of a complete breeder reactor system would be developed and optimized as a single entity and could in fact, if desired, all be made an integral part of a single plant.

The IFR is based, in one way or another, on the earlier Argonne directions made newly relevant for two basic reasons. First, new discoveries had been made within the Argonne program that indicated new possibilities in fuels, safety, and fuel cycle technology. Second, when the new factors affecting nuclear power were recognized, reactor system properties not thought to be important before now seemed very important indeed.

In the summer of 1984 the IFR program was started. The program was governed from its inception by four overriding requirements:

- Passive or inherent safety characteristics
- Economically competitive
- Environmentally sound
- Proliferation- and diversion-resistant.

For the concept to be feasible, three basic developments were needed: a specific metal alloy was required; establishing concomitant improvements in reactor safety was essential; and showing the feasibility of the new metal-based fuel cycle was perhaps the most important of all.

Fuel

The fabrication of any metallic fuel alloy promised to be cheap, and readily adapted to remote operation. The EBR-II fuel had been made at Argonne for years, with one simple casting operation instantly producing enough fuel for one assembly. As noted above, in the period 1964-69, fuel had been made remotely for EBR-II.

Yet the standard EBR-II metal fuel then available would not do, outstanding in-reactor though it was, because it didn't use plutonium. In a closed cycle breeder system, plutonium is the bred material, so any IFR alloy had to include plutonium.

The alloy selected was a (Uranium-Plutonium)-Zirconium alloy that had very limited trials in the late 1960s, but appeared to have the basic characteristics needed. It used plutonium; it had a high melting point and a high eutectic point with stainless steel, even higher than those for EBR-II fuel.

But would the U-Pu-Zr alloy provide adequate burnup? In the fall of 1984, a new plutonium fuel fabrication capability was put in place. The Experiment Fuels Laboratory, or EFL, was created in just four months, once again demonstrating the simplicity of the fabrication process. Early in 1985, three lead assemblies of the new IFR fuel were put into EBR-II.

The fuel development has been a remarkable success. In Fig. 1, the improvement in burnup through the years is shown, for the uranium-bearing alloy before -1988, and more recently for the IFR alloy. Experience with the latter is examined in more detail in Fig. 2, where the present data base on IFR-alloy metal fuel is depicted (these are intact fuel elements either discharged from EBR-II at the burnups shown, or still in the reactor with present burnups quoted). The data base with IFR fuel will now grow at a significant rate, for as of the beginning of 1989, EBR-II was completely fueled with prototypic IFR alloys.

Safety

It was important to demonstrate the unique safety properties made possible in the IFR with the use of metallic fuel. On April 3, 1986, two carefully planned tests were carried out.(2) From full power in EBR-II, with the normal safety systems temporarily bypassed, the power to the primary pumps was shut off, simulating station blackout, or loss-of-flow without scram. The reactor shut itself down without safety-system or operator action, because of the reactivity feedback characteristics of the IFR. No damage occurred to either the fuel or to any of the system structures. Later in the day, the reactor was brought back to full power and a loss-of-heat sink without scram test was also carried out. The result again was without harm of any kind. These tests dramatically demonstrated what is possible for incorporating passive safety features in IFR plants.

Parenthetically, later in that month, the Chernobyl accident occurred and the stark contrast between the consequences of these two loss-of-flow events in the same month gave much added impetus to IFR development.

EBR-II is an electricity-generating power reactor, which although small (20 MWe), has a power density typical of that in larger fast reactors. The features of EBR-II which allowed it to shut itself down in these two tests, are typical of larger IFR plants as well.

The third of the classical fast reactor Anticipated Transient-Without-Scram (ATWS) events, the transient overpower (TOP) accident, is also reduced in consequence because of the metal fuel. The higher core conversion ratio offered by the higher fuel atom densities achievable with metal gives rise to reduced reactivity swings during a cycle. This in turn reduces the control requirements, allowing lower-worth control rods. The initiator of TOP events is the control rods and the transient initiated by control rod withdrawal, can be made much less severe than would otherwise be the case. The goal is to limit the available excess reactivity contained in control rods to levels which would cause no damage if inadvertent rod runout at power were to occur.

The safety case is further strengthened by the fact that significant margin exists before fuel failure would occur in fast reactivity transients. Tests in the TREAT reactor have demonstrated that power levels can be increased by 4.5 times above normal before fuel failure occurs, and this motion of the fuel in the cladding acts to shut the reactor down. Tests at EBR-II addressing other plant transients, such as overcooling associated with a sudden increase in the speed of coolant pumps or a rapid depressurization of the steam system, have also been done and show that they can also be accommodated without safety system action.(3)

Fuel Cycle

Metal fuel opens up the possibility of using a much different process for reprocessing spent fuel, and this process is described more fully elsewhere.(4) Electrorefining, instead of solvent extraction, can be used. Electrorefining has very different properties, and some of them are very advantageous.

The basic process is electrochemical. The fuel to be processed forms the anode of an electrolytic cell. The electrolyte is a molten salt and the product heavy metal is collected on a cathode. Proper selection of the voltage draws uranium and plutonium from the spent fuel, leaving the fission product waste behind. The separation is done in this single step, at relatively low temperatures (about 500°C) and the device in which this is done is very small and compact; a 1.5 m diameter module would be sufficient for a CRBR-size plant. The process separates uranium and plutonium from the fission products adequately for fast reactor purposes, but leaves a highly radioactive diversion-resistant product.

Development began on a few-gram scale, and both a uranium-only process (necessary to recycle uranium for the breeder blanket) and a uranium-plutonium process (for the core) are now proven. The two processes differ only in cathode design. The uranium-only process has now been scaled up and operates routinely at plant scale, about 10 kg per cathode (see Fig. 3). The U-Pu process scale-up awaits the completion of our Idaho fuel cycle demonstration facility.

In tests conducted recently, fuel segments sheared from a fuel element irradiated to 10% burnup have been successfully dissolved in an experimental apparatus. This was done electrolytically, essentially the reverse of electrorefining. We found that the heavy metal could be driven quantitatively from the cladding (only 0.04% of the heavy metal remained) in a one hour period. We thus have evidence that within a single electrorefiner, fuel can be successfully dissolved electrolytically, and electrotransported selectively to cathodes. The key reprocessing steps of dissolution and separation are thus achievable in a simple, compact, piece of equipment.

Importantly, also we have found that the transuranics go with the product, so the waste product radiological lifetime is dramatically reduced, since the transuranics can be recycled and burned in the reactor. In an IFR reactor, with the high-energy neutron spectrum unique to a metal-fueled fast reactor, these elements are efficiently fissioned, and essentially provide more fuel, not waste.

Future IFR Program Activities

The basic feasibility of all elements of the IFR have now been proven. The next important step will be to close the fuel cycle at EBR-II. EBR-II is our prototype. It is sodium-cooled; it is a pool-type reactor configuration; it is now completely fueled with IFR fuel; and when we have the new processes in operation, we will have the complete prototype -- integral cycle and all. It will demonstrate each of the essential features of the IFR: Passive safety, ease of operation, fuel performance, reprocessing and recycle, and transuranic burnup to improve the waste form.

Modifications are in progress to fully demonstrate the new fuel cycle at the EBR-II Fuel Cycle Facility. Following its use in the 1960s, this facility was converted to an examination facility (and re-named the Hot Fuel Examination Facility/South). The facility is being modified to bring it up to today's level of standards and regulations for such a facility. The facility modifications are detailed elsewhere.(5) Briefly, they are: (1) confinement improvements, (2) provision of a new class 1-E emergency power system, (3) installation of a new safety-class exhaust system, and (4) construction of a new area within the facility in which to repair contaminated equipment. All of the work associated with these four areas is scheduled for completion in September 1990.

The process equipment is now in fabrication. There are nine items of main equipment (all quite compact, in all cases able to pass through a 2 m diameter, 2.5 m tall transfer lock):

- assembler/dismantler machine
- element chopper
- electrorefiner
- cathode processor
- injection casting furnace
- pin processor
- element settling furnace
- element welder
- leak-detection module

Together with a small amount of other support equipment, all these equipment items are also scheduled for installation in the hot cells in September 1990, ready for cold operations.

In early 1991, we will start reprocessing and refabricating fuel for EBR-II, and the Fuel Cycle Facility will have a dual mission: produce all the fuel needed for EBR-II, and serve as a test bed for optimization of the process.

There is still basic development to be done, and this will be going on simultaneously with fuel cycle operations and experiments in FCF. But through the early 1990s, the IFR prototype will be recycling fuel; the recycled fuel will be tested and proven and the whole system (fuel, fuel cycle, and waste process) optimized.

All of this will be done on the ANL-Idaho site, which has all the necessary facilities, and all done without large expenditures. Our colleagues from General Electric, with the PRISM system based on the IFR, will be ready -- and perhaps others as well -- to proceed with the next step.

And what does the IFR promise?

- In safety, fuel with larger overpower margins, resilience to transients, completely nonreactive with the coolant; a reactor with built-in ability to survive both, loss-of-heat sink and loss-of-flow without scram events.

- In breeding, metallic fuel is the best possible. In addition to the obvious resource conservation reasons, this also allows the limited control rod worths that help in Transient Overpower (TOP) situations, adding again to safety.

- A simple closed fuel cycle, with recycle, and reuse of uranium, plutonium, and the other transuranics as well. All transuranics go with the fuel product, and are not left in the waste.

- Recycled plutonium fuel always accompanied by uranium, always carrying the other transuranics, and some small amount of fission products as well, removing diversion concerns, and adding nothing incremental to proliferation risk.

- No transportation of fuel, or spent fuel, and if desired on-site storage of wastes for the life of the plant.

- A waste product that has all long-lived transuranics removed, such that the carcinogenic risk from the waste has decayed to less than the original ore in about two hundred years. A change in the kind of risk, not just in degree, in the product the public is asked to accept in waste disposal.

Although no one attribute may make the case by itself, taken together all its attributes make the IFR system a truly revolutionary improvement in fission energy for the future.

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EBR-II DRIVER FUEL BURNUP CAPABILITY

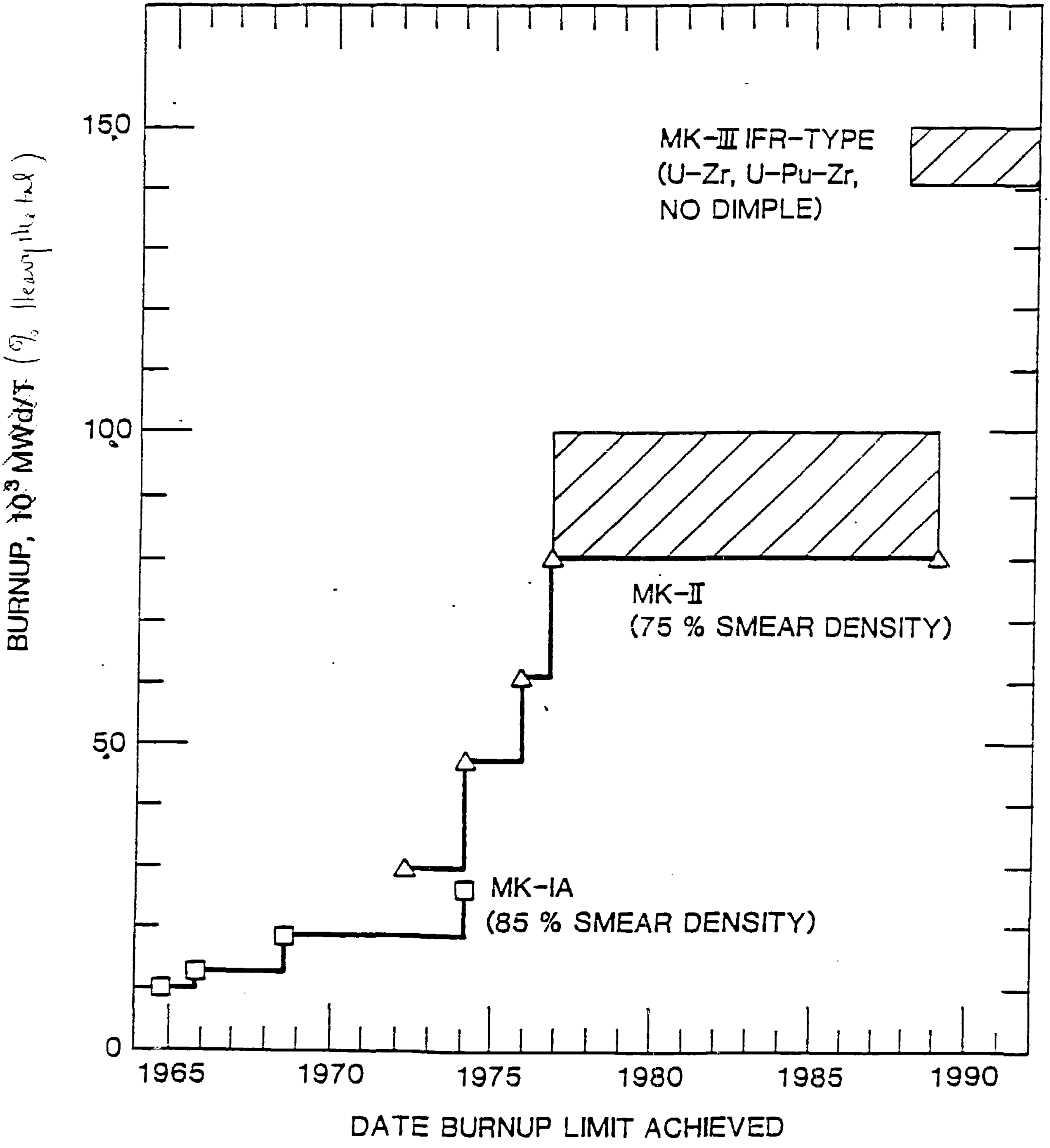

Figure 1: EBR-II Metal Fuel Burnup Capability

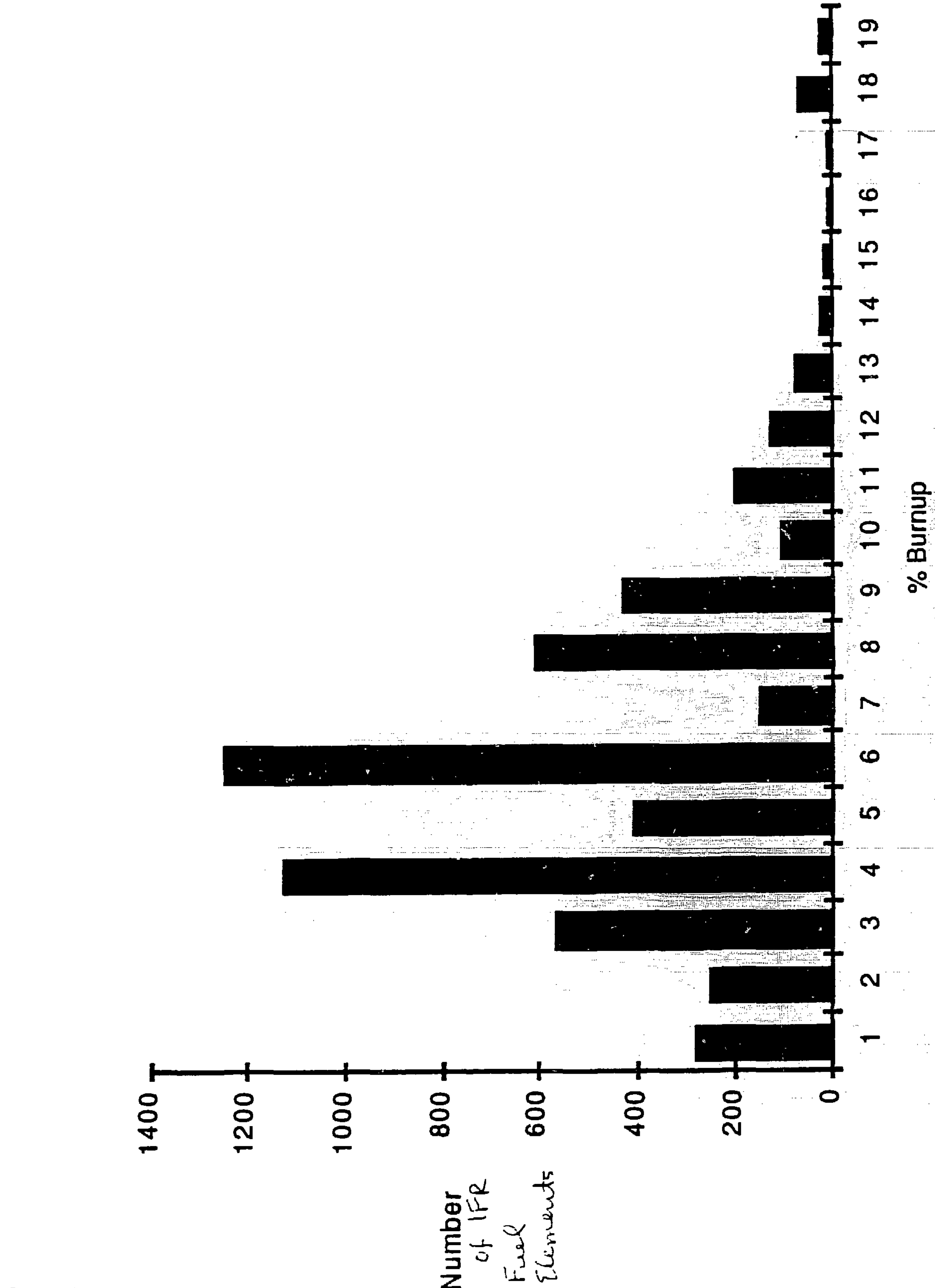

Fig. 2. Histogram of IFR Fuel Element Burnup in EBR-II.

Fig. 3. Uranium Cathode Deposit
(approximately 10 kg product)