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EXECUTIVE SUMMARY

BRAYTON ISOTOPE POWER SYSTEM

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GENERAL ELECTRIC
SPACE DIVISION

AIRESEARCH MANUFACTURING COMPANY
OF ARIZONA

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Isotope space power systems have been a high priority activity in the Space Division for over 15 years. Systems were produced for some of the Nation's most important missions – Apollo, military space communications and outer plant exploration. Each of the systems has exceeded its design performance requirements, and similar success is expected with the Brayton Isotope Power System.

This system is the next logical step in providing the United States with an important option for space missions of the 1980's and beyond. General Electric's broad involvement with the Government and industry aerospace community will enable us to assure that the system will be designed for their needs. I will constitute an Applications Review Board to oversee the project from this viewpoint.

DOE can be confident that we will provide the manpower, facilities and management attention required to produce the flight test system on schedule and within our estimated cost.

- L. L. Farnham, General Manager
Space Division

The Garrett Corporation, with management responsibility located in the AiResearch/Arizona Division, is the world's largest producer of small open and closed cycle gas turbine engine systems. Virtually all closed Brayton cycle technology developed in this country is a product of over \$30,000,000 in prime contracts awarded AiResearch for the study, design, fabrication and testing of closed Brayton cycle systems. Closed cycle systems, including those for space power, have been built and tested under NASA Navy, AEC/ERDA/DOE and commercial sponsorship. This extensive closed cycle systems experience is providing the strong base for the development of the Mini-Brayton components used in the Brayton Isotope Power System.

We, at AiResearch, are looking forward to the BIPS Phase II/III Programs and to the subsequent initial flight of the nation's first nuclear dynamic power system. I offer full support of my office in meeting the goals of the program.

Jack Marinick, Vice President and General Manager
AiResearch Manufacturing Company of Arizona

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General Electric, with Garrett AiResearch as a major subcontractor, proposes to complete for DOE the development of the Brayton Isotope Power Flight Test System begun in Phase I – Ground Demonstration System.

PROGRAM OBJECTIVE

This program will provide the United States with long-life, safe, highly survivable space power, based on

- Flight-qualified isotope heat sources, whose safety has been thoroughly verified, and which have been flown on several spacecraft.
- Brayton power conversion technology, whose reliability has been demonstrated aboard thousands of civilian and military aircraft.

DEVELOPMENT STRATEGY

The Flight Test System design (Phase II) of the program will

- Make maximum use of components developed for the Ground Demonstration System
- Focus on the major engineering objective left to be accomplished – verification of structural integrity in the dynamic launch environment.

The fabrication activity (Phase III) will place major emphasis on producing ultra-reliable prime hardware.

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PROGRAM TEAM

General Electric and Garrett/AiResearch bring to the program the Nation's most experienced team for the required technologies and their application.

- Nuclear Systems for 9 space missions
- Brayton Isotope Power System Technology
- Communication, weather, Earth resources and other satellites.

During Phase I (power conversion technology emphasis)*AiResearch, with its extensive Brayton machinery development and fabrication background, was prime contractor. For Phase II and III (space system emphasis) GE, with its long experience in space nuclear power and spacecraft integration, will be prime contractor.

*GE AND GARRETT HAVE PLAYED KEY ROLES IN THE GOVERNMENT
PROGRAM TO DEVELOP THE BRAYTON ISOTOPE POWER SYSTEM*

PROGRAM BACKGROUND

TECHNOLOGY

NASA Miniature Brayton Rotating Unit

NASA Recuperator

NASA Heat Source Assembly

1974-1977

PRIOR NUCLEAR FLIGHTS

DOE Heat Sources
LES 8/9 and Voyager Missions

1969-1977

SYSTEM DEVELOPMENT

DOE Phase I - Ground
Demonstration System

1976-1978

PROGRAM EVOLUTION

The project covered in this proposal is part of the broader Government program to develop the Brayton Isotope Power System. Technology development began over a decade ago.

The specific component configurations to be used for the Flight Test System have been under development since 1974 and the Ground Demonstration System (Phase I) will be completed in June, 1978.

The design and fabrication of the Flight Test System is a continuation of the program initiated in 1976. It consists of two additional phases

- Phase II - Design Qualification (July, 1978 - June, 1980)
- Phase III - Production (April, 1980 - December, 1981)

Launch is targeted for the 4th Quarter of CY-82.

FLIGHT TEST

DOE Phases II and III - Flight Test System

- Based on Ground Demonstration Components
- Power: 1300 Watts (e)
- Specific Power: 2.2 Watts/Lb

1978-1982

MISSION DESIGN

Optimized Flight System (projected)

- Weight reduced by material substitution and optimized component sizing
- Power: 650 to 1950 Watts (e)
- Specific power: 2.6 Watts/Lb

MISSION OPERATIONS

Flight Test System

ISOTOPE HEAT SOURCE (2 PER SYSTEM)

- 24-100 Watts non-volatile $\text{Pu}^{238}\text{O}_2$ spheres
- Iridium clad for post-impact protection
- Graphite shell on each sphere for impact protection
- Polycrystalline Graphite for Re-entry protection.

HEAT SOURCE ASSEMBLY

- Helical coil Hastelloy-X heat exchanger to transfer isotope heat to He/Xe working fluid
- Radiant heat transfer from heat source
- Pd-Ni multi-foil insulation system
 - Melts for emergency cooling system
 - Thermal shorting when filled with inert gas for auxiliary cooling
- Aluminum housing

BRAYTON ROTATING UNIT

- Only one moving part – Turbine, Compressor, Alternator on single shaft
- Foil gas bearings – no rubbing contact
- Solid rotor, brushless alternator.
- Inert, single phase, noncorrosive working fluid
- Constant speed operation (no transient after startup)

SYSTEM CONTROLS

- Accurate
 - Speed < 0.1%
 - Power < 1%
 - Zero Drift
- Reliable
 - Redundant Microprocessors
 - Self Check Capability
- Efficient
 - Low Power Consumption
 - Programmable Performance
- Reduced Switching
 - Digital Parasitic Load
 - Reduced Filtering

SYSTEM PARAMETERS

Power Output-----	1300 W(e)
Voltage-----	28 VDC
Thermal Input-----	4800 W(e)
Efficiency-----	27%
Turbine Inlet Temp.-----	1400 °F
Rotation Speed-----	52,000 RPM
Working Fluid-----	He/Xe
Gas Pressure-----	50 PSIA
Weight-----	600 lbs.

RADIATOR

- Rejects waste heat to space
- Provides meteoroid protection
- 0-200°F operating temperature
- Gas radiator unaffected by zero "g"

RECUPERATOR

- Minimizes waste heat
- Rejection - high system efficiency
- Very high effectiveness
- Low pressure loss
- Hastelloy-X

DUCTING

- Contains and transports He/Xe working fluid
- Hastelloy X
- Designed for 1% creep
- In-line bellows for flexibility

CYCLE DIAGRAM **OPERATING PRINCIPLES**

This closed cycle hermetically sealed system uses a stable gas (mixture of Helium and Xenon) to drive a turbine-alternator set. The gas is pumped by a turbocompressor. Heat is added by two radioisotope heat sources, and waste heat is rejected by a tube-fin radiator, which also serves as the main structural element. Efficiency is enhanced by a recuperator heat exchanger. Constant DC voltage is obtained by passing the alternator output through a solid-state rectifier. Load changes are accommodated by dissipating excess electric power with parasitic resistors.

The major components are depicted here.

TECHNICAL APPROACH

Nuclear Safety

US NUCLEAR FLIGHTS

- 22 US spacecraft with isotope power supplies flown.
- 3 missions aborted.
- In every case, the nuclear safety system functioned precisely as designed and resulted in no injury to people or damage to the environment.

DOE SAFETY REQUIREMENTS

- Maximum allowable radiation exposure standards based on no exposure of operating personnel or the general public.
- Fuel containment to be effected for all potential accidents.
- Missions based on having no planned re-entry before isotope decays to insignificant hazard, except for Shuttle recovery operations.
- Covers potential accidents for entire mission – ground handling, launch, space operation, re-entry, impact and post-impact.

NUCLEAR SAFETY PROGRAM

- Re-entry, Impact, Post-impact
The GE-developed heat source has been approved and flown on missions with environmental requirements which equal or exceed those of the test flight.
- Launch Abort
Heat Source targeted for a Shuttle-launch mission (Galileo Space Probe) scheduled earlier than the test flight.
 - Required analyses and testing will be accomplished in time for this flight.
 - If any deficiency in the data should exist, appropriate measures will be included in the safety program.
- Emergency Cooling
Heat Source Assembly incorporates a feature for ultra-reliable over-temperature protection if heat removal capability is lost.
 - Multi-foil insulation melts before excessive temperature is reached.
 - Technique demonstrated in technology program performed by GE for NASA and the Phase I Ground Demonstration.
 - Specific configuration and materials for Flight Test System will be tested in this program.
- All the necessary analyses needed to support DOE in obtaining flight approval will be documented in Safety Analysis reports, developed in cooperation with appropriate Government agencies and industrial contractors.

Heat Source Safety Features

FUEL

- Solid, non-volatile, insoluble $\text{Pu}^{238}\text{O}_2$ ceramic
- 1.5 inch diameter
- 100 watts (thermal)
- Fully characterized for long-life compatibility with encapsulation

FUEL SPHERE ASSEMBLIES

- High-strength composite graphite impact shell
- Noble metal (iridium) post-impact shell
- Impact survival (no fuel release) thoroughly verified by impact testing at heat source terminal velocity and 2500°F against granite

HEAT SOURCE

- Graphite re-entry protection
- Re-entry survival thoroughly verified by testing at re-entry conditions exceeding requirements for any earth orbital missions.
- Flown on two Lincoln Experimental Satellites - 8&9 and two Voyager Spacecraft.

TECHNICAL APPROACH

Brayton Rotating Unit

BRAYTON ROTATING UNIT FOR FLIGHT TEST SYSTEM

CONSERVATIVE DESIGN

- Only one moving part—the two pound rotating group
- Supported on foil gas bearings
- No rubbing contact of bearings or seals
- Solid rotor, brushless alternator
- Low turbine and compressor stresses
- Inert, single phase, non-corrosion working fluid (Xe-He)
- Constant speed, pressure and temperature operation.

ROTOR

ALTERNATOR STATOR

FEATURES

- Operates at lower stress than most gas turbine engines
 - Lower tip speeds
 - Lower temperature
 - Clean environment (compared to open cycle)
 - Constant speed, temperature and pressure (precludes cyclic fatigue problems)
- Performance demonstrated in Phase I
 - 24.5% total system efficiency measured
 - 26% calculated with flight thermal insulation configuration
 - 27% projected for Flight Test System (no heat source electrical leads and reduced instrumentation)

**AN OPTIMIZED FLIGHT SYSTEM WILL BE SUBSTANTIALLY
LIGHTER THAN THAT USED FOR THE FLIGHT TEST**

TECHNICAL APPROACH

Weight Reduction Potential

- The Program Plan for the Flight Test System is based on using Ground Demonstration System (Phase I) hardware to the greatest extent feasible to minimize program cost.
- The Flight Test System will be designed, however, to permit incorporation of weight and performance improvements – such as those shown below in later flight systems.

STRUCTURE

- Change from Aluminum to Lockalloy – save 11 lbs.

THERMAL INSULATION

- Reduce foil thickness – save 12 lbs.

RADIATOR

- Change from aluminum to beryllium – save 40 lbs.

HEAT SOURCE ASSEMBLIES

- Change housing from aluminum to beryllium – Save 25 lbs.
- Reduce thickness of multifoil insulation – save 18 lbs.

- A system incorporation of all these improvements would increase the specific power from the estimated flight test value of 2.2 Watts/Lb to over 2.6 Watts/Lb— about 20%.

FLEXIBILITY

• **POWER LEVEL**

Changing the number of heat sources, adjusts power level in the range of 650 W(e) to 1950 W(e) with minimum power system components requalification required.

• **LAUNCH VEHICLE**

Compatible with both Shuttle and Titan – IIIC

TECHNICAL APPROACH

Component Development Status

The components for the Brayton Isotope Power System are under development in the BIPS Phase I Program – Ground Demonstration System – and in related programs such as the NASA Mini-Brayton Rotating Unit Program.

COMPONENT	FLIGHT DEMONSTRATION SYSTEM REQUIREMENTS/OBJECTIVES
ISOTOPE HEAT SOURCE	<ul style="list-style-type: none">• Qualified for seven years operation at 1100°C surface temperature in a vacuum environment and to satisfy all nuclear safety requirements• 2400 W(t) (2 Required)
HEAT SOURCE ASSEMBLY	<ul style="list-style-type: none">• 7 years at 115 psi, 760°C (heat exchanger conditions)• < 1% creep• 200°C maximum HSA surface temperature while in launch vehicle• Emergency cooling: (heat source ~ 1200°C equilibrium)
BRAYTON ROTATING UNIT	<ul style="list-style-type: none">• 7 years at 27% cycle efficiency• 1300 W(e) output at BOM
RECUPERATOR	<ul style="list-style-type: none">• 97% efficient high pressure side• 95% efficient low pressure side• Minimum heat loss to surroundings
RADIATOR	<ul style="list-style-type: none">• Minimum weight• 160 ft²• Compatible with Shuttle and Titan-IIIC launch vehicles• Meteoroid non-puncture probability: 0.99 for 7 years
CONTROLS	<ul style="list-style-type: none">• Hybrid solid state — constant load control• Minimum volume• All cooling by radiation• 0 to 100% power with 20 ms response time• 0.99 reliability for five years
DUCTING	<ul style="list-style-type: none">• Contain working fluid for 7 years with .99 non-puncture probability• Accommodate relative misalignment, thermal growth and creep

The summary statements below are based on expected status at the completion of Phase I. Should any of the objectives of that phase not be achieved when Phase II starts, they will be completed in the initial Phase II effort.

WHERE ARE WE	HOW WE WILL GET THERE
IHS already flight qualified for longer operating period and higher temperatures than requirement. Safety approval obtained and hardware successfully flown on LES 8/9 and Voyager Spacecraft.	Use identical design developed for Voyager. Obtain safety approval for this mission based on analyses and test to account for differences in mission conditions.
Phase I hardware meets design requirements.	Use GDS design. Consider material substitutions to reduce weight.
Work Horse Loop efficiency measured at 24.5%. Extrapolated performance indicates GDS efficiency of 26%. Hardware design complete.	Use GDS design. Removal of instrumentation and Electric Heat Source leads will reduce thermal losses and increase efficiency to 27%.
Phase I hardware meets design requirements.	Use Phase I design.
Phase I GDS used heat rejection heat exchanger to simulate radiator.	Radiator will be designed in Phase II using GE/ AiResearch design and fabrication experience with radiators and light weight structure.
Control logic successfully demonstrated on Work Horse Loop and GDS. Hardware in breadboard form.	Package into flight configuration and add redundancy to increase reliability.
Phase I hardware meets design requirements.	Use GDS design.

TECHNICAL APPROACH

TECHNICAL ISSUE

Confidence in the Brayton Rotating Unit bearings must be demonstrated.

- Foil gas bearings of the type employed in the Brayton Rotating Unit are used in hundreds of Brayton-driven units aboard civilian and military aircraft. Once development is complete (i.e., dimensions are established) they have an outstanding reliability record. See below.
- Excessive drag was observed in the Ground Demonstration System. A team of experts has been established in cooperation with NASA Lewis Research Center, and problem resolution is underway.
- The strong consensus of National experts is that the bearing is properly applied and that the solution to the current problem will be found.
- In the unlikely event that foil bearing development would jeopardize the Program schedule, tilting pad bearings – a proven alternative – will be used.

FOIL BEARING APPLICATIONS

- No contact with shaft at operating speed
- Over 9 million hours operating experience
- 30,000 start-stop cycles with no degradation demonstrated.

Ground Support Equipment (GSE)

The GSE will be based on General Electric experience in eleven nuclear launches over the past decade. GSE from the Multi-Hundred Watt RTG and the Phase I - Ground Demonstration System Programs will be used as they are or with minimum modification, when applicable (see Table below). GSE common to system acceptance tests and launch integration will be sent from GE/Valley Forge to ETR. This will assure that it has been thoroughly de-bugged before use at the launch site and will also reduce Program costs.

**ELECTRIC HEAT
SOURCE**

**POWER SUPPLY
AND READOUT
CONSOLES**

**POWER SYSTEM
STORAGE CONTAINER**

**ISOTOPE HEAT SOURCE
SHIPPING CONTAINER**

**POWER SYSTEM FUELING
FIXTURE**

GSE STATUS

PHASE II/III

	<u>No. Req'd</u>	<u>Refurbished and Reapplied</u>	<u>New</u>
• Electric Heat Source	7	3	4
• Power Supply and Test Consoles	7	2	5
• Isotope Heat Source Shipping Container	4	4	-
• Various Non-Fueled Equipment Shipping and Storage Containers	10	3	7
• Handling Tools and Sling	4	2	2
• Gas Service Cart	2	1	1
• Flight Fueling Fixture	2		2
• Electric Heat Source Loading Fixture	3	2	1
• Storage Protection Container for Isotope Heat Source	5	5	
• Ground Coolant Loop Module	2		2
• Auxiliary Startup Module	2		2
• Mass Model	1		1
• Thermal Model	1		1

SPACECRAFT INTEGRATION

- Test flight on Long Duration Exposure Facility (LDEF)
- Brayton Isotope Power System meets mass distribution requirements
- Thermal interface requirements satisfied
 - Radiator surface temperature no higher than passive surface exposed to sun
 - Joints designed to limit conduction to less than 100 Watts (thermal)
- Spacecraft stability
 - Proper orientation of rotating unit (parallel to pitch axis) enhances stability by gyroscopic effect
 - Reduces yaw uncertainty.

IN-ORBIT OPERATION SEQUENCE

- Heat Source Assembly gas released to space vacuum
 - Increases effectiveness of multifoil insulation to full value
 - Allows heat source and Brayton working fluid temperature to rise.
- Apply power to alternator
 - Motors rotating unit to self-sustaining speed
 - Power system is operational

- Engage Spacecraft with Manipulator and remove from Shuttle
- Place Spacecraft in proper inertial orientation
- Release Manipulator

- Spacecraft Operational

The Brayton Isotope Power System Development Program (Phase II and III) structure is shown in this milestone and flow chart. Various aspects of the work flow are described in the following pages.

Phase II is scheduled to commence immediately on completion of Phase I - Ground Demonstration System. The Program will have the benefit of a large array of prior and on-going work at GE, AiResearch, several DOE Laboratories, NASA, and USAF installations. The Program team has prepared a plan to take full advantage of this technology and application base.

Program Schedule and Milestones

PDR & FDR Preliminary and Final Design Reviews
 PSAR, GSAR, USAR & FSAR: Preliminary, Ground, Updated and Final Safety Analysis Reports

PROGRAM PLAN

Program Elements

DESIGN QUALIFICATION

Performance dynamic characteristics will be verified by test at the component, subsystem and system levels.

Design qualification will be achieved by building a complete Brayton Isotope Power System (flight design) and testing it first to Acceptance Levels, and then to Qualification Levels, with an Isotope Heat Source.

Other environmental testing will include acceleration, thermal-vacuum, magnetic field and acoustics.

FLIGHT SYSTEM PRODUCTION

- Two flight systems will be built and assembled, acceptance tested and delivered to ETR.
- A complete set of subsystems will also be built, but not assembled into a system unit.

GROUND SUPPORT EQUIPMENT

- GE has evaluated GSE from prior projects (Multi-Hundred Watt RTG and Phase 1 of this program) for re-use. Those identified as applicable will be used as they are, refurbished or modified.
- GSE not available from prior projects will be designed and built. See Page 15 for details.

LAUNCH SUPPORT

- GE will prepare plans and procedures, working closely with the Spacecraft and Shuttle Integration contractors, the USAF and ETR personnel.
- A plan will be prepared for continued GE assistance at ETR after completion of Phase III. This plan will include such activities as heat source installation, mating the Power System with the Spacecraft and subsequent integration with the Kick Stage and Shuttle. These activities are similar to those performed by GE on other programs.

NUCLEAR SAFETY

- This activity will accomplish all analysis, testing and documentation required for safe launch and space operations and support of flight approval.
- The heat source has been flown and is targeted for Shuttle-launch before the Brayton flight test. Maximum use will be made of prior data and those developed in on-going programs.

GROUND FLOW PLAN

The sequence of operations summarized here meets all requirements for fabrication, testing, and integration of the Brayton Isotope Power System for the Shuttle-launch of the flight test. Personnel, facilities and procedures will be provided to:

- Assure meeting all mission objectives
- Comply with all standards and procedural requirements for the handling, shipment, storage and launch of nuclear-fueled equipment
- Be completely compatible with the spacecraft and launch site equipment and procedures.

Program Control

The extensively proven General Electric management approach will be used to control the program. These procedures will be the same as those employed in such programs for DOE as those which so successfully produced the Multi-Hundred Watt generators for the LES-8/9 and Voyage missions, and SNAP-27 for Apollo.

The cornerstones are:

MANAGEMENT AUTHORITY

Program Manager, George Drenker, will have the authority to:

- Plan the program.
- Select the personnel.
- Direct the technical performance.
- Control costs and schedules.

He will be the chief Company spokesman to DOE and major participants in the program.

PROGRAM PLANNING

Detailed Work Plan will:

- Be based on the Work Breakdown Structure.
- Specify tasks, subtasks and work elements, including objectives, approach, schedules and cost allocations to provide a successful Flight Demonstration Program.
- Be updated as necessary.

REAL-TIME CONTROL

Program Manager will:

- Meet frequently (several times/week) with key team members.
- Review technical, schedule and cost status.
- Identify potential problems.
- Review status of current Action Items.
- Define new Action Items, if required.

Program Control (Cont'd)

MANAGEMENT REVIEW

Regularly scheduled meetings with higher management will review program status, resource requirements and relationships with the Government and major subcontractors:

- Bi-weekly by the Manager of Advanced Energy Programs, B.J. Tharpe.
- Monthly by the General Manager of the Space Systems Operation L.W. Warzecha.
- Bi-monthly by the General Manager of the Space Division, L. L. Farnham.

Key members of the Brayton Isotope Power System team in the Nuclear Programs Control Room

PROBLEM RESOLUTION

The program management and control system provides:

- Early problem identification.
- Timely corrective action by the Program Manager and his team.

If problems require resources beyond those of the program team:

- Higher management, already familiar with program status, are alerted immediately.
- Additional manpower, skills, facilities or other resources are provided to meet Company commitments.
- For major problems, a "tiger team" works with the Program Manager to investigate, determine causes, identify solution alternatives. This action is especially important for Phases II and III, where program success depends heavily on sequential accomplishments.

Corporate Locations of Program

- General Electric and Garrett/AiResearch represent an experienced industrial team with in-place skilled personnel and facilities to assure DOE a minimum risk project.
- The Brayton Isotope Power System Program has high management interest in both corporate organizations.
- The program provides General Electric the opportunity to maintain its historical leadership role in the space nuclear power field, and allows us to continue to serve the aerospace community with the latest technology.
- The program provides AiResearch the opportunity to maintain its historical leadership in the development of systems based on small gas turbines and advanced heat exchanger equipment.
- The program organization has been strategically located for corporate visibility in both GE and Garrett, and is structured to give the Program Manager direct access to the resources of both companies.

CORPORATE ROLES

General Electric will manage and have overall responsibility for the program performance. In addition, it will have direct responsibility for the following areas:

- Heat Source and Heat Source Assembly
- Radiator and Power System Mounting Structure
- Power System Assembly and Testing
- Ground Support Equipment
- Spacecraft Integration
- Launch Support
- Nuclear Safety

Garrett/AiResearch will have responsibility for the following areas:

- Brayton Rotating Unit
- Recuperator
- System Controls
- Ducting
- Power Conversion Subsystem Assembly and Testing

APPLICATIONS REVIEW BOARD

General Electric will form this group to oversee the program from the viewpoint of achieving one of its major objectives – laying the basis for fulfilling requirements for a broad spectrum of DOD and NASA missions. Certain members have been selected. The others will be identified before initiation of Phase II.

Appointed Members are:

- M.C. Cramer (Chairman)
General Manager, Military Programs
General Electric Space Division
- D.W. Keller
Manager, Advanced Systems Programs
General Electric Space Division
- R. Roberts
Director of Engineering
AiResearch Manufacturing Co.

The following organizations will be asked to appoint representatives:

- DDR&E (DoD)
- USAF
- NASA
- DoE
- Spacecraft Integration Contractor.

Program Team

Every key post in both the GE and AiResearch teams is filled by a person with a successful track record in directly applicable programs. A quick perusal of their recent experiences shown below will show their depth in isotope and Brayton systems. Further, they have been working together for years.

The two Companies have collaborated effectively for the past decade on various programs related to space nuclear power. They have established close person-to-person relationships during Phase I of this program. This successful team will be continued.

MHW: Multi-Hundred Watt Radioisotope Thermoelectric Generator
 LES 8/9: Lincoln Laboratory Experimental Satellites
 VOYAGER: Voyager Jupiter/Saturn Probe
 BIPS: Brayton Isotope Power System
 BRU: Brayton Rotating Unit

Nuclear-qualified shock and vibration table at GE. Isotope-fueled MHW-RTG shown.

GE acceptance and qualification tests will include the thermal-vacuum environment.

GE's present Nuclear Assembly and Storage Facility will be enlarged to accommodate Brayton system.

Response to acoustic noise is an important part of design qualification.

Power Conversion Subsystem will be put together in the AiResearch's Space Power Assembly Area.

Power Conversion Subsystem Testing will be operated from the AiResearch Space Laboratory Control Room.

The full systems will be assembled by GE in this Final Assembly Area.

Data management is an important element in the development program.

Isotope Space Power Systems
SNAP - 27

APOLLO 12, 13, 14, 15, 16, 17
LAUNCHED 1969-1972

This project, preceded by a series of studies and technology programs, developed the power systems for the Lunar Surface Experiments deployed by the Apollo astronauts. GE executed the design, qualification and fabrication of the hardware and provided extensive support to each of the six launches.

MULTI-HUNDRED WATT

LES-8&9
LAUNCHED 1976

The first application of this modular power system placed two 150-watt generators aboard each of the DOD experimental satellites. The compact, long-lived isotope power systems provided special advantages to this mission.

MULTI-HUNDRED WATT

VOYAGER - 1&2
LAUNCHED 1977

Distant outer planet exploration is made feasible by nuclear power. The mission had an extremely narrow launch window-making on-time delivery of hardware and safety qualification essential. The heat source is in the exact configuration to be used for the Brayton Isotope Power System Test Flight.

PERFORMANCE STATUS

PROJECT	DESIGN REQUIREMENT	ACTUAL POWER	LIFE
APOLLO (SNAP-27)	63.5 Watts 1 Year	71 $\pm$ 1 Watts (5 Sys.)	All 5* deployed, functioned until NASA stopped data in 1977.
LES-8&9 (MHW-RTG)	290 Watts 5 years	304 Watts (2 Sys.)	2 years in orbit Still above requirement.
Voyager-1 & 2 (MHW-RTG)	438 Watts	465 Watts	On the way to Jupiter, still functioning perfectly.
*Apollo 13 aborted. Heat Source survived re-entry and impact with no fuel release - as designed.			

- AiResearch—Phoenix is world's largest producer of small gas turbines.
- AiResearch—Los Angeles has produced over 750,000 heat exchangers for a wide spectrum of applications.

- Average of 2.5 engine designs per year (including propulsion)
- Design goals exceeded by every closed cycle engine system
- Millions of operations hours
 - 60,000 hour continuous runs (industrial)
 - NASA Brayton Rotating Unit (one of forerunners of this program):

NEW ENGINE DESIGNS

AVERAGE TIME TO FIRST RUN ≈ 1.0 YEAR
AVERAGE TIME TO FIRST PRODUCTION ≈ 2.0 YEARS

LEGEND

- ▽ FIRST RUN
- ▼ MOT, FAA CERTIFICATION, OR FIRST DELIVERY, AS APPLICABLE
- PROPULSION ENGINES
- AUXILIARY POWER UNITS
- GAS TURBINE ENGINES
- OTHER

AVERAGE OF 2% NEW ENGINE DESIGNS PER YEAR

1959 1960 1961 1962 1963 1964 1965 1966 1967 1968 1969 1970 1971 1972 1973 1974 1975 1976 1977 1978

Spacecraft and Subsystems

The knowledge of spacecraft requirements is fundamental to development of a versatile isotope space power system. General Electric Space Division has gained this knowledge in over 16 years of successful spacecraft and subsystems development and production. Examples are shown below.

SPACECRAFT

- Nimbus Weather Satellites
- Landsat Earth Observatory Satellites
- Biosatellite
- Defense Satellite Communication System (DSCS III)
- Japanese Broadcast Satellite Experiment
- Military Satellites

MAJOR SUBSYSTEMS

- Skylab
- Orbiting Astronomical Observer
- Global Positioning System
- Viking Orbiter (VO-75)

RECORD

- 25 spacecraft-years of successful in-orbit operations
- 10 years successful major subsystem in-space operations.

SHUTTLE INTEGRATION

One of the requirements of the Brayton Isotope Power System is that it be fully compatible with the Shuttle (Space Transportation System). GE has participated in Shuttle payload definition and design since the inception of the program. Example contracts are listed below:

- Long Duration Exposure Facility (LDEF) Implementation Support - (NASA NAS 1-14375)
- Evaluation of a DSCS III Single Launch on Shuttle - USAF/SAMSO F04701-77-C-0036)
- Applications Payload/Bus Designs for IUS Delivery - (NASA/GSFC NAS 5-24022)
- Payload Utilization of SEPS - (NASA/MSFC-Boeing NAS 8-31444)
- Earth Observation Satellite Phase B Study - (NASA/GSFC NAS 5-20518)
- Space Transportation Systems Payload Data and Analysis (NASA/MSFC - Convair NAS 8-29462)
- Shuttle Experiment Integration Study - AAFE - (NASA-LeRC NAS 1-13815)
- Standard Earth Observations Package Study (SEOPS) (NASA-JSC NAS 9-14335)
- Shuttle Payload Procedures Study - (NASA/ARC - NAS 2-19121)
- Space Processing Payload Equipment (SPPE) - (NASA/MSFC NAS 8-31495)
- Atmospheric Cloud Physics Lab (ACPL) - (NASA/MSFC NAS 8-31845)
- Earth Viewing Applications Laboratory (EVAL)-(NASA/GSFC NAS 5-24022)
- Onboard Experiment Data Support Facility (OEDSF) (NASA/JSC NAS 9-14651)

The Extra Measure of Effort**PROGRAM DESCRIPTION**

Title: MHW-RTG for Voyager

Customer: DOE (ERDA)

Contract: EX-76-C-16-3066

Value: \$19,866,000

MHW-RTG is the isotope fueled electric power supply providing 300 W(e) for each of the DOD LES 8&9 satellites and providing 450 W(e) for each of the NASA Voyager 1 and 2 outer planet mission spacecraft.

PROBLEM

The end caps of the graphite heat source re-entry protection aeroshell are found to be cracked on the qualification test isotope heat source when received at GE (before testing).

RESOLUTION

GE set up an investigation team of experts in various disciplines. GE personnel came from:

- Nuclear Programs and Materials Laboratories
- Re-entry and Environmental Systems Division
- Space Sciences Laboratory

In addition, we enlisted the capabilities of:

- POCO Graphite (manufacturer of the graphite)
- Oak Ridge Y-12 Plant, Union Carbide Nuclear Company
- Mound Laboratory, Monsanto Research Corp.
- Sandia Laboratories
- Southern Research Institute

The cause of failure was identified as a unique combination of material impurities plus accidental exposure to water vapor at high temperature.

Operational procedures were modified to preclude exposure. Additional testing was specified to verify material composition of all flight hardware and to demonstrate the material met or exceeded mission requirements.

These corrective actions were taken without impacting schedule, cost, or performance.

PROGRAM DESCRIPTION

Title: S-193
 Customer: NASA/JSFC
 Contract: NAS 9-11195
 Value: \$14,806,000

S-193 is the Skylab's sensor consisting of a radiometer, scatterometer, and altimeter for scanning and evaluating earth resources.

PROBLEM

Arcing in high voltage system of altimeter due to cracking of electronics encapsulant.

RESOLUTION

A team of GE experts was established from:

- Transformer Department High Voltage Laboratory
- Corporate Research and Development Center
- Silicone Products Department

In concert with Space Division engineering personnel, they characterized the problem, and a new encapsulant material was invented and produced by the Company's Silicone Products Dept.

RECENT NUCLEAR PROGRAM COST AND SCHEDULE PERFORMANCE

PROGRAM	CUSTOMER	NEGOTIATED CONTRACT VALUE (THOUSANDS)	CONTRACT PERIOD OF PERFORMANCE	PERFORMANCE	
				ACTUAL COST (THOUSANDS)	SCHEDULE
Stirling Isotope Power System (SIPS)	DOE	\$ 5,843	6/76-9/79	On Target	On Schedule
Brayton Isotope Power System, Ph. I, Ground Demonstration System Program	AiResearch	\$ 1,024	7/75-6/78	On Target	On Schedule
Voyager RTG Program	DOE	\$19,866	10/74-12/77	\$19,729	Delivered on Schedule to Tight Launch Window Sch.
High Performance Generator	Teledyne	\$678	12/75-11/77	\$606	Delivered Ahead of Schedule
NASS 2 KW(e) Unattended Power System Study	DOE	\$119	6/76-6/77	\$119	Completed on Schedule