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MASTER

Applicability of EBR-II Experience to Commercial LMFBF's¹

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Argonne National Laboratory,
Argonne, Ill.

EBR-II has operated at power for more than six years and has produced more than 40,000-MW days of power (thermal) and over 250 million kwhr of electricity. Although primary operating emphasis has been shifted to experimental irradiation of LMFBF fuels and structural materials, the plant has been operated as a load generating station. Operation has verified the design objectives and demonstrated the operability of this type of plant, including on-site fuel processing and fabrication. The experience gained by design, construction, operation and maintenance is applicable to large LMFBF's. It is already being applied to such reactors.

¹Work performed under the auspices of the U. S. Atomic Energy Commission.

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INTRODUCTION

EBR-II is an experimental sodium-cooled fast breeder reactor plant operated as a base-load generating station on an electric utility system. EBR-II is located at the National Reactor Testing Station (NRTS) in Idaho, and the net electrical power generated is fed into the NRTS power distribution loop. The Idaho Power Company supplies power to the NRTS, and EBR-II must be synchronized with their system. The electrical load on the NRTS distribution system exceeds the 20,000-kw gross electrical capacity of EBR-II, with the result that Idaho Power is always delivering some power to the system. However, at times the EBR-II sup-

plies a significant fraction of the total load (approaching 100 percent), and plant operation is carefully coordinated with the NRTS system dispatcher.

EBR-II contains all of the features of a power station on a utility system, but the plant system (and buildings) are somewhat separated to provide experimental flexibility as shown in Fig.1. In addition, the capability is provided to operate the reactor at full power without generating electricity; the condenser can accommodate the total design thermal power (62.5 MW), as superheated steam and the cooling towers can dissipate the heat.

Fig.1 EBR-II overall plant

EBR-II began operating at power in August 1964. The first authorized power level was 45 MWt. The basic operability of the plant was verified and the initial fuel burnup limit was established at this power level. Experimental fuel irradiations were begun and the foundation for the irradiation program was established. The authorized power level was increased to 50 MWt in August 1968 and to 62.5 MWt in September 1970 to accommodate the experimental irradiation program. During this entire period, EBR-II has been operated as an experimental LMFBR base-load power plant, because it operates best in this mode. The core loading was expanded significantly (from about 70 to 90 subassemblies) to accommodate the large number of experimental irradiation subassemblies, but the basic plant and systems remain essentially unchanged.

This paper will deal with the design and operation of EBR-II as an experimental power plant. It will emphasize the experience obtained in this mode of operation and its applicability to commercial LMFBR power plants.

EBR-II DESIGN PHILOSOPHY

EBR-II was designed to resolve as many technical problems as possible, and to establish technical feasibility to the extent practicable with a 20-MWe experimental power plant. These goals were established at a time when a 150-MWe plant was "large" and 300 MWe represented "future extrapolated plant size." Even though the commercial plant size, which was selected as a comparative base, was extremely conservative, the design emphasis proved to be appropriate. In the latter half of the 1950's, the important technical questions appeared to be:

1 Was it feasible to achieve the thermal performance that appeared necessary for LMFBR's to achieve economic feasibility — i.e., power density in the range of 1 MW/l of core volume, heat flux in the range of 1 million Btu/sq ft-hr, coolant velocity in the range of 25 fps, coolant temperature rise in the range of 10 F/in. of core height?

2 Could reliable fission product decay heat removal be provided under all the conceivable circumstances which might be encountered after reactor shutdown and during fuel handling?

3 Could total fuel inventory be held to acceptable levels in the face of the high enrichment, high burnup rates, and high specific activity of typical fast reactor fuel?

4 Could a fast out-of-pile fuel cycle be achieved to minimize out-of-pile inventory — since this appeared to be necessary in conjunction with the projected achievable fuel burnup?

Fig.2 EBR-II primary system

5 Could the variety of mechanical requirements related to the compact core, control drives, and fuel handling be met?

6 Could components, such as pumps, heat exchangers, steam generators, instrumentation, sodium purification systems, etc., be developed to provide adequate performance?

7 Could reliable overall plant operation be achieved and plant maintenance be performed consistent with commercial power station requirements?

The EBR-II design addressed each of these questions and attempted to provide solutions which had the potential capability to be extrapolated to large commercial reactors. Also, the EBR-II design attempted to make the largest practicable extrapolation from EBR-I experience — the only fast reactor operating experience available at that time.

THERMAL PERFORMANCE

The thermal performance requirements for EBR-II resulted in two basic design features. Requirements for power operation led to the fuel element-subassembly concept [EBR-I and the Dounreay Fast

Fig.3 EBR-II subassembly fuel element and upper and lower blanket elements

Fig.4 Reactor vessel and grid-plenum assembly

Reactor (DFR) employed individual fuel elements] designed to accommodate high power density. Requirements for shutdown cooling led to a primary system concept which emphasized the prevention of loss of coolant and reliability of heat removal under all normal and abnormal circumstances. The combination resulted in a relatively unique design concept which has been applied to large-size IMFBR's under construction in England, France, and Russia. The salient feature of this design concept are summarized in the following.

The EBR-II reactor and primary sodium cooling system are contained in a large primary tank with the reactor and major components submerged in sodium, as shown in Fig. 2. This concept has the virtue of being very compact (thereby minimizing the shielded building volume occupied by the radioactive primary system) and the virtue of providing a very simple and reliable container for the primary system sodium (thereby minimizing the possibility of loss of coolant). The advantages of this "submerged primary" or "pool" concept have been described previously.² Experience with EBR-II has demonstrated the technical feasibility of the concept for both operation and maintenance. The basic concept has been adopted by the English for their 250-MWe Prototype Fast Reactor (PFR), by the French for their 300-MWe Phenix, and the Russians for the 600-MWe BN 600. All of these reactors are well along in construction. The applicability of EBR-II experience is best demonstrated by the major commitments made by these countries to this concept. Two United States reactor manufacturers also have adopted this concept for their large IMFBR designs.

The EBR-II reactor design employs free-standing, close-packed subassemblies of hexagonal cross section as shown in Fig. 3. They are positioned and supported in a combination grid-inlet coolant plenum shown in Fig. 4. Because of the large coolant pressure drop through the subassembly, they are subjected to a hydraulic lifting force. The EBR-II design provides a "hydraulic holddown force" produced by the high pressure coolant in the subassembly acting across the closed bottom end of the subassembly. This piston-like effect, coupled with the weight of the subassembly, counteracts the lifting force and eliminates the need for mechanical holddown methods. The feasibility of this concept has been estab-

lished by EBR-II, and it has been adopted for several commercial reactor designs (including the USSR BOR 60 now in operation, and BN-350 under construction).

The EBR-II subassembly is reasonably typical of large reactor subassemblies appropriately scaled down in size. In each case, the size is determined largely by the desire for "manageable packages" of fuel elements. A comparison of pertinent data for EBR-II and a typical 1000-MWe IMFBR is given in Table 1. Note that EBR-II contains a larger total number of subassemblies that is anticipated in a large reactor as a result of the very large number of blanket subassemblies in EBR-II. (A thick blanket was provided to permit blanket optimization studies.)

EBR-II was designed to achieve a maximum power density in excess of 1 MW/l, which is somewhat higher than the present design basis for large reactors. There has been no evidence of overheating or marginal thermal performance which provides assurance that the large reactors will have a reasonable performance margin.

Coolant flow in EBR-II is orificed in each row of subassembly to approximately match the power generated in that row and to achieve the same maximum fuel temperature in each row. This is accomplished by a series of steps in the lower grid plate which cover the appropriate coolant inlet holes in the subassembly. This arrangement is shown in Fig. 5 (refer also to Fig. 4) where the stepped construction can be seen for the five rows of the core and the two rows of the inner blanket. (The outer blanket utilizes low-pressure coolant and only two zones of orificing because of the very low power generation.) With this arrangement, all core subassemblies are identical and are

Table 1 Fuel Element and Subassembly Comparison

	EBR-II	1000 MWe ^a
Power-MWt	62.5	2500
Core height, in.	14	30
Core subassemblies, No.	67	275
Blanket subassemblies, No.	570	125
Total subassemblies	637	400
Subassembly pitch, in.	2.320	6.0
Subassembly can thickness, in.	0.040	0.100
Fuel elements per subassembly	91	271
Fuel element diameter, in.	0.174	0.275
Overall length of subassembly, ft	~7-1/2	~12

^a Representative parameters for comparative purposes — not optimized

² Koch, L. J., et al., "Construction Design of EBR-II: an Integrated Unmoderated Nuclear Power Plant," Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy, Vol. 9, Nuclear Power Plants, Part 2 (Geneva 1958) Paper 1782, pp. 323-347.

Fig.5 Enlarged view of grid-plenum assembly

correctly orificed automatically by position in the reactor. The same is true of the two rows of innerblanket subassemblies. Operating experience has been entirely successful and has demonstrated the feasibility of avoiding orificing-loading errors. This experience is applicable to large reactors where proper flow-power matching will be much more important.

The submerged primary concept has been shown to provide an excellent arrangement for shutdown cooling and fuel handling. The large reservoir of sodium provides a very large heat capacity to accommodate fission product decay heat and thus provides time to begin removing heat from the system. The large volume provides space for fuel-handling operations under sodium where adequate cooling can

Fig.6 EBR-II fuel subassembly spacer buttons

be assured. The system also assures constant reactor inlet coolant temperature, relatively independent of changes in the steam system.

MECHANICAL PERFORMANCE

The EBR-II subassemblies are supported in and by the two parallel plates comprising the lower grid structure. They are free standing and permitted to move within the confines of the close-packed geometry. The EBR-II core and subassembly design was predicated on free, but predictable, movement of the subassemblies in response to the forces acting upon them. In addition, major emphasis was placed on minimizing the inward bowing of subassemblies toward the center of the core to minimize the positive bowing reactivity coefficient which was observed in EBR-I. This was accomplished by the use of spacer buttons on each subassembly at the approximate mid-plane of the core, as shown in Fig.6. The spacer buttons provide essentially metal-to-metal contact between subassemblies and thus minimize inward bowing. EBR-II power coefficient measurements³ were found to be consistent with predictions, including the bowing coefficient permitted by the small clearances at the grid support and spacer buttons and

Fig.7 High burnup subassembly

³ Monson, H. O., "EBR-II Initial Operation — Highlights," Fast Breeder Reactors, Proceedings of the London Conference organized by the British Nuclear Energy Society, Vol. 103, May 1966, pp.135-152.

Fig. 8 EBR-II fuel-handling system

the relatively large clearances at the top of the subassemblies.

At the time EBR-II was designed, fast-neutron irradiation-induced swelling in stainless steel had not been discovered (or produced to a measurable extent). A nominal clearance of 0.030 in. was provided between subassemblies (except at the spacer buttons) to accommodate some distortion and still permit fuel handling. Experience has shown that this clearance will accommodate a significant amount of stainless-steel swelling, probably at least in part because irradiation-induced creep

tends to partially offset the swelling. Fig. 7 shows an experimental subassembly after approximately 100,000 Mwd/t burnup of the fuel and exposure to a fast neutron fluence of $\sim 8 \times 10^{22}$. As can be seen, the subassembly has expanded to the extent that significant scoring occurred during fuel handling. It should also be noted that the spacer button has taken a permanent set in a compressed configuration. This has been shown to be a typical pattern for highly irradiated subassemblies and thimbles in EBR-II. Although a considerably better understanding is needed of both ir-

Fig.9 Reactor plant

radiation-induced swelling and irradiation-induced creep, EBR-II experience demonstrates, at least qualitatively, that these phenomena can be accommodated to a considerable extent.

FUEL HANDLING

The design of the EBR-II fuel-handling system was determined largely by the requirements resulting from the following basic assumptions relative to LMFBR fuel cycles:

1. High burnup rate resulting in a short residence time in the reactor, coupled with high specific activity of the irradiated fuel requiring a long cooling time prior to processing would tend to produce a large external fuel inventory.

1. PASSAGEWAY BETWEEN REACTOR AND FUEL CYCLE FACILITY
2. AIR-ATMOSPHERE PROCESSING CELL
3. ANNULAR ARGON-ATMOSPHERE PROCESSING CELL
4. EXTERNAL AREA FOR OPERATING PERSONNEL; AUXILIARY LABORATORIES
5. SERVICE AREA BENEATH CELLS
6. SUSPECT STACK
7. CENTRAL AREA FOR OPERATING PERSONNEL

Fig.10 Fuel cycle facility

2 The desirability of partial core reloading coupled with short residence time in the reactor would require frequent fuel changes.

3 Since achievable burnup in (water-cooled) power reactors at that time was (conservatively) estimated to be between 5 and 10,000 Mwd/t, fast reactor refueling systems should be based on an assumed burnup of not more than 10 to 20,000 Mwd/t.

The combination of these assumptions resulted in requirements for a fuel-handling system which could make partial fuel loadings as frequently as every few weeks. As a practical matter, this kind of frequency would demand that fuel handling be performed during periods of low power demand on the system, and the EBR-II fuel-handling system was designed to accomplish refueling during a short shutdown comparable to the reduced power demand which occurs weekends. To provide a little latitude, this required that a normal refueling shutdown should be completed in about one day; i.e., approximately 24 hr from reactor shutdown to return to power.

The EBR-II fuel cycle (which will be discussed later) placed an additional demand on the fuel-handling system; namely, that about one subassembly per day should be "shipped" from the reactor and that the fuel should "cool" for about two weeks prior to shipment.

The combination of requirements resulted in a fuel-handling system which incorporated an intermediate storage step (inside the primary tank) as shown in Fig.8. The arrangement permitted rapid refueling of the reactor, with the exchange of one subassembly approximately every half hour between the reactor and the storage basket, and convenient "shipping" with the exchange of one subassembly approximately every day between the storage basket and the fuel unloading machine and interbuilding coffin. The first step, "unrestricted fuel handling," can be performed only with the reactor shut down. The second step, "restricted fuel handling," can be performed with the reactor shut down or operating, but normally is performed with the reactor operating. Fig.9 shows the configuration of the reactor plant during restricted fuel handling and the path of the interbuilding coffin through the equipment airlock to the Fuel Cycle Facility. Reactor building containment is maintained, and the reactor may remain in operation during fuel transport.

Almost 5000 subassembly transfers have been made between the reactor and storage basket. This is far more than the number of operations necessary to maintain power operation of the reactor. This is one phase of operation where the experimental irradiation program generates much larger demands on the system. These demands result from

the necessity to rearrange core loadings to accommodate experiments and the extra handling of the experimental subassemblies. About 2200 transfers have been made between the storage basket and the fuel unloading machine. Again, this involves much more than the subassemblies required for power operation. It includes the irradiation experiments, special subassemblies for physics measurements, reflector experiments, and many miscellaneous assemblies. Only about half of these operations have involved subassemblies necessary to produce power. In spite of these additional demands, the system has operated extremely well.

It is interesting to note that the U.K. designers of the PFR will utilize a similar fuel-handling philosophy but arrived at their decision via a different route. The U.K. gas-cooled power reactors utilize on-line refueling, and they gave serious consideration to attempting on-line refueling in their PFR, but settled for "off-peak-load" refueling instead. Their objective is to accomplish partial refueling with the plant shut down for only 24 to 36 hr during off-peak-load periods on weekends. They will be prepared to perform refueling operation as frequently as once a week. Various fuel-handling concepts were evaluated and compared previously,⁴ but on-line refueling was not included. The EBR-II fuel-handling experience is directly applicable to the PFR requirements.

FUEL CYCLE

The EBR-II fuel cycle was based on the assumed burnup limit of 10,000 to 20,000 MWd/t and the desire to minimize out-of-pile fuel inventory by rapid fuel processing and fabrication. A pyrometallurgical refining process was selected which only partially decontaminated the fuel and required that fabrication operations be performed by remote control. An on-site plant, the Fuel Cycle Facility (FCF), provided a closed, close-coupled fuel cycle. The design of the facility and the processes have been described previously.⁵

A cutaway of the FCF is shown in Fig.10. The Argon Cell (area 3 in Fig.10) was filled with

argon in August 1963. The first irradiated fuel was processed in September 1964. Until July 1969, it processed and refabricated all of the fuel used in the reactor. It was also used in support of the experimental irradiation program. Since July 1969, it has been used exclusively in the experimental irradiation program, and new fuel has been fabricated commercially. During the approximately five years that the FCF was in production, more than 38,000 fuel elements were processed and fabricated and 366 subassemblies and 66 control and safety rods were assembled. The fuel completed five cycles through the reactor and fuel cycle, and until the commercial supply was established, the FCF was the only source of fuel for the reactor.

All of the processing and fabrication operations were performed without removing the argon atmosphere and without personnel entry into the cell. All maintenance, removal, and repair of equipment was performed remotely.

Although this specific fuel cycle applies to metallic alloy fuel, the experience obtained with the FCF operation is extremely significant and applicable to commercial IMFBR's as follows:

1 The feasibility of on-site processing has been demonstrated. This is applicable to the operation of nuclear parks.

2 The operation of a power reactor can be integrated with the operation of a fuel processing and refabrication plant. In EBR-II, fuel storage facilities were minimized by providing storage of irradiated fuel in the primary tank until required by the FCF. This requires a fuel handling and transport system which is independent of reactor operation.

3 EBR-II fuel fabrication and assembly involved relatively complex and sophisticated operations performed on very radioactive material. This experience demonstrates that these kinds of operations can be performed remotely and is relevant to commercial IMFBR fuel cycles which may involve residual radioactivity in the fuel due to fission products or due to radioactive fissionable and fertile isotopes.

4 Some IMFBR designs utilize a refueling cell above the reactor. Such a cell must contain an inert gas atmosphere, and relatively complex machinery must be operated and maintained inside the cell. The experience in the FCF with lighting, viewing, cooling, maintaining the inert gas atmosphere, and operating and maintaining equipment is very similar and applicable. The demonstrated capability of materials and components to function satisfactorily in the high radiation, dry inert gas atmosphere is directly applicable.

The emphasis in the IMFBR fuel development

⁴ Koch, L. J., "Fast Reactor Fuel Handling," ANS-100, Fast Reactor Technology, pp. 333-347.

⁵ Levenson, M., et al., "The Pyrometallurgical Process and Plant for EBR-II," Second United Nations International Conference on the Peaceful Uses of Atomic Energy, Vol. 17, Processing Irradiated Fuels and Radioactive Materials, (Geneva 1958), Paper 541, pp. 414-420.

Fig.11 Simplified flow diagram

Table 2 EBR-II Annual Power Production

Year	Authorized power level MW (th)	MW days (thermal)	Plant factor, percent ^a
1965	45	4345	26
1966	45	7195	43
1967	45	3296	19
1968	45 and 50	7162	42
1969	50	7800	43
1970	50 and 62.5	11,313	58

^a Plant Factor defined as: MWd of power produced/authorized power level (MW) x 365

program has shifted to achieving much higher burn-up (50,000 to 100,000 MWd/t) which reduces the magnitude of the out-of-pile inventory. However, the EBR-II experience demonstrates that a fast turnaround time is feasible, and the basic technology is available to extrapolate to large commercial LMFBR operations.

OVERALL PLANT OPERATION

An LMFBR generating station includes a large number of components and systems which are new to the utility industry. The use of sodium as a high-temperature heat-transfer fluid represents a significant departure from established power plant practice, and the operating experience with EBR-II sodium systems and components is directly applicable to future LMFBR plant operation.

The EBR-II flowsheet is shown in Fig. 11. The temperature and steam conditions are somewhat lower than modern fossil-fueled stations, but are substantially higher than light water reactor stations. High-pressure steam extraction for the No. 4 feedwater heater represents a conservative design feature to raise the feedwater temperature and minimize temperature differences in the steam generator. The same extraction is used to drive the turbine-driven feedwater pump. The system has operated quite well, but may represent unwarranted conservatism.

Since overall plant operation provides a good measure of the operability of all of the systems (concurrently), it provides a good measure of the reliability of each. EBR-II annual power production is shown in Table 2 and provides a convenient indication of overall plant operations.

The plant factor in 1967 was reduced significantly by two problems which resulted in prolonged shutdowns, because sufficient information was not available to immediately resolve the questions raised. The first involved copper corrosion of two bus bars in the primary sodium system and

Fig. 12 Primary sodium pump removal

consequent uncertainty as to the possible effects of the copper in the system. It was subsequently reasonably well established that the copper probably deposited in the cold trap because of the temperature dependence of copper solubility in sodium. The second problem involved a change in power coefficient which followed the substitution of stainless steel for depleted uranium in part of the radial blanket (to improve reflector characteristics and experimental irradiation capability). The change was found to have caused a change in radial temperature distributions and resultant bowing of core subassemblies. The physical changes were estimated to be very small, and final verification of the reactivity effect could only be provided by returning to an all-uranium blanket. Both of these problems resulted in significant reactor shutdowns, while various hypotheses to explain the observed conditions and their possible consequences were evaluated.

Fig.13 Evaporator assembly

All of the original systems and components are still in operation. Problems have been encountered and corrected. Improvements have been made, but the basic plant remains essentially unchanged. A brief summary of experience with major systems and components follows:

Primary Sodium System

The two primary sodium pumps failed during preoperational testing in operating temperature sodium (700 F). The pumps were removed into a caisson filled with inert gas to avoid contaminating the primary sodium system and cover gas as shown in Fig.12. The pump shafts apparently warped and wiped out the lower labyrinth vapor seals. New shafts were fabricated with improved heat treatment (to minimize warpage), and the labyrinth clearance was increased. The pumps have performed satisfactorily, accumulating approximately 32,000 hr of operation, since the modification was made (in February 1964). The intermediate heat exchanger has performed in accordance with predictions and has given no indication of leakage. Some sodium flow instrumentation has failed, but satisfactory operation has continued with redundant systems.

Secondary Sodium System

The linear a-c electromagnetic sodium pump duct developed a small crack which was ascribed to vibration induced by reduced pressure in the duct due to pressure drop in the inlet transition section of the pump. The crack was repaired by welding in a small new section, and the adverse pressure differential was corrected by operating the pump casing at reduced pressure. This resulted in a net positive internal pressure in the duct tending to force the duct out against the pump stator and eliminating the potential for vibration in the thin duct. The pump has performed satisfactorily since this correction was made (in June 1964). (A new pump of improved design was procured; it is available on standby if the original pump experiences future difficulty.)

Steam System

The KBR-II evaporator design is shown in Fig.13. It is a double tube, double tube sheet unit with the space between the two tube sheets open to the atmosphere. A very small steam leak to the atmosphere occurred in February 1965 at one tube-to-steam tube sheet weld. The steam-water outlet pipe was removed at the steam outlet reducer, and the leak, which was apparently due to a small inclusion in the weld, was repaired in place. This is the only difficulty which has arisen with the steam generator assembly; the eight evaporators

and two superheaters have operated as predicted and have been entirely trouble free.

Reactor Components

Very early in the operating program (October 1964) a linear ball bearing in an experimental oscillator rod drive failed, and some of the loose balls caused jamming of the two adjacent control rods and drives. It was necessary to remove the two control drives for repair and to replace the oscillator drive. This was an extremely difficult repair operation, because the control rods had jammed in their thimbles which required special procedures to effect removal. Also, a variety of operations were developed to remove the loose balls that had escaped, including high velocity coolant flow through special strainers. This correction was, perhaps, the most difficult encountered and resulted in the reactor being shut down for almost 4¹/₂ months. Although some of the balls from the failed bearing were not retrieved, no additional difficulties have arisen due to this failure. Control rod drives have been removed for routine maintenance and repair, but these operations have been relatively routine and much easier to perform because no jamming of the rods or drives has been involved.

Fuel Handling

As described earlier, the KBR-II fuel-handling system probably has performed more operations than would be required to support operation of the reactor for its normal lifetime as a power plant. Some difficulties have been encountered with the mechanisms, but they have been repairable without significant difficulty. Improvements have been made to the force-limiting drives and to the position-indication systems to minimize the probability of maloperation. The most difficult repair involved the transfer arm which required removal in February 1966 to repair an improperly welded bell crank in the locking pin linkage. Because of the shape of this unit, it is necessary to remove a relatively large shield plug (with the arm attached). The inert gas-filled plastic bag technique was used to remove the arm and plug to avoid contaminating the primary sodium. This method of removal proved to be very satisfactory and considerably easier than the caisson system used for removing the primary pumps. The entire operation was completed in less than three weeks, and the unit has operated satisfactorily since that time.

A rather persistent sticking problem existed with the gripper unit in the fuel unloading machine (FUM) which can best be categorized as a "nuisance problem." The gripper operates in sodium (in the primary tank) and in argon gas (in the

FUM); it must make the transition between these two environments each time a subassembly is transferred. Sodium oxide buildup occurs, and the gripper must be cleaned to remove this buildup. A new gripper, which has operated very satisfactorily and requires cleaning much less frequently, was designed with significantly increased clearances between the moving parts. Since the FUM is used for "restricted fuel handling," which is normally performed with the reactor operating, this problem has had very little effect on power operation.

CONCLUSIONS

EBR-II was designed as an experimental LMFB power plant, but it has been used primarily as an experimental irradiation facility for LMFB fuels and structural materials. It has been effective as an irradiation facility; more than 1,200 experimental fuel elements and samples have been irradiated, and it has become relatively routine to have 30 to 40 experimental subassemblies in the reactor at one time with as much as 10 to 15 percent of the power being generated in the experimental fuel elements. It has also operated very effectively as an LMFB generating station; more than 250 million kwhr of electricity have been produced.

A variety of problems have arisen during EBR-II operation, but it is important to note that:

- 1 The major problems occurred during the early phases of operation; in fact, several occurred during preoperational testing.

- 2 All of these major problems were solvable and were corrected the first time. The original solution was satisfactory and provided a "permanent fix."

EBR-II experience suggests that reliable operation of large commercial LMFB power plants can be achieved. It also suggests that the early commercial plants (prototypes and full-size plants) should be able to accommodate a reasonable amount of experimentation and still achieve reliable performance as generating stations. This would indicate that some allowance should be made for self improvement or "bootstrapping" in these early plants.

The LMFB technology is complex and difficult. It probably represents another level of technical sophistication for the utility industry in their progression from fossil-fueled plants, to light water reactors to LMFB's. EBR-II experience has provided a basis for confidence that such a level of sophistication can be achieved by the industry. The European commitments to the LMFB (by the U.K., France and the U.S.S.R.) appear to reflect such confidence.