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Dual Throat NaK Pump Performance Evaluation (Conceptual Design of Prototype)

AUTHOR

J. L. Johnson

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EVALUATION
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APPROVALS

E. Matlin

O. P. Steele, III

T. S. Nakae

T. Moss

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An evaluation of the performance of the dual throat NaK pump for the 5 Kwe Reactor TE System is discussed. Performance at nominal operating conditions and at startup conditions is predicted. The basis for selection of this pump design is presented.

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I. INTRODUCTION

This report provides the electrical/hydraulic conceptual design of the prototype TE pump assembly for the 5 Kwe reactor TE system. This TE pump assembly is very similar to the developmental pump assembly that was previously designed for the ZrH program ~ 4 years ago, both from a configuration and materials standpoint. The developmental pump of that assembly is currently being tested (Ref. 1) for this program. The conceptual prototype TE pump assembly is shown in Figure 1.

II. PERFORMANCE REQUIREMENTS

The present 5 Kwe reactor TE system pumping requirements are as follows:

TABLE I
SYSTEM PUMPING REQUIREMENTS

	<u>SPACE OPERATION</u>		<u>GROUND OPERATION</u>	
	<u>BOL</u>	<u>EOL</u>	<u>BOL</u>	<u>EOL</u>
Primary Loop Flow, Lb/sec	4.72	4.73	4.68	4.68
Secondary Loop Flow "	2.88	2.88	2.86	2.86
Primary Loop Pressure Drop, PSI	.80	.80	.78	.78
Secondary Loop Pressure Drop, PSI	1.26	1.26	1.25	1.24
Primary Throat Temp, F	1048	1105	1054	1104
Secondary Throat Temp F	562	590	579	605

The pump is designed to provide 15% additional pressure to that shown in Table I at the flow rates shown.

The performance requirements of the pump power supply are more general than the above, as shown in Table II:

TABLE II
PUMP POWER SUPPLY REQUIREMENTS

<u>General Requirements</u>	
Efficiency	Maximum
Voltage	Matched to pump
Flow Rates (Pri & Sec)	Similar to Power Module
Pressure Drop (Pri & Sec)	" "
Temperatures (Pri & Sec)	" "
Module Design	Similar to TEM 14A

E.M. PUMP & T.E. CONVERTER

Figure 1

The operating life of the system is 5 years with the temperatures increasing uniformly from the BOL temperature to the EOL temperature of Table I during this period. The pump shall be capable of providing from 1-100% of design flow in the primary loop with an external power source, and there shall be a continuous progressive relationship between applied electrical current and flowrate. Voltage taps shall be located on the throats in the fringe flux region and will be used to measure flow. In addition, the pump must be capable of withstanding the 5 KWe Reactor TE system environmental requirements as specified in Ref. 2.

III. DESIGN PERFORMANCE EVALUATION

Performance of this pump design has been evaluated at the nominal operating temperatures and at 100F to determine startup characteristics. Performance of the pump at the off-design conditions encountered during startup and shutdown is dependent upon the performance of the pump modules at off-design temperatures and will be evaluated when such information is received from the pump module supplier. The analytical method used for these evaluation is discussed in Section IV.

A. PUMP OPERATING CHARACTERISTICS

The pump designed to provide the hydraulic pumping power requirements of Section II at the end-of-life, will have the design characteristics summarized in Table III below:

TABLE III

Dual Throat Pump Design Requirements

	<u>Primary Throat</u>	<u>Secondary Throat</u>
Flow Rate - lb/sec	4.73	2.88
Pressure - PSI	0.92	1.45
(Includes 15% Design Margin)		
Temperature -F	1105	590
	<u>Pump</u>	
Pump Current - Amperes	1560	
Magnetic Flux Density - Gauss	2380	
Voltage - Volts	0.195	
(Includes .022 volt loss in module end rings)		
Weight - Lbs	55	
Dimensions - Inches		
Pump Length	21	
Pump Width	13	
Pump Height	10	

See Figure 2 for individual throat dimensions

Figure 3 shows the pressure developed and the efficiency in each throat as a function of flowrate at end-of-life conditions. Figure 4 shows the pressure developed in each throat as a function of flowrate for applied currents of 1360, 1560 and 1760 amperes at end-of-life conditions. The performance of the pump at the beginning of life conditions when the temperatures are lower (see Section II) and the current supplied is slightly higher, is practically identical to that at end-of-life. In fact, the performance is so close to that shown in Figures 3 and 4, that similar BOL head vs flow curves are not plotted, as the differences are not discernable to the viewer. If the temperature increases in a uniform fashion during the 5-year life of the system, the performance curves shown (Figures 3 and 4) would be applicable to the pump throughout its design life. Figure 5 shows the pressure developed as the magnetic flux density and the current in the primary throat is varied. The pressure developed at the design flow rate is quite insensitive to small changes in the flux density. A 10% change in flux density results in less than a 2% reduction in pressure. This figure also shows the strong relationship between developed pressure and current. For example, at the design point, a 7% increase in current results in better than a 15% increase in pressure developed. For this pump design, additional pumping requirements can only be accommodated by increasing current as increasing flux density degrades performance.

B. TE PUMP MODULE OPERATION CHARACTERISTICS

Based upon the voltage and current requirements of the pump, and upon the general performance characteristics listed in Table II, the overall performance requirements and characteristics for the pump power supply were determined in concert with 5 KWe Reactor TE System Trade Study (Ref. 3). These are listed below in Table III for an assembly of three TE pump modules connected electrically in parallel.

PUMP CHARACTERISTICS		
VOLTAGE	(volts)	.195
CURRENT	(amps)	1560
EFFICIENCY	(%)	13.1
POWER IN	(watts)	304
WEIGHT	(lbs)	55

THROAT CHARACTERISTICS		PRIMARY	SECONDARY
VOLTAGE	(volts)	.072	.043
EFFICIENCY	(%)	26.8	24.4
FLOWRATE	(lbs/sec)	4.73	2.88
FLUX DENSITY	(gauss)	2380	2380
TEMPERATURE	(F)	1105	590
PRESSURE	(psi)	.92	1.45

FIGURE 3.

DUAL THROAT VAK PUMP PERFORMANCE

FIGURE 4.

DC PUMP HEAD-FLOW CHARACTERISTICS

FIGURE 5

PUMP PRIMARY THROAT CHARACTERISTICS

(PRESSURE VS. FLUX DENSITY)

FLOW = 4.73 LBS/SEC

a = 1.3 IN

R = 0.6 IN

X = 2.5 IN

FIGURE 5.

MAGNETIC FLUX DENSITY - GAUSS

9-14-72

TABLE IV

TE POWER SUPPLY OPERATING CHARACTERISTICS

	<u>SPACE OPERATION</u>		<u>GROUND OPERATION</u>	
	<u>BOL</u>	<u>EOL</u>	<u>BOL</u>	<u>EOL</u>
Average Hot Clad Temp, F	1080	1124	1085	1141
Average Cold Clad Temp, F	501	513	520	539
Axial T Hot Clad, F	87	95	86	94
Axial T Cold Clad, F	131	144	129	141
Primary Pressure Drop, PSI	.23	.23	.22	.22
Secondary Press. Drop, PSI	.52	.52	.51	.51
Primary NaK Flow Rate, lbs/sec	.522	.522	.517	.517
Secondary NaK Flow Rate, lbs/sec	.318	.318	.315	.315
Primary NaK to Clad T, F	12	12	12	12
Secondary NaK to Clad T, F	5	5	5	5
Match Load Voltage, Volts	.195	.195	.191	.191
Power In, Kilowatts	9.68	10.47	9.51	10.26
Power Out, Kilowatts	.310	.304	.292	.285
Efficiency, %	3.20	2.90	3.07	2.78
Current, Amperes	1580	1560	1552	1533

C. TE PUMP ASSEMBLY OPERATION CHARACTERISTICS

Based upon the performance requirements of the pump (Table I) and of the TE pump converter assembly (Table IV) the overall performance characteristics of the thermoelectric pump assembly were determined, and are listed below in Table V.

TABLE V

TE PUMP ASSEMBLY PERFORMANCE CHARACTERISTICS

	<u>SPACE OPERATION</u>		<u>GROUND OPERATION</u>	
	<u>BOL</u>	<u>EOL</u>	<u>BOL</u>	<u>EOL</u>
Power In, Kilowatts	9.68	10.47	9.51	10.26
Hydraulic Pumping Power Out, KW	.037	.037	.037	.037
Overall efficiency, %	.38	.35	.39	.36

Maximum shunt loss through bus between primary and secondary throat - 600 Watts.

D. STARTUP CHARACTERISTICS

During startup it is necessary to provide flow in the system to transmit heat from the reactor to the pump converter modules. To provide power to the pump during the period before sensible heat is

received in the pump TE converter, an external power source is provided. Figure 6 shows the current required across each throat as a function of percent of design flow. This evaluation was performed at 100F and it was assumed that the developed pressure at each flow condition was related to the flowrate by the expression

$$P = K Q^2, \text{ PSI}$$

where

$$K_p = \frac{.92}{(4.73)^2}, \text{ PSI}$$

$$K_s = \frac{1.45}{(2.88)^2}, \text{ SEC}$$

$$Q = \text{Flowrate, lb/sec}$$

Providing the current shown in Figure 6 across the throat is compounded by the fact that a parallel current path is provided through the pump TE converter assembly so that the current supplied must be appreciably higher to obtain these values. The resistances of the various components in this circuit at 100F (Fig. 7) are as follows:

Primary Throat	60 microhms
Secondary Throat	60 microhms
Copper Bus	15 microhms
Converter Module	30 microhms
Assembly	

If current is applied across both throats the resistance across these throats and one third of the bus is 125 microhms, while the resistance through the remainder of the circuit is 40 microhms. Therefore, to provide the current across the throats shown in Figure 6 the total current supplied would need to be ~ 4 times greater. For example, 200 amperes supplied to the pump would provide ~ 50 amperes across the throats.

FIGURE 6

FIGURE 7

PUMP-TE CONVERTER ELECTRICAL CIRCUIT

WITH CURRENT (I) SUPPLIED ACROSS POINTS A + D:

$$\text{CURRENT THRU THROATS} = \frac{40}{165} I$$

$$\text{CURRENT THRU CONVERTER} = \frac{125}{165} I$$

WITH CURRENT (I) SUPPLIED ACROSS POINTS A + B

$$\text{CURRENT THRU PAI. THROAT} = \frac{105}{165} I$$

$$\text{CURRENT THRU REST OF CIRCUIT} = \frac{60}{165} I$$

If the external current supply is connected across the primary throat then it has a lower resistance (60 microhms) than the parallel path consisting of the bus, secondary throat and TE converter assembly (105 microhms). In this case the total current required to provide 50 amperes across the primary throat is less than 80 amperes, or a factor of about 1.6 times greater. However, the current (30 amps) passing through the parallel path would be passing through the secondary throat in a negative direction causing reverse flow through the secondary system. The effect of reverse flow through the secondary loop and of reverse electrical current through the TE module assembly has not been determined.

IV. ANALYTICAL METHOD

The general configuration for the dual throat NaK pump for the 5 Kwe Reactor TE System was selected on the basis of a previous study (Ref. 4) and based on previous development conducted on this concept for the ZrH reactor program. The general equation describing the DC pump relationships and the characteristics typical of this design are as follows:

$$\begin{array}{rccccccc}
 P & = & M_1 G I & \times & K_{AR} & - & M_2 G^2 Q & - & M_3 G^2 Q & - & M_4 Q^2 \\
 \text{Net Developed} & = & \text{Gross} & \times & \text{Armature} & - & \text{Back} & - & \text{Eddy} & - & \text{Hydraulic} \\
 \text{Pressure} & = & \text{Pressure} & \times & \text{Reaction} & - & \text{EMF} & - & \text{Current} & - & \text{Losses,} \\
 & & & & & & \text{Factor,} & & \text{Losses,} & & \\
 \text{PSI} & & \text{PSI} & & & & \text{PSI} & & \text{PSI} & & \text{PSI}
 \end{array}$$

where:

G = Magnetic flux density, gauss

I = Current, amperes

Q = NaK flow rate, lbs/sec

K_{AR} = Armature reaction, dimensionless and ≤ 1

M_1, M_2, M_3, M_4 - Geometric Factors

Primary (0.92 = 2.80 - .08 - .85 - .55 - .40) PSI

32.8% = 100% - 2.9% - 30.4% - 19.6% - 14.3%

Secondary (1.45=2.83 - .07 - .72 - .48 - .11) PSI

51.3% = 100% - 2.5% - 25.4% - 16.9% - 3.9%

The technique used to obtain pump dimensions and performance characteristics is the same as described in Ref. 3. For a given set of input parameters (flowrate, pressure, throat length, throat width and throat height) a pump configuration is established that requires minimum electrical current input. The magnet flux density is computed for this value of current, and using the maximum energy product of the magnet, its area and length are determined. The magnet size, in turn, determines the size of the remaining components of the pump such as yokes, pole pieces and pump structure. The input current determines the size of the current buses between the throats and between each throat and the TE converter assembly. A bus length of 25 inches and a bus efficiency of 67% were additional assumptions made for this analysis.

The pump design selection for the 5 Kwe Reactor TE System is made on the basis of low pump weight, minimum pumping system weight and low current input. Pump weight includes the weight of the current buses, yokes, pole pieces, magnet entrance and exit NaK diffusers, throats, the NaK contained within the throats and the diffusers, plus an additional assessment of 16 lbs for support structure. Pump system weight includes the pump, the pump TE modules and the system weight associated with heat rejection from the pump TE modules. For the latter, an assessment of 8 lbs for each kilowatt of heat rejected was used. A fixed weight penalty of 24 lbs was used for the pump TE modules. An EOL pump module efficiency of about 3% was used in determining heat rejection requirements.

Pump performance and size information is computed for many combinations of throat dimensions by varying the throat height (distance between the magnets), the throat width, (distance between the bus electrodes) and throat length, (length of the bus-throat braze joint in the direction of NaK flow). Selected performance and weight information is plotted as a function of each of the throat dimensions. For the pump design selected for this application these data are shown plotted in Figures 8, 9 and 10. The design point selected is influenced by the desire to keep the pump weight, and therefore its size, as small as possible without severely penalizing overall system weight. Integration and support of the pump becomes more difficult as its size increases. In Figures 8 and 9, the design points selected for throat length and width are at minimum pumping system weight, while in Figure 10, the design point selected for throat height is at minimum current for the reasons discussed above.

V. CONFIGURATION AND MATERIALS

The configuration of the pump TE assembly is shown schematically in Figure 1. The materials that will be used for this pump are:

Bus	- OFHC Copper
Yoke	- ARMCO iron
Magnet	- ALNICO V-7
Throat & Diffusers	- 316 Series Stainless Steel
Pole Piece	- HIPERCO 27

VI. REFERENCES

1. IP-652-330-001, "Test Plan for Performance Test of Development Pump", J. L. Johnson, 7-17-72
2. SS652-N170001, "Environmental Design and Test Requirements for 5 KWE ZrH Reactor TE Space Power System", W. D. Dauterman.
3. TSR-652-640-002, "5 KWE Reactor TE System Design Point and Configuration Modification Study", by R. A. Anderson.
4. TSR-652-330-001, "NaK Pump Performance Evaluation Trade Study", J. L. Johnson, 6-6-72.

FIGURE 8.

DUAL THROAT NAK PUMP PERFORMANCE CHARACTERISTICS

FIGURE 9.

DUAL THROAT NAK PUMP PERFORMANCE CHARACTERISTICS

TEMPERATURES 1105/590 F
FLOWS 4.73/2.88 LBS/SEC
PRESSURES .92/1.45 PSI
THROAT HEIGHT 0.6 IN
THROAT LENGTH 2.5 IN

FIGURE 10.

DUAL THROAT NAK PUMP PERFORMANCE CHARACTERISTICS