Steel
Bump

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ATOMICS INTERNATIONAL A Division of North American Aviation, Inc.		NAA-SR TOR NO 7258	APPROVALS <i>K.A. Davis</i>
TECHNICAL DATA RECORD		PAGE 1 OF 25	<i>M.A. Perlow</i>
AUTHOR K. A. Davis *		DEPT & GROUP NO 722-22	DATE 4-2-62
TITLE Liquid Metal Pump powered by Lead Telluride Thermoelectric		GO NO 7580	S A NO 2146
PROGRAM SNAP 10A		SUBACCOUNT TITLE Heat Transfer Sub-System Development	
DISTRIBUTION USE AN ASTERISK (*) TO INDICATE THOSE WHO ARE TO RECEIVE COMPLETE COPIES		STATEMENT OF PROBLEM To design construct, and test a lead telluride powered thermoelectric liquid metal pump for use on SNAP 10A.	
M. A. Perlow (15) SNAP 10A Dist. *		ABSTRACT <p>A liquid metal, d. c. conduction pump powered by an integrally mounted lead telluride thermoelectric generator was designed, constructed and tested. One thousand hours of operation was obtained under SNAP 10A conditions in a vacuum environment. The tests demonstrate the feasibility of such a pump along with the advantages and disadvantages of the selected design.</p> <p>Design criteria, fabrication techniques, test data and an overall analysis of the design are contained herein.</p>	

I. Introduction

The SNAP 10A system is described as a 500 watt electrical nuclear power source for space application where by the energy conversion from thermal to electrical is accomplished directly by thermoelectrics. The system is unique in that no moving parts or rotating machinery exist. The mechanism for transferring the reactor coolant (NaK-78) to the radiator-converter is by a liquid metal D. C. Conduction Pump powered by an integrally mounted thermoelectric source.

The purpose of this report is to present one such design of this pump using Lead Telluride (PbTe) elements as the generators. These elements consist of PbTe wafers and iron shoes and are fabricated by compacting and sintering the powders.

PbTe inherently has little or no strength in tension. This design mounts the elements such that they are in constant compression.

II. Pump Construction

A photograph of the pump is shown in Figure 1. The sketches of Figures 2 and 3 show the various components.

a. Pump throat

The pump throat was made of two pieces of 20 mil type 304 stainless steel, sheet each piece folded to form a U shape, and the two U shapes were welded together to form a 0.75 x 0.75 inch square duct. The duct length was 7 inches.

b. Electrodes

Copper blocks, nominally 1 x 0.75 x 2 inches, were furnace brazed to the pump throat. Their function was to serve as a mounting base for the thermoelectric elements and to provide good electrical and thermal conductivity from the pump throat wall to the thermoelectric elements.

c. Thermoelectric elements

The thermoelectric elements are made by a powder metallurgy technique using PbTe and Fe powders

Figure 1 Thermoelectric Pump

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- 1 Pump throat, 0.75" x 0.75" cross section, 0.020" wall, 304 SS
- 2 PbTe thermoelectric elements 2" x 0.75" x 0.1"
- 3 Copper conductor & radiator
- 4 Compression bar, 304 SS
- 5 Copper electrodes

FIGURE 2

Sketch of pump throat with attached electrodes, thermoelectric elements, and radiator.

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- 1 Pump throat
- 2 PbTe thermoelectric element
- 3 Copper conductor and radiator
- 4 Compression bar
- 5 Copper electrode
- 6 Alnico V magnet
- 7 Magnet pole pieces

FIGURE 3

Transverse view of pump showing the magnets.

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compacted into a thin wafer with the PbTe nominally 100 mils thick between two layers of iron, each 30 mils thick. The powders are placed into a die cavity 0.75 x 4 inches to form the Fe-Pb Te-Fe wafer and this is cold pressed at 60,000 psi. The resulting compacts are 0.160 inches thick. They are sintered at 1200°F for two hours. Upon completion they are cut to form 2 x 0.75 inch elements and are diffusion bonded to the copper electrodes.

d. Radiator

The radiator plates are formed from 0.125 inch copper plate nominally 5 x 6 inches cut as shown in Figure 2 to accommodate the magnet. The radiator plates are diffusion bonded to the "cold" side of the thermoelectric elements. Compression bars placed over the radiator plates keep the elements in 2000 psi compression (at room temperature). In addition to conducting and radiating heat, the plates serve to complete the electrical circuit. After assembly, the plates are coated with a high emissivity coating.

e. Magnet

The magnet is made of 2 commercial C-shaped magnets connected in parallel with mild steel pole pieces between them. The arrangement is shown in Figure 3.

f. Instrumentation

A total of 14 thermocouples are embedded in the copper electrodes and radiator plates. They are suitably located to determine the temperature at the hot and cold sides of the thermoelectric elements, and at the tip of the radiator. (NaK inlet and outlet temperatures are measured by immersion thermocouples in the test loop). Number 14 copper wire leads are brazed to the copper electrodes and to the radiator plates to permit measuring the voltage across the elements and across the pump throat.

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III. Performance Computations

1. NaK temperature, T_{NaK} 1000°F
2. Hot junction temperature (electrode temperature), T_n 970°F
3. Cold junction temperature (radiator plate temperature at the plate-electrode interface), T_c 700°F
4. ΔT , $T_n - T_c$ 270°F
5. Seebeck coefficient S_p , p element (measured prior to element installation in pump) 138×10^{-6} volts °F
6. Seebeck coefficient S_n , n element (measured prior to element installation in pump) 103×10^{-6} volts °F
7. Total voltage developed,
 $E = \Delta T (S_p + S_n)$ 65.1×10^{-3} volts
8. Resistance of p element (measured) 312×10^{-6} ohms
9. Resistance of n element (measured) 78×10^{-6} ohms
10. Resistance of copper conductors (portion of radiator plate) per circuit $R_{cu} = \rho_{cu} \frac{l}{a}$ where ρ_{cu} is resistivity, l is length of conductor and a is cross sectional area of conductor 31×10^{-6} ohms
11. Resistance of NaK in channel
 $R_{NaK} = \rho_{NaK} \frac{l}{a}$, where ρ_{NaK} is resistivity of NaK, l is length of the conductor (width of the pump throat), a is the cross sectional area of the conductor (the throat height times the length of throat covered by the electrode plus an additional length equal to 0.4 the throat width to account for the fringe electric field)

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12. Resistance of stainless steel wall (both)

$R_{ss} = \rho_{ss} \frac{l}{a}$ where l is length of conductor (width of pump throat, and a is the area of the conductor equal to the wall thickness times the length of throat as defined in item 10 above.

728×10^{-6} ohms

13. Total resistance per circuit

$$R = R_p + R_n + R_{cu} + \frac{R_{NaK} + R_{ss}}{2}$$

427×10^{-6} ohms

14. Current through circuit

$$I = \frac{E}{R}$$

152.5 amperes

- 14a. Total current (two circuits in parallel)

305.0 amperes

15. Magnetic field, B (measured 2800 gauss at center; averaged to 2450 gauss over the region involved)

2450 gauss

16. Length of current path through NaK, L

2 cm

17. Force on NaK due to magnetic and electric fields

$$F = BIL \times 10^{-1}$$

1.5×10^5 dynes

18. Pressure developed

$P = \frac{F}{A}$ where A is cross sectional area of throat, 4 cm^2

3.75×10^4 dynes/cm²

- 18a. Pressure conversion of dynes/cm² to psi,

$$\text{dynes/cm}^2 \times 1.45 \times 10^{-5} = \text{psi}$$

0.545 psi

This computation has shown the magnitude of the pressure developed. However when flow occurs, there are several factors which reduce the available pressure. These are back emf, end effect losses due to magnetic field gradient, and hydraulic losses.

1. Back emf. This is a voltage generated as the result of a conductor (NaK) moving through a magnetic field, and has the value

$$e = FVL \times 10^{-8} \text{ volts}$$

where v is the linear velocity of the NaK. For this pump, the value of e is plotted as a function of flow rate in Figure 4. This voltage causes a current to flow through the circuit. The current, computed from the back emf divided by the circuit resistance, is plotted as a function of flow rate in Figure 5. The pressure developed by this current is plotted in Figure 6 and is computed as in items 17, 18, and 18a above. However, since this current is in the direction opposite to that of the applied voltage, its effect is to reduce the pressure.

2. Edge effect loss. This is a loss in pressure as a result of a conductor (NaK) passing through a magnetic field gradient. The loss is given by the equation

$$P_L = \frac{0.371 \times B^2 v \times 10^{-9}}{\rho_{NaK}} \text{ dynes/cm}^2$$

This loss is plotted as a function of flow rate in Figure 7.

3. Hydraulic loss. This is the fluid pressure loss through the 7-inch length of straight pump throat. Its value is given by the equation

$$P_h = \rho \times \frac{L}{D} \times \frac{v^2}{2g}$$

where ρ is the NaK density, f is the friction factor, L is length of pump throat, D is diameter, v is linear velocity, and g is the acceleration due to gravity. This loss is plotted as a function of flow rate in Figure 8.

Figure 9 shows the pressure developed at zero flow. Also shown, are the three factors explained above which reduce the available pressure due to motion of the NaK. These are subtracted from the value at zero flow and the resultant is plotted as a solid line.

FIGURE 6

Pressure decrease due to back EMF

$$\Delta P = \frac{0.27 B^2 v l \times 10^{-9}}{\rho} \text{ dynes/cm}^2$$

$$B = 2.45 \times 10^3$$

$$l = 2 \text{ cm}$$

$$\rho = 70.7 \text{ ohm cm}$$

Flow, GPM

FIGURE 7

Pressure loss due to magnetic field gradient

FIGURE 9
Pressure-Flow Characteristic

IV. Pump Test

To simulate space operating environment, and preserve the thermoelectric elements, the pump was tested in a vacuum. To accomplish this, a conventional test loop was fitted with a bell jar and base plate so that the portion of the loop containing the pump was under a vacuum in the bell jar. The pump was mounted in a vertical position as shown in the photograph in Figure 10. The magnet, which provides the magnetic field across the pump throat, is not connected to the throat assembly. Instead, the magnet is supported separately on four legs which rest on the base plate. A separate support likewise is planned in the SNAP 10A application.

Six pumps of the type described herein were constructed in sequence and numbered 1 to 6. Their status is summarized in Figure 11.

The vacuum testing facilities were not ready at the time the first pump was completed and ready for test. Since an immediate and tentative evaluation of the pump was needed, the pump was tested in air. It was operated for 8 hours and during this time it performed satisfactorily. At that time, information on the effect of thermal cycling on the elements was needed so the pump was placed in a thermal cycle loop. It was cycled from room temperature to 1000°F (NaK temperature) 10 times. The performance was evaluated by the voltage developed, and by this criteria there was no degradation until the ninth cycle when the voltage decrease was noticeable. However, this test did not prove conclusively that the voltage decrease was due to thermal cycling since by the ninth cycle, the pump had operated approximately 80 hours in air. This alone could decrease the performance in the absence of any cycling. However, the objective of the test was accomplished and it was shown that the pump could perform satisfactorily and thermal cycling was not a critical factor. Subsequent tests on other pumps operating in a vacuum, showed no deleterious effects resulting from thermal cycling.

Figure 10 Thermoelectric Pump Mounted on Base Plate

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Pump #	Operating Environment	Operating Time/hrs	Initial Flow gpm	Flow at 100 hrs gpm	Flow as of Column 3	Present Status
1	air	8	5.2	-	-	Discontinued operation as a pump. Elements were thermal cycled. Performance was satisfactory.
2	air	90	8.35 *	-	-	Performance degraded rapidly. Discontinued test at 90 hours and subjected pump to environmental test. Returned pump to test for 300 hours. No damage due to environmental test was noted. Cut pump apart for examination and found thermoelectric damaged by oxygen.
3	vac	1059	5.6	5.1	3.73	Still in test. Performance described in detail in report.
4	vac	702	5.2	4.5	3.4	Still in Test
5	vac	397	4.8	4.3	3.6	Still in Test
6	-	-	-	-	-	Fabrication complete, awaiting test.

* A 4000 gauss magnet was used on Pump number 2. Pump number 3 and 4 used a magnet of nominally 2800 gauss, and pump number 5 used a magnet of nominally 2400 gauss.

FIGURE 11

Status of First Series of Thermoelectric Pumps

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During the fabrication of the elements of pump number 2, the argon atmosphere in which they were fabricated became contaminated with oxygen. The extent of this was not known nor was the extent of the detrimental effect on the PbTe known. The pump using these elements was tested and since the vacuum facilities were not yet available the test was conducted in air. Some difficulties with fitting the magnet pole pieces in place necessitated an improvisation which resulted in a higher field strength than originally planned. This of course boosted the pump capabilities considerably but had no effect on the basic objective. The initial performance of the pump was satisfactory but upon operating 8 hours the performance had dropped to 74% and by 90 hours the performance was only 29%. This rapid decrease was attributed to either the contamination of PbTe during manufacture or during operation or both.

Although the thermoelectrics in pump number 2 had deteriorated electrically, they were assumed to be satisfactory mechanically. Accordingly, the pump was subjected to the standard shock and vibration test in order to obtain a quick evaluation prior to the production of the succeeding pumps. The shock and vibration produced no significant change and the pump was returned to test. Upon starting up, the pump performance was the same as it was before the shock and vibration. With continued operation, the deterioration continued and the curve of performance as a function of time showed no significant change due to removing the pump from the loop and subjecting it to shock and vibration. During 300 additional hours of operation, the performance had decreased considerably, so the pump was removed from test and was dissected for examination. Examination confirmed the presence of oxygen in the PbTe and the degradation in pumping capacity was attributed to this. The bonding between pump throat and electrodes and between the thermoelectric elements and the electrodes and radiator plates were examined and were found satisfactory. The test on pump number 2 demonstrated the need for avoiding oxygen contamination, and showed that the pump was mechanically satisfactory.

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The loop had been fitted with vacuum testing facilities by the time pump number 3 was ready for test. This pump, mounted on the base plate is shown in Figure 10. In this view the instrumentation wires have not yet been connected.

Upon completion of the installation, the bell jar was placed over the pump and was pumped down. A vacuum of less than 1 micron was readily attained. The test was then conducted as usual. The base plate was water cooled so it remained cool but the bell jar became hot. The ΔT was only 240°F initially but by cooling the bell jar with fans and otherwise improving the heat sink, a ΔT of 270 was achieved.

The pressure as a function of flow rate was measured and is plotted in Figure 9. A difference between the calculated and experimental performance is evident. At this point in the pump development program this is not of major concern as several factors which contribute to this difference are known to exist but these have not been evaluated quantitatively yet. Some of the factors in the experimental work which contribute some error pertain to the exact measurement of pressure. For example, the pressure transducers must be calibrated at operating temperature for maximum accuracy and this requires a zero Δp . However there is no convenient way of achieving a Δp of zero at temperature since the pump pressure rises as the NaK temperature rises. The only way of stopping the pump to achieve Δp of zero, is to heat the radiator so that there is no ΔT across the thermoelectric elements. While this may be feasible, it involves considerable effort and time and such was not considered warranted. The factors not used in the calculation include:

- 1) armature reaction which is a shift in field distribution;
- 2) shunting of back emf through the NaK boundary layer;
- 3) reduced magnetic field in the fringe electric field,
- 4) heat and current distribution in the thermoelectric elements.

Factors such as these can be taken into account although some may be difficult and time consuming to evaluate.

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The most important matter however is the long term behavior of the thermoelectric elements. In other applications of PbTe thermoelectric elements the acceptance of the elements was limited by their poor mechanical properties notably lack of tensile strength and rapid deterioration of electrical conductivity at temperatures above about 900°F.

In some applications there is no simple way of alleviating the problems associated with the low tensile strength. However, the pump offered greater latitude in design and mounting and permitted the use of a relatively large, heavy device for maintaining the elements in high compression at all times.

The thermoelectric elements were fabricated by a process different from those previously used, in that an integral element was formed from powders in one step. It was hoped that the "integral" nature of the element would result in better and permanent bonding and thereby maintain high electrical conductivity over a long period of time.

During the first 1000 hours of pump number 3, the behavior was as shown in Figures 12 and 13. Figure 12 shows the temperature at the various significant points as a function of time. Except for minor short term fluctuations resulting from imperfect temperature control equipment, and two occasions of complete shut off due to electric service power failure, the temperatures and thermoelectric ΔT may be regarded as constant.

Figure 13 shows pressure dropping rapidly at first but remaining nearly constant after 500 hours. Likewise the flow rate decreased rapidly at first but decreased much more slowly after 500 hours. At about 900 hours it began to decrease slightly faster. The voltage across the NaK, which is indicative of the current flowing and hence the driving force follows the same pattern. The voltage across the elements increased rapidly at first and the increase diminished at about 500 hours. This voltage rise was not due to an increase in thermoelectrically generated voltage. If it were, a greater pumping capacity would have been produced rather than the observed diminished capacity.

FIGURE 12

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FIGURE 13

Thermoelectric Pump No. 3, 1000 hour test

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However, an increased circuit resistance would reduce the current and the load on the elements so that they would show a greater terminal voltage. The reduction of current would reduce the pump performance. The assumption of an increased circuit resistance is consistent with the observed data. Resistivity measurements have been made through out the circuit and the erratic readings in the 13-10 and 12-10 circuit leads to the belief that the difficulty is in that part of the circuit.

Pumps 4 and 5 were tested in the same manner as number 3. Generally the behavior of these two have been the same as number 3 although pump 4 performance began to deteriorate more rapidly at 535 hours. Concurrently there was a rapid rise in voltage across one pair of thermoelectric elements. Resistivity measurements were made throughout the circuit and erratic behavior was shown in the circuit showing the increased voltage. Pending further analysis, this is tentatively attributed to detrimental stresses in the thermoelectric elements with resultant fractures or cleavages in either the lead telluride or in the iron or at the interface. Pump 4 will be removed from test and cut apart for analysis.

Pump 6 will be tested in the same manner as numbers 3, 4, and 5 but the instrumentation will be slightly different in order to obtain temperature data on different parts of the pump. Also experiments on operation from a separate power source will be conducted.

Laboratory Notebooks B 081101 and B 104151 contain the original experimental data.

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