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THE DEVELOPMENT OF PUMPS FOR USE IN FAST-REACTOR-SAFETY INTEGRAL-LOOP EXPERIMENTS

by

L. E. Robinson and
R. D. Carlson

MASTER

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April 1968

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ABSTRACT

This report describes the design of an annular linear-induction pump suitable for use in a radioactive environment. The pump was designed for an in-pile sodium loop in which fast-reactor safety studies were to be conducted. The pump is capable of operating at 500°C and will deliver 10 gpm at 20 psi with an efficiency of 3%. At 200°C, the pump will deliver 20 gpm at 20 psi with an efficiency of 5%. The pump tube is capable of withstanding a static pressure of 340 atm.

I. INTRODUCTION

Fast-reactor safety studies concerned with reactor-fuel meltdowns in flowing sodium are being performed in small integral loops¹ (Mark I) which are irradiated in the Transient Reactor Test Facility (TREAT). In these studies, various types of reactor fuel are subjected to an intense neutron pulse. The transient heating of these specimens causes the fuel to melt and, in some cases, disintegrate vigorously. This type of fuel failure and the subsequent vaporization of sodium can cause large pressure pulses to occur within the integral sodium loop. Initial fuel-meltdown experiments in flowing sodium were conducted in loops (Mark I) using a thin-walled Faraday-type pump. The strength of the tube wall was found to be inadequate for the higher-energy-release experiments. A pump having a greater static pressure rating was therefore developed. Some of the fuels under study will contain plutonium, and this additional hazard requires an assurance of containment.

This report describes the development and testing of an Annular Linear Induction Pump (ALIP) to be used in the high-pressure, high-temperature Mark II integral sodium loop. The pump has a static pressure rating at 350 atm and can move 10 gpm of sodium at 500°C (932°F) through a differential pressure of 20 psi, with an efficiency of approximately 3%. At 200°C (392°F), the pump will deliver 20 gpm at 20 psi with an efficiency of approximately 5%.

II. DESCRIPTION OF MARK II LOOP

Figure 1 is a simplified layout of the Mark II loop. Requirements of a large test section and high pressure rating made it impossible to keep the volume required for the device within that available in a single TREAT fuel element. Housing the loop complex in a shell the same size as two TREAT elements made it possible to achieve a satisfactory arrangement. With the increased space, a closed-circuit, direct-flow, recirculating system becomes possible. Such a simplified loop offers the advantages of an uncluttered view of the fuel-containing test section; lower hydraulic losses in the sodium flow; ease of instrumenting the inlet, interior, and outlet of the test section; and less difficulty in assembly and disassembly of successive experiments by remote handling.

The Mark II loop is a Class A nuclear vessel, as prescribed by the ASME Boiler and Pressure Vessel Code.² The design point for specifications is a static pressure rating of 340 atm at a steady-state temperature of 538°C (1000°F) in the loop proper.

Type 316 stainless steel is the highest-strength material at the design temperature, of ready availability, and having full compatibility with sodium and high weldability. The Mark II loop body, piping, hydraulic attachments, and accessory components are made wholly of Type 316 stainless steel, certified to have greater than 0.4% carbon and to be heat-treated to a minimum of 982°C (1800°F). As an added safety factor, the maximum allowable design stress at 538°C (1000°F) for Type 316 stainless steel was derated to 0.90 of full value, despite rigid specifications for full-penetration and fully radiographed welds which permit a rating of unity.

The material exception in the loop system is the pressure shell of the sodium pump and joining flanges, which are made of Inconel X-750. The Inconel X-750 alloy has not been qualified by the ASME Code for Nuclear Vessels. However, the maximum allowable design stress for the superalloy in the Mark II loop has been calculated according to the most conservative of the methods used by the Code, using the physical properties of the short-treated or low-temperature metal. As an added safety factor, the calculated wall thickness of 0.218 cm required for the design temperature and pressure was increased 16.25% to 0.254 cm.

All joining flanges are of the split-C autoclave-clamp type, in fully heat-treated Inconel X-750, with Type 316 stainless steel, solid, double-oval O-ring seals. This type of flange is used to join the Inconel pump shell to the loop body and to attach the pressure-instrumentation taps to the loop instrumentation sections (as shown in Fig. 2).

Fig. 1
Layout of the Mark II Integral
TREAT Sodium Loop

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Fig. 2. Inconel X-750 Autoclave Clamp and Flanges
with Double-oval Stainless Steel O-ring Seal

place with a Conoseal clamp flange. Since this closure flange is outside the loop enclosure can, well away from the heat sources associated with the loop proper, the sealing clamp is fabricated of Type 316 stainless steel instead of the Inconel X-750 used elsewhere.

The fuel holder, with a removable extension, is loaded into the test section through the top access flange. The closure of the flange by the tapered clamps exerts a predetermined downward axial force on the holder through compression of a stack of Belleville washer springs. The force on the holder assembly presses the hemispherical base of the fuel holder into a 45° conical seat in the bottom of the test section, resulting in a line-contact seal between the holder flow channel and the flow tube of the loop body.

The test section has an inner diameter of 3.254 cm, a wall thickness of 0.917 cm, and an overall length of 75 cm, which permits accommodation of fuel elements over 65 cm long. At the inlet and outlet of the test section, there is a 12.7-cm-long instrumentation section fitted for measurement of sodium flow and pressure.

The loop bends connecting the test section with the sodium pump and closing the fluid circuit have an inner diameter of 1.905 cm and a wall thickness of 0.635 cm.

III. DESIGN OF AN ANNULAR LINEAR INDUCTION PUMP FOR THE MARK II LOOP

The factors placing the most stringent requirements on the sodium pump were (1) the overall design pressure capability of 340 atm (5000 psi), (2) a steady-state design temperature of 482°C (1000°F), and (3) the size limitation which requires the finished loop assembly to fit into a rectangular cross section of 10 x 20.3 cm (4 x 8 in.). Other capabilities involving operational parameters were considered desirable (within limits), but not

The test section is located in the loop leg opposite the sodium pump, with an extension above the loop proper, through the top plate of the enclosure can and into the plenum above the reactor core. Access to the loop interior for experiment loading and internal maintenance is through a top-closure flange, which consists of a heavy plate centrally penetrated by a fuel thermocouple exit assembly and sealed into

absolutely necessary for the experimental usability of the integral loop. These factors included a high flow capability (9 m/sec optimum), a programmable variability of flow, reversibility of flow direction, ease of replacement in the event of failure, reasonable efficiency, and versatility of pumping performance to meet a wide range of experimental requirements.

The combination of pressure, containment, and temperature criteria eliminated the Faraday-conduction-type electromagnetic pumps, which characteristically require very thin walls for operation at measurable efficiencies, and most of the mechanically rotatable field pumps, which rely on closest coupling of a permanent magnetic field with the conductive liquid metal being pumped. The size limitation effectively eliminated the polyphase helical and the mechanical axicentrifugal type pumps. Geometry and the difficulty of obtaining adequate stator cooling removed the flat linear induction pump from consideration.

The only electromagnetic pump offering a geometry and functional design conducive to miniaturization of the order required in a configuration capable of containing the internal design pressure of the Mark II loop was the Annular Linear Induction Pump (ALIP). The geometry used as a basis for the design of the Mark II ALIP was originated by Blake of the United Kingdom³ and was tested in a high sodium flow (~400-700 gpm) at up to 600°C. This was a direct-flow, simple-annular, polyphase pump, although a more sophisticated modification of the annular induction pump was designed and constructed by the French for specialized use.⁴ The eight-pole, 35.5-cm-diam, 127.0-cm-long British ALIP was compacted into a four-pole, 8.9-cm-diam, 48.3-cm-long pump for the Mark II facility. An isometric view of the Mark II ALIP is shown in Fig. 3.

Fig. 3. Annular Linear Induction Pump for Mark II
Integral Sodium TREAT Loop

The pump tube and flanges are composed of fully age-hardened Inconel X-750, rather than stainless steel, because of the necessity for obtaining the thinnest possible wall, in a readily available, easily fabricable material. The wall thickness of the tube as designed is 0.254 cm (0.100 in.) thick. By contrast, a minimum thickness of 0.218 cm (0.086 in.) is sufficient

to meet code prescriptions for the steady-state loop design pressure of 340 atm at 538°C (1000°F). The ALIP is approximately 65 cm (25.75 in.) long overall, and is installed in the Mark II integral loop by mating flanges at each end which use solid stainless steel double-oval O-ring seals, and autoclave C-type flange clamps shown in Fig. 2.

The stator of the pump is composed of 12 yokes of laminated 1%-silicon transformer iron, spaced at 30° intervals about the periphery of the thermally insulated cylindrical pump tube. Each yoke is made of 27 sheets of 29-gauge (0.014-in.) silicon iron, riveted into rigid bundles, and containing six field-coil slots per pole, with two coils per phase. With yokes of approximately the same length, the four-pole version of the pump used 24 coils, while a five-pole version used 30 field coils. The field coils were designed to consist of flat ribbon-wound pancake coils of fully anodized EC aluminum. The use of anodized aluminum as the electrical conductor nominally permits a maximum operating temperature of about 260°C; however, this type conductor has been wound without interleaving insulation and has been successfully operated as the primary of a 60-cycle, one-phase, 230 V ac stepdown transformer at 425°C for over 500 hr without malfunction or failure.⁵

A return magnetic path is provided by the installation of a 0.5- to 0.875-in.-diam central core within the pump tube and along the pump axis, thus forming a thin annular flow space for the sodium. The central core may vary in size and composition, from solid Armco Ingot Iron, to silicon transformer iron, depending upon the conditions for a given experiment and the pump performance desired.

As protection for stator yokes and coils against heat conducted from the hot sodium within the loop, and to facilitate pump cooling, the stator assembly is separated from the pump tube by an evacuated heat barrier consisting of a laminate of electropolished stainless steel sheet and fine-wire, large-mesh screen. This laminate "Dewar" barrier comprises the inner wall of a sealed annular housing enclosing the entire stator assembly, through which a low-viscosity silicone liquid coolant is passed.

The ALIP unit operates on 230-V, three-phase, 60-cycle electrical power, with its field coils connected in a delta arrangement to ensure a constant 120° electrical separation between phases. Power is supplied to the pump by high-current feed-through connections inserted in the end plates of the pump cooling housing. The polyphase pump consumes about 7.5 kW of power at maximum capacity.

IV. PROTOTYPE TESTS

Two models of the ALIP pump were fabricated for testing. The prototypes used the same pump housing and pump tube, but the laminated stator and coils were of different dimensions to allow for the difference in pole pitch. The four-pole pump had twenty-four 5/16-in. coil slots; the five-pole pump had thirty 1/4-in. coil slots. The prototype coils were wound from 16-gauge anodized aluminum wire and were potted in an epoxy resin. Mica washers were placed on each side of the coils as additional insulation between the coil and the steel laminations. The design calls for fully anodized aluminum strip coils; however, because of easy procurement, anodized aluminum wire was used for the prototype.

The pumps were first assembled using ungraded coils. Grading here is defined as decreasing the number of turns on the end coils of the pump so as to gradually decrease the strength of the magnetic field. There are several methods of grading; a very gradual grading method may be used where every coil contains a different number of turns, or the grading may be rather abrupt. The more gradual grading method has the highest theoretical efficiency, but is more difficult to achieve in construction. After the test with ungraded coils, the pumps were reassembled using a grading method where the number of turns were reduced only on the four end coils.

A solid Armco Ingot Iron central core was used first on the prototype. The solid core was used because it was most easily fabricated and because the dimension of the core diameter could readily be changed. Later a core laminated of soft iron wire was tested. Various sizes of central core have been tested.

The intended steady-state operating temperature of the pump installed in the Mark II loop is to be 482°C (900°F); hence, tests at about 500°C were planned.

For testing, a pump was placed in the test loop shown in Fig. 4. This loop consisted of two barrels located on a beam balance, as indicated in Fig. 5. The barrels were connected with piping in which were located the pump, flowmeters, and pressure transducers.⁶ The barrels were continuously weighed by a force transducer, and as sodium was pumped from one barrel to the other, the weight change was measured as a function of time. This measurement was used to compute the flow rate and calibrate the flowmeters. The pressure transducers measured the pressure differential across the pump section. The data from the instruments were recorded on strip-chart recorders or taken automatically with a Hewlett Packard data-acquisition system. The punched-paper tape from the data system was used by a computer to process the data directly.

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Fig. 4. ALIP in the Component Test Sodium Loop

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Fig. 5. Geometry of the ALIP in the Component Test Sodium Loop

V. RESULTS

Figure 6 gives the results of tests on the four-pole pump fitted with a solid central core and operated at relatively low temperatures. The zero-slip flow rate was the flow rate computed when the fluid moved at the same velocity as the magnetic field; for the four-pole pump, this velocity was 22.7 ft/sec. The calculated point for zero slip was obtained by computing the frictional pressure loss for the fluid moving at the same velocity as the magnetic field through the pump annulus. This pressure was plotted as negative on the pump performance curves because the pump could not supply this energy when the slip was zero. This calculation supplied a point through which all pump performance curves must pass. The figures indicate that a core size can be selected to give the required pump performance, that is, high pressure and low flow rate, or high flow rate and low pressure.

Figure 7 shows the increase in efficiency when graded coils are used in inlet and outlet poles of the pump. This graded pump is 100% more efficient than the ungraded pump. Figure 7 also shows preliminary indications of an increase in efficiency with the use of a wire-laminate central core, and a decrease in overall efficiency at the elevated temperature of 500°C.

The five-pole pump has not been tested.* Since a pump for the Mark II was to be produced with a minimum of development, extensive testing of the two versions of the ALIP to optimize performance in terms of pump geometry, coil values, central core design or operating temperatures, was not performed. However, sufficient data have been obtained

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Fig. 6. Performance Curves for Four-pole Annular Linear Induction Pump (solid iron core) with Ungraded Coils

*The five-pole pump was built as a backup in case the four-pole unit produced unacceptable ripple in the pump pressure. However, four-pole pump ripple proved not to be a problem.

112-8937

Fig. 7 Performance Curves for Four-pole Annular Linear Induction Pump (wire laminated core) with Graded Coils

to define the design of the pump to be used initially with the Mark II loop. This will be a four-pole pump, with step-graded coils over the inlet pole only, fitted with strip-wound coils of fully anodized EC aluminum without interleaving, and having a 1.90-cm (0.750-in.) diam solid iron core.

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