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FABRICATION AND TEST OF A SPACE POWER BOILER FEED ELECTROMAGNETIC PUMP

II - Test Facility and Performance Test

by A. H. Powell, J. C. Amos, C. L. Ehde, and J. W. Gahan

Prepared by
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16. Abstract

A three-phase helical induction electromagnetic pump, designed for the boiler-feed pump of a potassium Rankine-cycle space power system, was built and tested. The pump was tested over a range of potassium temperatures from 900° to 1400° F, flow rates from 0.75 to 4.85 lb/sec, developed pressures up to 340 psi, net positive suction heads (NPSH) from 1 to 22 psi, and NaK coolant temperatures from 800° to 950° F. The maximum efficiency at the pump design point of 3.25 lb/sec flow rate, 240 psi developed pressure, 1000° F potassium inlet temperature, and 800° F NaK coolant temperature was 16.3 percent. The tests also showed successful operation of the pump at an NPSH as low as 1.5 psi without cavitating.

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I. SUMMARY

The General Electric Company, under Contract NAS 3-9422, has completed the building and performance testing of an electromagnetic pump for use as a boiler feed pump in a potassium Rankine cycle, space electric power system. The pump has a design flow rate of 3.25 lb/sec at a developed pressure head of 240 psi, when pumping potassium at a temperature of 1000°F.

This report (Part II of three parts) describes the design and building of the test facility, installation of the pump in the test loop, operation check-out, and extensive performance tests over nearly 200 test conditions. Part I of this report described the pump design, fabrication, and assembly. A subsequent report (Part III) will cover the 10,000 hour endurance test and final analysis of the pump performance.

The test facility, built to permit essentially unattended operation at design conditions, provided the necessary flow, pressure, power and temperatures required to test the pump at all "off-design" points. It is enclosed in a steel cubicle to provide protection and control of any liquid alkali metal leaks. Controls are centralized in a separate room and provide all desired information on temperatures, pressures, flows, power, etc.

A total of nearly 200 different test conditions were established during the performance test series to obtain data over the entire range of pump capability (within established design limits) as shown below:

K Temperature	900 to 1400°F
K Flow Rate	0.75 to 4.85 lb/sec
Pressure Developed	Up to 340 psi
NPSH	1 to 22 psi
NaK Inlet Coolant Temp.	600 to 900°F
NaK Δt	50 and 100°F
Voltage (phase)	Up to 142 V
Current (line)	Up to 190 A
Maximum Efficiency	17.39%

The pump operated throughout the test series without any problems, and demonstrated prompt response to adjustments in voltage, flow and/or pressure. Satisfactory pumping at design flow and developed pressure was demonstrated at a net positive suction head (NPSH) as low as 1.5 psi.

II. INTRODUCTION

Based on the EM pump design study under NASA Contract NAS 3-8500, as reported in detail (Reference 1), a flight type pump was built for boiler feed applications, to meet the following design specifications.

	Design Point	Off-Design Range
Potassium Temperature, °F	1000	900 - 1400
K Flow Rate, lb/sec	3.25	0.75 - 4.25
Pressure Rise, psi	240	35 - 300
NPSH, psi	7	1 - 22
NaK Coolant Temperature, °F	800	700 - 900
Voltage, V	135	30 - 165

As described in Part I of this report, the pump included T-111 alloy for the duct, with bimetal transition joints to permit welding into the test loop which was made of austenitic stainless steel. The pump stator, with a Hiperco 27 magnetic structure, Ni clad Ag conductors, and high purity alumina or "S" glass tape insulation included a cooling section through which NaK is circulated by the test facility during operation.

The wide range of test conditions specified required that a facility be provided for comprehensive control of all parameters and extensive instrumentation output. The facility to accomplish the testing is described in this report. In addition, the results of the performance tests are presented and compared with the expected performance, calculated during the design study.

III. TEST FACILITY

The test facility for the EM boiler feed pump was designed and built especially for this program. The test loop and pump is in a steel enclosure, while control of the facility is centered in a series of panels which include all recording as well as adjusting functions and is located in an adjoining room.

A. Test Facility

The EM Pump Test Facility consists essentially of a pump loop and a coolant loop as shown in schematic form in Figure 1. The electrical schematic diagram of the test pump power and control arrangement is included as Figure 2.

Design criteria for the facility are as follows:

Pump Loop

a. Fluid, potassium.

b. Maximum temperature, 1500°F.

c. Maximum pressure, 350 psia.

d. Flow, 0.75 to 5.0 lb/sec.

e. Design life, 10,000 hours.

f. Materials of construction, AISI type 321 stainless steel.

g. Pump inlet pressure range net positive suction head (NPSH), 0-35 psi.

h. Pump inlet temperature range, 900°-1400°F.

i. Maximum oxide level in potassium, 40 ppm.

j. Circulating potassium loop to be inside of a sheet metal enclosure which is vented to a scrubber.

Coolant Loop

a. Fluid, NaK - 78.

b. Temperature range, 600°-1000°F.

c. Maximum pressure, 50 psia.

d. Flow, 0.7 lb/sec @ 1000°F.

e. Design life, 10,000 hours.

f. Materials of construction, AISI type 304 stainless steel.

g. Maximum developed pressure, 25 psi.

h. Maximum oxide level in NaK, 50 ppm.

i. Circulating NaK loop to be inside of a sheet metal enclosure which is vented to a scrubber.

B. Pump Loop

The general arrangement of the test facility piping and components is shown in Figure 3. The pump loop contains pump discharge and inlet pressure transducers, a throttling valve for controlling pump discharge pressure, an EM flowmeter in series with a calibrated orifice, a by-pass type hot trap, a sampling station, an air cooler for removing heat input from the test pump, and a head tank to control pump inlet pressure. A potassium dump tank, including an internal hot trap along with the necessary cover gas (argon) and vacuum systems, is also provided.

The pump loop main stream piping is 1-1/2 inch Schedule 40 type 321 stainless steel with the exception of the run between the pump discharge and throttling valve inlet. This section is 1-1/4 inch Schedule 160 to withstand the high pressure possible in this area. The by-pass hot trap piping is 1/2 inch Schedule 40, as is the piping to the dump tank and the head tank. At the design flow of 3.25 lb/sec, potassium velocity

in the 1-1/2 inch piping is approximately 5.5 ft/sec which insures a low pressure drop due to piping losses. The entire loop piping and components are trace heated with electrical heaters which can be independently controlled during facility start-up and operation. To minimize piping stresses due to thermal expansion, the entire loop is mounted on spring hangers. Blanket type insulation is installed over Inconel foil (approximately 3-1/2 inch of insulation used on 1400°F lines). Figure 4 shows a portion of the loop after insulation has been installed. Figure 5 shows the outside of one wall of the facility enclosure which also includes portions of the argon, air, and vacuum systems.

Loop Components

Throttle Valve

One of the major components in the pump loop is the valve for throttling the potassium flow. The throttle valve is shown in Figure 6. This valve, like most alkali metal valves, contains a bellows sealed stem, Stellite plug and seat, and is fabricated from a type 321 stainless steel forging. The bellows is rated for 270 psi at 1500°F. Since the potassium enters the valve under the plug the bellows is never exposed to the high pump discharge pressure. Argon gas can be supplied to the inside of the bellows to offset the ΔP across the bellows wall if necessary. The valve inlet port is 1-1/4 inch and the discharge is 1-1/2 inch. The inner valve is 1 inch and has a flow coefficient (Cv) of 13.0 which gives it a broad range of control capability. The valve has a standard 0-20 psi air operator and positioner for fine control.

Hot Trap

The zirconium hot trap is designed to handle only a small portion of the main stream flow (approximately 1%). The driving pressure is obtained by placing the inlet in parallel with the orifice plate used to calibrate the EM flowmeter. In order to obtain effective gettering, the portion of main stream flow entering the hot trap is heated to a maximum of 1300°F with a clam shell type heater mounted on the 1/2 inch piping preceeding the hot trap. The hot trap contains approximately 16 pounds of zirconium in the form of 0.015 inch thick sheets. The surface area of zirconium used is based on 1.0 $inch^2$ of surface per 4.3 grams of potassium in the system at operating temperature, a value established by previous research and extensive experience on other test loops. A manually operated valve at the inlet to the hot trap heater can be adjusted to establish the proper flow depending on main stream temperature and the need for hot trapping based on periodic analysis of the potassium.

Cooler

The loop cooler is designed to remove heat input to the potassium from the test pump. An axial finned tube with an air jacket to contain the cooling medium is used. Shop air at approximately 100 psi and less than 70°F is used as the cooling medium. A remotely operated valve controls air flow depending on heat to be removed. The discharge air, normally at 300-400°F, is removed via an exhaust duct to the atmosphere. Depending on pump operating conditions, the cooler can remove up to 10 kW of heat from the potassium stream.

Head Tank

The height of the liquid to argon cover gas interface at the top of the tank determines the pressure in the system and directly controls the pump inlet pressure. The tank is approximately 8 feet long and contains three liquid level probes so that the liquid level can be determined at any point in the tank. At low net positive suction head (NPSH) the amount of head on the pump can be determined by the height of liquid in the head tank. At high NPSH's argon gas is introduced into the top of the tank to create the proper NPSH. The top 1/3 of the tank contains a clam shell type electric heater which can be used to heat the potassium in this portion of the tank up to 1400°F. The resulting vapor pressure of potassium can be used to provide the NPSH required without introducing any argon cover gas. Argon and vacuum lines leaving the top of the tank are guard heated to maintain isothermal conditions during this type of operation. These lines are also fitted with vapor traps.

Dump Tank

The pump loop dump tank is designed for 1400°F at 75 psi and is a code stamped pressure vessel. The tank has sufficient volume to contain 100 lbs of potassium at 1400°F with sufficient free board for the argon cover gas. A titanium hot trap inside of the tank provides a method of gettering oxygen from the potassium after the main loop is initially flushed and during standby operation. A liquid level probe, and argon/vacuum and filling connections are provided. Electrical heaters (approximately 8 kW) surround the tank so that it may be heated to 1300°F for effective hot trap operation.

Instrumentation

The pump loop contains three slack diaphragm type pressure transducers for potassium pressure measurement. Two of these are installed on the piping at the pump discharge and one at the pump inlet. The two units at the pump discharge are required to cover the broad range of pressure measurement required. One is a 0-150 psia unit, the other a 0-350 psia unit. Both were calibrated at 450°F with argon gas prior to installation. Each unit has its own heater so that the temperature at the diaphragm can be maintained constant (500°F) throughout the range of test conditions imposed on the pump. The pump inlet transducer covers a range of 0-50 psia and was calibrated in a similar manner to the discharge units. All pressure measurements from the units can be recorded on the strip charts on the control console.

The EM flowmeter, with a tolerance of $\pm$ 2%, provides a precise and repeatable output after suitable calibration. To provide for calibration, an orifice, which had been carefully calibrated at a hydraulic laboratory, was placed in the test loop in series with the EM flowmeter. Conventional stainless steel bourdon tube gages, mounted in a heated chamber and arranged for convenient calibration, are used to measure the orifice pressure drop for calibration of the EM flowmeter, and are valved off when not being so used. EM flowmeter readings are recorded during all testing, on continuous strip charts.

Conventional I and J probe liquid level indicators are used in dump and head tanks.

Chromel-alumel type thermocouples are attached to pipe walls throughout the facility to monitor potassium temperature.

All instrumentation readouts are located on the control console described later in the report.

C. Coolant Loop

The coolant loop contains an EM pump, pressure transducer, EM flowmeter, heater, cooler, head tank and dump tank. The general arrangement of this loop is also shown in Figure 3. Argon cover gas system and vacuum system are shared by the two loops (pump and coolant) with adequate valving for independent operation. The coolant loop piping system is 1/2 inch Schedule 40 AISI type 304 stainless steel. Like the pump loop, the coolant loop is supported on spring type hangers for flexibility. Since NaK-78 is a liquid at room temperature, no trace heaters are required. "Preformed" type of pipe insulation is used throughout this loop.

Coolant Loop Components

The major component of the coolant loop is the EM pump. This is a helical induction type EM pump rated at 0.7 lb/sec (flow) NaK, 1000°F, 25 psi. The pump voltage (3 phase, 240 volts) is controlled by a variable autotransformer to provide a wide range of voltage and coolant flow rates. The pump contains an integrally mounted air blower for cooling the stator winding. The pump duct is type 316 stainless steel and chromel-alumel type thermocouples are mounted on the duct and in the stator windings to monitor pump operation.

To remove the heat picked-up by the NaK coolant from the test pump, an air cooled finned tube cooler is employed. Operation and design are identical to the pump loop cooler. Approximately 5 kW of heat can be removed from the NaK stream with this unit.

The coolant loop head tank provides the needed volume for thermal expansion of the NaK during heat up, serves as a means of pressurizing the coolant loop if necessary (i.e., argon cover gas may be introduced to the top of the tank), and acts as a container for a liquid level indicator so that the operator knows at all times the level of NaK in the system. It is located at the highest point in the loop and a vacuum line connection provides a means of removing all gases from the system.

The coolant loop dump tank is designed for 1400°F at 75 psi and is a coded pressure vessel. The tank has sufficient volume to contain 50 lbs of NaK at 1400°F. This tank is also equipped with a hot trap (titanium) for gettering oxygen from the NaK. The NaK may be heated to 1300°F with electric heaters strapped to the tank to aid in the hot trapping.

Clam shell heaters mounted on the 1/2 inch piping are used to bring the coolant loop NaK up to operating temperature. Approximately 3.5 kW of heat can be introduced in this manner.

Instrumentation

The coolant loop contains one slack diaphragm type transducer located in the piping on the discharge side of the coolant pump. The unit has a range of 0-50 psia. The pneumatic signal from this unit is read out on a receiver gage on the control console.

An EM flowmeter is used to monitor coolant flow with an accuracy of $\pm$ 2%. Chromel-alumel type thermocouples are used to monitor NaK temperatures at various points in the loop.

D. Test Facility Control

Electrical and pneumatic control of the facility is accomplished from the control console (refer to Figure 7). Electric heaters are controlled by autotransformers mounted on the panels. Ammeters indicate the current flow to the heaters, and meter relays connected to contactors automatically control certain critical heater circuits. Approximately 30 kW of 240 volt power is available for the various heating circuits in both loops.

Start-stop controls for both pumps, switches for open-closed control of pneumatic valves, and circuit breakers for heater circuits, are all mounted on the control console. Remote operated valves are all pneumatically operated, and panel loaders with air pressure gages are panel mounted. An annunciator to warn the operator of out-of-limits conditions is mounted at the top of the center panel. These out-of-limit alarms are also relayed to adjacent buildings in the event no operator is at the console when trouble occurs.

Interlocks which will provide annunciator signals, and/or shut down of the test pump are as follows:

Information Provided	Function/Output	
"K" Test Pump Winding Over Temperature	Hi Set Point:	Shut off power to pump
	Low Set Point:	Activate alarm and annunciator
NaK Loop Heater Temperature Control	Hi Set Point:	Activate alarm and annunciator
	Low Set Point:	On-off control
"K" Dump Tank Temperature Control	Hi Set Point:	Activate separate indicating Light L-10 - no alarm
	Low Set Point:	On-off control
"NaK" Dump Tank Temperature Control	Hi Set Point:	Activate separate indicating Light L-11 - No alarm
	Low Set Point:	On-off control

Information Provided	Function/Output
Head Tank Dome Heater Temperature Control	Hi Set Point: Activate alarm and annunciator Low Set Point: On-off control
Hot Trap Heater Temperature Control	Hi Set Point: Activate alarm and annunciator Low Set Point: On-off control
"K" Test Pump Exit Over Pressure	Hi Set Point: Shut off power to pump Low Set Point: Activate alarm and annunciator
Voltage Limit	Hi Set Point: Activate alarm and annunciator
Current Limit	Hi Set Point: Activate alarm and annunciator
Test pump Argon Stator Cavity Pressure	Low Set Point: Activate alarm and annunciator
K Liquid Level Detect in Duct Cavity	Circuit closure activates alarm and annunciator; also shuts off power to pump
NaK Low Flow	Low Set Point: Activate alarm and annunciator
Vacuum Over Pressure	Activate Light L-8
Argon Over Pressure	Activate Light L-9

Facility Enclosure

The entire liquid metal containing facility is housed in a steel enclosure which in turn is vented to a water wash type scrubber. In the event of an alkali metal leak, the normal oxide smoke is given off and this is detected by sensitive smoke detectors which warn the operator of a fire. Atmospheric exhausts are then closed manually and the entire 10,000 cfm scrubber capability is connected to the EM pump facility enclosure.

Facility Construction

All stainless steel piping, fittings, etc. used in the alkali metal containing sections of the facility were ultrasonically inspected prior to installation. All components such as dump tanks, head tanks, etc. were helium mass spectrometer leak checked prior to welding into the

system. All welded joints were X-rayed, and the entire system was mass spectrometer leak tested prior to filling with potassium or NaK. All components falling under the jurisdiction of the Unfired Pressure Vessel Code Section VIII, were designed, inspected, and tested per this code. All piping and components were cleaned with trichlorethylene before assembly into the facility.

Test Pump Power

The test pump power was supplied, as shown in Figure 2, from the 480 volt, 3-phase, 60 Hz plant power supply. Power goes to a combination type magnetic starter which in turn connects to a 0-480 volt, 3-phase motor operated variable autotransformer. The secondary of the autotransformer feeds a 45 KVA, 3-phase, 480/240 volt transformer connected in delta-delta. Approximately 60 KVAR of capacitance type load is applied to the transformer secondary for power factor correction.

Voltage and current (using current transformers) are measured at the pump stator terminals, with an overall accuracy of $\pm$ 2%. A Hall effect two-element type wattmeter, with an accuracy of $\pm$ 1% at 0.5 power factor (the normal pump power condition), is connected in the same manner as the other instruments. Scale selector switches on the control panel permit accurate meter readings at all levels of voltage, current, and power.

Checkout

A functional checkout of all valves, controls, instrumentation wiring, etc. was performed after installation and before the test pump was placed in the loop. A complete mass spectrometer leak test was performed prior to filling the system with alkali metal after installation of the test pump.

IV. PUMP INSTALLATION AND CHECK-OUT

A. Test Pump Installation

The test pump was supported in the test facility by two stainless steel strap hangers, and the potassium inlet and outlet nozzles and the NaK coolant lines were butt welded to the facility piping as shown (by arrows) in Figure 8. All final nozzle welds were X-ray inspected and helium mass spectrometer leak checked. Two calibrated sheath type chromel-alumel thermocouples were installed on each of the potassium inlet and outlet nozzles, and the NaK coolant inlet and outlet nozzles. Four calibrated thermocouples were installed in the pump stator winding thermocouple wells. The test pump was then insulated with approximately 3 inch of blanket type alumina silicate fibre insulation to minimize heat losses to the ambient air. The pump installation, with thermal insulation in place, is shown in Figure 9.

The facility check-out procedure, and plans for the performance test, including the scheduled series of data points, is included in Appendix A.

Instrumentation Calibration

1. Prior to installation, test pump thermocouples were calibrated in aluminum (1220°F) and zinc (787.1°F) freeze furnaces. All thermocouples used deviated from the calibrated temperatures by less than ± 3/8%.

2. Prior to start of test operation, and each 30 days during performance and endurance testing, all temperature, pressure and flow recorders are calibrated by supplying a variable millivolt signal

from a potentiometer with an accuracy of + 0.05% of reading plus 3 microvolts traceable to the National Bureau of Standards. Prior to testing, all instruments met the allowable accuracy limits of ± 0.25% of full scale.

3. Prior to installation of the test pump, discharge pressure transducers were calibrated while preheated to 450°F ± 50°F by supplying argon to the loop pump discharge pipe with the throttle valve closed. Transducer mV output versus argon pressure was recorded in 10 psi steps from 0 to 150 and 350 psia, respectively, for the two pump discharge transducers. The calibration was repeated by reducing the pressure to verify that the over-pressure on the 0-150 psia transducer had no adverse effects on its calibration. The test pump suction pressure transducer was calibrated in a similar manner over the range of 0-50 psia by connecting the argon supply to the facility pump inlet pipe. Argon pressure was measured with a ± 0.1% accuracy pressure gage traceable to the National Bureau of Standards.

   Calibration curves are shown for these transducers in Figures 10 and 11. Calibration of these transducers was also checked over the range of 0 to 50 psia during the test shutdown after 248 hours of performance testing, and they will be rechecked during any shutdown during endurance testing. Results of the recalibrations indicated less than ± 1% deviation from the original calibration.

4. During facility checkout, the potassium EM flowmeter calibration was compared to a calibrated orifice meter installed in series with the EM flowmeter. The orifice meter had been calibrated with

water by the Hydraulics Laboratory of Ohio State University to an accuracy of ± 1%. Figure 12 shows the orifice calibration data. The relation of the EM flowmeter output to the orifice flow measurement is shown in Figure 13. The results indicate the difference between the measurement methods (as described in Part B of this Section) is essentially constant (curves nearly parallel) over the range of flow rates. At design point (3.25 lb/sec) the difference is 9%.

Loop Evacuation and Liquid Metal Filling

The NaK system was evacuated to below 1 micron, and 50 pounds of NaK were transferred to the dump tank. Samples for analysis were taken by connecting a sampler to the dump tank fill line (only when the facility was shutdown). Analysis of the sample taken following this transfer indicated 6 ppm oxygen (as Na_2O) in the NaK, as shown in Table 1, Column 5.

The potassium loop was preheated to between 400°F and 600°F for approximately 100 hours and evacuated to 1×10^{-5} torr using a turbomolecular pump. Final bakeout of the test pump T-111 duct was accomplished by filling the NaK coolant loop and circulating the NaK at 400°F for 6 hours. A final outgas rate of 0.7 micron-liter per minute was attained prior to transferring 100 lbs of potassium to the potassium dump tank. Analysis of a potassium sample taken after filling indicated 5 ppm oxygen (as K_2O), as shown in Table 1, Column 1.

Potassium samples are taken by connecting a sample tube between valves installed upstream and downstream of the flow measuring orifice for this purpose. Potassium is bypassed through the sample tube for

a minimum of 15 minutes to assure that a representative loop sample is obtained. This arrangement enables sampling of the potassium without an interruption to test pump operation.

B. Pump Checkout and Facility Checkout

The checkout test plan called for initial operation with 100 volts supplied to the pump, for five flow conditions, with a potassium inlet temperature of 1000°F and an inlet pressure of 8 psia (7 psi NPSH). NaK coolant inlet temperature was set at 600°F, and cooling set for a NaK ΔT through the pump of 50°F. Actually, eight flow rate data runs were made at this condition. In addition, six data runs were made with a pump voltage of 135 volts. Three of these runs were made with NaK coolant inlet temperature of 600°F and three were made with a temperature of 650°F, all with a 50° ΔT. The 100 V checkout data was plotted as shown in Figure 14, and the results reviewed for consistency.

Pump checkout data was obtained over a three day period. During the checkout, an essentially constant difference (approximately 9% at 3.25 lb/sec) was observed in the flow measurements from the EM flowmeter and the calibrated orifice. A facility shut down of 12 hours to obtain a second NaK sample was also used to recheck the potassium EM flowmeter magnet flux density for comparison with original data. This flux value agreed with the initial reading taken before potassium was put in the test loop. The orifice pressure gages were also rechecked and found to be correct.

It should be noted that flow rates from an EM flowmeter are normally calculated from the milli-volt readings, using carefully developed

equations (Reference 2). These equations generally predict the correct relation of flow versus mV output and thus the slope of the resulting curve, but aren't dependably correct as to the exact magnitude of the flow. Thus the calibrated orifice provided a means of establishing the correct EM flowmeter output values for various flow rates as shown by the lower curve in Figure 13. The difference between the theoretical and calibrated curves (9% at 3.25 lb/sec) is within expected deviations.

Analysis of potassium samples taken during checkout operation, as shown in Table 1, indicated oxygen levels of 4 to 6 ppm (Column 2) confirming that the facility by-pass hot trap was very effective at maintaining a low level of oxygen in the system. Analysis of the NaK sample taken at the 12 hour shutdown period indicated 13 to 15 ppm oxygen (as shown in Table 1, Column 6) which was well below the specified allowable limit for the NaK of 50 ppm.

Since at the completion of the pump checkout data runs all facility components and instrumentation were performing properly, and the above mentioned checks had established all instrumentation calibrations, performance testing proceeded in accordance with the schedule in the formal test plan (See Appendix A).

V. PERFORMANCE TEST

The program to explore the performance of the test pump through all "off-design" conditions, was initiated immediately after the successful check-out of the facility and pump operation. The schedule for the series of performance tests is given in the table which is included as part of the Test Plan, included in this report as Appendix A.

A. Test Plan and Procedure

Throughout performance testing the specified test conditions were established quite easily by making the following adjustments in the order listed, for each test number (see the table in Appendix A).

1. Specified pump voltage was established by adjusting the motor operated variable voltage transformer which supplied power to the test pump, and observing the pump voltage on the precision voltmeter located on the console.

2. Specified potassium flow rate was then established by adjusting the potassium throttle valve.

3. Specified potassium pump inlet temperature and NaK coolant pump inlet temperature were established by adjusting the air supply valves to the respective potassium and NaK air coolers.

4. Pump inlet pressure was established by adjusting the head tank dome heaters. This adjustment set the pump inlet pressure by producing the required potassium vapor pressure in the head tank. Since the dome heaters were automatically controlled to maintain a constant dome temperature, this adjustment was required only when the test plan called for a change in pump inlet pressure.

5. The final adjustment was to obtain the specified ΔT between the pump NaK coolant inlet and outlet by adjusting the power to the NaK coolant pump, along with some air to cooler adjustment. It was found that the normal 50°F ΔT could be maintained for all tests except with low test pump voltage (45 V) when the maximum ΔT was 25°F.

Prior to recording data for a performance run, all temperatures were observed to remain constant within $\pm$ 10°F for a minimum period of 15 minutes without making any adjustments to the test facility. Pump winding temperatures were the slowest to reach equilibrium condition. The time required to change from one test plan condition to the next condition normally varied from 1 to 3 hours depending on the magnitude of the change. For a series of performance runs at the same pump voltage and temperature conditions, only adjustments 2, 3 and 5 above were required.

B. Test Results

All basic performance test results are tabulated in Table 2, showing the major data of interest in studying the pump behavior. A comparison with the list in the plan shows a total of 40 extra data runs were made where the plot of performance data indicated that additional points were required to better define the performance curves. Test performance curves, for the conditions of major interest, plotted from the data taken at each test point, are shown in Figures 15 through 23 for a NaK inlet of 800°F and K temperatures of 1000°F, 900°F, and 1300°F. These curves show developed pressure, power input, efficiency, and power factor versus potassium flow rates at the various test voltages.

The original test plan was followed very closely with the exception that a 150 volt test series was substituted for the planned 165 volt series (P31 through P35). This was due to the fact that the test pump produced somewhat higher head than predicted at the 165 volt condition, and would have exceeded the 300 psia pressure normal maximum rating of the test pump and test facility. Near the end of the performance test program a special brief test run (P60A) was made at a pump discharge pressure of 348 psia to determine the effects on pump efficiency of the higher developed head.

Also, several sets of test conditions were repeated to determine the repeatability of the data, as shown in Table 2. Compare, for example, test runs C3-C3A, P6A-P6B, P9-P9A, P20-P20A, and P21B-P21C. The differences between the calculated efficiency for these repeated runs ranged from a minimum of 0.08 percentage points for the maximum efficiency (14.13%) run, to a maximum of 0.57 percentage points between the lowest flow and efficiency (2.02%) runs. The results undoubtedly would have been closer on the low flow conditions except that all parameters (flow, pressure, etc.) could not always be duplicated.

Cavitation Tests

The final phase of performance testing consisted of three cavitation tests performed at a constant flow, head, and voltage, with the pump inlet pressure constantly reduced until pump cavitation was indicated by a reduction of flow and pump discharge pressure. A sound pickup was installed on a stainless steel strap welded to the pump inlet nozzle and cavitation sounds were recorded on tape. The sound of cavitation was quite audible and occurred at the time the first reduction

in pressure and flow occurred and stopped at the point where the flow and pressure fully recovered. Throughout the performance testing and these three cavitation tests, pump inlet pressure was controlled by potassium vapor pressure in the head tank adjusted by changing the head tank dome temperature.

The first of the three cavitation tests (P-111) was repeated with argon in the head tank and the pump inlet pressure adjusted by changing the argon pressure in the head tank. In both cases, cavitation started as the inlet pressure dropped to about 2 psia representing 1.0 psi NPSH for 1000°F potassium inlet temperature and design flow of 3.25 lb/sec. The pump came out of cavitation when the inlet pressure was raised to 2.5 psia (1.5 psi NPSH).

For a maximum flow condition of 4.25 lb/sec and 1000°F inlet temperature (P-112) cavitation started at between 5 and 5.5 psia inlet pressure representing a NPSH of 4 to 4.5 psi. For the 1300°F potassium inlet temperature and maximum flow of 4.2 lb/sec (P-113) cavitation started at 10 psia inlet pressure representing a NPSH of 1.2 psi. Flow and pressure traces for the cavitation run at design conditions are shown in Figures 24 and 25 (test P-111).

Reverse Flow Tests

At the end of the scheduled performance testing, pump power was reversed and three special low head test runs were made to observe the effect of reverse pump operation on pump performance. These data points (P11A, B, & C - Rev., in Table 2) are compared with results in the normal flow direction from data points P11, 12 and 13, in Figure 26.

Post Performance Test Plans

Performance testing required a total of 419 hours of pump operation, performed in two "round the clock" testing periods of 248 hours and 171 hours. The facility was shutdown between these two periods to evaluate data, finalize the remainder of the test plan, and recalibrate the instrumentation. All instrumentation was found to have the same calibration within $\pm$ 1% of initial calibration. Immediately following the completion of performance testing, endurance testing was started at the conditions listed below.

Potassium Flow Rate: 3.25 lb/sec $\pm$ 10%

Potassium Inlet Temperature: 1000°F $\pm$ 15°F

Potassium Inlet Pressure: 8 psia $\pm$ 1 psi

Potassium Discharge Pressure: 248 psia $\pm$ 5 psi

NaK Inlet Temperature: 800°F $\pm$ 10°F

NaK ΔT: 50°F $\pm$ 10°F

Performance of the pump at the design point (3.25 lb/sec flow of 1000°F potassium and with 800°F NaK - ΔT of 50°F) was not noticeably affected by the extremes in temperatures, flows, voltage, etc., to which the pump was subjected during the test series. However, the coil (winding) resistance to ground, which could be affected by any contamination of the alumina slot insulation end surfaces, decreased from the initial value of about one megohm (at 1000°F) to about 200 kilohms (at the same temperature). Data during the latter part of the performance test indicated the 200 kilohms value was not decreasing further, and was still completely satisfactory for the endurance test program.

VI. RESULTS AND DISCUSSION

The data obtained from the extensive series of performance tests is the end result of a major portion of the program. Basic data from each test are summarized in Table 2 and the curves in Figure 15 through 23, showing results from the extensive series of tests at major temperature conditions. These data will be analyzed in this section of the report.

A. Comparison with Design Calculations

Comparison of the test results with the design calculations indicated generally good agreement. The behavior of the pump was basically as predicted. The general shapes of the test data curves, plotted against flow rate, were consistent and similar to the calculated curves. The curves for the actual tests (Figures 15 through 23) may be compared directly with the calculated curves which are in Part I of this report, but to simplify the comparison, the calculated performance for the standard design conditions of 1000°F potassium and 800°F NaK (50°F Δt) are included in this report in Figures 27, 28, and 29, along with actual performance results for 3 line voltages.

At the design point flow rate (3.25 lb/sec), a comparison of the curves in Figure 27 will show that the developed pressure from the performance tests was very nearly the same as that predicted in the design calculations. For example, with 135 V applied to the pump, the pressure was 245 psi, only 5 psi above the predicted value. At 4.0 lb/sec flow with 135 volts, the values were the same. At voltages below 135 V, and at lower flow rates, the actual performance tests showed the pressure to be up to 8% higher than predicted.

The power input data, shown in Figure 28 indicates that at the design point flow condition and with 135 V applied, the actual power input was about 22 kW, while the predicted power was about 18 kW, a difference of about 18%. At lower voltages, however, the actual was closer to the predicted value. For example, with 70 volts it was 6 kW versus 5.5 kW, a difference of about 10%.

The higher power required, especially near the design point, resulted in a lower than predicted efficiency. Reference to the curves in Figure 29 show that for the 135 V condition (design point flow rate) the efficiency was just over 16% while the predicted value was over 18%. Furthermore, the predicted peak was at the design point while the performance test showed a peak at about 3.12 lb/sec or 16.6% with 135 V power input. The peak efficiency, while slightly below the expected value, is of course much better than with any previously available EM pumps of similar ratings and heavier weight.

At lower flows and voltages than the design point conditions, the performance test results (Figure 29) show the efficiency is much closer to the predicted value. With 70 volts input, for example, the actual efficiency was slightly above the predicted at 11.6%. When the voltage was raised above the normal 135 V, the efficiency increased slightly, but as the flow was increased above the 3.25 lb/sec rate the actual efficiency decreased more rapidly than predicted. For example, with 135 V and a flow rate of 4.25 lb/sec, the actual efficiency was 10.5%, while the predicted value was 15.5%, a decrease of 5 percentage points, or change of nearly 30%.

Performance data for tests with 900°F potassium are shown by the additional curves in Figures 18, 19 and 20, while the data for tests with 1300°F potassium are shown in Figures 21, 22 and 23. The calculated predictions for pressure, power, and efficiency at 100 and 135 volts, are shown by the dash lines on these curve sheets. It is obvious that the pump develops more pressure than was predicted for the same potassium flow rate and applied voltage. However, the power input is higher than predicted, resulting in a lower than expected efficiency.

The Power Factor values calculated from the test data, are shown by the additional curves on Figures 17, 20 and 23. A single curve very closely defines the results of the tests over the range of voltages shown by Figures 20 and 23. However, the wide range of test voltages shown in Figure 17 resulted in a greater spread in the power factor values and, for information purposes, additional curves are included for the maximum and minimum test voltages.

A comparison of actual and calculated values for the power factor is shown by the two curves in Figure 29. It will be noted that the actual is about 5% higher than expected, at the design point, i.e., 52% vs. 47.5%.

B. Analysis of Pump Performance

Pressure

A review of the "summary" curves in Figure 27 shows that developed pressure varies more rapidly with flow than was predicted in design calculations. The curves are "steeper" than expected, especially above the design point flow (3.25 lb/sec).

There may be several interrelated reasons for the steeper flow curves. Since the phenomenon is directly related to flow, being more pronounced at the higher flow rates, it is most likely related to a hydraulic effect which causes higher hydraulic loss at the higher flow rates than originally predicted. This would then show up as a lower developed pressure and higher losses resulting in a lower efficiency.

One possible hydraulic effect that could be responsible for the lower than predicted pressure at high flow is vortex action at the end of the duct after the fluid leaves the helical passage and enters the center return pipe at a smaller diameter. The fluid is undoubtedly "spinning" as it leaves the helix and could create a vortex in its attempt to conserve angular momentum as the flow path moves radially inwards and enters the smaller diameter center pipe. This particular phenomenon could possibly be overcome by reversing the direction of flow thru the pump in future designs. One series of tests were attempted to verify this fact. While performance seemed to improve when flow was reversed, the results were not conclusive because the system and instrumentation set-up prevented running any tests with developed pressures greater than 50 psi. Hence only three points were taken and these did not cover a wide enough range of performance. The data is shown by the curves in Figure 26.

As noted by the power factor curves in Figure 17, there was a spread of values at different voltages although this was not expected to be very great because the reactive component of the power input is a large item and changes in useful input power does not have a major effect on the total KVA. The greatest change in "trend" was noted

with data from the 45 V test, but because of the low values of KVA and kW involved, and the large effect that the kW measurement would have, it is felt that the data is not completely typical.

A check of Figure 29 shows that the actual power factor was several percentage points higher than expected, due probably to the higher I^2R losses in the windings. This makes the kW power input higher, the PF higher, but the efficiency lower, as noted in Figures 17, 20 and 23.

The total KVA inputs were very close to the calculated values, indicating basic parameters in the computer program used in the design work are very good.

Efficiency

Overall, it appears that the steeper pressure flow curves, and the lower efficiency (higher losses) at high flow rates as shown by the summary curves in Figures 27, 28 and 29 may very well be due to some undetermined hydraulic effect. The vortex action, as already mentioned, and unexpected pressure drops in the helix, would subtract directly from the electromagnetically developed pressure, resulting in higher losses and increased power requirements, and is a direct function of flow rate.

Another possible cause for some of the additional losses and the drop-off in efficiency at the design point and higher flow rates is possible saturation in the stator iron or center iron core. This could cause a higher magnetizing current resulting in higher winding I^2R as well as iron losses. The interlaminar insulation varies from 0.001 - 0.002 inches thick on each punching lamination and hence could possibly represent as much as 10% of the total stator stack length, at the upper

tolerance limit. This would reduce the useful magnetic material to 90% of the stack length, thereby increasing the flux density in the iron until it is very much nearer the region of saturation than its normal value which was used for the design calculations.

The thermal insulation (dimpled Nb-1% Zr foil) between the duct and stator proved to be quite as effective, as was predicted, in limiting the heat transfer between the duct and stator. At the same time, the heat transfer between the windings, stator core and the NaK coolant in the stator frame heat exchanger appears to be very good. Variations in potassium temperature between 900°F and 1400°F did not substantially affect overall winding temperature. The performance was not as good at 1400°F due mostly to the increased electrical resistivity of the potassium which led to higher potassium, stator iron and winding currents, and thus, losses. The relative changes in performance with voltage and potassium temperature were consistent with the predictions.

Heat Balance

To establish the validity of the measured electrical power and calculated hydraulic power used to determine pump efficiency, heat balances were calculated from the measured temperature rise in the potassium and NaK for a number of performance runs. A calculated heat loss to ambient through the 3 inch thermal insulation covering the pump of 350 watts was added to the heat losses calculated from the fluid temperature rise and compared with the pump losses determined by subtracting the hydraulic power from the total measured electric power. The results of this comparison are shown below. In all instances the deviation shown is less than would result from an error in measurement of the potassium ΔT of 1°F.

Test Number	Calculated Losses to K & NaK, Plus Loss to Ambient KW	Total Losses - (Measured Power Less Hydraulic Power) KW	Deviation %
P1	17.66	17.99	-1.8
P2	19.55	18.72	+4.4
P3	19.45	18.88	+3.0
P6	5.56	5.57	-0.2
P7	6.16	5.75	+7.1
P8	6.22	5.97	+4.2
P16	9.71	10.18	-4.6
P17	11.11	10.39	+7.0
P18	11.29	11.33	-0.3
P31	20.39	21.07	-3.2
P33	22.22	21.78	+2.0
P34	22.72	22.02	+3.3

General

The pump potassium flow responded immediately to control adjustment of voltage, which is a major advantage of EM pumps in that they can readily be controlled simply by varying voltage. By adjusting the pressure with the throttle valve, the flow was also quickly and positively adjusted.

The test results indicated that inlet (suction) pressure could be varied appreciably without any effect on performance. To carry this to the extreme, a series of tests were made to check the cavitation performance of the pump. These were tests P-111 thru P-113 in Table 2. The results at the design point flow rate and pressure (P-111 to P-111-5) are particularly interesting. The pressure measurements are shown in Figure 25 and the corresponding flow measurements in Figure 24. It can be seen that cavitation starts at 2 psia inlet pressure, which with

1000°F potassium is equivalent to the very low NPSH of 1 psi. The pump rather suddenly came out of cavitation after the inlet pressure was raised to only 2.5 psia (1.5 psi NPSH).

During operation of the pump, the winding temperatures were measured at each test data point by means of thermocouples inserted in wells which were attached to the winding end turns. In addition, a check on average winding temperature was made periodically by removing power and immediately measuring the winding resistance between terminals while the unit was hot. By taking measurements at several intervals of time, the resistance at the moment of shut down can be extrapolated and thereby give an indication of average winding temperature, and a check of readings from thermocouples mounted on the end joints of the windings. These measurements indicated winding temperatures (the average from the four thermocouples) of about 1050°F at the design flow point, and by resistance of about (average) 1100-1150°F. The lower thermocouple readings are due to the loss of heat thru the thermocouple well by conduction, and the electrical "S" glass tape insulation between the thermocouple well and the conductor material.

The average winding temperature, by design calculation, was expected to be about 1050°F. The higher measured temperature (1100-1150°F) by resistance is due to the slightly higher losses than predicted, mentioned previously. The stator winding temperature rise above the 800°F NaK coolant is about 20% higher due to the additional current and resulting losses. While this raises the probable stator hot spot temperature somewhat above its predicted 1200°F value, it is still satisfactory and below the established design limit of 1400°F for the stator materials and the brazed joint design and material.

VII. CONCLUSIONS

The electromagnetic (EM) pump, designed for pumping 1000°F potassium at high pressure for the boiler feed application in a Rankine cycle space power system has been tested over a wide range of voltages, flow rates, developed pressures, and potassium temperatures to provide an extensive map of pump performance. The pump performance reached a maximum of 16.3% efficiency at and near its design point condition of 3.25 lb/sec, 1000°F potassium, with an input voltage of 135 V and a developed pressure of 240 psi.

A review of the performance data indicates that the pressure developed in the pump varied more rapidly with change of flow than was expected. This may indicate greater hydraulic losses in the duct than predicted. Efficiency was slightly below expected values although higher than ever obtained from any comparable pump.

Winding temperatures were somewhat higher than predicted, indicating additional I^2R losses and possibly iron losses due to some saturation of the stator iron or center iron core. However, the maximum temperatures at the brazed coil joints were higher than predicted but well below the limits for the special joint design that was developed during the stator design and fabrication phase of the program.

The pump was very responsive to voltage change, indicating an easy method of flow/pressure control when in service. Furthermore, the suction pressure could be adjusted over a wide range without appreciably affecting performance, and the NPSH could be reduced to as low as 1.5 psi without having the pump go into cavitation with the resulting loss of developed head and flow, and risk of cavitation damage.

Overall, the test facility and the test pump performed in a very acceptable manner, confirming all design estimates and expectations.

Following the completion of performance testing, standard (design) conditions were established and the pump endurance test of 10,000 hours duration was initiated.

APPENDIX A

PUMP PERFORMANCE TEST PLAN

Prior to recording performance data, temperatures must remain constant within ± 10°F and flows must remain constant within ± 10% for a minimum of 15 minutes.

1. Initial performance data point will be established as follows:

   Pump voltage 135 V ± 1 volt

   Pump inlet pressure 8 psia ± 1 psia

   Pump inlet temperature 1000°F ± 10°F

   NaK coolant flow adjusted as required to maintain the NaK Δt at 50°F ± 10°F

   NaK inlet coolant temperature 800°F ± 10°F

   Potassium throttle valve wide open or throttled as necessary to obtain a maximum flow of 4.25 lb/sec

2. Reduce potassium flow by adjusting throttle valve in ~20% steps to obtain potassium flows indicated on test plan down to 0.75 lb/sec flow or 300 psia pump exit pressure, whichever occurs first, and make necessary cooler adjustments to maintain other conditions constant. Do not allow pump exit discharge pressure to exceed 300 psia, or flow to drop below 0.75 lb/sec, without approval.

3. Perform test runs in sequence as indicated on test plan tabulation. Record all data indicated on Performance Test Data Sheet, and check results before proceeding to the next setting.

4. At the beginning of each series of tests with a different NaK inlet temperature the power to the test pump will be turned off and the NaK flow reduced to one gpm. After one hour for temperature

stabilization the NaK flow Δt across the pump will be recorded to determine the heat losses from the pump to the ambient environment.

5. Set winding temperature meter relay trip "high set point" at 1250°F. Set alarm "low set point" at 50°F to 100°F above reading. Maximum setting to be 1200°F for the alarm "low set point".

6. After points P5 and P40 have been taken, test data will be reviewed to consider possible revision to the test plan.

APPENDIX A (Cont'd)

EM BOILER FEED PUMP PERFORMANCE TEST CONDITIONS

Test No.	Pump Inlet psia	K-Pump Inlet Temp. °F	NaK Inlet Temp. °F (1)	Pump Voltage Volts	Potassium Flow Rate lb/sec
C1	8	1000	600	100	4.25
C2	↑	↑	↑		3.25
C3					2.45
C4			↓		1.65
C5			600		0.75
P1			800	135	4.25
P2			↑		3.25
P3					3.0
P4					2.45
P5					2.0
P6				70	3.25
P7					2.45
P8					2.0
P9					1.65
P10					0.75
P11				85	4.25
P12					3.25
P13					2.45
P14					1.65
P15					0.75
P16				100	4.25
P17					3.25
P18					2.45
P19					1.65
P20					0.75
P21				125	4.25
P22					3.25
P23					2.45
P24					2.0
P25					1.65
P26				142	4.25
P27					4.0
P28					3.5
P29					3.25
P30					3.0
P31				165	4.25
P32					4.15
P33					4.0
P34					3.75
P35					3.5
P36				45	2.45
P37					2.0
P38					1.65
P39	↓	↓	↓		1.0
P40	8	1000	800		0.75

APPENDIX A (Cont'd)

Test No.	Pump Inlet psia	K-Pump Inlet Temp. °F	NaK Inlet Temp. °F (1)	Pump Voltage Volts	Potassium Flow Rate lb/sec
P41	7.4	900	800	135	4.25
P42					3.25
P43					3.0
P44					2.45
P45					2.0
P46				125	4.25
P47					3.25
P48					2.45
P49				100	4.25
P50					3.25
P51					2.45
P52					1.65
P53					0.75
P54				85	3.25
P55					2.45
P56					1.65
P57					0.75
P58				165	4.25
P59					4.0
P60	7.4	900	800		3.5
P61	15.8	1300	800	135	4.25
P62					3.25
P63					3.0
P64					2.45
P65					2.0
P66				125	4.25
P67					3.25
P68					2.45
P69				100	4.25
P70					3.25
P71					2.45
P72					1.65
P73					0.75
P74				85	3.25
P75					2.45
P76					1.65
P77					0.75
P78				165	4.25
P79					4.0
P80	15.8	1300	800		3.5
P81	22.2	1400	800	135	4.25
P82					3.25
P83					3.0
P84					2.45
P85					2.0
P86				125	4.25
P87					3.25
P88	22.2	1400	800		2.45

Test No.	Pump Inlet psia	K-Pump Inlet Temp. °F	NaK Inlet[1] Temp. °F	Pump Voltage Volts	Potassium Flow Rate lb/sec
P89	22.2	1400	800	100	4.25
P90					3.25
P91					2.45
P92					1.65
P93					0.75
P94				85	3.25
P95					2.45
P96					1.65
P97					0.75
P98				165	4.25
P99					4.0
P100		1400	800		3.5
P101		1000	800	135	4.25
P102			(Allow NaK Delta-T		3.25
P103			to increase to 100°F)		3.0
P104					2.45
P105					2.0
P106			900	135	4.25
P107					3.25
P108					3.0
P109					2.45
P110	22.2	1000			2.0

Note: For the following data runs establish conditions indicated with 15 psi NPSH and then reduce NPSH until inception of cavitation is indicated by a reduction of head and/or flow. Control NPSH by potassium vapor pressure in head tank.

P111	15 to 1	1000	800	Voltage Required to Produce 240 psi pump head.	3.25
P112	15 to 1	1000	800	165	4.25
P113	15 to 8	1300	800	165	4.25

(1) With NaK Δt of 50°F except as noted.

IX. REFERENCES

1. Diedrich, G. E. and Gahan, J. W., "Design of Two Electromagnetic Pumps", Report NASA CR-911, General Electric Co., November 1967.

2. Affel, R. G., et al, "Calibration and Testing of 2 Inch and 3 1/2 Inch Magnetic Flowmeters for High-Temperature NaK Service", Report ORNL-2796, Oak Ridge National Laboratory, March 1960.

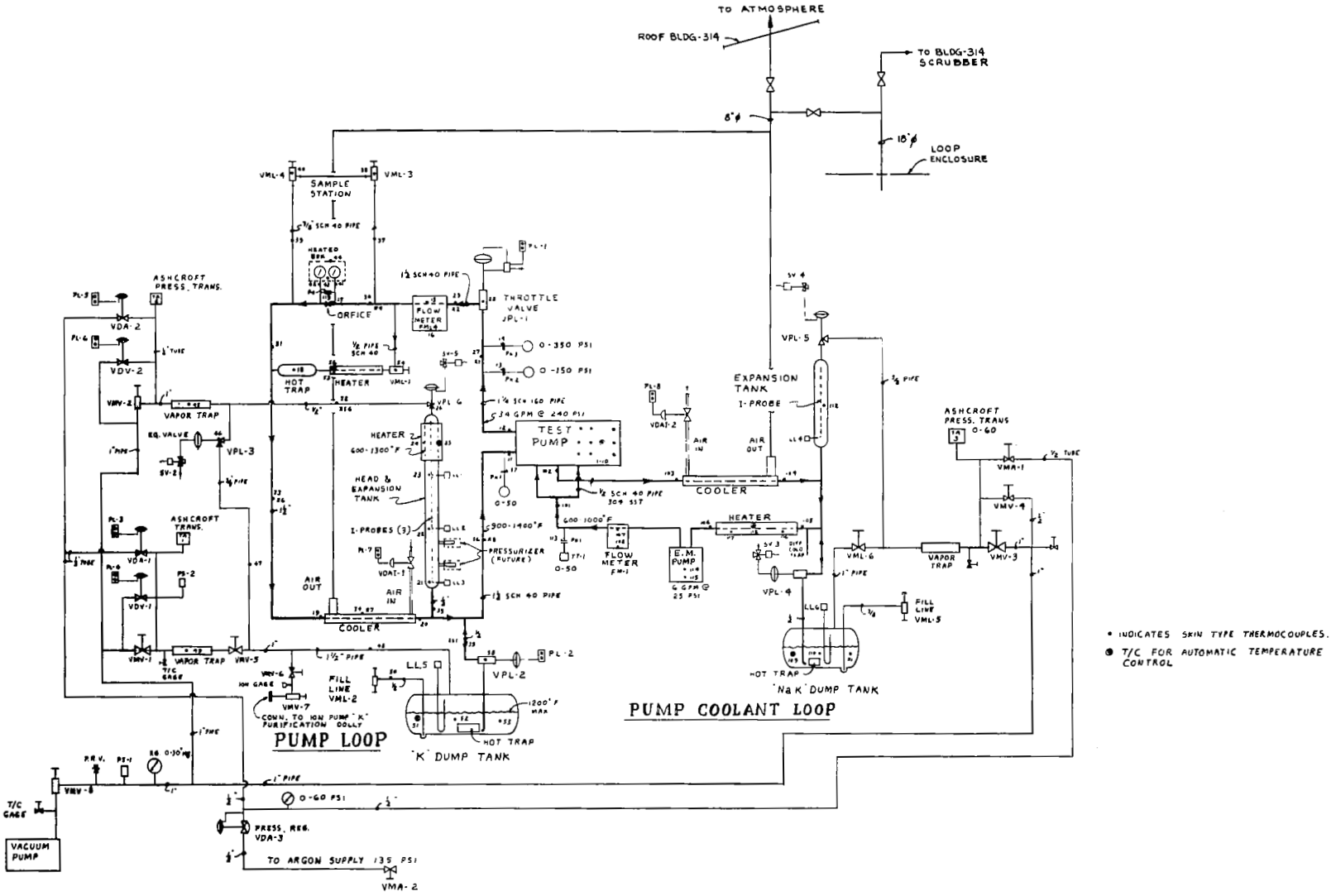

Figure 1. Schematic Diagram of Test Facility Showing Test Pump and Cooling Loops.

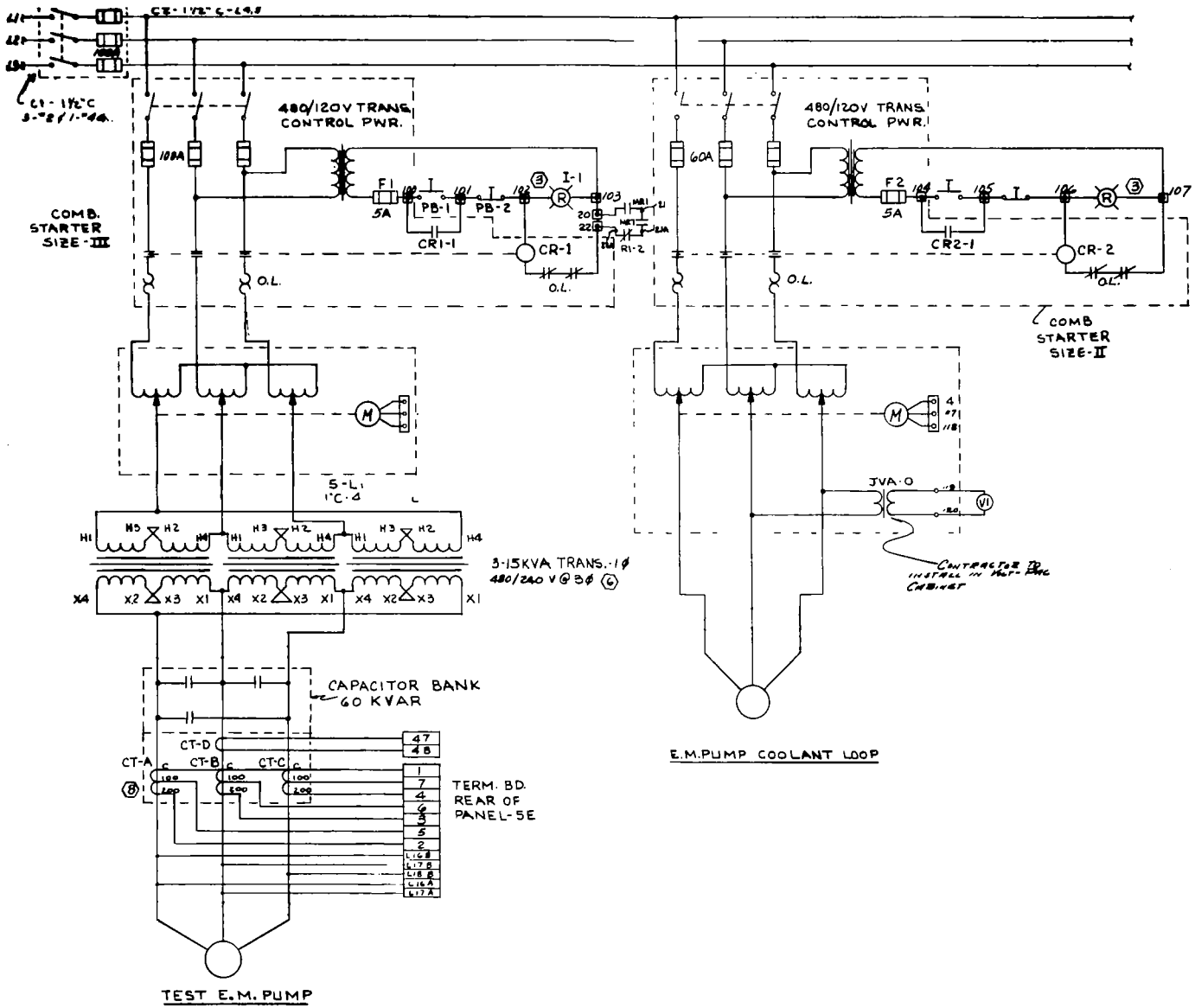

Figure 2. Electrical Schematic Diagram of Power and Control Circuits for Test Pump and Cooling Pump.

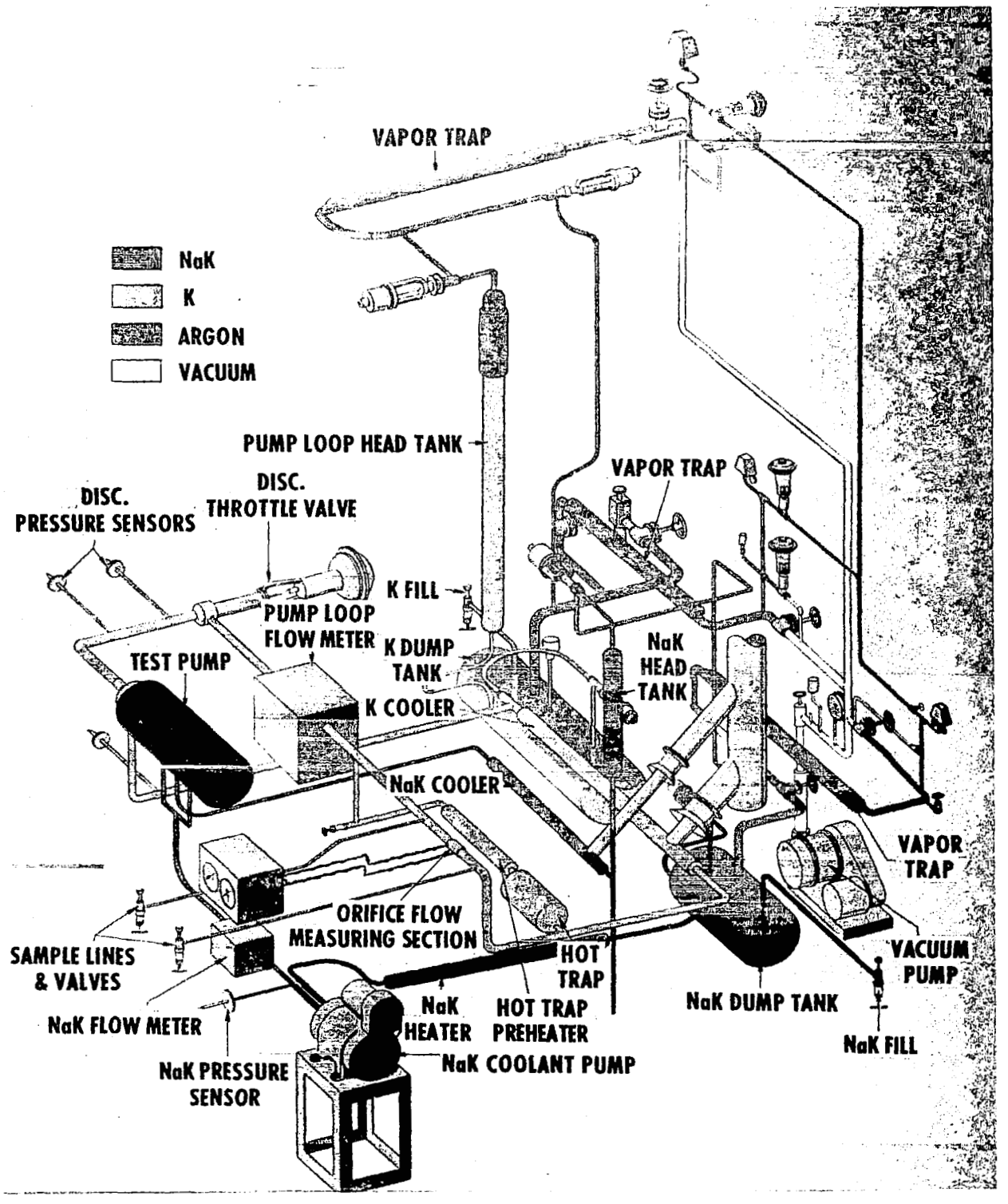

Figure 3. Sketch (Isometric) of EM Boiler Feed Pump Test Facility.

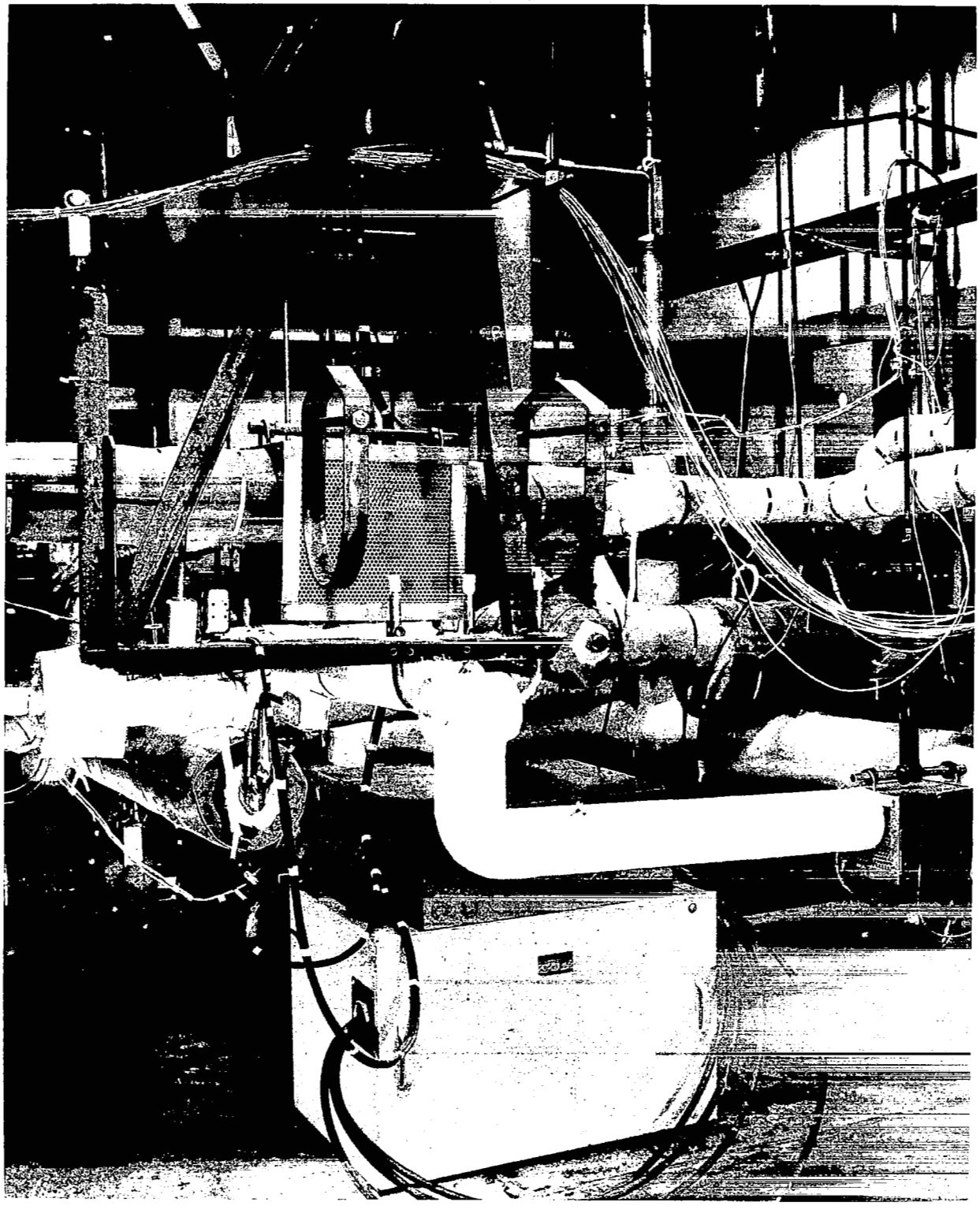

Figure 4. Part of the EM Boiler Feed Pump Test Facility After Installation of Piping Insulation, Ready for Pump.

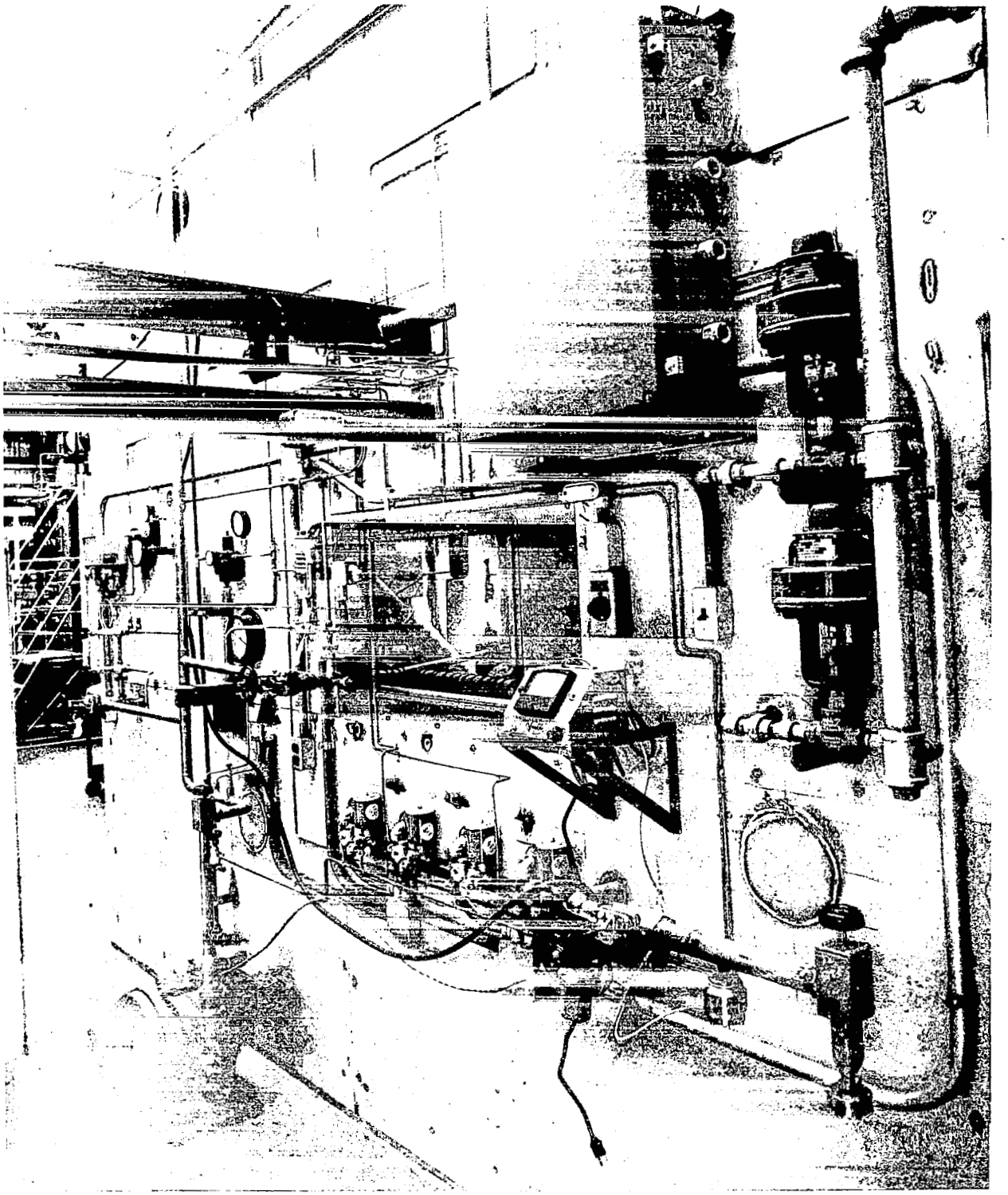

Figure 5. Outside of One Wall of Pump Test Facility Steel Enclosure.

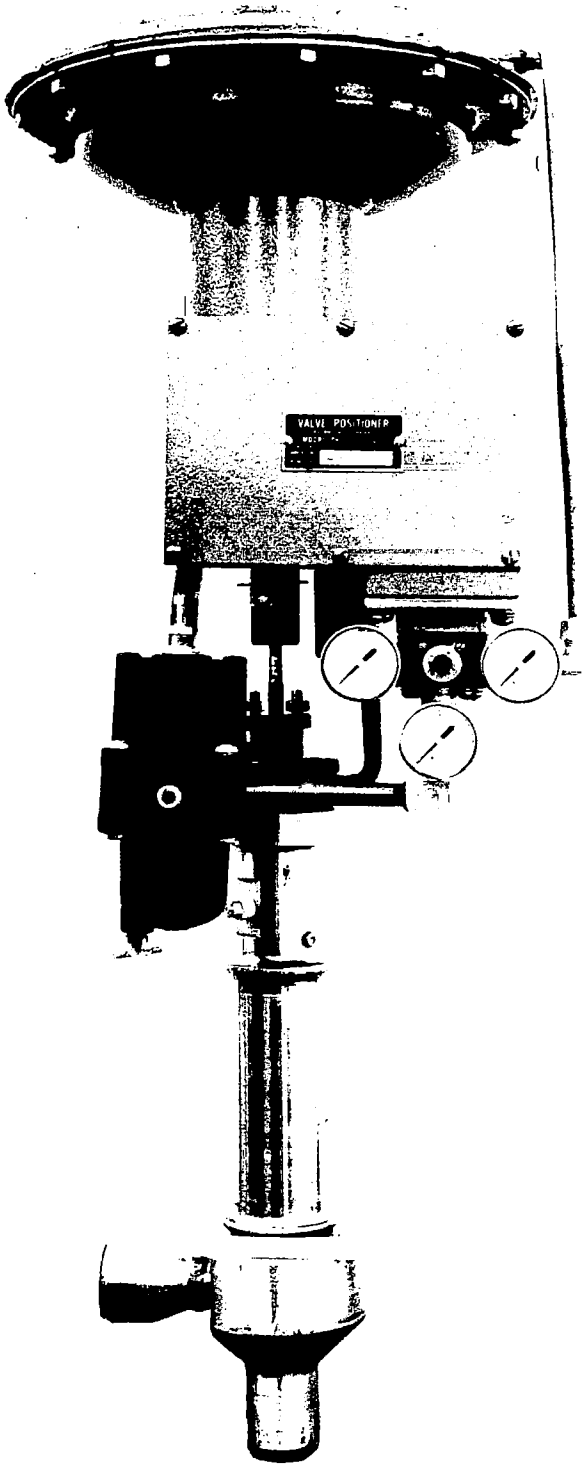

Figure 6. EM Test Pump Loop (Potassium) Throttle Valve with Air Operator.

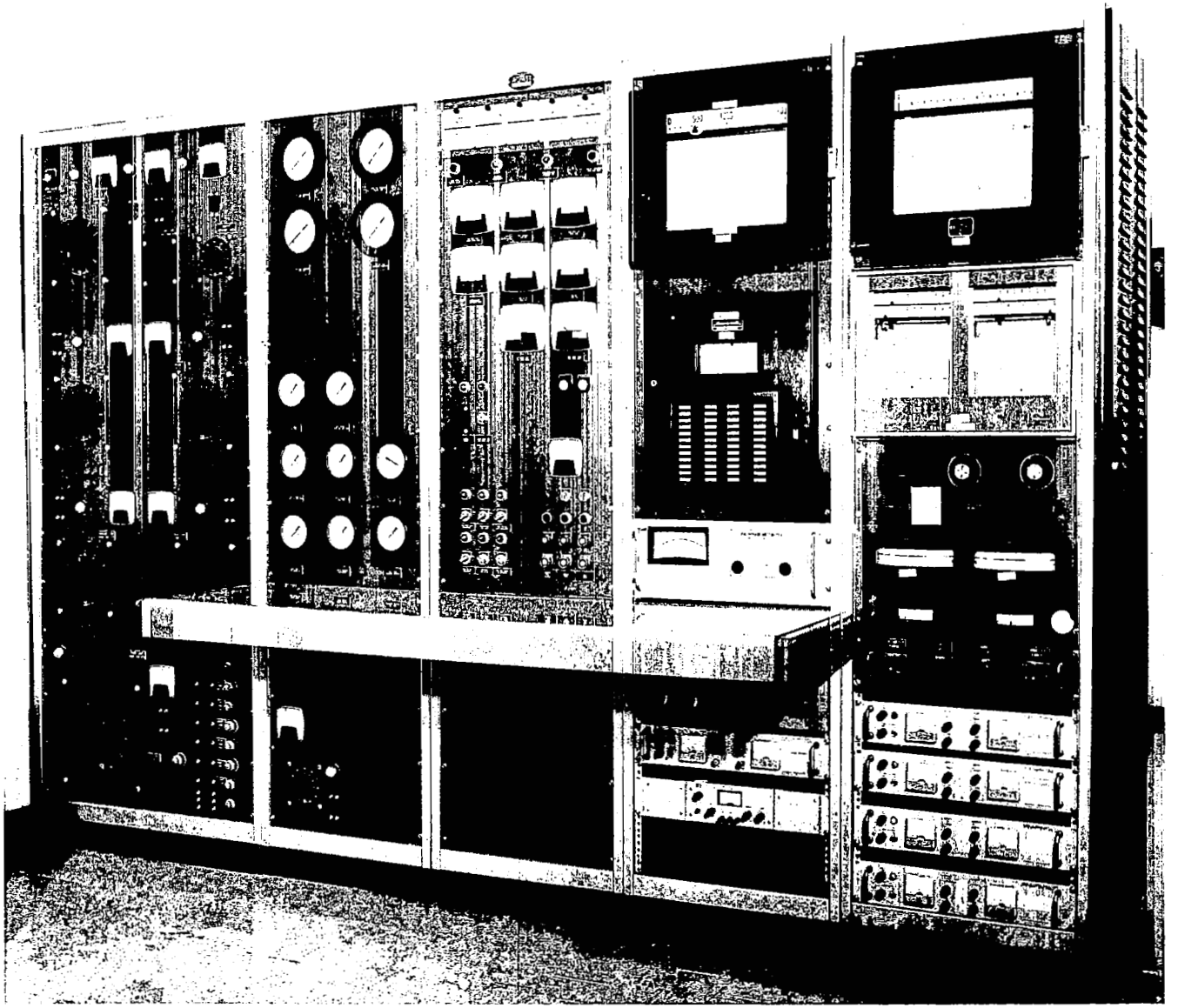

Figure 7. EM Pump Test Facility Control and Recording Console.

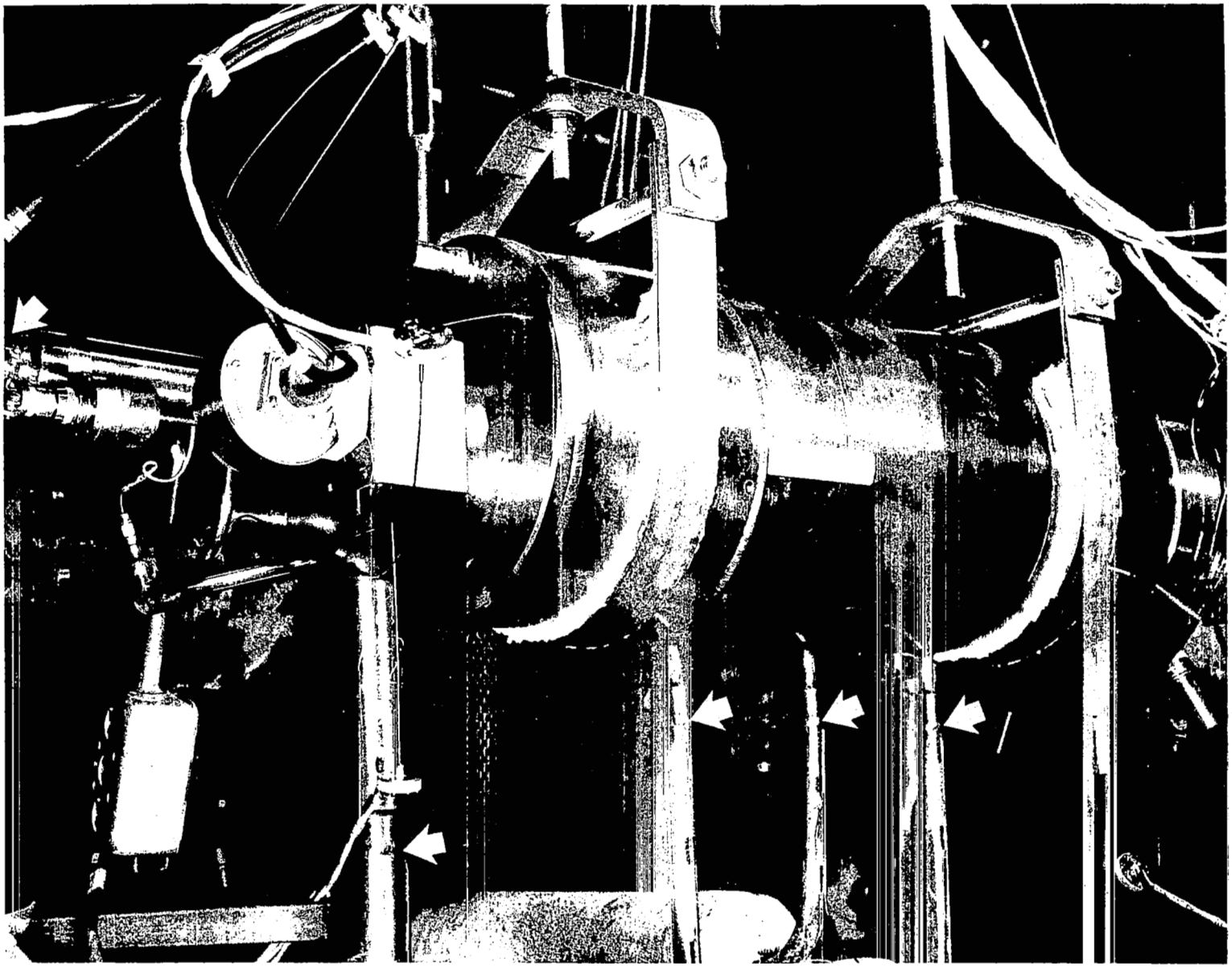

Figure 8. Close-up of EM Test Pump After Mounting in Facility and Welding (Shown by Arrows) of the K and NaK Pipes.

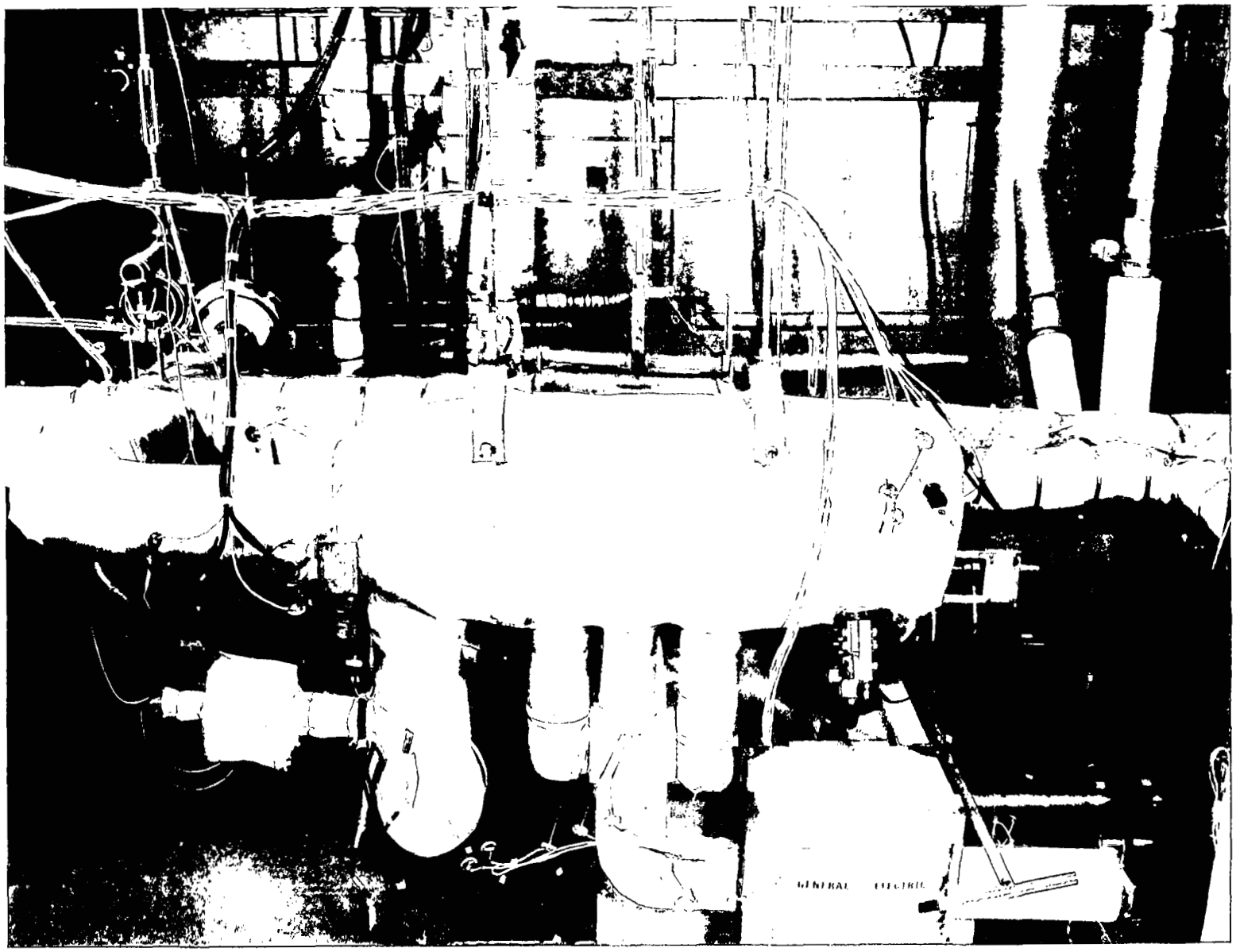

Figure 9. EM Pump Test Facility After Installation of Test Pump (Foreground) with Its T/C's, Power Leads and Final Insulation.

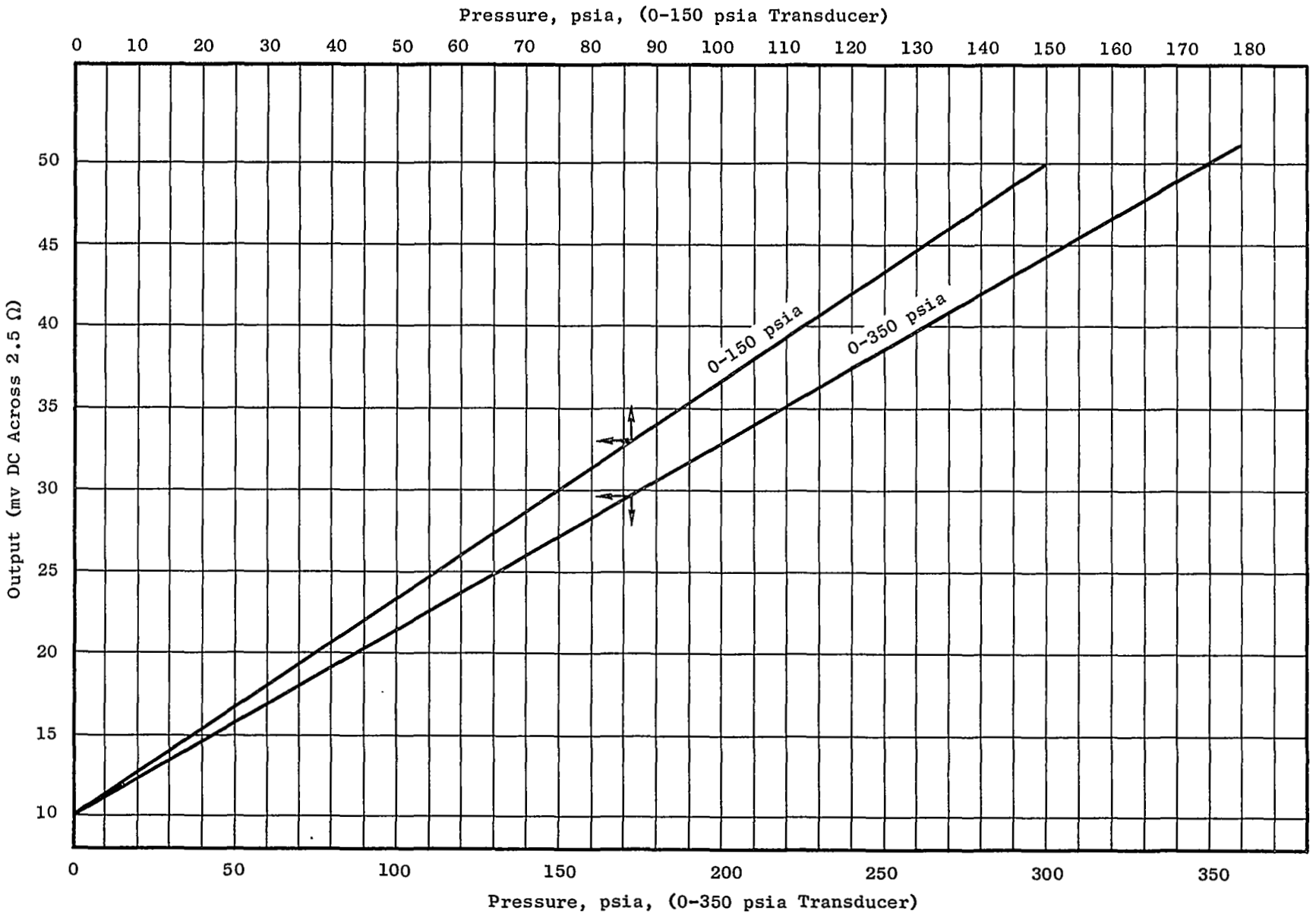

Figure 10. Pump Outlet (Potassium) Pressure Transducer Calibration Curves Made at 450°F ± 50°F.

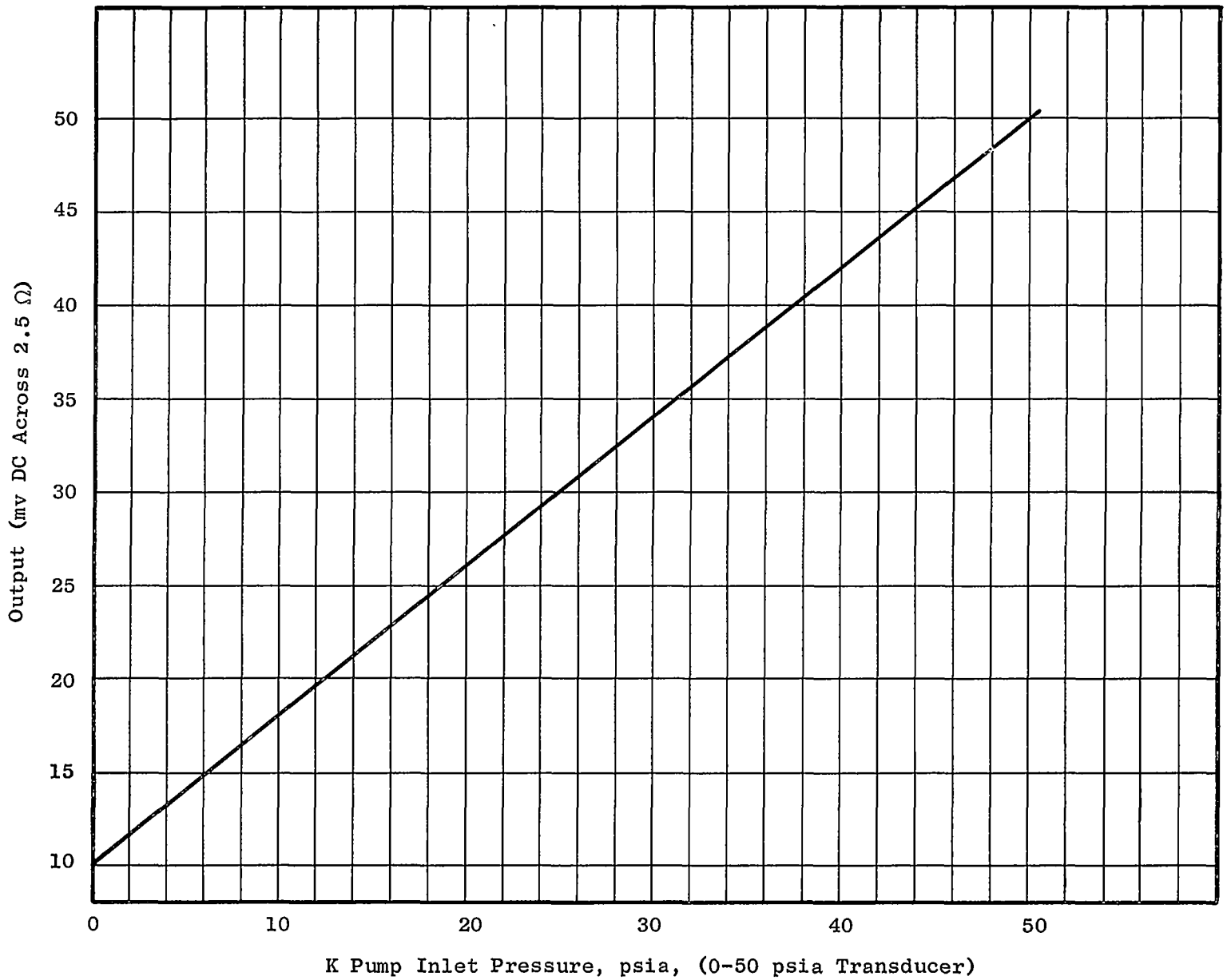

Figure 11. Pump Inlet (Potassium) Pressure Transducer Calibration Curves Made at 450°F ± 50°F.

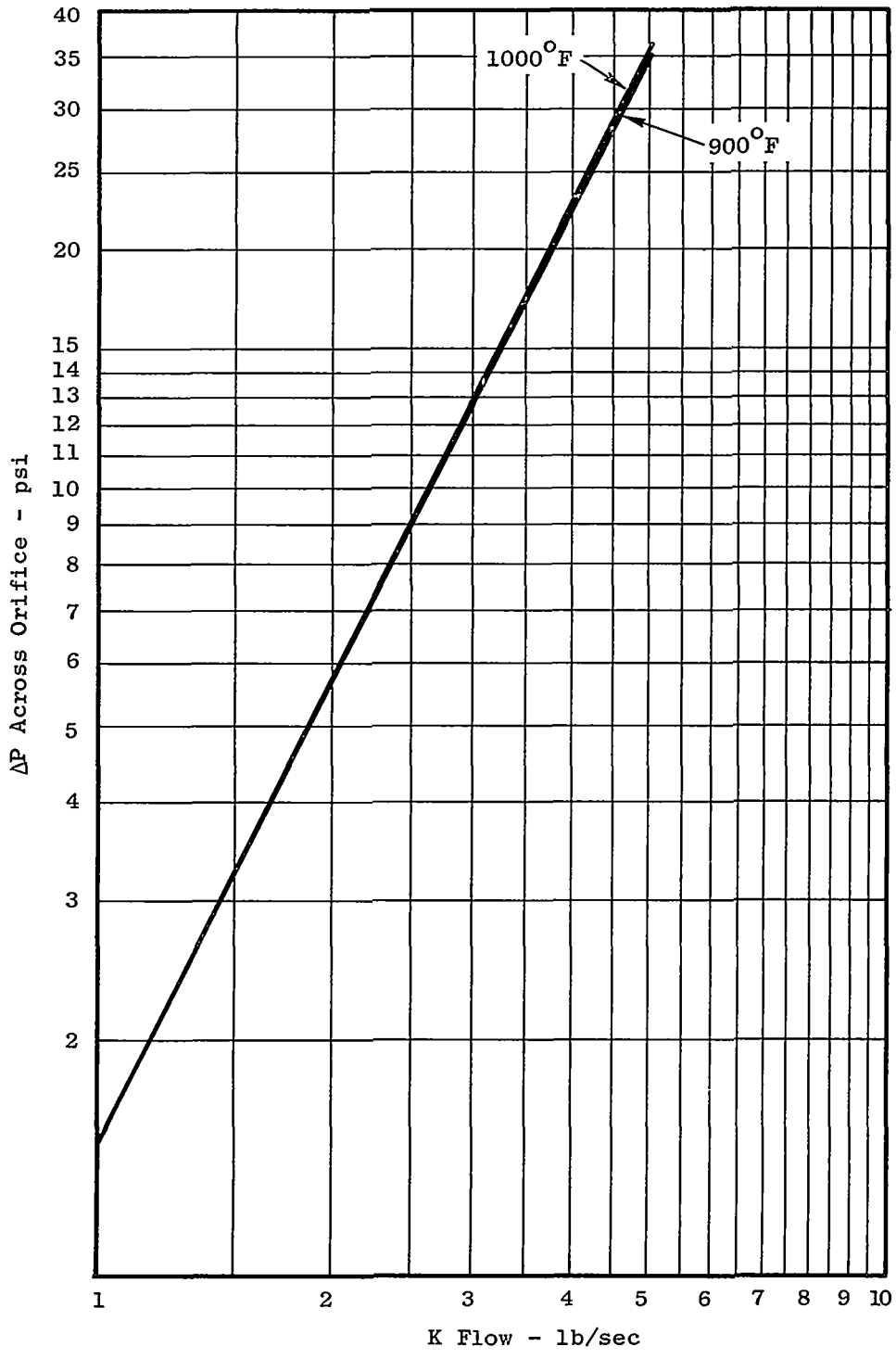

Figure 12. Pump Outlet Pipe Orifice Flow Rate Calibration Curve, Based on Date from Hydraulic (Water) Test.

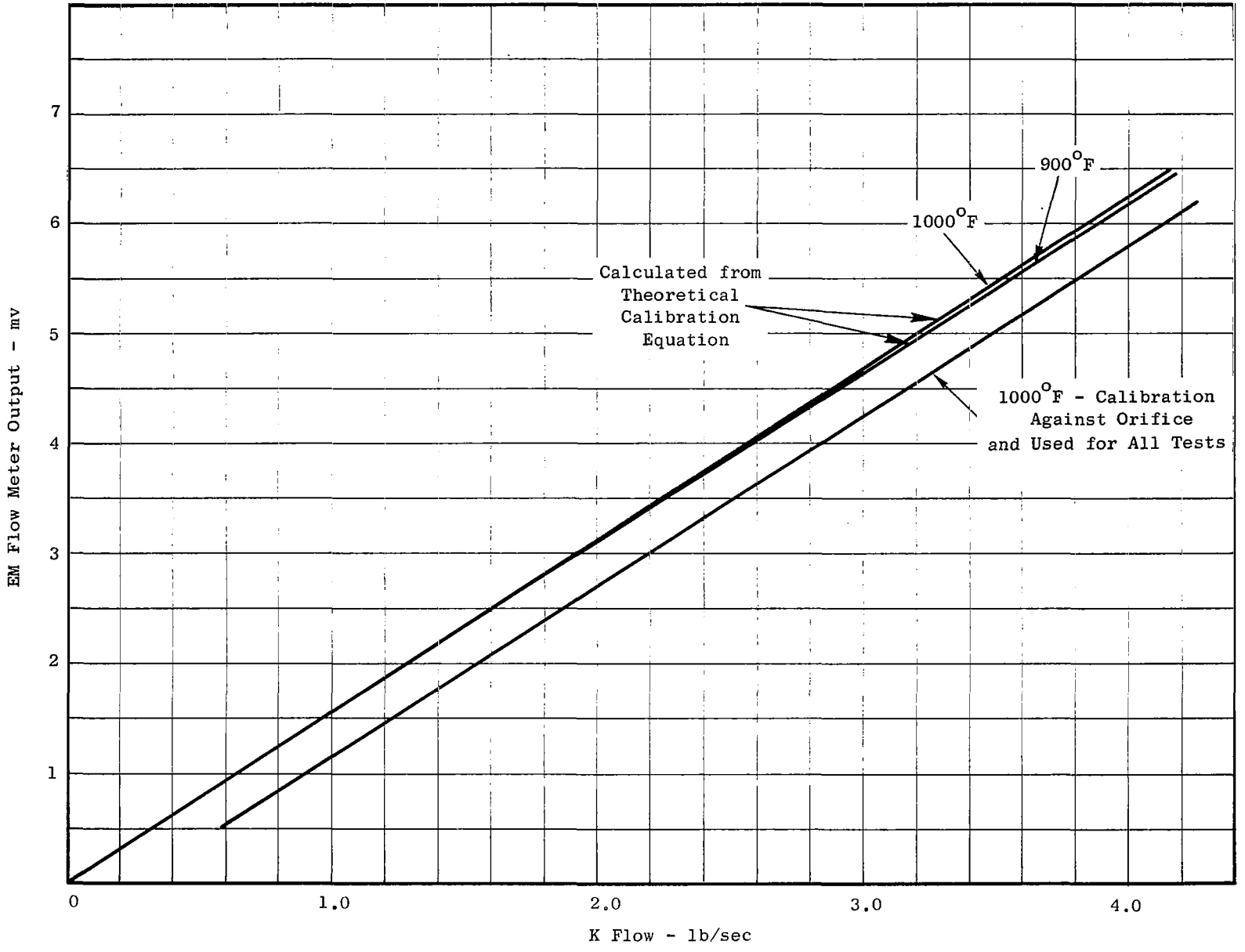

Figure 13. Pump Outlet Pipe EM Flow Meter Calculated Output Curves, and Adjusted Curve Based on Orifice Data.

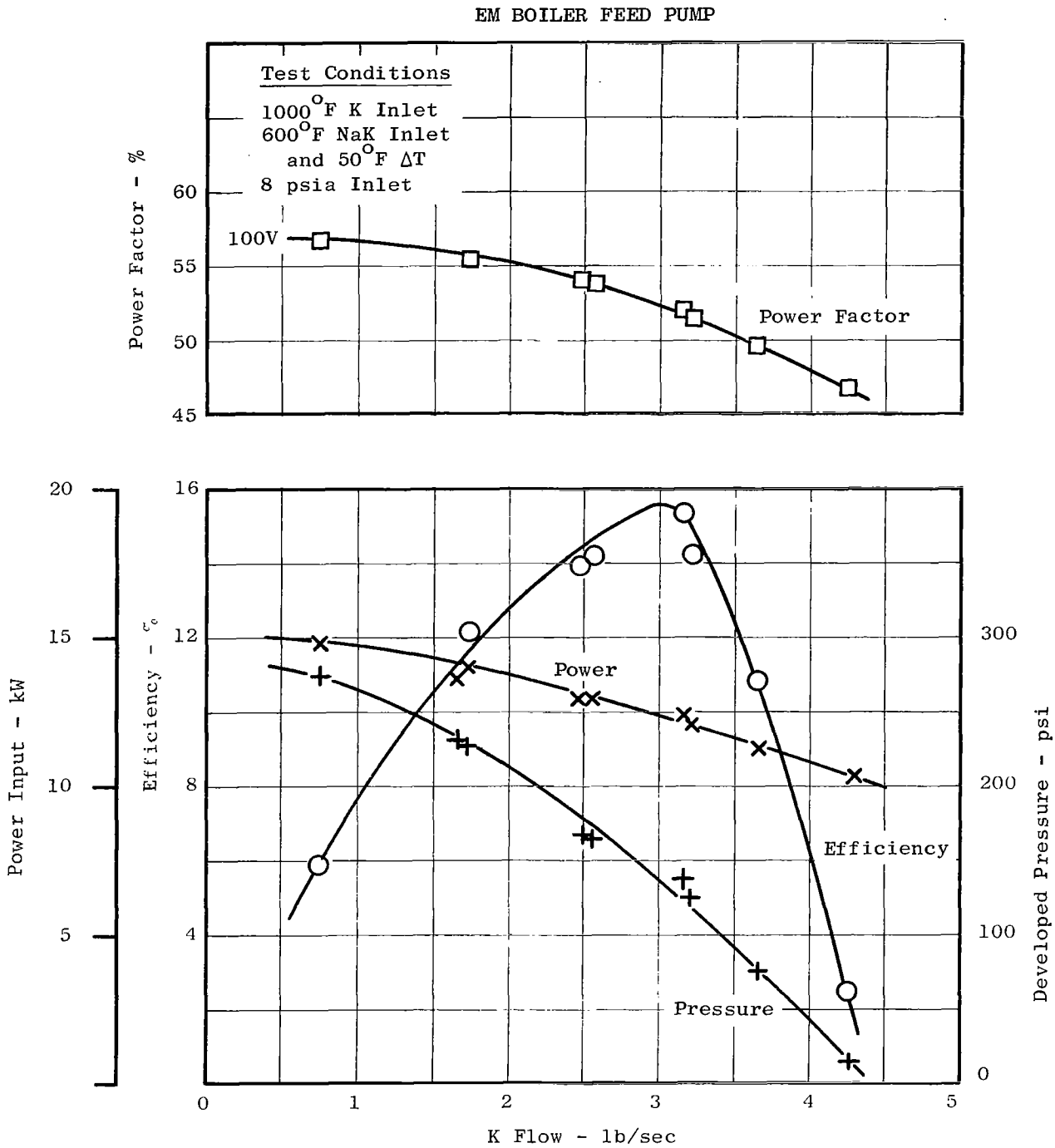

Figure 14. EM Pump Check-Out Test Data Curves Showing Pressure, Power, Power Factor and Efficiency for the Check-Out Test Conditions.

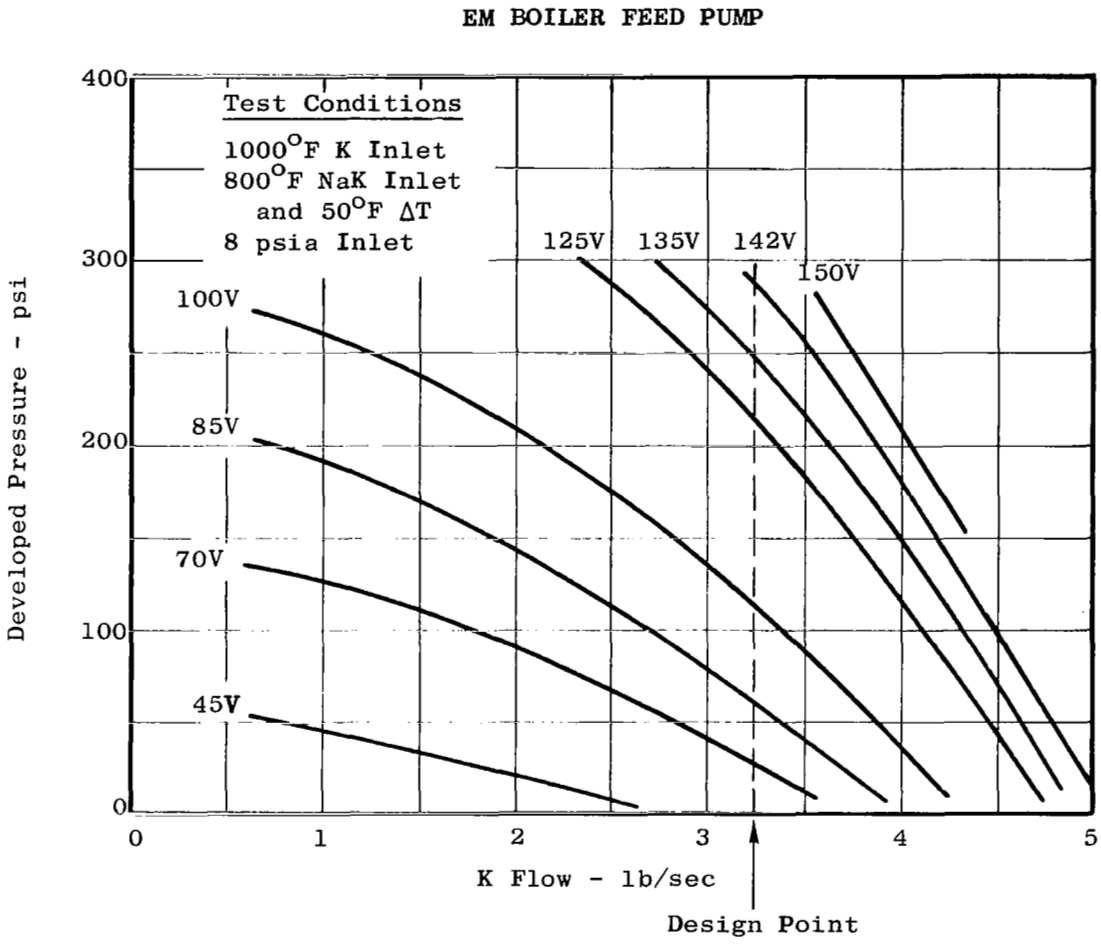

Figure 15. Performance Test Curves for Developed Pressures Over Full Range of Voltages, with 1000°F K, and 800°F NaK.

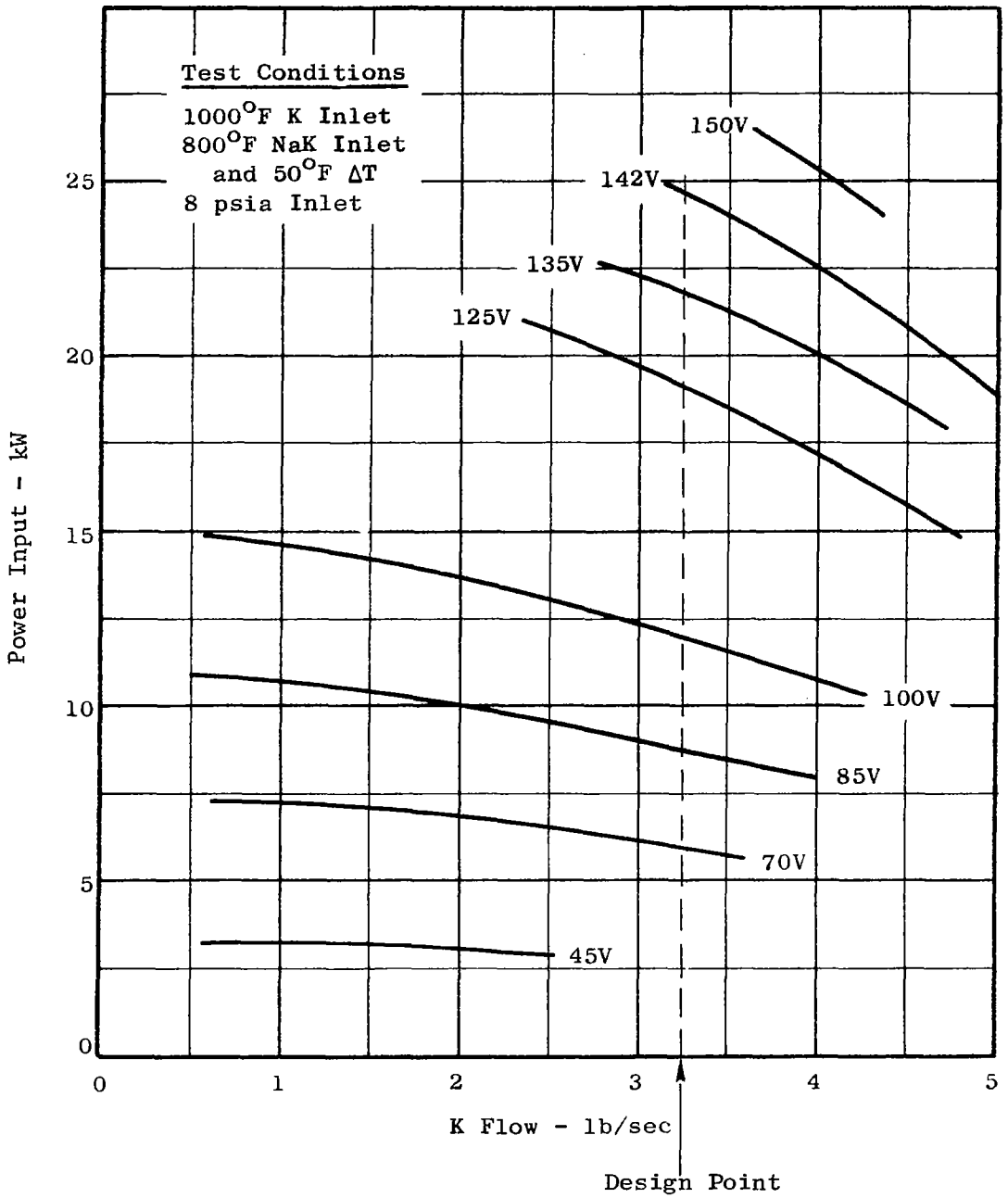

Figure 16. Performance Test Curves for Test Power Input Over Full Range of Voltages with 1000°F K and 800°F NaK.

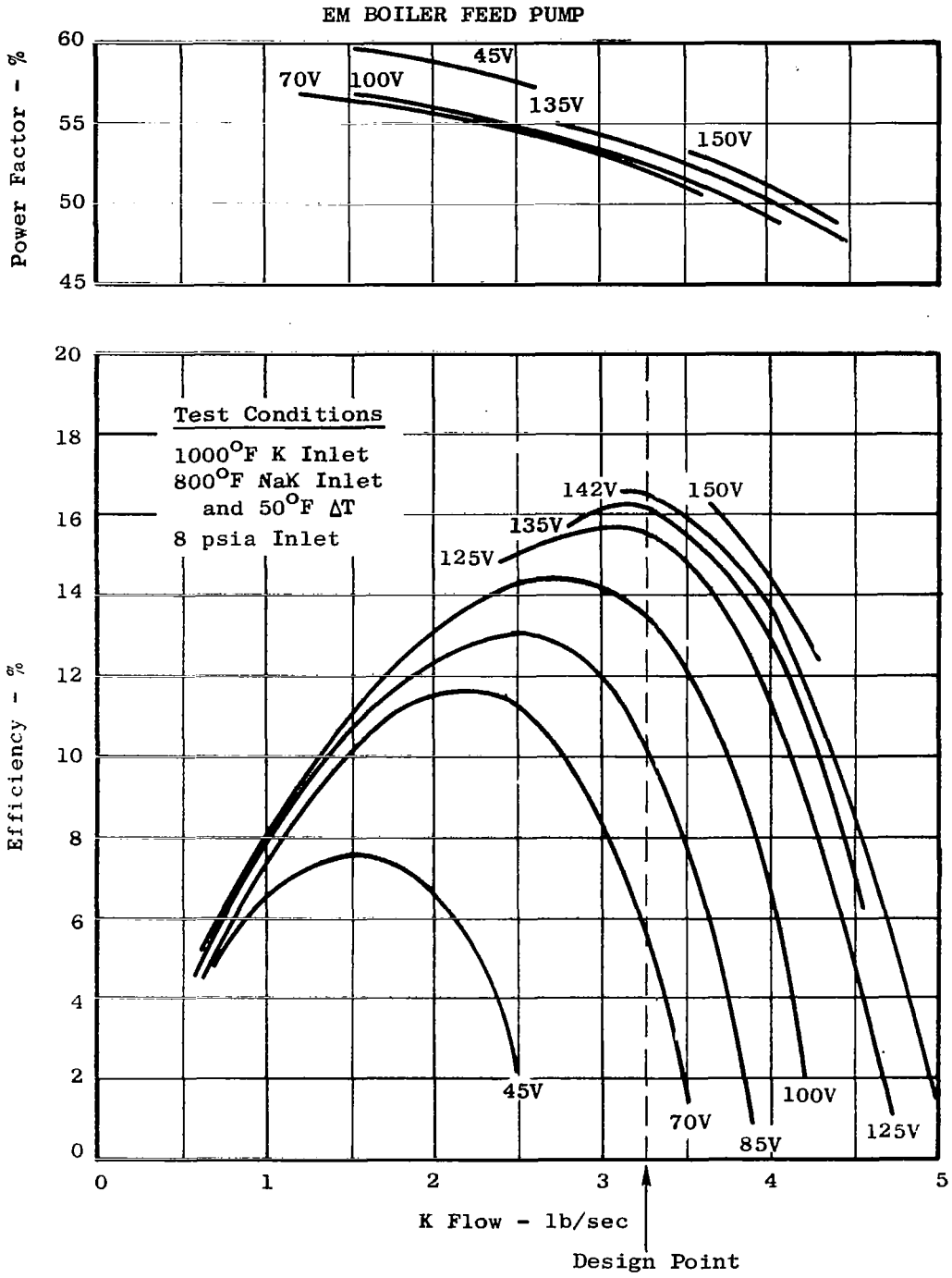

Figure 17. Performance Test Curves for Calculated Efficiency and Power Factor Over Full Range of Voltages with 1000°F K and 800°F NaK.

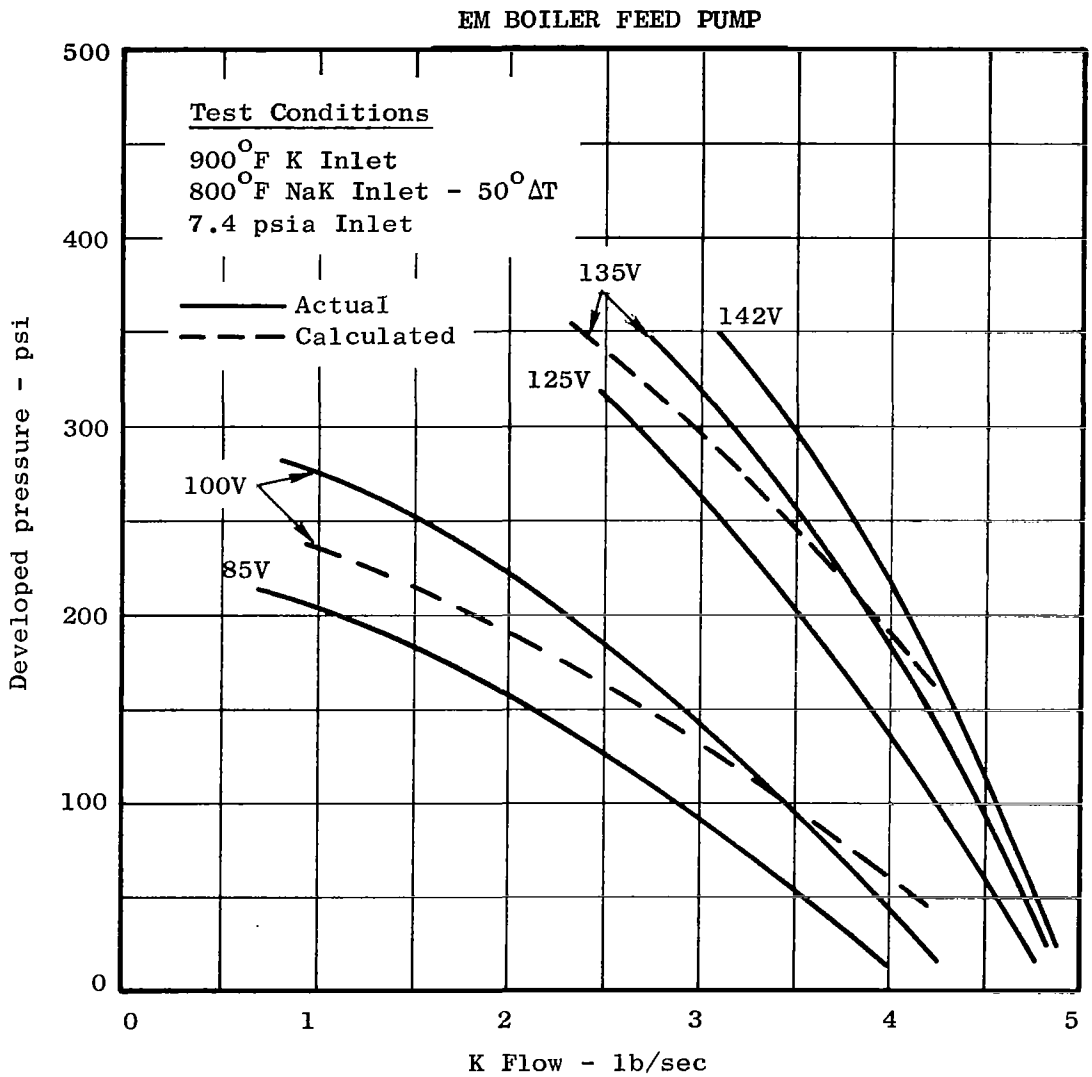

Figure 18. Performance Test Curves for Developed Pressure Over Indicated Range of Voltages, with 900°F K, and 800°F NaK.

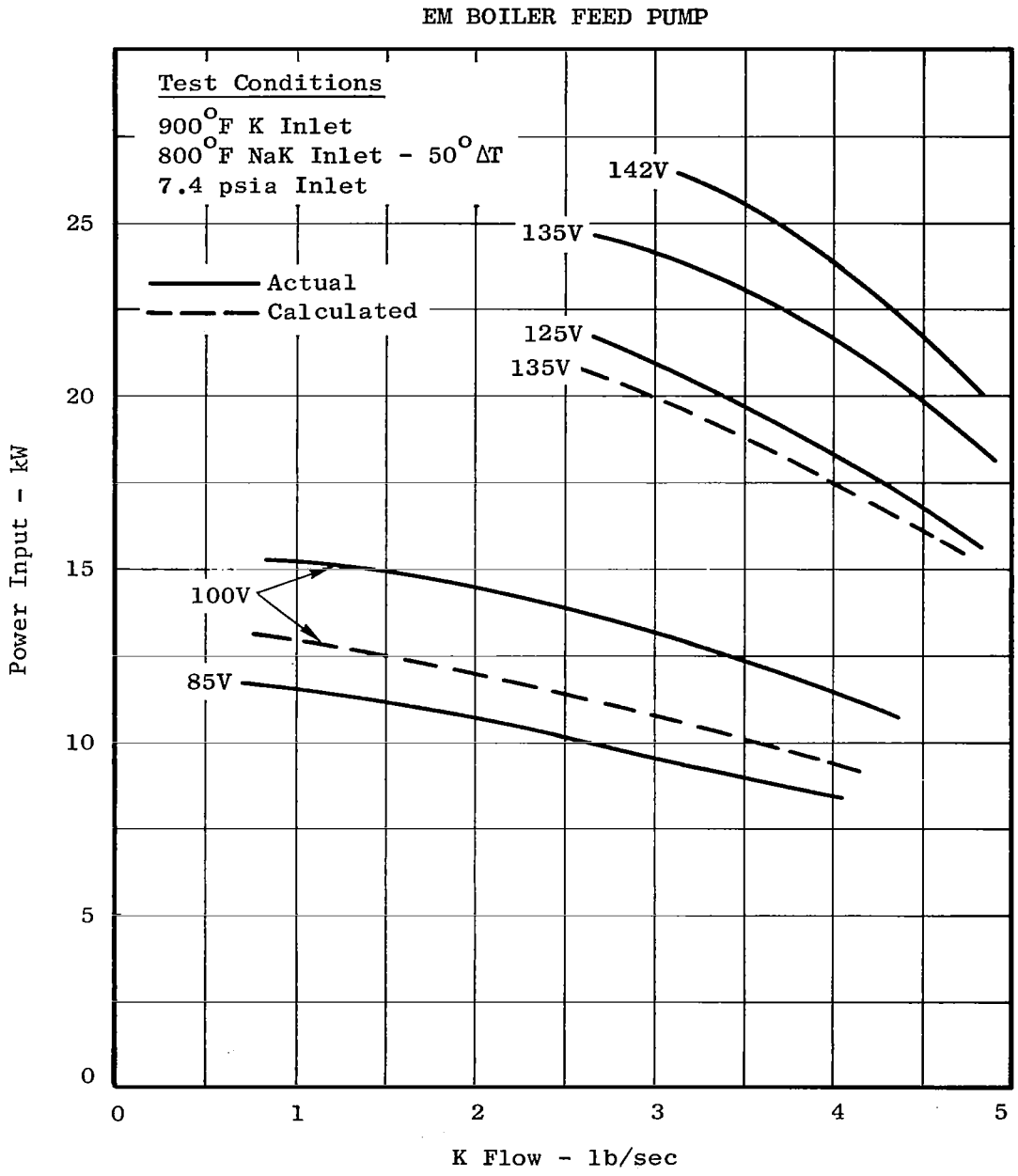

Figure 19. Performance Test Curves for Test Power Input Over Indicated Range of Voltages with 900°F K and 800°F NaK.

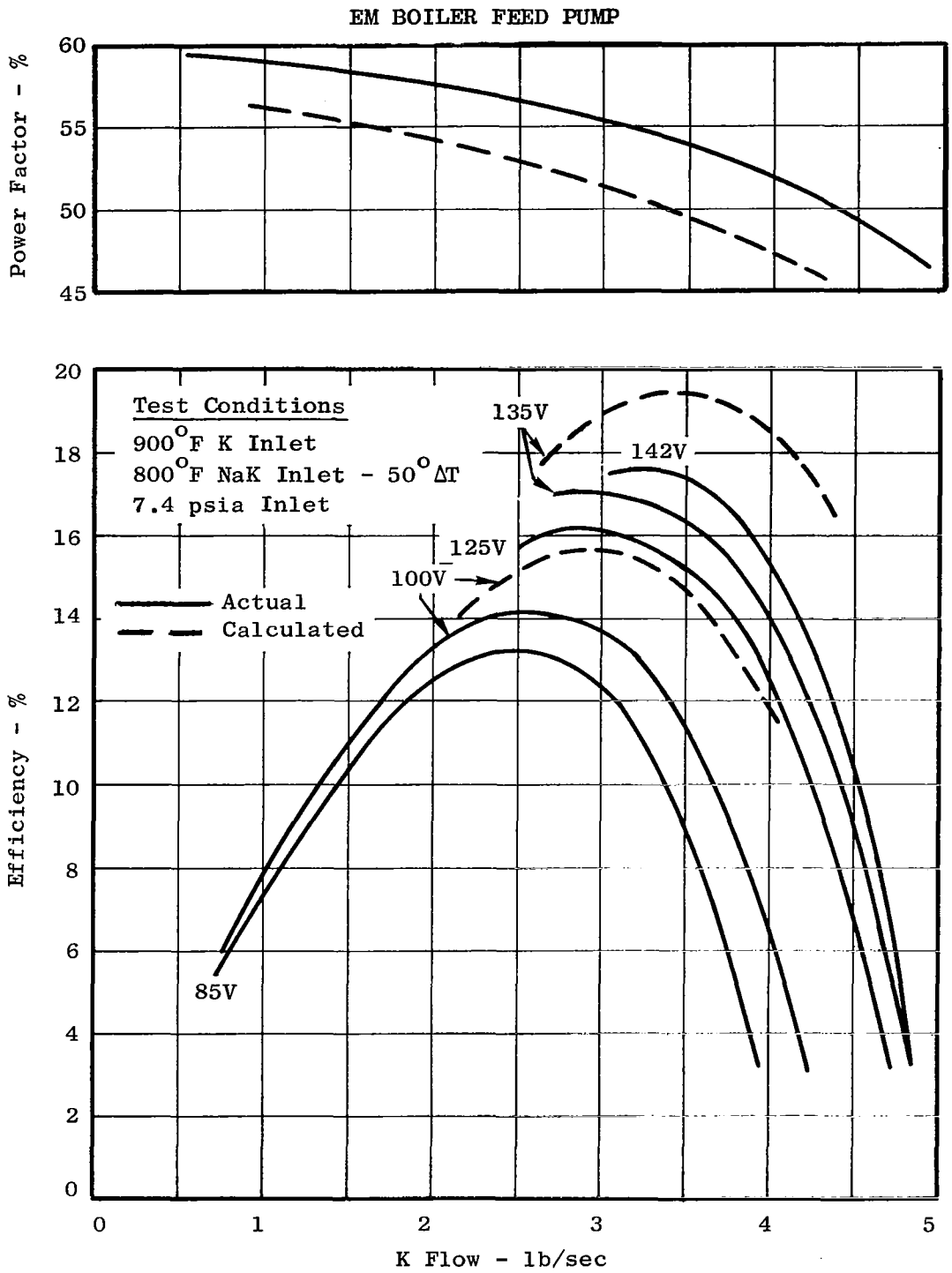

Figure 20. Performance Test Curves for Calculated Efficiency and Power Factor Over Indicated Range of Voltages with 900°F K and 800°F NaK.

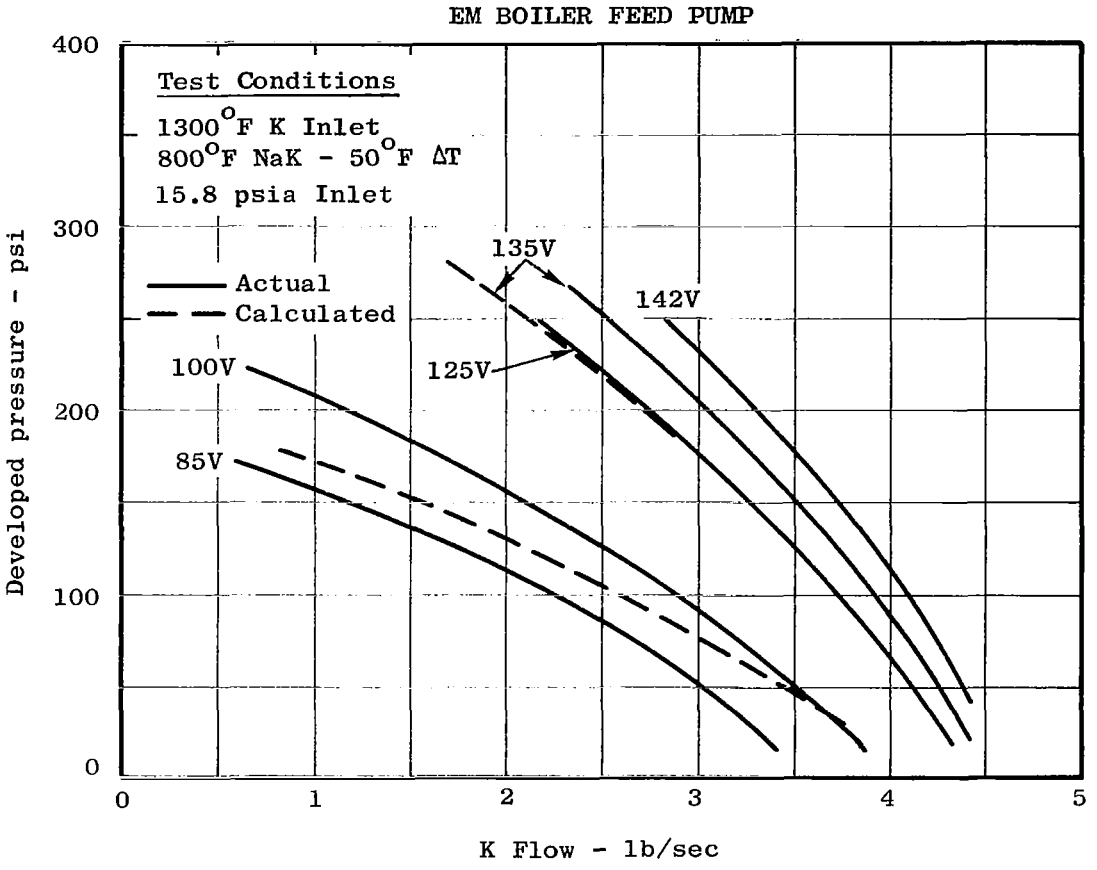

Figure 21. Performance Test Curves for Developed Pressures Over Indicated Range of Voltages, with 1300°F K and 800°F NaK.

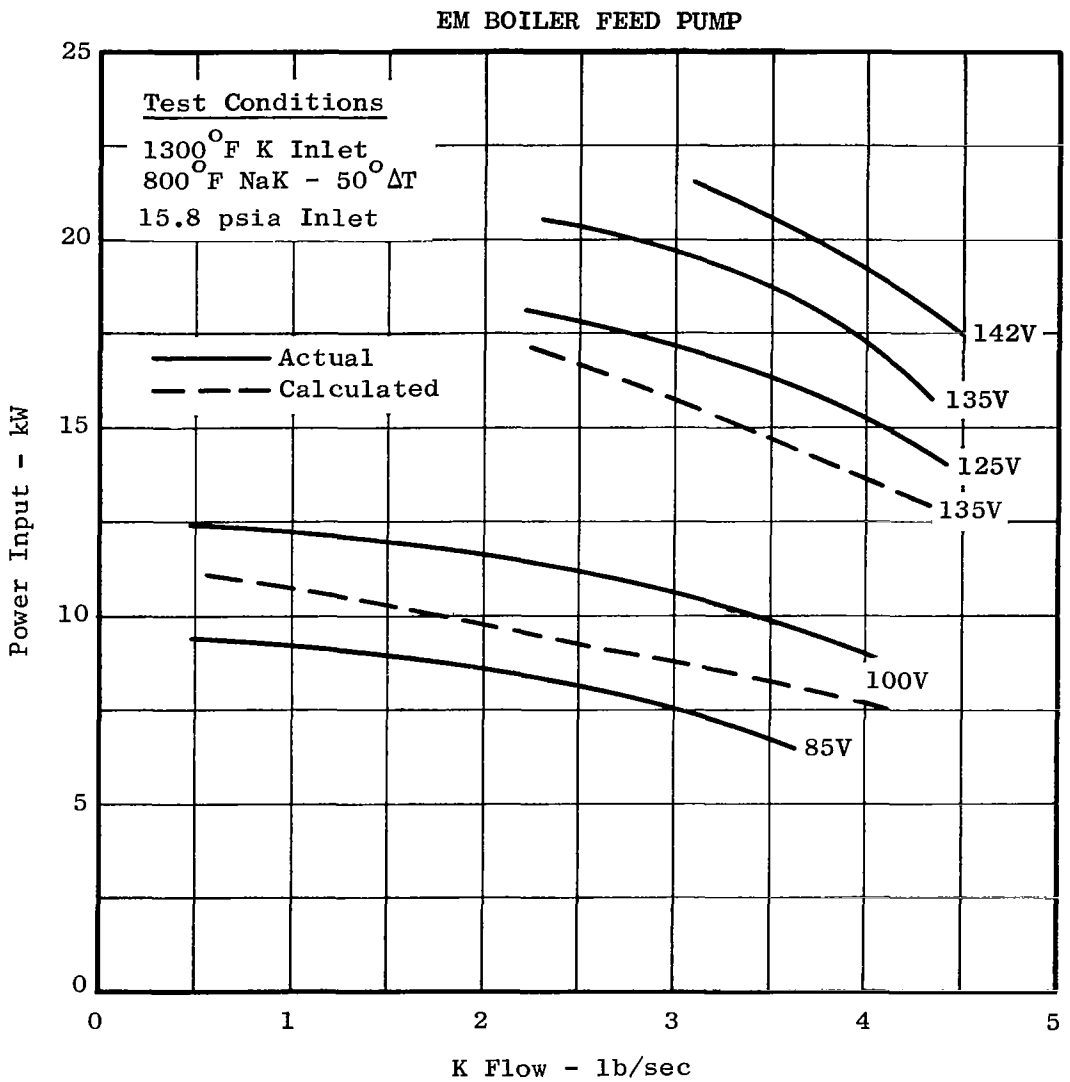

Figure 22. Performance Test Curves for Test Power Input Over Indicated Range of Voltages with 1300°F K and 800°F NaK.

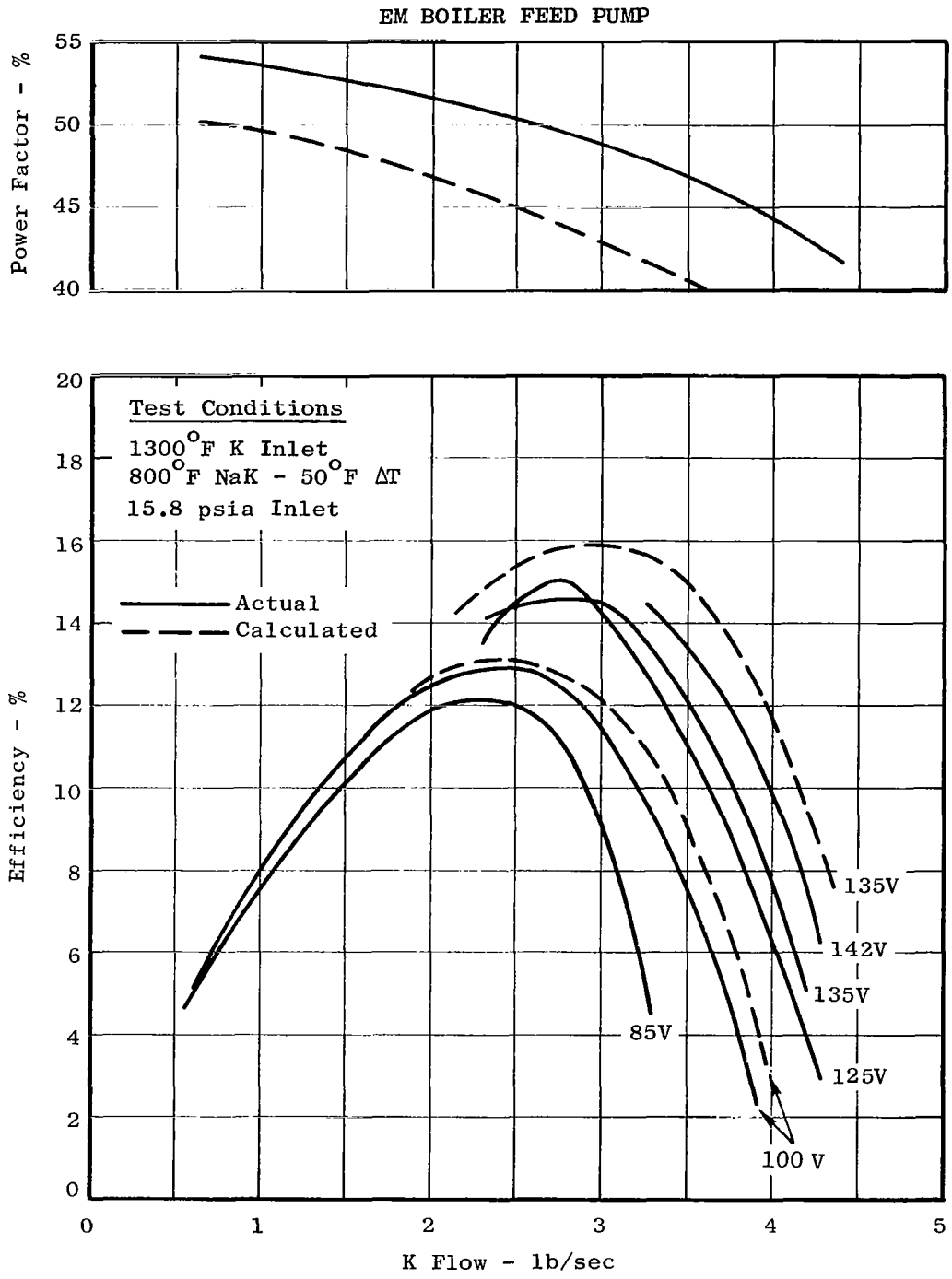

Figure 23. Performance Test Curves for Calculated Efficiency and Power Factor Over Indicated Range of Voltages with 1300°F K and 800°F NaK.

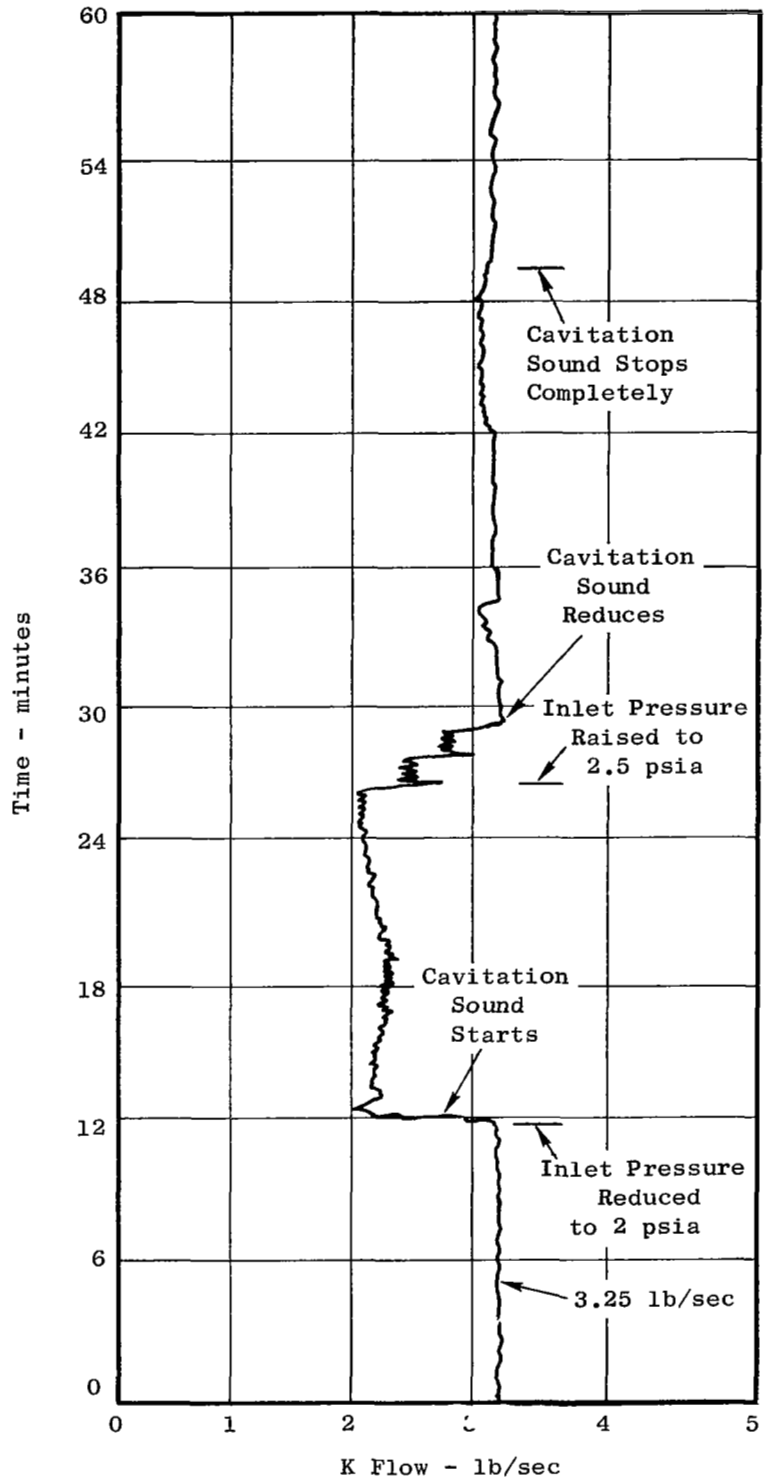

Figure 24. Potassium Flow as Measured on Recording Chart During Cavitation Test Sequence Number P-111 with NaK Flow Constant at 0.58 lb/sec and 800°F Inlet.

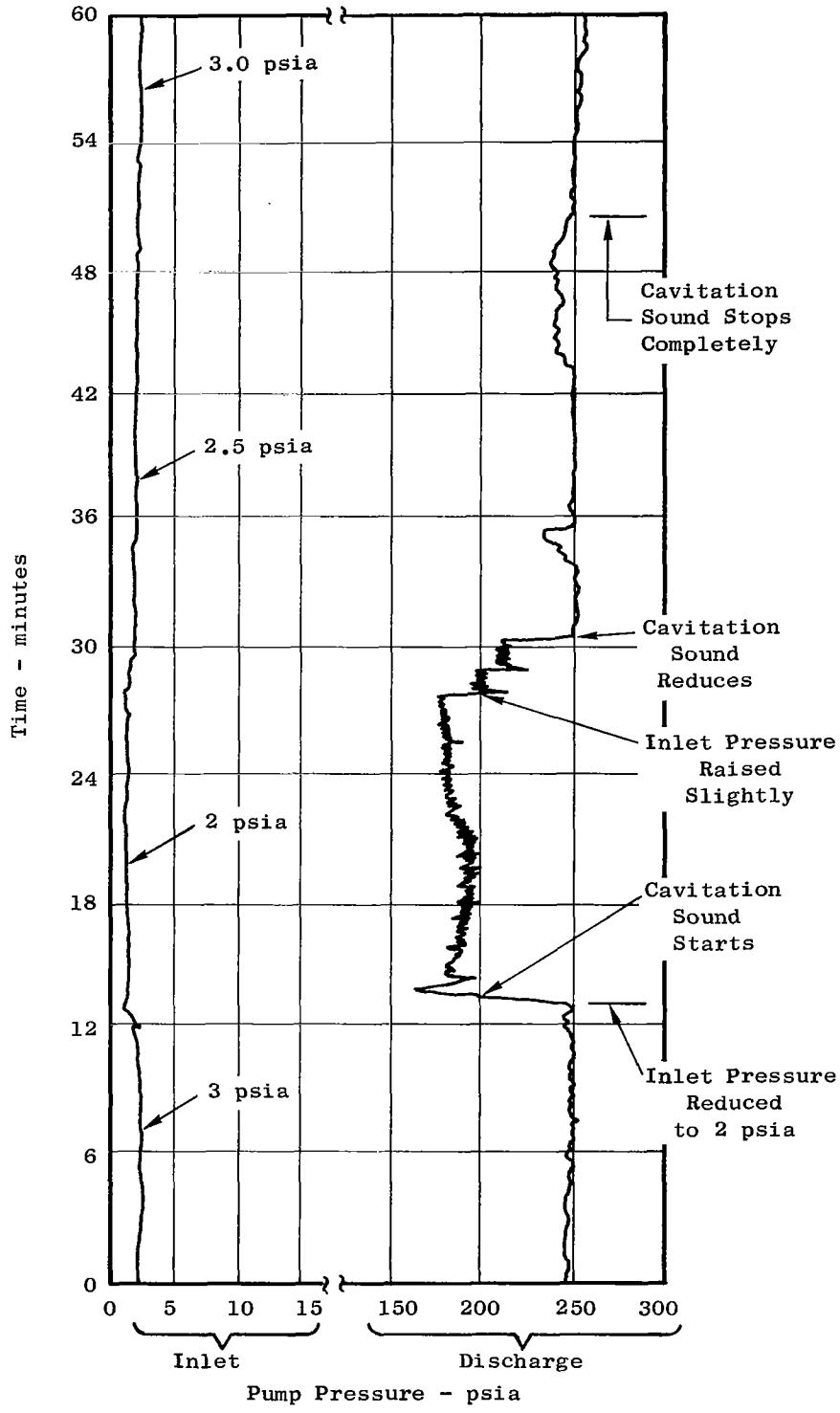

Figure 25. Potassium Inlet and Outlet Pressure as Measured on Recording Chart During Cavitation Test Sequence Number P-111.

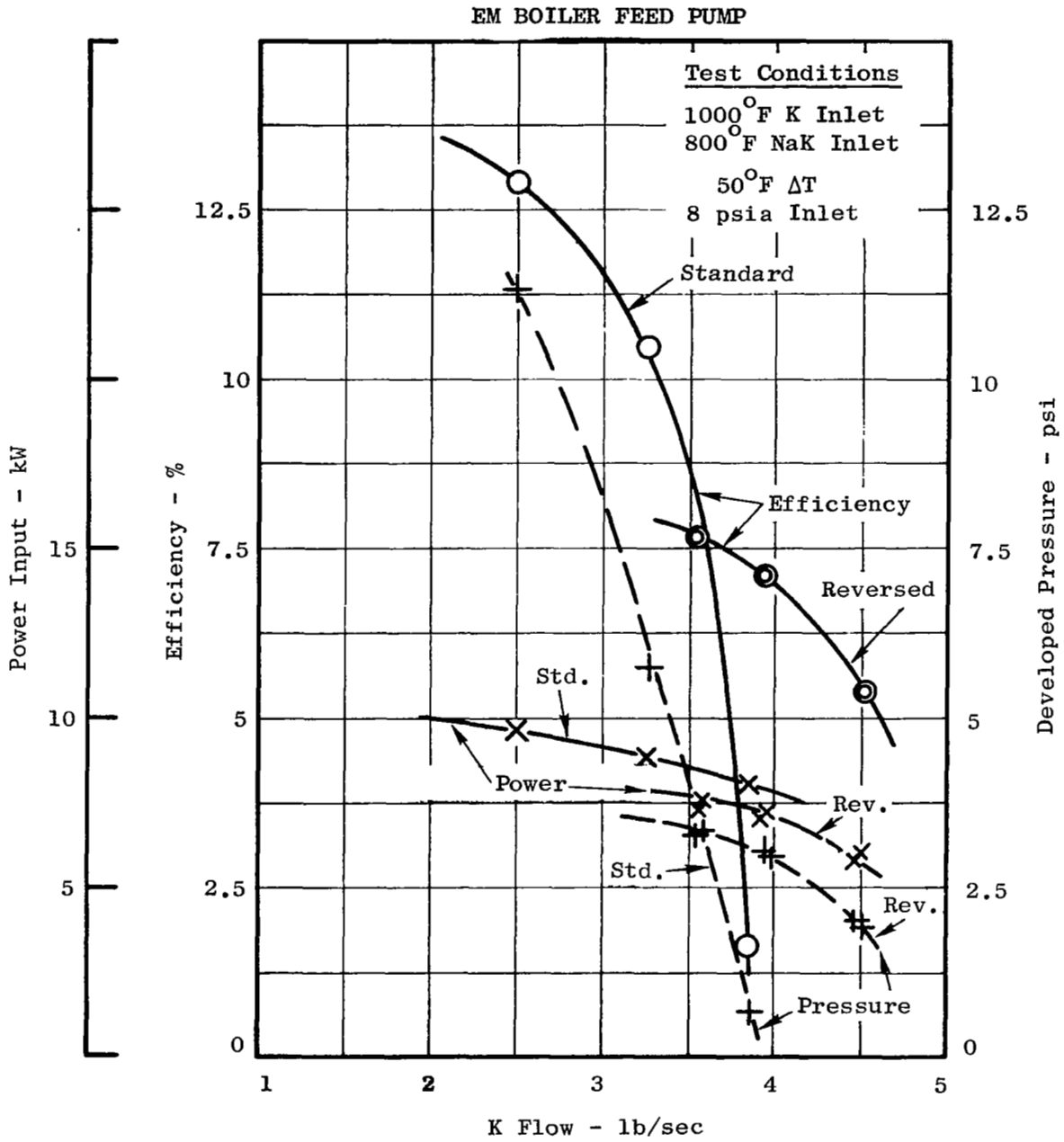

Figure 26. Performance Test Curves for Pressure, Power Input, and Efficiency, with 100 V and 1000°F K, and the Test Pump Operating in the Standard and Reversed Direction.

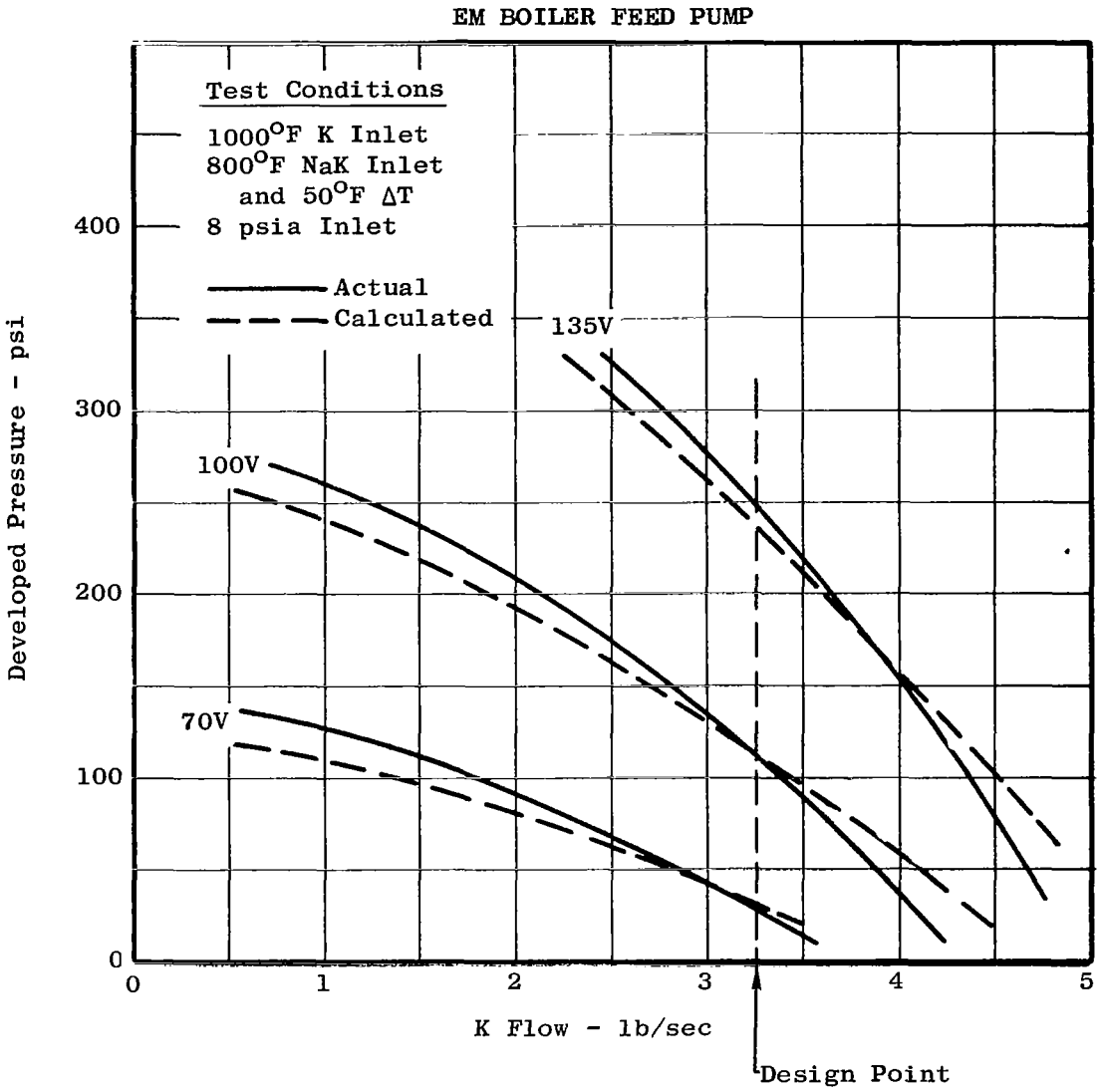

Figure 27. Calculated and Actual Performance Curves for Developed Pressure at Three Voltages with 1000°F Potassium and 800°F NaK Coolant.

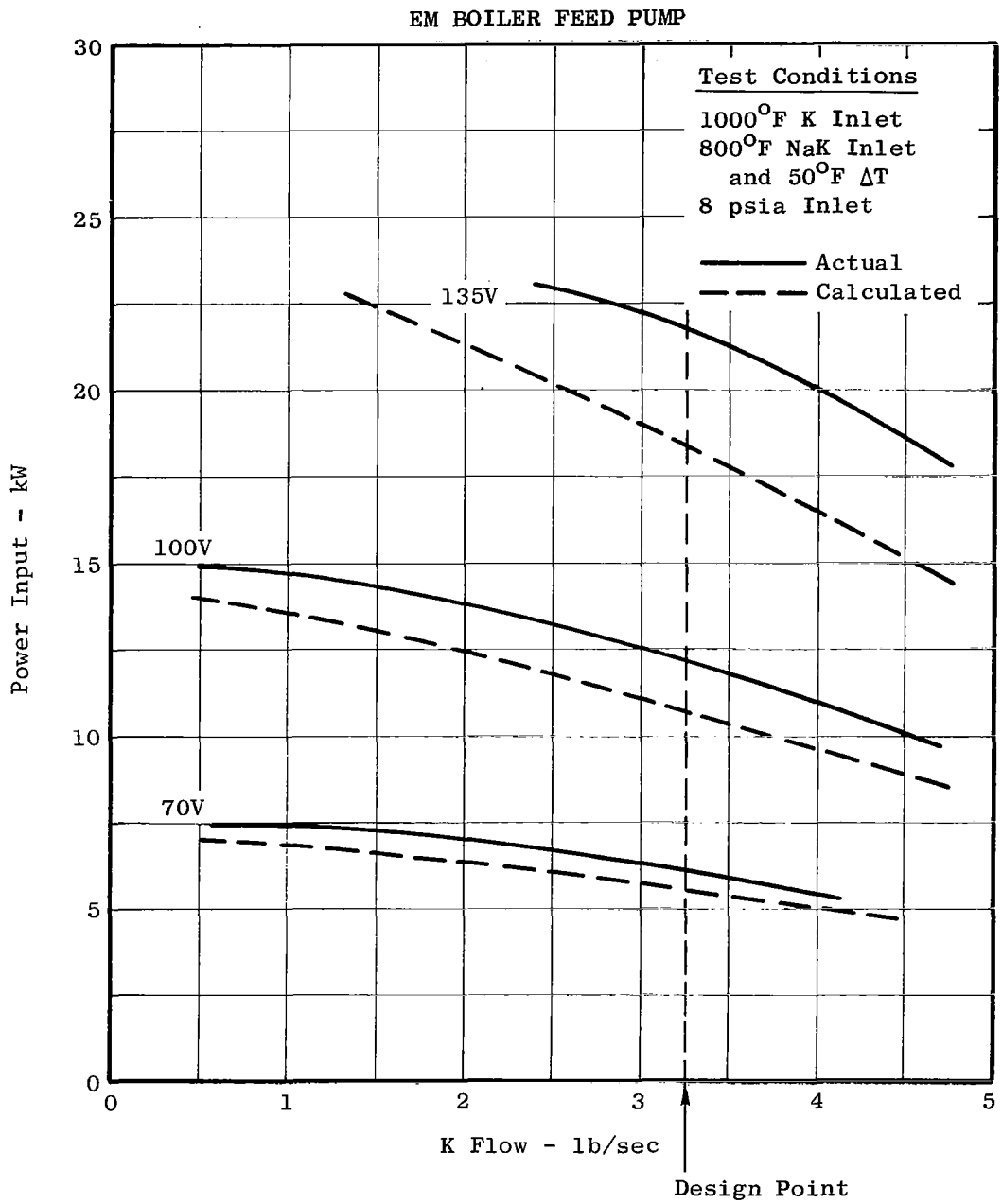

Figure 28. Calculated and Actual Performance Curves for Power Input to Pump at Three Voltages with 1000°F Potassium and 800°F NaK Coolant.

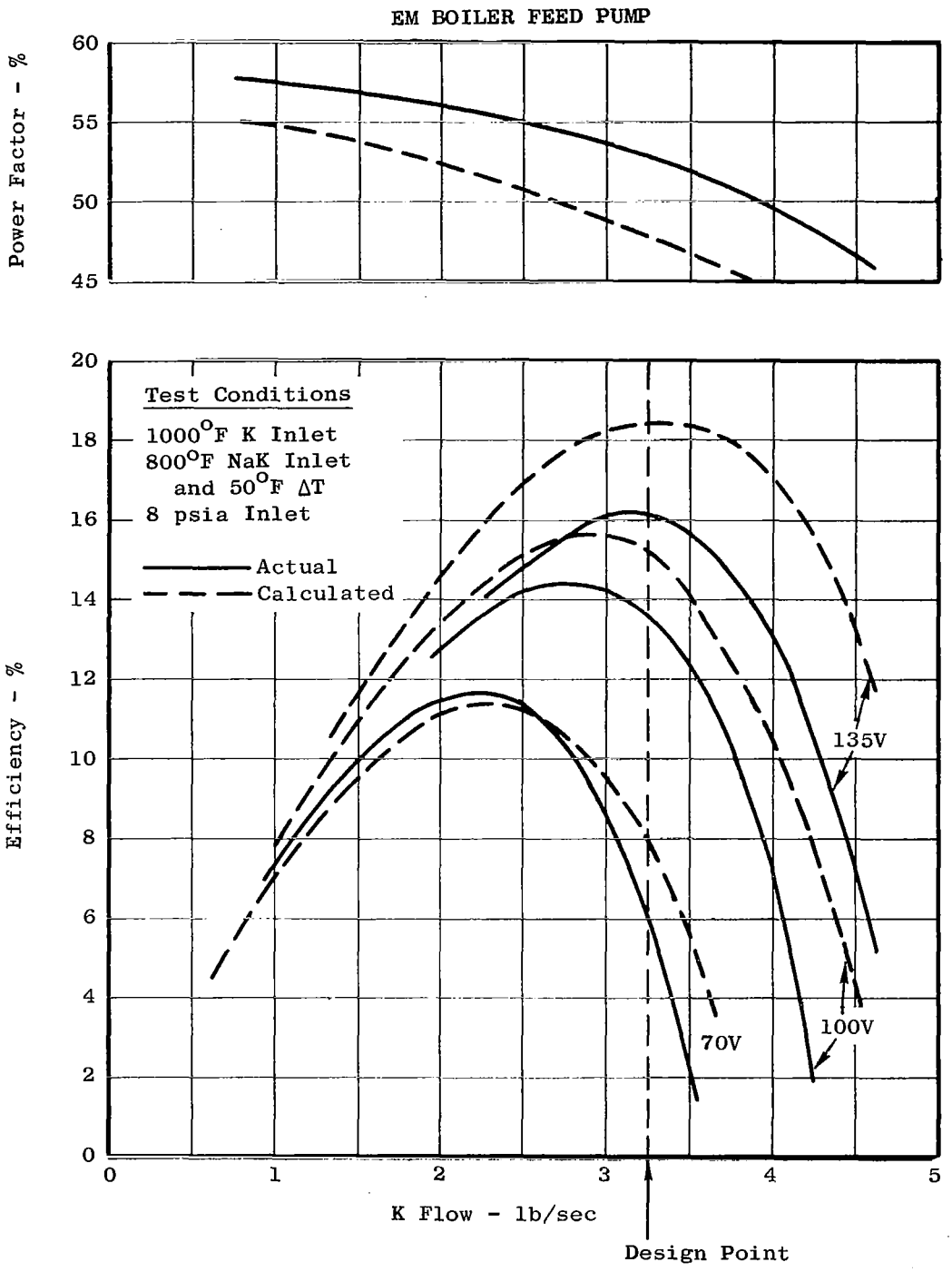

Figure 29. Calculated and Actual Performance Curves for Efficiency and Power Factor of Pump at Three Voltages with 1000°F Potassium and 800°F NaK Coolant.

TABLE 1

ANALYTICAL RESULTS FOR SAMPLES FROM TEST FACILITIES LOOPS

	Potassium				NaK		
	1	2	3	4	5	6	7
Date	7-17-69	7-21-69	7-31-69	8-19-69	7-11-69	7-23-69	8-4-69
	ppm	ppm	ppm	ppm	ppm	ppm	ppm
Oxygen	3,5	4,4,5,6	3,4	3	5,6	13,15	8,9
Carbon	39	56	30	28	32	32	21
Ag	<2	<2	<2	Not Determined	<2	Not Determined	2
Al	<2	10	10		<2		26
B	<20	<30	<30		<20		<20
Ba	<20	<20	<20		<20		<20
Be	<2	<2	<2		<2		<2
Ca	<2	2	2		<2		<2
Cb	<10	<10	<10		<20		<20
Cu	2	2	2		<2		4
Co	<2	<2	<2		<2		<2
Cr	<6	10	2		<6		<6
Fe	<2	2	2		<2		10
Li	<2				<2		<2
Mg	2	2	2		<2		2
Mn	<2	<2	<2		<2		<2
Mo	<6	<2	<2		<6		<6
Ni	<6	<2	<2				<6
Pb	<10	<20	<20		<10		<10
Si	<10	10	20		<10		36
Sn	<6	<10	<10		<6		<6
Sr	<10	<2	<2		<10		<10
Ta	<2		<2		<2		<2
Ti	<2	<10	<10		<2		<2
V	<6	<10	<10		<6		<6
Zr	<6	<10	<10		<6		<6
Na		<50	<50				

TABLE 2

SUMMARY OF DATA FROM PUMP PERFORMANCE TEST PROGRAM

	Test Conditions[1]						Results			
Test No.	Pump Inlet psia	K Inlet °F	NaK Inlet °F	NaK Δ T °F	Nom. Line Volts	K Flow lb/sec	Disch. Press. psia	Power Input kW	Efficiency %	Power Factor %
C1	8.2	1000	600	50	100	4.26	21.0	10.4	2.28	46.6
C1A	6.8					3.70	82.5	11.2	10.89	49.6
C2	7.4					3.14	146.5	12.4	15.33	52.1
C3	7.4					2.46	175.0	12.8	14.05	53.7
C3A	8.8					2.50	175.0	12.8	14.13	53.6
C4	8.0					1.72	235.0	14.0	12.15	55.6
C5	8.3		600		100	0.75	280.0	14.8	5.98	56.5
C6	8.0		650		135	3.3	262.5	22.0	16.13	51.7
C6A	8.0					3.3	258.0	22.0	15.84	52.1
C6B	8.0		650			3.26	258.0	22.0	16.08	52.1
C7	8.2		600			3.15	286.0	22.4	17.01	52.6
C8	8.0					4.20	144.0	19.8	12.56	48.2
C9	8.5				135	2.65	342.0	23.6	16.31	54.2
C10	8.0		600		100	3.20	130.0	12.0	14.16	51.4
P1	8.8		800		135	4.3	110.0	19.2	9.89	48.4
P1A	8.8					4.0	158.0	20.4	12.76	50.5
P1B	8.8					3.74	193.0	20.8	14.42	51.2
P1C	9.0					3.5	227.0	21.2	15.65	52.1
P2	8.8					3.22	245.0	22.0	14.95	52.9
P2A	9.4					3.24	269.0	22.4	16.33	53.3
P3	10.2				135	2.9	290.0	22.4	15.80	54.1
P6	8.0				70	3.26	31.0	5.90	5.54	52.4
P6A	8.0					3.5	15.0	5.74	1.85	51.5
P6B	7.7					3.5	12.5	5.68	1.28	50.9
P7	8.0					2.45	78.5	6.50	11.55	55.2
P8	8.0					2.04	96.5	6.75	11.64	56.2
P9	8.0					1.64	118.5	7.00	11.27	56.1
P9A	8.2					1.7	114.5	7.00	11.25	56.2
P10	8.2				70	0.72	140.0	7.20	5.73	57.6
P11	7.7				85	3.86	15.2	8.00	1.56	50.3
P11A-R[2]	28.0					4.5	48.0	7.20	5.44	46.2
P11B-R[2]	19.2					3.94	49.3	7.20	7.17	46.8
P11C-R[2]	14.0					3.55	50.0	7.20	7.73	46.3
P12	8.0					3.24	74.0	8.80	10.50	52.4
P13	7.8					2.5	121.5	9.60	12.89	55.2
P14	8.0					1.56	175.0	10.4	10.91	57.5
P15	8.0					0.75	208.0	10.9	5.99	58.4
P16	8.0				85	4.2	20.0	10.4	2.11	48.0
P17	8.0				100	3.24	123.0	12.0	13.48	52.3
P18	8.0					2.45	184.0	13.2	14.22	54.7
P19	8.0					1.64	238.0	14.0	11.73	56.5
P20	8.0	1000	800	50	100	0.75	277.0	14.8	5.93	57.8

TABLE 2 (Continued)

Test Conditions[1]							Results			
Test No.	Pump Inlet psia	K Inlet °F	NaK Inlet °F	NaK Δ T °F	Nom. Line Volts	K Flow lb/sec	Disch. Press. psia	Power Input kW	Efficiency %	Power Factor %
P20A	8.0	1000	800	50	100	0.72	274.0	14.4	5.79	57.1
P21	8.2	↑	↑	↑	125	4.2	90.0	16.4	9.07	48.5
P21A	8.0				↑	3.75	160.0	18.1	13.70	51.4
P21B	8.1				↕	4.68	35.0	15.6	1.87	45.3
P21C	8.0					4.7	23.0	15.2	2.02	45.5
P22	8.0				↓	3.25	222.0	19.0	15.92	53.1
P23	8.0				125	2.45	300.0	20.8	14.97	55.6
P26	8.0				142	4.25	140.0	21.6	11.30	49.1
P27	8.0				↑	4.0	188.5	22.6	13.91	50.6
P28	8.0				↕	3.5	262.0	24.0	16.13	52.4
P29	8.0				↓	3.25	290.0	24.5	16.28	53.5
P30	8.0				142	4.95	24.0	19.0	1.81	44.5
P31	8.0				150	4.25	172.0	24.4	12.43	49.4
P32	8.0				↑	4.10	194.0	24.8	13.39	50.2
P33	8.0				↕	4.0	217.0	25.4	14.28	51.0
P33A	8.0			↓	↓	3.87	238.0	25.7	15.07	51.1
P34	8.0			50	150	3.75	265.0	26.2	15.98	51.8
P36	7.5			25	45	2.45	15.0	2.90	2.76	57.5
P37	7.5			↑	↑	2.0	32.0	3.05	6.55	58.9
P38	8.0			↕	↕	1.65	41.0	3.10	7.42	59.6
P39	8.2	↓		↓	↓	1.0	57.0	3.23	6.50	60.7
P40	8.2	1000		25	45	0.75	61.0	3.33	5.19	60.8
P41	7.4	900		50	135	4.25	142.0	20.5	11.89	50.7
P41A	7.4	↑		↑	↑	4.82	37.0	18.4	3.31	47.0
P41B	7.4	↕		↕	↕	3.75	228.0	22.5	15.70	53.4
P42	7.4				↓	3.25	289.0	23.6	16.56	54.9
P43	7.0				135	2.9	340.0	24.2	17.04	54.6
P46	7.5				125	4.24	106.0	17.6	10.11	50.3
P46A	7.4				↑	4.7	35.0	16.0	3.46	47.2
P46B	7.2				↕	3.8	170.0	18.8	14.04	53.0
P47	7.5				↓	3.22	234.0	19.8	15.76	54.4
P47A	7.2				125	2.9	284.0	21.2	16.17	56.2
P49	7.5				100	4.22	28.0	11.1	3.31	50.5
P50	7.1				↑	3.20	131.0	12.8	13.20	54.5
P51	7.1				↕	2.40	197.0	13.8	14.13	56.6
P52	6.8				↓	1.70	250.0	14.8	11.96	57.8
P53	7.5				100	0.85	287.0	15.2	6.67	57.7
P54	7.4				85	3.25	81.0	9.2	11.10	54.1
P54A	7.4				↑	3.9	26.5	8.5	3.74	51.8
P55	7.4				↕	2.45	135.5	10.1	13.27	56.6
P56	7.4				↓	1.6	184.0	11.0	10.97	58.8
P57	7.4				85	0.72	219.0	19.4	5.62	59.7
P58	7.3				142	4.25	174.0	23.0	13.17	51.1
P58A	7.4				↑	4.83	39.5	20.0	3.31	46.1
P59	7.4	↓	↓	↓	↕	4.0	220.0	23.8	15.26	52.1
P60	7.4	900	800	50	142	3.57	297.0	25.4	17.39	54.1

TABLE 2 (Continued)

Test No.	Test Conditions(1) Pump Inlet psia	K Inlet °F	NaK Inlet °F	NaK Δ T °F	Nom. Line Volts	K Flow lb/sec	Results Disch. Press. psia	Power Input kW	Efficiency %	Power Factor %
P60A	7.3	900	800	50	142	3.15	348.0	26.4	17.37	55.5
P60.5A	15.8	1100	↑	↑	135	3.2	250.0	22.4	14.87	54.6
P60.5B	15.8	1200			↑	3.2	219.0	20.2	14.55	50.1
P61	15.7	1300				4.2	66.0	16.4	5.93	42.5
P61A	15.6	↑				3.74	110.0	18.0	9.07	45.9
P62	15.8					3.25	195.0	19.2	14.00	48.4
P63	15.8					2.98	223.0	19.6	14.59	49.2
P64	15.4				↓	2.45	274.0	20.4	14.36	50.7
P64A	15.2				135	2.66	250.0	20.0	14.30	50.1
P66	15.0				125	4.30	37.0	14.4	2.96	43.4
P66A	15.7				↑	3.75	110.0	15.4	10.60	46.0
P67	15.0					3.2	162.0	16.4	13.23	48.5
P67A	15.8				↓	2.8	218.0	17.3	15.13	50.1
P68	15.5				125	2.45	239.0	17.8	14.21	51.1
P69	15.8				100	3.82	33.0	9.40	3.22	44.8
P70	15.8				↑	3.2	85.0	10.2	10.02	47.6
P71	15.8					2.45	144.0	11.2	12.95	50.7
P72	15.8				↓	1.65	197.0	12.0	11.50	52.3
P73	15.7				100	0.76	229.0	12.4	6.03	53.1
P74	15.7				85	3.16	50.5	7.48	6.79	47.9
P75	15.6					2.45	103.0	8.20	12.06	50.3
P75A	15.8				↑	2.20	117.5	8.40	12.24	51.5
P76	15.0					1.65	140.0	9.30	10.08	56.4
P76A	15.5				↓	1.65	145.0	8.90	11.09	53.1
P77	15.4				85	0.75	180.0	9.40	6.06	54.7
P78	16.0				142	4.25	78.8	18.4	6.69	44.0
P79	16.0	↓			↕	3.95	126.0	19.4	10.35	45.5
P80	15.9	1300			142	3.49	188.0	20.6	13.46	47.8
P81	22.2	1400			135	4.25	56.0	16.0	4.23	42.6
P81A	22.2	↑			↑	3.75	127.5	17.4	10.71	45.0
P82	22.2					3.2	185.0	18.4	13.32	46.9
P83	22.0				↓	3.0	212.0	19.2	14.01	48.3
P84	22.0				135	2.55	252.0	20.0	13.80	49.9
P86	22.2				125	4.2	43.0	14.0	2.93	42.2
P86A	22.2				↑	3.78	93.0	14.4	8.75	43.9
P87	22.2					3.2	154.0	15.6	12.73	46.5
P87A	22.3				↓	2.85	190.0	16.4	13.72	48.4
P88	22.2				125	2.5	220.0	16.8	13.87	49.4
P89	22.2				100	3.76	41.5	9.24	3.70	44.1
P90	22.2				↑	3.25	80.5	9.72	9.18	46.0
P91	22.2					2.45	140.0	10.9	12.39	49.4
P92	22.2				↓	1.65	190.0	11.6	11.24	51.4
P93	22.2				100	0.93	226.0	12.2	7.48	53.0
P94	22.5				85	3.2	54.0	7.10	6.69	46.1
P94A	22.2	↓	↓	↓	↕	2.87	74.5	7.42	9.53	47.4
P95	22.5	1400	800	50	85	2.45	100.0	7.70	11.61	49.4

TABLE 2 (Continued)

Test No.	Test Conditions[1] Pump Inlet psia	K Inlet °F	NaK Inlet °F	NaK Δ T °F	Nom. Line Volts	K Flow lb/sec	Results Disch. Press. psia	Power Input kW	Efficiency %	Power Factor %
P96	22.5	1400	800	50	85	1.70	133.0	8.30	10.66	51.3
P97	22.5				85	0.75	174.0	9.00	5.94	53.6
P98	23.0				142	4.25	78.0	18.0	6.12	42.5
P98A	22.0					4.45	66.0	17.4	5.13	41.6
P99	23.0					4.0	108.0	18.8	8.52	44.1
P99A	22.0					3.67	146.0	19.2	11.16	45.9
P100	22.2	1400		50	142	3.5	174.0	20.0	12.50	46.5
P101	8.0	1000		100	135	4.25	124.0	19.8	11.62	49.3
P101A	8.0					4.8	33.6	18.0	2.97	46.6
P102	8.0					3.25	259.0	22.4	15.85	53.5
P102B	8.0					3.73	196.0	21.2	14.40	51.7
P103	8.0		800	100		2.9	299.0	23.2	15.83	54.9
P106	8.0		900	50		4.25	124.0	20.0	10.73	50.1
P106A	8.0					3.75	192.0	21.4	14.02	52.0
P106B	8.0					4.7	52.0	18.2	4.95	47.3
P106C	8.0					4.85	32.0	18.0	2.81	46.9
P107	8.0		900		135	3.3	261.0	22.6	16.08	54.1
P111-0	15.4		800		130	3.24	255.0	20.8	16.25	53.7
P111-1	10.0					3.20	250.0	20.8	16.08	53.7
P111-2	5.0					3.2	248.0	21.2	15.97	54.1
P111-3	4.0					3.17	244.0	20.8	15.92	54.1
P111-4	3.0					3.20	242.0	20.9	15.95	53.3
P111-5	2.0				130	2.5	192.0	19.2	10.77	49.2
P111A	1.8				100	1.28	203.0	13.6	8.24	55.7
P112	15.2				132	4.2	122.0	18.6	10.48	49.1
P112-1	10.5					4.2	124.0	18.8	11.04	49.0
P112-2	5.5					4.2	115.0	18.6	10.69	49.0
P112-3	5.0					4.0	84.0	17.5	7.85	47.4
P112-4	9.0					4.38	92.5	18.2	8.74	48.3
P112-5	10.25	1000			132	4.38	93.5	18.2	8.72	48.2
P113	15.0	1300			135	4.25	70.0	17.0	6.35	44.5
P113-1	12.0					4.25	68.0	16.9	6.51	44.3
P113-2	10.0					4.2	66.0	16.8	6.42	43.9
P113-3	9.2	1300	800	50	135	2.5	29.7	14.8	1.64	38.9

(1) Temperatures within 10°F of value shown. Voltage maintained within 1V of value listed.

(2) Flow reversed in pump to check performance.

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