TID-27251--

PRELIMINARY FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS (FMECA) BRAYTON ISOTOPE POWER SYSTEM FLIGHT SYSTEM

76-311709 January 12, 1976

MASTER

GARRETT

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

DISCLAIMER

BIPS-GDS

COORDINATION MEMO

TO Distribution FROM J. E. McCormick. *JMc*

MEMO NO: BIPS-GDS- A0106

DATE: 1-23-76

REPLY BY:

SUBJECT: Preliminary Failure Modes, Effects and Criticality Analysis (FMECA) for BIPS FS

REFERENCE: AIRPHX Report 76-311709, dated 1-12-76
Contract E(04-3)-1123

ATTACHED: BIPS Design Integrity Checklist, 1-23-76

☐ REQUEST ☒ INFORMATION

☐ REPLY TO:

COMMENT:

The referenced FMECA represents a thorough review of the conceptual BIPS FS to identify areas of concern and activities necessary to avoid premature failures. To assure that the activities recommended by the FMECA are effected in both the GDS and FS, the attached checklist was prepared for tracking progress on efforts to eliminate or minimize the probability of those failure modes which rated highest in criticality ranking. Additional failure modes identified on the FS FMECA worksheets and the subsequent GDS FMECA will be reviewed and added to the checklist as appropriate. The checklist will be updated periodically.

Confidence exists that conservative design techniques implemented with effective quality assurance programs at AIRPHX and its subcontractors in conjunction with detailed checklists carefully monitored by the BIPS Program Quality and Reliability Manager will reduce possible failures to extremely low probabilities.

Nothing contained herein shall be deemed to change the terms of any purchase order or contract.

APPROVED BY: *H. W. Longee* DATE: *1-23-76*

DISTRIBUTION TO:

AIRPHX internal distribution per Rept. No. 76-311709; D. Kenney, ERDA NRA; W. Von Flue, ERDA SAN; T. Schaffhauser, ORNL; C. Alexander, BCL; B. Migra, NASA LeRC; D. Hemler, GE; F. Huffman, TECO.

BIPS DESIGN INTEGRITY CHECKLIST

Criticality Ranking Order Number (Note 1)	Area Of Concern	Data or Action Required (From FMECA)	Planned or Required Activity		
			Definition Document	Responsible Agency	Status
1	Rupture of Mini BRU turbine plenum	Adequacy of plenum design is dependent upon authenication of C-103 creep rupture data (including contamination effects)	Integrated Program Plan (Note 2), Sections 3.3.1 thru 3.3.1.2.6	ORNL, BCL, NASA LeRC	In process; under continuing review by MARSCOM
2	Rupture, cracking, fracture of HSA-HSHX	Adequacy of HSHX design is dependent upon authenication of C-103 creep rupture data (including contamination effects)	Integrated Program Plan (Note 2), Sections 3.3.1 thru 3.3.1.2.6	ORNL, BCL, NASA LeRC	In process; under continuing review by MARSCOM
(16)	Diffusion welds of HSHX	Perfection of the fabrication and inspection procedures is yet to be demonstrated	TBD	NASA/GE	In Process
(22)	Leakage of HSHX header weldments	QA inspection will detect defects	TBD	NASA/GE	In process
3	Penetration of radiator skin fin surface	Measures required to assure that failure does not result from material defects or mishandling (if used as pressure vessel on the pad)	TBD	AIRPHX	Will be addressed when Task 2 is resumed in October, 1976
(6)	Loss of, or damage to radiator emissivity coating	Proper selection of emissivity coating and method of application is extremely important. Performance effect will be determined.	TBD	AIRPHX	Will be addressed when Task 2 is resumed in October, 1976

Note 1: From FMECA - BIPS FS, AIRPHX 76-311709, dated January 12, 1976

Note 2: BIPS Phase I Integrated Program Plan, AIRPHX 75-311574, dated November 20, 1975 (hereafter, "IPP")

BIPS DESIGN INTEGRITY CHECKLIST (CONTD)

Criticality Ranking Order Number (Note 1)	Area of Concern	Data or Action Required (From FMECA)	Planned or Required Activity		
			Definition Document	Responsible Agency	Status
4	Delayed melting of HSA insulation blanket-HSIS (in ECS mode)	A full scale meltdown test is expected to provide evidence to aid in determining if the ECS functions in the manner intended. Backup designs are being evaluated.	TBD	NASA/GE	In planning stage; materials on order.
(24)	Loss of helium from HSIS when in ACS mode	Premature loss of helium could result from a malfunction/failure of the auxiliary vooling valve or a premature ground command to gas venting system. Reliability tests are required to confirm reliable design.	TBD	GE/AIRPHX	Design concept not yet chosen for FS-HSA. (Design for GDS will differ from that required for FS) Possibility of initiating start as function of HSA temperature being evaluated.
(31)	Self-welding of adjacent layers of foil in HSIS	Close QA can assure proper coverage of zirconia on foils.	TBD	NASA/GE	TBD
5	Cracking of braze joint between flange & side plate of MBR	Prototype will be subjected to cyclic life test to determine if low cycle fatigue problem exists.	TBD	NASA/AIRLA	Cyclic life test to begin in March 76.
(19)	Rupture of this braze joint as result of braze voids	As inspection technique should be developed to assure adequate braze joint coverage	TBD	NASA/AIRLA	TBD

BIPS DESIGN INTEGRITY CHECKLIST (CONTD)

Criticality Ranking Order Number (Note 1)	Area of Concern	Data or Action Required (From FMECA)	Planned or Required Activity		
			Definition Document	Responsible Agency	Status
7	Mini BRU turbine blade fatigue	Proper design will preclude problem. Inspection will verify the part conformance to the B/P requirements. Blade resonant frequencies will be determined by test.	AIRPHX Quality Plan, QC-048	NASA/AIRPHX	Fundamental frequency of turbine blade will be determined when test article is available in February, 1976. Turbine test rig expected to confirm performance - Feb 76.
(13)	Turbine blade creep rupture	Close quality assurance inspection procedures are necessary	AIRPHX Quality Plan, QC-048	NASA/AIRPHX	Turbine wheel inspection has been completed. (GDS Hardware)
8	Mini BRU compressor impeller fatigue	Inspection will verify the part conformance to the B/P requirements. Blade resonant frequencies will be determined by test.	AIRPHX Quality Plan, QC-048	NASA/AIRPHX	Blade frequency tests scheduled for Jan 76.
9	Rupture of the splitler-to-core matrix braze joint in the MBR	Prototype will be subjected to cyclic life test to determine if low cycle fatigue problem exists	TBD	NASA/AIRLA	Cyclic life test to begin in March 76.
10	Rupture of MBR pan assembly (excessive loads resulting from thermal growth)	BIPS integrator will perform an interface study to assure that duct loads transmitted to the MBR do not exceed design allowables.	TBD	AIRPHX	System mounts are deing defined with MBR design group involved.
(20)	(excessive g-loads at duct interfaces)	BIPS FS qualification tests must substantiate that excessive g-loads are not applied during launch and other mission environments. Mission environment data is needed	TBD	AIRPHX	FS qualification tests will be a Phase II activity. The GDS reflects FS structural design within the current limits of mission environment definition.

BIPS DESIGN INTEGRITY CHECKLIST (CONTD)

Criticality Ranking Order Number (Note 1)	Area Of Concern	Data or Action Required (From FMECA)	Planned or Required Activity		
			Definition Document	Responsible Agency	Status
(21)	Pan Assembly rupture due to low cycle fatigue	Prototype will be subjected to cyclic life test to determine if low cycle fatigue problem exists	TBD	NASA/AIRLA	Cyclic life test to begin in March 76
11	Rupture of MBR mount assemblies	BIPS assembly procedures must assure correct installation and alignment. A test is required to assure that mounts slide freely during thermal growth and that no galling or welding occurs because of exposure to space vacuum.	TBD	AIRPHX	Assembly procedures to be prepared; test to be devised.
12	Cracking of bellows weld joints or convolutes	Correct design is essential. If double or triple plys are used, method of cleaning and purging of volume between layers must be developed.	TBD	AIRPHX/ Subcontractor	Bellows subcontractor, when selected, will be required to propose method of cleaning, purging and inspection of bellows.
14	Short circuit in alternator stator power winding output as result of faulty insulation or insulation breakdown	Alternator offgassing tests and the GDS endurance test should provide confidence in the ability of the carefully selected insulating materials to withstand the high temperatures for prolonged periods	Technical Proposal AIRPHX Report, 75-311676, 12-12-75; Also see IPP, Section 3.3.1.3	NASA/AIRPHX	Alternator offgassing tests to be conducted by Battelle Columbus Lab under contract to AIRPHX. Program initiation expected momentarily.

BIPS DESIGN INTEGRITY CHECKLIST (CONTD)

Criticality Ranking Order Number (Note 1)	Area Of Concern	Data or Action Required (From FMECA)	Planned or Required Activity		
			Definition Document	Responsible Agency	Status
(17)	Power winding shorts to self as result of wire failure; end turns most susceptible	Alternator offgassing tests and the GDS endurance test should provide confidence in the ability of the carefully selected insulating materials to withstand the high temperatures for prolonged periods	Technical Proposal, AIRPHX Report, 75-311676, 12-12-75; Also see IPP, Section 3.3.1.3	NASA/AIRPHX	Alternator offgassing tests to be conducted by Battelle Columbus Lab under contract to AIRPHX. Program initiation expected momentarily.
(18)	Power winding opens as result of insulation breakdown	Close control of assembly process is required to assure that winding of coil does not introduce excessive stress at end turns.	Stator assembly Dwg 2045426; Notes 8 & 10 (insulation Tests: 1) Resistance to ground, 2) 1130 VAC Hi pot.) Also slot liner extends to prevent abrasion or cutting of the insulation	AIRPHX/AIRLA	Present design incorporates tests as noted.
15	Leakage of working fluid as result of defective fit of Mini BRU case joints and electrical terminal feed thrus	Close quality control is required during fab and assembly	AIRPHX Quality Plan QC-048	NASA/AIRPHX	Initial development unit being evaluated.
23	Defective weld joints in HSA inlet-outlet headers	Close quality control is required during fab and assembly	TBD	NASA/GE	TBD

BIPS DESIGN INTEGRITY CHECKLIST (CONTD)

Criticality Ranking Order Number (Note 1)	Area Of Concern	Data or Action Required (From FMECA)	Planned or Required Activity		
			Definition Document	Responsible Agency	Status
25	Premature opening of the auxiliary cooling valve during time HSIS is used in ACS mode	Premature loss of helium could result from a malfunction/failure of the auxiliary cooling valve or a premature ground command to gas venting system. Reliability tests are required to confirm reliable design	TBD	GE	Design concept not yet chosen for FS HSA. (Design for GDS will differ from that required for FS). Possibility of initiating start as function of HSA temperature being evaluated.
26	Crack or weld failure in radiator tubes	Close quality control is required.	TBD	AIRPHX	Development effort may be initiated as part of Task 9, Phase I
27	Penetration or fracture of a radiator tube by micrometeoroid	Proper design to meteoroid armor criteria will be performed.	TBD	AIRPHX	Will be addressed when Task 2 is resumed in October 1976
28	Cracking or failure of bimetallic joint or transition section in ducting	Program is underway to evaluate several methods of joining dissimilar metals - C-103/Hastelloy-X	IPP, Sections 3.3.3.1 and 3.3.3.5	NASA/ORNL/ AIRPHX/BCL	In process; under continuing review by MARSCOM
29	Failure of power supply submodule of the control system	Reliability can be achieved thru conservative design, high quality redundant components, and extensive development testing	TBD	AIRPHX	Design under development
30	Structural failure of multifoil high temp insulation	Proper design is required to preclude highllocalized heat loss	AIRPHX SOW, Rept 75-311499A, dated Dec 15, 1975	AIRPHX/TECO	Subcontractor, Thermo Electron Corp is proceeding with design and development of super insulation system.

PRELIMINARY FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS (FMECA) OF THE CONCEPTUAL BRAYTON ISOTOPE POWER SYSTEM (BIPS) FLIGHT SYSTEM

76-311709 January 12, 1976

Prepared in support of ERDA Contract E(04-3)-1123
by
AiResearch Manufacturing Company of Arizona

Prepared by: L. G. Miller, BIPS Reliability Manager

Approved by: J. E. McCormick, BIPS Program Manager

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

REPORT NO. 76-311709

TOTAL PAGES 16

ATTACHMENTS: Appendix - FMECA Worksheets
Drawing L3621582

REV	BY	APPROVED	DATE	PAGES AND/OR PARAGRAPHS AFFECTED

TABLE OF CONTENTS

ABBREVIATIONS

ACS - Auxiliary Cooling System (for HSA)

BIPS - Brayton Isotope Power System

BRU - Brayton Rotating Unit

CCD - Configuration Control Document

ECS - Emergency Cooling System (for HSA)

FMECA - Failure Modes, Effects and Criticality Analysis

FS - Flight System

GDS - Ground Demonstration System

GMV - Gas Management Valve (Helium vent in HSA)

HS - Heat Source (see IHS)

HSA - Heat Source Assembly

HSHX - Heat Source Heat Exchanger (in HSA)

HSIS - Heat Source Insulation System

IHS - Isotope Heat Source

MBR - Mini-Brayton Recuperator

MHW - Multi-Hundred Watt

MJS - Mariner Jupiter Saturn

PICS - Post Impact Containment Shells

QA - Quality Assurance

RTG - Radioisotope Thermoelectric Generator

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

PRELIMINARY FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS (FMECA) OF THE CONCEPTUAL BRAYTON ISOTOPE POWER SYSTEM (BIPS) FLIGHT SYSTEM

1. INTRODUCTION

A Failure Modes, Effects and Criticality Analysis (FMECA) has been made of the Brayton Isotope Power System Flight System (BIPS-FS) as presently conceived. Details of the analysis are discussed in the following paragraphs.

It is to be noted that effort in support of Task 2 (Preliminary BIPS Flight System Design) has recently been suspended and will not be resumed until FY77. Hence, it is not planned to publish an updated edition of this Preliminary FMECA until sometime after the resumption of Task 2. However, since much of the contents has a direct impact upon the Ground Demonstration System presently being designed and will in fact be directly applicable to the FMECA to be prepared on the GDS, comments of the reader are solicited now and on a continuing basis.

2. BIPS-FS CONCEPTUAL CONFIGURATION

The BIPS-FS is being developed by the ERDA as a 500 to 2000 W_e, 7 year life space power system. The system utilizes a closed Brayton cycle to convert thermal energy emanating from an isotope heat source to electrical energy at a net efficiency exceeding 25 percent. The working fluid is a mixture of helium and xenon having a molecular weight of 83.8. The baseline design utilizes two of the multihundred-watt isotope heat sources (MHW/IHS) developed by General Electric Energy Systems Programs Space Division. The heart of the system is a turbine-compressor-alternator rotating machine, the Mini-BRU (for Miniature Brayton Rotating Unit). The Mini-BRU is being developed by the AiResearch Manufacturing Company of Arizona (AIRPHX), A Division of The Garrett Corporation. The major components which will comprise the BIPS-FS are briefly described in the following paragraphs. For additional information, the reader is referred to the BIPS Configuration Control Document (CCD), AIRPHX 75-311274A, dated September 23, 1975, which is to be revised periodically.

The major components of the BIPS-FS consist of the following:

2.1 Mini-BRU

This machine contains a radial-flow turbine, a radial-flow compressor, and a radial-gap alternator. These components are mounted on a common shaft which rotates at 52,000 rpm and is supported on gas lubricated hydrodynamic journal and thrust bearings. The alternator is cooled by the compressor discharge; the foil bearings are cooled with compressor bleed cooling. The complete Mini-BRU assembly includes a flight-type housing, turbine and compressor inlet and exit ducting, and an output terminal block. Mounting pads are provided to permit the unit to be installed in the BIPS-FS. Power output is 1300 W_e with input of 4800 W_t (two MHW heat sources).

2.2 Heat Source Assembly (HSA)

The purpose of the HSA is to receive heat by radiation from the Isotope Heat Source and transfer it to the working fluid by forced convection within the Heat Source Heat Exchanger (HSHX). In addition to the HSHX, the HSA consists of a multifoil insulation blanket, an outer housing with mounting points and instrumentation leads, an auxiliary cooling system and an emergency cooling system.

2.3 Mini-Brayton Recuperator (MBR)

The purpose of the MBR is to transfer thermal energy from the working fluid coming from the Mini-BRU turbine discharge to the compressor discharge working fluid prior to its return to the Heat Source Heat Exchanger of the HSA. This recovery of thermal energy serves to increase cycle efficiency by reducing the required heat source output for a given power level. The MBR is a counterflow heat exchanger fabricated entirely from Hastelloy X. The core assembly is brazed using a gold braze alloy applied in foil form.

2.4 Space Radiator

The purpose of the radiator is to reject the waste heat of the Brayton cycle and thereby maintain the compressor inlet temperature at a low level. A number of possible radiator configurations have been studied. The present concept is of cylindrical tube fin design which will enclose the remainder of the BIPS components (except for cylinder ends), thereby contributing to the protection of other components from micrometeoroid impact. Either aluminum or beryllium will be selected as the radiator material.

2.5 Ducts and Bellows

The Mini-BRU, MBR, HSA, and radiator will be connected by means of a system of ducts and bellows. Multiple bellows will be required to absorb the relatively large thermal growths of the major components of the BIPS-FS. Ducts and bellows will be fabricated from Columbium (C-103 alloy) and from Hastelloy-X. Certain sections will require bimetallic joints or transition sections (C-103 to Hastelloy-X; Hastelloy-X to Aluminum or Beryllium).

2.6 Insulation System

The high operating temperatures of the BIPS, the relatively low output power, and the high cost and weight of the radioisotope require the use of a low loss insulation system in order to increase cycle efficiency and keep overall weight and cost within limits. Multiple layers of thin metallic foil (zirconia coated nickel and zirconia coated molybdenum) have tentatively been selected to shroud the Mini-BRU, MBR, and the hot ducts and bellows of the BIPS-FS.

2.7 Controls

The BIPS Control System provides for engine starting, load-following (control of output), system component protection, and engine shutdown. The present baseline design provides considerable latitude for improvements in reliability and functional characteristics through redesign and the addition of redundant components.

2.8 Isotope Heat Source (IHS)

The Isotope Heat Source as developed for and utilized in the MHW-RTG is an integral part of the BIPS-FS as presently conceived. The IHS was included in the Preliminary FMECA for the MHW-RTG prepared by General Electric (GESP-7094 dated June 5, 1973) and has been analyzed in a series of Safety Analysis Reports, the latest being the General Electric-prepared Final Safety Analysis Report for the MHW-RTG (GEMS-419 dated March 1975).

The MHW-IHS configuration for the BIPS will differ in at least one respect from the present design. The present iridium outer clad has been eliminated from the IHS for use in the MJS and future applications. (It may, however, be necessary to replace the clad with some other material - possibly, PT3008 alloy - if it is determined that the "bare" IHS would result in exposure of the C-103 HSHX to an objectionable level of contaminants.) In addition, GE has proposed improving the MHW Post Impact Containment Shell (PICS) helium vent design in order to enhance its reliability. However, these changes are not expected to significantly alter the overall safety and reliability of the MHW-IHS. Hence, the MHW-IHS has not been included in this FMECA because it is already a flight qualified entity but will be treated in the Preliminary System Safety Review to be conducted later in the ERDA-BIPS Phase I program.

3. DISCUSSION

The collection, tabulation, and analysis of failure mode data followed traditionally accepted practices. Each of the major components or subsystems comprising the BIPS-FS was reviewed to determine possible modes or manner of failure, their probable cause, and the effect of the failure on the system. Means of minimizing the failure mode were also investigated and recorded. The data was recorded on worksheets, copies of which have been included in the Appendix to this report.

An attempt was then made to quantify the degree of criticality of each failure mode and its potential effect. Columns headed "A", "B", and "C" on the FMECA worksheets were used for this purpose. The likelihood of the failure mode actually occurring was ranked on a relative scale from 1 to 100 (with 100 being the most likely) and this number placed in Column "A". The effect of the failure on the overall system was then estimated on a scale of 1 to 100 (with 100 being the most severe) and this number placed in Column "B". Numbers in columns A and B were then multiplied together to produce a criticality ranking or rating and this number was recorded in Column "C". Failure modes having the highest rating (most critical) were then tabulated in a separate summary listing (see Section IV, Table I). For the reader who is accustomed to seeing hazards categorized in accordance with MIL-STD-882, a hazard category (HAZ CAT) column was included in the worksheets. Entries in this column denote the estimated severity of the effects of failure in accordance with the following categories:

I - Negligible - will not result in personnel injury or system damage

II - can be counteracted or controlled without injury to personnel or major system damage

III - Critical - will cause personnel injury or major system damage, or will require immediate corrective action for personnel or system survival

IV - Catastrophic - will cause death or severe injury to personnel or system loss

While it may be seen that each hazard category equates to both system damage and personnel injury, the vast majority of the possible failures will not endanger personnel.

The contents of the FMECA worksheets and Table I (at the end of Section 4) will be periodically reviewed as the design of the BIPS-FS progresses. Criticality ratings will undoubtedly change as the design evolves. It is also inevitable that there will exist widespread disagreement with the ratings assigned. They are, after all, simply the concensus of a few and are, at best, educated guesses. Notwithstanding the recognized weaknesses, these ratings do provide a relative measure of the criticality of component failures and are therefore considered useful. Failure modes identified as being most critical will be given special emphasis for elimination or minimization during the system development effort. In addition, consolidated lists of critical components and processes will be generated as a direct output of this FMECA. These check lists will be utilized not only as guidance for the project engineers responsible for the FS (and the GDS) design but also to alert quality assurance personnel to the critical components and processes and their critical parameters. In addition, copies of this FMECA will be placed in the hands of all key BIPS program personnel.

4. SUMMARY

Worksheets listing failure modes considered most credible have been reproduced as an appendix to this report.

Failure modes and effects found to have the highest rating (most critical to system) have been listed in Table I which follows. There were thirty-one entries estimated to result in a criticality ranking exceeding 100. These appear in Table I in descending order of criticality ranking. (Note, however, that components having more than one failure mode with relatively high criticality ranking have been grouped together in Table I.)

The Mini-BRU Turbine Plenum and the HSA Heat Source Heat Exchanger were judged to constitute the highest potential source of system failure. This is due to the fact that both components are designed to be produced from Columbium (C-103). However, the wide range of criticality rankings (1 to 2500) serves to emphasize the uncertainty which prevails in regard to the strength of the parent material (C-103) when subjected to long term high temperatures, particularly in a contaminating environment. Adequacy of the design is dependent upon the authentication of C-103 creep rupture data through planned tests.

Another component scoring high in the criticality ranking was the radiator fin skin surface area. Here, again, there exists a wide range of uncertainty but, in this case, the uncertainty results in part from the fact that the radiator is in a very early phase of conceptual design. The FMECA serves to point out only the most obvious potential failure modes. If the radiator skin is not required to serve as a pressure vessel (to protect the BIPS while operating on the launch pad) then criticality of small penetrations as a result of material defects becomes inconsequential. When in orbit, micrometeoroid penetration of the radiator skin (fin area) is of minimal concern although penetration of a tube becomes catastrophic.

The Heat Source Insulation System in the HSA is another component which ranks high on the list of potentially high criticality rankings. This is primarily due to questions concerning the effectiveness of the HSIS to serve as an Emergency Cooling System for the IHS. The planned melt down test of the HSIS may serve to confirm the ability of the HSIS to fulfill the ECS requirement.

Tests and analyses, planned or already underway, are expected either to confirm or to eliminate most of the other areas of concern which appear on the "most critical" list.

As noted earlier, it is not planned to publish an updated version of this preliminary FMECA until sometime after the resumption of Task 2 of the BIPS Phase I effort. However, the contents of this document will be periodically reviewed and used as a basis for the issuing of consolidated lists of critical components and processes. Too, much of the contents has a direct impact upon the Ground Demonstration System presently being designed and will in fact be directly applicable to the FMECA to be prepared on the GDS. For these reasons the comments of the reader regarding contents, omissions, etc., are solicited and will be appreciated by the BIPS Program Manager and his staff.

Action by the BIPS Program Manager is already underway to prepare a checklist of actions required to assure quality and design integrity. Based upon an item by item review of this FMECA, the checklist will detail the actions required (in addition to those already underway) to acquire the materials test data, to develop reliable hardware, and to prepare the quality inspection procedures which will result in a highly reliable BIPS flight system.

TABLE I

Most Critical Failure Modes And Effects - BIPS-FS

Order No.	Item	Criticality Ranking	Comments
1	MINI-BRU Turbine Plenum	1-2500	Rupture of plenum due to embrittlement of C-103 as result of contamination would be catastrophic. Wide range of ranking serves to emphasize present uncertainty regarding strength of parent material (C-103). Adequacy of plenum design is dependent upon authentication of C-103 creep rupture data. Long term creep tests are planned to determine magnitude of C-103 strength degradation.
2	HSA-Heat Source Heat Exchanger	1-2500	Rupture, cracking, or fracture of the HSHX due to embrittlement of the C-103 as result of contamination would be catastrophic. As with the turbine plenum, the wide range of ranking indicates the existing uncertainty regarding the strength of the parent material when subjected to long term high temperature, particularly in a contaminating environment. Adequacy of the design is dependent upon authentication of C-103 creep rupture data through planned tests.
(16)		250	Another possibly critical failure mode of the HSHX involves the diffusion welds of the ribs to the outer cylinder. The possibility exists that these welds may open as a result of a process defect or excessive thermal or dynamic stress. This would result in degraded heating of the working fluid but the criticality is yet to be determined. Perfection of the fabrication process is yet to be demonstrated. Inspection by holographic and ultrasonic methods is planned.
(22)		200	A third possibly critical failure mode of the HSHX is leakage at the header weldments as a result of defective welds. The weld process will be checked with destructive samples and QA inspection should detect defects.
3	Radiator Skin (Fin Surface Area)	1-2000	Small penetrations of the radiator fin skin between tubes as a result of micrometeoroid impact would cause inconsequential losses in heat rejection capability. On the other hand, the radiator may be required to serve as a pressure vessel to protect the BIPS while operating on the launch pad. In this case, any penetration of the fin skin as a result of material defects or mishandling could result in exposure of the hot C-103 plenum to atmospheric contamination.

TABLE I (Cont'd)

Order No.	Item	Criticality Ranking	Comments
(6)		250-1000	Loss or damage to the emissivity coating will directly affect the efficiency of the radiator and, in turn, the efficiency of the BIPS cycle. Degradation resulting from spalling and long term exposure to ultraviolet light must be countered through careful selection of material and methods of application. Loss or damage to the coating as a result of the effects of offensive nuclear weapons poses another potentially catastrophic danger. The threat is a function of many factors such as weapon yield, proximity of burst, character and level of radiation, etc. On the one hand, the entire satellite could be destroyed and any passive survivability design measures incorporated in the BIPS would be useless. On the other hand, the system must be able to survive those levels of radiation against which the other satellite systems are hardened. The emissivity coating appears to be the most vulnerable element of the BIPS. Therefore, careful selection of coating and method of application is extremely important.
4	HSA Insulation System (HSIS)	1500	Delayed melting of the multi-foil insulation (in the Emergency Cooling System mode) may subject the IHS to overtemperatures which will result in serious degradation of the strength of the iridium in the Post Impact Containment Shells (PICS). The weakening of the iridium would, in turn, cause the ability of the PICS to survive subsequent earth impact to be questionable, thereby introducing a potentially serious impact on nuclear safety. A full scale melt down test is expected to provide evidence to aid in determining if a real problem exists. If, indeed, the ECS does not function in the manner intended, redesign will probably become mandatory.
(24)		200	Another possible failure which could adversely affect nuclear safety is the loss of helium gas surrounding the HSIS. If this should occur during a period when the ACS is short circuiting the insulation, the ECS would be initiated, resulting in meltdown of the insulation and a possible degradation of PICS strength. This premature loss of helium could result from a malfunction/failure of the Auxiliary Cooling Valve or a premature ground command to the gas venting system.
(31)		150	A third mode of failure of the HSIS is the self welding of adjacent layers of nickel foil. This could result from the absence of zirconia particles in a broad area of one or more foils. Long term degradation of BIPS power output would then occur. Test results have already shown that no appreciable loss of zirconia occurs from vibration during launch. Close QA can assure proper coverage of zirconia on foils.

TABLE I (Cont'd)

Order No.	Item	Criticality Ranking	Comments
5	MBR Manifold Attachment Flange	1000	Cracking of the braze joint between the flange and side plate of the MBR was observed to occur as a result of repeated thermal cycling of a sub-module of the MBR. Loss of working fluid through such a crack would result in the rapid or eventual shutdown of the BIPS, depending upon the size of the crack. A design change is being incorporated into the prototype MBR currently being fabricated. This prototype will be subjected to cyclic life tests which will determine if a low cycle fatigue problem still exists.
(19)		200	Rupture of the braze joint between the flange and side plate may also occur as a result of braze voids (incomplete braze alloy coverage) and subsequent creep or yield of the parent metal. Development tests have been conducted to verify that manufacturing techniques provide full braze coverage on similar parts. An inspection technique should be developed to assure adequate braze joint coverage.
7	MINI-BRU Turbine Wheel	50-1000	Turbine blade fatigue is a potential failure mode of rotating machinery. It can result from improper design, blade motion at high stress levels, material flaws and impurities, and high and low cycle fatigue. The consequences vary over a wide range depending upon the size of the crack occurring or the size of the piece of material which separates from the wheel. The Mini-BRU turbine wheel has been conservatively designed with factors of safety exceeding those usually encountered in rotating equipment. Nevertheless, testing will be required to confirm the validity of the design and close quality assurance procedures followed in order to guarantee adequate flight system quality.
(13)		25-500	Another possible critical failure mode is turbine blade creep rupture resulting from faulty design, improper selection of material, or excessive temperature. The effects impact can vary over a wide range from minimal to catastrophic. A light rub of the blade on the shroud is not necessarily a major problem but greater interference would result in bearing failure and shutdown of the BIPS. As indicated above, the turbine wheel design is very conservative but close quality assurance inspection procedures are necessary to assure reliable operation.

TABLE I (Cont'd)

Order No.	Item	Criticality Ranking	Comments
8	MINI-BRU Compressor Impeller	50-1000	Compressor blade fatigue is another common failure mode of rotating machinery. It can result from the same causes enumerated in the preceding entry. The compressor impeller like the turbine blade in the Mini-BRU is of very conservative design. Testing and close quality assurance procedures are required to guarantee adequate flight system hardware.
9	MBR Splitters	500	Rupture of the splitter-to-core matrix braze joint in the MBR would allow bypass flow of the high pressure gas to the low pressure side with a resulting decrease in system power output. Cracks in the braze joint may result from low cycle fatigues induced by repeated startup and shutdown thermal transients. A prototype of the MBR will be subjected to tests to verify cyclic life. Inspection procedures (radiographic) have been established to insure adequate braze alloy coverage.
10	MBR Pan Assemblies	500	Rupture of a pan assembly could occur as a result of improper installation of the MBR within the BIPS. Excessive loads can occur at duct interfaces during thermal growth and damage becomes cumulative through repeated cycles. BIPS integrator will perform an interface study to assure that duct loads transmitted to the MBR do not exceed design allowables.
(20)		200	Rupture may also result from excessive g-loads at duct interfaces. BIPS-FS qualification tests must fully substantiate that excessive g-loads are not applied during launch and other mission environments.
(21)		200	Another possible failure mode is rupture due to low cycle fatigue. Prototype of MBR will be subjected to test to verify cyclic life.
11	MBR - Mount Assemblies	500	Rupture of one or more mount assemblies could result from excessive vibration or acceleration, material defects, mechanical damage, or improper installation. Improper installation could cause binding and plastic deformation during thermal growth. Cumulative damage because of cyclic operation may result in rupture of attaching ducting with subsequent loss of working fluid and failure of BIPS. Self aligning bearing mounts have been proposed to insure free movement. A test should be conducted to assure that mounts slide freely during thermal growth and that no galling or welding occurs because of exposure to space vacuum.

TABLE I (Cont'd)

Order No.	Item	Criticality Ranking	Comments
12	Bellows	100-500	Cracking of welds or of convolutes would result in loss of working fluid and failure of BIPS if single ply bellows are utilized. If double ply bellows are used, failure of inner ply may result in introduction of contaminants (trapped between plys) into working fluid. Correct design of bellows will be essential in order to compensate for centerline misalignment due to thermal expansion and lateral deflection. If double or triple plys are used, method of cleaning and purging of volume between layers must be developed so as to preclude contaminating working fluid in event of inner layer cracking.
14	Mini-BRU Alternator Stator - Power Windings	300	Short circuit in output resulting from faulty insulation or insulation breakdown from prolonged exposure to heat will cause Mini-BRU to overspeed, failing the bearings and stopping the rotating group.
(17)		240	Should the power winding short to itself, loss of phase voltage, increased ripple, and severe output degradation would result. Some useful output would probably remain, assuming that the load is compatible with 2-phase supply voltage, but the failure mode is clearly undesirable.
(18)		200	A third possible failure mode is the opening of the power winding as result of wire failure. This can occur as a result of stress introduced during assembly, especially at the end turns. These three possible failure modes point up the importance of close control of the assembly process. High potential tests should be performed prior to final assembly. Materials have been carefully selected to be compatible with temperatures predicted by a detailed thermal analysis. Alternator off-gassing tests and the GDS endurance test should provide confidence in the ability of the insulating materials to withstand the high temperature for prolonged periods.
15	Mini-BRU Housing	300	Leakage of working fluid may result from defective fit of the Mini-BRU case joints and electrical terminal feed throughs. Close quality control during assembly is an obvious requirement. Leakage test will detect gross leaks.
23	HSA-Inlet-Outlet Headers	200	Defective weld joints may result in leakage of working fluid and eventual shutdown of BIPS. Proof pressure test and quality inspections should detect gross leakage. GE analysis has shown that donut shaped header has reduced thermal stress relative to the referenced design.

TABLE I (Cont'd)

Order No.	Item	Criticality Ranking	Comments
25	HSA - Auxiliary Cooling Valve	200	Premature opening of the Auxiliary Cooling Valve would vent the helium gas which is used to short circuit the HSIS during the time that the HSIS is being used as an Auxiliary Cooling System. This premature opening could result from primary valve failure or a premature ground command to the gas venting system. The result would be activation of the ECS which in turn could adversely impact nuclear safety by weakening the PICS of the IHS. Design concept is not yet chosen for the Auxiliary Cooling Valve for the flight system. (GDS will utilize a valve unlike that required for the flight system.)
26	Radiator - Tubes	200	A crack in the parent metal or a weld failure where tube joins the inlet or outlet header would result in loss of working fluid and eventual shutdown of BIPS. Proper design and quality assurance inspections are necessary.
27		200	Penetration or fracture of a tube by micro-meteoroid impact is another possible failure mode. Radiator must be designed to provide high probability ($\geq$0.99) that radiator survives 7 year mission.
28	Ducts	200	Cracking or failure of bimetallic joint or transition section would result in loss of working fluid and eventual shutdown of BIPS. Program is currently underway to evaluate several methods of joining dissimilar metals - C-103/Hastelloy-X.
29	Controls - Power Supply	200	The power supply appears to be the most failure prone submodule of the BIPS controls. Failure of components may result in loss of control circuits leading to turbine stall. (Upon loss of power to control circuits, parasitic load turns "full on" and the stator field saturates.) Reliability will be achieved through conservative design, triple redundancy, high quality components, and extensive development testing. A similar approach is being pursued for the other submodules of the control system.

TABLE I (Cont'd)

Order No.	Item	Criticality Ranking	Comments
30	High Temperature Insulation (Multi-Foil)	100-200	Structural failure of the multi foil insulation which covers high temperature portions of the BIPS-FS will result in high localized heat loss. This in turn may result in induced thermal failure of high temperature components and subsequent loss of working fluid. Structural failure may result from excessive mechanical and/or thermal stress in the insulation retaining system. The importance of proper design of the insulation system has been recognized,as evidenced by the fact that the insulation is the subject of a major subcontract.

APPENDIX

FMECA WORKSHEETS

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

SYSTEM BIPS - FLIGHT SYSTEM

SUBSYSTEM MINI-BRU

COMPLETED BY L. G. Miller

DATE 1-9-76

COMPONENT	FAILURE MODE (S)	PROBABLE CAUSE	EFFECT OF FAILURE	FAILURE MODE MINIMIZATION	*A	*B	*C	HAZ CAT	SAFETY ACTION OR COMMENTS
Rotating Group Assembly - Tie-Bolt	Loss of tension	Incorrect assembly, material creep, improper design	Loss of axial lockup force; wheel rubs; unbalance; possible bearing overload and failure	Proper design and correct assembly procedure should preclude this type of failure	1	100	100	IV	
	Fracture	Low cycle fatigue, high cycle fatigue, over/under torque of tie-bolt	Catastrophic rotor failure	Proper design and correct assembly procedure should preclude this type of failure	1	100	100	IV	
Alternator-Stator-Field Coils and Related Excitation Circuit	Field coil winding (or switching regulator) open circuits or short circuits	Random component failure, insulation breakdown from excessive heat	Loss of redundancy	Circuit design redundancy assures that single point failure will not result in alternator output loss due to lack of field excitation. (Ref. CA:JPW:0212:073175 and CA:JWP:0214:080575) Perform high pot. tests prior to final assembly; use burn-in technique to minimize early component failure; rigid quality control. Stator is conduction cooled (assisted by 2% bleed for turbine bearing cooling).	3	1	3	I	

*A MODE LIKELIHOOD (1 TO 100) - *B EFFECTS IMPACT (1 TO 100) - *C CRITICALITY (A x B)

FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS WORKSHEET

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

76-311709
Appendix
Page 2

SYSTEM BIPS - FLIGHT SYSTEM

SUBSYSTEM MINI-BRU

COMPLETED BY L. G. Miller

DATE 1-9-76

COMPONENT	FAILURE MODE (S)	PROBABLE CAUSE	EFFECT OF FAILURE	FAILURE MODE MINIMIZATION	*A	*B	*C	HAZ CAT	SAFETY ACTION OR COMMENTS
	Field coil winding shorts to self, decreasing number of turns	Insulation breakdown from excessive heat	Nondiscernible	Four field coils in parallel; either of two pairs is sufficient for full power output; stator is conduction cooled (assisted by 2% bleed for turbine bearing cooling)	3	1	3	I	
Alternator Stator - Power Windings	Power winding (armature conductor) opens	Wire failure due to stress or bending, especially at end turns.	Alternator failure or decreased output and phase unbalance	Close control of assembly process to ensure that workmanship meets high standards; perform high pot. test prior to final assembly.	2	100	200	III - IV	Probably key to long life; AI RPHX rep observe assembly process
	Short circuited output	Vibration; faulty insulation; insulation breakdown from prolonged exposure to heat	Mini-BRU will overspeed, failing bearings, and stopping the rotating group	Close control of assembly process to ensure that workmanship meets high standards; perform high pot. test prior to final assembly.	3	100	300	IV	

*A MODE LIKELIHOOD (1 TO 100) - *B EFFECTS IMPACT (1 TO 100) - *C CRITICALITY (A x B)

FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS WORKSHEET

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

SYSTEM ________ COMPLETED BY ________

SUBSYSTEM MINI-BRU DATE ________

COMPONENT	FAILURE MODE (S)	PROBABLE CAUSE	EFFECT OF FAILURE	FAILURE MODE MINIMIZATION	*A	*B	*C	HAZ CAT	SAFETY ACTION OR COMMENTS
	Power winding (armature conductor) shorts to itself.	Insulation breakdown from prolonged exposure to heat; vibration	Loss of phase voltage; increased ripple; severe output degradation	Stator is conduction cooled (assisted by 2% bleed for turbine bearing cooling); close control of assembly process is necessary	3	80*	240	III-IV	*Assumes load compatibility with 2-phase supply voltage
Alternator Rotor	Bimetallic joint failure	Overspeeding of rotating group; defective braze	Burst of rotor; failure of BIPS	Rotor has been designed and will be spin tested to assure that minimum burst speed is twice the design stress. Rotors will be subjected to tests to confirm quality braze and then spun to 88,000 rpm which	1	100	100	IV	

NOTE: While there exists reasonable confidence in the ability of the insulating materials to withstand prolonged exposure to heat without exposing the windings to shorts, there is concern over the possible offgassing of the several organic materials for insulating and "potting" of the alternator stator. Introduction of organic contaminants into the working fluid may severely damage the hot refractory metal in the turbine plenum and in the HSA. A test is planned which will attempt to determine the products and release rates of any decomposition of organic material from the stator at simulated operating temperature and working fluid flow.

*A MODE LIKELIHOOD (1 TO 100) – *B EFFECTS IMPACT (1 TO 100) – *C CRITICALITY (A x B)

FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS WORKSHEET

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

SYSTEM ______ COMPLETED BY ______

SUBSYSTEM MINI-BRU DATE ______

COMPONENT	FAILURE MODE (S)	PROBABLE CAUSE	EFFECT OF FAILURE	FAILURE MODE MINIMIZATION	*A	*B	*C	HAZ CAT	SAFETY ACTION OR COMMENTS
Alternator Rotor (Contd)	Bimetallic joint failure (Contd)			is calculated to subject rotor to twice design stress (development rotor was spun at 134,000 rpm with no growth detected; normal speed for mini-BRU is 52,000 rpm).					
	Rotor seizure	Bearing failure	Failure of BIPS	Foil bearings are inherently reliable; QA will assure proper fabrication and correct assembly of bearings and rotating group.	1	100	100	IV	
Compressor Impeller	Impeller hub burst	Faulty design; overspeed; material impurities	Failure of BIPS	Impeller has been designed to assure that minimum burst speed has factor of safety of 4.0 over normal maximum operating conditions.	1	100	100	IV	

*A MODE LIKELIHOOD (1 TO 100) – *B EFFECTS IMPACT (1 TO 100) – *C CRITICALITY (A x B)

FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS WORKSHEET

SYSTEM ____________

SUBSYSTEM MINI-BRU

COMPLETED BY ____________

DATE ____________

COMPONENT	FAILURE MODE (S)	PROBABLE CAUSE	EFFECT OF FAILURE	FAILURE MODE MINIMIZATION	*A	*B	*C	HAZ CAT	SAFETY ACTION OR COMMENTS
Turbine Wheel	Blade fatigue	Faulty design; blade motion at higher stress levels; material impurities	Vibration; shaft excursion; loss of performance; failure of bearings; failure of BIPS	Impeller design is very conservative; stresses extremely low at operating conditions; detailed testing of material lot sample.	10	5-100	50-1000	II-IV	Effects impact can vary over wide range from minimal to catastrophic.
	Wheel hub burst	Faulty design; overspeed; overtemperature; material impurities	Failure of BIPS	Turbine wheel has been designed so as to assure that minimum burst speed has factor of safety of 3.5 over maximum operating conditions; inspect for voids or impurities in castings; inspect machined wheels and detailed testing of lot samples.	1	100	100	IV	
	Turbine blade fatigue	Faulty design; blade motion at higher stress levels; material impurities; low cycle fatigue; high cycle fatigue	Vibration; shaft excursion; loss of performance; failure of bearings; failure of BIPS	Turbine wheel design is very conservative; stresses extremely low at operating conditions; fundamental frequency of blades will be determined to confirm design	10	5-100	50-1000	II-IV	Effects impact is dependent upon size of crack or piece separated.

*A MODE LIKELIHOOD (1 TO 100) - *B EFFECTS IMPACT (1 TO 100) - *C CRITICALITY (A x B)

FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS WORKSHEET

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

SYSTEM ______ COMPLETED BY ______

SUBSYSTEM MINI-BRU DATE ______

COMPONENT	FAILURE MODE (S)	PROBABLE CAUSE	EFFECT OF FAILURE	FAILURE MODE MINIMIZATION	*A	*B	*C	HAZ CAT	SAFETY ACTION OR COMMENTS
	Turbine blade creep rupture	Faulty design; improper selection of material; excessive temperature	Blade rubs on shroud; failure of bearings; failure of BIPS	Design is very conservative; stresses low; (creep has been calculated to be exceptionally small-0.1% in 7.43 x 10^6 hrs; at this rate, probability of wheel touching shroud in 10 yrs is essentially zero)	5	5-100	25-500	II-IV	Effects impact can vary over wide range from minimal to catastrophic. A light rub, for example, is not necessarily a major problem.
	Turbine blade erosion	Evaporation of metal at operating temperature	Very gradual weakening and loss in performance	Analysis and testing required to determine if evaporation is of consequence in "pure" He-Xe atmosphere; GDS should give conclusive evidence.	1	5	5	II	

*A MODE LIKELIHOOD (1 TO 100) -*B EFFECTS IMPACT (1 TO 100) - *C CRITICALITY (A x B)

FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS WORKSHEET

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

SYSTEM ____________

SUBSYSTEM MINI-BRU

COMPLETED BY ____________

DATE ____________

COMPONENT	FAILURE MODE (S)	PROBABLE CAUSE	EFFECT OF FAILURE	FAILURE MODE MINIMIZATION	*A	*B	*C	HAZ CAT	SAFETY ACTION OR COMMENTS
Turbine Plenum	Crack, rupture, or puncture of plenum	Faulty design; embrittlement of C-103 as result of contaminants in working fluid or contaminants from outside loop	Loss of working fluid; failure of BIPS	Adequacy of plenum design is dependent upon authentication of C-103 creep rupture data; long term creep tests are planned to determine magnitude of C-103 strength degradation; offgassing tests of alternator stator will be performed; high quality He/Xe required as working fluid; introduce getters in loop to absorb contaminants; cleaning procedures for pre-storage and post-assembly of components must be developed to eliminate levels of contaminants determined to be harmful to C-103; quality must be carefully controlled in the area where vanes	1-25	1-100	1-2500	IV	Criticality ratings dependent upon size of crack and results of Cb tests to be conducted in contaminated environment at operating temperature.

*A MODE LIKELIHOOD (1 TO 100) – *B EFFECTS IMPACT (1 TO 100) – *C CRITICALITY (A x B)

FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS WORKSHEET

SYSTEM
SUBSYSTEM MINI-BRU
COMPLETED BY
DATE

COMPONENT	FAILURE MODE (S)	PROBABLE CAUSE	EFFECT OF FAILURE	FAILURE MODE MINIMIZATION	*A	*B	*C	HAZ CAT	SAFETY ACTION OR COMMENTS
Turbine Plenum (Contd)	Crack, rupture, or puncture of plenum (Contd)			are welded to the shroud to assure high integrity weld joints; need to assure that Cb spec is adequate and is followed.					
Foil Bearings	Bearing seizure	Excessive loading of bearings if BIPS is operating during launch vehicle acceleration	Failure of BIPS	Design the bearings with capacity sufficient to support launch load of rotating shaft (performance degraded because of bearing losses); investigate g-loads to be sustained in changing orbits to determine ability of Mini-BRU to operate if required; increase load capability of journal bearings (with small sacrifice in efficiency) if required to align Mini-BRU in horizontal orientation.	1	100	100	IV	

*A MODE LIKELIHOOD (1 TO 100) –*B EFFECTS IMPACT (1 TO 100) – *C CRITICALITY (A x B)

FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS WORKSHEET

SYSTEM ______ COMPLETED BY ______

SUBSYSTEM MINI-BRU DATE ______

COMPONENT	FAILURE MODE (S)	PROBABLE CAUSE	EFFECT OF FAILURE	FAILURE MODE MINIMIZATION	*A	*B	*C	HAZ CAT	SAFETY ACTION OR COMMENTS
Foil Bearings (Contd)	Bearing seizure	Incorrect assembly of foils or improper design	Failure of BIPS	Design, quality control, and proper assembly procedures will assure reliability of bearings (experience from aircraft subsystem applications provides confidence in inherent reliability of foil bearings).	1	100	100	IV	
	Loss of bearing coating	Overheating of bearing (turbine journal bearing limited to 500°F)	Increased torque required for start-up; possible loss of restart capability	Coating needed only for start-up	1	10	10	II	
Housing	Crack propagation	Flaw in material; gross overpressure	Leakage of working fluid; rupture of case	Proper design; quality control of fabrication; failure extremely remote	1	100	100	IV	
	Leakage of working fluid	Defective fit of case joints, electrical terminal feed-throughs	Leakage of working fluid	Quality assurance, vendor control should preclude; leakage test will detect	3	100	300	IV	

*A MODE LIKELIHOOD (1 TO 100) – *B EFFECTS IMPACT (1 TO 100) – *C CRITICALITY (A x B)

FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS WORKSHEET

SYSTEM BIPS-FS

SUBSYSTEM MINI-BRAYTON RECUPERATOR (MBR)

COMPLETED BY

DATE

COMPONENT	FAILURE MODE (S)	PROBABLE CAUSE	EFFECT OF FAILURE	FAILURE MODE MINIMIZATION	*A	*B	*C	HAZ CAT	SAFETY ACTION OR COMMENTS
Fins	Rupture due to creep or yielding of the parent metal.	Extensive exposure to overpressure and/or overtemperature operating conditions.	Loss of internal support with subsequent damage to tube plates and side plates; minor impairment of performance unless multiple passes break.	Control system must preclude off limit operation.	1	5	5	II	
	Rupture due to creep or yielding of the fin-to-tube plate braze joint.	Incomplete brazing of fins to tube plate and/or excessive braze alloy penetration of the thin gage (0.004 thick) fins.	Loss of internal support with subsequent damage to tube plates and side plates; minor impairment of performance unless multiple passes break.	Gold-base braze alloy has been specified in order to obtain braze alloy wetting and flow with minimum alloying and penetration; proof pressure acceptance test will detect gross braze voids.	1	5	5	II	
	Rupture due to low cycle fatigue	Accumulated damage as a result of thermal stresses induced by startup and shutdown transients.	Loss of internal support with subsequent damage to tube plates and side plates; minor impairment of performance unless multiple passes break.	Unit designed to withstand 1000 start up cycles (400 seconds to reach steady-state operating conditions); start up thermal transient now anticipated to be much more severe. Cyclic	10	5	50	II	

*A MODE LIKELIHOOD (1 TO 100) –*B EFFECTS IMPACT (1 TO 100) – *C CRITICALITY (A x B)

FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS WORKSHEET

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

SYSTEM ____________

SUBSYSTEM MINI-BRAYTON RECUPERATOR (MBR)

COMPLETED BY ____________

DATE ____________

COMPONENT	FAILURE MODE (S)	PROBABLE CAUSE	EFFECT OF FAILURE	FAILURE MODE MINIMIZATION	*A	*B	*C	HAZ CAT	SAFETY ACTION OR COMMENTS
Fins (Continued)	Rupture due to low cycle fatigue (Continued)			life will be reduced but will still exceed operational system requirements; prototype of MBR will be subjected to test to verify cyclic life.					
Tube Plates	Rupture due to creep or yielding.	Extensive exposure to over-pressure and/or overtemperature operating conditions.	Bypass flow of high pressure gas to low pressure gas with resulting small decrease in system power output.	Control system must preclude off-limit operation.	1	5	5	II	
	Rupture due to low cycle fatigue.	Accumulated damage as a result of thermal stresses induced by startup and shutdown transients.	Bypass flow of high pressure gas to low pressure gas with resulting small decrease in system power output.	Unit designed to withstand 1000 startup cycles (400 seconds to reach steady-state operating conditions); start up thermal transient now anticipated to be much more severe. Cyclic life will be reduced with will still exceed operational system requirements; prototype of MBR will be subjected to test to verify cyclic life.	10	5	50	II	

*A MODE LIKELIHOOD (1 TO 100) – *B EFFECTS IMPACT (1 TO 100) – *C CRITICALITY (A x B)

FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS WORKSHEET

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

SYSTEM ____________

SUBSYSTEM MINI-BRAYTON RECUPERATOR (MBR)

COMPLETED BY ____________

DATE ____________

COMPONENT	FAILURE MODE (S)	PROBABLE CAUSE	EFFECT OF FAILURE	FAILURE MODE MINIMIZATION	*A	*B	*C	HAZ CAT	SAFETY ACTION OR COMMENTS
Tube Plates (Continued)	Development of "pin-hole" leak.	Mechanical damage incurred during fabrication results in excessively thinned parent material (less than 0.003 in.) in localized areas. Void then occurs during subsequent brazing operations.	Bypass flow of high pressure gas to low pressure gas with resulting small decrease in system power output.	Inspection procedures have been established to preclude installation of defective plates. Special handling and storage procedures have been established to prevent damage.	2	5	10	II	
		Reaction of silicon carbide abrasive particles with gold base braze alloy to form low melting point silicon-gold eutectic.	Bypass flow of high pressure gas to low pressure gas with resulting small decrease in system power output.	Manufacturing procedures have been established to preclude use of silicon carbide grinding or cutting tools; procedures should also be established to preclude the use of silicon carbide grinding or cutting tools during system installation and/or removal of the recuperator.	2	5	10	II	

*A MODE LIKELIHOOD (1 TO 100) – *B EFFECTS IMPACT (1 TO 100) – *C CRITICALITY (A x B)

FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS WORKSHEET

SYSTEM ______ COMPLETED BY ______

SUBSYSTEM MINI-BRAYTON RECUPERATOR (MBR) DATE ______

COMPONENT	FAILURE MODE (S)	PROBABLE CAUSE	EFFECT OF FAILURE	FAILURE MODE MINIMIZATION	*A	*B	*C	HAZ CAT	SAFETY ACTION OR COMMENTS
Header Bars	Rupture due to creep or yielding of the parent metal	Extensive exposure to overtemperature or overpressure operating conditions; undetected thinning of header bar web during machining operation rewuired to prepare surface for brazing of the seal plate.	Localized loss of structural integrity (loss of working fluid is prevented by seal plate).	Header bar stress levels are moderate because of its large cross section; seal plate will act as a backup structure.	1	5	5	II	
	Rupture due to creep or yielding of the header bar-to-tube plate braze joint.	Incomplete brazing of the bars to the tube plates (braze voids)	Localized loss of structural integrity (loss of working fluid is prevented by seal plate).	Seal plate will act as a backup structure; gold base braze alloy has been specified in order to obtain optimum alloy wetting and flow with minimum alloying and penetration.	1	5	5	II	
	Rupture due to low cycle fatiague.	Accumulated damage as a result of thermal stresses induced by startup and shutdown transients.	Loss of structural integrity; failure most likely to occur in header bar-to-tube plate braze joint (seal plate will prevent loss of working fluid in the event of cracking).	Unit designed to withstand 1000 startup cycles (400 seconds to reach steady state operating conditions); start up thermal transient now anticipated to be much more severe. Cyclic life will	5	5	25	II	

*A MODE LIKELIHOOD (1 TO 100) – *B EFFECTS IMPACT (1 TO 100) – *C CRITICALITY (A x B)

FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS WORKSHEET

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

SYSTEM ____

SUBSYSTEM MINI-BRAYTON RECUPERATOR (MBR)

COMPLETED BY ____

DATE ____

COMPONENT	FAILURE MODE (S)	PROBABLE CAUSE	EFFECT OF FAILURE	FAILURE MODE MINIMIZATION	*A	*B	*C	HAZ CAT	SAFETY ACTION OR COMMENTS
Header Bars (Continued)	Rupture due to low cycle fatigue.			be reduced but will still exceed operational system requirements, prototype of MBR will be subjected to test to verify cyclic life; gold-base braze alloy is ductile and will therefore resist LCF; channel-type header bars selected to obtain minimum mass and thereby improve the bar thermal response relative to the plates.					
Splitters	Rupture due to creep or yielding.	Extensive exposure to pressure differentials or operating temperatures greater than design limits.	Bypass flow of high pressure working fluid to low pressure side with resulting decrease in system power output.	Startup and shutdown procedures should be reviewed to insure that excessive pressure differentials are not developed.	1	50	50	III	
	Rupture of splitter-to-core matrix braze joint	Undetected braze voids	Bypass flow of high pressure gas with resulting decrease in system power output.	Inspection procedures (radio graphic) have been established to insure adequate braze alloy coverage.	2	50	100	III	

*A MODE LIKELIHOOD (1 TO 100) – *B EFFECTS IMPACT (1 TO 100) – *C CRITICALITY (A x B)

FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS WORKSHEET

SYSTEM __________ COMPLETED BY __________

SUBSYSTEM MINI-BRAYTON RECUPERATOR (MBR) DATE __________

COMPONENT	FAILURE MODE (S)	PROBABLE CAUSE	EFFECT OF FAILURE	FAILURE MODE MINIMIZATION	*A	*B	*C	HAZ CAT	SAFETY ACTION OR COMMENTS
Splitters (Continued)	Rupture of splitter-to-core matrix braze joint.	Accumulated damage as a result of thermal stresses induced by startup and shutdown transients		Prototype of MBR will be subjected to test to verify cyclic life.	10	50	500	III	
Side Plates	Rupture due to creep or yielding Rupture due to low cycle fatigue	Extensive exposure to over-temperature or over-pressure operating conditions Accumulated damage as a result of thermal stresses induced by startup and shutdown transients	Loss of working fluid with eventual shutdown of BIPS	Unit designed to withstand 1000 startup cycles (400 seconds to reach steady state conditions); startup thermal transient now anticipated to be more severe. Cyclic life will be reduced but will still exceed operational system requirements; prototype of MBR will be subjected to test to verify cyclic life; Side plate machined to provide optimum thickness for pan attachment.	1	100	100	IV	

*A MODE LIKELIHOOD (1 TO 100) – *B EFFECTS IMPACT (1 TO 100) – *C CRITICALITY (A x B)

FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS WORKSHEET

SYSTEM ______ COMPLETED BY ______

SUBSYSTEM MINI-BRAYTON RECUPERATOR (MBR) DATE ______

COMPONENT	FAILURE MODE (S)	PROBABLE CAUSE	EFFECT OF FAILURE	FAILURE MODE MINIMIZATION	*A	*B	*C	HAZ CAT	SAFETY ACTION OR COMMENTS
Seal Plates	Rupture due to creep or yielding.	A void, larger than 1/2 inch in diameter, present in the braze joint between seal plate and core assembly; pressure allowed to develop in a void as a result of a defect in the adjacent header bar-to-tube plate joint (double defects)	Loss of working fluid with eventual shutdown of the BIPS.	Double failure not likely to occur. Inspection technique should be developed to detect large braze voids. Braze alloy applied in foil form to facilitate brazing of the large flat surfaces.	1	100	100	IV	
	Rupture due to crack propagation.	Crack developed in header bar-to-tube plate joint as a result of low cycle fatigue which acts as a stress riser and induces crack in the seal plate.	Loss of working fluid with eventual shutdown of the BIPS.	Braze joint interface acts to prevent crack propagation.	1	100	100	IV	
	Rupture due to low cycle fatigue.	Accumulated damage as a result of thermal stresses induced by startup and shutdown transients; low cycle fatigue cracks would be developed in areas adjacent to the side flanges and mounting assemblies.	Reduction in load carrying ability of the mounting assemblies and the side flanges (high load carrying capability only needed for launch).	Prototype of MBR will be subjected to test to verify cyclic life.	1	5	5	II	

*A MODE LIKELIHOOD (1 TO 100) – *B EFFECTS IMPACT (1 TO 100) – *C CRITICALITY (A x B)

FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS WORKSHEET

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

SYSTEM ______________________ COMPLETED BY ______________________

SUBSYSTEM MINI-BRAYTON RECUPERATOR (MBR) DATE ______________

COMPONENT	FAILURE MODE (S)	PROBABLE CAUSE	EFFECT OF FAILURE	FAILURE MODE MINIMIZATION	*A	*B	*C	HAZ CAT	SAFETY ACTION OR COMMENTS
Manifold Attachment Flange	Rupture due to creep or yielding in the flange-to-seal plate braze joint.	Incomplete braze alloy coverage (voids)	Loss of working fluid with eventual shutdown of the BIPS	Development tests have been conducted to verify that manufacturing techniques yield full braze alloy coverage on similar parts: inspection technique should be developed to insure adequate braze joint coverage.	2	100	200	IV	
	Cracking in braze joint between flange and side plate	Low cycle fatigue.	Loss of working fluid with eventual shutdown of the BIPS	Joint design to be verified by thermal cycle test (prototype MBR)	10	100	1000	IV	
Pan Assemblies	Rupture due to creep or yielding.	Extensive exposure to over-pressure or over-temperature operating conditions.	Loss of working fluid with eventual shutdown of the BIPS.	Control system must preclude off-limit operation.	1	100	100	IV	
	Rupture due to low cycle fatigue.	Accumulated damage as a result of thermal stresses induced by startup and shutdown transients	Loss of working fluid with eventual shutdown of the BIPS.	Unit designed to withstand 1000 startup cycles (400 seconds to reach steady state conditions); startup thermal transient now anticipated to be more severe. Cyclic life will be	2	100	200	IV	

*A MODE LIKELIHOOD (1 TO 100) – *B EFFECTS IMPACT (1 TO 100) – *C CRITICALITY (A x B)

FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS WORKSHEET

SYSTEM ______ COMPLETED BY ______

SUBSYSTEM MINI-BRAYTON RECUPERATOR (MBR) DATE ______

COMPONENT	FAILURE MODE (S)	PROBABLE CAUSE	EFFECT OF FAILURE	FAILURE MODE MINIMIZATION	*A	*B	*C	HAZ CAT	SAFETY ACTION OR COMMENTS
Pan Assemblies (Continued)	Rupture due to low cycle fatigue.			reduced but will still exceed operational system requirements; prototype of MBR will be subjected to test to verify cyclic life.					
	Rupture	Improper installation within BIPS causes excessive loads at duct interfaces during thermal growth; damage accumulates because of cyclic operation and a low cycle fatigue results;	Loss of working fluid with eventual shutdown of BIPS.	BIPS integrator will perform an interface study to assure that duct loads transmitted to recuperator do not exceed design allowances.	5	100	500	IV	
		Excessive g-loads at duct interfaces.	Loss of working fluid with eventual shutdown of BIPS.	BIPS-FS qualification tests must fully substantiate that excessive g-loads are not applied to duct interfaces during launch and other mission environments.	2	100	200	IV	
Mount Assemblies	Plastic deformation due to creep or yield.	Excessive acceleration (g-loads); Improper alignment in system installation;	Minimal effect on mission success if plastic deformation is not cyclic.	A final layout inspection should be performed to assure that the assembly has not	10	10	100	II	

*A MODE LIKELIHOOD (1 TO 100) – *B EFFECTS IMPACT (1 TO 100) – *C CRITICALITY (A x B)

FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS WORKSHEET

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

SYSTEM ____________

SUBSYSTEM MINI-BRAYTON RECUPERATOR (MBR)

COMPLETED BY ____________

DATE ____________

COMPONENT	FAILURE MODE (S)	PROBABLE CAUSE	EFFECT OF FAILURE	FAILURE MODE MINIMIZATION	*A	*B	*C	HAZ CAT	SAFETY ACTION OR COMMENTS
Mount Assemblies (Continued)	Plastic deformation due to creep or yield.	Improper machining; Mechanical damage		been deformed during manufacture or test operations; BIPS assembly procedures must assure correct installation alignment.					
	Rupture	Excessive vibration or acceleration; Improper installation causes binding and plastic deformation during thermal growth. Damage accumulates because of cyclic operation and a low cycle fatigue failure results; Material flaw; Mechanical damage	Deformation and possible rupture of attaching ducting with subsequent loss of working fluid and shutdown of BIPS	Mount assembly should be subjected to 100% radiographic and ultrasonic inspection. BIPS assembly procedures must assure correct installation alignment; self aligning bearing mounts have been proposed to insure free movement. A test should be conducted to assure that mounts slide freely during thermal growth and that no galling or welding occurs because of exposure to space vacuum.	5	100	500	IV	

*A MODE LIKELIHOOD (1 TO 100) – *B EFFECTS IMPACT (1 TO 100) – *C CRITICALITY (A x B)

FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS WORKSHEET

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

SYSTEM ______

SUBSYSTEM MINI-BRAYTON RECUPERATOR (MBR)

COMPLETED BY ______

DATE ______

COMPONENT	FAILURE MODE (S)	PROBABLE CAUSE	EFFECT OF FAILURE	FAILURE MODE MINIMIZATION	*A	*B	*C	HAZ CAT	SAFETY ACTION OR COMMENTS
Mount Assemblies (Continued)	Rupture			BIPS-FS qualification tests must fully substantiate that mounting system will resist the g-loads which occur during launch and other mission environments.					

*A MODE LIKELIHOOD (1 TO 100) – *B EFFECTS IMPACT (1 TO 100) – *C CRITICALITY (A x B)

FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS WORKSHEET

SYSTEM ______

SUBSYSTEM HEAT SOURCE ASSEMBLY (HSA)

COMPLETED BY ______

DATE ______

COMPONENT	FAILURE MODE (S)	PROBABLE CAUSE	EFFECT OF FAILURE	FAILURE MODE MINIMIZATION	*A	*B	*C	HAZ CAT	SAFETY ACTION OR COMMENTS
Heat Source Heat Exchanger (HSHX)	Penetration of cylinder walls or headers	Micrometeoroid impact	Loss of working fluid with eventual shutdown of BIPS; complete loss of working fluid will activate ECS.	Material thickness conforms to NASA specification; failure mode is considered to be extremely remote since penetration of beryllium housing, insulation (60 foils), and C-103 cylinder wall would be required.	1	100	100	IV	
	Cracking or fracture of C-103	Embrittlement of C-103 as result of contaminants	Loss of working fluid with eventual shutdown of BIPS	Long-term creep tests required to determine magnitude of C-103 strength degradation; problem similar to that of Mini-BRU turbine plenum; contamination of carbon, CO/CO_2 from heat source can be avoided by cladding HS can with PT 3008 alloy or silicide coated C-103 (both require development)	1-25	100	2500	IV	Criticality ratings dependent upon size of crack and results of Cb tests to be conducted in contaminated environment at operating temperature.

*A MODE LIKELIHOOD (1 TO 100) -*B EFFECTS IMPACT (1 TO 100) - *C CRITICALITY (A x B)

FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS WORKSHEET

SYSTEM ____________

COMPLETED BY ____________

SUBSYSTEM HEAT SOURCE ASSEMBLY (HSA)

DATE ____________

COMPONENT	FAILURE MODE (S)	PROBABLE CAUSE	EFFECT OF FAILURE	FAILURE MODE MINIMIZATION	*A	*B	*C	HAZ CAT	SAFETY ACTION OR COMMENTS
HSHX (Contd)									
	Leakage at header weldments	Defective welds	Loss of working fluid with eventual shut-down of BIPS; complete loss of working fluid wil will activate ECS.	Proof pressure test and leak test will be per-formed on each HSHX; QA inspec-tion on welds should detect de-fects; weld process will be checked with de-structive speci-mens.	2	100	200	IV	
	Diffusion welds (ribs to outer cylinder) may open.	Process defect; ex-cessive thermal or dynamic stresses	Degraded heating of working fluid; criticality yet to be determined.	Perfect the fabri-cation process; inspection by holographic and ultrasonic methods planned.	10	25	250	II	Perfection of fabrication process yet to be demonstrated.
	Fracture of flow channel fins	Process defect	Single fin frac-ture not detec-table; multiple fractures could result in detectable cross flow and reduced lifetime.	Inspection by holographic and ultrasonic methods planned; qualif-ication tests are expected to con-firm integrity of design.	1	5	5	I	

*A MODE LIKELIHOOD (1 TO 100) – *B EFFECTS IMPACT (1 TO 100) – *C CRITICALITY (A x B)

FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS WORKSHEET

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

SYSTEM ____________ COMPLETED BY ____________

SUBSYSTEM HEAT SOURCE ASSEMBLY (HSA) DATE ____________

COMPONENT	FAILURE MODE (S)	PROBABLE CAUSE	EFFECT OF FAILURE	FAILURE MODE MINIMIZATION	*A	*B	*C	HAZ CAT	SAFETY ACTION OR COMMENTS
Inlet-Outlet Headers	Leakage at weld joints.	Defective weld	Loss of working fluid with eventual shutdown of BIPS	Proof pressure test and QC inspections should detect gross leakage. GE-PIR5215 documents the analysis of redesigned header geometry; donut shaped header has reduced thermal stress relative to reference design.	2	100	200	IV	
HSHX Mounting Supports ("L" Brackets)	Fracture of one support	Excessive dynamic loading	None - other seven supports will adequately support the HSHX	Proper design should eliminate failure.	1	1	1	I	
Heat Source End Supports	Loss of preload during launch	Material fracture	Possible damage to HS or HSHX resulting in low power output	Design has been proven by MHW qualification tests	1	50	50	III	
Heat Source Mounting Brackets	Fracture of one bracket	Excessive vibration during launch or ground handling at room temperature after thermal cycle (when material is brittle)	None - Other seven brackets will adequately support the HS	Proper design should eliminate failure.	1	1	1	I	

*A MODE LIKELIHOOD (1 TO 100) - *B EFFECTS IMPACT (1 TO 100) - *C CRITICALITY (A x B)

FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS WORKSHEET

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

SYSTEM ____________

SUBSYSTEM HEAT SOURCE ASSEMBLY (HSA)

COMPLETED BY ____________

DATE ____________

COMPONENT	FAILURE MODE (S)	PROBABLE CAUSE	EFFECT OF FAILURE	FAILURE MODE MINIMIZATION	*A	*B	*C	HAZ CAT	SAFETY ACTION OR COMMENTS
End Enclosures	Fracture of one spoke of one end enclosure	Shock or vibration during launch	None - other five spokes would adequately support the HS	Design has been proven by MHW qualification tests.	1	1	1	I	
Preload Fitting	Loss of preload	Assembly defect; creep effect due to overtemperature of fitting.	Movement of HS; possible damage to HSA causing cracks in aero shell or leakage of working fluid.	Design has been proven by MHW qualification tests	1	50	50	III	
Be External Support Housing of End Domes	Cracking of shell or end dome.	Material defect or shock load	Loss of He coolant (if BIPS not operating) which, in turn, results in activation of EGS, melting multifoil insulation in HSA, and consequential BIPS failure.	Design is similar to that of MHW which has passed qualification tests; quality control of fabrication should assure reliable component.	1	100	100	IV	Potentially adverse impact on nuclear safety.
Insulation Blanket (HSIS)	Self welding of Ni layers	Zirconia particles absent in broad area of Ni foil	Long term degradation of BIPS output power	QA will assure proper distribution of zirconia; shown that no appreciable loss of zirconia occurred from launch environment (vibration)	5	30	150	III	

*A MODE LIKELIHOOD (1 TO 100) - *B EFFECTS IMPACT (1 TO 100) - *C CRITICALITY (A x B)

FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS WORKSHEET

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

SYSTEM ____________

SUBSYSTEM HEAT SOURCE ASSEMBLY (HSA)

COMPLETED BY ____________

DATE ____________

COMPONENT	FAILURE MODE (S)	PROBABLE CAUSE	EFFECT OF FAILURE	FAILURE MODE MINIMIZATION	*A	*B	*C	HAZ CAT	SAFETY ACTION OR COMMENTS
Insulation Blanket (HSIS) (Continued)	Abnormal heat leak	Process defect causing tear in blanket layers during processing or non uniform edge joint.	Decrease in BIPS power output	QA should preclude negligible probability of occurrence during launch or orbit.	2	50	100	III	
	Loss of He coolant during ACS operating period	Malfunction/failure of auxiliary cooling valve; premature ground command to gas venting system.	Premature venting of He results in activation of ECS (meltdown of insulation) and BIPS failure.	ACS gas venting system must and can be designed so as to be highly reliable; design concept not yet chosen for FS; design for GDS will not be that required for FS.	2	100	200	IV	Potentially adverse impact on nuclear safety.
	Delayed melting of foil (in ECS mode)	Middle and outer layers of foil do not melt as intended.	Overtemperature of heat source resulting in probable degradation of strength of iridium in PICS to point where impact survival is questionable.	Full scale meltdown test planned to determine extent of ECS may be necessary.	30	50	1500	III	
Insulation Blanket Support Structure	Fracture or distortion of support members	High g-load during launch	Collapse of blanket around HSHX generates leaks resulting in some loss of heat energy to space.	GE-PIR5374 concludes that the structure as designed will support the HSIS under a 15g load without exceeding yield value.	2	50	100	III	

*A MODE LIKELIHOOD (1 TO 100) - *B EFFECTS IMPACT (1 TO 100) - *C CRITICALITY (A x B)

FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS WORKSHEET

SYSTEM ______ COMPLETED BY ______

SUBSYSTEM HEAT SOURCE ASSEMBLY (HSA) DATE ______

COMPONENT	FAILURE MODE (S)	PROBABLE CAUSE	EFFECT OF FAILURE	FAILURE MODE MINIMIZATION	*A	*B	*C	HAZ CAT	SAFETY ACTION OR COMMENTS
Auxiliary Cooling Valve	Opens prematurely	Valve failure; premature ground command to gas venting system; premature firing of squib in valve.	Vents helium coolant; results in activation of ECS (meltdown of of insulation) and BIPS failure (unless BIPS is started within required interval of time)	Gas venting system must and can be designed so as to be highly reliable.	2	100	200	IV	Potentially adverse impact on nuclear safety; design concept not yet chosen for FS; design for GDS will be unlike that required for FS; NOTE: Auxiliary cooling valve should not be confused with gas management valve. The GMV is required to vent He generated by radioactive decay of the isotope. Design concept for the GMV has not been chosen for FS and none will be required or installed in HSAs for BIPS-GDS.
	Fails to open	Defective squib or failure of ground command actuating signal	Helium would continue to short circuit insulation thereby preventing working fluid from attaining temperature sufficient to sustain operating cycle; BIPS failure.	Gas venting system must and can be designed so as to be highly reliable.	1	100	100	IV	

*A MODE LIKELIHOOD (1 TO 100) – *B EFFECTS IMPACT (1 TO 100) – *C CRITICALITY (A x B)

FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS WORKSHEET

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

SYSTEM BIPS

SUBSYSTEM Radiator

NOTE: Radiator design is in an early conceptual stage; refinement of the design will not evolve until late in Phase I or possibly, will await Phase II.

COMPLETED BY

DATE

COMPONENT	FAILURE MODE (S)	PROBABLE CAUSE	EFFECT OF FAILURE	FAILURE MODE MINIMIZATION	*A	*B	*C	HAZ CAT	SAFETY ACTION OR COMMENTS
Inlet and Outlet Headers	Crack in parent material	Material defect; improper fabrication (conceptual design is extruded aluminum tubing, formed into a toroid, and sealed with a seam weld)	Loss of working fluid; eventual shutdown of BIPS.	Proper design and quality assurance inspection procedures should preclude.	1	100	100	IV	
	Weld failure	Defective weld; joint overstressed by thermal expansion of header or structure; faulty design	Loss of working fluid; eventual shutdown of BIPS.	Proper design and quality assurance inspection procedures should preclude.	1	100	100	IV	
	Penetration of header	Micrometeroid impact	Loss of working fluid; eventual shutdown of BIPS.	Design to NASA specification; size components to provide probability of >0.99 that radiator survives 7 year mission.	1	100	100	IV	
Tubes (32 total)	Penetration; fracture of tube	Micrometeroid impact	Loss of working fluid; eventual shutdown of BIPS.	Design to NASA specification; size components to provide probability of >0.99 that radiator survives 7 year mission.	2	100	200	IV	
	Crack in parent material; weld failure where tube joins inlet or outlet header	Material defect; defective weld; improper design	Loss of working fluid; eventual shutdown of BIPS.	Proper design and quality assurance inspection procedures should preclude.	2	100	200	IV	

*A MODE LIKELIHOOD (1 TO 100) – *B EFFECTS IMPACT (1 TO 100) – *C CRITICALITY (A x B)

FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS WORKSHEET

SYSTEM BIPS-FS

SUBSYSTEM Radiator

COMPLETED BY

DATE

COMPONENT	FAILURE MODE (S)	PROBABLE CAUSE	EFFECT OF FAILURE	FAILURE MODE MINIMIZATION	*A	*B	*C	HAZ CAT	SAFETY ACTION OR COMMENTS
Panel (Skin, Fin Surface Area)	Loss of emissivity	Damage to emissivity coating from effects of nuclear weapon detonation; aging effects of exposure to ultraviolet rays from sun; poor bond between coating and metal panel.	Degradation of radiation efficiency; gradual or instantaneous loss of BIPS cycle efficiency; eventual shutdown of BIPS.	Careful selection of emissivity coating is required to minimize adverse effects; approved method of coating application and close quality control required to assure good bonding.	10 (?)	25-100	250-1000	II - IV	Ratings assume that level of nuclear effects is sufficient to damage emissivity coating but insufficient to seriously impair other BIPS components.
	Penetration, rips, or tears, in skin between tubes	Micrometeoroid impact; damage through mishandling; material defects.	Minimal loss of heat rejection capability (however, may be critical if radiator is required to serve as pressure vessel for operating BIPS on ground).	Handle with care during ground operations; design special handling fixture.	1-20	1-100	1-2000	I-IV	Inconsequential unless radiator is required to serve as pressure vessel for operating BIPS on launch pad.
	Separation of panel from tubes	Defective brazes (or welds)	Limited separation probably of no consequence; extensive separation will weaken structurally and degrade radiator efficiency.	Perfect the fabrication process; develop effective method of inspection of brazes (or welds).	5	10	50	II	

*A MODE LIKELIHOOD (1 TO 100) – *B EFFECTS IMPACT (1 TO 100) – *C CRITICALITY (A x B)

FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS WORKSHEET

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

SYSTEM BIPS-FS

SUBSYSTEM Ducts and Bellows

COMPLETED BY

DATE

COMPONENT	FAILURE MODE (S)	PROBABLE CAUSE	EFFECT OF FAILURE	FAILURE MODE MINIMIZATION	*A	*B	*C	HAZ CAT	SAFETY ACTION OR COMMENTS
Ducts	Cracks in welds or parent material	Defective weld	Loss of working fluid with eventual shutdown of BIPS; BIPS shutdown activates ECS.	Perfect the welding procedures; inspect welds and ducts using holography and/or X-ray methods; inspect, NDT each weld as it is completed; insure proper alignment using fixtures during assembly; consider double containment weld joints where feasible.	1	100	100	IV	
	Cracking or failure of bimetallic joint or transition	Defective process	Loss of working fluid with eventual shutdown of BIPS; BIPS shutdown activates ECS.	Perfect the fabrication process (program underway to evaluate several methods of joining dissimilar metals - C-103/Hastelloy X); incorporate close quality control inspection program.	2	100	200	IV	

*A MODE LIKELIHOOD (1 TO 100) - *B EFFECTS IMPACT (1 TO 100) - *C CRITICALITY (A x B)

FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS WORKSHEET

SYSTEM ____________

COMPLETED BY ____________

SUBSYSTEM Ducts and Bellows

DATE ____________

COMPONENT	FAILURE MODE (S)	PROBABLE CAUSE	EFFECT OF FAILURE	FAILURE MODE MINIMIZATION	*A	*B	*C	HAZ CAT	SAFETY ACTION OR COMMENTS
Bellows	Cracking of weld (at end) or in bend (convolute) of bellows.	Defective welds; thinning of metal during forming of convolute; high stress due to center-line misalignment.	If single ply, loss of working fluid with even-tual shutdown of BIPS; if double ply bellows, fail-ure in outer ply - no immediate effect - but failure of inner ply may result in introduction of contaminants (trapped between plys) into work-ing fluid.	Correct design of bellows will be essential in order to compensate for centerline mis-alignment due to thermal expansion and lateral de-flection; close quality control of fabrication and assembly will be required; if double or triple ply bellows are used, method of cleaning and purging of volume between layers must be developed so as to preclude contaminating working fluid in the event of inner layer cracking.	5	20-100	100-500	II-IV	Ratings depend upon whether single or multi-ply material is used.

*A MODE LIKELIHOOD (1 TO 100) -*B EFFECTS IMPACT (1 TO 100) - *C CRITICALITY (A x B)

FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS WORKSHEET

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

SYSTEM BIPS - FLIGHT SYSTEM

SUBSYSTEM Insulation

COMPLETED BY

DATE

COMPONENT	FAILURE MODE (S)	PROBABLE CAUSE	EFFECT OF FAILURE	FAILURE MODE MINIMIZATION	*A	*B	*C	HAZ CAT	SAFETY ACTION OR COMMENTS
High Temperature Insulation	Loss of spacer material - ZrO_2	Severe vibration, abrasion; chemical decomposition or attack	Degradation of insulation properties, diffusion welding of adjacent foils, long term progressive failure.	Vibration test during development, decontamination procedure for FS.	1	50	50	III	
	Structural failure of insulation resulting in high local heat loss	Excessive mechanical and/or thermal stress in insulation retaining system.	Degradation of insulation properties, possible induced thermal failure of high temperature components loss of working fluid.	Redundant structure for 20 to 30 foil groups, development proof testing and analysis.	2	50-100	100-200	III-IV	
	Oxidation or contamination of foil surfaces.	Residual contaminants at engine start or migration of volatiles from elsewhere in system.	Minor degradation of insulation performance, reduced power capability	FS preparations, bakeout, pumpdown, component storage precautions.	5	10	50	II	

*A MODE LIKELIHOOD (1 TO 100) -*B EFFECTS IMPACT (1 TO 100) - *C CRITICALITY (A x B)

FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS WORKSHEET

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

SYSTEM BIPS-FS

SUBSYSTEM Controls

COMPLETED BY

DATE

COMPONENT	FAILURE MODE (S)	PROBABLE CAUSE	EFFECT OF FAILURE	FAILURE MODE MINIMIZATION	*A	*B	*C	HAZ CAT	SAFETY ACTION OR COMMENTS
Power Supply	Semiconductor failure; passive component failure; transformer/inductor failure	Voltage transients; overloads; vibration/shock; nonconservative design (insufficient derating).	Loss of control circuits with turbine stall resulting (upon loss of power to control circuits, parasitic load turns on full and field saturates).	High quality components; low parts count; extensive QA program; triple redundancy; conservative design; extensive development testing.	2	100	200	IV	
Output Current Sensor	Current transformer failure (open or short); semiconductor failure; passive component failure (open, short drift)	Severe vibration/shock; unexpected temperature extremes; flaw in manufacturing process; nonconservative design; power supply transient.	Error in output current feedback signal to parasitic load control, results in incorrect application of parasitic load with customer load changes; could result in stalled or runaway rotating group under certain conditions; poor speed regulation.	Electronic circuits will be triple redundant; interface circuits between output current sensor and parasitic load control will select best of three independent output signals; current transformers to be prime reliable with extreme QA procedures; input power supply filters with clamping circuits to be used; Extensive "burning in" and derating will preclude nonconservative design;	1	100	100	III - IV	"A" is likelihood of failure that results in zero or maximum indication from current sensor.

*A MODE LIKELIHOOD (1 TO 100) – *B EFFECTS IMPACT (1 TO 100) – *C CRITICALITY (A x B)

FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS WORKSHEET

SYSTEM ______________ COMPLETED BY ______________

SUBSYSTEM Controls DATE ______________

COMPONENT	FAILURE MODE (S)	PROBABLE CAUSE	EFFECT OF FAILURE	FAILURE MODE MINIMIZATION	*A	*B	*C	HAZ CAT	SAFETY ACTION OR COMMENTS
Output Current Sensor (Continued)	Current transformer failure (open or short); semiconductor failure; passive component failure (open, short drift) (continued)			use of highest quality semi-conducting and passive components.					
Speed Sensor/ Transducer	Monopole failure; semiconductor failure (open, short, drift)	Severe vibration/ shock; unexpected temperature extremes; flaw in manufacturing process; nonservative design; power supply transient.	Error in speed feedback signal to parasitic load control; poor speed regulation; could result in stalled or runaway rotating group under certain load conditions if speed error signal is greater than a few percent.	Speed transducer and pickups triple redundant; interface circuits between speed sensor and parasitic load control will select best of three output signals; extreme QA procedures; extensive developmental testing, "burn in"; and derating will preclude nonconservative design; use of highest quality semiconductors and passive components; input power supply filters with clamping circuits to be used.	1	100	100	III - IV	

*A MODE LIKELIHOOD (1 TO 100) – *B EFFECTS IMPACT (1 TO 100) – *C CRITICALITY (A x B)

FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS WORKSHEET

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

76-311709
Appendix
Page 34

SYSTEM ______ COMPLETED BY ______

SUBSYSTEM CONTROLS DATE ______

COMPONENT	FAILURE MODE (S)	PROBABLE CAUSE	EFFECT OF FAILURE	FAILURE MODE MINIMIZATION	*A	*B	*C	HAZ CAT	SAFETY ACTION OR COMMENTS
T_6 (Turbine Inlet) Temp. Transducer	Thermocouple failure (open); Semi conductor failure; Passive component failure	Severe vibration/ shock; unexpected temperature extremes; flaw in manufacturing process; nonconservative design; power supply transient.	Erroneous T_6 indication to parasitic load control; incorrect parasitic load applied, resulting in undesired T_6 operating point; reduction or increase in available power, depending upon sign of error	T_6 transducer is intended to correct for isotope decay and will have limited authority; triple redundancy with "Best of Three" employed; Parallel thermocouples; extensive developmental testing and "Burn in" to preclude non conservative design.	1	10	10	II	
Parasitic load control	Semi conductor failure; passive component failure	Severe vibration/ shock; unexpected temperature extremes; flaw in manufacturing process; nonconservative design; power supply transient.	Shift in references - mini-BRU will go to new, undesired speed/ power operating point; Gross failure - Mini-BRU will either stall or run away; gain shift/compensation failure - load will oscillate, causing speed fluctuations and perhaps voltage fluctuations, making output unusable	Control will be triple redundant throughout, with "Best of Three" Logic employed to ignore erroneous outputs; High quality parts used throughout; extensive developmental testing and "Burn in" to preclude non conservative design and insufficient derating	1	100	100	III - IV	"A" is estimated likelihood of the complete failure of the parasitic load control

*A MODE LIKELIHOOD (1 TO 100) - *B EFFECTS IMPACT (1 TO 100) - *C CRITICALITY (A x B)

FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS WORKSHEET

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

SYSTEM ______________ COMPLETED BY ______________

SUBSYSTEM CONTROLS DATE ______________

COMPONENT	FAILURE MODE (S)	PROBABLE CAUSE	EFFECT OF FAILURE	FAILURE MODE MINIMIZATION	*A	*B	*C	HAZ CAT	SAFETY ACTION OR COMMENTS
Parasitic Load (including individual rectifier sets)	Rectifier failure; resistive element failure (open); semi conductor load driver failure (short open)	Severe vibration/shock; unexpected temperature extremes; flaw in manufacturing process; nonconservative design; power supply transient; voltage transients; long term over-current.	Rectifier failure-unbalanced alternator load; excessive ripple; high alternator current; resitive element failure - reduction of applied power; slight speed increase; semi conductor load driver failure - short: Excessive parasitic load applied, reduction in speed; - open: insufficient parasitic load applied, increase in speed	Parasitic load consists of three independent loads/rectifiers, any two of which can limit speed upon loss of third. Each load employs series/parallel diodes in rectifier set, double redundant switching transistors in series/parallel in load drive, and double redundant logic; six resistive elements are used in each load. The loss or shorting of any resistor will be compensated for by power control loop. Extensive developmental tests and "Burn in" will preclude non conservative design.	- 1	75	75	III	"A" is estimated likelihood of one complete parasitic load failing full on

*A MODE LIKELIHOOD (1 TO 100) -*B EFFECTS IMPACT (1 TO 100) - *C CRITICALITY (A x B)

FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS WORKSHEET

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

SYSTEM ____________ COMPLETED BY ____________

SUBSYSTEM CONTROLS DATE ____________

COMPONENT	FAILURE MODE (S)	PROBABLE CAUSE	EFFECT OF FAILURE	FAILURE MODE MINIMIZATION	*A	*B	*C	HAZ CAT	SAFETY ACTION OR COMMENTS
Field current control (including voltage regulator)	Current transformer failure (open, short); semiconductor failure; passive component failure (short, open, drift); Alternator field failure (short, open)	Severe vibration/shock; unexpected temperature extremes; flaw in manufacturing process; nonconservative design; power supply transient.	Field saturates-voltage possibly exceeds 120 vdc, output power increases, mini-BRU slows, and could possibly stall under certain customer load conditions; Zero or reduced field current - voltage drops, possibly resulting in insufficient power available to control speed, and mini-BRU could run away; output voltage above or below nominal could damage user loads if protective device fails	Field current control system consists of two independent current and voltage regulators. Failure of either will have only slight effect on output voltage; redundancy within each control system will prevent failure of the control system with numerous semi conductor and passive component failures; highest quality electronic components to be used; extensive developmental testing, "burn-in" and derating will preclude non conservative design.	1	100	100	III - IV	"A" is estimated likelihood of one of two field controls failing completely.
Rectifier Set	Diode Failure (Short, open)	Severe vibration/shock; unexpected temperature extremes; flaw in manufacturing process; nonconservative design; excessive current; voltage transient.	Open Diode- High ripple, deduction in average output voltage; Shorted Diode - High current in alternator output, high ripple, reduction in average output voltage.	Series/Parallel arrangement of diodes in rectifier set precludes possibility of shorts and opens due to failure of any single diode; voltage regulator will reduce effect	1	50	50	III	"A" is estimated likelihood of single series/parallel diode failure "B" is impact if "A" occurs

*A MODE LIKELIHOOD (1 TO 100) - *B EFFECTS IMPACT (1 TO 100) - *C CRITICALITY (A x B)

FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS WORKSHEET

SYSTEM

SUBSYSTEM CONTROLS

COMPLETED BY

DATE

COMPONENT	FAILURE MODE (S)	PROBABLE CAUSE	EFFECT OF FAILURE	FAILURE MODE MINIMIZATION	*A	*B	*C	HAZ CAT	SAFETY ACTION OR COMMENTS
Rectifier Set (continued)	Diode Failure (continued)			of average output voltage changes; Output filter following rectifier will reduce effect of any changes in ripple; Highest quality diodes will be used; extensive developmental testing, "burn-in" and derating will preclude non-conservative design.					

*A MODE LIKELIHOOD (1 TO 100) – *B EFFECTS IMPACT (1 TO 100) – *C CRITICALITY (A x B)

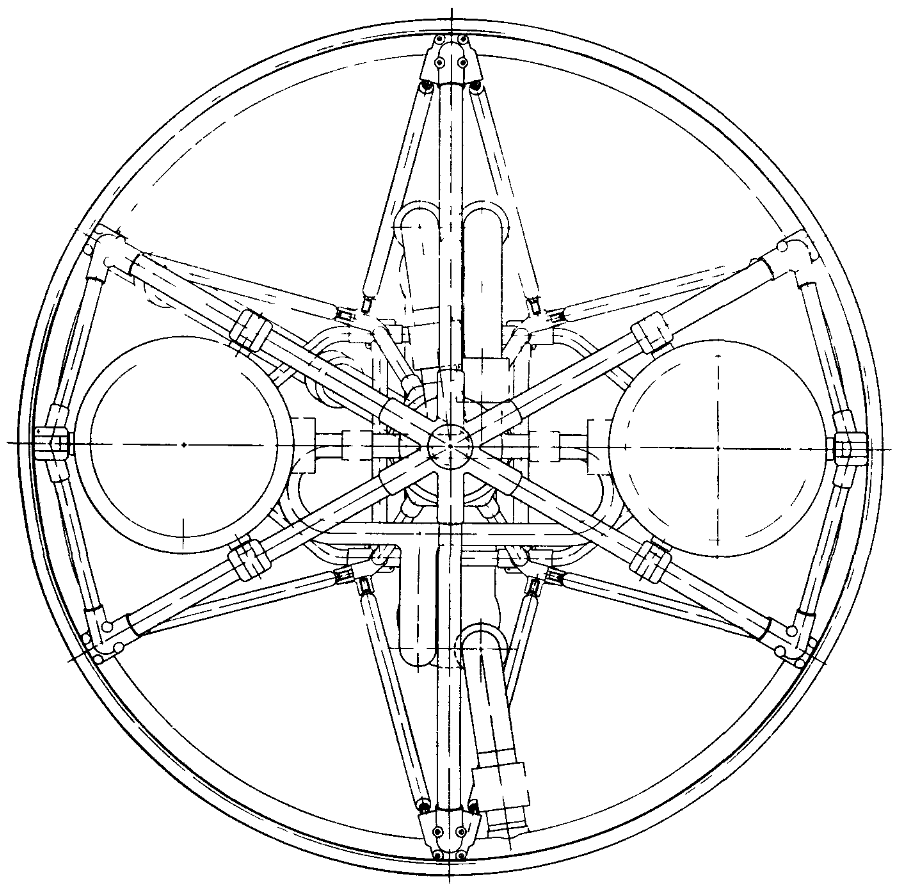
FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS WORKSHEET

REVISION STATUS OF SHEETS

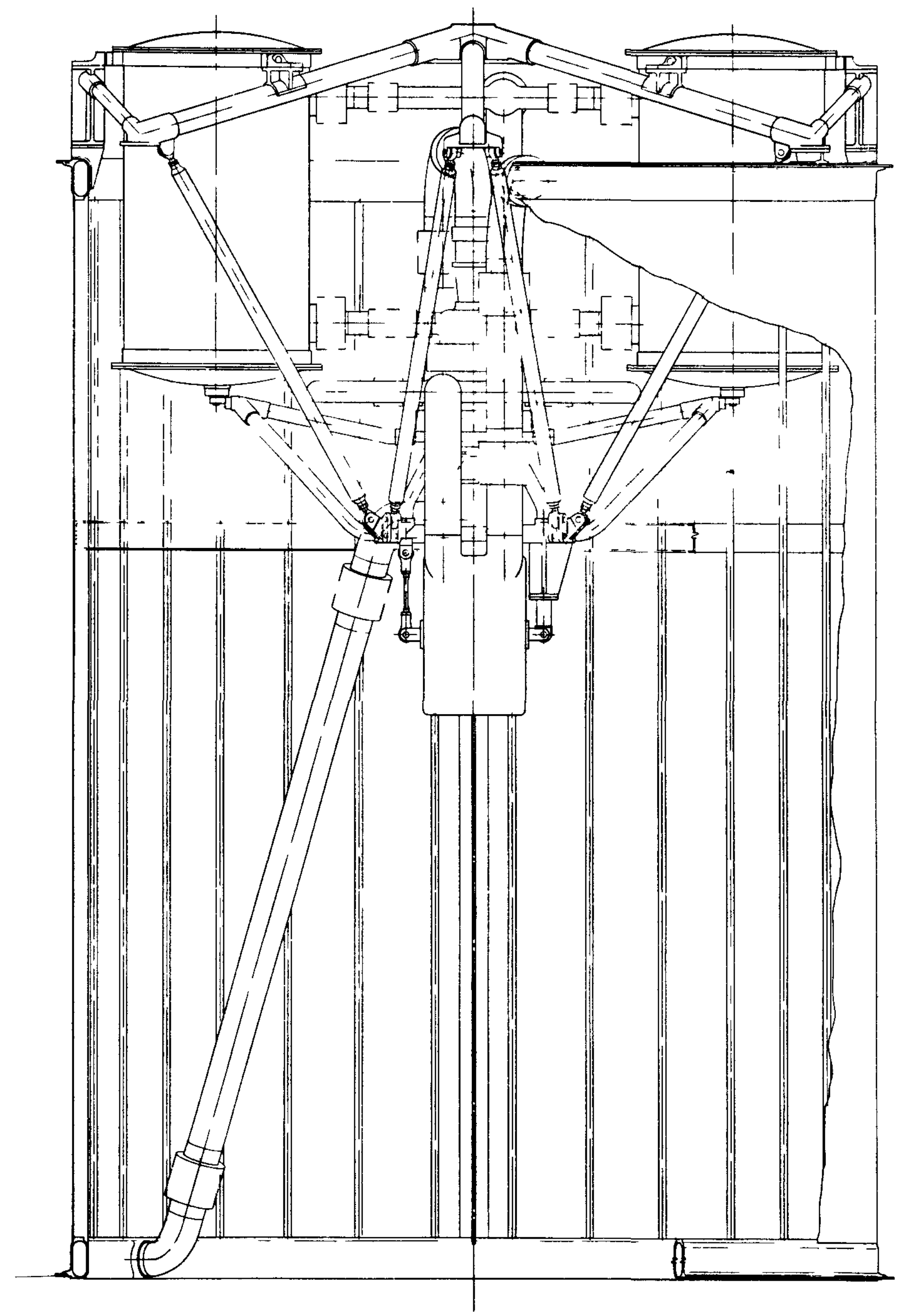
REV									
SHEET									

REVISIONS

ZONE	LTR	DESCRIPTION	DATE	APPROVED



TOP VIEW



PROPRIETARY NOTICE

STARTED 1 6 76

SCALE 1/4

MODEL CCPS2-1

LAYOUT

BIPS FS

LAYOUT NO. L3621582

SHEET 1