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THE PROVEN RELIABILITY OF THE GAS-TURBINE ENGINE

MASTER

BIPS PHASE I

USERDA CONTRACT . . . EY-76-C-03-1123
GFE COMPONENTS NASA CONTRACT
. . . NAS 3-18517, NAS 3-18029 & NAS3-16810

NOVEMBER 1976

BRAYTON ISOTOPE POWER SYSTEM

AIRESEARCH
MANUFACTURING
COMPANY
OF ARIZONA

MS 4242-0

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INTRODUCTION

The Garrett Corporation, one of the Signal Companies, has several divisions and subsidiaries that design and manufacture a wide variety of products for the aerospace and transportation industries. The Corporation is organized into 24 different product lines, each of which has a complement of facilities and personnel to cover the entire life of a product from its inception through research, design, development, testing, manufacturing, sales and delivery product support.

The AiResearch Manufacturing Company, a division of the Garrett Corporation, specializes in the manufacture of gas turbines. Over 30 years of experience, 25 models, and 30,000 production units have provided the foundation for the closed gas turbine work presently underway. Over \$30M and 15 years of **continual effort has** been directed specifically toward the development of the closed cycle gas turbine concept at AiResearch.

As a major subcontractor to Garrett, General Electric Space Division brings to the contractor team the extensive background and experience of **a leading nuclear power system contractor**. GE has proven its capability to produce high quality reliable nuclear power devices for over 10 years. The GE SNAP 27 nuclear power unit has operated on the surface of the moon since 1969 and generated over **13 million watt-hours** of power, and is still operating.

24 PRODUCT LINES

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ELECTROMECHANICAL
& TURBOMACHINERY

AEROSPACE SYSTEMS

HEAT TRANSFER
& CRYOGENICS

URANIUM ENRICHMENT

INDUSTRIAL ENGINES

GROUND TRANSPORTATION
& INDUSTRIAL POWER SYSTEMS

ELECTRONICS

AIRCRAFT PROPULSION
SYSTEMS

GAS TURBINE
POWER SYSTEMS

PNEUMATIC
SYSTEMS

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CLOSED BRAYTON CYCLE PROGRAMS

Garrett's research and development activity in closed Brayton cycle power systems is unequalled. The more than \$30M of research and development effort has resulted in Garrett's preeminence in the area of closed Brayton cycle components; especially turbo-machinery, heat exchangers, alternators, controls, gas bearings, and systems engineering. Fifteen years of continuous concentrated effort on closed Brayton cycle technology advancement coupled with the vast GE nuclear capability, provide the experience and expertise that will make the Brayton Isotope Power System (BIPS) the "**standard power source**" for future spacecraft and satellite systems.

BIPS DESIGN SPECIFICATION

Operating Characteristics

Electrical Power Output	BOM	1300 Watts
	EOM	5 year — 1235 Watts
		7 year — 1200 Watts
Design Life		7 years
Output Voltage DC		120 V DC —
		Optional 120 V AC — 3 Phase
		Optional 28 V DC
Specific Power		2.9 Watts/LB
Length		96 Inches
Diameter		60 Inches
Weight		450 Lbs
Net Conversion Efficiency		25% (Min.)
Design Sink Temperature		-70°F

General Specifications

Accel, Shock & Vibration — compatible with shuttle launch and IUS
Mechanical, Electrical, and Thermal Interface — Space Shuttle Compatible

Reliability — $R = .95$ for 5 years

Meteoroid Protection: NASA SP8013

The current Phase I Program will lead to the complete **performance mapping of a flight type BIPS during ground testing**. Phase I was preceded by a 10-year effort sponsored by NASA to achieve "**technology readiness**." With this goal successfully achieved and over **31,000 hours** of successful testing of a **10 KW e closed Brayton system**, the technology is now being applied to the lower power equipment which will be required for satellite applications of the 1980's and 1990's.

CLOSED BRAYTON PROGRAMS

CUSTOMER	DATE	TYPE OF PROGRAM	\$ VALUE
USAF	1962	DEVELOPMENT OF MINIATURE 80°K CLOSED CYCLE COOLER	670,000
NASA AND USAF	1963-1965	ADVANCED COMPONENT DESIGN, DEVELOPMENT AND FABRICATION	740,000
ARMY, SATCOM	1963	DEVELOPMENT OF 4.2°K CRYOGENIC REFRIGERATOR	460,000
NASA LEWIS	1963-1965	DEVELOP AND CONSTRUCT 10 kW _e TWO-SHAFT ENGINE	1,491,000
USAF	1964	DEVELOPMENT OF 3.6°K HE REFRIGERATOR	965,000
NASA, NAA, MCD-DOUGLAS	1964-1971	SPACE STATION/BASE POWER SYSTEM STUDIES	203,000
NASA HOUSTON	1963-1971	DESIGN-CONSTRUCT-TEST 3kW _e DEMONSTRATOR ENGINE	169,000
NASA LEWIS	1966-1972	DESIGN-CONSTRUCT-TEST 10 kW _e SINGLE-SPOOL ENGINE	6,154,000
NASA LEWIS	1970-1972	DESIGN-CONSTRUCT-TEST 100 kW _e TURBO-ALTERNATOR-COMPRESSOR FOR REACTOR HEAT SOURCE	3,000,000
USAF	1970	CHARACTERIZATION OF TURBOMACHINERY REFRIGERATION SYSTEMS	255,000
NASA/AEC/USAF/GE	1972-1974	STUDY OF 0.5 TO 2.0 kW _e MINI-BRAYTON SYSTEM FOR SATELLITES	130,000
NAVSHIPS	1969*	STUDY AND DEVELOPMENT OF PROPULSION ENGINES	5,050,000
NSRDC AND NAVSEC			
AEC/WECO	1972	DESIGN-CONSTRUCT-TEST 3kW _e DEMONSTRATOR ENGINE FOR USE WITH C060 HEAT SOURCE	100,000
MARAD	1973	STUDY OF A 9,000 HP ENGINE FOR LNG REFRIGERATION AND A 40,000 TO 80,000 SHIP PROPULSION ENGINE	310,000
AECL	1973	STUDY OF A 30 kW _e UNDERWATER POWER SYSTEM	25,000
PFE	1973	25 HP REFRIGERATED RAILCAR GENERATOR SET DEMONSTRATION UNIT	450,000
AGA	1973	10 HP ROOFTOP REFRIGERATION DEMONSTRATION UNIT	700,000
NASA LEWIS	1974*	500 TO 2500 WATT MINI-BRAYTON TURBOALTERNATOR AND RECUPERATOR	3,300,000
ERDA	1975*	DESIGN, FABRICATION AND TEST OF A 1.3 kW _e MINI-BRAYTON GROUND DEMONSTRATION SYSTEM	5,600,000
EPRI	1975*	DESIGN AND RESEARCH OF A CERAMIC COMBUSTOR/HEAT EXCHANGER FOR CLOSED GAS TURBINES USING OIL AND COAL AS FUELS	960,000
DREO/DSS	1976*	SURVEY OF THERMAL POWER SOURCES FOR PROPULSION OR AN UNDER-ICE VEHICLE	50,000

*IN PROCESS

TOTAL 30,582,000

DESIGN CAPABILITY

Key to the successful closed cycle engine designs has been the development of an extensive and unique **computer design capability**. Computer programs, **verified by test** results, which have **accurate** weight, volume and performance estimating routines built in, allow a complete engine to be analyzed and designed in detail. Much of the correlative data for these computer models as well as many of the analytical procedures come directly from the **gas turbine industry** at large. Routines are built into the computer programs which rigorously design each component of the closed cycle engine. For components such as the turbine and compressor, **empirical data from existing configurations** are used to estimate the efficiency of the new design. In general, hundreds or even thousands of engine designs done in considerable detail are rapidly completed by the computer for a given application. An envelope of minimum weight and volume is then obtained on a plot of specific weight versus efficiency and on a plot of specific volume versus efficiency. The designer can rapidly select the smallest and lightest engine that will deliver the desired efficiency. This procedure is repeated using smaller and smaller steps in the parameter variation until a truly optimum design is achieved. In addition, computer programs for thermal, stress and dynamic analysis are employed to insure that mechanical design goals are met.

COMPUTER DESIGN AIDS

BRAYTON ISOTOPE POWER SYSTEM (BIPS)

- Reliable — 7 year life ($R = .952$ @ 5 years)
- High power density
- Proven hardware
- Flexible electrical power output

The BIPS is a 500 to 2000 W_e, **7 year life space power system**. The system utilizes a closed Brayton cycle engine to convert thermal energy provided by an isotope heat source to electrical energy at a net efficiency exceeding 25%. The heart of the system is the Mini BRU (miniature Brayton rotating unit), a turbine-compressor-alternator rotating machine, an offspring of the NASA BRU which has **just completed 31,000 hours** of testing. The other major components include the recuperator, heat source assembly, radiator, and controls. Each of the major components and their inherent reliability is discussed in the following pages.

The BIPS (1.3 KW_e) is just one more power unit in the family of very successful closed Brayton cycle systems developed by Garrett/AiResearch. An excellent record of reliable operation and high efficiency has been demonstrated in a variety of power system sizes.

The following **proven designs** provide the capability to **cover a broad spectrum** of applications from 500 Watts to 125 KW.

	Year	
• 3 KW Demonstrator	1965	20%
• 15 KW NASA BRU	1968	30%
• 30 KW CCPS 40-1	1975	33%
• 125 KW TAC	1971	(160 lb. rotating unit successfully run on foil gas bearings before program completion)

BRAYTON ISOTOPE POWER SYSTEM

MS 3986-7

MINI BRU

TECHNOLOGY BASE

The Mini BRU, based on 15 years of closed cycle technology development, has a **lineage of proven hardware**. In addition to the closed cycle engines below, numerous materials, component, and subsystem tests have been and are being performed. This hardware development coupled with the unique analytical capabilities of Garrett AiResearch provide the technology base necessary to insure the high reliability of the Mini BRU.

CONSERVATIVE DESIGN

The conservative design features listed below further establish the inherent reliability of the Mini BRU:

- 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.

MINI-BRU

BRU

BCD

PFE

CCPS40-1

COMPRESSOR AND TURBINE

By comparison, the Mini BRU compressor and turbine wheels operate at **lower tip speeds** (i.e., **stress levels**) and **temperatures** and in a less demanding environment than many of the wheels in AiResearch open cycle gas turbines such as the Garrett 831 which has run continuously for over 60,000 hours. In addition, the Mini BRU constant speed, pressure and temperature operation **precludes cyclic fatigue problems** due to transients.

Gas turbine rotating machinery design for reliability is predicated on several life limiting factors: Burst margin = minimum burst speed $\div$ maximum operating speed, creep = wheel/shroud interference, and stress rupture life. The small diameters of the Mini BRU wheels and resultant low tip speeds result in the conservative design margins shown in the table below:

Factor	Compressor	Turbine
Burst Margin	3.8:1	3.5:1
Wheel/Shroud Interference	Zero probability in 7 years	Zero probability in 7 years
Stress Rupture Life	>10 ⁸ hours	10 ⁸ hours

Operation in an inert, sealed environment prevents corrosion and foreign object damage.

COMPRESSORS AND TURBINES

MS 3986-11

RICE ALTERNATOR

The high efficiency (93%) Rice alternator is a simple 4 pole brushless design. The solid **rotor contains no windings** and has a burst margin of 2:1. A development rotor has been spun to 134,000 rpm with no growth (design speed = 52,000 rpm). All rotors are proof-tested to 180% design speed before assembly in the Mini BRU. **Redundant field coils** and excitation circuits in the stator assure a single point failure will not result in loss of alternator voltage. The operating temperatures are less than 400°F everywhere in the alternator stator. Consequently, **proven insulating materials** can be used. Thousands of hours of successful operation of a similar alternator on the NASA BRU provides a high degree of confidence in the Mini BRU alternator design.

RICE ALTERNATOR

FOIL BEARINGS

The only moving part in the BIPS, a 2 pound Mini BRU rotating group, is supported on two foil gas journal bearings and one foil gas thrust bearing. These unique bearings are in contact with the shaft only during start up and shutdown and literally **"fly" during operation at speed.** Tests of over **30,000 start-stop cycles with no degradation** have been demonstrated. These bearings which have **no moving parts** in contact with the rotating group at speed, therefore **theoretically have infinite life.** AiResearch has gained extensive experience (**over 8.9 million hours**) with foil bearings in air cycle machines installed in DC-10 aircraft. MTBFs of hundreds of thousands of hours on these bearings in the severe environment (dirt, shock, vibration, multiple start/stop cycles) of aircraft operation have been experienced. This background coupled with the clean, essentially shock and vibration free operation, and minimal start-stop cycles (less than 10 during the life of a flight unit) provide extreme confidence in the reliability of the Mini BRU bearing system.

FOIL BEARING APPLICATIONS

RECUPERATOR

The Mini BRU recuperator (MBR) is another heat exchanger in a long line of heat transfer devices produced by Garrett AiResearch. This **background** coupled with the extensive development of closed cycle recuperators over the last **15 years** **provides** the **data base** to **insure the reliability** of the MBR. The larger BRU recuperator delivered in 1968 has undergone over **30,000 hours of test** in the NASA BRU. The testing of this recuperator, which was essentially undeveloped hardware, provided invaluable insight into modifications to improve later designs. Over **\$2 million** has been expended during the **last three years to develop** and improve the design. This effort has **culminated in highly successful recuperator** component and system tests for other closed cycle engines. Accelerated low cycle fatigue tests on MBR submodules during the design phase have **resulted in substantial margin** in the current design. In addition, a prototype will undergo extensive testing to verify the overall design. This intensive development and background provide a high degree of confidence in the reliability of the MBR.

HEAT TRANSFER AND CRYOGENICS PRODUCTION

HEAT SOURCE ASSEMBLY

The HSA (Heat Source Assembly) consists of an IHS (Isotope Heat Source), a heat source heat exchanger, high performance multifoil insulation and supporting structure and outer housing. **The IHS gives 100 percent reliability of heat generation.** The MHW (Multi-hundred Watt) fuel block uses Plutonium 238 as the fuel. It is a proven, **flight qualified** design which is currently being used to supply thermal energy to the power sources for LES 8/9 (Lincoln Experimental Satellites) earth orbiting communications satellites used by the Air Force.

The heat source heat exchanger is a **simple static device**. The gas to be heated makes one pass thru the flow passages in an axial direction along the IHS. **The heat exchanger operates at temperatures below those currently being experienced** by the thermoelectric converters currently being flown by the Air Force in the LES 8/9 MHW-RTG (Multi-hundred Watt-Radioisotope Thermoelectric Generators). Likewise the **IHS operating surface temperatures are lower than those currently used in space satellites**. High reliability of this component accrues because there is at least a 50 percent design stress margin, and there are few thermal cycles in this application. The unit is designed to experience less than 1% total creep (material fiber relaxation due to fatigue) in 7 years.

HEAT SOURCE ASSEMBLY

**HEAT SOURCE
ASSEMBLY**

CONTROLS

Achieving high reliability for electronic controls is an objective common to many space systems. Aircraft and space experience has kept Garrett AiResearch at the forefront of the rapid development of improved electronic devices. Miniaturization has relieved size and weight limitations and allowed the **implementation of circuit redundancy** and backup control functions. Thus the desired reliability can be attained thru the use of:

- Circuit and component **redundancy**
- Temperature and stress **derating**
- Use of proven **high reliability** parts

The actual control functions and circuits required for closed Brayton systems have been implemented in real hardware for the NASA 15 KW _e BRU and tested for over 30,000 hours by NASA LeRC. The concepts and design principals of the BIPS controls have thus been successfully proven.

CONTROL EXPERIENCE

**NASA
BRU
CONTROL
SYSTEM**

- AUTOMATIC CONTROL
- SELF CHECKING
- FAIL SAFE
- 82 ANALOG PARAMETERS
- 26 CONTROL AMPLIFIERS
- OVERSPEED SHUTDOWN
- 30,000 HOURS OF OPERATION

RADIATOR

The space radiator is located in the coldest part (0-200°F) of the system. It is made of conventional materials such as aluminum or beryllium. There are approximately 32 tubes welded to headers at each end of the radiator. All welds are fully inspectable and repairable during the fabrication process. All radiators experience proof testing to 150% of operating pressure and helium leak testing before and after flight acceptance testing.

Each tube is **protected by armor against penetration by meteroids**. The design models for determining armor thickness have been well established by the NASA from work done beginning back in the early 1960s (e.g., Mariner and Explorer flight experiments).

The surface coating is selected not only for superior radiation heat transfer properties but also thermal and optical stability. Work done in support of a number of space programs including OSO-III (Orbiting Solar Observatory III) and Apollo **have demonstrated coatings** which have been stable for over four years in service.

The gas radiator is **unaffected by zero "g" operation** and can operate in **any altitude** on earth or in space.

RADIATOR

RADIATOR PANEL GEOMETRY

OVERALL DIAMETER, INCHES	35.5
OVERALL HEIGHT, INCHES	40.1
NUMBER OF TUBES	23
TUBE INSIDE DIAMETER, INCH	0.308
TUBE OUTSIDE DIAMETER, INCH	0.438
NUMBER OF INTERNAL FINS	16
RADIATIVE FIN THICKNESS, INCH	0.015
INTERNAL FIN THICKNESS, INCH	0.006
EMISSIVITY	0.913

PERFORMANCE

ARGON FLOW RATE, LBS/HR
HEAT REJECTION, BTU/HR/FT²
INLET TEMPERATURE °R
OUTLET TEMPERATURE °R
INLET PRESSURE, PSIA
PRESSURE DROP, PSI
EQUIVALENT
SINK TEMPERATURE °R

TEST	PREDICTED
276	276
11,960	10,723
939	936
588.2	623.4
19.24	19.24
2.95	3.02
385.8	385.8

OPERATING EXPERIENCE

Millions of hours of operation of Garrett AiResearch gas turbines (aircraft propulsion engines, aircraft APUs, land-based generator sets, marine engines, etc.) provide a massive data base which can be focused on the BIPS design and development. **Where high reliability is of prime importance, the power system selected is the gas turbine;** e.g., an AiResearch 831 industrial turbine, which is used to drive a generator to provide power for essential computers for one of the major airlines, has run continuously for over 60,000 hours (almost 7 years) under much more demanding conditions than the BIPS will experience. The "track record" of closed cycle engine systems is equally impressive. **Every closed cycle engine system that has been built has met or exceeded its design goals** with *no limited* development, an extraordinary accomplishment. The NASA BRU is a prime example: while exceeding the power and efficiency goals, over **31,000 hours** of operation were accumulated, and a recent scheduled detailed inspection **found no degradation** of any of the components.

BRAYTON ROTATING UNIT (BRU)

HIGH RELIABILITY BECAUSE:

- **FEW PARTS**
- **SIMPLE DESIGN**
- **NO RUBBING CONTACT**

MS 3986-25

BIPS — DYNAMIC POWER FOR SPACE

- **LONG LIFE AND RELIABILITY**
- **PROVEN GAS TURBINE TECHNOLOGY BASE**
- **HIGH EFFICIENCY OVER BROAD POWER RANGE**
- **DESIGN FLEXIBILITY**
- **MEETS MANY MISSION REQUIREMENTS**
- **GROWTH POTENTIAL**
- **FLIGHT QUALIFIED IN 1981**

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