

**NASA TECHNICAL
MEMORANDUM**

NASA TM X- 52834

NASA TM X- 52834

**CASE FILE
COPY**

HYBRID THERMOCOUPLE DEVELOPMENT PROGRAM - A STATUS REPORT

by W. J. Bifano, L. P. Garvey, and R. A. Straight
Lewis Research Center
Cleveland, Ohio

TECHNICAL PAPER proposed for presentation at
Fifth Intersociety Energy Conversion Engineering Conference sponsored
by the American Institute of Aeronautics and Astronautics
Las Vegas, Nevada, September 21-24, 1970

HYBRID THERMOCOUPLE DEVELOPMENT PROGRAM - A STATUS REPORT

by W. J. Bifano, L. P. Garvey, and R. A. Straight

Lewis Research Center
Cleveland, Ohio

TECHNICAL PAPER proposed for presentation at
Fifth Intersociety Energy Conversion Engineering Conference sponsored
by the American Institute of Aeronautics and Astronautics
Las Vegas, Nevada, September 21-24, 1970

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

HYBRID THERMOCOUPLE DEVELOPMENT PROGRAM - A STATUS REPORT*

by W. J. Bifano,
NASA-Lewis Research Center
Cleveland, Ohio

L. P. Garvey and R. A. Straight
Radio Corporation of America
Harrison, New Jersey

Abstract

The description and development status of a Hybrid thermocouple, which employs both PbTe and SiGe thermoelectric materials, is presented. Hybrid couple performance is predicted by means of an analytical model and beginning-of-life couple efficiency is compared to that of an all SiGe couple. A preliminary design of a planar RTG, employing Hybrid couples and a water heat pipe radiator, is described as an example of a possible power system application.

Introduction

The thermoelectric materials most often considered for purposes of energy conversion in space are alloys of silicon and germanium and alloys of lead and tellurium. Each alloy has unique advantages.

Silicon-germanium (SiGe) alloys are capable of operating in either air or vacuum up to 1100° C (2000° F) and exhibit good mechanical strength and machinability. The thermoelectric properties of the p-type SiGe are invariant with time from room temperature to 1100° C (2000° F). The n-type SiGe alloys exhibit a slight change in electrical resistivity and Seebeck coefficient with time because of a temperature dependence of the solid solubility of dopant. The majority of this change occurs at temperatures below about 600° C (1100° F) (Ref. 1). Metallurgical bonds are employed for hot and cold shoe contacts in SiGe couples.

Lead telluride (PbTe) alloys can be operated from room temperature to about 600° C (1100° F), however they must be protected from the environment in most applications. The main attractiveness of tellurides is their excellent ability to convert heat to electricity, reflected by the so-called "figure-of-merit." Up to temperatures of about 550° C (1100° F), the tellurides have a higher figure-of-merit than the SiGe alloys. Although some problems have been encountered with metallurgically bonded PbTe couples, indications are that the n-type PbTe bonds are reliable.

A careful review of the operating characteristics of both alloys suggested a thermocouple design having a segmented SiGe-PbTe n-leg and a SiGe p-leg. In the segmented n-leg, the n-type PbTe is used up to temperatures of about 600° C (1100° F) and SiGe at higher temperatures. This arrangement takes advantage of the high figure-of-merit of PbTe below 600° C (1100° F) and stable performance of n-type SiGe above 600° C (1100° F). The p-leg is fabricated in the form of a hollow cylinder and used to encapsulate the segmented n-leg, thereby protecting the PbTe. This configuration, called the Hybrid thermocouple, should provide a high performance device with stable electrical characteristics. Details of the Hybrid couple are shown schematically in Figure 1. Both ends of the p-type SiGe cylinder are metallurgically bonded, one to the silicon-molybdenum hot shoe and the other to the cold-stack assembly. The cold-stack assembly is attached to a mounting stud. Two electrical insulators in the cold-stack assembly provide electrical isolation of the two thermocouple legs from each other and from the stud. Each leg is contacted to an electrical connector. The n-type PbTe thermoelement is contacted to metal shoes. The n-type PbTe cold shoe is bonded through a stress compensator to the cold-stack assembly. The n-type PbTe hot-shoe is bonded through a stress compensator to the cold shoe of the n-type SiGe. The hot end of the SiGe element is bonded to the SiMo hot shoe. The space between the p-type and n-type thermoelements is filled with thermal insulation. Finally, the couple is sealed in an inert-gas atmosphere to inhibit sublimation of the PbTe.

On January 23, 1969, a contract was awarded to RCA, Harrison, New Jersey, by NASA LeRC to design and develop the Hybrid couple. The program was divided into 5 major tasks as follows:

- TASK I. Thermocouple Parametric Design Analysis
- II. Thermocouple Fabrication and Testing
- III. Preliminary Converter Design
- IV. Detail Thermoelectric Module Design
- V. Fabrication of Modules

The following ground rules were established for the program:

1. Incident heat flux to TE converter -- 2 watts/cm²
2. Hot junction temperature 926° C (1700° F)
3. Mission life 5 years
4. End-of-life power 250 watts
5. Heat pipe radiator to be considered analytically (no hardware development)

The status of the Thermocouple Parametric Design Analysis, Task I, Thermocouple Fabrication and Testing, Task II, and Preliminary Converter Design, Task III, are presented herein.

Design and Analysis

A computer program was developed to estimate the performance of a radioisotope thermoelectric generator incorporating Hybrid thermocouples. The generator is assumed to consist of a heat source, a planar array of thermocouples and a heat rejection subsystem. The combination of the thermocouple array and heat rejection subsystem is referred to as a thermoelectric converter. Initially, the Hybrid thermocouple is considered analytically, independent of the converter. Hot and cold junction temperatures are assumed for both the SiGe and PbTe segments and the temperature-averaged thermoelectric properties are determined. For the analysis, properties for the 63 at. % Si, SiGe alloy and 3N PbTe (3M Co.) were used. Couple performance is determined for a range of geometries (i.e., element lengths, areas, etc).

For selected couple geometries, converter characteristics are then determined assuming a square array of thermocouples. For a nominal output power of 250 watts (e), both the required number of couples and the thermal power input to the converter are determined. Next, the total thermal power required by the generator is computed, i.e., the sum of the thermal power input to the converter, the thermal loss through insulation around the heat source and the thermal loss through the heat source supports. Generator efficiency is determined from the electrical output power and total thermal input power.

The radiator analysis is carried out after the generator efficiency is determined. A rectangular, heat pipe radiator is assumed. The total system weight is computed after the radiator area and weight have been calculated. The results of the design effort are described in subsequent sections.

Hybrid Thermocouple Design

By use of the computer program, the effect of a wide range of design parameters on Hybrid thermocouple performance was investigated for the following operating temperatures:

Hot junction	-	926° C (1700° F)
Interface (PbTe hot junction)	-	538° C (1000° F)
Cold junction	-	232° C (450° F)

The input parameters selected were:

1. p-type SiGe element length, L: 2.54, 3.17, 3.81 cm, (1.0, 1.25, 1.5 inches).
2. Ratio of n-type SiGe/PbTe area to p-type SiGe area, A_n/A_p : 1.0, 1.4, 1.6, 1.8, 2.2 (Numerically referred to PbTe area for cases where n-SiGe and n-PbTe areas are unequal).
3. Ratio of n-type SiGe to n-type PbTe area, A_{n1}/A_{n2} : 0.4, 0.7, 1.0.

* Resalab, Inc., Menlo Park, California, contributed to the analytical phase of the program.

Selected results of the analysis are illustrated in Figures 2 through 5. Figure 2 shows Hybrid couple efficiency as a function of n-SiGe/n-PbTe area ratio, A_{n1}/A_{n2} , for an element length of 3.18 cm (1.25 in.) and various A_n/A_p ratios. This curve indicates that by appropriate selection of A_n/A_p (in the range of 1.4 to 1.8), couple efficiencies of 7.2 to 7.4 percent result for A_{n1}/A_{n2} ratios of 0.4 to 1.0. The wall thickness of the p-SiGe cylindrical element is plotted against the radius of the n-PbTe element, r_{n2} , in Figure 3 for various values of A_n/A_p . The p-leg wall thicknesses appear reasonable from the standpoint of fabrication feasibility for A_n/A_p ratios of 1.5 to 1.8 over the range of r_{n2} considered. For example, for an r_{n2} of 0.476 cm (0.1875 in.) and a A_n/A_p of 1.6, the p-leg wall thickness is 0.116 cm (0.046 in.). A cross-plot of Figures 2 and 3 with A_n/A_p fixed at 0.7 and an element length of 3.17 cm (1.25 in.) is presented in Figure 4. Note that for a fixed r_{n2} , increasing A_n/A_p results in an increase in l/A and hence an increase in couple efficiency. (l/A is defined as the ratio of element length to its own cross-sectional area.) Additional geometrical relationships are shown in Figure 5. For any given couple length, the lengths of the n-type PbTe and SiGe segments can be found using this figure.

Upon the completion of the parametric analysis three couple designs, described in Table I, were selected for evaluation in the subcomponent development phase of the program. These design selections were based not only on couple efficiency but also on an evaluation of fabrication feasibility, materials and bond system availability, and mechanical integrity.

The indicated Hybrid couple efficiencies of 7.1 to 7.5 percent represent a beginning-of-life improvement of 10 to 15 percent over an all SiGe thermocouple (63 at % Si alloy) operating at the same junction temperatures.

Generator Design

Subsequent to the thermocouple design study, a preliminary design was defined to establish the performance of the Hybrid couple in a planar generator. Couple design B (Table I) was selected for the study. For the analysis, a square planar array of Hybrid couples and a water heat pipe radiator is assumed. Multifoil insulation (metal foils with opacified paper separators) surrounds the thermocouples and the entire converter. A sketch of such a generator, recessed into a flight vehicle, is shown in Figure 6a. The radiator, shown schematically in Figure 6b, consists of a number of 0.94 cm (0.37 in.) diameter copper heat pipes, positioned at intervals in an aluminum honeycomb support structure, covered with a 0.03 cm (0.012 in.) thick aluminum skin. The radiator size and weight is based on heat rejection from one side only. The design objective is specified to be 250 watts (e) at 28 volts at the end of a five year mission. A total degradation of 10 percent is assumed to account for the combined effects of fuel source decay, thermoelectric material degradation, insulation degradation, etc. Results of this preliminary study are presented in Table II. Generator designs B-I and B-II employ 289 couples (17 by 17 array) while design B-III has 324 couples (18 by 18 array). The heat pipe radiator designs were chosen on the basis of minimum weight.

Note that the specific power remains essentially constant at about 4 watts/kg (1.8 watts/lb) for cold junction temperatures from 122° C (250° F) to 232° C (450° F). The lower cold side temperatures result in increased efficiency at the expense of an increase in radiator area. For applications where radiator area is critical, the heat pipe radiator could be reduced in size (e.g., by increasing skin thickness or decreasing spacing between heat pipes) with a small addition in radiator weight. Obviously, further investigation would be required to design such a generator for a specific mission.

Improvements in the Hybrid couple (e.g., through the use of the 80 at. % Si n-SiGe alloy and the improved n-PbTe-GeTe alloy) and increased hot junction temperature would significantly increase the generator specific power. As shown in Table III, incorporation of these improvements in generator design B-III would increase the generator specific power to about 5.3 watts/kg (2.4 watts/lb).

Development

Subcomponent Development

The objective of this phase of the program was to evaluate bond systems and further define fabrication constraints for the subcomponents to be used in the construction of three

Hybrid couple designs (Table I). The following subcomponents were evaluated:

- A. SiGe p-type cylindrical leg bonded to hot and cold shoes.
- B. SiGe n-type leg bonded to hot and cold shoes.
- C. PbTe n-type leg bonded to hot and cold shoes.
- D. Intermediate bond system (PbTe hot shoe bonded through a gold compensator to SiGe cold shoe).
- E. Cold stack (electrical connectors, insulators, compensators and mount stud).

A. p-SiGe Element

The p-SiGe element consists of a p-SiGe cylinder metallurgically bonded to a p-SiMo heat receptor plate and a tungsten cold shoe. Several methods of fabricating the p-SiGe cylinder were investigated, including Elox machining, ultrasonic machining, and diamond core drilling. Of these, the diamond core drilling process produced the most uniform, mechanically sound cylinders. Attempts to fabricate cylinders of Design A, 3.81 cm (1.5 in.) length and 0.091 cm (0.036 in.) wall thickness, were unsuccessful due principally to radial cracking. Design C, 2.54 cm (1.0 in.) length and 1.58 cm (0.622 in.) O.D., was also found to be impractical since there was insufficient material in the largest size ingot that could be fabricated in presently available equipment to obtain mechanically sound cylinders having uniform wall thickness. As a result, all testing of p-SiGe element subcomponents was conducted with Design B cylinders, i.e., 3.17 cm (1.25 in.) length, 1.34 cm (0.527 in.) O.D. and 0.117 cm (0.046 in.) wall thickness.

Life tests at 982° C (1800° F) for 300 hours and at 1090° C (2000° F) for four hours, and thermal cycling tests from 982° C (1800° F) to 150° C (300° F) were conducted to assess the mechanical and thermal capability of the hot side SiGe to SiMo bond. No changes in electrical resistance or microstructure were noted in the life tested specimens, however, microcracks developed in the bond region resulting in loss of hermeticity in those specimens subjected to both high temperature soaking and thermal cycling. This condition was corrected by substituting 80 at. % Si p-SiGe alloy (which is a better thermal expansion match to the p-SiMo alloy) for the 63.5 at. % Si p-SiGe alloy. This new alloy-bond combination was successfully subjected to 10 thermal cycles from 982° C (1800° F) to 150° C (300° F). Thermal cycling with the tungsten cold shoe brazed to the p-SiGe cylinder also resulted in leak-tight bonds after 10 cycles from 315° C (600° F) to 93° C (200° F). The tensile strength of as-fabricated and life-tested specimens (982° C (1800° F) for 300 hours and 1090° C (2000° F) for 4 hours) averaged 3300 psi and 2550 psi, respectively. These values are typical for SiGe with the fractures occurring in the bulk SiGe. The tensile strength of as-fabricated and life-tested specimens (315° C (600° F) for 4032 hours with the tungsten cold shoes attached), averaged 2300 psi with the break occurring in the bulk SiGe. The cold shoe bond of the p-SiGe cylinders has been tested for 6200 hours at 315° C (600° F) with no observable change in resistance.

B. n-SiGe Element

The n-SiGe element consists of a n-SiGe pellet metallurgically bonded to a n-SiMo heat receptor plate on one end and a tungsten cold shoe on the other end. Elements tested at 982° C (1800° F) for 300 hours and 1090° C (2000° F) for 4 hours showed no change in electrical or physical properties. Metallographic examination indicated normal n-SiGe-W and n-SiGe-n-SiMo bonds.

A summary of the tensile and shear strength tests made on as-fabricated and life tested specimens is given in Table IV. These strength values are normal for SiGe with the fractures occurring in the bulk SiGe material.

C. n-PbTe Element

The n-PbTe element consists of a 3N PbTe pellet metallurgically bonded to 303 stainless-steel shoes, which have been pretreated with a tungsten diffusion-barrier layer. The tensile and shear strength of as-fabricated PbTe elements of 0.635 cm (0.250 in.) and 0.951 cm (0.375 in.) O.D. are given in Table V.

Note that the strength of the elements is lower than that of the pellets. The element strength, however, still exceeds design requirements for the device. The current technique of shear testing was not suitable for elements with 0.635 cm

(0.250 in.) O.D. and no shear strength data was obtained for these elements. Resistance measurements made before and after isothermal life tests of the 0.635 cm (0.250 in.) O.D. and 0.951 cm (0.375 in.) O.D. PbTe elements are tabulated in Table VI. Note that the sum of the PbTe bulk and contact resistances do not equal the total measured resistance since some of the bulk resistance is included in the measurement of the contact resistance. Only minimal changes occurred in the electrical resistance and physical appearance of the elements subjected to isothermal life tests. Metallographic examination of the life tested specimens showed sound structures with very little discernable change in the PbTe-W barrier-303 stainless steel bond structure. In general, the n-PbTe elements subjected to life tests have shown good stability.

D. Intermediate Bond System

The intermediate bond coupon system consists of a gold disc bonded between a 303 stainless-steel disc and a tungsten disc. The 303 stainless-steel disc, which simulates the PbTe hot shoe, is nickel plated. The tungsten disc, which simulates the SiGe cold shoe, also is nickel plated. Tensile testing resulted in separation of the specimens in the Au-Ni bond region, as expected. Specimens subjected to accelerated life-testing had approximately the same strength as as-bonded specimens (i.e., 6200 and 11,900 psi as-bonded compared to 8600 and 6400 psi after life test). The tensile test results are summarized in Table VII. Shear strength of as-fabricated specimens was 11,500-13,800 psi. Metallographic examination showed that the bonds were sound, both before and after life tests. Overall integrity of this bond system was excellent.

E. Cold Stack

The cold stack consists of the n- and p-electrical connectors, ceramic insulators, compensators, mount stud and copper exhaust tubulation brazed together into a single sub-assembly. As-fabricated cold stacks, bolted to an aluminum radiator base plate with a 50 in.-lb. torque applied, showed no distortion of any parts and the ceramic insulators were intact. (A force of 10-15 in. lb. is normally sufficient to assure good contact between the mount stud and radiator base plate.) The tensile and shear strength of the as-fabricated cold stacks averaged 7400 psi and 7100 psi, respectively, with the fracture occurring through the ceramic insulator ring. Specimens isothermally life tested at 204° C (400° F) for 300 hours and at 316° C (600° F) for 2304 hours had tensile strengths of 3000 psi and 3553 psi, respectively, with the fracture again occurring through the ceramic insulator ring. All structures as-fabricated and life-tested were vacuum tight. Metallographic examination of all structures showed sound, void free bonds.

Thermocouple Development

Based on the results of the subcomponent development program, the following materials were selected for the Hybrid couple:

- a. Heat receptor: 85 Wt. % Si - 15 Wt. % Mo, p- and n-type SiMo.
- b. p-type cylindrical leg: 80 at. % Si - 20 at. % Ge
- c. n-type segmented leg
 - 1) 70.0 at. % Si - 30.0 at. % Ge
 - 2) 3M Co. - 3N PbTe

In addition, a p-type cylindrical leg having a length of 3.17 cm (1.25 in.), an O.D. of 1.34 cm (0.527 in.), and a wall thickness of 0.117 cm (0.046 in.) was found acceptable. Therefore, couple Design B (Table I) was selected as the basis for the couple development study.

The fabrication steps required to assemble the Hybrid couple are described below. The assembly sequence is schematically illustrated in Figure 7.

A. Heat Receptor Subassembly

This assembly consists of a n-SiMo disc, 0.81 cm (0.320 in.) O.D., 0.050 cm (0.020 in.) thick, metallurgically bonded via a diffusion barrier to a 0.317 cm (0.125 in.) thick p-SiMo heat receptor plate.

B. SiGe Subassembly

The heat receptor assembly, p-type SiGe cylinder, n-type SiGe segment and the tungsten cold shoe are simultaneously bonded together.

C. n-Type PbTe Subassembly

The n-type PbTe segment and the W coated 303 stainless steel shoes are bonded together prior to being incorporated into the next assembly.

D. Thermocouple Subassembly

The SiGe subassembly, n-type PbTe subassembly and the gold compensators are diffusion bonded in two steps to form the thermocouple subassembly. The bond between the n-SiGe cold shoe, gold compensator and the PbTe hot shoe is made as the first stage operation and the bonding of the lower gold compensator to the PbTe cold shoe as the second stage operation. This was found to be necessary because in a single stage bonding operation, sufficient deformation occurred in the lower gold compensator to cause a reduction in pressure at the top gold compensator which resulted in a poor bond between the n-SiGe cold shoe, gold compensator and the n-PbTe hot shoe.

E. Cold Stack Subassembly

The entire cold stack subassembly is simultaneously brazed together.

F. Hybrid Thermocouple Final Assembly

The thermocouple subassembly (D) and the cold stack subassembly (E) are brazed together to form the Hybrid thermocouple. Prior to this final brazing operation, the gap between the n-segment and the wall of the p-SiGe cylinder is filled with 99.5 percent aluminum oxide powder and microquartz to reduce the heat transfer through this space. Following the final braze, the couples are backfilled with argon and the copper tubulation is pinched off.

Hybrid Thermocouple Evaluation

A number of thermal stress problems were encountered initially in testing complete Hybrid thermocouples. Typically, the failures consisted of cracks or separations in the bond regions of the p-SiGe and n-PbTe segments. Although, as previously stated, these bonds maintained integrity during sub-component testing, apparently somewhat higher stress levels are encountered in the complete couple assemblies. In order to alleviate the problem, a gold ring, formed from 0.127 cm (0.050 in.) diameter gold tubing, was inserted between the p-leg tungsten cold shoe and the cold stack prior to the final braze to add additional compliance to the structure. Several couples have since been fabricated incorporating this modification and the major mechanical problems appear to be solved; however, additional testing will be required to confirm this. Three couples are presently being tested at reference design temperatures, the longest test time being 1550 hours. All three couples follow a general trend of increasing in resistance by about 10 percent during the first few hundred hours of operation with no subsequent change in resistance. The cause of the resistance increase has not yet been determined.

Summary of Results

The results of the work performed to date under the Hybrid Thermocouple Development Program are as follows:

1. An analytical study to estimate Hybrid couple efficiency and define Hybrid thermocouple geometries of interest has been completed. The study indicated that the beginning-of-life Hybrid couple efficiency would be 10 to 15 percent better than all-SiGe (63 at. % Si) couples.
2. A preliminary design of a planar generator using Hybrid thermocouples and a water heat pipe radiator was prepared. A specific power of 4.0 watts/kg (1.8 watts/lb) was estimated for a generator using current-design Hybrid couples operating at a hot junction temperature of 926° C (1700° F). A specific power of 5.3 watts/kg (2.4 watts/lb) is projected assuming the use of improved thermoelectric materials and operation at a hot junction temperature of 1000° C (1832° F).
3. Several Hybrid thermocouples have been fabricated, three of which are currently on life test at reference design conditions.

References

1. V. Raag, private communication.

TABLE I
HYBRID COUPLE DESIGNS SELECTED FOR SUBCOMPONENT DEVELOPMENT PROGRAM

DESIGN PARAMETERS

Geometrics	Units	A	B	C
n-leg to p-leg area ratio, A_n/A_p		1.6	1.6	1.6
n-SiGe to n-PbTe area ratio, A_{n1}/A_{n2}		0.7	0.7	0.7
PbTe element, r_n	cm(in.)	0.381(0.150)	0.476(0.1875)	0.571(0.225)
p-leg wall thickness, t	"	0.091(0.036)	0.117(0.046)	0.142(0.056)
Gap between n-leg and p-leg	"	0.076(0.030)	0.076(0.030)	0.076(0.030)
Length of p-type SiGe, L	"	3.81(1.50)	3.17(1.25)	2.54(1.00)
Length of n-type SiGe, l_1	"	2.32(0.915)	1.87(0.736)	1.42(0.558)
Length of n-type PbTe, l_2	"	0.983(0.387)	0.798(0.314)	0.613(0.241)
Heat receptor area	cm ² (in. ²)	3.05(0.473)	5.69(0.882)	11.5(1.78)
p-SiGe cylinder O.D.	cm(in.)	1.10(0.432)	1.34(0.527)	1.58(0.622)
Operational	Units	A	B	C
Couple efficiency	%	7.5	7.35	7.1
Power per couple	watts	0.476	0.886	1.570
Voltage	volts	0.186	0.186	0.186
Current	amps	2.56	4.76	8.45
Internal resistance	ohms	0.061	0.033	0.018
Hot junction temperature, T_{HJ}	°C(°F)	926(1700)	926(1700)	926(1700)
Interface temperature, T_I	"	538(1000)	538(1000)	538(1000)
Cold junction temperature, T_{CJ}	"	232(450)	232(450)	232(450)
Incident heat flux	watts/cm ²	2.0	2.0	2.0

TABLE II
PRELIMINARY GENERATOR DESIGNS

Parameter	Units	B-I	B-II	B-III
No. of couples	---	289	289	324
Power output (BOL)	watts	312	277	273
Efficiency	%	7.2	6.8	6.4
Hot junction temperature	°C(°F)	926(1700)	926(1700)	926(1700)
Cold junction temperature	"	122(250)	177(350)	232(450)
Converter weight	kg(lb)	22.7(50)	22.7(50)	25.4(56)
Heat-pipe radiator weight	"	24(53)	15.4(34)	10.4(23)
Fuel source weight*	"	32.2(71)	30.8(68)	33.1(73)
Total generator weight	"	79(174)	69(152)	69(152)
Specific power	watts/kg(watts/lb)	3.95(1.8)	4.0(1.82)	3.96(1.8)
Radiator area	m ² , (ft ²)	8.7(94)	4.7(51)	3.1(33)

* A specific power of 60 watts/lb has been assumed for the fuel source.

TABLE III

PROJECTED IMPROVEMENTS IN PERFORMANCE FOR GENERATOR DESIGN B-III

Converter Modification	Generator Specific Power		Generator Efficiency, %
	watts/kg	(watts/lb)	
Reference design with $T_{HJ} = 926^\circ\text{C}$ (1700°F) and $T_{CJ} = 232^\circ\text{C}$ (450°F)	4.0	(1.8)	6.4
Increase T_{HJ} to 1000°C (1832°F)	4.6	(2.1)	7.2
Substitute PbTe-GeTe alloy for 3N PbTe and use 80 at. % Si n-type SiGe	5.3	(2.4)	8.4

TABLE IV

TENSILE AND SHEAR STRENGTH OF n-SiGe ELEMENTS

Design	Number of Specimens	Tensile Strength*, psi			Shear Strength*, psi	
		As-bonded	After 300 hrs. @ 982°C (1800°F)	After 4 hrs. @ 1090°C (2000°F)	As-bonded	After 300 hrs. @ 982°C (1800°F)
A	15	3600-4000	3500-3800	3500-3800	2000-2500	2000-2500
B	15	3600-4000	3700-4000	3700-4000	2300-2500	2000-2500
C	15	3600-4000	3700-4000	3700-4000	2300-2600	2000-2500

* Measured at room temperature.

TABLE V

TENSILE AND SHEAR STRENGTH OF n-PbTe ELEMENTS

Specimen O.D., cm (in.)	Specimen Number	Tensile Strength, psi
0.635(0.25)	Pellet	1080
	Element 1	712
	2	1570
	3	*
0.951(0.375)	4	361
	5	*
	6	729
		Shear Strength, psi
0.951(0.375)	7	284
	8	203

* Broke while attaching tensile fixtures.

TABLE VI
RESISTANCE OF PbTe ELEMENTS SUBJECTED TO
ISOTHERMAL LIFE-TESTING IN ARGON

Test No.	Element O.D. cm(in.)	Soak Temperature, °C(°F)	Time at Temperature, hrs.	RT Resistance, milliohms			
				Total	Contacts		Bulk PbTe
					1	2	
1	0.951(0.375)	RT	AB	0.313	0.030	0.020	0.30
		540(1000)	330	.341	.020	.020	.32
2		RT	AB	.32	.025	.025	.30
		540(1000)	330	.335	.025	.020	.30
3		RT	AB	.34	.020	.020	---
		593(1100)	138	.385	.025	.020	.345
4		593(1100)	252	.365	.025	.030	.330
		RT	AB	.32	.015	.020	---
5	593(1100)	138	.343	.015	.020	---	
	RT	AB	.92	.015	.025	.910	
6	540(1000)	475	.99	.030	.040	.960	
	RT	AB	.92	.022	.035	.905	
7	540(1000)	475	.98	.020	.030	.950	
	RT	AB	.93	.020	.025	.890	
8	593(1100)	159	.935	.025	.030	.900	
	RT	AB	.94	.020	.030	.915	
8	593(1100)	159	.97	.030	.040	.935	

RT Room temperature
 AB As-bonded

TABLE VII
TENSILE STRENGTH OF INTERMEDIATE BOND COUPONS

Specimen No.	Soak Temperature °C(°F)	Time at Temperature, hrs.	RT Tensile Strength, psi
1	RT	AB	6200
2	RT	AB	11,900
3	593(1100)	330	8600
4	649(1200)	4	6400
5	593(1100)	481	9660
6	649(1200)	4	11,890*

* Attachment failure, coupon did not rupture.

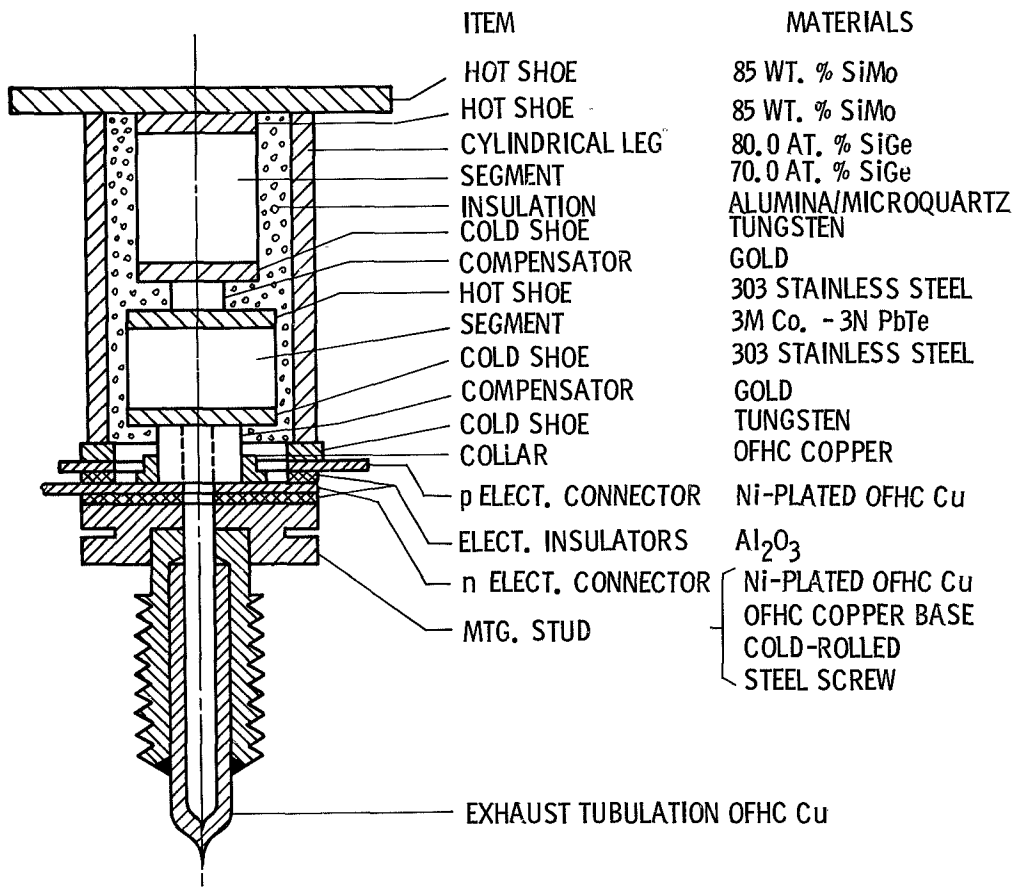


Figure 1. - Hybrid thermocouple assembly.

JUNCTION TEMPERATURES, °C (°F)

HOT 926 (1700)

INTERFACE 538 (1000)

COLD 232 (450)

INCIDENT HEAT FLUX 2 WATTS/CM²
ELEMENT LENGTH 3.18 CM (1.25 IN.)
RADIUS OF n-PbTe 0.476 CM
(0.1875 IN.)

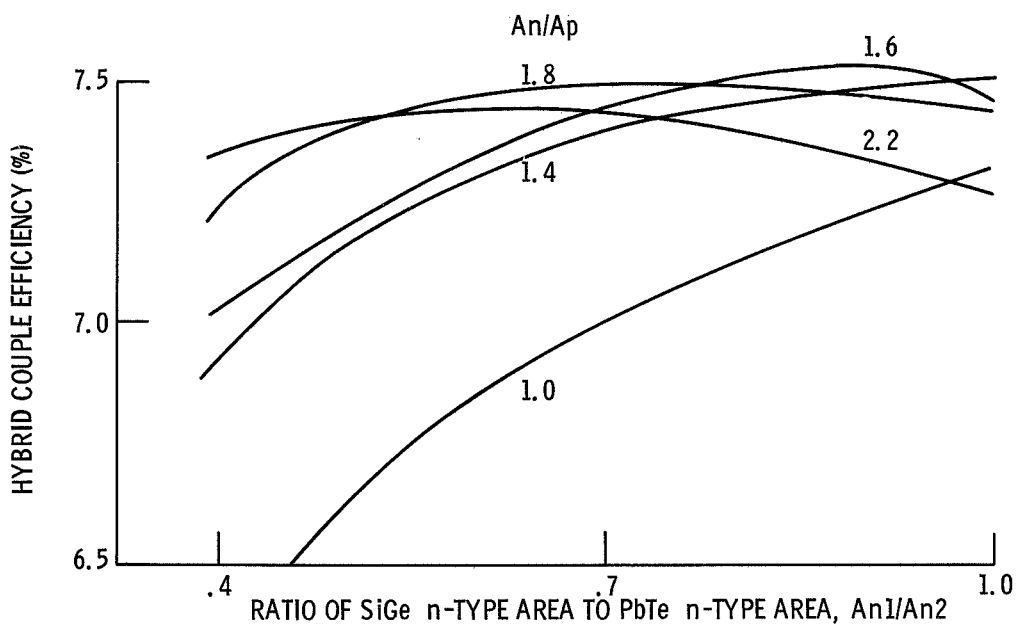


Figure 2. - Efficiency versus ratio of n-type SiGe to n-type PbTe area A_{n1}/A_{n2} for various A_n/A_p .

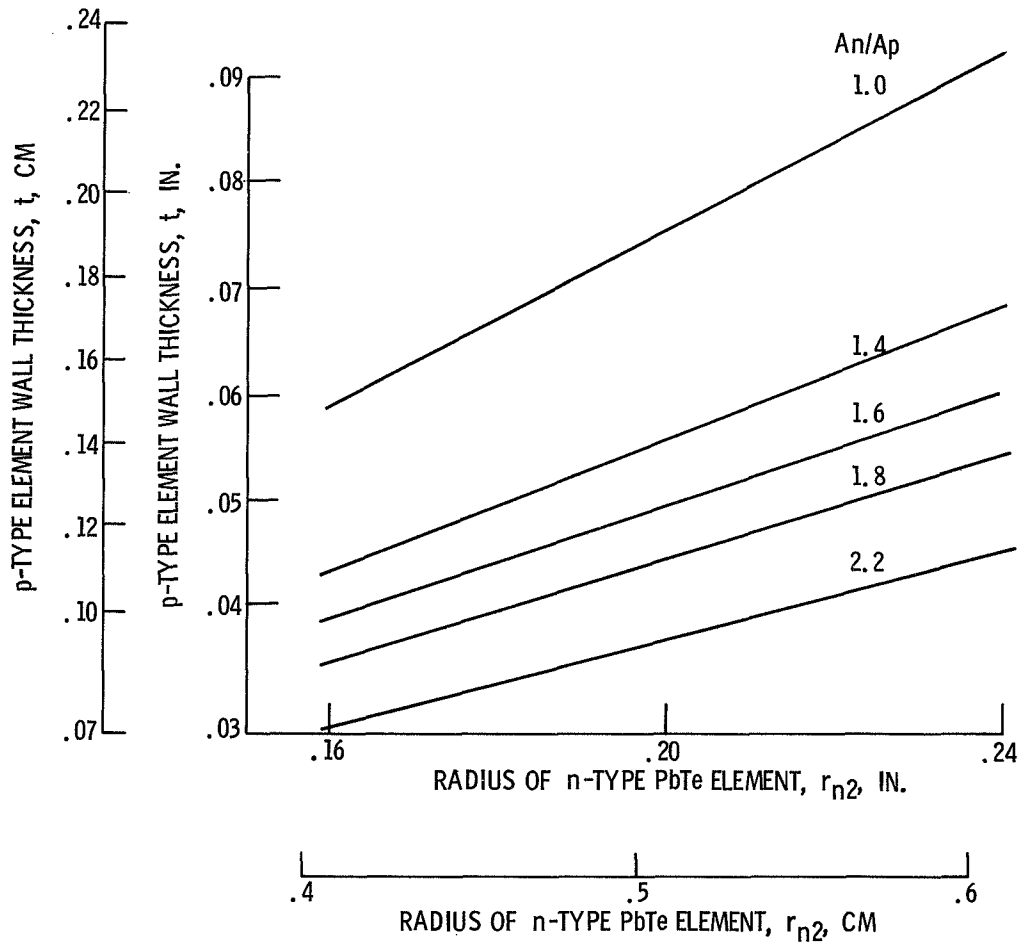


Figure 3. - p-Type element wall thickness versus radius of n-type PbTe element for various An/Ap.

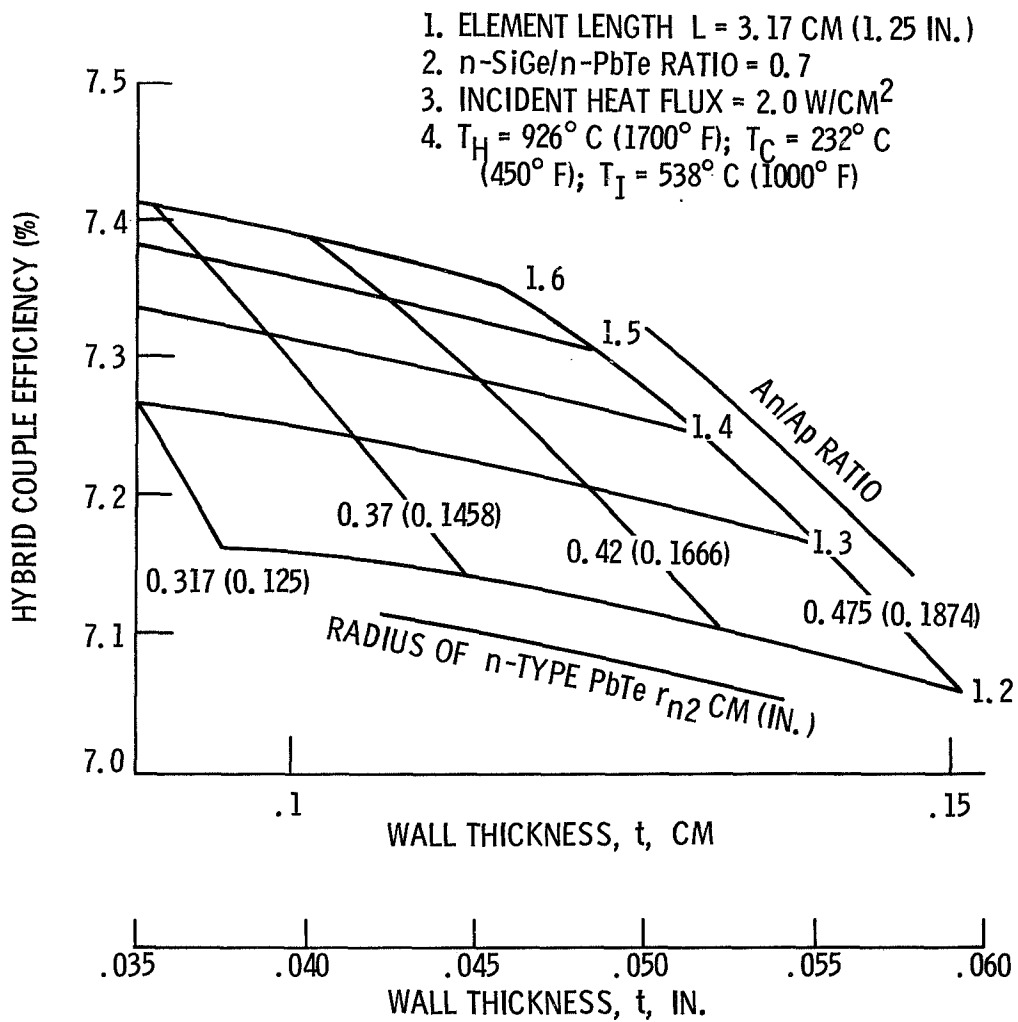


Figure 4. - Couple efficiency as a function of cylinder wall thickness, An/Ap ratio and radius of n - PbTe.

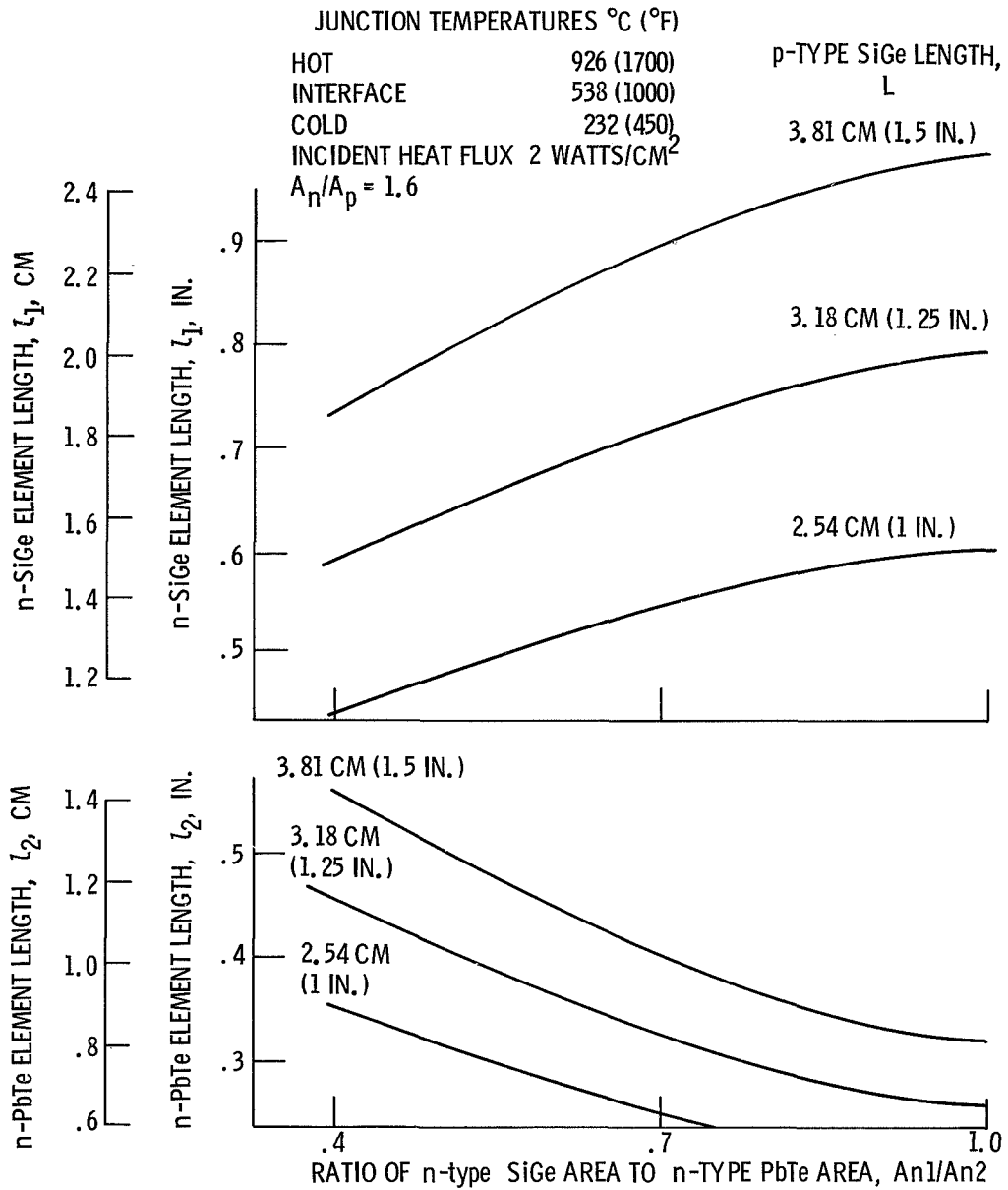


Figure 5. - Length of n-type SiGe and n-type PbTe segments versus ratio of n-type SiGe area to n-type PbTe area, A_{n1}/A_{n2} for various p-type element lengths, L.

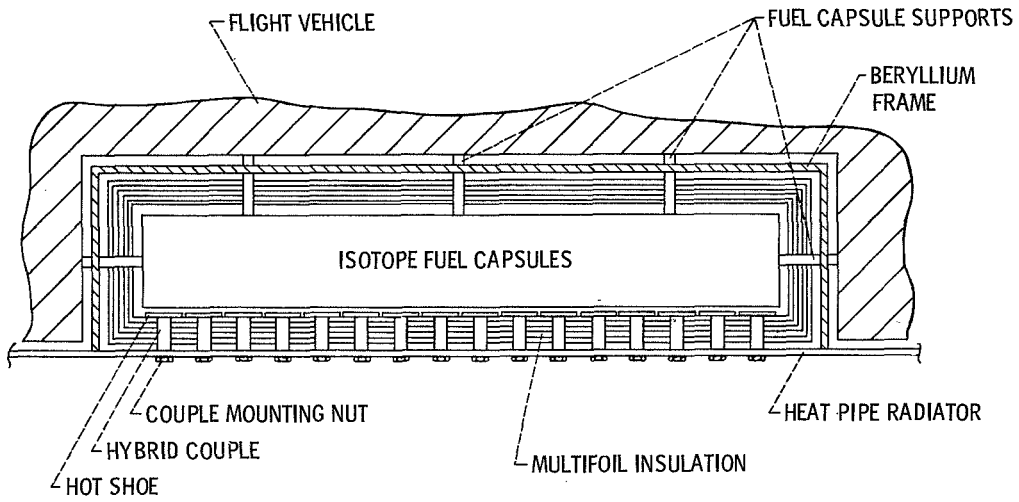


Figure 6(a). - Planar converter recessed into flight vehicle.

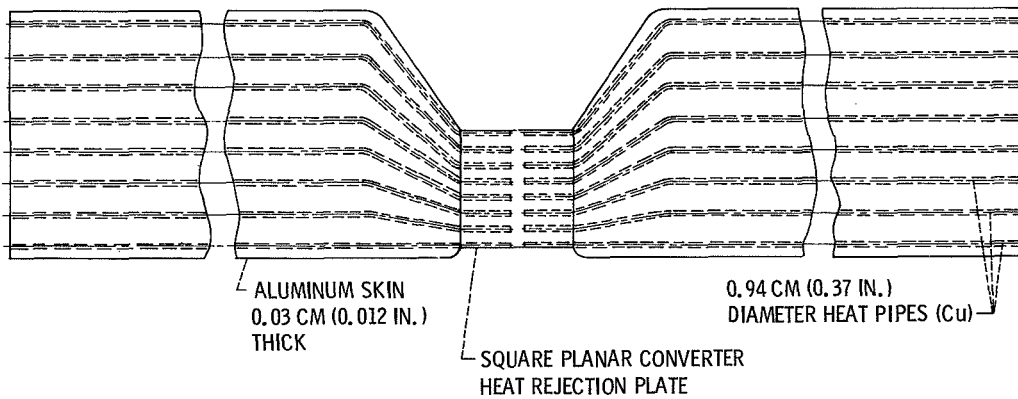


Figure 6(b). - Typical heat pipe radiator for hybrid generator.

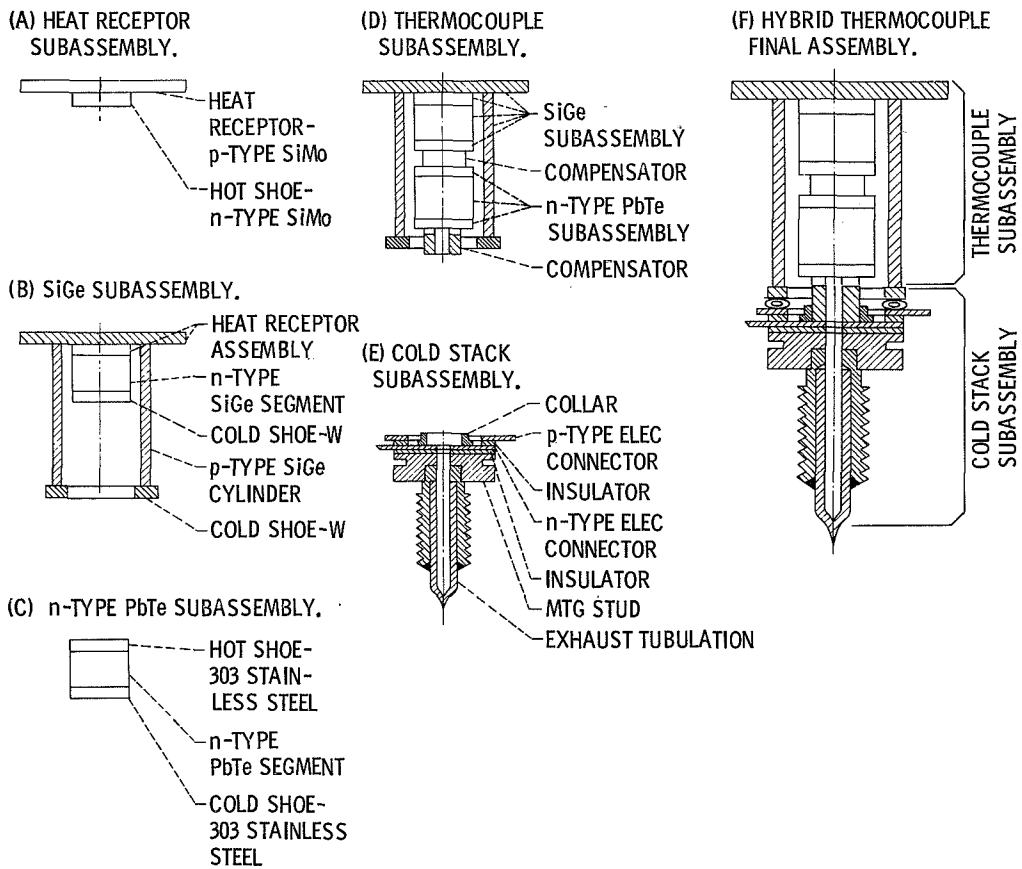


Figure 7. - Hybrid thermocouple assembly sequence.