A88-42558

Thermoelectromagnetic pumps for space nuclear power systems

Robert J. Campana and T. Ciarlariello

Electro Technology Corporation, 11180 Roselle, Suite G, San Diego, California 92121
and Advanced Systems Div., Mine Safety Appliances Company, Evans City, Pennsylvania 16033

ABSTRACT

A ThermoElectroMagnetic Pump (TEMP) is the integration of a thermoelectric generator (TEG) and an electromagnetic pump (EMP) into a single component. TEMPs are ideally suited for space nuclear power systems (SNPSs) currently being developed to provide sustained power sources for the Stategic Defense Initiative (SDI). They are unique safety devices used in the removal of decay heat after reactor shutdown because the decay heat itself is used as the source of energy for pumping power to circulate the coolant. TEMPs may also be used as pumps in the main coolant loops. This paper is a status report on an on-going systematic study of TEMPs for the sustained SDI NSPSs and technolgies being developed, namely thermoelectric, thermionic, and Stirling cycle conversion. TEMPs for power systems ranging from 100ekW to 10eMW are being considered with temperatures ranging up to 1500 K. Permanent magnet, electromagnet, and coreless magnet TEMPs are included. Current and advanced thermoelectric, permanent magnet, electromagnet, and high temperature electrical conductors materials are being evaluated and selected for TEMP designs. The characteristic of TEMP specific mass, i.e., their mass as a function of their hydraulic power output, is the prime criterion of performance. Configuration changes required as a function of pump power and the identity of critical development issues to be resolved in Phase II will be presented in a future report.

1. INTRODUCTION

A ThermoElectroMagnetic Pump (TEMP) is the integration of a thermoelectric generator (TEG) and an electromagnetic pump (EMP) into a single component. TEMPs are ideally suited for space nuclear power systems (SNPSs) currently being developed to provide sustained power sources for the Stategic Defense Initiative (SDI). They are unique safety devices used in the removal of decay heat after reactor shutdown because the decay heat itself is used as the source of energy for pumping power to circulate the coolant. TEMPs may also be used as pumps in the main coolant loops. They are static devices: i.e., they have no moving, sliding or rotating parts, no bearings, and no seals. In addition, the TEG and the EMP can be ideally matched since both are inherently high-current, low-voltage devices. TEMPs are expected to be extremely reliable and maintenance free based on their development and use in the SNAP-10A SNPS, SNAPSHOT, that was flown in 1965 and as demonstrated in the separate performances of the two major components in other applications.

The objectivess of this development study are to:
(1) determine the feasibility of TEMPs as decay-heat removal system and main loop pumps in SNPSs for the SDI
(2) determine TEMP specific mass as a function of pump work
(3) determine under what conditions permanent magnet, electromagnet, or coreless magnet are best
(4) determine if and at what pump and system power levels TEMP configurations change
(5) select preferred TE, magnet, and electrical conductor materials
(6) estimate survivablility
(7) identify critical issues

The approach used in the study is to first review the published descriptions of the three SP-100 SNPSs to characterize the systems and to establish a base of pertinent information such as the arrangement of the major heat transport components, the coolant and containment materials, the operating temperatures, volumetric flowrate, and coolant loop pressure losses. This information was then used to project over the power range of interest to establish a set of pump specifications sufficient in number to allow characteration of the TEMP specific mass as a function of TEMP or SNPS power level. The second step was to develop TEMP configurations for the various pump types. Then, the methodology and the computer codes were developed and debugged, and trial calculations performed. That is where the study stands now. In the remaining work, it is expected that about 24 different TEMPs will be designed. After a basic set of TEMPs have been designed to establish specific mass curve, then single TEMPs will be designed incorporating advanced materials, variations in designs and configuration, and other features suggested by trends, the results, etc. Differential performance can be evaluated, preferred materials selected, and critical development issues identified.

In the remainder of this report, the following topics will be presented in order: SNPS pumping requirements, basic EMP and TEG concepts, TEMP configurations, methodology and computer codes, the design of TEMP2, discussion of some results to date, and some speculation about the work ahead.

2. SNPS PUMPING REQUIREMENTS

Pumping requirements for the range of SNPSs of interest have been estimated to use as a basis for developing TEMP specific mass as a function of the hydraulic power level. Estimates were made for both main and decay-heat pumps.

2.1. Main loop pump requirements.

Main loop pumping requirements are considered first because the piping is sized for full power operation. Decay-heat pumps use the same piping to circulate coolant when the SNPS is shut down. Pumping requirements at the 100kW SNPS level were used as the basis for extrapolation over the range of interest from 0.1 MW(100kW) to 10 MW. The objective here was to obtain a reasonable range of parameters for the study although no great accuracy was required .

The hydraulic power to the pumps must increase as the power of the SNPS increases. The pumping power is P(h)=deltaP*Q using a consistent set of units, where P(h) - hydraulic power; deltaP - delivered pressure; and Q - volumetric flowrate.

A review of the thermal management systems of the SP-100 candidates was conducted to establish a base from which to extrapolate pumping requirements to the higher power levels associated with the SNPS levels of interest. In spite of the significant differences in conversion technologies employed, coolants, and in operating regimes, it was found that the pumping requirements were surprisingly similar. This makes it possible to derive and use a single set of pumps that will be adequate for all of these SNPS over the power range of interest. The delivered pressure was extrapolated as the 1/3 power of the ratio of the higher output SNPSs to the 100 ekW level. Volumetric flowrate was taken to be directly proportional to the SNPS power level. Thus the hydraulic pumping power required, the product of the delivered pressure, and the volumetric flowrate, increases as the 4/3 power of the SNPS capacity. The results are given in Table 1. This set of pumps will be used in the remainder of the study for developing the mass per unit of hydraulic power curve of the various kinds of TEMPs.

However, all of the pumping power need not be delivered by a single pump. In fact, for system reliability and safety reasons, it will not be delivered by less than 3 pumps connected in parallel flow. Thus each pump must deliver the full required deltaP but only one-third of the required flowrate. The required pumping power may be delivered by more than three pumps if there is some advantage. Where more than three pumps are to be used, a combination of series and parallel connections can be used with three parallel streams as a minimum. From a scoping standpoint for this study, only all-parallel-connected arrangements were considered because they increase the range of pump power at the low end. Series-parallel pump connection introduces the need for a higher level, more complex valving to prevent backflow when some pumps are off. The added components and complexity can significantly reduce system reliability and is best avoided.

2.2 TEMP requirements for Decay-Heat-Removal Systems (DHS).

DHSs must employ TEMPs, if the main loops do not, in order to continue coolant circulation even though the remainder of the system is shut down. The decay-heat-removal pumping requirements are very modest even at the 10 MW(e) system power level. The reason is that the heat generated in the reactor after shutdown falls to ~5% of that at full power in only a fraction of a second and then continues to fall less rapidly after that. Thus the maximum mass and volumetric flowrates to be provided by the DHS TEMP is only 5 % or 1/20th of the full power flowrate requirement. However, the system piping, sized for full-power flow, offers little resistance at such low flowrates. Thus, the pressure at which the flow is to be delivered by the TEMP is then very low.

Conservatively assuming the flow in the SNPS to be laminar over the range from full to 5% power, the reduction factor would be 20 each for both the flowrate and the delivery pressure or a factor of 400 in the hydraulic power required. The DHS TEMP requirement for 10 MW(e) SNPSs, included in Table 1 below, is about the same as that for one of the three redundant main loop TEMPS for the 100kW(e) SNPSs. Thus, it appears that DHS TEMPs for SNPSs of 10MW(e) and higher are feasible and practical with near "state-of-art" technology.

Table 1 TEMP Design Specifications

TEMP No.	Delivered Pressure (psi)	Volumetric Flowrate (gpm)	Hydraulic Power (W(h))	*SNPS Power (kW(e))
DH1	<1.0	780	365	10000
M2	4.0	100	174	64
M3	7.9	780	2680	500
M4	10.9	1563	6798	1000
M5	15.9	6250	43228	4000
M6	19.1	10938	90878	7000
M7	21.5	15625	146813	10000

* Assumes three, one-third capacity pumps connected in parallel

3. BASIC CONCEPTS

There are two major components of TEMPs, the EMP and the TEG. The basic concept of these components will be briefly reviewed prior to arranging them to comprise TEMPs.

The basic process in the EMP is the interaction of the normal vectors of a magnetic field and an electric current which results in a force vector which is normal to the plane of the first two. This is shown diagramatically in the upper left of Fig. 1. The force vector is directed according to Fleming's left-hand or motor rule. Application of the vector arrangement is apparent in the pumping cell depicted in Fig. 1 by the arrangement of the magnet poles and current electrodes. The force applied to the liquid metal in the pump cell raises the pressure and causes flow through the pump and the externally connected hydraulic circuit. It should be noted that EMPs are static devices, i.e., except for the liquid being pumped there are no moving parts, no rotating or sliding parts, and no bearings, stuffing boxes, or seals. Electricity must be supplied to power the pump. The pumps of interest to TEMP are d.c., conduction pumps, also known as Faraday pumps. Typically, these pumps are high-current (kA), low-voltage (100 mV) devices. Power supplies for Faraday pumps frequently limit their utility. TEGs, however, are well suited for that purpose.

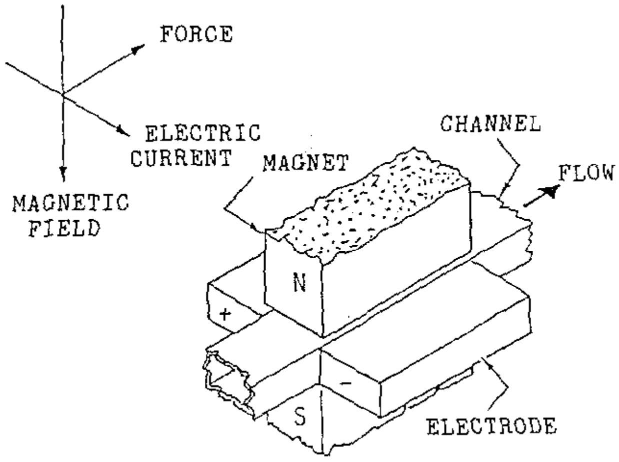

Fig. 1. EMP Concept

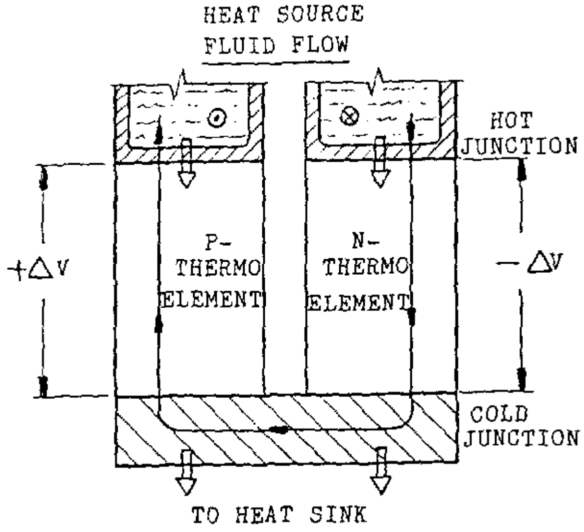

Fig. 2. Thermocouple Concept

The magnetic field of the EMP may be produced by permnanent magnets (PM), electromagnets (EM), or other magnetic field producers, e.g., sets of Helmholtz coils (HM). The PM and EM are well understood and need no further comment. However, a brief description of the HM seems warranted here. The HM is considered here as a coreless magnet which is not subject to loss of ferromagnetism such as may occur in PMs and EMs if the Curie temperature is approached or exceeded. Once the loss occurs in a PM, its residual magnetism can only be restored by subjecting it again to a magnetizing field. In an EM, its ferromagnetism returns when the temperature falls below the Curie point. HMs, because they do not suffer such loss, may have some potential advantages which are to be considered in this study. The HMs have the property that at a certain separation of the coils, the axial magnet field is nearly constant over a large fraction of the diameter and falls precipitously to essentially zero outside the coils. HMs can be designed so that their pump ducts can be located in the uniform flux region.

The TEG is the assembly of one or more semiconductor thermocouples (See Fig. 2) and thus ultilizes the Seebeck, Peltier, and Thompson Effects. The semiconductors are selected for their superior thermoelectric properties, namely high Seebeck coefficient, low thermal conductivity, and low electrical resistivity. When the thermocouples junctions are subjected to a temperature difference, a Seebeck voltage is generated, and when connected to an external circuit, current will flow. By this process, a fraction of the heat that flows through the thermocouples to maintain the temperature difference between the junctions will be converted to electricity. Like the EMP, the TEG is also a static device. Inherently, the size of the Seebeck coefficients, even in semiconductors, and the available temperature differences makes the TEG, like the EMP a high-current, low-voltage device. This makes the TEG an ideal power source for the EMP.

The source of heat for the TEG is the liquid metal coolant flowing through the pump duct. The heat sink for the TEG could be the colder liquid metal stream returning to the reactor. Otherwise, the waste heat from the TEG can be "dumped overboard", i.e., radiated into space. The latter heat sink was selected for this study so the TEMPs are independent of the radiator temperature determined and dictated by the main converter and system constraints and optimization. In addition, this choice also assures an adequate temperature difference to drive the TEMP in long-term removal of decay heat.

4. CONFIGURATIONS

Three preliminary configurations selected for PM, EM, and HM TEMPs are shown in Figs. 3, 4, and 5 respectively. Based on early analysis, double, self-compensating pumping cells were assumed as more mass and energy efficient than single- or other self-compensating multiple cells. The armature current (or the current passing through the liquid) distorts the magnetic field created by the magnet if an equal and oppositely direct current does not pass nearby so as to essentially cancel the magnet distortions of the first pass. The lower resistivity and density of the liquid metals and the added pumping action of the second cell make this arrangement superior to solid busbar compensators. The cells pump in opposite directions and must be connected serially in the external piping. This can be accomplished by a simple U turn or by connection to pipes going to and from the reactor, heat exchanger, or converter where they pass close to each other.

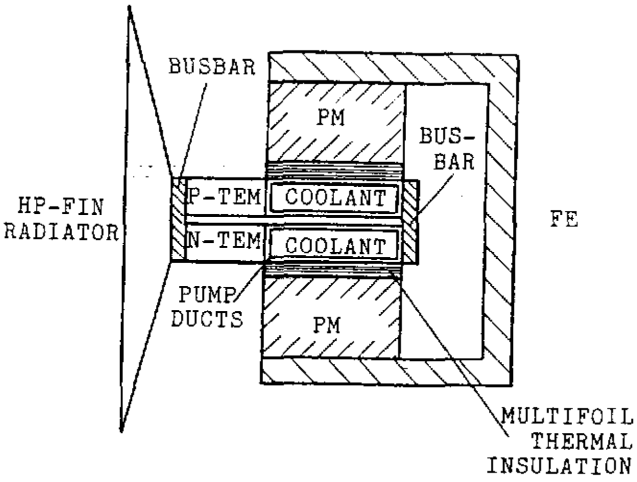

Fig. 3. PM Configuration

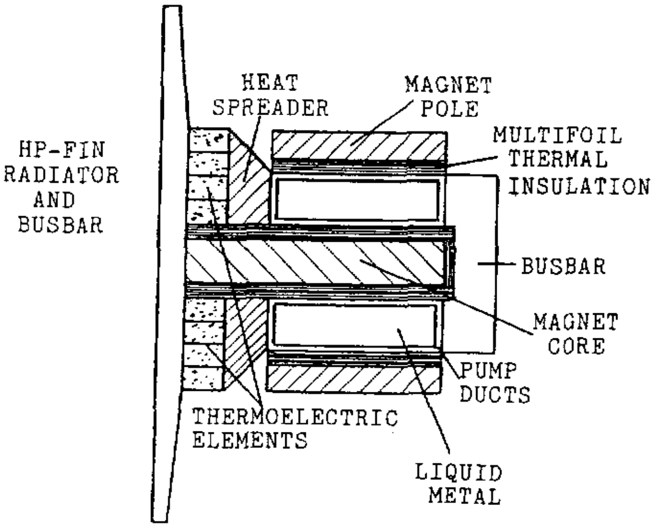

Fig. 4. EM Configuration

The integral heat sinks are heat-pipe, finned radiators. These must be single-sided radiators so as not to interfere with other SNPS components. They must be located with the thermoelectric elements so as to reject their waste heat. The evaporators of the radiator heat pipes are located in the busbar that interconnects the cold-side of the thermoelectric elements.

The permanent magnet and electromagnet are located above and below the pumping section sandwich. The permanent magnet core return path passes on the opposite side of the pumping section from the thermoelectric elements and radiator. The electromagnet core follows a complex path between the poles and the central induction leg. From the poles the paths pass parallel to the pumping section in opposite directions until they are clear of the busbars before they can turn around the pump ducts to connect with the central induction leg. The HM has no core. For series-connection, the HM rings are connected together and become the busbar for interconnecting the thermoelectric elements. For parallel-connected rings, as shown and most likely to be used, they must be connected to the duct-side or ouput side of the thermoelectric elements. In this location, their connection enters into the thermal circuit upstream of the TEG.

There are obviously other arrangements of the components or configurations. As pump sizes increase, it may become more difficult to integrate the components as completely as indicated in these configurations. At some point it may be found that better results will be attained by less highly integrated configurations. To learn if and when that occurs is one of the objectives of the study which has not yet been reached.

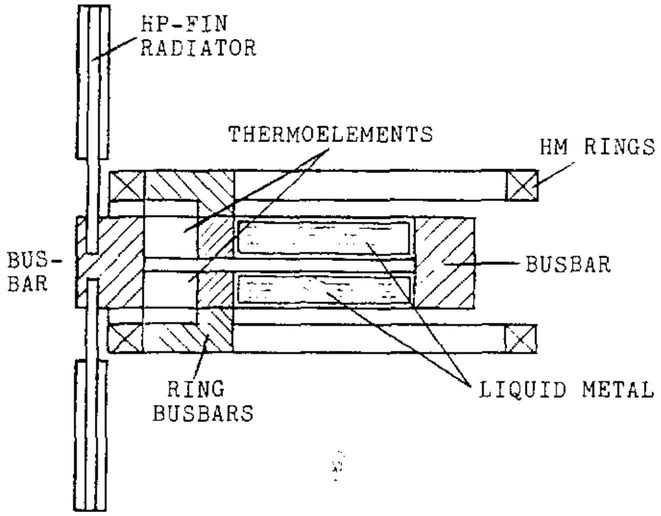

Fig. 5. HM Configuration

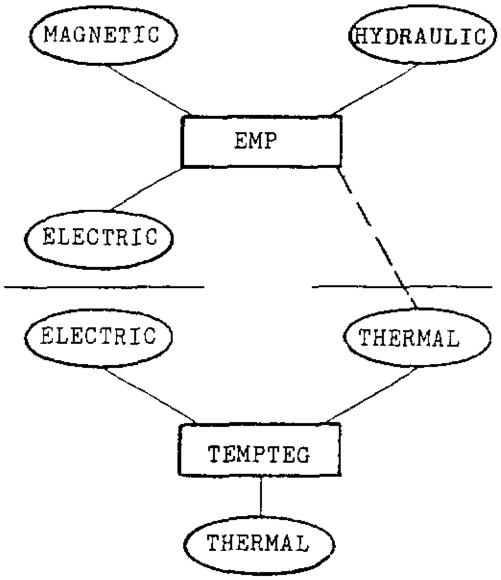

Fig. 6. Methodology Scheme

5. METHODOLOGY

The overall methodology is described first. Detailed analytical models are not presented but their sources are referenced.

5.1. Overall methodology

The methodology developed accommodates the four circuits involved in the TEMP design and analysis; namely thermal, electric, magnetic and hydraulic as implied by the device name. The models for representing these circuits and their inter-relationships have been incorporated into two major computer programs, EMP and TEMPTEG. These programs are supplemented by a number of specialized computer programs; namely THEAT, HTPIPE, PM, EM, and HM1. THEAT is an ETC proprietary, multivariate-optimization, thermoelectric design Fortran code. HTPIPE is the Los Alamos National Laboratory heat pipe design and performance Fortran code[1]. All of the other programs were written for this study using non-formatted, iterative solving software. The methodology arrangement of circuits and computers program modeling is shown in Fig. 6. Matching of the electrical circuits of the two major TEMP components, EMP and TEG, is required but easily accomplished. The terminal voltage of the TEG is the input voltage to the EMP, and the electric current is common to both EMP AND TEG. There is also an implied matching of the thermal circuit required.

However, this is accomplished by transferring the inter-related thermal and hydraulic parameters from EMP into TEMPTEG as depicted by the dotted line in the figure. Thus, the thermal matching is automatically and entirely done within the heat exchanger section of the TEMPTEG code. In Fig. 6, two thermal circuit indicators are shown to reflect the heat exchanger part of the thermal circuit uptemperature of the TEG and the heat-pipe radiator part downtemperature. Material properties are incorporated into the codes using polynomial fitting of the data where necessary.

SI and cgs practical units of measure were used throughout. English engineering units were used only in pump specifications and were converted at the beginning and/or end of all programs as appropriate.

5.2. EMP methods

The methods of Barnes[2] and Johnson[3] were used to model the electromagnetic effects including the total pressure developed by the pump, pressure losses from electromagnetic braking, entrance and exit edge effects of current and flux fringing and mismatching, friction in the pump throat, and contraction and expansion in the nozzles and diffusers. An optimization of the flux with respect to the current is included. The terminal voltage of the pump, which involves the counter EMF generated by the flowing liquid metal in the magnetic field, is also covered here.

Modeling of the PM circuit used the methods of a commercial magnet manufacturer[4]. The model utilizes the maximum energy product point of the demagnetization curves. No specialized methods have been applied to the EM yet although some may need to be developed for any unusual geometry involved. Modeling for the HM are based on the methods for representing coil conductors of significant cross-sectional area by equivalent point cross-section conductors[5]. The magnetic field distributions involve eliptical integrals of the first and second kinds.

5.3. TEMPTEG methods

Standard heat exchange equations are used for heat transfer from the liquid stream to the wall of the duct where the thermoelements are located. The heat transfer coefficient correlation used is that developed by Lyons, et al.[6]

The TEG uses the average parameter methods of Ioffe[7], including optimization of the generator efficiency at a current gradient that is a constant for given deltaT between the hot and cold junctions and the thermoelectric properties of the materials. Using these methods, the TEGs are matched to the EMPs at the maximum efficiency rather than the maximum power point.

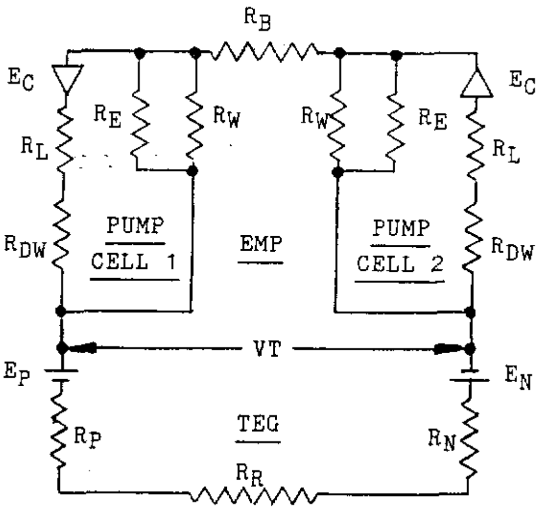

Fig. 7. TEMP2 Electric Circuit

The electric circuit for PM TEMPs is shown in Fig. 7 where:
E - EMF
R - resistance
Subscripts refer to:
P - thermoelectric elements
N - thermoelectric elements
R - cold-side connector
C - counter
W & DW - walls of pump duct in parallel and in series respectively to current flow
L - liquid
B - EMP busbar
E - effective fringe.

6. DESIGN OF TEMP2, AN EXAMPLE

TEMP2 was defined in Section 2 as a 4psi - 100 gpm requirement. It has been selected as an example to help develop and test the methodology described above. In this section, the results of the design of TEMP2 will be presented and some of the things learned in its design will be discussed.

The materials selected for TEMP2 are shown in Table 2. Table 3 shows the power requirements and conversion efficiencies of TEMP2. Neither EMP nor TEG efficiencies were maximized since the primary criterion of performance is the TEMP2 mass. However, the EMP conversion efficiency is near its maximum to reduce the TEG mass. The TEG conversion efficiency has been somewhat reduced and would be further reduced if it were not constrained to match EMP voltage. With a fixed hot junction temperature, raising the cold junction temperature reduces the thermocouple deltaT and the output voltage.

Table 2. Materials

Thermoelectric	SiGe+GaP
Coolant	Li
Duct and fittings	Nb-1%Zr
Magnet	Alnico V
Busbars	Proprietary
Heat pipe fluid	Na
Heat pipe container & wick	Nb-1%Zr
Fins	CC composite

Table 3. Energy Requirements and Efficiencies

	Power(W)	Efficiency(%)
EMP Hydraulic	174	
Electric/hydraulic		32.1
TEMP Electrical	542	
Thermal/electric		4.4
TEG thermal	12461	
Overall thermal/hydraulic		1.4

The mass of TEMP2 and its distribution among its components is listed in Table 4. This mass is considered to be near optimum for this configuration and the materials selected. The 24 kg of the EMP comprises ~58% of the TEMP2 total with the PM, the most massive single item, comprising 45% alone. It was found that the EMP without the constraints imposed by the TEG could meet the pumping specifications with a mass of less than 5 kg but with an efficiency of less than 10%. The resulting electric power requirement made the mass of the TEG 3 to 4 times the value shown in Table 4 and the TEMP2 mass far from optimum. As a result, it was necessary to increase the length of the EMP to increase efficiency to nearly its maximum attainable value, about 30% (see Table 3).

The second most massive component is the set of 10 heat pipes in the TEG waste-heat radiator which comprises about 25% of the TEMP2 total of 42 kg. Fewer heat pipes of longer length could have been used with reduced mass but with reduced redunancy and therefore reliablility of the radiator. Furthermore, the heat-pipe design was not optimized and is probably more massive than necessary.

The third component in order of mass are the busbars, one in the EMP, which connects the two pumping cells, and the other is the cold-side connector in the TEG which connects the two thermoelectric elements. Together the busbars comprise about 16 % of the TEMP2 mass. This is a significant fraction of the total mass. But even more importance should be assigned to the busbars since their mass is based on the use of a proprietary material having a low value of the product of its electrical resistivity and density, which is a measure of its value as a space system conductor. Replacing the proprietary material with Mo would add about 2.2 kg to the total mass and increase the busbar mass to about 21%.

Table 4. TEMP2 Mass Distribution

Component/Part	TEMP Mass kg	%
Permanent Magnet	18.90	45.3
Cell and Converter Busbars	7.20	17.5
Radiator Heat Pipes (10)	10.21	24.5
Radiator Fins (0.85 m^2)	3.27	7.8
Remainder	2.05	4.9
TEMP2 Total	41.72	100.0

Table 5. Some Key Parameters

TE figure-of merit, 10^{-3}/K	0.916
Open circuit voltage,mV	161
Terminal voltage, mV	93.7
Total current,kA	5.787
Magnetic flux density, mT	169.8
Magnetic air gap, mm	65
Flange-flange length, mm	611
Radiator area, m^2	0.85

The cold junction temperature of the TEG, and thus the radiator temperature, was raised as far as possible within other constraints to accommodate reduction in the size and mass of the radiator. The radiator comprises about 32% of the total mass and is sensitive to the fourth power of the radiation temperature. However, as the radiator temperature is raised, the deltaT across the thermocouple decreases and with it the terminal voltage of the TEG, which must match that needed by the EMP. But the voltage of the EMP goes down only as its length and mass go up. The use of series-connected multiple thermocouples to provide more flexibility in voltage has not yet been investigated but would require significant changes in all of the basic configurations developed to date.

The heat source to power TEMP2 and the heat exchange to tranfer the heat from the liquid stream to the TEG were not found to be a constraint on TEMP2's specific mass at TEMP2 capacity.

Some key parameters in the design are shown in Table 5. The overall dimensions of the pump and the waste heat radiator are included.

Tables 6 and 7 show the temperatures along the heat path from source to sink and the distribution of the developed pressure rise among the loss mechanisms, respectively.

Table 6. TEMP2 Temperature Distribution

Heat Path Pts.	T(K)	Pt.-Pt. DeltaT
Fluid entering EMP	1211	
		11
Hot junction	1200	
		300
Cold junction	900	
		30
HPCondenser OD	870	
		233
Fin tips	636	
		380
Space near Earth	256	
		954

Table 7. TEMP2 DeltaP Distribution

Components	DeltaP(kPa)
Delivery Pressure	-27.6
Magnetic Braking	-20.8
Fringe Effects	-10.2
Friction, contraction-expansion	-3.5
Developed Head	+62.1

7. SUMMARY AND CONCLUSIONS

A midpoint review and status report of the subject study has been presented. Specifications were developed for a set of TEMPs adequate for decay-heat removal and main pumps for SNPSs ranging in electrical power output from 0.1 to 10 MW. The methodology for the design of TEMPs in the specified set was developed and was briefly described. It will be used to derive the characteristic mass per unit hydraulic power relationship. Three types of magnetic field producers will be evaluated: PM, EM, and HM. Also the effects of current and advanced materials technology will be evaluated. Critical issues in the development will be identified and potential solutions recommended.

The design of TEMP2, a PM pump, was used to demonstrate the methodology, and the results were presented and discussed. The methodology was successfully demonstrated by this exercise. The software and the organization of the codes provides great flexibility and speed in design optimization and performance estimation. With these tools, the remainder of the study can be rapidly completed.

8. ACKNOWLEDGEMENTS

The authors wish to acknowledge our sponsors who make this work possible. This work is performed under an SDIO-SBIR award and is conducted under USAF Contract F33615-87-C-2751 with the Aeropropulsion Laboratory, Air Force Wright Aeronautical Laboratories, Aeronautical Systems Division (AFSC), USAF, WPAFB, OH 45433-6543

9. REFERENCES

1. F.C. Prenger, Jr., Heat Pipe Computer Code (HTPIPE), Users Manual, LA-8101M (1979).
2. A.H. Barnes, Direct Current Electromagnetic Pumps, Nucleonics, Vol. 1, No. 1, pp. 16-21 (1953).
3. J.L. Johnson, Thermoelectric Performance and Computer Code, AI-AEC 13095, Atomics International Div., Rockwell International (1973).
4. Thompson and Skinner, Inc., Permanent Magnet Design - Bulletin M303 McAdams
5. H.B. Dwight, Electrical Coils and Conductors, McGraw-Hill, New York (1945).
6. R.N. Lyons, et al., Liquid Metal Handbook, Na-NaK Supplement, USAEC and Dept. of Navy (1955).
7. A.F. Ioffe, Semiconductor Thermoelements and Thermoelectric Cooling, Infosearch Ltd., (1957).