74286

NASA TECHNICAL MEMORANDUM

NASA TM X-1765

NASA TM X-1765

AMPTIAC

PERFORMANCE AND EVALUATION OF TWO LIQUID-METAL PUMPS FOR SODIUM-POTASSIUM SERVICE

by Sol H. Gorland, Thomas P. Hecker, and Roy A. Lottig

Lewis Research Center
Cleveland, Ohio

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • APRIL 1969

NASA TM X-1765

PERFORMANCE AND EVALUATION OF TWO LIQUID-METAL PUMPS FOR SODIUM-POTASSIUM SERVICE

By Sol H. Gorland, Thomas P. Hecker, and Roy A. Lottig

Lewis Research Center
Cleveland, Ohio

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

For sale by the Clearinghouse for Federal Scientific and Technical Information
Springfield, Virginia 22151 – CFSTI price ~~$3.00~~

ABSTRACT

Two identical hermetically-sealed motor-driven centrifugal pumps operated for 1483 hours in NaK loops, one at 1150° F (895 K) and the other at 450° F (505 K). The pumps incorporate NaK-lubricated tilting-pad journal and thrust bearings, and were designed to withstand a nuclear radiation environment. The induction motors were "canned" inside the pump housings to eliminate the need for absolute seals between the pump and the motor. Both pumps operated successfully for the 1483 hours without maintenance. There were no parametric excursions outside the envelopes considered safe for 10 000 or more hours of operation.

PERFORMANCE AND EVALUATION OF TWO LIQUID-METAL PUMPS FOR SODIUM-POTASSIUM SERVICE

by Sol H. Gorland, Thomas P. Hecker, and Roy A. Lottig

Lewis Research Center

SUMMARY

Two identical hermetically-sealed motor-driven centrifugal pumps operated for 1483 hours in NaK loops, one at 1150° F (895 K) and the other at 450° F (505 K). The pumps incorporate NaK-lubricated tilting-pad journal and thrust bearings and were designed to withstand a nuclear radiation environment. The induction motors were "canned" inside the pump housings to eliminate the need for absolute seals between the pump and the motor. Both pumps operated successfully for the 1483 hours without maintenance. There were no parametric excursions outside the envelopes considered safe for 10 000 or more hours of operation.

INTRODUCTION

Centrifugal pumps for liquid metals are required by Rankine-cycle space power systems in which zero external leakage, reliability, and component endurance are of primary interest. Other important design requirements are minimum size and weight as well as high efficiency. In the development stage of a complex system, such as the SNAP-8 power conversion system, several copies of a given component are evaluated in order to ensure reproducibility of performance and to aid in the analysis of the results. The subjects of this report are two identical hermetically-sealed motor-driven centrifugal pumps operated with NaK for 1483 hours, one at 1150° F (895 K) and the other at 450° F (505 K). These pumps were tested at Lewis Research Center from September through November of 1967. Evaluations of other pumps are reported in reference 1. Some of the main elements considered in the original design concept such as bearings, hydraulics, materials, and motors are discussed in reference 2. These elements were used in earlier liquid-metal pump designs (e.g., refs. 3 and 4).

The NaK pumps tested incorporated NaK-lubricated journal and thrust bearings and

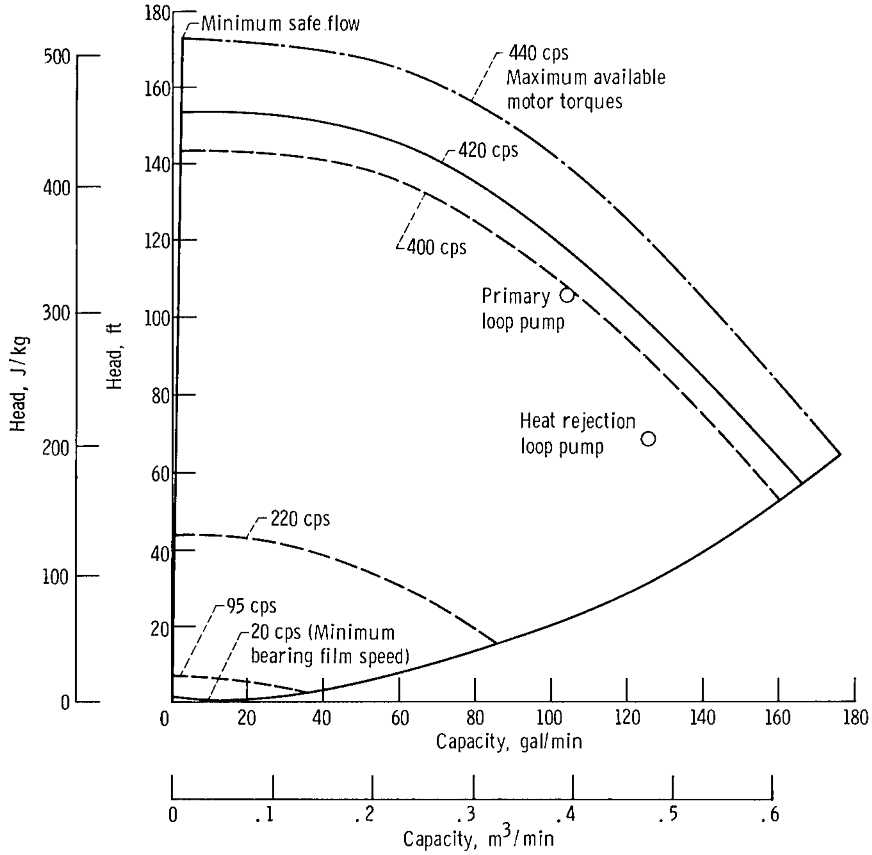

Figure 1. - Operational envelope (Head as function of capacity) for NaK pump. (From ref. 1.)

were designed to withstand a nuclear radiation environment. The pumps were enclosed or "canned" inside the pump housings to eliminate the need for a seal between the pump and motor. Induction motors eliminated the need for motor brushes.

The purpose of this investigation was to determine experimentally if the pumps would perform satisfactorily in a SNAP-8 system without maintenance. The operating envelope for minimum requirements are shown in figure 1.

TEST FACILITY

The test facility in which the pumps were operated was designed for performance testing of a simulated SNAP-8 system. SNAP-8 is a 35-kilowatt nuclear-electric space power system operating on a Rankine cycle. As shown by figure 2, a four-loop system was used in the test, two NaK loops, one mercury loop, and an oil loop. The four-loop simulated SNAP-8 system is described in reference 5.

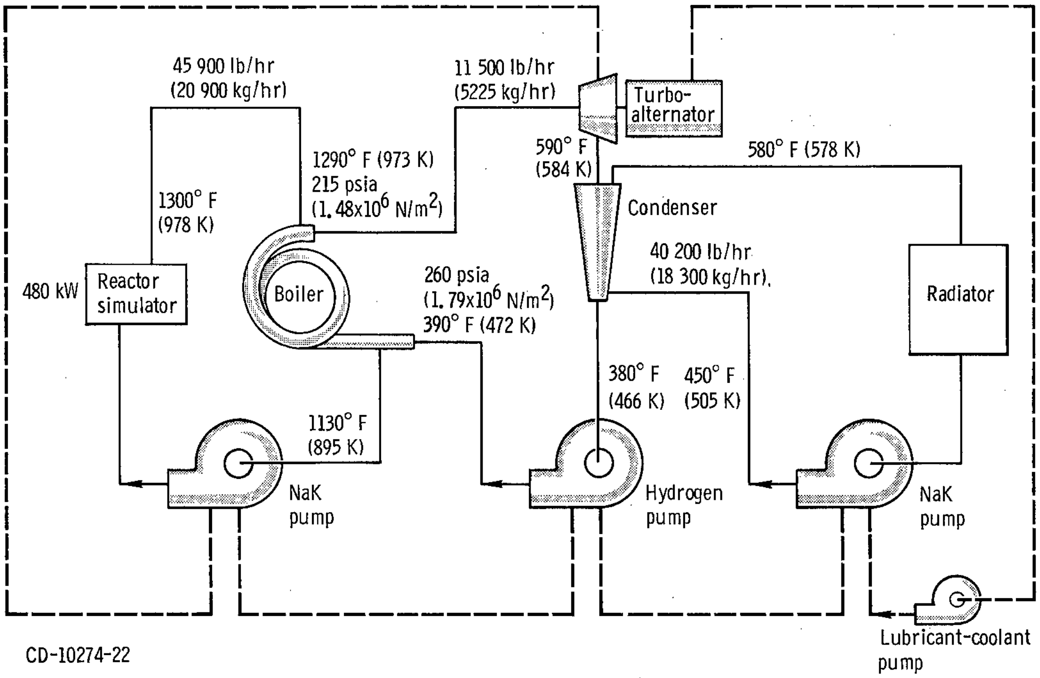

Figure 2. - Four-loop SNAP-8 system.

In the primary loop, an electric heater (simulating the reactor) is used as the heat source for the eutectic sodium-potassium (NaK) alloy. The NaK pump is driven by a NaK-cooled motor, and the bearings are lubricated by NaK. The primary loop is coupled to the mercury loop by a tube-in-tube boiler, described in reference 6. Vaporized mercury from the boiler expands through the turboalternator producing the system electrical output. After passing through the condenser, the mercury is recirculated by a pump. The mercury pump is cooled and lubricated by the oil loop. A NaK heat rejection loop removed heat from the condenser and rejected it in an air-cooled heat exchanger in lieu of a space radiator. The NaK is circulated by a pump identical to the one used in the primary loop. The oil loop removes heat from the three pump motors and alternator as well as lubricates the mercury pump and turboalternator bearings. The most significant system parameters are shown in figure 2.

The pumps were powered by two different sources, facility power and alternator power. They were started on facility power at 60 hertz and at reduced voltage in order to provide high starting torques. Then they were transferred to a 200-2000 hertz variable-frequency motor-generator set. The motor-generator set had been previously set for approximately 400 hertz ±5 percent. When the system reached steady state at the design operating condition, the pumps were switched to the SNAP-8 turboalternator. The turboalternator speed was controlled and output frequency maintained at 400 hertz ±1 percent.

To ensure good pump performance, care must be exercised in the filling of the NaK loop. Precautions must be taken to remove any entrapped gas in the NaK lubricant-coolant recirculation loop, or its flow may be affected. The entrapped gas is removed from the motor housing and pump by starting and stopping the pump several times.

Another potential problem is oxide buildup. If the NaK is not kept free of oxides and the pump is idle for long periods of time, NaK oxide may collect in the bearings and prevent pump rotation. During a hot flush to remove NaK oxides from the system piping, the NaK pump was isolated from the rest of the system by additional valving in order to prevent oxide contamination of the pump. Filters were also installed in the inlet lines of the NaK pumps. The pumps were packed in vermiculite to reduce thermal loss.

INSTRUMENTATION

Instrumentation necessary to evaluate pump performance consisted of flowmeters; pressure transducers; thermocouples; power, current, and voltage transducers; and electromagnetic speed pickups. Flow measurement in the primary NaK loop was made by an electromagnetic (EM) flowmeter, while in the heat rejection loop an EM flowmeter and a calibrated venturi were used. Agreement between the venturi and the EM flowmeter was within 2 percent. Turbine flowmeters (±1 percent accuracy) were used to measure flow in the oil loop. Temperatures were measured at the flowmeter inlet so that the mass flow rate could be calculated more accurately.

A 20-pound-per-square-inch (1.4×10^5-N/m^2) (1-percent full-scale accuracy) differential-pressure transducer was used to measure the pressure drop from inlet to throat of the venturi. Absolute-pressure transducers (1/2-percent full-scale accuracy) were located at the inlet and outlet of each pump. The inlet transducers had a range of 0 to 50 pounds per square inch absolute (0 to 3.4×10^5 N/m^2) and the outlet transducers had a range of 0 to 100 pounds per square inch absolute (0 to 6.9×10^5 N/m^2). All pressure transducers were of the diaphragm type utilizing NaK filled capillary tubes.

Chromel-alumel type K thermocouples were used at the inlet and outlet of the NaK pumps, the EM flowmeter, and the venturi locations. Hermetically-sealed ceramic insulated electrical and chromel-alumel thermocouple terminals were provided on the motors. Iron-constantan type J thermocouples were used on the NaK pump recirculating systems and the oil loop.

Power, current, and voltage were measured using ac single-phase transducers. The power transducers had an accuracy of ±1 percent in the frequency range of 50 to 500 hertz and at a power factor in the range 0.7 to 1.0. The current and voltage transducers had an accuracy of ±0.5 percent. Pump speeds were measured using electromagnetic speed pickups.

All acquired data used in performance calculations were recorded on magnetic tape with an automatic high-speed digital recording system.

CALIBRATION PROCEDURE

The pressure transducers were calibrated before and after installation in the system and after the test completion. Preinstallation calibrations were made at room temperature and at the estimated operating temperature. The change in output due to temperature was less than 0.4 percent of maximum transducer output. Differential pressure transducers were calibrated by applying pressure to the high-pressure side with the low-pressure side maintained at ambient pressure. Calibration after installation was done in the same manner as the bench calibration but at ambient temperature. Provision was made for installation of a reference Bourdon-type pressure gage (0.1 percent full scale) without removal of the transducer from the system.

Field strength of the magnets in the EM flowmeters was checked using a gaussmeter, and the theoretical calibration curve plotted agreed within 1 percent of the manufacturer's calibration. Each venturi was calibrated against a standard orifice plate in bench tests before installation. The turbine flowmeters were calibrated by the manufacturer using a fluid with similar viscosity to that used in the oil loop.

Chromel-alumel type K thermocouples were referenced to a 150° F (338 K) oven while the iron-constantan type J thermocouples were referenced to a 32° F (273 K) source. All thermocouples received an electrical continuity check and a heat check to ensure proper thermocouple lead connection and temperature response.

Power, current, and voltage transducers were calibrated by feeding in actual (1/2-percent accuracy) ac signals into the transducer and reading the output on a digital dc integrating voltmeter. In actual use, however, the signal was then sent to conditioning equipment having fixed gain amplifiers. These amplifiers had a tendency to drift causing a 2 to 3 percent additional error. Calibration after the completion of the test lends more credence to the later data by eliminating this error due to drift. Since the NaK pumps had a power factor lower than 0.7, the accuracy of the power transducers was less than that stipulated by the manufacturer. The slightly distorted wave form output of the turboalternator caused a 2 to 3 percent error in the electrical transducers when the pumps were being powered by the turboalternator. The total error in the recorded power measurement was 5 to 10 percent.

The electromagnetic speed pickups were calibrated by feeding in a frequency approximating the pump operating frequency. Linear output of the pickup was assumed and by calibrating at approximate operating speed the error was negligible. However, signal conditioning equipment produced approximately a 1 percent error.

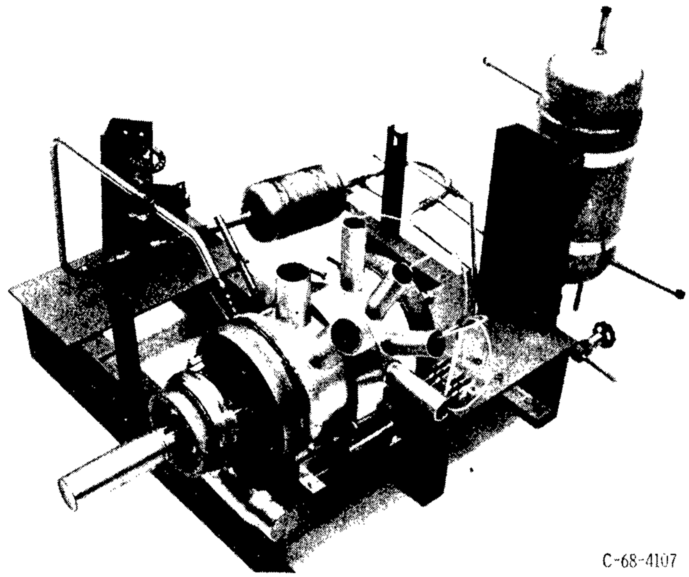

Figure 3. - NaK pump.

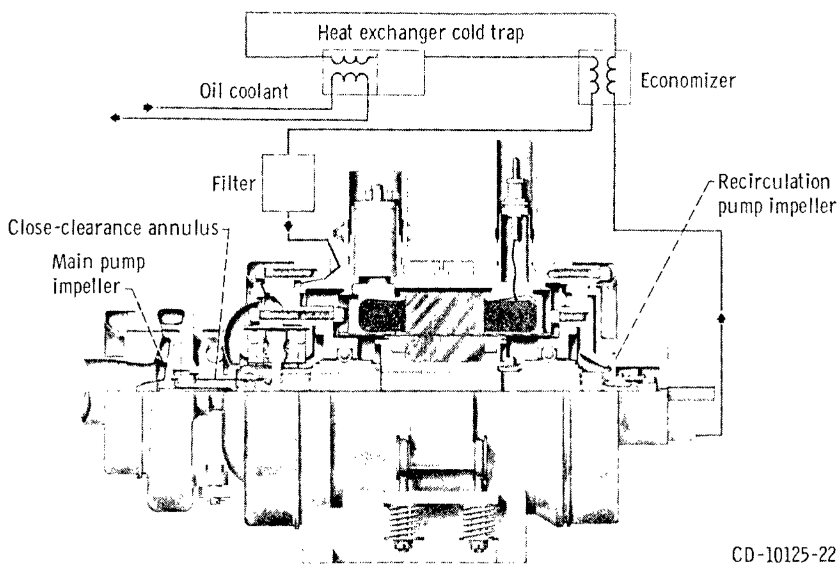

Figure 4. - NaK pump cross section.

PUMP DESCRIPTION

The NaK pump shown in figures 3 and 4 is a hermetically-sealed unit incorporating on a single shaft a centrifugal pump, a "canned" 400 hertz 3-phase induction motor, NaK lubricated tilting-pad journal and thrust bearings, and an internal NaK lubricant-coolant recirculation pump. Two identically designed NaK pumps are used, one in the primary loop at an operating temperature of 1150° F (895 K), while the second is used in the heat rejection loop at an operating temperature of 450° F (505 K). The motors for both pumps at design conditions operate at 350° F (450 K). Each pump weighs approximately 200 pounds (90 kg).

In this design no static or dynamic shaft seals were necessary. A unique feature of this pump is that the heat from the hot NaK is thermally isolated from the motor by minimizing the heat conduction paths between the two. This is done by providing the shaft and housing with a close clearance in the area between the pump impeller and the motor. This close clearance annulus forms a nominal seal preventing any substantial interchange of the hot NaK being pumped with the cooler NaK in the motor cavity. This limited NaK oxide precipitation in the bearing area. Any oxides that do migrate into the bearing area are removed in the recirculation loop where cold trapping takes place.

The NaK pump has its own self-contained lubricant-coolant loop. The NaK recirculation loop cools the motor and supplies the bearings with oxide-free NaK. It consists of an internal NaK lubricant-coolant recirculation pump, an economizer, a heat exchanger cold trap, and a filter. The recirculation impeller pumps the NaK from the motor cavity through the recirculation loop. Oxides are precipitated out in the heat exchanger cold trap which is cooled by the oil coolant fluid. The economizer adds heat to the NaK leaving the cold trap to prevent oxide removal in the filter. The filter is used only to remove foreign particles.

RESULTS AND DISCUSSION

The two NaK pumps were run for 1483 hours, all but approximately 20 hours at design operating conditions. Forty-one startups were made on the primary loop pump and 49 startups were made on the heat rejection loop pump. As seen from table I most of these starts were to remove any entrapped gas. The pumps had to be prefilled with clean NaK to minimize the possibility of oxides.

Data were taken over the entire 1483 hours of pump operation during steady-state condition, startups, early system testing, and the final shutdown. For comparison with previously tested pumps in reference 1, all data presented in the performance curves have been corrected to 5815 rpm for the primary NaK pump and 5810 rpm for the heat re-

E-714

TABLE I. - NaK PUMP OPERATION

Pump	Start	Duration of run	Remarks
Primary loop	1 to 17	30 sec (each)	Jog
	18 to 38	30 sec (each)	Jog
	39	391.8 hr	System hot flush and test
	40	0	Pump checkout
	41	1091.8 hr	System test
Total, 1483.8 hr			
Heat rejection loop	1 to 8	30 sec	Jog
	9 to 20	0 sec	Pump checkout
	21	10 sec	Pump checkout
	22 to 37	15 sec (each)	Jog
	38	20 hr	System test
	39 to 42	2 min (each)	System checkout
	43	371.5 hr	System test
	44	10 sec	Pump checkout
	45 to 48	2 min (each)	System checkout
	49	1091.8 hr	System test
Total, 1483.4 hr			

jection loop pump. The corrections were made using the usual similarity relations for flow, head, and power.

NaK Pump Operated at 1150° F (895 K)

The primary NaK pump was tested at speeds from 5860 to 6100 rpm with the steady-state endurance speed normally between 5860 and 5880 rpm. The pump performance curve (fig. 5) shows a lower head-flow curve than was produced in reference 1. The variance was approximately 8 feet (24 J/kg) at 60 gallons per minute (0.23 m^3/min) and 20 feet (60 J/kg) at the endurance condition of 125 gallons per minute (0.47 m^3/min). There appears to be no significant change in pump performance with time. Early data were taken during the first 30 hours of pump operation.

It was assumed that the motor characteristics were the same as those of reference 1; therefore, the input power was corrected assuming the similarity relation for power (i.e., the power would vary as the cube of the speed). Corrected input power was approximately 250 watts higher than the curve from reference 1. However, experimental uncertainties for power measurements were ±5 to ±10 percent, which could easily account for 250 watts of power.

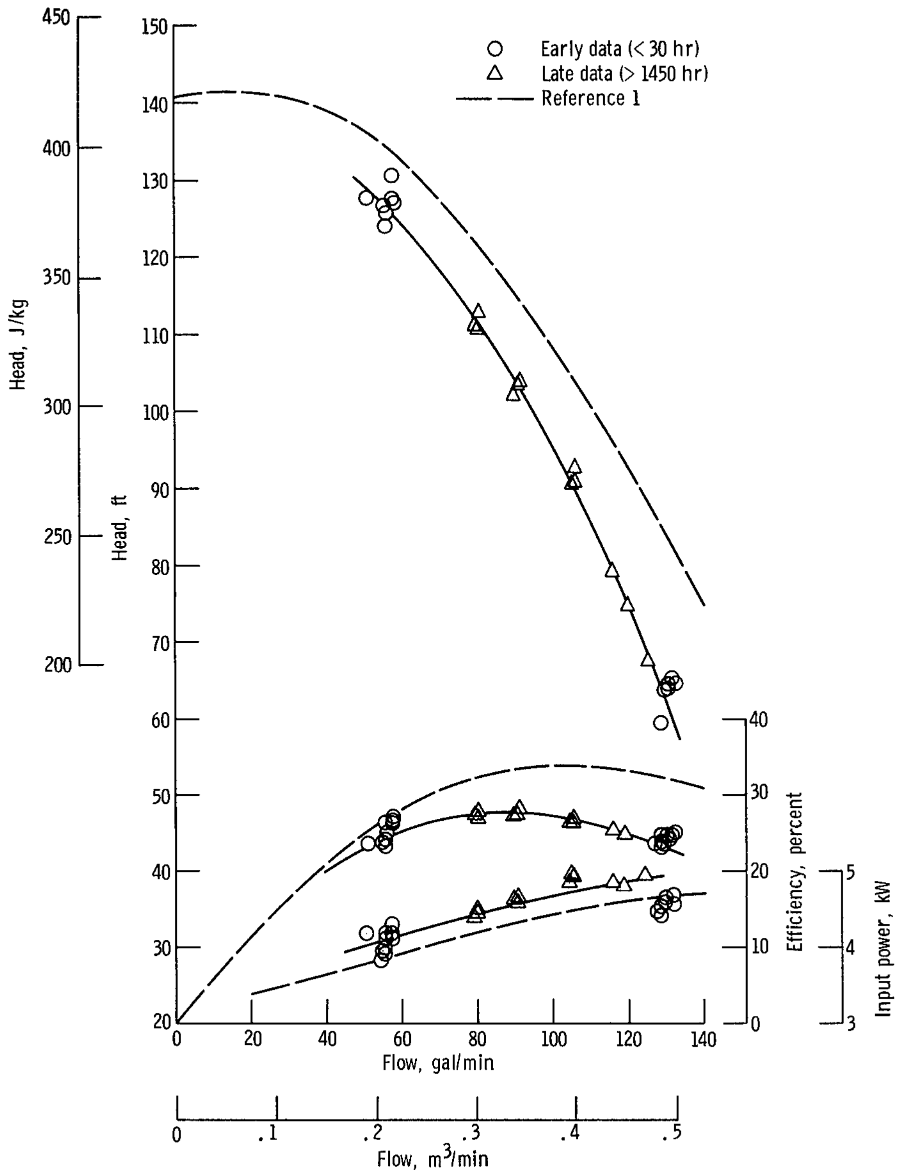

Figure 5. - Performance curve for NaK pump operating at 1150° F (895 K).

Pump efficiencies obtained were lower than those of reference 1, varying by 3 percent at 60 gallons per minute (0.23 m^3/min) and 9 percent at 125 gallons per minute (0.47 m^3/min). The lower efficiencies were due to the combination of lower head-flow curves and higher power consumption.

The recirculating NaK loop of the pump removed waste heat and transferred it to the oil. The heat removed ranged from 800 watts at 60 gallons per minute (0.23 m^3/min) to 1440 watts at 125 gallons per minute (0.47 m^3/min) as seen from figure 6. The data scatter is actually quite small when it is considered that there is only a 4^o to 7^o F (2 to 4 K) temperature rise across the NaK cold traps. Although the precision of the readings is

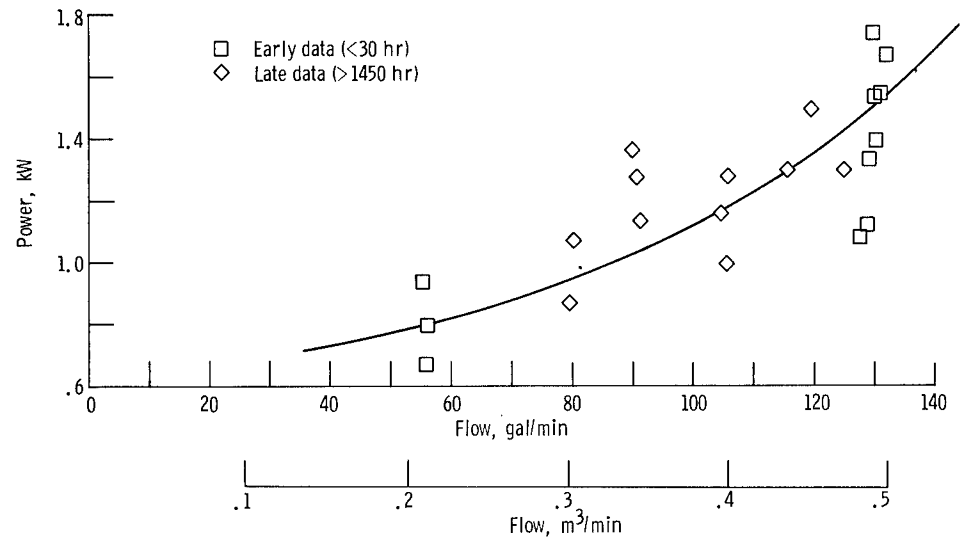

Figure 6. - Power transferred to lubricant coolant fluid by primary NaK loop pump.

good the thermocouples themselves are only accurate to $\pm 2^{\circ}$ F (± 1 K) which can cause a large error in the heat balance calculation for power transferred to the oil. Design NaK flow in the recirculation loop was 1.6 gallons per minute (6×10^{-3} m^3/min) with a motor inlet temperature of 300° F (410 K) and an outlet temperature of 350° F (450 K). Actual flow was not measured but the measured inlet and outlet temperatures were 325° F (435 K) and 375° F (465 K), respectively.

Table II is a comparison of the pump performance with the design conditions and

TABLE II. - PRIMARY LOOP PUMP PERFORMANCE DATA

Component and parameter	Design	Reference 1 test data	Lewis Research Center test data
Pump, centrifugal:			
Flow, lb/hr (kg/hr)	45 900 (20 900)	45 900 (20 900)	46 500 (21 200)
Inlet temperature, $^{\circ}$F (K)	1100 (865)	1110 (871)	1150 (894)
Speed, rpm	5800	5815	5860
Inlet pressure, psia (N/m^2)	28.6 (1.97×10^5)	30.8 (2.12×10^5)	21.8 (1.50×10^5)
Outlet pressure, psia (N/m^2)	60.1 (4.14×10^5)	59.1 (4.07×10^5)	43.4 (2.99×10^5)
Head, ft (J/kg)	99 (297)	89 (267)	68.6 (206)
Hydraulic power, kW	1.71	1.54	1.20
Pump efficiency, percent	61	64.2	----
Shaft input power, kW	2.81	2.39	----
Motor, induction:			
Motor electric efficiency, percent	70.2	74.4	----
Motor overall efficiency, percent	61.8	53	----
Input power, kW	4.71	4.52	5.02
Power factor	0.53	0.555	0.57
Combined overall efficiency, percent	36.3	34.1	23.9

reference 1. The data presented are not corrected for speed. Individual data on pump efficiency and motor efficiency could not be obtained in this test.

During testing the primary NaK loop was not cold trapped to remove oxides. The resulting high NaK oxide content was evident when the mercury boiler was cut into for examination. This higher NaK oxide content may be partially responsible for the lower performance of this pump if internal deposition had occurred.

NaK Pump Operated at 450° F (505 K)

The heat-rejection loop pump was tested at speeds from 5890 to 6100 rpm with the steady-state endurance speed normally between 5890 and 5920 rpm. The pump performance curve (fig. 7) shows a lower head-flow than reference 1 for the flow range tested.

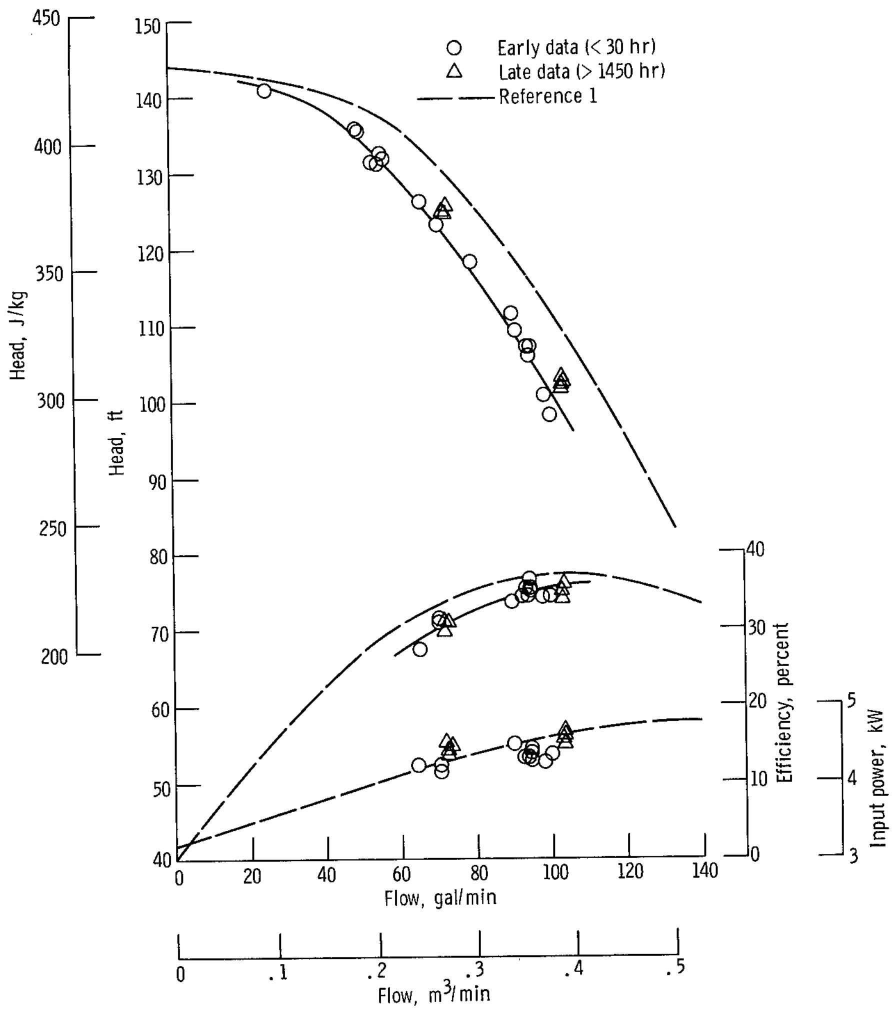

Figure 7. - Performance curve of NaK pump operating at 450° F (505 K).

The variance is approximately $4\frac{1}{2}$ feet (13.4 J/kg) at 50 gallons per minute (0.19 m^3/min) and $10\frac{1}{2}$ feet (31.3 J/kg) at the endurance condition of 100 gallons per minute (0.38 m^3/min). There appears to be an increase in head of approximately 3 feet (9 J/kg) at the end of the test period. A head change of 3 feet (9 J/kg), however, is within the experimental uncertainty of the instrumentation.

The input power to the pump was approximately the same as that shown in reference 1. Data scatter of ±200 watts for both the early and late data is within the 5 to 10 percent accuracy of the recorded power measurements. Here, as in the primary pump, the power data were corrected using similarity parameters and assuming the motor chatacteristics of reference 1. The input power data for the lower flow rate was lost due to early instrumentation problems.

The higher powers corresponding to the higher heads of the later data combined to produce an efficiency curve which showed no significant change with time. However, the efficiency was 2 to 3 percent lower than the pump in reference 1.

The heat from the pump absorbed by the oil varied from 1070 watts at 50 gallons per minute (0.19 m^3/min) to 1300 watts at 100 gallons per minute (0.38 m^3/min) as shown by figure 8. The data scatter is small when the temperature rise of 5° to 7° F (3 to 4 K) is considered. Again, thermocouple accuracy can cause significant uncertainties in the calculation of power transferred to the oil. Design NaK flow in the recirculating loop was 1.6 gallons per minute (6.0×10^{-3} m^3/min) with a motor inlet temperature of 300° F

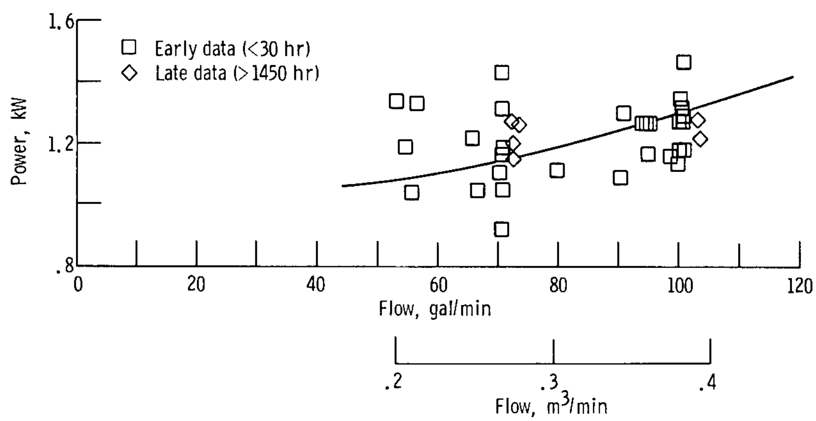

Figure 8. - Power transferred to lubricant coolant fluid by heat rejection loop pump.

TABLE III. - HEAT REJECTION LOOP PERFORMANCE DATA

Component and parameter	Design	Reference 1 test data	Lewis Research Center test data
Pump, centrifugal:			
Flow, lb/hr (kg/hr)	40 200 (18 300)	40 200 (18 300)	42 500 (19 300)
Inlet temperature, $^{\circ}F$ (K)	495 (530)	495 (530)	445 (500)
Speed, rpm	5800	5810	5900
Inlet pressure, psia (N/m^2)	15.0 (1.03×10^5)	15.0 (1.03×10^5)	19.7 (1.36×10^5)
Outlet pressure, psia (N/m^2)	15.0 (1.03×10^5)	15.0 (1.03×10^5)	19.7 (1.36×10^5)
Head, ft (J/kg)	118 (354)	113 (339)	105.8 (317)
Hydraulic power, kW	1.79	1.715	1.69
Pump efficiency, percent	63.4	68.5	----
Shaft input power, kW	2.83	2.51	----
Motor, induction:			
Motor electric efficiency, percent	70.4	75.5	----
Motor overall efficiency, percent	60.0	54.6	----
Input power, kW	4.72	4.6	4.83
Power factor	0.53	0.555	0.565
Combined overall efficiency, percent	38.0	37.3	35.0

(410 K) and an outlet temperature of 350° F (450 K). Actual flow was not measured but the recorded inlet and outlet temperatures were 315° F (430 K) and 375° F (465 K), respectively.

Table III is a comparison of the pump performance with reference 1 and with the design conditions. The data are not corrected for speed. As in the primary pump, data could not be obtained on the pump or motor individually.

Figure 1 taken from reference 1 shows the operational envelope for both NaK pumps with the actual operation point marked. Both pumps are within the operational envelope which is considered safe for the 10 000 hours of operation necessary for the SNAP-8 system. However, the nominal operating head for the heat rejection loop pump was 10.5 feet (31.3 J/kg) less and the primary loop pump was 20 feet (60 J/kg) less than for the pump tested in reference 1.

SUMMARY OF RESULTS

Analysis of the performance of two motor-driven centrifugal pumps, operated with NaK as the working fluid, in a simulated SNAP-8 system yielded the following results:

1. The pumps were operated successfully for 1483 hours, 1092 hours being continuous. Forty-one start-stop cycles were performed on the primary loop pump operated at 1150° F (895 K) and 49 start-stop cycles on the heat rejection loop pump operated at 450° F (505 K). No structural, mechanical, or material problems were encountered

during the entire test and zero external leakage was exhibited by both pumps.

2. Input power corrected for speed showed that the primary NaK pump required approximately 250 watts greater power, while the heat rejection loop pump required approximately the same amount of power as previously tested pumps. No bearing or motor problems developed. The average motor temperatures were maintained at or below 350^{0} F (450 K) while the pumps operated at system temperature.

3. Although the heat rejection loop was cold trapped and the primary loop was not, no significant changes in pump performance occurred during the 1483-hour test period.

4. The primary pump operated at 5860 rpm with a flow of 46 500 pounds per hour (21 200 kg/hr) and produced a head of 68.6 feet (206 J/kg) at an overall efficiency of 23.9 percent. The heat is approximately 20 feet (60 J/kg) lower than was found from previously tested pumps resulting in an efficiency which was approximately 9 percent lower.

5. The heat rejection loop pump operated at 5900 rpm with a flow of 42 500 pounds per hour (19 300 kg/hr) and produced a head of 105.8 feet (317 J/kg) at an overall efficiency of 35 percent. The head is approximately $10\frac{1}{2}$ feet (31.3 J/kg) lower than previously tested pumps resulting in an efficiency which was approximately 3 percent lower.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, November 27, 1968,
701-04-00-02-22.

REFERENCES

1. Chalpin, E. S.; Colker, C. P.; and Foss, C. L.: Design and Development of Pumps for High Temperature NaK Service. AIAA Specialists Conference on Rankine Space Power Systems. Vol. 1. AEC Rep. CONF-651026, vol. 1, 1965, pp. 186-200.

2. Wood, G. M.: Status of SNAP-50 SPUR Pump Development Program. Rep. CNLM-6308, Pratt & Whitney Aircraft, May 27, 1965.

3. Ferguson, C., et al.: LCRE Secondary Coolant Pump and Sump. Rep. PWAC-385, Pratt & Whitney Aircraft, Jan. 10, 1964.

4. Ferguson, C., et al.: LCRE Primary Coolant Pumps and Sump. Rep. PWAC-383, Pratt & Whitney Aircraft, Nov. 22, 1963.

5. Macosko, Robert P.; Hanna, William T.; Gorland, Sol H.; and Jefferies, Kent S.: Performance Evaluation of an Experimental SNAP-8 Power Conversion System. TM X-1732, 1969.

6. Gertsma, L. W.; Thollot, P. A.; Medwid, D. W.; and Sellers, A. J.: The Double Containment Tantalum-Stainless Steel SNAP-8 Boiler. Presented at the Intersociety Energy Conversion Engineering Conference, Boulder, Colo., Aug. 13-16, 1968.