OPERATING EXPERIENCE WITH SODIUM PUMPS
AT EBR-II

by

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ABSTRACT

Several types and sizes of sodium pumps have been used at EBR-II since initial operation of the primary sodium system in April 1963. Two 4500-gpm centrifugal pumps provide flow in the primary sodium system, and one 6500-gpm linear-induction electromagnetic (EM) pump provides the main flow in the secondary sodium system. A 500-gpm permanent-magnet dc EM pump operates continuously in the primary system to ensure removal of decay heat from the reactor if both primary pumps are lost. Smaller pumps in sodium use are two 100-gpm dc EM pumps, a 100-gpm ac EM pump (for NaK), two ac linear-induction EM pumps, and several EM sampling pumps. The measured hydraulic performance of all pumps has been adequate for their applications at EBR-II.

Modification of the main primary-sodium pumps eliminated binding of both pumps which occurred during initial testing. Repair of the main secondary pump and an increase in differential pressure across the pump duct has resulted in successful operation to flow rates needed for 62.5-MWt operation. Several auxiliary pumps have operated trouble-free since they were installed. Others have had to be replaced or repaired because they failed in service.

I. INTRODUCTION

Experimental Breeder Reactor II (EBR-II) was designed and initially operated to demonstrate the feasibility of operating a sodium-cooled fast

breeder reactor in an integrated station comprising a reactor, power plant, and fuel-reprocessing facility. Since this capability was demonstrated, emphasis has shifted to using EBR-II for irradiating candidate fuel, cladding, and structural materials for the Liquid Metal Fast Breeder Reactor Program. Concurrently, EBR-II is being used as an engineering test facility to provide information on performance of components and systems for fast breeder reactors under fast-neutron irradiation in sodium environments at elevated temperatures.

The sodium pumps used at EBR-II have provided valuable experience and information relative to design, application, and operation of a variety of types and sizes of sodium pumps. This information should prove useful in the design of future fast breeder reactor plants.

II. PUMPS OF PRIMARY SYSTEM

A. Description of System

An airtight steel containment building houses the reactor, primary system, and primary auxiliary systems. EBR-II uses the primary-tank concept shown in Fig. 1, in which the reactor, major primary-system components and piping, and most of the fuel-handling equipment are submerged in a large, double-walled tank containing over 80,000 gal of 700°F sodium. Two centrifugal primary pumps, each rated at 5500 gpm but pumping 4500 gpm, take suction from the bulk sodium. This sodium is circulated in a single pass through the reactor, the single outlet pipe, the intermediate heat exchanger (IHX), and back to the bulk sodium. An auxiliary dc EM (electromagnetic) pump in the outlet pipe ensures coolant flow through the reactor at all times. A battery bank supplies emergency power to this pump if the normal rectifier power supply is lost.

B. Main Coolant Pumps

1. Description

a. Mechanical

The two main primary-coolant pumps operate in parallel to

Fig. 1. EBR-II Primary Cooling System

supply 9000 gpm of 700°F sodium to the lower plenum of the reactor at approximately 49 psig. Each pump assembly (see Fig. 2) consists of a 27-in. centrifugal pump, a baffle assembly, a shield plug, a hermetically sealed 350-hp drive motor, and a shaft. The pumps were specifically designed for liquid-sodium service. All portions of the pump assembly submerged in liquid sodium are constructed of Types 304 and 316 stainless steel, except for the hydrostatic bearing surface, which is Colmonoy.

Each pump is driven by a hermetically sealed 350-hp, 480-V, 3-phase, variable-speed motor. The motor frame is a modified vaporproof design. Because the atmosphere in the motor communicates with the primary-tank blanket gas, it is filled with argon. This argon is internally circulated by a shaft-mounted fan through an argon-to-air heat exchanger that is an integral part of the motor frame. Cooling air circulates through the heat-exchanger tubes to remove heat from the motor.

The upper motor bearing is a combination of two ball bearings arranged so that the upper ball bearing carries the normal downward thrust load and the lower ball bearing will take any upward thrust that might occur. Both bearings carry the radial load. They are lubricated by an oil bath. The lower bearing carries no thrust load, only radial, and is a grease-lubricated roller bearing.

The pump motor is connected to the impeller and the lower hydrostatic-bearing assembly by a 10.75-ft-long shaft fabricated from solid and tubular sections welded together. The sections are made of Types 304 and 316 stainless steel. The pump shaft is mechanically connected through a rigid coupling section to the drive-motor shaft.

The pump shaft passes through the 6-1/2-ft-deep shield section just below the drive motor. This section is constructed in three zones: The first, 34 in. deep, is heavy concrete; the second, 8 in. deep, is thermal insulation; the third, 33 in. deep, is steel balls.

Just below the shield section is the baffle assembly, a cylindrical structure approximately 3-1/2 ft long and 20 in. in diameter, and which contains four horizontal baffles. The pump shaft passes through the center of each baffle with a clearance of 0.187 in. on the upper three baffles and 0.120 in. on the lower baffle. Three sets of double slinger grooves in the baffle assembly prevent sodium from creeping up the shaft.

Fig. 2. EBR-II Primary Pump

One aluminum-bronze labyrinth seal is at the upper end of the baffle assembly, and another is at the top of the drive shaft, just below the drive motor. A felt seal also is at the latter location. These seals minimize the upward flow of argon gas, which could be contaminated with radioactive gases and sodium vapor.

A constant purge of 5-7 cfh of argon gas is supplied at the motor housing. This gas passes down along the shaft, further inhibiting the upward flow of sodium vapor.

The hydrostatic-bearing assembly is integral with the pump impeller. About 3% of the sodium from the pump outlet is routed through internal passages in the pump case and into the four bearing pockets (see Fig. 3). At low speeds, when the hydrostatic bearing does not center the shaft effectively, galling is prevented and wear reduced by Colmonoy bearing pads.

The entire pump assembly is designed for removal from the primary tank by a vertical lift. The pump is connected into the primary sodium system piping by a ball-joint connector, shown in Fig. 4. This connector is spring-loaded so that with the pump in its normal position, the ball and socket are held together with a force of approximately 6000 lb.

b. Pump Control

Sodium flow rate is changed by varying the speed of the pumps. Power is supplied to the pump drive motors from motor-generator (M-G) sets that have variable-slip couplings between the motor and generator. The speed of the generator, and thus its output, is varied by the coupling. The speed of the motor remains constant at all times.

The motor of each M-G set is a 400-hp, 1175-rpm unit operating on 2400 V. The generator is a field-excited synchronous unit rated at 375 kV at 480 V and 1090 rpm. It is capable of delivering 451 A at a maximum frequency of 54.4 Hz; field excitation of 125 V dc is supplied by an exciter mounted on the motor shaft.

The variable-slip coupling uses the eddy-current principle to control generator speed. Water is circulated through the coupling to maintain winding temperatures at an acceptable level. The coupling is excited by a solid-state pump-speed control circuit. A pump-tachometer

Fig. 3. Hydrostatic Bearing of Primary Pump

Fig. 4. Ball-joint Connector for Primary Pump

feedback signal is used to maintain constant frequency. Pump speed is continuously variable between 20 and 100% of full speed.

2. Operating History

The primary pumps were installed during the final phase of EBR-II construction and were first operated in sodium April 16, 1963. During the initial testing of the primary system, both pumps bound after operating less than 200 hr. The only prior testing of the pumps had been done in room-temperature water, by the manufacturer.

Pump No. 1 failed on April 23, 1963, after only a few hours of low-speed operation, when attempts to rotate the pump with the normal drive system failed. After the end cap was removed from the drive motor, manual rotation was attempted. A torque of 600 ft-lb was required to obtain movement, and a very high torque was required for rotation through 340°. Rotation over the remaining 20°, however, was essentially free. Further evaluation and tests indicated that the pump should be removed from the primary tank for inspection and repair. Figure 5 shows the pump and shaft after removal from the tank.

After the pump was removed, it was cleaned and disassembled. Inspection indicated severe galling of the lower labyrinth seal and the pump shaft. (See Figs. 6 and 7). The shaft was bowed 0.050 in., and the baffle plates were off center by 0.075 in. and rubbing the shaft.

Repairs involved remachining the baffle plates to center them and provide a 0.187-in. clearance on the lower baffle. All labyrinth-seal clearances were increased to 0.115 in. A new shaft and labyrinth were fabricated and installed.

While the No. 1 pump was being repaired, pump No. 2, after less than 200 hr of operation, failed on August 18, 1963, in a similar manner. Inspection revealed essentially the same problem. Pump No. 2 was repaired, using the same procedure that was used for pump No. 1. Both pumps were reinstalled in the primary tank and have operated successfully for over 31,000 hr since their repair.

Three incidents of minor binding of pump No. 1 have occurred since the pumps were repaired. The first, on July 12, 1965, and the second,

Fig. 5. No. 1 Primary Pump and Shaft during Disassembly

on July 17, 1965, were similar. Each occurred during a long shutdown period and was attributed to accumulation of sodium and/or sodium oxide in the running clearance between the shaft and the lower labyrinth seal. Manually rotating the shaft freed the sodium deposit and allowed normal pump operation. To help eliminate this problem, the pump argon purge was increased from approximately 1 cfh (which was used originally) to 5-7 cfh. This increase in purge apparently further retarded migration of sodium vapors up the shaft. Although several long shutdowns and reductions of tank temperature to 350°F have occurred since the July 17, 1965, incident, no further problems of this nature have been encountered.

On May 18, 1970, while the reactor was being shut down from 50 MWt, an increasing current and power requirement for pump No. 1 was noted. The pump speed was maintained constant for several minutes by the speed-control circuit, but then the flow signal indicated that the pump tripped

Fig. 6. Damaged Labyrinth Seal of No. 1 Primary Pump

Fig. 7. Gall Marks on Shaft of No. 1 Primary Pump

and stopped. The reactor was scrammed, and the pumps were manually tripped. An apparent pump overspeed, sensed from the generator of the M-G power supply, caused the pump to trip. Upon restart of the pumps, the speed, flow, and power requirements for the pump were normal.

It was postulated that the accumulation of sodium and/or sodium oxide along the shaft left a clearance at the lower labyrinth seal of only a few mils. As the reactor power and temperature were reduced, the change in the temperature environment of the pump reduced the clearance. As rubbing occurred, the power required to turn the pump increased. The resultant local heating further aggravated the binding. When the reactor and the pumps were shut down, temperatures returned to normal, and the binding disappeared.

Although the same exact conditions of power and temperature have been reproduced several times since this incident, no detectable binding has occurred. Subsequent testing and routine operation of the pumps through August 1970 have been trouble-free. Close monitoring of the No. 1 pump during similar power and temperature conditions has revealed no adverse conditions.

3. Pump Removal

To remove a main pump from the primary tank, such as was done for the binding problems in 1963, the 27-ft-long, 27-ton assembly must be lifted into an inert-atmosphere enclosure. This procedure is necessary to prevent rapid oxidation of the sodium in and on the pump assembly, as well as to prevent entry of air into the primary-sodium tank. Such an enclosure was designed and fabricated for the initial pump removal and has been retained as a maintenance tool for subsequent removals. Figure 8 shows this enclosure, a cylindrical caisson.

Pump removal is accomplished by the following general steps:

- a. Cool the sodium in the primary tank to approximately 300°F.
- b. Remove the pump drive motor.
- c. Install the adapter section. This section provides a seal to the primary-tank cover and has a seal door to close the opening in the cover after the pump is removed.

Fig. 8. Equipment for Removing Primary Pump from Reactor

- d. Remove the seal and bolts from the pump plug.
- e. Attach the lifting yoke, and seal the lifting caisson to the adapter section.
- f. Purge the adapter and caisson with argon gas.
- g. Raise the pump with the reactor-building crane. Sufficient argon gas must be supplied to the primary tank to prevent tank pressure from going negative.
- h. Close the seal door, and allow the pump to cool to room temperature.
- i. Permit air to slowly enter the caisson and oxidize the sodium. The pump is inserted by essentially the reverse of this procedure.

C. Primary Auxiliary Pump

1. Description

Figure 9 depicts the primary auxiliary pump, a permanent-magnet dc electromagnetic (EM) unit located in the 14-in. discharge pipe of the reactor. This pump provides a minimum coolant flow through the reactor at all times when the reactor-vessel cover is in its down position. The most important function of this pump is to provide cooling to the core immediately after power operations if the main primary pumps become inoperative. Normal power to the pump, 1.4 V at 9000 A, is supplied by a rectifier. If normal power fails, a battery bank provides the needed power for an additional half hour of pump operation. The pump is rated at 500 gpm at 0.25-psi discharge pressure. The temperature of the pumped sodium is the reactor outlet temperature, usually between 700 and 885°F.

A double-walled box or case encloses the pump. The box is filled with sodium, which communicates with the primary-tank sodium through the integral fill tubes. Insulated copper busbars penetrate the primary-tank cover and extend into the pump case, but have no mechanical connection with the pump duct. This arrangement permits differential movement between the bars and the pump assembly and also allows removal of the bars for inspection and maintenance. The lower ends of the bars are uninsulated and originally were bare copper.

Fig. 9. Primary Auxiliary Pump

The pump duct is an integral part of the discharge pipe and has the same cross-sectional shape and area as the pipe. Electrical contact between the busbars and the pump tube is provided by the sodium in the box. A small amount of current leaks out of the box through the fill tubes (see Fig. 10).

The magnetic field for the pump is provided by a large Alnico V magnet, which surrounds the pump tube. Flux density at the center of the gap is about 1000 G at the operating temperature of 700°F.

2. Operating History

Operation of this pump has been satisfactory and trouble-free. The one problem related to this pump had little effect on its performance. Early in 1967, copper was found plated on the inside of the piping in the primary plugging loop.* The exposed electrodes in the primary auxiliary pump appeared to be the most likely sources of the copper. The busbars were removed, and it was clearly evident that there had been significant copper loss from each of the electrodes (see Fig. 11). After the sodium was cleaned from the bars, the amount of copper eroded, as measured by water-displacement tests, was found to be about 10 lb.

Each busbar was machined to a uniform diameter and press-fitted with a stainless steel sleeve, as shown in Fig. 12. The lower end of the sleeve was welded to the copper electrode with a copper-silver weld rod to ensure a good current path (see Fig. 13). The end of the sleeve was then capped with a stainless steel disk (see Fig. 14), leaving no copper of the busbar exposed to the sodium. Pump operation has been entirely satisfactory since the repair of the busbars, and pump characteristics changed very little as a result of the modification.

III. PUMPS OF SECONDARY SYSTEM

A. Description of System

The nonradioactive secondary system removes heat from the primary

*The plugging loop is a small loop made of 1/2-in. stainless steel tubing and contains an economizer, throttle valve, and plugging valve. By lowering the temperature of the plugging valve and observing the point at which sodium flow starts to decrease, the operator can determine oxygen content of the sodium.

Fig. 10. Current Paths in Primary Auxiliary Pump

Fig. 11. Anode Busbar of Primary Auxiliary Pump

Fig. 12. Sleeve Pressed over Busbar of Primary Auxiliary Pump

*Fig. 13. Transition Weld between Sleeve and Busbar
of Primary Auxiliary Pump*

Fig. 14. Completed Repair of Busbar of Primary Auxiliary Pump

tank via the intermediate heat exchanger (IHX) and transfers the heat to the superheaters and evaporators. From the evaporators, the coolant is circulated to the surge tank, the high point in the secondary system. The surge tank provides a constant suction head on the main secondary ac EM pump and also permits entrained gases to escape from the sodium at the sodium/argon interface. Sodium is pumped back to the IHX from the surge tank at 580°F.

A secondary-sodium recirculating system provides continuous flow from a storage tank, which can hold the entire inventory of secondary-system sodium, to the surge tank. This excess flow ensures that the level of sodium in the surge tank will not drop if sodium leaks through the drain valves and back to the storage tank. An overflow standpipe in the surge tank returns the excess sodium to the storage tank and fixes the operating level in the surge tank. A portion of the recirculating sodium may be routed through the secondary purification system (the system for purifying the secondary sodium) for removal of oxides and other impurities..

Two small ac EM linear-induction pumps, installed in parallel, maintain this recirculating flow. One pump normally operates when the system is full, and the second is kept in hot standby. During the actual filling, both pumps are operated in parallel.

B. Main Secondary EM Pump

1. Description

The main secondary pump is an enclosed, water-cooled, linear-induction EM pump designed to circulate 6500 gpm of 700°F sodium at a 53-psi head. It is designed to operate in a temperature range of 500 to 700°F, although it will operate at any temperature between the freezing point of sodium (211°F) and 700°F.

The pump (Fig. 15) is composed of three major subassemblies: the pump-duct assembly, the two stator assemblies, and the pump-casing assembly.

The principal parts of the pump-duct assembly are the nozzles, the expansion joint, the transition pieces, and the pump duct. All parts of the pump-duct assembly are made of AISI Type 347 stainless steel. Suction

Fig. 15. Main Secondary EM Pump

and discharge nozzles are 12-in. Schedule 10S pipe with welded connections. The expansion joint permits differential thermal expansion between the pump duct and the pump casing. It is comprised of two flexible bellows and supporting and positioning parts. The two bellows are in series so that both would have to leak for sodium to get into the pump casing.

The inlet and outlet transition pieces transform the flow cross-section of the sodium from circular (in the expansion joints and nozzles) to rectangular (in the duct), and vice versa. Tubular heaters are between the stiffening frames of the transition pieces.

The duct has a cross section of 1.5 x 32 in. and is 49.4 in. long. Its wall is 1/16 in. thick. Pumping action takes place in the duct as the liquid sodium flows through the moving magnetic field produced by the stator windings.

Internal supports, or spacers, prevent collapse of the duct if it is evacuated. The spacers are formed, oriented, and arranged to afford minimum resistance to flow of the liquid sodium and to the electric current in the sodium. They are welded at one duct wall and free at the other. The duct is not self-supporting when pressurized internally, but it is supported by the stators when positioned in the pump casing.

Each stator assembly consists of a laminated punching stack, form-wound coils, coolant tubes, a structural stator plate, and metallic thermal insulation. The two stator assemblies are electrically and mechanically independent. Power is supplied to each stator through ceramic-to-metal brazed terminals, which provide a seal at the pump casing. Cooling water is supplied to each stator by a 1-in. Schedule 40 AISI Type 300 stainless steel pipe. The laminated punching stack provides a low-reluctance path for the magnetic flux, as in a conventional induction-motor stator. Every fourth punching is made of copper to increase the thermal conductivity of the stack.

The coils are similar to the formed coils used in large induction motors, except that the two coil slides lie in parallel planes because the slots in the punchings are parallel. The coils are form-wound and insulated with glass-backed, silicone-bonded mica tape. They are arranged to form an eight-pole magnetic field with a linear synchronous speed of 55.4 fps.

The punching stack is fastened to a steel plate by tapered split wedges that fit into dove-tailed slots in the punching stack and the plate. The plate is bolted to the structural stator plate. The stator plate supports the punching stack and provides the required external restraint for the pump duct. It is made of carbon steel plate and structural I-beams.

The thermal insulation, located between the surface of the punching stack and the duct, provides a thermal barrier between the windings and the hot liquid sodium in the duct. It consists of alternate layers of stainless steel screen and narrow strips of thin stainless steel.

The casing is a welded frame that positions the other parts of the pump. It is primarily a structural member and a secondary containment in the event of a sodium leak in the pump duct.

The pump is served by two power supplies. The normal power supply is a 350-kW, 3-phase, 60-cycle M-G set. This supply is used for all flow rates above 6% of full flow. An alternate power supply--a motor-driven variable transformer--operates the pump below flow rates due to natural convection (~6% of full flow). This transformer will operate the pump either forward or reverse, and is also connected to the emergency electrical power so control of secondary flow can be maintained if the normal 480-V system fails.

The generator field in the M-G set is excited by a full-wave, bridge-type rectifier. Rectifier output voltage is varied by a motor-operated variable transformer that supplies power to the diode bridge. Pump flow is adjusted manually through a raise-lower control switch that operates the drive motor of the transformer, which changes the excitation voltage and in turn the voltage to the pump. Pump flow can be increased from 0 to 100%, or decreased from 100% to 0, in 34 sec.

The motor-driven variable transformer of the alternate power supply is connected to a 3-phase stepdown transformer. Output from the stepdown transformer is connected to the pump through an ac contactor. Output from the alternate supply is limited to 40 V, which corresponds to a 10-12% flow.

To retard natural-convection flow, the pump is usually energized in the reversed-head condition during plant standby. Reversed circulation in the system is not ever permitted; thus, precise and stable flow control is required to prevent inadvertent reversed flow.

2. Operating History

The secondary system was filled with sodium and placed in operation in August 1963. Intermittent operation of the system continued until April 1964, when the primary and secondary systems were first placed in combined operation. The pump has been operated continuously since then, except for one or two months each year when the secondary system was drained. Of the approximately 42,000 hr of pump operation, approximately 26,000 hr have been at flows above 6%. The other 16,000 hr have been primarily in a reversed-head condition at low flow.

3. Failure and Repair of Pump Duct

A sodium leak occurred in the pump duct on April 16, 1964, after 1385 hr of operation. This leak was caused by three separate fatigue cracks in the stainless steel duct. A probe-type leak detector in the pump case actuated the leak alarm. Because there was no change in the electrical characteristics of the pump, further investigation was made to verify that an actual leak had occurred. The leak probe was removed, and the sodium leak was visually confirmed. About 40 min elapsed between the time of the initial alarm and the confirmation of the leak. During this time, the pump continued to operate without any change in its indicated parameters. After the leak was confirmed, the secondary system was drained to the storage tank, and the plant was shut down.

The pump was disassembled under the supervision of a representative of General Electric Company, the pump manufacturer. Disassembly included removal of the top stator and the entire duct assembly. The duct was cleaned by circulating alcohol through it, and the stators were scraped and washed with steam.

Two of the fatigue cracks were in the top duct wall, and the third was in the bottom duct wall. All were about 15 in. from the inlet

of the duct and were transverse to the flow direction. Figure 16 shows one of these cracks. Further inspection of the duct for cracks by X-ray, dye-penetrant, ultrasonic, and microscopic examination showed no other defects.

Fig. 16. Fatigue Crack in Duct of Main Secondary Pump

Most of each cracked area was removed with a hole saw, and circular patches were welded in the holes. A typical patch is shown in Fig. 17. After the welding, the duct was X-rayed and helium leaktested. Then, the pump was reassembled. Figure 18 shows the pump duct after the repair was complete.

The duct failure was investigated by the pump manufacturer, who concluded that the failure was caused by a combination of low inlet pressure at high flow rates, electromagnetically induced pressure pulsations near the inlet, and a duct resonance approaching the 120-Hz exciting frequency near the inlet.

To prevent a recurrence of the problem, the differential pressure between the duct and the pump case was increased by installing a vacuum control system on the pump case. This system maintains the pump case at a pressure of 6 to 7 psia, thereby keeping the pump duct expanded against the stators to eliminate flutter or vibration. With the increased pressure

Fig. 17. Completed Repair of Crack in Duct of Main Secondary Pump

differential and a surge-tank pressure of 6 in. H_2O , a limit of 5000 gpm was set on the flow. Since then, most of the operation of the pump has been between 4400 and 4800 gpm. The pump was operated for about four days at 5300 gpm during 62.5-MWt operation (in run 38A). For this higher flow rate, the surge-tank pressure was increased from 6 in. H_2O to 7 psig to further increase the differential pressure across the duct. There were no indications of increased vibration or other difficulties with the pump at the higher flow rates. Future operation will be at the higher flow rate associated with the design power operation of 62.5 MWt.

C. Secondary Recirculating Pumps

The two secondary-system recirculating pumps (both ac EM) were built in 1953 by the General Electric Company. After being used several years by Knolls Atomic Power Laboratory, they were obtained by Argonne National Laboratory in 1958 as surplus equipment. A small sodium leak in one pump had been repaired in 1956. The other pump was tested before being installed at EBR-II to determine the suitability of the type of pump for use in the recirculating system. The test was satisfactory, and both pumps were selected for use.

Fig. 18. Duct of Main Secondary Pump after Repair of Fatigue Cracks

Each pump is rated at 60 gpm with a discharge pressure of 30 psi. Sodium temperature is 580°F. Basic components of each pump are the case, water-cooled stator, duct, and suction and discharge nozzles. Variable voltage is supplied to each pump from an autotransformer to provide flow rates from 0 to 60 gpm.

The recirculating pump is illustrated in Fig. 19. The case, a rectangular steel box structure, is 27 in. high, 24 in. deep, and 9 in. wide. Penetrations are provided in the case for the sodium-inlet and -outlet nozzles and the electrical wiring. The nozzles are 2-in. Schedule 40 Type 347 stainless steel pipe; the inlet nozzle is below the outlet nozzle. Inside the case, the pump duct is welded to openings cut in the nozzle walls, and the nozzle ends are capped. Internal supports in the duct permit it to withstand full vacuum.

The pump stators, located adjacent to the large, flat duct surfaces, are made of laminated punching stacks, form-wound coils, water-cooling jackets, and stator support plates. Each pump is equipped with a set of four tubular resistance heaters to maintain operating temperatures.

There have been no significant problems with either pump since the secondary system was originally filled in 1963.

IV. PUMPS IN PRIMARY AUXILIARY SYSTEMS

A. Sodium-purification System

1. Description of System

Primary sodium is continuously purified by a recirculating cold-trapping system. Major components of this system are: the cold trap, which includes a regenerative heat exchanger; a surge tank; and a 100-gpm dc EM pump. Sodium at 700°F is pumped from the primary tank, through the surge tank, and down to the shielded purification cell. In this cell, the sodium flows through the pump, is cooled in the regenerative heat exchanger, and is further cooled in the cold trap by NaK flowing through a jacket around the trap. After leaving the cold trap, the sodium is reheated in the regenerative heat exchanger before it is returned to the primary tank.

A 100-gpm ac EM pump circulates the NaK between the cold trap and a heat exchanger in which it is cooled by silicone.

Fig. 19. Secondary EM Recirculating Pump

2. Main EM Pump (dc)

a. Description

The main sodium pump of the primary purification system is a dc conduction electromagnetic pump. Power is supplied to the pump by an air-cooled silicon rectifier with a maximum capacity of 15,000 A at 1.7 V. Although the pump was originally mounted horizontally in the purification cell, it was moved to a vertical position during modification of the purification system in 1968.

Details of the pump are shown in Fig. 20. The pump duct is a flat, rectangular tube placed in the air gap between two electromagnets. Current is supplied through two electrodes brazed to the pump duct. The electrodes are nickel-plated copper and are extremities of the internal bus of the pump. Bellows welded to each end of the pump duct allow for thermal expansion during temperature changes in the duct. The pump internals are enclosed in the pump housing, which is designed to contain any sodium leak resulting from failure of the pump duct. A probe for detecting sodium leaks is positioned in the base of the pump housing. Type 304 stainless steel is used for the pump housing and other parts that operate in the 700°F sodium.

Two cylindrical busbars are attached inside the pump housing to the pump bus. The busbars extend through the pump housing and are joined to the dc supply bus, which penetrates the purification cell and extends to the rectifier. Bellows provide the seal between the busbars and the pump housing.

b. Operating History

The pump has been in service for 7-1/2 yr. Total operating time accumulated to date is 27,120 hr. For the most part, operation has been with sodium at 700°F, but substantial pump operation has been performed at sodium temperatures of 350 and 580°F. The pump has been cycled from ambient temperature to 700°F more than 50 times during routine startups of the purification system. System flow has varied between 20 to 60 ppm, with a normal flow of 30 gpm. A flow of 30 gpm requires a power input of 3500 A at 0.31 V.

Fig. 20. Main EM Sodium Pump of Primary Purification System

c. Difficulties with Pump

In March 1964, difficulties were encountered in establishing flow in the primary purification system. The trouble was traced to a high-resistance connection in the dc bus supplying power to the pump. The connection is immediately adjacent to the pump. Rectangular copper busbars, 2 in. by 4 in., are silver-soldered to the pump busbars to form the connection. A single steel bolt fastens each rectangular busbar to the pump busbars to provide a tight joint.

Inspection revealed that the connection was loose and that the mating surfaces had oxidized. To provide a superior electrical connection, the mating surfaces were thoroughly cleaned, tinned, and silver-soldered. In addition, Belleville washers were installed with the bolts when the connection was reassembled, thereby ensuring that a snug joint is maintained during temperature changes.

Examination of the remainder of the supply bus disclosed arcing at the point the bus passes through the wall of the purification cell. At the wall penetration, circular copper busbars pass through carbon steel liners. Arcing was eliminated by insulating the busbars from the wall liners. Rework consisted of machining 0.050 in. from the diameter of the copper busbars and wrapping the pieces with glass insulating tape.

Except for the faulty bus connection, the pump has operated without difficulty since April 1963.

3. NaK-circulating EM Pump (ac)

a. Description

The 100-gpm EM pump used for circulating the NaK between the cold trap and the NaK/silicone heat exchanger is an ac Faraday type supplied by MSA Research Corporation (see Fig. 21). Single-phase, 240-V ac power is supplied to the pump. The pump duct is mounted vertically and has a wall thickness of 0.109 in. Pump internals, including the pump duct, are supported in a perforated steel cage that provides rigidity and minimizes vibration. The pump needs no cooling.

Fig. 21. NaK-circulating EM Pump of Primary Purification System

b. Operating History

The pump has been in service for seven years and has operated approximately 1130 days. Pump flow has been almost exclusively 80 gpm with a NaK temperature of 200°F. No problems have been encountered with operation of the pump. Periodic examinations have shown the exposed parts of the pump to be in excellent condition.

B. Fuel-element-rupture Detection (FERD) System

1. Description of System

Another primary-system sodium loop external to the primary tank is the FERD system. This loop samples primary sodium from the discharge of the intermediate heat exchanger (IHx) and monitors the sodium for delayed neutrons. The detection of neutrons would indicate the presence of fission products in the sodium stream and exposure of fuel in the core. After passing through the neutron-detector area, the sodium is returned to the primary tank.

A 100-gpm dc conduction EM pump is used in this loop. Two surge tanks for filling the loop are valved out during normal system operation.

2. FERD-system Pump

a. Description

The internals of the FERD pump are similar to those of the main primary purification pump. Modifications of the pump duct, current-carrying bus, and support arrangement, however, have improved the operating characteristics and provided a more versatile pump than the purification pump. As with the purification pump, the internals of the FERD pump are mounted in a Type 304 stainless steel housing. The duct is also Type 304 stainless steel with a 32-mil-thick wall. Figure 22 shows the pump with the housing removed. Leak detection is provided in the housing to indicate a sodium leak from the pump duct. Power for the pump is supplied from an air-cooled silicon rectifier rated at 8000 A and 1.5 V.

*Fig. 22. EM Pump of Fuel-element-rupture Detection System,
with Housing Removed*

b. Operating History

Three dc EM pumps of identical design have been used in the FERD system. The original pump was placed in operation in July 1964, when flow was initially established through the FERD system. After 1680 hr of operation, the pump duct developed a sodium leak. The second pump was installed as a direct replacement, but was relocated at a lower elevation than the original pump. Performance of the second pump was satisfactory until September 1969, when difficulty was experienced in holding a constant flow. Intermittent variations in the resistance of the pump winding caused step changes in the flow, so the pump was removed and disassembled to determine the reason for the instability. This second pump was replaced in April 1970, after 34,980 hr of operation.

The three pumps have been operated almost exclusively at 100 gpm and with a sodium temperature of 700°F. Limited operating time has been accrued at temperatures between 350 to 700°F. The current operating time of the third pump is 4380 hr.

c. Difficulties

(i) Failure of Pump Duct, 1964

During the initial operational checkout, chronic gas

entrainment in the first FERD pump made it difficult to establish and maintain stable flow in the system at low flow rates. At flow rates above ~20 gpm, however, the sodium velocity was sufficient to sweep out the gas, and the pump would perform in a normal manner.

Two months after initial operation, a sodium leak developed in the pump duct during startup. All leaking sodium was contained within the pump housing. Figure 23 shows the duct after removal and disassembly of the pump. The extensive melting observed in the pump duct was caused by the increased resistance and over-temperature that resulted from gas bubbles in the duct.

Fig. 23. Failed Duct of Original Pump in Fuel-element-rupture Detection System

In the original design, a surge tank was used for removing entrained gas from the system. The FERD piping was filled by pulling a partial vacuum on the tank. When sodium reached the tank, the remainder of the system filled by gravity. Any gas left in the system would tend to rise to the high spot in the piping, the surge tank. Both the inlet and outlet

pipes, however, were installed in the primary bulk sodium with long dip-legs to prevent gas from being sucked from the primary cover gas.

Several system modifications were made to eliminate the gas entrainment. The replacement pump was located 3 ft below the elevation of the original pump, and the single surge tank was replaced by two surge tanks, one on the inlet and one on the outlet line. Shutoff valves permitted isolating the surge tanks after sodium filling, which minimizes the possibility of gas entering the system because of a leak or loss of vacuum in the surge tanks.

Operational testing of the replacement pump showed that the modifications had eliminated the original design deficiencies of the system. The pump performed satisfactorily during startup and up to 100-gpm flow.

(ii) Problems with Electrical Connection, 1969

The replacement pump operated without trouble until September 1969, when step changes in flow were observed. Changes in the pump voltage and current showed the characteristics of a loose electrical connection. Inspection of the dc bus supplying power to the pump revealed that the busbar connection immediately above the pump had heated excessively. Severe oxidation resulted on the mating surfaces of the connection. Figures 24 and 25 show the connection in two stages during its disassembly. Two pole pieces from the pump join a series of flat, rectangular plates to form the busbar connection.

All parts of the busbar connection are made of copper. Copper bolts were used to provide a rigid connection, and the mating surfaces had been silver-soldered. Oxidation occurred because the connection had become loose, causing arcing at the mating surfaces. Since the faulty connection was close to the pump, it was subjected to much higher temperatures than the other busbar connections. The joint was thermally cycled during startup of the pump and when the primary bulk sodium temperature was varied within the acceptable range of 350 to 700°F. A combination of the high temperature and thermal cycling allowed the joint to gradually loosen, resulting in the eventual deterioration of the electrical connection.

Fig. 24. Busbar Connection Immediately above Top of Pump in Fuel-element-rupture Detection System

The connection was temporarily repaired by cleaning the mating surfaces and hand-plating the surfaces with silver. Subsequent operation of the FERD system revealed that the dc bus resistance had been substantially reduced, but intermittent step changes in flow still occurred. In the next seven months, the frequency and severity of the flow perturbations became increasingly worse.

The pump was removed in April 1970. As with the first pump, the second pump was replaced with a spare pump of identical design. Because the FERD system functions during operation of the reactor at power, the spare pump was installed and the system was returned to operation before the old pump could be disassembled and inspected to determine the exact cause of the problem. Interchanging of the pumps required one week.

Along with the pump replacement, permanent repairs of the busbar connection were made. The copper bolts were replaced with steel bolts, which had a coefficient of expansion similar to that of copper, and

Belleville washers. During reassembly of the connection, the bolts were tightened to a torque of 40 ft-lb while hot. This clamping arrangement holds the connection in compression during all operating conditions and should substantially reduce oxidation of the mating surfaces. Periodic measurements of the electrical resistance across the joint have revealed no deterioration of the busbar connections.

After the second pump had been removed from the FERD system and thoroughly cleaned of sodium, it was disassembled. Preliminary inspection showed the pump components to be in good condition except for two items. Four of the five stainless steel bolts holding the internal bus coil to the pump duct were loose. This loose connection apparently caused the erratic behavior of the pump. Figures 26 and 27 show the pump duct and connecting bus coil pieces. Localized arcing occurred near and around a number of the bolt holes, but little oxidation occurred, because

Fig. 25. Busbars with Oxidized Surface Extending through Casing of Pump in Fuel-element-rupture Detection System

Fig. 26. Duct and Internal Bus Coil of Pump of Fuel-element-rupture Detection System, Showing Effect of Localized Arcing around Bolt Holes

Fig. 27. Closeup of Effect of Localized Arcing Near Bolt Hole

the pump housing was filled with argon. The connection probably loosened gradually because of thermal cycling of the pump during its five years of operation. The difference between the expansion coefficients of the copper bus coil and the stainless steel bolts was sufficient to cause a combination of relaxation and stretching.

Besides the loose connection, the unconstrained surfaces of the pump duct were slightly bowed outward. No visible cracks were present, however, and the slight deformation of the pump duct was not a contributing factor to the unsatisfactory pump performance.

d. Future Plans

A replacement pump will be procured as a spare. If a commercial pump is available that meets the temperature and radioactivity criteria of the FERD system, it will be obtained. If no such pump is available, an improved pump based on the original FERD pump will be built. To minimize the recurrence of previous problems, the following changes would be included in the pump:

- (1) The internal bolted connections of the pump bus will be improved to prevent their coming loose. Either a better clamping arrangement will be designed or the joints will be brazed.
- (2) A better bolting arrangement will be used to provide a tight electrical connection at the external busbar connections. An inert atmosphere may also be provided to retard oxidation.
- (3) Additional instrumentation will be included to aid troubleshooting and locating electrical problems.

C. Sampling and Plugging Systems

1. Description of Systems

The sodium-sampling systems provide for removal of primary-system sodium from the primary-purification and FERD systems for chemical and

radiological analysis. Plugging loops are used to measure oxide concentrations in the sodium from these same systems. Small EM pumps have been used in both sampling loops and in the FERD plugging loop. At present, however, all have been removed from service, and improved pumps for these applications are under test.

2. Pumps of Systems

a. Description

All three pumps that have been used in this service are small dc EM conduction units, and all operated at flow rates of less than 5 gpm and at temperatures up to 700°F. Two were 3/4-in. pumps, and the third was a 1/2-in. pump. The 3/4-in. pumps, which were used in both sampling systems, were identical in construction except for the current-carrying cores and minor details. One of these pumps had a laminated core and was designed for ac service, but was wired for dc. The other, used for dc service, had a solid core.

The 3/4-in. pumps had thin-wall (0.035-in.) pump ducts made of Type 304 stainless steel. Copper electrodes were solidly brazed to opposite sides of the duct with a eutectic silver-copper braze alloy. The pump duct, which is flattened during fabrication, passed through the gap between two electromagnets. These small conduction pumps differed from the main pumps of the purification and FERD systems in that they were not provided with secondary containment (canned).

Except for its smaller size, the 1/2-in. pump, which was used in the FERD plugging loop, was similar to the 3/4-in. pumps. It had a laminated core, and the electrodes were originally brazed to the pump duct with a eutectic silver-copper braze alloy. Before the pump was installed, however, the braze failed, and the electrodes became loose. The pump was repaired by removing the braze material and welding the electrodes to the pump duct using the TIG (tungsten inert gas) process.

All three pumps were located where radiation levels were high and access was limited. Each 3/4-in. pump was installed with Conoseal couplings to allow them to be removed without cutting into the sodium piping. The 1/2-in. pump was welded into the piping.

b. Operating History

The FERD sampling and plugging systems were installed and operationally tested in late 1967. They served initially to provide the capability for monitoring coolant quality while the primary purification system was shut down for replacement of the cold trap. After the purification sampling and plugging systems were back in service, the FERD systems were used to obtain analytical results which could be compared with the results obtained with the regular systems.

The FERD sampling pump was placed in operation on December 7, 1967. It failed on January 23, 1969, after 59 samples had been taken. During sampling, the sodium and pump temperatures were cycled from ambient to 700°F, and the pump operated 16-1/2 hr. The electrical input to the pump was varied from 250 to 400 A, a range corresponding to flow rates of 2 to 3 gpm.

The FERD plugging pump was started two weeks after the FERD sampling pump. The pump operated successfully until it was shut down after failure of the primary purification sampling pump on April 3, 1969. During its 17-month operating period, the pump accumulated 8800 hr of trouble-free operation. During normal steady-state operation, the sodium temperature was 700°F. When plugging temperatures were being determined, the pump temperature was cycled between 225 and 700°F.

The primary purification sampling system was extensively modified when the primary cold trap was replaced in early 1968. The modification included installation of one of the 3/4-in. conduction pumps in the sampling system to provide greater flow capability. Operation of that pump began November 23, 1968, and ended April 3, 1969, when the pump failed. Twenty samples were taken before failure, and the total operating time for the pump was about 5-1/2 hr. Each time a sample was taken, the pump temperature was cycled from ambient to 700°F. The electrical input to the pump ranged from 200 to 1000 A, with an average input of 500 A.

c. Difficulties

The FERD sampling pump and the 3/4-in. pump in the primary purification system failed within three months of each other. Erratic flow

and a high current requirement were first experienced with the FERD sampling pump. The pump was removed and was being examined when the primary purification sampling pump failed and caused a small sodium fire.

Examination of the primary purification sampling pump showed that the brazes between the electrodes and the duct had fractured. One of the electrodes had separated from the duct, and subsequent electrical arcing from the electrode had melted a hole about $3/64$ in. in diameter in the duct (see Fig. 28). An estimated 3.5 lb of sodium leaked from the system and caused the small sodium fire in the vicinity of the pump. The pump has been replaced with a pipe spool piece until a suitable replacement pump becomes available. Meanwhile, the differential pressure across the main purification EM pump is being used as the driving head to provide flow through the sampling system. The sampling system was returned to operation six days after the fire. Since then, operation of the system has been routine and satisfactory.

*Fig. 28. Hole in Duct of Primary Purification Sampling Pump
Caused by Arcing*

The FERD sampling pump failed in the same manner as the primary purification sampling pump. The electrodes broke loose from the pump duct, and arcing occurred; however, there was no penetration of the duct, and no sodium leaked from the pump.

Examination of the pumps revealed two apparent reasons for the braze failures. The pump ducts were deformed; rather than being

rectangular in cross section, they bulged. This deformation probably occurred while the sampling-system sodium was being melted in preparation for sampling. Sodium in the duct must have melted before the adjacent sodium, thereby causing an outward hydraulic force on the duct. Three times as many samples had been taken with the FERD sampling pump, and its duct was deformed even more.

The other factor contributing to failure was inadequate brazing of the electrodes to the pump duct. Examination of the braze area indicated that contact of the braze alloy with the mating surfaces was incomplete. The problems of brazing were two-fold for this particular pump design: (1) The area of the mating surfaces was small (0.260 in. x 0.190 in.), and (2) brazing required bonding the relatively thick section of the electrode to the thin wall of the pump duct.

As stated previously, the FERD plugging pump was secured after the two sampling pumps failed. While the main FERD pump was being replaced in April 1970, the plugging pump was removed for inspection. This pump, in which sodium had not routinely been permitted to solidify, showed no evidence of failure and was in excellent condition.

d. Corrective Action

After the failure of the two sampling pumps, a program was initiated to provide small reliable sodium pumps for the EBR-II sampling systems. A hermetically canned EM conduction pump has been designed and is being fabricated. When completed, this pump will be used to reactivate the FERD sampling system.

The canned EM conduction pump is the same size as the original pump, but is improved in design. The pump duct is built with ears protruding from each side. The duct and ears are integral and were machined from a single piece of Type 304 stainless steel. Copper electrodes are TIG-welded to the ears to provide a stronger bond that will be more mechanically resistant for the cyclic operation the pump will receive in the FERD sampling system.

The pump is provided with double containment similar to that of the main FERD and primary purification pumps. The pump duct and electromagnets are in a stainless steel housing which will contain any sodium leak

that would result from a failure of the pump duct. A leak-detector probe in the bottom of the housing will indicate sodium leakage. These features should eliminate the difficulties encountered with the original 3/4-in. EM conduction pumps.

Besides the canned EM conduction pump, an annular linear-induction pump has been designed. This pump does not require an auxiliary cooling system. Two of these pumps have been fabricated, one of which is being tested in a small sodium loop. If the pump completes successful testing, the other pump will be installed in the primary sampling system. The annular linear-induction pump will provide a higher sample flow rate for this sodium-sampling system.

V. CONCLUSIONS

The experience with pumps in operating sodium systems at EBR-II has delineated many areas where design and use of such pumps can be improved.

Difficulties with the sodium pumps at EBR-II can be traced to many sources. The design of the critical clearances or the type of heat treatment probably played an important role in the binding of the primary pumps. Proper system operating conditions could have prevented the leak in the main secondary pump. Had the problem of erosion of current-carrying copper in 700°F sodium been recognized, the loss of copper from the busbars in the primary auxiliary pump could have been prevented. Electrical connections that remain tight through severe environmental changes were needed on both the purification and the FERD pumps. Installation of the original FERD pump at a lower elevation in the system might have prevented the melting of the duct and the leakage of sodium. The problems of brazing the electrodes to the pump tubes in the sampling pumps and of the heating of these pumps have required further developmental effort in the design and operation of small sodium pumps.

The variety of problems encountered illustrate the difficulties facing designers of sodium pumps and systems. However, the problems have been ones of basic design and can be readily solved. The knowledge gained in handling the problems should be useful to others. Since the basic difficulties were corrected, excellent service has been obtained from each of the pumps.

Except for the very large pumps of the future, experience has shown that sodium pumps should cause no significant delays to planned liquid-metal fast breeder reactors.