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CONSIDERATIONS FOR ADVANCED REACTOR DESIGN BASED ON EBR-II EXPERIENCE[a]

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ABSTRACT

The long-term success of the Experimental Breeder Reactor-II (EBR-II) provides several insights into fundamental characteristics and design features of a nuclear generating station that enhance safety, operability, and maintainability. Some of these same characteristics, together with other features, offer the potential for operational lifetimes well beyond the current licensing time frame, and improved reliability that could potentially reduce amortized capital costs as well as overall operation and maintenance costs if incorporated into advanced plant designs. These features and characteristics are described and the associated benefits are discussed.

I. INTRODUCTION

EBR-II, a pool-type, sodium-cooled reactor and power plant, operated for thirty years as a proof-of-concept demonstration plant, a fuels and materials test and irradiation facility, and an operational test bed for liquid-metal reactor components. It also served as an operational safety transient testing facility, and finally as a prototype for the Integral Fast Reactor program, all while generating electrical power supplied to the regional electrical grid. Given the variety of programs and missions supported by EBR-II, increasing demands were placed on the facility that went well beyond the originally planned mission and duty-cycle.

That EBR-II was able to maintain high operational availability factors through these missions and remain in excellent operating condition at the time of its shutdown in September 1994, provides an opportunity to evaluate the features and characteristics that contributed to this record.

II. BACKGROUND

EBR-II went into operation in August 1964 to demonstrate the technical feasibility of operating an integrated power-producing, closed fuel-cycle, sodium-cooled breeder reactor. It was also intended to provide the technical bases for succeeding plants through: component improvement (pumps, steam generators, instrumentation and controls, etc.), development of fuels and materials, and evaluation of reliability and safety.[1,2] EBR-II was designed for a five to ten year mission to accomplish these goals.

The EBR-II facility consisted of the reactor and primary system enclosed in a containment structure; the Sodium Boiler Building containing the steam generating system; the Power Plant containing the turbine generator and condenser; the main cooling tower; and other related support facilities. EBR-II was a pool-type reactor with the reactor vessel submerged at the bottom of the primary tank containing 86,000 gallons of sodium maintained at 700°F. An inert gas (argon) blanket was maintained at a slightly positive pressure in the head space over the primary

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sodium surface.

The primary system consisted of two centrifugal pumps and an intermediate heat exchanger (IHX) submerged in the primary tank. The pump suction was from the sodium pool, and the sodium was piped into the bottom of the grid-plenum assembly. The reactor core grid plate has 637 positions and could accommodate various core configurations and test assemblies. During operation, the basic core design consisted of five rows of sodium-bonded metallic driver fuel, two inner blanket rows and eight outer blanket rows. Reflector assemblies have been used to replace both inner and outer blanket assemblies for various core configurations. Figure 1 shows the layout of the reactor and primary system in the containment building.

The secondary sodium system transferred heat from the IHX in the primary tank to the two superheaters and seven (initially eight) evaporators that make up the steam generating system in the Sodium Boiler Building. The secondary sodium system is non-radioactive. Superheated steam generated in the Sodium Boiler Building was piped to the turbine generator in the Power Plant where up to 19.5 MW of electrical power were generated to supply the ANL-W site power needs and the regional electrical grid.

Because of the missions supported by EBR-II over the thirty years of operation, it was subjected to a larger number of startup, shutdown, and rapid shutdown (scram) transients than would be expected to occur over a much longer operational lifetime if it were

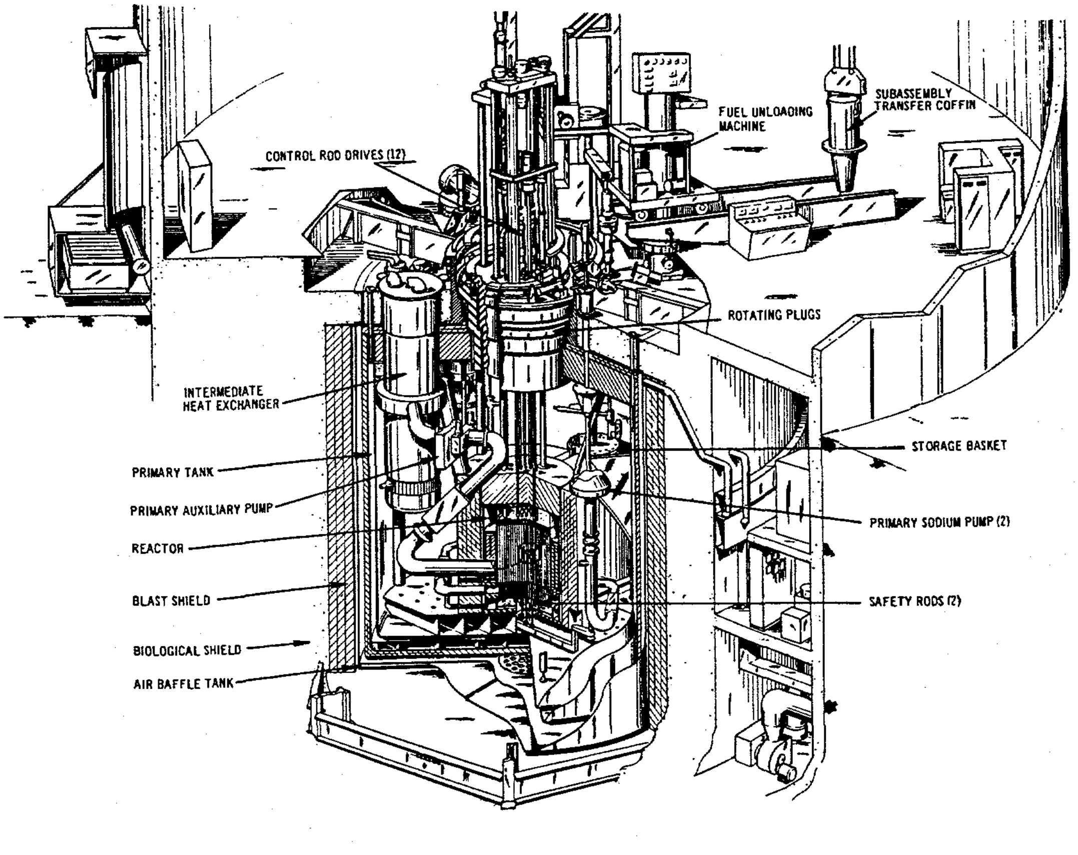

Fig. 1. EBR-II Reactor and Primary System

operated as a steady-state power reactor. In addition, EBR-II was subjected to test transients that had greater fatigue damage than normal startup, shutdown, and scram transients. The most demanding of these tests were the Shutdown Heat Removal Tests performed in 1986. This test series was run to verify and demonstrate plant system and fuel response to loss-of-flow-without-scram tests, transient overpower tests, and related off-normal operational events.[3] Even through the most demanding of test programs, the operational reliability of EBR-II was notable, achieving annual plant capacity factors as high as 81% and plant availability factors as high as 90%.

In addition to continued reliability, operational life extension studies indicated that the minimum expected operational lifetime could easily reach fifty years.[4,5] This is notable considering that operational lifetime was not a consideration nor a design goal in the EBR-II design. With consideration of extended operational lifetime as a design goal, features that are projected to be life-limiting in the current design could be replaced, eliminated, or redesigned to support extended-life operation.

III. KEY FEATURES

There are several key features and characteristics that contributed to the reliability of EBR-II as demonstrated by its track record and excellent operating condition at shutdown in 1994. Some of these features are discussed below.

A. Liquid Metal Coolant

The choice of a liquid metal coolant, sodium, provides several direct benefits, as well as secondary beneficial effects in reliability, maintainability, longevity, and potential reduced capital expenditures in certain areas compared with light-water reactors. The characteristics of liquid metal that can be beneficially exploited in a reactor design include compatibility with reactor materials (metals) used for construction of components, structures, and fuels. Corrosion is minimal and impurities in the sodium are easily removed by cold trapping.

Another characteristic of sodium is the high boiling point (~1700°F) which allows the primary and secondary systems to be designed and constructed as low-pressure systems thus avoiding thick-wall design issues and minimizing material costs in major components. For example, the EBR-II primary tank is 26 feet in diameter and is constructed of ½-inch thick type 304 stainless steel.

A secondary benefit to low-pressure cooling systems is the minimal potential for high-pressure ejection of coolant. A leak in a low-pressure sodium line or vessel is most likely to be seepage or a small, slow drip, both of which are typically easily detected and repaired based on EBR-II experience.

Another significant advantage of sodium as a coolant is the high thermal conductivity which provides rapid heat removal from the fuel under both normal and off-normal events. This provides benefits not only in fuel and thermal-hydraulic designs (not discussed herein) but also simplifies the design of decay heat removal systems.

The use of sodium (or other coolant that freezes above room temperature) also provides a maintenance advantage over a water-cooled system, and that is the ability to allow the coolant to freeze in-place when repairs are required. This fixes contamination in-place, greatly reducing the potential for spreading contamination compared to a water system. Exposure rates for EBR-II operations and maintenance personnel have routinely been considerably lower than those for LWRs.

Other metals and metal alloys such as lead and lead-bismuth, may provide similar advantages.[6,7]

B. Pool-type Primary System

The EBR-II pool-type primary system configuration provides several distinct advantages over a piped primary cooling system.

The pool configuration provides a large inventory of primary coolant which also serves as a passive heat sink for the reactor core, maintains the primary coolant and primary components in one vessel in one location, and allows the primary coolant containment boundary to be designed with no penetrations below the coolant level.

These features provide the following benefits:

1. Minimizes thermal stresses on major primary system components thus reducing cyclic thermal fatigue and enhancing extended component lifetimes;

2. Eliminates the need for large primary coolant piping and valves together with their associated

cost and reliability and maintainability liabilities;

3. Minimizes the potential for loss of primary coolant by eliminating primary coolant piping external to the primary tank except for small sample and purification lines for which the penetrations in the primary vessel are above the coolant level. Also, the primary system piping internal to the primary tank is not required to be leak tight;

4. Minimizes the potential for spread of contamination because the entire inventory of the contaminated primary coolant is contained in one vessel and not piped to other areas of the facility except for small sample and purification lines;

5. The built-in heat sink provides significant margins to temperature limits of structures and components in the event of loss of active cooling systems thus allowing incorporation of a simple, passive decay heat removal system;

6. Provides room and passive cooling for an in-tank fuel storage system which can be accessed during reactor operation providing rapid refueling capability.

C. Robust Balance of Plant

The two superheaters and seven evaporators that make up the EBR-II steam generating system, are designed with duplex tubes to minimize the potential for sodium to contact water or steam. The duplex tubes are concentric tubes that are either brazed or swaged together. This duplex tube design was dictated by the design philosophy that the balance of plant systems and components should be sufficiently robust such that overall plant availability and reliability is not controlled by the balance of plant. In other words, the system is designed to provide a high degree of assurance that when the nuclear system is available to operate, the balance of plant will be also.

This philosophy worked well with EBR-II as indicated by the high overall plant availability factors aided by the 100% availability of the steam generators since early 1965 when a construction defect was found in a tube-to-tube sheet weld.[8] Also, there has never been a sodium-water reaction in the EBR-II steam generating system. This experience differs from that in other sodium-cooled reactors where several steam generator problems have been encountered. The robust, duplex tube design of EBR-II is the notable difference in designs. While the cost to construct duplex tube steam generators would be somewhat higher than more conventional designs, the increased reliability should more than compensate for that over the life of the plant.

D. Metal Fuel

The use of metallic driver fuel (U-Zr and U-Pu-Zr), together with the use of metal coolant and a pool-type primary system configuration, provide significant passive safety characteristics that can be exploited in minimizing and simplifying active safety systems in a plant design. This topic has been evaluated and reported extensively[1,9] and is not covered herein.

IV. COST CONSIDERATIONS

The design features and characteristics discussed above, plus others, all contributed to the success of EBR-II. How these features are considered when developing a new design will depend upon many factors. Since no attempt was made to quantify the potential savings in capital costs or operation and maintenance costs that could be realized by incorporating any of these features, it is difficult to compare against the costs of more conventional nuclear power systems. It is expected, however, that integrating these features or concepts into new designs will result in lower operating or maintenance costs, simplify safety and control systems, and increase overall plant life expectancy. A detailed life-cycle cost evaluation is necessary in order to quantify potential cost savings. This is beyond the scope of this overview.

V. SUMMARY

Several characteristics and features of the EBR-II facility have been described herein that have contributed to the long-term reliability and operational record of EBR-II. As advanced reactor designs are conceptualized and developed, these features should be evaluated and exploited to potentially increase design lifetimes, improve long-term reliability and maintainability, and thereby reduce overall cost.

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