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DESIGN AND OPERATING EXPERIENCE OF EBR-II INTERMEDIATE HEAT EXCHANGER

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Design and Operating Experience

Of

EBR-II Intermediate Heat Exchanger

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Experimental Breeder Reactor II (EBR-II) has operated for over 15 years at the Idaho National Engineering Laboratory near Idaho Falls. EBR-II has served the nation in providing information on fuels, materials, and components under conditions approaching those expected for commercial power plants. In addition, EBR-II is a power plant generating electricity with an availability of about 70%. A key component, the Intermediate Heat Exchanger (IHX), of any Liquid Metal Fast Breeder Reactor (LMFBR) must perform with a high degree of reliability for successful commercialization. The design and operating experience gained from EBR-II demonstrates that the IHX can be built and operated with confidence that its performance and reliability will be satisfactory.

ABSTRACT

Experimental Breeder Reactor II (EBR-II) has operated for over 15 years at the Idaho National Engineering Laboratory near Idaho Falls. EBR-II has served the nation in providing information on fuels, materials, and components under conditions approaching those expected for commercial power plants. In addition, EBR-II is a power plant generating electricity with an availability of about 70%. A key component, the Intermediate Heat Exchanger (IHX), of any Liquid Metal Fast Breeder Reactor (LMFBR) must perform with a high degree of reliability for successful commercialization. The design and operating experience gained from EBR-II demonstrates tht the IHX can be built and operated with confidence that its performance and reliability will be satisfactory.

NOMENCLATURE

A_f = Flow area

A_{ht} = Heat transfer area

C_p = Heat capacity

D = Diameter

De' = Equivalent diameter in inches

h = Film heat transfer coefficient

k = Thermal conductivity

Nu = Nusselt number, dimensionless, hD/k

Pe = Peclet number, dimensionless, $DV\rho C_p/k$

T = Primary sodium temperature

t = Secondary sodium temperature

U = Overall heat transfer coefficient

V = Velocity

ρ = Density

SUBSCRIPTS

h = hot

c = cold

INTRODUCTION

The EBR-II reactor is a pool-type design where all primary system components are located in a large sodium filled tank. The general arrangement of the system is shown in Fig. 1. The primary pumps are in the cold leg piping and take their suction from the pool. The flow is directed through the reactor, where it is heated by nuclear fission. From the reactor, the hot sodium flows to the IHX and then returns to the pool. In the IHX, heat from the radioactive primary system is transferred to the secondary sodium. The secondary sodium system is essentially nonradioactive and is used to transfer heat from the radioactive primary system located inside a containment building to the steam generating equipment located outside the containment building.

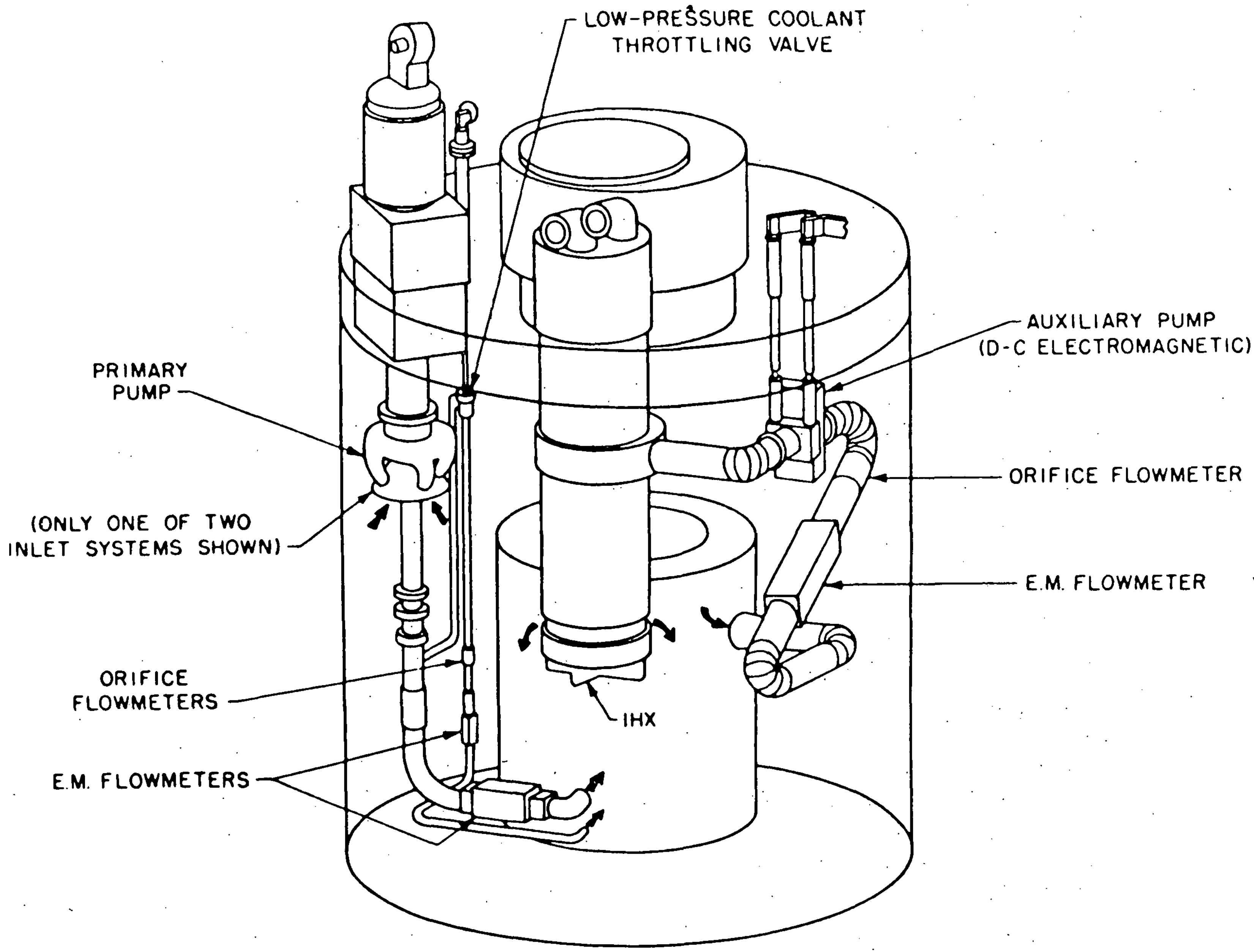

Fig. 1 EBR-II PRIMARY COOLANT SYSTEM SHOWING LOCATION OF THE IHX

This paper is concerned with the design, thermal performance, and operating experience of the Intermediate Heat Exchanger (IHX), the component providing a boundary between the primary and secondary sodium systems. Included is a discussion of the original design philosophy, heat transfer design and performance, description of the IHX, and a summary of the operating experience after approximately 15 years of service. Listed in Table 1 are design data for the EBR-II IHX.

DESIGN PHILOSOPHY

The basic philosophy utilized in the establishment of design criteria for the IHX was based on the belief that existing design methods, standards, and codes were adequate or could be extended sufficiently to provide bases for the design of a component that would reliably perform throughout its service life, without the capability for inservice inspection or in-place repair. Reliability was a prime design consideration that was not to be compromised by maintenance or repair requirements.

To achieve high reliability, repair capability, and adequate performance characteristics, the IHX was designed to satisfy the following basic requirements:

(1) Design, fabrication, and testing were to be in accordance with the rules of Section VIII, "Unfired Pressure Vessels," of the ASME Boiler and Pressure Vessel Code, 1959 edition. The rules of the Code were to be extended to provide further design criteria specifically related to sodium heat exchangers, where these were not adequately addressed within the existing Code.

(2) The heat exchanger was to be designed to facilitate natural convection cooling of the reactor during low-power operation or after reactor shutdown.

(3) The tube-bundle section of the heat exchanger was required to be removable to facilitate repair or replacement.

(4) Materials were to be selected with consideration of stress corrosion, carbon mass-transport problems, and compatibility with other primary-system materials.

(5) Sections of the heat exchanger that would be subjected to temperatures or rates of temperature change that could cause excessive thermal stresses were required to be protected by thermal shields.

(6) The heat exchanger was required to be designed for a low shell-side pressure drop. This requirement was desirable to minimize the internal pressure of the reactor upper plenum, and was also necessary for the enhancement of natural convection cooling.

(7) Uniform flow distribution at all coolant flowrates, on both the primary and secondary sides of the heat exchanger, was a requirement. This requirement was considered necessary to ensure adequate performance characteristics and to minimize structural design problems.

(8) The radiation shielding was required to be adequate to reduce all radiation from the vicinity of the heat exhanger to a biologically tolerable level. Shielding was also to be provided to minimize neutron activation of the secondary sodium.

(9) Tube-to-tubesheet attachments were to be designed with the need for weld reinforcement taken into consideration. Both the advantages and disadvantages of tube rolling were to be considered.

(10) The heat exchanger was to be designed as a straight-tube unit having fixed tubesheets. Consideration was to be given to the effects of differential expansion between tubes and tubesheet support structures.

(11) All pressure boundaries were required to be leak free, as determined by helium mass spectrometry test, in addition to the pressure tests required by the ASME Code.

A detailed conceptual design was developed by Argonne National Laboratory to achieve these objectives. Additional detailed design was performed by the fabricator. Stress analyses were done by an independent laboratory.

MECHANICAL DESIGN

The IHX (See Fig. 2) consists of three basic structures.

(1) Well casing
(2) Tube bundle
(3) Shield plug

The well casing is a cylindrical Type 304 stainless steel structure, approximately 18.5 ft (5.64 m) long and 6 ft (1.83 m) in diameter. This structure is an extension of the heat-exchanger nozzle of the primary-tank cover. It provides the support structure for the primary-flow inlet diffuser and neutron shielding that surround the heat-exchanger tube bundle. The tube bundle and shield plug form an integral unit that slides into the well casing from the top of the primary tank.

To achieve suitable thermal convection characteristics, the heat exchanger is arranged so that the primary inlet is approximately 12 ft (3.66 m) above the reactor outlet plenum. Because of this requirement, the overall length of the heat exchanger and the tube length are limited, and the resulting heat exchanger is a short, large-diameter unit with a length-to-diameter ratio of approximately 2.3.

If heat-exchanger maintenance is ever necessary, the tube bundle and shield plug can be removed from the well casing. Removal is accomplished by draining the secondary sodium, cutting the secondary inlet and outlet piping, breaking the upper mounting flange, and lifting the tube bundle and shield plug out of the well casing. Since an inert-gas blanket must be maintained at all times, a caisson or similar mechanism must be used during the removal procedure. After removal, the tank nozzle must be closed with a temporary plug.

The material selected for all pressure boundaries or sodium-wetted surfaces was Type 304 stainless steel. Possible problems with stress corrosion or carbon mass transport were considered to be neglibible in consideration of the relatively benigh chemical effects of sodium on the stainless steel surfaces at the operational temperatures of 883°F (472.8°C) for the primary coolant and 872°F (466.7°C) for the secondary coolant. Portions of the secondary coolant circuit contain ferritic 2.25 Cr-1 Mo materials; however, loss of carbon from these materials to the stainless steel in the heat exchanger was not considered to be a problem.

Protection against high temperatures and thermal transient effects is provided by thermal barriers at the primary-coolant surfaces of the upper and lower tubesheets. The secondary-coolant side of the upper head is thermally protected by a thin liner spaced away from the head surface.

The heat exchanger was designed with a low length-to-diameter ratio, which is compatible with the philosophy of a low-pressure-drop heat exchanger. The pressure drop was further reduced by maintaining axial flow to the maximum practical extent. No provisions were made for cross flow, and the support-baffle flow areas were maximized by the use of convoluted-ribbon-type supports, rather than the more conventional drilled-plate-type support. A maximum-pressure-drop criterion of 5 psi (34.4 kPa) for both primary and secondary coolant was easily achieved. Values at full power operation are approximately 2.1 psi (14.5 kPa) and 3.5 psi (24.1 kPa) respectively.

Because of an unusually low length-to-diameter ratio for the heat exchanger, a situation was created in which the primary flow could readily become imbalanced. With imbalanced flow, much of the primary sodium would not penetrate the tube bundle and would therefore bypass the center tubes. This situation could cause a loss of overall efficiency and produce excessive thermal stresses in the tubes and tube-to-tubesheet welds. To achieve balanced primary flow, the heat exchanger was designed to provide an equal static pressure drop, with proper

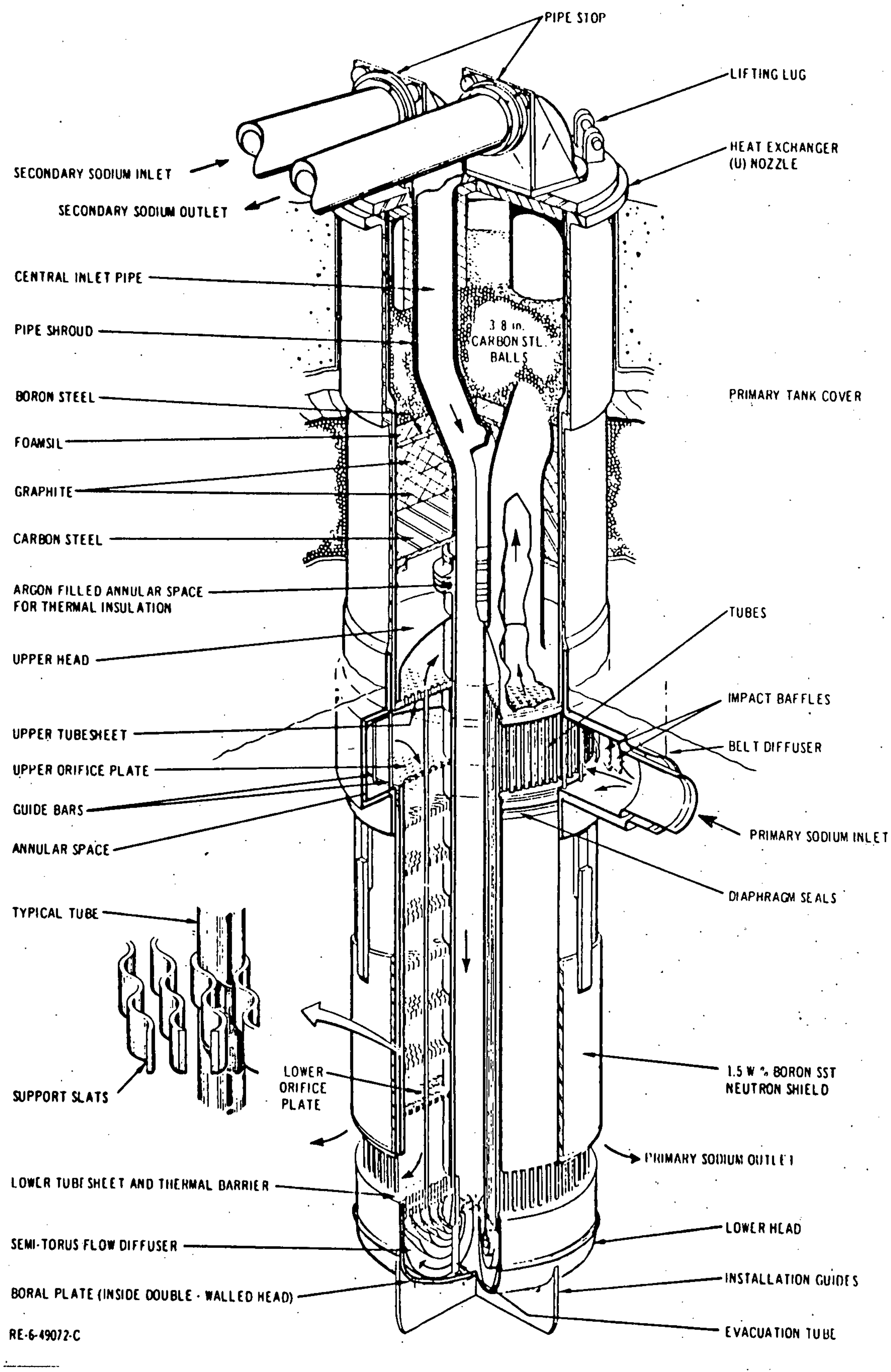

Fig. 2 EBR-II Intermediate Heat Exchanger Assembly

flow for every possible flow path. Since good thermal-convection characteristics were a requirement, cross-flow baffles were considered to be unacceptable for use in the heat exchanger. As an alternative to baffles, the belt diffuser and two orifice plates were used to achieve equal pressure drops for all possible flow paths.

The belt diffuser is positioned eccentrically around the primary-coolant inlet. This structure serves as a coolant inlet plenum and is designed to provide flow paths of equal pressure drop for all points where the primary coolant enters the tube bundle.

The orifice plates used in the heat exchanger are located at two points: one plate is positioned immediately below the primary-coolant inlet, and the other plate is located immediately above the coolant outlet. All of the heat-exchanger tubes pass through holes drilled in the orifice plates. To achieve the desired coolant flow balance, the hole sizes were varied: the smaller-diameter holes toward the periphery of the plate and the larger holes toward the center. Hole sizes were calculated to counteract the gradually increasing pressure drop as the sodium coolant flows toward or away from the center of the tube bundle.

The secondary side of the heat exchanger was also required to have balanced flow and good thermal-convection characteristics. The physical arrangement of the secondary side was also designed to promote natural convection flow. The secondary sodium enters the heat exchanger through an insulated pipe and flows down to the lower ellipsoidal head. Within the head, the flow must make a 180-degree turn before flowing up through the tubes. A semi-torus-shaped diffuser is enclosed within the lower head to turn the flow the required 180 degrees; the diffuser also distributes the coolant to provide a balanced secondary flow.

Radiation shielding is provided by shield materials within the shielding plug and by an offset in the secondary inlet and outlet piping. The offset in the piping is sufficient to eliminate direct-line streaming of radiation through the secondary coolant. All radiation shielding material is installed in the shield plug, except for neutron shielding. The neutron shields consists of a 1-in.-thick (25.4-mm) layer of 1.5 wt % boron stainless steel that covers the lower 48 in. (1.22 m) of the well casing, and a layer of 0.25-in.-thick (6.4-mm) Boral contained between the lower heads.

Various methods of attachment of tubes to tubesheet were considered. The selected design relies on a welded closure for both sealing and mechanical strength. Rolling of tubes into tubesheets was considered but eliminated because of concern that cold work introduced in the tube during an expansion process would have a bad effect on the behavior of the tubes in service.

STRESS CONSIDERATIONS

The rules of Section VIII, "Unfired Pressure Vessels," of the ASME Boiler and Pressure Vessel Code, 1959 edition, were used in the design of the heat exchanger. The Code rules were extended to cover the effects of thermal stresses that were not a requirement of the Code. The effects of thermal fatigue were considered, but not specifically evaluated since data did not exist to provide a basis for determination. Complete interaction of all bodies was considered, using conventional solutions for individual bodies where such solutions were available. Solutions were developed where conventional solutions were not available. Both tubesheets were considered as one body formed by two plates connected by an elastic foundation. Analyses were performed using a statically redundant system, which consisted of 52 reactions between various bodies. Stresses were calculated for the following four different loadings:

(1) Steady state pressure and dead weight loadings with a secondary-sodium pressure of 150 psi (1.03 MPa) and a reaction force of 1271 lb. (5654 N) on the 14-in.-diameter (375-mm outside diameter) center shell around the secondary-sodium inlet pipe.

(2) Steady-state thermal loading with the mean temperature of the center shell 20.9°F (11.6°C) higher than that of the tubes.

(3) Transient thermal loading for a reactor scram that causes the mean temperature of the center shell to be 60°F (33.3°C) higher than that of the tubes.

(4) Transient thermal loading for a failure of the secondary-sodium pump that causes the mean temperature of the center shell to be 60°F (33.3°C) lower than that of the tubes, accompanied by a 200°F (111.1°C) rise in temperature at the outer edge of the lower tubesheet.

All four of the above loadings were considered separately and stresses computed separately, since the criteria for structural adequacy were different for each loading, involving the type of loading and the expected number of cycles. Results for the four loadings were calculated, with the following conclusions:

(1) Because of the steady state pressure and dead weight loading, there was only one point, where the inner wall of the bottom head joins the ring body of the lower tubesheet, at which plastic strain would occur. It was expected the first plastic cycle during hydrostatic testing would produce sufficient plastic yielding so that subsequent operation would be in the elastic range.

(2) Thermal stresses resulting during steady state and reactor-scram operation were within acceptable levels.

(3) Thermal stresses resulting from secondary pump failure were within acceptable limits. Fatigue damage as a result of a 1000-cycle limit was judged to be acceptable.

HEAT-TRANSFER DESIGN AND ANALYSIS

The EBR-II IHX is a single-pass counter-current exchanger with primary sodium on the shell side and secondary sodium on the tube side. The design philosophy was to use a large heat-transfer area so that the approach temperature between the primary and secondary sodium would be small at the hot end of the exchanger. A conservative design was also used to compensate for the large possible uncertainty in predicting the Nusselt number on the unbaffled shell side of the exchanger. The low approach temperature at the hot end was desired to maximize the thermal efficiency of the reactor system.

Tube-side Heat-transfer Coefficient. The prediction of the heat-transfer coefficient of the secondary sodium on the tube side is easily obtained for the well-defined geometry. For the design of all EBR-II heat-transfer components, the Lubarsky-Kaufman (1) correlation was used.

$$Nu = 0.625\ Pe^{0.4} \qquad (1)$$

Using a calculated Peclet number of 170 for 62.5-MW flow and temperature conditions, a Nusselt number of was assumed that the differences would be the same at power conditions. Based on reactor operation conditions at this time (1968), an overall heat-transfer coefficient of 1280 Btu/hr·hr²·°F (7.27 kW/m²·K) was measured, as compared to the calculated value of 1350 Btu/hr·ft²·°F (7.67 kW/m²·K) for the 50-MWT power operation. This measured coefficient was only 5% less than the design correlation. The uncertainty was high, since a 1°F (0.56°C) error at the hot end of the exchanger would result in a 7% change in the overall heat-transfer coefficient. For initial operation at 62.5 MW, it was found that the measured performance was 1230 Btu/hr· ft²·°F (6.98 kW/m²·K), 89% of the design value of 1380 Btu/hr·ft²·°F (7.84 kW/m²·K). The difference is probably due to thermocouple recording drift between the time of isothermal thermocouple calibration and the initial power operation at 62.5 MW (September 1969). As mentioned above, a 1°F (0.56°C) error in the differential temperature at the hot end of the exchanger would account for the observed difference.

TABLE 2

HEAT-TRANSFER CORRELATIONS,

UNBAFFLED SHELL SIDE OF EBR-II IHX

Correlation	NUSSELT NUMBER TUBE*	NUSSELT NUMBER EQUIVALENT*
$Nu = 0.625\ Pe^{0.4}$	5.4	5.1
$Nu = 0.031\ (De'\ Pe)^{0.8}$ (3)	1.4	
$Nu = 61.2\ Pe^{0.6}(A_f/A_{ht})^{1.2}$ (4)	0.53	
$Nu = 0.106\ (De'\ Pe)^{0.6}$ (5)	1.85	

*Diameter used in Peclet Number

Summary of Heat-transfer Performance. The overall heat-transfer performance of the EBR-II IHX has been in agreement with the design correlation. Considering the unknown channeling of hot sodium on the inside and outside of the unit, which would lower the overall performance, the system condition was adequately described by the design correlations initially used.

DESCRIPTION OF THE SHIELD PLUG AND TUBE BUNDLE

The removable portion of the EBR-II IHX consists of the shield-plug and tube-bundle assembly. The reader is referred to Fig. 2 as each of the components are described.

Secondary-sodium Piping Connections. The secondary-sodium piping connections are provided above the shield plug, which is level with the primary-tank shielded cover. The inlet and outlet elbows are 12-inch Schedule 20 piping (324-mm outside diameter, 6.35 mm wall thickness). These elbows are anchored to the cover to prevent the transmission of axial and rotational displacements from the connecting piping. The connecting secondary-sodium piping must be butt-welded to these elbows after installation.

predicting shell side coefficients for the designer. Because the EBR-II design equation gives a larger coefficient than the other correlations, the measured performance could be significantly lower than predicted if the other correlations describe the EBR-II IHX. If the shell-side Nusselt numbers were given by the lower factors, the shell-side coefficient would be controlling in the performance of the exchanger.

Prediction of System Temperature Conditions. The primary-sodium temperatures are determined by the system conditions of 700°F (371°C) tank (or heat-exchanger outlet) temperature, a primary-sodium flow rate of 9000 gpm (0.568 m³/s), and a reactor power level of 62.5 MW. This will result in a reactor outlet and (assumed) exchanger inlet temperature of 883°F (473°C). For the secondary sodium, the exchanger inlet temperature is maintained near 580°F (304°C), about the saturation temperature of the steam. The design outlet temperature of the secondary sodium for the intermediate heat exchanger may be obtained from the following exchanger rate equation:

$$Q = UA_{ht} \frac{(T_h - t_h) - (T_c - t_c)}{\ln[(T_h - t_h)/(T_c - t_c)]} \quad (3)$$

Combining all of the individual heat-transfer coefficients given above and neglecting any fouling, an overall heat-transfer coefficient of 1380 Btu/hr·ft²·°F (7.84 kW/m²·K) was obtained. Using the total heat-transfer area of 3950 ft² (367 m²) and this equation, a secondary-sodium outlet temperature of 876°F (497°C) was obtained; i.e., an approach of only 7°F (3.9°C) was realized at the hot end of the exchanger. On the other hand, if the Nusselt number was 1.0 as indicated by the other correlations in Table 2, the overall heat-transfer coefficient would have been 690 Btu/hr·ft²·°F (3.92 kW/m²·K) and the secondary outlet temperature would have been 805°F (429°C) for a 78°F (43°C) approach.

Measurement of Performance. The system temperature sensors indicated that the overall heat transfer correlation was predicted by the Lubarsky-Kaufman (1) correlation rather than the other correlations given in Table 2. Consequently, the accuracy of the temperature sensors at the hot end of the exchanger is very important in determining the measured heat-transfer coefficient. The temperature sensors in the secondary sodium system are resistance thermometers, and they were removed for calibration for this study. The resistance thermometers in the primary system had failed before the exchanger performance study. Therefore, in-place thermocouples were used. The accuracy of ISA thermocouples is ± 0.75% in this temperature range, which represents errors of up to ± 6°F (3.3°C). These uncertainties are unacceptable for the low approach temperatures possible. In order to calibrate the nonremovable primary-system thermocouples, an "isothermal test" was conducted on the primary and secondary sodium systems. During this test, primary and secondary sodium was circulated at 580°F (304°C) and the output of selected thermocouples and resistance thermometers obtained. Corrections were made for measured and calculated heat additions or losses, and a comparison was obtained between the primary and secondary IHX temperature sensors. It

4.8 was obtained, which corresponds to a film coefficient of 4720 Btu/hr·ft²·°F (26.8 kW/m²·K) for the inside heat-transfer area of the tubes. A recent review (2) of heat-transfer correlations recommends the more conventional Subbotin correlation for the tube-side heat transfer.

$$Nu = 5 + 0.025\ Pe^{0.8} \qquad (2)$$

Using this correlation, a film coefficient of 6340 Btu/hr·ft²·°F (36.0 kW/m²·K) was obtained. If this correlation was used, the overall design coefficient would be increased by 8%.

Wall Heat-transfer Coefficient. The Type 304 stainless steel 0.625-in. (15.9-mm) outside diameter tube with a 0.052-in. (1.32-mm) wall thickness represents the lowest coefficient, and the controlling resistance, in the heat-transfer process. The equivalent film coefficient, based on the inside heat-transfer area of the tube, would be 2960 Btu/hr·ft²·°F (16.8 kW/m²·K).

Shell-side Heat-transfer Coefficient. The heat-transfer coefficient of the primary sodium on the shell side has a large uncertainty because of the lack of adequate heat-transfer correlations for sodium-heated unbaffled shells. For the shell, flow distribution is accomplished by the orifice plates near the top and bottom of the exchanger. Tube support is accomplished by six slat supports spaced between the orifice plates. Since there is no forced cross flow in the exchanger, heat is transferred by the primary sodium flowing parallel to the tubes containing the secondary sodium. As discussed later under OPERATING EXPERIENCE, part of the primary sodium is known to short-circuit the tubes by flowing near the inside annulus or the outside shell of the exchanger. This sodium is not forced to mix with the cooler sodium adjacent to the tubes until the flow reaches the lower orifice plate. This stream of uncooled primary sodium would lower the performance predicted by the design correlation. For the upper and lower part of the exchanger, the flow is across rather than parallel to the tubes. This section of the exchanger would have a different heat-transfer coefficient. For this analysis however, it will be assumed that the correlation applicable to the parallel-flow condition is also applicable to the cross-flow portion, which represents a much smaller heat-transfer area of the exchanger.

The Lubarsky-Kaufman (1) design correlation was used to predict the shell-side coefficient. There is some question as to whether the outside tube diameter or equivalent diameter should be used in the correlation. For the EBR-II exchanger, the effect is not significant, since the diameters only differ by 15%. Since the film coefficient is a function of the diameter to the -0.6 power, this reduces the difference in the coefficient to 9%. The Nusselt number is given in Table 2 for both conditions. Using the equivalent diameter, the Nusselt number corresponds to a heat transfer coefficient of 5720 Btu/hr·ft²·°F (32.5 kW/m²·K), based on inside tube area. Also shown in the table are other Nusselt numbers obtained from other correlations for unbaffled shells. The large variation in Nusselt numbers illustrates the uncertainty in

Inlet and Outlet Pipes. The inlet and outlet pipes pass through the shield plug, each with a 15-inch (0.381 m) offset to prevent a path for radiation to stream through the shield plug. The inlet pipe passes through the center of the tube bundle to the lower tubesheet, where it is welded. An outer pipe, sometimes called a strongback, surrounds the inlet pipe and is welded to both the upper and lower tubesheets. This double-wall construction is carried through the upper head above where the enclosed space is sealed with a bellows. The space between the two pipes was sealed after being backfilled with argon gas. This gas space, 0.6875 in. (17.5-mm), between these pipes effectively insulates the inlet pipe and sodium from the hot primary sodium in the shell. Double-wall construction is also carried through the shielded plug for both the inlet and outlet pipes. However, in this case, the gas annulus is not sealed but open to the atmosphere.

Shield Plug. The shield plug is a stepped cylindrical structure located above the tube bundle. Two basic functions are served by this structure:

(a) To provide the only support for the tube bundle.

(b) To maintain the integrity of the primary-tank biological shield.

The shielding material consists of the following (from bottom to top):

(1) 11 in. (0.28 m) of carbon steel

(2) 10 in. (0.25 m) of graphite

(3) 1.5 in. (38.1 mm) of boron (1.5%) steel

(4) about 20 in. (0.51 m) of 0.375-in. (9.5-mm) carbon steel balls.

Three in. (76.2 mm) of foam-glass thermal insulation is located between the boron steel and the steel balls.

A set of lifting lugs is provided on the top cover of the shield plug.

Tube Bundle. The heat-exchanger tube bundle comprises the following parts:

(1) Heads and lower head diffuser

(2) Shell

(3) Upper and lower tube sheets, thermal barriers, and shock plates

(4) Central inlet pipe

(5) Tubes

(6) Orifice plates

(7) Slat support plates

(8) Diaphragm seals.

The upper head is the secondary outlet plenum and covers the top of the tube bundle. This structure is an ellipsoidal head spun from 0.875-in. (22.2-mm) Type 304 stainless steel. The secondary-coolant outlet is a flued opening, formed as a part of the head. This opening tapers, and is welded to the 12-in. Schedule 20 outlet pipe (324 mm outside diameter, 6.35 mm wall thickness). A 0.25-in.-thick (6.35-mm) thermal shock plate closely conforms to the contour of the upper head; there is a 0.25-in. (6.35-mm) space between the two structures.

The lower head consists of two concentric ellipsoidal heads separated by a 0.438-in. (11.1-mm) gas-filled space. A 0.25-in.-thick (6.35-mm) Boral plate is formed to fit in the gas-filled annular space, closely following the inner contour of the outer head. This Boral plate serves as neutron shielding for the secondary sodium. Before sealing, the gas space was purged and filled with argon to a pressure of 15 psig (103.42 kPa).

A semi-torus-shaped flow diffuser is contained within the lower head assembly. The flow diffuser contains five diffuser troughs, assembled to form a single unit. Each trough is spun from 0.062-in. (1.6-mm) Type 304 stainless steel. All edges of the diffuser are rounded and all support vanes are streamlined.

A set of guides is welded to the outside of the lower ellipsoidal head. These guides serve to align the heat exchanger for insertion into the heat-exchanger nozzle of the primary tank.

The upper and lower tube sheets are 3 in. thick (76.2-mm) and are forged stainless steel. Each tube sheet contains integral lips for attachment welds. Both tube sheets were ultrasonically tested before installation in the heat exchanger. The lower tube sheet is a circular structure, with a hole through the center for the secondary inlet sodium. A 2.25-in.-thick (57.2-mm) thermal barrier is mounted on the top of the tubesheet. Both the tubesheet and the thermal barrier are drilled to accept the tubes. Tube clearance is identical for both units. The thermal barrier also extends upward and surrounds the lower portion of the outer secondary inlet pipe. A shock plate is also located immediately below the upper tubesheet. This structure is formed of 0.75-in.-thick (19.1-mm) plate. An extension of the shock plate is formed around the outer pipe of the secondary sodium inlet and extends downward for about 6 in. (152-mm).

The tube bundle comprises 3026, Type 304 stainless steel tubes. Each tube has an outside diameter of 0.625 in. (15.9-mm) and a minimum wall thickness of 0.052 in. (1.3-mm). Each tube was ultrasonically tested to ensure that no flaws existed. Tubes are arranged on a 0.8125-in. (20.6-mm) triangular pitch, and the tube bundle is packed to the maximum to minimize all bypass areas. The tubes pass through the two orifice plates that fit between the heat-exchanger shell and secondary inlet pipe. These plates are designed to provide equal flow distribution to the shell side of the heat exchanger. The heat-exchanger tubes are supported at six elevations by support slats. The tube ends were welded to the tubesheets manually by the tungsten-inert-gas process without the addition of filler metal.

The heat-exchanger shell is a double-wall structure, which encloses the tube bundle and provides support for the lower orifice plate and the six groups of support slats. The inner and outer walls are each 0.500 in. (12.7-mm) thick and enclose a 1.500-in. (38.1-mm) sodium-filled annulus, which is vented both top and bottom for filling and draining.

Instrumentation. Thirty-four thermocouples were installed to provide temperature data at various locations on the primary-sodium side (shell side) of the heat exchanger. Eight of these thermocouples were installed at various locations just below the top orifice plate. Eighteen were at various locations below the bottom orifice plate. Four each were positioned to monitor the primary-sodium inlet and outlet temperatures.

These thermocouples provided little usefull information because most of them had failed early in life (prior to raising power above 45 MW). Data apparently were not systematically recorded and/or reported early in life from these thermocouples, so no performance data are available.

No instrumentation was provided to measure secondary-sodium temperatures or any pressures or pressure drops within the assembly.

OPERATING EXPERIENCE

The IHX was installed in the EBR-II primary tank in November 1962, before the system was filled with sodium. The primary system was filled with sodium in February 1963 and the secondary side of the IHX was filled in April 1964. Except for a 2.5-month period in 1970-1971 when the secondary side was drained for removal of the evacuation tube, the assembly has been flooded with sodium continuously since initial fill. Hence, the unit has been in essentially continuous service for 16 years. Table 3 presents a summary of operating history.

TABLE 3

EBR-II INTERMEDIATE HEAT EXCHANGER

OPERATING HISTORY

Operating Period
February 1963 - December 1978

Years of service	15 years	
Time drained of sodium		
primary side	0	
secondary side	3 months	
Hours at power 45 MW	~10,000 hours	
50 MW	~10,000 hours	
62.5 MW	43,000 hours	
Energy transferred	3.6 x 106 MW-hr	
Transients experienced		
Startups	approximately 528	
Upset shutdowns		
Normal reactor scram		335
Loss of secondary flow		27
Loss of primary flow		25

Except for a minor problem in November 1970, when it was necessary to remove the permanently installed evacuation tube, service has been trouble-free. The investigation of the noise caused by the evacuation tube and the activities involved in the repair are reported in detail in Reference (6). The abstract from this reference adequately describes, for the purpose of this presentation, the problem and subsequent repair.

> "On the night of November 14, 1970, a loud banging noise was heard in the vicinity of the EBR-II Intermediate Heat Exchanger (IHX). Indications were that the noise source was within the IHX inlet pipe. A port for access to the IHX internals was installed on the inlet-pipe elbow. Visual examinations using both a periscope and a remote TV system revealed that of the two supports clips holding a 1-in. (25.4-mm) diameter evacuation tube in place, the top clip was loose and the bottom clip was missing. This condition allowed the evacuation tube to move because of the secondary sodium flow stream and vibrate against the wall of the 12-in. (3.24-mm O.D.) diameter inlet pipe. Evidence of wear on both the 12-inch (324-mm O.D.) pipe and the 1-in. (25.4-mm) tube was found.
>
> The upper clip was removed; the evacuation tube was cut at the top and bottom and removed. The lower clip was not found.
>
> The section cut out of the inlet elbow was rewelded in place and the secondary system was restored to operational status. Quiet operation of the IHX verified that the repair was successful."

Temperature measurements from the installed instrumentation indicated that some of the primary sodium is short-circuiting the tube bundle and traversing the unit essentially uncooled. This occurs in the open areas in the tube bundle next to the center pipe and at the outer periphery next to the shell. This uncooled sodium is not forced to mix with the cooler sodium until the flow streams reach the lower orifice plate. Temperatures have been measured near the inner and outer peripheries of the tube bundle below the lower orifice plate, after some mixing has occurred; these temperatures are of the order of 820°F (438°C). This compares with an average outlet temperature of 700°F (371°C). This measurement was made at full power when the hot primary inlet temperature was 883°F (473°C). This bypass flow lowers the performance of the exchanger and would explain why the measured performance is less than design, as previously discussed.

One other observation, which has caused some minor operational concern but has not resulted in any real problem, is worth mentioning. When primary flow is established through the tube bundle, the pressure in the belt diffuser is equal to the pressure drop through the shell side. This causes primary sodium to rise in the annulus between the shield plug and nozzle casing. With a pressure drop of 2.1 psi (14.48 kPa), the sodium rises as much as 5 feet (1.52 m) up the annulus. With flow changes, this causes a washing action in this annulus as the level moves up and down. As a result, higher than normal temperature and radiation levels have been observed in and above the primary-tank cover in the vicinity of the IHX. Another concern is the thermal stress cycling that occurs as a result of this washing action at the weld joining the 1-in.-thick (25.4-mm) well casing to the 2-in.-thick (50.8-mm) bottom plate of the reactor-tank cover.

CONCLUSIONS

Except for a minor problem in November 1970, when the permanently installed evacuation tube came loose and was removed, service has been trouble-free. In consideration of the successful operating history, it would appear that the basic design and operating requirements have been adequate.

Great progress has been made in the development of design methods since the EBR-II IHX was designed. The present philosophy of the ASME Boiler Code for nuclear vessels is to make better use of modern methods of stress analysis. A detailed evaluation of actual stresses permits substituting knowledge of localized stresses, and an assignment of more rational margins, in place of a large safety factor which reflected lack of knowledge.

This technique "design by analysis" does not necessarily provide a more conservative design, but it does provide confidence that the degree of conservatism is known and a much more rational assessment may be made of the expected performance of a component.

The measured thermal performance is slightly less than design, but because the unit was designed with a large heat-transfer area, minimizing the approach temperature at the hot end of the heat exchanger, this has an insignificant effect on the overall performance.

The heat-exchanger tube bundle has never been removed, hence any abnormalities that could have occurred without affecting performance have not been observed, even if they exist. A limited visual examination of the secondary sodium side was possible in 1970, when the evacuation tube was removed. No abnormalities were observed at that time.

REFERENCES

(1) B. Lubarsky and S. J. Kaufman, "Review of Experimental Investigation of Liquid Metal Heat Transfer," Report NACA-1270, 1956, National Advisory Committee for Aeronautics.

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(3) K. W. Foster, "Thermal Performance of the FRE Main Intermediate Heat Exchanger," NAA-SR-3775, June 15, 1960, Atomics International, Canoga Park, California.

(4) R. N. Lyon, ed., Liquid Metals Handbook, 2nd ed., Chap. 6, NAVEXOS P-733 (Rev), June 1952.

(5) "30 Megawatt Heat Exchanger and Steam Generator for Sodium Cooled Reactor System, Vol. I, Thermal and Hydraulic Design," APAE-112, January 31, 1962, Alco Products, Inc.

(6) H. W. Buschman, B. C. Cerutti, A. F. Clark, "Noise Investigation and Repair of the EBR-II Intermediate Heat Exchanger," ANL-7834, August 1971, Argonne National Laboratory.

TABLE 1
EBR-II IHX DATA

Code Stamp: ASME B&PV Code Section VIII, 1959

Built 1960 - 1961

Construction Material 304 Stainless Steel

Design Pressure and Temperature

Shell side	75 psig, 1000°F (517 kPa, 538°C)
Tube side	150 psig, 1000°F (1034 kPa, 538°C)
Shield plug	
Internal	50 psig, 1000°F (345 kPa, 538°C)
External	75 psig, 1000°F (517 kPa, 538°C)

Tube Bundle Assembly

Overall length	24.4 ft. (7.44 m)
Maximum diameter	5.5 ft. (1.68 m)
Tube-bundle outside dia.	56 in. (1.42 m)
Weight without shielding balls	42,700 lb. (190 kN)
Weight with shielding balls	57,700 lb. (257 kN)
Weight flooded, both sides	68,533 lb. (305 kN)

Tube Bundle

Shell side, primary sodium
- Flow downward - 2.9 ft/s (0.88 m/s)
- Unbaffled
- Tube supports - slats or wiggle bars every 12 inches (0.305 m)
- Inlet and outlet orificed.

Tube side, secondary sodium
- Flow upward - 2.8 ft/s (0.85 m/s)
- Tube pitch - 0.8125-in. triangular (20.6-mm)
- Tube outside diameter - 0.625 in. (15.9 mm)
- Tube minimum wall - 0.052 in. (1.3 mm)
- Number of tubes - 3026
- Heat-transfer area - 3950 ft^2 (367 m^2)
- Tube length - 124.438 in. (3.16 m)
- Tube sheet thickness - 3 in. (76.2 mm)