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SYSTEMS IMPLICATIONS OF THE
ADVANCED THERMOELECTRIC MATERIALS PROGRAMS

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I. INTRODUCTION AND SUMMARY

An RTG research and development program should be structured to optimize the system performance of a radioisotope thermoelectric generator in the context in which it is to be used. Current programs are focused on the development of materials and/or elements independent of the systems in which they are required to perform. As a result, there has been too much concentration on element and module efficiency and too little attention paid to how these elements and modules may be configured into a flight qualified generator.

The criteria for evaluating the potential of the current DOE thermoelectric R&D programs must concentrate on attainable system performance and the costs and risks associated with developing that system. This study attempts to evaluate the potential of each of the three competing programs in the context of the performance, cost and risk involved in the development of a flight qualified system.

Figure 1 shows, for each of the competing systems, a summary of the specific power which may be attained from each of the systems analyzed. The evolutionary nature of the systems proposed within the SiGe technology is emphasized. It is important to note that no new materials developments are needed to effect substantial performance advances. The importance of working from an existing data base cannot be overemphasized. Table I shows a comparison of the unresolved feasibility issues as they are presently known. State points and potential system power-to-weight ratios are also shown. These evaluations are made assuming that the various materials developments which are underway will be as successful as claimed by their proponents. The probability of achieving these claims varies substantially among the claimants. A brief discussion

FIGURE 1

POTENTIAL SYSTEM PERFORMANCE AS A FUNCTION
OF REALIZED TECHNOLOGY GOAL

TABLE I SYSTEMS EVALUATION

SYSTEM	T_h °C	T_c °C	GPHS MODULES (250 WATTS)	POWER OUTPUT WATTS	SYSTEM EFF. %	POWER WEIGHT WATTS/LB	RISKS	BENEFITS
GPHS-SiGe	1000	300	18	290	6.4	2.34	Current production model.	Proven materials. Low risks.
1/2 Element Length GPHS-SiGe	1000	328	18	302	6.7	3.21	Unproven insulation behavior.	Proven basic material stability. Substantial improvement in performance at low risk and low development cost.
1/2 Element Length GPHS-SiGe + GaP	1000	331	14	300	8.6*	3.94	Unproven insulation behavior. Stability and performance of material unknown.	Greatly improved system performance at moderate risk. Proof of the GaP alloying advantages could be accomplished with a relatively low cost development program. Attractive back-off position.
MITG-Standard SiGe	1000	300	18	300	6.7	3.42	Unproven insulation. Unproven structural behavior and performance. Proof of module adequacy will increase development costs.	Proven basic material stability. Greatly increased performance. Output power modularity. Potential for high output voltage. Attractive back-off position.
MITG-SiGe + GaP	1000	300	12	282	9.4	4.71	Unproven insulation. Unproven structural behavior, performance and material stability. Substantial development costs to prove principle.	Huge improvement in system performance. Output power modularity. Potential for high output voltage. Attractive back-off position.
Isotec-SiG	750	136	12	265	8.8	3.14	Unproven insulation. Unproven bonding technique. Unproven structural feasibility. Unproven basic material stability. Weight estimates based on very preliminary analyses. Proof of feasibility will be expensive and uncertain. No back-off position.	Performance improvements over current SiG may offer potential for higher (~4.0 w/lb) performance using progressively risky assumptions.
Conventional SiG (Bellows)	815/ 850	150	11	286	10.4	3.7	Proposed system has no hot frame. Structural feasibility unproven. Unproven basic material stability. Unproven cold frame design. Undemonstrated thermoelectric performance. Proof of feasibility will be costly and uncertain. Weight estimates based on very preliminary analyses. No back-off position.	Greatly improved performance over current production model.

*Includes 1.187 effective safety factor which results from GE properties factors.

of the risk elements involved in the evaluation of the systems configured from modules currently under development is presented in the Technical Discussion chapter.

The Isotec system was evaluated using information presented in various documents by General Atomic personnel. The MITG and optimized conventional systems performance assessments are based on designs prepared by A. Schock of Fairchild Industries. The conventional SIG generator assessment is based on a design prepared by A. Schock in 1978, but it has been updated to include the latest 3M performance information.

Inspection of Table I shows that the conventional SIG system does not afford potential power-to-weight ratios concomitant with the risks involved in developing this system. The Isotec-SIG system appears to offer the greater payoff for a selenium based generator if the risky performance claims can be realized. Either selenium configuration has the highest development risks of any of the systems. The basic problem with the Isotec-SIG approach is that the structural environment of the shuttle is much more severe than that encountered by previous Isotec systems. The current SIG-Isotec design is a scale-up of the Isotec system which was launched on a Scout. No analyses of the proposed system dynamic responses to the shuttle environment have been performed. It is not at all clear that a large-area low-mass system (even one of cylindrical rather than panel geometry) can survive the shuttle acoustic environment.

The MITG system promises a large payoff, but has significant risks. The advantage of the MITG system is that effort expended in developing improved materials could be used in a fall-back position, i.e., an improved conventional SiGe generator.

A risk-benefit ratio is relatively easy to establish for the competing system: The MITG system is the clear winner. There are, however, significant uncertainties, especially in the bonding, which put the system at substantial risk. The advantage of attempting to develop the MITG system is that all material improvements which can be made could accrue to the back-off optimized SiGe generator design. If the SiO₂ bonded thermoelectric module proves to be structurally unsound in the shuttle environment, the investment in the new material development will not be lost.

Neither of the selenium based systems has an attractive back-off position. This combined with the uncertainty of the material stability leaves one with the impression that continued development of selenium systems is a high risk endeavor with only a marginal payoff potential.

II. TECHNICAL DISCUSSION

A brief description of the characteristics of the materials being developed under current DOE contracts is presented in the following paragraphs.

1. "Isotec-SIG"

An "Isotec" system using the selenium materials has been under development by General Atomic personnel for some time. M. Eck of Fairchild Industries, visited General Atomic on September 10, 1980 to discuss the system characteristics with N. Elsner and other GA personnel. GA personnel were presented with a list of questions and asked to comment on the details of their system design. The questions were designed to flesh out the assumptions used by General Atomic personnel in their systems analyses. The purpose of these questions was to establish the maturity of the design and the validity of the data base used in the design analyses which had been conducted. These questions are presented in Appendix I. To date GA personnel have not responded to these questions; however, some answers were given during the discussions held at their facility. In general, the conclusion was drawn that the design was not very mature. Most of the analyses were simply a scale-up of what was done on the Transit system. The shuttle launch acoustic, shock and vibration environments are much more severe than those of the Scout vehicle on which the Transit was launched. The discussion at GA led to the conclusion that most of the analyses which have been conducted are not very well founded. The specific items in the outline shown in Appendix I for which there were answers appear to be very shallow. The following discussion is keyed to the paragraph headings and items shown in Appendix I.

a. Mechanical Environment. As was mentioned earlier, all of the shock, vibration, acoustic, and material working stress responses were scaled from the Transit and ring converter. Essentially, no new calculations (other than scaling have been performed in arriving at the adequacy of the proposed design. The thermal stress calculations show that the P-element is probably adequate; however, there is no apparent solution for the N-element thermal stress problem.

Although the heat source and generator dynamic analysis is essentially a scale-up from previous designs, the shuttle launch environments were not known to GA analysts who arrived at the conclusion that the structural design was adequate. Lateral vibration tests have not been conducted and a solution to holding the stack of Isotec fuel modules together has been worked out only conceptually. Basically, the stack is held by four carbon-carbon bolts which are cantilevered from the generator shell bottom and are guided at the top to preclude lateral deflection of the stack. There is no analysis to demonstrate the adequacy of the shell to support the lateral loads. A detailed comparison of the design criteria used for the Isotec-SIG and the ISPM generators is presented in Appendix II. Examination of these data show why there is so much concern for the structural adequacy of the Isotec-SIG design.

Data for the composite materials which are proposed for use in the radiator shell were taken from Hercules data sheets. Carbon-carbon properties were taken from FMI data sheets. No work was done to establish the degree of outgassing of these materials which will vent to the selenium thermo-element occupied space of the generator. The carbon-carbon can probably be outgassed to a sufficiently low level so that there is no problem.

However, the out-gassing characteristics of the carbon composite materials are unknown at the high temperatures at which the composite is operating. The GA assumption that out-gassing is not a problem is very speculative.

The reentry mechanical design is essentially nonexistent. Of course, there has been no break-up analysis because there is no reference spacecraft analysis. The GA designers were unaware of the need to separate the fuel modules during reentry. As a result, they have used carbon-carbon bolts and nuts in developing their cantilevered module stack. When this flaw was pointed out they suggested that the carbon nuts could be made of stainless steel. It was then pointed out that the temperature was too hot for stainless steel and they suggested the use of molybdenum. It was then pointed out that molybdenum and carbon react rather rapidly at the operating temperatures and that this would not be a suitable solution. It is not clear that a structural solution for the current concept is available. The stack load must be high enough to prevent module separation during the launch environments and the stack support structure must be sufficiently heat sensitive to ensure disassembly of the stack during reentry. To satisfy these dual constraints will be very difficult using the structural concepts which are currently embodied in the GA reference design. If the stack preloads must be applied by reflecting tensile stress into the shell, the light weight shell concept may not be feasible. It appears that the heat source support and reentry disassembly system is a primary area for weight growth in any practical SIG-Isotec design.

The current design requires that the insulation weight be carried by the thermoelectrical elements. There are some lashings to stabilize the insulation pack; however, these probably will not be loaded in the launch shock and vibration environment. The insulation pack may remain attached to the heat source and this will have a significant effect on the heat pulse which arrives at the fuel module stack fasteners. Failure to separate the insulation from the module pack will increase the uncertainty of module dispersal and raise the possibility of the module stack reentering as a unit. The entire area of reentry mechanical design is suspect both from a practicality and risk standpoint as well as from a weight estimate standpoint.

b. Thermal Environment. The basic Isotec design has one clever feature. It makes the flux transformation where the availability of the heat is high. Conventional generator design makes this flux transformation where the availability of the heat is low. The value of this design is increased where the radiator temperature is as low as it is in the proposed selenium system. The temperature drop between the cold junction and the active heat rejection surface is minimized by this approach. Unfortunately, the use of carbon-epoxy systems adds a high resistance to the heat rejection path. The net effect of this is to reduce the radiator efficiency. Several methods of improving the temperature drop in the radiator have been proposed. These include the addition of BeO and aluminum rods in the carbon-epoxy system. Given the requirement for electrical insulation between the thermoelement cold shoes and the radiator shell, it would seem that the BeO solution would have the more favorable reliability impact. It should be pointed out that neither of these

techniques has been tried and the use of this approach involves another uncertainty in any potential development program. The radiator efficiency without these conduction enhancements is currently estimated at 75 percent.

Eighty to 90 percent of the inside area of the generator is covered by the hot junction collectors. These operate at a temperature of 800°C. Under these conditions the operating temperature of the Iridium fuel clad will be approximately 1000°C. There will be some heat loss through the inter-collector area. The design of the insulation pack will have a strong effect on the thermal efficiency of the generator. The multi-material insulation pack proposed has not been proven at the temperature level necessary for reasonable SIG operating temperatures. This is a development area which must receive much more attention before a reasonable data base is in hand.

GA has performed some calculations which show that high system performance is attainable with the Isotec approach. A weight breakdown of the proposed system is given in Table II and the methods used in claiming 4.0 w/lb are shown in Table III. A brief look at the feasibility issues shows that this is a high risk approach which has very little in the way of a fall-back position in the event that some current design facet proves fatal. Although this approach offers performance advantages over the conventional SIG, it has neither a proven technology nor a sound material data base.

1. "Conventional" SIG

The optimized conventional SIG design study is based on a paper by A. Schock of Fairchild Industries, dated November 1978. This particular

ISOTEC-SIG WEIGHT SUMMARY

ITEM	750°C REFERENCE DESIGN
OUTER SHELL (INCLUDING COATING)	8.1
EPOXY	1.1
COLD CONDUCTORS	4.8
"N" ELEMENTS	1.6
"P" ELEMENTS	1.7
GROMMETS	2.1
COLLECTORS	4.1
SIDE INSULATION	2.4
END INSULATION	4.6
END STRUCTURE	2.4
HEAT SOURCE SUPPORT	5.2
COVERS	2.1
ELECTRICAL CONNECTOR	0.3
PRESSURE RELIEF DEVICE	<u>1.0</u>
CONVERTER WEIGHT	41.5
HEAT SOURCE	<u>35.1</u>
TOTAL	76.6
10% CONTINGENCY	<u>7.7</u>
ESTIMATED GENERATOR WEIGHT	84.3
BOL SPECIFIC POWER ($\frac{\text{WATT}}{\text{LB}}$)	3.39

TABLE III

METHODS OF OBTAINING
4 W/LB

- MORE DETAIL DESIGN TO ELIMINATE CONTINGENCY (3.73 W/LB)
- GO FROM DOUBLE TO TRIPLE SEGMENTATION ON N-LEG (4.0 W/LB)
- INCLUDE TAGS ON P-LEG (>4.0 W/LB)
- IMPROVE BAFFLING (>4.0 W/LB)
- INCREASE T_H FROM 750°C TO 800°C WITH 3 SEGMENTS
ON P-LEG (>4.0 W/LB)

design does not use a hot frame. The thermoelectric elements bear directly on the external surfaces of the aeroshell. 3M personnel have revised this design to update the power output their most recent efficiency predictions and to include the most recent GPHS module weight. Their detailed performance summary based on a new and untested cold strap design. The detailed weight summary for the 3M design is shown in Table IV. The weight summary for the basic Schock design is shown updated for current conditions in Table V. Both designs use heat-pipe-fin radiators of the type designed by Teledyne for the SIG-Galileo mission. Both designs have been updated to the weights and sizes of the GPHS fuel module currently used in the GE-ISPM design.

There are a number of feasibility issues to be settled before a design of this type can be given serious consideration for a space flight. Most important among these is the fact that the basic material stability of the P-leg has never been established. A designed experiment has shown that the acceleration factors which are used to predict long term life do not correlate very well with the most recently available data. Further, all long term tests completed under the nominal operating conditions have been failures. A number of systems for the suppression of selenium sublimation have been proposed and some have been tested. The efficacy of the bellows and increased P-leg-spring-pressure-fixes has not been established. The fall-back position to improve the reliability of this material would be to reduce the P-leg hot junction temperature. This temperature has already been reduced from 850°C to 815°C. Further reduction would adversely affect the system power-to-weight ratio.

TABLE IV

COMPANION OF 3M DESIGN AND FI DESIGN FOR CONVENTIONAL SIGs

Design		3M	3M	FI	FI
T _{Hot}	, °C	815/850	815/850	850/850	850/850
T _{Cold}	, °C	150	150	150	150
Bellows		No	Yes	No	No
N-Leg Spring Pressure	, psi	600	150	300	300
P-Leg Spring Pressure	, psi	300	150	300	300
Number of GPHS Modules	, %	11	11	11	11
Thermoelectric Efficiency	, %	11.8*	11.8*	10.4*	11.8*
Thermal Efficiency	, %	90	90	92.2	92.2
System Efficiency	, %	10.6	10.6	9.6	10.9
Power (BOL)	, watts	286**	286**	263	299
Weight	, lbs	76.7	75.9	79.5	79.5
Specific Power	, w/lb	3.73	3.77	3.31	3.76

*10.4% has been demonstrated for BOL based on partially calculated performance and a system degradation which is unacceptably high. The 11.8% is completely theoretical.

**It should be noted that this number cannot be derived from the system efficiency. 3M personnel supplied the power output as well as the elements which make up system efficiency.

TABLE V

B.O.L. WEIGHT SUMMARY (LB) REFERENCE DESIGN

MISSION	SOLAR POLAR
HEAT SOURCE: (2750 WATT)	37.88
FUEL	] 35.2
IRIDIUM	
GRAPHITE	
MODULE SUPPORT SYSTEM	1.30
TRANSITION PIECES	1.38
CONVERTER: (352 COUPLES)	16.6
END INSULATION	0.34
SIDE INSULATION (INTERMODULE)	1.19
SIDE INSULATION (INTRAMODULE)	0.33
HOT FRAME	0.00
HOT SHOES (INCL. DIELECTRICS)	1.88
GIMBALS, FOILS, DISCS, PINS	1.51
THERMOELECTRIC LEGS	3.90
COLD STRAPS	0.36
COLD-END HARDWARE	7.13
COLD FRAME (INCL. GOLD FOILS)	0.0
GENERATOR: 299 WATT	12.3
HOUSING (INCL. SADDLES, RIBS)	9.00
END COVERS	1.21
MOUNTING LUGS	0.25
MISCELLANEOUS (WIRING, ETC.)	0.50
ELECTRICAL CONNECTOR	0.30
MAGNETIC COMPENSATING LOOP	0.00
PRESSURE RELEASE DEVICE	1.00
HEAT REJECTION SYSTEM:	12.7
RADIATORS, STUBS, GUSSETS	2.85
RADIATOR HEATPIPE SADDLES	1.23
ADDITIONAL STIFFENING RIBS	0.18
COPPER STRIKE & SOLDER	1.19
HEATPIPES	5.13
AUXILIARY COOLANT TUBES	0.60
EMISSION COATING	1.49
TOTAL WEIGHT	79.48
SPECIFIC POWER (W/LB)	3.76

The designs summarized in Table IV are based on the assumption that the generator could be fabricated without a hot frame. This assumption is unproven. 3M personnel have reviewed a paper by A. Schock and A. Shostak which shows that the maximum deflection of an 18 GPHS module heat source subjected to the stack shuttle launch environments is 37 mils. This is essentially a rigid body analysis; system responses are not considered. The effect of any amplifications within the generator are not considered. The 3M proposed system contains only 11 modules. As a result the stack height is 30 percent less than the Schock design. It is, therefore, significantly more rigid. 3M personnel use this fact to justify the claim that the stack will have a resonant frequency high enough to justify the rigid body assumption. They further state that the cold stack can accommodate a deflection of 37 mils without losing continuity. While this assumption may be valid, it does not deal with what may prove a more insidious problem.

The proposed 3M design covers two faces of the GPHS heat sources with thermoelectric elements. No problem is perceived as long as the vibration of the heat source is coincident with the axis of the thermoelectric elements. When the vibration is orthogonal to the axis of the thermoelectric elements, a significant shear force will be developed. This combined with the differential expansion of the housing and the heat source stack will have the effect of causing the insulation wrap of the elements to be laterally displaced in relation to the face of the hot shoe. As a result, a significant selenium conductance path may be developed through the wrap near the hot shoe. Such a development would be fatal to the system because it would lead to a rapid loss of selenium and the subsequent unacceptable degradation of the power output.

Given that this program has been funded for eleven years and that a viable design has yet to be developed, it seems highly conjectual that the proposed design can be brought to fruition within a reasonable time for a reasonable number of development dollars.

A review of the Table IV shows that the proposed power-to-weight ratio of 3.7 watts per pound is based on a thermoelectric element efficiency of 11.8 percent. To date this efficiency has not been demonstrated by any of the long term tests. Again, this is an item of some conjecture. The back-up position here is to reduce the efficiency to a value of 10.4 percent. This efficiency has been demonstrated in short term tests. Use of this later value causes a reduction in the power-to-weight ratio to 3.3 watts per pound. The general impression one has when looking at the weight and efficiency estimates is that they are extremely optimistic. It is true that most of the systems proposed make optimistic assumptions and it is also true that this system has had many more development dollars expended on it than have the competing systems. Because of this, considerably more is known about the system. One might, therefore, consider that the projected generator performance is somewhat better known than it would be for the competing systems. This may be true; however, the more that has been discovered about the selenium system, the more difficult has been its reduction to generator practice. SiGe has, in conventional generators, an even greater maturity of data base than the SiG. Some of the more sophisticated SiGe designs have very small data bases. However, the large successes which have been enjoyed in the past SiGe development programs give a confidence that at least some of the potential advantages

of the more sophisticated proposals could be realized. The conclusion must be drawn that there is no mature data base for selenium materials at this time. Given the long and checkered history of this development program, one must conclude that the pursuit of even a conventional selenium system must be considered a high risk endeavor.

3. Modular Isotopic Thermoelectric Generator

The Modular Isotopic Thermoelectric Generator (MITG) was discussed in detail by A. Schock of Fairchild Industries on October 9, 1980 at DOE. This generator uses the GPHS heat source module and the SiGe thermoelectric module built by Synchal as its principle building blocks. The MITG is the first truly modular design developed in the current generation of thermoelectric isotope systems. Each generator section consists of a standardized housing cross-section, insulation and radiator sections, plus one heat source module, eight thermoelectric modules and one circuit module having a nominal electrical output of 25 watts at 28 or 30 volts dc. The modules are stacked axially to produce the desired power output. Some analysis and housing redesign is, of course, necessary with applications which require varying power levels and varying launch and operational environments. This redesign, however, is nominal in relation to the problems of designing a new generator. The thermoelectric module is the key to the modularity of the system. The use of a 28 or 30 volt output module allows great flexibility in the system design.

Each thermoelectric module consists of 18 N-legs and 18 P-legs. These legs are potted in a SiO_2 glass which contains nominal additions of TiO_2 and opacifiers. Syncal has developed a manufacturing process which has been demonstrated on several programs. At present there is a program to establish the performance and reliability characteristics of this module. The basic module configuration could use either the conventional proven SiGe material or the improved (GaP) material. The system power-to-weight ratio that can be achieved from the intelligent configuration of the Syncal module into a generator design is quite impressive. Probably the greatest advantage of this system is that attractive back-off positions are available. There is no need for the GaP development program to be successful in order to develop a generator which has an attractive power-to-weight ratio.

Table VI shows the effect of thermoelectric material changes on generator power-to-weight ratio. The GPHS current design is shown for reference. Inspection of this table shows that the use of the currently available SiGe material in a MITG design yields a potential specific power 50 percent greater than the current GPHS design. This improvement can be effected without any material improvement. The development of both the Syncal-type module and the GaP alloyed SiGe leads to a potential power-to-weight ratio of 4.7 watts per pound for a 280 watt BOL system. This constitutes a factor of two improvements over current practice. A detailed summary of the characteristics of the MITG design is presented in Table VII.

Considerable analysis has been performed to establish the validity of the proposed MITG design. A number of tests on the thermoelectric module have

TABLE VI

SPECIFIC POWER COMPARISON

RTG DESIGN	T/E MATERIAL	GPHS MODULES	POWER (w)	WEIGHT (lb)	TE MODULE EFF. %	SPEC. POWER (w/lb)
GPHS	SiGe	18	290	123.8	7.3*	2.34
MITG	SiGe	18	300	87.6	7.3	3.42
MITG	SiGe	12	200	59.9	7.3	3.34
MITG	SiGe/GaP	12	282	59.9	10.0	4.71

*This value contains a 1.106 safety factor for thermoelectric properties.

TABLE VII

DESIGN SUMMARY (BOL)

Heat Source:			Heat Balance (w):		
Number of GPHS Modules	12		Thermal Power	3000	
Thermal Power per Module (w)	250		End Losses	75	
BOL Thermal Power (w)	3000		Side Losses	100	
Thermoelectric Converter:			Heat to TE Couples	2825	
Number of Thermoelectric Modules	96		Heat from TE Couples	2469	
Number of Couples per Module	18		Total Heat Rejection	2723	
Leg Width and Thickness (in)	0.057		Electrical:		
Module Width and Thickness (in)	0.360		Couples in Series	144	
Leg Length (in)	0.300		Couples in Parallel	12	
Generator Dimensions (in):			Module Voltage	3.50	
Housing Side	5.75		Module Current (amp)	0.82	
Heat Source Height	25		Generator Voltage	28	
Generator Height	27		Generator Current (amp)	9.8	
Generator Span	18		Power Output (w)	282	
Temperatures (°C):			Efficiency (%):		
	T	ΔT	Thermal (excl. module losses)	94	
Fuel Capsule	1269	169	Thermoelectric Material	10.5	
Heat Source Surface	1100	4	Thermoelectric Module	10.0	
Hot-Shoe Corner	1096	76	System	9.4	
Hot-Shoe Root	1020	20	Weight (lbs):		
Hot Junction	1000	700	Heat Source	38.4	33.5
Cold Junction	300	15	Converter	21.5	21.5
Cold Shoe	285	15	Total	59.9	55.0
Housing	270	25	Specific Power (w/lb):		
Fin Root	245	75		4.71	5.12
Fin Tip	170				

Aeroshell fillets removed, and walls reduced to twice the predicted recession

been run by Syncal. A materials efficiency vs. load voltage plot for the SiGe/GaP material is shown in Figure 2. A detailed weight breakdown of the components that go into the MITG design and their comparison to the current weight estimates for the GPHS RTG are shown in Table VIII.

The long term tests which would be required to demonstrate the reliability of the MITG thermoelectric module have not been performed. Given that the materials prove stable, the principle feasibility concerns with the proposed module involve:

1. the basic strength of the SiO_2 sublimation suppression;
2. the effectiveness of the proposed multi-foil insulation both in terms of compliance and self support capabilities; and
3. the performance of the heat source support concept under lateral launch loads.

The fact that the heat source is radiatively coupled to the thermoelectric element hot shoe, significantly reduces the interaction between the launch shock and vibration and the shear loads applied to the thermoelectric elements. This isolation is a marked contrast to the conventional selenium spring loaded design. This advantage is shared with the Isotec selenium design.

There are substantial feasibility issues to be proven before one could commit this system to a scheduled launch. The potential advantages, however, and the back-off positions which are available, make the pursuit of this approach appear very attractive for near term development by DOE.

FIGURE 2

THERMOELECTRIC MATERIAL EFFICIENCY OF SiGe/GaP

$T_H = 1000^\circ\text{C}$, $T_C = 300^\circ\text{C}$, 36 Legs per Module
(includes Joule-Thompson Effect)

TABLE VIII

PRELIMINARY WEIGHT COMPARISON (LBS)

GPHS RTG (SiGe, 290 w)				MITG (SiGe/GaP, 282 w)		
Item	No.	Wt.		Wt.	No.	Item
<u>Housing:</u>			10.66			
Outer Shell	1	14.25	8.25	6.00	1	
Fins	8	4.32	2.02	2.30	4	
Emissive Coating	X	0.33	0.08	0.25	X	
Auxiliary Cooling Tube Manifold	1	0.57	0.27	0.30	1	
Nuts	8	0.11	0.04	0.07	4	
<u>Converter:</u>			25.82			
T/E Unicouples	576	11.98	8.18	3.80	96	T/E Modules
T/E Sealing Screws	576	1.54	1.54	-	-	
T/E C-Seals	576	0.13	0.10	0.03	96	
Rivets and Washers	608	0.59	0.59	-	-	
T/E Spacers (Al ₂ O ₃)	576	0.64	0.64	-	-	
Nut Plates	288	0.80	0.45	0.35	96	Nuts
Foil Insulation - T/P	1	13.00	10.90	2.10	1	
Foil Insulation - Ends	2	1.33	1.13	0.20	2	
Insulation Support Frame	1	1.65	1.65	-	-	
Power Connector	1	0.35		0.35	1	
Gas Management Assembly	1	0.29		0.29	1	
Electrical Straps	X	1.08	0.68	0.40	X	
PRD	1	0.90		0.90	1	
C-Seal - Domes	2	0.08	0.02	0.06	2	
Other Insulation	X	0.20	0.10	0.10	X	
Pressure Dome	2	1.25	-0.22	1.47	2	End Caps
Screws - Pressure Dome	44	0.23	0.06	0.17	32	
RTG Assembly	1	1.00		1.00	X	Pads & Bushings
<u>Heat Source Support System:</u>			8.41			
Inboard Support	X	4.77		0.35	8	Load Spreaders
				0.04	8	PG Buttons
				0.09	8	Bushings
Mid-Span Support	X	3.10		0.14	16	Belleville Springs
				0.32	8	Pistons
Outboard Support	X	1.85		0.06	40	Compression Plates
				0.31	8	Preload Screws
Heat Source Modules, 4464 w(t)	18	57.44	19.02	38.42	12	3000 w(t)
TOTAL		123.78	63.91	59.87		

4. Optimized Conventional GPHS SiGe Generator

The current GPHS design uses the same thermoelectric element as was used in the MHW generator. The decision to use this configuration in a known off-optimum situation was made because of the schedule difficulty in re-establishing the SiGe technology. The length of the thermoelectric elements used in the GPHS design is based on maintaining the same insulation concept and packaging as was used in the MHW design. Significant advances in the development of multi-foil insulation have occurred since the MHW was designed. Work done by Teco on the BIPS program established that the use of zirconia sprayed foil makes it possible to fabricate an insulation pack which is more effective and significantly thinner than the MHW design. The application of this development to the design of an optimized uncouple results in a substantial improvement in the power-to-weight ratio of a GPHS-type generator configuration. Figure 3 shows schematically the large affect of the unnecessary thermal element length on the size of the generator housing. The use of the reduced length uncouple increases the attainable power-to-weight ratio by approximately 40 percent.

The second major area for system design improvement is the use of the GaP alloyed SiGe material. The combination of the reduced length element and the improved material offers 70 percent improvement in the attainable power-to-weight ratio over the current GPHS design.

Table IX shows the effect of the various improvements which could be made in the conventional uncouple and their relation to the MITG and GPHS designs. It should be noted that the MITG designs do not have the 1.106 safety factor on resistivity, Seebeck and thermal conductivity that GE uses. The last item in Table IX is included to draw the effect of this factor on performance and to put the MITG and one half length modules as an equal basis. From this table it is clear that the back-off

FIGURE 3

DIFFERENCES BETWEEN REFERENCE AND 1/2 LEG SiGe DESIGNS

TABLE IX
SPECIFIC POWER COMPARISON

RTG DESIGN	T/E MATERIAL	GPHS MODULES	POWER (w)	WEIGHT (lb)	TE MODULE EFF. %	SPEC. POWER (w/lb)
GPHS*	SiGe	18	290	123.8	7.3	2.34
MITG	SiGe	18	300	87.6	7.3	3.42
MITG	SiGe/GaP	12	282	59.9	10.0	4.71
GPHS*	SiGe/GaP	14	292	96.8	9.4	3.02
GPHS*	SiGe/Half Length	18	302	94.0	7.3	3.21
GPHS*	SiGe/GaP Half Length	14	300	76.0	9.4	3.94
GPHS	SiGe/GaP Half Length	14	319	76.0	10.0	4.2

*NOTE: These designs contain 1.106 safety factor which is not included in MITG designs.

position to a one half length uncouple and GaP alloyed SiGe is an extremely attractive system. Even if the GaP alloying program is not successful, substantial improvements in system performance could be made by using the one half length SiGe element. Only the suitability of the BIPS insulation for this application needs to be demonstrated before a significant improvement to the power-to-weight ratio can be achieved.

A comparison of the standard and GaP alloyed SiGe effect on minimum RTG weight is presented in Figure 4. The trend lines show an increasing power-to-weight ratio for both materials as the required power level increases. It should be noted that the specific power of both of the optimized designs using these materials shows a substantial improvement over the standard GPHS design at all power levels of interest.

The primary reason for pursuing a system of the type described in this section is as a back-up for the MITG design. If there is a negative result to the environmental testing of the modules, this design is a logical fall-back position. It is also a substantial improvement, in its own right, over what is currently being produced. If one had limited funds and sought to pursue a development program that had a reasonably high probability of success, and also offered a substantial improvement in power-to-weight ratio, the proposed design would be an obvious way to go. The programmatic question which needs to be answered is whether DOE wishes to pursue parallel development or serial development. The decision here is primarily one of the availability of funding. The maximum payoff scenario is to use the MITG

FIGURE 4

COMPARISON OF STANDARD AND IMPROVED SILICON-GERMANIUM
EFFECT ON MINIMUM RTG WEIGHT-VERSUS-POWER ENVELOPES

NOTE: These values contain the 1.106 factor on performance GE uses for safety.

design with the GaP alloyed SiGe. That program could be conducted in parallel with a conventional generator optimization of the type discussed above and in parallel with a program to establish the performance and stability of the SiGe-GaP materials. The least risk system would involve the development of the one half length SiGe elements with neither the development of MITG or the improved GaP alloyed material. Even this approach offers a substantial improvement over what is now being produced; it also holds this promise at a relatively low risk. The direction which DOE proceeds in this area is strongly dependent upon the risks DOE wishes to assume. In any event the GaP alloying program, the MITG module program and the one half length conventional generator could all be pursued as independent programs that cross-feed their developments. At this time the logical place to start seems to be first in demonstrating the stability and reliability of the GaP alloyed materials. This can be accomplished either in the conventional, one-half-length conventional or MITG element context. The improvements which are available from the GaP alloying are sufficiently great to warrant further investigation of this material independent of the system into which it is to be configured.

III. CONCLUSIONS AND RECOMMENDATIONS

The conclusions and recommendations presented in the following paragraphs are based on the information in hand, December 1, 1980. The programs being reviewed are ongoing. It is possible that new information will become available prior to making a selection among the competing systems. It is unlikely that such new information will substantially change the following conclusions and recommendations.

1. General Considerations

- The principal discriminant among competing systems should be power-to-weight ratio not efficiency.
- Within a given configuration, efficiency is important as it affects the total heat transferred at each level of availability.

2. Isotec SIG

- This concept has greater performance promise than the conventional SIG design.
- This concept has large inherent risks which are related both to material stability and structural feasibility.
- The potential benefits of this type system do not justify taking the concomitant risks.

3. Conventional SiG

- This system has substantial risks associated with material stability and structural feasibility.
- The potential performance improvements over an optimized conventional SiGe system do not justify the associated risks.

4. MITG

- The MITG system offers the highest potential power-to-weight ratio of those designs reviewed.
- There are substantial risks that the potential performance advantages may not be realized.
- Secure back-off positions are available within SiGe technology if the GaP alloying program or the MITG module development itself is unsuccessful.
- The potential benefits of pursuing this pathway justify accepting the inherent risks.

5. Optimized SiGe Generator

- The pursuit of this program offers a significant performance pay-off even if the GaP alloying program is unsuccessful.
- The performance increase attainable if the GaP alloying program is successful is impressive.

- This technology has a mature data base and should be pursued either as a back-up to the MITG program or as an interim step toward the MITG system.
- This approach affords the lowest risks/benefits ratio and could probably be brought to fruition at the lowest possible development cost.

6. Programmatic

- It is unwise, in times of scarce resources, to count on new, unproven materials for use in flight systems.
- Future development programs should concentrate on a single material technology and make evolutionary improvements; always building on a mature data base.
- Programs which do not build on a mature data base are risky and they divert attention from the linear development of the breed.
- In a constrained budget environment, those programs which detract from the linear development of proven materials should be discontinued. Ample development opportunity exists within the SiGe technology to allow significant evolutionary development for the next 3-5 years.
- Programs to evaluate the stability and performance of the GaP alloyed SiGe should be initiated and/or expanded.
- Programs to evaluate the strength, stability and performance of the MITG module should be initiated and/or expanded.

- The suitability of the zirconia insulation should be established in the context of one of the above technology programs.
- The time-phasing of the above recommendations should be determined by budgeting considerations. Either parallel or serial development is practical. The GaP alloying program has the greatest near term impact. Each concept is independent of the success of the other.

APPENDIX I

I. CONCEPTUAL SYSTEM FLIGHT READINESS

A. Assumptions

a. Mechanical Environment

1) Design Criteria

a) Elements

1. Shock, Vibration, Acoustic
2. Material Working Stress (% of yield, % of ultimate)
3. Thermal Stress

b) Heat Source and Generator Assembly

1. Shock, Vibration, Acoustic
2. Material Working Stresses
3. Thermal Stresses
4. Compression needed to hold pucks together at launch
5. Stresses in Lower Support Structure

2) Properties

- a) Composite Material Properties at 200-300°C (Source)
- b) Alloy Working Stresses
- c) Carbon-Carbon Stress Allowables (Source)
- d) Permeability of Composites (How Seal Ends?)
- e) Outgassing to Se space prior to venting

3) Reentry Mechanical

a) Generator Break-up Analysis

1. How Separate Pucks
2. Terminal velocity if no separation
3. Insulation pack stability

b. Thermal Environment

1) Properties

- a) K of Composite (Source)
- b) Composite Anisotropy
- c) Carbon-Carbon (Source)
- d) Metal Alloys

2) Operating Conditions (How Selected and What)

- a) T_{hot} (shoe: junction)
- b) T_{cold} (shoe: junction)
- c) η_{TE}
- d) η_{Sys}
- e) Voltage
- f) Where on I-V Curve (η_{max} ? P_{max} ?)
- g) Current
- h) How set series parallel strings?
- i) Power/Weight

- 3) Heat Source
 - a) Surface Temp
 - b) Ir Operating Temp
 - c) Support Temp and Gradients
- 4) Radiator
 - a) Fin η
 - b) Contact Cond. (to cold strap)
 - c) Component stability at temperature (data base)
 - 1. Ref Mtl.
 - 2. Mtl not defined for K

B. Results:

- a. Power-to-Weight
 - 1) How sensitive to radiator η , T_{cold}
 - 2) Shock, Vibration, Acoustic effect Sensitivity
- b. Life (Reliability)
 - 1) Data base
 - 2) Sensitivity to T_{hot} , T_{cold}
Shock, Vibration, Acoustic

C. Risks:

- a. GA Assessment of Success Probability
 - 1) Power/wt
 - 2) Life
 - 3) Schedule
 - 4) Funding
- b. Eck Assessment of Success Probability
 - 1) Power/wt
 - 2) Life
 - 3) Schedule
 - 4) Funding

CRITERIA COMPARISON
TRANSIT RTG REQUIREMENTS
VS.
ISPM-RTG REQUIREMENTS
OF
ISOTEC-RTG WITH GPHS & GRFP
DECEMBER 2, 1980

	TRW Transit RTG Spec Qualifications 10/7/69	TRW Transit RTG Spec 11/9/70	Culif LC-Ring Converter 1/1974	ISOTEC GPHS & GRFP 1/1979	Solar Polar RTG G.E.
Standard Longitudinal	10-18 1.0 18-44 .06"DA 44-65 6.0 65-100 4.5 100-175 33.0 175-2000 7.0	10-62 .5"DA 62-95 10. 95-135 *33. 135-240 4.5 240-350 7.0 350-2000 4.5 *56 g max - notch			5-24 .92" 24-50 27. g 50-100 9. 100-300 4.5
Transverse	15-2000 4.5 (2 oct./min.)	15-30 .31"DA 30-45 14. 45-150 13. 150-300 4.5 200-2000 1.5 2 oct/min			Response G's at RTG C.G. for 5 cycles
Random	20-2000 .045 g ² /Hz 9.4 GRMS (2 min.)	20-2000 .045 g ² /Hz 9.4 GRMS (4 min.)	20-900 3dB/oct 900-1400 .1870 g ² /Hz 1400-2000 -15 dB/ oct 15.1 GRMS		20-80 6. dB 80-400 .1g ² /Hz 400-2000 -6. dB 8.2 GRMS
Asymetric Overload	124 dB (2 min.)		145 dB		147 dB (3 min.)
Shock	3 half sine pulses 30 g peak 10 msec		1000 g at 5000 Hz response spectrum or 775 g peak at .2 msec sine		Q = 20 shock response 700 Hz 100 g 6000 Hz 1100 g
Acceleration	24 g long. 3 min. 3 g lat. 1 min.				3 g all axis STS 8.5 IUS
Static Design Load					Lateral 40 g Axial 40 g
Factor of Safety			1.25		1.4

Comparison of TSM transit RTG specs to ISPM-RTG specs for validation of Isotec with GPHS & GRFP.

ASSUMPTION #1.

Isotec GPHS & GRFP RTG meets all transit specs with 0.0 margins of safety.

ASSUMPTION #2.

Isotec GPHS & GRFP RTG has the same resonant frequencies as the transit RTG.

SINUSOIDAL VIBRATION

The ISPM requirements in the tranverse direction are 2 times higher, up to 100HZ, then the transit requirements.

Based on Assumptions #1 & #2 isotec - GPHS & GRFP would be subject to re-analysis and test.

RANDOM VIBRATION

The transit random spec is flat between 20 HZ and 2000 HZ resulting in a 9.4 GRMS. ISPM requires 8.2 GRMS but between 80 & 400 HZ the input leve is 2 times that of the transit ($.045 \text{ g}^2/\text{Hz}$ to $.10 \text{ g}^2/\text{Hz}$)

Based on Assumptions #1 & #2, the isotec - GPHS & GRFP would be subject to re-analysis and test.

ACOUSTIC

Transit calls for 124 db qualification level whereas the ISPM-RTG calls for 147 db. The effective pressure of the ISPM-RTG spec is 14.6 times greater than that of the transit spec.
Again the isotec - GPHS & GRFP would be subject to test.

SHOCK

Transit calls for a shock pulse input of 30g peak for 10 msec half sine shaped input. ISPM - RTG calls for a shock response spectrum peaking to 1000 g at about 4000 HZ. These two cannot logically be compared for this evaluation. The isotec - RTG would have to be tested to satisfy this shock criteria.

MARGINS OF SAFETY

Transit does not call for any margins of safety. Therefore it would indicate that if RTG was designed for qualification levels, the structure would result in zero margins of safety.

QUASI-STATIC DESIGN LOADS

Transit calls for 3 g lateral and 24 g on axis. ISPM - RTG shuttle and IUS calls for 8.5 g lateral and 3 g on axis. This is 2.8 times more severe in lateral bending of the RTG.

In addition to flight accelerations, the ISPM - RTG calls for a 40 g design requirement in all three axes.

TRANSIENT VIBRATION DESIGN REQUIREMENTS (QUALIFICATION)

RANDOM VIBRATION DESIGN REQUIREMENTS (CONTINUATION)

ACOUSTIC DESIGN TESTS
(CONTINUATION)

CENTER FREQUENCY (Hz)	SOUND PRESSURE LEVEL (20 REF. 20 μ N/m ²)	TRANSIT
ONE-THIRD OCTAVE	dB	
32	123	
40	123	
50	124.5	
63	126	
80	126.5	
100	124.5	
125	126	
160	127	
200	127.5	
250	127	
315	126	
400	125	
500	126	
630	126	
800	120.5	
1000	120	
1250	123	
1600	127	
2000	126	
2500	125	
3150	126	
4000	122.5	
5000	124	
6300	119.5	
8000	118	
10000	116.5	
OVERALL	147 dB	124.46
DURATION: 3 MINUTES		2.400
DATE: 8-11-68		1070 Hz

DIFFERENTIAL
(AMPLIFICATION)

GENERAL
ELECTRIC

DESIGN FACTORS OF SAFETY

YIELD STRESS	1.0
ULTIMATE STRESS	1.25

$$M.S. = \frac{\text{ALLOWABLE STRESS}}{F.S. \times \text{CALCULATED STRESS}} - 1$$

NOTE: ULTIMATE STRESS F. S. ≥ 1.4 ON FLIGHT LOADS WHERE FAILURE WOULD RESULT IN POTENTIAL HAZARD TO CREW.

22-00000
22-00000
22-00000

ACCELERATION DESIGN LIMITS

S/C AXIS	EVENT	LEVEL - G's		TRANSIT	
		ICPM	GALILEO		
<u>ALL AXES</u>	SYS OPERATION	± 3.0	± 3.0	3.	4.0/1.2
THRUST AXIS	IUS THRUST	-0.5	-0.2	24.	THRUST
	IUS SPIN	0.7	-		

BASED ON ACCELERATION OF CG AT 20 RPM (~ 59 INCH RADIUS)