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VOLUME II MASTER

BRAYTON ISOTOPE
POWER SYSTEM

SYSTEM EVALUATION ATTRIBUTES

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MARCH 15, 1978

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GENERAL ELECTRIC
SPACE DIVISION

AIRESEARCH MANUFACTURING COMPANY
OF ARIZONA

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Prepared by Engineering Staff

Initial Issue E. E. Strain
Approved by E. E. Strain, BIPS Program Manager

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1.0 INTRODUCTION AND SUMMARY

This volume of the Brayton Isotope Power System, Phase II Plan, contains the self-evaluation by AiResearch, GE, and TECO, addressing Section 3 of "The Dynamic Systems Evaluation Criteria and Procedures" established by the Department of Energy. These evaluation criteria address:

- (a) Component Feasibility
- (b) Flight System Design Performance
- (c) GDS Test Results
- (d) Reliability and Practicality
- (e) Safety
- (f) Spacecraft Integration
- (g) Cost and Risk

Included in each of these general categories are several attributes, each of which addresses a separate component, feature, or area of interest related to the power system, its development status, degree of preparedness for proceeding into a flight program, and/or the contractors' performance during Phase I.

The key elements which indicate the readiness of a radioisotope power system to progress into a flight qualification program are:

- (a) An advanced state of development of the power conversion system
- (b) Demonstrated or exhibited potential for space systems standards of reliability
- (c) Evident capability of meeting system safety requirements

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- (d) Favorable cost/benefit tradeoff considering projected missions and technology advancement potential
- (e) Proven feasibility of fabricating and qualifying a flight system and integrating it with a candidate spacecraft and launch vehicle

As a result of considerable government investment in Brayton system component development, the MHW isotope heat source and the BIPS Phase I Ground Demonstration System, the BIPS is at a more advanced state of development than any previous radioisotope power system technology. Evidence of this can be noted in Table I-1 which presents a summary of the salient features as related to evaluation of the DoE attributes and the AiResearch/GE self-evaluation. Table I-2 provides a summary of all of the attributes and the self-evaluation rating. Space is also provided for the evaluation committee rating, significance factor, and attribute score.

Section 2 provides a complete review of the attributes, the contractor recommended ratings, and the rationale for the self-evaluation.

Two copies of Table I-2 are provided in this document. The second copy is for the convenience of the Evaluation Board and is intended to be torn out of the document and used to compute the attribute score for the BIPS.

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TABLE I-1

KEY ATTRIBUTE SUMMARY

Reference Attribute	Salient Feature	Remarks
3.2.2	High Efficiency	Initial tests have demonstrated an efficiency exceeding 25 percent. Minor changes are required to achieve the design objective of 27 percent at 1300 W _e .
3.1.2.1, 3.1.4.1, 3.1.4.2, 3.1.2.6	Basic Simplicity High Reliability	The basic design results in elimination of all dynamic components other than the single shaft rotating group. Because the components are static, redundancy is easily implemented. The 52 single point failures are rigorously addressed with conservative design. Use of an inert, single phase working and cooling fluid obviates seals and separation problems and assures long term stability.
3.1.x.x	Proven Hardware	The hardware is backed by years of development directed toward a dynamic space power conversion system for isotope heat sources. Over 45,000 hours of operation of a slightly larger system at NASA LeRC is complemented by the successful flight record of the MHW Heat Source. This hardware technology base is evident in the demonstrated performance of the BIPS components and system.
3.2.7	Growth Potential	The growth potential for the BIPS is excellent. The technology is directly extendable to all power levels presently contemplated. An extensive data base is available for developing high temperature conversion systems for the high temperature heat sources now being considered. The performance of the system improves significantly for higher power and higher temperature heat sources. Development of the refractory version should be extended to maximize the growth potential.
3.2.7, 3.2.3, 3.6.x	Flexibility and Spacecraft Interaction	The design provides a great deal of flexibility for mission planners. Numerous variations relative to operation and packaging are readily accommodated. The unit was designed to allow orienting the rotating group in the vertical or axial position with a minimum change to the ducting. The angular momentum is very low. Thermal exchanges with the spacecraft are easily controlled. Rapid start-up and near rated output during orbital transfer allow mission planning flexibility.
3.5.1 through 3.5.6	Safety	Nuclear safety aspects have been proven on the MHW program. The only features requiring further development and analysis are a loss of coolant accident and a pad abort.
	System Readiness	Detailed analytical capabilities allow rapid evaluation of component life, temperature, stress and output performance under various operating conditions. This capability coupled with the extensive development of Brayton power conversion equipment at NASA LeRC and the materials and bellows work at ORNL and BCL results in a very sound base for the qualification phase.
	Problems	The major area where the initial objective has not been met is weight. The decision to change from refractory to superalloy high temperature material accentuated this problem. Of concern at this time is the failure of the journal bearing to perform as predicted. Current information will be provided to DoE as required.

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TABLE I-2 (Contd)

Paragraph	Attribute Title	Self-Evaluation Rating	DoE Evaluation Rating	x	Significance Factor	= Attribute Score
3.3.6.9	Waste Heat Sink FS Similarity	0				
3.3.7	Observed Materials Stability	+ 6				
3.4.1	Reliability Analysis	+10				
3.4.2	Failure Mode Analysis	+ 3				
3.4.3	Number of Single Point Failures	+14				
3.4.4	Quality Assurance Plan	+14				
3.4.5	Fabricability	+10				
3.4.6	Assembly Procedures	+14				
3.4.7	Inspectability	+13				
3.5.1	Loss of Cooling Accident	0				
3.5.2	Pad Abort	- 5				
3.5.3	Reentry	0				
3.5.4	Impact	+ 5				
3.5.5	Burial or Loss at Sea	0				
3.5.6	Nuclear Criticality	+10				
3.6.1	Power System Envelope	-11				
3.6.2	Thermal Interchange	+15				
3.6.3	Dynamic Capability	0				
3.6.4	Torque Effects	+ 9				
3.6.5	Hardenability	+ 4				
3.6.6	Ground Handling	+ 5				
3.7.1	Milestones on Schedule	- 3				
3.7.2	Cost Control	- 2				
3.7.3	Estimated Cost to Flight System	No rating				
3.7.4	Estimated Production Cost	No rating				
3.7.5	Unresolved Problems	-10

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TABLE I-2

DOE
DYNAMIC SYSTEMS EVALUATION CRITERIA
ATTRIBUTES SUMMARY

Paragraph	Attribute Title	Self-Evaluation Rating	DoE Evaluation Rating	x	Significance Factor	=	Attribute Score
3.1.1.1	Thermal Environment of Heat Source	+10					
3.1.1.2	Emergency Cooling	+ 5					
3.1.1.3	Venting/Gas Management	+12					
3.1.2.1	Heat Transfer Fluid	+15					
3.1.2.2	Ducting, Bellows, Valves, Transitions	+13					
3.1.2.3	Recuperator	+13					
3.1.2.4	Radiator	+12					
3.1.2.5	Condensing Heat Exchanger	+15					
3.1.2.6	Materials Stability	+10					
3.1.2.7	Transient Stresses	+10					
3.1.2.8	Fatigue Stresses	+ 6.6					
3.1.2.9	Creep Stresses	+10					
3.1.2.10	Thermal Insulation Stability	+10					
3.1.2.11	Heat Source Heat Exchanger	+12					
3.1.3.1	Turbine	+ 8					
3.1.3.2	Compressor	+ 8					
3.1.3.3	Alternator and Rotor	+15					
3.1.2.2.1	Electrical Insulation	+15					
3.1.2.2.3	Magnetic Field	-12					
3.1.3.4	Bearings	+ 5					
3.1.4.1	Loop Control	+15					
3.1.4.2	Electrical Control	+10					
3.2.1	Flight System Weight	-15					
3.2.2	Flight System Efficiency	+12					
3.2.3	Start-Up	+15					
3.2.4	Orbital Transfer Power	+ 9					
3.2.5	Power Degradation	+14					
3.2.6	Micrometeorite Protection	+ 5					
3.2.7	Growth Potential Flexibility	+15					
3.3.1	Power Output	0					
3.3.2	Performance at 90% Input Power	8.5					
3.3.3	Voltage Control	+ 7.5					
3.3.4	Demonstration of Mission Profile	+ 5					
3.3.5	Maximum Duration Unattended Operation	-15					
3.3.6.1	HSA and ECS FS Similarity	-10					
3.3.6.2	Ducting, Bellows, FS Similarity	+12					
3.3.6.3	CRU FS Similarity	+10					
3.3.6.4	Recuperator FS Similarity	+ 9					
3.3.6.5	Control System FS Similarity	-10					
3.3.6.6	Thermal Insulation FS Similarity	+ 5					
3.3.6.7	Configuration Structure FS Similarity	+ 5					
3.3.6.8	Condenser FS Similarity	+15

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3.5.2	Pad Abort	- 5				
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3.7.5	Unresolved Problems	-10

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2.0 DETAILED EVALUATION OF ATTRIBUTES

This section presents the AiResearch/GE/TECO performance factor ratings for each of the DoE evaluation criteria attributes with the exception of 3.7.3 and 3.7.4. These two attributes are "Estimated Cost to Flight System" and "Estimated Unit Production Costs." The performance factor is based on the difference in estimated costs between BIPS and the competition. Since competitor costs are not available to the BIPS team, these two attributes were omitted.

For each of the rated attributes, a summary of the rationale for the selected rating, a technical discussion in support of the rating, and references for more technical details are presented.

3.1.1.1 Thermal Environment of the Heat Source

This item covers the thermal history of all components of the heat generating sub-system, frequently called the HSA. Although the heat source is GFE, its thermal history, and that of associated components, is controlled by the HSA design and the system operating plan. Assurance is required that during all normal operating modes the PICS in particular and all other components as well are not degraded in properties to the extent that subsequent performance is jeopardized. Modes of degradation to be considered include annealing, recrystallization, grain growth, chemical reaction, reaction of dissimilar metals, and similar processes.

3.1.1.1 Thermal Environment of Heat Source

RATING = +10

REF: VOLUME I, BOOK 3
SECTION 2.7

SUMMARY OF RATIONALE FOR RATING

During the two normal operational modes (ACS and vacuum) maximum material temperatures occur on all components during vacuum operation.

The maximum PICS temperature of 1200°C is acceptable for the iridium from the standpoint of its effect on impact capability.

The Hastelloy heat exchanger coil maximum temperature of 787°C is acceptable from the standpoint of structural properties. There will be some sublimation of Fe, Ni and Cr, but the rates are acceptable at this temperature. The potential reaction with Co from the IHS can be eliminated by proper processing of the IHS graphitic parts.

The palladium-nickel foil maximum temperature is 763°C. At this temperature the sublimation rate is expected to be sufficiently low to preclude significant material loss over a 7 year mission life. The pure nickel foil will be below 610°C which will preclude any significant sublimation. The foil system has been demonstrated to perform as predicted.

The outer case during normal operation in vacuum is 116°C. This temperature level is acceptable for Be, Al or Lockalloy, the candidate HSA case materials. An active cooling system will be required during ACS operation to meet the very low allowable payload bay heat inputs.

TECHNICAL DISCUSSION

Table 1 shows the temperature profile for normal vacuum operation.

PICS

The PICS vacuum operating temperature of 1150°C is acceptable because recrystallation has been shown to be insignificant at this temperature as evidenced by examination of specimens from 20,000 hour creep tests. Current predictions for operation at temperatures up to 1200°C show that allowable operating life is 2×10^5 hours for impact at 1050°C and 2×10^6 hours for impact at 1350°C (to insure 15 percent impact elongation).

Tests have shown complete compatibility between fuel, iridium and carbon to 1500°C over a period of ~ two years.

Hastelloy Heat Exchanger Coil

There will be some loss of Cr, Fe and Ni at the operating temperature of 787°C. The pressure of the 30 mil thick first foil will maintain the net material loss to an acceptable level for a seven year mission. This will be further verified during Phase II.

Foil Insulation System

Zirconia coated Pd-Ni and Ni foils are used around the heat source heat exchanger. Thus the possibility that vaporization products from the MULTI-FOIL might react with the IHS components must be evaluated. The possibility of organic vaporization products reaching the HSA was a legitimate concern with the older zirconia coating technique using an organic binder (TECO Process Specification No. 3161). However, the more recent electrostatic coating technique (TECO Process Specification No. 3162) uses no binder.

The maximum temperature of the MULTI-FOIL outside of the heat source heat exchanger during normal operation is about 1560°F. At this temperature the vapor pressures of the palladium and nickel used in the MULTI-FOIL are 1.1×10^{-8} and 6×10^{-10} torr, respectively. The vapor pressure of zirconia at 1560°F is not available but is much less than 10^{-10} torr since the vapor pressure at 3500°F is only 4×10^{-5} torr. Such low vapor pressures should preclude any significant interaction with the IHS. In addition, material transport from the MULTI-FOIL to the IHS is minimized by: 1) the steep temperature gradient, 2) the dynamic pumping away from the HSA due to the vacuum environment, and 3) the shielding of the heat exchanger and foil support structure which are interposed between the MULTI-FOIL and the IHS.

Also the number of foils lost in the hot zone over a 7-year mission has been calculated to be 3 or 4 foils, which is acceptable from the standpoint of thermal performance. Testing underway confirms the foil components compatibility, namely, the interface, Hastelloy-NiPd, NiPd-ZrO₂, NiPd-Ni. Five foil packet tests are in the present program plan; two for melt tests at TECO and three for 1000 hour stability tests at Battelle. See Volume I, Book 3, Section 3.2 for results of the first test at TECO.

Other Material Interfaces

Waspalloy/Moly

Bonding may occur at this interface at the heat exchanger support pins. The extent and ramifications of which will be determined during Phase II.

Carbon-Zirconia Interface in heat source support is protected by tungsten and iridium barriers developed and proven during the MHW RTG Programs.

Outer Case

During normal vacuum operation, the outer case maximum temperature will be 116°C. During this mode, most of the HSA heat is removed by the Brayton cycle working fluid; however, during ACS operation with cycle fluid flow stopped, the entire thermal inventory must be rejected from the HSA surface. In this case, the HSA surface temperature is determined by the details of its environment. Table 2 shows the HSA temperature profile for ACS operation (i.e. helium inside the HSA and air external to the HSA). The outer case temperature is $\sim 224^{\circ}\text{C}$ (435°F). This temperature level is unacceptable in the presence of hypergolic fuel vapors present in the space shuttle environment; the upper limit for surfaces in the presence of these vapors being 380°F.

Forced convection gas flow over the HSA surface on the pad could be used to control the surface temperature to less than 380°F, however, at 380°F the radiated heat from each HSA surface would be ~ 1400 watts. This would violate the shuttle payload bay allowable heat gain as shown in Table 3. These low allowable heat inputs dictate that the HSA surface be cooled to approximately 100°F. Temperature profiles for this condition are given in Table 4.

In orbit when convective cooling outside the HSA is lost, the HSA surface temperature in the ACS mode could rise to approximately 550°F (see Table 5). Therefore, to control the HSA surface temperature and heat fluxes to the bay walls requires an active cooling loop around the HSA surface.

Hastelloy Creep Data, BIPS-GDS-AO521 (9-21-77)

General Purpose Heat Source; GPHS Review, December 19/20, 1977,
A. Schaffhauser, ORNL

CONTINUATION OF TECHNICAL DISCUSSION

Table 1
VACUUM OPERATION TEMPERATURE PROFILE

PICS	2102°F (1150°C)
AEROSHELL	1507°F (819°C)
HASTELLOY COIL	1448°F (787°C)
FOIL (PdNi)	1406°F (763°C)
OUTER CASE	240°F (116°C)

Table 2
ACS MODE - HELIUM IN HSA - AIR OUTSIDE HSA

PICS	1958°F (1070°C)
AEROSHELL	1235°F (668°C)
HASTELLOY COIL	1164°F (629°C)
OUTER CASE	435°F (224°C) [1]

[1] Radiation and natural convection from HSA surface.

CONTINUATION OF TECHNICAL DISCUSSION

Table 3
PAYLOAD BAY WALL THERMAL ENVIRONMENT

Condition	Design Minimum	Design Maximum
Prelaunch	+40°F (4.5°C)	+120°F (49°C)
Launch	+40°F (4.5°C)	+150°F (65.5°C)
On-Orbit (doors closed)	See C&D	See A&B
Entry and postlanding	-100°F (-73°C)	+200°F (93.5°C)
Heat leak criteria into or out of a 100°F (37.5°C) constant payload are as follows:		
A. Total bay heat gain, average	$\leq 0 \text{ Btu/ft}^2 \cdot \text{hr} \text{ (0 Watt/Meter}^2\text{)}$	
B. Heat gain, local area	$\leq 3 \text{ Btu/ft}^2\text{-hr (9.5 Watt/Meter}^2\text{)}$	
C. Total bay heat loss, average	$\leq 3 \text{ Btu/ft}^2\text{-hr (9.5 Watt/Meter}^2\text{)}$	
D. Heat loss, local area	$\leq 4 \text{ Btu/ft}^2\text{-hr (12.6 Watt/Meter}^2\text{)}$	

CONTINUATION OF TECHNICAL DISCUSSION

Table 4
ACS MODE - HSA SURFACE COOLED TO 100°F

PICS	1850°F (1010°C)
AEROSHELL	1020°F (549°C)
HASTELLOY COIL	930°F (499°C)
OUTER CASE	100°F (38°C)

Table 5
ACS - HELIUM IN HSA - VACUUM OUTSIDE HSA
NO ACTIVE COOLING OF HSA SURFACE

PICS	1994°F (1090°C) [1]
AEROSHELL	1304°F (707°C)
HASTELLOY COIL	1244°F (673°C)
OUTER CASE	544°F (284°C)

[1] Radiation from HSA surface to 200°F sink
(outer case temperature is only 45°F
cooler for a -100°F sink).

3.1.1.2 Emergency Cooling System

The flight system design must provide protection against overheat damage to the isotope heat source in the event of any malfunction leading to loss of normal cooling. Continued protection of the isotope fuel against release in all credible accidents is required after emergency cooling.

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3.1.1.2 Emergency Cooling System

RATING = +5

REF: VOLUME I, BOOK 3
SECTION 5

SUMMARY OF RATIONALE FOR RATING

In the event of a malfunction leading to the loss of normal heat extraction from the HSA, reliable overtemperature protection of the isotope heat source will be provided by meltdown of the multi-foil insulation located between the heat exchanger and the HSA case. The meltdown of the foil insulation will result in a low thermal resistance between the isotope heat source and the HSA case, limiting the temperature excursion of the iridium PICS. The results of transient thermal analyses performed by AiResearch, Los Angeles, for the planned foil system predict a peak temperature of the PICS during the ECS mode to be 1474°C. Predictions by A. C. Schaffhauser of Oak Ridge National Laboratory indicate a permissible duration of approximately 1000 hours in this temperature range for DOP-26 iridium to avoid reducing the impact elongation of the iridium below 15 percent and degrading impact capability. It is expected that this requirement can be readily met by proper selection of the outer foil materials. The eutectic melt temperature of the inner palladium-nickel foils has been verified by test.

TECHNICAL DISCUSSION

The function of the emergency cooling system for the heat source is to prevent the isotope heat source from rising to excessive temperatures in the event that the normal modes of heat extraction become inoperative. Excessively high temperatures can: (1) degrade the impact capability of the iridium post impact shells due to grain growth, (2) change the characteristics of the fuel possibly resulting

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in degraded impact capability, (3) or in the event of an extreme temperature rise, result in melting of the post impact shell. Because of the impact on nuclear safety, it is essential that the emergency cooling system have high reliability. The foil meltdown system is inherently capable of high reliability since it does not depend on operation of any actuation mechanisms which may malfunction. Verification of the performance of the meltdown system can be accomplished during a full-scale safety test of this type.

As presently planned, the baseline flight system will contain approximately 60 layers of foil (≈ 0.0005 inch thickness) wound between the heat exchanger and the HSA case. The 30 inner layers are expected to be palladium-nickel (60 percent Pd - 40 percent Ni), and the 30 outer layers are expected to be nickel.

In the event of a malfunction leading to loss of the normal modes of heat extraction, the temperatures in the HSA will rise until the inner foils reach the eutectic melt temperature of 1237°C . Melting of the foils will progress outward toward the outer case. The melting of the foils will provide a high thermal conduction path from the heat source to the outer case which will dissipate the thermal energy through radiation to the surrounding components.

The results of transient thermal analyses performed by AiResearch, Los Angeles, for the Pd-Ni ECS system predict that the innermost foil will melt 120 minutes after loss of flow of the working fluid in the heat exchanger. During this time period, the PICS temperature will rise from 1143°C to 1410°C . As the melting of foils progresses, the PICS temperature will reach a peak of 1474°C at the end of 180 minutes. At the end of 240 minutes, the PICS temperature will drop to 1465°C . Since the analysis did not predict melting of the outer foils (12 cylinder foils and 7 end-cap foils per end remain), the PICS temperature has been predicted by this analysis to drop only to 1458°C after

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an infinite period of time. Further investigation is required to determine if additional outer foils will actually melt or fuse in a short period of time or if the material of these outer foils should be changed to lower the melt temperature of these foils. Results of a preliminary analysis indicate that should the remaining outer foils fuse and act as one solid foil, the PICS temperature will be reduced to 1120°C in less than 50 hours. It is anticipated that this problem will be solved without much difficulty and that a rapid drop in PICS temperature will occur with the final loss of insulation. With proper melting of the outer- foils, temperature excursion of the PICS above 1250°C should last less than 50 hours, and no significant grain growth of the iridium should occur.

The melt temperature of the palladium-nickel eutectic at 1237°C has been verified by tests at BMI.

Present plans are to build five insulation test packets. Two will be subjected to meltdown tests at TECO, and three will be subjected to 1000 hour stability tests at BMI. It is anticipated that the results of these tests will provide the additional verification to justify proceeding with the detail flight system design incorporating this ECS system. These meltdown and compatibility tests began in March 1978.

Considerable work has been done by TECO in Phase I to evaluate the ECS and interpret the meltdown characteristics of miniature MULTI-FOIL assemblies. The meltdown tests of miniature MULTI-FOIL insulation assemblies are described in Thermo Electron Report No. TE4219-62-77 (Meltdown Tests of MULTI-FOIL Insulation assemblies, January 1977). These miniature assemblies had the following factors in common with the HSA MULTI-FOIL insulation configurations under consideration at the time of these tests: (1) half-mil foil thickness, (2) 60-layer foil assemblies, (3) 5-mil layer spacing, (4) binary material combinations, (5) zirconia coating, (6) approximate ratio of length to

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diameter, and (7) 3-mil stainless steel containment shell. In addition to providing a data base of temperature-time profiles for several MULTI-FOIL configurations, the meltdown tests demonstrated that:

(1) the meltdown temperature was characteristic of the binary eutectic melting point rather than that of the pure nickel, (2) the post-meltdown MULTI-FOIL thermal conductance was approximately ten times higher than the pre-meltdown conductance (for all foil configurations tested), (3) the period of primary meltdown was of the order of ten minutes, (4) in composite foil configurations, the meltdown is initiated at the stepped joint where hot planar foils butt against cooler cylindrical foils, and (5) the design approach of grading the distributions of dissimilar foils to optimize the ECS mechanism as a viable design concept.

In order to evaluate the ECS problems and interpret better the meltdown characteristics of the miniature MULTI-FOIL assemblies, a computer program called FOIL was formulated to calculate the transient temperatures of the foil and HSA components in the event of a conversion system failure. The analytical model is one-dimensional and factors in the individual heat capacities of the HSA components and the insulation foils as well as the heat of fusion of the foils. The insulation properties of MULTI-FOIL were taken from the experimental data given in Thermo Electron Report No. TE 4209-100-76 (Application of MULTI-FOIL Insulation to the Brayton Isotope Power System and Conceptual Design of MULTI-FOIL Insulation for the Flight System, June 1976). The heat transfer through the HSA was normalized to data from General Electric. The numerical solution of the equations used the third-order Runge-Kutta method. The computer program, along with sample cases, is described in Thermo Electron Report No. TE4219-65-77 (meltdown Analysis of MULTI-FOIL Assemblies, December 1976). The calculated results from Program FOIL were in agreement with experimental data in regard to: (1) period of meltdown, (2) drop in inside

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temperature after meltdown, and (3) extent of meltdown. The experience with Program FOIL indicates that it is useful for estimating HSA temperature response after a loss of coolant accident (LOCA) and is also an aid in interpreting the meltdown characteristics of miniature MULTI-FOIL assemblies.

"Isotope Fuel Cladding Development for the General Purpose Heat Source," A. C. Schaffhauser, Presented December 19-20 at the General Purpose Heat Source Review.

3.1.1.3

Venting/Gas Management

This factor covers the design and functioning of the venting and gas management system that is auxiliary to the isotope heat source. These components must assure safe disposition of the alpha helium from the fuel and prevention of unacceptable contamination from fuel particulate release. They will usually consist of a vent to release helium from the primary encapsulation through a filter and provision for releasing the helium from the total power system. Failure modes to be considered must cover both performance degradation and reduction of nuclear safety during normal operation.

3.1.1.3 Venting/Gas Management

RATING = +12

REF: BIPS PHASE II PLAN, VOLUME I,
BOOK 3, SECTION 2.7

SUMMARY OF RATIONALE FOR RATING

MHW test data verifies acceptability of this Venting/Gas Management flight system design. The MHW Fuel Sphere Assembly (FSA), consisting of the PICS vent/filter assembly and the Graphite Impact Shell (GIS) is a proven containment system flown on the LES 8/9 and MJS missions. A sealed HSA and high quality gas cart similar to that used on LES 8/9 and MJS Programs assure safe disposition of the fuel-generated helium and prevention of unacceptable contamination. High quality space application squib-fired and solenoid-operated vent systems are state-of-the-art components normally flown on spacecraft for high reliability.

TECHNICAL DISCUSSION

The flight system design of the venting/gas management system will incorporate proven aspects of the MHW FSA and gas management system designs. The MHW PICS vent and GIS have been shown to be effective redundant particulate filters as well as a "reliable helium venting system." The sealed HSA will utilize a gas management system similar to that used on the MHW programs to controllably vent the HSA prior to installation of the BIPS into the spacecraft.

LASL has conducted long term exposure tests to evaluate fuel particulate release and contamination characteristics of MHW FSA's. FSA's have been tested for as long as 18,000 hours at operating conditions, with no permeation of significance noted. Table 1 shows fuel containment within the GIS, in some cases after impact testing. For details of this evaluation, see PIR 5892 and GEMS-423.

Sample No.	EXPOSURE CONDITIONS			Filter Design	Total Pu μ g
	Time, h	Temp. °C	Atmosphere		
MHFT-15	7395	1450	vacuum	pre-flight	19
MHFT-18	1332	1250	helium	pre-flight	17
MHFT-19	1100	1450	vacuum	pre-flight	56
MHFT-20	18293	1450	vacuum	pre-flight	305
MHFT-21	4500	1250	helium	pre-flight	8
MHFT-22	3400	1450	vacuum	pre-flight	625
MHFT-39 (1,2)	2009	1335	vacuum	flight	720 (3)
MHFT-40 (1,2)	2009	1335	vacuum	flight	15 (3)
MHFT-41 (1)	2009	1335	vacuum	flight	8
MHFT-42	5440	1335	vacuum	flight	1600
MHFT-45 (1,2)	720	1335	vacuum	flight	460
MHFT-47 (1,2)	720	1335	vacuum	flight	18700 (3)
MHFT-48 (1,2)	720	1335	vacuum	flight	14700 (3)
MHFT-49 (1,2)	720	1335	vacuum	flight	160 (3)
MHFT-54 (2,5)	720	1335	vacuum	flight	51 (3)
MHF -27	200	1220	Q-1 heat source, He	flight	38
MHF -29	200	1220	Q-1 heat source, He	flight	0.05 (4)

(1) SVT sample

(2) Impacted

(5) U.S. Type W3 Iridium

(3) Measured after PISA fracture on impact

(4) Measurement at ML/MRC; all others by LASL

TABLE 1. TOTAL PLUTONIUM CONTENT IN MHW-IHS GIS'S

The qualification IHS for the LES 8/9 Program was disassembled after dynamic testing, and the FSA's re-introduced into the Qualification IHS for the MJS Program. Table 2 documents the extreme effectiveness of the PICS filters, demonstrated by the PICS contamination levels measured before and after the dynamically tested qualification IHS.

The ACS mode will utilize a passive charge of inert gas. An active ACS mode of flowing gas through the HSA insulation is discarded as a small but finite increased probability of contamination release. By passively gas charging the insulation system via closed system gas cart for the ACS mode, and then evacuating through radiological filters and a gas cart similar to that on the MJS Program, high reliability is assured.

During normal operation, a solenoid valve or pressure relief device (PRD) will be operated by radio command (squib). Performance tests on the MHW LES 8/9 and MJS RTG's proved the complete adequacy of venting through a pressure relief device.

Venting the HSA's is the same as deactivating ACS. It is absolutely necessary for BIPS full power. Normal approach to reliability of venting is to design the PRD's in a parallel system. To accommodate failure to close a solenoid valve for reactivating ACS in the event of a return to the transport vehicle, manual valves may be included in the system design in series with the solenoid valves. This complete system will be mounted external to the radiator or at some location which is remote from the HSA's and is accessible in the unlikely event hand operation is required. This approach to gas management and venting of the HSA's assures maximum nuclear safety during all phases of BIPS operating and even adds redundancy and flexibility

→ AFTER Q-1 TRANSPORTATION, DYNAMIC TESTING,
AND QUALIFICATION HANDLING, NO INCREASE
IN CONTAMINATION →

RADIOLOGICAL CONTAMINATION IN Q-1/IHS

FSA No.	PISA DPM	GIS, DPM At IHS Ass'y
MHF-1	10	32
MHF-3	338	16
MHF-4	<10	28
MHF-5	51	74
MHF-7	<1000	16
MHF-8	<10	32
MHF-9	<41	72
MHF-10	310	0
MHF-11	38	48
MHF-12	30	8
MHF-13	353	56
MHF-15	151	28
MHF-16	<10	30
MHF-17	126	48
MHF-18	29	26
MHF-21	<20	16
MHF-22	<20	56
MHF-23	<20	52
MHF-24	<20	0
MHF-26	<20	34
MHF-27	<800	42
MHF-28	<1000	58
MHF-29	<1000	32
MHF-30	<1000	46
		$\Sigma = 850$
Specification	2000	1000/24

Q-1 IHS: No Direct Wipe Taken; MRB 114

RADIOLOGICAL CONTAMINATION IN Q-2R/IHS

	FSA Number MHF-	GIS ²³⁸ Pu Activity DPM
Top 8-Pack (made new)	21 (old)	10
	64 (new)	8 Tray - New
	15 (old)	10
	161 (new)	24
	162 (new)	12
	165 (new)	22
	166 (new)	10
	164 (new)	24 120
Middle 8-Pack (from Q-1/IHS)	22 (old)	6
	5 (old)	8
	17 (old)	8
	9 (old)	2 Tray - 0 DPM
	4 (old)	16
	16 (old)	14
	11 (old)	4
	23 (old)	0 58
Bottom 8-Pack (all FSA's from Q-1/IHS)	26 (old)	12
	24 (old)	12
	18 (old)	0 Tray - 2 DPM
	8 (old)	10
	3 (old)	6
	10 (old)	12
	12 (old)	2
	7 (old)	10 54
		232

TABLE 2. MHW PICS FILTER EFFECTIVENESS

of the GMS for reactivation of the ACS in the event the BIPS is returned to the transport vehicle.

MMW-LES 8/9 RTG Assembly Records/Log

MMW-MJS RTG Assembly Records/Log

MMW-LES 8/9 Q-2A IHS Post Mortem

GE-PIR 5892, "Potential Contamination Release from the MMW-MJS-IHS"

GE-PIR 5961, "Potential Release of 220Rn at KSC During Spacecraft Integration Operations"

GE-PIR 5128, "Results of the Q-1A Performance Tests with Helium Venting"

3.1.2.1 Heat Transfer Fluid

This factor considers all modes of degradation of properties of the working fluid and of degradation of the components contacted by the fluid caused by the fluid. These modes include dissociation, polymerization, deposition of solids, reaction of components with the fluid, material transport, extraction of constituents from solids contacted, response of the fluid to radiation, etc., under the dynamic conditions of system operation.

3.1.2.1 Heat Transfer Fluid

RATING = +15

REF: VOLUME I, BOOK 3,
SECTION 2.7

SUMMARY OF RATIONALE FOR RATING

The BIPS heat transfer fluid is a mixture of two noble gasses, xenon and helium, in proportions to achieve an equivalent molecular weight of 83.8 mole^{-1} . The gas mixture therefore does not: (1) dissociate, (2) polymerize, (3) solidify, (4) react chemically with components, (5) enter chemically into material transport, (6) chemically extract constituents from solids, or (7) react adversely to radiation under dynamic system conditions.

TECHNICAL DISCUSSION

The working fluid constituents have been thoroughly characterized as to thermo/physical properties in the literature.

Dissociation, per se, of monatomic gasses cannot occur. Ionization of monatomic has been observed at extreme temperatures or environments, but no harmful system effects could be hypothesized other than possible effects on the bearings. (This aspect is addressed in Section 2.4.3.)

Polymerization of noble gasses is unknown throughout the realms of science.

Solidification of xenon requires extreme cryogenic temperatures. Solidification of helium requires the lowest temperature of any known element.

Both heat transfer fluid constituents are noble gasses and are chemically inert except under the most intense electrical or temperature conditions.

The heat transfer fluid will not become chemically involved in mass transport reactions, but, like any other medium, may transport material vaporized or disassociated by its own kinetics.

The inert fluids will not chemically extract constituents from solids.

Noble gasses, as any other material, may be ionized or subject to decay in a radioactive environment. No adverse behavior, however, could be expected due to the type and level of radiation in a flight system.

3.1.2.2

Ducting, Bellows, Valves, Transitions

It is the intent of this factor to consider all system components *and a mechanical function.* that contain the working fluid with respect to potential loss of fluid. Failure modes to be considered are; faulty welds or flanges, fatigue cracks, creep leakage or bursting, thermal expansion cracking, transition piece failures, etc., anywhere in the system.

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A DIVISION OF THE GARRETT CORPORATION
PHOENIX, ARIZONA3.1.2.2 Ducting, Bellows, Valves, Transitions

RATING = +13

REF: VOLUME I, BOOK 3,
SECTIONS 2.7.1.4 AND 3.1SUMMARY OF RATIONALE FOR RATING

A rating of 13 is based on the extensive work done in this area during Phase I. Extensive analytical studies led to the design, fabrication, and testing of the bellows. Destructive testing of the bellows by ORNL has resulted in excellent LCF correlation with the designs. Long term creep and combined LCF/creep damage tests are in progress.

TECHNICAL DISCUSSION

The basic system layout was evolved considering factors of relative orientation of components, launch orientation of the Mini-BRU, minimized flange loading due to thermal growth and pressure loading and thermal loss and pressure drop.

The design developed to meet these basic requirements is shown on Figure 3.1.2.2-1. Short lengths of straight ducting were utilized, wherever possible, to minimize flange loading, especially in the turbine plenum area where temperatures and stresses are highest. By reducing the number of bends, pressure drop is minimized, and short duct lengths minimize thermal loss. Multiple bellows links are used to absorb the relative thermal growths of components.

The material used in the "cold" sections of ducting/bellows is 347 series stainless steel with Hastalloy-X being utilized in the "hot" areas. These metals possess the properties required for satisfactory operation of the system under the operating conditions. In addition, a substantial data base exists for these materials and is

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FIGURE 3.1.2.2-1

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being expanded through various tests and programs being run as part of the BIPS program.

The critical area of the ducting design is the bellows. Formed bellows are utilized in all locations and designed to possess one redundant ply for pressure loading. The bellows designs were evolved using computer programs developed by the AiResearch L.A. Division. In addition to physical inspections of the actual hardware, assembly and testing in the BIPS, a total of 34 bellows were ordered for the purpose of reliability testing at Oak Ridge National Laboratories. The test program for these bellows was so designed to test for low cycle fatigue, creep, combined LCF and creep, and bellows "squirm." Destructive squirm tests were also conducted by the vendors, and witnessed by AiResearch, on five of the bellows designs. Applicable design and analyses reports are AIRLA 77-14427, 77-14596, 77-14601, and 77-14602. The ORNL test plan is covered in 77-14077.

All testing to date has verified the bellows design adequacy. Actual failures in test have resulted in good correlation with computer design program predictions.

Attachment of the bellows to the adjacent ducting as well as the longitudinal seam in the bellows' tubes have been of concern due to the uncertainty of weld-joints. The longitudinal weld in all ducting will be eliminated in all future hardware (bellows or ducts) by use of close tolerance seamless tubing. The majority of the circumferential assembly welds will be eliminated by use of a unique process of forming bellows in position in relatively long ducting runs. This method has the added attraction of giving redundancy to all of the piping system instead of just the bellows and results in a lighter assembly. In summary, these uni-formed ducting/bellows will result in: 1) better reliability due to elimination of longitudinal and circumferential welds, 2) added reliability due to redundant plies for all ducting, and 3) lighter system weight due to elimination of

flanges, transitions, etc. Though this concept is unique, the manufacturing methods and processes are standard; well within the present state-of-the-art.

3.1.2.3 Recuperator

The following classes of potential flaws may exist in recuperators:

1. Fluid dynamics: poor flow distribution, high pressure drop
2. Strength: creep, thermal stress, thermal fatigue
3. Chemistry: materials reactions, outgassing, reaction with fluid
4. Practicality: internal crevices, inspectability.

The inspection and test procedures used should be adequate to insure that none of these potential defects are present at such a level as to limit system performance.

3.1.2.3 Recuperator

RATING = +13

REF: VOLUME I, BOOK 3,
SECTION 3.1.2

SUMMARY OF RATIONALE FOR RATING

The recuperator fluid dynamics have been verified in AiResearch prototype and engine tests. Both the flow (temperature) distribution and fluid pressure drop have been determined to be as predicted.

Numerous NDT procedures, transient tests, proof tests were performed to insure recuperator integrity during Phase I. Additional verification tests will be conducted during Phase II.

Extensive braze development, vaporization and volatilization tests have been completed. No significant material reactions or reaction with working fluid have been identified. A bake-out procedure has been formulated and performed which limits outgassing of the recuperator to 2 mg over the mission duration.

AiResearch has extensive experience in recuperator fabrication, quality control, space system cleanliness procedures, NDT, and braze development. Numerous MBR, prototype, sample and braze development cores have been fabricated using the BIPS/MBR footprint. The design has been verified to be practical from a fabrication standpoint. Additional work will be performed in Phase II to refine inspection procedures. Several design modifications were implemented early in Phase I to eliminate virtual leaks in the assembly.

TECHNICAL DISCUSSION

Fluid Dynamics - Analytical design tools were used to calculate the flow distribution and its effect on performance of the unit. Results indicated the flow to be well distributed, with little effect

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on performance of the unit. Prototype and engine testing during Phase I confirmed these predictions. Performance testing during Phase II will provide further verification.

Analytical predictions based on scale factors and margins derived from Phase I testing indicate that the pressure drop (ΔP) is within the envelope specified for the preliminary operational conditions of the Phase II system. Engine tests have been conducted during Phase I which verify the predicted ΔP -values.

Therefore, this class of flaws is considered eliminated by test.

Strength - Considerable structural testing has been done on the Phase I design. This includes accelerated tests covering all three types of flaws. These tests have established critical areas in the unit. Subsequent changes in the design of these areas were implemented, and the unit retested, proving the effectiveness of these improvements. Further testing is planned for Phase II. The objective of these tests will be to expand and deepen the data base on the mechanical properties of the materials, as well as to test the soundness of the structural design. However, because these tests can only yield approximate data on the long-term (7 year) behavior of the recuperator structure, this class of flaws is considered partly eliminated by test and partly by design analysis.

Chemistry - Brazing tests were conducted by AiResearch for the NASA Hypersonic Ramjet Engine program and the various NASA Brayton Cycle heat exchanger programs to evaluate the interalloying reaction between the Hastelloy X (nickel-base) structural alloy and the palladium-nickel-gold braze alloy. As part of these tests, the ductility and the fatigue resistance of the brazed joint were also investigated. These test data form the basis for the recuperator design and show a satisfactory design. Tests planned for Phase II will further expand the data base.

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With many long term Brayton cycle system tests having been conducted in the past, there has never been any evidence of deleterious contamination of the inert working fluid due to outgassing. Furthermore, evaporation experiments conducted at Oak Ridge National Laboratory and Battelle Columbus Laboratory showed this not to be a problem at recuperator operating temperatures.

A vacuum bake-out procedure was formulated and tested at BCL which diminishes outgassing of the recuperator to less than 2 mg (primarily CO) over the mission duration.

Tests, theory, and practical experience have also shown that no reaction occurs between the inert working fluid and the construction materials.

Practicality - Being heavily involved in the aerospace industry, AiResearch uses well-established and proven procedures to ensure strict quality control of its products, especially where spacecraft-class cleanliness and reliability standards are required. On the recuperator, past efforts in these areas consisted of development testing, as well as routine procedures to prevent as well as to detect internal flaws. Brazing development tests were performed to improve the quality of the braze joints. This work involved the formulation of an appropriate brazing cycle, along with the determination of the proper amount of a gold-base braze alloy for superior brazing characteristics. Phase II efforts in the area of product assurance will be based on established procedures such as proof tests, helium leak checks, radiographic weld inspections and visual inspection to eliminate flaws. Therefore this class of flaws is considered eliminated by tests.

3.1.2.4

Radiator

Factors to be considered are flow stability in zero gravity, fabricality, joint reliability, thermal adequacy, possibility of freezing of working fluid, ability to survive or recover from launch accelerations, and long-term factors such as the build-up of contaminants and non-condensables that affect performance or reliability. Micrometeoroids are considered elsewhere. If no full-scale models have actually been constructed, the performance factor count is to be reduced by 5.0 if the design is state-of-the-art or by 10.0 if it is not.

3.1.2.4 Radiator

RATING = +12

REF: BIPS PHASE II PLAN,
VOLUME I, BOOK 3, SECTION 2SUMMARY OF RATIONALE FOR RATING

The combined analytical, experimental, and flight experience on radiator design and performance has been demonstrated over a number of programs. Consideration of fabrication techniques, impact protection, and thermal performance has been demonstrated on full scale models in laboratory tests as well as flight hardware, thereby justifying a merit factor rating of +12.

TECHNICAL DISCUSSION

The design of a space radiator to dissipate excess heat takes on primary importance in the control of the thermal environment as a consequence of the vital interactions with most spacecraft subsystems. Thermal performance, material protection, structural integrity, fabrication feasibility, material compatibility, working fluid pressure drop when coupled with weight, costs, and reliability must be examined to determine an optimum radiator configuration. The General Electric Company has developed a series of codes known as the SPARTAN Radiator Analysis Programs. These programs consider optimization techniques for gaseous, liquid, and two-phase flow systems. These programs have been used to conduct a number of studies on various geometric configurations, for both high and low temperature radiators. Over 1500 radiator designs have been analyzed with the aid of these programs.

Coupled with the analytical capability, General Electric has developed experimental experience as well as demonstrated flight hardware performance. The latter was accomplished in the 30 day Biosatellite Program. Extensive testing was performed on a full scale

model prior to launch indicating compatibility with prediction techniques. Moreover, a significant test program was conducted that considered fabrication techniques, impact protection and thermal performance on a full scale section of an aluminum cylindrical radiator panel (similar to the candidate configuration of this study). These tests (NASA CR-72307, AIAA 67-0839) were conducted in concert with the use of the SPARTAN III Program (TIS64SD224B). Finally, extensive analytical, experimental, and flight hardware experience of several spacecraft systems has shown proven capability of structural integrity for survival or recovery conditions from launch accelerations.

Flight experience and space simulator (vacuum) tests have indicated that flow stability will not be a problem in zero gravity. Moreover, the use of a gaseous mixture (Helium/Xenon) for the working fluid will not leave residue for contamination build-up to affect performance or reliability over a long period of time.

General Electric TIS-645D224B

Biosattellite: ASE Paper 67-0839

AIAA Paper 70-855

NASA Cr-72307

AEC-SNS0-6

Several Related Papers/Studies

3.1.2.5

Condensing Heat Exchanger

Factors to be considered are flow stability in zero gravity, fabricability, thermal adequacy, ability to operate through, survive, or recover from launch accelerations as appropriate, freedom from plugging, and long-term factors, such as the build-up of contaminants and non-condensables that affect performance or reliability.

3.1.2.5 Condensing Heat Exchanger

RATING = +15

SUMMARY OF RATIONALE FOR RATING

The component is not required in the closed Brayton system thereby justifying full credit of +15.

3.1.2.6 Materials Stability

This factor is concerned with the chemical stability of all components during mission lifetime. It includes differential expansion, spalling, selective or total vaporization, diffusion, mass transport, and chemical reaction. Leaking of transition joints and strength effects are considered elsewhere.

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A DIVISION OF THE GARRETT CORPORATION
PHOENIX, ARIZONA3.1.2.6 Materials Stability

RATING = +14

REF: VOLUME I, BOOK 3
SECTION 3.1.2.6SUMMARY OF RATIONALE FOR RATING

The rating is based on literature surveys of vacuum evaporation data, HTGR test work, and data measured by BCL; all indicate the chemical effects on the materials will be minimal. The only reason for dropping one point is that the post-test analysis of long duration specimens in the BIPS will not be available to reconfirm the literature and lab test data.

TECHNICAL DISCUSSION

The question of vaporization has been answered by maintaining the temperature of the system below the level where vaporization is of significance. The level was set for the HSHX hot spot temperature after a survey of the literature on vacuum evaporation phenomenon and confirmed by initial tests at BCL. Combination of the data shows that less than one mil of the HSHX material (Hastelloy-X) would be affected in the seven year life if the system were at the vacuum required for the vapor pressure of the individual constituents. Since the material is in an alloy form and the evaporation is suppressed by overpressure, the reaction between the working fluid and materials is nil.

The loss of strength in HTGR helium has been flagged as a potential problem. One instance has been formed to support this claim, the creep testing of Inconel 617 alloy in an oxidizing contaminated atmosphere. The General Atomics work, conducted in partially carburizing helium, contradicts this work. If one accepts the impurity levels defined by these programs, analysis of the BIPS atmosphere shows gas purity levels

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better than those shown to have an effect on the materials. The components and the partial pressures analyzed indicate also that if there was an effect, it would be slightly carburizing and thus actually strengthen the material. This data will be supported by analysis of the hardware after long duration test.

Since thermal insulation stability, per se, is discussed in Section 3.1.2.10 and the implications of MULTIFOIL use in the thermal environment of the heat source is discussed in Section 3.1.1.1, this attribute is considered from the viewpoint of how the use of MULTIFOIL might impact materials stability of system components other than the heat source.

The maximum temperature of the MULTIFOIL insulation around the heat source is 1390°F. The material of choice is 60 percent Pd, 40 percent Ni foil brazing material produced by Western Gold and Platinum. Although the vapor pressure of palladium in vacuum is slightly higher than the vapor pressure of nickel, tests at BCL show that the recession rate of the palladium nickel alloy is equivalent to nickel (i.e., at 1390°F the recession rate of nickel is 8.7×10^{-13} g/sec/cm² and 60 percent Pd - 40 percent Ni is 1.17×10^{-12} g/sec/cm² or less than 1 percent of a 1 mil foil in 7 years). Note that the electrostatic coating process eliminates the use of a binder previously employed with MULTIFOIL. Any material interactions at such low concentrations should be benign. As with the heat source, material transport will be minimized by the temperature gradient and the dynamic pumping away from the HSHX and IHS by the ambient vacuum.

GE has reported* on a 1000 hour test of Ni/ZrO₂ MULTIFOIL with a source temperature of 1800°F. Linear regression analysis indicated a

*Daniel Wien, "Development of a Heat Source Assembly for an Isotope Brayton Space Power Conversion System," Record of the 10th Inter-society Energy Conversion Engineering Conference (1975).

95 percent confidence level that the conductivity was not time dependent. The 1000 hour, 1800°F test should have yielded higher interaction of materials if either diffusion or vaporization controlled, than the 7 year mission duration at 1400°F.

The only instability in the system is the aging effect of Hastelloy-X as a result of carbide precipitation. Early ORNL data shows that the primary symptom is a partial loss in ductility in the alloy but only in room temperature tests. Continuing studies at ORNL have led to values that have little effect on calculation of the allowable loads noted in Sections 3.1.2.7, 3.1.2.8 and 3.1.2.9. The effect on ductility at operating temperature has been shown to be quite unimportant. One method of eliminating the loss in ductility is to limit the ground operation time of the system prior to launch to less than 100 hours.

The creep to leakage phenomenon has been reduced to a minimal level in the failure criteria based on tests conducted at BCL and ORNL. In these tests, no leakage has been found to occur before rupture takes place. This will further be confirmed by tests on thin wall bellows stack and by creep tests on bellows assemblies.

3.1.2.7 Transient Stresses

This factor covers all mechanical and thermal stress situations in the system in which yield or ultimate stress is the controlling parameter. Only normal operation is considered. The materials are to be considered in an aged condition characteristic of the point in system lifetime at which peak stresses occur. Evaluation is to be based on the worst case. Factor of safety is defined as:

$$\frac{\text{allowable}}{\text{actual}} - 1.0$$

3.1.2.7 Transient Stresses

RATING = 10

REF: VOLUME I, BOOK 3
SECTIONS 2.5 AND 3.0SUMMARY OF RATIONALE FOR RATING

The BIPS interface structures and the Mini-BRU turbine plenum supporting structure are design governed by the material's yield strength. The interface structures are subject to dynamic loading, while the plenum supporting structure is subject to mechanical and thermal loadings.

BIPS interface structures are designed to have sufficient stiffness to avoid resonant frequency interaction from space shuttle, yet no stiffer than necessary to minimize the shock and vibration responses. This requirement results in high strength in all the interface structure. All the components mounting pads are designed capable of resisting a 50-g loading, while the interface structures are capable of resisting a 25-g loading.

Stresses in the Mini-BRU plenum supporting structure are calculated under normal operation condition. The transient thermal stresses are insignificant compared with the steady state stresses. The materials properties used are in an aged condition, approximately 150-200 hrs aging time. The margin of safety is calculated based on the worst case, and the material's -2σ strength.

TECHNICAL DISCUSSION

The BIPS is subjected to vibration and shock loading during launch. The principal source of structural vibration occurs during space shuttle powered ascent. The principal source of shock occurs when using pyrotechnic devices on the IUS vehicle. The shock and

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vibration levels at various interfaces are estimated by using data from the shuttle and Titan IIIC. The actual shock and vibration levels the BIPS will experience depends on the payload dynamic response to the principal sources of excitation.

The BIPS is designed for rigidity and strength. The basis for BIPS design criteria is established upon the assumption that the payload consisting of the BIPS-spacecraft-IUS assembly is cantilever mounted to the space shuttle.

The basis of the design criteria are:

- (1) Avoid interaction of the natural frequencies of the cantilevered payload with the natural frequencies of the space shuttle. Best information available to AIRPHX shows the natural frequencies of the space shuttle are 3, 8 and 13 Hz.
- (2) Avoid interaction of the natural frequencies of the BIPS components with the natural frequencies of the cantilevered payload. Specifically, this criteria requires that the natural frequency of the BIPS components be 60 cps as a lower limit.
- (3) It is desirable to maintain the upper limits of the natural frequencies of the BIPS components no higher than necessary to satisfy (1) and (2) in order to minimize the dynamic response of the BIPS components to shock and vibration.
- (4) The acceleration levels experienced during the qualification testing of the MHW-RTG by G.E. for the LES 8 and 9.

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- (5) Provide higher structural capability for the BIPS components and mount pads than for the interface structure to compensate for statically determinate mounting system as compared to the redundancy of the interface structures.

BIPS Design Criteria

- (1) Lower limit of the fundamental natural frequencies of the BIPS components to be approximately 60 Hz.
- (2) Limit loading of the BIPS components to be 50 g's.
- (3) Limit loading on the BIPS interface structure to be 25 g's.

Although there are many uncertainties regarding design specification at this time, it is felt that the BIPS design criteria outlined here is a sound approach to achieve a design that will be compatible with the space shuttle, IUS and payload system.

The margin of safety is defined as

$$M.S. = \frac{-2\sigma \text{ Yield Strength}}{\text{Actual Stress}} -1 \text{ on yield}$$

$$M.S. = \frac{\text{Minimum Natural Frequency}}{\text{Frequency of Source of Excitation}} -1 \text{ on frequency}$$

The BIPS is designated to be mounted at the top of the radiator, thus separating the hot components from the spacecraft payload, also attenuating the shock input.

The 50-g loading requirement provides increased structural integrity for BIPS components and mount pad. This is needed to compensate for the lower degree of mounting redundancy than the interface support structure which is designed for 25-g loading.

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The limit loading should satisfy requirement for all other loading such as pre-launch, launch, operational environment and crash landing, etc.

The BIPS is intentionally designed to meet the frequency requirement with built-in strength that will exceed the limit g-loading.

The margin of safety is calculated based on the use of a Lockalloy interface structure.

The following table shows the maximum stresses in various components. For detailed design criteria and material property charts, see Volume I.

The recuperator and heat source heat exchanger (HSHX) are the two heat exchanger components which have undergone analysis for low cycle fatigue and for life prediction as a function of 1 percent creep. This study begins with a system transient analysis using a computer program, BRTDYN, which includes models of all of the heat exchangers, ducts, and turbomachinery in the closed cycle engine. It is then possible to use BRTDYN with appropriate assumptions, i.e., inventory of gas, heat source heat exchanger temperature, heat rejection sink temperature, etc., to predict the thermal transient on all of the components during startup. The flow rate and inlet temperature rate of change are then used in a detailed nodal analysis of the heat exchanger to determine the temperature on the outlet side and to verify that the slope of the temperature versus time curve agrees with that predicted by the system program. The two programs are then used in an iterative manner until a satisfactory solution to the time rate of change of temperature is derived.

This ramp is then used to determine the low cycle fatigue life of the heat exchanger. A detailed discussion of analysis performed on

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TABLE I. THE DESIGN OF THE FOLLOWING COMPONENTS IS GOVERNED BY "YIELD".

Component	Material	Maximum Stress (psi)	Minimum Yield Strength (psi)	M.S.
Mini-BRU Mount Ring	347 S.S.	11,000	34,000	2.0
MBR Mount	INCO 718	40,000	120,000	2.0
HSA Mount	17-4 PH	40,000	120,000	2.0
Interface Structure	Lockalloy	11,600	35,000	2.0
Mini-BRU Turbine Plenum Supporting Structure	Hastelloy X	14,500	44,000	2.0

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the recuperator and HSHX is found in Sections 2.7.1.2.3 and 2.7.1.6.1, respectively. The recuperator has undergone cyclic testing which has verified life exceeding 200 startup cycles without external leakage. Analysis of the HSHX shows cyclic life in excess of 300 startup cycles. Both components have life in excess of 7 years for 1 percent creep.

3.1.2.8

Fatigue Stresses

This factor covers all mechanical and thermal stress situations in which the stress varies and the number of cycles to failure is the controlling parameter. Only normal operation is considered. The materials are to be considered in an ageing or aged condition characteristic of the period in the system lifetime at which the cycles occur. Evaluation is to be based on the worst case. Factor of safety is defined as:

$$\frac{\text{cycles of failure}}{\text{actual cycles}} - 1.0$$

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3.1.2.8 Fatigue Stress

RATING = +6.6

REF: VOLUME, I BOOK 3
SECTION 3.0

SUMMARY OF RATIONALE FOR RATING

Bellows are the components "most critical for low-cycle fatigue." All the bellows are designed to have sufficient margins of safety on minimum LCF. Detailed stress analyses, thermal and mechanical, were performed on all bellows using the most promising analytical tool, Kalnin's shell program cycle life is evaluated based on maximum stiffness and the worst dimensional and thermal mismatch. All the bellows are tested at elevated temperature to ensure a minimum life in service. The test results and the predicted life are in excellent agreement. The carbide aging reaction in Hastelloy X, which affects the ductility of the material, is slow enough so that a reasonable test period (100 hours at least) on the ground, prior to launch, can be allowed. If the system is launched hot, ductility will be restored. However, to be conservative the margin of safety was calculated using the predicted minimum life based on material properties in an aged condition.

TECHNICAL DISCUSSION

Of all the components in the system, the bellows are the most critical for LCF life. Stresses in bellows due to dimensional and thermal mismatch are generally high. Critical areas are usually at the convolution roots near the ends. Cycle life of a bellows depends not only on design, but also on fabrication and quality control. Material data used in LCF prediction are generally obtained in controlled conditions, while material at critical locations in a bellows may be under complex conditions, such as biaxial stress, strain concentration, creep interaction, and residual stresses. Strain hardening due to forming is seldom accurately known. Although local strains can

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be calculated using the most promising analytical tool, they are evaluated only approximately in regard to plastic components. With regard to all of these factors, all the bellows in the BIPS are designed with a high margin of safety, which is defined as:

$$M.S. = \frac{\text{Calculated Life in Cycle}}{25} - 1$$

where 25 is the number of start cycles defined by Paragraph 2.1.7 of the DOE Dynamic System Evaluation Criteria before launch. The calculation of life is based on the maximum stiffness and the worst mismatch condition. For high temperature bellows, creep and fatigue interaction is handled by the linear damage law. It is well-known that fatigue tests of materials show a wide scatter in life. When a bellows is fabricated from the same material, scatter may be anticipated from both material and manufacturing. A scatter factor of 10 was used in the BIPS bellows design. This factor is the result of many statistic analyses on fatigue data. It is sufficiently conservative in BIPS components design. The scatter factor can be altered when more statistical data is available. The margin of safety is calculated based on the predicted minimum life. Of all the BIPS componets, the turbine inlet bellows, which have a calculated LCF life of 190 cycles, have the lowest margin of safety on LCF. Stresses in the turbine plenum and ducting are relatively low. Design is governed by creep and LCF is not expected. The attached table shows the margin of safety for LCF on BIPS major components. A summary chart of bellows LCF/ creep test progarm at ORNL is shown below. For detailed descriptions, see AIRLA Report 77-14077 (Torrance).

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MARGIN °F SAFETY FOR LCF ON BIPS MAJOR COMPONENTS

Component	Material	Temperature °F	Predicted Min. Life (Cycle)	Margin Of Safety
Mini-Bru Turbine Plenum	Hastelloy X	1385	>400	High
Bellows (HSA Outlet)	Hastelloy X	1400	190	6.6
HSMA	Hastelloy X	1500	320	High
Recuperator	Hastelloy X	1335	250	9.0
Ductings	Hastelloy X	1435	>400	High

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BELLOWS TEST PROGRAM AT ORNL

BELLOWS PART NO.

TEST PARAMETERS	418 -1	418 -2,-3	418 -4	419 -1,-5, -6	419 -2,-3	419 -4	420 -1,-2 -3	421 -1,-2, -3
CREEP TEST: Temperature, °F Pressure, psig Creep Deformation in 2000 Hr, Percentage		1500 100 5	1475 100 5		1500 67	1450 67		
LCF TEST: "Cold" Conditions Temperature, °F Axial Tension, in. "Hot" Conditions Temperature, °F Pressure, psig Axial Compression, in. Hold Time/Cycle, min	600 -3.5°*	600 -3.5°*		600 0.5	600 0.5	600 0.5	70 0.250	170 0.095
	1300 100 +3.5°*	1300 100 +3.5°*		1300 67 0.5	1300 67 0.5	1330 67 0.5	70 67 0.200	170 100 0.095
	60	60		60	60	60	--	--
LCF PLUS CREEP LCF Cycles Creep EST. LENGTH OF TEST		100 5%		80 Cyc. (2 wks)	Approx. 40 Cyc. to 5% Elong. 4 Mo	Approx. 40 Cyc. To 5% Elong. 1 Yr	<1 Wk	<1 Wk

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PARTIAL TEST RESULTS FROM ORNL

Bellows No.	Test Purpose		Predicted Life in Cycles	Observed Life in Cycles
		Cold temp: 300°F		
		Axial tension: 0.317 inch		
467	LCF	Hot temp: 1330°F	167	267
		Axial compression: 0.497 inch		
		Pressure: 70 psig		
		Hold time: >20 min/cycle		
		Cold temp: 500°F		
		Axial tension: 0.095 inch		
466-1	LCF	Hot temp: 1385°F	107	126
		Axial comp: 0.095 inch		
		Pressure: 102 psig		

3.1.2.9

Creep Stresses

This factor covers all mechanical and thermal stress situations in which stress to produce 1% creep at EQM is the controlling parameter. Only normal operation is considered. The materials should be evaluated in their normal operating environment. Evaluation is to be based on the worst case. Factor of safety is defined as: $\frac{\text{stress for 1\% strain at EQM}}{\text{actual stress}} - 1.0$. The creep data must relate to actual operating environments. If this is accomplished by using data taken under non-contaminated conditions and correcting for the operating conditions, the performance factor is to be

reduced by 5.0. If the creep data is based on an extrapolation of more than one decade in time, the performance factor is to be reduced as follows:

- 2 decades, reduce by 5.0
- 3 decades, reduce by 10.0
- more than 3 decades, reject.

If the "creep to leakage" theory is borne out by current experiments, this failure mechanism must also be considered.

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3.1.2.9 Creep Stresses

RATING = 10.0

REF: VOLUME I, BOOK 3
SECTION 3.1

SUMMARY OF RATIONALE FOR RATING

Hot bellows, ductings, the HSHX, and the Mini-BRU turbine plenum are subject to high temperature creep during the BIPS entire mission. The consequence of large creep deformation is leakage and/or rupture. It is currently assumed that creep leakage starts at the onset of tertiary creep. Kling tests are now underway at ORNL to verify the creep-to-leakage theory. In order to ensure a leakproof system for 7 years, the maximum allowable creep strain is limited to 1 percent for pressure loading. The creep relaxation rate of Hastelloy X is very fast. Ninety percent of the thermal stresses will be relaxed during the primary stage of creep. Both mechanical and thermal stresses are calculated under the BIPS normal operating condition. The heat-to-heat variation in Hastelloy X creep strength is accounted for in the BIPS design. Data examination shows that adequate design can be achieved by using material's -2σ creep strength. Additional conservatism is gained by using contaminated air data in design, while the system is operated in noncontaminated helium environment. Data shows that the creep strength of Hastelloy X is higher in helium than in air. The 7-year creep strength is based on extrapolation of less than one decade in time. Of all the components, bellows are particularly critical to creep-leakage because of the thinness of their plies. The turbine inlet bellows are the most critical ones. The margin of safety is calculated based on the worst case.

TECHNICAL DISCUSSION

Creep deformation is a function of stress, temperature, time and material heat. Since time is the most critical factor, it seems more logical to define the margin of safety as follows:

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$$M.S. = \frac{1\% \text{ Creep Life (Hrs)}}{7 \text{ Yr Mission Life (Hrs)}} - 1$$

Calculation of creep life begins with stress analysis. The turbine plenum is modeled using in-plant developed finite element program ISOPDQ. Bellows and ductings are modeled using Kalinin's shell program. Calculated bellows stresses were verified by tests using strain gages. Parametric studies were performed on Hastelloy X for creep data up to 8000 hrs. Extrapolation to 7 year creep strength were independently made by AIRPHX⁽¹⁾ using the Larson-Miller parameter and NASA-Lewis⁽²⁾ using Dorn-Sherby parameter. Recent data analysis by ORNL⁽³⁾ concluded that AIRPHX results describe the available data for 1 percent creep reasonably well. The L-M parameter is more reliable than the D-S parameter in extrapolation. The constant "C" in the L-M parameter is determined by the least-square method. System reliability is further achieved by using 2σ material properties and applying a safety factor of 1/1.15 to the allowable stresses (which reduces the values to less than 3σ, which is very conservative).

ORNL will be continuing the analysis of the data to derive curves of creep versus time, given the stress and temperature. This work will be completed in time for a final reevaluation of the design prior to fabrication of Phase II hardware; however, based upon results to date, such changes will be minor.

Detailed creep analyses were performed at all critical locations in bellows, plenum, HSA, recuperator, and ductings. Components are designed by using air data in contaminated condition. Test results show creep strength of Hastelloy X is higher in helium than in air. Of all the components in the system, bellows are particularly critical

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to creep-leak damage because of the thinness of their plies. The M.S. is calculated based on the worst case. A summary of the margin of safety on creep for BIPS major components is shown below.

As for fatigue stresses, a table showing analytical results by item or component would be very beneficial. This table could include item, material, maximum operating temperature, allowable stress, calculated stress and M.S.

- Ref: (1) J.A. Hadley (AIRPHX)
"Analysis of and Design Limits for Hastelloy X Creep Data"
BIPS-GDS memo A of 21 September 1977
- (2) Letter, W.D. Klopp to J.A. Hadley November 1977
- (3) M.K. Booker
Evaluation of the 1 percent Creep Strength of
Hastelloy X, February 1978

MARGIN OF SAFETY FOR CREEP ON BIPS MAJOR COMPONENTS

Component	Mat'l	Temp. (°F)	Max. Creep Strain at EOM	Allowable Creep Strain at EOM	1% Creep Life (hr)	Margin of* Safety on Time
Mini-BRU Turbine Plenum	HX	1385	0.25%	1%	245,300	3.00
Bellows (HSA Outlet)	HX	1400	0.33%	1%	184,000	2.00
HSHX	HX	1485	0.27%	1%	234,800	2.83
Recuperator	HX	1435	0.26%	1%	243,300	2.97

$$M.S. = \frac{\text{Calculated 1\% Creep Life (hrs)}}{61,320 \text{ (7-yr mission life in hrs)}} - 1$$

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RATIONALE FOR REDEFINING THE DEFINITION
"MARGIN OF SAFETY" FOR CREEP STRESS

The margin of safety (factor of safety) for creep stress is defined in Paragraph 3.1.2.9 of reference (1) as:

$$M.S. = \frac{\text{Stress For 1 Percent Strain at EOM}}{\text{Actual Stress}} - 1$$

Creep deformation is a function of stress, temperature, time, and material heat. Theoretically, the margin of safety on creep can be defined in terms of strain or temperature or time. However, it is much more appropriate to define the margin of safety in terms of time, as follows:

$$M.S. = \frac{\text{Calculated 1 Percent Creep Life (Hrs)}}{7 \text{ Years Mission Life (Hrs)}} - 1$$

The reasons are:

(1) For a given temperature and material heat, creep stress is a function of time. As the material creeps, thermal stress will be relaxed. Bending stress due to pressure will be redistributed. Only membrane stress due to pressure remains practically unchanged. Therefore, the margin of safety defined in terms of stress will change with time. One can define the minimum margin of safety by using the initial elastic stress as the actual stress. However, the value obtained does not truly reflect the design margin.

(2) For the bellows and turbine plenum, the creep strain in the hoop direction is the most critical component of strain. However, hoop strain depends not only on the hoop stress, but also on the axial stress and shear stress. Therefore, not only is the elastic stress

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not appropriate for calculating the margin of safety, it is not clear which of the stress components should be used or how they should be combined into a single elastic stress to be used in the calculation.

(3) The margin of safety can also be defined in terms of creep strain or turbine inlet temperature as:

$$M.S. = \frac{\text{Maximum Creep Strain at EOM}}{1 \text{ Percent Creep Strain}} - 1$$

$$M.S. = \frac{\text{Maximum Allowable Turbine Inlet Temperature}}{\text{Designed Turbine Inlet Temperature}} - 1$$

However, creep strain and turbine inlet temperature are design specifications, not design goals. Margin of safety defined in terms of strain or temperature does not reflect the system life, which is the ultimate design goal.

In conclusion, it is much more logical to define the margin of safety in terms of time.

3.1.2.10 Thermal Insulation Stability

Fibrous and foil insulation should be evaluated relative to design and performance parameters. Vaporization, degradation of basic thermal/physical properties and impurity volatilization should be considered with reference to detrimental system performance and compatibility effects under representative thermal conditions. The design of insulation for extended areas should adequately provide for launch depressurization.

"Primary effect" is an increase in thermal losses.

"Secondary effect" is degradation of other components due to behavior of thermal insulation.

3.1.2.10 Thermal Insulation Stability

RATING = +10

REF: VOLUME I, BOOK 3,
SECTION 2

SUMMARY OF RATIONALE FOR RATING

The temperature stability of the heat source insulation system (HSIS) is covered under specific attributes elsewhere in this document. The material stability of insulation elsewhere in the system operates at temperatures below 1400°F where the most conservative vaporization and diffusion rates yield recession or migration rates involving 1 to 10 micro-inches of insulation material over the mission duration.

The compatibility of nickel and zirconia have been favorably characterized at temperatures well in excess of 1400°F. The nickel foil in the hottest areas are in proximity to nickel-base alloys where any interaction would have no deleterious effect.

The use of coating binder which may volatilize has been eliminated by TECO process improvement. Testing has been performed which yields a high confidence that the insulation properties are not time dependent.

No evidence has been noted that depressurization is harmful to the insulation system. Should this effect be observed, however, accommodation of depressurization loads can be easily accomplished.

TECHNICAL DISCUSSION

The maximum temperature of the MULTI-FOIL outside of the heat source assembly is approximately 1390°F. Zirconia coated nickel foils will be used in all these regions. At 1400°F, the vapor pressure of nickel is between 1.3×10^{-12} and 1.8×10^{-11} torr (depending on source.) The vapor pressure of zirconia is much lower than that of nickel since the vapor pressure of zirconia at 3500°F is only 4×10^{-5}

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torr. Note that the electrostatic coating process eliminates the use of a binder previously employed with MULTI-FOIL. Any material interactions at such minor concentrations should be benign. As with the heat source assembly, material transport will be minimized by the temperature gradient and the dynamic pumping away from the loop components by the ambient vacuum.

Based on compatibility tests of zirconia coated nickel at Thermo Electron, Battelle, and General Electric; these foil materials should be stable at temperatures up to 1600°F (in excess of the maximum temperature of nickel foils in BIPS GDS and FS). These test results are consistent with vendor data (Zirconium Corporation of American Technical, Data Sheet No. 6) and other available literature (High Temperature Materials and Technology, Ed. by I. E. Campbell and E. M. Sherwood, John Wiley & Sons, 1967). The compatibility tests at Thermo Electron are summarized in Report No. TE4219-28-77 (Zirconia-Foil Compatibility Test, October 1976).

The stability of the zirconium coated nickel is related to the large negative free energy of formation ($-207 \text{ K cal/mole as } \text{ZrO}_2(\text{C})$ at 1700°F) of zirconia and the much smaller negative free energy of formation associated with nickel oxide ($-31 \text{ K cal/mole as } \text{NiO}(\text{C})$ at 1700°F). However, contaminating oxides should be avoided.

GE has reported* on a 1000 hour test of Ni/ZrO_2 MULTI-FOIL with a source temperature of 1800°F. Linear regression analysis indicated a 95 percent confidence level that the conductivity was not time dependent. The 1000 hour, 1800°F test should have yielded higher interaction of materials, if either diffusion or vaporization controlled, than the 7 year mission duration at 1400°F.

*Daniel Wien, "Development of a Heat Source Assembly for an Isotope Brayton Space Power Conversion System."

3.1.2.11 Heat Source Heat Exchanger

The following potential flaws may exist in heat source heat exchangers:

1. Fluid dynamics: high pressure drop, poor flow distribution, poor flow stability, sensitivity to acceleration
2. Thermal performance: inadequate surface area, non-condensable build up
3. Strength: creep, thermal stress, thermal fatigue
4. Chemistry: materials reactions, outgassing reactions with fluid
5. Practicality: internal crevices and inspectability

3.1.2.11 Heat Source Heat Exchanger

RATING = +12

REF: VOLUME I, BOOK 3,
SECTION 2.7.1.6.1

SUMMARY OF RATIONALE FOR RATING

Four classes of flaws will be eliminated by testing. Strength flaws will be eliminated by careful design analysis based on solid test data for the Hastelloy-X material.

TECHNICAL DISCUSSION

All potential fluid dynamics flaws will be eliminated by test. Pressure drop tests are included in the Phase II program plan; design analysis indicates acceptable levels. The single flow passage HSHX has no flow distribution problems. Flow stability and acceleration problems are essentially nonexistent for the single phase, single flow passage, highly turbulent flow (the Reynolds number is about 25,000 for the reference design conditions).

Thermal performance flaws will also be completely eliminated by the GDS test. Design analysis indicates heat transfer capabilities in excess of the BIPS requirements. Performance testing of the GDS unit during Phase I should substantiate the design. Noncondensable buildup is inherently not a problem for the purified inert gas, single-phase flow regime used in BIPS.

Potential strength flaws have been eliminated through careful design analysis. A good data base already exists for stress properties of the Hastelloy-X material and the Palniro braze joints. This base will be improved upon in the Phase II testing. Shock, acceleration, vibration, proof, and the fatigue thermal cycling tests should verify

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the design. Since a full seven year life test will not be conducted, all flaws cannot be positively eliminated by testing.

Potential chemistry flaws have been almost completely eliminated in testing conducted primarily at Battelle Columbus Laboratory (BCL) and Oak Ridge National Laboratory (ORNL). Materials reactions can be classified into two main areas -- diffusion of the braze filler metal into Hastelloy-X and age embrittlement. Test results from BCL predict that there will be less than 0.0001 in. penetration of braze filler into Hastelloy-X in seven years. Low cycle fatigue and crack propagation tests conducted at ORNL after aging at 1400°F indicate minimal age embrittlement effects. Potential outgassing reactions include the evaporation of Hastelloy-X and contamination of the working fluid with subsequent grain boundary embrittlement. Tests at BCL indicate that evaporation rates of 1450°F will be extremely slow for Hastelloy-X. Contamination of the working fluid under simulated operating conditions has been measured and was found to be very slight. No grain boundary embrittlement is expected.

Potential practicality flaws will be eliminated by inspection procedures. One of the advantages of the single tube design is the inherent ease of inspectability. Internal crevices should not be a problem with the welded and drawn tubing.

3.1.3.1 Turbine

This factor is used to evaluate the ability of the turbine to perform adequately for the entire mission. Inability to perform adequately may be caused by: (a) erosion; (b) nozzle plugging; (c) plenum creep; (d) wheel rubbing; (e) blade path problems (efficiency, etc.).

3.1.3.1 Turbine

RATING = +8

REF: VOLUME I, BOOK 3,
SECTIONS 2.7.1.1 AND 3.1SUMMARY OF RATIONALE FOR RATING

The Mini-BRU turbine wheel is a very conservative aerodynamic and mechanical design. An extensive stress and thermal analysis has shown that the turbine wheel deflections are less than the deflections of the mating shroud and as a result the clearances increase when compared to the cold build clearances (0.008 in. radial and axial). The stress levels due to centrifugal and gas pressure effects are very low and contribute to the very high life of the wheel. The only significant stress levels are due to compressive thermal stress, and the wheel will never creep into the shroud; the life limiting component is turbine plenum creep in a region not affecting aerodynamic performance. The performance level of the turbine wheel has been verified by rig testing in which it met its design goal. Workhorse Loop testing shows a level consistent with previous rig testing.

TECHNICAL DISCUSSION

The turbine vanes will creep open very slowly, but from the rate shown by analysis, it would take much longer than 7 years to have any noticeable effect on system performance. Output power loss would be less than $2 W_e$. No other time dependent performance degradation mode has been identified.

Because of the very clean environment of the BIPS system and previous experience with the NASA BRU (which did not have such a clean environment), in over 30,000 hours of operation, no problems with erosion or nozzle plugging is predicted.

This section will address the five degradation modes listed in the above attribute:

- (a) Erosion and
- (b) Nozzle Plugging

Neither erosion nor nozzle plugging is a known degradation mode of closed Brayton cycle turbines. In over 5000 hours of Brayton cycle demonstrator testing or 46,000+ hours of NASA BRU testing, neither of these problems was found. In the case of WHL experience, neither of these problems has been noted. In the case of the BIPS, the super-cleaning of all components will limit the amount of debris available to cause this damage to an almost infinitesimal level. The low flow velocities in most of the ducts and lower velocity in the recuperator should succeed in filtering out of the gas stream most of the very small amount of debris. Filtering will occur because of the centrifugal force in the duct turns and recuperator manifolds or impingement upon the 600,000 fin leading edges in the recuperator.

- (c) Plenum Creep

For the 2-HSA configuration, the Hastelloy X turbine plenum meets the new design criteria. For the 3-HSA configuration, the creep strain due to hoop tension slightly exceeds the 2σ design criteria but is not considered serious.

The Mini-BRU turbine plenum was re-analyzed for the 2-HSA configuration. The maximum turbine inlet pressure is 62 psia. The turbine inlet gas temperature is 1385°F, and the metal temperature in the plenum is assumed to be 1375°F. The design life is seven years. Both the GDS and the FS will be operated with 2-HSA's. However, all the components, with the exception of the high pressure hot bellows and inlet turbine plenum ducting are designed with the potential of being operated with 3-HSA's, with a pressure of 105 psia.

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The following is a summary of the new design criteria:

- (i) The design is governed by strain rather than by stress.
- (II) For non-relieving stress conditions, such as hoop tension in the plenum due to pressure, the maximum allowable creep strain at seven years is one percent.
- (iii) For stress relieving conditions, such as thermal stress, the maximum allowable creep strain at seven years is three percent. (It is judged that tertiary creep will not start at three percent within the temperature and stress ranges BIPS is operated).
- (iv) All creep strains are predicted using minus 2σ material properties.
- (v) Larson-Miller parameter will be used in the creep analysis with $C = 17.9$.
- (vi) A time extrapolation factor $1/1.15$ is to be applied.

The turbine inlet flange loading has been calculated by AIRLA for the 2-HSA configuration as follows:

Pressure	62 psia
Axial Compression	140 lbs
Shear	28 lbs
Moment	78 in.-lb

Table I show the design margin of the turbine plenum for 2- and 3-HSA configurations using minus 2σ and typical material properties.

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The design margin at the duct-plenum juncture for the 3-HSA configuration was based on the same flange loading calculated for the 2-HSA configuration. Bellows designed for the 2-HSA configuration have one-ply redundancy. The same bellows when installed in the 3-HSA configuration will lose this redundancy. Therefore if the one-ply redundancy for the 3-HSA is required, new bellows and ducting must be designed and the flange loads will increase. As a result, the design margins at the duct-plenum juncture would be lower than those shown below.

TABLE I

DESIGN MARGIN OF THE HASTELLOY-X
TURBINE PLENUM

	2-HSA		3-HSA	
	-2δ	Typical Data	-2δ Data	Typical Data
Hoop Tension	0.96	5.67	-0.17	4.56
Vane Trailing Edge	6.89	>10	4.36	>10
Duct-Plenum Juncture	1.30	8.40	4.45	>10

NOTE:

(1) Design Margin = $\frac{\text{Allowable creep strain for 7 years}}{\text{Calculated creep strain for 7 years}}$ $-1 \geq 0$

(2) See design criteria for allowable creep strain

A negative design margin exists for hoop tension for the 3-HSA configuration. This is because the radial creep deformation due to hoop tension slightly exceeds the one percent limit.

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The maximum stress at the duct-plenum juncture is at the forward (compressor side) bend and is shown below in tabular form for 2- and 3-HSA configurations.

TABLE II
CREEP DEFORMATION OF THE HASTELLOY-X
TURBINE PLENUM FOR THE 2-HSA CONFIGURATION AT 7 YEARS

Critical Area	Creep Property	-2 σ Data	Typical Data	Criteria
	Hoop Tension	0.51%	0.15%	<1%
	Vane Trailing Edge	0.38%	0.10%	<3%
	Duct Juncture	1.30%	0.32%	<3%

TABLE III
CREEP DEFORMATION OF THE HASTELLOY-X
TURBINE PLENUM FOR THE 3-HSA CONFIGURATION AT 7 YEARS

	Creep Property	-2 σ Data	Typical Data	Criteria
	Hoop Tension	1.2%	0.18%	<1%
	Vane Trailing Edge	0.56%	0.17%	<3%
	Duct-Plenum Juncture	0.55%	0.15%	<3%

It is noted that creep deformation at the juncture is lower for the 3-HSA configuration than for the 2-HSA configuration. This is because the pressure produces compression stress at the inside of the bend and tensile stress at the outside, while the axial compression load produces just the opposite effect. The net stress for the 3-HSA configuration is lower than those for the 2-HSA configuration, therefore, the corresponding creep deformation is lower. The lateral load and bending moment at the turbine inlet flange are calculated from the axial stiffness of a solid bellows, (single ply).

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There is a definite relationship in solid bellows between the axial, lateral and bending stiffness. However, for a laminated bellows, this relationship depends upon whether there is relative motion in each ply. Every bellows is different. The flange load in this report was based upon the assumption of a solid bellows which is on the conservative side.

Wheel Rubbing

Thermal analysis of the compressor wheel and shroud have shown that if the cold build axial and radial clearances are the 0.007 to 0.009 inches intended, it is impossible for the compressor wheel to touch the shroud even during startup and shutdown transients. The detailed analysis was performed on the system with the columbium alloy Cl03 plenum, and the results can be translated to the Hastelloy-X design. The Hastelloy plenum tends to grow twice as much as the Cl03 which means that the clearances will open during steady state operation. The opposite was true with the Cl03 design because of its lower coefficient of thermal expansion. The plenum tended to close more during the shutdown transient but would never touch the non-rotating wheel. The Hastelloy-X plenum will have more margin in this regard.

Detailed analysis of a turbine wheel design almost identical to that used in the BIPS showed a life to 0.1 percent creep of 7.43×10^6 hours and a low cycle fatigue life of better than 1×10^6 cycles.

This analysis was performed on the turbine intended for 1600°F inlet temperatures. Examination of the stress which life is based upon, shows a 30,000 psi maximum in the 1150°F temperature system. This stress is compressive and temperature related so that it will creep and relax. Computing the Larsen Miller parameter for this and checking the 0.1 percent creep curve with -3σ properties for IN713LC shows that this element at the turbine tip will creep less than 0.1 percent in 7 years. This stress will eventually reduce leaving only

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a small (6 KSI) residual stress due to centrifugal effects. The turbine wheel might grow 0.003 in. on the diameter in 10 years, but the turbine plenum has also been displaced radially outward from its cold build location by some 0.030 inches due to thermal growth and the gas pressure loading of the plenum structure. The turbine wheel will never rub the plenum structure.

Blade Path Problems

The design efficiency of the Mini-BRU turbine was confirmed during extensive rig testing. Workhorse Loop testing again shows a good level of turbine performance although the exact efficiency cannot be calculated. Experience with gas turbines in general and closed cycle engines in particular show that turbine performance will not degrade except as a function of some other problem. The NASA BRU system performance has not degraded in over 30,000+ hours of testing, and it must be inferred that the turbine is in good shape. Physical examination of the turbine after 30,000 hours of testing showed no problem areas and no measurable growth.

3.1.3.2

Pump - Compressor

This factor is used to evaluate the ability of the pump or compressor to perform adequately for the entire mission. Inability to perform adequately may be caused by: (a) erosion, (b) cavitation, (c) impellor or compressor blade rubbing, (d) deposits, (e) blade path problems (efficiency, etc.).

3.1.3.2 Pump - Compressor

RATING = +8

REF: VOLUME I, BOOK 3,
SECTIONS 2.7.1.1 AND 3.1SUMMARY OF RATIONALE FOR RATING

The Mini-BRU compressor stage is capable of operating in a satisfactory manner throughout its life. The wheel and diffuser sections are extremely rugged by design intent and are operated in a region where creep is not discernable. No problems with erosion or deposit have been identified in either the Workhorse Loop testing or the 46,000+ hours of BRU testing. This problem is even less likely to occur in the BIPS because of the cleanliness standards adhered to during component assembly. The compressor stage has exceeded its design goals in the compressor rig testing and meets its operating goals in the WHL. This compressor, being a very conservative design, has better than 30 percent surge margin at steady state. The overall stage design is very conservative in both its aerodynamic and mechanical design, and no degradation of its performance over the design life is expected.

TECHNICAL DISCUSSION

The ability of the compressor to perform adequately is discussed below according to the categories listed under the attribute.

The working fluid of the Mini-BRU is a monotomic gas mixture, and it circulates through a series of components which are super-cleaned. The reservoir of particles which could cause erosion damage is very small, and the gas velocity which would carry these particles is very small.

The axial velocity in the duct immediately upstream of the compressor is 10 fps; the velocity in the case of the recuperator is 2 fps. These are also a large number of stagnation areas, i.e., the recuperator headers, duct turns, etc., where particles would leave the

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gas stream. The strongest evidence of the above statement is the BRU experience, where, in over 45,000 hours, no evidence of erosion exists. No evidence has been found in either the Mini-BRU compressor test rig or in the Workhorse Loop.

The Mini-BRU impeller stress and deflection analysis was performed using a finite element computer program ISOPDQ. The analysis included rotation of the impeller at 62,400 rpm (120 percent speed), a 3,000 lb axial tie bolt load, and the thermal gradient.

Impeller displacements result primarily from the thermal gradient and the tie bolt load. Axial deflection at the exducer (flowering) is 0.0015 inches, and the maximum axial displacement at the inducer is 0.00038 inches. Radial displacements of the impeller are, in general, smaller and less significant than axial deflections.

Deflection analysis of the compressor shroud shows that the compressor axial clearance will decrease by 0.0029 inch when the Mini-BRU is running at the 3-HSA pressure level. The design axial running clearance of the Mini-BRU is 0.006 inches which requires that the Mini-BRU be shimmed for 0.009 inches when built. The radial clearance at the inducer during operation will remain in the as-built condition or 0.006 inches.

The tip speed of the compressor is relatively low. The 3,000 lb tie bolt load causes highest stresses at the inducer hub. The maximum stress (principal) reached is 37,100 psi in this area. The high axial stress is due to the limited amount of hub area at this location. Since the yield strength of SS410 is 99,000 psi (100°F), it is clear that the material will be lightly loaded. Peak tangential stresses are lower than peak axial stresses.

The axial stress on the wheel causes a compressive tangential component which partially neutralizes bore tangential stresses due to

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rotation. Compressive tangential stresses are (-11,600 psi) in the hub beneath the inducer. Bore stresses reach a maximum of 24,200 psi.

Burst margin at 62,400 rpm (120 percent speed) for the impeller is defined by the equation:

$$N_{\text{burst}} = \frac{0.85 \times \text{ultimate stress}}{\text{Average Tangential Stress}}^{1/2}$$

and is 3.8. This large number indicates the low stresses in the wheel.

A blade stress analysis (steady state) was conducted for the Mini-BRU impeller using the finite element (BOSS1) computer program. The relatively simple blade has a thickness of 0.015 in. at the shroud all along the blade. At the hub, the thickness is 0.025 in. and varies linearly from the hub to the shroud. There is no reduction of blade thickness at the inducer or exducer, because the low speed reduces effect of shock losses at these regions.

Highest stresses occur near the discharge where centrifugal forces tend to straighten the backward curved blades. The stress level is 12,000 psi. It is evident that the blades are lowly stressed for steady state conditions, leaving a large margin for vibrational stresses.

Mode shapes and frequencies of the compressor blade design were investigated. The blade is thick for its height ("B" width) and this results in high blade natural frequencies. The fundamental mode occurs at 27,977 cps. Maximum stresses for this mode occur near the inducer hub as indicated.

The second mode occurs at a very high frequency, 68,284 cps. Maximum stresses for this mode occur in several locations. Several higher modes were also calculated at 76,299 cps, 96,380 cps, and 104,084 cps. These frequencies are sufficiently high to preclude possible excitation from traditional excitation sources. In fact,

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a 25/rev excitation is required to excite the fundamental blade frequency at 27,977 cps. Hence blade vibration is not a problem for this design.

The Mini-BRU compressor wheel is a very conservative aerodynamic design; because of the small pressure ratio required for this design, it is possible to obtain very high surge margin with no compromise of efficiency. During steady state operation, the surge margin of the Mini-BRU compressor stage is in excess of 30 percent. The system flow rate has been monitored during Workhorse Loop testing, and at no time during startup or shutdown did the engine have any surge indication.

Because of the very clean environment of the BIPS system, it is very difficult to envision any danger from deposits. None have been noted in the Workhorse Loop or in the BRU testing for the 46,000+ hours test.

No efficiency problems have been identified in the Mini-BRU compressor stage. The present design exceeds the design goal of 75 percent efficiency by 2 percent and is an extremely rugged design, even by aerospace standards. No degradation of the blade path for this type of compressor has been identified; the previously presented structural analysis indicates the design tolerance of the compressor stage.

3.1.3.3

Alternator and Rotor

This factor is used to evaluate the ability of alternator and rotor to perform adequately for the entire mission duration. Inability to perform adequately may be caused by : (a) rotor fragmentation or shearing, (b) rotor rubbing, (c) performance (efficiency, etc.).

3.1.3.3 Alternator and Rotor

RATING = +15

REF: VOLUME I, BOOK 3,
SECTION 2.7.1.1 AND 3.1

SUMMARY OF RATIONALE FOR RATING

The alternator is of the same design as the alternator in the NASA BRU unit which has operated successfully for over 46,000 hours on two units (over 35,000 hours on one unit). The 35,000 hour unit showed no sign of degradation upon critical inspection after 20,568 hours. A typical Mini-BRU rotor (52,000 rpm nominal) was spin tested to 130,000 rpm with no diametral growth. All rotors are acceptance tested at 88,000 rpm which represents a stress factor of 2. The alternator organic materials were evaluated for long term stability in tests at BCL and found quite satisfactory. Performance is based upon empirical data which corresponds well with prediction.

TECHNICAL DISCUSSION

The alternator, which serves as a motor during start-up, is a four pole Rice machine (sometimes referred to as a modified Lundell). The machine was designed for high efficiency over a wide range of load conditions and for good performance with a rectifier load. The basic design was for a 120 vdc rectifier load; however, 28 vdc can be obtained simply by rewinding the stator.

A complete description of the alternator design and design methods is found in AiResearch report 75-311211, "Final Report - Mini Brayton Alternator Design Contract NAS3-18517." Test results are found in reports 75-311407, "Summary Report - Fabrication and Manufacturing Process Verification of the Alternator Rotor" and AiRPHX Report No. 31-2316 and 31-2316A, "Test Report - Mini Brayton Alternator Performance and Motor Characteristics."

The net dc efficiency of the unit was found to be 84.2 percent compared to 85.1 percent predicted. The stray load loss was the major contributor to the higher than predicted losses; a slight change to the stator winding (more circuits of smaller wire) would tend to reduce the eddy currents generated in the core under load conditions and raise the efficiency to that predicted. Motoring tests demonstrated the predicted start performance shown in Figure 2-30 of 76-311937, "Controls Design Report, BIPS GDS Phase I." The unit was accelerated to 45 percent speed in 28 seconds using a 28 vdc supply. A typical start is achieved with 1500 watt-seconds of dc power.

3.1.3.4

Bearings

This factor covers the performance of the bearings in the CRU and any other rotating components, the failure of which results in system failure. Failure might occur due to: (a) wear, (b) lubricant contamination, (c) zero g instability by oscillation, (d) rotor imbalance, (e) flooding (f) launch vibration, (g) start-up, (h) orbital transfer, (i) power consumption of bearings. All possible modes of failure must be considered.

3.1.3.4 Bearings

RATING = +5

REF: VOLUME I, BOOK 3,
SECTIONS 2.7.1.1 AND 2.4.3

SUMMARY OF RATIONALE FOR RATING

The basic foil bearing design has clearly demonstrated its ability to run for long unattended periods in production air cycle turbomachinery although under different conditions (air) and larger sizes.

TECHNICAL DISCUSSION

The journal bearing design for the Mini-BRU consists of an 8-pad compliant foil bearing configuration, versions of which have been used on production and development turbomachinery for the past 15 years.

The thrust bearing is a 10-pad double-acting configuration located between the compressor journal bearing and the compressor impeller.

The bearing parameters were empirically developed from data derived on the highly successful DC-10 air cycle cooling turbine and verified on test rigs fabricated for the NASA Mini-BRU program.

Extensive tests on these rigs provided data which completely characterized the bearing performance in load capacity and power loss. Subsequent testing in the dynamic simulator and alternator test rig verified the stability in a magnetic field environment.

Data obtained from the bearing test rigs indicated the bearings would have adequate load capacity to sustain 10G environment vibration load during operation.

The journal bearings have been operated in all attitudes including the zero-g vertical with no stability problems encountered. Lubricant contamination is non-existent in the closed cycle environment, thus precluding bearing damage from outside foreign object ingestion.

The Mini-BRU rotating group, because of its stiff, compact structure, can be easily balanced to 0.00005 in CG eccentricity levels. The unit has been operated with rotor unbalance levels up to 0.0005 in CG, thus adequate margin exists for changes in unbalance during the lifetime operation of the unit.

Bearing flooding is not a factor since the bearings are process fluid (Xe-He) lubricated.

The power consumption of the bearings has been characterized under all possible operating conditions and the heat so generated found to be readily removed by conduction or convection to the cycle gas.

Rubbing contact occurs in the bearing only during start-up. Start-ups are expected to occur only 2 or 3 times during the life of the unit. Tests have shown that up to 100 starts poses no threat of degradation to the bearing.

A properly developed bearing will operate with a complete hydrodynamic lubricating film at design conditions, thus precluding wear as a long term failure mechanism.

3.1.3.3.1 Electrical Insulation

All electrical insulation should be evaluated with reference to thermal degradation of electrical properties. Insulation and organic structural components, such as potting compounds and varnish, should be evaluated for stability. Gaseous species volatilized into or leached by the working fluid should be assessed relative to thermal conditions and system effects for periods representative of mission conditions. "Primary effect" is an increase in electrical losses. "Secondary effect" is degradation of other components due to the behavior of electrical insulation.

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3.1.3.3.1 Electrical Insulation

RATING = +15

REF: VOLUME I, BOOK 3,
SECTION 3

SUMMARY OF RATIONALE FOR RATING

Test work by BCL has shown that the materials in the alternator will not degrade enough to cause a change in insulating properties or produce enough effluent to affect the other components of the BIPS system.

TECHNICAL DISCUSSION

The alternator stator material was extensively studied by BCL and reported in "Final Report on Mini-BRU Alternator Offgassing Rates," Alexander, C.A., Roush, M.P., March 18, 1977. The report states that the volatile components can be eliminated by a bake-out cycle in vacuum or helium. The long term offgassing constituent is primarily a silica, which would be inert in the system. The total hydrocarbon loss would be less than 1.4 grams over the life of the BIPS which is significantly below the amount required to have any adverse effect on the metallic components. Testing of the stator prior to and after long term vacuum heating showed no change in electrical properties.

3.1.3.3.2 Magnetic Field

There is a Flight System Requirement (2.4.7) limiting the stray magnetic field. This will be difficult to measure accurately on the electrically heated GDS but since there may be significant differences between conversion systems, it is desirable to make a preliminary determination. This determination will be the maximum calculated value of the stray field caused by the alternator running at full load, determined at a radius of 10 feet. Alternately, it may be measured during a component test procedure or, if practical, during the GDS test.

3.1.3.3.2 Magnetic Field

RATING = -12

REF: VOLUME I, BOOK 3,
SECTION 2.7.3

SUMMARY OF RATIONALE FOR RATING

Since there is no data available from a direct measurement of the magnetic field, it was necessary to base this parameter on the enclosed calculation.

TECHNICAL DISCUSSION

The maximum calculated stray field at 10 feet is strongly dependent on the method used in making the calculation. It is requested that DOE define in detail the method for determining this value.

A preliminary calculation indicates the magnetic field at 10 feet will be 11.83 gamma.

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$$F_{MAX} = 2 * (17.9 + 15.3 + 63) \\ = 192.4 \text{ AMP TURNS}$$

Conservative Solution (Assume Entire End Bell Surface Is At F_{MAX})

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Ref: Electromagnetics, John D. Krans, McGraw-Hill, 1953

$$M = NI/l, \quad Q_m = AM$$

$$Q = NIA/l \text{ amp-meters}$$

$$= 192 \times (0.785 \times 4.15^2) / 3.67 \times 0.0254 \text{ m/in.} = 17.97 \text{ amp/meters}$$

$$\beta = \mu_0 Q_m / 4 \pi r^2 \text{ Webers/meter}^2$$

$$\text{Say } K = \mu_0 Q_m / 4 \pi; \text{ then } \beta = K/r^2$$

$$C = l/2$$

B at point on axis:

$$B]_R = B_N - B_S = K \times \left(\frac{1}{(R-C)^2} - \frac{1}{(R+C)^2} \right)$$

$$= K \times \left(\frac{4RC}{(R^2 - C^2)^2} \right)$$

$$\text{for } R \gg C: B]_R = 4KC/R^3$$

(B at point on normal plane through center of magnet = $2KC/R^3$ per Handbook of Chemistry and Physics, page 2867.)

$$B]_{R=10 \text{ ft}} = 4 \times \mu_0 \times Q_m / 4 \pi \times (3.67/2 \times 0.0254 \text{ m/in.}) / (10 \text{ ft} \times 12 \text{ in./ft} \times 0.0254)^3$$

$$= 1.183 \times 10^{-8} \text{ w/m}^2 \text{ or } 1.183 \times 10^{-4} \text{ gauss or } 11.83 \text{ gamma}$$

3.1.4.1 Loop Control

This factor considers the control of fluid flow in the loop and its behavior when perturbed by isotope decay, variations in load, ~~and~~ occultation by the earth, *and system degradation.*

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3.1.4.1 Loop Control

RATING = +15

REF: VOLUME I, BOOK 3
SECTION 2.5.2.5

SUMMARY OF RATIONALE FOR RATING

Perturbations in fluid flow caused by isotope decay, variations in load, occultation by the earth, and system degradation require no special control in the BIPS. Fluid flow is an inherent characteristic of the light gas working fluid when operating with the rotating machinery. The only control on this system is parasitic electrical load control of engine speed. Stability has been experimentally demonstrated, therefore, a +15 rating is justified.

TECHNICAL DISCUSSION

This criteria is based on the control of fluid flow in the loop.

The BIPS does not require any loop fluid flow control device, as such, as the gas is automatically circulated at the proper rate by the Mini-BRU compressor/turbine. The described perturbations are accommodated as follows:

Isotope Decay - As the isotope decays over the seven year mission, the engine control will act to maintain turbine inlet temperature at 1845°R. (See attached Performance vs Time plot). This can be seen on the plot as a rotor speed reduction as the temperature decreases. The result is that at the end of seven years the output power is 1200+ watts, engine speed is near 97 percent, and turbine inlet temperature remains at 1845°R. The only control action was the resetting of the engine speed by the parasitic load speed control. See the figure of Performance vs Time.

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Variations in Load - The parasitic load control automatically changes parasitic load as soon as user load is changed in a manner to compensate and hold total load constant. The actual change in engine load is then very small (on the order of 2 watts) for a 1300-watt user load change. This small load change applied to a 580 watt/percent load line results in an engine speed change of less than 3 rpm out of 52,000 rpm for a 1300 W_e load change. Again, all compensation for the load change was accommodated by the parasitic load control and no action was required to achieve engine loop flow control.

Occultation by the Earth - The 1300 watt output will occur when the radiator is in the sun. As the satellite passes into the earth shadow, the thermodynamic cycle becomes more efficient and power produced increases about 60 watts. The increased power will produce an engine speed increase along the load line. Parasitic load will increase 60 watts, which will result in a speed increase of $\frac{60}{580} \times N/100$ or about 1/10 of 1 percent. Again, no control of loop fluid flow is required.

System Degradation - System degradation is similar to power changes such as discussed above for isotope decay. Degradation from loss of radiator surface, for example, will result in a change in turbine inlet temperature. The parasitic load control will adjust engine speed set-point, either up or down as required, to maintain the turbine inlet temperature; engine power is again the only controlled variable.

In summary, the BIPS has no need for controlling fluid flow as a controlled variable. It is concluded that a performance factor of +15 best represents the demonstrated capability.

3.1.4.2 Electrical Control

This factor considers the control of the electrical output of the power system when perturbed by isotope decay, variations in power demand, occultation by the earth, ^{and system degradation.} Control of voltage and power output must be considered.

3.1.4.2 Electrical Control

RATING = +10

REF: VOLUME I, BOOK 3,
SECTION 2.7.1.5 AND 3.1

SUMMARY OF RATIONALE FOR RATING

Test data taken during workhorse loop and simulator test rig operation indicates control is satisfactory for various combinations of input power and user load demands. Changes anticipated are to effect redundancy and automatic control and will not affect performance.

TECHNICAL DISCUSSION

The workhorse loop control is a hand-wired digital control intended to duplicate input and output functions of the flight system processor control. Gains, sampling rates, and word lengths are identical.

The nominal operating point of the control is entered via a set of thumbwheel switches. (The nominal operating point is the speed at which 1300 watts electrical is available from the system.) The gain of the control is 580 watts/percent N around this point.

Step changes in user load have been made to determine effects on speed, output voltage, power capability, power quality, and loop temperatures. Based on this data, the control is fully satisfactory over the full range of operating points.

A rating of +10 is justified since the workhorse loop control is like the FS control except it does not contain T_6 trim (although it can be simulated by entering a new number on the thumbwheel switches) and does not have the ability to automatically set in its own nominal operating point. The flight system control will have both these features.

3.2.1 Flight System Weight

This factor is the estimated weight of the flight system at 1300 w(e) and 28 volts DC $\pm$ 2% output. The weight includes all components of the power system that would be aboard the spacecraft but excludes any items such as auxiliary cooling, start-up equipment, etc., that might be required on the Space Shuttle. The estimate will be based on the flight system preliminary design, adjusted as appropriate by GDS test results and other quantitative test data available.

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3.2.1 Flight System Weight

RATING = -15

REF: VOLUME I, BOOK 3,
SECTION 2.6

SUMMARY OF RATIONALE FOR RATING

The weight shown herein includes all of the components and equipment required for operation of the BIPS in space. The BIPS does not meet the weight goal because of the penalty in radiator and recuperator size and weight which must be paid to meet the 1300 W_e goal with a superalloy design. The projected overall weight for this design is 561 lb. This figure is preliminary since the radiator is still in the preliminary design stage.

TECHNICAL DISCUSSION

The original BIPS system utilized a refractory turbine plenum, heat source heat exchanger, and connecting ducting; the advantage of using these components was the 1600°F turbine inlet temperature which permitted high thermodynamic efficiency (27 percent) and relatively low weight. An optimized system with these components would require a 120 sq ft radiator and an 80 lb recuperator. The decision to go to a superalloy system caused an increase in weight to meet the 1300 W_e output with only 2 HSAs.

By decreasing the turbine inlet temperature to 1400°F, the Carnot efficiency with the same compressor inlet temperature is decreased by some 3 points. The thermal model predicts a loss in efficiency of 4 points because it accounts for the real hardware and the resultant increase in compressor inlet temperature caused by a higher heat rejection rate to a fixed temperature sink. In order to bring the efficiency back to the level (27 percent) of the original design goals,

it is necessary to lower the compressor inlet temperature (and therefore the power absorbed by the compressor) beyond the original level and/or increase recuperator effectiveness and/or decrease system pressure drop. All of these changes require an increase in weight and system volume. The final configuration selected included a larger radiator (some 160-180 sq. ft.) and a recuperator midway between the size estimated for the refractory design and the current GDS recuperator.

The weights are listed below:

Flight System Weight

Mini-BRU	36
HSA	180
Radiator	120
Recuperator	100
Bellows and Ducting	24
Insulation (except HSA)	30
Structure	46
Controls and Harness	<u>25</u>
	561

The positive side of the high weight of this system is increase in design margin for all of the components. The 200°F temperature decrease results in higher design margin for creep and thermal cycling which results in better assurance of system life. System thermal losses are also decreased which makes possible a small reduction in the weight of insulation. Nevertheless, the weight is some 90 lb heavier than for a refractory system.

3.2.2

Flight System Efficiency

The efficiency will be evaluated for a 1300 electrical watt *and 28VDC* output flight system. It will be estimated from the flight system preliminary design value and adjusted according to data obtained from the GDS and component tests. This factor is primarily concerned with the fuel cost and safety advantages of more efficient power conversion systems.

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3.2.2 Flight System Efficiency

RATING = +12

REF: VOLUME I, BOOK 3,
SECTION 3.1

SUMMARY OF RATIONALE FOR RATING

Evaluation of actual BIPS WHL performance along with conservatively estimated performance gains from component improvement and improved HSA heat loss estimates point to the BIPS meeting the performance goal of 27 percent efficiency at 1300 W_e , 28 vdc output power for the flight system.

TECHNICAL DISCUSSION

Workhorse loop (WHL) performance data indicates a system net efficiency of 0.245 at a compressor inlet temperature of 10°F and a turbine inlet temperature of 1400°F (see attached). With the recent improvement of insulating the turbine backface, approximately 300 W_t from the alternator heat exchanger can be converted to electric power at an estimated efficiency of 27 percent; approximately two percentage points of compressor efficiency improvement is also anticipated by using tighter clearance.

Analysis from AIRLA indicates HSA heat losses are 100 W_t less than we calculate. Heat loss through instrumentation in the hot regions of the BIPS is approximately one watt per penetration. This is based on TECO/GE data. Converting 50 W_t at 25 percent efficiency will result in a 12 W_e increase in output power.

From previous bearing test data (conducted in air and argon), the total bearing losses in Xe-He 83.8 at the 1.3 kW_e output power level were calculated to be approximately 230 W. Current bearing test data from tests conducted in krypton indicate that the bearing losses are closer to 200 W. The 30-W difference is directly convertible to output power.

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- 80% INVENTORY
- 100% INVENTORY
- 120% INVENTORY (APPROXIMATE)

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

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The evidence is strong that the 1300 W_e output requirement at 28 vdc will be met for the flight system.

Requirement: 1300 W_e , 28 vdc, $\eta_{cy} = 0.27$

WHL Test Data:

$\eta = 0.245$ at $T_1 = 10^\circ\text{F}$, $T_6 = 1400^\circ\text{F}$	1.176 kW_e
Convert 300 W_t from alt. HX at 27 percent	<u>+0.81</u>
	1.251
Rewind alt. for 28 vdc out of rectifier	<u>-0.063</u>
	1.194
Heat loss estimate	<u>+0.030</u>
	1.224
Improved bearing performance and	<u>+0.042</u>
elimination of instrumentation penetrations	1.266
Increased compressor performance (2 points)	<u>+0.48</u>
TOTAL	1.312 W_e

3.2.3

Start-up

It is a requirement that the powerplant come up to 95% power in 6 hours. The only serious problem arises if startup takes so long as to become a multishift operation and instabilities develop. Hence penalties accrue depending on how many shifts are required. Multiple-start capability in a hands-off condition is beneficial, but not required, hence a bonus of +5 performance factor is earned if this capability exists, no penalty if it does not. Flight system start-up will be demonstrated with the GDS. Full credit is given if the start-up equipment and procedure is flight typical. A debit of 5 performance points is assessed if a flight typical start cannot be

demonstrated with the GDS.

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3.2.3 Start-up

RATING = +15
(with +5 bonus)

REF: VOLUME I, BOOK 3
SECTION 3.2.2

SUMMARY OF RATIONALE FOR RATING

During WHL testing multiple starts have been made in a hands-off condition. Several starts made have been flight typical, and data indicates that 95 percent power is achieved in less than 2 hours (see Section 3.2.2). Therefore, full credit or a +15 rating is justified.

TECHNICAL DISCUSSION

Engine starts throughout WHL testing, have been accomplished per DT-6812-10 procedures. The procedures contained in that document are formulated to determine two engine start characteristics:

- (a) The system self-sustaining turbine inlet as a function of compressor inlet temperature
- (b) The start transient temperatures and characteristics which exist during "hot starts" beginning at various heat source temperatures.

Figure 3.2.2-1 (of Volume I, Book 3) presents the self-sustaining temperatures which have been determined as a function of compressor inlet temperature in tests to date. Figure 3.2.2-2 is a summary of transient temperatures and rotor speed during a "hot start" with a heat source temperature of approximately 1000°F.

The "hot start" data is quite encouraging in two respects: (1) The 1000°F heat source temperature is considerably below the anticipated starting heat source temperatures for a flight system, and

(2) the heat capacity of flight system heat sources is considerably higher than the WHL heaters due to the quantity of carbon structure.

Based on the observed start characteristics, it is anticipated that the BIPS flight system (starting from the presently defined ACS conditions) would experience a very minimal, if any, sag in turbine inlet temperature following start and would be capable of at least 60 percent full design power in less than 1 minute. The self-sustaining turbine inlet temperatures are of little concern now due to the large margin in the presently defined flight system start procedure.

The start-up equipment and procedure is flight typical, and thus full credit (15 points) was achieved. The WHL was started by simply pushing the start button after the electric heat source was hot, and a fully automatic start occurred.

The WHL has demonstrated multiple starts in a hands-off condition which is a bonus +5 performance factor.

During "hot start" testing, it was also determined that the use of a check valve in the closed loop flowpath (used to establish correct flow direction during start) was not necessary. A "hot start" was accomplished without the check valve installed. A cyclic flow instability (reversing) at approximately 3 Hz was initially noted when motoring commenced, but the proper flow direction was quickly established when the turbine inlet temperature reached approximately 250°F.

3.2.4

Orbital Transfer Power

Mission requirement is 300 w(e) during orbital transfer.

Less power can be a serious mission perturbation. More power is of small benefit. The performance factor scale is therefore split into two linear regions. Determination of power availability will be based on flight system design and component test.

3.2.4 Orbital Transfer Power

RATING = +9

REF: VOLUME I, BOOK 3
SECTION 2.5

SUMMARY OF RATIONALE FOR RATING

The only additional losses expected during orbital transfer are in the bearings. Based on test data, the additional bearing losses are estimated to be 20 watts. Assuming the losses are of any value less than 100 watts and the rating of +10 is given for 1300 watts output, it is anticipated that a rating of +9 will be achieved.

TECHNICAL DISCUSSION

This evaluation is based upon the ability of the system to produce power under the acceleration forces imposed during orbital transfer. In BIPS the only factor which is acceleration dependent is the bearing power dissipation as the bearing load is increased by the g forces being imposed. It is estimated that Interim Upper Stage (IUS) acceleration forces will be a maximum of 2 g's lateral and 5 g's axial. The following bearing losses resulting from the IUS loading are based upon using available bearing data which was run in air, argon, and krypton. Data with krypton (which has the same molecular weight as the He-Xe working fluid mixture) shows that the losses in krypton are about 21 percent higher than air as predicted.

Journal bearing losses are presented in Figures 3.2.4-1 through 3.2.4-3. The first two figures show the journal bearing loss characteristics as a function of load and ambient pressure in air and argon. The third figure shows the relationship of losses in air, argon, and krypton. This is the power loss vs load for a single journal in argon. The rotating group weighs 2.5 pounds. At 2 g's a bearing load of 5 pounds (2.50 pounds per bearing total) will result. From

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the figures, this represents an increase of approximately 4 watts. The gas being changed to He/Xe is not expected to change the slope of this curve (i.e. the delta power change) by a significant amount. (The nominal bearing cavity pressure is 50 psia.)

Testing of the thrust bearing in air and argon provided similar data for predicting thrust bearing losses at higher thrust loads. The system as it operates in the WHL or GDS is under a load of 1g. The additional 4g thrust load amounts to 10 pounds. From the load loss plot, the slope is 1.5 watts loss per pound of load. The 10 pound additional load then represents 15 watts of added bearing loss. The test data is in air; additional testing in krypton is planned for correlation.

The total additional losses are then 4 watts for the journal bearings and 15 watts for the thrust bearings or about 20 watts.

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CALCULATED BY	RPM	8 TEFLON S FOILS, 6.0/5.3 MIL THICK, .770" LONG, .61" RAD., 1.0702" CARRIER, .0066" SWAY, 52 K RPM
TRACED BY		
CHECKED BY		
APPROVED BY		
UNIT NO		AirResearch Manufacturing Company of Arizona

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FIGURE 3.2.4-1

CALCULATED BY MANNING

TRACED BY

CHECKED BY

APPROVED BY

UNIT NO.

8 TEFLON S FOILS, 0.0/6.3 MIL THICK,
 .770" LONG, .61" RAD., 1.0702"
 CARRIER, .0066" SWAY, 52 K RPM

AiResearch Manufacturing Company of Arizona

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FIGURE 3.2.4-2

CALCULATED BY	MANNING	8 TEFLON S FOILS, 6.0/6.3 MIL THICK, .770" LONG, .61" RAD., 1.0702" CARRIER, .0066" SWAY, 52K RPM
TRACED BY		
CHECKED BY		
APPROVED BY		
UNIT NO.		AiResearch Manufacturing Company of Arizona

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3.2-16

FIGURE 3.2.4-3

3.2.5

Power Degradation

Power output will necessarily degrade at a low rate because of the isotope decay. In practice, most real systems are found to suffer additional slow power loss due to degradation of thermal insulation, conversion components, etc. Performance rating will be based upon steady state degradation established after the initial burn-in, if any. If the initial burn-in exceeds 5%, performance factor is to be reduced 5 points. Degradation values in scale below are in addition to isotope decay.

3.2.5 Power Degradation

RATING = +14

REF: VOLUME I, BOOK 3,
SECTION 2.5.2.5

SUMMARY OF RATIONALE FOR RATING

A control system has been chosen to make optimum use of available energy from the decaying isotope and maximize power output. The degradation due to thermal insulation, conversion components, etc. is believed to be less than one percent. Also, losses due to burn-in are expected to be less than one percent. It is, therefore, concluded that a rating of near 15 is justified.

TECHNICAL DISCUSSION

The isotope decay predicted is shown in the plot of performance vs time. The engine control operates in a fashion to hold turbine inlet temperature constant. As the heat input from the isotope reduces, the temperature sensor sees lower temperature. This calls for reduced engine speed until turbine temperature increases to 1845°R. As the plot shows, speed reduces to somewhat less than 97 percent at the end of 7 years, and the power output is over 1200 watts.

The system performance losses due to degrading insulation and other components is expected to be very small. The insulation is a foil type, and emissivity is not expected to change with time. The control circuitry is digital to avoid drift and degradation associated with analog controls.

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PERFORMANCE VS. TIME

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All power conversion equipment is solid state electronic equipment, and performance should not degrade by any measurable amount. The only moving element in the system is the engine rotating group (compressor/turbine shaft). This is mounted on foil bearings and no change in drag is expected over the life of the system.

In summary, other than isotope decay, system performance changes should be unmeasurable and a performance factor of close to +15 is justified.

3.2.6

Micrometeorite Protection

This factor covers the possibility of puncture of a fluid duct anywhere in the power system leading to a loss of fluid. Both primary impact by a meteorite and secondary impact by spallation debris must be considered.

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3.2.6 Micrometeorite Protection

RATING = +5

REF: VOLUME I, BOOK 3
SECTION 2

SUMMARY OF RATIONALE FOR RATING

The micrometeorite protection criteria adopted in this investigation considers the state-of-the-art empirical armor protection correlation based on micrometeoroid flux measurements and hypervelocity impact test data. In order to optimize protection characteristics with weight considerations, a survival probability of 0.99 has been chosen, thereby justifying a merit factor rating of +5.

TECHNICAL DISCUSSION

The possibility of a micrometeoroid or spallation debris impact on the radiator loop can have a substantial effect upon the design of the radiator. In order to limit the probability of penetration, weight optimization of the radiator design results in smaller tube diameters, fewer tubes and larger tube thicknesses than would be desirable from other system considerations. Several difficulties are apparent in the selection of a design criterion to minimize the probability of meteoroid penetration. Data obtained from satellite experiments, measurements from zodiacal light, and radar photographic observations of meteors show a range of discrepancies. On the other hand, simulation by hypervelocity impact tests are considered inadequate because of the inability to achieve meteoroid velocities. Therefore, modeling penetration criteria based on observed meteoroid flux and hypervelocity impact data is the only source of information available for characterizing radiator designs.

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Several criteria for determining armor protection have evolved including the early works of Loeffler et al and the culmination of experiments (Explorer and Pegasus) leading to NASA SPEC SP-8013 which defines a meteoroid environmental model. This work has been upgraded (AEC-SNSO-6) and is currently used in the General Electric SPARTAN III Program. Moreover, recent spacecraft (Voyager and Viking) did not indicate any serious impact problems as a result of micrometeoroids. It should be noted that the candidate design considers a cylindrical configuration with fin-tube offset geometry. The fin arrangement provides a bumping effect and allows for sound structural numbers.

It has been determined that significant weight penalties are ascribed to a radiator design for survival probabilities greater than 0.99. For example, a weight penalty of approximately two is realized when changing the probability from 0.99 to 0.999 when considering the BIPS system.

AEC-SNSO-6
NASA-SP-8013
General Electric TIS-64SD224B
Loeffler et al ARS Paper 2543-62

3.2.7

Growth Potential and Flexibility

The basic Flight System should be capable of any power output from 500 to 2000 watts (EOM) with minimum redesign and requalification. The advantage of a flexible modular design approach for a power system allows coverage of a wide range of system requirements at lower development cost, increased reliability, and increased maintainability. It also provides the mission planner the luxury of proceeding with the development of a power system without knowing the exact power level that will ultimately be required. Power level changes require the following system changes:

3.2.7 Growth Potential Flexibility

RATING = +15

REF: VOLUME I, BOOK 3
SECTION 2.7

SUMMARY OF RATIONALE FOR RATING

The Flight System is capable of being adapted to provide power over the range of 500 to 2000 watts (EOM) with a minimum of redesign and requalification. The Mini-BRU as designed is suitable for this full range of operation without modification. The recuperator core should be sized for a particular power requirement for optimum efficiency. This can be accomplished by simply increasing or decreasing the core thickness. The inlet and outlet duct sizing and manifold will remain unchanged. The thermal energy supplied by the HSA can be treated in a modular fashion using one HSA for a power requirement in the 500 watt range, two HSAs for a power requirement in the 1300 watt range, and three HSAs for a power requirement in the 2000 watt range. Fine trimming can be attained by off-loading the fueling in the IHS's.

The radiator sized for the present 1300 watt power requirement can be readily modified for other power requirements by increasing or decreasing the length.

Therefore, no basic design changes of the thermal components will be required for applications having power requirements in the 500 to 2000 watt (EOM) range.

TECHNICAL DISCUSSION

The BIPS Flight System can be considered to be basically a modular system since no major redesign of any of the thermal components is required to meet any power requirement in the 500 to 2000 watt (EOM) range.

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The constant speed Mini-BRU has high performance characteristics over the full 500 to 2000 watt range. The weight penalty associated with using this current Mini-BRU for lower power requirement application is negligible. Therefore, the current Mini-BRU design will be used for all applications in the 500 to 2000 watt range.

For an optimum design, a tradeoff study should be made between recuperator size and radiator size for a specific power requirement. However, design changes in these components will be minimal and essentially modular in nature. For the BIPS system, the volumetric flow rate remains relatively constant over a wide power range although the mass flow rate is changed. Therefore, the inlet and outlet ducts and manifold of the recuperator will remain unchanged. Only the core will be increased or decreased in thickness for changes in power requirements. Similarly, it is anticipated that the desired changes in the radiator for different power requirements will consist of changes only in radiator length. The material and the design of the headers and cross-sections of the radiator would remain unchanged.

The HSA design containing one IHS each offers a particularly attractive modular approach since the selection of one, two, or three HSAs provides complete coverage of the 500 to 2000 watt power range with fine trimming available by off-loading the fuel in the IHS's. Thermal loading can be adjusted in relatively fine increments by replacing selected fuel spheres with dummy spheres. It is particularly important that this modularity of the HSA's be maintained to avoid excessive expense in requalifying the HSA/IHS to meet safety requirements.

BIPS Phase I Configuration Control Document,
75-311274, Rev. C.

3.3.1 Power Output

With steady thermal input equal to isotope design input, established by electric heat input and cable loss compensation, the net electrical output of the GDS is determined.

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3.3.1 Power Output

RATING = 0

REF: VOLUME I, BOOK 3,
SECTION 2.5

SUMMARY OF RATIONALE FOR RATING

SEE ATTRIBUTE 3.2.2
FLIGHT SYSTEM EFFICIENCY

3.3.2

Performance at -10% Input Power

It is desirable that the system have a flat performance profile in the vicinity of the design point to provide stability in the face of isotope decay and other random forms of system degradation. A flat profile also suggests that it will be easy to convert the system to other power output levels.

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3.3.2 Performance at -10 Percent Input Power

RATING = +8.5

REF: VOLUME I, BOOK 3,
SECTION 2.5.2.5

SUMMARY OF RATIONALE FOR RATING

A 10-percent loss of input power corresponds to over 13 years of Plutonium 238 isotope degradation. With BOM conditions of 1300 W_e, T₆ = 1400°F, N = 52,000 rpm, and 4.8 kW_t thermal input, an eventual 10-percent loss of thermal input would result in a net 11.5 percent loss of the BOM output power. As the isotope decay proceeds, the BIPS control system would decrease the BRU rotating speed to retain a constant turbine inlet temperature of 1400°F. Allowing the output power level to "slide down" the constant temperature line of Figure 3.3.2-1 minimizes the usable power loss.

OUTPUT POWER VS. TIME

FIGURE 3.2.2-1

3.3.3

Voltage Control

Flight System Requirement 2.1.2 defines the output voltage as 28 volts DC $\pm$ 2.0% with less than 0.1% ripple at full power. If the output voltage is stable but displaced from the 28-volt design point, a correction can easily be made in the flight system. However, voltage ripple and/or a tendency for the average voltage to drift or wander, either inside or outside of the tolerance band, would be more troublesome to the user. Accordingly this factor will be based primarily on voltage stability during the 1000 hour endurance run. A penalty of 5 performance factor points is assessed if the base voltage is not within the 28 $\pm$ 2% band at initiation of the endurance run.

Ripple and drift will be evaluated separately, their performance factors added, and the sum multiplied by the significance factor.

3.3.3 Voltage Control

RATING = +7.5

REF: VOLUME I, BOOK 3,
SECTION 2.4.4

SUMMARY OF RATIONALE FOR RATING

Data required for this rating is available from Workhorse Loop and simulator test rig testing.

The BIPS GDS system is a 120 vdc nominal system and is capable of maintaining 120 vdc ± 0.25 percent or better. This was verified by data taken during the WHL test. Based on a percent drift of 0.25 percent, the performance factor, including the 5 point penalty for a base voltage not within the 28 ± 2 percent band at the initiation of the run, will be $(12.5 - 5 =) 7.5$.

TECHNICAL DISCUSSION

If the proposed 28 vdc alternator were used with the GDS control, it is anticipated that the percent drift would remain at the ± 0.25 percent value, yielding a performance factor of 12.5.

The BIPS WHL system is expected to meet the ripple requirements of AiResearch Specification SC-76-312008. Applicable portions of this specification are attached.

Assuming "Percent Ripple" is defined as $(\text{Ripple RMS} \div \text{dc voltage}) \times 100$, it is anticipated that the WHL and GDS percent ripple would be 1.18 percent with the original design. To meet the requirement of 0.1 percent, additional filtering will be added to the GDS. If this requirement is realistic for the flight system, it is estimated that a weight increase of approximately 2 pounds will result.

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It should be noted that MIL-STD-704B, used as a guide for the preparation of AiResearch Specification SC-76-312008, requires the "distortion factor," defined as ripple RMS $\div$ Average dc, to not exceed 0.02 for a 38 vdc system and 0.03 for a 270 vdc system. These are an order of magnitude greater than the nominal values specified for this attribute.

It is recommended that DOE re-evaluate this requirement in view of the possible weight saving.

The following are excerpts from AiResearch Specification SC-76-312008:

The dc voltage shall be within 110 to 125 volts.

The dc distortion factor shall not exceed 0.025 nor shall the dc distortion spectrum exceed the limits shown in Figure 5-1. Ripple shall not exceed 2.5 volts (peak).

The maximum value of dc voltage surge shall not exceed the limits shown in Figure 5-2.

The system electromagnetic compatibility aspects of voltage spikes shall be controlled as defined in MIL-E-6051.

The dc overvoltage values shall not exceed the upper limits shown in Figure 5-3, and dc undervoltage shall be restored to steady state limits within 5 seconds after exceeding the lower limit of Figure 5-2. Interruption following the period of these overvoltages or undervoltages shall be as specified in 4.2 (See also 3.8, 3.12 and 3.13).

3.3.4 Demonstration of Mission Profile

This factor relates to Flight System Requirements 2.1.4, 2.1.5, and 2.1.7. The following cycles are defined:

- (1) start-up with maintenance: power system goes from zero to full power using full GDS equipment and manual assistance
- (2) start-up unattended: power system goes from zero to full power using flight typical automatic start-up equipment
- (3) mission cycle: power system goes from zero to full power to simulate orbital check-out, returns to an operating mode for 8 hours, during which the power changes hourly between 100% and 75% of full load to simulate variations

SIGNIFICANCE
FACTOR=

in spacecraft demand.

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3.3.4 Demonstration of Mission Profile

RATING = +5

REF: VOLUME II, BOOK 3
SECTION 2.3.7

SUMMARY OF RATIONALE FOR RATING

Testing to date with the WHL has accumulated nearly 60 hours of running plus 170 motor starts. These include 5 system starts from cold conditions. It is anticipated that this running should give a rating of over +5, and that sufficient additional running will be achieved to obtain a rating of near +10.

TECHNICAL DISCUSSION

WHL testing to date (March 1978) justifies a rating of +5. It is anticipated that sufficient GDS testing will be completed by May 15 to raise the performance factor to above +10.

Table I summarizes running completed as of January 1, 1978. Cold starts refers to engine start-up from room temperature. Hot restarts refers to re-starting the engine very shortly after shutdown with all components hot. Motor starts are accelerations from zero speed, the large number being associated with control checkout and loop cleanup procedure. Engine hours of run time is above 95 percent speed.

During the nearly 57 hours of running, the load was cycled many times. The control system is designed to accept user load changes while maintaining total load constant so the effect on engine speed or load from user load changes is nearly undetectable. It is believed the 57 hours to date should be at least the equivalent of 5 mission cycles, each being 8 hours. This corresponds to a performance factor of +5. As stated earlier, anticipated GDS testing will result in a performance factor above +10.

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TABLE I

SUMMARY OF BIPS WHL RUNNING AS OF JAN. 1, 1978

<u>Date</u>	<u>Cold Starts</u>	<u>Hot Re-Starts</u>	<u>Motor Starts</u>	<u>Hours Above 95 Percent Speed</u>
Sept. 4	1			O.S. Shutdown
Sept. 24	1			1:28
Nov. 4,5	1			18:56
7	1			34:09
8		1	70	0:01
Dec. 22	1		103*	3:16
	<u>5</u>	<u>1</u>	<u>170+</u>	<u>56:50</u>
				(56 Hr; 50 Min)

*plus 100 start/stop cycles on bearings in STR

3.3.5

Maximum Duration Unattended Operation

Although a true life test is impossible within the time available in the GDS program, it will be of some interest to note the maximum time span that it is possible to operate the power system in a steady state hands-off condition after shake-down. This will be an indicator of how much trouble the contractor had in getting this first unit to operate properly and how stable it is.

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3.3.5 Maximum Duration Unattended Operation

RATING = -15 (-1)

REF: VOLUME I, BOOK 3
SECTION 3

SUMMARY OF RATIONALE FOR RATING

The BIPS test program requires completion of numerous development tests prior to initiation of the endurance test. The maximum continuous test which has been scheduled to date is 120 hours. The maximum test duration completed to date has been 53 hours during performance mapping. This test duration dictates a rating of (-15).

The initiation of the endurance test, however, is currently scheduled for May 1. Based on this, a total of 720 continuous hours should be achieved prior to evaluation and should yield a rating of (-1).

3.3.6.1

HSA and ECS

These components are to be compared to the corresponding item in the FS design.

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3.3.6.1 HSA and ECS

RATING = -10

REF: VOLUME I, BOOK 3
SECTION 2.7

SUMMARY OF RATIONALE FOR RATING

The GDS HSA performs as required for its specified test purpose. The flight system will perform similarly, with additional capability as follows:

- o The insulation system will have a lower melt temperature for acceptable ECS performance. The GDS HSIS does not require ECS performance.
- o The housing will be sealed and fabricated of a lighter material such as aluminum, lockalloy, or beryllium to reduce system weight. The GDS stainless steel housing is adequate for test purposes, and does not depreciate the test results.
- o The ACS and gas management system for the flight system will utilize well-established MHW concept - valves, gas cart, and inert gas. The GDS HSA uses an unsealed housing; therefore, has no need for gas management or ACS.

Each of these material substitutions and design modifications improve the performance characteristics of the HSA.

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TECHNICAL DISCUSSION

The HSA functions to receive radiator heat, from a heat source, and imparts this heat to the working fluid. This is accomplished through the Heat Source Heat Exchanger (HSHX). The FS heat source will be isotopic. However, for the GDS an electrical heat source (EHS) is used.

The HSA is designed to accommodate the DoE Multi-Hundred Watt (MHW) isotope heat source (IHS) and the MHW EHS.

The HSA consists of the following major components:

- (a) The Heat Source Heat Exchanger (HSHX)
- (b) A Multifoil Insulation System (HSIS)
- (c) An outer housing with mounting points, closure seals and instrumentation (Housing)
- (d) Gas Management System (GMS)
- (e) Auxiliary Cooling System (ACS)
- (f) Emergency Cooling System (ECS)

All material changes and design modifications for the HSA flight system improve performance characteristics. The changes are summarized in Table 1, and the associated development involved with these changes is assessed in Table 2.

COMPONENT	GDS	CHANGE	FLIGHT SYSTEM
HSHX	HAST-X SINGLE TUBE 10 COILS HELIX	DECREASE WEIGHT (?)	HAST-X SINGLE TUBE 10 COILS HELIX
HSIS	60 Ni FOILS ZrO ₂ POWDER BARRIER	CHANGE MATERIALS FOR LOWER MELT TEMPERATURE (ECS)	30 PdNi FOILS; 30 Ni FOILS ZrO ₂ POWDER BARRIER
HOUSING	304 STAINLESS STEEL UNSEALED	SEAL; DECREASE WEIGHT WITH ALTERNATIVE MATERIAL	ALUMINUM HOUSING WILL DE- CREASE SYSTEM WEIGHT BY 30 POUNDS. BERYLLIUM HOUSING WILL DE- CREASE WEIGHT BY 40 POUNDS.
GMS	NONE REQUIRED (UNSEALED HSA; NO ISOTOPE)	ADD GMS FOR: - HSA VENTING - ACS	<ul style="list-style-type: none"> ● SQUIB FIRED VENT DISK ● SOLENOID VALVE ● INTERFACE FOR GROUND HANDLING
ACS	NONE REQUIRED (GDS TESTING IN VACUUM CHAMBER, UN- SEALED HSA, EHS)	ADD ACS CAPABILITY WITH SEALED HSA AND GMS	<ul style="list-style-type: none"> ● HELIUM BACKFILL THROUGH GMS
ECS	NONE REQUIRED - SAFETY INTERLOCK IN GDS FACILITY SHUTS DOWN EHS	CHANGE HSIS FOIL MATERIAL FOR CORRECT MELT TEMPERATURE	30 PdNi FOILS; 30 Ni FOILS T _{FOIL MELT} = 1237°C T _{PICS MAX} = 1474°C

TABLE 1. HSA COMPONENT CHANGES FROM GDS TO FLIGHT SYSTEM

COMPONENT	DESIGN CHANGE FROM GDS TO FS	PROGRAM RISK
SHSX	DECREASE WEIGHT (WALL THICKNESS?)	NONE
HSIS	PdNi AND Ni FOILS	SLIGHT - PRESENT TEST DATA FROM BCL AND TECO INDICATE GOOD PERFORMANCE; 1000 TO 6000 HR. TESTS TO BE PERFORMED - COM- PATIBILITY AND STABILITY.
HOUSING	ALTERNATE MATERIAL: CANDIDATES ARE Al, Be, LOCKALLOY SEALED HOUSING; REQUIRES BELLOWS FROM HOUSING TO DUCTS FOR ACS GAS CONTAINMENT.	SLIGHT TO MODERATE - ALUMINUM IS SLIGHT RISK, BUT ABOUT 10 POUNDS PER BIPS HEAVIER THAN THE MODERATE RISK ASSOCIATED WITH BERYLLIUM.
GMS	ADD VALVES, PDR, AND GAS CART ACCOMMODATION	NONE - STATE-OF-THE-ART; MHW DATA BASE AND EXPERIENCE.
ACS	PROVIDE HELIUM VIA GMS	NONE - SEE GMS
ECS	PdNi FOILS	SLIGHT - SAME AS HSIS

TABLE 2. RISK ASSOCIATED WITH HSA CHANGES FOR FLIGHT SYSTEM

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The major changes in the HSA are material changes in the housing and the insulation. The heavy GDS stainless steel housing will be changed to a lighter housing of aluminum, lockalloy, or beryllium. Aluminum is recommended for minimum cost and ease of fabrication. Most of the weight savings can be made with aluminum, although a further weight-optimized housing may be achieved with beryllium, but at higher cost. Lockalloy cost, weight, and fabrication easily lie between aluminum and beryllium.

The lighter flight system HSA housing contributes significantly to an improved BIPS power density for space application. GDS testing is not jeopardized by this change.

A beryllium housing reduces the HSA weight by 20 percent. For point of discussion, if one assumes a nominal 550 pound BIPS, the power density can be improved from 2.36 w/lb. to 2.55 w/lb. by changing from stainless steel to beryllium housing.

The GDS insulation nickel foils have a melt temperature (ECS activation) of about 2650°F. The inertia of the HSA is such that the PICS temperature peaks well above the PICS temperature at ECS activation. A flight system design utilizing 50 percent PdNi foils and 50 percent nickel foils reduces the foil melt temperature to about 2260°F. This reduced ECS activation temperature allows the PICS temperature to safely peak at a more desirable temperature of 1474°F.

Compatibility, stability, miniature meltdown, and long term tests are presently being conducted on PdNi foils by Battelle and TECO.

The insulation performance as the HSIS component in the GDS test is representative of the flight system. The substitution of PdNi for Ni foils in the FS HSA affects only the ECS operation, which is not part of the Ground Demonstration plan.

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With a sealed housing and PdNi foil insulation, the flight system HSA design incorporates ACS and ECS capabilities not included in the GDS. A state-of-the-art gas management system (GMS) incorporating standard spacecraft quality valves, squibs, and disconnect fittings will be added to the flight system HSA.

The flight system HSA must include a cooling system to remove ACS heat from the housing during ground, launch pad, launch and orbital operations prior to BIPS start-up, or at least prior to Shuttle bay door opening. A typical cooling system design is shown in Volume I, Book 3, Section 2.7 of this Phase II Plan. Cooling coils are attached, by brazing, to the housing external surface, and terminate at two quick disconnect fittings outside of the radiator. This interface is manually made and unmade with an independent radiator or heat exchanger assigned to the transportation vehicle. This heat exchanger weight would not be charged to the BIPS.

The cooling system is a state-of-the-art heat exchanger which will not introduce significant risk to the flight system design. Attachment of the tubes to the housing is a relatively straightforward braze providing the housing is aluminum or lockalloy. For this reason, it appears most desirable to select the most easily fabricated and least expensive aluminum for the flight HSA housing rather than attempt to save another ten pounds with beryllium.

BIPS Phase I Configuration Control Document, 75-311274, Rev. C.

3.3.6.2

Ducting, Bellows, Transitions

These components are to be compared to the corresponding component in the FS design. Ducting evaluation shall consider the ducting runs as well as fabrication and materials; bellows evaluation shall consider design for reliability as well as function.

3.3.6.2 Ducting, Bellows, Transitions

RATING: +12

REF: VOLUME I, BOOK 3
SECTION 2.5.2.4 AND 3.1

SUMMARY OF RATIONALE FOR RATING

A rating of +12 is justified by the fact that (1) the materials are identical in the FS as those used in the WHL and GDS, (2) the design remains basically the same, and (3) fabrication processes will be the same. Bellows reliability and function will continue to be prime considerations as they have been in Phase I.

TECHNICAL DISCUSSION

Ducting, bellows, and transition designs used in the GDS will be used in the FS. Thorough analytical design resulted in duct sizes and runs, bellows designs, and transition designs that have proven themselves satisfactory in Phase I. The only changes the FS will incorporate are secondary detail changes to increase the quality or reliability by such things as utilizing seamless tubing in place of seamed tubing to eliminate the weld joint, or uni-formed ducting/bellows to eliminate circumferential welds in the ducting runs.

The materials in the FS will remain the same as those in the WHL and GDS, i.e., 347 stainless steel in the "cold" areas of the loop and Hastelloy-X in the "hot" areas. These materials have well established properties and fabrication processes and techniques. The data base is being further expanded in specific areas through on-going materials programs as a part of the Phase I program.

The physical design of the piping system will remain as in Phase I. Duct routing, bellows locations, tube lengths, diameters, and bellows designs are the same. The design philosophy remains the

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same using systems of three link-type bellows, allowing expansion/contraction in all planes by pure rotational deflection of the bellows about their centrally located links. Close tolerance multi-ply tubes, in place of rolled and welded tubing, and bellows formed-in-place in ducting runs, instead of separate bellows and ducting welded to each other, represent the extent of FS changes. These changes will result in the elimination of the majority of welds in the system, afford redundancy in the ducting as well as the bellows and reduce the system weight. From a system standpoint, there would be no change in form, fit, or function.

The FS hardware will be fabricated using well established processes and techniques. The bellows convolutes will be formed from the same tooling and in the identical manner as in the case of WHL/GDS bellows. The significant change in the fabrication of FS hardware will be the implementation of documents 31-2704, "Bellows Assemblies Fabrication and Inspection Requirements Specification for BIPS, Phase II;" and 31-2767, "BIPS General Fabrication and Inspection Requirements Specification Flight System Qualification, Phase II." This will result in much more stringent process and quality control in the fabrication cycle, resulting in increased quality and higher reliability.

This component is to be compared with the corresponding component in the FS design.

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3.3.6.3 CRU

RATING = +10

REF: VOLUME I, BOOK 3,
SECTION 2.7.11

SUMMARY OF RATIONALE FOR RATING

Basic Mini-BRU unit has exhibited aerodynamic and thermal performance equal to or greater than design goals, therefore there is no reason to modify the basic design for a flight system.

TECHNICAL DISCUSSION

The basic Mini-BRU design shown in Figure 3.3.6.3-1 contains a turbine, compressor, and alternator all mounted on a common shaft. The rotating group is supported by foil type journal and thrust bearings. This basic arrangement has been well substantiated in a series of applications including the NASA-Houston BCD, the NASA-LeRC BRU, the NASA-LeRC TAC, and the Navy CCPS40-1.

The compressor shroud contains provision for 3 monopole speed pickups for motor-start rotor position sensing which are isolated by a thick wall from the loop working fluid but yet are sensitive enough to sense the passing frequency of the compressor blades. Two compressor blades are notched to provide position feedback for the synchronous start system. The shroud also has provision for seal welding to the main body for hermetic leak tightness.

The turbine nozzle/plenum assembly also contains provision for hermetic seal welding to the main body. Turbine plenums have been designed and fabricated from C-103 alloy, Hastelloy-X, and Waspalloy for compatibility with systems utilizing materials required for 1200-1600°F turbine inlet temperatures.

MINI BRAYTON ROTATING UNIT

31-2845
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3.3-26

A35747

Figure 3.3.6.3-1

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The materials used throughout the Mini-BRU are shown on Drawing 3604385 and will not require any changes to upgrade to a flight system.

All power and instrumentation feedthroughs utilize glass sealed hermetic insulators with proven leak tightness.

The assembly techniques for the Mini-BRU are simple and straightforward. One trial build is required to establish correct shimming, and the build thereafter is completely repeatable.

Test results have shown that no interferences exist during either fast or slow thermal transients. Furthermore measurements indicate that all bearing temperatures are well below the design limit.

The compressor performance is documented in AiResearch Report No. 31-2365, dated April 11, 1977; the turbine performance in AiResearch Report No. 76-312077, dated October 6, 1976, and the alternator performance in AiResearch Report No. 31-2316 dated July 1, 1977.

3.3.6.4

Recuperator

This component is to be compared with the corresponding component in the FS design.

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3.3.6.4 Recuperator Similarity to FS Design

RATING = +9

REF: VOLUME I, BOOK 3,
SECTION 2.7.1.2

SUMMARY OF RATIONALE FOR RATING

The GDS design could be utilized for the FS, but performance optimization has shown the potential for substantial weight reduction and thermal loss reduction in the FS. The FS recuperator differs from the GDS recuperator only in the stack height and a few detail parts. The FS design will yield higher reliability and will be easier to fabricate. The single sandwich design is unchanged.

TECHNICAL DISCUSSION

The FS recuperator could be made identical to the Phase I GDS unit (MBR). This would give it a rating higher than +10. However the resulting unit would be over 30 lb heavier than a smaller size FS recuperator with similar performance. Use of the original unit is thus, a tradeoff of rating versus weight of the FS and GDS units (intermediate weights have no significance). Because weight is an important factor, the primary approach selected for the FS unit was the reduced stack height. Nevertheless, the resulting recuperator has the following similarity characteristics:

1. The MBR footprint is used. This means that the dimensions, geometry, and construction of the FS unit in the single sandwich plane are unchanged from the MBR.
2. The counterflow core and end section fins are identical to the MBR.
3. The manifold cross-sectional area is the same.

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4. The same materials are used.
5. Except perhaps for the manifolds, MBR material thicknesses are adopted for use throughout the FS unit. Manifold material thickness reduction may be possible due to the lower operating pressures associated with the FS. This also represents an area of potential weight savings.
6. Exterior construction details are the same. The FS unit is expected to feature all the advanced structural design features developed as a result of work performed during Phase I.
7. The same mount design will be adopted, pending results of vibration tests to be conducted with the existing MBR during Phase II.

On the other hand, there are a few differences, namely

1. Smaller Stack Height - This means lower material costs, lighter weight, and simplified brazing operation because of the smaller number of plate-fin sandwiches and a lower thermal mass.
2. Smaller external surface area - The smaller external surface area due to the smaller size of the FS reduce the thermal losses through the insulation, which is quite important in a high effectiveness unit.
3. Higher Creep Strength - The 2-HSA FS unit operates at lower temperature levels than the 3-HSA MBR. Therefore, it may be expected to exhibit a higher creep strength. This will be investigated by tests during Phase II.

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4. Lower Thermal Mass - The lighter weight FS unit will have a different thermal response from the MBR. Thus, temperature gradients and stress levels are expected to be somewhat different. Again, this area of concern will be investigated by additional analysis and testing during Phase II.

3.3.6.5

Control System

This component is to be compared with the corresponding component in the FS design. The GDS system may contain additional features without penalty if required for the GDS test procedures. It is important that FS control capability be demonstrated.

3.3.6.5 Control System

RATING = -10

REF: VOLUME I, BOOK 3,
SECTIONS 2.7.1.5 AND 3.1

SUMMARY OF RATIONALE FOR RATING

The existing workhorse loop control is a hybrid, discrete component and integrated circuit version of the microprocessor system planned for the flight system. The control demonstrates the viability of the concept developed around existing technology. Material changes are required to implement the concept with flight hardware, and a design variation will be required to provide the redundancy required to achieve the desired reliability and the turbine inlet temperature sensor reset capability.

TECHNICAL DISCUSSION

The workhorse loop control is a hardwired digital control intended to duplicate input and output functions of the flight system process control. Gains, sampling rates, and word lengths are identical. Designed to operate in a lab environment only, the design does not make provision for the shock, vibration, temperature, radiation, and reliability requirements of the flight system.

A detailed description of the control is provided in AiResearch Document 76-311937.

3.3.6.6 Thermal Insulation

This component is to be compared with the corresponding component in the FS design.

3.3.6.6 Thermal Insulation

RATING = +5

REF: VOLUME I, BOOK 3,
SECTION 2.7.1.4

SUMMARY OF RATIONALE FOR RATING

The flight system insulation system is now defined as a Ni/ZrO₂ MULTI-FOIL assembly; with a Ni and Pd/Ni/ZrO₂ ECS system for the heat source assemblies (HSA's).

The WHL and GDS insulation systems use the techniques (e.g. tape wrapped, cylindrical, and planar) and materials in the same configuration as a flight system design.

The GDS utilizes an all Ni HSIS as a result of cost and schedule considerations. The GDS includes a vast amount of instrumentation in comparison to a flight system. In this respect the flight system design is simpler than the GDS system.

Since the HSIS for the HSA is covered by Attribute 3.3.6.1, this paragraph addresses the other insulation in the system.

TECHNICAL DISCUSSION

The thermal insulation in the FS design is expected to be quite similar to that for the GDS. The identical materials (i.e., zirconia coated nickel) will be used. A minor modification anticipated in the thermal insulation design is the use of electroformed MULTI-FOIL in selected regions in order to minimize the heat losses associated with joints and complex configurations.

3.3.6.7

Configuration and Structures

This aspect of the GDS is to be compared with the FS design. It is recognized that the GDS will contain additional instrumentation, etc., as required for GDS test procedures; no penalty shall accrue for meeting this requirement. Evaluation is to be based on the extent that the GDS demonstrates FS feasibility.

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PHOENIX, ARIZONA3.3.6.7 Configuration and Structures

RATING = +5

REF: VOLUME 1, BOOK 3
SECTIONS 2.5 AND 3.1SUMMARY OF RATIONALE FOR RATING

A rating of 5 on this attribute is justified since the configuration and structures of the FS will be of the same design and use essentially the same materials as the GDS. The design is based upon using Lockalloy for the support structure but was fabricated from aluminum for cost reasons on the GDS.

TECHNICAL DISCUSSION

With the exception of the support structure, the FS materials will remain unchanged from the GDS. Basically, the loop materials are Hastelloy X in the hot areas and 300-series stainless steel in the colder areas. Support structures in the GDS are aluminum. The aluminum supports could be retained with minor sizing design changes.

The FS configuration will not change from the WHL/GDS. All major component designs are the same except for differences in instrumentation. All component manufacturing processes will remain the same, however, much more stringent quality and process control will be exerted on FS components to ensure long life and high reliability required.

The system assembly will be simplified in the FS due to a lesser amount of instrumentation and the uni-forming of bellows and ducts. The latter will have the effect of greatly reducing the number of details to be assembled, however, the system configuration will remain the same.

The tooling and assembly techniques developed for the WHL/GDS will be identical for the FS since the FS assembly will consist of the same assembly steps, only fewer of them. The reduction in instrumentation of the FS over the GDS will also act to simplify the assembly.

3.3.6.8

Condenser

This component is to be compared with the corresponding component in the FS design. If the component is not required in either GDS or FS, a rating of +15 should be given.

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3.3.6.8 Condenser FS Similarity

RATING = +15

SUMMARY OF RATIONALE FOR RATING

THE CONDENSER IS NOT REQUIRED IN THE BIPS

3.3.6.9

Waste Heat Sink

Both GDS systems employ a waste heat sink in place of a FS radiator. Evaluation is to be based upon the extent to which the GDS component duplicates the predicted thermal and fluid flow performance of the FS radiator, both steady state and transient.

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3.3.6.2 Waste Heat Sink FS Similarity

RATING = 0

REF: VOLUME I, BOOK 3
SECTION 3

SUMMARY OF RATIONALE FOR RATING

The Waste Heat Sink System which simulates the performance of the FS Radiator during GDS testing is comprised of a Heat Rejection Heat Exchanger (HRHX), a refrigeration system, and a DATA-TRAC temperature controller. Acceptance testing of the Waste Heat System as well as testing with the Workhorse Loop (WHL) have demonstrated performance equivalent to the FS Radiator, thereby justifying a merit factor rating of 0.

TECHNICAL DISCUSSION

The Waste Heat Sink System has been fabricated, acceptance tested, and integrated with the Workhorse Loop. The HRHX was designed to reject 4150 watts (for the 3-HSA WHL test condition) so its heat rejection capability far exceeds that required for the FS Radiator, namely, 2844 watts. Sufficient test data is available (see referenced documentation) to evaluate the performance of the Waste Heat System relative to the required performance of the FS Radiator.

Steady State Performance

In order to duplicate the FS Radiator, the Waste Heat System must:

- (a) Achieve the required compressor inlet temperature at flight operating conditions
- (b) Duplicate the pressure drop at same conditions

- (c) Contain the working fluid consistent with FS Radiator requirements

Table I summarizes the measured performance of the Waste Heat System during WHL testing and compares that to FS radiator performance requirements. The data indicates performance capability equivalent to that required for the FS radiator. This statement is supported by the plot shown in Figure 3.3.6.9-1. The performance of the HRHX during WHL testing is plotted parametrically as a function of gas exit temperature. Also plotted is the required performance of the HRHX to duplicate the FS radiator. The curves are nearly identical and therefore demonstrate that the HRHX can duplicate FS radiator steady state performance. The HRHX is designed with interchangeable orifice plates so that the FS radiator ΔP can be duplicated once it is specified. The pressure drop measured during WHL testing correlated well with the sigma delta pressure calculation (see referenced documentation). The measured leakage of the HRHX was $<1 \times 10^{-10}$ scc He/sec which satisfies FS radiator requirements.

Transient Performance

The Waste Heat System must also simulate the response of the FS Radiator to system transients, such as engine startup and occultation by the earth during orbit. Such transients are simulated by the DATA-TRAC Controller which controls compressor inlet temperature according to the expected time-temperature profile which is programmed. The dynamic response of the Waste Heat System was measured for step changes in working fluid and coolant flow. The data indicated:

- (a) A 5° step in the set point of the controller results in a response corresponding to a time constant of 0.25 second

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TABLE I
HRHX PERFORMANCE COMPARISON

2 <u>HSA Condition</u>	<u>He/Xe Design</u> (1)	<u>WHL Test Data</u> (2)
Heat Rejection	2500 Watts (8525 Btu/Hr)	2880
Mass Flow Rate	0.1985 lb/sec	0.208
Inlet Temperature	208°F	227
Outlet Temperature	5°F	6
Inlet Pressure	35.3 psia	35.5
Total Pressure Drop	0.4 psi	Adjustable

(1) Reference CCD, AiResearch 75-311274C

(2) Reference scan Nov. 5, 1977, 20:45:46

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WASTE HEAT SINK SYSTEM DEMONSTRATOR PERFORMANCE
EQUIVALENT TO FS RADIATOR

FIGURE 3.3.6.9-1

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- (b) The time constant for step changes in working fluid flow to changes in compressor inlet temperature is from 13 to 30 seconds, depending on flow rate
- (c) The heat exchanger response to step changes in coolant flow is ~.10 to 13 seconds.

The composite response times of the controller and HRHX are considered fast relative to the response anticipated for the FS Radiator. It is concluded therefore, that the HRHX and associated controls are inherently capable of simulating the radiator/engine system thermal transients.

As previously stated, the function of the DATA-TRAC Controller is to duplicate compressor inlet temperature resulting from system transients. The DATA-TRAC Controller and HRHX were tested to duplicate start-up and orbital simulation conditions. Further confirmatory testing is planned with the WHL, but based on satisfactory results from the tests mentioned, it is expected that the Waste Heat Sink System can reasonably duplicate dynamic responses resulting from flight system transients.

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GE-BIPS-40-001

3.3.7 Materials Stability Observed During Retrofit or Repair Operations

Post-test examination of the GDS should include a thorough examination of all components for evidence of physical instabilities such as material contamination (coupon tests), working fluid degradation or leaking, bearing wear, thermal insulation degradation, weld or component cracking or deformation, electronic component failure, and similar effects.

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3.3.7 Materials Stability Observed During Retrofit or Repair Operations

RATING = +6

REF: VOLUME I, BOOK 3, SECTION 3

SUMMARY OF RATIONALE FOR RATING

The only evidence of degradation to date was with the foil bearings. It is anticipated that testing in the system will continue to confirm the laboratory tests on the superalloy components.

TECHNICAL DISCUSSION

The effects on the components have been defined by extensive laboratory testing at AiResearch, ORNL, BCL, NASA, TECO and industry at large. Metallurgical effects, atmosphere effects, and interdiffusion of dissimilar materials including brazes have been investigated. All tests have provided positive indications for seven year life. In addition, coupons have been designed, and locations chosen on the BIPS-GDS to determine the maximum effects. Components in the system have been earmarked for destructive analysis as part of a comprehensive post test evaluation plan (AiResearch document 75-311574A (IPP)).

Reliability Analysis

Flight System Requirement 2.2.1 calls for .93 probability of full design power after 7 years. It is assumed that both contractors will present a Reliability Analysis that provides the required reliability. Evaluation is thus based upon the credibility of the analysis. The Reliability Analysis will be graded on the scale below on each of two characteristics, to yield two performance factors, which are added and the sum multiplied by the significance factor. The two characteristics are:

1. analytical procedures
2. data base

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3.4.1 Reliability Analysis

RATING = +10

REF: VOLUME I, BOOK 3,
SECTION 2.3.6

SUMMARY OF RATIONALE FOR RATING

It is anticipated that this rating will increase based upon:

- o Results of tests now in progress
- o Design and analytical refinements based upon these test results.

Analytical methods reflect state of the art techniques in virtually all cases. Where empirical constants and parameters are lacking, such as low cycle fatigue strain range partitioning, braze alloy strength, etc., the supportive experimental programs have been defined and in most cases are under way. These are to establish the experimental constants and parameters and to verify design integrities.

TECHNICAL DISCUSSION

In addition to the materials and component test programs specifically designed for the BIPS program, the data base is derived from AiResearch turbomachinery experience approaching 100 million field operating hours.

A particular reference is the experience at NASA-LeRC with the 10.5 kW_e BRU system, AiResearch report 31-2360A, "Relevance of the NASA BRU Experience of the Mini-BRU, BIPS Reliability Analysis."

The summary and conclusions of the report follow:

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- o BRU S/N 1 - Operator error caused failure after 700 hours; unit rebuilt and placed on standby.
- o BRU S/N 2 - Total of 33,480 hours (3.82 years) successful operation as of December 20, 1977; unit continuing to operate. Inspection after 20,568 hours revealed no apparent wear or failure mode that would prevent attainment of the NASA 5-year life objective.
- o BRU S/N 3 - Operator error caused failure after 4 hours; unit rebuilt, upgraded to 15 kW_e power output capacity, retrofitted with gas foil bearings, and redesignated BRU-F. Unit placed on standby, never operated.
- o BRU S/N 4 - Total of 11,217 hours successful testing. Inspections after 5730 hours 11,217 hours found the unit in excellent condition.

Two BRUs (S/N 2 and 4) have logged a total of 44,467 hours (5.07 years) as of December 20, 1977 and BRU No. 2 is still operating.

A thorough review of NASA testing experience and a comparison of the two systems (i.e., NASA BRU and DoE BIPS Mini-BRU) permit the following conclusions to be made:

- o The two systems are similar in design, operating characteristics, materials, and configuration. Operating experience on the NASA BRU test loop is relevant, to a significant degree, to the DoE BIPS.
- o The DoE BIPS is a more conservative engineering design. This is especially true for the rotating unit, where tip speeds, mechanical stresses, and operating temperatures are lower in the Mini-BRU than in the NASA BRU.
- o Major dissimilarities for the two systems include differences in: (a) types of thermal insulation, (b) gas bearing configuration, (c) turbine inlet temperature, and (d) method of alternator cooling.
- o System conversion efficiency did not degrade during the lengthy operation of the BRUs. Furthermore, no failure modes were observed in the NASA BRUs.
- o The turbine scroll was the only potential life-limiting BRU component identified. (This potential weakness has been eliminated in the Mini-BRU by redesign.)

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- o The recuperator exhibited a low cycle fatigue weakness. (This experience resulted in a design change for the Mini-Brayton Recuperator in the BIPS loop; tests during past two years have confirmed design integrity.)
- o NASA BRU test loop ducting and bellows remained leak tight throughout all testing.
- o Both engines contain a gas bearing supported rotating group consisting of a single stage compressor, a turbine, and a solid rotor, all on a single shaft.
- o Each loop contains a plate fin, pure counterflow recuperator, a simulated radiator (HRHX), and inter-connecting ducting with multiple ply bellows.
- o Materials are similar throughout, and identical in many respects.

Basic differences are shown below:

<u>NASA BRU</u>	<u>BIPS GDS</u>
o Turbine Inlet Temperature - 1600°F	o Turbine Inlet Temperature - 1385°F
o BRU Alternator Cooled by Cooling Fluid (Dow Corning 200)	o Mini-BRU Alternator Cooled by Working Fluid (He-Xe) from Compressor Flow
o Pivoted Pad Gas Bearings	o Foil Gas Bearings in Mini-BRU
o Ceramic Fiber Thermal Insulation (Tested in Atmosphere)	o Multifoil Thermal Insulation (Tested in Vacuum)
o Workhorse HSHX (Tube Bundle Heaters)	o Prototype Heat Source Assembly HSHX with Electric Heat Source to Simulate Isotope Heat Source

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Key operating conditions compare as follows:

	<u>NASA BRU</u>	<u>BIPS GDS</u>
o Turbine Inlet Temp (°F)	1600	1385
o Turbine Inlet Pressure (psia)	26	62
o Turbine Tip Speed (ft/s)	781	644
o Compressor Inlet Temp (°F)	80	39
o Compressor Pressure Ratio	1.9	1.6
o Output Power (W_e) (as operated)	6000	1300

The following table provides a comparison of the materials in the two units.

Specific areas where the data base is being expanded as follows:

- o Bellows reliability testing - ORNL
- o Hastelloy-X LCF, creep and rupture properties
 - ORNL
 - BATELLE
- o Foil bearing analytical design and reliability, experimental development, AiResearch, Phoenix

The data base for Hastelloy-X in terms of creep, creep rupture, and short time properties is superior to all other feasible material candidates. Tests now in progress are specifically directed to component design verifications with Hastelloy-X and certain behavioral physics of Hastelloy-X, such as intergranular leakage by helium. All defined failure mechanisms with Hastelloy-X for the BIPS application are being pursued through supportive experimentation.

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TABLE I
BRU-MINI-BRU MATERIAL COMPARISON

ITEM NO.*	COMPONENT BRU LISTING	BRU MATERIALS	MINI-BRU MATERIALS	ITEM NO.**	COMPONENT MINI-BRU LISTING
1	Compressor wheel	CRES 403	CRES 410	1	Impeller, comp.
2	Compressor spinner	6061-T6 Alum	N/A		N/A
3	Compressor scroll	CRES 347	CRES 17-4 PH	21	Diffuser comp.
4	Compressor back shroud	CRES 347	CRES 347	19	Seal comp. Back shroud
5	Tie bolt washer	17-4 PH	CRES 347	4	Washer, tie bolt
6	Thrust bearing stators	M-2 Tool steel	17-4 PH stainless	15	Plate, thrust brg.
7	Thrust bearing rotor	4340 steel	6260 steel	5	Rotor, thrust brg.
8	Gimble assembly	17-4 PH	N/A		N/A
9	Thrust bearing carrier	CRES 347	N/A		N/A Combined with 6 See 15 above
10	Journal bearing carrier	4340 steel	4340 steel	14	Ret foil journal
11	Journal bearing mounts	17-4 PH	N/A		N/A
12	Journal bearing pad	RX-49	CRES 302	9	Foil brg., journal
13	Gas Brng thermal shunts	Copper	Copper	8	Heat shunt
14	Tie bolt	Inconel 718	Inconel 718	2	Tie bolt
15	Alternator rotor	4340 steel Inconel 718	HP9-4-20, Inconel 713LC	7	Rotor, alternator
16	Alternator stator frame and end plates	Ingot iron	1018 steel	22 23 24	End bell, comp. End bell, turbine HSG alternator
17	Main housing outer shell	CRES 347	CRES 347	24	HSG alternator
18	Alt stack laminations	AL 4750 steel	AL 4750 steel	34	Stack laminators
19	Alt frame support beams	4340	N/A		N/A
20	Scroll mounting flanges	CRES 347	CRES 347	24	HSG alternator
21	Housing hermetic seals	CRES 347	CRES 347	29 30	Ring, hermetic seal Ring, hermetic seal
22	Turbine scroll suppt shell	Inconel 718	N/A		N/A
23	Radiation shield	Copper	N/A		N/A
24	Turbine nozzle shroud	Inconel 713	Hastelloy X	26***	Plenum, turbine
25	Turbine wheel	Inconel 713	Inconel 713LC	6	Turbine wheel
26	Turbine torus	Hastelloy X	Hastelloy X	26***	Plenum, turbine
27	Turbine scroll inlet and exit flange	Hastelloy X	Hastelloy X	26***	Plenum, turbine
28	Alt convection shields	Asbestos phenolic 150 RPD	N/A		N/A

NOTES: * From Table 2

** From Table 3

*** Redesign to plenum

Refer to Figure 3 for locations of BRU material

Refer to Drawing 3604385 for location of Mini-BRU materials

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Bellows and Controls

The basic approach for the analysis is illustrated by the Preliminary Reliability Analysis, 75-311282, prepared early in the program. Figure 3.4.3-1 shows the Indenture Tree. This model will be updated as the controls are finalized and the materials and bellows data base is completed. The reliability allocation and preliminary assessment is provided in 76-311851, "Preliminary Reliability Allocation and Estimation."

MINI-BRU RELIABILITY INDENTURE TREE

FIGURE 3.4.3-1

3.4.2

Failure Mode Analysis

This factor focuses on system behavior. In a complex integrated system there are usually a variety of different scenarios whereby degradation or malfunction in one area leads inevitably to a widening circle of related effects and eventually to system failure. The flight system FMECA is used to isolate potential failure modes and rank their criticality. Potential failure modes which lead to a major loss of power are to be tabulated from the FS FMECA as a basis of the performance.

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3.4.2 Failure Mode Analysis

RATING = +3

REF: VOLUME I, BOOK 3,
SECTION 2.3.6

SUMMARY OF RATIONALE FOR RATING

The primary failure modes which could lead to a major loss of power are listed in the attached table. These are modes whose criticality exceeds 100, where criticality is computed as the product

[Mode likelihood (1 to 100)] x [effects impact (1 to 100)]

as defined in DoE (AEC) Reliability Engineering Program Requirements Publication SNS-2.

Where numerous components of the same type are involved whose failure modes are virtually identical (e.g., bellows), only one entry is made. Twelve critical failure modes are identified. These failure modes were identified in the BIPS-FS FMECA, AiResearch Document 76-311709.

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<u>Order No.</u>	<u>Item</u>	<u>Criticality Ranking</u>	<u>Comments</u>
3	MBR Splitters	500	Rupture of the splitter-to-cone 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 fatigue 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.
4	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.
6	Bellows	2 X 100 = 200	Cracking of welds or of convolutes would result in loss of working fluid. Correct design of bellows will be essential in order to compensate for centerline misalignment due to thermal expansion and lateral deflection.
7	Mini-BRU Alternator Stator - Power Windings	200	A 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 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.
8	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.

150-3°

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<u>Order No.</u>	<u>Item</u>	<u>Criticality Ranking</u>	<u>Comments</u>
9	High Temperature Insulation (Multifoil)	100-200	Structural failure of the multifoil 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.
10	Mini-BRU Foil Bearings	200	Bearing failure causes immediate system shut-down. Development and analytical work now in progress must result in design that is rigorously analytically tractable and which shows by empirical demonstration and analytical prediction to be failure free. Necessary and sufficient conditions for ultimate high reliability must be established and verified.

3.4.3 Number of Single Point Failure Sites

As an indirect but powerful indicator of reliability, a count shall be made of the number of individual components in the system, the failure of which would normally lead to a major power loss in the system. For purpose of this count a "component" is defined as a valve, a bearing, a seal, a bellows, a weld, an electronic component, a pressure vessel, a sensor, an intricate fabricated part, a turbine or impeller, a jet, an orifice, etc. Single point failure sites shall be as determined in the FS FMECA and the program reliability plans

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3.4.3 Number of Single Point Failure Sites

RATING = +14

REF: VOLUME I, BOOK 3,
SECTION 2.3.6

SUMMARY OF RATIONALE FOR RATING

The BIPS system has a very limited number of single point failures due to the fact that all control functions are implemented via the electrical load where redundancy can be employed with solid state circuitry. Because of this, a rating of very nearly +15 is justified as only 52 single point failures are identified.

TECHNICAL DISCUSSION

The detailed FMECA is provided in AiResearch document 76-311709. The "BIPS Design Integrity Checklist" 76-311971 provides supplementary information in this area. The attached charts provide summary information relative to the single point failure sites, the most likely failure modes, and the means required to obviate failure for each of the primary failure sites.

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SINGLE POINT
BIPS FS FAILURE SITES

<u>FAILURE SITE(S)</u>	<u>TOTAL NUMBER</u>
Mini-BRU Turbine Plenum	1
Mini-BRU Housing	1
Mini-BRU Tiebolt (Rotating Group)	1
Mini-BRU Turbine Wheel	1
Mini-BRU Compressor Impeller	1
Mini-BRU Alternator (Phase Wiring)	3
Mini-BRU Rotor Bi-Metallic Joint	1
Mini-BRU Journal and Thrust Bearings	3
Recuperator Side Plates and Junctions	5
Recuperator Seal Plate Junctions	2
Recuperator Manifold Attachment	
Recuperator Flange Brazes	4
Recuperator Pan Assemblies and Junctions	6
Heat Source Assembly - Heat Exchanger	2
Radiator - Panel	1
Ducting System - Bellows	18
Insulation	2
	<hr/>
	52

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TABULATION OF SINGLE POINT FAILURE
SITES, BIPS FLIGHT SYSTEM

Subsystem: Mini-BRU

<u>Component</u>	<u>Critical Failure Mode</u>	<u>Base for Failure Minimization/Elimination</u>
Rotating Group Tie Bolt	Fracture	Design is to preclude creep. Slight creep would also result in reduced axial load which would preclude fracture. Mission introduces no cyclic loading.
Alternator		
- Field coil winding, open or closed circuits	Component failure insulation breakdown	Design redundancy
- Stator power windings	Open circuit, short circuit	System designed to isolate Mini-BRU from structural vibration. High standard workmanship in assembly process required.
(Alternator Bl metallic joint)	Braze fracture	Design minimizes braze stress. Mission introduces no cyclic stress. Braze yielding relieves shear stress. Axial stress in compression.
Journal and Thrust Bearing System	Seizure	Analytical design and development program now underway will result in life unlimited bearings.
Compressor Impeller turbine wheel	Blade or hub burst	Resonant vibratory excitations source frequencies removed from design speed, no start-stop cycle requirement preclude high cycle fatigue of blades. Hub and blade stresses preclude creep.
Turbine plenum	Fracture (Rupture) Gas leakage	Rigorous LCF and creep analyses, extensive materials properties data, design margin criteria, intergranular gas leakage tests, all justify high design integrity.
Mini-BRU Housing	Fracture, gas leakage	Low stress and temperature environment, high strength material, detailed thermal and stress analyses justify high design integrity.

Subsystem: Recuperator

Side plate and junctions	Fracture, gas leakage, loss of working fluid	Material selection, design margin with respect to applied stresses and loads justify high design integrity.
Seal plates and junctions	Fracture, gas leakage, loss of working fluid	Material selection, design margin with respect to applied stresses and loads justify high design integrity.
Manifold attachment flange brazes	Gas leakage, loss of working fluid	Full braze alloy coverage, inspection, procedure, proof testing required.
Pan assemblies and junctions	Gas leakage, loss of working fluid	Applied stresses and temperatures assure design margin to justify high design integrity.

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TABULATION OF SINGLE POINT FAILURE
SITES, BIPS FLIGHT SYSTEM (Contd)

Subsystem: Heat Source Assembly

<u>Component</u>	<u>Critical Failure Mode</u>	<u>Base for Failure Minimization/Elimination</u>
Heat exchanger	Micrometeoroid impact	Penetration of housing, insulation, and cylinder wall first required. (insulation by itself will stop penetration.)
	Fracture, loss of working fluid	Material selection, design criteria justify high design integrity.

Subsystem: Radiator

Panel (Skin fin surface area)	Loss of emissivity, loss of cycle efficiency, shutdown	Selection of coating to preclude ultra-violet ray degradation, bonding problems (Design + Q.A.)
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Subsystem: Ducts and Bellows

Bellows	Fracture of convolutions	Rigorous LCF + creep design, component tests.
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Subsystem: Insulation

Insulation	Loss of spacer material, long term progressive failure due to insulation degradation	vibration isolation, decontamination procedures, Q.A.
	Structural failure, high local hot spots, ultimate loss of working fluid	Design minimizes thermal stress to acceptable margin.

Subsystem: Controls

Power Supply	Loss of control circuits	Vibration isolation, <u>redundancy</u> , design conservatism
Output current sensor	Possible loss of speed control	Vibration isolation, <u>redundancy</u> , design conservatism
Temperature sensor	Possible overtemperature	Vibration isolation, <u>redundancy</u> , design conservatism
Speed sensor/transducer	Senses alternator frequency	Vibration isolation, <u>redundancy</u> , design conservatism
Parasitic load control	Senses alternator frequency	Vibration isolation, <u>redundancy</u> , design conservatism
Field current control	Senses alternator frequency	Vibration isolation, <u>redundancy</u> , design conservatism

3.4.4

Quality Assurance Plan

The Quality Assurance plan and the contractors performance related to it are to be reviewed to determine that they provide an adequate guarantee of product quality. Completeness and practicality of plan, contractor response to the plan, adequacy of follow-up procedures, and adaptability to problem areas are to be considered. The QA plan is to be quantitatively evaluated by the performance factor scale independently for: (1) Acceptability of QA Plan and (2) Contractor performance under the plan. These two scores are added and the sum multiplied by the significance factor.

3.4.4 Quality Assurance Plan

RATING = +14

REF: VOLUME I, BOOK 4,
SECTION 1.0

SUMMARY OF RATIONALE FOR RATING

The BIPS Quality Program Plan rated as +14. Performance under the Phase I Quality Program Plan and the demonstrated capability to meet the upgraded quality requirements defined in the Phase II Plan is rated as +13.

The Phase I Quality Program Plan, QA-053, evolved from many inputs from the Department of Energy, Nuclear Research and Applications, (DOE/NRA) personnel and their designees as related to flight system requirements. The Phase I and Phase II Quality Program Plans have been structured to provide a sound foundation for future flight system requirements. Many of the disciplines and controls envisioned for Phase II Quality requirements have been demonstrated, refined, and implemented in Phase I.

TECHNICAL DISCUSSION

The BIPS Phase II Quality Assurance Program Plan (QA-054) meets the general intent of the Nuclear Research and Applications Specification #NRA-1. This plan provides for very stringent Quality Assurance requirements throughout all phases of contract performance in order to support the reliability and mission objectives. The Phase I Quality Assurance Plan was upgraded during the course of the program in response to DOE requests and currently incorporates many of the requirements of NRA-1.

Specifications have been established for the fabrication and inspection requirements for BIPS parts. Detail Inspection Instructions, (DII's) are initiated for each part defining in detail each quality

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requirement as related to material, processing, fabrication, inspection and test. The DII also provides for measurement and documentation of each characteristic by the supplier and AiResearch. Emphasis is directed towards conformance to requirements through the incorporation of check off sheets for supplier and AiResearch usage.

Potential suppliers for Phase II have had preliminary indoctrination into the fabrication and inspection requirements. The value of the DII has already been demonstrated on selective parts that have been ordered for the Phase I Ground Demonstration System, (GDS). Coordination with bellows and insulation suppliers has been accomplished and has resulted in the establishment of specifications that are compatible with the Quality Program Plan.

A considerable effort has been put forth relative to compliance with the Quality Requirements as defined in the Phase I Quality Plan. In response to audits and DOE inputs, this plan has been constantly refined and upgraded. This experience has been of great value and is reflected in the Phase II Quality Plan.

3.4.5

Fabricability

The design of the power system and the materials employed should be such that the system can be manufactured within the current state of the art. All processes and procedures should be fully specified and results should be predictable. Scrap and rework levels should be within reasonable limits. "Existing standards" are defined as pre-existing, established standards of a contractor, NASA, DoD, ASTM, etc.

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3.4.5 Fabricability

RATING: +10

REF: VOLUME I, BOOK 4
SECTION 7.0

SUMMARY OF RATIONALE FOR RATING

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

Development of tooling and fabrication processes in Phase I will carry over to Phase II. Controlled rework procedures used and approved in Phase I are to be used in Phase II to assure compliance to specifications and a minimum of rejections.

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

TECHNICAL DISCUSSION

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

The Mini-BRU is very similar to the NASA BRU, two of which have operated for over 46,000 hours, and is comparable to the many gas turbines manufactured by AiResearch. Likewise, the recuperator uses techniques developed for the NASA BRU recuperator; the recuperator is built by the AiResearch Torrance Division which specializes in heat exchanger equipment. A prototype unit was cycled through 200 start cycles and is still available as a back-up unit.

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Fabrication of foil bearings has been developed to a high degree both prior to and during Phase I. Precision foil sheet stock is coated by spraying with Teflon-S. The required surface finish is then obtained by buffing the surface. The required foil pads, whether journal or thrust, are then formed by photo chemical machining (PCM). These pads are then hand finished.

For journal bearings, the preformed radius is then shaped, and the foil keeper bar is then welded in place. Next, each foil is completely inspected and assigned to groups of eight wherein lot numbers and serial numbers are marked.

For thrust bearings, the individual pads are welded onto base-plates after which each assembled unit is then inspected. Finally, the lot number and serial numbers are marked.

Each set is then packaged individually and stored for future use.

Fabrication of the heat source assemblies was also accomplished during Phase I. The heat exchanger design was changed to a single coil to simplify fabrication and improve inspectability.

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

Considerable effort was expended during Phase I to develop a bellows and ducting system that would be within the state-of-the-art and meet the life objectives. Testing of the bellows at ORNL has provided a data base that is establishing confidence in the design.

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Results of ORNL tests through February 27, 1978 are as follows:

<u>Bellows Part No.</u>	<u>Predicted Cycles</u>		<u>Actual Cycles</u>
	<u>Minimum</u>	<u>Normal</u>	
3606466	16	107	126
3606466	16	107	*
3606467	26	167	267

*As of February 27, 1978, approximately 105 cycles - No Failure

Samples of five other bellows part numbers are soon to undergo squirm, creep, and low cycle fatigue tests to provide additional confidence in design and fabricability.

The primary fabrication and installation steps for MULTI-FOIL thermal insulation as applied to the Workhorse Loop have been included in the Engineering Assembly Instruction for BIPS. These accepted methods are documented in (1) TECO Process Specification No. 3163A (Cleaning Procedure for MULTI-FOIL Insulation), (2) TECO Process Specification No. 3162 (Electrostatic Coating Procedure for MULTI-FOIL Insulation), (3) TECO Process Specification No. 3163 (Heat Treating of MULTI-FOIL Insulation), and (4) TECO Specification 4219-1 (MULTI-Foil Assembly Procedures for BIPS), as well as in the EAI. Based on the effort to date, tolerances have been established, and means of monitoring these tolerances have been defined by the TECO Quality Assurance program. On completion of the GDS, reproducibility should be demonstrated. A new standard is being finalized for the few electroformed foils that will be used in selected regions of the GDS and FS.

Lockalloy is being considered for the support structure to reduce weight. Fabrication techniques have been demonstrated on many applications using existing standards. These processes will be evaluated and typical structures and bonds will be evaluated early in Phase II at ORNL. Fabrication of aluminum support structure was established during Phase I.

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

Accessories requiring development, such as the parasitic load and T_6 sensor, will utilize design configurations that can be fabricated from military or commercial standard materials. Reproducibility of these materials must be demonstrated or documented by the supplier prior to fabrication of the component part using these materials. Detailed design drawings for each component will specify tolerances that are compatible with the known properties of the materials selected and existing fabricating techniques.

3.4.6

Assembly Procedures

Reliable, effective, and convenient procedures should be available for system assembly and preparation for start-up. The procedures must include assembly of the thermal insulation, outgassing, flushing/pre-treatment of the working fluid passages, working fluid fill, as required, and verification of initial conditions. The design should not introduce any unusual constraints or difficulties to these procedures.

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A DIVISION OF THE GARRETT CORPORATION
PHOENIX, ARIZONA3.4.6 Assembly Procedures

RATING = +14

REF: VOLUME I, BOOK 4
SECTION 7.0SUMMARY OF RATIONALE FOR RATING

The assembly procedures are rated +14 because detailed instructions are provided for every step of the assembly process and preconditioning. These assembly instructions were developed during Phase I and are covered in the engineering assembly instruction manuals and the preconditioning prior to running is covered in the operators manual. These manuals proved to be of great value during Phase I of the BIPS program; and they have since been revised and updated for Phase II.

TECHNICAL DISCUSSION

The procedures to be followed in assembling the BIPS GDS are described in detail in the engineering assembly instruction manuals; 76-312228A for the Mini-BRU and 31-2624 for the GDS Loop. The Flight System assembly procedures are expected to be nearly identical since the GDS closely resembles the Flight System.

These instructions cover the cleaning of parts, the verification and recording of significant dimensions, the sizing and trimming of ducts, the sequence of assembly, the installation of instrumentation, the sequence and type of insulation to be used, the support, assembly and inspection tooling to be used, and the type of weld sample and weld configuration to be employed. It further provides for visual and X-ray inspection of the welds as well as leak check of each weld assembly.

Engineering Assembly Instructions 31-2624 and 76-312228A; Operators Manual 31-2502.

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

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

The preconditioning of the loop prior to operation is described in the Operators Manual 31-2502. To ascertain that the working fluid meets all the requirements of space operation, the following procedures are outlined in detail; the preconditioning of the working fluid management system, the gas and moisture analysis, the purging of the loop with argon to drive out contaminant gases (to achieve <15 ppm reactive contaminants and a total of all contaminants reactive and inactive of <200 ppm), and the moisture analysis of the closed loop. Once these requirements are met, the loop is evacuated and filled with xenon/helium and the moisture content of the gas is again analyzed. The operators manual lists all the development instructions to be followed during this procedure to ascertain that the required conditions are met for GDS operation.

3.4.7

Inspectability

Established inspection procedures shall be available for all critical features of the flight system. Acceptance levels are defined and adequacy of these levels is established. The design permits adequate access so that valid inspections can be performed on all critical components.

3.4.7 Inspectability

RATING = +13

REF: VOLUME I, BOOK 4
SECTION 1.0

SUMMARY OF RATIONALE FOR RATING

The attribute of "Inspectability" at this phase in the BIPS Program is rated as +13. The Phase I Program Plan has been upgraded several times during Phase I through close coordination with DOE in order to provide a foundation for follow-on Phase II and subsequent requirements. Many of the Quality Requirements revised and planned for Phase II have been tried and proven as reliable tools during Phase I for the assurance of quality and inspectability requirements in the future.

TECHNICAL DISCUSSION

Assurance of "Inspectability" is achieved on the BIPS Program through direct involvement of Quality Assurance in all phases of contract performance. These activities and related responsibilities have been reviewed in depth and have been refined, formalized and defined in the Phase I and Phase II Quality Program Plans.

Detail Inspection Procedures and Instructions are utilized to assure compliance with the quality requirements. The applicable inspection procedures are defined in Quality Control General Instruction, (QCGI #144). Detail Inspection Instructions, (DII), are established for each part having provisions for 100 percent inspection and documentation of each characteristic. This inspection is accomplished by both the supplier and AiResearch to assure compatibility of inspection technique and gages. The acceptance criteria is defined on the applicable drawings and specifications, and is incorporated in the DII. Provisions are incorporated in each inspection instruction to reflect the quality requirements as defined in the Quality Program Plan.

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The BIPS system design provides adequate access for inspection of critical parts and components. Special fixed process and inspection controls have been established for the inspection of BIPS detail parts and assemblies. Design of the Workhorse Loop Design (WHL) has provided access for inspection during assembly and after test. Experience to date has demonstrated accessibility for inspection via disassembly of the WHL in conjunction with the foil bearing test program.

Utilization of X-ray in conjunction with image enhancement has provided a particularly valuable method of inspection in the processing and assembly of BIPS parts and assemblies.

Fabrication and Inspection Requirements Specifications have been established to define the requirements for all BIPS parts. These specifications are specified on the applicable drawings to trigger the implementation of these quality disciplines. These specifications encompass the requirements as defined in the Nuclear Research and Applications Specification, (NRA-1) which is the basic control document utilized in the structuring of the BIPS Quality Program Plan. Supplier indoctrination into these specifications has been accomplished with follow-on coordination to be provided on an as required basis.

3.5.1

Loss of Cooling Accident

Numerous credible accidents can be postulated that lead to loss of cooling of the isotope heat source and a subsequent rise in its temperature. The system design must insure that no credible event of this nature will result in such degradation of the isotope heat source as to increase the nuclear hazard potential for all subsequent credible mishaps to an unacceptable level. If auxiliary components or functions are required to survive loss of normal cooling, their reliability must be acceptable to the safety analysis.

3.5.1 Loss-of-Cooling Accident (LOCA)

RATING = 0

REF: VOLUME I, BOOK 3
SECTION 2.3.5

SUMMARY OF RATIONALE FOR RATING

Analysis indicates that the LOCA transient takes the PICS temperature into the 1400° - 1500°C range, recent test data indicates that the PICS would most likely experience little or no degradation of its impact capability.

TECHNICAL DISCUSSION

An analysis of the loss-of-cooling accident transient was performed by AIRLA on a HSA similar to the one for the BIPS with the results being given in the first footnote reference. The HSA analyzed consisted of the superalloy HSHX developed for the BIPS GDS with Palladium-Nickel multifoil insulation and the MHW MJS heat source. This analysis modeled the superalloy helical tube heat exchanger, the 60-layer foil insulation system, and the Isotope heat source, including the PICS.

The results of the transient analysis indicate that a peak PICS temperature of 1474°C is reached at approximately 3 hours after a loss of coolant. After this time, the PICS temperature decreases slowly until the steady state temperature of 1457°C is reached. This analysis assumed that all melting foil condensed out on the next adjacent foil after which this foil would increase to the melting temperature and so forth. The analysis indicated that 48 cylindrical foils melted and that 53 end-cap foils melted. In the real meltdown case, it is likely that the molten foils would intermingle with the remaining unmelted foils to form a somewhat solid mass. (This has been observed in meltdown tests of Ni-Mo and Ni-Nb systems.) In this latter case, the eventual steady state temperature would be much lower.

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A recent review of the General Purpose Heat Source (GPHS) program (Reference 2) covered two areas of heat source development pertinent to the selection of the subject rating. These involve the development and testing of a homogeneous PuO_2 fuel and the development and testing of dopant controlled iridium material for the PICS. The results of impact tests on capsules containing fuel pellets made from the GROG-type feed material, pressed and sintered to a density of 85-88 percent, have shown that they produce less distortion of the clad material and less breakup as well as fewer fines than does the lower density fuel or fuel containing shards. These trends hold at least over an impact velocity range of 140-280 fps (43-85 m/s) and a test temperature range of 760-1300°C (1400-2370°F). Typical diametral strains were 3-8 percent over the velocity and temperature ranges indicated as opposed to strains of 11-15 percent for the lower density and shards fuels.

Based on grain size/impact elongation correlation and grain growth behavior, the DOP-26 material is predicted to be capable of operating at a temperature of 1500°C (2732°F) for 200 hours and impact at a temperature of 1050°C (1922°F) and still have an elongation of 15 percent before failure. For an impact temperature of 1350°C (2462°F), the time increases to an allowable 500 hours at 1500°C. These values are based on tests at 280 fps (85 m/s). Equivalent times for the DOP-4 material are 1 hour for impact at 1050°C and 60 hours for impact at 1350°C for the same 15 percent elongation. The undoped materials used for the PICS in the MHW MJS (Voyager) Heat Source had less capability than did the DOP-4 material.

Based on a comparison of the transient analysis results with the capability of the DOP-26 material and GROG type high density fuel, the following reasoning has been followed in arriving at the selected rating:

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The transient shows the temperature of the PICS to stay below 1500°C during meltdown. The material capability has been shown to be 200 hours at 1500°C for an elongation of 15 percent for impact at 1050°C (which is slightly lower than the lowest impact temperature of the PICS predicted for the MHW Heat Source for typical re-entry conditions). In addition, the stronger GROG fuel effects maximum diametral strains of 8 percent or less, thus gaining some capability over the reference value of 15 percent. All factors considered, it is possible that a small amount of degradation of the capability for impact of the MHW type heat source could result from a LOCA transient. However, the effects of any expected degradation are not expected to increase the magnitude of the resulting source terms significantly. Another significant factor that must be recognized is that this capability or the reduction in capability is referenced mainly to the most severe re-entry and impact conditions, namely:

- o the low end of impact temperature range
- o the maximum impact velocity
- o the hardest impact surface medium

Alternate HSA Study Final Report, AIRLA Contract With NASA, NAS3-20816.
GPHS Program Review at DoE; 19, 20 Dec. 1977.

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Alternate HSA Study Final Report, AIRLA Contract With NASA, NAS3-20816.
GPHS Program Review at DoE; 19, 20 Dec. 1977.

3.5.2

Pad Abort

The hazards to the heat source created by a launch vehicle abort on or near the launch pad include blast, shrapnel, fall-back impact, and fire. The heat source has already been qualified against these hazards when used as part of the MHW. It remains to be demonstrated that the new system environment, and the possibility of a Shuttle launch, do not, separately or together, create a new hazard situation that the fuel containment cannot survive. Analysis should consider the increased energy content of the Shuttle, and changed strength characteristics of the new HSA.

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3.5.2 Pad Abort

RATING = -5

REF: VOLUME I, BOOK 3,
SECTION 2.3.5

SUMMARY OF RATIONALE FOR RATING

Shuttle (STS) pad abort environments may be one to three orders of magnitude greater in overpressures than previous MHW mission environments. Insufficient analysis and testing has been done to date to draw a firm conclusion regarding the possible pad abort accident for the STS.

TECHNICAL DISCUSSION

Preliminary considerations of the Space Transportation System (STS) environments and the recent meeting on Shuttle data held by the Inter-agency Nuclear Safety Review Panel (INSRP) (first footnote reference), have shown that the Shuttle/Booster explosion overpressures can be as much as three orders of magnitude greater than that for the Titan IIIC and upwards of two orders of magnitude over that for the Titan/Centaur. This arises because of several factors:

- o Much larger quantity of total propellants (1,600,000 lb. for STS vs 357,600 lb. for Titan/Centaur or 351,700 for Titan IIIC).
- o Higher yield and greater overpressure propellants (LOx/LH₂ for STS vs. N₂O₄/Aerozine-50 for Titan; Centaur also uses LOx/LH₂).

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- o Proximity to propellant tanks (thus, explosion centers) can be around the same and even nearer for payloads on the STS than for the nearest steps of the Titan IIIC and the Titan/Centaur.

NOTE

The Saturn V launch vehicle had a much larger quantity of propellants (5,760,000 lb) than does the STS (1,600,000 lb), but payload distances were far enough away (35 feet for S-IVB stage to 200 feet for S-IC stage) that peak overpressures were a factor of 2-3 less than the currently predicted maximums for the STS.

Even with the considerably higher overpressures possible with the STS, the effect of an upper limit explosion on the MHW heat source, especially as it is configured with the HSA on the launch pad, would not be expected to cause a breach of any of the FSA's. The more important consideration, however, is that of projectiles generated by the effects of the explosion on the STS and also on the BIPS. Projectiles with velocities approaching 3500 feet/second were predicted for explosions of the Saturn V vehicle (Apollo program) at the SNAP-27 position. Since the STS maximum effective overpressures (and impulses) can possibly be higher than those of the Saturn V, projectile velocities for the STS could consequently be somewhat higher.

Projectile tests were conducted for the SNAP-27 program (Reference 2) with velocities up to 2800 feet/second for plate fragments in edge-on and flat-on impingement orientations. The edge-on test resulted in severe damage to the fuel capsule, having had to cut through a 0.70 inch thick hemispherical graphite (Pyrocarb-406) end cap, a 0.75 inch thick fiberfrax insulation cap, a 0.125 inch thick titanium cover plate and the 0.080 inch thick Haynes-25 clad and liner of the

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fuel capsule. These materials could be considered to roughly approximate those of the BIPS HSA and the MHW Heat Source (MJS or Voyager configuration). Other intervening materials might or might not be present in the STS/BIPS abort situation, depending on the source of the projectiles and the orientation of the BIPS with respect to the Shuttle. Nevertheless, the conclusion is reached that in the worst case situation (upper projectile velocities with edge-on orientations and upper explosion overpressures), at least one and possibly several FSA's could be breached if projectile impingement on the HSA occurred. It should be pointed out that on the SNAP-27 Program (and it is expected that it would be similar on BIPS) it was shown that the probability of a pad abort accident which would result in a projectile situation similar to that used in the test would have a very low probability of occurrence.

INSRP Shuttle (STS Data Meeting, October 26-27, 1977.
DIN: 6300-300R2 Supplement No. 2, SNAP-27 Safety Report Volume II.
Accident Model Document 24, Jan. 1969.

3.5.3

Reentry

The evaluation will be based on the determination of whether the design of the power system can degrade the existing capability of the heat source to survive reentry. Degradation of reentry capability could occur if:

Excessively high or low operating temperatures or ECS excursions are credible that could lead to clad melting or degradation.

Structural attachments of high melt materials are used that could result in ill-timed release of the IHS.

Structural attachments are used that could alter the reentry configuration of the HSA's leading to high thermal stress conditions.

SIGNIFICANCE
FACTOR=

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3.5.3 Reentry

RATING = 0

REF: VOLUME I, BOOK 3,
SECTION 5

SUMMARY OF RATIONALE FOR RATING

There are no potential conditions that could exist for the STS/STP that would present any more severe reentry conditions than have previously been analyzed for MHW missions.

TECHNICAL DISCUSSION

The operating temperature of the PICS's in the BIPS at full power is around the same as that for the MHW/MJS application, or around 2300°F (1260°C). Thus, the majority of reentries for the BIPS/STP would start out with the PICS's at the same temperature as they would be for MHW/MJS reentries. If the BIPS had not been started (i.e., with auxiliary cooling applied), the temperature of the PICS's would be around 1920°F (1049°C), and the starting temperature for reentry would thus be lower than for MHW/MJS.

The other situation to consider is the PICS temperature if the BIPS were to reenter during the peak part of the LOCA transient.

(NOTE: This situation has been shown to be rather improbable in Reference 1. The overall mission probability was shown to be on the order of 6×10^{-7} , whereas the probability for no transient prior to reentry was 0.08, and the probability for the full LOCA transient to have been completed prior to reentry being 3×10^{-4} .) The peak temperature during a LOCA has been shown in 3.5.1 to be 2685°F (1474°C). The maximum temperature increase for any of the MHW/MJS reentries occurred for the minimum entry angle, high velocity reentry ($\delta_{\min}$), and the PICS went from 2295°F (1257°C) to 2900°F (1593°C), or an

increase of about 600°F (see Reference 2). Considering that the reentry thermal response of the BIPS heat source should be essentially the same, the incidence of the LOCA transient couples with the $\delta_{\min}$ reentry could result in PICS temperatures around 3300°F (1816°C) as a conservative estimate. This would be 700°F below the carbon-iridium eutectic and 1100°F below the iridium melt point, so that melting of the fuel clad (PICS) would not occur. While the overall temperature levels in the graphite aeroshell would be expected to be higher, the thermal gradient through its thickness would probably be essentially the same as for the MHW/MJS reentry, and so would the stress levels.

Between the analyses performed for MHW/MJS (Reference) and those for MHW/LES 8 and 9 (Reference 3), the question of the effects of the spacecraft truss network and attachment devices for the power system (BIPS) is considered to have been addressed sufficiently to indicate that these devices should not alter the reentry capability of the BIPS heat source significantly from that for MHW/MJS. The factors of time of release and attitude at release were treated comprehensively, especially in Reference 2, as to the effects on heat source motion and stability and the consequent thermal and structural response. The conditions that will be imposed on the BIPS by its integration with the STP platform are therefore not deemed to be significantly different from those already studied with regard to reentry behavior.

Another factor is that the ultimate reentry response of the heat source has been found in previous analyses to be primarily affected by the time and method of release from its parent body (i.e., from the HSA, in the BIPS application) and to a lesser degree by the parent body release from the spacecraft. The release of the BIPS heat source from the HSA is expected to occur at similar times and by similar mechanisms as from the MHW RTG because of the similarities in geometry and method of supporting the heat source. The differences in

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materials between the RTG converter and the HSA case, insulation, and heat exchanger are believed to have only minor effects on the manner of reentry disassembly.

- 1) Bradshaw, T., "BIPS-Transient Probability Study," General Electric Internal Report PIR U-5668, 13 Nov. 1974.
- 2) 77SDS4206, "Final Safety Analysis Report for the MJS-77 Mission," January 1977.
- 3) GENS-419 "Final Safety Analysis Report, Volume II, Accident Model Document for LES 8 and 9," March 1975.

3.5.4

Impact

Impact survivability can be impaired by excessive operating or reentry temperatures causing grain growth embrittlement or by too low an impact temperature, also reducing ductility. This factor considers any changes in established MHW behavior that may be caused by the new system, design, operating mode, or reentry behavior.

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3.5.4 Impact

RATING = +5 (I)
 0 (II)

REF: VOLUME I, BOOK 3,
 SECTION 5

SUMMARY OF RATIONALE FOR RATING

- (I) Improved performance of iridium material (DOP-26) and the use of GROG-type fuel and pressing parameters, which are assumed to be used for the MHW/BIPS, will enhance survivability on impact over that for the MHW/MJS or MHW/LES 8 and 9.
- (II) This rating applies only to the situation in which a LOCA has occurred prior to reentry and impact as discussed in the Loss-of-Cooling Accident rating.

TECHNICAL DISCUSSION

(I) The discussion presented in paragraph 3.5.1 for the Loss-of-Cooling Accident applies here as related to the improved capability of the DOP-26 iridium material and the GROG-type PuO_2 fuel. The failures that occurred in the MHW heat source system verification (SV) impact test (see Reference 1) that would result in a prompt source term were minimal. With the use of the DOP-26 iridium and the GROG-type fuel in the FSA's for the BIPS heat sources, there would be no failures expected as a result of impact following reentry arising from the usual types of incidents (neglecting LOCA).

(II) In the event that a LOCA occurred prior to reentry and impact, the impact capability of the FSA's could have been degraded slightly as a result of the thermal transient. The discussion previously given in paragraph 3.5.1 applies here.

1) 77SDS4206 "Final Safety Analysis Report for the MJS-77 Mission," January 1977.

3.5.5 Burial, Loss at Sea

The power system design, launch procedures, and operating mode must be reviewed to determine that the predicted LHS behavior on post reentry burial or loss at sea is not different than the predicted behavior of MHW.

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3.5.5 Burial, Loss at Sea

RATING = 0

REF: VOLUME I, BOOK 3
SECTION 5

SUMMARY OF RATIONALE FOR RATING

There have been neither changes in the heat source design nor are there other factors in the power system design, launch procedures, and operating mode that would alter the burial or sea immersion capability of the individual FSA's.

TECHNICAL DISCUSSION

The consideration of the capability of the FSA's (PICS's) to withstand impact following the reentry environment has been addressed in paragraphs 3.5.3 and 3.5.4. There will be an enhancement of impact capability over that for the MHW/MJS or MHW/LES 8 and 9 with the use of the DOP-26 iridium and the high density GROG-type fuel in the FSA's. On the other hand, if a LOCA occurs prior to reentry and impact, some degradation in impact capability could occur, even with the DOP-26 material and GROG fuel, as previously discussed. However, the history of the FSA response and the consequential FSA condition up to and including impact have minimal bearing, if any, on the burial or sea immersion capability of the FSA's. Whether the PICS survives or whether it is breached as a result of the impact, either in the MHW/MJS and MHW/LES 8 and 9 or in the BIPS application, the subsequent capability of the FSA/PICS to survive burial or sea immersion does not change. One might argue that the enhancement in ductility of the DOP-26 iridium material would consequently enhance its capability for survival in deep ocean submergence. This would not occur since the temperature of the iridium PICS in water is below the ductile-to-brittle transition point, and the enhancement in ductility applicable in the hot impact

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condition would not occur. There would also be no significant difference expected in the sea water corrosion capability of the various iridium materials nor in the soil compatibility for the higher temperature, deep burial condition.

3.5.6 Nuclear Criticality

Design of the heat source assemblies and the power system must be such as to preclude the possibility of a nuclear criticality event under all credible normal and abnormal situations. Evaluation of the design is to be done in two stages: first, determine if criticality is possible under any conditions; second, if it is possible, determine the probability of its occurrence.

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3.5.6 Nuclear Criticality

RATING = +10

REF: VOLUME I, BOOK 3
SECTION 5

SUMMARY OF RATIONALE FOR RATING

Although there is enough PuO_2 material in two MHW-type heat sources to form a critical mass, there are no credible mechanisms that could be effected as a result of accidents or malfunctions occurring in the BIPS/STP that would result in a critical configuration.

TECHNICAL DISCUSSION

Various configurations of MHW-type RTG's, of heat sources, of fuel sphere assemblies (FSA's), and of post impact shell assemblies (PISA's) (the latter two both unreflected and reflected by steel, concrete, and water) were analyzed by LASL; and the results were reported in Reference 1. The results are summarized in Table 3.5.6-1. The most reactive configuration can be seen to be the 5 x 5 x 5 array of PISA's reflected by water which has a $k_{\text{eff}} = 0.84$. Of course, two MHW heat sources have only 48 PISA's; the k_{eff} would be lower than for the 5 x 5 x 5 array.

1) Letter from David R. Smith, P-5 LASL, to Dr. G. P. Dix, USAEC/SNS, dated April 18, 1973, w/enclosures.

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TABLE 3.5.6-1

NUCLEAR CRITICALITY ANALYSIS
(PERFORMED BY LASL)

FUEL INVENTORY FOR BIPS MISSION

HEAT SOURCE 6.05 Kg
BIPS/STP 12.1 Kg

MINIMUM CRITICAL MASS (PuO_2)

BARE, SPHERICAL MASS 19 Kg
REFLECTED (30 cm Fe or SiO_2) 8.2 Kg

<u>CONFIGURATION</u>	<u>M</u>	<u>k_{eff}</u>
o Heat Source Assembly (HSA)		
Single - Discrete	1.21	0.173
- Homogenized	1.18	0.152
Two Stacked - Discrete	1.23	0.187
Multiple - Homogenized		
	1.36	0.265
	1.33	0.248
o Fuel Sphere Assembly (FSA)		
Single	1.18	
125 Cubic Array (5x5x5)		
Unreflected	1.54	0.35
Steel Reflected	1.96	0.49
Water Flooded/Reflected	2.17	0.54
o Post Impact Shell Assembly (PISA)		
125 Cubic Array		
Unreflected	2.56	0.61
Steel Reflected	5.55	0.82
Concrete Reflected	5.0	0.80
Water Flooded/Reflected	6.25	0.84
o RTG - 5 Grouped	1.21	0.173
o RTG Shipping Container		
Single - Water Filled	1.33	0.25
- Water Removed		0.24 - 0.32
Multiple - Infinite Array	1.33	0.25

16 Group Neutron Cross Sections (Hansen and Roach, 1961)
Monte Carlo Criticality Programs
Keno, Andy

3.6.1

Power System Envelope

Size and shape of the power system, primarily determined by the radiator, affect the problem of integration with the spacecraft and the launch vehicle. We shall consider the maximum area of the spacecraft envelope as projected upon a plane containing the axis of the system to be the significant parameter. The specified maximum envelope has a projected area of 40 ft.².

3.6.1 Power System Envelope

RATING = -11

REF: VOLUME I, BOOK 3
SECTION 2.7.1.3

SUMMARY OF RATIONALE FOR RATING

The maximum projected envelope of the BIPS is 51 ft². This envelope is consistent with the BIPS having a radiator surface area of 160 ft², capable of rejecting the BIPS thermal inventory while maintaining the compressor inlet temperature within the specified requirements to produce 1.3 kW of electrical power. Based on the defined criteria, this envelope results in a performance factor of -11.

TECHNICAL DISCUSSION

The size and shape of the power system is primarily determined by the radiator. For this reason, the discussion will center about the radiator. Several factors are of major importance to radiator design. These include thermal performance, material protection, structural integrity, fabrication feasibility, material compatibility, and working fluid pressure drop. These factors coupled with weight must be examined to determine optimum radiator configurations.

Past studies by the General Electric Company have considered both flat panel and cylindrical radiators. This work has indicated that although flat panel radiators are thermally more efficient, the reduced micrometeoroid armor requirements and structural capability of the cylindrical configuration makes this design the preferred choice. Also, the characteristics of the cylindrical radiator are generally more attractive for integration in a compact manner with the remainder of the power system and the spacecraft.

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The specific weight of the BIPS is such that the cost for STS launches as regarding the power system would be based on volume (shuttle bay length). Based on this criteria, the radiator diameter could be enlarged to approximately 14 feet. This would reduce the radiator length to less than the remaining portion of the power system. With this type of configuration, the cost of the launches would not be influenced by radiator size and therefore reduces the significance of the 40 ft² projected area criteria.

Space Shuttle System Summary - 76SSV8098F
Rockwell International

3.6.2

Thermal Interchange

Thermal feedback from the power system to the spacecraft is generally undesirable as it complicates thermal control of the spacecraft. Thermal input includes conduction through the mounting structure and radiation from the entire power system. The power plant design shall be such that, with nominal control of spacecraft surface emissivity and internal conductivity and an average spacecraft temperature of 20°C, thermal input to the spacecraft can be limited to a nominal value of 200 watts. This heat input includes the 100 watts by conduction specified in 2.4.5.

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3.6.2 Thermal Interchange

RATING = +15

REF: VOLUME I, BOOK 3
SECTION 2.7

SUMMARY OF RATIONALE FOR RATING

It is assumed that the flight power system will be mounted to the spacecraft as a separate module. For the representative configuration described in the Phase II Plan, the total heat transferred from the power system to the spacecraft will be less than 125 watts. This can be assured by orienting the low temperature end of the radiator adjacent to the spacecraft and placing a lightweight multi-foil thermal barrier between the power system and the spacecraft if necessary.

TECHNICAL DISCUSSION

Because of the relatively low surface temperature in the BIPS, no difficulty will be encountered in limiting the heat flow from the power system to the spacecraft to less than 125 watts. Heat conduction from the power system to the spacecraft can occur due to conduction through the mounting structure and radiation from those elements of the power system which are higher in temperature than the spacecraft elements.

Two basic structural mounting systems are:

- (1) Support the BIPS internal assembly from the high temperature end of a cylindrical radiator and attach the power system to the spacecraft at the low temperature end of the radiator using appropriate interface structure to mate with the spacecraft hard points.

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- (2) Support the BIPS internal assembly using a truss configuration attached to the hard points of the spacecraft. Support the radiator from the internal BIPS structure and the BIPS mounting truss. Orient the radiator with the low temperature end adjacent to the spacecraft.

The spacecraft is assumed to have an average temperature of 20°C (68°F). The low temperature end of the radiator will be less than -12°C (10°F). Therefore, even with a direct attachment of the radiator to the spacecraft, heat would not be conducted from the radiator to the spacecraft. It is more likely that heat would be conducted from the spacecraft to the radiator. For this reason, it may be more desirable to thermally isolate the radiator from the spacecraft as much as possible by employing the second mount method described above. A rough approximation of the heat conducted from the hot parts of the BIPS to the spacecraft can be made by making the following assumptions:

Number of truss members	12
Length	76 in.
Diameter	1.25 in.
Wall thickness	0.04 in.
Material	Aluminum
Hot end of truss (conservative)	300°F
Spacecraft end of truss	68°F
Thermal conductivity	31.6 Watts/ft ² /°F/ft

The resultant heat flow is:

$$Q = C \frac{A}{L} \Delta T$$

$$= 15 \text{ Watts}$$

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The use of other materials such as titanium would result in even lower heat flow rates.

Radiation heat transfer from the power system to the spacecraft is expected to be less than 100 watts if no shielding is employed. However, the radiation heat transfer between the power system and the spacecraft can be significantly reduced by a simple thermal barrier of multifoil placed at the interface between the power system and the spacecraft. As an example, Figure 3.6.2-1 shows the heat transfer through a foil barrier eight feet in diameter having the cold side at 20°C (68°F) and the hot side at 93°C (200°F) and 120°C (250°F). From inspection of Figure 3.6.2-1, it is apparent that the radiant heat transfer can be readily maintained below 50 watts using a relatively thin, lightweight radiation barrier if necessary.

Based on these considerations, it is not anticipated that heat transfer from the power system to the spacecraft will present any problems.

TYPICAL HEAT TRANSFER THROUGH A FOIL BARRIER

Figure 3.6.2-1

3.6.3

Dynamic Capability

This factor covers the ability of the power system to survive without damage the launch vibrations that it will see in use. Test and/or analysis should be conducted in the same operating mode that it is intended the system be launched.

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3.6.3 Dynamic Capability

RATING = 0

REF: VOLUME I, BOOK 3
SECTIONS 2.7.3 and 2.7.4

SUMMARY OF RATIONALE FOR RATING

The dynamic vibration environment imposed on the BIPS is due to the lift-off acoustic field, aerodynamic excitations, and transmitted structure-borne vibration. The cantilever-mounted BIPS is designed to have the minimum natural frequencies adequately separated from the spacecraft's fundamental frequencies. This will ensure the power system will survive without damage during space shuttle powered ascent.

TECHNICAL DISCUSSION

The BIPS consists of a cylindrical radiator within which four discrete masses are supported by means of interface structure consisting of beams and struts. The four discrete masses are; two heat source assemblies, recuperator, and Mini-BRU power package. As currently defined, the BIPS will be mounted to the spacecraft, which could be mounted to the interim upper stage (IUS). The IUS would be mounted in a cradle or carrier in the space shuttle orbiter. This series of components comprises the orbiter payload. The Space Shuttle and IUS specifications imply that the payload is cantilever-mounted, from the orbiter mount points when in the stowed configuration.

The principal source of structural vibration occurs during Space Shuttle powered ascent. Principal vibration levels the BIPS will experience depend on the payload dynamic response to orbiter vibration with the payload in the stowed configuration.

The principal source of shock occurs when using pyrotechnic devices on the IUS vehicle, such as that used for spacecraft separation.

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Principal shock levels the BIPS will experience depend on the payload dynamic response to pyrotechnic explosions, with the payload in the deployed configuration.

Shock and vibration levels at various interfaces, as estimated for conceptual design by the various referenced sources, as shown below.

(a) Peak Random Vibration Levels

- o Shuttle Vehicle Payload Interface (Reference 1) - $0.1 \text{ g}^2/\text{Hz}$ (90 to 275 Hz) estimated response for an unloaded interface structure. Actual response should be lower due to mass of payload.
- o IUS-Spacecraft Interface (Reference 2) - $0.125 \text{ g}^2/\text{Hz}$ (100 to 1000 cps) recommended for conceptual design.
- o BIPS-Spacecraft Interface (Reference 3) - $0.1875 \text{ g}^2/\text{Hz}$ (900 to 1400 Hz) GE estimate based on LES 8/9 and Voyager experience.

These vibration levels appear to represent a vibratory amplification through the payload. However, the levels are assumed to be estimates of the three reference sources that were determined independently. It will not be known whether the vibratory input to the payload will be amplified or attenuated until the total payload structure is defined and total payload dynamic analyses are conducted.

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PHOENIX, ARIZONA(b) Peak Shock Levels

- o IUS-Specification (Reference 2, Figure 6) - The shock response spectra give a dynamic response of 115 g at the IUS-Spacecraft interface with a "Q" equal to 10 for a 100 Hz system. Although the BIPS response to shock at the IUS-Spacecraft interface is undefinable at this time, it will be attenuated due to cantilever mounting and remoteness from the interface.
- o GE Specification Recommendations (Reference 3) - 50-g dynamic response for the Isotope Heat Source, and support structure and the HSA housing and 25-g dynamic response for the overall BIPS structure, based on a shock response to a 775-g half sine pulse of 0.2 millisecond duration.

As noted above, actual shock and vibration levels the BIPS will experience depend on payload dynamic responses to the principal sources of excitation.

The Space Shuttle is well defined, and the BIPS is conceptually defined. However, the spacecraft, IUS, and IUS support structure to the shuttle craft, are currently undefined except for the decision to utilize a solid rocket motor. It is anticipated that the solid rocket motor and structure will possess a high degree of stiffness. Because of many unknowns, no meaningful dynamic analyses can be made, at this time, for predicting BIPS, vibratory and shock responses. However, criteria do exist that require system dynamics to maintain BIPS responses within tolerable structural design limits. These are:

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- (a) The cantilevered payload support structure must be designed to avoid coupling payload and Space Shuttle fundamental frequencies. To avoid this interaction the cantilevered payload fundamental frequencies should be at least two times greater than Space Shuttle fundamental frequencies. The shuttlecraft fundamental frequency range is estimated to be within 3 and 13 Hz. Therefore, the fundamental of the cantilevered payload should not be less than 24 Hz.
- (b) Support structures of BIPS discrete masses should be designed to avoid coupling the cantilevered payload fundamental frequencies with the rigid body fundamental frequencies of the BIPS masses. This means that BIPS components fundamental frequencies should be approximately 60 Hz.
- (c) Criteria (a) and (b) define cantilevered payload and BIPS components fundamental frequency limits. However, it is desirable to maintain the upper limits of natural frequencies no higher than necessary to satisfy (a) and (b), and to minimize BIPS components dynamic responses to shock and vibration. It is anticipated that the cascade of components, comprising the cantilevered payload, will respond to shock as a succession of simple systems, when each succeeding structure has a low mass relative to the next supporting structure.

Design Results

BIPS FS components (i.e., HSA, MBR, Mini-BRU) and mounting pads have been designed to a minimum limit loading of 50 g. BIPS interface structures (i.e., struts, beams, etc.) have been designed to a

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minimum limit loading of 25 g. These loads are applied simultaneously at the center of the component in the X, Y, and Z directions. The higher acceleration loading requirement provides increased structural integrity for BIPS components and mount pads. This is needed to compensate for the lower degree of mounting redundancy than the interface support structure (i.e., beams and struts). In the case of a statically determinate mounted component such as the MBR, failure of a single mount could result in separation of the component, whereas the interface structure is a many times redundant system capable of tolerating a number of member failures without total failure. The design criteria of providing sufficient stiffness to the BIPS interface structure, to maintain BIPS component natural frequencies above 60 cps, will inherently result in high strength for the structure.

In fact, the built-in strength exceeds 25 g. This limit loading should satisfy requirements for all other loadings such as pre-launch, launch, and operational environments, and in the case of an abort mission, crash landing requirements. This design criteria is adequate for the BIPS preliminary design phase. After IUS and spacecraft definitions, dynamic analyses will be conducted on the orbiter cantilever-mounted payload, and the payload as deployed from the orbiter. The cantilevered payload and support design should minimize the BIPS dynamic response. Considerable latitude exists in designing the payload structure to minimize BIPS dynamic loading.

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Foil Insulation

General Electric has subjected the MULTI-FOIL thermal insulation to the expected shock, vibration and acceleration launch vibrations. No change in the thermal characteristics of the MULTI-FOIL could be detected. Because of its layered structure, any deformations during launch would be expected to spring back as soon as the unit is in orbit. There is no evidence from either the heat flux tests at Thermo Electron or the Workhorse Loop tests at AiResearch that launch depressurization of the MULTI-FOIL insulation constitutes a problem. If any evidence of a launch depressurization problem should appear, it will be solved by: (1) random holes in the foil to increase its permeability and (2) a retaining wire structure to accommodate the pressure differential.

3.6.4 Torque Effects

Dynamic power systems have the potential of transferring excessive amounts of torque to a spacecraft and overwhelming its attitude control system, either as a result of load following or because of speed oscillations in the speed control system. The power plant must be designed to minimize these effects. The effect is evaluated in terms of the maximum angular impulse that is transmitted to the spacecraft by the power system during all normal operations.

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RATING = +9

REF: VOLUME I, BOOK 3
SECTION 2.7.3SUMMARY OF RATIONALE FOR RATING

The angular impulse imposed on the spacecraft by the BIPS is easily calculated and is primarily a function of the long term decrease in speed due to isotopic decay.

TECHNICAL DISCUSSION

The Mini-BRU will have speed variations due to the following causes:

- 1 - Control Accuracy ± 10 rpm
- 2 - Sink temperature variations (± 20 rpm)
- 3 - Decay of the isotopic heat source
(linear decrease of 1800 rpm over the 7 year period)
- 4 - 100 percent user load change (± 2.5 rpm)

Of the changes due to the control, these will be updated and corrected over a 0.050 second time span. The period of the speed change due to sink temperature variations will be twice per day; the speed will increase as the BIPS view factor of the sun decreases and decrease as the solar heat load on the radiator increases.

$$\Delta \text{ Angular Impulse} = \int_{t_1}^{t_2} T dt = \int_{t_1}^{t_2} I \alpha dt = \Delta \text{ Angular Momentum}$$

As can be seen from the equation, angular impulse is solely the function of the largest speed change that the system will see.

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From the four sources listed above, the maximum speed change is 1833 rpm or 3.5 percent of the nominal operating speed. The nominal angular momentum is 0.5763 lb-ft-sec and the angular impulse is 3.5 percent of 0.5763 lb-ft-sec, or 0.02 lb-ft-sec.

3.6.5

Hardenability

Ability to survive nuclear attack may be a concern in some future satellite systems. The critical damage mechanism is likely to be damage to the emissivity coating from the radiator. This factor will therefore be based on the loss in power output caused by complete loss of the coating from 50% of the radiator surface.

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RATING = +4

REF: VOLUME I, BOOK 3,
SECTION 2.3.3 AND 2.7.3SUMMARY OF RATIONALE FOR RATING

The off-design performance program was used to model the loss of half of the radiator coating. The control will hold the turbine inlet temperature at the set point and allows the output power to decline to its natural level. The radiator base material is assumed to be anodized aluminum; the emissive coating is Sl3G or Silicated ZnO. The coating has an emissivity of 0.92 and absorptivity of 0.12 to 0.16, the anodized surface has an emissivity of 0.8 and an absorptivity of 0.16. Two primary effects will occur when the radiator coating is lost: first, compressor inlet temperature will increase by 20° because of increased sink temperature and decrease emissivity and second, rotor speed will increase by about 1000 rpm to maintain the turbine inlet temperature set point with fixed gas inventory and thermal input. The output power will decrease because of these two reactions by some 80 watts or 6.2 percent.

The system design should permit a simple and convenient operation of fueling the system at the launch site and checking out performance prior to mating with the launch vehicle. The spacecraft contractor should have the option of checking the spacecraft under nuclear power. The system must allow for reasonable hold periods before and after mating with the launch vehicle. Technicians should have reasonable access to the spacecraft with the power system installed. These functions should not require extensive and specialized support equipment. The design is to be evaluated by the performance factor scale in the three characteristics listed,

the three performance factors added, and the sum multiplied by the significance factor.

The characteristics are: 1.) Fueling, unfueling possible with ease; 2.) Necessary access possible without undue personnel exposure; 3.) Ground check-out of power system and spacecraft possible.

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3.6.6. Ground Handling

RATING = +5

REF. VOLUME I, BOOK 3
SECTION 5

SUMMARY OF RATIONALE FOR RATING

The BIPS system design has been configured to permit ease of access for fueling and unfueling. Fueling station design and use minimizes radiological exposure to personnel. Ground checkout of the power system at partial power can be performed at acceptable cost in labor and facilities. These costs may be uncomfortably high for launch site ground checkout of the system at full power if a vacuum facility is not available at the launch site.

TECHNICAL DISCUSSION

The BIPS system design permits a convenient method for fuel loading of the HSA's at the launch site. The HSA's are located at the upper end of the radiator, opposite the spacecraft interface, offering an unobstructed access for fuel loading. Fuel loading thus can be accomplished prior to or after PCS mating with the spacecraft. Due to radiological safety considerations, the fuel loading sequence will be performed using a Mobile Loading Chamber (MLC). The MLC will mate to the upper flange on the HSA and provide a containment envelope for environmental control and radiological safety during fuel loading or unloading. This approach offers both an acceptable cost in facilities and minimizes possible radiological exposure to personnel. It also offers relative ease of fueling and unfueling due to the minimum interface requirements with the BIPS.

The system with the BIPS mated to the spacecraft will permit limited physical access to the upper spacecraft surfaces due to the relative close spacing of the radiator of the spacecraft. Technicians will have complete access to all other spacecraft surfaces. Exposure

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to such personnel will be minimized due to the relative distance of the HSA's with respect to the BIPS spacecraft mating interface.

Spacecraft checkout under nuclear power could be accomplished at full power if a vacuum facility capable of housing the BIPS spacecraft system is available. The cost of building a new vacuum facility may be quite high if that is required at the launch site. To obviate the requirement for such a facility, it is recommended that the BIPS be run at partial power for a nuclear powered checkout of the spacecraft. This could be accomplished by enveloping the BIPS spacecraft in a tent/cocoon to provide a containment envelope for environmental control. This envelope would be purged and backfilled with a low thermal conductivity cover gas to provide a suitable atmosphere for the multi-foil insulation. In addition, a radiator cooler may be required to attain proper thermal balance of the system during checkout. HSA thermal balance will be controlled by a similar cover gas and the HSA ground cooling module. This approach would result in considerable savings in facility costs.

Ground checkout of the spacecraft at full power would be accomplished through use of an auxiliary power supply. As an option, this power supply could be part of the launch vehicle payload (but not part of the separation payload) and serve the dual purpose of spacecraft on-pad checkout and BIPS start-up in space.

The system design allows for an indefinite holding period after fueling of the HSA's. This possibility exists as a result of the use of the HSA cooling module. This module will maintain acceptable temperatures on the system before and after mating with the launch vehicle. For additional protection of the system during holding periods prior to mating to the launch vehicle, the BIPS spacecraft system can be held in a sealed storage container which would be purged and backfilled with inert gas. During storage, thermal control would be maintained by the HSA cooling module and also a storage container cooling system if required. Typical flow plans for factory to flight operations are shown in Figures 3.6.6-1 through 3.6.6-7. A conceptual design of the MLC is depicted in Figure 3.6.6-8.

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FIGURE 3.6.6-1
GROUND FLOW PLAN OVERVIEW

FIGURE 3.6.6-2
GROUND FLOW PLAN
IHS SHIPMENT FROM FUELING AGENCY TO BIPS CONTRACTOR

FIGURE 3.6.6-3
BIPS FLIGHT ACCEPTANCE TEST FLOW PLAN

FIGURE 3.6.6-5
GROUND FLOW PLAN
SPACECRAFT INTEGRATOR'S FACILITY

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FIGURE 3.6.6-6
GROUND FLOW PLAN - LAUNCH SITE

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NOMENCLATURE

SAEF	SPACECRAFT ASSEMBLY AND ENCAPSULATION FACILITY
PCS	POWER CONVERSION SYSTEM
EHSD	ELECTRIC HEAT SOURCE - DYNAMIC
IHS	ISOTOPE HEAT SOURCE
SC	SPACECRAFT OR SHIPPING CONTAINER OR STORAGE CONTAINER
ISB	ISOTOPE STORAGE BUILDING
PCR	PAYLOAD CHANGEOUT ROOM
LC	LAUNCH COMPLEX
EHFS	ELECTRICALLY HEATED FLIGHT SYSTEM
MLC	MOBILE LOADING CHAMBER
FA	FUELING AGENCY
VFSC	VALLEY FORGE SPACE CENTER
ETR	EASTERN TEST RANGE
IF	INTEGRATOR FACILITY

(LEDF)

FIGURE 3.6.6-7
TYPICAL FLIGHT OPERATIONS SEQUENCE

MOBILE LOADING STATION (MLS)
CONCEPTUAL DESIGN
FIGURE 3.3.6-8

PART NO. 31-2845		REV. 1		DATE 10/1/68	
DRAWN BY: [blank]		CHECKED BY: [blank]		APPROVED BY: [blank]	
TITLE: MOBILE LOADING STATION (MLS) CONCEPTUAL DESIGN		PROJECT NO. 31-2845		PAGE 1 OF 1	
SCALE: NONE		UNIT: IN - LBS		SHEET: 1 OF 1	

3.7.1

Milestones on Schedule

The performance of the contractor on the GDS program is a strong indicator of his probable performance on the flight systems program. The success of the follow-on program is strongly related to the effectiveness of the contractor. This factor considers his ability to maintain schedule on the GDS program; evaluation is based upon the cumulative percentage overrun or underrun in time of all major scheduled accomplishments. Rescheduling due to design changes is allowable but rescheduling in acknowledgment of slippages is not; basis reverts to the original schedule.

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3.7.1 Milestones on Schedule

RATING = -3

REF: None

SUMMARY OF RATIONALE FOR RATING

The GDS Phase I program schedule was lengthened two months due to three major events:

1. Change from columbium to superalloy ducting, HSA, etc.
2. Addition of the workhorse loop to the program.
3. More stringent Quality Assurance requirements than anticipated.

While these additional tasks involved a considerable increase in the program effort, program rescheduling and replanning resulted in an accommodation of this effort approximately within the original schedule. While it is difficult to separate the discreet effect of the additional tasks from the effects of the WHL assembly delay and the schedule perturbation resulting from bearing problems, a two-month schedule slippage has been acknowledged.

$$\begin{aligned}\text{Overrun percent} &= \frac{\text{Overrun Months}}{\text{Total Program Months}} = \frac{2}{35} = 5.7 \text{ percent} \\ &= \text{Performance Factor} = -3\end{aligned}$$

3.7.2

Cost Control

This factor is simply the percentage overrun or underrun in dollars of the original cost estimate. Program changes arising out of requirement changes or by direction of ERDA are to be added to the cost estimate. Negotiated changes necessitated by deficiencies in the original concept or its execution are to be considered as overrun.

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3.7.2 Cost Control

RATING = -2

REF: None

SUMMARY OF RATIONALE FOR RATING

The Phase I cost growth is considered to be primarily related to program changes arising out of requirement changes that evolved during the course of the program. That growth which occurred as a result of workhorse loop and bearing problems falls more logically in the cost overrun category. This amounted to approximately \$250,000 Operating, as invoiced to the Government.

$$\text{Overrun} = \frac{\text{Overrun } \$250}{\text{Total Program Costs } \$7,139,839} = 0.035$$

Hence, Performance Factor = -2

TECHNICAL DISCUSSION

The Phase I funding history is shown below.

BIPS FUNDING HISTORY

ITEM	DATE	OPERATING	FIXTURES	TOTAL
Basic Contract	6-13-75	\$4,809,797	\$775,845	\$5,585,642
WHL, Mod. 4	9-8-76	<u>54,926</u>	<u>59,994</u>	<u>114,920</u>
SUBTOTAL		\$4,864,723	\$835,839	\$5,700,562
Advanced Development Add-Ons, etc., Mod. 7	2-8-77	<u>144,175</u>	<u>-0-</u>	
SUBTOTAL		\$5,008,898	\$835,839	\$5,844,737
WHL Testing, etc., Mod. 11	3-11-77	<u>79,963</u>	<u>-0-</u>	
SUBTOTAL		\$5,088,861	\$835,839	\$5,924,700
Superalloy HSA, Mod. 12	4-1-77	<u>419,893</u>	<u>-0-</u>	
SUBTOTAL		\$5,508,754	\$835,839	\$6,344,593
Mod. 16:	3-78			
Working Fluid Management, etc.			99,161	
Vacuum Tank Feed-Thrus			25,000	
Superalloy System		670,192		
Overrun		<u>249,980</u>		
SUBTOTAL		\$6,428,926	\$960,000	\$7,388,926

The major program changes involved the use of superalloys versus columbium and the addition of the workhorse loop (WHL). The last task shown on the table reflects the overrun resulting from WHL assembly and bearing related problems.

AiResearch and GE did cost share during Phase I. AiResearch provided \$238,000 to minimize the impact of WHL and bearing problems and the preparation of the Phase II Plan. In addition, AiResearch devoted considerable indirect Quality Assurance related effort to support the more stringent than anticipated QA requirements. GE contributed the expense of their Phase II Plan preparation and support to resolve the bearing problem.

3.7.5

Unresolved Problems

It is possible that review of the two development programs at the end of the GDS test program may reveal residual problems not previously considered. Alternately, test results may reveal that solutions previously considered to be adequate are not adequate at all. To the extent that such problems are not covered elsewhere, they are to be considered here. Since they are not presently definable, the degree of penalty to be levied must be left largely to the judgment of the Evaluation Board. Each problem that is recognized by the Board to be an independent problem not previously considered,

is to be reviewed and evaluated separately.

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3.7.5 Unresolved Problems

RATING = -10

REF: VOLUME I, BOOK 3
SECTIONS 2.4.3 AND 3.0

SUMMARY OF RATIONALE FOR RATING

The only problem associated with the BIPS at this time is with the journal bearing system. A comprehensive program is currently underway at AIRPHX, AIRLA, NASA-LeRC, and BCL to resolve the problem.

The problem is categorized as moderate because of the extensive history of trouble-free operation of bearings of the same basis design.

TECHNICAL DISCUSSION

As discussed in Attribute Section 3.1.3.4, the selected bearing design is particularly well suited to this application based upon past performance.

The bearing was operated for over 50 hours in the loop when failure occurred. An extensive program is underway to characterize the failure mode and develop a cure. This program involves personnel from organizations noted in the summary as well as GE and Sandia.

Because of the dynamic nature of the problem a complete presentation is deferred until the final presentation.