GA-A12915

PROJECT DEVELOPMENT PLAN AND COST ESTIMATE
ERTG PROGRAM

FINAL STATUS REPORT

by
Advanced Materials Branch

Prepared under
Contract AT(04-3)-943
for the
San Francisco Operations Office
U.S. Atomic Energy Commission

Date Published - April 5, 1974

MASTER

GENERAL ATOMIC

GENERAL ATOMIC COMPANY
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1. INTRODUCTION

The economical radioisotope thermoelectric generator (ERTG) program plan assumes that the first flight generator will be launched in mid-1978. This report describes a program that attempts to meet this goal and outlines the tasks that must be accomplished as well as the costs associated with the five phases of the program.

In the technical presentation of the Phase I study (Ref. 1), essentially two routes were shown for accomplishing the desired goals:

1. The RING converter could be built using present in-house technology. A demonstration of this technology is in the 18-in.-diameter RING converter segment utilizing PbTe-PbSnMnTe/BiSbTe and now on test at a T_H of 450°C.
2. The RING converter could be built with the newer, more efficient TPM-217 family of alloys; however, a major technology effort would be required to incorporate these alloys in the RING converter.

It is recommended in the program plan that in Phase 2, both approaches be pursued for the following reasons:

1. The PbTe-PbSnMnTe/BiSbTe materials can always do the job; and if the TPM-217 materials can be fabricated, then their incorporation in the RING converter could be readily accommodated and large gains (approximately 50%) in efficiency would be realized.
2. Although the TPM-217 materials might not be incorporated at the end of Phase 2, they will probably be incorporated at a future date that will allow the large gains in efficiency to be attained.

2. APPROACHES AND ASSUMPTIONS

Listed below are the approaches and assumptions that were utilized in preparing the program plan. The primary sources of information for preparing the plan are from experience in developing and fabricating the TRANSIT converter and in fabricating the 18-in.-diameter RING converter segment.

1. An overall schedule for the program* is given in Appendix A along with the major milestones to be accomplished.
2. The tasks to be accomplished under each of the phases are listed in Appendix B.
3. The overall program costs are given in Appendix C. The cost analyses for the 36-in.-diameter RING converter segment are based upon the actual costs incurred in building the 18-in.-diameter RING segment. These detailed costs are given in Tables 1 and 2 of Appendix C. The major effort presented in this program plan concerns the thermoelectric converter, since this was the only area of the system covered under the study contract.
4. The manufacturing plan for the TRANSIT converter was rewritten, incorporating all the newly developed fabricating processes and philosophy incorporated in the 18-in.-diameter RING segment. This document is part of the program plan but is submitted as a separate document (Ref. 2).

The equipment utilized in building the 18-in.-diameter RING segment and the anticipated equipment required to build this generator are listed in Appendix A of the manufacturing plan.

* As given in Ref. 1.

3. MAJOR CONCLUSIONS

1. The low cost RING converter can meet all system objectives using the existing technology of PbTe-PbSnMnTe/BiSbTe if the maximum heat source cost is \$150/W(th).
2. The low cost RING converter is a growth vehicle since the TPM alloys can be implemented in the converter with minimal impact. This implementation will greatly lower cost and reduce size and weight.
3. The RING converter allows minimal constraints on the heat source development program.

REFERENCES

1. "Economic Radioisotope Thermoelectric Generator Study," USAEC Report E-108-329, General Atomic Company, January 1974.
2. "Manufacturing Plan. ERTG RING Converter," USAEC Report GA-A12914, General Atomic Company, April 1974.

APPENDIX A

APPENDIX B

PHASE 2 - UTILIZING PbTe-PbSnMnTe/BiSbTe AS THE THERMOELECTRIC MATERIALS

1. Vibration/Structural Qualification of Existing 18" Diameter Ring
 - A. Fabricate four simulated 18" diameter rings, with no active thermoelectric elements.
 - B. Fabricate simulated end covers.
 - C. Assemble five rings into Ring Converter.
 - D. Perform Vibration/Structural tests with active 18" Ring in different positions.
2. Characterization of PbTe-PbSnMnTe/BiSbTe Modules at Temperatures of $\geq 450^{\circ}\text{C}$ in Vacuum
 - A. Fabricated same as 18" diameter ring.
 - B. Containing advanced vapor suppression coatings and/or baffles.
 - C. Fabricated from several batches of PbTe, PbSnMnTe and BiSbTe.
3. Evaluation of Super-Insulation
 - A. Relative thermal conductivity tests to evaluate different joint designs.
 - B. Relative thermal conductivity tests to evaluate alternative restraint designs.
4. Evaluation of Thermal Control Coating (Z-93)
 - A. Determine effects of temperature, air and vacuum on radiator coatings.
 - B. Determine optical property measurements in situ in vacuum under simulated space conditions.

5. Evaluate Radiator Samples
 - A. Determine optimum Al_2O_3 coating thickness and epoxy adhesive coating thickness versus ΔT and electrical insulation.
 - B. Life test radiator assemblies up to 250°C to determine thermal stability of mechanical adhesive and effect on ΔT across insulation gap.
6. Evaluate Heat Source Support Structure
 - A. Fabricate prototype structures and evaluate to vibrational specification.
 - B. Evaluate prototype structure with respect to thermal losses.
7. Evaluation of Variable Conductance Heat Pipe Concept
 - A. Design studies
 - B. Fabrication
 - C. Life Testing and Diagnostics
8. Evaluation of Power Flattening through Controlled Evaporation of High Emissivity Material
9. Conceptual Design of End Covers
10. Evaluation of 36" Diameter Ring Segment
 - A. Design
 - B. Fabrication of one to three Ring Segments
 - C. Thermal and Structural evaluation

PHASE 2 - UTILIZING TPM-217 MATERIALS
AS THE THERMOELECTRIC MATERIALS

1. Initiate materials fabrication effort in CuAgSe and GdSe (this effort could be with the assistance of 3M).
 - A. Property Measurements versus Preparation Procedures.
 - B. Vaporization Behavior versus Temperature and Time.
 - C. Detail studies in fabricating the alloys with mesh-in-cap bonds.
 - D. Initiate life testing of elements in two-couple modules. Perform tests at 500° to 900°C and perform diagnostics on tested elements.
 - E. Generate long-term data at desired T_H on ten two-couple modules.
2. Super-Insulation Evaluation
 - A. Select optimum range of materials for the anticipated temperatures interval.
 - B. Evaluate insulation materials in gradient (it is expected the materials for $\leq 500^\circ\text{C}$ will be the same as Transit, but above 500°C other materials such as Ni-foil and quartz cloth will be utilized).

PHASE 3 - SYSTEM DEVELOPMENT AND QUALIFICATION

1. Design Requirements
 - A. Integration Constraints
 - B. Power, Height, Volume
 - C. Layout
2. Parametric Analysis
 - A. Design Comparisons
 - B. Design Selection
3. Detailed Design Analysis
 - A. Assembly Configuration
 - Detailed Engineering Drawings
 - Mountings to Spacecraft
 - B. Insulation Design
 - Thermal Analysis
 - Restraints
 - End Covers
 - Protrusions
 - C. End Cover Design
 - Attachment of Ring Segments
 - Couple Arrangement
 - Insulation Attachments
 - D. Thermoelectric Element Design
 - Property Data
 - Life Test Data

E. Heat Source Configuration

- Arrangement
- Mounting to Base

F. Structural Analysis

- Vibration Input Response
- Weight Tabulations

4. Analytical Studies

- Element Sizing
- Heat Losses
- Effect of Cold Side Temperature
- Radiation View Factor
- Transient Thermal Model
- Aerodynamic and Re-entry Analyses

5. Manufacturing and Test Facilities

Set up manufacturing facilities for fabrication of the structural, thermal and qualification models. Manufacturing facility to be designed to allow for fabrication of generators in Phases 4 and 5.

Set up test facility to allow for thermal performance of associated hardware. Test facilities for structural evaluation (vibration, shock, etc.) will not be set up. This required testing will be subcontracted.

6. Fabrication and Evaluation of Three Generators

A. Structural Model - number of active Ring Segments to be determined.

Variable control heat pipe evaluation will verify structural integrity,

sinusoidal vibration, shock, random vibration, flight and qualification levels, and sealing characteristics (optional).

B. Thermal Model - number of active Ring Segments to be determined. Non-active panels have insulation to duplicate active Ring conductance. Variable control heat pipe evaluation will verify thermal and electrical performance.

C. Qualification Model - all active Ring Segments and Variable Control Heat Pipe. Full quality control implemented.

Evaluation - Qualification testing of Ring Converter in all respects.

PHASE 4 FLIGHT SYSTEM FABRICATION

1. Fabricate two flight generators.
2. Evaluate both generators to flight specifications with both electrical and nuclear heat sources.
3. Evaluate generators at user facility to check out integration with spacecraft.
4. Provide launch support services at launch facility.
5. Evaluate flight data initially and at monthly intervals.
6. Perform scale up and cost reduction studies in preparation of Phase 5.
7. Continue life testing of modules and other critical components to better predict lifetime performance.

PHASE 5 FOLLOW-ON PRODUCTION

1. Fabricate, test and ship 2-4 generators every six months.
2. Provide launch services at launch facility for each generator.
3. Evaluate flight data of each generator and predict future degradation rates.
4. Continue life testing of modules and other critical components to better predict lifetime performance.

APPENDIX C
COST BREAKDOWN BY TASK

	<u>COST (\$1,000)</u>	
PHASE 2A	\$ 370	
PHASE 2B (OPTIONAL)		\$ 250
PHASE 3	1,470	
PHASE 4	<u>1,000</u>	
	\$2,840	
EQUIPMENT	<u>400</u>	
TOTAL (THROUGH PHASE 4) =	\$3,240	\$ 250
PHASE 5		
36" DIAMETER RING WITH 20% QUALITY CONTROL	$\$40K/RING^1 \times 5 =$	\$ 200
25% SUPERVISION		
CONE WITH THERMOELECTRICS		\$ 40
HEAT PIPE ASSEMBLY AND HEAT SOURCE SUPPORT		\$ 40
PERFORMANCE TESTING		<u>\$ 10</u>
		\$ 290

¹THE DETAILED COSTS OF THE 36"-DIAMETER RING, WHICH ARE SHOWN IN TABLE 1, ARE BASED UPON THE COST ESTIMATES GENERATED WITH THE 18"-DIAMETER RING THAT ARE SHOWN IN TABLE 2. FOR COMPARATIVE PURPOSES, THE COST OF A TRANSIT 3-WATT PANEL WAS \$15,000.

TABLE 1
36" DIAMETER RING - ESTIMATE

	<u>Man Hours</u>	<u>Cost</u> (Dollars)
1. <u>BASIC RING STRUCTURE</u>		
A. Material plus machining		\$ 400 est.
B. Elec. feed-through and tie-down hole machining (12 ea.)	1	
C. Machine insulators for Item B (12 ea.)		50
D. Installation of Item C components	1	
E. Alumina spray coating	1	
F. Z-93 exterior painting	1	
2. <u>RADIATOR STRAPS</u>		
A. Forming and cutting (152 1/2-width straps - 0.25 ea.)		38
B. Button manufacturing and material (1216 x 0.25)		304
C. Button cleaning and firing	8	
D. Button to strap bonding (8 buttons/ strap - 152 1/2-width straps)	24	
E. Sand-blasting (for laser welding preparation)	8	
F. Strap bonding to ring (152 1/2-width straps, 10 min. per strap)	25	
G. Cold-side instrumentation	4	
3. <u>COLLECTOR FAB.</u>		
A. Forming and punching (\$1 apiece)		608

	<u>Man Hours</u>	<u>Cost</u> (Dollars)
3. <u>COLLECTOR FAB. (cont'd)</u>		
B. Grommet material and machining (0.25 ea. x 1216)		\$ 608
C. Collector to grommet bonding (24-36/day)	24	
D. Painting and bake-out (608)	8	
E. Grommet sand-blasting (for laser welding)	8	
4. <u>ELEMENT FAB.</u>		
A. Hot-cap material and machining (1216 x 0.25 ea.)		304
B. Cold-cap material and machining (1216 x 0.25 ea.)		304
C. Mesh Fab. (2432 x 0.10 ea.)		243
D. Mesh to cap spot-welding (1216 16/hr.)	76	
E. Elem. powder preparation	12	
F. Vac. hot-pressing, lapping (16 elements per run, 2 runs/day, P&N - 1216)	100	
G. Washer punching and bake-out (.05 ea. x 1216)	4	608
H. "N" cold-side bond: includes vap. coating, washer loading (4 runs/day)	48	
I. "P" epoxy to cap, clean up, vap. sup. and washers	24	
J. "P" cold-side soldering and clean up	16	
K. Elem. room temp. elec. testing and length (5 min./elem.)	101	
L. Elem. sand-blasting	50	

	<u>Man Hours</u>	<u>Cost</u> (Dollars)
5. <u>ASSEMBLY TASKS</u>		
A. Elem. silver epoxy bond to buttons	8	
B. Cold-side laser welding (5 min/joint)	50	
C. Strap trimming	4	
D. Final strap sealing, Kapton insulation	4	
E. Blanket insulation (vendor pre-punch and cut)		\$ 10,000 ¹
F. Blanket insulation bake-out	8	
G. Insulation, lay-up, short checks	16	
H. Tie-down posts and parts manufacturing	8	
I. Collector to hot-side anchoring and laser welding	60	
J. Collector re-shaping and touch-up painting	8	
K. Hot-side instrumentation	4	
NON-EXEMPT TOTAL MAN HOURS (COST AT \$18/HR) ²	714	12,852
VENDOR, MATERIAL COSTS		<u>13,163</u>
COMBINED SUB-TOTAL		\$ 26,015
QUALITY CONTROL (20% OF 714 HRS AT \$18/HR) ²		2,574
SUPERVISION (25% OF 714 HRS AT \$25/HR)		4,475
ESTIMATED COST/RING	\$ 33,064	
CONTINGENCY	<u>6,936</u>	
TOTAL COST/RING	\$ 40,000	

¹The cost of the super-insulation is approximate. It is thought this cost can be greatly reduced in production.

²The cost of the non-exempt labor rate can be appreciably lower in a manufacturing organization. The \$18/Hr cost is the present-day cost for a skilled laboratory technician.

TABLE 2
18" DIAMETER RING CONVERTER COST ANALYSIS

These figures are based on actual time and costs. For some items, it was necessary to estimate the man loading.

	<u>Man Hours</u>	<u>Cost</u> (Dollars)
1. <u>BASIC RING STRUCTURE</u>		
A. Material plus machining		\$ 770
B. Elec. feed-through and tie-down hole machining (12 ea.)	4	
C. Machine insulators for Item B (12 ea.)		50
D. Installation of Item C components	2	
E. Alumina spray coating	4	
F. Z-93 Exterior Painting	12	
2. <u>RADIATOR STRAPS</u>		
A. Forming and cutting (40 ea.)	8	
B. Button manufacturing and material (300 ea.)		1270
C. Button cleaning and firing (300 ea.)	4	
D. Button to strap bonding (40 straps- 8 elements)	40	
E. Sand-blasting	4	
F. Strap bonding to ring - 40 straps	20	
G. Cold-side instrumentation (22 T.C.'s)	24	
3. <u>COLLECTOR FAB.</u>		
A. Forming and punching (144 ea.)	40	

	<u>Man Hours</u>	<u>Cost</u>
3. <u>COLLECTOR FAB. (cont'd)</u>		
B. Grommet material and machining		\$ 500
C. Collector to grommet bonding (24-36/day)	40	
D. Painting and bake-out	24	
E. Grommet sand-blasting	24	
4. <u>ELEMENT FAB.</u>		
A. Hot-cap material and machining (300 ea.)		900
B. Cold-cap material and machining (300 ea.)		1875
C. Mesh Fab. (500 pcs.)	12	
D. Mesh to cap spot-welding (300 ea.)	18	
E. Elem. Powder preparation	4	
F. Vac. hot-pressing, lapping (1 run/day)	288	
G. Washer punching and back-out	24	
H. "N" cold-side bond: includes vap. coating, washer loading (1 run/day)	72	
I. "P" epoxy to cap, clean up, vap. sup and washers	32	
J. "P" cold-side soldering and clean up	30	
K. Elem. room temp. elec. testing	40	
L. Elem. sand-blasting	24	
5. <u>ASSEMBLY TASKS</u>		
A. Elem. silver epoxy bond to buttons	32	
B. Cold-side laser welding	40	

	<u>Man Hours</u>	<u>Cost</u>
5. <u>ASSEMBLY TASKS (cont'd)</u>		
C. Strap cutting	4	
D. Final strap sealing, Kapton insulation	4	
E. Blanket insulation (vendor pre-punch and cut)		\$ 8,000 ¹
F. Button insulation rework	8	
G. Blanket insulation bake-out	24	
H. Final insulation rework lay-up, short checks	80	
I. Tie-down posts and parts manufacturing	16	
J. Collector to hot-side anchoring and laser welding	56	
K. Collector re-shaping and touch-up painting	20	
L. Hot-side instrumentation (22 T.C.'s)	24	
6. <u>MISCELLANEOUS COSTS</u>		
A. Special time, set-up, laser repair	80	1,235
B. Optical supplies		300
		<hr/>
TOTAL MAN HOURS (COST AT \$21/HR) ²	1182	\$ 24,822
VENDOR & MATERIALS COSTS		14,900
		<hr/>
TOTAL RING COST (DOES NOT INCLUDE ANY SUPERVISION OR QUALITY CONTROL)		\$ 39,722

¹This insulation was actually left over from the TRANSIT program.

²The \$21/Hr cost was the actual non-exempt rate charged to the program at the time of manufacture.