ECONOMIC RADIOISOTOPE THERMOELECTRIC GENERATOR STUDY PROGRAM

PROGRAM PLAN
NOVEMBER 1973

Prepared for Space Nuclear Systems Division, U. S. Atomic Energy Commission, Germantown, Maryland
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TELEDYNE ISOTOPES

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CORRIGENDUM FOR VOLUME 3, IESD-3112 - PROGRAM PLAN

- Page v: Under FY 74 - 1174 should read 1147.
- Page 12: Last line - Task 13 should read Task M.
- Page 25: Line 21 - (1) first assembly should read (1) assembly of...

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FOREWORD

This document was prepared for the United States Atomic Energy Commission, Space Nuclear Systems Division by the Energy Systems Division of Teledyne Isotopes under Contract SNSO-3. This is Volume III, Program Plan, Economic Radioisotope Thermoelectric Generator Study. Volume I is the Final Technical Report, Volume II the Appendices for Volume I, and Volume IV is the Cost Effectiveness Study.

The following organizations participated in this program plan.

Teledyne Isotopes	System Integrator
Oak Ridge National Laboratory	Fuels and Encapsulations
Minnesota Mining & Manufacturing Company	Thermoelectric Technology
Dynatherm, Inc.	Heat Pipe Technology

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SUMMARY

This program plan describes the effort required to develop, test, and manufacture 400 watt(e) (EOM) Economic Radioisotopic Thermoelectric Generators for space application. The program is divided into five phases as described below.

Phase I	Study - Reference Design and Program Plan
Phase II	Component Development and Test
Phase III	System Development and Test
Phase IV	First Flight System
Phase V	Production (10 or 20 RTG's)

Phase I has been completed and is reported in the documented series IESD-3112 of which this Program Plan is Volume III. Phase II is scheduled to start in February 1974. The first flight system is scheduled for delivery in November 1977. Phase V follows the first ERTG flight and is scheduled to provide 10 or 20 units, one every two months, on a production schedule and cost basis. A summary schedule is presented on the following page, which describes the phases and delineates major hardware deliveries. The schedule has been integrated with the participating organizations referenced in the Foreword.

Costs for component and system development including the first flight (Phases II through IV) are presented below:

	K\$					
	FY 74	75	76	77	78	Total
ESD	1174	3832	4363	3436	2089	14,867
3M	520	800	950	375	336	2,981
ORNL	<u>134</u>	<u>1001</u>	<u>1023</u>	<u>583</u>	<u>563</u>	<u>3,304</u>
	1801	5633	6336	4394	2988	21,152

IESD-3112

Cost of the fuel for the prototype, flight and backup will be \$1.4M additional.

Costs subsequent to the development program are \$1.29M per ERTG, including fuel, on a 10 or 20 unit production schedule.

Costs and Statements of Work from participating organizations are shown in Appendix A.

Energy Systems Division Costs are detailed in Volume IV, "Cost Effectiveness Study."

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I. INTRODUCTION

The ERTG reference design is based on the use of selenide thermoelectric materials. These materials have exhibited the potential for system efficiencies greater than 12 percent. The resultant RTG design, compared to prior RTG systems, yields a nominal 50 percent reduction in fuel inventory, generator size and weight. These improvements in system performance significantly contribute to a more economical space nuclear power supply. Costs for production ERTG's are shown to be \$2,500/W(e) at BOL or \$ 3,200 /W(e) at EOM (5.5 years) including fuel.

To achieve these performance and cost goals, the selenide thermoelectric materials and associated RTG hardware must be developed to the production stage. Selenide thermoelectric materials currently on couple test and available for module design and test programs exhibit efficiencies up to 9 percent. These "current" materials will be used in the module and ETG system designs and tests. The improved selenides (efficiencies greater than 12 percent) will be developed for production manufacturing by the 3M Company during phases II and III of the program. The improved selenides are scheduled for incorporation into the prototype RTG. The Reference Design Prototype ERTG is expected to yield a system efficiency of 10.6 percent at EOM.

In addition to the selenide thermoelectric materials and associated RTG hardware, a modular ²⁴⁴curium sesquioxide fueled heat source will be developed by ESD in conjunction with Oak Ridge National Laboratory. ESD will provide the design, procurement, fabrication and piece parts to ORNL for live fuel tests, and prototype heat source assembly. Safety tests with simulated fuel will be ESD's responsibility. ORNL will also be responsible for fueling and testing of the Prototype ERTG and subsequent production units. A detailed Statement of Work from ORNL is included in Appendix A.

A. PROGRAM HARDWARE DEFINITION

A total of six generator units will be fabricated under Phases III and IV of the ERTG program as follows:

1. 1/5 Scale Module ETG

This unit will be used as the test bed for developing RTG fabrication and assembly techniques. Since the ERTG is a modular system, this 80 watt(e) module will incorporate all the design features of a full 400 watt(e) unit. Once the 80 watt(e) module has been assembled and tested, it will be put on life testing.

2. Engineering Model ETG

This unit will be a full assembly consisting of 10 thermoelectric modules. It will be fully instrumented to provide the necessary thermal and electrical power data required to verify the design performance analyses. The ETG will be qualification tested and put on life test.

3. Spacecraft Integration ETG

This unit will be fabricated along with the Engineering Model, qualification tested, and delivered to the user agency for integration studies.

Auxiliary ground equipment to be provided with the ETG include:

- Portable monitoring equipment
- ETG power supply and cables
- Dummy load bank
- Fin insulation pads
- ETG handling tools

4. RTG Prototype

This unit will be the first radioisotope fueled system. It will incorporate the improved selenide thermoelectric elements. It will also incorporate any modifications developed as a result of the ETG assembly or test program. It will be fueled and tested

at ORNL. After one year of operation, it will be diagnostically disassembled (including the heat source) and evaluated on a component interaction basis.

5. Flight RTG System

Two complete RTG systems will be provided; one for flight and the second unit as backup. These units will also be fueled and acceptance tested at ORNL and shipped to the launch site for spacecraft integration.

Auxiliary ground equipment to be provided with the RTG's include:

- Portable monitoring equipment
- Dummy load banks
- RTG handling tools
- Spacecraft mounting console and personnel shield

B. FACILITIES AND TOOLING REQUIREMENTS

The increased size of the ERTG will require enlarging some of the facilities at ESD to accommodate fabrication and testing. The major facilities and tooling items are summarized below:

- Vertical TV Chamber (5' x 8' test area)
- Electron Beam Welder
- 10-12 Ton Press
- Module Testers (5 ea.)
- Plating and Cleaning Tanks
- Heat Pipe Bonding Tool
- Min-K and Graphite Bakeout Retorts
- Modified Outgassing Station

A complete list of facilities and capital equipment requirements is given in Volume III.

To accommodate the new equipment required for the ERTG program, ESD will provide a new \$200,000 structural addition to the current manufacturing and test facilities. This structure will provide the necessary working areas for module testing, ERTG final assembly, and the TV test chamber.

Since the ERTG Reference Design incorporates a sealed thermoelectric section, no new fueling chamber (submarine) will be required. Fueling will be accomplished in the ORNL hot cell facilities.

II. PROGRAM PLAN AND SCHEDULES

The ERTG program plan is defined on a task basis as follows:

Task 1	Program Management
Task 2	Design and System Engineering
Task 3	Fabrication and Assembly
Task 4	System Analysis and Test
Task 5	Safety and Reliability
Task 6	Ground Support Equipment
Task 7	Quality Engineering

A. PHASE II COMPONENT DEVELOPMENT AND TEST

The object of this phase is to provide technical data to verify component operation and/or identify problem areas which are critical to the success of the total system.

Line schedules for Phase II follow in the task descriptions.

1. Task 1 - Program Management

This task will establish and maintain the program plan. Early in Phase II, a detailed statement of work will be prepared, following the guidelines of the program plan, which is mutually acceptable and integrated with the goals of SNS-ERTG program management, ESD, and the participating government agencies and industrial corporations.

This task will provide subcontract direction and liaison activities with all participating agencies and corporations to integrate their respective efforts into a successful product deliverable at the scheduled times.

Schedule and cost control will be maintained and reported under Task 1.

Technical and administrative direction will originate in Task 1.

Documentation and progress reporting will be accomplished under this task.

The ERTG Program Organization Chart is shown on the following page.

2. Task 2 - Design and Systems Engineering

During Phase II, the majority of RTG components will be developed and tested to demonstrate compliance with applicable design and performance requirements. The one exception to the component development will be the design and fabrication of an 80 watt(e) ERTG module, i.e., a 1/5 segment of the ERTG. This is necessary to demonstrate assembly techniques and to evaluate system performance prior to building a full scale, 5 module unit. The development program necessary to demonstrate components and technology is described as follows:

a. Heat Source Design for ORNL

Prototype heat source modules will be designed and fabricated to facilitate ORNL testing to assure compatibility of heat source materials and ²⁴⁴curium fuel. Detailed drawings and specifications will be prepared, materials procured, and module piece parts fabricated (under Task 3) for delivery to ORNL.

b. Ribbed Isolation Can

A representative portion of the heat source isolation can will be designed, fabricated, assembled, and tested to demonstrate structural adequacy. Structural analyses will be conducted to predict the response to the static load from the thermopile. Tests will be conducted at room temperature and at 825°C to determine centerline deflection, maximum stress, and creep behavior. The welded seams will be checked for hermeticity before and after structural testing.

**ECONOMIC RADIOISOTOPE THERMOELECTRIC GENERATOR
PROGRAM ORGANIZATION**

* Reports to Manager, Power Systems Department

** Reports to Vice President and General Manager, ESD

CAB Corrective Action Board

CCB Change Control Board

MRB Materials Review Board (Fueling Operations)

c. Electrical Heat Source

A small scale, high temperature, expandable electrical heater block will be developed, designed, fabricated, assembled, and tested. The technology developed by NASA Lewis and GE will be used for reference. The testing will consist of demonstrating capability to react the thermopile load in order to prevent excessive creep of the isolation can and thermal mapping of the heater block to verify adequate simulation of the temperature profile of a fueled heat source.

d. Heat Source Structural Support

The Min-K end insulation discs which support, by preloading, the heat source will be designed, fabricated, and tested. Structural analyses will be performed to predict the response to both static and dynamic loading conditions. The testing will consist of vibrating end insulation discs which support the simulated heat source mass to Titan III C qualification levels. After measuring the appropriate responses, the end insulation discs will be tested to failure to determine the margin of safety.

e. Structural Properties of Insulation

Min-K insulation TE 1400 and 2000 of various densities will be tested to determine the compressive yield strength, compressive ultimate strength, the modulus of elasticity, the damping ratio, and the load relaxation properties at room temperature and with a hot face temperature of 825°C. These tests will be conducted in the edge restrained and unrestrained conditions.

f. Bellows

The bellows, which joins the isolation can to the fueling port in the upper cover, will be sized, procured, and tested. Test will determine the feasibility of welding the bellows to the isolation can and the upper cover and will measure the temperature drop from hot to cold side.

g. Heat Source Channel Spacer

The heat source channel spacer will be designed, fabricated, and tested. The design will employ a maximum use of lightening holes consistent with structural adequacy. This will be verified by structural analysis and dynamic testing with a simulated heat source.

h. High Temperature Insulator

Samples of high temperature electrical insulators, e.g., mica, alumina, beryllia, zirconia, boron nitride, silicon carbide, and lava, will be tested to determine dielectric strength at 825°C. Tests will be conducted at compressive loads representative of TPM thermopile spring pressure, e.g., 150-500 psi. Compatibility data with associated materials, e.g., Haynes 188, tungsten, molybdenum, copper selenide, and gadolinium selenide, will be generated.

i. Fueling Port Closure

The Marmon clamped fueling port closure will be designed, fabricated, assembled, and tested. The test will demonstrate the hermeticity of the design and its structural adequacy under dynamic loading. An all welded alternate design will be evaluated only if the clamped design is inadequate.

j. Burst Disc

A burst disc device, similar to the one developed by GE, will be designed, fabricated, and tested. The tests will demonstrate the capability of the device to function once placed in a vacuum and will measure the internal gas pressure which fails the disc in the event it is not punctured. This characterization will be conducted both at room temperature and expected operating temperature.

k. Capsule Vent

At least two types of vents will be integrated with simulated capsule components and tested to monitor helium leak rate as a function of time, temperature, and gas pressure. Two SNAP 19, IRHS vent configurations will be designed and fabricated of PtRhW to be used in fueled capsule vent tests at ORNL.

l. Hydraulic Diaphragm

A hydraulic diaphragm, which has the potential to replace the spring loaded piston cold end hardware with a substantial weight savings, will be developed and designed to provide the required unique pressure to both N and P legs of the thermopile. This device will be fabricated, assembled, and tested. The test program will demonstrate the capability of providing the exact loading for all legs, and it will provide thermal characteristics of the device. Structural and thermal analyses will be provided in support of the design.

m. Heat Pipe Qualification Fin

A single heat pipe augmented fin will be designed, fabricated, and assembled. This heavily instrumented fin will be subjected to a qualification level vibration test. After pretest, test, and post test responses have been determined, the fin will be subjected to increasing vibration levels in three axes until failure occurs. This test will demonstrate the margin of safety of the fin design.

n. Generator Instrumentation

A study will be conducted of available pressure transducers, RTD's, and thermistors. After components have been selected and procured, they will be tested to demonstrate adequate performance under all expected environmental conditions. The result of the test program will be instrumentation which is qualified for use in an ERTG.

o. 1/5 Stack ETG

An electrically heated 80 watt generator, which is 1/5 the size of an ERTG will be designed, based upon the experience gained in the component/technology demonstration tests. It will have a heater block representing 3 heat source modules, 2 thermoelectric modules, and 2 fins each 1/5 the height of an ERTG fin and each containing 4 heat pipes. The 1/5 stack ETG will be fabricated, assembled, and tested. Thermal, thermoelectric, and structural analyses will be conducted to augment the design. The test program will consist of performance life testing of the unit using the same test sequence as a full scale ETG, including acceptance and qualification level dynamic testing, which will be concluded by the performance life test. Building a 1/5 stack generator will demonstrate assembly techniques, and the test sequence will evaluate system performance prior to committing to build a full scale ETG.

p. Design Support for Other Component Demonstrations

Design support and structural analyses will be provided for the following component/system demonstrations which are detailed in other tasks: TPM characterization and demonstration, copper/water heat pipe demonstration, variable conductance heat pipe development and demonstration, controlled leak device development and demonstration, and cold end hardware demonstration and performance evaluation.

q. Bimetallic Seal

The hermetic bimetallic seal between the Haynes 188 heat source isolation can bellows and the 6061 aluminum alloy hosing end plate shall be accomplished by means of a weld transition joint. Three different type weld transition joints shall be evaluated: explosive bonded, friction welded, and brazed. Design configurations suited to each type weld transition joint shall be developed. Weld techniques and procedures for

incorporating the transition joint into the structure shall be established. A prototype housing end cover/heat source can sub-assembly employing the preferred weld transition joint shall be designed, fabricated, and tested under simulated service conditions. This task shall be integrated with subtask f.

r. Electrical Receptacle to Housing Joint

A hermetic joint between the 20CB-3 stainless (or 321 stainless) steel electrical receptacle shell material and the 6061 aluminum alloy housing shall be made via a weld transition joint. Two different type weld transition joints shall be evaluated: explosive bonded (304 stainless/0.03" silver/6061 aluminum) and friction welded. Weld transition joint evaluation shall be coordinated with the similar activity in subtask q. Design configurations suited to each of type weld transition joints shall be developed. Weld techniques and procedures for incorporating the transition joint into the structure will be established. Selection of a preferred configuration/joint system shall be made on the basis of accelerated performance tests -- thermal cyclic and soak tests. Eight samples of the selected prototype design shall be fabricated and subjected to long term simulated service tests. Failure modes and safety margins shall be evaluated.

s. Heat Pipe Bonding

A solder type heat pipe attachment method, similar to that employed on the HPG-150 S/N 2 generator, shall be developed for bonding the copper/water heat pipes to the 6061 aluminum alloy case-fin structure. Solder substrate and application methods shall be established. Solder compositions, in particular Sn, Sn-Ag, Sn-Sb, Pt-In, and Pb-Ag types, flux types, joint configuration, heating atmosphere and methods shall be evaluated and a preferred process established. The preferred process shall be demonstrated on six full size prototype 2 heat pipe/fin-case samples, the 1/5 segment ETG, and the heat pipe qualification, Task 13. The prototype 2 heat pipe/fin-case samples shall be

employed for long term performance evaluation, both thermal and mechanical.

Non-destructive test techniques shall be screened for bond quality evaluation and a suitable non-destructive test procedure shall be established.

Adhesive bonding shall be screened as both a competitive and backup process for the solder heat pipe attachment process.

3. Task 3 - Fabrication and Assembly

Manufacturing of all test components for the various tasks will occur under this task. The quality control and inspection function is also included under Task 3 and includes inspection, documentation, recording, testing, calibration, source inspection, receiving, surveys, and delivery acceptance.

Manufacturing requirements include:

- a. Capsule piece parts and vents for ORNL testing
- b. Heat shield reentry body modules for aerodynamic tests
- c. Heat pipe qualification fins for heat pipe development
- d. One 1/5 scale module ETG
- e. Thermoelectric module testers
- f. Associated tooling for various structural tests defined under subtasks a, d, and e.

4. Task 4 - System Analysis and Test

a. Analysis

System analysis activities will be performed to support and direct the design and testing of RTG components and nuclear safety programs. Primary emphasis of these activities is in the area of thermal analysis and power performance. A significant portion of Task 4 activities will involve liaison with the 3M Company in the area of thermoelectric design, performance, and integration in the ERTG design.

(1) Orbit Definition and T_{sink} Analysis

Customer liaison will be established to define pertinent characteristics of the spacecraft flight path. Orientation and sun exposure of the RTG will be determined. The solar absorptivity will also be considered, and the complete thermal radiation environment of the RTG will be defined for the mission duration. An equivalent sink temperature will be calculated accounting for the predicted mission thermal radiation environment. This sink temperature will be used to determine generator radiator temperature in subsequent analyses.

(2) Optimum Radiator Temperature Analysis

The radiator temperature producing maximum generator end-of-mission specific power will be determined for an 800°C hot junction temperature. The study will be repeated for various values of fin surface emissivity and solar absorptivity. Results will be presented as a plot of radiator temperature versus system weight. For this analysis, a preliminary choice of heat pipe size and configuration will be held fixed. Radiator size-heat loss calculations will be made using string method or average view factor method for actual temperature calculations.

(3) Heat Pipe Configuration Analysis

Studies of RTG weight vs heat pipe spacing for various web tapers and thicknesses will be performed to permit selection of an optimum design. Heat pipe diameter will also be varied consistent with heat rejection requirement and spacing considerations. An additional consideration that will enter into the choice of spacing is modularity. That is, the generator should be constructed so that it could be easily divided into several lower-powered units if desired. Minimum heat pipe wall thickness to satisfy pressure, bending, and handling considerations will be determined.

(4) Heat Pipe Meteoroid Analysis

The probability of survival for the fin heat pipes in the space environment implied by the flight path defined in Item 1 will be determined. Probabilities for one heat pipe failure, two heat pipe failures, three heat pipe failures, etc., on each fin will be calculated. Survival probabilities will be found parametric with heat pipe wall thickness, diameter, and number of pipes. Consideration will be given to the use of Monte Carlo uncertainty analysis to accommodate uncertainties of meteoroid velocity and mass as well as the angular distribution of meteoroids.

(5) Multinode Radiator Segment Model

A computer model will be constructed of a cross sectional slice through the generator. End effects, anticipated only near the top and bottom of the generator, will be neglected. Heat source, thermoelectric, housing, and radiator details will be included for accuracy. If appropriate, several individual models will be utilized, and iterations performed until they interface correctly. Temperature maps will be constructed giving component temperatures at critical locations for various operating and malfunction conditions.

(6) Multinode Total Radiator Model

A computer model of the entire radiator system will be constructed, utilizing symmetry to reduce the overall model size and permit greater attention to detail. The effects of spacecraft interference to radiator views of space and mounting hardware thermal transport will be considered. Heat pipe dryout will be simulated with the model, as well as normal operating conditions. Fin sizing will be confirmed. Axial and radial temperature gradients will be evaluated.

(7) Experimental Verification with ETG Data

ETG radiator temperatures will be accurately measured in a vacuum or other environment easily simulated by the multinode total radiator model. Additional runs of the model will be made (if necessary) to exactly simulate test conditions. Test results and computer model predictions will be compared. Areas of disagreement will be investigated and the results used for future updating of the model, if advisable.

(8) Launch Ascent RTG Model

A computer model of the fueled generator will be constructed to demonstrate satisfactory thermal performance during the transient environmental conditions experienced in launch and ascent. Several prelaunch steady state temperature profiles will be used as inputs to the program. The program will predict the continuous response of the generator to the changing environment as convective cooling ceases and radiation to the surroundings becomes the sole mode of heat transfer. Heat pipe dryout (due to acceleration loads) will be accounted for, and several different durations of dryout will be considered.

(9) Thermal Loss Analysis

A good thermal efficiency prediction requires accurate knowledge of the thermal losses. These losses will be calculated parametric in gas, gas pressure, material properties, insulation thickness, etc. Temperatures within the generator will be estimated for determination of heat flows.

After ETG and RTG construction, the actual heat losses will be determined experimentally. These values will be compared to the predicted values and differences resolved. Excessive heat loss paths will be identified. Modifications, if possible, will be proposed to lessen or eliminate unacceptably high losses.

(10) Thermal Support of Design

Adequate design of many generator components (such as choice of materials) depends on accurate predictions of the thermal environment in which the component resides. These predictions will sometimes involve computer models, but will normally be hand calculations. Typical components studied will be electrical connectors, pressure transducers, etc., and the output of the studies will be expected component operating temperatures.

(11) Electrical Heat Source Temperature Analysis

The initial design of the electrical heat source will require preliminary prediction of component temperatures. Heater operating temperature is particularly important and will be carefully studied. For the most part, hand calculations of component temperatures will suffice during the preliminary design phases.

As physical dimensions of the electrical heat source are finalized, a multinode computer model will be constructed. The model will incorporate nodes representing significant locations of all heat source materials. After construction and checkout of the model, the anticipated operating conditions within the generator will be used for production runs. These runs will be used to verify tolerable temperatures at all internal locations. Problem areas identified by these temperature predictions will be resolved through design or procedural changes. The computer model will then be updated accordingly. Ideally, the predicted ETG heat source surface temperatures will identically match the predicted RTG heat source surface temperatures for similar operating conditions.

(12) Isotopic Heat Source Temperature Analysis

A multinode thermal computer model of the isotopic heat source will be constructed to predict heat source component temperatures for typical test and normal operating conditions. These temperatures will serve as goals for the design of the ETG heat source.

Temperature predictions will be reviewed to determine problem areas. Appropriate action will be taken to assure tolerable temperatures, and the computer model revised accordingly.

(13) Temperature Analysis of Bare Heat Source

The temperatures of significant locations on the surface of and within the bare heat source will be determined. External environments similar to those in the hot cell where the generator will be fueled (or other situations where the bare heat source will be used) will be simulated. These simulated environments programmed into the heat source thermal model will be used to predict significant temperatures.

The temperature obtained thusly will permit accurate determination of dimensional changes due to heatup from room temperature (essential for good fits, estimation of stresses, etc.). Also, selection of handling tools and procedures will be aided.

(14) Heat Source/Capsule Storage Container Thermal Analysis

Any storage container used with either the heat source or capsules after fueling must be thermally analyzed to assure maintenance of satisfactory temperature levels within the heat source or capsule. This work will be done in conjunction with ORNL, since the design and construction of such storage containers as may be needed by them will be their responsibility.

(15) 3M and ESD T/E Monitoring

3M data will be obtained for ESD use and converted to appropriate formats as required. ESD requirements will be coordinated with 3M, and design specifications exchanged. All intercompany communications and responses will be channeled through this area. Checking of data for apparent conflicts and transmission problems will be accomplished on receipt from 3M. All 3M test, design, analysis, and manufacturing operations pertinent to the ERTG program will be closely watched. Status of major program efforts will be reported periodically independent from standard 3M status reports. Problem areas, particularly with substantial schedule or technical impact, will be immediately reported to program management.

(16) T/E Computer Program

A computer program capable of predicting generator electric performance (based on selenide thermoelectric material properties) will be constructed. The program will include 3M technology presently incorporated in their couple performance prediction code. In addition, Monte Carlo capability will be incorporated to permit the use of probability distributions on various input functions.

b. Testing

(1) T/E Life Tests

A T/E life test program on the module component level is required for the following purposes:

- (a) To verify performance as indicated from single couple tests and associated analysis predictions prior to a generator hardware build;
- (b) To provide meaningful life test data suitable for a reliability assessment;
- (c) To observe systems interactions at the less expensive component level (e.g., Min-K with T/E, hot side dielectric with can and hot shoes, effect of vacuum vs inert cover gas, etc.); and
- (d) To permit use of higher density instrumentation (particularly thermocouples and voltage taps) that can be incorporated in full generators.

It is proposed that a 12-couple module be used as the primary unit for the life tests. This size is a good compromise between cost and the acquisition of meaningful systems level data. It permits a good mockup of the cold strap configuration and a realistic insight of system efficiency and yet uses less than 2% of the couples required for a complete 400 watt generator.

The requirements for the complete thermoelectric component test program are shown in Table 1. The life test portion is given by the first three entries in that table and is seen to consist of thirty-eight 12-couple modules. This totals to only about two-thirds of the couples required for construction of a complete generator and thus is a reasonably modest expenditure.

TABLE 1
T/E COMPONENT TEST MATRIX INDICATING QUANTITY
OF MODULES

		BOL HOT JUNCTION TEMPERATURE (°C)			
		<u>800</u>	<u>900</u>	<u>1000</u>	<u>1100</u>
1.	12-Couple Module Constant Q Life Test, 1/3 Atm. Argon				
	Current Standard TPM	5	3	3	
	Improved TPM (2 sets)	10			
2.	12-Couple Module Vary Q Life Test, 1/3 Atm. Argon				
	Current Standard TPM	3			
	Improved TPM (2 sets)	6*			
3.	12-Couple Module Constant Q Life Test, Vacuum				
	Current Standard TPM		2	1	1
	Improved TPM (2 sets)		4*		
4.	12-Couple Module, n, γ Tests + Performance Checks (ORNL Reactor - 2 times, 3 hot junction temperatures)	2	2	2	
5.	12-Couple Module Thermal Shock Test + Performance Checks	2			
6.	66-Couple Module Vibration Test + Performance Checks	2			

* Temperature might be higher if RTG is uprated.

These thirty-eight modules are broken into three subsets:

- (1) Eighteen made of current standard TPM and placed on test during the first year of the program.
- (2) Ten made of improved TPM and placed on test prior to construction of the first prototype RTG employing this material. Approximate test date would be mid 1976.
- (3) Ten more modules of improved TPM (possibly improved over the previous set) placed on test prior to construction of the first flight RTG. Approximate test date for these ten would be Spring of 1977.

On each of these subsets, three types of tests are envisioned

(see Table 1):

- (1) Constant fuel inventory test with about one-third atmosphere of argon, the reference design fill gas.
- (2) Varying fuel inventory test (to simulate fuel decay of $^{244}\text{curium}$ with one-third atmosphere of argon).
- (3) Constant fuel inventory test with internal vacuum to simulate the effect of a loss of fill gas. Note from Table 1 that this test is conducted approximately 100°C higher on hot junction temperature to correctly simulate conditions resulting from a loss of gas.

On each of the above tests "performance mapping" will be conducted at six month intervals to more completely assess the life behavior of these systems. In general, it will consist of load voltage parametrics at various hot and cold junction temperatures. Additionally, life test data will be taken on a weekly basis.

(2) Thermoelectric n, γ Exposure

This test (item 4, Table A) shall determine the effect of exposure on 12-couple thermoelectric modules to appropriate radiation from a reactor at ORNL or equivalent facility. The modules will be tested at three hot junction temperatures (e.g., 800°C, 900°C, 1000°C) and for two durations (e.g., three months and twelve months) to determine the sensitivity of the thermoelectrics to these parameters. Exposures in all cases will be about 10^{15} neutrons/cm² and 10^6 rads.

Containers will be designed to hold the modules during the n, γ testing without appreciably attenuating incident radiation. Necessary portable test equipment to measure module electrical performance will be obtained or built.

Pre- and post exposure performance checks will be made to measure the effects of the radiation exposure on the thermoelectrics. Electrical output will be measured for several junction temperature combinations.

(3) Thermoelectric Module Vibration Tests

Two generator size thermoelectric modules, incorporating sixty-six couples each, will be subjected to a vibration test series (entry number 6 in Table 1). Electrical performance measurements will be made prior to, during, and after the vibration tests. Visual examinations before and after the test will be made to reveal cracks, etc., signifying structural deterioration. Vibration will be accomplished in each of three mutually perpendicular axes. Test levels will be adjusted according to assumed launch vehicle environment. In addition, failure of one unit will be accomplished if deemed advisable.

(4) T/E Thermal Shock Tests

Two 12-couple T/E modules (similar to life test modules) will be tested to determine what effects, if any, will result from fueling a cold generator. These

tests are shown as the fifth entry in Table 1. Hot junction and cold junction temperatures will be controlled to predetermined temperature-time profiles. Each module will be performance checked prior to the thermal shock test to establish its operating characteristics. Post test performance measurements when compared to the pretest measurements will show if any power loss resulted from the thermal shock conditions. Test hardware will be disassembled and visually examined, specifically the bonds, to determine if any weakening or failure occurred due to thermal stresses during the test.

(5) Data Reduction Computer Code Development

A computer code will be written which provides a rapid method of obtaining a tabulation of T/E module life test data. This type of program also can be used with plot routines so that life test data are graphed mechanically through use of digital controlled equipment. Normalization routines in the program will permit the data to be normalized to specified power input, cold junction temperatures and load voltages so that test results from all specimens can be compared to each other.

(6) Module Diagnostic Analysis

It is planned that up to five of the 12-couple life test modules will be removed from test and diagnostically disassembled. The most likely specimens for inspection would be those exhibiting an unexpected or large change in performance during the life test.

In general the inspection would consist of the following for each module:

- (a) Microprobe analysis on four samples, most likely an N-leg, a P-leg, and the associated hot shoe contacts.
- (b) Vacuum fusion analysis on an N-leg and a P-leg to identify presence of O_2 and/or N_2 resulting from air leakage.

- (c) Arc spectroscopy on four samples to identify metallic constituents.
- (d) Metallography on ten samples, most of these on the N and P thermoelectrics.
- (e) Other analysis as indicated by the above four analyses.

(7) Cold End Hardware Test

This is a thermal test designed to evaluate the temperature drop across the cold end hardware as a function of heat flux, gas, gas pressure, and vacuum. This test will be conducted on both the reference design hardware (i.e., springs, flat bottom pistons, etc.) and an advanced design component entitled diaphragm cold end hardware.

(8) Min-K Outgassing Development

A proper outgassing procedure must be specified for the generator insulation to minimize the possibility of oxidizing the thermoelectrics. To maintain minimum production costs, the generators will be assembled in an air environment. Therefore, before each generator is sealed, the Min-K insulation must be outgassed so that water is driven off from the insulation and removed from the generator without oxidizing the elements in the process. Thermogravimetric analyses (TGA) will be performed to determine percent of moisture driven off at various temperature levels. This information will provide the basis for several outgassing procedures to be evaluated by (1) first assembly a test module in a dry inert environment using moisture free insulation (previously outgassed by high temperature vacuum process), (2) performance checking module, (3) cooling down module to room temperature and exposing to air environment to simulate air assembly, (4) outgas by one of selected procedures, (5) performance check specimen and compare with previous test data, (6) repeat above steps using new modules and different outgassing procedure, and (7) select outgassing procedure

which has minimum effect on T/E performance. After TGA results, it is anticipated that four outgassing procedures will be evaluated on each of two types of candidate Min-K insulation.

(9) Pressure Transducer Evaluation

Vibration testing of selected pressure transducer designs will be performed. At minimum, four pressure transducers from each of two vendors will be tested. Each pressure transducer will be mounted in a test fixture to simulate the temperature and gas environment of the generator. Pre-vibration test pressure measurements will be made and compared to a standard transducer. Vibration testing will follow with test levels approximating the vibration spectrum and duration of the anticipated ERTG launch vehicle. Continuous output monitoring will show performance during the test. Post test performance measurements will be compared to pretest data. Differences in performance will be documented and if necessary appropriate design changes recommended. Following performance testing, the pressure transducers will be life tested for approximately six months. Output will be monitored frequently and compared to the standard.

(10) Controlled Leak Device

Advantages and disadvantages of porous plugs, permeable membranes, capillary tubes, etc. will be examined. The two apparently most practical leak control systems will be selected for further study, with emphasis on the apparent best system. Theoretical pressure profiles will be developed and desired flow rates selected.

Test loops will be constructed to develop the details of the leak device. The chosen systems will be subjected to various pressure differentials and the flow response noted. Design variations will be tested to select the optimum configuration. The most promising designs will be life tested to verify the stability of flow properties.

(11) Thermal Conductivity of Min-K Insulation Tests

Thermal conductivity testing of Min-K will be accomplished by the vendor. Preliminary discussions have been held with Johns Manville personnel concerning detailed thermal conductivity testing with the specific gases and pressures considered for ERTG. The conductivity will be determined for several hot and cold side temperatures, gas fills, and Min-K compositions.

(12) Heater Evaluation

Electrical heaters to be used in the ETG's and with component level module tests must be capable of high temperature operation. A literature search of available heater systems will first be made to select a heater type to be used with both the ETG's and the component level tests, i.e., same type but different size and configuration. Possibly more than one heater type may be incorporated into the component level testing. Life tests on the heater type(s) will, in effect, be obtained during the 12-couple T/E module life tests. This data will be used to confirm the performance characteristics of a heater type before final selection and design of an ETG heater.

(13) Dynatherm Liaison

Heat pipe development and testing will be the responsibility of a subcontractor, Dynatherm Corporation. Both copper-water (primary, low temperature) heat pipes and Inconel-sodium (thermal control, high temperature) variable conductance heat pipes will be developed by Dynatherm. To insure that satisfactory communication and similar interpretation of test results (with respect to the generator design and its operating characteristics) exists between Energy Systems Division and Dynatherm, a close liaison will be maintained between the two contractors. Heat pipe testing will be monitored closely by Energy Systems Division personnel. Potential problems can be discovered sooner and coordinated measures initiated to resolve them.

(14) Thermal Integration of RTG and Spacecraft

Heat transport between the generator and the spacecraft will be determined through analysis. Information concerning the thermal interface characteristics of the generator will be communicated to the spacecraft contractor. All RTG/spacecraft thermal integration tests and measurements will be the responsibility of the spacecraft contractor.

(15) Intermodule Connector Testing

The module-to-module and module-to-receptacle electrical connections will be tested to determine their mechanical strength. Pull tests will be performed to assure that adequate strength exists in the connections to withstand all handling during assembly.

5. Task 5 - Nuclear Safety and Reliability

The ERTG program phases represent a logical, sequential plan leading to the development of a qualified economical radioisotopic thermoelectric generator. In the same manner, the safety plan was developed, as shown in Table 2, with milestones signifying topical reports which eventually will lead to flight approval.

In Phase II final heat source design modifications will be made to optimize all safety attributes. An initial safety assessment will be conducted to identify potential problem areas and delineate detailed test program requirements. Data requirements necessary for the preliminary SAR will also be delineated.

Phase III will encompass all safety testing (qualification and proof) as recommended in Phase II. Also in Phase III a preliminary safety analysis will be conducted and a PSAR issued.

The final safety analysis will be conducted in Phase IV with an FSAR being issued. Safety analyses required for launch support and post launch analysis will also be included in Phase IV.

TABLE 2
SAFETY PLAN SUMMARY

PHASE II TECHNOLOGY DEMONSTRATION

- Heat Source Optimization Study
- Initial Safety Assessment
- Identification of Problem Areas
- Test Program Recommendations
- Data Requirements

PHASE III SYSTEM DEVELOPMENT AND QUALIFICATION

- Safety Qualification Tests
- Preliminary Safety Analysis Report

PHASE IV FLIGHT SYSTEM FABRICATION

- Final Safety Analysis Report
- Launch Support and Post Launch Analysis

PHASE V PRODUCTION

- Safety Support

Phase V will include any support work required due to ERTG design modifications, new input data, flight trajectory variances, etc. Post launch analysis support will be available if required for any launch.

a. Heat Source Optimization Study

At the initiation of Phase II, effort will be directed toward the optimization of the heat source. This will be accomplished by evaluating each of the component parts, including coatings, and optimizing them in regard to safety attributes.

The heat source study will follow the flow plan shown in Figure 1. Results from compatibility tests being conducted at ORNL will be used to measure the containment characteristics of the liner material as a function of both time and temperature. Oxidation test results will be used as input in an analysis to determine the optimum liner thickness to complement search and recovery. Vent tests will be conducted to assure satisfactory gas flow requirements. Compatibility and emissivity coatings and thicknesses will be evaluated to determine infusion of material and heat transfer between the liner and strength member.

The emissivity coating for the strength member will be evaluated for its adherence characteristic and heat transfer properties. An impact and shrapnel analysis will then be conducted to determine the optimum strength member thickness for these combined environments. Exploratory type impact tests will then be conducted to evaluate the energy absorption characteristics of the fuel capsule. Results from the impact tests will also be used to select the optimum location for the capsule welds. With the completion of the fuel capsule analysis the heat source will be evaluated to determine the optimum heat shield thickness from the standpoint of reentry heating, recession and thermal stress.

Figure 1. HEAT SOURCE SAFETY STUDY PLAN

Reentry trajectories, characteristic of the mission, producing maximum heating rates will be used for the reentry thermal analysis. The heat shield recession analysis will also utilize trajectories producing the maximum recession. The thermal stress analysis will use the results from the previous analyses to evaluate the stress concentrations due to the heat shield thickness, end plug threads and lightening holes. If required, modification of the heat shield to obtain the maximum safety attributes will be made.

The ERTG heat source, modified by the results of the optimization study, will then be used in the initial safety assessment.

b. Initial Safety Assessment

An initial safety assessment will be performed based on typical mission parameters and input data furnished by the launch vehicle contractor, fueling agency, and launch site contractor. The purposes of this assessment are to define potential problem areas, delineate test program requirements, identify the major contributors to the overall risk, and document areas where additional support data is required.

The safety assessment will be initiated with the definition of mission parameters. This will include all time phases where a safety assessment must be considered. A vehicle FMEA analysis will be conducted to define accidents and aborts as a function of mission phases. Occurrence probabilities associated with each accident or abort will be determined based on input data from the vehicle contractor. Analytical environmental models, based on vehicle contractor input data and applicable test data, will be developed. Environment variables will also be considered and included in establishing environment distributions. The nuclear system FMA will include consideration of initial states, state transition, and final states. The end product of this analysis will be the establishment of conditional fuel release probabilities.

A source term analysis in conjunction with population exposure statistics will be used to establish conditional exposure probabilities. These data will then be used in a combinatorial analysis which will combine the results from the occurrence probability study, conditional fuel release study and conditional exposure statistics to form the basis for the risk assessment.

From these study results any potential problem areas requiring additional analysis or design modification will evolve. Areas requiring additional substantiation will be the basis for planning of the test program. Additional data requirements which may alter the results or increase the confidence level will be delineated.

Shielding analytical models will be developed in conjunction with ORNL. These models will then be used to perform a preliminary analysis of all shielding concerns.

c. Reliability

The Reliability Plan for the ERTG program is presented in Appendix B.

d. High Temperature Heat Source Study

During the past several years, numerous investigations have been undertaken to achieve an optimum system of containment for radioisotopic fuels. This effort is evidenced, in part, by the particular attention given to the chemical compatibility of the candidate fuel with the primary containment material under specific operating conditions of time, temperature, and environment(s). The demanding technology required of future missions which imposes higher temperatures, heterogeneous environments, and more stringent nuclear safety testing, requires design and materials that will surpass previous performance, safety and reliability requirements.

Obviously, there are many special problems relating to the behavior of materials in a heat source design which arise from the variety and severity of environments and conditions encountered during mission lifetime. Suffice it to say that everything there is to know about materials is most desirable but not realistic in light of present day technology. However, the Materials Engineering effort scoped for the Economical RTG program is a technological study to ascertain and accumulate known materials and systems data in order to recommend to the engineering design groups the best material(s) for the application. Specifically, the study is divided into five tasks - one to evaluate non-metallics and another to evaluate metallics. Because of the material(s) unique application, two tasks are scoped to evolve data in the areas of fuel compatibility, fuel characteristics, thermal protection, and related material system(s) required to permit the heat source to fulfill its design requirements. Lastly, the remaining task shall support the aforementioned areas of effort by liaison with research and development facilities and bring to light data requirements subject to further experimental work or new activities.

6. Task 6 - Ground Support Equipment

No effort Phase II.

7. Task 7 - Quality Engineering

This task encompasses the Quality Engineering activities to be conducted in support of the Economic Radioisotope Thermoelectric Generator program. A Quality Program Plan, included as a part of a Product Definition Plan, will be submitted to the AEC ninety days after contract start and will define compliance with SNS-1, "Quality Assurance Program Requirements for Space Nuclear Systems," dated April 1972. The Quality Program Plan will contain a thorough description of Quality functions and will

include individual Quality Directives that pertain to the program. These directives will be extracted from a Quality Manual presently maintained by the Quality Operations Department of Energy Systems Division in order to detail and direct the activities of Quality personnel on all programs and projects.

Specific tasks to be accomplished continually during the ERTG program include:

(1) Document Review

Technical documents requiring Quality Engineering review and approval prior to release include production drawings, material specifications, process specifications, test procedures, shipping and handling procedures, system specifications, drawing change notices and operation manuals. The review is to check clarity, completeness, compatibility with inspection requirements and capabilities, definition of acceptance criteria, compliance with contractual requirements, etc.

Quality Engineering will review and process procurement documents to assure that appropriate certification and test data is received and that proper receiving inspection is specified.

(2) Quality Planning

Control of deliverable hardware is achieved by means of quality logs which specify data collection requirements, test and inspection requirements, and acceptance criteria. Approved statistical quality control techniques will be implemented during inspection when appropriate. A personnel skill program will be administered and maintained to assure that critical manufacturing processes are performed by certified personnel. Inspection and acceptance instrumentation will be calibrated and maintained in accordance with accepted standards and provide traceability to the National Bureau of Standards.

TASK 2 - PHASE II DESIGN AND SYSTEM ENGINEERING	FY	1974	1975	1976	1977	1978	1979
	CY	1974	1975	1976	1977	1978	1979
Heat Source Design for ORNL							
Ribbed Isolation Can							
Electrical Heat Source							
Heat Source Structural Support							
Structural Properties of Insulation							
Bellows							
Heat Source Channel Spacer							
High Temperature Insulator							
Fueling Port Closure							
Burst Disc							
Capsule Vent							
Hydraulic Diaphragm							
Heat Pipe Qualification Fin							
Generator Instrumentation							
1/5 Stack ETG							
Design Support for T/E Components							
Bi-metallic Seal							
Electrical Receptacle Joining							
Heat Pipe Bonding							

TASK 3 - PHASE II FABRICATION AND ASSEMBLY	FY	1974	1975	1976	1977	1978	1979
	CY	1974	1975	1976	1977	1978	1979
Capsule Piece Parts for ORNL							
Heat Shield Reentry Body							
Heat Pipe Qualification Fins							
1/5 Scale ETG							
Thermoelectric Module Testers							
Tooling for Test Fixtures, etc.							

TASK 4 - PHASE II SYSTEM ANALYSIS	FY	1974	1975	1976	1977	1978	1979
	CY	1974	1975	1976	1977	1978	1979
Orbit Definition and T_{sink}							
Optimum Radiator Temperature							
Heat Pipe Configuration							
Heat Pipe Meteoroid							
Multinode Radiator Segment Model							
Multinode Total Radiator Model							
Experimental Verification							
Launch Ascent RTG Model							
Thermal Loss							
Thermal Support of Design							
Electrical Heat Source							
Isotope Heat Source							
Bare Heat Source							
Storage Container							
3M and EST T/E Monitoring							
T/E Computer Program							

TASK 4- PHASE II		FY	1974	1975	1976	1977	1978	1979
TEST		CY	1974	1975	1976	1977	1978	
T/E Module Tests Program								
Develop Plans								
Design Hardware								
Process Materials								
Manufacturing								
Test Procedures								
T/E n, Exposure Test								
Vibration Test								
Thermal Shock Test								
Data Reduction Computer Code								
Module Diagnostic Analysis								
Cold End Hardware Test, Pistons								
Cold End Hardware Test, Diaphragm								
Min-K Outgassing								
Pressure Transducer Evaluation								
Controlled Leak Device								
Thermal Conductivity								
Heater Evaluation								
Dynatherm Liaison								
Thermal Integration Spacecraft								
Connector Tests								

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TASK 5 - PHASE II SAFETY AND RELIABILITY	FY	1974	1975	1976	1977	1978	1979
	CY	1974	1975	1976	1977	1978	1978
Mission Definition Study							
Vehicle FMEA							
Analytical Model Development							
Heat Source Optimization							
Initial Safety Assessment							
Nuclear System FMA							
Fuel Dispersion and Biological Exposure							
Fuel Response							
Risk Analysis							
Combinatorials							
Error Analysis							
Shielding Analysis							
Safety Test Definition							
Reporting, Planning, and Meetings							
High Temperature Heat Source Study							

(3) Nonconforming Material

Established written procedures to control conforming and nonconforming production hardware fabricated at Energy Systems Division or purchased from a vendor will be employed. Systems to prevent the mixing of scrap and salvage hardware with acceptable production materials and to provide for the orderly and economical disposition of scrapped and salvaged materials will be implemented.

Production hardware deviating from applicable drawings or specifications will be initially dispositioned by Quality Engineering as "Scrap," "Rework," or "Refer to Corrective Action Board." On nonconformances referred to it by Quality Engineering, the Board provides for material disposition and specifies corrective action. The Board has the option of reviewing any Quality Engineering disposition. Corrective Action Board membership includes one representative from each of the following three disciplines: Quality Engineer, Reliability, and Systems Engineering, with the Quality Engineering representative serving as chairman.

A computer program will be used to determine and report non-conformance trends by categorizing and listing discrepancies and computing discrepancy rates for both Energy Systems Division and vendor fabricated hardware.

B. PHASES III AND IV SYSTEM DEVELOPMENT, TEST AND FLIGHT

The object of these two Phases is to develop and system engineer the qualified components of Phase II into a 400 watt(e) system, capable of meeting the mission requirements, and produce a flight qualified ERTG.

1. Task 1 - Program Management

Same as Phase II.

2. Task 2 - Design and System Engineering

a. ETG Prototype Design

Based on the 1/5 stack ETG experience and the component/technology demonstration, the ETG prototype will be designed and developed. The design phase will consist of layout preparation, detail and assembly drawing preparation, and checking, and will result in a complete set of deliverable drawings.

b. ETG S/C Integration Design

Based on the ETG prototype design and other predecessors, the spacecraft integration ETG will be designed and developed. The design phase will consist of layout preparation, detail and assembly drawing preparation, and checking, and will result in a complete set of deliverable drawings.

c. ETG/RTG Qualification Design

Based on the ETG spacecraft integration design, the ETG prototype design, and the prototype heat source design and subsequent testing at ORNL, the qualification ETG/RTG will be designed and developed. The design phase will consist of layout preparation detail and assembly drawing preparation, and checking, and will result in a complete set of deliverable drawings.

d. Flight/Backup RTG Design

Based on the ETG/RTG qualification design and other predecessors, the flight/backup RTG's will be designed and developed. The design phase will consist of layout preparation, detail and assembly drawing preparation, and checking, and will result in a complete set of deliverable drawings.

e. Test Support and Fixture Design

In support of component, subsystem, and system testing, the necessary fixtures and tools will be designed and checked. The drawings will be formalized sketches and not deliverable.

f. Tool Design

The tools and fixtures required to fabricate the components, subassemblies, and assemblies of all ETG's and RTG's will be designed, developed, and checked. The drawings will be formalized sketches and not deliverable.

g. Facilities Design/Installation

Design support will be provided for the selection and installation of the necessary facilities to fabricate, assemble, and test the ERTG.

h. Procedures

The applicable assembly and test procedures will be prepared, checked, and/or reviewed.

i. Specifications

The applicable component, material, and process specifications will be prepared, checked, and/or reviewed.

j. Manufacturing Liaison

Manufacturing liaison will be established and maintained throughout all phases of the program. This service will be provided to assure manufacturing understanding of design, engineering requirements, and to establish active two-way communication between design and manufacturing.

k. Structural Analysis

Structural analyses will be performed on all segments of the generator design which react static and/or dynamic loads to assure structural adequacy of all components. Wherever practical, component tests will be conducted to verify the analyses. Components to be analyzed include heat source isolation can, heat source load support insulation, housing, fin, end closure, fueling port, electrical receptacle, and heat pipe bond.

l. Spacecraft Interface Activity

Contact will be established with the appropriate agencies to establish necessary interface requirements. These requirements, as they evolve, will be translated into the generator design to assure compatibility of the ERTG and the users spacecraft and launch facility. Applicable documentation including interface drawings and specifications will be prepared.

m. System Specification

A system specification will be prepared which will fully define ERTG system characteristics and performance requirements. This document will be maintained throughout the program to reflect changes in design or user requirements.

n. Monitor Documentation

Program documentation will be monitored to assure compatibility with systems objectives.

o. Weight Monitoring

A system of weight monitoring of component parts, subassemblies, and assemblies will be established and maintained throughout the program. Weight monitoring will facilitate accurate predicting of total system weight prior to building the first ETG and first RTG, and will provide weight control of production units.

p. CAB/EDCS

A Corrective Action Board (CAB) and an Engineering Design Change System (EDCS) will be established at the appropriate time and maintained throughout the duration of the program. The CAB will be responsible for recommending corrective action for all product and test discrepancies, subject to customer approval. The EDCS will be established to maintain configuration control of the generator after appropriate design freezes. Design support will be provided both CAB and EDCS.

q. Drawing Maintenance

After the baseline drawings, procedures, and specifications have been prepared for the production RTG's, drawings revisions and DCN's will be provided as necessary.

r. Final Report

A design and systems input to the final report will be provided. This will include a detailed presentation of all significant design milestones.

3. Task 3 - Fabrication and Assembly

The following major hardware will be fabricated under this task.

50 heat source capsule piece parts for simulant fueling at ORNL
and subsequent safety testing

2 ETG's

1 Prototype RTG

2 Flight RTG's

Plus associated ground support equipment

4. Task 4 - System Analysis and Test

a. Analysis

(1) Generator Performance Prediction

A complete generator flight path will be examined, lasting from launch to end-of-mission. Significant times will be chosen for detailed analysis of generator performance. At each time chosen, the power output, load voltage, open circuit voltage, and other generator performance parameters will be calculated.

As additional information and test data become available, the program inputs will be updated and new runs made. Particular attention will be paid to updating the T/E material property distribution data for Monte Carlo use.

(2) ETG T/E and Performance Analysis (Current Standard Material)

Optimum size and number of thermoelectric couples to power the ETG (current standard material) will be calculated. Due to use of current standard material for the thermoelectric elements, the electrical power output will be below the requirement for flight units. Effective thermal inventory and heat source external temperatures will closely match values anticipated for the flight units.

(3) ETG Experimental Verification Analysis

ETG test data will be compared to the analytical performance predictions. Areas of disagreement will be resolved and appropriate corrections made to the computer program or input parameters, if necessary. Additional runs will be made so that analytical predictions can be demonstrated to nearly match actual test data.

(4) RTG Prototype T/E and Performance Analysis (Improved T/E Material)

Optimum size and number of thermoelectric couples to power the RTG prototype (using improved T/E material) will be calculated. Calculational techniques developed for ETG analysis will be utilized. Mission power requirements and updated T/E material properties will be used for the thermoelectric design and performance analysis.

(5) RTG Prototype Experimental Verification Analysis

RTG prototype test data will be compared to the analytical performance predictions. Areas of disagreement will be resolved and appropriate corrections made to the computer program or input parameters, if necessary. Additional runs will be made so that analytical predictions can be demonstrated to nearly match actual test data.

(6) RTG Flight T/E and Performance Analysis (Improved T/E Material)

Optimum size and number of thermoelectric couples to power the RTG flight unit will be calculated. Results of the RTG prototype T/E and performance analysis will be utilized as much as possible. ETG test data and revised ETG performance predictions will be reviewed to provide the latest information on correlation between test results and computer predictions.

(7) RTG Flight Experimental Verification Analysis

RTG flight data will be reviewed and compared to analytical predictions. Areas of disagreement will be identified, resolved, and appropriate corrections made to the computer program or input parameters as necessary. Additional program runs will be made so that analytical predictions can be demonstrated to nearly match actual test data.

(8) Malfunction Performance Analysis

The performance of both the ETG and RTG configurations will be determined under various malfunction conditions. Current standard and improved T/E material properties will be used. Failures to be examined include heat pipe dryout, bellows or can failure, housing failure, open circuit conditions, etc. The generator power, temperature, voltage, and other responses to the chosen malfunctions will be determined. A preliminary determination of malfunction response shall be prepared prior to ETG operation. After ETG test data is available, the preliminary work will be updated by using the latest revision of the generator performance program.

(9) Magnetic Analysis

The magnetic field due to current flow immediately around the generator will be determined and mapped. Customer specifications will be reviewed, and compliance with these specs determined. If compensation loops are required, the appropriate analysis of these loops will be generated. An additional magnetic field map will then be made, including the compensation loop.

(10) ETG/RTG Instrumentation Recommendations

The instrumentation requirements of both ETG's and RTG's will be reviewed. Particular attention will be paid to determination of malfunction modes and fault tracing (should it ever be required) through a review of instrumentation output. A recommendation will be prepared listing the instrumentation which is desirable to have on each generator. Furthermore, those items considered absolutely necessary, without which performance monitoring would be seriously impeded, will be noted.

(11) Design Reviews

Analysis of system performance will be specifically prepared for design reviews. Appropriate data demonstrating satisfactory achievement of analysis milestones will be presented. Problems and their subsequent solution will be listed. Preparations will be made for review of the ETG, RTG prototype, and first flight system.

(12) Housing Meteoroid Analysis

The probability of housing penetration by meteoroids will be investigated. Given the flight path, the probability and energy of collisions will be known. From the thickness of the housing material, its strength, and the probable meteoroid size, the chance of penetration will be determined.

(13) Heat Source Cavity Gas Analysis

Heat source cavity pressure vs time profiles will be generated. Various leak rates will be considered to simulate production differences between leak control devices.

(14) RTG Shipping Container Thermal Analysis

The significant temperatures of a generator within the shipping container will be calculated for normal shipping environments. Capability of the shipping container to maintain satisfactory temperature levels will be verified.

Accident conditions as specified by D.O.T. regulations will be identified. Generator temperatures will be calculated for these accident environments. These temperatures will be demonstrated below critical temperatures for containment. If any temperatures appear to threaten safety of the system, the shipping container will be modified appropriately and reanalyzed.

(15) RTG S/C Mounting Console on Launch Pad

The generator to spacecraft loading device will be thermally analyzed to predict temperatures of critical components. Accident conditions, such as a hydraulic fluid hose resting on a hot RTG surface, will be considered. Capability to withstand maximum anticipated temperatures will, in general, be designed into the loading device. However, any problem areas uncovered by analysis will form the basis for recommendations to change the design appropriately.

(16) Flight Data Analysis

Flight data will be reduced, appropriate corrections applied (for resistance of cabling, etc.), and actual generator performance determined. This corrected data will be reviewed and compared to predicted performance. Deviations from predicted values will be investigated.

Prior to launch, customer liaison will provide details of anticipated telemetry. Accuracy, resolution, and range of the spacecraft telemetry system will be determined. Data interpretation methodology will be established.

(17) Gas/Fuel/Vent System Analysis

The practicality of a thermal control system utilizing the controlled leak of a highly conductive gas will be investigated further. Thermal conductivity data on multifoil insulation will be generated or obtained from the manufacturer or other users. Controlled leak devices will be examined. Performance of a generator utilizing a gas management thermal control system will be determined. Analyses necessary to support the design of the most practical working system will be provided.

(18) VCHP System Analysis

The practicality of a thermal control system utilizing variable conductance heat pipes will be investigated further. Test data will be accumulated and reviewed to provide a basis for selecting the working fluid, pipe configuration, etc. Generator performance with the VCHP system for thermal control will be predicted. Analysis necessary to support the design of the most practical working system will be provided.

(19) Burial Analysis

Temperatures at significant locations throughout the heat source will be determined for various degrees of burial. Several types of soil will be considered, and the bare capsule will be analyzed as well as the complete heat source with its heat shield. The temperatures will be reviewed for potential problem areas.

(20) Vacuum (Gas Loss) Analysis

Heat source temperatures will be determined assuming the heat source is exposed to the vacuum of space. Conditions studied will include (1) a bare heat source, (2) a complete heat source in the RTG with all (both converter and heat source cavity) gas loss, (3) with converter gas only lost, and (4) with only the heat source cavity gas lost. The temperatures at critical heat source locations will be reviewed to determine any potential problem areas.

(21) Monthly Reports

Progress in all significant work areas will be summarized. Problem areas will be identified, and solutions suggested when practical. Work started during the reporting period will be mentioned as well as completed tasks. A finished report will be sent to the customer on a predetermined date each month, containing the progress of the previous month.

(22) Final Report

A final report analysis input shall be prepared.

b. Testing

Phase III test efforts are summarized as follows:

Continuation of the Fifth Stack Converter Life Test

Outgassing and Acceptance Testing of three full scale generators

Performance characterization of ERTG's

ETG/RTG Operations Training

RTG Fueling

ETG/RTG Qualification Level Dynamic Testing

Commencement of ETG/RTG Endurance Tests

(1) Fifth Stack Generator Life Tests

Long term performance evaluations of one FSG will commence during Phase II and these will continue for a total period of 22 months. Efforts which follow the initial setup consist of maintaining the generator at simulated operational temperatures in air to accrue performance histories and system reliability data. Monitoring and evaluation of test data will be continuous throughout the period and progress reports will be issued periodically.

(2) Outgassing and Acceptance Testing

Production tests of three full scale generators will be monitored. Procedures will be released to control the performance of void volume measurements, cold leakage checks, outgassing and initial performance checks at various conditions parametric in load voltage, gas fill, fill gas pressure, heater input level, and fin temperature. Each ETG will be checked for leakage and individual sources will be isolated.

Three generators will be subjected to acceptance tests, including hot generator acceptance level vibration tests, and post vibration leakage measurements, and performance evaluation in vacuum. Of these, the ETG prototype generator will be held in vacuum for a period of two weeks to evaluate degrees of performance and leakage stabilities, and to test the radiator temperature profiles. The RTG prototype will eventually be fueled whereas the third generator, an ETG, will be delivered for spacecraft integration by the user agency.

(3) Performance Characterization

Beginning of Life (BOL) performance characterization tests of the ERTG include the systematic evaluation of the influence of any single parameter or other generator parameters, including such variables as fin temperature, power input, load voltage, and hot junction temperature. Other planned studies include generator-to-generator variations, generator response to transients (thermal, electrical and mechanical), and variation of performance with time. Procedures will be developed to conduct these tests. Results will be recorded in topical and progress reports when available. The mass properties of one ERTG will be measured and reported.

(4) ETG/RTG Operations Training

Liaison will be maintained with subcontractor agencies such as Fairchild Industries for dynamic environmental tests, and with suppliers of functional ERTG component hardware. Personnel will be instructed and trained to accomplish such generator handling and operations as required following delivery of the ERTG to ORNL for fueling. Liaison will be maintained with customer agencies to provide data services and consultation for pre-launch operations planning.

(5) Fueling

The procedures for ERTG fueling will be developed in cooperation with ORNL participating groups. Crew training sessions will be arranged and dry runs performed prior to actual fueling of the prototype ERTG. Performance and leakage tests will be conducted. Critique of procedures and a topical report will complete these efforts.

(6) ETG/RTG Qualification

The electrically heated prototype ERTG will be vibrated to a qualification level specification supplied by the customer. In addition, shock syntheses will be performed as required. Both tests will be executed at facilities of Fairchild Industries. Qualification level vibration of the fueled prototype generator will be accomplished on ORNL equipment within adequately shielded areas. Following vibration, the integrity of the generator will be confirmed based on results of post vibration performance and leakage tests.

(7) ETG/RTG Endurance Tests

Two prototype generators, one ETG and one RTG, will be placed on life test at simulated operational conditions as to radiator temperature and load. Stability of power output and temperatures will be monitored, and parametric tests in load voltage performed at intervals of 6 months or less. Generator endurance test data will be analyzed. Results will be documented in progress reports and performance deviations where detected will be diagnosed. The duration of endurance tests will be 18 months minimum.

(8) Flight System Fabrication

Test efforts during Phase IV periods will be centered on adapting results and conclusions from the prototype generator tests toward development of efficient flight system test procedures, equipment, and data analysis tools. In addition,

two ERTG flight systems will be processed through acceptance tests and fueling during the period. Also, the ETG/RTG prototype endurance testing which was commenced during Phase III will be concluded. Assistance will be rendered to flight system production test efforts, and liaison maintained with customer and system user agencies.

5. Task 5 - Nuclear Safety and Reliability

a. Safety Qualification Tests

The initial safety assessment conducted in Phase II will provide the input data for establishing the qualification test program. Areas requiring additional substantiation due to lack of support data or as a result of the probabilistic results obtained in Phase II will be included in the test program. Analytical response of the nuclear system to some accident or about environments; impact, solid fire, thermal stress, sequential environments, etc., may not produce the confidence level required for flight approval thereby dictating the need for specific test programs. These considerations will be included in establishing the safety qualification test program. The results obtained from the qualification test program will be used as input to the preliminary safety analysis.

b. Qualification and Proof Test Program

One of the objectives of the Phase II program was to delineate the test program requirements. The criteria for selection of the tests to be conducted are: (1) to provide the required data for analytical model development, (2) substantiate analytical results, (3) provide failure predictions when no analytical model is applicable, and (4) for qualification of system states.

Based on past programs' experience, a typical test program is shown in Figure 2. This program may be the same one used for the ERTG program, depending upon the result obtained from the Phase II study. It is anticipated that the ERTG test program will be of the same magnitude. The information gained from these tests will

	<u>Specimen</u>	<u>No. of Specimens</u>	<u>No. of Tests</u>	<u>Test Facility</u>	<u>Comments</u>
Launch Pad Sequential Test	RTG	2	2	Sandia	2 Total RTG's (Use will be made of rejected or spare parts)
Overpressure					
Fragment					
Liquid Fire					
Solid Fire					
Fragment Test	Can & Heat Source	1-2	6	Sandia	2 Heat Sources in each can. The rest could be dummies
	Capsulettes	4	4		
Solid Fire Test	Heat Source	2	1	Sandia	
	Capsulette	2			
Impact Test	Heat Source	6	6	LASL	Heat Source should be exposed to reentry heating prior to test
	Capsulette	12	12		
Thermal Stress Test	Heat Source	6	6	Langley	(Electrical heated capsules - no liner)

Figure 2. Typical Test Program

be used in the manner mentioned above. For example, the fragment test will provide the data for analytical model development. The solid fire test will provide failure predictions due to the lack of adequate analytical models. The impact tests will serve both as qualification tests and to substantiate analytical findings. The thermal tests will be used to supply data for analytical model development. The thermal tests will be used to supply data for analytical model development.

When finalized, the test program plan will maximize utilization of the test data and be designed to provide failure probability distributions.

c. Preliminary Safety Analysis Report (PSAR)

The preliminary safety analysis report represents the initial effort of providing a risk assessment for the ERTG mission. Historically, this report has been used as the basis for modifying and updating, periodically, in response to changes in mission parameters, vehicle contractor input data, design, criteria and analytical rationale.

The safety study will be of a probabilistic nature as shown on Figure 3. The initial input data will be supplied by the vehicle contractor and is used in the vehicle failure modes and effect analysis. From these data, environments are delineated for both normal and accident conditions. For each accident or abort, a corresponding occurrence probability will be established. The results of this input data will then be used to initiate the nuclear system analyses.

Effort in the nuclear system analysis will be directed toward the development of applicable environmental analytical models and the methods of determining representative environment distributions for the known accident and abort conditions. The conditional

Fig. 3 Safety Evaluation - Logic Sequence

environment distribution along with the cumulative occurrence probabilities will be integrated with the results from the nuclear system FMA to determine state transition probabilities and final conditional fuel release probabilities.

To obtain conditional exposure probabilities will involve the integration of the source term and population exposure statistics shown in Figure 3. Input data such as respirable fractions, population density distributions, etc., will be supplied by NUS and the fueling contractor. Probabilities on fuel response and source term will be substantiated by live fuel tests. These test data will be used to modify the appropriate analytical modes.

The combinatorial analysis will make use of Monte Carlo techniques in integrating the previous results, determining the variance and ultimately the mission risk.

Based on the shielding models developed in conjunction with ORNL in Phase II, a shielding study will be performed. This study will encompass all areas of shielding concerns, from transport of the fuel to recovery of the fuel as a consequence of an abort.

d. Final Safety Analysis Report

The final safety analysis will follow the safety evaluation logic sequence used in the PSAR. It is anticipated that additional input data concerning the mission parameters, vehicle abort characteristics, occurrence probabilities, etc., will be made available. These new data will then have to be evaluated to determine the effect on the mission risk due to changes in analytical models, study parameters, or uncertainty factors.

e. Shielding

The shielding models generated in Phases II and III will be updated to include all relevant changes or new input data. The shielding analysis will include all mission shielding concerns and will be conducted in conjunction with work being done at ORNL.

f. Launch Support and Post Launch Analysis

Launch support analysis will be conducted to delineate potential problem areas or time delaying events. Backup safety support personnel will be available to analyze launch problems or to conduct a post launch study.

6. Task 6 - Ground Support Equipment

a. Associated Ground Equipment (Mechanical)

AGE will be developed, designed, fabricated, assembled, tested, and delivered, as required during the course of the program. The mechanical AGE will include shipping containers for ETG's, RTG's, and fueled heat source (if required); ETG and RTG handling tools; and devices which will transport the RTG from storage to the launch pad, and which will mount the RTG to the spacecraft. The design phase will consist of layout preparation, detail and assembly drawing preparation, and checking, and will result in a complete set of deliverable drawings. Thermal and structural analyses will be conducted to demonstrate adequate performance based on applicable design standards.

b. Associated Ground Equipment (Electrical)

Electrical AGE will be developed, designed, fabricated, assembled, tested, and delivered. The electrical AGE will include ETG power supplies and load banks, RTG portable monitor packages, and associated interconnecting cables. The design phase will include layout preparation; detail, subassembly, and assembly drawing preparation; and checking, and will result in a complete set of drawings and user's manuals. Thermal, electrical, and structural analyses will be conducted to demonstrate adequate performance based on applicable design standards.

c. Manufacturing Liaison

Manufacturing liaison will be maintained throughout all phases of AGE fabrication and assembly. This will be provided to assure manufacturing understanding of design/engineering requirements and to establish active two-way communications between manufacturing and design.

III

IV

TASK II PHASE III & IV DESIGN AND SYSTEM ENG	FY	1974	1975	1976	1977	1978	1979
	CY	1974	1975	1976	1977	1978	1979
ETG Prototype Design							
ETG S/C Integration Design							
ETG/RTG Prototype Design							
Flight/Backup RTG Design							
Test Support and Fixture Design							
Tool Designs							
Facilities Design/Installation							
Procedures							
Specifications							
Manufacturing Liaison							
Structural Analysis							
Spacecraft Interface Activities							
System Specifications							
Monitor Documentation							
Weight Monitoring							
CAB/EDCS Activity							
Drawing Maintenance							
Final Report							

IESD-3112

TASK III PHASE III & IV FABRICATION AND ASSEMBLY	FY	1974	1975	1976	1977	1978	1979
	CY	1974	1975	1976	1977	1978	
50 Heat Source Capsule Piece Parts							
25 Heat Source Modules							
2 ETG's							
Prototype RTG							
Flight RTG							
Backup RTG							
AGE for ETG							
AGE for RTG							
Spacecraft Mounting Console							

III

IV

TASK IV PHASES III & IV	FY	1974	1975	1976	1977	1978	1979
	CY	1974	1975	1976	1977	1978	
Generator Performance Predictions							
ETG Performance							
ETG Experimental Verification							
RTG Prototype Performance							
RTG Prototype Verification							
RTG Flight Performance							
RTG Flight Verification							
Malfunction Performance							
Magnetic Analysis							
ETG/RTG Instrumentation							
Meteoroid Analysis							
Heat Source Gas Analysis							
Shipping Thermal Analysis							
RTG/S/C Mounting Console Analysis							
Flight Data Analysis							
Gas Vent System Analysis							
VCHP System Analysis							
Burial Analysis							
Vacuum Gas Loss Analysis							
ERT/RTG Testing							

IESD-3112

TASK V PHASE III SAFETY AND RELIABILITY	FY	1974	1975	1976	1977	1978	1979
	CY	1974	1975	1976	1977	1978	
Vehicle FMEA							
Abort Environment Definition							
Analytical Model Update							
Nuclear System FMA							
Fuel Dispersion & Biological Exposure							
Fuel Response							
Risk Analysis							
Combinatorials							
Error Analysis							
Shielding Analysis							
PSAR							
Qualification Test Program							

TASK V PHASE IV SAFETY AND RELIABILITY	FY	1974	1975	1976	1977	1978	1979
	CY	1974	1975	1976	1977	1978	
Final Vehicle FMEA							
Update Environmental Models							
Final Safety Analysis							
FSAR							
Complete Shielding Study							
Launch Support & Post Launch Analysis							
Post Launch(es) Support							
Mission Perturbation Safety Analysis							

IESD-3112

TASK VI PHASE III & IV GROUND SUPPORT EQUIPMENT	FY	1974	1975	1976	1977	1978	1979
	CY	1974	1975	1976	1977	1978	1979
ETG Power Supplies							
ETG Monitoring Package							
ETG Shipping Container							
Heat Source Shipping Container*							
RTG Shipping Container							
RTG Monitoring Package							
RTG-S/C Mounting Console							
Miscellaneous AGE							
* If required							

d. Specifications and Procedures

The applicable assembly and test procedure and component, material, and process specifications will be prepared, checked, and/or reviewed.

e. Drawing Maintenance

After the baseline drawings, procedures, and specifications have been prepared for production AGE, drawing revisions and DCN's will be provided as necessary.

f. Final Report

A design and systems input to the final report will be provided. This will include a detailed presentation of all significant design milestones.

7. Task 7 - Quality Engineering

Same as Phase II.

C. PHASE V PRODUCTION

During Phase V, production RTG's can be produced and tested at the rate of one every two months. A cost analysis between a production of ten versus twenty RTG's did not indicate any significant difference in price. This was also true for the estimates submitted by ORNL and 3M.

During Phase V, Task 1 - Program Management, Task III - Fabrication and Assembly, and Task 7 - Quality Engineering will be active in the production of RTG's. Task 2 - Design, Task 4 - Analysis, Task 5 - Safety and Reliability, and Task 7 - Ground Support Equipment will operate at a liaison effort. Post launch data reduction and analysis will be conducted under Task 4 - Test. Data reduction will continue for a period of six months after each launch.

The scope and sequence of flight generator acceptance testing is shown below:

- Outgassing Monitoring and Post Outgassing Performance Checks
- Pre-Vibration Performance Evaluation - Power Output and Leakage
- Acceptance Level Vibration of the Electrically Heated ERTG
- Post Vibration Performance Evaluation - Power Output and Leakages
- Fueling at ORNL
- Post Fueling Performance Evaluation - Power Output and Leakages
- Pre-Launch Verification Tests - Performance and Visual
- Launch Support

All significant activities will be documented in progress reports and the final report as required.

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APPENDIX A

STATEMENTS OF WORK AND COSTS OF PARTICIPATING
ORGANIZATIONS

1. Oak Ridge National Laboratory Statements of Work and Cost

OAK RIDGE NATIONAL LABORATORY

OPERATED BY
UNION CARBIDE CORPORATION
NUCLEAR DIVISION

POST OFFICE BOX X
OAK RIDGE, TENNESSEE 37830

September 18, 1973

Mr. W. E. Osmeyer
ERTG Program Manager
Energy Systems Division
Teledyne Isotopes, Inc.
110 W. Timonium Road
Timonium, MD 21093

Dear Bill:

The production costs for the source proposed for the Teledyne Isotopes, Inc., ERTG system have been estimated. The estimate is \$92,000 per source on a production basis of 10 or 20 units over a 3-1/2 year period. The estimate for a single source is \$135,000 on a "one-shot" first source basis. This number carries significantly more technical support costs and set-up charges not included in the production cost figure for 10 or 20 sources. These costs are representative of costs to the government in a government-owned facility such as ORNL. The bases and assumptions on which these estimates are made are attached for your information.

Also attached is the assumed loading and assembly sequence used in making time and cost estimates for your source. Please review this sequence carefully and make any appropriate comments since the information on which it was based was somewhat preliminary.

Very truly yours,

A handwritten signature in cursive script, appearing to read "Gene".

Eugene Lamb
Assistant Superintendent
Isotopes Development Center

EL:KWH:mms

Attachments

cc: R. T. Carpenter, AEC-SNS
A. P. Litman, AEC-SNS
K. W. Haff
C. L. Ottinger

BASES FOR ERTG PRODUCTION ESTIMATES

A. Facilities

1. An integrated fuel receipt-fuel forming-encapsulation facility is assumed, with a common crew conducting all phases of the ^{244}Cm operation. This facility is assumed to be part of a larger operation, thus sharing general support services with several other facilities.
2. The encapsulation system is assumed to be a line of manipulator cells operated in series with the first cell of the encapsulation line being adjacent to the last cell of the fuel-forming line.
3. The encapsulation cells are assumed to be specifically designed for production of the type units being estimated. All necessary equipment and services are taken to be installed and tested.
4. The number of encapsulation cells may vary with the operational plan (see below). For estimating purposes, it is assumed that there are no two cells in which identical operations are conducted.
5. Facilities for direct support activities such as metallurgical examination of test pieces, checking of loaded generators, etc., are assumed to be available within the ^{244}Cm facility.

B. Operations

1. For each estimated source assembly sequence, an operational plan is prepared showing the incremental operations according to cell.
2. Based on the incremental operational breakdown, manpower and elapsed time estimates are made. These are based on extrapolations of previous experience insofar as possible. In cases where techniques not yet developed are assumed, these values are more or less arbitrary.
3. The basic cell crew consists of two operators and one QA technician. Certain operations require less than a full crew.
4. Shift operations are assumed for all cases, with options being 3-shift, 5-day or 3-shift, 7-day operation.
5. A downtime factor of 25% is applied; this includes both equipment breakdown and source reject downtime.
6. The production rate is assumed to be limited only by the most time-consuming incremental (i.e., one-cell) operation and the downtime. Production rates below the maximum are directly manpower-dependent.
7. All encapsulation estimates start with the assumption that fuel pellets ready for encapsulation are provided from the fuel-forming line at no cost to the encapsulation project.

C. General

1. No development costs are included. It is assumed that the operational plan describes a routine, qualified series of operations producing multiple identical units.
2. The only materials costs included are for routine supplies. Equipment spare parts, and especially encapsulation materials costs, are specifically excluded. These items are assumed to be available either as capital items or as supplied by the customer.
3. Costs are estimated on the basis of operating cost including required support and administrative factors but not including added factors for depreciation, insurance, or profit. The facility is assumed to be a part of a larger facility or complex offering all general support services. Specifically, costs are based on current ORNL operating experience and services.

LOADING AND ASSEMBLY SEQUENCE

<u>Cell or Area</u>	<u>Operation</u>
Service Area	<p>A. Preparatory</p> <ol style="list-style-type: none">1. Inspect customer-supplied pieces for one cycle2. Pretreat and package pieces3. Repeat A.1 and A.2 six times
Cell 1	<p>B. Liner Encapsulation</p> <ol style="list-style-type: none">1. Receive 2 preassembled test liners, 4 liner bodies with caps, 8 inserts from service area2. Establish inert atmosphere3. Receive 8 pellets from production line4. Load and cap 4 liners5. Weld precycle test liner6. Weld 4 liners7. Weld postcycle test liner8. Transfer 2 test liners to inspection area9. Preclean 4 fueled liners10. Transfer 4 liners to Cell 211. Repeat B.1 - B.10 six times
Cell 2	<p>C. Liner Acceptance Tests</p> <ol style="list-style-type: none">1. Establish inert atmosphere2. Receive 4 fueled liners from Cell 13. Leak test 4 liners4. Assay 4 liners on calorimeter5. Decontaminate 4 liners6. Puncture vent plugs7. Verify venting8. Check contamination9. Transfer vented liners to Cell 310. Repeat D.1 - D.9 six times
Cell 3	<p>D. Capsule Fueling</p> <ol style="list-style-type: none">1. Receive 2 preassembled test capsules, 4 capsule bodies with caps from service area2. Establish inert atmosphere3. Receive 4 fueled, vented liners from Cell 24. Load and cap 4 capsules5. Weld precycle test capsule6. Weld 4 fueled capsules7. Weld postcycle test capsule8. Apply flame-spray coating to 2 test pieces and 4 capsules9. Transfer 2 test pieces to inspection area10. Transfer 4 capsules to Cell 411. Repeat D.1 - D.10 six times

Cell or Area	Operation
Cell 4	<p>E. Capsule Acceptance Tests and HSM Assembly</p> <ol style="list-style-type: none"> 1. Insert HSM subassemblies from service area 2. Establish inert atmosphere 3. Receive 4 fueled capsules from Cell 3 4. Check capsule dimensions (4) 5. Verify capsule venting 6. Check capsule contamination 7. Assemble 2 HSM's 8. Transfer 2 HSM's to Cell 5 9. Repeat E.1 - E.8 six times
Cell 5	<p>F. HSM Acceptance Steps</p> <ol style="list-style-type: none"> 1. Establish inert atmosphere 2. Receive 2 HSM's from Cell 4 3. Test HSM's <ol style="list-style-type: none"> a. Calorimetry b. Radiography c. Dimensions 4. Store 2 HSM's in controlled storage 5. Repeat F.1 - F.4 six times
Inspection Area	<p>G. Sample Inspection</p> <ol style="list-style-type: none"> 1. Section 4 test pieces 2. Prepare 8 sample mounts 3. Microscopically inspect 8 samples 4. Develop and read radiographic films 5. Repeat G.1 - G.4 six times
Cell 5	<p>H. Generator Loading</p> <ol style="list-style-type: none"> 1. Prepare generator for fueling 2. Insert generator into Cell 5 3. Establish argon atmosphere 4. Remove 14 HSM's from storage, make final inspection 5. Load 14 HSM's into generator 6. Seal and test generator 7. Remove generator and prepare for shipment

OAK RIDGE NATIONAL LABORATORY

OPERATED BY

UNION CARBIDE CORPORATION

NUCLEAR DIVISION

POST OFFICE BOX X

OAK RIDGE, TENNESSEE 37830

September 27, 1973

Mr. W. E. Osmeyer
Energy Systems Division
Teledyne Isotopes, Inc.
110 W. Timonium Road
Timonium, MD 21093

Dear Bill:

We have made the estimates on the cost of producing platinum 3008 material on a production level for the Teledyne Isotopes ERTG unit. As it turns out, the material required for 10 ERTG units is about "one ingot's worth," i.e., this would be the batch size for the operation. The cost estimates given below are for 10 units. The total cost of 20 units would be exactly double. The material costs are based on current market prices of platinum of \$150 per troy ounce and of rhodium of \$220 per troy ounce. The cost per ERTG unit will be \$10,700. This number includes labor for fabrication of the material and forming the capsule parts and the cost of the material including recovery. It does not include the cost of final machining of the capsule parts.

Please see the attached breakdown of the cost estimate for details. Also note in the breakdown that \$85,000 worth of materials are recoverable and up to an estimated 10% of the materials are assumed lost in the fabrication, rolling, forming, and recovery processes. The \$85,000 would have to be made available initially for purchase of materials. It would be returned as the material is recovered. Also note that these costs are representative of costs to the government in a government-owned facility such as ORNL. They are estimated on the basis of operating costs including required support and administrative factors but not including added factors for depreciation, insurance, or profit. The facility is assumed to be a part of a larger facility or complex offering all general support services. Specifically, costs are based on current ORNL operating experience and services. No development costs are included. It is assumed that the operational plan describes a routine, qualified series of operations producing multiple identical units similar to but on a larger scale than that procedure which we now employ.

Mr. W. E. Osmeier

2

September 27, 1973

If you have additional questions concerning the estimate, please call me.

Very truly yours,

Karl W. Haff
Isotopes Development Center

KWH:mms

Attachment

cc: R. T. Carpenter, AEC-SNS
A. P. Litman, AEC-SNS
E. Lamb
C. L. Ottinger
R. G. Donnelly
A. C. Schaffhauser
G. M. Adamson, Jr.

Cost Estimate for Producing Platinum 3008 Encapsulation
Material for Teledyne Isotopes, Inc., ERTG

Labor and overhead ^a		\$ 40,000
Material ^b		
Initial material purchase	\$131,000	
Recoverable material value	85,000	
Net cost of material	<u>46,000</u>	
Labor and overhead for recovery	6,000	
Net cost of material and recovery	\$52,000	52,000
Piece-forming costs ^c		<u>15,000</u>
Total cost for 10 units ^d		<u>\$107,000</u>
Cost per unit		\$10,700

^aIncludes NDT of sheet material.

^bBased on current market prices: platinum - \$150/troy ounce
rhodium - \$220/troy ounce

Also assumes 25% of materials end up as fabricated parts,
65% is recoverable, and up to 10% is lost in processing and
fabrication.

^cIncludes only simple dye penetrant inspection.

^dDoes not include final machining of parts.

OAK RIDGE NATIONAL LABORATORY

OPERATED BY
UNION CARBIDE CORPORATION
NUCLEAR DIVISION

POST OFFICE BOX X
OAK RIDGE, TENNESSEE 37830

October 11, 1973

Mr. W. E. Osmeier
ERG Program Manager
Energy Systems Division
Teledyne-Isotopes, Inc.
110 W. Timonium Road
Timonium, MD 21093

Dear Bill:

Attached are descriptions, schedules, and cost estimates of the proposed ORNL development programs in support of the ERG program. Costs are presented on a fiscal year basis. In preparing these projected cost summaries and schedules, the following basic assumptions were made:

1. There would be two follow-on contractors through the development phase — one to develop a static (thermoelectric) system and one to develop a dynamic (organic Rankine or mini-Brayton) system.
2. There would be two different source configurations, one for each of these two systems.
3. The development schedule was made to conform generally with the guidelines in R. T. Carpenter's letter of guidance. Schedules can be considered flexible to conform to your proposed development schedule and planning. However, since two contractors are being considered in the ORNL plans as being assisted on the same schedules, any significant alteration of schedule could result in a higher cost. This would result from the fact that administrative, services, and overhead costs would be stretched out over longer periods of time if a serious mismatch in development schedules between the contractors existed. For this reason, we emphasize that ORNL must be advised of any mismatch in our schedule with yours so that costs may be reestimated.
4. The items covered in these estimates and schedules are specific to the ERG program and do not include items which are anticipated to be carried in our base line curium fuels development program. Some of the items of particular interest to contractors which are carried in the base line program are: all compatibility work with the curium fuels including the large ERG compatibility mockup couples, impact testing of curium fuels, and fuels property data.

October 11, 1973

5. The prototype source test described is independent of the comments made in Item 3. It is assumed specific to your unit and is not "piggy-backed" with any other contractor. Should you desire rescheduling, we request only that you notify us.
6. The costs and schedules are estimated on the basis of ORNL experience in similar programs and are based on current, FY 1974, operating costs. The costs are representative of costs to the government in a government-owned facility, specifically ORNL. They include required support and administrative factors but do not include added factors for depreciation, insurance, or profit.

Please call me if you have comments or questions on the attached material.

Very truly yours,

Karl W. Haff
Isotopes Development Center

KWH:mns

Attachments

cc: R. T. Carpenter, AEC-SNS
A. P. Litman, AEC-SNS
V. Cook
R. G. Donnelly
J. R. DiStefano
E. Lamb
A. J. Moorhead
C. L. Ottinger
A. C. Schaffhauser
T. A. Butler

CONTRACTOR LIAISON

Scope

ORNL will provide personnel to perform liaison with contractors in developing specifications and design reviews for loading, handling, and fabrication of heat sources to be used in the specific contractor system designs. Information on developments and progress in the ORNL programs will be coordinated. It is anticipated that periodic meetings will be held at least quarterly either at ORNL or the contractor site to review progress being made in both ORNL and contractor programs.

It is anticipated that this program will extend to and through FY 1980. General description of the program for each FY are as described above. Therefore no breakdown by FY is included.

DEVELOPMENT OF COATING- AND COATING-INSPECTION PROCEDURES

Scope

This task includes the development of procedures for the application of a thin coating to the outside of the strength member of the capsule, and for the subsequent destructive and nondestructive examination of the coating to determine its integrity. Our experience in this field has shown that (depending on the combination of coating and substrate) the development of such procedures can require a considerable amount of work. For example even the preparation of a coated sample for metallographic examination sometimes has required the development of special techniques for cutting and mounting to insure that the coating is not damaged during these operations. Naturally the likelihood of having to deposit and inspect the coating in a hot cell significantly increases the complexity of this operation. The expected accomplishments for this task, broken down by fiscal year, are given below.

FY 1975

Our first efforts would be in the design and fabrication of a fixture to hold preheat test coupons during coating. We would develop optimum techniques for surface preparation and determine the values of application variables (such as powder feed rate and gas flow rates) necessary to produce a tightly-adherent coating. Coating examination techniques would be developed in conjunction with application techniques. We anticipate that destructive techniques will be developed in a shorter time and will therefore be used almost exclusively during the first quarter of the fiscal year for characterization of the coating. The nondestructive examination techniques (probably eddy current and ultrasound) will require a longer lead time but will be utilized more later in the year. By the end of the fiscal year we would expect to have developed our preliminary application and inspection procedures.

FY 1976

Our main accomplishment during this year will be transfer of our coating technology to the hot cell. This will require additional equipment procurement, design, and fabrication and is expected to be a relatively difficult task. We will qualify our procedures in-cell and begin the coating of test capsules.

NONDESTRUCTIVE TEST DEVELOPMENT

Scope

This task is directed toward the development of new or improved non-destructive examination techniques that are required to assure the necessary quality of materials, components, and assembled capsules. The test methods will initially include ultrasonic, eddy-current, and other potential NDT methods for specific problems (i.e., radiography and/or penetrant examinations of certain welds or materials). The developmental effects include: selection and modification of existing techniques; establishment of reference standards; determination of technique sensitivity, reproducibility, and other parameters of performance; and the development of design criteria and hardware for both laboratory and remote inspection systems. For each method, changes in materials, thicknesses, and configurations will affect details of the examination techniques and/or equipment development.

Expected Results in FY 1975

Feasibility studies on the different materials and the capsule design to establish inspection methods, sensitivities, and reference standards will be made. Components to be used in fabrication studies will be inspected and documented to in-house-generated quality assurance requirements. Particular attention will be given to prototype procedures and equipment development for seal or closure weld inspections. These procedures along with destructive testing will be used to help establish welding parameters.

Expected Results in FY 1976

The development and use prototype inspection techniques for correlation with destructive and welding studies will be continued. This will allow establishment of final procedures and remote inspection equipment as well as the evaluation of capsules to be fueled. Reference standards will be developed and appropriate inspection specifications drafted.

DEVELOPMENT OF WELDING PROCEDURES

Scope

This task covers the development of welding procedures for joining capsules and includes work on both the liner and strength member for the capsule. In addition, a procedure for attaching a vent to the capsules must be developed. Although there is some degree of difficulty in anticipating the major problem areas which must be overcome in carrying out this task, there is one factor which is definitely known at this time which will have great influence on all phases of this task - the relatively high temperatures produced in the capsules by the fuel. It is roughly estimated that this temperature will be in the 400 to 500°C range. It will be necessary to simulate this thermal behavior in essentially all of our work from the initial development of welding parameters, to the making of welds on test coupons for mechanical property testing, and finally in all prototype capsule welds. This thermal requirement will obviously increase the times needed for all phases of this task and will influence the design of the various welding fixtures. In addition, our efforts will be constrained by the realization that all procedures must eventually be carried out in the hot cells. We would expect our accomplishments for the two fiscal years (FY 1975 and FY 1976) to be as below:

FY 1975

During the first two or three quarters of this year we would carry out weldability studies on the capsule materials. We would want to determine the effect of the procedural variables (such as pre-weld heat treatment, cleaning techniques, and welding process and parameters) on the weldability and mechanical properties (such as bend ductility and tensile strength) of the capsule materials. For example, we will compare the electron beam and gas tungsten-arc process to see if either has definite advantages over the other for a given material with respect to weldability and/or mechanical properties (including aging phenomena). Preliminary welding parameters would be developed at this time for the material thicknesses called for in the design.

During the latter part of this year we expect to design and build fixturing for holding the various components during welding, and to begin the development of procedures for welding full-size parts with geometries (including restraint) as close as possible to the actual parts. We would be acquiring the necessary data on weld shrinkage and the effect it has on dimensional tolerances. Characterization of the welds would be continued during this period.

FY 1976

The first quarter of this year we would refine both our welding procedures and fixturing, aiming toward a transfer of both to in-cell work. We would be welding on capsules as close to final configuration as possible and would use fuel simulants to mock-up the necessary restraint and cleaning problems. The acquisition of dimensional data will continue. We will devote the last three quarters of the year to qualifying our procedures in-cell, making final fixturing design changes and to the fabrication of the capsules required for safety testing purposes.

FABRICATION DEVELOPMENT

Scope

To provide the required quantities of Pt-3008 material for fabrication of ERG source capsules the small scale existing fabrication techniques must be scaled up to economical operating range. This task is intended to investigate that scale up. This task must be started early to have the required amounts of material for other testing and development tasks.

Expected accomplishments by fiscal year are as given below:

FY 1974

Scaleup of melting and fabrication processes for the Pt-3008 will be initiated. Based on current research in progress, it may be necessary to electron-beam melt all starting materials and vacuum arc melt the final ingot. A 30- to 40-lb ingot will be produced by the melting method selected. A hot extrusion process for primary breakdown of the ingot to sheet bar will be developed. Homogeneity of composition and trace impurities will be determined by extensive chemical analysis and testing.

FY 1975

Sheet rolling schedules for optimum formability will be determined. Capsule forming processes based on deep drawing and hydroforming will be developed. Selection of a forming process will be based on quality, dimensional tolerances, capsule yield, mechanical properties, and cost of formed parts. The recrystallization and grain growth behavior of formed parts will also be determined. Complete material specifications and fabrication procedures will be written.

PHYSICAL METALLURGY SUPPORT

Scope

This task provides a broad technology evaluation of materials for use in isotopic heat sources for advanced space power applications. Specifically, the effects of trace contaminants on the structural integrity of capsule component materials will be determined.

Expected Results in FY 1975-FY 1976

Long-term aging stability and/or compatibility of these materials with oxygen and/or graphite will be determined. The mechanical properties of candidate alloys will be measured under or after exposure to simulated heat source conditions to determine if environmental reactions or alloy instabilities lead to degradation such as embrittlement or loss in strength.

SHIELDING DESIGN STUDIES

Scope

The contractor system and satellite shield will be designed utilizing programs developed for use in the SNAP-10 reactor program. The program will design shields for minimum weight for the desired dose. The neutron and gamma radiation spectra will be measured for the production grade fuel and this data will be used for the final shield design. Assistance will be provided to contractors in their work on ground handling shielding requirements and to fabrication facility designers for shielding required for the fabrication facility.

Expected accomplishments by fiscal year are as given below:

FY 1974

A cursory look at the shielding required for the conceptual source design will be performed. This calculation will be made to determine a general shielding configuration and requirements.

FY 1975

A detailed shielding analysis will be made for the source configuration and satellite using existing data.

FY 1976

A measurement will be made of the neutron and gamma radiation spectra and these data utilized to calculate the detailed shield configuration. Primary effort will be shield integration into the satellite design.

VENT EVALUATION

Scope

In cooperation with systems source designers, venting concepts will be examined with regard to their application to use with curium fuels. An experimental program using active curium fuel, which will augment the systems designer's tests and development program with inactive materials, will be performed on contractor-furnished vents. Tests will be performed at temperature to determine plugging, compatibility, and helium flow characteristics under use conditions and anticipated accident conditions.

Expected accomplishments by fiscal year are as given below.

FY 1974

In this year it is anticipated that an experimental plan will be designed and evaluated in which the contractor-designed vent concept will be incorporated into a test device.

FY 1975

During this fiscal year the vent test device will be fabricated and curium sources will be fabricated, and the devices will be experimentally tested under the stated conditions of use and anticipated accident conditions.

FY 1976

During FY 1976 tests begun in the latter part of FY 1975 will be completed and examined. A final report will be written.

SOURCE CRITICALITY STUDIES

Scope

The criticality implications of the higher ^{245}Cm isotopic content of power reactor curium products (7.16% vs 0.729% in SRL material) need to be investigated. While it is true cursory examination of the source configuration does not indicate that a problem exists, it is believed that a detailed calculational examination is called for. This task is intended to provide those calculations.

Expected accomplishments by fiscal year are as given below:

FY 1974

A scanning type calculation using existing cross section data will be performed. This is intended to confirm that no serious problem of criticality exists.

FY 1975

Detailed calculation, using "worst case" condition, will be made for the source design configuration. Verification of the "worst case" condition will be made by examining various conditions of reflection, geometry, and moderation. During this time it is anticipated that improved cross section data on curium isotopes will become available from other programs.

FY 1976

Final type calculations will be made on the "worst case" situation using improved cross section data.

FUEL SIMULANTS

Scope

In performing the series of safety tests, i.e. fire, impact, etc., it is required, from an economical standpoint, that preliminary tests be conducted using a relatively inexpensive fuel simulant in place of the relatively expensive curium fuels. This task is intended to examine potential fuel simulants that will closely approximate the physical characteristics of curium fuel materials and to provide an acceptable fuel simulant for use in the safety testing program.

Expected accomplishments by fiscal year are as given below:

FY 1974

Literature will be searched to establish potential candidates as acceptable fuel simulants for curium fuels. It is anticipated that the materials can be narrowed down to four or less in the period.

FY 1975

During this fiscal year pellets of the candidate materials will be fabricated and a number of them tested in the fuel impact gun facility to compare their fines production similarity to the curium fuel form. (Impact testing of curium fuel will be performed in the base line curium development program). It is expected that one of the potential simulants will be selected as the simulant for use in the safety tests.

FY 1976

During FY 1976 additional tests will be performed to determine effects of density and other parameters on the suitability of the selected simulant.

LOADING AND HANDLING PROCEDURES, TOOLS AND EQUIPMENT

Scope

Tools, equipment, and procedures for loading and handling the ERG source during its fabrication, loading with fuel, and subsequent handling must be developed for in-cell use. This task shall include the development and fabrication of these items to include cooling devices, calorimeters, tools for handling, and loading.

Expected accomplishments by fiscal year are given below:

FY 1975

Basic procedures for loading fuel into the source and in-cell handling will be developed. Design of handling and loading tools, cooling devices, storage containers, etc., will be accomplished. Fabrication of some items, not of a capital expenditure classification, needed in other tasks will begin.

FY 1976 - FY 1977

Fabrication of needed items will continue.

PROTOTYPE TEST

Scope

This task includes the fabrication and testing of a fueled full-up prototype ERG unit. The task includes the fueling and loading of the source, loading the source into the ERG unit, running approximately a one year operational test on the unit, and the destructive examination of the source and recovery of the fuel.

Expected accomplishments during each of the fiscal years are as follows:

FY 1976

The experiment will be designed during FY 1976. Design will include the monitoring equipment required to monitor the electrical output and testing to be accomplished during the testing phase.

FY 1977

During the first two quarters of FY 1977 the source will be fabricated and loaded into the ERG system and test assembly. During the last two quarters of the fiscal year the system would be placed on test.

FY 1978

The system will be on test during the first two quarters of FY 1978. During this time the system would be monitored for electrical output, temperatures, and other pertinent information.

The system would be disassembled during the last two quarters of FY 1978 and the heat source destructivity examined. The electrical systems and generator would be returned to the contractor for examination.

FY 1979

Completion of the examination of the source will be accomplished and a final report will be written.

FLIGHT SAFETY TESTS

General Comments

The ORNL involvement in physically performing flight safety testing is not yet clearly defined since the AEC has established equipment and facilities at other sites for essentially all of these tests. It is not anticipated that these facilities will be duplicated at ORNL. However, it is anticipated that those tests involving fueled units will be performed at ORNL since other sites do not have facilities for handling curium fuels. Contractors have been asked to define those areas in which they expect fueled tests to be performed. Oak Ridge National Laboratory will then provide estimates on performing those specific tests.

The specific tests and/or services requested by your organization to date are discussed below:

Vibration Test - FY 1978

The ERG unit will be subjected to vibration testing over the range of ~5 to 2000 cycles per second utilizing alpha ~2500 force pound shaker table so that forces up to 10 g can be applied to the unit. The force table will be installed in a hot cell facility with monitoring and control equipment located outside.

Capsule Fabrication for Safety Testing - FY 1976-FY 1977

Fifty capsulettes assumed to be loaded with a fuel simulant will be fabricated and delivered to the contractor for testing during these two fiscal years.

ORNL DEVELOPMENT PROGRAM IN SUPPORT OF TELEDYNE
ISOTOPES ERG PROGRAM - OPERATING
COST BREAKDOWN BY FISCAL YEAR

<u>Task</u>	<u>Cost (Thousands of Dollars)</u>						
	<u>FY 74</u>	<u>FY 75</u>	<u>FY 76</u>	<u>FY 77</u>	<u>FY 78</u>	<u>FY 79</u>	<u>FY 80</u>
* Contractor Liaison	5	13	13	12	12	12	12
* Coating Procedures	-	52	92	-	-	-	-
* Non destructive Test	6	86	106	26	-	-	-
* Welding Procedures ¹	-	116	135	15	-	-	-
Fabrication Development	80	160	-	-	-	-	-
* Physical Metallurgy Support	-	20	20	10	-	-	-
* Shielding Design Studies	5	15	30	-	-	-	-
* Vent Evaluation	3	20	8	-	-	-	-
* Source Criticality Studies	2	6	6	-	-	-	-
* Fuel Simulants	3	10	5	-	-	-	-
* Loading and Handling Procedures							
Tools and Equipment	-	33	18	15	-	-	-
Prototype Test ²	-	-	50	230	120	30	-
Flight Safety Tests							
Vibration Test	-	-	-	-	30	-	-
Capsule Fabrication ³			80	40			
Summary	<u>104</u>	<u>531</u>	<u>563</u>	<u>348</u>	<u>162</u>	<u>42</u>	<u>12</u>

¹Includes special materials for weld development.

²Does not include the cost of the fuel.

³Includes material cost for 50 units.

ORNL DEVELOPMENT PROGRAM IN SUPPORT OF TELEDYNE
ISOTOPES ERG PROGRAM - CAPITAL EQUIPMENT
COST BREAKDOWN BY FISCAL YEAR

<u>Task</u>	<u>Cost (Thousands of Dollars)</u>					
	<u>FY 74</u>	<u>FY 75</u>	<u>FY 76</u>	<u>FY 77</u>	<u>FY 78</u>	<u>FY 79</u>
Coating Procedure	-	50	50			
Nondestructive Test	-	80	120	40		
Welding Procedures	-	40	60	20	-	-
Fabrication Development	-	220	-	-	-	-
Physical Metallurgy Support	20	-	-	-	-	-
Vent Evaluation	-	30	20	-	-	-
Loading and Handling Procedures Tools, and Equipment			60			
Prototype Test			100	50	50	
Vibration Test				75		
Miscellaneous	10	50	50	50	50	50
	<u>10</u>	<u>50</u>	<u>50</u>	<u>50</u>	<u>50</u>	<u>50</u>
Summary	30	470	460	235		

2. Dynatherm Corporation Statements of Work and Cost

DTM-73-14

ECONOMIC RTG HEAT PIPE STUDY
DEVELOPMENT PLAN

September 13, 1973

Prepared under Purchase Order B-66347

for

Teledyne Isotopes, Inc.
Timonium, Maryland

by

Dynatherm Corporation
Cockeysville, Maryland

A-30

SECTION I

INTRODUCTION

This Development Plan defines the effort required for development and production of heat pipes for Teledyne Isotopes' proposed Economic RTG. The plan is based on the Reference Design presented by Isotopes at the Mid-Term Status Review on July 25, 1973. It is recognized that this particular reference design may be subject to future changes. Accordingly, the required heat pipe development effort may also have to be adjusted to reflect those potential changes.

The following sections present a task-by-task description of the required effort. In some instances, the technical discussion covers both low and high temperature heat pipes within the same task. These efforts are clearly separated, however, in the presentations of schedules and projected cost, which are given in Section 3 of this Development Plan.

SECTION 2
PROGRAM TASKS

The development program will be performed in four phases:

- Phase I - Configuration Definition
- Phase II - Heat Pipe Development
- Phase III - Detailed Design and Qualification
- Phase IV - Fabrication, Testing and Delivery of
 Prototype and Flight Hardware

A detailed discussion of the required effort for each phase and task and a Statement of Work is given below.

Phase I - Configuration Definition

A preliminary definition of the proposed heat pipes for the ERTG has been made during the current ERTG Heat Pipe Study. The reference design which evolved from that study utilizes two (2) types of low temperature (Cu-H₂O) heat pipes to isothermalize the radiator and a set of high temperature (liquid metal) heat pipes to control the heat rejection path. Details of the heat pipe geometries, performance specifications, interfaces with radiator and fuel block, and qualification requirements remain to be established. Also, the final trade-off between generators with and without thermal control has not been completed. The objective of the first phase of the development program is to finalize the definition and specification of the heat pipes.

Task I-1 - Evaluation of Reference Design and Trade-Off Analysis

Statement of Work

Dynatherm will provide assistance to Isotopes in the finalization of the number,

sizes, geometries, and interfacing of the low and high temperature heat pipes. The required heat pipe parameters will be established in terms of heat transport capability, heat transfer performance, assembly procedures, pressure retention, interfacing with the various generator components, and compatibility with processing procedures. A detailed performance analysis will be conducted along with a trade-off study which will consider weight, performance, complexity, cost, and technology status of each design. These data will be submitted to Teledyne Isotopes to factor into optimization of the reference design.

Task I-2 - Preparation of Heat Pipe Specifications

Statement of Work

Technical support will be provided to Isotopes in the generation of the procurement specification for the heat pipes for the ERTG. The specifications will define the required performance characteristics, physical geometries, operating and nonoperating environmental conditions, reliability requirements, and the quality assurance provisions.

Phase II - Heat Pipe Development

During this phase the existing technology of low and high temperature heat pipes will be expanded to meet the requirements of the ERTG application.

Task II-1 - Extension of Cu-H₂O Heat Pipe Technology to Higher Temperatures

In the area of low temperature Cu-H₂O heat pipes the basic technology has been already developed under the HPG program. But further effort is required to extend the operational temperature range from the current 150°C to approximately 200°C.

The internal surfaces of the HPG heat pipes were treated with a solution of Ebonol "C" to enhance the wetting of these surfaces by the water working fluid. This treatment produces a surface that is jet black, chemically stable, very adherent, and according to

the compound manufacturer will withstand temperatures to about 200^oC. At higher temperatures, slow oxidation of the base copper occurs underneath the coating which may cause its destruction after prolonged exposure. Other surface treatments have been proposed and tested which promise a somewhat higher temperature capability. In addition to long-term operation, the heat pipes will probably be subjected during installation to short-term temperature cycles up to 300^oC. Task I of the development phase will be aimed at expanding the temperature range of Cu-H₂O heat pipes to at least 200^oC and to permit short-time processing cycles up to 300^oC.

Statement of Work

- (1) Obtain and review all available information and data on various passivation and surface wetting processes applicable to copper-water heat pipes such as steam oxidation, high concentration oxygen oxidation, super cleaning, and others.
- (2) Select the five (5) most suitable techniques (Ebonol treatment plus four others) and fabricate 10 heat pipes of the basic HPG reference design for each of the selected processes.
- (3) Performance test two heat pipes from each group to assess the wetting characteristics of each process.
- (4) Subject three heat pipes from each group to a simulated soldering cycle and evaluate the effects of this exposure.
- (5) Place at least five heat pipes from each group on a development life test consisting of extended operation at different temperatures within the range of potential RTG application.

- (6) Evaluate the test results to determine the process which will provide the best expected operational life for the ERTG.

Task II-2 - Development of Axially-Grooved Cu-H₂O Heat Pipes

The reference design of the ERTG employs Cu-H₂O heat pipes for longitudinal isothermalization of the radiator. These heat pipes will only be required if temperature control via VCHP's is used. Preliminary parametric studies have shown that the HPG wick design will not be adequate to transport sufficient heat under these conditions. Instead, an axially-grooved copper heat pipe design was selected which has adequate heat transport capability for this application. Axially-grooved heat pipes have been used extensively in the past and have been flight qualified on several spacecraft. But all axially-grooved heat pipes that have been produced, to date, have been made of aluminum. Although the necessary technology for fabricating axially-grooved copper tubing is presently available, performance mapping of such a design will be required to substantiate its use in the ERTG heat pipes.

Currently, the most practical method of manufacturing the axially-grooved heat pipe tubes is by the cold forging process in which annealed predrawn tubing is passed over an internal mandrel which is machined with desired size and groove form. As the tube passes over the mandrel, external rotating hammers simultaneously reduce the outer diameter and force the raw material to flow over the internal mandrel to produce the desired groove form. Since this process relies on cold working, ductile materials such as copper and aluminum are used. Internally-grooved copper pipes for heat exchangers have been produced using this process; however, the internal grooves are not of the size and shape required for heat pipe operation. But, with some development effort, the desired size and shape can be produced.

During Task II-1 the technology of axially-grooved Cu-H₂O heat pipes for the ERTG application will be developed.

Statement of Work

- (1) Perform a detailed design analysis to define the optimum groove geometry with consideration given to the capability of existing fabrication techniques.
- (2) Generate procurement specifications and procure grooved copper tubing.
- (3) Fabricate and test at least five (5) heat pipes, each containing a different volumetric fluid charge.
- (4) Evaluate various processing techniques, including cleaning, outgassing, welding, and charging.
- (5) Place five (5) heat pipes, which have been processed in accordance with the selected technique, on continuing life test at different temperatures.

Task II-3 - Breadboarding of Low Temperature Heat Pipes

The reference ERTG design is based on two types of low temperature heat pipes -- slab-wick and axially-grooved Cu-H₂O heat pipes. The basic technology of the slab-wick was established during the HPG and other previous programs. The extension of the operational temperature range of Cu-H₂O heat pipes will be investigated during Task II-1. The development of axially-grooved Cu-H₂O heat pipes is the subject of the proposed Task II-2.

The purpose of this task is to fabricate and test breadboard heat pipes of both the slab and the axially-grooved designs which are representative of the heat transport requirement and geometry of the ERTG reference design. The end result of this effort will be a fully developed reference design of the required low temperature heat pipes. The

reference design parameters can then be incorporated into the procurement specifications.

Statement of Work

- (1) Fabricate at least four (4) heat pipes of the exact geometry which will be used in the ERTG design.
- (2) Perform a complete performance mapping including the effect of gravity, maximum and minimum temperature, and transient performance.
- (3) Establish optimum fabrication process, define leak tightness criteria, develop welding, charging, and processing techniques.
- (4) Evaluate, through testing, the compatibility of the selected design with ERTG installation and processing procedures.

Task II-4 - Basic High Temperature Heat Pipe Development

Although a large variety of liquid metal heat pipes have been built and tested in the past, their state-of-the-art is not as far advanced as that of their low temperature counterparts. Specifically, no high temperature liquid metal heat pipes have been qualified to date for space-flight application. Therefore, the data needed to verify heat transport capability, long-term stability and reliability will have to be generated.

Statement of Work

- (1) Design and fabricate four breadboard model liquid metal heat pipes (2 different wick designs; 2 different working fluids).
- (2) Performance test the heat pipes to obtain, at a minimum, the following data:
 - Axial heat transport capability.
 - Heat transfer coefficients at evaporator and condenser.
 - Tilt performance in a gravity field.
 - Cold start-up and transient behavior.
 - Performance at various temperatures.

- (3) Perform a study (backed up by tests as required) to determine the best processing technique which will have the highest probability of meeting long-term performance requirements.
- (4) Based on the results in the preceding steps, select two (2) wick designs or wick/fluid combinations and fabricate eight (8) additional heat pipes. Each of these heat pipes will first be performance tested to verify heat transport capability and then will be placed on an accelerated development life test. At intervals of two, six, and twelve months, two heat pipes (one of each type) will be removed from test and the internal surfaces examined and evaluated for possible deterioration. The remaining two heat pipes will be kept indefinitely on life test.
- (5) Evaluate the results of all tests and select the optimum wick/fluid combination.

Task II-5 - Development of High Temperature, Variable Conductance Heat Pipes

This task will follow the basic development of high temperature liquid-metal heat pipes during Task II-4. The purpose of the VCHP is to provide an auxiliary heat rejection path at the beginning of life of the isotope while, at the same time, maintaining the heat flux through the thermoelectric converter nearly constant. The development of a VCHP requires the verification of the control performance under typical heat load and environmental conditions. Furthermore, because of the strong influence of the environment, the VCHP must not only be tested as an individual component but also when installed in a mock-up of a representative section of the ERTG.

Statement of Work

- (1) Perform a detailed thermal analysis of the control requirements of the VCHP.
Define heat fluxes and environmental temperatures for all parts of the projected mission.

- (2) Fabricate five (5) VCHP's in accordance with the selected design and specifications.
- (3) Conduct parametric tests on three (3) of these heat pipes under various source, sink, and load conditions. Determine basic control performance from these tests.
- (4) Install two (2) of the heat pipes in a mock-up of a representative section of the fuel block and radiator and subject the assembly to an accelerated, but simulated, ERTG mission.

Phase III - Heat Pipe Design and Qualification

During this phase, the detailed design for both low and high temperature heat pipes will be generated, procedures and test plans formulated, and a qualification test program conducted.

Task III-1 - Final Design Analysis

Statement of Work

Design drawings and supporting analysis will be generated for the low and high temperature heat pipes. This will include a complete set of drawings suitable for release to manufacturing for fabrication and assembly of all parts of these heat pipes. The supporting analysis will cover thermal performance lifetime prediction, stress analysis, and (in the case of VCHP's) the thermal control characteristics.

Task III-2 - Manufacturing Processes, Tooling and Fixtures

Statement of Work

The fabrication, assembly, welding, cleaning, surface treatment, and charging procedures for each type of heat pipe will be developed. This effort will include the

processing of representative samples in order to qualify critical steps of the manufacturing process. A quality assurance log will be generated with check-off sheets for each step in the entire fabrication and testing process. In addition, all necessary tooling and fixtures will be designed and fabricated under this task.

Task III-3 - Procedures and Test Plans

During this task all procedures for fabricating and assembling the low and high temperature heat pipes will be finalized and released. Also, the plans and procedures for qualification and acceptance testing will be prepared.

Part of the qualification program will be extensive life testing of both the low and the high temperature heat pipes. Some life tests were included in the development effort described in Phase II. Those life tests are of a developmental nature; i.e., their purpose is to evaluate optimum processing techniques and designs. The life tests included as part of the qualification program are of a different nature. Heat pipes of the selected final design will be life tested to establish confidence in their long-term performance.

Statement of Work

Develop procedures and test plans to accomplish the following qualification and acceptance tests:

- (1) Perform qualification tests on at least ten individual low temperature heat pipes of each required design.
- (2) Conduct low temperature heat pipe life tests on two groups of heat pipes (12 pipes per group) of the two reference wick designs. The tests will be conducted over a period of five years to verify their operational life. At intervals of six months, one heat pipe from each group will be removed from test (until a total of 10 have been removed), the internal surfaces examined, and an analysis of the working

fluid performed.

- (3) Perform qualification tests on at least four high temperature liquid metal VCHP's.
- (4) Conduct high temperature VCHP life tests on 15 VCHP's for a period of five years with the input power and source temperature periodically reduced to simulate the isotope fuel decay. At intervals of six months, one VCHP will be removed from test and the internal surfaces examined for possible deterioration.
- (5) Conduct qualification tests with a mock-up of a representative section of an ERTG to verify that both the low temperature heat pipes and the VCHP's will function and perform as required under simulated environmental and operational conditions.
- (6) Perform acceptance tests on each deliverable low temperature heat pipe. These tests to consist of, at a minimum, a thermal performance test, gas check, leak test, X-ray inspection, and weight determination.
- (7) Conduct acceptance tests on each deliverable high temperature VCHP. In addition to the tests performed on the low temperature heat pipes, the VCHP's will also be acceptance tested for their control characteristics.

Task III-4 - Qualification of Low Temperature Heat Pipes

Statement of Work

During this task, the heat pipes required for the qualification program will be fabricated and tested in accordance with the test plans delineated under Items 1 and 2 of Task III-3. Also during this task, Teledyne Isotopes will furnish a representative section of an ERTG consisting of one primary radiator fin and part of the heat source block. (The latter is only required if temperature control with VCHP's is used.) Dynatherm will fabricate the required number (approximately 25) of heat pipes and deliver them to Teledyne Isotopes for installation in this mock-up ERTG section. After installation, the unit will be shipped

to Dynatherm for qualification testing in accordance with Item 5 of Task III-3.

Task III-5 - Qualification Testing of High Temperature VCHP's

Statement of Work

During this task, the liquid metal heat pipes required for the qualification and life test program will be fabricated and tested in accordance with Items 3 and 4 of Task III-3. Liquid metal VCHP's will also be installed in the ERTG mock-up and tested in accordance with the test plan generated under Task III-3, Item 5.

Phase IV - Fabrication, Test, and Delivery of Prototype and Flight Hardware

Statement of Work

During this phase, complete generator sets of heat pipes will be fabricated in accordance with the procedures developed during Phase III. The current reference design calls for a total of 50 Cu-H₂O heat pipes and 4 liquid metal VCHP's per ERTG. Although the initial sets will be used by Isotopes in prototype or electrically heated generators, no distinction exists between the heat pipe sets for prototype and flight hardware.

SECTION 3

SCHEDULES AND COST ESTIMATES

This section presents the projected schedules and cost estimates for the development and production of heat pipes for the ERTG.

1. Schedules

Figure 1 gives the schedule for the low temperature radial-fin heat pipes. A program start on March 1, 1974 was assumed and a first delivery of a complete set of these pipes by October 1, 1975. Figure 2 gives the schedules for the low temperature axial-distributor pipes and the high temperature VCHP's. The same program start of March 1, 1974 was used. But it was assumed that the ERTG's launched during the first year will not utilize temperature control. Thus, the development schedules shown in Figure 2 have been extended by one (1) year. But it should be noted that the schedules could be compressed to make temperature control available for the first launch date.

2. Cost Estimates

Cost estimates for each of the described tasks are presented in Table I. The table contains three columns. The first one applies to the radial-fin pipes which are the only ones required if thermal control is not used. The second column gives the cost associated with the axial-distributor heat pipes. They will only be used in conjunction with the VCHP's. The third column represents the cost for the high temperature VCHP's.

The estimate for complete hardware sets (Phase IV) is based on the current reference design which contains 50 low temperature (36 + 14) and 4 high temperature heat pipes. Minor changes in this design should not perturb the development costs

PHASE/TASK	CY 1974	CY 1975	CY 1976	CY 1977
I. Configuration Definition				
1. Evaluation of Reference Design & Trade-Offs	△—△			
2. Heat Pipe Specifications	△—△			
II. Heat Pipe Development				
1. Cu-H ₂ O Heat Pipes for 175-200°C Operation	△—	-----△		
3. Breadboarding of Low Temperature Heat Pipes	△—△			
III. Heat Pipe Design and Qualification				
1. Detailed Design and Analysis		△—△		
2. Manufacturing Procedures, Tooling, & Fixturing		△—△		
3. Test Plans and Procedures		△—△		
4. Qualifications of Low Temperature Heat Pipes		△-----	-----	-----
IV. Fabrication, Test, and Delivery				
1. Fabrication and Testing		△—△		
2. Delivery		△	△-----	-----

FIGURE 1
DEVELOPMENT AND FABRICATION SCHEDULE FOR
LOW TEMPERATURE RADIAL-FIN HEAT PIPES

PHASE/TASK	CY 1974	CY 1975	CY 1976	CY 1977
I. Configuration Definition				
1. Evaluation of Reference Design & Trade-Offs	△ — △			
2. Heat Pipe Specification		△ — △		
II. Heat Pipe Development				
2. Axially Grooved Cu-H ₂ O Heat Pipe Development	△ — △			
3. Breadboarding of Low Temperature Heat Pipes		△ — △		
4. High Temperature Heat Pipe Development	△ — △			
5. Variable Conductance Heat Pipe Development		△ — △		
III. Heat Pipe Design and Qualification				
1. Detailed Design and Analysis		△ — △		
2. Manufacturing Procedures, Tooling, & Fixtures		△ — △		
3. Test Plans and Procedures		△ — △		
4. Qualification of Low Temperature Heat Pipes		△ —	-----	
5. Qualification of High Temperature Heat Pipes		△ —	-----	
IV. Fabrication, Test, and Delivery				
1. Fabrication and Testing		△ — △		
2. Delivery			△ △ △ —	-----

FIGURE 2
DEVELOPMENT AND FABRICATION SCHEDULE FOR LOW TEMPERATURE
AXIAL-DISTRIBUTOR HEAT PIPES AND HIGH TEMPERATURE VCHP's

PHASE/TASK		Low Temperature Radial	Low Temperature Axial	High Temperature VCHP
PHASE I	I-1 : Evaluation of Reference Design & Trade-Off	7,700	--	11,500
	I-2 : Heat Pipe Specifications	1,900	--	3,800
PHASE II	II-1 : Cu-H ₂ O Heat Pipes for 175-200°C Operation	25,700	--	--
	II-2 : Axially Grooved Cu-H ₂ O Heat Pipe Dev.	--	8,000	--
	II-3 : Breadboarding of Low Temp. Heat Pipes	8,600	8,600	--
	II-4 : High Temperature Heat Pipe Development	--	--	33,000
	II-5 : Variable Conductance Heat Pipe Development	--	--	46,200
PHASE III	III-1 : Detailed Design and Analysis	4,300	1,400	11,500
	III-2 : Mfg. Procedures, Tooling and Fixturing	9,800	3,300	18,600
	III-3 : Test Plans and Procedures	2,900	1,000	5,700
	III-4 : Qualification of Low Temperature Heat Pipes	42,800	14,700	--
	III-5 : Qualification of High Temperature Heat Pipes	--	--	64,000
TOTAL DEVELOPMENT & QUALIFICATION COST		103,700	37,000	194,300
PHASE IV	1 - Generator Set	16,600	4,900	11,800
	10 - Generator Set	140,900	41,900	99,800
	20 - Generator Set	267,400	80,200	190,300

TABLE I
COST ESTIMATE FOR LOW AND HIGH TEMPERATURE HEAT PIPES

significantly. Changes in the number of heat pipes per generator would roughly be reflected proportionally in the cost of complete sets.

3. Thermoelectric Technology Support Cost, 3M Company, St. Paul, Minnesota

The following estimates were received from Mr. E. F. Hampl, Jr., on October 24, 1973.

1. AEC/SNS Technology Program - Current Contract AT(11-1)-2331

It is assumed that the TPM-217 technology program continue at a funding of approximately \$600,000/year in parallel with the ERTG program.

2. ERTG Program: Technology and/or Component Demonstration (Phase 2)

Basis of Estimate:

- a. A minimum 18-month program (longer if desired).
- b. Tests to be highly instrumented.
- c. Assume AEC Contract AT(11-1)-2331 continues at a pace of \$600,000/year to develop TPM-217 technology.

Cost Estimate:

a. TPM-217 couple technology	\$ 175,000
b. Test fixtures (material/shop costs)	
10 each 2-couple units	50,000
20 each 10-couple units	200,000
10 each 66-couple units	550,000
(6 x 11 couple array)	
c. Manpower for assembly of test devices	120,000
d. Test and analysis	<u>175,000</u>
	\$ 1,270,000
Capital equipment expenditures	\$ 250,000

Electrically Heated and Prototype RTG:

It is estimated that it will cost approximately \$750,000 to provide the necessary couple technology and auxiliary hardware for the initial test and qualification testing required under the ERTG program.

Production of Converters:

It is estimated that the all TPM-217 thermoelectric converters in quantities of 10 to 20 units can be supplied for an approximate cost of \$420/watt(el) for up to 400 watts at EOL of 5-year requirement. This cost does not include the radiator structure, heat source encapsulation, system integration, etc. Some expenditures for capital equipment may be necessary to augment the production requirement.

APPENDIX B
RELIABILITY PLAN

APPENDIX B
RELIABILITY PROGRAM PLAN

I. INTRODUCTION

This document constitutes the Reliability Program Plan for the Economic Radioisotope Thermoelectric Generator (ERTG) power supply system for the DOD/USAF SURVSAT Program. It delineates the tasks that are to be accomplished by Teledyne Isotopes and its subcontractors during the design, development, fabrication, test, and field operations of the Radioisotope Thermoelectric Generator (RTG), Electrically Heated Generator (ETG) and associated Aerospace Ground Equipment (AGE).

The plan is formulated using specification SNS-3, dated October 1971, titled "Reliability Program Requirements for AEC Space Nuclear Systems" as a basis. Here, the applicability of each task, identified and listed in the identical sequence shown in the specification, is indicated. For each task, a description of requirements and scope of the task is identified.

The plan is organized into three sections, in addition to the Introduction, with identity and contents as follows.

The Reliability Management section is related to the administration of the Reliability Program Plan. It involves monitoring of the tasks, determining their current status in regard to milestone time in the overall program, identifying and resolving problems, planning and reporting the results of the evaluation and analysis activities.

The Reliability Engineering section is related to the establishment of the system reliability goals and formulates criteria to be used in detail design and component test evaluation. The criteria provide for maximum utilization of test and design data

to assess attainment of the reliability goals. Detail analyses at the subsystem, component and part levels utilize the criteria established by the system analysis. These analyses form the basis for selection of components and the development of fabrication and test criteria.

The Testing and Evaluation section deals with the establishment of the applicability of a test to reliability and where applicable the defining of appropriate criteria as to sample size, test type, duration and test profile. It also relates to the establishment of a data bank, and evaluation of the reliability of the RTG, ETG, or components to the applicable mission goal.

Tasks to be accomplished during Phases II, III, IV, and V of the program are designated in the Reliability Program Plan Tasks Schedule, Table B-1.

The ERTG Reliability Plan presented herein defines the total Reliability effort without further need for cross reference to the AEC specification.

II. RELIABILITY MANAGEMENT

A. RELIABILITY PROGRAM (REF.: PARA. 2.1, SNS-3)

The ERTG Reliability Program, as defined by this plan, is formulated and will be implemented to assure that reliability is considered in the design, development, fabrication, and test of the ERTG Power Supply System. The program is scoped to provide in depth coverage of the RTG and ETG with coverage of the GSE limited to those areas which directly impact RTG/ETG performance or mission goals.

The major objectives of the program are:

- Define the scope of the reliability tasks to be performed and identify their place as an integral element of the overall design, development, fabrication, and test process.

TABLE B-1. RELIABILITY PROGRAM PLAN TASKS SCHEDULE.

- Provide planning and management control of the tasks, identify the method and frequency of reporting and perform reviews to verify the effectiveness of the program.
- Establish quantitative reliability apportionments and performance criteria to which component test design and RTG/ETG reliability performance may be assessed.
- Perform analyses to establish criteria and controls in design, fabrication, and test areas that will enhance the probability of attaining the reliability apportionments.
- Assess the reliability-performance of the RTG/ETG against the program apportionment through use of analytical and test data generated during the ERTG Program or from other programs.

B. ORGANIZATION (REF.: PARA. 2.2, SNS-3)

Figure B-1 presents the overall ERTG Program Organization with specific identification of the reliability function. The Reliability Lead Engineer reports to the Safety Evaluation and Reliability Engineer, who in turn reports to the ERTG Program Manager.

The Reliability Lead Engineer has the authority and resources to plan and manage the Reliability Program and ensure its effective execution.

C. PROGRAM PLAN (REF.: PARA. 2.3, SNS-3)

The ERTG Reliability Plan identifies the tasks to be implemented during the program. A brief description of requirements and scope of each task is presented along with the approach to be used in its implementation, the techniques or methods to be applied, and the manner for controlling and monitoring. The specific output, form of output, reporting frequency, and updating requirements are indicated, as applicable.

ECONOMIC RADIOISOTOPE THERMOELECTRIC GENERATOR

PROGRAM ORGANIZATION

* Reports to Manager, Power Systems Department

** Reports to Vice President and General Manager, ESD

CAB Corrective Action Board

CCB Change Control Board

MRB Materials Review Board (Fueling Operations)

AEC/Teledyne Isotopes Reliability Program Reviews of one (1) day duration, will be conducted at the milestones shown on Table B-1. These reviews will be held to evaluate the effectiveness of the Reliability Plan and to identify the need for changes which will increase its effectiveness.

The agenda for each review meeting will be coordinated with AEC/SNS in advance and will include as a minimum:

- Review of action items from prior meeting
- Review of accomplishment and results of tasks and subtasks
- Review of schedule status
- Identification of action items resulting from the review

The results of these reviews will be reported in the Top Summary or Technical Letter Report, as applicable.

Reliability Engineering will participate in other program type reviews on an "as required" basis. These reviews include preshipment, readiness, and test evaluation, which are identified in more detail elsewhere in this plan.

D. PROGRESS REPORTING (REF.: PARA. 2.4, SNS-3)

1. Formal Reporting

Written reports will be prepared by Reliability Engineering to document the results of the ERTG management, analysis, and assessment task activities. These reports will be prepared using Teledyne Isotopes standard formats. The type of reports, method of submittal, and frequency for reporting will be as follows.

a. Contract Reports

A Reliability Program Plan and a Reliability Analysis and Assessment Report will be prepared and updated for each major program phase. These two reports will be submitted and distributed in accordance with the ERTG Contractor Data Requirements List (CDRL).

b. Semi-Annual Progress Reports

Progress reports will be used for documenting the technical results of the reliability engineering and evaluation tasks. For each of these reports, the scope, approach or method, data sources, and results achieved will be indicated. A summary, conclusion or recommendation will be included, where applicable, for each reported task.

c. Technical Reports

Monthly letter reports will be used for documenting the technical status of the reliability program task activity. Pertinent conclusions and recommendations will be included in these reports.

d. Monthly Reports

Top Summary reports will be used to document the reliability management task activity. Task and milestone accomplishments, schedule status, and task/schedule problem areas will be identified.

2. Formal Reporting

Reporting between AEC and Energy Systems Division will be augmented by day-to-day informal reports, either verbal or written, on pertinent reliability matters on an "as occur" basis.

E. RELIABILITY TRAINING (REF.: PARA. 2.5, SNS-3)

Indoctrination of ERTG program personnel with reliability disciplines, techniques and procedures will be performed by Reliability Engineering on an "as needed" basis. The purpose of these indoctrination activities will be to increase the awareness of personnel in the importance of their contribution to the enhancement of the overall product reliability. Formal identification of such indoctrination activities is not planned.

A formal training program for reliability personnel is not planned, since personnel experienced in the reliability discipline are assigned to the program. Should training be necessary for some specific area, the personnel will be trained "on the job." Formal identification of such training activities is not planned.

F. SUPPLIER CONTROL (REF.: PARA. 2.6, SNS-3)

1. Suppliers Required to Utilize Reliability Programs

The ERTG Program, as currently envisioned, has two subcontractors upon which a reliability program will be imposed. They are 3M Company for design, development and test of thermoelectric elements/couples, and Dynatherm Corporation for design, test, and fabrication of heat pipes.

A subcontractor's program plan will be reviewed and approved by Teledyne Isotopes and included as part of the formal procurement agreements with the subcontractor. A copy of the subcontractor program plan will be submitted to AEC for information.

2. Supplier Not Required to Utilize Reliability Programs

Supplier procurement specifications will be prepared, as applicable, for parts, devices, and materials to define form, fit, and function and applicable environment, reliability, and test requirements. Reliability Engineering will identify the need for inclusion of reliability requirements and criteria in such specifications based on the criticality of the item in relation to performance requirements. Specific requirements will be generated using failure mode analyses, results of qualification tests, and application experience. Reliability Engineering will approve all such specifications to assure that reliability is adequately treated.

III. RELIABILITY ENGINEERING

A. DESIGN SPECIFICATIONS (REF.: PARA. 3.2, SNS-3)

1. Scope

Design specifications will be prepared by Systems Engineering for the RTG and ETG and may be prepared for other deliverable hardware end items. These specifications define the physical and functional requirements of the item, identify qualification and acceptance tests, show interface relation to other items, and depict delivery acceptance requirements.

2. Review and Audit

The review procedure described in the ERTG Product Definition Plan will be applied to design specifications to the extent specified therein. The design specification requirements will become part of the data package of applicable design reviews. Audit of the design specifications will be through the design review activity, systems engineering and reliability engineering reviews. No formal AEC review procedures are planned.

B. RELIABILITY PREDICTION (REF.: PARA. 3.3, SNS-3)

1. Block Diagram and Mathematical Model (BD/MM)

A system level BD/MM will be prepared for the following system configurations:

- RTG/Portable Monitor Package (PMP)/Load Bank
- RTG Spacecraft Loader
- ETG/PMP/Power Supply/Load Bank

The subsystem level BD/MM for the RTG and ETG will be prepared to the component level. For the AGE, the BD/MM will be prepared to that level where failures could impair the RTG/ETG performance. The failure mode, effects, and criticality analysis (FMECA) - Task 3 - will be the primary source for identifying the level to which these BD/MM will be prepared.

2. Allocations

Based on numerical reliability requirements or goals to be provided in the ERTG contract documents, allocations will be assigned to the system, subsystem, and component level based on engineering judgment and past experience of generator system manufacture, test, field use, and disassembly histories.

3. Preparation

A reliability-power prediction model and prediction for the RTG will be prepared and updated periodically. The prediction will be prepared for the RTG power supply system at the end-of-mission. No reliability prediction is planned for the ETG or AGE. The prediction will be prepared in close coordination with the failure mode, effects and criticality analysis and to a depth that will identify areas critical to reliability. All experience from other Teledyne Isotopes RTG programs will be utilized.

4. Critical Design Areas

Critical reliability design areas in the RTG/ETG/AGE will be identified by use of the FMECA. Studies will be made to evaluate design improvements, using redundancy, component/part substitutions and other circuit/equipment item changes to improve reliability. Elimination of single failure points and/or improving critical reliability design areas will be the primary purpose of this subtask.

5. Statistical Analysis

The prediction model for the RTG power supply system will be formulated by combining the probabilities associated with operational (catastrophic) and performance (non-catastrophic) failure classifications. The operational failure probabilities will take into account redundancies in the system. The performance probabilities will consider the power output variation characteristics for any point in time. The mathematical model for combining these two probabilities is given by the following equation:

$$P(GE) = P(OP) \times P(PM)$$

where:

$P(GE)$	=	Total RTG system reliability at any power
$P(OP)$	=	Operational reliability-probability that the RTG functions throughout the mission
$P(PM)$	=	Performance reliability-probability that the RTG power will equal or exceed the specified end-of-mission value

a. Power Variation

The power output variation will be computed by combining values of non-linearly related variables (e.g., helium release rate, generator leak rate, initial power, thermoelectric degradation rate, fuel inventory). A combination of Monte Carlo and analytic techniques will be used to sample input distributions randomly and to produce the probability density function (PDF) of RTG output power. For a given set of input parameters, corresponding to a specific time during the mission, the non-linear input functions are evaluated and the corresponding generator power is computed.

The output of the reliability prediction task will be a prediction model, functional/equipment block diagram, total reliability-power prediction at the end-of-mission, catastrophic failure probability, and power performance variation.

C. FAILURE MODE, EFFECTS AND CRITICALITY ANALYSIS

(REF.: PARA. 3.4, SNS-3)

Failure mode, effect and criticality analyses (FMECA) will be performed at system, subsystem, and component levels to identify critical design areas for ground operations. At the system level, the analysis will include the configurations:

- RTG/Portable Monitor Package (PMP)/Load Bank
- RTG/Spacecraft Loader
- ETG/Power Supply (PS)/PMP

After launch/mission, RTG/Spacecraft operation will be considered. These analyses will identify the type of failure which could occur in the ancillary AGE equipment which could result in failure of RTG/ETG to meet performance or mission objectives.

At the subsystem/component level, the analyses will include the RTG and ETG to that depth necessary to verify contract objectives. Subsystem elements PMP, PS, Load Bank, and RTG Loader analyses will be restricted to those functional areas identified in the system analysis as critical to RTG and ETG. The result of these analyses will be to identify single failure points critical to RTG/ETG operational reliability. Emphasis will be placed on elimination of single failure points from the system by use of redesign or redundancy. Where this is not practical, Failure Mode Analyses (FMA) will be performed at the part level to identify failure mechanisms and verify that the failure occurrence is extremely low. Tests will be proposed to support the FMA as applicable.

The results of the FMECA will also be used to establish the elements of the system and subsystem functional block diagrams, mathematical models, establish criteria for test programs, provide a basis for reliability trade-off studies, and identify critical design areas.

Failure effect categories will be classified as follows:

- Failure that will result in a catastrophic or imminent loss of RTG/ETG performance
- Failure that will result in a discrete step reduction in RTG/ETG performance to below specified requirements
- Failure that will result in a catastrophic loss or out of tolerance condition in some system, subsystem, or function without affecting RTG/ETG performance.

Reliability Engineering will establish the need for an FMECA. Systems Engineering, Design, and Materials groups will prepare or provide appropriate inputs for the analyses. Reliability Engineering will verify the adequacy of the analysis.

D. MAINTAINABILITY AND ELIMINATION OF HUMAN-INDUCED FAILURES (REF.: PARA. 3.5, SNS-3)

A formal maintainability program is not planned for the ERTG system pending system/subsystem availability requirements being specified in contract documents. The RTG and ETG are nonrepairable in the field. Since the total quantity of AGE, although repairable, is small and has a short scheduled operational usage, a formal program does not appear cost effective. Reliability will, however, consider maintainability and elimination of potential human induced failures during reviews of design specifications, manufacturing processes, and engineering drawings.

E. DESIGN REVIEWS (REF.: PARA. 3.6, SNS-3)

1. Teledyne Isotopes Reviews

Teledyne Isotopes will conduct four formal Design Reviews of the RTG/ETG and associated tests. These reviews are identified and scoped as follows:

a. Design Review No. 1

This design review will be accomplished subsequent to the completion of ERTG Phase II. The review is proposed to evaluate the results of the development tests:

- T/E modules performance
- Fuel capsule/heat shield
- Fabrication/test
- Heat pipe performance
- Thermopile seal

b. Design Review No. 2 (Review of Proof Design)

This design review will be accomplished on the design proposed for the ETG. The review will include ETG and associated AGE design.

c. Design Review No. 3

This design review will be accomplished on the design proposed for the first set of RTG's and associated AGE design.

d. Design Review No. 4 (Review of Final Design)

This design review will be accomplished on the design proposed for the first set of RTG's assigned as flight hardware and associated AGE design.

Teledyne Isotopes will conduct informal design reviews on an "as required" basis. The reviews will include appropriate technical disciplines so that all facets of the design are evaluated. Reliability Engineering will participate as a member of the formal and informal reviews.

Notification will be given to the AEC fifteen (15) working days in advance of each review. A data package containing the necessary information for evaluating the design as previously defined in the individual design review scope. Minutes of the meeting will be submitted to the AEC within five (5) working days after the meeting. The minutes will identify the decisions reached, actions to be taken, and responsibility for the action. A design review report will be submitted within thirty (30) working days. The report will identify the actions recommended as a result of the meeting, the technical opinions, conclusions and required actions with accompanying schedule.

2. Supplier Design Reviews

Supplier design reviews will be conducted in accordance with the reliability program plan submitted by the subcontractor per the subcontractor reliability program requirements.

A formal design change control program will be implemented on the ERTG program to control changes occurring subsequent to the establishment of the baseline design configuration. Control of design changes will be accomplished through the Change Control Board (CCB). The Product Definition Plan describes the program design change and control activity.

Reliability will serve as a member of the Change Control Board. Approval of a change will signify that the necessary data and evaluations have been conducted to identify the effect of the proposed change on performance and reliability.

F. PROBLEM/FAILURE REPORTING AND CORRECTION (REF.: PARA. 3.7, SNS-3)

Teledyne Isotopes has a single reporting system for both nonconforming and problem failures. The system covers both hardware and software discrepancies. A description of the methods used to report, investigate and dispose of all such discrepancies and to provide for corrective action may be found in Quality Program Plan.

The program as defined in the Quality Plan conforms to the requirements of paragraph 3.7 of SNS-3 except that suspected nonconformances as defined in paragraph 3.7.1(b) are not included, problem/failures are not categorized by criticality as defined in paragraph 3.7.1(e), and status summaries as defined in paragraph 3.7.1(h) are not provided.

Reliability Engineering will participate in the problem/reporting and correction activity to the following extent:

- Participate as a member of the Corrective Action Board (CAB) to assure that disposition of nonconforming item is acceptable and that the corrective action recommended is acceptable from a reliability viewpoint.
- Perform or assist in the performance of analyses to determine cause(s) of failure or nonconformance of an item.
- Reliability engineering will monitor, review and take appropriate action as required on failures reported from:
 - Subcontractor operations - Supplier nonconformance and failure report will be furnished to Teledyne Isotopes Quality Engineering in accordance with the program plan.
 - Engineering Tests - Test procedures will specify notification of all failures or malfunctions during engineering test to the responsible test, reliability and/or safety engineer
 - Field Operations - No formal reporting system is planned for failures on delivered hardware.

G. STANDARDIZATION OF PRACTICES AND PROCEDURES (REF.: PARA. 3.8,
SNS-3)

1. Teledyne Isotopes Standardization

Design, drafting, processes, and inspection methods specified in Teledyne Isotopes practices and procedures manuals will be used. Modifications to these practices, due to factors unique to the ERTG program, will be defined in the Product Definition Plan.

Reliability Engineering will review design drawings, standard process and other pertinent documents used in the design, fabrication and test of the ERTG equipment to ascertain their adequacy in meeting the reliability requirements of the program. The specific documents which reliability reviews and approves are defined in the ERTG Product Definition Plan.

AEC design or process standards will be considered if recommended by AEC, as applicable to the ERTG Program. Reliability engineering will verify the applicability of such standards and take the appropriate actions to incorporate them in the program.

2. Supplier Standardization

Supplier practice and procedure standardization will be controlled through review and approval of processes, material and parts lists supplied in accordance with the subcontractors reliability Program Plan.

H. PARTS, DEVICES AND MATERIALS PROGRAM (REF.: PARA. 3.9, SNS-3)

1. General

A program covering selection, application, qualification and control for parts, devices and materials will be implemented on the ERTG. Reliability contribution to that program will relate to the determination of the adequacy of specifications, qualification status, and handling for those items determined from analyses to be critical to performance. The reliability activity is planned for RTG/ETG parts, devices and materials and for that portion of AGE where failure is determined to have an adverse effect on the RTG/ETG performance and reliability.

2. Organization

The design group will be responsible for the parts, devices and materials program with assistance from materials, test, quality and reliability. There is no plan to have a group of qualified specialists to act as advisors to the design group.

3. Selection

Parts, devices and materials will be selected on the basis of their suitability in the specific application and on their qualification to the requirements of their respective specifications. Reliability will review the qualification data for applicability and recommend the need for additional testing.

4. Specifications

Parts, devices and materials used in RTG/ETG/AGE fabrication will be defined by either an engineering drawing, supplier (procurement) specification, or otherwise adequately identified. Reliability will review and approve the specifications for parts, devices and materials used in RTG/ETG/AGE hardware to verify that criteria and tests are defined.

5. Qualification

A parts, devices and materials qualification program will be prepared; the program will identify the qualification status of all supplier supplied items used in the ERTG RTG/ETG design. A qualification status list is planned for GSE for critical design areas. The list will be reviewed in conjunction with AEC to determine the adequacy of qualification program. The list will identify each item by part number, specification number, supplier qualification category and qualification test report.

Qualification method will be classified as follows:

- Teledyne Isotopes tests
- Government or industry tests
- Commercial or generic data
- Prior use on SNAP 19 Pioneer, Nimbus, Viking Programs

6. Lists

No detailed parts, devices and material lists are planned for the ERTG program.

7. Application Review

No parts, devices and materials application review is planned for the ERTG program.

8. Handling

Appropriate handling procedures and requirements for parts, devices and materials will be specified in the applicable drawing or process specification.

Reliability will, in the course of review and sign-off of drawings and processes, verify that handling and storage controls are included, taking into consideration the criticality of the item.

9. Failure Analysis

The ERTG program will use the Corrective Action Board (CAB) to identify the need for failed part, device or material analysis. A detailed description of the activities of the CAB and the handling of nonconformances and failures may be found in the Product Definition Plan.

Reliability will determine the importance of a failure to RTG/ETG performance and provide such findings to the CAB.

I. PRODUCT VARIABILITY CONTROL

1. Analysis

The results from the "Prediction" Task, para. 3.2, will be used to identify the critical design areas and performance parameters for which a product variability control program will be imposed during the fabrication process. The effort under this task will be to establish acceptance criteria and appropriate controls.

2. Criteria

Reliability engineering will identify the need for acceptance criteria and will determine where it will be applied to parts, components and subassemblies during receiving inspection, in-process fabrication assembly and final acceptance. Reliability engineering will develop or support the development and/or approve the acceptance criteria. This subtask will include the areas of thermoelectric electrical parameters, enclosure seals, heat pipes, electrical heaters, instrumentation.

3. Control

Reliability engineering will analyze in-process recorded data, recommend corrective methods, and redirection as applicable, based on:

- Yield, Trend and Rejection Analysis
- Statistical Assessment - Shewhart Process Control Charts
- Correlation Studies - Regression Analysis, Canonical Analysis

IV. TESTING AND RELIABILITY EVALUATION

A. RELIABILITY EVALUATION PLAN (REF.: PARA. 4.2, SNS-3)

An analysis of the test program defined in the ERTG Program Plan will be performed to identify those tests that are expected to yield data directly applicable to reliability assessment. In general, the method for identifying the applicable test is illustrated by the type shown in Table B-2. Here the sources for deriving reliability assessment data for each appropriate part, component or subsystem is identified. This analysis will be updated and made available for each design review and reliability program review.

B. TESTING

Reliability engineering will provide inputs to each test procedure to assure obtaining usable data for the assessment of the component or subsystem. These inputs will include sample size, test sequence, test duration and method for recording data. The test will, wherever practical, be designed to verify failure modes identified by the failure mode analysis.

A reliability analysis of each test having data judged to be applicable to reliability will be prepared. Here, the number of hours and cycles, number of failures, parameter distribution and failure modes will be identified.

C. ASSESSMENT

A reliability assessment will be performed and updated. The results will be available for each design review and each reliability program review. The assessments at system or subsystem level will include quantitative probabilities where

TABLE B-2. RELIABILITY ASSESSMENT MATRIX

Identification		Vibration			Shock		Thermal	
Ref. Design	Name	Random	Sinewave	Acoustic	Pyrotechnic	Acceleration	Soak	Cycle
R_E	Receptacle Electrical							
RF_W	Ring/Fitting Weld							
Ref: Block Diagram/ Math Model	Ref: Engineering Drawing				Environments - Ref: Mission Requirements Documents.			

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contract requirements and goals are specified. Quantitative or qualitative assessments will be prepared for each component and part with assessment made for the specific application or applications in which the item is applied.

All quantitative assessments will be made at a 50% confidence level and will include the effect of sample size. Standard statistical methods will be used and identified along with assumptions made. Failures will be identified and justified as countable or not countable. Ground rules for defining failures are:

- The failure of the item (part) would result in out-of-specification condition for the generator performance.
- The failure mode that caused the failure could exist under mission conditions.

If the failed item design is altered to eliminate the possibility of the recurrence of the failure, that failure will not be counted. However, should another failure of the same type occur, both the original and duplicate failure will be counted.

D. RELIABILITY INPUT TO READINESS REVIEWS (REF.: PARA. 4.5, SNS-3)

1. Input to Design and Program Reviews

Reliability engineering will provide technical support to the Design Review Program. The reliability input to this (and the reliability) Review Program will include the following as a minimum:

- RTG Reliability-Performance Prediction
- RTG/component Reliability Assessment
- RTG/ETG Failure Modes and Effects Analyses
- Review of ETG/RTG/GSE failures in service

Action taken or proposed with regard to failures experienced in service.

2. Input to Pre-shipment Reviews

A pre-shipment review will be conducted prior to delivery sign-off of each item identified in the ERTG Program Plan schedule. The review will be conducted using the Deliverable End Item Data Package and will include as a minimum the following:

- Configuration status of top level product definition documents
- Evidence of compliance to End Item acceptance requirements
- Review of Quality logs and Test Data
- Review of Failure History during acceptance testing
- Review of each nonconformance and identification of any open non-conformance items

Review of waivers and deviations

Reliability Engineering will provide technical support to the End Item Pre-Shipment Review.

3. Input to Readiness Reviews

Reliability Engineering will provide technical support on an "as required" basis to the AEC Flight Readiness and AEC/NASA Flight Readiness Reviews conducted on RTG's designed for flight status. The support will provide recommendations and supporting data to permit verification of the acceptability of the RTG's for flight.

E. RELIABILITY EVALUATION PROGRAM REVIEWS (REF.: PARA. 4.6, SNS-3)

Evaluation program reviews are included as part of the Reliability Program Review which will be performed at appropriate milestones during the implementation of the program. The scope, content and frequency of these reviews will be defined as part of the Reliability Program Reviews.