Experimental Breeder Reactor II (EBR-II),

Instrumentation for Core Surveillance

by

L. J. Christensen
Argonne National Laboratory
P.O. Box 2528
Idaho Falls, Idaho
83403-2528

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Introduction

The Experimental Breeder Reactor-II (EBR-II) is a small but complete liquid-metal-cooled reactor (LMR) power plant. It has a nameplate peak thermal power of 62.5 MWt and a corresponding electrical output of 20 MWe; it has been operated over a range of power including a peak of 70 MWt, as experimental program needs have dictated, for 25 years. This facility is located at Argonne-West site of the Idaho National Engineering Laboratory, state of Idaho, USA.

Description of EBR-II plant

The EBR-II plant consists of a primary system and a secondary system both using molten sodium as the coolant and a rather conventional steam system, as shown in figure 1. The primary system is located in a large double-walled tank, as shown in figure 2. The tank contains about 340 m$^3$ of sodium at 371° C under normal operating conditions. The two primary pumps take their suction directly from the tank and deliver a combined flow to the reactor of 485 kg/s at a
power of 62.5 MW. The corresponding mixed-mean temperature of the sodium coolant leaving the reactor is 473°C.

The reactor consists of an array of hexagonal subassemblies 5.817 cm across flats on 5.893 cm centers. The core region extends out through row 7, the reflector region through row 10, and the blanket region out another 5-1/2 rows. The core region may be smaller than the full seven rows. There are two safety rods (fuel-bearing) in row 3. There are 12 control rod positions in row 5, although only nine contain control rods (fuel-bearing) at present. The remaining three control rod positions are available for special in-core instrumented subassemblies, such as those used for the thermal-hydraulic (T-H) testing. The current fuel for EBR-II (Mark II) is a uranium alloy initially containing 5% simulated fission products, enriched to 66% in $^{235}$U. The fuel is a pin 0.3302 cm in diameter in type 316 annealed stainless steel cladding, 0.4420 cm outer diameter x 0.0305 cm wall. Sodium is used as a thermal bond between the pin and its cladding. Each such fuel element is wrapped with 0.1245 cm diameter spacewire. There are 91 elements in a regular fuel subassembly and 61 in a control or safety subassembly.

The primary flow to the reactor splits into two streams, one entering the high-pressure plenum that feeds the first seven rows and the other entering the low-pressure plenum that feeds the remaining rows. About 84% of the flow goes into the high pressure plenum and the remaining 16% goes into the low pressure plenum. The high and low pressure sodium streams mix in the reactor outlet plenum, go through the outlet pipe to the primary auxiliary pump (a DC electromagnetic device), and then to the intermediate heat exchanger (IHX) in which it transfers its heat to the secondary sodium. The primary sodium leaving the IHX dumps directly back into the primary tank. Power to the auxiliary pump is provided by a rectifier backed up by a battery floating on the line. In case of a power failure, an emergency 480 volt diesel generator provides
power to the rectifier. If the emergency power system fails, the battery takes over the load. Recent testing and analysis indicated that the auxiliary pump is not needed as an engineered safety feature for operation of EBR-II.

The secondary system sodium is driven by a single electromagnetic pump at a flowrate of 315 kg/s. The heat in the secondary system is transferred to the steam system in seven evaporators and two superheaters, all of the Argonne double-wall heat exchanger tube design.

The steam is used in a conventional turbine-generator to produce electricity. At full-power (62.5 MWt) the superheaters deliver 32 kg/s of steam at 438°C and 8.70 MPa to the turbine.

A more detailed description of the EBR-II plant is given in Reference [1].

Figure 3 shows the instrumentation associated with the primary coolant system when the plant was built. Of the original 10 flow sensors, only three are still in operation today. All three of these sensors are part of the reactor shutdown system (RSS). An instrument probe has been installed through the reactor cover into the outlet plenum region that provides an additional flow sensor in the form of a delta pressure measurement. This sensor signal is also part of the reactor RSS flow trip circuit. The scram contacts are arranged in a two of four trip logic. Engineering effort is presently ongoing to qualify digital speed sensors mounted on the primary pump motor shafts as flow trips. A toothed nut on the shaft produces pulses in a magnetic sensor. This pulse signal is proportional to pump speed which in turn is proportional to flowrate.

Figure 3 also shows the location of two ultrasonic flowmeters located in the low pressure plenum inlet piping at the throttle valves. These flowmeters are recent additions to the flow instrumentation and are in final checkout before being placed in operation. Figure 4 is a diagram of a ultrasonic flowmeter assembly. The system consists of a sensor assembly and an electronic control subsystem. The sensor assembly is suspended from the valve plug of the
throttle valve so that the full sodium flow in the four inch pipe flows axially in line with the sensors. The sensors are both transmitters and receivers. The ultrasonic travel time in sodium at $371^\circ$ C is about 2377 m/s. The travel time for 35.6 cm is 150 ns with a difference of 1.0 ns difference between the up time and the down time. To resolve the travel time to approximately ±2 ns requires at least 100 pulse times be counted and averaged. Fast electronic circuits and a control computer are used for this purpose.

Figure 5 shows the placement of the subassembly outlet thermocouples that monitor the temperature of selected subassembly coolant streams. These temperature signals provide a diverse and independent backup to the loss of flow trips, and four of the signals are part of the RSS and trip on high temperature from subassembly flows.

Thermal-hydraulics testing at EBR-II

The thermal-hydraulic testing program at EBR-II, initially conducted to support the continued safe and reliable operation of EBR-II, has evolved into an experimental and supporting analytical program contributing to the design and performance assessment of advanced liquid-metal-reactors, with special emphasis on inherent safety. These efforts, which essentially started in 1974, have been primarily directed towards understanding the detailed response of EBR-II to a wide variety of upset conditions and utilizing this knowledge to validate general purpose thermal-hydraulic-neutronic computer codes for application to new plant designs. Initial emphasis was placed upon reactor and primary heat transport system phenomena, and more recently, the focus of the work has been on whole-plant dynamic behavior. The success of this program has been immeasurably aided by the availability of fully-instrumented and calibrated in-core fueled and non-fueled assemblies, XX07, XX08, XX09 and XX10 [2,3,4]. These assemblies give direct, real time measurements of in-core
sodium temperatures. These measurements were a prime basis for "bootstrapping" from test to test and for use in an overtemperature scram circuit. These assemblies, with their extensive temperature and flowrate measure capabilities, have permitted the generation and documentation of comprehensive data sets that have been used to validate codes modeling single and multiple assemblies, and whole core behavior.

The in-core instrumented assemblies XX07 and XX08 have been previously described in [3,4] while XX09 and XX10 (latest probes) were discussed in [2]. However, due to the importance of these instrumented probes to the conduct and interpretation of the testing, XX09 and XX10 will be discussed in detail.

The fueled assembly, XX09, contains 61 elements, 59 of which are Mark-II metal fuel and 2 serve as hollow conduits for below-core instrumentation leads. There are 28 thermocouples measuring the three-dimensional temperature field throughout the assembly, ranging from below core to assembly outlet; these include thermocouples within the fueled region and in the inter-assembly bypass flow region. Two permanent-magnet flowmeters are located in tandem within the assembly below the core and have been calibrated over a flowrate range covering rated conditions down to both upward and downward natural convective flow (i.e., from -0.3 to +3.2 l/s). The normal operating conditions are 468 kW (25.6 kW/m, peak), 3.14 l/s, and 136° C coolant temperature rise. It is orificed for a flow of 9340 kg/h and the mixed mean outlet temperature is 519° C (based on an inlet temperature of 371° C).

In XX10, there are 19 elements, 18 of which are solid stainless steel (type 316) and 1 serving as a hollow conduit for below-core instrument leads. As with XX09, there are 2 below-core permanent-magnet flowmeters calibrated over the expected flowrate range from -0.04 to +0.44 l/s. A total of 26 thermocouples are included providing full coverage from below-core to assembly exit regions. The particular choice of materials and dimensions used for XX10 was based upon
standard thermal-hydraulic scaling laws so that the relative dynamic performances of XX09 and XX10 would closely approximate that of fueled and blanket assemblies in a large reactor [5].

**Subassembly Design Considerations**

The presence of an instrumented driver fuel subassembly in the core of EBR-II played an important part in the loss of flow without scram (LOFWS) tests and loss of heat sink without scram (LOHSWS) tests, as it provided the ability to measure coolant flows and temperature at different axial elevations during each test. Thus, the accuracy, reliability, and range of operation of the instrumentation had to meet required specifications.

However, there was another consideration, a conceptual functional requirement in which XX09 had to represent a prototypical subassembly. That is, XX09's T-H characteristics were designed to be similar to those of other liquid metal cooled reactor (LMR) core designs so that the data could be reasonably extrapolated to these reactor designs. Previous experience in EBR-II [6] indicated the importance of determining the whole-core behavior during natural convective transients, and the need to holistically describe the entire core, which includes both driver and blanket subassemblies.

An analysis was performed on a conceptual design subassembly, applicable to either a driver or blanket, and nine nondimensional parameters were established. Of these, six were used in a steady-state comparison between two large LMR designs and EBR-II. As a result of this comparison, two instrumented subassemblies were designed, one a driver type (XX09) and the other a blanket type (XX10), with significantly different T-H characteristics. These were built for use during the Shutdown Heat Removal testing (SHRT) program [7]. Details of the conceptual design basis, the large plant comparison, and description of the blanket subassembly are given in [8].
The instrumented subassemblies XX09 and XX10 were designed to fit into control rod positions located in the fifth row of the core. The full assembly consists of three components: the subassembly, an extension tube, and a terminal box. The XX09 subassembly is representative of a standard EBR-II driver. The extension tube connects the subassembly to outside the primary tank. It provides a protected conduit for the instrument leads and permits movement of the subassembly during fuel handling. The terminal box provides a junction area from which the instrument leads are connected to the DAS, which records, processes, and stores the test data. A schematic diagram of the XX09 assembly configuration is shown in figure 6.

The lifetime of XX09 is dependent upon the time-to-breach for the Mark-II elements, and that generally has occurred at a burnup of about 9 at% (2 years in the reactor).

There are two flowmeters located in the lower shield below the active core region. Both flowmeters were calibrated; the flow inaccuracy was less than 2% in the operating range of 390 to 9800 kg/h. The flowmeters were also calibrated for reverse flows up to 980 kg/h.

The spacer-wire thermocouples are contained in a metal sheath of 316 stainless steel and are made of Type K chromel/alumel with magnesium oxide insulation. The thermocouples are butt-welded to the wire wraps, and the length adjusted so that the thermocouple junction is at the specified core elevation when the wire wrap is spirally wound onto the elements. They have been fabricated to the U.S. Reactor Development and Technology (RDT) standards. The standard deviation was 0.7°C for an out-of-core calibration in the operating range between 427°C and 593°C.

There are a total of 28 thermocouples. There are two located in the flowmeters near the inlet, five at the core midplane (MTC), thirteen near the top-of-core (TTC), four above the core (14TC), two at the subassembly outlet.
COTC), and two in the thimble region of the subassembly (ATC). Fig 7 gives the specific instrument loading.

A T-H analysis was performed for XX09 on steady-state data obtained during EBR-II run 129C (June 1984). The T-H code THI-3D [9] was used to predict the coolant temperatures. THI-3D is a steady-state, single-phase, multi-channel code that uses the laws of mass, energy, and momentum conservation to calculate the temperature field in both the axial and radial direction. The turbulent interchange, radial thermal conduction, and wire-wrap forced flow between subchannels are considered explicitly. The model consisted of a total of 149 radial nodes, with 120 nodes for the XX09 subassembly and 29 for the surrounding annular thimble region between XX09 and the outer control-rod hex can. There are 49 axial nodes, each 12.7 mm long, modeling the entire Mark-II element length. The THI-3D code was used previously in thermal-hydraulic modeling and worked very well, especially when the annular thimble region around XX09 was included. Also, modeling of the adjacent subassemblies was not necessary, as they have a similar power-to-flow ratio, and the effects of intersubassembly heat transfer are negligible. The agreement is very good, with most of the data being within 5° C of the predicted temperature. Temperatures at the midplane were found to be higher than expected. However, this discrepancy can be explained by a number of factors, of which, a wire-wrap hot-spot effect appears most plausible. Details on the XX09 subassembly and thermal-hydraulic analysis are given in [10]. The most exciting T-H tests were the LOFWS test 45 that was conducted in April, 1986 [11]. The loss-of-flow-without-scram tests involve bypassing the normal loss of flow scram function and tripping the main coolant pumps. All of the tests demonstrated passive power reduction caused by reactor feedback mechanisms. Figure 8 presents pretest predictions and temperatures measured with a representative thermocouple in XX09 near the top of the core for a LOFWS from
100% power. A companion test, loss-of heat-sink-without-scram (LOHSWS) test was conducted the same day. LOHSWS involved a loss of normal means of transferring heat from the sodium pool to the balance of plant where electricity is generated. Figure 9 shows the tests results. The key observation from these test is that EBR-II core can ride through two severe transients without damage.

Conclusions

EBR-II has operated for 25 years in support of several major programs. During this time period, several of the original, non-replaceable, flow sensors, RDT sensors and thermocouples have failed in the primary system. This has led to the development of new sensors and the use of calculated values using computer models of the plant. It is important for the next generation of LMR reactors to minimize or eliminate the use of non-replaceable sensors.

EBR-II is perhaps the best modeled reactor in the world, thanks to a dedicated T-H analysis program. The success of this program relied on excellent measurements of temperature and flow in subassemblies in the core. The instrumented subassemblies of the XX series provided that measurement capability. From this test series, EBR-II calculations showed that the core could withstand a loss-of-flow without scram accident and a loss-of-heat sink without scram accident from full reactor power without core damage. From this, reactor designers can now design with confidence, inherently safe reactors.

EBR-II is an integral part of Argonne's IFR Program (Integral Fast Reactor) and will continue the T-H program. Additional series XX in-core instrumented subassemblies will be required.
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Fig. 1. Schematic of EBR-II plant.
Fig. 2. EBR-II primary system.
SODIUM LEVEL

AVERAGE OF FOUR SUBASSEMBLY OUTLET TC's

REACTOR UPPER PLENUM PRESSURE SYSTEM

LOCATED IN UPPER PLENUM INSTRUMENT PROBE

ULTRASONIC FLOWMETER MOUNTED IN LOWER PORTION OF THROTTLE VALVE

REACTOR AT CALCULATED FROM IHX HEAT BALANCE

ULTRASONIC FLOWMETER LOCATED IN LOWER PORTION OF THROTTLE VALVE

PRIMARY COOLING SYSTEM INSTRUMENTATION

Figure 3
EXISTING VALVE
PLUG - P₁ & P₂
LOCATIONS

TRANSUCER SUPPORT ASSEMBLY

FLOWMETER
LEADS

FLOWMETER LEADS

FLOWMETER TRANSUCERS
(2 PAIRS)

SECTION A - A

THROTTLE VALVE FLOWMETER
VALVE PLUG AND FM TRANSUCER SUPPORT ASSEMBLY

Figure 4
CONTROL ROD POSITIONS AND DEVICES INSTALLED

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<th>DEVICE INSTALLED</th>
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<td>12</td>
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<td>CONTROL ROD</td>
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LEGEND

1 SECTORS A to F
2 CONTROL RODS C
3 SAFETY RODS (2) S
4 THERMOCOUPLES (26) ●
5 FIXED SHUTDOWN ●
6 NEUTRON SOURCE N
7 GRID POSITIONS:
   - CORE 81
   - INNER BLANKET 88
   - OUTER BLANKET 810
8 TOTAL 637
9 BFTF B
10 AUTOMATIC CONTROL A
11 REACTOR SUBASSEMBLY
12 SHUTDOWN THERMOCOUPLES 503C, D, F, & H

REACTOR SUBASSEMBLY ARRANGEMENT

Figure 5
Figure 6
Figure 7

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<th>Abbreviation</th>
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Figure 7
Figure 8
Figure 9