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A LINEAR INDUCTION PUMP FOR LIQUID METALS

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A LINEAR INDUCTION PUMP FOR LIQUID METALS

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ABSTRACT

A linear induction pump of a special design was used to circulate molten sodium through a mockup of an experimental "overflow" type of sodium-cooled reactor.

The distinctive features of this pump are that no seals or moving parts are required; no piping is required to carry sodium to the pump or away from it because the pump is mounted directly on the reactor vessel, with the windings outside of the vessel and the magnetic flux return path inside the vessel.

The pump develops 342 gpm at 6.2 psi when pumping sodium having a temperature of 600°F with an efficiency of 4.7%.

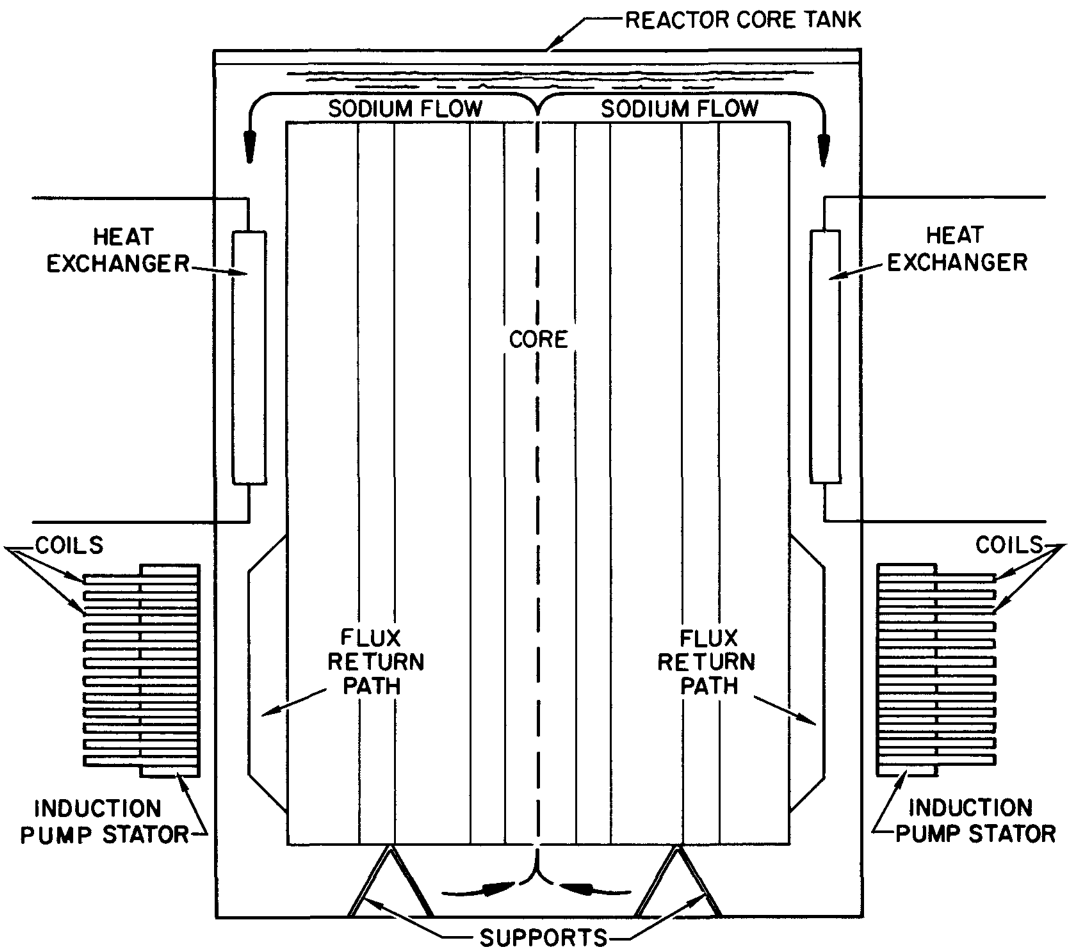

Figure 1. Schematic View of Overflow Reactor

I. INTRODUCTION

A. GENERAL

Liquid metal-cooled reactors can be operated quite satisfactorily with electromagnetic pumps. Commercial "in-line" pumps are available, and theory of their operation is well known. In order to perform service on these pumps, they must generally be removed from the piping system in which they are installed, and at the very least, the compartment in which they are located must be entered. Because of the induced radioactivity in the primary circuits of sodium cooled reactors, this often results in a delay while Na-24 activity is decaying.

In an attempt to minimize down-time necessitated by sodium decay, a primary circuit completely enclosed in a single tank has been proposed.[1] In order to circulate sodium past the various heat transfer components installed in this tank, an electromagnetic pump, in which removable windings are outside the primary tank, was designed. These windings, which are the most likely parts of the pump to require maintenance, are not in contact with liquid metal and are not significantly activated by neutron bombardment because of neutron shields placed within the reactor tank. Only magnetic flux return paths of silicon steel, jacketed with stainless steel, are actually placed in the sodium; no maintenance problems are expected from these flux return paths. Therefore, maintenance or replacement of vital parts of these pumps could be expected not to create long delays when the system is shut down for maintenance.

In order to demonstrate the feasibility of this concept, and to check theoretical performance predictions, a mockup of this pump was made and tested. All components then were sized to fit a proposed experimental reactor; performance exceeded predicted values of flow, pressure rise, and efficiency.

B. PUMP DESCRIPTION

Each pump consists of two major parts: these are the stator and the flux return path. The stator is outside the annulus; the flux return path is inside the annulus (Figures 1 and 2).

1. Pump Stator

The stator has a distributed winding similar to that of an ordinary 3-phase motor; when the windings are connected to a 3-phase source of power, current

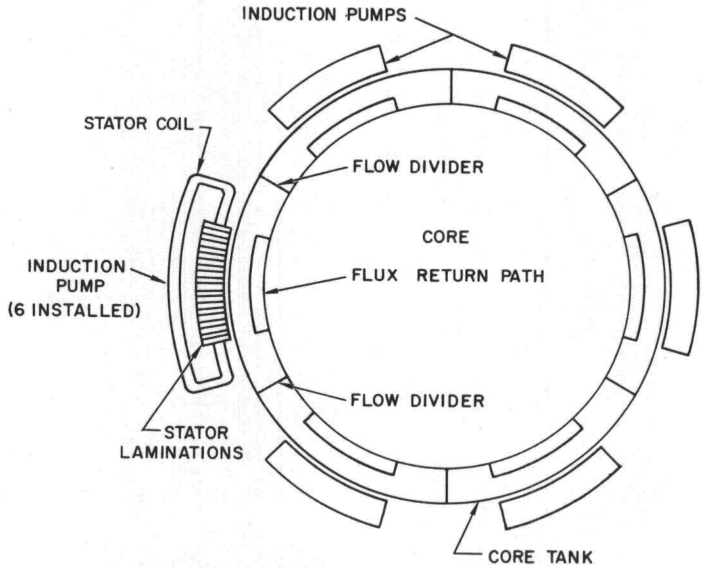

Figure 2. Top View of Reactor Showing Pumps

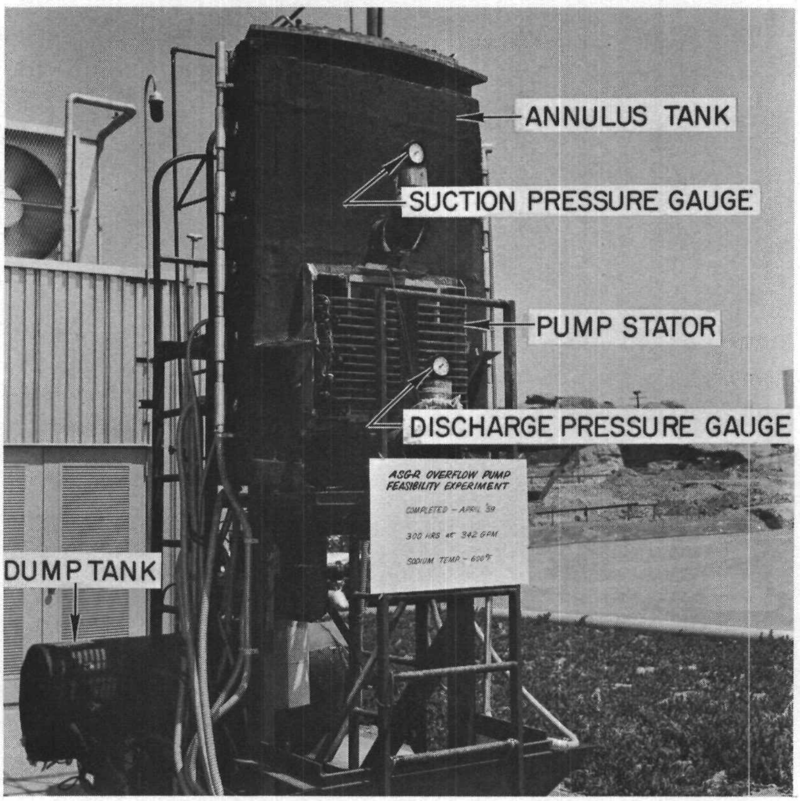

Figure 3. Photograph of Pump on Test Loop

flowing in the stator windings sets up magnetic flux which passes through the outer wall of the annulus, through the sodium, into the flux return path, within the flux return path in a vertical direction, then back out through the sodium and annulus wall to the stator.

As the currents in successive portions or "pole-phase-groups" of the vertically distributed stator winding come to maximum values, the magnetic flux in the sodium moves downward inducing eddy-currents in the sodium. Reaction between the magnetic fields of eddy-currents and stator currents causes pumping action to take place.

A distinctive feature of this pump is its division into an active magnetic surface (the stator) and a passive magnetic surface (the flux return path). A linear induction pump, as ordinarily constructed, has the stator in two parts, one on each side of the sodium passage.[2,3,4]

Another distinctive feature of this pump is its coil construction. The coil is flat, which makes it easy to wind. The coil arrangement permits circulation of cooling air to three-fourths of the coil surface. (See Figures 3, 6, and 8.)

Another advantage of the coil construction is that each coil (or pair of adjacent coils) is required to satisfy the magnetic field conditions at only one location. In ordinary linear induction pump construction, each coil is shaped so that both sides are in slots which are spaced nearly one pole pitch apart. The discontinuous or open-ended magnetic circuit, in a linear induction pump, causes the character of the magnetic field to be different in the mid-portion of the pump as compared to its character at the ends. This means that the magnetizing current in each coil of an ordinary linear induction pump cannot satisfy the air-gap magnetic field conditions at the coil side locations.

2. Control of Flow Rate

Flow rate control is achieved by adjustment of the a-c voltage supplied to the pump terminals. This requires the use of a device such as a variable-voltage autotransformer, or an induction voltage regulator. Saturable-core reactors may be used in place of the autotransformer or the regulator.

II. DESCRIPTION OF THE APPARATUS USED IN THE PUMP TEST

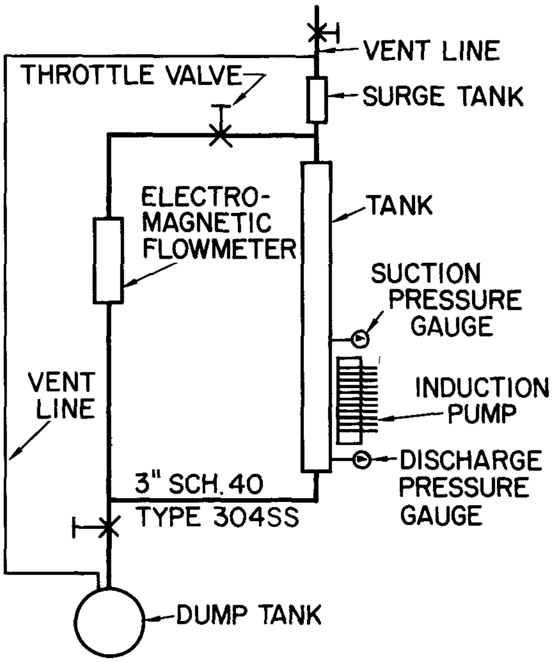

Figure 4. Elevation of Pump Test Loop

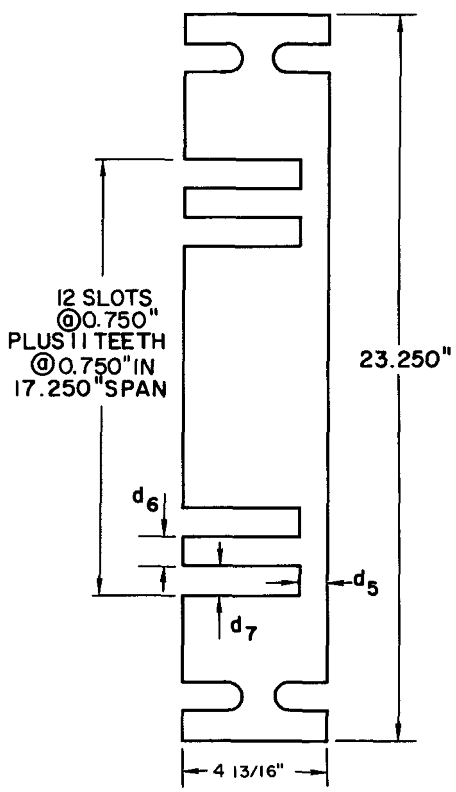

Figure 5. Stator Lamination

Refer to Figure 3, which shows the pump mounted on the test loop and to Figure 4, which is a schematic elevation of the test loop. It must be kept in mind that the only purpose of the pipe circuit was to provide a loop for circulation of sodium to obtain test data. In an actual installation of the pump on a reactor, the pump "loop" would consist of the annulus and core passages.

A. PUMP DETAILS

1. Stator

The pump stator consists of a 17.5 in. wide stack of steel laminations each 0.014 in. thick, with slots as shown in Figure 5. The stator winding consists of 12 coils; a typical coil is detailed in Figure 6.

2. Flux Return Path

The flux return path consists of silicon steel laminations having the same thickness and width as the stator, but without slots. The flux return path is sealed in a jacket of stainless steel 1/16-in. thick to prevent sodium from coming in contact with the silicon steel.

The stator and flux return path are mounted opposite each other with the stator on the outside and the flux return path on the inside of a tank which is part of the test loop.

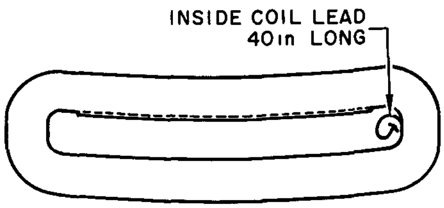

Figure 6. Stator Coil

B. PUMP TEST LOOP

The pump test loop is fabricated from Type 304 stainless steel; all piping in contact with sodium is 3-in. schedule 40. The vent lines are 1-in. mild steel pipe. The outer and inner annulus walls are 1/4-in. thick. Figure 7 is a cutaway view of the tank showing relative positions of stator and flux return path in addition to some of the tank dimensions. Figure 8 is a top view showing width of stator and flux return path. Suction and discharge pressure gauges and an electromagnetic flowmeter are used to obtain pressure rise and flow rate developed by the pump. The throttling valve is used to simulate a variable hydraulic load.

C. FLOW RATE CONTROL

Control of pump current is obtained through the use of a variable auto-transformer having an output rating of 90 amp at 540 v, 3-phase, 60-cycle.

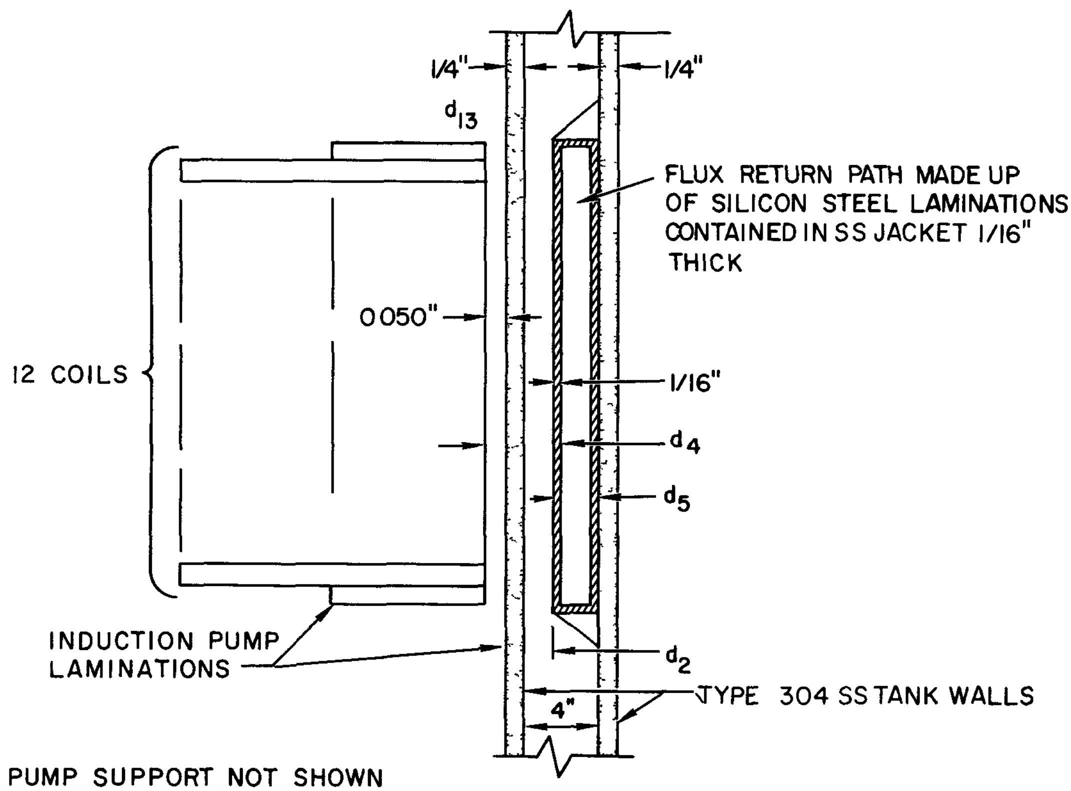

Figure 7. Cutaway View of Tank and Pump

D. AUXILIARY COOLING EQUIPMENT

A blower of 900 ft^3/min capacity furnishes cooling air to the stator coils. The blower keeps the outside coil surface temperature from exceeding 300°F after 8 hours of steady-state operation when pumping sodium at 600°F. The coil temperature is measured by a surface thermocouple-type pyrometer held against the surface of a coil where the coil emerges from the stator slot.

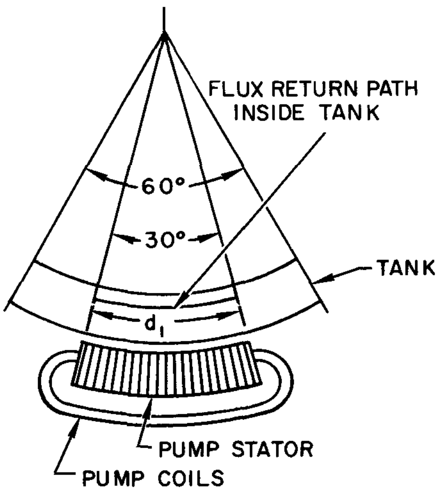

Figure 8. Top View of Test Loop Tank and Pump

III. OUTLINE OF TEST PROCEDURE

After first drying the loop and purging with inert gas, all parts to be in contact with sodium were preheated to 350°F with rod heaters. When the loop was filled with sodium, with the throttle valve wide open, the pump was energized from a 3-phase source at 400 v obtained by means of a variable autotransformer. Readings were taken of suction and discharge pressures, flow rate, and power input to the pump.

The flow was reduced 10% by the throttling valve, and readings were taken again. This procedure was followed until shutoff valve position was reached. At each step, the flow was reduced by 10% of that obtained when the valve was wide open.

Sodium temperature was maintained at an average value of 600°F, with swings of ± 75°F.

IV. PROCESSING OF TEST DATA

A. CALCULATION OF PRESSURE RISE ACROSS PUMP

The net pressure rise across the pump is the difference between discharge and suction pressures, corrected for the difference in initial readings of the discharge and suction pressure gauges (Figures 3 and 4).

To illustrate the procedure for calculating net pressure rise, assume that with the pump ready for a test run, the readings on the gauges before turning on the power are P_1 psi on the discharge gauge and P_2 psi on the suction gauge. Assume that after turning on the power, the discharge gauge reads P_D psi and the suction gauge reads P_S psi, and that the flow of sodium is Q gallons per minute. The net pressure rise P due to pump action is

$$P = (P_D - P_1) - (P_S - P_2) = P_D - P_1 + P_2 - P_S \ .$$

B. CALCULATION OF PUMP EFFICIENCY

The efficiency $\underline{e}$ is calculated from the equation

$$\underline{e} = \frac{0.435PQ}{\text{Power input to pump}} \ .$$

See Appendix C for derivation of the factor 0.435.

V. DISCUSSION OF CURVES OBTAINED FROM PUMP TEST

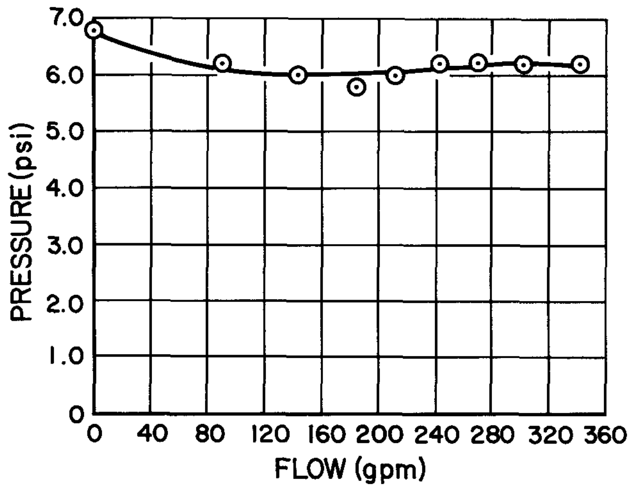

Figure 9. Curve of Pressure vs Flow

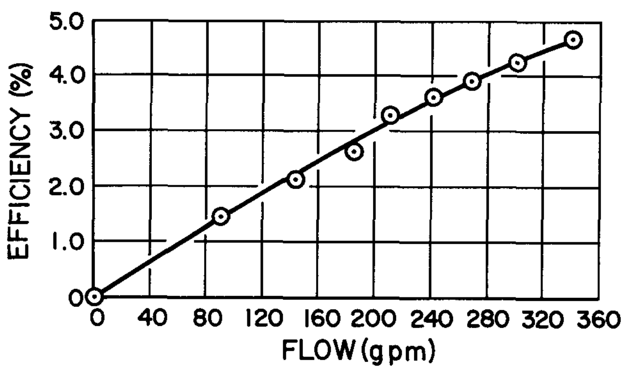

Figure 10. Curve of Efficiency vs Flow

The curve for pressure vs flow of this pump (Figure 9) shows a relationship which is typical for an induction pump. It is possible to design an induction pump that will develop its maximum pressure at any flow from shut-off to a flow which will be within 10% of synchronous flow. Synchronous flow is the flow rate that would be obtained if the sodium traveled through the pump at the velocity of the traveling field. In this respect, induction pump design follows the same pattern as induction motor design, in that an induction motor can be designed for maximum torque at speeds from standstill up to about 5% of synchronous speed.

The curve of efficiency vs flow of this pump (Figure 10) shows that the maximum efficiency occurs at some flow rate above the highest flow rate obtained (342 gpm). This is a typical relationship for an induction pump.

VI. CONCLUSIONS

The pump met the flow rate requirement of 240 gpm; the pressure rise across the pump at this flow rate was 6.1 psi. The specified requirement of 10 psi could not be met due to the limit imposed by the rating of the variable autotransformer which supplied the pump.

The results obtained in the pump tests verify the application of Rudenberg's equation[4] to the design of this type of electromagnetic pump. The procedure that is given in this report can be used to design similar larger induction pumps for reactors whose outputs may run to hundreds of megawatts.

APPENDIX

A. DESIGN PROCEDURE

This is the procedure that was followed in designing the linear induction pump for the mockup test of the overflow type reactor.

Symbol	Meaning	Magnitude
Q	Volumetric flow rate of liquid metal through pump.	240 gpm
V_1	Velocity of liquid metal through pump. The magnitude of V_1 was set at 156 in./sec from hydraulic considerations.	156 in./sec
P	Pressure to be developed by the pump, measured across the pump at points of connection to the pipe system.	10 psi
d_1	Width of liquid metal path. See Figure 8. This quantity is fixed by the reactor design.	17.5 in.
d_2	Thickness of liquid metal path (Figure 7) $$d_2 = \frac{3.85Q}{v_1 d_1} .$$	0.400 in.
f	Frequency of power source.	60 cps
d_3	Pole pitch. The procedure is to assume an initial value for d_3, then work out the coil current I_3, and recheck d_3 to make certain that the pump will fit into the available space. The value given here is the final value after two trials.	9 in.
r_1	Electrical resistivity of liquid metal. For sodium, the value of r_1 at the desired operating temperature of 600°F is 7.1×10^{-6} ohm-in.[5]	7.1×10^{-6} ohm-in.
r_2	Electrical resistivity of Type 304 stainless steel. The value of r_2 at 600°F is 36.8×10^{-6} ohm-in.[6]	36.8×10^{-6} ohm-in.

Symbol	Meaning	Magnitude
d_4	Distance from surface of stator teeth to flux return path (Figure 7).	0.513
n_1	Number of poles produced by the stator winding in the air-gap flux wave.	2
v_2	The velocity of the traveling field relative to the stator. $$v_2 = 2fd_3$$	1,080 in./sec
B_1	Peak value that must exist in the traveling flux wave in order to develop the pressure P.[7] $$B_1 = \left[\frac{r_1 P\left\{\left[\frac{1.016 \times 10^{-8}(v_2 - v_1)d_1 d_2}{r_1 d_4}\right]^2 + \left[\frac{d_1}{d_3} + \frac{d_3}{d_1}\right]^2\right\}}{2.22 \times 10^{-16}(v_2 - v_1)n_1 d_1\left[\frac{d_1}{d_3} + \frac{d_3}{d_1}\right]}\right]^{1/2}$$	36,200 lines/in.^{2}
n_2	Number of slots per pole per phase.	2
ϕ_1	Useful air-gap flux per pole in maxwells $$\phi_1 = 0.636\, B_1 d_1 d_3 \;.$$	$3.6^2 \times 10^6$
d_5	Depth of each stator lamination behind the slots; also width of the silicon steel strips that make up the flux return path (Figures 5 and 7). For a flux density of 60,000 lines/in.^{2} in the silicon steel $$d_5 = \frac{\phi_1}{12 \times 10^4 d_1} \;.$$	1.78 in.

Symbol	Meaning	Magnitude
d_6	Tooth width (Figure 5). For this pump, with a 3-phase winding, two slots per pole per phase, assuming equal tooth and slot widths $$d_6 = \frac{d_3}{12} .$$	0.750 in.
d_7	Slot width (Figure 5).	0.750 in.
c_1	Dimensionless quantity entering into the calculation of the Carter coefficient[8,9] $$c_1 = 1 - 0.636 \arctan\left(\frac{d_7}{2d_4}\right) + 0.636\left(\frac{d_4}{d_7}\right)\log_e\left[1 + \left(\frac{d_7}{2d_4}\right)^2\right] .$$	0.667
J_1	Initial value of current density in the coil conductor. Assume $J_1 = 4{,}000$.	4,000 amp/in.^{2}
C_2	The Carter coefficient, used in calculating the ampere-turns per pole necessary to set up the magnetic field $$c_2 = \frac{1 + \frac{d_7}{d_6}}{1 + \frac{c_1 d_7}{d_6}} .$$	1.2
n_3	Peak ampere-turns per coil $$n_3 = \frac{0.417\, B_1 d_4 c_2}{n_2} .$$	4,660 amp-turns

Symbol	Meaning	Magnitude
E_1	Voltage across pump terminals.	440 v
C_3	Winding distribution factor.[10,11,12,13]	0.966
C_4	Winding pitch factor.[10,11,12,13]	1.00
n_4	Number of turns per coil. For this pump, the windings are delta-connected; hence $$n_4 = \frac{E_1 \times 10^8}{2.22 f \phi_1 c_3 c_4 n_2} \ .$$	47 turns
I_1	Coil magnetizing current (rms value) $$I_1 = \frac{n_3}{1.414 n_4} \ .$$	67 amp
n_5	Cross-sectional area of coil conductor, for a current density of 4,000 amp/in.^{2} $$n_5 = \frac{I_1}{4{,}000} \ .$$	0.020 in.^{2}
d_8	Bare conductor width assuming a square conductor is used $$d_8 = \sqrt{n_5} \ .$$	0.14 in. (use No. 8 AWG square wire - d_8 = 0.129 in.)
d_9	Overall conductor width allowing 0.015 in. total for double glass insulation with silicone impregnation[14] $$d_9 = d_8 + 0.015 \ .$$	0.144 in.

Symbol	Meaning	Magnitude
d_{10}	Coil width over conductors allowing 0.040 in. thickness for mica-mat glass tape,[15] plus 1/16 in. on each side of coil for asbestos board.[16] $$d_{10} = d_7 - 0.205 \quad .$$ Refer to Figure 6.	0.545 in.
n_6	Number of conductors in coil width $$n_6 = \frac{d_{10}}{d_9} \quad .$$	3
n_7	Number of conductors in slot depth $$n_7 = \frac{n_4}{n_6} \quad .$$	17
d_{11}	Coil depth over conductor $$d_{11} = n_7 d_9 \quad .$$	2.45 in.
d_{12}	Slot depth, allowing 1/4-in. clearance between coil and top of slot $$d_{12} = d_{11} + 0.330 \quad .$$ If d_{12} is greater than 3 in., it will be necessary to increase the slot width to reduce d_{12} to 3 in., to keep the slot leakage flux from becoming excessive.[17]	2.78 in.
d_{13}	Annulus wall thickness. The magnitude of d_{13} was fixed by structural considerations in the design of the tank.	0.250 in.

Symbol	Meaning	Magnitude
W_1	Power input to sodium $$W_1 = 0.435PQ\left(1 + \frac{v_2}{v_1}\right) .$$	9,600 w
W_2	Power loss in annulus wall $$W_2 = \frac{2.5 \times 10^{-17} v_2^2 \; n_1 d_{13} d_1^2 \left(\frac{d_1}{d_3} + \frac{d_3}{d_1}\right) B_1^2}{r_2\left[\left(\frac{1.02 \times 10^{-8} \; v_2 d_{13} d_1}{r_2 d_4}\right)^2 + \left(\frac{d_1}{d_3} + \frac{d_3}{d_1}\right)^2\right]} .$$	31,400 w
W_3	Stator and flux return path iron loss. This item is calculated by determining total weight of silicon steel laminations and multiplying by 3 w/lb.[18]	2,000 w
W_4	Copper loss in stator winding. Since this item cannot be accurately determined without knowing the value of total coil current, and since total coil current cannot be determined until all losses are known, assume $W_4 = W_3$.	4,000 w
W_5	Total power input $$W_5 = W_1 + W_2 + W_3 \quad .$$	45,000 w
I_2	Energy component of coil current (rms value) $$I_2 = \frac{W_5}{3n_1E_1} .$$	17.1 amp

Symbol	Meaning	Magnitude
I_3	Total coil current (rms value) $$I_3 = \sqrt{I_1^2 + I_2^2} \quad .$$	69 amp
J_2	Final value of current density in coil conductor $$J_2 = \frac{I_3}{n_5} \quad .$$ If J_2 is greater than J_1, the magnitude of d_8 must be increased sufficiently to reduce J_2 to J_1.	3,440 amp/in.^{2}
e_1	Efficiency of pump $$e_1 = \frac{0.435PQ}{W_5} \quad .$$	2.42% (min) Note: This calculated value is conservative when compared to experiment. (pg 25)

B. DERIVATION OF EXPRESSION FOR n_3, THE PEAK AMPERE-TURNS PER COIL

$$ATP = \text{ampere-turns per pole}$$

$$0.313\ B_1 d_4 c_2 = \text{ATP for one crossing of the gap whose length is } d_4$$

$$0.626\ B_1 d_4 c_2 = \text{ATP total}$$

$$0.626\ B_1 d_4 c_2 = 1.5\ \text{ATP/phase}$$ [17]

$$\text{ATP/phase} = n_3 n_2$$

$$n_3 = \frac{0.417\ B_1 d_4 c_2}{n_2}$$

C. DERIVATION OF THE FACTOR 0.435 IN THE EQUATION FOR EFFICIENCY (IV B)

When the pump is operating at a constant flow of Q and a constant differential pressure across the pump of P, the pump is working at a rate of W_0 watts, given by the equation

W_0 = (Net force in pounds due to differential pressure) times (velocity of sodium flow in feet per minute) times (2.26×10^{-2} watts per foot pound per minute).

Now the net force (lb) is equal to the differential pressure (psi) times the internal cross-section area (in.^{2}) of the sodium flow passage.

The velocity of sodium flow (ft/min) is equal to the flow (gal/min) times 0.134 (ft^3/gal) divided by the quantity (internal cross-section area in square in. divided by 144 in.^{2}/ft^2.

Denote the internal cross-section area (in.^{2}) by A; the velocity of the sodium flow (ft/min) by v; and the net force (lb) by F.

Then

$$P = P \cdot A$$

$$v = \frac{Q \times 0.134}{\frac{A}{144}} = \frac{Q}{A} \times 19.3$$

$$W_0 = F \times v \times 2.26 \times 10^{-2} = P \cdot A \cdot \frac{Q}{A} \cdot 19.3 \times 2.26 \times 10^{-2}$$

$$W_0 = 0.435 \; PQ \text{ watts.}$$

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