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U. S. EXPERIENCE WITH FAST POWER REACTORS: EBR-II

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INTRODUCTION

The primary objective of the U. S. Fast Breeder Reactor program is the development of large, reliable and economic fast reactor power stations which can be constructed and operated on electric utility systems. U. S. experience with fast power reactors is contributing to that objective.

The U. S. has two operational liquid metal cooled fast breeder reactors (LMFBR) power plants: the EBR-II and the Fermi-I power stations. This is more fast power reactor operating capacity than exists in the rest of the world, but England, France and Russia each have greater capacity in plants under construction.

There are two basic concepts for LMFBR power stations: (1) the Loop concept and (2) the Pool concept. Fermi-I is a Loop-type system, while EBR-II is a Pool type. The Loop concept consists of the traditional arrangement of primary system components, wherein the reactor vessel, pumps, heat exchangers, etc., are separated from each other and interconnected by piping (to form "loops"). Since this concept has been used extensively for liquid and gas cooled reactors of all types, a broad experience with Loop-type systems exists. The Pool concept consists of an arrangement of the primary system components within a large tank where they operate submerged in sodium (in a "pool" of sodium). Since this concept has been applied only to the LMFBR and the EBR-II is the only reactor of this type which has been constructed and operated, experience with this concept is much more limited. It should be noted, however, that the PFR under construction in the U. K., the Phenix under construction in France, and the BN-600 under construction in the U. S. S. R., are Pool-type systems.

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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 kWh of electricity. EBR-II represents a significant fraction of the U. S. experience with design, construction and operation of fast power reactors and the only experience with the Pool-type LMFBR.

The primary operating emphasis for EBR-II has been shifted to experimental irradiation of LMFBR fuels and structural materials, but the plant continues to be operated as an experimental base-load generating station. The major effects of this change in emphasis has been on the core loading, where about 25% of the subassemblies normally consist of experimental subassemblies (producing about 10% of the total power) and on the fuel handling system which is required to make a very large number of fuel loading changes to accommodate the requirements of the experimental irradiation program.

This paper will describe EBR-II experience as it relates to its design, construction and operation as a 20 MWe experimental LMFBR power station with particular emphasis on those aspects of the design which relate to the Pool concept.

PRIMARY TANK AND SODIUM SYSTEM COMPONENTS

A major hurdle which must be overcome in the early phases of any new concept involves its overall practicability or feasibility as a system. The design, construction and operation of EBR-II resolves some of the major problems in this category and provides a technological base for the plants now under construction. Although the EBR-II is relatively small, the experience is more relevant than a direct comparison of size would suggest. This is true because: (1) some important plant features and characteristics are essentially independent of plant size or power, and (2) most of the features which are size dependent are less than linear with power in this dependency.

EBR-II contains a full complement of instrumentation and control systems which measure and control the basic parameters involved in fast power reactor operation, including: neutron flux; sodium flows, pressures and temperatures; feedwater, steam and cooling water parameters; and voltage, frequency and synchronization with the electrical distribution system. These operating variables are being measured and controlled under conditions and in an environment comparable to what will exist in a large commercial station. Perhaps more important, they interact with each other (including feedbacks) and exhibit similar characteristics to the larger plants. Similarly, the requirements for quality of design, fabrication, and construction are comparable and equally stringent; it is just as important that a 12-inch sodium pipe not leak as a 24- or 36-inch pipe. The same is true for the performance of pumps, heat exchangers, steam generators and fuel elements.

The basic EBR-II Pool-type design raised questions of feasibility of design, construction and operation (including maintenance) and introduced unique design and construction problems. The EBR-II primary system is contained in a primary tank 26 feet in diameter and 26 feet deep as shown in Fig. 1. It contains approximately 80,000 gallons of sodium and the total weight of the tank, sodium and internals is approximately 900 tons. The normal operating temperature of the sodium (and tank) is 700°F, but the system was designed to accommodate occasional temperature changes from 250 to 750°F. Therefore, the EBR-II primary system presents the typical structural-thermal design problems associated with this design concept.

Demonstration plants and large commercial LMFBR's probably will require a primary tank at least twice as large (50 to 60 feet in diameter) containing about ten times as much sodium (500,000 to 1,000,000 gallons). Nevertheless, the EBR-II experience is very applicable because: (1) EBR-II required an inordinate proportion of field erection relative to its size because of its isolated location

and the requirements of truck transport of components to the site, and (2) EBR-II demonstrated principles of construction, assembly and installation which can be directly extrapolated to larger size systems and components.

The EBR-II primary tank was field assembled and erected except for the cover assembly which was shop fabricated in two halves (see Fig. 2). The tank was assembled and tested in (and above) the shield cavity in which it is now positioned (see Fig. 3). The upper structure was installed after the tank was completed, totally enclosing the tank and providing the support for the tank which is "hung" from the six radial beams as shown in Fig. 1. The design and construction, including the detailed analyses and detailed quality control procedures have been described in detail.⁽¹⁾ Construction, erection and testing proceeded in accordance with plans and conformed to specifications in all respects.

It is interesting to note that the construction of the PFR reported⁽²⁾ by the U. K. has proceeded along similar lines except that they subdivided the upper structure into six segments (also for reasons of shipping) which were field assembled and erected. They encountered welding difficulties in this "roof" structure due to lamellar defects in the steel which caused schedule delays before they were corrected. Also, they adopted a similar construction sequence involving the construction of the supporting structure around the completed vessel. They have utilized the technique of "floating" the tank to position it during erection.

Thermal tests were conducted on the EBR-II primary tank before and after filling with sodium to verify the thermal expansion characteristics and to measure actual displacements of the tank and specific nozzles in the tank cover. They were generally in agreement with predictions but (20-40%) smaller in magnitude than the calculated values. The roller-hanger supports provide adequately for thermal expansion while retaining dimensional control of critical components. The results of these tests and evaluations have also been reported in detail.⁽¹⁾

The Pool concept presents special problems and requirements related to the operability and maintainability of the components in the primary system. The EBR-II design utilizes a "plug-in" concept for these components. This concept requires that each component be removable as a unit with direct personnel access only to the external part of the component. All of the components enter through, and are supported from, the top structure and cover of the primary tank. Each component includes an integral shield plug which is positioned within the corresponding nozzle in the top cover, thereby providing the "handle" for the component and simultaneously completing the top biological shield. The top cover contains 70 nozzles and as can be seen from Fig. 2 they are a variety of sizes and shapes. They house components ranging from primary pumps, heat exchangers, fuel handling components, sodium heaters and instrumentation to spares for future experiments.

Each of the components installed into these nozzles is removable as a unit. Some required relatively unique design to achieve "plug-in" operation. The primary pumps and the intermediate heat exchanger are two such components.

The EBR-II primary system employs two sodium supply loops each containing a single stage centrifugal pump driven by a variable-speed motor supplied by a motor-generator set providing variable voltage and frequency. At full reactor power each pump delivers approximately 4500 gpm at 50 psig. The pump (see Fig. 4) employs a radial hydrostatic bearing immediately above the impeller to which sodium is supplied directly from the impeller discharge. The pump is connected to the inlet piping by a spring loaded ball seat connector. This connection is automatically "broken" when the pump is removed and "connected" when the pump is installed. Tests have shown that this connection leaks about 10 gpm at rated operating conditions. The integral pump shield plug contains about 33 inches of carbon steel balls and 34 inches of high-density concrete.

The pumps were removed for repairs in early 1964 during preoperational testing and one pump was removed in late 1970 for a scheduled inspection and

maintenance after 32,000 hours of operation. The "plug-in" capability has been adequately demonstrated as well as the reliable operation of these units.

The intermediate heat exchanger must also provide "plug-in" capability. The shell is permanent but the tube bundle with attached shield plug is a removable unit. This was accomplished by bringing the secondary sodium inlet through the center of the unit to the lower header as shown in Fig. 5. The heat exchanger has not been removed since the plant went into operation, but its plug-in capability (see Fig. 6) was demonstrated during initial construction since it was the last major component installed and closed off the last means of access into the tank. Consequently, it was the only major component to be installed into the primary tank "blind"; i. e., no observers were in the tank during this final installation.

The intermediate heat exchanger has successfully met some rather stringent operating requirements. It was designed to ensure natural circulation after reactor shutdown for fission product decay heat removal. To ensure circulation irrespective of heat removal in the heat exchanger, the unit was made short and set at a high elevation; the primary sodium outlet at the bottom of the heat exchanger is approximately 7-1/2 feet above the vertical center of the reactor. Secondly, it was designed for low velocity on the shell side which required extensive baffling to avoid channeling. The thermal-hydraulic performance of this unit has been excellent throughout the operating range.

FUEL HANDLING

Fuel handling is a critical function in an LMFBR power station because (1) it involves complex mechanical operations in high temperature sodium, (2) fission product decay heat removal requires a very high degree of reliability of cooling and (3) the economics of the fuel cycle demand that the fuel handling operations be performed with minimum reduction of plant availability. EBR-II employs a "quick-

frequent" fuel handling system. It was designed to accommodate on-site fuel processing requirements and it exploits the inherent capabilities of the Pool concept. It demonstrates some basic features which can be extrapolated rather directly to large commercial power stations.

The EBR-II fuel handling system (see Fig. 7) employs two basic steps.

The first consists of a transfer of subassemblies between the reactor and the storage basket with the reactor shut down. The second consists of a transfer of subassemblies between the storage basket and the Fuel Cycle Facility via the Interbuilding Coffin (or to a shipping facility, etc.) while the reactor is operating. The first step (called "unrestricted fuel handling") is performed quickly to minimize reactor shutdown time and is accomplished by preloading the storage basket with the required new subassemblies. Also, since these operations are performed with the subassembly entirely submerged in sodium they can be performed immediately after reactor shutdown with completely reliable fission product decay heat removal. The design objective for unrestricted fuel handling was to accomplish partial reactor loading in less than two days to correspond with periods of low power demand such as would occur on a power system over a weekend. Although EBR-II refueling schedules are established primarily by the requirements of the experimental irradiation program, the refueling shutdowns have been characteristically short and the feasibility of weekend-type refueling shutdown has been demonstrated many, many times. Almost 5,000 subassembly transfers have been made between the reactor and storage basket which is several times the number which would have been required to support power only.

The second step (called "restricted fuel handling") involves the removal of the subassembly from the primary tank and therefore a change in (cooling) environment. This involves a change from sodium cooling to argon gas cooling and the transition occurs in the Fuel Unloading Machine. These transfers can be scheduled

when the fission product decay heat rate has decreased to more manageable levels. The nominal cooling period in EBR-II is 15 days, but this can be tailored to the processing or shipping schedule. More than 2,000 such transfers have been made in EBR-II, again reflecting the added load imposed by the irradiation program.

EBR-II experience has amply demonstrated that the use of frequent fuel handling shutdowns of short duration are entirely feasible and that plant unavailability for fuel handling can be scheduled for periods of low power demand—periods as short as those that normally occur on weekends. The U. K. is planning to operate the PFR on such a schedule.

STEAM GENERATOR

One of the most critical components in the LMFBR is the sodium to water/steam heat exchanger. Because of the violent chemical reaction between sodium and water, it is essential that these units be absolutely leak tight.

A primary objective of the EBR-II design was to achieve reliable operation of the steam generator. To accomplish this objective several relatively conservative features were incorporated into the plant. As can be seen from the flow sheet (Fig. 8), the No. 4 feedwater heater utilizes superheated steam extraction to heat the feedwater to 550°F (approximately 30°F below the saturation temperature) to minimize the possibility of thermal shock to the units. Separate evaporators and superheaters are used in a natural circulation system with a drum. The individual evaporator and superheater units are of shell and tube design with double tubes and double tube-sheets. Details of an evaporator assembly are shown in Fig. 9. The superheaters are essentially identical except that a "core tube" is included inside each tube to reduce the cross sectional area of the tube to increase the steam velocity in the resulting 1/8 inch annulus.

It should be emphasized that the steam generators and the secondary sodium system were designed to favor the water/steam side of the system. Chloride stress

corrosion was of major concern, and the evaporators and superheaters were arranged to avoid all crevices on the water side—the crevices were placed on the sodium side. Secondly, 2-1/4 Chrome-1 Moly steel was used for the steam system because of its superior chloride stress corrosion resistance as compared to 304 stainless steel, which was preferred for the sodium systems. As a result, the primary sodium system is all 304 stainless—including the intermediate heat exchanger; the steam system is chrome-moly—including the steam generator, and the secondary sodium system is a mixture of the two.

It is quite possible that the EBR-II steam system design is too conservative, but it is responsive to the design criterion to achieve maximum practicable reliability of this system. A primary design objective was to maximize reactor operation and to minimize loss of plant availability due to failure of supporting systems. No alternate "heat sink" was provided for the power generated by the reactor. Provisions were made to accept full power delivery of superheated steam to the condenser and thereby operate the reactor at power without operation of the turbine-generator, but the energy must be converted to steam before it can be dissipated.

A very small steam leak to the atmosphere occurred in February 1965 at an upper tube to steam tube sheet weld. The steam outlet pipe was removed at the steam outlet reducer (see upper righthand view of Fig. 9) and the leak was repaired in place. This leak, which was apparently due to a small inclusion in the weld, is the only leak which has occurred in these units. They have performed extremely well in all respects and in accordance with design.

It is not the purpose of this paper to promote double tube steam generators or any particular degree of design conservatism, but EBR-II experience has shown that units can be conservatively designed to provide reliable service. Boiler manufacturers in the U. S. and in Europe have concluded that economic requirements dictate that single tube-single tube sheet units must be used and that once-through units are

preferred. This may be correct, but it is extremely important that this does not result in decreased reliability, particularly in the early phases of the program when experience is limited. For example, the emphasis on once-through units may be misplaced at this early stage of the program since these units have a greater potential for developing part-load instabilities and could reduce operational flexibility and overall plant reliability. A conservative design philosophy may be justified in the early plants to ensure reliability and achieve the more advanced designs as a stronger base of experience is developed.

OVERALL PERFORMANCE

EBR-II was designed to operate at power levels up to 62.5 MWt, but because thermal performance at that power represented such a large extrapolation from existing experience, extensive operation at 45 MWt was planned to verify performance and performance margins. Extensive analyses of predicted performance at 45 MWt⁽³⁾ indicated that reliable performance could be achieved at that power level. As a result, the initial approach to power, in August 1964, scheduled operations in steps to 45 MWt. Operation at 50 MWt was authorized in 1968 and at 62.5 MWt in 1970.

Operating data and plant factor for each year are tabulated in Table I. It should be emphasized that the plant factor shown is based on the most conservative method of computation and no allowance is made for the loss of power operation necessitated by the experimental irradiation program and supporting activities. It should also be noted from the electrical power generated that EBR-II generates electricity virtually all of the time that the reactor operates at significant power levels. (Note, the thermal efficiency varies slightly depending on power level and mode of operation; i. e., amount of steam by-pass, steam turbine driven vs electric motor driven boiler feed pump, etc., but 30% is a representative average.)

The primary system has operated very well and in accordance with expectations. The inherent advantages which were attributed to this concept have been verified: (1) there has been no indication of any problems with the integrity of the system and consequently the probability of loss of coolant is desirably small, (2) the large volume of sodium provides excellent heat capacity and temperature stability to the inlet sodium, (3) the system provides complete reliability of fission product decay heat removal under all conditions and (4) the primary tank and associated structure provides an excellent environment for a reliable and extremely versatile fuel handling system.

One question that EBR-II cannot resolve involves the extrapolation of the Pool-type design to large plant sizes. There has always been some concern that this concept may be size limited. In this respect, it should be noted that the British and the French have both given this matter considerable attention in relation to the design of the PFR and Phenix. The British state:⁽²⁾ "No information has arisen either in the PFR design process or during its construction to lead us to change from the single tank concept for the first 1300 MWe commercial reactor." The schedule for this 1300 MWe LMFBR calls for construction to begin early in 1974. The French state:⁽⁴⁾ "No important difficulty due to the choice of a pool reactor was found during the design and construction of Phenix, and the same choice will be made for the next reactor." They are in the process of developing conceptual designs of 1000 MWe Pool-type reactors with a selection to be made at the end of this year. Detailed design will then proceed with construction to begin in 1974.

It is interesting to note that the French are attempting to develop a "plug-in" cold trap system. If they are successful, they could eliminate all primary sodium piping external to the primary tank and further enhance the reliability of the Pool-type system against loss of coolant.

CONCLUSIONS

Experience with the design, construction and operation of EBR-II has demonstrated the feasibility of the Pool-type design of LMFBR's. It has verified the advantages attributed to this concept and has provided a technical basis for extending the concept to larger reactors. This is being done by the U. K., France and the U. S. S. R. Experience to date in those countries has apparently been favorable, and will extend the EBR-II experience to larger size Pool-type systems.

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TABLE I

EBR-II Annual Power Production

<u>Year</u>	<u>Auth. Power Level MW (th)</u>	<u>MW Days (thermal)</u>	<u>Plant Factor* (thermal)</u>	<u>MW Hours (electric)</u>	<u>Plant Factor** (electric)</u>
1964	45	705	--	3,480	--
1965	45	4,345	26%	29,532	94%
1966	45	7,195	43%	44,311	86%
1967	45	3,296	19%	19,348	82%
1968	45 & 50	7,162	42%	47,913	93%
1969	50	7,800	43%	51,291	91%
1970	50 & 62.5	11,313	58%	69,177	85%

* Plant Factor (thermal) = $\frac{\text{MWD of Power Produced}}{\text{authorized power level (MW)} \times 365}$

* Plant Factor (electric) = $\frac{\text{MWh Electricity Produced}}{\text{thermal power} \times 30\% \text{ thermal eff.}}$

Fig. 1. The Primary System of EBR-II in Cutaway Perspective

Fig. 2. Primary Tank Cover Half

Fig. 3. Primary Tank During Fabrication

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Fig. 5. Intermediate Heat Exchanger

Fig. 6. Heat Exchanger Installation

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Fig. 7. EBR-II Fuel Handling System

Fig. 8. EBR-II Skeleton Flow Diagram

Fig. 9. EBR-II Evaporator Unit