CONF-860422--1

DE86 010502

Received by OSTI

MAY 1 9 1986

CONF-860422--1

Proceedings of the American Power Conference

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THE INTEGRAL FAST REACTOR CONCEPT

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ABSTRACT

The Integral Fast Reactor (IFR) is an innovative LMR concept, being developed at Argonne National Laboratory, that fully exploits the inherent properties of liquid metal cooling and metallic fuel to achieve breakthroughs in economics and inherent safety. This paper describes key features and potential advantages of the IFR concept, technology development status, fuel cycle economics potential, and future development path.

KEY FEATURES

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.

The IFR fully exploits the inherent properties of liquid metal cooling to achieve breakthroughs in economics and safety. 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 (~1600°F) and the coolant operating temperatures (typically 650°F inlet and 950°F 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, allowing pool configuration with large thermal inertia. To take full advantage of this property, a complementary selection of fuel material is required.

The metallic fuel provides the critically important property of high thermal conductivity giving a low-temperature fuel with negligible positive reactivity feedback on power reduction. The combination of a large coolant thermal inertia and negligible positive feedback on power reduction gives a high degree of inherent safety.

Once the decision is made to adopt metal fuel, a few-step compact metallurgical processing, and a few-step simple casting fabrication, become possible, providing the potential for real economic breakthroughs. Superior neutronics follow automatically, and can also be utilized in a number of ways to improve the system, including breeding when necessary in the future.

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 the pyro-process similar to that proposed for the IFR. A schematic of EBR-II Reactor and Fuel Cycle Facility is shown in Figure 1.

There has been a few technology developments during the past decade that changes the outlook for metallic fuels and the pyrometallurgical fuel cycle.

First, it is developments in metallic fuel design of recent years that now make IFR a promising development choice. Metallic fuel was originally downgraded because of its poor irradiation behavior in the 1950's and early 1960's. Discoveries at EBR-II in the late 1960's and design developments and irradiation experience in the 1970's totally changed the picture. Generic metallic fuel can be designed now for very superior irradiation performance. Over twenty thousand older-design EBR-II fuel pins achieved their 80,000 MWD/T design burnup without an individual failure. With simple design changes the EBR-II new fuel now has a design burnup of 140,000 MWD/T. The evolution of burnup limit for the EBR-II driver fuel is shown in Figure 2. This figure illustrates only the trend in operating limits. There are over 2,500 pins that actually achieved burnups greater than 100,000 MWD/T. In fact, one full assembly of 30 pins achieved 185,000 MWD/T.

Secondly, very recent metallurgical processing discoveries and developments have radically altered both the process itself and the outlook for major breakthroughs in both fuel and blanket processing. Pyroprocessing was not fully adequate 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 two new steps, one for the fuel and one more for the blanket. Electrorefining, using a liquid cadmium anode and a fused chloride salt, extracts the fuel uranium-plutonium mixture from the dissolved mixture of fuel, steel, and fission products at temperatures around 500°C with low losses in a single step. Halide slagging of the blanket material again using a fused chloride salt, with controlled addition of oxidant,

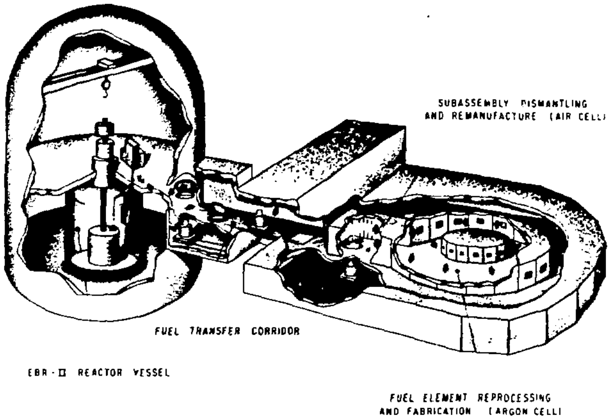

Figure 1--EBR-II Reactor and Fuel Cycle Facility.

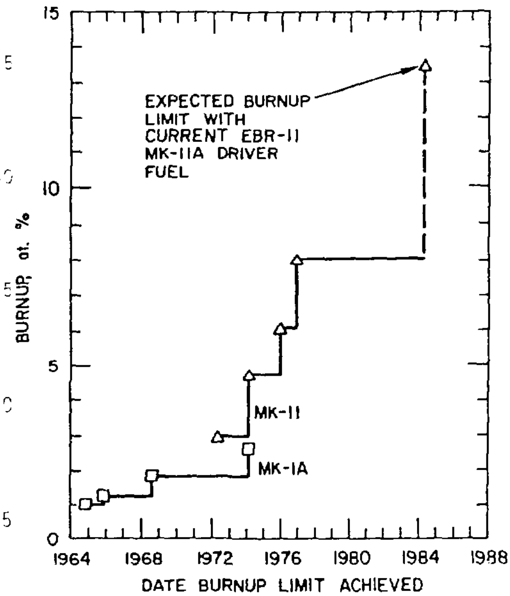

Figure 2--EBR-II Driver Fuel Burnup Capability.

enriches the blanket product in plutonium sufficiently for feed to the fuel product.

Thirdly, very recent fabrication developments have simplified metallic fuel fabrication even further. EBR-II fabricates its own fuel. Until recently an alloy preparation step was required in addition to the casting step (which produces about 100 pins at a time). IFR-related development now allow both to be done in a single step.

Finally, accumulating evidence from relatively recent theoretical and experimental investigations indicate that the safety characteristics of metal fuel are in all cases either superior or equal to that of oxide fuel.

POTENTIAL ADVANTAGES

The IFR concept has a number of specific technical advantages that collectively address the potential difficulties facing the LMR today. These advantages are in the areas of fuel performance, fabrication, reprocessing, safety, economics, waste, transportation, diversion and theft resistance, and flexibility in plant size and deployment strategy.

The potential features and advantages of the IFR are the following:

1. The system has excellent fuel performance. Metal fuels have now been developed to allow extremely high burnups, at least as high as oxide fuel. Metal fuel was the original choice in early reactor development and has a strong neutronic advantage over oxide fuel. The reason it was supplanted by oxide fuel many years ago was at that time metal fuel could only achieve a low burnup, approximately 10,000 MWD/T.

2. The IFR metal fuel is extremely easy to fabricate. The injection-casting technique used for EBR-II fuel for many years produces fuel pins in a process far simpler and more direct than that used to produce pelletized oxide fuel.

3. Reprocessing techniques involving pyrometallurgy and electrorefining can remotely, quickly, and simply reprocess the fuel. This process is much smaller and simpler than the standard Purex process used for oxide fuel.

4. The metal fuel promises a much higher degree of inherent safety, with better safety characteristics all across the board from normal behavior all the way to postulated severe accidents.

5. The IFR economics, both the plant capital cost and the fuel cycle cost, are expected to be in the LWR range, and significantly better than for other LMR choices.

6. The amount of radioactive waste is minimal and can be easily managed.

7. Because the fuel is always highly radioactive during reprocessing and refabrication and need never leave the nuclear plant, the problem in transportation of radioactive material over significant distances can be avoided.

8. Because of the above features, the IFR also has very strong theft and diversion-proof characteristics.

9. The system is extremely flexible with respect to size of plant and deployment strategy. The system is equally well suited to designs all the way from the 100 MWe range to the above 1000 MWe range. Similarly, the IFR is well suited to a single plant or to a reactor park with a small number of plants, and even to a many reactor plant deployment strategy.

TECHNOLOGY DEVELOPMENT STATUS

There are several aspects of the IFR concept still to be proven; namely, demonstration of U-Pu-Zr fuel performance, development of new pyroprocesses involving electrorefining and halide slagging, and demonstration of safety characteristics. The 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 a substantial progress has been made to date.

FUEL PERFORMANCE DEMONSTRATION

The basic physical properties of the IFR fuel and the fuel/cladding interactions over a range of conditions, compositions, and temperatures have to be established. This work is proceeding across the board at the present time. Out-of-reactor experiments to establish the compatibility of the IFR fuel with advanced cladding materials, to characterize the distribution of the alloying elements within the fuel, to measure the thermal and physical properties of the fuel, and to establish calculational methods of modeling the fuel behavior, are all underway.

Another major objective is to expand the IFR U-Pu-Zr fuel irradiation data base to provide the technical bridge between this alloy and the extensive EBR-II data base already in hand on a related metal fuel. The initial task was to quickly establish the capability for IFR U-Pu-Zr fuel fabrication, then to fabricate prototypical fuel subassemblies for irradiation in EBR-II and FFTF.

The fuel fabrication capability is now fully operational. A single step injection-casting capability for U-Pu-Zr fuel has been fully developed and the newly established Experimental Fuels Laboratory (EFL) has successfully produced over 100 batches fuel castings. The lead irradiation test assemblies in EBR-II have reached burnup in excess of 50,000 MWD/T as of February 1986, and are continuing their irradiation to 140,000 MWD/T or to cladding breach. Interim postirradiation examinations have been performed at various burnup levels. No failures have been seen or are expected.

PYROPROCESS DEVELOPMENT

The objective of this task is to establish the chemical feasibility of the proposed processes for recycle of discharged core and blanket materials and for disposal of the fission product waste. The major process steps are electrorefining, which will be used for the core material, and halide slagging, which will be used for the blanket. The work is to establish that product yields will be adequate, fission product removal will be sufficient, container materials and process reagents can be specified and will perform as expected, and that the processes are adaptable to remote operations.

Electrorefining experiments were successfully conducted with plutonium at 10 g scale and with uranium at 300 g scale to establish chemical feasibility. A glove box facility has been constructed to perform pilot scale experiments, and the first series of electrorefining runs in this facility has been completed, which demonstrated that uranium could be electrorefined from a cadmium anode pool using an electrolyte containing rare earth fission products at their steady-state concentration. Two halide-slagging experiments were also completed in which $PuCl_3$ was extracted into a salt phase from a molten U-Pu-Zr alloy. The results are in agreement with theoretical predictions and confirm the chemical feasibility of halide-slagging process.

DEMONSTRATION OF SAFETY CHARACTERISTICS

The overall objective of this task is to provide the experimental data to validate unique inherent safety features and fully characterize the totality of safety features associated with metal fuel through detailed analysis, calculation modeling, TREAT in-pile tests, and out-of-pile experiments.

The new metallic fuel promises sharply improved inherent safety characteristics due to some unusual properties of the fuel. Its high thermal conductivity results in a very favorable reactivity feedback characteristics under loss-of-flow accident conditions so that the severity of such events is significantly reduced.

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 generic anticipated-transient-without-scram (ATWS) events. The analytical predictions are being validated through a series of EBR-II testing that has been performed to demonstrate inherent passive shutdown capability. The loss-of-flow without scram demonstration from full power is scheduled to be conducted in EBR-II in April 1986. This test will demonstrate the ultimate inherent safety potential of the IFR because the EBR-II reactivity coefficients and test conditions are prototypical of larger size IFRs.

Further, fission gases entrapped within the fuel alloy matrix itself is expected to provide a self-dispersive mechanism that plays an important role in the termination of transient overpower accidents. Three TREAT tests performed to date demonstrate a large margin to cladding failure threshold and indicated that the fission-gas driven axial expansion in fact takes place and provides the favorable negative reactivity feedbacks.

FUEL CYCLE ECONOMICS

The radical changes in the IFR fuel cycle promise dramatic simplifications and cost reductions in all three areas of reprocessing, fabrication, and waste. All processes are extraordinarily compact and involve batch-operations. The quantification of the IFR fuel cycle economics, along with the inherent safety potential of the metal core designs, was performed in conjunction with the industrial innovative LMR design projects: PRISM designed by General Electric and SAFR designed by Rockwell International.

In order to provide a firm technical basis for quantifying the IFR fuel cycle economics, a detailed conceptual design of a commercial-scale IFR fuel cycle facility was developed with the throughput capability for a 1200-1400 MWe generating capacity, equivalent to 9 PRISM reactor modules or 4 SAFR power paks.

As illustrated in Figure 3, the fuel cycle facility is very compact: 96 ft x 105 ft, with a height of 44 ft. The key part of the facility is the inert-atmosphere process cell, which is 1760 ft^2 in area and 14 ft in height. Overhead handling systems have been eliminated through use of both process and repair robots. The process cell rests directly on the seismically qualified basement. The feed-throughs for the equipment systems come through the cell ceiling, allowing high utilization of the process-cell floor area. Also, the final fabrication of the fuel and blanket assemblies has been simplified, which permits much of the work to be done out-of-cell.

The facility size and process cell volume are very small, less than equivalent Purex facility by a large factor. Similarly, a capital cost reduction by a large factor is expected for the IFR fuel cycle facility, as compared to a conventional Purex based fuel cycle facility of the same size. A preliminary estimate indicates that the capital costs of this IFR fuel cycle facility would be about $48 million, which includes construction of the building, provision of engineering and construction services, and procurement and installation of equipment for reprocessing, fabrication, waste packaging, and interim storage. The estimate does not include the costs associated with R&D and equipment development, nor contingencies. The annual operating and maintenance cost is estimated at only $12 million/yr, excluding the cost associated with assembly hardware supplies.

A low capital cost of the fuel cycle facility, combined with a low operating and maintenance cost, promises a very competitive fuel cycle cost even for a small-scale deployment of the IFR fuel cycle. The following IFR fuel cycle cost analysis is performed on constant 1985 dollar basis for a 1400 MWe generating capacity. It is illustrative to consider the following five components of the levelized fuel cycle cost.

Capital Fixed Charges: The capital cost estimated at $48 million is an "overnight" cost. Including the estimated allowance for funds used during construction and the owner's cost, the initial capitalized investment is $57 million. Traditionally, a higher fixed charged rate is used for reprocessing plants as compared to reactor plants, reflecting higher market risks and different capital structure of private corporations. However, for the IFR fuel cycle facility, which is an integral part of the reactor plant project, it would be more appropriate to use the same fixed charge rate as the reactor plant. On a constant dollar basis, the levelized fixed charges for the capital investment result in 0.5 mills/kWhr.

Operating and Maintenance Cost: The operating and maintenance cost of the IFR fuel cycle facility, which includes costs for process personnel and support personnel, process consumables and utilities, translates to 1.2 mills/kWhr.

Driver and Blanket Hardware Components: The cost for driver and blanket assembly hardware components, such as cladding tubing, end plugs, wires, duct hardware, etc. is separated out from the process consumables, because these items are independent of the fuel type, the process type, as well as whether the fuel is recycled or not. The assembly hardware cost is strictly a function of the core design, independent of the fuel cycle scenarios. For the example presented here, the assembly hardware costs contribute about 1.3 mills/kWhr to the levelized fuel cycle cost.

Fissile Inventory Carrying Charges: The IFR fuel cycle can be started up with either plutonium or ^{235}U. The supply source and price range for large quantities of plutonium for potential commercial LMR plants are difficult to project at the present time. For this analysis, an arbitrarily chosen $25/gm was used to estimate the inventory cost for the Pu startup scenario.

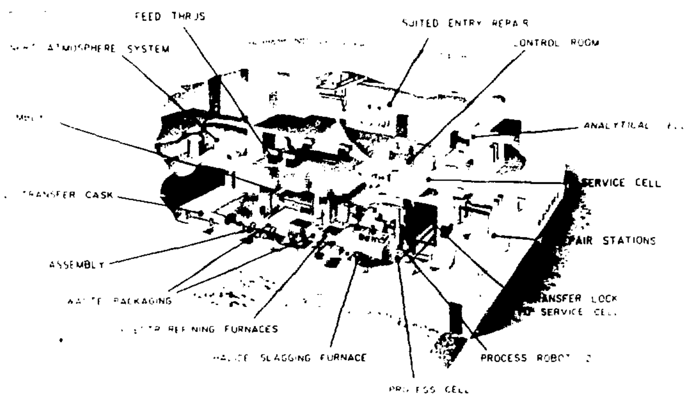

Figure 3--Commercial-Scale IFR Fuel Cycle Facility.

The IFR provides a flexibility for initial startup with ^{235}U. Because of a superior neutron economy associated with the metal core, no fissile makeup is required beyond the initial startup, and self-generated recycle of Pu would be more than sufficient for subsequent reloads. The uranium startup option eliminates uncertainties associated with plutonium supply source, and furthermore, the institutional barriers associated with establishing a plutonium commerce could be dealt with more easily. However, at currently projected uranium and enrichment costs, the *uranium* startup option results in 3.5 mills/kWhr of inventory carrying charges, whereas the $25/gmPu assumption results in 1.5 mills/kWhr. In this analysis, the initial core and one reload inventory is treated as a nondepreciable working inventory, where the carrying charge rate is given by the effective tax-adjusted cost of money divided by one minus income tax rate. Since the inventory carrying charge is rather significant for LMRs, alternative options for treating the inventory cost need to be developed.

Waste Disposal Cost: The 1 mill/kWhr fee levied on the present LWRs for waste treatment and disposal is assumed to be applicable to the IFR as well, although the treatment of high level wastes and interim storage until the heat generation is reduced to level acceptable in a permanent repository are already included in the facility design and operating cost estimates.

The summary of the fuel cycle cost is presented in Table I. The IFR fuel cycle cost in the 5.5 to 7.5 mills/kWhr range is less than that of the present LWRs, which is in the 8 mills/kWhr range on a constant dollar basis. More importantly, the fuel cycle facility capital fixed charges account for less than one-tenth of the levelized fuel cycle cost. Hence, even a smaller scale deployment (less than 1400 MWe assumed in this analysis) could be made economically competitive.

TABLE I
LEVELIZED FUEL CYCLE COST

Component	mills/kWhr
Capital Fixed Charges	0.5
Operating and Maintenance	1.2
Driver/Blanket Hardware	1.3
Fissile Inventory Charge	1.5-3.5
Waste Disposal	1.0
Total	5.5-7.5

FUTURE DEVELOPMENT PATH

Following successful completion of the feasibility demonstration, the next step is to demonstrate the practicality of the entire fuel cycle using the EBR-II complex and the refurbished HFEF/S facility. These facilities are already in place. The HFEF/S facility, which served as the original EBR-II Fuel Cycle Facility, has been decontaminated and is ready for the new equipment. The total cost is expected to be very 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. 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/South facility (which is decontaminated and ready) will equip the system with plant-scale metallic processing and fabrication modules. In this way, a complete prototype IFR can be available 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. Furthermore, the capacity of HFEF/S will be sufficient for few hundred MWe follow-on plant.