UNCLASSIFIED

NAA-SR-9486

COPY

129 PAGES

UNCLASSIFIED

MASTER

32999

SNAP 10A

THERMOELECTRIC PUMP DEVELOPMENT

(Title Unclassified)

AEC Research and Development Report

DEFENSE INFORMATION

THIS DOCUMENT CONTAINS INFORMATION AFFECTING
THE NATIONAL DEFENSE OF THE UNITED STATES
WITHIN THE MEANING OF THE ESPIONAGE LAWS, TITLE
18 U.S.C., SECTIONS 793 AND 794. ITS TRANSMISSION
OR THE REVELATION OF ITS CONTENTS IN ANY MANNER
TO AN UNAUTHORIZED PERSON IS PROHIBITED BY LAW.

GROUP 3

*Downgraded at 12-yr intervals;
Not automatically declassified*

ATOMICS INTERNATIONAL

A DIVISION OF NORTH AMERICAN AVIATION, INC.

UNCLASSIFIED

CONFIDENTIAL

1 4697

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, express or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

Printed in USA

Price \$2.45

Available from the

U. S. Atomic Energy Commission
Technical Information Extension,
P. O. Box 1001
Oak Ridge, Tennessee.

Please direct to the same address inquiries covering the procurement of other classified AEC reports.

UNCLASSIFIED

~~**CONFIDENTIAL**~~

Exempt from CCRP Re-review Requirements
(per 7/22/82 Duff/Caudle memorandum)
HA 3/1/04

NAA-SR-9486
SNAP REACTOR,
SNAP PROGRAM
-3679 (34th Ed.)

UNCLASSIFIED

Classification cancelled (or changed to)

by authority of

by

GO

DTIE, date

5/24/73

letter 4/17/73

Frank Feldman

Div of Class. & Wash DC

SNAP 10A

THERMOELECTRIC PUMP DEVELOPMENT

(Title Unclassified)

By

M.A. PERLOW

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

DEFENSE INFORMATION

THIS DOCUMENT CONTAINS INFORMATION AFFECTING THE NATIONAL DEFENSE OF THE UNITED STATES WITHIN THE MEANING OF THE DEFENSE LAWS, TITLE 18 U.S.C., SECTIONS 793 AND 794. TRANSMISSION OR THE REVELATION OF ITS CONTENT IN ANY MANNER TO AN UNAUTHORIZED PERSON IS PROHIBITED BY LAW.

ATOMICS INTERNATIONAL

A DIVISION OF NORTH AMERICAN AVIATION, INC.
P.O. BOX 309 CANOGA PARK, CALIFORNIA

UNCLASSIFIED
~~**CONFIDENTIAL**~~

CONTRACT: AT(11-1)-GEN-8
ISSUED: JUNE 3, 1964

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

GO

DISTRIBUTION

SYSTEMS FOR NUCLEAR AUXILIARY POWER (SNAP)-REACTOR SNAP PROGRAM M-3679 (34th Ed.)

	No. of Copies
Aerojet-General Corporation (NASA)	1
Aerojet-General Nucleonics	1
Aeronautical Systems Division	2
Aerospace Corporation	1
Aerospace Test Wing (AFSC)	1
Air Force Weapons Laboratory	2
AirResearch Manufacturing Company, Phoenix	1
Army Ballistic Research Laboratories	1
Army Materials Research Agency	1
Army Missile Command	1
Army Nuclear Defense Laboratory	1
ARO, Inc	1
Air University Library	1
Argonne National Laboratory	1
Army Combat Developments Command	1
Astropower, Inc.	1
Avco Corporation	1
Battelle Memorial Institute	1
Bendix Corporation (AF)	1
Brookhaven National Laboratory	1
Bureau of Naval Weapons	2
Bureau of Ships	2
Bureau of Yards and Docks	1
California Patent Group	1
Central Intelligence Agency	1
Chicago Patent Group	1
Defense Atomic Support Agency, Sandia	1
Department of the Army	1
Director of Defense Research and Engineering (OAP)	1
Edgerton, Germeshausen and Grier, Inc., Goleta	1
Foreign Technology Division (AFSC)	1
General Atomic Division	1
General Dynamics/Astronautics (AF)	1
General Dynamics/Fort Worth	1
General Electric Company, Cincinnati	1
General Electric Company (FPD)	2
General Electric Company (MSVD)	1
General Electric Company, Richland	2
General Electric Company, San Jose	1
General Electric Company, San Jose (AF)	1
General Technologies Corporation	1
Institute for Defense Analysis	1
Ion Physics Corporation	1
Jet Propulsion Laboratory	2
Johns Hopkins University (APL)	1
Lockheed-Georgia Company	1
Lockheed Missiles and Space Company	1
Los Alamos Scientific Laboratory	1
Martin-Marietta Corporation, Denver	1
Monsanto Dayton Laboratory	1
NASA Ames Research Center	1
NASA Goddard Space Flight Center	2
NASA Langley Research Center	1
NASA Lewis Research Center	4
NASA Manned Spacecraft Center	1
NASA Marshall Space Flight Center	1
NASA Scientific and Technical Information Facility	3
National Aeronautics and Space Administration, Washington	1
NASA Western Operations Office	1
Naval Air Development Center	1
Naval Ordnance Laboratory	2
Naval Postgraduate School	1
Naval Radiological Defense Laboratory	1
Naval Research Laboratory	2
Naval Underwater Ordnance Station	1
Navy Marine Engineering Laboratory	1
New York Operations Office	1
New York Operations Office, Canal Project Office	1
North American Aviation, Inc., Downey	1
Nuclear Metals, Inc.	1
Office of Naval Research	2
Office of the Assistant General Counsel for Patents (AEC)	1
Office of the Chief of Engineers	1
Office of the Chief of Naval Operations	3
Office of the Chief of Naval Operations (OP-03EG)	2
Office of the Chief of Transportation	1
Phillips Petroleum Company (NRTS)	4
Pratt and Whitney Aircraft Division	1
Pratt and Whitney Aircraft Division (NASA)	1
Rand Corporation	1
Republic Aviation Corporation	1
Sandia Corporation	1
School of Aerospace Medicine	1
Union Carbide Corporation (ORNL)	8
USAF Headquarters	1
University of California, Livermore	1
Westinghouse Electric Corporation (NASA)	1
Division of Technical Information Extension	40
AI Library (Includes 2 copies to CPAO, 2 copies to AEC, Washington, 2 copies to COO)	69

NAA-SR-9486

CONTENTS

	Page
I. Introduction and History	9
A. Objectives	12
B. Development Plan	13
II. Thermoelectric Pump Design	15
A. General Theory	15
B. D-C Conduction Pump	17
1. Channel	17
2. Magnetic Field and Circuit Resistance	27
3. Magnet Design	29
C. Thermoelectric Generator Design	33
1. Thermoelectric Elements	33
2. Voltage Required to Meet Pump Requirements	35
D. System Integration Factors	36
III. Test Data and Analysis	45
A. Test Requirements and Description	45
B. Pump Instrumentation	47
C. Method of Analysis	51
D. Pump Data	55
IV. Fabrication and Element Development	83
A. Thermoelectric Element Development	83
1. Standard Pump Element	83
2. Diffusion Barrier Element	89
3. Test Results and Recommendations	98
B. Thermoelectric Element and Pump Fabrication	99
1. Element Fabrication	99
2. Pump Fabrication	104
C. Posttest Examination	109
1. Procedures	110
2. Metallographic Results	111
3. Metallographic Conclusions and Recommendations	124
References	129

TABLES

	Page
1. Values Used in Computing Performance of Pump 010	68
2. Pump 010 Electric Currents.	70
3. Comparison of Performance and Various Electrical Quantities of Pumps 011 and 013	74
4. Electrical Resistance and Seebeck of Cold Pressed and Sintered N-Type PbTe Elements, 3/4 by 2 by 0.170 in.	85
5. Electrical Resistance and Seebeck of Cold Pressed and Sintered P-Type PbTe Elements, 3/4 by 2 by 0.170 in.	85
6. Weight Loss on PbTe Pellets	88

FIGURES

1. Thermodynamic Cycle.	9
2. SNAP 10A Thermoelectric Pump Design Development.	13
3. SNAP 10A Thermoelectric Pump Flight Design Development	14
4. D-C Conduction Pump Powered by a Thermoelectric Generator	15
5. Cross Sectional View of a D-C Conduction Pump	16
6. Thermoelectric Generator	18
7. Cross Section View of Thermoelectric Pump.	18
8. Hydraulic Power Loss as a Function of Length, Cross Sectional Area, and Height-to-Width Ratio.	21
9. Magnetic Breaking Power Loss as a Function of Length, Cross Sectional Area, and Height-to-Width Ratio	21
10. Effective Electrical Length of Channel in Relation to Physical Length	22
11. Power Loss in NaK as a Function of Length, Cross Sectional Area, and Height-to-Width Ratio.	23
12. Power Loss in Channel Walls as a Function of Length, Cross Sectional Area, and Height-to-Width Ratio	25
13. Total Power as a Function of Length	26
14. Total Power Loss as a Function of Cross Sectional Area.	26
15. Total Power Loss as a Function of Height-to-Width Ratio	26
16. Pressure as a Function of Circuit Resistance at Various Magnetic Fields	28

FIGURES

	Page
17. SNAP 10A Thermoelectric Pump Magnet Assembly	30
18. Magnetic Field Measured in the Pump Channel as a Function of Distance "Upstream and Downstream" from the Center.	32
19. Thermoelectric Element Sintered	33
20. Thermoelectric Pump Electric Circuit.	35
21. Temperature Distribution of the Pump to the Hot Junction	39
22. SNAP 10A Thermoelectric Pump Radiator Fin Analysis	41
23. SNAP 10A Flight-Type Pump	42
24. Pump Power vs Channel Height and Magnetic Field	43
25. Pump Power vs Channel Width and Magnetic Field	43
26. Pump Power vs Thermoelectric Thickness	43
27. Prototype I Test Loop Schematic.	46
28. SNAP 10A Pump Acceptance Test Loop	46
29. SNAP 10A Pump Operating in Acceptance Test Loop.	48
30. SNAP 10A Pump Qualification Test Loop	49
31. SNAP 10A Pump Mounted in Qualification Test Loop.	50
32. SNAP 10A Thermoelectric Pump Instrumentation, Front View of N Element	51
33. SNAP 10A Thermoelectric Pump Losses vs Flowrate	53
34. Prototype I Thermoelectric Pump	57
35. Prototype I Thermoelectric Pump Mounted on Base Plate	57
36. Pressure vs Flow, Pump 8	58
37. Flow vs Time, Pumps 7, 8, 10, and 11 Life Tests.	60
38. Pressure vs Flow Characteristics of Pumps FQ2 and FQ4 at 1010°F NaK Temperature	61
39. Pressure and Flow vs NaK Temperature, Pump 010.	63
40. Flowmeter and Wall Voltage Output as a Function of NaK Temperature, Pump 010	63
41. Pressure vs Flow at Indicated NaK Temperatures, Pump 010	64
42. Flowmeter Output and Wall Voltage vs Flow at 800, 900, and 1000°F, Pump 010	65
43. Equivalent Electrical Circuit of D-C Conduction Pump	66
44. Pressure vs Flow at 1010°F NaK Temperature, Pump 010	68

FIGURES

	Page
45. Current as a Function of Flow, Pump 010.	71
46. Load Resistance as a Function of Flowrate, Pump 010	71
47. Thermoelectric Element Terminal Voltage as a Function of Flowrate.	72
48. Pressure vs Flow Characteristics of Pumps 010, 011, 013, 014, and 015.	75
49. Pressure vs Flow Characteristics of Pumps 016, 017, and 018 . . .	77
50. Flow and Wall Voltage as a Function of Thermal Cycles for Pump 011	77
51. SNAP 10A Pump Life Test Data at 1010°F NaK Temperature	79
52. Measured Pressure and Wall Voltage vs Flow at 1010°F NaK Temperature, Pump 011	81
53. Typical Cold Pressed and Sintered Elements.	84
54. Tellurium Vapor from Telluride in Thermoelectric Element (N Element).	92
55. Tellurium Vapor from Telluride (P Element)	93
56. Two P Elements in the Test Fixture After 100-Hr Environmental Test.	95
57. Thermoelectric Element Section Showing Aluminum Foil Barrier in the Iron Layer	97
58. P Element Without Barrier After 100-Hr Environmental Test	98
59. Die Parts for Compacting PbTe Elements.	101
60. Element Bonding Fixture, End View	102
61. Weld Assembly Fixture, End View	106
62. Support Bracket Alignment Fixture, Side View	107
63. Throat Assembly Fixture, Front View	108
64. Photomicrographs of Stainless Throat Brazed to Copper Block With Grade-615 Premabrazed, Pump 11	112
65. Photomicrographs of Diffusion Bonds of Hot Copper to Iron Powder Made With Grade 615 Premabrazed Foil, Pump 11	113
66. Photomicrographs of Hot Side of Iron Powder Adjacent to Hot Side of PbTe, Pump 11	114
67. Photomicrographs Taken of PbTe Between the Centers and Cold Side of the Thermoelectric Material, Pump 11	115

FIGURES

	Page
68. Photomicrographs of Cold Side of Thermoelectric Elements, Pump 11	116
69. Photomicrographs of Premabrazed Joints on Cold Side of the Thermoelectric Elements, Pump 11	117
70. Microprobe Scan of N Element for Copper, Pump 11	120
71. Microprobe Scan of P Element for Copper, Pump 11	121
72. Microprobe Scan of P Element for Lead, Pump 11	122
73. Microprobe Scan of P Element for Tellurium, Pump 11	123
74. Microprobe Scan of P Element for Silver, Pump 11	125

~~CONFIDENTIAL~~

ABSTRACT

The SNAP 10A system and pump requirements are presented to define the developmental objectives of the thermoelectric pump. Design equations and procedures are included along with operating data and their respective analyses. Fabrication problems are discussed, and the procedure for manufacture of both the elements and the pump assembly is included. Posttest examination by metallographic means was performed on pumps subsequent to 1000°F NaK operation.

ACKNOWLEDGMENT

The Project Coordinator wishes to acknowledge the cooperation extended by the following contributors to this report.

K. A. Davis	N. H. Katz
C. T. Armenoff	E. Reed
F. DeProsse	F. L. Henderson

~~CONFIDENTIAL~~

I. INTRODUCTION AND HISTORY

During December of 1960, the SNAP 10 program demonstrated that the use of a dc conduction pump would increase the power of the system from 300 to 500 watts net electrical. The SNAP 2 reactor core was coupled to the radiator-converter by flowing NaK-78 at a reactor outlet temperature of 1000°F. The power necessary to drive the pump was also shown to be compatible with that generated by thermoelectrics and would only involve about 3% of the total power generated.

With the operation of one dc pump proved, the program was redesignated SNAP 10A, and a reference design employing the SNAP 2 reactor and a PbTe converter was adopted. NaK-78 was selected as a coolant primarily because of its vapor pressure and low melting-point characteristics. Additional advantages of the revised SNAP 10 program were more net electrical power, no reactor development costs, and no moving parts, with the exception of flowing NaK. A schematic of the SNAP 10A system is shown in Figure 1.

4-16-63

7561-0032 C

Figure 1. Thermodynamic Cycle

Redirection of the SNAP 10 program initiated a new area of development, the SNAP 10A thermoelectric pump. Various schemes for accomplishing the initial hydraulic objectives (12 gpm of 1000°F NaK-78 against a pressure head of 0.7 psi) were reviewed, and a firm list of ground rules was established. Primarily, this consisted of demonstrating (under actual operating conditions) the operation of a dc conduction pump powered by an integrally mounted thermoelectric material. PbTe was selected as the reference thermoelectric.

With the above objectives in mind, a firm development program was initiated in May 1961. Development was separated into two phases — design and analysis of the pump throat and associated magnet, and thermoelectric element development and pump fabrication. Efforts to develop and fabricate thermoelectric elements were integrated, because development was known to always control fabrication procedures in the past and because of PbTe's weak structural characteristics.

Separate power source testing of pumps verified the design of the throat section and magnet assemblies. A theoretical model for pump performance evolved from this data and previous experiments. At this time, the element development program was yielding thermoelectric compacts low in output but satisfactory enough to construct and demonstrate the feasibility of an integrally mounted thermoelectric pump. A design was established and six pumps fabricated during the ensuing 6 months.

Each of these pumps operated in a 1000°F NaK environment, with performance improving in each model as development commanded changes. At the time the sixth prototype pump was tested, enough data were logged to justify confidence in a full-scale pump design. Also, material development yielded the use of PbSnTe for the P material. PbSnTe exhibited greater stability and strength at temperature with voltage output only slightly lower.

The design of a thermoelectric pump meeting the full-flow conditions (now changed to nominally 1 psi at 13 gpm) and utilizing PbTe as the N and PbSnTe as the P materials was initiated. Aluminum radiators and compressive loading on the thermoelectric elements were both used in the second prototype pump.

At this time (December 1961) the converter development program changed reference design thermoelectric materials. Silicon-germanium replaced PbTe, and a study immediately followed to determine its application feasibility to pump design.

Analysis showed that use of SiGe was practical for the SNAP 10A pump application, and a backup effort was initiated. Pump throat and magnet sections remained essentially unchanged from the PbTe pump, and efforts centered on the thermoelectric element and fabrication processes. The first pumps fabricated yielded encouraging results — about 50% of design output. However, they pointed to a more serious problem: thermal stresses and associated element failure. Redesign centered about floating the thermoelectric elements between flexible connectors. Four of these pumps demonstrated the potential and problem areas of SiGe. In May 1962 the majority of the flight design objectives were being achieved. A comparison between the two designs was made, and the SiGe effort was dropped, the results indicating that the SiGe pump would weigh approximately 10 lb more than its competitor and that associated development times and costs were higher. Because it deals only with the flight design, this report will no longer reference the SiGe thermoelectric pump.

Five Prototype II pumps were fabricated, each demonstrating various phases of the flight design objectives. Included were long-term stability tests in excess of 6000 hr at temperature, thermal cycle tests, and environmental shock and vibration qualification testing. The data logged on these pumps both verified the theoretical model and provided the basic information necessary to establish the final flight design. By July 1962, pumps had operated at design conditions for over 15,000 hr.

Prior to firming design of the flight pump, all associated problems concerning system integration and performance were considered. Preorbital flow requirements and degradation characteristics were given prime consideration to ensure satisfactory system output during all phases of the SNAP 10A mission. The flight design selected incorporated all of the features of developmental pumps and was scaled up to meet the final hydraulic specification (i.e., 13.2 gpm against a pressure head of 1.1 psi of 1010°F NaK).

Drawings and fabrication specifications were released for the flight design in December 1962. Now included were flow instrumentation, a single support

scheme where pump throat and magnet assembly formed an integral unit, tapered radiator fins for weight reduction, low-flow power taps, and slightly modified geometry to ensure no interference. Pumps were immediately fabricated and tested according to defined acceptance and qualification test specifications. Data enabled project personnel to make minor design changes as final flight pumps came closer to reality.

During 1963, a total of 12 flight pumps for SNAP 10A were completed and tested. All of the major objectives as defined in the pump specification for the flight system were obtained. A total of 33,000 hr of pump testing was logged up to December 1963, establishing data for the present qualification program and for future design.

A. OBJECTIVES

To list all of the interim objectives of the pump program is not consistent with the final product. Hence, the objectives detailed below reflect the final revised flight objectives consistent with the overall SNAP 10A system as of December 1963.

The primary objectives of the pump are:

- 1) Deliver 13.2 gpm of NaK-78 at 1010°F
- 2) Develop a net pressure 1.1 psi at design flow
- 3) Deliver 0.48 gpm of 100°F NaK-78 to the system with an auxiliary power unit supplying 40 amp to the pump
- 4) Weigh no more than 22 lb
- 5) Have a life of one year with flow being no less than 10.5 gpm at that time against the system hydraulic characteristic
- 6) Withstand the loads imposed by vehicle launch (shock, vibration, and acceleration) and retain at the inception of orbital operation the minimum full flow requirements
- 7) Have a means for measuring flow
- 8) Be compatible with operation above the reactor head with no shielding provided, fitting geometrically into the package
- 9) Provide for self-contained thermoelectric power generation and have the capability for rejecting waste heat

B. DEVELOPMENT PLAN

At the beginning of the program, all phases of pump design had to be investigated to determine critical development tasks and associated emphasis. The schedule and breakdown of major areas of development are shown in Figure 2. Although theory was supposedly defined for the operation of dc liquid metal pumps, reports were reviewed, past data analyzed, and specific tests devised to verify the analytic model.

The conclusion of the first development phase produced the analytic model which defined pump throat geometry and the required magnetic field. Also, the critical areas of thermoelectric element development, pump fabrication and their effect on the overall design were recognized and proper emphasis established.

The definition of a qualified flight pump imposed test conditions difficult to simulate. Programmed thermal cycles from ambient to 1000°F temperature conditions, flow and pressure measurement with accuracies of $\pm 3\%$ at temperature, 5000 hr vacuum stability tests — all required detailed test design. The

Figure 2. SNAP 10A Thermoelectric Pump Design Development

Figure 3: SRM Top Thermoelectric Pump Flight Design Development

II. THERMOELECTRIC PUMP DESIGN

A. GENERAL THEORY

The thermoelectric pump consists of a direct-current, conduction liquid metal pump powered by a thermoelectric generator. The thermoelectric generator obtains its heat from the liquid metal being pumped and delivers electrical energy directly to the conduction pump. The nature of the conduction pump and the thermoelectric generator make an integral design feasible, and such a design is favored by the inherent low electrical transmission losses.

The principle of operation is illustrated in Figure 4.

4-7-64

7561-01168

Figure 4. D-C Conduction Pump Powered by a Thermoelectric Generator

A d-c conduction pump consists of a duct or channel with electrodes on the two opposite sides so that an electric current can be passed through the liquid metal normal to the desired direction of flow. A magnetic field, also passing through the liquid metal in the region traversed by the electric current, and normal to the current and flow causes a force on the liquid metal in accordance with the well-known force relation $F = BI\ell$ where F is the force on the conductor, B is the magnetic field, I is the current, and ℓ is the width of the channel, i.e., the length of path in the liquid metal through which the current passes. Since

pressure is force per unit area, the equation is converted to the form used in pump design and analysis:

$$P = \frac{BI}{b}$$

where

P = the pressure developed, and

b = the channel height.

The conduction pump is illustrated in Figure 5, which shows a cross section through the channel. The pressure is in the direction normal to the section shown and is directed toward the viewer.

4-7-64

7561-01169

Figure 5. Cross Sectional View of
a D-C Conduction Pump

The thermoelectric generator consists of a slab of thermoelectric material, one face of which is in contact with the heat source and the other face with a heat sink. The voltage generated is the product of the Seebeck coefficient of the thermoelectric material and the temperature difference between the two faces;

$$E = S\Delta T$$

The power capability of the element is a function of the voltage developed and the internal resistance, which is governed by the resistivity of the material and the element geometry. The operation is illustrated in Figure 6.

To form the thermoelectric pump, the generator illustrated in Figure 6 is superimposed on the pump illustrated in Figure 5 in the manner shown in Figure 7. Here, four elements are so mounted that the pump electrodes also serve as heat conductors to form the heat source for the elements. A radiating fin attached to the opposite faces of the elements radiates heat to space, its heat sink. By joining the radiating fins electrically as shown in Figure 7, the electric circuit is completed, so that the voltage generated by the thermoelectric elements causes a current to flow through the liquid metal and thereby develops pressure. The electric current path is shown by the closed loops. The heat flow is flowing out through the radiating fins.

The principle of the pump has been illustrated, and the fundamental operation as presented is relatively simple. There are, however, many interdependent additional factors and these complicate the design and analysis. To demonstrate the design procedure and illustrate the parameters involved, the analysis is separated into four parts:

- 1) D-C conduction pump
- 2) Thermoelectric generator
- 3) Integration of the generator and pump
- 4) Additional pump functions — separate power operation from batteries, and flowmeter

B. D-C CONDUCTION PUMP

The SNAP 10A system requires a pump to deliver 1010°F NaK at a flow rate of 13.2 gpm at a pressure of 1.1 psi. This basic requirement is the starting point for the pump design. Weight and space limitations for the pump are not so stringent as to impose a specific design feature. The design is based primarily on achieving an efficiency as high as practical.

1. Channel

The channel selected for the flight design is formed of 1- by 0.093-in. wall Type 347 stainless steel tubing. The center section is drawn to reduce

4-7-64

7561-01170

Figure 6. Thermoelectric Generator

4-7-64

7561-01171

Figure 7. Cross Section View of Thermoelectric Pump

wall thickness and formed to the width and height dimensions shown. A 3-in. dimension represents the length over which the electrodes contact the channel.

The efficiency, η , equals power output divided by power output plus power losses. The power output is $1.1 \text{ psi} \times 13.2 \text{ gpm} \times 0.434 = 6.3 \text{ watts}$. For the flight design, the sum of the power losses is 9.59 watts, giving an efficiency of 39.7%. It is of interest to examine the various power losses and determine the factors governing them. The power losses in a conduction pump are attributed to:

- a) Hydraulic losses
- b) Magnetic braking due to the motion of the NaK relative to the magnetic field
- c) Electrical resistance losses in the NaK
- d) Electrical resistance losses in the channel walls.

The first two losses listed result in a pressure loss. Hence, the pump electrical power must be increased to accommodate the pressure loss. This means that, in addition to the 1.1-psi system pressure requirement, the hydraulic pressure drop of 0.152 psi and the magnetic braking pressure drop of 0.258 psi must be included in the electrical design requirements. The total pressure requirement is 1.51 psi.

a. Power Loss — Hydraulic

In the flight design this loss is 0.87 watts. The flow in the channel is turbulent, so the applicable pressure loss equation is:

$$\Delta p = \frac{2f\rho v^2 L}{gD}$$

where

$$f = \text{friction factor} = 0.079 R_e^{-0.25}$$

$$R_e = \text{Reynolds number} = DV\rho/\mu$$

$$D = 2b\ell/b + \ell$$

$$b = \text{channel height, } 0.4 \text{ in.}$$

$$\ell = \text{channel width } 1.0 \text{ in.}$$

V = velocity 127 in./sec

ρ = density 0.0268 lb/in.³

μ = viscosity 0.46 lb/hr-ft

The length of the round tubing-to-rectangular channel transitions is great enough that the angle is small, and the losses in the transitions are substantially the same as for an equivalent length channel. Hence, a separate treatment of these is unnecessary. The hydraulic losses are shown in Figure 8. The losses vary with length, cross-sectional area, and height-to-width ratio as shown. For minimum loss, the channel should be square and as short and as large in cross section as practical. However, the curves also show that within practical ranges the values are not critical. Moreover, the hydraulic power loss is only 9.1% of the total power loss, so the selection of these dimensions is governed primarily by other factors.

b. Power Loss — Magnetic Braking

This power loss is of a less familiar nature than the other losses. It is the result of emf generated in a conductor (NaK) moving in a magnetic field with the resulting current flow through the conductor (a resistance) producing a power loss. The current so generated, which flows through the NaK in the region defined by the electrodes, is opposite in direction to the applied current used to drive the pump. The product of the resultant current and the emf generated is the power developed by the pump. However, not all the current generated by the moving conductor (NaK) interacts with the driving current. The currents which flow outside the region defined by the electrodes are "short circuited," closed current paths are formed and energy is dissipated in I^2R losses. The equation which expresses this magnetic braking power loss is

$$P_{mb} = \frac{0.27 \times 10^{-9} B^2 Q^2}{\rho_n b}$$

where

B = magnetic field, 2400 gauss

Q = flowrate, 834 cm³/sec

4-7-64

7561-01172 4-7-64

Figure 8. Hydraulic Power Loss as a Function of Length, Cross Sectional Area, and Height-to-Width Ratio

7561-01173

Figure 9. Magnetic Breaking Power Loss as a Function of Length, Cross Sectional Area, and Height-to-Width Ratio

ρ_n = NaK resistivity, 72×10^{-6} ohm cm

b = channel height 1.015 cm [0.4 in.].

Upon substitution of the values given above, the power loss is 1.48 watts, 15.4 % of the total power loss. Figure 9 shows the effect of varying the length, cross-sectional area, and height-to-width ratio. As the equation shows, height b is the only dimension involved, so the effect of cross-sectional area changes and height-to-width ratio changes are of influence only as b is involved. The power loss is, and remains, small for any dimensional variations over a practical range. The dominant factor in this loss is the magnetic field strength. At values significantly higher than 2400 gauss, the loss becomes large, as will be shown later.

c. Power Loss — Electrical, NaK Resistance

The flow of the electric current through the NaK in the region defined by the electrodes produces an electric power loss expressed by the relation

$$P_n = I_n^2 R_n,$$

where

I_n = current through the NaK

R_n = resistance of the NaK.

The resistance of the NaK is given by the relation

$$R_n = \frac{\rho_n \ell}{bL^*},$$

where

ρ_n = NaK resistivity 72×10^{-6} ohm cm

ℓ = channel width 2.54 cm [1 in.]

b = channel height 1.015 cm [0.4 in.]

L^* = channel length, electrical, 8.76 cm [3.45 in.]

As the result of current flowing through the channel in the region outside the 3-in. length established by the electrodes, the effective electrical length is greater than the physical length. This is illustrated in Figure 10. For the 3-in. length, the effective electrical length is 3.45 in., as determined experimentally. In any subsequent calculation involving channel resistance, the effective electrical length will be used. This fringing is a function of the channel width and is independent of channel height. The relation $L^* = L + 0.45 \ell$, is valid over the range of interest. It is to be noted that the extent of this fringing is much less than the magnetic field fringing, and (in general) the magnetic field interacts with the current flowing in this extended region, producing pressure. Hence, in the normal design, fringe current flowing in this region does not constitute a power loss, as one might think.

Figure 10. Effective Electrical Length of Channel in Relation to Physical Length

Returning to the matter of determining power loss in the NaK, we determine the current, I_n , by rearranging the basic pump equation, obtaining

$$I_n = \frac{10 Pb}{B} ,$$

where

P = pressure required (1.04×10^5 dynes/cm² [1.51 psi])

B = magnetic field (2400 gauss).

Then the power loss in the NaK is

$$P_n = \frac{100 P^2 b^2}{B^2} \times \frac{\rho_n \ell}{bL} = \frac{100 P^2 \rho_n}{B^2} \times \frac{b\ell}{L} .$$

This power loss, 3.98 watts or 41.6% of the total power loss, is a large factor affecting the pump efficiency. The effect of varying the length, cross-sectional area, and height-to-width ratio is shown in Figure 11. The graph shows that so far as this source of power loss is concerned, height-to-width ratio is not involved, and the losses increase with cross-sectional area and decrease with length, becoming very high for a very short length pump.

d. Power Loss, Electrical, Wall Resistance

The passage of current through the channel walls results in a power loss proportional to the product of resistance and square of the current. The

Figure 11. Power Loss in NaK as a Function of Length, Cross Sectional Area, and Height-to-Width Ratio

4-7-64

7561-01175

channel walls should be as thin as possible to minimize this loss, but the minimum thickness is determined by structural factors, which dictated 0.02 in. of type 347 stainless steel. The loss in the two walls carrying current from the electrodes to the NaK, 0.56 watts, is only 5.8% of the total and will be neglected for purposes of determining effect of channel dimensions. The value, however, will be included in the summation of all losses.

The loss in the other two walls, i. e., those shunting the current through the NaK, is relatively large. The basic equation for this power loss is

$$P_w = \frac{E_w^2}{R_w} ,$$

where

E_w = voltage across the wall shunting the NaK (voltage from electrode to electrode)

R_w = resistance of the wall, $\rho_w \ell / TL$

ρ_w = type 347 stainless steel resistivity, 107×10^{-6} ohm cm

T = channel thickness 0.1015 cm, [0.4 in.] (both walls).

The wall voltage E_w is the sum of the voltage drop in the NaK, $I_n R_n$, and the counter emf, $BQ \times 10^{-8}/b$. Substituting these terms into the power loss equation and using for I_n the relation

$$I_n = \frac{10 Pb}{B} ,$$

we obtain

$$P_w = \frac{100 P^2 \rho_n^2 T}{B^2 \rho_w} \times \frac{\ell}{L} + \frac{20 \times 10^{-8} P \rho_n Q T}{\rho_w} \times \frac{1}{b} + \frac{10^{-16} B^2 Q^2 T}{\rho_w} \times \frac{L}{b^2 \ell} ,$$

where all values are the same as previously given.

Upon substituting the values we obtain

$$P_w = \frac{0.924 \ell}{L} + \frac{1.182}{b} + \frac{0.379 L}{b^2 \ell} .$$

The power loss in the walls is 2.70 watts, 28.2% of the total. The variation of wall loss with channel length, cross-sectional area, and height-to-width ratio is shown in Figure 12. The dominant factor here is the cross-sectional area. At values much less than 0.4 in.^2 , the loss becomes large. The loss is much less affected by changes in height-to-width ratio. The loss is nearly independent of length.

4-7-64

7561-01176

Figure 12. Power Loss in Channel Walls as a Function of Length, Cross Sectional Area, and Height-to-Width Ratio

Figures 13, 14, and 15 show the total power loss as a function of the length, cross-sectional area, and height-to-width ratio. Figure 13 shows that the pump length is about as short as it can be without incurring excessive losses. Figure 14 shows that the pump cross-sectional area is very near the minimum loss value. Figure 15 shows that the height-to-width ratio is about as low as it can be without incurring high losses.

In summary, the curves show that the dimensions selected for the reference design are satisfactory so far as efficiency is concerned, and none of the dimensions are critical. By lengthening the pump and using a square cross-section channel, the efficiency can be increased to about 45%. However, there are several other factors involved in the selection of dimensions, and at the time the flight design was established the satisfaction of the other requirements was considered more important than a gain of 5% in conduction pump efficiency.

4-7-64

7561-01177

Figure 13. Total Power Loss as a Function of Length

4-7-64

7561-01178

Figure 14. Total Power Loss as a Function of Cross Sectional Area

4-7-64

7561-01179

Figure 15. Total Power Loss as a Function of Height-to-Width Ratio

2. Magnetic Field and Circuit Resistance

The choice of magnetic field strength is dependent upon the circuit resistance. A portion of the circuit resistance, the channel, is determined by the dimensions of the channel. In selecting channel dimensions, a value of magnetic field of 2400 gauss was used when the field strength was involved. As indicated in the introductory remarks, many of the factors in the pump design are interdependent, hence an iterative process is used. Having selected channel dimensions, the equation for pressure developed is

$$P = \frac{BE}{10 b R} - \frac{B^2 Q \times 10^{-8}}{10 b^2 R} - \frac{B^2 Q \times 0.27 \times 10^{-9}}{B \rho_n} ,$$

where

B = magnetic field, gauss

E = open circuit thermoelectric generator voltage ($S\Delta T$), 60×10^{-3} volts

b = channel height 1.015 cm (0.4 in.)

R = total circuit resistance in ohms. (Channel resistance + bus-bar resistance + thermoelectric element resistance, two P elements in parallel in series with two N elements in parallel.)

Q = flowrate $835 \text{ cm}^3/\text{sec}$ (13.2 gpm)

ρ_n = NaK resistivity 71×10^{-6} ohm cm.

Figure 16 shows the pressure developed as a function of circuit resistance R for a range of magnetic field strengths from 500 to 3000 gauss. This graph shows that 2400 gauss will give 1.25 psi* with a circuit resistance of 84 μ -ohm.

A magnetic field higher than 2400 gauss would add relatively little to the pump performance, and beyond 2800 gauss the performance would decrease as indicated in the curve for 3000 gauss. Moreover, the higher magnetic field requires a heavier magnet. The steepness of the curves at the higher field

*Note that the equation for the pressure developed considered electrical quantities only. The hydraulic loss, 0.152 at 13.2 gpm, must be added to the desired pressure of 1.1 psi to give 1.25 psi. This is the pressure for which the electrical factors must be selected.

4-7-64

7561-01180

Figure 16. Pressure as a Function of Circuit Resistance at Various Magnetic Fields

strengths indicates a relatively high sensitivity of performance to circuit resistance changes. This is an unfortunate circumstance, as it is a significant factor in the degradation problem.* Obviously, a low magnetic field pump is relatively insensitive to circuit resistance changes as shown in Figure 16.

However, a field strength low enough to be of value in this manner is too low to produce the required pressure. The value 2400 gauss[†] is nearly optimum for the the reference design. The exact value is not critical as the curves show. For example, over the range from 2000 to 2800 gauss the pressure changes by only 0.15 psi. This relative insensitivity to magnetic field exists at the high flow rates, i.e., around 13.2 gpm, the design value. At zero velocity the pressure is directly proportional to the field strength.

*Pump performance degradation is primarily the result of increased thermoelectric generator resistance as a function of time.

†The specifications call for establishing a magnetic field of 2560 gauss in manufacturing. The difference allows for a decrease in field strength from 2560 gauss at room temperature to 2400 gauss at the operating temperature.

As indicated above, the maximum circuit resistance which will result in an adequate pressure is 84 μ -ohm. When the reference design was selected, a value of 80 μ -ohm was assumed. However, with improved element fabrication and assembly technology, the circuit resistance of typical pumps is in the range of 65 to 70 μ -ohm. As a result, a higher pressure is developed.

3. Magnet Design

A number of factors are involved in selection of the magnet design. Weight is one of the more important, since the magnet accounts for approximately 30% of the total pump weight. Shape is important, because in the pump the electrical and thermal circuits must share space. Temperature effects must be considered, since the magnet must be in the vicinity of the 1010°F NaK components and be mechanically attached to the NaK channel for physical support. Reasonable effort in minimizing heat transfer to the magnet will result in a magnet temperature of the order of 550°F. Operation in a high nuclear radiation field is another consideration, since in the SNAP 10A system the pump is mounted on top of the nuclear reactor.

All the requirements can be adequately met by selection of Alnico 5 magnet material which has a maximum energy product of 5×10^6 gauss-oersteds. Special grades of Alnico 5 and a few other Alnico materials have energy products as high as 7.2×10^6 gauss-oersteds. Use of these would result in a weight saving.

Conventional commercial Alnico 5 magnets were selected for the flight design because they were satisfactory and readily available. The magnet assembly is illustrated in Figure 17.

The design equations are

$$\frac{B_d}{H_d} = \frac{F A_g L_m}{f A_m L_g}$$

and

$$B_g = \frac{B_d A_m}{F A_g},$$

where

A_g = gap area, 1.8 in.²

L_g = gap length, 0.5 in.

4-7-64 7561-01181

Figure 17. SNAP 10A
Thermoelectric Pump
Magnet Assembly

A_m = magnet cross-sectional area 1.63 in.²

L_m = magnet length 5.7 in.

f = leakage constant 1.2

F = leakage constant 4.1

B_d = value obtained from demagnetization curve for magnet material,
Alnico 5

H_d = value obtained from demagnetization curve for magnet material,
Alnico 5

B_g = field strength in the gap, gauss

Substitution of the above values into the equation gives

$$\frac{B_d}{H_d} = 43 \quad .$$

From the curve for Alnico 5 we read

$$B_d = 11900 \text{ gauss};$$

$$H_d = 280 \text{ oersteds}.$$

Substituting these values into the equation for field strength we obtain

$$B_g = 2630 \text{ gauss}.$$

This value is sufficiently above the nominal reference design's specified value of 2560 to allow for manufacturing tolerances and stabilization. In practice, the magnet assembly is fully magnetized to saturation in place on the pump. Then the field strength is reduced by a standard demagnetizing procedure to the nominal value of 2560 gauss.

Note that the value of F used is higher than would be computed for the geometry indicated in Figure 17. In the magnet assembly shown, the value of F is much smaller and the resulting magnetic field is of the order of 3000 gauss. However, in use on the pump, the magnetic field leakage is increased substantially by the iron in the thermoelectric elements. Accordingly, the magnet field available in the gap (channel) is reduced. It will also be noted that the load line, B_d/H_d is steeper than desired. The value 43 does not correspond to the maximum energy product. However, making allowance for the demagnetizing effect of the pump currents moves the operating point and the line toward the optimum value of 20. A value of 20 corresponds to the maximum utilization of the magnet.

The magnetic field profile is shown in Figure 18. This shows that within the region defined by the electrodes, the field is sufficiently uniform. The field outside this region is of concern in the flowmeter and prereactor startup applications to be discussed in another section.

4-7-64

7561-01182

Figure 18. Magnetic Field Measured in the Pump Channel as a Function of Distance "Upstream and Downstream" From the Center

C. THERMOELECTRIC GENERATOR DESIGN

The basic requirement of the thermoelectric generator is 28.75×10^{-3} volts at 534 amp at the wall of the pump channel. In computing the generator requirements, an allowance must be made for the transmission line (bus bar) loss.

The generator consists of a thermoelectric element with contacts, and a heat source and sink arranged on the dc conduction pump, as illustrated in Figure 7.

Continuing the approach used in describing the conduction pump, this discussion describes the reference design and then discusses the possible variations.

1. Thermoelectric Elements

Discussion of the thermoelectric elements is directed primarily toward the electrical aspects. The thermal aspects will appear in the next section which deals with heat flow and radiator design. Fabrication of the thermoelectric element is also described in a later section. Here we are concerned with the basic dimensions and materials as related to Seebeck coefficient and resistivity. The thermoelectric material is PbTe which is contacted by iron. The arrangement and pertinent dimensions are as shown in Figure 19.

4-7-64

7561-01183

Figure 19. Thermoelectric Element Sintered

The thermoelectric material has the following properties:

N type (TEG-3N, 3MCo.)

$$S = 100 \times 10^{-6} \text{ volts/}^\circ\text{F at } 800^\circ\text{F}$$

$$\rho = 920 \times 10^{-6} \text{ ohm in. at } 800^\circ\text{F}$$

P type (TEG-3P, 3MCo.)

$$S = 100 \times 10^{-6} \text{ volts/}^\circ\text{F at } 800^\circ\text{F}$$

$$\rho = 1110 \times 10^{-6} \text{ ohm in. at } 800^\circ\text{F}$$

The data supplied by the manufacturer indicates a higher Seebeck coefficient, S , but the value used here is determined on completely fabricated assemblies. The resistivity value was obtained by using the room temperature value supplied by the manufacturer and applying a temperature correction factor. The values used must be regarded as nominal values.

The iron used to contact the thermoelectric material is compacted powdered iron. The value of resistivity, ρ_{Fe} , for the iron in this form is unknown. For solid iron at 800°F , however, the value is 18×10^{-6} ohm in. We may assume the powdered iron has an 11% higher resistance from void fraction data and use 20×10^{-6} ohm in. for the powdered iron.

For computations of element resistance, the average temperature 800°F is used.

$$R_N = \frac{\rho_n^t}{wL} = \frac{9.2 \times 10^{-4} \times 10^{-1}}{0.89 \times 3} = 34.5 \times 10^{-6} \text{ ohms} .$$

$$R_{\text{Fe}} = \frac{\rho_{\text{Fe}}^t}{wL} = \frac{20 \times 10^{-6} \times 64 \times 10^{-3}}{0.89 \times 3} = 0.48 \times 10^{-6} \text{ ohms} .$$

By experiment it has been shown that a contact resistance of approximately 8×10^{-6} ohms exists in these elements. For the N element, the total element-with-contact resistance is 43×10^{-6} ohms.

$$R_P = \frac{\rho_p^t}{wL} = \frac{11.1 \times 10^{-4} \times 10^{-1}}{0.89 \times 3} = 41.6 \times 10^{-6} \text{ ohms} .$$

Adding the iron and contact resistance, gives a total element-with-contact resistance of 50×10^{-6} ohms.

2. Voltage Required to Meet Pump Requirements

The transmission line or bus bar consists mainly of a portion of the radiator. This resistance, at 600°F (the nominal radiator base operating temperature) is 18×10^{-6} ohms. The electrodes contacting the channel walls have 0.87×10^{-6} ohms. The electrical circuit is as shown in Figure 20.

NOTE: RESISTANCES ARE INDICATED IN MICROOHMS, 10^{-6} OHMS; VOLTAGES ARE INDICATED IN MILLIVOLTS, 10^{-3} VOLTS; ALL VALUES ARE AT STANDARD OPERATING TEMPERATURE.

4-7-64

7561-01184

Figure 20. Thermoelectric Pump Electric Circuit

To determine the open-circuit thermoelectric-element voltage, the voltage drop in the bus-bar and element resistances must be added to the wall voltage requirement. The wall voltage required, 28.75×10^{-3} volts, has been computed to the inside of the channel. The sum of the resistances in the remainder of the circuit is 59.68×10^{-6} ohms. At a current of 534 amp, the

voltage drop is $534 \times 59.68 \times 10^{-6} = 31.9 \times 10^{-3}$ volts. The thermoelectric elements must generate an emf of $28.75 \times 10^{-3} + 31.90 \times 10^{-3} = 60.55 \times 10^{-3}$ volts. Using the relation $E = S\Delta T$, we have

$$\Delta T = \frac{60.55 \times 10^{-3}}{200 \times 10^{-6}} = 302^{\circ}\text{F} \quad .$$

This is a simplification, since the thermal conductivities of the N and P elements are not identical, hence the ΔT 's will not be identical. For purposes of this discussion, however, this is sufficiently accurate.

The elements, as described, will provide sufficient power to the conduction pump to meet the pumping requirement, if the average thermoelectric temperature is about 800°F (value used for the calculations), and a temperature difference across the thermoelectric material is at least 302°F . The matter of achieving this temperature difference follows.

The sum of all the resistances shown in Figure 20 (Equivalent Circuit) is 77.44×10^{-6} ohms. This is slightly better than the value (84×10^{-6} ohms) required as shown in the section on magnetic field and circuit resistance.

D. SYSTEM INTEGRATION FACTORS

The primary consideration in integrating the pump to the system is to ensure operation at design conditions within the boundary limitations imposed. The radiator design is paramount because of the restricted area for mounting and the associated high-temperature components atop the reactor.

The design of the pump radiator fins is not a straight-forward solution because of the heat input from the reactor head, manifold piping, and control-element drive motors. To demonstrate the methods used, this section of the report will deal with the equations and a representative hypothesis. In actuality, a digital computer was used wherein all the equations, their interdependency and the design boundary conditions were solved simultaneously to arrive at the flight-design configuration.

Before the fin can be designed, the total heat and base fin temperature must be calculated. With the required thermoelectric ΔT of 302°F established and a NaK inlet temperature of 1010°F provided, the following equations were used to

obtain the fin input. Since a computer was used for pump optimization, a variation of the critical geometric parameters and their effect on the design will be presented to give the reader an insight to the associated tradeoffs.

$$Q_{\text{rejected}} = \frac{\Delta T_{\text{TE}}}{\text{TE thermal resistance}} + IT_{\text{cj}}S + \frac{I^2 (R_N + R_P)}{2}$$

(conduction heat) (Peltier Heat) (Joule heat)

where

T_{cj} = temperature at cold junction ($^{\circ}\text{F}$)

R_N = electrical resistance of negative TE element

R_P = electrical resistance of positive TE element

K = average conductivity $K_P + K_N/2$

A = thermoelectric area.

The thermal resistance of the thermoelectric is defined by the geometry established from the electrical analysis and the material properties.

$$R_{\text{TE}} = \frac{X}{KA} = \frac{0.1}{(0.014) * (2.74)} = 2.6^{\circ}\text{F/watt} ,$$

therefore, the conduction heat is

$$Q_c = \frac{\Delta T}{R_{\text{TE}}} = \frac{302^{\circ}\text{F}}{2.6^{\circ}\text{F/watt}} = 464 \text{ watts} .$$

The Peltier heat is equal to

$$Q_P = (534) 1090 (200 \times 10^{-6}) \cong 116 \text{ watts} .$$

*Reference 1

The Joule heat through the thermoelectric is

$$Q_j = \frac{I^2 (R_N + R_P)}{2} = \frac{(534)^2 (25 \times 10^{-6} + 21.5 \times 10^{-6})}{2} = 6.6 \text{ watts} ,$$

where

$$R_N = 21.5 \times 10^{-6} \Omega$$

$$R_P = 25 \times 10^{-6} \Omega$$

$$Q_{\text{rejected}} = 464 + 116 \pm 7 \cong 587 \text{ watts} .$$

$$\begin{aligned} \text{Electrical pump output} &= IS\Delta T - I^2 (R_N + R_P) \\ &= 32.1 - 13.2 \\ &= 18.9 \text{ watts} \end{aligned}$$

Therefore, the total heat from the NaK = 587 + 19 = 606 watts.

At the design flowrate of 13.2 gpm of NaK at 1010°F, the temperature drop associated with the transfer of 606 watts of heat is approximately 2°F. For purposes of practicality, this heat source was assumed infinite at 1009°F.

The total heat being dissipated from the NaK channel can be assumed to be divided equally, one-half being directed through the P elements and the other half through the N elements. Losses from the NaK channel on the sides tangent to the magnet pole pieces are negligible in vacuum operation.

Calculating the heat transfer coefficient of the NaK from Reference 2, the ΔT across the NaK film is

$$\Delta T_{\text{NaK}} = \frac{Q}{2hA} = \frac{606 \times 3.413}{2 \times 2940} \times \frac{144}{1.2} = 42^\circ \text{F} .$$

Similarly, the ΔT across the stainless steel tube was calculated.

$$\Delta T_{\text{ss}} = \frac{Q}{2 K_{\text{ss}} A} = \frac{606 \times 3.413}{2 \times 13.2} \times \frac{0.20 \times 144}{12 \times 1.2} = 15.7^\circ \text{F} .$$

The temperature distribution in the copper electrodes adjacent to the stainless steel channel was obtained by dividing the cross-sectional area into four equal nodes and performing a heat balance. No losses by thermal radiation from the copper to space were assumed to occur, as the emittance of polished copper is $\bar{\epsilon} \approx 0.05$ and the interchange medium of the closely mounted magnet operates at 600°F. The results from the program indicated that, for design purposes, the copper electrode hot-junction temperature could be considered a constant because of the high thermal conductivity and the decreasing heat flux toward the exposed surface. Figure 21 depicts the temperature distribution of the pump to the hot junction.

Figure 21. Temperature Distribution of the Pump to the Hot Junction

As described in Section IV, the only successful means found for satisfactorily bonding the PbTe thermoelectric elements was with iron shoes, hence, the temperature drop across these surfaces must be considered. Each iron shoe, nominally 0.030 in. thick, was fabricated of 70% theoretical density powdered electrolytic iron. The ΔT was calculated to be

$$\Delta T_{Fe} = \left(\frac{Q}{4}\right) \frac{Fe}{0.7 KA} = \frac{606}{4} \times \frac{0.030 \times 144 \times 3.413}{12 \times 0.7 \times 27 \times 2.73} = \sim 4^{\circ}F$$

The base temperature of the radiator can now be calculated by subtracting the temperature drops of the components described from the 1009°F NaK coolant. A summation of these ΔT 's is tabulated below.

NaK film	42°F
Stainless steel wall	16°F
Copper electrode	21°F
Hot junction iron shoe	2°F
Thermoelectric element	302°F
Cold junction iron shoe	<u>2°F</u>
Total temperature drop	385°F

$$\text{Radiator base temperature} = 1009 - 385 = 624^{\circ}\text{F}.$$

In the design of the radiator, the following boundary limits and assumptions were made:

- 1) The height of the fin is fixed at 6.85 in.
- 2) Surface emissivity $\epsilon = 0.90$
- 3) Effect of fin edges on heat transfer is negligible
- 4) Sink temperature = 100°F
- 5) Fin material 1100 type aluminum
- 6) Maximum allowable fin length is fixed at 8.5 in.

Both rectangular and triangular profile fins were investigated for minimum weight. Methods of fin analysis described in Reference 3 and 4 were employed. In all cases considered, the triangular profile fin gave the lightest weight. Also, calculations were performed to determine the heat input from the reactor head, manifold piping, and reflector drive motors. The heat input was established at 100 watts maximum. On the bases of these criteria, a fin capable of rejecting 700 watts at a base temperature of 624°F was designed. Figure 22 is a plot of a triangular fin showing the minimum weight, design length, and base thickness. Note that the minimum weight fin occurs at a length of ~8 in.

To complete the magnetic circuit, cutouts in the radiator fins were made in the region of prime radiator surface. Hence, the fin design described by Figure 22 is no longer applicable. To keep the fin within the required length and reject 700 watts with the magnetic cutouts, the fin base thickness was

4-7-64

7561-01185

Figure 22. SNAP 10A Thermoelectric Pump Radiator
Fin Analysis

increased. The final flight design radiator fin has a length of 8.25 in. and a base thickness of 0.6 in. Figure 23 is a photograph of a flight design pump depicting the final radiator design, magnetic circuit and mount.

No one formula can be presented to describe the minimum weight pump design. However, in all cases run through the computer program, the minimum weight design was close to the minimum heat transferred. To give the reader an insight to the critical parameter trade-offs in obtaining the flight design, Figures 24 through 26 are presented. They demonstrate the effects of channel geometry and magnetic field against total heat transferred.

2-27-64

7561-54787CN

Figure 23. SNAP 10A Flight-Type Pump

Figure 24. Pump Power vs Channel Height and Magnetic Field

Figure 25. Pump Power vs Channel Width and Magnetic Field

Figure 26. Pump Power vs Thermoelectric Thickness

BLANK

III. TEST DATA AND ANALYSIS

A. TEST REQUIREMENTS AND DESCRIPTION

Little experience could be brought to bear on designing facilities to test the thermoelectric pump. To learn the critical test loop conditions by establishing costly exotic loops without testing a prototype pump would undoubtedly delay the program. Thus, the first phase of testing concentrated on a simple loop of familiar components. The data obtained were to be accurate enough to determine trends, verify theory, and establish the basis of second-phase pump development and testing. Loop requirements were

- 1) 1000°F temperature capability
- 2) Flow and pressure measurement within 10% accuracy
- 3) Vacuum environment with 100°F sink temperature
- 4) Temperature readout (minimum 10 channels)
- 5) Variable orifice or valve to obtain pump characteristics.

With these objectives, three loops were fabricated of the design shown in Figure 27. Prototype pumps 1 to 6 were tested in these loops.

With development of the pump proceeding on schedule, test requirements were now dictated by the flight qualification program.

Following is the list of tests, in sequential order, that each pump in the qualification test program must experience:

- 1) Pump magnetization and checkout
- 2) Low-level vibration testing
- 3) NaK operation at 1010°F for 20 hr
- 4) Performance map at 1010, 900, and 800°F NaK
- 5) Pre-reactor flow test at 100°F NaK
- 6) Install pump in qualification loop and check out
- 7) Perform 10 thermal cycles from 100 to 1010°F NaK
- 8) NaK operation for 40 hr at 1010°F NaK
- 9) High-level shock, vibration, and acceleration testing

3-30-64

7561-01186

Figure 27. Prototype I Test Loop Schematic

3-30-64

7561-01187

Figure 28. SNAP 10A Pump Acceptance Test Loop

- 10) Performance map at 1010°F NaK
- 11) Initiate life stability test at 1010°F NaK
- 12) Complete 6000-hr life test.

It was impossible to obtain all of the test conditions in one test loop and maintain the budget within the allotted figures. Therefore, two loops were designed (identically) to perform all ΔP vs flow data with great accuracy. To measure pressure accurately at temperature, liquid-level manometers were employed. The difference in height was recorded with the use of a search coil. The pressure taps were so located that at least 30 diameters of straight pipe existed upstream. Figure 28 is a schematic of this test loop. Note that the pump tested in a vacuum vessel was a significant piping distance from the pressure taps. To calibrate this tare value, this section of piping was simulated and tested in a water loop. Using model analogy, the tare value which is added to the measured pressure was determined. Figure 29 shows a flight-type pump mounted in the loop, ready for performance testing.

The second loop was designed with life testing and thermal cycling as prime test objectives. Figure 30 is a schematic of this test loop. No pressure taps were provided on this loop. Pressure was determined from the electrical and hydraulic measurements obtained on the performance mapping test loop. Figure 31 shows a flight-type pump installed in a qualification test loop. Eight qualification loops have been fabricated and all are presently occupied with operating test pumps.

Common to both test loop designs are E.M. flowmeters (calibrated against a standard venturi meter), bellows sealed throttling valve, mechanical vacuum pumps (with 10^{-3} Torr capability), a refrigeration system for cold trapping, and cal-rod heaters. The instrumentation on both loops consists of a calibrated Rubicon potentiometer, multipoint temperature recorder, hour meter, millivolt strip chart recorder for flow measurement, and standard bourdon pressure gages for cover gas control.

B. PUMP INSTRUMENTATION

All pumps tested were instrumented with thermocouples and voltage probes to measure critical temperatures and voltages. The following is a list of this instrumentation.

1-10-64

7561-18398

Figure 29. SNAP 10A Pump Operating in Acceptance Test Loop

1 in. BELLOWS-SEAL ANGLE VALVES

3-30-64

7561-01188

Figure 30. SNAP 10A Pump Qualification
Test Loop

1) Thermocouple locations

- a) NaK inlet
- b) NaK outlet
- c) Hot junction (N elements)
- d) Hot junction (P elements)
- e) Cold junction (N elements)
- f) Cold junction (P elements)
- g) Base radiator
- h) Radiator tip

2) Voltage probe locations

- a) Wall voltage (N side)
- b) Wall voltage (P side)
- c) P element voltages
- d) N element voltages

6-7-63

7561-18311

Figure 31. SNAP 10A Pump Mounted in Qualification Test Loop

A schematic of the pump (Figure 32) depicts these locations. Calibration of the pump throat and critical resistances enabled the voltages to yield resistance measurements.

The magnetic field of the pump was measured with the use of a Hall-Meter probe. Measurements were taken prior to the pump's being welded into the loop. This permitted the probe to be inserted directly into the throat and allowed various readings to be taken at different positions. Standard temperature correction curves for Alnico V were used to compensate for temperature operation.

C. METHOD OF ANALYSIS

The raw data, as recorded in the lab notebooks, did not represent the true performance of the pump. To the measured pressure data, the tare hydraulic pressure must be added to obtain the net pressure (because of tap location).

$$\Delta P_m + \Delta P_{tare} = \Delta P_{net}$$

3-30-64

7561-01189

Figure 32. SNAP 10A Thermoelectric Pump Instrumentation, Front View of N Element

The ΔP_{net} plotted against the flow describes the pump characteristic at various temperatures. These are normally plotted for each pump, and along with the associated temperatures and voltages, the entire pump electrical equivalent circuit can be calculated.

R_N the resistance of the NaK channel is first determined. At zero flow, no losses exist and the back emf generated in throat is zero. Hence, the current flowing through the NaK is entirely converted to a measured pressure value, ΔP_0 , the shutoff pressure head.

The pumping current is determined from the basic Faraday expression, I_n .

$$I_n = \frac{P_0 b}{B \times 8.83 \times 10^{-8}}$$

From the measured wall voltage, E_{w_0} , R_N is calculated from $R_N = E_{w_0} / I_n$.

The leakage resistance (R_w) of the pump throat has been measured in separate tests. Using this value, the total pump current is calculated, $I_w = E_w / R_w$. The total current is the sum of the pumping and leakage currents.

To calculate the other critical resistances, a number of assumptions have to be made.

- 1) The total current splits equally in both parallel circuits
- 2) The Seebeck value of $100 \mu\text{v}/^\circ\text{F}$ is used for both P and N elements. These values are demonstrated on the elements prior to final pump assembly.
- 3) All end leakage current is converted to useful pressure by means of extending the magnet pole pieces.

Also, to obtain the total current at any flowrate other than zero, the developed pressure must be calculated. The developed pressure ΔP_d consists of the net pump pressure plus channel losses; i. e., magnetic braking (MHD) loss (as explained in Section II) and hydraulic loss. Both values have been measured and calculated, and they are plotted for 1000°F NaK in Figure 33. Therefore, the pumping current at any flow is presented by

4-16-64

7561-01376

Figure 33. SNAP 10A Thermoelectric Pump Losses vs Flowrate

$$I_n = \frac{(\Delta P_m + \Delta P_{tare} + \Delta P_{MHD} + \Delta P_{HYD})b}{B \times 8.83 \times 10^{-8}} .$$

It is now possible to calculate all resistances throughout the pump and to determine their change with time and temperature to compare with theoretical values.

R_{TE} , the thermoelectric element resistance, is obtained from the measured voltage across the element and the hot and cold junction temperatures.

$$E_{TE} = \frac{(S\Delta T - I_T R_{TE})}{2}$$

$$R_{TE} = \frac{S\Delta T - E_{TE}}{I_T/2} .$$

The resistance of the return bus-bar and associated bonds is obtained from

$$\frac{E_{TE} - E_w}{I_T/2} = R_B$$

where E_{TE} is the sum of voltages recorded for the P and N elements in one circuit.

D. PUMP DATA

Thirty pumps have been produced in the pump development program. The first pumps produced facilitated the development of manufacturing techniques and the acquisition of voltage and temperature data to check the design equations. Upon completing several phases of the development, two flight design pumps were produced for systems use. These pumps were generally satisfactory for this application. However, their pumping capacity was not quite as great as desired, the degradation of pumping capacity with operating time was greater than desired, and the auxiliary functions — operation from a battery during pre-reactor startup, and the flowmeter — were not entirely satisfactory. Another series of development pumps was produced, at this point, to reduce the shortcomings.

These stages of the program and the associated number of pumps produced are shown below:

<u>Description</u>	<u>Pump Designation</u>	<u>Number Produced</u>
Prototype I	No. 1 through 6	6
Prototype II	No. 7 through 11	5
Flight Development	FD-1 through 3	3
Flight Qualification	FQ-1 through 4	4
Systems	FSM-1, FS-1	2
Flight	FQ-5 and No. 010 through 018	9

As stated above, the main interest in pumps 1 through 6 was to obtain information on fabrication techniques and design factors. These pumps were characterized by the following general features:

- 1) Channel, 3/4 by 3/4 by 2 in.
- 2) Elements, 2 by 0.74 by 0.10 in.
- 3) Compression, simple bars providing approximately 2000 psi loading
- 4) Radiator, 2 copper plates 5 by 9 by 1/8 in.
- 5) Magnetic field, a range of values from 2015 to 4000 gauss

Figure 34 shows one of these pumps with magnets removed to show the voltage and temperature probes. Figure 35 shows the pump with magnet in place and mounted in a test loop.

The results of the tests yielded the following information:

- 1) A thermoelectric pump of this size could develop 6.5 gpm at 0.16 psi initially, and after 2000 hr of operation would deliver 2.5 gpm.
- 2) Thermal cycling was not damaging to the pump.
- 3) Shock, vibration, and acceleration at values specified for SNAP 10A components were not damaging.
- 4) The element design and mounting was acceptable but needed further development to reduce the degradation.
- 5) The design equations were satisfactory.

At the time the fabrication of pump 7 was initiated, a new improved P-type thermoelectric material became available and was used. Concurrently with this change, the pump radiator area was increased. These changes marked the beginning of the Prototype II stage. Pump 7 was used to evaluate the new thermoelectric material. The previous tests had indicated that the degradation was related primarily to the P material and that degradation was controlled primarily by mechanical factors.* Since the new P material was reported by the supplier to have better mechanical properties, the interest in the test of pump 7 centered about the degradation problem. This pump delivered 8.6 gpm when first placed in operation. The flow was 6.7 gpm at the end of the life test (5832 hr). The degradation of 2.1 gpm or 0.36 gpm/1000 hr was much lower than had been experienced on the earlier pumps.

At this stage, it was evident that achieving the desired flowrate of 13 gpm at 1.1 psi was simply a matter of scaling-up the pump. This was done, and pumps 8, 9, and 10 were produced according to the design for full power.

These pumps were like the earlier pumps except that the channel length was increased from 2 to 3.5 in., the element length was increased from 2 to 3.5 in., and the radiator design was improved to radiate a greater quantity of heat. The

*Pump 2 had a very high degradation rate, but since this pump was tested in air, the high degradation was attributed primarily to oxidation. Pumps tested in vacuum showed a much lower degradation rate.

1-22-62

7580-5540

Figure 34. Prototype I Thermoelectric Pump

1-8-62

7580-5477E

Figure 35. Prototype I Thermoelectric Pump
Mounted on Base Plate

magnetic field strength was 2350 gauss. Pump 8 met the basic performance requirement, as shown in Figure 36. The pump was subjected to a thermal cycle test consisting of cooling the NaK at a uniform rate from the normal operating temperature of 1000°F to room temperature, and raising it to 1000°F again during an 8-hr period. Upon completion of 10 thermal cycles, there was no degradation attributable to the cycling, and the pump was then operated 5705 hr. At the end of this time, the pump was sectioned and examined in the metallographic laboratory. The results of the posttest examination are discussed in Section IV.

3-30-64 7561-01190
Figure 36. Pressure vs Flow,
Pump 8

The channel of pump 9 leaked, so this pump was not tested in a loop. It was sent to the environmental test laboratory for shock, vibration, and acceleration tests. So far as could be determined by visual inspection and electrical resistance tests, the pump was not damaged by the environmental test.

Pump 10 was tested on a loop, and its pumping power was the same as that of pump 8. Pump 10 was used for several special tests, and the tests showed that:

- 1) For operation from a separate power supply (pre-reactor startup) with current applied directly to the thermoelectric pump electrodes, the current required was 180 amp/gpm, and of this, 44 amp were used in the pumping action and the remainder was wasted in the current shunted through the thermoelectric elements.
- 2) In the temperature region of 92 to 225°F, a thermal shock of 532°F/min caused no damage.

- 3) The sensitivity of the pump to a temperature difference across the elements was 0.0346 gpm/°F at room temperature.
- 4) Removal of the compression bars reduced the pumping rate from 15.19 to 12.55 gpm, and restoring the compression bars returned the pumping rate to 14.33 gpm. Comparison of the element voltages and temperatures, during the time the bars were off, with the pump-7 voltages and temperatures showed similar behavior. At that time pump 10 was new whereas pump 7 had 2700 hr of operating time. It was observed that the 2700 hr of operation produced the same effects as removal of compression bars, and this supported the view that the degradation in pump 7 was the result of mechanical effects, most probably the partial release of compression due to creep with the resultant increase in electrical and thermal resistance. The pump was operated 2996 hr, and at the termination of the test was delivering 11.1 gpm.

Pump 11 was like pumps 8, 9, and 10 except that its channel was rectangular, 1/2 by 1 in. Its pumping capacity was slightly less than that of pumps 8 and 10. The pump was operated for 6535 hr.

The life data on Development II pumps is shown in Figure 37. Several events occurred during the test of pumps 8 and 11 which were potentially detrimental. These included loss of vacuum (due to a power failure), shutdown and relocation of facilities, and power failures. In most instances these events were accompanied by a change in pump characteristics. As a result of these factors, the life test inadvertently included a test of pump vulnerability to various test malfunctions. The test of pump 7 was free of such test malfunctions; hence, the life test data, as such, are more meaningful.

Upon the completion of performance tests on pump 8, which showed the feasibility of the pump, a design modification was initiated to incorporate features desired in the flight pump. These features included:

- 1) Design of a magnet support to attach the magnet to the pump throat
- 2) Design of radiator to be bonded to the elements and to have minimum weight for the required radiating capacity

3-30-64

7561-01191

Figure 37. Flow vs Time, Pumps 7, 8, 10, and 11 Life Tests

- 3) Design of electrodes to be placed on the pump channel to provide for a flowmeter and for operation from a separate power source (pre-reactor startup)
- 4) Design of extended magnet pole face to provide an adequate magnetic field in the region of the flowmeter and separate power electrodes
- 5) Design of the pump channel to provide high efficiency and meet the electrical and thermal requirements imposed.

Concurrent with these design changes, the fabrication techniques, inspection and quality control, and testing were reviewed and specifications requiring more stringent control were placed in effect. This resulted in a delay in the production of the intended flight design pumps. While awaiting the production of the flight pumps, an intermediate group of pumps, similar to the flight designs, was manufactured using the materials and facilities available. Three such pumps designated FD-1, -2, and -3 were made and tested. The purpose was to provide preliminary evaluation of some of the features being incorporated in the flight design.

Pump FD-1 included all the new design features, except that an experimental radiator was used and there was some relaxation in the inspection and quality control requirements. The radiator was made of roll-bonded copper-clad aluminum. This pump delivered 14 gpm initially, and at the end of the test (4211 hr), the pump was delivering 12.95 gpm. This gave a degradation rate of 0.25 gpm/1000 hr. This was the lowest degradation rate of all pumps tested.

Pumps FD-2 and -3 were essentially flight design pumps, but lacked rigorous quality control. Pump FD-2 delivered 14.4 gpm upon initial operation and at the end of 936 hr of operation delivered 13.1 gpm. Pump FD-3 delivered 13.9 gpm, and further tests were curtailed.

Pumps FQ-1 and FQ-2, the first two flight pumps, were identical. The pressure vs flow characteristic of these pumps is shown in Figure 38. The curve for FQ-2 is plotted; FQ-1 is substantially identical. Since the pumping capacity of these pumps was lower than desired, two pumps (FQ-3 and FQ-4) were manufactured having a rectangular radiator fin rather than the flight-design tapered fin. This provided a slightly higher heat radiating capacity with the consequent greater pumping capacity. The performance of these pumps also is shown in Figure 38. The curve for FQ-4 is plotted; the curve for FQ-3 is substantially identical.

Figure 38. Pressure vs Flow
Characteristics of Pumps
FQ2 and FQ4 at 1010° F
NaK Temperature

3-30-64

7561-01192

The radiator thickness was increased significantly to achieve a further increase in pumping capacity. The new radiator design was essentially the same as that used on pumps FQ-1 and FQ-2, except that the fin base thickness was increased from 0.23 to 0.60 in. (The design is discussed in Section II.) This

improved the radiator radiation capability, and the additional thickness at the base reduced the electrical resistance in the thermoelectric generator circuit. The first pump produced with this larger radiator, and a few other small improvements, was FQ-5. The power of this pump was high, as was anticipated in the design change. The pump pressure was 1.6 psi at 13.2 gpm. Analysis of the pump data showed some evidence of poor bonding. This was further substantiated by the pronounced decrease in pumping capacity as the result of environmental testing. The testing of this pump was curtailed and the pump was sent to the laboratory for posttest examination.

The test of FQ-5 demonstrated the high pumping capacity of that design. Some fabrication improvements were incorporated in the succeeding pumps of this series of larger pumps, and the new numbering system was adopted.

Pump010 was the first of the new series pumps. Its performance has been excellent and when the time came to fix the design for the pump to be delivered to the FSM-4 system, this was selected as the model. The previous description of pumps and the test results have been relatively cursory, since they were all interim development pumps and the presentation of a detailed analysis of each here would be too voluminous. A detailed analysis based on pump010 follows.

Pump010 was fabricated in accordance with a set of engineering drawings and specifications, and was tested in accordance with established test specifications. These documents are described in References 5 through 8. A description of the basic design features has been given in previous sections. Also, the thermoelectric element fabrication, pump fabrication, and radiator coating are described in previous sections.

Figure 39 shows the pressure and flow developed as the NaK was heated from room temperature to 1010°F. Figure 40 shows the pump flowmeter and wall voltage as a function of temperature during the same heating interval. During this heating period the test loop throttling valve was fixed at the wide-open position. Upon attaining full operating temperature (1010°F), the throttling valve was partially closed to establish the design flow of 13.2 gpm. The pump was operated with that valve setting for 20 hr. As was generally the case, no

Figure 39. Pressure and Flow vs NaK Temperature, Pump 010

3-30-64

7561-01193

3-30-64

7561-01194

Figure 40. Flowmeter and Wall Voltage Output as a Function of NaK Temperature, Pump 010

significant change in performance occurred during this period. Upon completion of the 20-hr test, pressure vs flow values were obtained by varying the valve setting. These values were obtained at NaK temperatures of 1010, 900, and 800°F. The plot of these values is shown in Figure 41. The wall voltages and pump flowmeter voltages as a function of flow are plotted in Figure 42.

3-30-64

7561-01195

Figure 41. Pressure vs Flow at Indicated NaK Temperatures, Pump 010

3-30-64

7561-01196

Figure 42. Flowmeter Output and Wall Voltage vs Flow
at 800, 900, and 1000 °F, Pump 010

Four aspects of the pump were considered, as was done in the general analysis. These aspects were (1) d-c conduction pump, (2) thermoelectric generator, (3) integration of generator and pump, and (4) additional pump functions (separate power operation from batteries, and pump flowmeter).

The essential parts of the d-c conduction pump as shown in Figure 20 are redrawn and shown in Figure 43. E_{wm} is the measured wall voltage. These

Figure 43. Equivalent Electrical Circuit of D-C Conduction Pump

3-30-64

7561-01197

terminals are not on the inside of the wall, but are in copper electrodes outside the wall. The current flowing through the resistance, R , results in a voltage drop. Subtracting this voltage drop through the copper electrodes and the 0.02 in. of SS wall gives the true E_w at the inside of the channel. This is the E_w composed of $I_n R_n + E_c$ and which is shunted by the channel wall.

E_w = wall voltage

R = resistance of wall and electrode from wall inside to the terminals at which E_{wm} is measured

E_c = counter emf

$$E_w = I_n R_n + E_c$$

$$E_{wm} - R(I_n + I_w) = I_n R_n + E_c$$

$$I_w = \frac{E_w}{R_w}$$

Solving for I_n ,

$$I_n = \frac{E_{wm} - E_c \left(1 + \frac{R}{R_w} \right)}{R_n + R + \frac{R R_n}{R_w}} .$$

For a given pump design, and at a given temperature, the values of resistances are a constant and are given in Figure 43. Using these values, the equation is reduced to

$$I_n = \frac{E_{wm} - E_c \times 1.01}{23.95 \times 10^{-6}} .$$

At 13.2 gpm, the measured wall voltage, E_{wm} , is 31.8×10^{-3} volts. The counter emf, E_c , cannot be measured directly in an operating thermoelectric pump. Its value may be obtained by opening the electric circuit and providing flow by some other means, or by calculation. Experimental data on special test pumps show excellent agreement between the calculated value and the value obtained on open circuit, hence the calculated value is always used. At 13.2 gpm, the counter emf is 19.7×10^{-3} volts. Using these values in the equation we obtain

$$I_n = \frac{31.8 \times 10^{-3} - 19.70 \times 10^{-3} \times 1.01}{23.95 \times 10^{-6}} = 497 \text{ amp} .$$

The pressure developed is

$$\Delta P = \frac{BI}{10b} = \frac{2.4 \times 10^3 \times 497}{10 \times 1.015} = 1.175 \times 10^5 \text{ dynes/cm}^2$$

or

$$1.175 \times 10^5 \times 1.45 \times 10^{-5} = 1.705 \text{ psi} .$$

As discussed earlier, there are two pressure losses which are inherent and which reduce the available pressure. These are magnetic braking and hydraulic pressure losses. At 13.2 gpm, their values are 0.257 psi and 0.152 psi, respectively. Upon subtracting these values from the generated pressure, we obtain

$$\Delta P_{\text{net}} = 1.705 - 0.409 = 1.296 \text{ psi}$$

The measured pressure was 1.395 psi. Figure 44 shows the computed pump characteristic and the measured characteristic. The resistance values used in the computation are shown in Figure 43, the wall voltage is shown in Figure 42, and the other values were obtained from the general analysis based on the 13.2 gpm design point. The values used are shown in Table 1.

3-30-64

7561-01198

Figure 44. Pressure vs Flow at 1010°F NaK
Temperature, Pump 010

TABLE 1

VALUES USED IN COMPUTING PERFORMANCE OF PUMP 010*

Q (gal/min)	E_{wm} (mv)	E_c (mv)	$E_{wm} - KE_c$ (mv)	I_n (amp)	P (lb/in. ²)	P_{mb} (lb/in. ²)	P_{hyd} (lb/in. ²)	P_{net} (lb/in. ²)
0	19.40	0	19.40	807	2.77	0	0	2.77
2	21.20	2.98	18.19	756	2.60	0.039	0.0035	2.558
4	23.10	5.97	17.06	709	2.43	0.078	0.0139	2.338
6	25.00	8.95	15.95	663	2.27	0.117	0.0313	2.122
8	26.90	11.90	14.88	618	2.12	0.156	0.0558	1.909
10	28.80	14.90	13.75	572	1.96	0.195	0.087	1.678
12	30.70	17.90	12.60	524	1.80	0.234	0.126	1.44
13.2	31.80	19.70	11.90	497	1.705	0.257	0.152	1.296
14	32.60	20.90	11.50	480	1.645	0.273	0.171	1.201
16	34.50	23.90	10.45	434	1.487	0.312	0.223	0.752

*Curve plotted in Figure 44.

The electrical properties of the thermoelectric generator, based primarily on manufacturers' data on properties of materials, were used in the general pump analysis (Figure 20). The element resistance, at operating temperature, was computed from room temperature measurements computed by the published temperature coefficient data. An independent measurement of the properties can be made on an operating pump from data readily available.

To analyze the thermoelectric generator electrical properties, it is necessary to know the current it is delivering. This and other useful quantities can be computed from the wall voltage.

The current through the stainless steel wall shunting the NaK is given by the relation

$$I_w = \frac{E_w}{R_w} = \frac{E_c + I_n R_n}{R_w} .$$

The total current, i. e., the current supplied by the thermoelectric generator, is

$$I_T = I_w + I_n = I_n \left(1 + \frac{R_n}{R_w} \right) + \frac{E_c}{R_w}$$

The electrical load resistance seen by the generator is

$$R_L = \frac{E_{wm}}{I_T} .$$

The values have been computed based on E_{wm} , and the established constants, and are presented in Table 2 for various values of flow, Q . The currents are shown in graph form in Figure 45, and the load resistance is shown in Figure 46.

The thermoelectric element terminal voltage across each element was measured throughout the testing. Figure 47 shows the terminal voltage as a function of flow. The terminal voltage is the emf generated, minus the voltage drop through the element internal resistance. The emf generated is the product of the Seebeck coefficient and the temperature difference and is independent of

TABLE 2
PUMP 010 ELECTRIC CURRENTS

Q (gal/min)	I_n (amp)	E_c (mv)	$\frac{E_c}{R_w}$ (amp)	$1 + \frac{R_n}{R_w}$	$I_n \left(1 + \frac{R_n}{R_w} \right)$ (amp)	I_T (amp)	E_{wm} (mv)	R_L (μ -ohm)	I_w (amp)
0	807	0	0	1.0674	861	861	19.4	22.5	54
2	756	2.98	9.74	1.0674	806	815.7	21.20	26.0	59.7
4	709	5.97	19.5	1.0674	756	775.5	23.10	29.8	66.5
6	663	8.95	29.2	1.0674	707	736.2	25.00	33.95	73.2
8	618	11.90	38.9	1.0674	659	697.9	26.90	38.5	79.9
10	572	14.90	48.7	1.0674	611	659.7	28.80	43.7	87.7
12	524	17.90	58.5	1.0674	559	617.5	30.70	49.7	93.5
13.2	497	19.70	64.4	1.0674	530	594.4	31.80	53.6	97.4
14	480	20.90	68.4	1.0674	512	580.4	32.60	56.2	100.4
16	434	23.90	78.1	1.0674	463	541.1	34.50	63.8	107.1

3-30-64

7561-01199

Figure 45. Current as a Function of Flow, Pump 010

3-30-64

7561-01200

Figure 46. Load Resistance as a Function of Flowrate, Pump 010

Figure 47. Thermoelectric Element Terminal Voltage as a Function of Flowrate

3-30-64

7561-01201

the current. The drop through the resistance is dependent upon the current. Using this fact, and attributing the change in terminal voltage shown in Figure 47 to the change in current, the resistance may be computed. The current as a function of flow is shown in Figure 45. Taking a range of 10 to 16 gpm, for example, the voltage difference divided by the corresponding current difference gives the following values:

$$R_N = \frac{(26.8 - 24.3) \times 10^{-3}}{659.7 - 541.1} = 21.4 \times 10^{-6} \text{ ohm}$$

$$R_P = \frac{(13.15 - 10.30) \times 10^{-3}}{659.7 - 541.1} = 24.05 \times 10^{-6} \text{ ohm}$$

The sum of the resistances is

$$21.40 \times 10^{-6} + 24.05 \times 10^{-6} = 45.45 \times 10^{-6} \text{ ohm}$$

These values are very close to those measured when the elements are fabricated (Figure 20).

The emf generated, i. e., the product of Seebeck coefficient S and temperature difference ΔT , is the sum of the terminal voltage and the voltage drop through the resistance. From Figures 42, 45, and 47, taking values at 13.2 gpm, for example, we have

$$(\Delta T)_N = 25.62 \times 10^{-3} + 594.4 \times 21.4 \times 10^{-6} = 38.32 \times 10^{-3} \text{ volt}$$

$$(\Delta T)_P = 11.82 \times 10^{-3} + 594.4 \times 24.05 \times 10^{-6} = 26.10 \times 10^{-3} \text{ volt} \quad .$$

The measured ΔT for the N and P elements was 302 and 331°F, respectively. The temperatures were not measured at the thermoelectric material surface because it is impractical to place thermocouples at this surface. The thermocouples are placed in the nearest practical locations — the copper electrodes and the aluminum radiator bases. Hence, the true ΔT differs from the measured value by the temperature drop between the thermoelectric material and the measuring point. Most of this temperature drop occurs in the powdered iron contacting the thermoelectric material. Calculations show that the correction should be 4°F. This gives ΔT values of 298°F for N and 325°F for P. Using these corrected values, we obtain:

$$S_N = \frac{38.32 \times 10^{-3}}{298} = 128.4 \times 10^{-6} \text{ volt/°F}$$

$$S_P = \frac{26.10 \times 10^{-3}}{325^\circ\text{F}} = 80.4 \times 10^{-6} \text{ volt/°F} \quad .$$

The sum of these is 208.3×10^{-6} . These Seebeck values differ from the values given in the general analysis; however, their sum as used in the design deviates by only +4%.

Pumps 011, 013, 014, and 015 were constructed like pump 010 so far as basic dimensions were concerned. However, the fabrication techniques, particularly the thermoelectric elements, were different in each pump. The measured performance of these pumps is shown in Figure 48. According to these data, pump 011 had the highest power capability. Its maximum hydraulic power of 10.3 watt was delivered at 16 gpm. Pumps 013 and 014 were nearly identical. Their peak power (7.6 watt) was delivered at 12 gpm. Pump 010 was intermediate in power capability. The variation in pumping power among these pumps was 30%.

The results of the analysis of pump 011 (representing the highest power) and pump 013 (representing the lowest power) are presented in Table 3. All values presented in this table, except as noted, are calculated in the same manner

TABLE 3

COMPARISON OF PERFORMANCE AND VARIOUS ELECTRICAL
QUANTITIES OF PUMPS 011 AND 013

	Pump 011	Pump 013
Q flowrate (gal/min)	13.2	13.2
pressure calculated (psi)	1.716	1.35
pressure measured (psi)	1.74	1.30
E_{wm} wall voltage measured (mv)	34.75	32.2
I_n NaK current (amp)	620	513.5
I_T total current (amp)	722.8	612.5
power output (watts)	9.82	7.74
power input (watts)	25.08	19.70
η efficiency (%)	39.1	39.3
E_N N element voltage, terminal (mv)	27.40	25.28
E_P P element voltage, terminal (mv)	13.60	12.30
$(S\Delta T)_N$ N element voltage, open circuit (mv)	44.90	41.28
$(S\Delta T)_P$ P element voltage, open circuit (mv)	30.90	25.55
S_N N element Seebeck (μ -v/ $^{\circ}$ F)	143.8	135.5
S_P P element Seebeck (μ -v/ $^{\circ}$ F)	95.6	78.20
R_N N element resistance (μ -ohm)	28.21	26.20
R_P P element resistance (μ -ohm)	27.10	21.65
R_G element resistance, sum (μ -ohm)	55.31	47.85
E element open circuit voltage, sum (mv)	75.80	62.18
R_B bus resistance (μ -ohm)	8.57	8.78
R_T total resistance of curcuit (μ -ohm)	87.83	80.58
R_L load resistance (μ -ohm)	48.1	52.6

Figure 48. Pressure vs Flow Characteristics of Pumps 010, 011, 013, 014, and 015

3-30-64

7561-01202

as was illustrated for pump 010. The object of the comparison is to determine the factors which contribute to the wide variation in the pump's power capabilities. In both pumps, the calculated pressure and measured pressure at 13.2 gpm are in good agreement. Both have substantially the same d-c pump channel efficiency. The magnetic fields were measured before and after the tests, and both pumps had the same magnetic field. These facts led to the belief that the difference in indicated pumping power was not attributable to test facility error or to a difference in the d-c conduction pump portion of the thermoelectric pump. The difference evidently was in the thermoelectric generator, as may be suspected, since the thermoelectric generator fabrication process was known to be different in each pump.

A comparison of the element properties shows that the Seebeck values on the pump 011 elements are substantially higher than those of pump 013. This, of course, would contribute to higher power. The element resistance of pump 011 is higher than that of pump 013, and this would reduce the power. However, the effect of the higher Seebeck value offsets the effect of the higher resistance.

It may be concluded that the performance differences of this group of pumps are related to the thermoelectric generator only and that the dominating factor is the Seebeck value. Otherwise, the pumps are essentially alike. The measured performance of pump 010 contains an error, as is evident in Figure 48. This is the reason for poor correlation of measured and calculated performance shown in Figure 44. The slope of the measured pressure vs flow characteristics is incorrect. This is easily verified by the following analyses.

The basic equation for pressure developed is

$$\Delta P = \frac{BE}{10bR} - \frac{B^2 Q \times 10^{-8}}{10b^2 R} - \frac{B^2 Q \times 0.27 \times 10^{-9}}{b \rho_n} - 5.75 \times 10^{-2} Q^{1.8} .$$

The slope of the line is obtained by differentiating P with respect to Q obtaining,

$$\frac{\partial P}{\partial Q} = \frac{-B^2 \times 10^{-9}}{b^2 R} - \frac{B^2 \times 0.27 \times 10^{-9}}{b \rho_n} - 10.35 \times 10^{-2} \times Q^{0.8} .$$

Insertion of the appropriate numbers gives 116.5 dynes/cm²/cm³/sec, which converted to psi/gpm by the factor 91.7×10^{-5} gives 0.1068 psi/gpm. The measured value is 0.098 psi/gpm. The measured value is 8.8% too low. A similar analyses performed on pump 011 gives a slope of 0.0998 psi/gpm calculated and 0.101 psi/gpm measured. Here, the measured value is 1.2% too high. The correlation is much better.

The poisoning of the thermoelectric material by copper and silver from the braze material is discussed in Section IV, fabrication. To avoid this poisoning, a series of pumps having an iron foil barrier between the element compact and the copper surfaces was made. Except for this change, these pumps are constructed like those described in the previous paragraphs. These pumps are designated 016, 017, 018, and their pressure vs flow characteristics are shown in Figure 49. To obtain data on the effect of a magnetic field change, the magnetic field of pump 017 was set at 2200 gauss rather than the design value of 2560 gauss. This lower field accounts for the lower power output.

The analyses of pump 016 show a d-c pump channel efficiency of 41.1%. The N thermoelectric elements had a resistance of 15.73 μ -ohm and a Seebeck value of 119.2 μ volt/°F. The P thermoelectric elements had a resistance of 18.29 μ -ohm and a Seebeck value of 86.4 μ volt/°F. These values are distinctly different than those of the preceding series of pumps.

In addition to determining the performance characteristics of the pump, the testing also involved thermal shock, thermal cycling, and long-time operation to determine degradation rate.

Figure 49. Pressure vs Flow Characteristics of Pumps 016, 017, and 018

3-27-64

7561-01203

The thermal shock and thermal cycle tests were combined. With the NaK temperature initially at 100°F, the temperature was raised to 500°F at 70°F/sec and from 500 to 1010°F at 7°F/min. Then the temperature was lowered at the rate of 5°F/min to 100°F. This constituted a thermal cycle. A number of the pumps have been subjected to this test and no degradation attributable to thermal cycling was observed. The results of the test are shown in Figure 50.

Several of the pumps have been placed on life test to determine their degradation characteristics. These are operated at the design NaK operating temperature 1010°F. The value in the test loop was adjusted to a specific initial flowrate. Thereafter, no change was made and the pumps operated until test termination. During this time the flowrate and the temperatures and voltages

Figure 50. Flow and Wall Voltage as a Function of Thermal Cycles for Pump 011

4-7-64

7561-01204

at selected points were measured each day. Figure 51 shows the flow as a function of time for five pumps. These curves are smoothed to demonstrate the long-term trends. Plot of the raw daily data shows irregularities resulting from such factors as power interruptions. Considering pumps 010, 011, 016, and 018, all decrease to about 92% of their initial value in the first 2000 hr. After 2000 hr, the degradation rate is less. Pump 010, which has the longest operating time of this group, has shown no degradation in the 2000- to 4000-hr interval. The rapid degradation of pump 013 in the interval from 400 to 700 hr is attributed to oxidation damage. During this period failure of the vacuum system occurred twice, and this permitted the pump to be at full temperature in an oxidizing atmosphere.

Mechanical Environmental Tests

A schedule of tests, outlined below, has been used to determine the ability of the pump to withstand the mechanical forces involved in the SNAP 10A system usage. The pump is mounted in a fixture in a manner to simulate, as nearly as is practical, the mechanical condition characteristic of the system use. The fixture is placed in the various testing machines, as required, with instrumentation to check the mechanical forces. In addition to visual inspection, the magnetic field and resistance of the electrical circuit are checked before and after each phase of the test to determine any damage.

The pump is subjected to vibration applied along three mutually perpendicular axes as follows:

Axis	Input (g)	Frequency (cps)	Limit (g)
X (longitudinal, in direction of flow)	1/2 in. DA	5 to 13	—
	4.5	13 to 30	5.5
	5.5	30 to 80	5.5
	3.75	80 to 2000	5.5
Y and Z (lateral)	1/2 in. DA	5 to 17	—
	6.5	17 to 50	6.5
	3.75	50 to 100	6.5
	1.0	100 to 250	6.5
	3.75	250 to 2000	6.5

NAA-SR-9486
79

3-30-64

7561-01205

Figure 51. SNAP 10A Pump Life Test Data at 1010°F NaK Temperature

The sweep rate is at constant octave proceeding from low to high in 30 min. The minimum input is 0.2 g.

The acceleration test is at the following load conditions.

Longitudinal (g)	Lateral (g)
+2.5	+6.25
-2.5	-6.25
+9.37	+1.25
-3.125	-1.25

Each load combination is obtained by orienting the pump so that the longitudinal and lateral directions are as specified. The load is applied for a period of 10 min in each direction. Following the test, visual inspection, magnetic field, and circuit resistance measurements are made.

The shock test consists of two impact shocks applied in each direction along the three axes. The shock duration is 6 msec at the following loads:

X (Longitudinal axis)	±20 g peak
Y and Z (lateral axis)	±10 g peak

Upon completion of the shocks, the pump is subjected to visual inspection, magnetic field, and electric circuit resistance checks.

Since the initiation of the flight design pumps, 11 pumps have been subjected to the environmental test and all have suffered some loss in performance as the result of this test.

The visual inspections have shown no easily discernible damage. The reliability of the electric circuit measuring technique was poor in the early part of the program. As a result, it did not reveal any resistance changes. With a refined technique, changes in resistance have been detected as the result of vibration. The measurement of magnetic field changes has shown that some pumps have no change, but a few have shown a small loss in magnetic field. The increase in circuit resistance and decrease in magnetic field would lower the pump performance. Of the two factors, the circuit resistance is the more critical factor, as was discussed earlier and shown in Figure 16.

The pump performance tests following the environmental test have shown that the pumps suffer a loss in pumping power. A comparison of performance before and after environmental test is shown in Figure 52. This pump had the highest initial performance and also suffered the greatest loss. Pump 013, which had a relatively low initial power output, also suffered the least loss in power. Pump 011, shown in Figure 52, had a magnetic field of 2525 gauss before the environmental test and 2450 gauss after the test. Making no allowance for measurement errors, this would indicate a 75-gauss decrease or a 3% decrease. The sensitivity of the pump is of the order of 0.00016 psi/gauss in this operating region, so the 75-gauss decrease would decrease the pressure by 0.012 psi. This amount is hardly measurable and clearly is less than the amount of pressure indicated in Figure 52. The sensitivity to resistance change is 0.0225 psi/ μ -ohm. To account for the 0.22-psi pressure loss indicated in Figure 52, a resistance increase of 10 μ -ohm would be required (assuming no other factor is involved). This is a 12.5% increase and is not unexpected. The curves showing a decrease in wall voltage after environmental test indicate a decrease in current. This would be the result of an increase in circuit resistance or decrease in generated emf. There is no factor involved which would be expected to affect the generated emf.

3-30-64 7561-01206
Figure 52. Measured Pressure and Wall Voltage vs Flow
at 1010°F NaK Temperature, Pump 011

BLANK

IV. FABRICATION AND ELEMENT DEVELOPMENT

In the early development stages of the pump, it was recognized that the thermoelectric element fabrication and process development was a major stumbling block. In essence, the inherent poor stability and structural semiconductor materials had to be forced to operate near peak theoretical limitations under high temperature and vacuum conditions.

The following discussion involves only the development history associated with lead telluride (PbTe) alloys. Detailed fabrication and process procedures for all methods are reviewed in Reference 9. Because of the large amount of data collected in this area, only detailed discussions concerning the final flight design pump are presented. Also presented are some unique metallographic analyses and results concerning PbTe operating in the SNAP 10A environment.

A. THERMOELECTRIC ELEMENT DEVELOPMENT

1. Standard Pump Element

Various pump designs and configurations were evolved, all of which centered about the thermoelectric element design. A review of the fabrication problems encountered by other investigators, as well as AI, demonstrated the need for a sound PbTe bond and material. The following bonding techniques were investigated.

- a) Roll bonding to stainless steel
- b) Isostatic pressing to stainless steel and iron
- c) Casting
- d) Cold pressing and sintering to iron.

The cold pressing and sintering technique provided the program with an element that performed with sufficient output to permit the design of a pump within the system objectives. All development efforts then concentrated upon the fabrication of elements for the Prototype I design to demonstrate feasibility.

The approach taken toward fabricating these elements was to cold press Fe-PbTe-Fe rectangular composites (3/4 by 4.000 by 0.160 in. thick) in a die capable of being completely disassembled. The die was designed with this feature to eliminate cracking of the weak green compacts caused by uneven

expansion during compact ejection. The procedure used to fabricate thermoelectric composites was based, to some extent, upon a previous development effort in pellet fabrication for the SNAP 10A converter program. Briefly, the procedure was to evenly distribute 11.3 gm of Fe powder (Anchor MH-100 grade) along the bottom die ram. To this was added 39.4 gm of N-PbTe (or 38.8 gm of P-type PbTe) powder. Another 11.3 gm of Fe powder were distributed above the PbTe. The powders were cold pressed at either 20 or 30 tsi. The green compact was carefully removed and sintered in a pure H_2 atmosphere at $1200^\circ F$ for 2 hr. The average thickness of the 30 tsi Fe and PbTe layers was: Fe (each) 0.035 in.; PbTe 0.100 in. Typical elements are shown in Figure 53. The sum of these values was approximately 7% greater for the 20-tsi element. Also, the 30-tsi element appeared to have more surface continuity and less porosity than the corresponding 20-tsi element. All subsequent elements were made at 30 tsi. Resistance and Seebeck measurements were obtained for most of the elements made by this new process. Typical values for N and P elements are given in Tables 4 and 5, respectively.

4-7-64

7561-01306

PbTe Elements 4 by 0.7653 by 0.1762 in.

Figure 53. Typical Cold Pressed and Sintered Elements

TABLE 4

ELECTRICAL RESISTANCE AND SEEBECK OF COLD PRESSED
AND SINTERED N-TYPE PbTe ELEMENTS, 3/4 by 2 by 0.170 in.*

Cold Junction (° F)	Hot Junction (° F)	Millivolts	ΔT	Microvolts/°F
360	620	13.0	260	50.0
310	570	15.0	260	57.5
315	585	16.0	270	59.3
320	600	17.0	280	60.7
325	620	18.0	295	61.0
330	640	19.0	310	61.3
340	670	20.0	330	60.5
340	680	21.5	340	63.2
350	700	22.0	350	62.9
355	710	23.0	355	64.8
405	740	25.3	335	75.5
415	740	27.5	325	84.6

*Resistance (at 5 amp, room temperature), R (μ -ohm), 5 to 10

TABLE 5

ELECTRICAL RESISTANCE AND SEEBECK OF COLD PRESSED
AND SINTERED P-TYPE PbTe ELEMENTS, 3/4 by 2 by 0.170 in.*

Cold Junction (° F)	Hot Junction (° F)	Millivolts	ΔT	Microvolts/°F
150	220	4.0	70	57.2
190	345	8.0	155	51.6
205	380	9.0	175	51.4
220	410	10.0	190	51.3
245	460	13.0	215	60.5
255	530	16.0	275	58.2
275	565	18.0	290	62.0
300	600	20.0	300	66.7
335	625	22.0	290	75.8
370	640	23.0	270	85.2
390	660	24.0	270	88.9
420	675	25.0	255	98.2
435	680	25.0	245	102.0
455	690	25.6	235	109.0

*Resistance (at 5 amp, room temperature), R (μ -ohm), 11.3 to 12.8

Thermoelectric elements produced by cold pressing powders and sintering, while having superior thermoelectric properties, had poor mechanical properties. This was due to the inherent brittleness of the intermetallic PbTe and the inability to sinter the Fe powder at temperatures high enough to make it a structural member. It was therefore necessary to avoid putting the element in tension. This was done by adding compression bar members to the pump design. An important objective of this design was to keep the elements in compression during pump fabrication as well as during actual pump operation.

Six pumps of the Prototype I design, containing PbTe elements fabricated as described, were tested. Each pump was subjected to a series of tests in a NaK loop. Performance data indicated a diminution of NaK flow with time, and electrical measurements indicated a continual rise in P-element resistance coinciding with a decreasing flowrate. It was concluded, therefore, that pump degradation was a function of the positive change in P-element resistance, which in turn was a function of time and temperature. A solution to the dilemma was sought by substituting a new P-type material for the standard sodium-doped, P-type, PbTe material. The new P material was required to have, in addition to the good thermoelectric properties of PbTe, stable electrical properties with time at elevated temperatures. Fortunately, the 3M Company recognized the problem with P-type PbTe and had under development an alternate material which they called Experimental-P TEG-S-3P. This subsequently was designated PbSnTe, derived from its composition PbTe + SnTe. The 3M Company and AI life tested cold-pressed and sintered elements composed of PbSnTe. Results showed that PbSnTe resistances remained relatively constant with increasing time, while the reference P-type PbTe material exhibited a gradual increase in resistance with time. Thus, PbSnTe was established as the new reference material for P-elements, and all pumps fabricated thereafter, including development and production pumps, contained PbSnTe elements. The procedure for fabricating thermoelectric elements did not change; N-elements still contained N-PbTe. Cold pressing at 30 tsi and sintering in H_2 at 1200°F for 2 hr was maintained for the first Prototype-II pump. For the second Prototype-II pump, the sintering time was changed to 4 hr and the temperature to 1300°F. These latter parameters were maintained for all production-type pumps fabricated thereafter.

In a study conducted on the vaporization characteristics of PbTe (Reference 10), it was found that appreciable evaporation of PbTe could be expected in a high vacuum at an operating temperature of 1000° F or higher. This verified what had been known empirically. Evaporation at the rates reported in the referenced report indicated that unprotected elements would lose significant quantities of thermoelectric material, which could lead to serious performance degradation and possible shorting of the elements. Considerable effort was applied in developing a suitable protective barrier coating to limit this loss of telluride material. The original requirements for the encapsulant were as follows.

- a) The weight loss of an encapsulated element shall be less than 0.5%/1000 hr when operated at 950° F in a vacuum (10^{-5} mm Hg) or at 1000° F in an inert atmosphere.
- b) The encapsulant must not have any detrimental effects on the thermal or electrical properties of the thermoelectric element material.
- c) The heat flow through the encapsulant shall be less than 5% of the heat flow through the thermoelectric element.
- d) The electrical loss through the encapsulant shall be less than 1%.
- e) The thermal coefficient of expansion of the encapsulant must be compatible with the expansion of the PbTe. This proved to be the most important requirement leading to the elimination of most of the materials tested.

The avenues of approach to the encapsulation problem were many and varied. A list of the approaches taken is given in Reference 9, along with a discussion of results. The best results to date have been obtained by applying a mixture consisting of a weight ratio of 4 parts Al-2 proprietary enamel to 1 part Li_2TiO_3 (lithium titanate). This formulation was called "enamel 41" and later designated as "4-1." Using various pellets, a series of weight loss tests was conducted on PbTe, and the results are presented in Table 6. The last column, labeled Ratio to Goal, is the actual weight loss divided by a goal of 0.5% weight loss in 1000 hr. Where the weight loss is negative, there was an actual gain in weight owing to oxidation of the iron caps. Chemical analysis

TABLE 6
WEIGHT LOSS ON PbTe PELLETS

Number	Type	Pellet Number	Coating	Temperature (° F)	Time (hr)	Weight Loss (mg)	Analytical Weight Loss	Weight Loss (mg/hr-cm ²)	Ratio to Goal
0	N or P	Goal	Reference	1000	10,000	-	-	0.017	1.00
1	N	HP-19, N ₂	None	900	5-1/4	8.1	-	0.61	36.00
2	P	HP-30, P ₂	None	900	6	10.0	-	0.66	39.00
3	N	HP-11, N ₁₆	Al-2	900	46	0.8	-	0.0069	00.40
4	P	HP-33, P ₄	Al-2	900	70	0.5	-	0.0028	0.16
5	N	HP-19, N ₂₁	PBX	900	38-1/2	3.0	-	0.022	1.29
6		HP-19, N ₂₁	PBX	900	81-1/2	-0.7	4.9	0.014	0.82
7	P	4-38B	PBX	900	46-1/2	1.4	-	0.012	0.71
8	N	3-4B	PT-404	900	45	8.9	-	0.078	4.60
9		3-4B	PT-404	933	48	36.4	-	0.30	17.65
10	P	4-52A	PT-404	900	45-1/2	9.0	-	0.078	4.60
11	P	4-51A	PT-209	933	70	27.6	-	0.156	9.16
12	P	4-51A	PT-209	933	87-1/2	3.4	3.9	0.018	1.06
13	P	4-51B	PT-805	933	70	15.8	-	0.089	5.23
14		4-51B	PT-805	933	87-1/2	-0.1	3.0	0.014	0.83
15	N	3-47B	8-1	933	62-1/2	2.0	-	0.012	0.71
16	N	3-48B	Al-2	933	48	2.2	-	0.0070	0.41
17	N	7-5	Al-2	1125	22-1/2	474.0	354.0	6.22	365.00
18	N	7-6	Al-2	1125	22-1/2	769.0	617.0	10.38	610.00
19	P	8-3	Al-2	1125	22-1/2	286.0	244.0	3.85	226.00
20	P	8-4	Al-2	1125	22-1/2	195.0	171.0	2.70	151.00
21	N	7-7	Al-2	933	190-1/2	30.6	6.3	0.012	0.71
22	N	7-8	Al-2	933	190-1/2	12.0	11.7	0.021	1.23
23	P	8-1	Al-2	933	190-1/2	10.2	7.4	0.015	0.88
24	P	8-2	Al-2	933	190-1/2	10.9	4.4	0.0088	0.52
25	N	7-14	Al-2	1025	24	97.3	11.0	0.181	10.64
26	N	7-16	Al-2	1025	24	44.3	3.8	0.055	3.24
27	P	8-41	Al-2	1025	24	57.5	15.2	0.233	13.70
28	P	8-44	Al-2	1025	244	118.6	113.4	1.65	97.00
29	P	8-35	8-1	900	54-1/2	0.2	-	0.0013	0.077
30	P	8-36	8-1	900	54-1/2	3.2	-	0.022	1.29
31	P	4-15B	No. 1990	900	123	10.1	-	0.027	1.59
32	N	7-20	4-1	900	147	0.1	-	0.0002	0.012
33	P	8-18	4-1	900	147	-1.5	-	Gain	-
34	N	7-41	4-1	900	161	-0.1	-	Gain	-
35	N	7-42	4-1	900	161	-0.6	-	Gain	-
36	P	10-18	4-1	900	161	-2.3	-	Gain	-
37	P	10-27	4-1	900	161	-1.4	-	Gain	-

of No. 33 through No. 37 was not made, but the average weight loss from these is estimated to be less than 2 mg, or a ratio-to-goal of about 0.3. Coating 4-1 was therefore established as the reference encapsulant for PbTe. A specification describing the procedure to be followed for encapsulation of PbTe is given in Reference 9.

2. Diffusion Barrier Element

The lead telluride material is dependent upon minute, controlled quantities of elements which cause it to function as a P- or N-type thermoelectric generator. Unwanted elements (impurities in the raw materials, incorporated during processing, or diffused into the thermoelectric generator during operation) can cause the generator to malfunction. The performance of the SNAP 10A pumps did degrade during operation. Many factors can cause the performance of a thermoelectric generator to degrade. For example, the resistance of the electric circuit can increase, the vital components of the element might vaporize under high-vacuum high-temperature conditions, the element might break up because of thermal expansion stresses, or the thermoelectric element might be poisoned by materials which are part of the pump generator system.

A number of pumps which had been subjected to prolonged qualification testing were disassembled and thoroughly examined. Metallographic examination of the thermoelectric elements revealed that some breakup of the elements did occur. The examination also revealed a grey and copper colored substance that was not there after fabrication. The material was present at the telluride-compacted powdered iron interface on the cold side of the element. (The side away from the liquid metal heat source and the side to which the heat rejection radiators are attached.)

The copper colored and grey colored materials were subjected to a number of identification tests. X-ray fluorescence, x-ray diffraction, and electron microprobe analysis were among the tests. Detailed results of these tests and other posttest examinations of pumps and elements are presented later in this report. The tests disclosed that the copper colored material was indeed copper, which also contained a small percentage of silver. The grey colored material contained copper, tellurium, and some silver. It was suspected that the grey phase was a eutectic alloy of copper and tellurium. Hot-stage microscope studies tended to confirm the existence of the eutectic. The

studies showed the existence of a substance which melted at about 600° F. Copper-tellurium eutectic, a 30 to 70% alloy, is reported to melt at 654° F.

A thermoelectric element, a compacted assembly consisting of a powdered lead telluride layer sandwiched between two powdered iron layers, was clamped between two strips of copper metal. The assembly was heated to 1300° F in an argon atmosphere for 16 hr. Metallographic examination of the element revealed copper colored and grey colored phases at the interface, between the copper and powdered iron, identical to those observed in pump elements subjected to prolonged operation. The test element subjected to isothermal conditions showed the copper and grey colored phases on both sides of the element where the copper was in contact with the powdered iron layers. The pump elements showed the phases only on the cold side of the element and at the telluride-powdered iron interface.

A section of the specimen was examined with the microprobe, the results verifying the visual observations — the grey material was composed of copper and tellurium. The results also showed that the iron layer contained lead. No silver was found since the test element contained no silver from brazing materials.

The copper found in the pump elements must have originated from the copper contacting shoes on the hot side of the element. The powdered iron layers in the element sandwich are porous. All the elements were fabricated from powdered ingredients, using powder metallurgical techniques. The 1300° F temperature used to sinter the three-layer (iron-lead telluride-iron) compacts was not high enough to cause much sintering or densification of the iron layers. In pump operation, the tellurium on the hot side of the element is thought to have vaporized, initiating element poisoning. The tellurium vapor then penetrated the porous iron and contacted the copper shoe surface, where a copper-tellurium eutectic was formed. This eutectic melted and then vaporized. Copper tellurium vapors then moved back through the porous iron and porous lead telluride to the cold side of the element where the temperature was below 650° F. The copper-tellurium eutectic then condensed out at the interface.

There is other evidence of the mobility of the tellurium and tellurium-copper eutectic. A pump removed from a test loop showed evidence of a black

deposit on copper components that were as far as 6 in. away from the pump thermoelectric elements. X-ray fluorescence analysis indicated that the black substance contained tellurium.

Figure 54 is a metallographic specimen of an element containing an iron foil barrier between the iron layer of the element and the copper shoe. It had been processed at 1300° F. The iron foil prevented the tellurium from contacting the copper directly through the porous iron layer. However, at the edges where the telluride and copper were uncovered, the tellurium vapor was able to bridge the space between the two components and form the network of copper-tellurium eutectic and copper visible on the left side of the specimen.

Figure 55 also shows an iron foil barrier between the element and the copper shoe. A small crack had developed along a grain boundary of the iron foil. Again, the tellurium vapor had passed through the porous iron powder layer and had penetrated the crack in the iron foil barrier to form the typical copper-tellurium and copper network in the copper shoe.

Some of the pumps fabricated contained a 2-mil-thick layer of Premabraz 615 brazing foil as a bonding agent between the powdered iron layer of the element and the copper shoe. Although the element assemblies of the pumps did not reach the melting point of the brazing foil (the assemblies were solid-state bonded by diffusion), the tellurium formed eutectics with both the copper and silver contained in the foil. Since the silver-tellurium eutectic melts at 697° F, only 20° F higher than the copper-tellurium, the silver also was transported into the elements. The microprobe and x-ray fluorescence analyses detected silver in the thermoelectric elements of the pumps.

There are several methods of preventing contamination of the thermoelectric elements:

- a) Eliminate the contaminating materials from the system.
- b) Lower the operating temperature of the thermoelectric system below the melting point of detrimental eutectics.
- c) Interpose a vapor barrier between the element and the contaminant.

The last method, introduction of a vapor barrier, was chosen so that the thermoelectric pump system would meet existing operational parameters. Three basic barrier techniques were investigated:

Tellurium vapor from telluride in TE element

N Element, Unetched, 100X
4431-2-1

Figure 54. Tellurium Vapor From Telluride in Thermoelectric Element (N Element)

Tellurium vapor from telluride

Compacted powdered iron layer

Crack

Iron foil barrier

Copper-tellurium eutectic and copper network

Copper contacting shoe

4-7-64

7561-01308

P Element, Unetched, 500X
4613-2-1

Figure 55. Tellurium Vapor From Telluride
(P Element)

- a) Solid iron barrier between the lead telluride and copper
- b) Aluminum foil in the powdered iron layer
- c) Means of decreasing the porosity of the powdered iron layer.

a. Solid Iron Barrier

Initially, iron barriers about 1/16-in.-thick were tried. Owing to the difference in thermal expansion between the iron barrier and lead telluride (11.76×10^{-6} vs 18×10^{-6} in./in./°C), however, no adherent bonds were obtained between the element and the barrier. Other techniques to bond the barrier plates to the elements were tried. "Sandpaper" barriers consisting of iron powder sintered to the barrier, and barriers consisting of grooves cut in a waffle pattern on one side, were tried without success. The grooved or sandpaper surfaces were pressed into the powdered iron layer of the element during the compacting cycle.

Thin iron barriers of 2-mil-thick foils were tried. These were successfully bonded to N-type elements. Apparently the thin foil yielded during the thermal expansion movement. However, the bonds to the P-type elements failed during the Seebeck test, which is used to qualify the elements for acceptance. The test applies a temperature difference across the element for measurement of Seebeck voltage.

The N-type elements were bonded at 1300° F for 4 hr in a dry hydrogen atmosphere. The elements were clamped in a fixture similar to the one shown in Figure 56.* Two elements were bonded at one time to the iron foil barriers, and copper shoes, in the fixture.

It was felt that the bond failures of the P-type elements could be caused by the lower ductility of the P-type material and to the presence of P former elements.

Attempts were made to "key" the barrier more securely to the element. An iron foil barrier was made by sintering a relatively thick layer of iron powder to the foil at a more favorable sintering temperature of 2000° F.

*Note the spalled encapsulant on one element and the formation of copper-tellurium eutectic on the copper shoes.

4-7-64

7561-01309

Figure 56. Two P Elements in the Test Fixture After 100-Hr Environmental Test

After the 30-mil-thick layer of iron powder had been placed on the foil, a magnetic field was used to cause the powder particles to stand up in "fingers" perpendicular to the plane of the foil. The powder was fixed in place by spraying with an acrylic resin binder. The binder was burned off during the sintering cycle.

The sintered barrier assembly was placed in the die and pressed into the iron powder layer of the element during the compacting cycle used to form the element. Excellent bonds were obtained between the element and the iron foil barrier containing the sintered, low-density iron powder. When thermal stresses were applied, however, the bond now failed at the iron foil-to-copper interface. Apparently the attainment of a good bond between the element and barrier transferred the stresses to another interface — the one between the barrier and copper contacting shoe. It also is possible to include the iron foil barrier as a non-bonded insert. If the components were kept clean during fabrication and storage, and if the vacuum were good during qualification testing of the pumps, the contact resistances might be kept low. Several pumps have been fabricated with such a mechanical stackup.

b. Aluminum Foil Barrier

Another barrier concept that was tried was the introduction of aluminum foil into the middle of the powdered iron layer of the elements. The foil effectively acted as a barrier to the tellurium vapor. No major difficulties were experienced in fabricating elements incorporating aluminum. The resistivity and Seebeck data from tested elements compared favorably with elements containing no aluminum. Two thicknesses of aluminum foil were used — 0.7 and 1.3 mil. Figure 57 is a photomicrograph of a section of an element showing the aluminum foil in the iron layer. As can be seen, a portion of the aluminum alloyed with the iron powder at the 1100° F bonding temperature. Although no confirmation has been obtained as yet, traces of material having the appearance of aluminum were found in the lead telluride of the processed elements.

c. Means of Decreasing Porosity of The Powdered Iron Layer

Several methods of decreasing the porosity of the powdered iron layer were examined. Among these were:

4-7-64

7561-01310

P Element, Unetched, 100X
4639-1-3

Figure 57. Thermoelectric Element Section Showing Aluminum Foil Barrier in the Iron Layer

- 1) Densification of the powdered iron layers by modified compacting techniques.
- 2) Reduction of porosity by filling the pores with aluminum powder and infiltration with molten aluminum metal.
- 3) Reduction of porosity by filling the pores with iron sulfide formed during sintering from 1% of sulfur added to the powdered iron.

Although the tests were not completed, little success was experienced with any of the three methods. The iron powder could be densified to some extent to reduce porosity, but the tellurium vapor still found its way through the remaining pores. The aluminum filled most of the pores, but again the tellurium vapor passed through. The aluminum also reacted with the alkaline encapsulating material. The sulfur had very little effect on porosity reduction as far as the tellurium vapor was concerned. The effect of sulfur on the telluride was not known.

3. Test Results and Recommendations

The more promising barrier systems were tested by subjecting them to high temperatures in a vacuum atmosphere. The test assembly (Figure 56) consisted of thermoelectric elements clamped between two Inconel compression bars. Copper contacting shoes were assembled to the elements before they were clamped in the test fixture. Clamping pressures used in the tests were the same, in most cases, as those used in actual pump assemblies. The test fixture containing the elements was heated for 100-hr in a vacuum at 1100° F. A vacuum of 10^{-4} mm of Hg was maintained during the test duration. It should be pointed out that the elements were in an isothermal state during the test. In pump operation, of course, a temperature difference exists across the elements. The iron foil was an effective barrier to the tellurium vapor for the duration of the 100-hr test. An intergranular crack in the iron foil (Figure 55) illustrates how the tellurium vapor can pass through small openings to cause formation of the eutectic. Figure 58* illustrates the result of no barrier in the element after

4-7-64

7561-01311

P Element, Unetched, 300X
4478-2-1

Figure 58. P Element Without Barrier After 100-Hr
Environmental Test

*The lead telluride portion of an element exposed to a 100-hr elevated temperature test. The element had no barrier between the lead telluride and copper contacting shoes. Note the massive melt caused by the formation of copper-tellurium eutectic.

a 100-hr environmental vacuum test. It shows a massive copper-tellurium eutectic and copper formation in the lead telluride of the element as a result of the transfer mechanism described earlier.

The aluminum foil barrier placed in the powdered iron layer of the elements was completely converted to an aluminum - iron intermetallic after the 100-hr test. Nevertheless, the layer apparently functioned as a barrier to the tellurium vapor. As mentioned before, some traces of an aluminum - like material were observed in the lead telluride; the material, however, has not been identified. No adverse effects were noted on the electrical properties of the elements during the tests.

The environmental 100-hr tests illustrate that the thermoelectric element will become contaminated with copper if no barrier is used between the copper and lead telluride. It is not known whether element degradation in thermoelectric pump systems is due to element contamination or some other cause. However, since contamination of the lead telluride can change its electrical properties, it was recommended that a barrier be incorporated into thermoelectric elements. Present data indicate that the barrier should be an iron foil known to be compatible with the lead telluride. The long-term effect of the aluminum is not known; thus, it is not recommended for use as a barrier until additional tests have been made. Methods and the necessity of bonding the barrier to the element and the copper contacting shoe need additional investigation.

It was also recommended that exposed copper surfaces in the vicinity of the elements be protected with a coating, perhaps chromium plating, to prevent reaction with any tellurium vapor exuded from the elements.

B. THERMOELECTRIC ELEMENT AND PUMP FABRICATION

1. Element Fabrication

This section contains only a synopsis of the thermoelectric element fabrication process. The applicable documents and the fabrication requirements including the equipment, materials, and safety precautions are covered in detail in specifications (References 7 and 8). The synopsis of the element process follows.

Powdered materials for cold pressing are prepared and weighed in an air conditioned room. After weighing, each unit of powdered metal is placed in a separate clean jar and stored with an identifying label.

The die for cold pressing the elements is cleaned, lubricated, and assembled for loading. The powders shall be added to the die cavity as follows:

- a) 9.9 gm of iron powder are distributed uniformly and leveled with a leveling device along the lower ram face.
- b) 34.75 gm of PbTe (N) or 28.53 gm of PbSnTe (P) powder are then sprinkled uniformly over the surface of the iron powder. Extreme care is to be taken during this step not to disturb the surface of the iron powder. The telluride powder is then leveled.
- c) 9.9 gm of iron powder are then carefully and uniformly distributed along the surface of the telluride powder and leveled.

The top ram is inserted into the die cavity and the die assembly (Figure 59) is placed onto the press table and aligned with the center of the press ram. A light positive pressure is applied and held while the alignment is rechecked. Pressure is then slowly applied until a pressure of 65 ± 5 ram tons is achieved, and then it is held for a minimum of 15 sec and released back to zero. The die is removed from the press table and carefully disassembled. The compact is removed from the die and inspected for cracks, chips, voids, or the extension of telluride through the iron. Dimensions and weights are recorded and the compacts are identified, packaged in tissue paper, and stored in a desiccator.

a. Sintering

First, the sintering retort is inserted into the furnace. Then the compacts are placed within a previously outgassed graphite sleeve. Compacts placed inside the sleeve are separated by outgassed graphite plates. The graphite sleeve containing the compacts is inserted into the sintering retort and the retort is sealed. The retort is purged with high-purity argon gas at a rate of 15 cfh for a minimum of 15 min. This argon flow is maintained until the compact temperature reaches 400°F . Ultra-pure hydrogen at a rate of 8 cfh is then substituted for the argon. The compacts are then heated to $1300 \pm 10^{\circ}\text{F}$ (at a rate not to exceed 500°F/hr) and held for $4\text{ hr} \pm 10\text{ min}$. The furnace is then shut off, but hydrogen flow is maintained. Upon cooling to 900°F , an argon flow of 15 cfh is introduced simultaneously with the hydrogen. Hydrogen flow is

3-12-63

7561-18162

Figure 59. Die Parts for Compacting PbTe Elements

shut off after 3 min, and the argon flow is maintained until the furnace has cooled to room temperature. The retort is then opened and the compacts are removed, inspected, identified, and stored.

b. Diffusion Bonding

Element components (copper plates, 615 braze alloy, and sintered compacts) are cleaned and stacked in the bonding jig (Figure 60) in the following sequence:

- One piece of graphite
- One piece of copper
- One piece of 615 alloy
- One sintered element
- One piece of 615 alloy
- One piece of copper
- One piece of graphite
- One piece of copper, and so on.

3-12-63

7561-18156

Figure 60. Element Bonding Fixture, End View

Parts are stacked and aligned in the jig with extreme care, the bolts are torqued down to 15 ft-lb and the jig is placed in the retort which has been inserted in the furnace. The retort is sealed and evacuated to 10μ . The retort is then backfilled with purified argon. The procedure of "evacuate-and-backfill-with argon" is done 3 times. A flow of 30 cfh of argon is then maintained while the furnace is heated to $1050 \pm 20^\circ \text{F}$ (at a rate of 500°F/hr) for N elements. This condition is maintained for 5 hr for diffusion bonding. The power is then shut off and the retort is allowed to cool to room temperature. The argon flow is maintained until the assembly is ready to be removed from the retort. The retort is then opened. The bonded elements are removed from the jig and inspected for dimensional requirements or defects, and then measured to determine their resistances.* For P elements, the procedure differs as follows: the 615 alloy is eliminated from the process, the bolts in the bonding jig are torqued down to 25 ft-lb, and the bonding cycle is run for 16 hr at $1100 \pm 20^\circ \text{F}$ instead of 5 hr at 1050°F .

c. Encapsulation

Prior to encapsulation, the sides and ends of the thermoelectric elements are lightly sandblasted, cleaned with acetone, and dried in a high-velocity air stream. All the copper surfaces are masked, leaving the compact side and end surfaces exposed. The encapsulant is applied to the exposed side and end surfaces of the compact with a camel-hair brush or a paasche air brush. The excess encapsulant is removed from the elements with a Q-tip. The masking is removed immediately after spraying the elements. The elements are placed in a curing furnace and supported in such a manner that the encapsulant does not come in contact with any other object. The furnace is purged for 5 min with flowing argon at 10 cfh. Then the furnace is heated to 220°F and held for 30 min, heated to 950°F and held for 30 min, and then heated to $1075 \pm 10^\circ \text{F}$ and held for 30 min. All firing is done in flowing, dry argon. The furnace is allowed to cool to 100°F before removing the elements. The flat surfaces of the finished elements are conditioned by sanding on fine sandpaper. Encapsulated elements are inspected for chippage, tearing, extrusion of thermoelectric material, cracks and pinholes, dimensional tolerances (flatness and parallelism), and resistance and Seebeck values.

*Elements shall meet the following resistance requirements at room temperature:

P $27 \pm 5\mu$ -ohm

N $13 \pm 3\mu$ -ohm

2. Pump Fabrication

SNAP 10A thermoelectric pumps are currently being fabricated in conformance with Reference 8. This specification covers the applicable drawing numbers, all materials and equipment required, and detailed steps for assembly of the pumps. A synopsis of these items follows. The following equipment is required for fabrication.

- a) Fixtures for welding, alignment, brazing, and bonding
- b) Blind nut gun (Model BG2500), and power unit (Model BP4000), Hi-Shear Corporation, or equivalent
- c) Acid cleaning facilities
- d) Ultrasonic cleaning tank (Model CT-170-1000), Gulton Industries, or equivalent
- e) Furnaces equipped for vacuum-and inert-atmosphere operation
- f) Industrial abrasive unit (Model D351-1699Y), S. S. White, or equivalent.

The following materials other than component parts are required for fabrication.

- a) Reagent grade acetone
- b) Reagent grade methyl alcohol
- c) Commercial grade trichloroethylene
- d) Nicoro 80, Western Gold and Platinum, or equivalent
- e) Premabraz 615, Handy and Harman, or equivalent
- f) Liquid argon
- g) Aluminum oxide with an average particle size of less than 27μ
- h) ATJ graphite as required.

The following steps outline the fabrication procedure:

a. Weldment Assembly

Step 1: Clean all parts ultrasonically with trichloroethylene and abrasively clean, heavy-oxide deposits in the weld area.

Step 2: Align the parts in the weld fixture to allow for shrinkage due to welding (Figure 61).

Step 3: Weld.

b. Pump Support Assembly Preparation

The following steps shall be adhered to in the fabrication of the FS design and FSM design:

Step 1: Identify and orient all pole faces and support bracket parts by using an alignment fixture (Figure 62).

Step 2: Locate holes and countersinks, and spotfaces.

Step 3: Fabricate the shim.

Step 4: Locate blind nut assemblies in all parts except the weld assembly.

c. Throat Assembly

The following steps shall be adhered to in the fabrication of the FS design and FSM design:

Step 1: Clean weld assembly ultrasonically.

Step 2: Cut Nicoro 80 braze to conform to braze joint.

Step 3: Insert the wiring sockets, using Nicoro 80 braze to fill the annulus.

Step 4: Clean all braze and copper surfaces with steel wool, acetone, and methyl alcohol.

Step 5: Fixture all parts by aligning and place Nicoro 80 in all braze joints (Figure 63).

Step 6: Braze in a furnace evacuated to a pressure no greater than 10^{-3} Torr and at a temperature between 1750 and 1800° F. The braze joint shall be at a temperature above 1700° F no less than 5 min and no longer than 25 min.

Step 7: Final machine throat assembly.

3-12-63

7561-18155

Figure 61. Weld Assembly Fixture, End View

NAA-SR-9486
107

3-12-G3

7561-18160

Figure 62. Support Bracket Alignment Fixture, Side View

3-12-63

7561-18159

Figure 63. Throat Assembly Fixture, Front View

d. Element Bonding

- Step 1: Cut Premabraz 615 to conform to the surfaces to be bonded.
- Step 2: Clean the braze and copper surfaces with steel wool, acetone, and methyl alcohol.
- Step 3: Fixture the encapsulated elements and brazed throat by aligning, and place Premabraz 615 in all bonding joints. Bond in a furnace evacuated to a pressure no greater than 10^{-3} Torr and at a temperature of $1050 \pm 25^{\circ}\text{F}$ for 5 hr.

e. Radiator Bonding

- Step 1: Clean the bonding surfaces on radiators and thermoelectric elements with steel wool, acetone, and methyl alcohol.
- Step 2: Assemble radiators, using compression bars and bolts.
- Step 3: Torque the bolts evenly until a 0.0015-in. shim will not pass between the end of the spacer and the compression bar.
- Step 4: Bond in a furnace evacuated to a pressure no greater than 10^{-3} Torr and at a temperature of $980 \pm 20^{\circ}\text{F}$ for 2 hr.

f. Pump Support Assembly

The following steps shall be adhered to in the assembly of the FS design and FSM design:

- Step 1: Locate blind nut assemblies in the aft support. Install the blind nut assemblies.
- Step 2: Assemble all support bracket parts, pole faces, and magnets.

C. POSTTEST EXAMINATION

Subsequent to NaK operation, all pumps were metallographically examined to correlate degradation and operating data. Standard metallographic techniques were employed where applicable and new procedures were developed to examine the brittle thermoelectric. An electron microprobe was used to identify alloys formed by volatilization of tellurium within the elements. The procedures involved in the examination of a pump, typical results, and conclusions are contained herein.

1. Procedures

A pump, when readied for metallographic examination, has had the magnets and support structure removed. No change in the thermoelectric element compression loading takes place. To ensure that the elements remain intact during these procedures, the entire assembly is wired or band-clamped together (with stainless-steel material). The entire pump is then potted and cast in EPOCAST epoxy mounting material. Sectioning of the various critical areas for detailed examination is then performed.

Standard metallographic procedures were used to polish the specimens. In some cases, it was necessary to use diamond grit all the way down through the final polishing operation to obtain a satisfactory polish on the P-type material. The formulation and technique developed for etching lead telluride are shown below.

a. Etchant for Lead Telluride

1) Solution (make up cold)

- a) 10 gm $K_3Fe(CN)_6$
- b) 10 gm KOH
- c) 100 cc H_2O .

2) Etching Procedure

- a) Swab surface for 10 to 15 sec
- b) Rinse in H_2O
- c) Rinse in isopropyl alcohol
- d) Dry surface with air blast.

After polishing, etching, and microscopic examination, these sections were analyzed with an electron microprobe. A brief description of the basic principle and operation of the microprobe follows.

The principle of the microprobe is practically the same as that for x-ray fluorescence, except for the size of the beam and the use of electrons instead of x-rays to induce secondary, characteristic x-radiation from a specimen. In the microprobe, an electron beam is focused to cover a 1- to 2μ -diameter spot on the surface of the test specimen. The intensity of this

electron beam is made sufficiently high to produce characteristic x-ray radiation from a specimen in the area covered by the electron spot. The x-ray radiations from this spot are diffracted from the surface of a curved, lithium fluoride crystal and detected with a proportional counter. The crystal and detector may be positioned and locked in such a manner that the radiation characteristic of a particular element is reinforced, and the output of the detector then may be compared with standards to give a quantitative measure of the percentage of the element present in the specimen.

2. Metallographic Results

Prototype-II pump No. 11 was selected to show typical photomicrographs of the critical joints and elements. The depicted joints in Figures 64 through 69 start with the stainless steel-to-copper block braze joints and proceed in order through the thermoelectric elements. Figure 64 shows typical stainless-steel throat sections brazed to the copper metal blocks with Grade 615 Premabraz alloy. It is not known whether the visible void areas developed during the prolonged performance test or whether they were present when the braze joints were made. In any case, the stainless-to-copper Premabraz joints, in general, showed a number of small voids and several large voids after the performance tests. Both silver and indium have high vapor pressures, so this is not a particularly good brazing alloy for vacuum service. It seems reasonable to assume that some of the voids could have formed during the long-time performance test.

Figure 65 shows typical N- and P-element photomicrographs of the diffusion-bonded Premabraz 615 joint at the copper block-to-hot-iron powder interface. Note the difference between the two joints. The Premabraz has penetrated the iron powder in the N element to some extent, but most of the Premabraz foil is still intact and there has been no visible erosion of the copper block. Contrast this with the interface between the copper and iron powder in the P element. Scarcely any braze material was left. Note how the copper block has been eroded. Not all of the P-element sections showed this much reaction, but this is a typical view of a number of the sections. None of the N elements showed any evidence of corrosion of the copper block at this interface. The photomicrograph exhibited is typical of all the N-element joints

Typical N-Element Joint, 250X

4-7-64

7561-01295

Typical P-Element Joint, 150X

Figure 64. Photomicrographs of Stainless Throat Brazed to Copper Block With Grade-615 Premabrazed, Pump 11

N Element, Hot Cu to Fe Joint, 150X

4-7-64

7561-01296

P Element, Hot Cu to Fe Joint, 150X

Figure 65. Photomicrographs of Diffusion Bonds of Hot Copper to Iron Powder Made With Grade 615 Premabrazed Foil, Pump 11

N Element, Hot Iron Powder, 150X

4-7-64

7561-01297

P Element, Hot Iron Powder, 150X

Figure 66. Photomicrographs of Hot Side of Iron Powder Adjacent to Hot Side of PbTe, Pump 11

N Element Between Center and Cold Side of
PbTe, 150X, Unetched

4-7-64

7561-01298

P Element Between Center and Cold Side of
PbTe, 150X, Unetched

Figure 67. Photomicrographs Taken of PbTe Between the Centers
and Cold Side of the Thermoelectric Material, Pump 11

N Element, Cold Side of PbTe, 150X, Etched

4-7-64

7561-01299

P Element, Cold Side of PbTe, 150X, Unetched

Figure 68. Photomicrographs of Cold Side of Thermoelectric Elements, Pump 11

N Element, Cold Premabrazed Joint, 150X

4-7-64

7561-01300

P Element, Cold Premabrazed Joint, 150X

Figure 69. Photomicrographs of Premabrazed Joints on Cold Side of the Thermoelectric Elements, Pump 11

in this area. Note the grey areas in the copper in the P element. Two of the globular, grey areas are visible just to the left of the word "copper" in the photograph. It has been established, from microprobe studies of P-type test elements that were heated in contact with copper, that these grey areas contain tellurium. Note how deeply the grey areas penetrated into the copper without any connecting path visible. This alloy probably had good diffusion characteristics. Similar grey areas, indistinct in the photograph, are visible in both of the elements within the iron powder. Not many areas of grey material show up in the N elements, but the P elements contain many globular-like areas similar to the ones visible within the massive copper. These results indicate that tellurium vapor penetrated the hot side of the iron powders and reacted with the Premabraz material. The presence of tin in the P elements appears to have aggravated this condition.

Figure 66 shows corresponding photomicrographs of N and P elements taken at the hot-telluride-to-iron-powder interface of the thermoelectric materials. Note that there is very little bonding of the iron powder to the telluride in the N element. This is typical. The N elements usually separate at this interface, but the situation is even worse with the P elements; they seemed invariably to separate at the interface. Note that the telluride material is missing in the P-element photograph. This specimen parted at this interface, presumably during the sectioning operation. Careful inspection of the iron powder at the lower left-hand corner in the P-element photomicrograph reveals some small, elongated, grey areas. This structure has been associated with the presence of an alloy of copper and tellurium which indicates that copper atoms have migrated this far into the thermoelectric element. Similar grey areas exist in the iron powder in the N element, but there are very few of these and they are difficult to see in the picture.

Photomicrographs of the elements in Figure 67 were taken midway between the center of the respective telluride materials and the cold side of the telluride. Neither the N material nor the P material was etched in this case. Note that the N material shows approximately the same degree of contamination as it did in the previous photograph, but note how much contamination is visible now in the lower half of the P material. There appears to be as much grey material present as there is white telluride material.

Figure 68 shows the cold side of the N and P telluride materials. Note the abundance of grey-phase contamination that has accumulated in the cold side of the P-type telluride. Compare this with the cold side of the N element. The width of this severe contamination in the P telluride material is variable, as may be seen by referring again to Figure 67, but in the sections from this pump it averaged approximately 20 mils in thickness. Figure 69 shows the bottom side of these cold iron powders where the cold copper plates were diffusion bonded to the iron powders with Grade 615 Premabraz. Note that the Premabraz-to-iron-powder interfaces are very smooth. There is very intimate contact of the braz foil to the iron powder surfaces. Note, also, that the bonds to the copper surfaces are excellent. Actually, a metallurgical bond is effected between the copper plates and the Premabraz. The thickness of the Premabraz foils is approximately 2 mils, the same as the thickness of the original preforms. The Premabraz layer in the N element was etched slightly by the basic ferricyanide solution used to etch the N-type lead telluride shown in some of the previous photomicrographs.

Elements from pump 11 were scanned with the microprobe for the presence of copper in the telluride material. Photographs of these scans are shown in Figures 70 and 71. The scan covered an area of approximately 12 mils on a side and was equally spaced across the telluride material. The scan shows significant contamination of the telluride with copper. The microprobe studies of P elements furnished conclusive proof that the P-type thermoelectric materials were being poisoned by an accumulation of silver and copper in the cold side of the telluride.

Figure 72 shows a microprobe scan of four areas to determine the concentration of lead in the telluride. Three areas show a uniform concentration of lead in the lead telluride, but the scan of the cold side of the telluride is entirely different. Refer to Figure 73, showing scan photographs of these same areas for tellurium. Note the uniform distribution of tellurium in the three areas. The scan of the cold side of the lead telluride shows tellurium where there was lead, in Figure 72, but also shows the tellurium as extending out into the black areas farther than the lead.

Cold Side of PbTe

4-7-64

7561-01301

Hot Side of PbTe

Figure 70. Microprobe Scan of N Element for Copper, Pump 11

Cold Side of PbTe

4-7-64

7561-01302

Hot Side of PbTe

Figure 71. Microprobe Scan of P Element for Copper, Pump 11

Cold Side of PbTe

4-7-64

7561-01303

Hot Side of PbTe

Figure 72. Microprobe Scan of P Element for Lead, Pump 11

Cold Side of PbTe

4-7-64

7561-01304

Hot Side of PbTe

Figure 73. Microprobe Scan of P Element for Tellurium, Pump 11

Figure 74 shows how silver also has accumulated at the cold side of the P telluride specimen. The two photographs at the bottom show only background levels and no silver contamination in the telluride that was toward the hot side of the element. These microprobe studies appear to show conclusive proof that the P-element thermoelectric material from this pump became contaminated with silver and copper during the performance tests. It is difficult to visualize how an element could have been fabricated originally with such an ordered distribution of copper in one side of the telluride.

3. Metallographic Conclusions and Recommendations

The following conclusions were drawn from the results of metallographic and microprobe examinations of SNAP 10A thermoelectric pump elements after performance testing:

- a) Premabrazed Grade-615 brazed joints connecting the NaK tubes to the copper electrode blocks were not satisfactory and were subsequently changed.
- b) Premabrazed Grade-615 foil diffusion bonded satisfactorily to the copper metal blocks, but the bonds to the iron powder surfaces appeared to provide only intimate contact — not a very strong bond.
- c) There was a significant difference between N elements and P elements in the performance of the Grade-615 Premabrazed foil at the hot-iron-powder to copper-metal-block joint. Extensive reaction of the Premabrazed joint was observed in P elements, but there was little change in the Premabrazed foils in N-type elements. There was evidence that tellurium vapor (or possibly tin-telluride vapor) had penetrated the P-element hot iron powders and reacted with the Premabrazed. The presence of tin in the P-type telluride probably accounted for the greater degree of reaction noted in P-type elements. Microprobe studies confirmed the presence of tellurium at the Premabrazed surface.
- d) Some of the N elements separated at the hot-iron-powder to telluride interface during sectioning, but practically all the P elements failed here. Since this interface represents the line

Cold Side of PbTe

4-7-64

7561-01305

Hot Side of PbTe

Figure 74. Microprobe Scan of P Element for Silver, Pump 11

of maximum differential expansion under operating conditions, it was concluded that there is possibility of failure here which could be a factor in pump degradation.

- e) Both the N- and P-type elements showed copper contamination in the telluride material after performance tests. Copper in the N-type elements was more or less distributed throughout the lead telluride. Copper in the P elements was concentrated in the colder side of the lead-tin-telluride material. The extent of copper contamination in the P-type telluride was much more severe than in the N elements. Copper poisoning of the thermoelectric materials probably was a significant factor in pump degradation.
- f) The N elements showed no evidence of contamination by silver, but the P-type elements showed significant amounts of silver contamination concentrated in the cold side of the lead-tin-telluride material. It was concluded that silver poisoning of the P-type thermoelectric material also was probably a significant factor in pump degradation.
- g) Very little evidence of contamination was found in the cold iron powders except where they were in contact with the telluride material. The Premabrazz foil in the cold side of the elements appeared to have been unaffected. It was concluded, therefore, that the copper and silver poisoning came from the hot side of the elements.
- h) Attempts to polish the P-type telluride specimens revealed that this material is significantly more friable or brittle than the N telluride material. A majority of the P-element specimens was shattered in the telluride when received for examination. It was concluded on the basis of working with this P-type material that its present poor mechanical properties may result in fracturing of the elements during service and thus contribute to pump degradation.

The following recommendations were made for improving the quality of SNAP 10A thermoelectric pump elements based upon the results of general observations and upon the results of the microprobe and metallographic examinations described above.

- a) Some sort of solid metal barrier needs to be provided between the porous, hot iron powder and the Premabrazed or copper metal block material to minimize poisoning of the thermoelectric materials. It is recommended that a thin, solid iron foil be inserted between the hot side of the iron powder and the Premabrazed foil, and that a technique be developed for bonding the iron foil to the respective materials involved.
- b) There is need to strengthen the lead-tin-telluride material in the P-type elements. It is recommended that efforts be made to accomplish this. Possibly iron metal whiskers could be mixed with the lead-tin-telluride powder to result in a stronger thermoelectric P-type material. Or perhaps a few tenths of a percent of free tin metal could be mixed with the lead-tin-telluride powder during fabrication to strengthen it without serious deleterious effect upon its electrical characteristics.

BLANK

REFERENCES

1. B. Katz and L. Lepisto, "SNAP 10A TE Pump Data Analysis," NAA-SR-MEMO-8948 (September 9, 1963)
2. B. Lubarsky and S. Kaufman, "Review of Experimental Investigations of Liquid Metal Heat Transfer," NACA Report 1270 (1956)
3. D. B. MacKay and E. L. Leventhal, "Radiant Heat Transfer From a Flat Plate Uniformly Heated on One Edge," NAA-MD58-187 (August 13, 1958)
4. E. Eckert and R. M. Drake, Jr., Heat and Mass Transfer (McGraw-Hill Book Company, New York, 1950)
5. "NaK Pump, Thermoelectric SNAP 10A, Acceptance Tests," AI Specification NA 0204-005 (February 27, 1963)
6. "NaK Pump, Thermoelectric SNAP 10A, Qualification Tests," AI Specification NA 0404-009 (February 27, 1963)
7. "Fabrication and Encapsulation of Thermoelectric Elements for SNAP 10A Pumps," AI Specification NA 0614-001 (May 1, 1963)
8. "Assembly of SNAP 10A Thermoelectric Pump," AI Specification NA 0120-003 (October 30, 1963)
9. E. Reed, "Fabrication and Posttest Evaluation of SNAP 10A TE Pumps," NAA-SR-MEMO-9447 (to be issued)
10. B. E. Pollock, "Vaporization of Lead Telluride," NAA-SR-TDR-6220 (March 28, 1961)