5
TID --28927
TLD
RECEIVED BY TIC AUG 28 1978

MASTER

NO STOCK

**BRAYTON ISOTOPE POWER SYSTEM
PHASE I
FINAL REPORT**

**PREPARED BY
AIRESEARCH MANUFACTURING COMPANY OF ARIZONA**

**PREPARED FOR
DEPARTMENT OF ENERGY**

31-2919

JULY 28, 1978

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

BRAYTON ISOTOPE POWER SYSTEM
PHASE I
FINAL REPORT

31-2919

July 28, 1978

Prepared by: Engineering Staff/RDG

Approved by: J E m^c Cormick
J. E. McCormick
BIPS Program Engineer

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION

REPORT NO. 31-2919

TOTAL PAGES 129

ATTACHMENTS:

REV	BY	APPROVED	DATE	PAGES AND/OR PARAGRAPHS AFFECTED

TABLE OF CONTENTS

	<u>Page</u>
1. INTRODUCTION	1-1
2. BACKGROUND	2-1
3. PROGRAM OVERVIEW	3-1
3.1 Flight System Design	3-1
3.2 GDS Design	3-3
3.3 Workhorse Loop Add-On Task	3-5
3.4 Quality, Reliability, and Safety	3-7
3.4.1 Quality	3-7
3.4.2 Reliability	3-7
3.4.3 Safety	3-8
3.5 Safety	3-8
3.5.1 Mini-BRU Background	3-8
3.5.2 WHL Bearing Problem	3-9
4. TECHNICAL DEVELOPMENT	4-1
4.1 FS Preliminary Design	4-1
4.2 GDS Design	4-14
4.2.1 BIPS Frequency and Stress Analysis	4-14
4.2.2 GDS Layout and Support Structure	4-20
4.2.3 BIPS Control System	4-20
4.2.4 Heat Source Assembly (HSA)	4-32
4.2.5 Heat Rejection Heat Exchanger (HRHX)	4-46
4.2.6 The Mini-Brayton Recuperator	4-50
4.3 GDS Detailed Analysis and Design	4-58
4.3.1 Materials Review	4-58
4.3.2 Contamination Sources	4-60
4.3.3 Alternator Stator	4-60
4.3.4 MBR Offgassing	4-61
4.3.5 HSA Offgassing	4-61
4.3.6 Workhorse Loop (WHL)	4-62
4.4 Fabrication and Assembly	4-64
4.4.1 Summary	4-64
4.4.2 Assembly Procedures	4-68

TABLE OF CONTENTS (Contd)

	<u>Page</u>
4.5 Test and Evaluation	4-70
4.5.1 Endurance Test Summary	4-70
4.5.2 WHL Mapping Tests	4-77
4.5.3 Mini-BRU 1000-Hr Post-Test Evaluation	4-89
4.6 Quality, Reliability, and Safety	4-92
4.6.1 Quality Assurance Plan	4-92
4.6.2 Reliability Plan	4-96
4.6.3 Safety Reports, Reviews, and Evaluations	4-97

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION
PHOENIX, ARIZONA

BRAYTON ISOTOPE POWER SYSTEM
PHASE I
FINAL REPORT

1. INTRODUCTION

This report summarizes the Brayton Isotope Power System (BIPS) Phase I efforts conducted per DoE Contract EY-76-C-03-1123. The Phase I program resulted in the development and ground demonstration of a dynamic power conversion system. The two key contractual objectives of 25 percent conversion efficiency and 1000 hours of endurance testing were successfully met.

As a result of the Phase I effort, the BIPS is a viable candidate for further development into a flight system capable of sustained operation in space. It represents the only known dynamic space power system to demonstrate the performance and endurance coupled with the simplicity necessary for reliable operation.

This final report follows thirty-five monthly reports. For expediency, it makes liberal use of referenced documents which have been submitted to DoE during the course of the program.

2. BACKGROUND

The purpose of the DoE Brayton Isotope Power System (BIPS) Program was to develop a closed gas turbine dynamic power conversion system for numerous space applications. The baseline system is shown on Figures 2-1 and 2-2. The design life for a number of space applications potentially using BIPS is seven years. The objective was to provide 1300 W_e utilizing the BIPS in conjunction with two 2400 W_t (Multi-Hundred Watt, MHW) isotope heat sources developed by General Electric for DoE.

Phase I of the projected three-phase BIPS Program consisted of a conceptual design of the flight system, and the design, development, and test of a prototype demonstration system. The initial intent of the Phase I program was to design, develop, and test a ground demonstration system (GDS). As a result of delays in the program, the GDS, per se, was not built or tested. In its stead, a Workhorse Loop System (WHL), composed of most of the elements of the GDS except for the G.E.-supplied heat source assemblies, was designed, developed, and tested.

The Phase I task, as originally scheduled and as actually accomplished, is shown on Figure 2-3. Shown on Figure 2-4 is the Phase II/III program schedule as provided in the G.E.-AiResearch Proposal for Phase II/III.

FIGURE 2-1

FLOW SCHEMATIC

HEAT SOURCE ASSEMBLY

MINI BRU

FLIGHT SYSTEM

RECUPERATOR

BIPS DESIGN SPECIFICATION

Design Life	7 years
Electrical Power Output	BOM 1300 W _e
	EOM { 5 years 1235 W _e
	{ 7 years - 1200 W _e
Output Voltage	120 V dc
	Optional 67 V ac L-N 3 phase
	1733 Hz
	Optional 28 V dc
Specific Power	6.4 W _e /kg (2.9 W _e /lb)
Physical Characteristics	
Length	244 cm (96 in.)
Diameter	152 cm (60 in.)
Weight	204 kg (450 lb)
Power Conversion Efficiency (Net)	25 percent minimum
Design Heat Sink Temperature	216°K (-70°F)

General Specifications

- o Mechanical Electrical and Thermal Interface Compatible with Space Shuttle
- o Reliability = 0.95 for 5 years
- o Meteoroid Protection in Accordance with NASA SP8013
- o Shock Design Criteria for Component Mounts = 50g
- o Support Structure = 25g
- o Resonant Frequency > 60 Hz
- o Vibration Design Criteria Compatible with Shuttle/ IUS Launch

FIGURE 2-2

BRAYTON ISOTOPE POWER SYSTEM (BIPS)

PHASE I

PROGRAM SCHEDULE

LEGEND:

PREDICTED SCHEDULE

ACTUAL SCHEDULE

31-2919
Page 2-4

FIGURE 2-3

PROPOSED PHASE II/III PROGRAM SCHEDULE

FIGURE 2-4

3. PROGRAM OVERVIEW

3.1 Flight System Design

The concept of the BIPS flight system evolved from early studies performed at NASA, by NASA contract, and during the Mini-BRU design and fabrication contract (NAS3-18517). During the proposal phase of the BIPS contract, a number of configurations using components available from the NASA hardware contracts or derivatives thereof were examined; the most promising of these was retained for detailed evaluation in the BIPS design phase. In the Flight System Design Phase, only preliminary design of BIPS components was undertaken.

The original flight system maintained the same 1600°F turbine inlet temperature as the NASA BRU; the BIPS, however, utilized columbium in the highest temperature components, namely the heat source heat exchanger, turbine plenum, and connecting ducting. The 1600°F turbine inlet temperature makes it possible to obtain high efficiency (27.1%) while minimizing the weight of the recuperator and radiator. Columbium exhibits high strength in the temperature regime of interest and was the only available material which would have seven-year life at less than 1 percent creep as required. Columbium requires a non-oxidizing environment at elevated temperatures, and the vacuum of space was felt sufficient to insure its cleanliness for the mission duration.

Important goals for the system were the production of 1300 W_e and 450 lb total system weight. From the system studies performed with the thermodynamic cycle analysis (which also sized the recuperator and radiator), it was found that these goals could be very nearly achieved. It was assumed that the NASA-supplied Mini-BRU and HSA would be used with minor changes, that the recuperator geometry would be similar to that used in the Mini Brayton Recuperator prototype (MBR), and that the output would be 120 vdc and therefore use the current Mini-BRU alternator design. It was also assumed that a weight effective

material such as Lockalloy or beryllium could be used for the radiator. It was found that $1300 W_e$ could be supplied to the user while using only two $2400 W_t$ MHW heat sources. A net cycle efficiency of 27.1 per cent could be obtained with a system weight as low as 460 lb. All major system parameters were studied and the results presented in the Configuration Control Document (CCD), AIRPHX 75-311274C. After the component weights and sizes were determined, the structure and component configuration were defined.

The component configuration selection was based upon a detailed logic network which evaluated the effect of the BIPS on the spacecraft. It was ascertained that the small angular momentum of the Mini-BRU would have a small effect on the spacecraft but, to minimize this effect, the Mini-BRU rotor should be located on the centerline of the spacecraft. In the case of a spin-stabilized spacecraft, the axis of the Mini-BRU should be parallel to the spin axis of the spacecraft. The penalty for operation through launch was also assessed, and it was determined that the Mini-BRU orientation should be parallel to or on the spacecraft axis. As the program developed, the mission was defined to occur with a Space Shuttle launch. The same conclusions as above hold true with the exception that no thrust bearing redesign would be required.

The next task performed was the design and mechanical evaluation of the structure. The individual structural elements were designed to withstand a minimum of 25 g's; the mount points were designed to withstand a minimum of 50 g's. Simultaneously, the constraint of maintaining the natural frequency above 60 Hz was applied; this last constraint is what really sized the structure. The structure was evaluated in Lockalloy, beryllium, and aluminum; the first two are much lighter because of their inherent higher stiffness.

Schemes were evaluated to allow operation on the launch pad and simultaneously allow the insulation to work as intended to prevent

oxidation of the columbium. These all presented penalties to the system weight but were evaluated through the preliminary design phase.

Optimization and design of the insulation system was undertaken by Thermo Electron Corporation (TECO), a principal subcontractor. Experiments were performed to prove the efficacy of multifoil insulation and the melting insulation concept of the HSA. The performance of the multifoil and melting insulation results were very encouraging.

Preliminary design of the controls was undertaken. The design which shows the highest reliability and best performance is the digital control which holds the rotor speed within a precise tolerance. The power produced at both beginning and end of mission was higher with a digital rather than with an analog control.

Within the Workhorse Loop Add-On task, superalloy lower temperature versions of the system were examined. It was determined that 1300 W_e could be produced with a 1400°F system if large recuperators and large radiators were selected. The weight penalty over the columbium system is about 100 lb, and the radiator area is necessarily larger. Another important concept pursued during Phase I was the design of a helical-tube heat source heat exchanger (HSHX). This design came to fruition during the latter part of the BIPS program when the HSA was converted to a Hastelloy-X HSHX. The present flight system design is an all superalloy design.

3.2 GDS Design

The Flight System (FS) Design phase provided the definition for the GDS Preliminary and Detail Design phases. The configuration of the FS was adapted as closely as possible for the GDS, and detail design of all assemblies other than those supplied (GFE) by NASA began at this time. It was possible to effect some minor changes to the

NASA-supplied hardware to make it flight prototypical. Criteria for the design of ancillary systems to control and monitor engine testing were defined and supplied to the appropriate facility design tasks. The GDS was designed to be as similar to the FS in performance and geometry as possible.

The NASA-supplied hardware included the Mini-Brayton Recuperator (MBR), Mini-Brayton Rotating Unit (Mini-BRU), Heat Source Assembly (HSA), and an analog control. The design of the MBR mount structure was modified under the NASA contract to conform to the structural concept of the FS. The Mini-BRU was accepted for the GDS as is. Modification of the HSA mount structure was required, and a design acceptable for the GDS was adopted. The NASA analog control was tested and modified; ultimately, a digital control was found to be more reliable and efficient and was adopted for the GDS. A breadboard digital control system was fabricated and used throughout the 1000 hour endurance test.

The GDS structure is geometrically similar to that which was selected for an FS but is fabricated from aluminum instead of beryllium or Lockalloy. The lower structure was designed to accept the NASA supplied MBR. The use of a smaller FS recuperator to effect a decrease in system weight might entail some small changes in the lower structure.

Material compatibility and concept feasibility testing was undertaken at this time. Work was performed at Battelle Memorial Institute and Oak Ridge National Labs on the following subjects:

- o Columbium compatibility with the environment of a BIPS system
- o Long-term life of columbium and superalloy in the BIPS environment

- o Organic material produced by the Mini-BRU alternator
- o Cyclic life testing of bellows
- o Material definition for melting insulation
- o Evaluation of Hastelloy/columbium bi-metallic joints

Detail design of the BIPS ducting and bellows was completed. Stringent cyclic life and creep standards were imposed on the bellows to make them as similar to the FS components as time would permit. Instrumentation for performance mapping was defined and incorporated in the duct or component designs as required.

Detailed design of the insulation system was accomplished by TECO during this phase. Predicted temperature levels for the columbium system were used to estimate the foil thickness required.

Detail design of the heat rejection heat exchanger (HRHX) was also completed. This component was designed to reject heat at as high a level as the three HSA thermal input condition. This unit was designed to completely preclude mixing of the coolant and working fluid.

3.3 Workhorse Loop Add-On Task

The Workhorse Loop allowed for early shakedown of the test facility, engine controls, and the engine. A considerable amount of performance mapping was planned for this unit. The Workhorse Loop was designed to use all the Ground Demonstration System (GDS) hardware except for the Heat Source Assembly (HSA), the Electric Heat Source (EHS), and the Hastelloy-X turbine plenum (see Figure 3.3-1). In

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION
PHOENIX ARIZONA

WORKHORSE LOOP ASSEMBLED IN VACUUM CHAMBER
OF BIPS SPACE POWER LABORATORY

place of the HSA and EHS system, a superalloy heater utilizing resistive heating elements supplied heat to the working fluid via the heat exchangers. Special support struts were designed to hold these heat exchangers and to thermally isolate them from the aluminum structure supporting the system. The heat exchanger was designed with the capability of operating at gas temperatures of 1600°F and thermal input equal to the three HSA condition (7.2 kW_t). The pressure drop of the heat exchanger closely matched the columbium heat source heat exchanger to be used in the GDS. A superalloy turbine plenum design from the NASA program was reviewed and adapted for use in the WHL, and superalloy bellows were designed for use in the superalloy BIPS.

The other portion of the study dealt with optimization of the system for lower temperature operation using lower temperature materials (superalloy). It was felt that the exclusion of columbium would enhance system reliability and confidence, albeit at the expense of weight and radiator size.

The candidate materials were Waspaloy and Hastelloy; Hastelloy was eventually selected because of the greater life data base available. The turbine inlet temperature was based upon the maximum gas temperature which could be obtained from a metal temperature not to exceed 1450°F . From fabrication, reliability, and heat transfer performance considerations, the single helical tube heat exchanger became the most attractive design concept for use in the HSA. This design was subsequently verified in a NASA contract and fabrication was accomplished for the eventual use in the BIPS all-superalloy GDS.

It was decided to maintain the system performance level of the columbium system and therefore system weight increased. Weight of the superalloy system was some 100 lb greater than the columbium system; this was the result of both larger radiator area and recuperator weight necessary to obtain the performance of 1300 W_e with 4800 W_t input.

Evaluation of the bellows design indicated that conversion to an all-superalloy system would result in minimum modification from the present design.

Minimum modification of the structure and duct design would be required. The insulation weight could be reduced because of the lower temperature of the hot components. The recuperator selected for this system would be slightly smaller than the current MBR.

3.4 Quality, Reliability, and Safety

3.4.1 Quality

The Quality Program Plan for BIPS Phase I and the Quality Assurance Program Supplement were approved by DoE/NRA in AiResearch Report No.'s QA-053, and QCGI 137. Extensive liaison during Phase I resulted in detail quality planning to develop flight system specifications for the control of fabrication, installation, and Quality Requirements for Bellows (Specification No. 31-2704), Insulation (Specification No. 31-798), and General Requirements (Specification No. 31-2767). The strong Phase I Quality Assurance Program Plan provided the foundation upon which the BIPS Phase II Quality Program Plan and Supplement were established in AiResearch Report No.'s QA-054 dated 3/1/78 and QCGI 144 dated 2/1/78.

3.4.2 Reliability

An aggressive reliability program was pursued during Phase I in accordance with the "Reliability Program Plan - BIPS GDS Phase I" (AIRPHX Report No. 75-311360 dated September 30, 1975 and its update, Report No. 31-1360A dated August 18, 1977). In addition to the preparation and publication of many reliability related reports and analyses covering the entire Brayton Isotope Power System, special attention

was devoted to analyzing and enhancing the reliability of key components of the system, i.e., the bellows and the hydrodynamic foil bearings.

3.4.3 Safety

The nuclear safety program during Phase I was conducted by AiResearch with the assistance of General Electric in accordance with the "System Safety Program Plan," AIRPHX Report No. 75-311221, dated September 30, 1975. As part of the Phase II Planning effort provided by General Electric, the Ground Safety Assessment Report (AIRPHX Report No. 31-2361) was updated, and the elements of this and a preliminary Conceptual Flight Safety Assessment Report were included in the Phase II Plan.

3.5 Bearing Development

3.5.1 Mini-BRU Background

The core of the BIPS is the Brayton Rotating Unit (BRU) turboalternator more commonly known as the Mini-BRU. The Mini-BRU was developed and cold tested under NASA Contract NAS3-18517 conducted from April 1974 through June 1978.

The Mini-BRU series of cold tests included five hours endurance at 52,000 rpm, five minutes at 120 percent speed, magnetic excitation (no load saturation), and motor starting after which the unit was transferred as Government Furnished Equipment (GFE) to the DOE BIPS program for installation in the WHL and later, the GDS loop.

The Mini-BRU was installed in the WHL in August, 1977 in preparation for system performance mapping and subsequent endurance test.

Simultaneously with the loop preparation, testing was also being continued with the Mini-BRU Simulator Test Rig (STR). The STR is a bench test rig which simulates the dynamic characteristics of the Mini-BRU and includes an alternator.

The STR tests revealed a possible journal bearing instability problem at high electrical loads. The problem could be accentuated by high temperature operation where it was expected that an increase in sway space might occur. A decision was therefore made to remove the unit from the loop and replace the bearings with "stiffer" ones. This modification was accomplished, and the unit was reassembled into the loop.

3.5.2 WHL Bearing Problem

On November 2, 1977, WHL operation was initiated. As the system was brought up to speed the Mini-BRU was electrically motored for substantial periods at speeds in the range of 14,000 to 30,000 rpm to circulate warm gas and aid in uniform heating of the loop. The unit became self-sustaining and automatically locked on speed and load at a turbine temperature of less than 800°F. The turbine-end bearing temperature was monitored by a thermocouple attached to the backside of a foil and reached a maximum of 444°F.

After 69 hours and 2 minutes of testing had been completed, the unit shut down on November 8, 1977. Twenty-four aborted starts were conducted in attempts to bring the unit back to operating conditions; however self-sustaining operation could not be achieved.

The unit was removed from the loop and disassembly revealed the compressor journal bearing to be severely deteriorated. A review of the trend recorder data revealed an erratic condition of unit electric power output just prior to the shutdown suggesting internal power absorption.

Figure 3.5-1 shows the historical and chronological sequence of events leading up to this and the subsequent WHL tests.

Examination of the totally failed compressor bearing and the relatively unscathed turbine bearing suggested that the long periods of low-speed motoring and perhaps bearing instability had contributed to the demise of the compressor bearing. As a result of this diagnosis, tests were conducted in the STR to duplicate the low speed motoring histogram. In addition, tests and analyses were conducted on the Mini-BRU, operating cold, to determine if instability existed in the rotor/bearing system. These tests proved negative so another WHL test was attempted with higher radius of curvature bearings, closer tolerance rotor balance, and no low-speed motoring.

Figure 3.5-2 provides a listing of pertinent foil bearing parameters selected for the following several WHL tests and other builds.

Testing with these modifications was initiated in the WHL on December 21, 1977. The installation of a multifoil insulation pack between the turbine backshroud and the turbine journal bearing resulted in a reduction of that bearing temperature from 440° to 350°F. After 3 hours and 30 minutes of testing, a unit overspeed initiated a loop shutdown. Review of trend recorder data revealed the load shedding phenomena to have again occurred. Consequently, the unit was again removed from the loop and disassembled.

Again the compressor-end bearing was found in a seriously deteriorated condition while the turbine-end bearing showed only minor wear. Fortunately, the imminent bearing failure had been caught early, and the bearing pads were in a condition amenable to mechanical and thermal analysis.

FIGURE 3.5-1

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION

	Current WHL*					
WHL Date	9-24-77	11-08-77	12-22-77	2-14-78	3-17-78 And 3-27-78 Build	3-22-78 And 3-28-78 Build
Lot No.	7318	7491	7517	8569	8592	8593
Foil Material	302 S.S.	302 S.S.	302 S.S.	302 S.S.	302 S.S.	302 S.S.
Pin Material (Mag/Non-Mag)	Mag.	Mag.	Non-Mag.	Non-Mag	Non-Mag.	Non-Mag
Material Thickness -- Base Total	0.0048/ 0.0058	0.0052/ 0.0062	0.0052/ 0.0061	0.0050, 0.0051/ 0.006	0.0050 0.0062	0.0050 0.0060
Radius of Curvature	0.59	0.57	0.61	0.59	0.57	0.57
Surface Finish (RMS)	30-45	26-34	20-33	30-48	8	8
Spring Rate (Lbs/In)	910	3845	2380	1000	1562	1351
Foil Coating	Teflon-S	Teflon-S	Teflon-S	Teflon-S	Teflon-S	Teflon-S
Cure Temperature	650°F	650°F	650°F	650°F	570°F	630°F
Foil Length	0.770	0.775	0.770	0.770	0.765	0.775
Foil Width	0.902	0.896	0.902	0.901	0.880	0.880
Sway Space - Compressor End	0.0092	0.0076	0.0082	0.0087	0.0091	0.0099
(Cold) - Turbine End	0.0092	0.0076	0.0080	0.0086	0.0084	0.0092
Balance - "M" Plane		0.0034	0.0010	0.0007		0.0007
Oz. In - "N" Plane		0.0027	0.0012	0.005		0.005

*Successfully Completed 1006.9 Hours on 5-22-78

MINI-BRU JOURNAL BEARINGS COMPARISON
FOUR WORKHORSE LOOP TESTS PLUS NEW MINI-BRU BUILDS

FIGURE 3.5-2

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION
PHOENIX, ARIZONA

The similarities and differences between the two failures increased concern to the extent that NASA extended the Mini-BRU program and provided funding for an intensive bearing investigation.

The specific elements of that investigation are shown in Figure 3.5-3.

During the period between the December 22, 1977 WHL test and the February 14, 1978 WHL test, the major thrust of the NASA bearing investigation was bearing performance, thermal analysis, bearing electrical arcing, materials analysis, and correlation testing in the Simulator Test Rig (STR) and Pressurized Bearing Test Rig (PBTR). The thermal analysis indicated foil and shaft temperatures on the order of 350°F which would not be detrimental to Teflon-coated bearing operation. The analysis however was based on certain assumptions which, at that time, remained to be proven. Consequently, a WHL test was initiated with the specific goal of measuring temperatures which would corroborate the thermal analysis. Thermocouples were installed on a compressor-and turbine-end journal foil. Thermal paint was coated onto the bearing carriers, the inside of the journal shaft, and the tie bolt.

The test was conducted on February 14, 1978 for a duration of 6 hours. Disassembly of the unit revealed the bearings to be in excellent condition. Thermocouple and thermal paint data agreed very closely with the predicted results, thus verifying the thermal analysis.

Continuing tests during this period in the STR and PBTR were still unable to simulate the bearing failure under cold bench test conditions. Results of material analysis conducted both at AiResearch and by NASA began to suggest that a poor Teflon coating bond may have contributed to the bearings demise. Consultation with AIRLA foil bearing experts suggested the use of another Teflon coating vendor who produced more uniform and better quality coatings. Samples from this vendor indeed indicated much better surface finish, better uniformity in coating quality and thickness, and better overall workmanship.

BEARING DEVELOPMENT PROGRAM

	POSSIBLE CAUSE	ACTION	STATUS (4/73)	TO DO (4/73)
1. COATING	{ COMPOSITION & PROCESS CLEANING ADHERENCE BLISTERS	STR TEST UNCOATED FOILS	BARE, DICHRONITE & MoS_2 COATED FOILS TESTED	TESTS CONTINUE
		WHL TEST UNCOATED FOILS , BCL MICROBALANCE TESTS (A)	PENDING FURTHER PBTR & STR TESTS COMPLETE	TESTS CONTINUE COMPLETE
		HOT STAGE MICROSCOPY (D,E)	COMPLETE - NO BUBBLING OR DE-BONDING	COMPLETE
	{ SOFTENING	HOHMAN WEAR TESTER (C,D,E)	CANNOT MEASURE TORQUE	NO LONGER APPLICABLE
2. TEMPERATURE	{ COATING DISTORTION OVERLOADS	WHL TEST W/INSTRUMENTATION	COMPLETE 2-14-73; TEMPS AGREE WITH ANALYSIS	COMPLETE
		ANALYZE RESULTS-CORRELATE WITH ANALYSIS - FIX	COMPLETE - THERMAL ANALYSIS CHECKS WITH TEST	COMPLETE
3. FOREIGN PARTICLES		IDENTIFY TI AND CR SOURCES	COMPLETE - PART OF TEFLON	COMPLETE
		SEM, EDAX (FOILS ?, SHAFT ?)	COMPLETE - ALL MATL IDENTIFIED AS TEFLON OR SHAFT	COMPLETE
		BRU BLOW-DOWN	COMPLETE - NEGATIVE EXCEPT FOR ONE LARGE PARTICLE OF ENCAPSULATING COMPOUND	COMPLETE
		LOOP BLOW-DOWN	COMPLETE - NO PARTICLES LARGER THAN 5-10 MICRONS	COMPLETE
4. ELECTRIC OR MAG EFFECTS	{ DISCHARGE MAG FOILS MAG FORCE	MEASURE POTENTIAL ANALYTICAL REVIEW	CHARGE/DISCHARGE OBSERVED STR	CHECK ON WHL 4/7/73
		CHECK MAGNETIC FORCE	COMPLETE - CRES 302 FOILS NOT ATTRACTED-MAGNETIC KEEPERS ARE	COMPLETE
5. STARVATION	{	ADDED PRESSURE INSTRUMENTATION ON WHL	ADDED PRESSURE INSTRUMENTATION ON WHL TO MEASURE BEARING ΔP (~FLOW)	CHECK ON WHL 4/7/73
6. STAGNATION				
7. DISTORTION	{	THERMAL ANALYSIS	THERMAL ANALYSIS INDICATES NO EXCESSIVE TEMPS	COMPLETE
		FOIL SURFACE EXAMINATION	NO FOIL DISTORTION MEASURED	COMPLETE
8. LOW SPEED MOTORING		REVIEW FIRST WHL TEST WHERE BEARINGS WERE CHANGED	PROLONGED MOTORING AT N-25,000 DELETED FROM TEST PROCEDURE; START/STOP WITH TEF-S COATED NOT A PROBLEM; START/STOP WITH MoS_2 COATED OK FOR LIMITED NUMBER OF STARTS MADE TO DATE	COMPLETE

Figure 3.5-3

BEARING DEVELOPMENT PROGRAM (CONTD)

POSSIBLE CAUSE		ACTION	STATUS (4/73)	TO DO (4/73)
9. WHL TESTS ENVIRONMENT GAS IN BRG COMP	INERT ATMOSPHERE	HOHMAN WEAR TEST IN XE-HE	NOT APPLICABLE	COMPLETE
	INTERACTION LUBRICITY	CTR TESTS	NOT IMPLEMENTED (DONE IN WHL)	COMPLETE
10. h_{MIN} MARGINAL-DESIGN VS ACTUAL		HYDRONAMIC ANALYSIS	MODELING OF FOIL DEFLECTING ZERO ECCENTRICITY CASE COMPLETE, GAS FILM PRESSURE COMPLETE	ANALYZE SELECTED CONFIGURATIONS
		COMPARE TO DC-10 BEARINGS NO MEASUREMENT	COUPLING OF GAS FILM LOAD - FOIL DEFLECTION IN PROGRESS	CHARACTERIZE SENSITIVITY TO BEARING PARAMETERS
11. ACTUAL BEARING LOADS		CALCULATE BEARING LOADS FOR ACTUAL OPERATING CONDITIONS (STATIC)	IN PROGRESS	CONTINUE ANALYTICAL DEVELOPMENT
12. MECHANICAL DESIGN & CONTROL		DIM ANALYSIS AND REVIEW CRITICAL CARDS	COMPLETE - DIMENSIONAL ANALYSIS INDICATES NO ABNORMAL INTER- FERENCES	COMPLETE
13. BRG PERFORMANCE	HIGH POWER LOSS IN KR AT PRESSURE	SBTR	TESTS IN PBTR UNDER WAY TO CHARACTERIZE UNCOATED, ALTERNATE COATINGS AND ALTERNATE CONFIGURA- TIONS IN AIR, ARGON, KRYPTON & XE-HE FROM 0-100 PSIA	PBTR TESTS CONTINUE

31-2919
Page 3-15

Figure 3.5-3

CON 1.

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION
PHOENIX, ARIZONA

During the period following the November bearing failure, a major effort was also directed at improving the method of fabricating the bearings and, equally important, inspecting the process and the finished product. This effort resulted in a great improvement in controlling radius of curvature, edge skew, material composition and thickness, and overall dimensional control.

Investigation into electrical arcing revealed that the phenomena could occur under conditions where the bearings were totally lifted off the shaft. This investigation, however, raised another question, that is, whether the foils were completely losing contact with the shaft. Electrical continuity measurements revealed that only on a seemingly random basis, was total loss of continuity achieved.

Continuity tests were conducted on the highly successful DC-10 foil bearing machine. With the sensing circuit on low sensitivity, continuity was apparently lost; however with high sensitivity, spikes of continuity were observed. This testing led to the design, fabrication, and installation of a continuity/ground probe for the Mini-BRU.

Subsequently, further detailed thermal analysis revealed that the compressor-end sway space was reduced at operating temperature by 0.0008 inch whereas the turbine-end sway space was reduced by 0.0005 inch. This was judged to be significant since both bearing failures had involved the compressor bearing.

Based on the analysis and test results of that date, another WHL test was scheduled. The design modifications to the Mini-BRU are tabulated in Figure 3.5-4.

This test was initiated on April 7, 1978, and was originally targeted as a 100 hour bearing verification test. The initial 100 hours were completed and indications were that the bearing was performing well. Figure 3.5-5 shows the chronology of continuity measurements

MINI-BRU DESIGN CHANGES FOR 4/4 WHL TEST

- INCREASED BLEED FLOW FOR BEARING COOLING (~50% INCREASE)
- SLOTTED RETAINER ON COMPRESSOR END JOURNAL BEARING
- INCREASED SWAY SPACE

0.0099 COMPRESSOR COLD (0.0091 HOT)

0.0092 TURBINE COLD (0.0087 HOT)

- CREST COATED JOURNAL FOILS

8 $\sqrt$ SURFACE FINISH

630°F CURE

- CONTINUITY/GROUND PROBE
- BEARING CAVITY ΔP INSTRUMENTATION
- PROVISION FOR ASSURING KEEPER IS ALWAYS WIDER THAN FOIL

APRIL 7
AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION
PHOENIX, ARIZONA

APRIL 8

1 K Ω

31-2919
Page 3-18

100 K Ω

BEARING CONTINUITY HISTORY
FIGURE 3.5-5a

APRIL 9

APRIL 12

1 K Ω

31-2919
Page 3-19

100 K Ω

BEARING CONTINUITY HISTORY

FIGURE 3.5-5b

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION

taken at intervals during the test. Note that the spikes of continuity are gradually diminishing with time. In addition to continuity, bearing temperatures remained absolutely stable throughout the test period.

A decision was made to continue the test to 250 hours. As the 250 hour test was achieved, management decided to continue the test for 1000 hours in lieu of a formal GDS test. A total operating time of 1006.9 hours was successfully completed in May 22, 1978.

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION
PHOENIX, ARIZONA

4. TECHNICAL ACHIEVEMENT

4.1 FS Preliminary Design

The FS was carried through a preliminary design phase to the extent necessary to derive a GDS which was flight prototypical within the constraints of time, budget, and the use of GFE hardware. Figure 4.1-1 lists the design objectives imposed by the BIPS contract.

The following is a list of constraints imposed by AIRPHX with DOE concurrence:

- o BIPS should be a stand alone system which depends on the spacecraft only for a mount flange. All of the BIPS components are tied to the radiator, and the radiator is mounted on the aforementioned flange.
- o The structure and components will be able to withstand all shuttle/IUS imposed loads.
- o Minimize weight where practical
- o Use 2 HSAs each with an MHW heat source and maximize efficiency.
- o Design the radiator for non-puncture probability of 0.99 for 7 years.
- o Use NASA Mini-BRU with minor changes
- o Use NASA HSA configured for minimum weight
- o Modify the design of the NASA MBR for minimum weight but retain all important design features.

BIPS DESIGN OBJECTIVES

- (1) The FS will be capable of power output from 500 to 2000 W_e , EOM, with minimum redesign and requalification.
- (2) 28 ± 2 percent vdc is the reference output voltage.

NOTE

A capability for higher ac voltage output may be advantageous if the output can be achieved directly from the generator.

- (3) The control system will be capable of modulating power to the spacecraft from 0 to 100-percent in 20 milliseconds response times. This will be accomplished by a parasitic load.
- (4) Partial power during launch is desirable.
- (5) Ability to operate with either non-spinning or spin stabilized spacecraft for orbital transfer and/or throughout the mission would be advantageous; however, most potential missions will be on nonspinning spacecraft.
- (6) FS life time requirements is $L = 7$ years and mean mission duration (MMD) = 5 years.

where $MMD = \int_0^L \frac{RDT}{R} dt$ (translates to $R = 0.60$ for 5 years)

- (7) Based on a GFE heat source cost of \$1000 per W_t , the recurring cost goal for the FS at 1300 W_e will be less than \$5000 per W_e .

- (8) FS weight goal, at 1300 W_e , is 450 pounds.
- (9) The FS will be capable of launch on the space shuttle.
- (10) Due to a potential explosive vapor environment, the on-pad temperature of exposed surfaces will be maintained below 380°F.
- (11) The system will be designed with an assumed sink temperature equal to, or greater than, that of a geo-synchronous orbit (19,323 NM). The system will be capable of stable operation with unbalanced solar input.
- (12) Thermal input to the spacecraft must be of an amount that will not cause the spacecraft to rise above 100°F.
- (13) The magnetic field at one meter is not yet defined.
- (14) The on-pad biological dose at one meter will be ≤ 0.20 rem per hour.
- (15) The FS will be resistant to natural and man-made radiations.
- (16) FS components will be inherently flexible in mounting to facilitate integration with the required spacecraft configuration.
- (17) On-pad and in-orbit fueling capabilities should be provided.

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION
PHOENIX, ARIZONA

The design study proceeded into a thermodynamic evaluation and a structural design effort. Description of the thermodynamic effort follows:

The system was optimized thermodynamically as shown in Figure 4.1-2. Each of the points shown in Figure 4.1-2 represents a system which was designed by varying compressor inlet temperature, recuperator effectiveness, radiator pressure drop, and recuperator pressure drop. These design points were generated using empirical descriptions of the Mini-BRU compressor, turbine, alternator and bearings, the recuperator fins, radiator coating, and the insulation performance in a sophisticated computer code. This code then described the geometry of the recuperator and radiator for each combination of parameters listed above. A system with minimum specific weight meeting the output power required was selected and represented by the cycle schematic shown in Figure 4.1-3. A weight summary is shown in Figure 4.1-4.

The item called the enclosure was included to provide the capability of providing part power at the launch pad. The enclosure must be used to provide a boundary for the low conductivity inert gas which allows the insulation system to operate at some level of efficiency and to protect hot columbium components from an oxidizing atmosphere while operating. A heavier enclosure (62 lb) would allow full power operation because it could provide a vacuum environment. The weight of both designs was predicated on the use of Lockalloy.

Detailed sensitivity analysis was performed and is presented in the BIPS Configuration Control Document (75-311274C). An abbreviated look is provided in Figure 4.1-5 which shows the effect upon overall system performance of small changes in system and component performance parameters. The BIPS configuration study was initiated with the examination of two component arrangements, the Mini-BRU vertical and horizontal as shown in Figure 4.1-6, other variations were investigated, evaluated, and discarded. The vertical Mini-BRU configuration was

TYPICAL WEIGHT OPTIMIZATION RESULTS

FIGURE 4.1-2

PSB17787

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION
PHOENIX, ARIZONA

FLIGHT SYSTEM CYCLE SCHEMATIC

FIGURE 4.1-3

PSB17790

FLIGHT SYSTEM WEIGHT SUMMARY

<u>COMPONENT</u>	<u>WEIGHT LB</u>	<u>COMMENTS</u>
HSA (2)	180	
RECUPERATOR	75	
MINI-BRU	38	
STRUCTURE	38	
PARASITIC LOAD RADIATOR	5	
INSULATION	30	
CONTROLS	10	
RADIATOR	63	134 SQ FT, 5-FT DIAMETER
ENCLOSURE	35	
DUCTING	<u>24</u>	
TOTAL	498	
DELETE ENCLOSURE	-35	134 SQ FT, 10-FT DIAMETER RADIATOR ADDS 12.5 LB
TOTAL	463	

31-2919
Page 4-6

PSB17788

FIGURE 4.1-4

BIPS SENSITIVITY FACTORS

	PARAMETER VARIATION	RESULTING CHANGE $\Delta\eta_{CY}$, %
COMPRESSOR η	1%	0.55
TURBINE η	1%	0.55
ALTERNATOR η	1%	0.32
E_R * 0.97 to 0.96	1%	1.2
β where $\beta = 1 - \frac{\Delta P}{P}$	1%	0.8
THERMAL LOSS	-160 watts	1.0
BEARING LOSS	-44.3 watts	1.0
COMPRESSOR INLET TEMP**	-16°F	1.0
TURBINE INLET TEMP	60°F	1.0
EMISSION	6.5%	0.5
SINK TEMP	-26°F	1.0

* E_R IS THE RECUPERATOR HIGH PRESSURE SIDE EFFECTIVENESS.

**ACHIEVED BY ADDING (12%) 14 FT² RAD. AREA. REFER TO FIGURE 1-7, CCD.

31-2919
Page 4-7

FIGURE 4.1-5

PSB17791

COMPARISON OF VERTICAL AND HORIZONTAL MINI-BRU CONFIGURATIONS

HORIZONTAL MINI-BRU

**VERTICAL MINI-BRU
(CURRENT BASELINE CONFIGURATION)**

FIGURE 4.1-6

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION
PHOENIX, ARIZONA

selected because it minimized the impact of the Mini-BRU's angular momentum on the spacecraft and was preferred for operation through launch since the launch load was taken through the Mini-BRU thrust bearing. Details of the logic which led to this decision are given in IBFS Miscellaneous Design Notes AiResearch Report {76-312000}.

After the component scheme was determined, work continued with the radiator to minimize length in the space shuttle bay. The configurations examined are shown in Figures 4.1-7, 4.1-8, 4.1-9 and 4.1-10. Figure 4.1-10 is expressly designed for interface with the IUS and hence minimum length in the shuttle bay. Note that all configurations show the optimum enclosure.

Among the important results of the system study were the acknowledgement that:

- o Ground and Airborn Support Equipment will be required to cool the MHW Heat Source.
- o Volume could be minimized if the spacecraft were integrated with the radiator.
- o A beryllium or Lockalloy radiator would be needed to approach the weight goal.
- o The Mini-BRU orientation has an important effect on component volume.
- o The BIPS should be launched quiescent aboard the Space Shuttle and started before the IUS is launched.

The configuration selected was carried into the GDS design phase as the concept to be translated into hardware. The two documents which show the detail of the FS is the Configuration Control Document (75-311274C) and the System Design Specification (SC-76-311742A).

BIPS-FS CONCEPTUAL STUDY - 5-1/2 FT RADIATOR ENVELOPE

FIGURE 4.1-7

PSB17782

BIPS-FS CONCEPTUAL STUDY - 5-1/2 FT RADIATOR ENVELOPE

FIGURE 4.1-8

PSB17783

BIPS-FS CONCEPTUAL STUDY – 5-1/2 FT INTEGRATED RADIATOR ENVELOPE

FIGURE 4.1-9

PSB17784

BIPS-FS CONCEPTUAL STUDY 10 FT RADIATOR ENVELOPE

31-2919
Page 4-13

FIGURE 4.1-10

PSB17785

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION
PHOENIX, ARIZONA

4.2 GDS Design

The GDS preliminary design was based upon the FS preliminary design. The recuperator, HSA, and Mini-BRU geometries were the focal points of the GDS design effort since these components were subject to only minor changes. Modifications of the preliminary design were made to account for this fact; design of the bellows, ducting, and structure proceeded at this time. Interfaces with the vacuum tank and facility were defined, and an instrumentation drawing was completed; the vacuum level and materials requirements of the BIPS, as well as accurate performance measurement were of primary consideration in this effort.

During the GDS effort, columbium was replaced as the material of choice for the turbine plenum, HSA, HSHX, and connecting ducting. The baseline GDS and FS were then based on a 1450°F maximum metal temperature with Hastelloy-X selected as the new material for these components. The performance penalties were evaluated and found not to be severe. One interesting fact is that the MBR was closer to the size required for a superalloy system than that required for a columbium system.

Also, proceeding from the WHL study was the alternate HSA (AHSA) study and subsequent follow-on under NASA sponsorship. The predicted performance shown in Figure 4.2-1 is based upon the AHSA and its ability to approach maximum allowable metal temperature better than any other of the designs considered. The single helical tube HSHX was selected specifically for its heat transfer, reliability, and fabricability features.

4.2.1 BIPS Frequency and Stress Analysis

A frequency and stress analysis was performed on the BIPS in accordance with the design criteria of Table I. The design criteria were based on the model of the dynamic system shown in Figure 4.2-2 and the rationale presented on Table II. The frequency analysis

1300 W_e @ 2 HSA WITH MBR

1349 WATTS
OUTPUT (GROSS)

NET OUTPUT 1305 W_e
NET EFFICIENCY 0.272

31-2919
Page 4-15

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION

FIGURE 4.2-1

SCHEMATIC OF DYNAMIC SYSTEM

FIGURE 4.2-2

BIPS DESIGN CRITERIA FOR PRELIMINARY RIGIDITY AND STRENGTH REQUIREMENTS

1. LOWER LIMIT OF FUNDAMENTAL FREQUENCIES OF THE BIPS MOUNTED COMPONENTS TO BE APPROXIMATELY 60 CPS.
2. LIMIT LOADING OF THE BIPS COMPONENTS TO BE 50 G's.
3. LIMIT LOADING OF THE BIPS INTERFACE STRUCTURE TO BE 25 G's.

TABLE I

BASIS FOR BIPS DESIGN CRITERIA FOR PRELIMINARY RIGIDITY AND STRENGTH REQUIREMENTS

REFERENCE 76-311998

UPON THE ASSUMPTION THAT THE PAYLOAD CONSISTING OF THE BIPS-SPACECRAFT-IUS ASSEMBLY IS CANTILEVERED MOUNTED TO THE SPACE SHUTTLE.

- A. AVOID COUPLING OF THE FUNDAMENTAL FREQUENCIES OF THE CANTILEVERED PAYLOAD WITH THE FUNDAMENTAL FREQUENCIES OF THE SPACE SHUTTLECRAFT (3-13 CPS).
- B. AVOID COUPLING OF THE FUNDAMENTAL FREQUENCIES OF THE DISCRETE MASSES OF THE BIPS WITH THE FUNDAMENTAL FREQUENCIES OF THE CANTILEVERED PAYLOAD. RESULTS IN A LOWER LIMIT OF THE NATURAL FREQUENCIES OF THE BIPS COMPONENT OF ABOUT 60 CPS.
- C. AVOID HIGHER FUNDAMENTAL FREQUENCIES OF BIPS COMPONENTS THAN NECESSARY TO SATISFY A. AND B. ABOVE IN ORDER TO MINIMIZE THE DYNAMIC RESPONSE TO SHOCK AND VIBRATION.
- D. SHOCK AND VIBRATION RESPONSE OF THE MHW-RTG FOR THE LES 8 AND 9 DURING QUALIFICATION TESTING.
- E. PROVIDE HIGHER STRUCTURAL CAPABILITY FOR THE BIPS COMPONENTS AND MOUNT PADS THAN THE COMPONENT INTERFACE STRUCTURE TO COMPENSATE FOR STATICALLY DETERMINATE MOUNTING SYSTEMS AS COMPARED TO THE REDUNDANCY OF THE INTERFACE STRUCTURES.

TABLE II

FREQUENCY ANALYSIS SUMMARY

REFERENCE 76-311998

APPROACH

1. FIRST APPROXIMATION OF THE FLEXURAL BENDING NATURAL FREQUENCIES OF THE CRITICALLY LOADED INTERFACE BEAMS AND STRUTS.
2. THE FUNDAMENTAL FREQUENCIES OF THE RADIATOR WERE DETERMINED BY KALNIUS SHELL PROGRAM LUMPING THE TOTAL MASS TOGETHER.
3. A DYNAMIC MODEL WAS SET UP TO DETERMINE THE FUNDAMENTAL FREQUENCIES OF THE INTERFACE STRUCTURES AS A SYSTEM.

HSA	180 LB
RECUP	100
MINI-BRU	38
INTERFACE STRUCTURES	42
MISC	20

TOTAL MASS 380 LBS

RESULTS

	LATERAL VIB (CPS)	LONG. VIB (CPS)	RADIAL VIB (CPS)
ALUMINUM	70	210	82
LOCKALLOY	139	417	163
BERYLLIUM	190	170	223

FUNDAMENTAL FREQUENCY OF THE RADIATOR

TABLE III

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION
PHOENIX, ARIZONA

summary is shown in Tables III and IV; the stress analysis summary is shown on Table V. For further information, Refer to AIRPHX Report Nos. 76-311998 and 76-311773.

4.2.2 GDS Layout and Support Structure

The GDS components, ductings, and support structure layout and interface requirements are included in AiResearch Report No. 76-311972. The GDS was a duplicate of the flight system, except for the radiator, control system, and portions of the ducting. The radiator and the structure mounting configurations are largely dependent on the spacecraft and mission requirements. The BIPS was designed to integrate effectively with almost any spacecraft. The support structure for the GDS, shown in Figure 4.2-3, was a flight prototypical configuration which serves to position and support the BIPS components within the GDS vacuum chamber or flight system radiator. The GDS interfaces and mount system are shown in Figure 4.2-4.

In order to minimize weight and maintain a high degree of stiffness and strength, tubular construction was selected. The FS was predicated on use of Lockalloy (a Be/Al composite); the GDS duplicated the FS structure using aluminum. The BIPS system has adequate stiffness and strength to avoid user integration problems. The BIPS GDS is shown in Figure 4.2-5.

4.2.3 BIPS Control System

4.2.3.1 Review

Early in the Phase I program, prior to the preliminary design review, three control systems were analyzed for possible use on the BIPS GDS and flight systems. An analog control, designed and bread-boarded by NASA-Lewis was provided as GFE and served as a baseline for comparison of the controls. This system was analyzed and tested and

FREQUENCY ANALYSIS SUMMARY

U = UPPER BEAM
L = LOWER BEAM

LOWEST NATURAL FREQUENCY OF THE BIPS (CPS)

UPPER LOWER	1-1/2x1/16	1-1/2x1/8	1-3/4x1/16	2x1/16	2-1/4x1/8	3x1/8
1x1/16	A 38 L 74 B 101					
1x1/8	A 42 L 82 B 112	A 56 L 110 B 153				A 70 L 138 B 190
1-1/2x1/16				A 54 L 108 B 149		
1-3/4x1/16			A 55 L 106 B 146			
2x1/16				A 63 L 125 B 171		
2-1/4x1/8					A 84 L 165 B 227	

NOTE: (1) A = ALUMINUM
L = LOCKALLOY
B = BERYLLIUM

TABLE IV

STRESS ANALYSIS SUMMARY

REFERENCE 76-311998

1. UPPER STRUCTURE, 1 1/2 X 1/16 LOCKALLOY TUBE, SUPPORTS THE HSA.
2. LOWER STRUCTURE, 1 X 1/16 LOCKALLOY TUBE, SUPPORTS THE MINI-BRU AND RECUPERATOR.
3. ALL LOADS TRANSMITTED TO THE RADIATOR.
4. ALL MOUNT PADS ARE DESIGNED FOR 50 G's. ALL INTERFACE STRUCTURES ARE DESIGNED FOR 25 G's.

31-2919
Page 4-22

TABLE V

FLIGHT PROTOTYPICAL SUPPORT STRUCTURE

FIGURE 4.2-3

GDS INTERFACES - MOUNT SYSTEMS

FIGURE 4.2-4

BIPS-GDS

(INSTALLED IN VACUUM CHAMBER)

FIGURE 4.2-5

AIRESRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION

provided information to form the basis for a second, improved analog control incorporating the basic NASA circuitry plus design changes to improve its reliability and performance.

A third control based on microprocessor technology was conceived and analyzed to provide a trade-off between an analog versus digital approach.

When the analyses of the three controls were complete, they were compared on the basis of reliability, performance, including speed control, load control, beginning of mission power, end of mission power, power quality, and EMI effects of the parasitic load switches. The tabulated results of this comparison appears in Figures 4.2-6 and 4.2-7. The computed reliability using the methods of MIL-HDBK-217B showed all three controls to be greater than 0.99 for five years.

Based on the greater flexibility, reliability, and performance of the microprocessor control, it was decided to proceed in the direction of a digital control. A hardwired digital control was breadboarded for use with the BIPS GDS in order to determine word-length, gain, throughput, and sampling rates required to provide stable control for the BIPS flight system.

This control, along with its integral synchronous start inverter, was used during all WHL and GDS operations during Phase I.

Rotor breakaway, acceleration to self-sustaining speed, and control of voltage and load at full rated speed have been demonstrated repeatedly. Transient response to load and speed perturbations was well within acceptable limits. Figure 4.2-8 illustrates transient responses to a gross speed change, a 50 millisecond removal of load at a loop gain of 580 watts/percent speed, and a 50 millisecond removal of load at a loop gain of 290 watts/percent speed. In this figure, power applied to the system by the parasitic load control is plotted as a function of time.

ANALYSES TRADE OFF

	NASA CONTROL	NASA IMPROVED	DIGITAL CONTROL
PERFORMANCE			
SPEED CONTROL	$\pm 2\%$	$\pm 0.5\%$	$\pm 0.1\%$
LOAD CONTROL	$\pm 10\%$	$\pm 10\%$	$\pm 1.0\%$
BOM POWER	1.095 KW	1.250 KW	1.300 KW
EOM POWER	0.915 KW	1.060 KW	1.200 KW
POWER QUALITY	PER SC-76-312008		
PARASITIC LOAD SWITCHING - (EMI)*	55A PWM	55A PWM	1.6A PWM

* ANALOG - 1540 W LOAD
DIGITAL - 2565 W LOAD

FIGURE 4.2-6

ANALOG VERSUS DIGITAL TRADEOFF

CONSTANT SPEED SYSTEM

	ANALOG	DIGITAL
RELIABILITY		
FAULT TOLERANCE	LIMITED	EXTENSIVE
RECONFIGURABILITY	NONE	EXTENSIVE
FLEXIBILITY	NONE	EXTENSIVE
GROWTH CAPABILITY	MINIMAL	HIGH
POWER REQUIREMENTS	MODERATE	SIMPLE
USER INTERFACE	POOR	GOOD
TELEMETRY INTERFACE	POOR	GOOD
PERFORMANCE	LOW	HIGH
WEIGHT AND VOLUME	COMPARABLE	COMPARABLE

FIGURE 4.2-7

WORKHORSE LOOP TEST RESULTS

- NO DETECTABLE SPEED (± 10 RPM) OR LOAD (± 1 WATT) CHANGE WITH USER LOAD CHANGE
- TRANSIENT STABILITY DEMONSTRATED
 - LARGE TRANSIENT (FULL POWER ACCEL)

- SMALL TRANSIENT (50 MSEC INTERRUPT)

FIGURE 4.2-8

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION
PHOENIX, ARIZONA

In the steady state, the system exhibits acceptable, stable performance in both the load and speed control. With a full rated user load change of 1300 watts, unit speed varies less than 10 rpm and total system load changes less than 1 watt, due to the action of the constant load control. Total output power is maintained at 1300 watts at 100 percent speed and varies at a gain of 290 watts/percent speed around that point.

Block Diagram

The control system block diagram appears in Figure 4.2-9 and represents both the GDS FS.

The start inverter provides conditioned three-phase power to the terminals of the alternator. As the unit rotates, feedback signals from the monopole pickup provide speed and rotor position information to the start inverter, allowing the driving waveform to lock into synchronism with the spinning rotor. At approximately 25,000 rpm, the loop becomes self-sustaining and the inverter is shut off. At approximately 95 percent speed, parasitic load begins to be applied as directed by the speed sensor and parasitic load control.

After the Mini-BRU has reached the self-sustaining speed of 26,000 rpm, it will accelerate, on its own, to the design operating speed of 52,000 rpm. Prior to the Mini-BRU reaching design speed, the alternator field is excited by the voltage regulator/exciter, and the alternator begins producing a three-phase ac voltage. The ac voltage is full wave rectified to provide 120 volts dc to the user load.

Design speed is held within ± 0.1 percent of the desired operating point by the speed control. Speed control is effected by a parasitic load in parallel with the user load. If the speed sensor senses an overspeed condition, the parasitic load will increase, and rotating speed will be restored to design point. Conversely, reduction in speed below the programmed setpoint results in a reduction in parasitic load.

SIMPLIFIED BLOCK DIAGRAM

FIGURE 4.2-9

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION
PHOENIX, ARIZONA

Once steady-state system operation (52,000 rpm, 1385°F turbine inlet temperature, and 1.3 kW_e output power) has been reached, the full user load can be applied. The load sensor maintains the total of user load plus parasitic load at a constant level. A change in user load results in an offsetting change in parasitic load so that total load on the system remains at a value which results in constant speed.

Performance

The performance map of the GDS and flight systems appears in Figure 4.2-10. Usable output electrical power is plotted versus rotor speed as a function of input isotope power (Q_{in}) and turbine inlet temperature (T₆). At the beginning of mission (BOM), the system operates at 100 percent speed to produce 1300 We from 4.8 kW_t isotope thermal power and at a resultant T₆ of 1385°F. At the end of the flight mission (EOM), assuming a seven year mission, the system operates with 4.5 kW_t input at a T₆ of 1385°F and produces 1220 Watts at a rotor speed of 96.8 percent of the 52,000 rpm BOM rotor speed. This approach allows the unit to operate at reduced turbine inlet temperature, thereby improving the system's reliability, yet providing maximum allowable end of mission power.

The breadboard digital control fabricated for use on the GDS is capable of causing system operation anywhere on the performance map of Figure 4.2-10, consistent with system input power, and was used to gather data at various operating points. Adjustment of operating point was accomplished by resetting thumbwheel switches on the front panel of the control.

4.2.4 Heat Source Assembly (HSA)

The development of the HSA for the GDS was carried out in three segments: the superalloy Heat Source Heat Exchanger (HSHX) was analyzed and designed by AIRLA, the HSHX was fabricated under AIRPHX

CONTROL THEORY

FIGURE 4.2-10

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION
PHOENIX, ARIZONA

control, and the HSA elements were assembled by GE Valley Forge utilizing the HSA housings and support structure initially intended to house the refractory HSHXs.

4.2.4.1 Superalloy HSHX Analysis and Design

Design Requirement

The need for an alternate heat source heat exchanger (HSHX) design was first identified during the heat source assembly (HSA) design review conducted during October, 1975. The review indicated a potential for substantial improvement in the HSA performance, life, and reliability by modifying the current annular plate-fin heat exchanger design.

It was suggested that a single tube formed in a helical coil would meet performance requirements and provide enhanced reliability and reduced development risk compared to the annular plate-fin configuration. Preliminary studies of straight and helical flow multiple designs confirmed the potential benefits of the single helical tube design.

Concurrently, system optimization studies indicated that the BIPS performance objectives could be met by optimizing at a reduced operating temperature level. A reduction in turbine inlet temperature permits the use of a superalloy for the HSHX rather than the refractory alloy, Columbium C-103, and this also produces enhanced reliability and reduced development risk.

Accordingly, a study was initiated to accomplish a detail design of a superalloy coiled tube HSHX. The objectives were to establish heat transfer performance, the structural design including an assessment of cyclic life, and a detail design of the single helical tube heat exchanger. The goal was to confirm the potential performance and reliability advantages of their particular configuration.

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION
PHOENIX, ARIZONA

Alternate HSA Study

The study effort at AIRLA for the BIPS superalloy HSA involved the analysis and design of a single tube helical coil HSHX to be constructed of Hastelloy X. The specific objectives included establishing the thermal performance and pressure drop at normal operating conditions, evaluating the structural characteristics including an assessment of low cycle fatigue (LCF) life, analysis of the auxiliary cooling system (ACS) mode of operation, and the preparation of a detailed design drawing of the HSHX.

SUMMARY

The HSHX design uses a coiled Hastelloy X tube consisting of 10 turns of 1.56 in. OD by 0.050 in. wall thickness and wrapped in a 9.42 in. mean coil diameter. The heat exchanger is designed to be installed in a heat source assembly where it receives heat by radiation from a 2400 watt isotope heat source. It can be installed without modification of the current HSA. The unit is designed to operate at maximum conditions for 7 years.

Heat transfer performance calculations have shown that the unit will heat xenon-helium gas (molecular weight = 83.8) from 1103° to 1394°F with a maximum heat exchanger wall temperature of 1450°F. The overall HSA heat loss is predicted to be 5.8 percent based on using a 60-layer nickel multifoil insulation system.

For an electric heat source, as used for ground testing, almost 3.0 hr. are required for the heat exchanger to reach a specified startup temperature of 1400°F with the unit initially at 70°F. During the heatup portion of the cycle, the maximum temperature gradient developed around the tube circumference is 160°F. When the heat exchanger reaches 1400°F, flow is initiated. Within 3.0 minutes, the metal temperature at the heat exchanger inlet has drooped to 850°F and a maximum circumferential temperature gradient of 267°F has been developed.

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION
PHOENIX, ARIZONA

In an auxiliary cooling mode, with the HSA filled with helium gas and the power system on the launch pad, the maximum temperature of a surface exposed to the launch pad environment is 174°F which is below 380°F hazard limit.

The best structural design was determined to be a configuration in which the individual coils are brazed together to form a continuous structure. The brazed coil natural frequency was determined to be above the specified 60 Hz lower limit. The heat exchanger mounts were designed to withstand a 50g inertial load.

Low cycle fatigue life of the heat exchanger was checked and found to be at least 300 cycles based on the combined thermal and pressure stress developed during a system startup transient. This life exceeds the 100 cycle design goal.

4.2.4.2 Superalloy HSHX Fabrication

The fabrication of the Hastelloy-X HSHX was initiated concurrently with the detail analysis and design of the unit by AIRLA. This was necessary because of the short GDS test schedule then in effect. This was accomplished quite handily by performing initial conservative stress calculations to establish the tube wall thickness and tube diameter. Envelope constraints were established by the existing refractory HSA core and support structure. Simple layouts revealed that a 10-turn spiral coil with 1.560 in. diameter tubing was optimum for the envelope, and that 0.050 in. wall thickness was adequate for the pressure containment.

The required Hastelloy-X tubing was ordered from Trent Tube, Milwaukee, Wisconsin, with a 6-8 week lead time. This allowed more than adequate time for the detail design/analysis iteration process to arrive at the configuration details.

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION
PHOENIX, ARIZONA

The final design was the configuration shown in Figure 4.2-11 (Drawing 3606334). The coil was brazed together into a rigid mass with gold braze alloy. The end elbows were fabricated in two halves by drawing, then welded together and to the coil. Mounting brackets were fitted and forged to the coil to match with the mounting slots on the HSA-end supports.

The next task was finding a vendor with the capability of forming the somewhat "tight" tube coil. Saffron Engineering Company, St. Claire Shores, MI. contracted to produce the first coil.

Saffron used a horizontal axis coil forming machine as shown schematically in Figure 4.2-12. The coil was fed through repeatedly each time reducing the coil radius slightly until the desired diameter was achieved.

The full-size HSHX required 27-foot lengths of tubing to produce a one-piece coil. Ten-foot lengths were procured to produce 3-turn sample coils to prove the process.

The 3-turn coils were formed to the proper diameter with some difficulty. The vendor then welded two 10-foot lengths together and rolled a 7-turn coil. This coil is shown in Figures 4.2-13 and 4.2-14. Of special note is the dimpled effect on the ID and the distress indicated on the axial sides of the tubing. The former occurred during the last two inches of coil forming, and the latter was the result of distress between the coil and the machine housing. In addition, the tubing was severely elliptical in cross-section with a diametral difference of 0.030 inch.

Saffron indicated little interest in trying to improve the technique to gain the quality required for the BIPS program. Fortunately, efforts to locate another capable vendor had achieved success. J.B.

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION
PHOENIX, ARIZONA

31-2919
Page 4-39

HORIZONTAL AXIS COIL FORMING MACHINE

FIGURE 4.2-12

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION
PHOENIX ARIZONA

SEVEN-TURN HSHX COIL

FIGURE 4.2-13

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION
PHOENIX, ARIZONA

SEVEN-TURN HSHX COIL

FIGURE 4.2-14

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION

Enterprises, Tustin, California, felt they had the technology required to form the coil. Their technique differed in that they used a vertical axis forming machine, Figure 4.2-15, and pressurized the tube to retain the circular cross section.

J.B. Enterprises formed a 3-turn coil and a 10-turn coil with great success. The 3-turn coil with one end elbow welded on is shown in Figure 4.2-16 and Figure 4.2-17. The clean surface finish and the absence of dimpling are to be noted. The cross section was nearly circular with a diametral difference of approximately 0.010 inch.

The 10-turn coils from J.B. Enterprise were then delivered to a Phoenix vendor, Mercury Tool and Die, for the final brazing and finishing operation. Their task was to achieve a finished product as shown in the Engineering Drawing 3606334.

The coil brazing operation was accomplished at AiResearch under the supervision of AiResearch metals joining engineers. The first operation was to stress-relieve the coil. This was done in the brazing fixture so that the coil would retain its shape. Such was not to be, for the coil shrank in diameter by about 0.090 inch. Fortunately, this had been allowed for in the design, so adequate clearance was still available with the EHS outer surface.

Spacers were then placed between the coil axial surface to get the required end-to-end distance. (This was a critical fixed dimension because of the existing HSA envelope.) The coil was then brazed; two passes through the furnace were required to fill all voids.

When the braze was completed, the unit was returned to Mercury for the fitting of the end elbow and mounting bracketry. This was accomplished; the coil elbows were fitted and welded and bracket mountings were tack-welded in place; a final pass was made through the braze furnace to complete the joining process.

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION
PHOENIX, ARIZONA

VERTICAL AXIS COIL FORMING MACHINE

FIGURE 4.2-15

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION
PHOENIX, ARIZONA

J. B. ENTERPRISES THREE-TURN COIL

FIGURE 4.2-16

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION
PHOENIX, ARIZONA

J. B. ENTERPRISES THREE-TURN COIL

FIGURE 4.2-17

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION
PHOENIX, ARIZONA

Finally, the inlet and outlet elbows were machined to the final tolerance, and the mounting pin holes were precisely drilled and reamed. The mounting pins were installed and tack welded in place and the coils were completed.

Photographs of the first HSHX are shown in Figures 4.2-18, 4.2-19, and 4.2-20.

The second heat exchanger was completed in a similar manner and both units were inspected, packaged, and shipped to GE for installation into the HSA.

4.2.5 Heat Rejection Heat Exchanger (HRHX)

The Heat Rejection Heat Exchanger (HRHX) was tested in Phase I of the BIPS program both as a component and as part of the WHL system. The HRHX was tested as a component to DT-6812-1. (This is Development Test Procedure ERDA/BIPS Heat Rejection System Performance Verification, Dynamic Response Determination, and Checkout.) The results of this component test are presented in development test report DTR-6812-1. In summary, the heat rejection system was tested to verify that it would be capable of functioning as required in the WHL. The HRHX system did operate as expected and was installed in the WHL.

The installation in the WHL resulted in operation as anticipated with minor modification. The pressure drop of the long, hard-line piping with many bends resulted in a reduction in liquid glycol cooling flow to where the sub-zero compressor inlet temperatures could not be maintained at high power (high turbine inlet temperature) engine operating points. A large diameter flexible line was then plumbed parallel with the hard line and allowed the high flows required to maintain high power operating points. The HRHX performance in the WHL can be seen from the loop performance program computer printouts. This performance is close to that predicted for the HRHX system, and the overall appraisal is that this system would be satisfactory for any future anticipated use as a ground system HRHX.

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION
PHOENIX, ARIZONA

FIRST HSHX WITH MOUNTS AND ELBOWS ATTACHED
FIGURE 4.2-18

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION
PHOENIX, ARIZONA

TOP VIEW OF FIRST COMPLETE HSHX
FIGURE 4.2-19

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION
PHOENIX, ARIZONA

31-2919
Page 4-49

MOUNTING BRACKETRY AND WELDED ELBOW OF HELICAL COIL HSHX

FIGURE 4.2-20

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION
PHOENIX, ARIZONA

4.2.6 The Mini-Brayton Recuperator

The Mini-Brayton Recuperator (MBR) was developed, built, and tested under the auspices of NASA Lewis Research Center (Contracts NAS3-15347, and NAS3-18029). These programs called for the evolution of a highly reliable high-performance heat recovery device suitable for use on Mini-Brayton cycle space power systems. The resulting recuperator features advanced design concepts combining the product of extensive heat exchanger technology development efforts with testing of a prototype unit.

Description of Unit and Design Features

The MBR is a high-effectiveness, high-temperature heat exchanger that has a low pressure penalty. The basic core configuration is shown in the sketch of Figure 4.2-21. The counterflow portion of the core is of rectangular shape with a flow width of 5.8 in., a flow length of 22.6 in., and a stack height of 10.9 in. The design is of the plate-fin type employing very compact offset fins to enhance the heat transfer. Triangular end sections and manifolds were added to provide access to the appropriate passages of the counterflow core. These were designed to provide good flow distribution into the core with small pressure drop and minimum weight penalties.

The mechanical design of the manifold and other elemental details were developed to provide superior reliability characteristics for the heat exchanger. Design features include:

- o Use of Hastelloy X as structural material
- o Gold-base alloy for enhanced joint integrity
- o Seal plates brazed to the counterflow matrix to reduce number of exposed joints

CORE CONFIGURATION OF MBR RECUPERATOR

FIGURE 4.2-21

S-23677

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION
PHOENIX, ARIZONA

- o Use of channel type header bars
- o Variable thickness outer tube plates
- o Special manifold construction
- o Splitter pan
- o Manifold flange reinforcements brazed onto the hot end of core
- o Minimum weight mounts

The channel type header bars reduce the thermal lag during the transient operation, reducing the severity of thermal stress buildup. The variable thickness tube plates in the four outer sandwiches on both sides of the unit provides a gradual transition between thick and thin plates. This feature improves the load distribution during a thermal transient.

High- and low-pressure manifolds on each end of the core assembly are designed as a continuous hoop with a splitter plate to separate the flow streams. The splitter is curved to better withstand pressure differential between the two fluids. The ends of the manifold hoop are attached to the side plates via Y-shaped extensions (flanges) that are brazed to the side plates. This flange configuration eliminates the need to weld directly to braze joints located in highly stressed areas. To improve the load distribution, the flanges are further reinforced by adding a gusset where the flange joins to the sideplate (hot end only). In addition, side plate doublers were extended past the ends of the gussets on the manifold attachment flanges to reduce the strain concentration and thereby alleviate the potential for fatigue cracking observed on the prototype cycle test. The manifold splitter

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION
PHOENIX, ARIZONA

is attached to the apex of the triangular end sections of the core by a tongue-in-groove arrangement. A cover plate at each end of the manifold is used to prevent direct exposure of the splitter-core braze joint to the environment.

The recuperator mounts are designed for a 50g load limit and are intended primarily to transmit loads in shear through the use of spherical bearings. This arrangement makes allowances for misalignment of the unit, for thermal expansion of the assembly, and for variations in manufacturing tolerances. To minimize heat loss from the recuperator, the mounts are designed with minimum contact area.

For very high temperature effectiveness recuperators such as that specified for this application, axial conduction, i.e., heat conduction from the higher temperature end of the recuperator to the lower temperature end can substantially reduce the performance of the recuperator. The use of relatively thin Hastelloy X tube plates and Hastelloy X side bars for this recuperator configuration, coupled with the long counterflow section flow length keeps the axial conduction at an acceptable level.

Another important consideration in the design of recuperators is to ensure that the fluid flow in the counterflow section be as uniformly distributed as possible. The effect of flow maldistribution on the unit performance is such that a 14 percent pressure drop imbalance reduces the effectiveness by 1 point.

During design of the unit, uniform flow distribution was achieved, by independently varying the end section height and adjacent side ratio at both ends of the recuperator, to obtain equal total pressure losses for equal mass velocities along all parallel flow paths. This was accomplished by using an AiResearch end section computer program and resulted in the asymmetrical end section shape of the MBR unit.

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION
PHOENIX, ARIZONA

The manifolds were designed to fit over the triangular end sections. For structural and pressure containment reasons, a cylindrical manifold shape, with an axial splitter plate to separate the high and low pressure fluids, was desirable. With this design constraint, the end section design essentially fixed the manifold design.

In order to ensure uniform flow into each of the recuperator core passages (stack height direction), specific manifold flow areas are required. These areas were determined using the AiResearch manifold design computer program. To meet both the flow area and overall cylindrical shape requirements, flow blockage inserts or baffles were used on the cold end of the recuperator.

Recuperator Performance

A full-scale prototype recuperator was built incorporating all the features discussed in the previous paragraphs. The unit was subsequently evaluated for thermal performance. The performance tests were conducted with air as the heat transfer medium at full temperature and near full pressure conditions. The test results compared favorably with analytical predictions, and scale factors were derived. These were used to predict the performance of the unit operating in a vacuum environment with Xe-He as the heat transfer fluid. The resulting analysis indicated that heat transfer performance with xenon-helium slightly exceeds requirements. The pressure drop exceeded the required value by less than 10 percent, but is offset by the available excess heat transfer capabilities.

The MBR was subsequently built at AiResearch. After passing the necessary acceptance tests, this unit was delivered and installed in the BIPS WHL.

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA

A DIVISION OF THE GARRETT CORPORATION
PHOENIX, ARIZONALow Cycle Fatigue

During the system startup transient, the prototype recuperator temperature response varies in the fins, plates, header bars, and manifolds. Large temperature differences can be produced in adjacent structures due to the difference in the mass and local heat transfer coefficient of the various components. This results in high thermal stresses that can produce plastic deformation in local areas. Damage produced by plasticity and creep during each operating cycle accumulates, and after a sufficient number of cycles, a low-cycle-fatigue (LCF) crack develops. This crack can propagate through the parent metal, weld, or braze joint. Cracking can result in internal bypassing of the working fluid resulting in a loss of system power output; or external loss of working fluid to space presumably resulting in a system failure.

In order to predict the LCF life to crack initiation, a detailed transient thermal analysis of the recuperator was performed. BIPS Start-up Run 101* was utilized for the recuperator inlet conditions. The temperature gradients predicted using Run 101 are large compared to results obtained using the NASA-specified startup transient which was used as the design basis for the MBR. The regions of large thermal gradients are between the header bar and the tube sheet at the junction between the manifold pan and the main core, and along the splitter plate between the manifold pan and the triangular end section of the recuperator.

The transient temperature predictions were used as inputs to a 2-dimensional finite element computer program which was used to compute the resultant thermal stresses and deflections. Local plastic deformation and creep relaxation effects were included in the LCF analysis. According to the conditions of Run 101, the recuperator is initially

*Transient Analysis Isotope Brayton Flight System, AiResearch-Phoenix Report 75-311279, May 19, 1975.

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION
PHOENIX, ARIZONA

soaked at -10°F and is subjected to a low pressure inlet gas temperature of 1600°F instantaneously. This large temperature change generates thermal stresses during startup. It was also found that the manifold pan temperature lags noticeably behind the triangular end section of the core. Maximum stresses are developed between 90 and 130 seconds into the startup at different locations in the unit. Computed life cycles to crack initiation for the critical core sections were as follows:

<u>Prototype (MBR) Elements*</u>	<u>Computed LCF Life (Cycle)</u>	<u>Type of Leakage</u>
Core (E427)	60-120	Internal
Splitter joint (E539)	30-60	Internal
Splitter-core braze joint (E531)	70-140	Internal
Low pressure pan joint (E379)	15-30	Internal
High pressure pan joint (E391)	100-200	Internal

*Elements refer to locations depicted in Figure 4.2-22.

The LCF life represents the number of cycles at which the first crack would form. Unless the stresses were relieved, the crack would propagate, and after a few additional cycles, a leakage path would develop. For the critical elements, the leakage path would be between the high and low pressure flow streams; there would be no external leakage.

Thermal cycling tests were performed on the full-scale prototype recuperator. There was no evidence of external leakage after 100 cycles. A small amount of internal leakage was detected; this leakage rate was not considered large enough to impact the BIPS power output.

ELEMENTS WITH MAXIMUM STRESS AND ELEMENTS ANALYZED
FOR THERMAL FATIGUE

FIGURE 4.2-22

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION
PHOENIX, ARIZONA

It should be noted that the Run 101 startup conditions were generated for a high turbine inlet temperature system (with a refractory alloy heat source heat exchanger) and did not consider the effect of the working fluid inventory in the ducts. More accurate startup runs for the latest BIPS conditions are quite different from Run 101 and will result in different LCF life predictions.

4.3 GDS Detailed Analysis and Design

The original choice of Columbium alloy C-103 for the HSHX, turbine plenum, hot ducting, and bellows led to several questions on the durability of a refractory BIPS flight system. The degradation of high temperature components due to interstitial contamination and the assembly of the C-103 components into the system were the major questions. A shift to a superalloy system was made to reduce the risk factor of C-103 use, and design data for Hastelloy X became the paramount issue. Data obtained to date has shown that the design of the C-103 system could be achieved with care, and that the design of the Hastelloy X system appears to be conservative.

4.3.1 Materials Review

Early in the program the MARSCOM (Material Review and Selection Committee) was formed to oversee the Phase I Materials effort. The committee most recently consisted of:

J. Hadley - AIRPHX (Chairman)
C. Alexander - BCL
J. Griffo - DOE
H. Kling - FI
W. Klopp - NASA
A. Schaffhauser - ORNL

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA

A DIVISION OF THE GARRETT CORPORATION
PHOENIX, ARIZONA

The original intent of the committee was to review the use of C-103, the data base for design, the anticipated system effects including assembly of C-103 to Hastelloy X, and sources of contamination. A comprehensive program was planned and presented in the IPP, AIRPHX Report 75-311574. Although most of this work has been completed, funding was curtailed when the BIPS-S was initiated. The major results of this work will be discussed in Sections 4.3.2 through 4.3.5.

When the system was changed to all superalloy construction, the MARSCOM surveyed the available superalloy data from the aerospace industry and nuclear fields. The decision was made that Hastelloy X, although not the highest strength alloy, had the widest established data base, including long term creep properties. In addition, work being done for HTGR will provide additional data on Hastelloy X before additional data becomes available for most other high temperature, wrought alloys. The available data has been collected from several sources. The initial data was published in AIRPHX Report 31-2626 "Superalloy Brayton Isotope Power System Design Report." The available data from Cabot Corporation and the HTGR program for Hastelloy X creep properties was analyzed, and the creep design curves were published in BIPS Coordination Memo BIPS-GDS-A0521. Additional data on the embrittling effect in Hastelloy X, creep-fatigue interaction, and continuing analysis of the creep data was published in BIPS-GDS-A0603.

Test work has also been initiated on tube creep specimens simulating the spiral wound HSHX. To date, the data lies well within the nominal curves predicted by AIRPHX. Thin wall tubes, representative of a single bellows ply, are available for testing at BCL. The tests are designed to evaluate the possibility of helium leakage at larger creep strains and in particular leakage prior to rupture.

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION

4.3.2 Contamination Sources

The primary sources of columbium contamination were identified as poorly cleaned parts, the alternator stator organic compounds, offgassing of the large surface area of the recuperator, the offgassing of the graphite heat source, and gas entrapment in the foil insulation.

Analysis of the thermal environment of the system, consideration of the materials in use, and confirming tests by BCL resulted in publication of AIRPHX Document 76-312282, "Decontamination Procedure for Brayton Isotope Power System Components."

Using the previously mentioned procedures, the residual contaminants in the loop were assessed, and a contamination model was proposed in BIPS-GDS-A0243. Tests at BCL showed that the smearing effect in the gas stream led to a much more benign effect than anticipated. However, using the model and the total assessed contamination, a calculation of the interstitial pickup of the columbium hardware showed that no position exceeded the limits for safe operation in seven year life. These data, both the model calculation and ORNL establishment of safe contamination levels, are presented in the AIRPHX Document Report No. 31-2375 ERDA BIPS Detail Design Review, presented in Germantown on March 1-4, 1977.

Use of an all-superalloy BIPS system partially alleviated the requirements for cleaning. However, only the component parts bakeout cycle was eliminated. All component parts were still cleaned to Class 100 clean room requirements.

4.3.3 Alternator Stator

The largest single source of contaminants in the BIPS system was considered to be the Mini-BRU alternator stator. Included in the construction are approximately 170 grams of organic materials for potting

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION

and insulation. A study by BCL, Final Report on Mini-BRU Alternator Offgassing Rates, March 18, 1977, stated that the stator could be baked out and the offgassing rate at operating temperature reduced so that less than 0.8 grams of the potting compound would be lost in the total system life. A long term soak and check of the alternator performance showed no degradation due to the material lost.

4.3.4 MBR Offgassing

The large surface area of the plate-fin structure of the recuperator and the accompanying gas load were considered to be a large source of contamination. To minimize the effect, the recuperator was subjected to a vacuum bakeout cycle. To check the effectiveness of the cycle, one port of the recuperator was closed, and a sample placed inside the port. Data from BCL, submitted as an acceptance test for the recuperator, showed that the offgassing rate of the recuperator sample was negligible at temperatures up to the vaporization point for chromium.

A second question on the recuperator concerned the amount of possible diffusion of braze alloy into the plate-fin structure. Data assembled from AIRPHX, BCL, and NASA showed that the greatest penetration of braze would be during the braze cycle, and further penetration would be virtually nonexistent.

4.3.5 HSA Offgassing

The graphite containment spheres and aeroshield in the HSA were expected to give off significant amounts of contamination. Data in a letter from A. Mowery to J. Lombardo, October 14, 1975, showed that the heat source could be baked out, reducing the level of residuals to be less than 0.1 gram. Subsequent data from BCL showed that the graphite in the heat source could be re-exposed to air with a virtually unmeasurable weight gain or loss. The expected contaminant level was included in the model calculation discussed in Section 4.3.2.

4.3.6 Workhorse Loop (WHL)

The Workhorse Loop Add-On Task included the study of the performance of an all-superalloy flight system as well as the design and fabrication of the all superalloy Workhorse Loop. The Workhorse Loop was intended to perform early check-out of the BIPS control system, Mini-BRU, and laboratory facility. It also was designed for performance mapping as described in AiResearch Document 31-2685 WHL Test Procedure.

In the Flight System Design Phase, the high temperature material selected was Hastelloy X due to its large data base. The turbine plenum, HSHX, and connecting bellows were redesigned in Hastelloy X. The HSHX was designed as a single helical tube with a resulting increase in heat transfer performance, reliability, and fabricability. This design was somewhat heavier than a design similar to the one used in the columbium unit, but the aforementioned advantages were traded off against the increase in weight. This HSHX was built under the hardware task and installed in the HSA for eventual use in the GDS.

The design tradeoff for turbine inlet temperature is shown in Figure 4.3-1. As can be seen, there was a 30 lb weight penalty for going to the new superalloy system. To this penalty, 20 lb should be added for the increase in weight due to the new AHSA and another 20 lb for modifying the alternator to provide 28 vdc. The total weight penalty for the switch to a superalloy BIPS was approximately 70 lb.

The HSHX has higher pressure drop and weight than the columbium configuration, but the gas temperature more closely approaches the metal hot spot temperature. The weight pressure drop penalties were examined against the gain in thermal performance, and the weight penalty was found to be acceptable.

The design of the Workhorse Loop included the design of a superalloy heater with resistance heating elements, a small amount of

SUPERALLOY STUDY
TURBINE INLET TEMPERATURE VARIATION

FIGURE 4.3-1

AIRESARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION

structure because of a mount point difference with the GDS, HSA, and connecting ducting and bellows. The heaters were based on the core geometry used in the BCD heaters with suitable modification of the wrap-up to allow for higher pressure modification. The heaters were designed to have the inlet and outlet ducts with the same spacing as the GDS and to have the same pressure drop.

New bellows were designed for use in the WHL, and because they were intended for temperatures up to 1600°F, they had lower design life than the GDS bellows. The heaters also were designed for a lower life, in this case, up to 5000 hour at 1400°F turbine inlet temperature. Total use of the WHL was estimated to be much less than 1000 hours.

The predicted operating point of the WHL is shown in Figure 4.3-2. This is for 120 vdc, and in addition, the performance has been degraded by two efficiency percentage points because of larger compressor clearances than originally intended. This performance could easily be regained.

4.4 Fabrication and Assembly

4.4.1 Summary

Fabrication techniques for the BIPS program were developed and demonstrated during Phase I using established procedures. Particular attention was given to inspectability, assembly, and disassembly aspects. Materials used are well characterized and where applicable, bonding techniques are well defined. Special tests were conducted at ORNL to confirm braze strength which was of concern.

Tolerances and processes were compatible with current manufacturing methods and equipment.

WHL AT 1300 W_e

31-2919
Page 4-65

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA

A DIVISION OF THE GARRETT CORPORATION

FIGURE 4.3-2

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION
PHOENIX, ARIZONA

Discussion

The BIPS WHL was comprised of a Mini-BRU (turbo-alternator), a recuperator, two heat sources, a radiator, interconnecting ducting, an insulation system, the support structure, and the controls.

The Mini-BRU is very similar to the NASA BRU, two of which have operated for over 46,000 hours, and is comparable to the many gas turbines manufactured by AiResearch. The fabrication of the Mini-BRU entailed the usual manufacturing techniques associated with gas turbine engines, with a few notable exceptions. The size of the unit was smaller than most AiResearch machines, but careful selection of manufacturing procedures and vendors to fabricate the small detailed components resulted in quality, close tolerance, aerodynamic components. Similar procedures and vendors have been used on previous programs at AiResearch; the most notable component being the gas management compressor for the CCPS40-1 engine, built for and tested by the Navy. The alternator rotor was fabricated from a high strength magnetic material with a non-magnetic separator to form the four poles of the alternator. In fabricating the recuperator, techniques were used that were developed for the NASA BRU recuperator; the recuperator was built by the AiResearch Torrance Division which specializes in heat exchanger equipment. The processes of punching fin matrices and brazing which are very important to the performance and life of the recuperator have been developed by AiResearch Torrance over the last several decades. A heat exchanger of note in the space power field built by these processes was the NASA Brayton Heat Exchanger Unit (BHXU) for the NASA BRU. A prototype Mini-BRU recuperator was thermally cycled through 200 start cycles prior to WHL tests to check the efficacy of the recuperator design and fabrication.

Fabrication of the heat sources was also accomplished during Phase I. The heat exchanger design was changed to a single coil to simplify fabrication and improve inspectability. For more details, see Section 4.2.4.2.

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION

Detailed fabrication procedures have not been demonstrated in the radiator; however, a similar radiator has been fabricated and tested by the Torrance Division. The unit performed as predicted and provides assurance that fabrication techniques are available. The possibility of using beryllium or Lockalloy should be considered in the future; however, the basic concept using aluminum assures that the radiator fabrication is state-of-the-art.

Considerable effort was expended during Phase I to develop a bellows and ducting system that would be within the state of the art and meet the life objectives. Testing of the bellows at ORNL has provided a data base that has established confidence in the design. Additional tests to further evaluate weld techniques are deemed appropriate for future system refinement.

The primary fabrication steps for MULTIFOIL thermal insulation as applied to the Workhorse Loop are documented and proven by (1) TECO Process Specification No. 3163A (Cleaning Procedure for MULTIFOIL Insulation), (2) TECO Process Specification No. 3162 (Electrostatic Coating Procedure for MULTIFOIL Insulation), (3) TECO Process Specification No. 3163 (Heat Treating of MULTIFOIL Insulation) and (4) TECO Specification 4219-1 (MULTIFOIL Assembly Procedures for BIPS). Based on the effort to date, tolerances have been established and means of monitoring these tolerances have been defined and proven by the TECO Quality Assurance program. Reproducibility should be demonstrated on the WHL. The only new standard to be finalized is for the few electroformed foils for use in selected regions of the GDS and FS.

The support structure is based upon using beryllium or Lockalloy to minimize weight. Fabrication techniques have been demonstrated on many applications using existing standards. These processes should be evaluated and typical structures and bonds will have to be evaluated.

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION
PHOENIX, ARIZONA

The flight system controls and accessories are considered to be 100 percent reproducible without the need for imposing unrealistic tolerance requirements. All electronic parts required in the control are commercially available to the reliability and quality control specification required.

Accessories requiring development, such as the parasitic load and T_c sensor, will utilize design configuration that can be fabricated from military or commercial standard materials. Reproducibility of these materials must be demonstrated or documented by the supplier prior to fabrication of the component part using these materials. Detailed design drawings for each component will specify tolerances that are compatible with the known properties of the materials selected and existing fabricating techniques.

4.4.2 Assembly Procedures

General

Detailed instructions were provided for every step of the assembly process and preconditioning. These assembly instructions were covered in the engineering assembly instruction manuals, and preconditioning prior to operation is discussed in the operator's manual. These manuals proved to be of great value during Phase I of the BIPS program.

Discussion

The procedures followed in assembling the BIPS-WHL are described in detail in the engineering assembly instruction manuals; AiResearch Report 76-312228A for the Mini-BRU and 76-312169 for the WHL.

These instructions cover the cleaning of parts, the verification and recording of significant dimensions, the sizing and trimming of ducts, the sequence of assembly, the installation of instrumentation,

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION
PHOENIX, ARIZONA

the sequence and type of insulation to be used, the support, assembly and inspection tooling to be used, and the type of weld sample and weld configuration to be employed. It further provides for visual and X-ray inspection of the welds as well as leak check of each weld assembly.

Reliable, effective and convenient procedures were developed in applying multifoil thermal insulation to the Workhorse Loop. These practical procedures (described in TECO Specification 4219-1, MULTI-FOIL Assembly Procedures for BIPS) may be refined in assembling the insulation for the GDS. On the basis of available Workhorse Loop data, the thermal performance and launch depressurization characteristics of MULTIFOIL are suitable for the full flight system.

The assembly instructions list the standards and specifications that control the assembly as well as the general activities to be performed in the contamination controlled area. These standards and specifications have all been in use at AiResearch for many years to control the production of gas turbines and/or space equipment or are derived from such documents and addressed specifically at the BIPS program.

The preconditioning of the loop prior to operation is described in the Operator's Manual 31-2502. To ascertain that the working fluid meets all the requirements of space operation, the following procedures are outlined in detail; the preconditioning of the working fluid management system, the gas and moisture analysis, the purging of the loop with argon, heating and motoring of the unit with argon to drive out any remaining acceptable levels contaminant gases, and the moisture analysis of the closed loop. Once these requirements are met, the loop is evacuated and filled with xenon-helium and the moisture content of the gas is again analyzed. The operator's manual lists all the development test instructions to be followed during this procedure to ascertain that the exact conditions are met for GDS operation.

4.5 Test and Evaluation

4.5.1 Endurance Test Summary

On May 22, 1978, a WHL build completed 1006.9 hours of testing without any engine problems. The longest continuous run, 402 hours, was achieved at the end of the 1000-hour test; four starts to 20,000 rpm for checkout purposes, three starts with the loop at design point temperatures, and three normal operating type starts with the heater brought up to 1200°F were accomplished during the test. Performance was measured at the beginning, middle, and end of the 1000-hour test and was found to be consistent throughout. The raw and reduced data are shown in Figures 4.5-1 through 4.5-6. During the latter phase of the test, it was observed that the ΔP transducer, which measured loop flow, had drifted from zero; corrections were introduced into the data reduction computer code when the engine was down long enough for the transducers to stabilize. The flow rate at the end of test was higher than that measured in April, 1978, because of the higher loop inventory as indicated by the higher loop pressure level.

The overall system efficiency is 24.5 percent, and this would approach 25 percent if the actual bearing bleed flow were used in the heater flow estimate. Instead, the more conservative approach of using the heat balance on the recuperator and, thereby, predicting higher heater flow rate and heat rate was incorporated in the efficiency calculation. The performance measured on May 22 was somewhat lower because of the higher compressor inlet temperature. For the fixed gas inventory case, as this is, 10 degrees in compressor inlet temperature is worth one percentage point in cycle efficiency. Using this fact as well as the fact that the compressor flow was lower than calculated because of the previously mentioned transducer drift, 24.5 percent cycle efficiency was the correct performance level for May 22. Some discrepancy in loop pressure was also seen, and this was attributed to

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA

A DIVISION OF THE GARRETT CORPORATION
PHOENIX, ARIZONA

SCAN NO. 31 SCAN TIME IS 01.05.32

PRE DATA = 5185 0

1	0.000000	2	-9.000000	3	0.000000	4	-9.000000	5	0.000000	6	12.000000
7	0.000000	8	0.000000	9	156.000000	10	158.000000	11	0.000000	12	154.000000
13	0.000000	14	1097.000000	15	0.000000	16	11.000000	17	0.000000	18	0.000000
19	0.000000	20	1093.000000	21	1144.000000	22	1132.000000	23	1140.000000	24	1133.000000
25	1375.000000	26	0.000000	27	1374.000000	28	0.000000	29	1158.000000	30	0.000000
31	1160.000000	32	1130.000000	33	0.000000	34	12.000000	35	0.000000	36	0.000000
37	201.000000	38	0.000000	39	-15.000000	40	0.000000	41	0.000000	42	131.000000
43	199.000000	44	0.000000	45	1119.000000	46	0.000000	47	1102.000000	48	1117.000000
49	1123.000000	50	1091.000000	51	1107.000000	52	0.000000	53	0.000000	54	1072.000000
55	1106.000000	56	1032.000000	57	1077.000000	58	1034.000000	59	1088.000000	60	971.000000
61	1044.000000	62	148.000000	63	1064.000000	64	0.000000	65	1313.000000	66	1379.000000
67	1374.000000	68	1311.000000	69	0.000000	70	0.000000	71	0.000000	72	0.000000
73	1292.000000	74	1301.000000	75	1289.000000	76	244.000000	77	0.000000	78	0.000000
79	111.000000	80	240.000000	81	0.000000	82	0.000000	83	0.000000	84	-9.000000
85	-9.000000	86	0.000000	87	0.000000	88	0.000000	89	0.000000	90	79.000000
91	155.000000	92	184.000000	93	0.000000	94	132.000000	95	88.000000	96	133.000000
97	0.000000	98	225.000000	99	0.000000	100	229.000000	101	212.000000	102	289.000000
103	422.000000	104	337.000000	105	459.000000	106	206.000000	107	0.000000	108	0.000000
109	0.000000	110	0.000000	111	209.000000	112	218.000000	113	212.000000	114	218.000000
115	202.000000	116	0.000000	117	5.000000	118	4.000000	119	4.000000	120	6.000000
121	6.000000	122	-13.000000	123	0.000000	124	-5.000000	125	0.000000	126	-18.000000
127	0.000000	128	75.000000	129	0.000000	130	0.000000	131	0.000000	132	0.000000
133	42.900000	134	0.000000	135	0.000000	136	67.100000	137	65.800000	138	65.000000
139	67.700000	140	66.700000	141	0.000000	142	66.500000	143	43.200000	144	43.300000
145	43.400000	146	42.600000	147	43.900000	148	0.000000	149	54.400000	150	17.000000
151	14.400000	152	204000	153	1.190000	154	2.071000	155	2.261000	156	4.350000
157	7.240000	158	7.079000	159	7.435000	160	0.000000	161	0.000000	162	3.470000
163	3.210000	164	123600	165	555000	166	555000	167	555000	168	793000
169	793000	170	791000	171	0.000000	172	412000	173	408000	174	413000
175	0.000000	176	0.000000	177	0.000000	178	0.000000	179	0.000000	180	451000
181	0.057000	182	0.051830	183	0.000000	184	0.000000	185	0.000200	186	0.012630
187	0.004030	188	0.005915	189	0.009978	190	0.000000	191	0.000000	192	0.029430
193	0.000000	194	0.000000	195	0.000000	196	0.000000	197	0.000000	198	0.000720
199	0.000730	200	0.000000	201	0.000000	202	0.000000	203	0.000000	204	0.000000
205	0.000000	206	0.000000	207	0.000000	208	0.000000	209	0.000000	210	0.000000
211	0.000000	212	0.000000	213	0.000000	214	0.000000	215	0.000000	216	0.000000
217	0.000000	218	0.000000	219	0.000000	220	0.000000	221	0.000000	222	0.000000
223	0.000000	224	0.000000	225	0.000000	226	0.000000	227	0.000000	228	0.000000
229	0.000000	230	0.000000	231	0.000000	232	0.000000	233	0.000000	234	0.000000
235	0.000000	236	0.000000	237	0.000000	238	0.000000	239	0.000000	240	0.000000
241	0.000000	242	0.000000	243	0.000000	244	0.000000	245	0.000000	246	0.000000
247	0.000000	248	0.000000	249	0.000000	250	0.000000	251	0.000000	252	0.000000
253	0.000000	254	0.000000	255	0.000000	256	0.000000	257	0.000000	258	0.000000
259	0.000000	260	0.000000	261	0.000000	262	0.000000	263	0.000000	264	0.000000
265	0.000000	266	0.000000	267	0.000000	268	0.000000	269	0.000000	270	0.000000
271	0.000000	272	0.000000	273	0.000000	274	0.000000	275	0.000000	276	0.000000
277	0.000000	278	0.000000	279	0.000000	280	0.000000	281	0.000000	282	0.000000
283	0.000000	284	0.000000	285	0.000000	286	0.000000	287	0.000000	288	0.000000
289	0.000000	290	0.000000	291	0.000000	292	0.000000	293	0.000000	294	0.000000
295	0.000000	296	0.000000	297	0.000000	298	0.000000	299	0.000000	300	0.033000
301	0.060000	302	0.000000	303	0.000000	304	0.000000	305	0.000000	306	0.000000
307	0.000000	308	0.000000	309	0.000000	310	0.000000	311	0.000000	312	0.000000
313	0.000000	314	0.000000	315	0.000000	316	0.000000	317	0.000000	318	0.000000
319	0.000000	320	0.000000	321	0.000000	322	0.000000	323	0.000000	324	0.000000
325	0.000000	326	0.000000	327	0.000000	328	0.000000	329	0.000000	330	0.000000
331	0.000000	332	0.000000	333	0.000000	334	0.000000	335	0.000000	336	0.000000
337	0.000000	338	0.000000	339	0.000000	340	0.000000	341	0.000000	342	0.000000
343	0.000000	344	0.000000	345	0.000000	346	0.000000	347	0.000000	348	0.000000
349	0.000000	350	0.000000								

RAW DATA FROM APRIL 9, 1978

FIGURE 4.5-1

SCAN	AC POWER KW	DC POWER KW	GROSS CY EFFY	NET CY EFFY	ALT AC EFFY BENCH	COMP EFFY	TURB EFFY	ROTOR SPEED RPM	RECUP EFFCT	COMPP RATIO	BETA PPT/ PRC	BLEED FLOW FRAC	TURB JBRG DEG F	CLR G EFFCT	COMP CIT DEG F	TURB TIT DEG F
31	1.236	1.170	.231	.266	.901	.717	.742	51850.	.970	1.561		.981	246.	.920	11.	1395.
31	COMP CIT DEG F	COMP CEX DEG F	COMP DT/T	P1 PSIA	P2 PSIA	COMP FLOW LB/SC	CORR SPEED RPM	CORR FLOW LB/SC	COMP POWP KW	COMPP RATIO	COMP EFFY	COMP JBRG DEG F	COMP TBRG DEG F	ALT TBRG DEG F		
31	11.			42.7	66.7	.255	54415.	.0837	2.044	1.561	.717	264.	151.	219.		
31	TURB TIT DEG F	TURB TET DEG F	TURB DT/T	P6 PSIA	P9 PSIA	TURB PHYSFLO LB/SC	TCORR SPEED RPM	TCORR FLOW LB/SC	TURB POWR KW	TURBP RATIO	TURB EFFY	TURB VFCTR	HTR EX DUCT 1 DEG F	HTR FX DUCT 2 DEG F		
31	1395.	1178.	.117	65.5	42.6	.251	27418.	.106	3.395	1.536	.742	.982	1396.	1394.		
31	RECUP ER HP	RECUP ER LP	RECUP HP DT DEG F	RECUP LP DT DEG F	RECUP HP IN DEG F	RECUP HP EX DEG F	RECUP LP IN DEG F	RECUP LP EX DEG F	RECUP HP DP PSID	RECUP LP DP PSID	RECUP DP/P	TURB TIT DEG F				
31	.970	.952	949.	931.	174.	1123.	1152.	221.	.207	0.000	.003	1395.				
31	CLP GASDT DEG F	COOLNT DT DEG F	CLR G EFFCT	CLR L EFFCT	CLR PWR KW	DP ALTHX PSID	DP 3T04 PSID	DPTURB/ PECLPIN PSID	DP CLR PSID	DPCLR/ COMP PSID	DP REC/HTR PSID					
31	209.	-8.	.920	.035	3.333	.133	.019	0.000	.218	0.000	0.000					
31	HTR1 TSKIN DEG F	HTR2 TSKIN DEG F	HEAT INPUT KWT	HTR DP PSID	DP HTREX PSID	DP RECHTR PSID	WINDAGE KW	BRGLOS KW	ERR BRU KW	ERR SYS KW						
31	1364.	1317.	4.396	0.000	0.000	1.000	.056	.154	-.231	-.189						
31	STPWR KW	PARSIT LOAD -KW-	FLOCUR AMPSDC	FLOVOL VDC	DCBUSS CURRNT -AMPS-	USER LD CURRENT -AMPS-	DCBUSS VOLTG -VDC-	COOLNT FLOW -CPS-	COOLANT SUMP T DEG F	COOL TW WATER DEG F	RTR SPD DDAS RPM					
31	.006	.475	1.263	0.000	9.928	5.915	117.800	0.	-18.	75.	0.					
31	TURB DISC DEG F	RECUP LP IN DEG F	RECUP HP FX DEG F	UPSTR OFTEE DEG F	HEATR INLT1 DEG F	HEATR INLT2 DEG F	HEATR DISCH DEG F	HEATR POWER KWT	HRHX INLET DEG F	HRHX DISCH DEG F	ALT HX POWER KWT	CYC EFF ESTIMAT INC HTL				
31	1178.	1152.	1123.	1114.	1160.	1153.	1395.	4.396	214.	5.	2.503	.245				
31	HEAT LOSSC KWT	DELTAP CONST PSID	HEISE DPSTA1 PSID	HEISE DPSTA3 PSID	HEISE DPSTA6 PSID	HEISE DPSTA9 PSID	TEMP BIAS CONST	RECUP HP EX CORR	HRHX DISCH PS/PT	FLOW PARA CALC	HRHX P DISC PSIA	CALCCLR P DISCH PSIA	RECUP LP IN CORR			
31	-0.000	-0.0000	-.9000	.1000	-1.0000	-.6000	-0.	5.	.9833	.2307	42.6000	42.4321	2.			
31	HPHX DP PSID	ALT HT GAIN KWT	C INLET HT GAIN KWT	C INLET 3PS HT KWT	4RHX HT REJ KWT	HT LOS REC-CLR KWT										
31	.1679	2.503	.035	-1.900	3.333	.112										

REDUCED DATA FROM APRIL 9 1978

13

FIGURE 1.7-1

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION
PHOENIX, ARIZONA

SCAN NO. 1 SCAN TIME 1 22.23.16

PRE DATA = 5188 0

1	-4.000000	2	-7.000000	3	0.000000	4	-7.000000	5	0.000000	6	14.000000
7	0.000000	8	0.000000	9	158.000000	10	16.000000	11	0.000000	12	156.000000
13	0.000000	14	1036.000000	15	0.000000	16	16.000000	17	0.000000	18	0.000000
19	0.000000	20	1091.000000	21	1146.000000	22	1130.000000	23	1142.000000	24	1133.000000
25	1375.000000	26	0.000000	27	1375.000000	28	0.000000	29	1158.000000	30	0.000000
31	1100.000000	32	1131.000000	33	0.000000	34	16.000000	35	0.000000	36	0.000000
37	203.000000	38	0.000000	39	-13.000000	40	0.000000	41	0.000000	42	126.000000
43	200.000000	44	0.000000	45	1117.000000	46	0.000000	47	1100.000000	48	1117.000000
49	1122.000000	50	1092.000000	51	1105.000000	52	0.000000	53	0.000000	54	1071.000000
55	1104.000000	56	1029.000000	57	1074.000000	58	1032.000000	59	1085.000000	60	964.000000
61	1042.000000	62	148.000000	63	1062.000000	64	0.000000	65	1205.000000	66	1373.000000
67	1372.000000	68	1234.000000	69	0.000000	70	0.000000	71	0.000000	72	0.000000
73	1284.000000	74	1302.000000	75	1256.000000	76	1299.000000	77	0.000000	78	0.000000
79	113.000000	80	243.000000	81	245.000000	82	1424.000000	83	0.000000	84	-7.000000
85	-7.000000	86	0.000000	87	0.000000	88	0.000000	89	0.000000	90	0.000000
91	156.000000	92	196.000000	93	0.000000	94	133.000000	95	90.000000	96	124.000000
97	0.000000	98	227.000000	99	0.000000	100	232.000000	101	213.000000	102	200.000000
103	417.000000	104	393.000000	105	471.000000	106	209.000000	107	0.000000	108	0.000000
109	0.000000	110	0.000000	111	211.000000	112	219.000000	113	214.000000	114	213.000000
115	210.000000	116	0.000000	117	0.000000	118	5.000000	119	4.000000	120	0.000000
121	6.500000	122	-13.100000	123	0.000000	124	-2.000000	125	0.000000	126	-20.000000
127	0.000000	128	64.000000	129	0.000000	130	0.000000	131	0.000000	132	0.000000
133	0.000000	134	0.000000	135	0.000000	136	65.900000	137	65.500000	138	66.300000
139	67.000000	140	67.100000	141	0.000000	142	65.500000	143	43.100000	144	43.400000
145	43.400000	146	42.500000	147	43.300000	148	0.000000	149	54.800000	150	14.900000
151	11.000000	152	1.226000	153	1.179000	154	2.128000	155	2.246000	156	-6.422000
157	0.000000	158	3.665000	159	7.555000	160	0.000000	161	0.000000	162	3.516000
163	3.344000	164	1.251000	165	5.580000	166	5.580000	167	5.580000	168	3.800000
169	0.000000	170	0.000000	171	0.000000	172	4.190000	173	4.190000	174	4.190000
175	0.000000	176	0.000000	177	0.000000	178	0.000000	179	0.000000	180	4.300000
181	0.000000	182	0.000000	183	0.000000	184	0.000000	185	0.000000	186	0.013070
187	0.004160	188	0.005927	189	0.010044	190	0.117800	191	0.017100	192	0.024220
193	0.000000	194	0.000000	195	0.000000	196	0.000000	197	0.000000	198	0.000720
199	0.000730	200	0.000000	201	0.000000	202	0.000000	203	0.000000	204	0.000000
205	11.742000	206	0.000000	207	0.000000	208	0.000000	209	0.000000	210	0.000000
211	0.000000	212	0.000000	213	0.000000	214	0.000000	215	0.000000	216	0.000000
217	0.000000	218	0.000000	219	0.000000	220	0.000000	221	0.000000	222	0.000000
223	0.000000	224	0.000000	225	0.000000	226	0.000000	227	0.000000	228	0.000000
229	0.000000	230	0.000000	231	0.000000	232	0.000000	233	0.000000	234	0.000000
235	0.000000	236	0.000000	237	0.000000	238	0.000000	239	0.000000	240	0.000000
241	0.000000	242	0.000000	243	0.000000	244	0.000000	245	0.000000	246	0.000000
247	0.000000	248	0.000000	249	0.000000	250	0.000000	251	0.000000	252	0.000000
253	0.000000	254	0.000000	255	0.000000	256	0.000000	257	0.000000	258	0.000000
259	0.000000	260	0.000000	261	0.000000	262	0.000000	263	0.000000	264	0.000000
265	0.000000	266	0.000000	267	0.000000	268	0.000000	269	0.000000	270	0.000000
271	0.000000	272	0.000000	273	0.000000	274	0.000000	275	0.000000	276	0.000000
277	0.000000	278	0.000000	279	0.000000	280	0.000000	281	0.000000	282	0.000000
283	0.000000	284	0.000000	285	0.000000	286	0.000000	287	0.000000	288	0.000000
289	0.000000	290	0.000000	291	0.000000	292	0.000000	293	0.000000	294	0.000000
295	0.000000	296	0.000000	297	0.000000	298	0.000000	299	0.000000	300	0.000000
301	3.439100	302	0.000000	303	0.000000	304	0.000000	305	4.994200	306	1.000000
307	0.000000	308	0.000000	309	0.000000	310	0.000000	311	0.000000	312	0.000000
313	0.000000	314	0.000000	315	0.000000	316	0.000000	317	0.000000	318	0.000000
319	0.000000	320	0.000000	321	0.000000	322	0.000000	323	0.000000	324	0.000000
325	0.000000	326	0.000000	327	0.000000	328	0.000000	329	0.000000	330	0.000000
331	0.000000	332	0.000000	333	0.000000	334	0.000000	335	0.000000	336	0.000000
337	0.000000	338	0.000000	339	0.000000	340	0.000000	341	0.000000	342	0.000000
343	0.000000	344	0.000000	345	0.000000	346	0.000000	347	0.000000	348	0.000000

RAW DATA FROM MAY 6, 1978

FIGURE 4.5-3

SCAN	AC POWER KW	DC POWER KW	GROSS CY EFFY	NET CY EFFY	ALT AC EFFY BENCH	COMP EFFY	TURB EFFY	ROTOR SPEED RPM	RECUP EFFECT	COMP RATIO	BETA PRT/ PWC	BLEED FLOW FRAC	TURB JRRG DEG F	CLR G EFFECT	COMP CIT DEG F	TURB TIT DEG F
9	1.229	1.183	.273	.263	.901	.726	.753	51880.	.968	1.572	.972	.943	244.	.915	9.	1391.
9	COMP CIT DEG F	COMP CEX DEG F	COMP DT/T	P1 PSIA	P2 PSIA	COMP FLOW LB/SC	COMP SPEED RPM	COMP FLOW LB/SC	COMP POWER KW	COMP RATIO	COMP EFFY	COMP JRRG DEG F	COMP TBRG DEG F	ALT TBRG DEG F		
9	9.	9.		42.7	67.1	.259	54577.	.0846	2.067	1.572	.726	261.	142.	216.		
9	TURB TIT DEG F	TURB TET DEG F	TURB DT/T	P6 PSIA	P9 PSIA	TURB PHYSFLN LB/SC	TCORR SPEED RPM	TCORR FLOW LB/SC	TURB POWER KW	TURBP RATIO	TURB EFFY	TURB VECTR	HTR FX DUCT 1 DEG F	HTR FX DUCT 2 DEG F		
9	1391.	1174.	.117	65.8	43.0	.254	27462.	.107	3.453	1.528	.753	.988	1392.	1391.		
9	RECUP ER HP	RECUP ER LP	RECUP HP DT DEG F	RECUP LP DT DEG F	RECUP HP IN DEG F	RECUP HP EX DEG F	RECUP LP IN DEG F	RECUP LP EX DEG F	RECUP HP DP PSID	RECUP LP DP PSID	RECUP DP/P	TURB TIT DEG F				
9	.968	.952	.946.	.930.	.172.	.1118.	.1149.	.219.	.213	0.000	.003	1391.				
9	CLR GASDT DEG F	COOLNT DT DEG F	CLR G EFFECT	CLR L EFFECT	CLR PWR KW	DP ALTHX PSID	DP 3T04 PSID	DPTURB/ RECLPIN PSID	DP CLR PSID	DPCLR/ COMP PSID	DP REC/HTR PSID					
9	209.	-11.	.915	.049	3.380	.134	.018	0.000	.622	0.000	0.000					
9	HTR1 TSKIN DEG F	HTR2 TSKIN DEG F	HEAT INPUT KWT	HTR DP PSID	DP HTRFX PSID	DP RECHTR PSID	WINDAGE KW	BRLDS KW	ERR BRU KW	EPR SYS KW						
9	1351.	1301.	4.500	0.000	0.000	.800	.056	.155	-.213	-.119						
9	STPWP KW	PARSIT LOAD	FIDCUR AMPSOC	FLDVOL VDC	DCBUSS CURRENT	USER LD CURRENT	DCBUSS VCLTG	COOLNT FLOW	COOLANT SUMP T	COOL TW WATER	RTP SPD RPM					
9	.004	.490	1.307	17.100	10.044	5.927	117.800	0.	-20.	64.	0.					
9	TURB DISC DEG F	RECUP LP IN DEG F	RECUP HP EX DEG F	UPSTR DETEE DEG F	HEATR INLT1 DEG F	HEATR INLT2 DEG F	HEATR DISCH DEG F	HEATR POWER KWT	HRHX INLET DEG F	HRHX DISCH DEG F	ALT HX POWER KWT	CYC EFF ESTIMAT INC HTL				
9	1174.	1149.	1118.	1109.	1154.	1149.	1391.	4.500	216.	6.	2.567	.242				
9	HEAT LJSSC KWT	DELTA CONST PSID	HEISE DPSTAI PSID	HEISE DPSTAB PSID	HEISE DPSTAG PSID	HEISE DPSTAG PSID	TEMP BIAS CONST	RECUP HP EX CORR	HRHX DISCH PS/P	FLOW PARA CALC	HRHX P DISC PSIA	CALCCLR P DISC PSIA	RECUP LP IN CORR			
9	-0.000	-0.0000	-5.0000	.3000	-1.7000	-2.0000	-0.	6.	.7322	.2331	42.6000	42.4293	2.			
9	HRHX DP PSID	ALT HT GAIN KWT	C INLET HT GAIN KWT	C INLET RRG HT KWT	HRHX HT REJ KWT	HT IDS REC-CLR KWT										
9	.1718	2.567	.047	-1.954	3.111	.052										

REDUCED DATA FROM MAY 6, 1978

FIGURE 4.5-4

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA

A DIVISION OF THE GARRETT CORPORATION
PHOENIX, ARIZONA

SCAN NO. 10 SCAN TIME 15.17.31.52

PPE DATA - 4117 0

1	-1.000000	2	0.000000	3	0.000000	4	0.000000	5	0.000000	6	1.000000
7	0.000000	8	0.000000	9	161.000000	10	144.000000	11	0.000000	12	1.000000
13	0.000000	14	1024.000000	15	0.000000	16	18.000000	17	0.000000	18	0.000000
19	0.000000	20	1090.000000	21	1144.000000	22	1127.000000	23	1140.000000	24	1120.000000
25	1276.000000	26	0.000000	27	1373.000000	28	0.000000	29	1150.000000	30	0.000000
31	1150.000000	32	1131.000000	33	0.000000	34	18.000000	35	0.000000	36	0.000000
37	0.000000	38	0.000000	39	-6.000000	40	0.000000	41	0.000000	42	131.000000
43	204.000000	44	0.000000	45	1115.000000	46	0.000000	47	1026.000000	48	1116.000000
49	1121.000000	50	1024.000000	51	1102.000000	52	0.000000	53	0.000000	54	1044.000000
55	1102.000000	56	1018.000000	57	1064.000000	58	0.000000	59	1020.000000	60	0.000000
61	1031.000000	62	137.000000	63	1054.000000	64	0.000000	65	1227.000000	66	1374.000000
67	1272.000000	68	1294.000000	69	0.000000	70	0.000000	71	0.000000	72	0.000000
73	1282.000000	74	1298.000000	75	1251.000000	76	1204.000000	77	0.000000	78	0.000000
79	115.000000	80	250.000000	81	252.000000	82	1423.000000	83	0.000000	84	0.000000
85	0.000000	86	0.000000	87	0.000000	88	0.000000	89	0.000000	90	0.000000
91	146.000000	92	180.000000	93	0.000000	94	140.000000	95	26.000000	96	16.000000
97	0.000000	98	210.000000	99	0.000000	100	212.000000	101	210.000000	102	274.000000
103	40.000000	104	375.000000	105	454.000000	106	190.000000	107	0.000000	108	0.000000
109	0.000000	110	0.000000	111	211.000000	112	218.000000	113	213.000000	114	21.000000
115	210.000000	116	0.000000	117	0.000000	118	8.000000	119	8.000000	120	10.000000
121	0.000000	122	-13.200000	123	0.000000	124	-1.000000	125	0.000000	126	-1.000000
127	0.000000	128	71.000000	129	0.000000	130	0.000000	131	0.000000	132	0.000000
133	43.000000	134	0.000000	135	0.000000	136	48.100000	137	44.000000	138	47.000000
139	0.000000	140	48.200000	141	0.000000	142	47.000000	143	44.000000	144	44.000000
145	44.000000	146	43.600000	147	44.000000	148	0.000000	149	54.000000	150	14.000000
151	11.000000	152	2.688000	153	0.143000	154	2.101000	155	0.222000	156	-0.264000
157	0.000000	158	3.739000	159	7.479000	160	0.000000	161	0.000000	162	3.472000
163	3.278000	164	0.124000	165	0.000000	166	0.000000	167	0.000000	168	0.000000
169	0.000000	170	0.000000	171	0.000000	172	0.000000	173	0.000000	174	0.000000
175	0.000000	176	0.000000	177	0.000000	178	0.000000	179	0.000000	180	0.000000
181	0.000000	182	0.000000	183	0.000000	184	0.000000	185	0.000000	186	0.000000
187	0.000000	188	0.000000	189	0.000000	190	0.000000	191	0.000000	192	0.000000
193	0.000000	194	0.000000	195	0.000000	196	0.000000	197	0.000000	198	0.000000
199	0.000000	200	0.000000	201	0.000000	202	0.000000	203	0.000000	204	0.000000
205	11.000000	206	0.000000	207	0.000000	208	0.000000	209	0.000000	210	0.000000
211	0.000000	212	0.000000	213	0.000000	214	0.000000	215	0.000000	216	0.000000
217	0.000000	218	0.000000	219	0.000000	220	0.000000	221	0.000000	222	0.000000
223	0.000000	224	0.000000	225	0.000000	226	0.000000	227	0.000000	228	0.000000
229	0.000000	230	0.000000	231	0.000000	232	0.000000	233	0.000000	234	0.000000
235	0.000000	236	0.000000	237	0.000000	238	0.000000	239	0.000000	240	0.000000
241	0.000000	242	0.000000	243	0.000000	244	0.000000	245	0.000000	246	0.000000
247	0.000000	248	0.000000	249	0.000000	250	0.000000	251	0.000000	252	0.000000
253	0.000000	254	0.000000	255	0.000000	256	0.000000	257	0.000000	258	0.000000
259	0.000000	260	0.000000	261	0.000000	262	0.000000	263	0.000000	264	0.000000
265	0.000000	266	0.000000	267	0.000000	268	0.000000	269	0.000000	270	0.000000
271	0.000000	272	0.000000	273	0.000000	274	0.000000	275	0.000000	276	0.000000
277	0.000000	278	0.000000	279	0.000000	280	0.000000	281	0.000000	282	0.000000
283	0.000000	284	0.000000	285	0.000000	286	0.000000	287	0.000000	288	0.000000
289	0.000000	290	0.000000	291	0.000000	292	0.000000	293	0.000000	294	0.000000
295	0.000000	296	0.000000	297	0.000000	298	0.000000	299	0.000000	300	0.000000
301	0.000000	302	0.000000	303	0.000000	304	0.000000	305	0.000000	306	0.000000
307	0.000000	308	0.000000	309	0.000000	310	0.000000	311	0.000000	312	0.000000
313	0.000000	314	0.000000	315	0.000000	316	0.000000	317	0.000000	318	0.000000
319	0.000000	320	0.000000	321	0.000000	322	0.000000	323	0.000000	324	0.000000
325	0.000000	326	0.000000	327	0.000000	328	0.000000	329	0.000000	330	0.000000
331	0.000000	332	0.000000	333	0.000000	334	0.000000	335	0.000000	336	0.000000
337	0.000000	338	0.000000	339	0.000000	340	0.000000	341	0.000000	342	0.000000
343	0.000000	344	0.000000	345	0.000000	346	0.000000	347	0.000000	348	0.000000
349	0.000000	350	0.000000	351	0.000000	352	0.000000	353	0.000000	354	0.000000

RAW DATA FROM MAY 22, 1978

FIGURE 4.5-5

SCAN	AC POWER KW	FC POWER KW	CPRESS CY EFFY	NET CY EFFY	ALT AC EFFY RENCH	COMP EFFY	TURB EFFY	FEED SPEED FPM	RECUP ELECT	CEMP PATTC	RETA POT/ PFC	DELTD FLOW DE I	TURB JPGG DE I	CLF ELECT	CEMP CIT EFC F	TURB TIT EFC F
59	1.227	1.144	.768	.258	.501	.730	.750	51870.	.067	1.568	.574	.887	246.	.003	14.	1388.
	CEMP CIT PFC F	COMP CEX EFC F	CEMP P1/T	P1 PSIA	P2 PSIA	COMP FLOW LR/SC	CEMP SPEED RPM	CEMP FLOW LR/SC	COMP POWER KW	CEMP PATTC	CEMP EFFY	CEMP JPGG DE I	CEMP JPGG DE I	ALT TIT EFC F		
59	14.	14.	6.000	43.6	68.4	.262	54292.	.0845	2.097	1.568	.730	266.	141.	277.		
	TURB TIT PFC F	TURB TET DEG F	TURB ET/T	P1 PSIA	P2 PSIA	PHYSFLO LR/SC	TURB SPEED RPM	TURB FLOW LR/SC	TURB POWER KW	TURB PATTC	EFFY	TURB VECTR	TURB DUCT 1 DEG F	TURB DUCT 2 DEG F		
59	1288.	1172.	.117	68.6	44.6	.259	27404.	.105	3.495	1.528	.750	.000	13.4.	141.7.		
	RECUP FR HP	RECUP FR LP	RECUP PP DT	RECUP LP DT	RECUP HP IN	RECUP HP EX	RECUP LP IN	RECUP LP EX	RECUP HP DP	RECUP LP DP	RECUP DP/P	TURB TIT				
59	.967	.955	927.	925.	177.	1114.	1146.	221.	.210	0.000	.003	1388.				
	CLP C/SCOT	CEMENT DT	CLF C ELECT	CLF L EFFECT	CLP PWR	DP ALTHX	DP 3104	DP FECLPIM	DP CLF	DP COMP	DP REC/ETR					
59	206.	-12.	.903	.053	3.379	.137	.014	0.000	1.472	0.000	0.000					
	HTR1 TSKIN	HTR2 TSKIN	HEAT INPUT	HTR DP	DP HTRFX	DP RECHTR	WINDAGE KW	APCLOS KW	EPD KW	EPD KW	EPD KW					
59	1249.	1295.	4.579	0.000	0.000	.800	.057	.156	-.204	-.041						
	TYPE KW	PARSIT LOAD	FLDUP AMPSDC	FLDVOL VDC	DCBUSS CURRENT	USER LD CURRENT	DCBUSS VOLTG	COOLNT FLEW	COOLANT SUMP T	COOL TV WATER	RTP SPD DDAS					
59	.004	.490	1.242	18.000	10.000	5.924	115.000	0.	-1P.	71.	0.					
	TURB DISC	RECUP LF IN	RECUP HP EX	HEATE INLT1	HEATE INLT2	HEATE DISCH	HEATE POWER	HEATE TIT	HEATE DEG F	HEATE DEG F	HEATE DEG F	HEATE DEG F	HEATE DEG F	HEATE DEG F	HEATE DEG F	HEATE DEG F
59	1172.	1146.	1114.	1104.	1144.	1144.	1388.	4.579	215.	9.	2.712	.220				
	HEAT DISC	HEAT INST	HEAT INST	HEAT INST	HEAT INST	HEAT INST	HEAT INST	HEAT INST	HEAT INST	HEAT INST	HEAT INST	HEAT INST	HEAT INST	HEAT INST	HEAT INST	HEAT INST
59	-0.000	-0.0000	-0.000	.4000	.4000	.4000	.4000	.4000	.4000	.4000	.4000	.4000	.4000	.4000	.4000	.4000
	HEATE DISC	HEATE INST	HEATE INST	HEATE INST	HEATE INST	HEATE INST	HEATE INST	HEATE INST	HEATE INST	HEATE INST	HEATE INST	HEATE INST	HEATE INST	HEATE INST	HEATE INST	HEATE INST
59	.1724	.212	.001	-2.052	2.	.004										

REDUCED DATA FROM MAY 22, 1978

FIGURE 4.5.6

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION

transducer drift. Considering that the data acquisition system was not calibrated for some seven weeks, the quality of the data was remarkably consistent.

The calculated turbine wheel performance appeared to be lower than was logically possible; examination of the work balance on the shaft showed that some 200 W more power was required to drive the rotor at the output power measured; the most likely explanation was that the turbine efficiency was higher than calculated.

Adding 200 W to the turbine work would add about 5 percentage points to the calculated turbine efficiency which would bring it up to the level expected; reinforcing this conclusion was the fact that the actual turbine work (temperature drop) was measured at a location where the temperature was characteristically higher than the average turbine discharge temperature, resulting in measurements indicating lower efficiencies.

4.5.2 WHL Mapping Tests

During WHL testing from November 4 through November 8, 1977, twenty-two system performance data points were completed. The performance testing was performed per AIRPHX DT-6812-15 procedures. These procedures were formulated to ensure valid test data by completion of manual data recording to supplement the automatic Digital Data Acquisition.

Of the 22 data points taken during the first 50 hours of BIPS-WHL testing, four points were taken at 80 percent inventory, nine at 100 percent inventory, and nine at 120 percent inventory. Five of these data points were at 95 percent of design rotating speed, 12 were at 100 percent speed, and five were at 105 percent speed. An additional data point at 100 percent inventory was acquired during the April-May, 1978, 1000-hour endurance test.

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION

Compressor inlet temperatures (T_1) ranged from 16°F to 99°F while the turbine inlet temperature (T_6) ranged from 1396°F to 1403°F. The dc output power ranged from 0.637 kW_e to 1.355 kW_e with cycle efficiencies varying from 0.152 to 0.233. From this data, the projected design point efficiency of the WHL was 0.245 at 10°F compressor inlet temperature.

The bearings may have been absorbing more power than anticipated during performance testing based upon heat picked up in the alternator heat exchanger and the turbine journal bearing temperature. Unfortunately, the amount of heat picked up in the alternator heat exchanger can also be affected by thermal loss from the turbine area. An insulation package was added to the turbine backface design for subsequent builds to help sort out the losses. In addition, feedthrough heat losses which required data correction were a present phenomenon which will not occur in flight systems.

To preface the ensuing paragraphs, a majority of the figures in this section present system performance rather than component performance. Insufficient data exist, at this writing, for extensive component mapping of the compressor, turbine, and recuperator; and data for only one turbine inlet temperature are available for the system performance evaluation.

Figure 4.5-7 shows the overall WHL cycle efficiency as a function of compressor inlet temperature (T_1). For the first 22 data points, it appears that one percentage point change in cycle efficiency occurs for every 10 degrees change in T_1 for constant gas inventory; this can be used to create the thermodynamic model which will predict the efficiency change at constant thermal input. Along with speed variations, slight variation in system pressure levels are visible for some of the 120-percent inventory data points.

BIPS-WHL CYCLE EFFICIENCY AS A FUNCTION OF COMPRESSOR INLET TEMPERATURE

TIT = 1400°F

FIGURE 4.5-7

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION
PHOENIX, ARIZONA

Figure 4.5-8 presents T_1 as functions of compressor inlet pressure (P_1), dc output power and thermal input at 100-percent speed, $T_6 = 1400^\circ\text{F}$, for 80, 100, and 120-percent inventories. Figure 4.5-8c shows the effect on T_1 on thermal input. As T_1 increases, the pressure available for expansion across the turbine is less, resulting in a higher turbine discharge temperature, thus allowing a larger system fractional heat recovery by the recuperator.

BIPS-WHL system efficiency is shown in Figure 4.5-9 as functions of dc output power and BRU rotating speed. The percentage of working fluid inventory (I), compressor inlet temperature (T_1), and turbine inlet temperatures (T_6) are constant for each curve. This allows the relative variations of T_1 and I to be compared with respect to the principal variables of the figure. Figure 4.5-10 shows dc power versus rotating speed. This is similar to the η versus N plot of Figure 4.5-9.

The BIPS-WHL recuperator performance is shown in Figure 4.5-11 and 4.5-12. The 80, 100, and 120 percent inventory data points are clustered in their respective groups. The average recuperator effectiveness decreases slightly with increasing average physical flow rates. This shows that the higher flow velocities tend to depress recuperator effectiveness by reducing the forced convection heat transfer coefficients. Pressure drop of the recuperator is shown in a modified form of Δ ($P\Delta P$) because of the relatively small change in average recuperator temperature. The data scatter is expected because of the accuracy of the transducer; each of these is a 1 psid transducer with 1 percent of full scale accuracy. The pressure measurement is about 0.1 psid, and therefore accuracy is ± 10 percent. Overall recuperator pressure drop $\frac{\Delta P}{P}$ is 1.0 to 1.3 percent, which is predicted.

On the basis of existing temperature measurements, the effectiveness of the recuperator appears to be slightly lower than expected. However, temperature gradients have been observed across the high

BIPS – WHL SYSTEM PERFORMANCE

N = 52,000 RPM (100% SPEED)

T1 = COMPRESSOR INLET TEMPERATURE, °F

TIT = 1400°F

FIGURE 4.5-8

BIPS - WHL SYSTEM PERFORMANCE

I = INVENTORY

TIT = 1400°F

100%N = 52,000 RPM

FIGURE 4.5-9

BIPS - WHL OUTPUT POWER AS A FUNCTION OF ROTOR SPEED

FIGURE 4.5-10

BIPS - WHL RECUPERATOR PERFORMANCE

TIT = 1400°F

lp = LOW PRESSURE

hp = HIGH PRESSURE

P = PSIA

ΔP = PSID

FIGURE 4.5-11

BIPS - WHL RECUPERATOR PERFORMANCE

FIGURE 4.5-12

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION

pressure discharge and low pressure inlets; this implies that the recuperator effectiveness could in actuality be higher than indicated by these calculations. More instrumentation is required to confirm this.

Mini-BRU compressor performance is plotted in Figure 4.5-13. Only compressor pressure ratio versus corrected flow rate is presented due to the number of data points available. The corrected speed lines have been drawn through their respective data points. While the data appears to be scattered, the flow scale is very large and changes of 1 percent in flow would make most of the data fall on the operating line.

Since the Mini-BRU was designed to operate at a T6 of 1600°F, the operating lines on Figure 4.5-13 are on the choke (right) side of the design operating point. An update of this performance map will be undertaken when additional data become available.

One observation has been made with respect to the Mini-BRU turbine. It appears that the performance may be a few percentage low. The compressor performance, however, appears to be as predicted based upon measured pressure ratio and rig data on compressor work.

It was noted during the first WHL test operations that the turbine journal bearing temperature was higher than expected. It was, however, well within the safe operating limits.

The exact amount of heat loss from the system cannot be determined from initial tests. The heat balance of the system has been calculated and does not permit an accurate definition of thermal loss. One item which was defined is the system time constant. In order to stabilize the hot end, approximately one hour is required; the low temperature side requires 2 to 3 hours because of the low heat transfer coefficients and metal conductivity in the recuperator. Therefore, accurate

BIPS - WHL COMPRESSOR PERFORMANCE

FIGURE 4.5-13

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION

definition of system efficiency can be defined in about one hour, but 2 to 3 hours are required to stabilize the overall heat balance. The use of thermography in future tests provided useful information in this area.

It is important to note that temperature and pressure readout errors have been eliminated from the reduced data. This is accomplished by comparing reference temperatures and pressures with the DDAS readouts and then incorporating the corrections into the computer data reduction program.

Subsequent to the November performance mapping test, a short duration test was conducted on December 22, 1977. This test was revealing in certain areas of BIPS thermal management particularly in the following areas:

- o Turbine journal bearing temperature indicated about 100°F lower than during previous testing indicating that the insulation package added at the turbine backface was very effective. Heat added in the alternator heat exchanger was also reduced by 200 watts.
- o Heat rejection was lowered by almost 13 percent indicating that the cycle efficiency should increase (this is partially a function of diminished heat transfer to the alternator HX).
- o Heat added in the alternator heat exchanger was very close to what was predicted.
- o Turbine efficiency must be 80-81 percent based upon the work balance on the shaft.

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION
PHOENIX, ARIZONA

- o Compressor inlet insulation package was very successful. Compressor inlet temperature profile was flattened and heat gain between the compressor inlet and HRHX was reduced by 60 percent.
- o The temperature error caused in the feedthrough plates was reduced to about 11°F from 16 to 18°F observed in the previous testing. This was possible due to improved feedthrough shielding.

From April 7 to May 22, 1978, the WHL was tested for 1006.9 hours; almost 700 hours were accumulated at the intended system operating temperature of 10°F at the compressor inlet and 1390°F at the turbine inlet. This performance point is shown on Figure 4.5-7.

The only changes to the Mini-BRU from the November performance test were additional bleedflow through the bearing cavity (a performance penalty), turbine backface insulation (a performance increase), and refinements in foil journal bearing design. The first two changes resulted in no net change in system performance.

4.5.3 Mini-BRU 1000-Hr Post-Test Evaluation

At the conclusion of the 1000-hour endurance test, the Mini-Brayton Rotating Unit was removed from the loop and disassembled.

All components including the bearings were found to be in excellent condition. The compressor and journal bearing set is shown in Figure 4.5-14 and the turbine bearing set in Figure 4.5-15. The black deposit on the turbine bearing set is carbon dust from the continuity probe. This dust was apparently carried through the system in the gas stream. The absence of black dust on the compressor bearings suggests a much reduced cooling gas flow rate through that bearing.

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION
PHOENIX, ARIZONA

31-2919
Page 4-90

BIPS COMPRESSOR END JOURNAL BEARING FOILS
FIGURE 4.5-14

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION
PHOENIX, ARIZONA

BIPS TURBINE END JOURNAL BEARING FOILS

FIGURE 4.5-15

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION

The bearing journal shaft is shown in Figure 4.5-16. No evidence of bumper ring contact is visible on the shaft or on the rings themselves.

The thrust bearing pads are shown in Figure 4.5-17 and 4.5-18. Slight burnishing is evident in some areas.

Metallurgical analysis revealed no signs of the distress experienced in the November and December, 1977 tests. No electrical arcing or other signs of Teflon deterioration were discovered. The bearings gave every indication of being capable of completing the full mission life.

4.6 Quality, Reliability, and Safety

4.6.1 Quality Assurance Plan

The Quality Program Plan status was reported each month during Phase I in AiResearch Report Nos. 75-311457(1) through 75-311457(35).

Under this task, the following quality plans and specifications were coordinated with DoE/NRA for Phase I and Phase II for approval and/or review. DoE/NRA comments and recommendations have been incorporated in each of these documents.

BIPS Phase I

- o Quality Program Plan - Report No. QA-053, Rev. 1 dated August 5, 1978 (DoE/NRA Approved)
- o Quality Program Plan Supplement - Report No. QCGI #137 dated July 7, 1977 (DoE/NRA Approved)

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION
PHOENIX, ARIZONA

31-2919
Page 4-93

BIPS JOURNAL SHAFT
FIGURE 4.5-16

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION
PHOENIX, ARIZONA

BIPS THRUST BEARING PADS

FIGURE 4.5-17

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION
PHOENIX, ARIZONA

BIPS THRUST BEARING PADS

FIGURE 4.5-18

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION
PHOENIX, ARIZONA

The Phase I Quality Program Plan is in compliance with the general intent of SNS-1 Specification.

BIPS Phase II

- o Quality Program Plan - Report No. QA-054, dated July 7, 1977 (DoE/NRA Reviewed)
- o Quality Program Plan Supplement - Report No. QCGI #144, dated February 1, 1978 (DoE/NRA Reviewed)
- o Bellows Assemblies Fabrication and Inspection Requirements Specification - Specification No. 31-2704 dated January 5, 1978, (DoE/NRA Reviewed)
- o Insulation Fabrication, Inspection and Assembly Requirements Specification - Specification No. 31-2798 dated January 7, 1978 (DoE/NRA Reviewed)
- o General Fabrication and Inspection Requirements Specification for Flight System Qualification - Specification No. 31-2767 dated December 22, 1977 (DoE/NRA Reviewed)

The Phase II Quality Program Plan is in compliance with the general intent of NRA-1 Specification.

4.6.2 Reliability Plan

"Reliability Program Plan - BIPS GDS, Phase I," AIRPHX Report No. 75-311360, dated September 30, 1975, was approved by ERDA and formed the basics of the reliability program conducted during Phase I. This plan was later revised, approved by DoE, and published as AIRPHX Report No. 31-1360A, dated August 18, 1977. With the approval of the revised

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION
PHOENIX, ARIZONA

plan, prime responsibility for reliability analyses and reports was shifted from the BIPS Engineering Project to the Supervisor of Reliability Engineering and Design Methods, Engineering Sciences.

Reliability related documents prepared and distributed during Phase I included the following:

- o AIRPHX Draft Paper - Endurance Test Rationale, dated July 1, 1975
- o AIRPHX/NASA - Recommended Acceptance/Reliability Tests for GFE Components, dated July 29, 1975
- o BIPS Phase I Integrated Program Plan (IPP), AIRPHX 75-311574, dated November 20, 1975 (Initial issue was prepared by BIPS Reliability; later revisions became a prime responsibility of Materials Engineering).
- o Preliminary Failure Modes, Effects and Criticality Analysis (FMECA) - BIPS Flight System, AIRPHX Report No. 76-311709, dated January 12, 1976
- o BIPS Design Integrity Checklist, COORD A0106, dated January 23, 1976; updated and published as AIRPHX Report No. 76-311971, dated June 10, 1976; updated and published as AIRPHX Report No. 76-311971A, dated February 15, 1977
- o Preliminary FMECA - BIPS GDS, AIRPHX Report No. 75-311965, dated June 1, 1976
- o Loop Containment Assessment - BIPS FS, AIRPHX Report No. 76-311791, dated June 1, 1976

- o Preliminary Reliability Allocation and Estimation - BIPS, AIRPHX Report No. 76-311851, dated June 1, 1976.

Reliability related memorandum and reports were issued internally to AiResearch covering the following topics:

- o Mechanical component design criteria
 - Design creep properties for Hastelloy X, including factor for long time extrapolation of data
 - Maximum allowable creep
 - LCF analytical model
 - Combined damage treatment of creep and LCF
- o Ducting system bellows
 - Weld designs and evaluations
 - Manufacturing and quality assurance requirements
 - Test program schedule for creep, LCF, and combined creep and LCF at ORNL
- o Foil bearing analytical results
 - Minimum operating film thickness versus sway space
 - Sensitivities of bearing performance to design parameters

Much of the above information was exchanged with DoE personnel during program and design review meetings.

Reliability was an agenda item at all design reviews held during Phase I. Previously published analyses and assessments were updated, as applicable, during these reviews.

Reliability Engineering, while active in design scrutiny and analysis of all BIPS components, provided exceptionally close attention to the bellows and, later in Phase I, to the reliability of the gas foil bearings.

4.6.3 Safety Reports, Reviews, and Evaluations

"System Safety Program Plan" AIRPHX Report No. 75-311221, dated September 30, 1975, was approved by ERDA and formed the basis of the safety program during Phase I. The plan was altered by guidance received in the ERDA letter, "Technical Direction TD-77-1; Contract E(04-3)-1123," dated November 26, 1976. Because of the unavailability of a Failure Mode and Effects Analysis (FMEA) for the Space Shuttle Launch System, with postulated failures and occurrence probabilities, it was necessary to reschedule (for Phase II) the preparation of a formal Preliminary Safety Analysis Report. However, the key elements of a preliminary Conceptual Flight Safety Assessment Report (CFSAR) were prepared by General Electric and were included in the Phase II Plan.

Safety-related documents prepared and distributed during Phase I included the following:

- o Preliminary Hazard Analysis - BIPS FS, AIRPHX Report No. 75-311629, dated October 31, 1975

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION
PHOENIX, ARIZONA

- o BIPS Transient Probability Study, GE-BIPS-73-001, dated November 13, 1975
- o Preliminary Hazard Analysis - GDS, AIRPHX Report No. 75-311665, dated November 30, 1975
- o Preliminary BIPS - Flight System Ground Safety Assessment Report (GSAR), AIRPHX Report No. 31-2361, dated February 15, 1977.

The GSAR provided a conceptual ground flow plan for the movement and processing of the Isotope Heat Source, the BIPS, the spacecraft, and other elements comprising the space power system. A conceptual method was presented for fueling the BIPS utilizing a proposed Mobile Loading Station (MLS). An initial evaluation of the nuclear safety implications was made with emphasis given to the nuclear fuel loading operation and its radiation exposure potential.

This initial analysis concluded that:

- o The conceptual MLS can provide a safe and efficient method of fueling the BIPS. While the analysis shows that an unshielded MLS would result in excessive radiation exposure rates to personnel, proper shielding will reduce the exposure rates to acceptable levels.
- o Nothing in the remaining sequence of handling, assembly, and storage operations suggests an unacceptable risk to personnel or to the environment. Many handling and movement operations involving the IHS can be similar or identical to presently accepted and proven methods.

AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION

- o Although many details of the BIPS system (as of May 1978) are yet to be identified, nothing now known suggests that the BIPS concept of operations will in any way violate the established level of nuclear safety in space programs.

This initial GSAR was recently updated by General Electric, and its key elements were included in the Phase II Plan. The conclusions of the initial analysis remain sound.