AIRESEARCH MANUFACTURING COMPANY OF ARIZONA
A DIVISION OF THE GARRETT CORPORATION

PRELIMINARY RELIABILITY
ALLOCATION AND ESTIMATION
BRAYTON ISOTOPE POWER SYSTEM

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A DIVISION OF THE GARRETT CORPORATION
PHOENIX, ARIZONA

BRAYTON ISOTOPE POWER SYSTEM
PRELIMINARY RELIABILITY ALLOCATION AND ESTIMATION

The purpose of this document is to present a summary of the Brayton Isotope Power System (BIPS) from the standpoint of its potential for long and reliable operation.

A five year reliability of 0.95 has been established by the BIPS developer, AiResearch, as an objective. In Table 1 is a summary of the system features which will contribute to the achievement of that objective. Table 2 contains a summary of the maximum failure rates allocated to each of the subsystems comprising the BIPS, as well as the failure rates presently estimated. Table 2 also indicates the 5 year point reliability probabilities associated with the failure rates.

The following pages contain the supporting rationale for the preliminary reliability estimates. These estimates will undergo continual revision as more data is accumulated.

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BIPS - FS

HIGH RELIABILITY AS RESULT OF:

o SOLID TECHNOLOGY BASE

- ✓ 15 years Closed Brayton Cycle Experience by AiResearch
- ✓ Mini-BRU and MBR are Second Generation Designs with proven ancestry (>32,000 hour testing by NASA)
- ✓ Extensive Materials Test Program underway (ORNL, NASA-LeRC, BCL)

o CONSERVATIVE DESIGN

- ✓ Only one moving part (constant speed Mini-BRU) and no rubbing contact
- ✓ Compressor and turbine have low tip speeds/are lightly stressed
- ✓ Alternator is brushless and has no rotating windings
- ✓ Bearings are essentially frictionless, gas foil type

TABLE 1

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BIPS - FS (Contd)

- ✓ Utilizes fully developed and flight operational isotope heat source
- ✓ Solid state control system utilizes derated and redundant components
- ✓ Closed loop contains clean, single phase, non-corrosive working fluid (helium/xenon Mixture)
- ✓ BIPS operates at constant temperatures and pressures
- ✓ Extensive design analyses with computer models verified by test results
- ✓ System can tolerate leakage far in excess of max allowable for components
- CLOSE QUALITY CONTROL
 - ✓ Quality assurance program meets exacting standards of ERDA for space nuclear systems
 - ✓ 100% inspection of all components and all assembly operations

BIPS - FLIGHT SYSTEM

PRELIMINARY RELIABILITY ALLOCATION/ESTIMATION

SYSTEM GOAL = 0.95 AT 5 YEARS

Subsystem	Failure Rate	R at 5 Years Allocated/ Estimated
	$\times 10^{-9}$ *Allocated/ Estimated	
MINI-BRU	229/173	0.990/0.992
RECUPERATOR (MBR)	125/125	0.995/0.995
HEAT SOURCE ASSEMBLY (HSA) - (2)	125/125	0.995/0.995
SPACE RADIATOR	229/229	0.990/0.990
CONTROLS	229/229	0.990/0.990
LOOP CONTAINMENT (JOINT INTEGRITY)	100/110	0.996/0.995
DUCTING AND BELLOWS	134/134	0.994/0.994
SYSTEM	1171/1125	0.950/0.952

*For failure rate justification and rationale, see following pages.

SYSTEM/ SUBSYSTEM	COMMENTS	FAILURE RATE X 10 ⁻⁹	
		ALLOCATED	ESTIMATED
Mini-BRU	<p>Culminates 15 years of development effort</p> <p>Previous-generation NASA 10 KW_e BRU accumulated 21,208 hours (>32,000 hours total on three units) with no degradation in performance.</p> <p>(Distribution of failure rate by sub-component discussed below)</p>	229 (Equates to R = 0.990 @ 5 yrs.	
Turbine (Mini-BRU)	<p>Very conservative design - small diameter results in low tip speed.</p> <p>Design factor of safety: $\frac{\text{MIN. BURST SPEED}}{\text{MAX. OPERATING}} = 3.5$</p> <p>Stress Rupture - Life calculated to be $>10^8$ hours ($\lambda_s = 10^{-8}$)</p> <p>Creep (wheel touches shroud) - calculated to be 0.1% in 7.43×10^6 Hrs.</p> <p>At this rate, probability of touch is ~ Zero in 10 yrs ($\lambda_c = 10^{-8}$)</p> <p>High cycle fatigue - Test for fundamental frequency has confirmed design predictions thereby reducing probability of failure mode comparable to that of stress and creep failure modes ($\lambda_f = 10^{-8}$)</p> <p>(Five year) $R = e^{-\lambda t} = e^{-t(\lambda_s + \lambda_c + \lambda_f)} = e^{-43,800 (3 \times 10^{-8})} = 0.99869$</p> <p>$\lambda_{\text{total}} = 3 \times 10^{-8}$ failures/hr</p> <p>Turbine operates in exceptionally clean, sealed working fluid environment - not subject to corrosive effects and foreign object damage suffered by open cycle engines.</p> <p>Inspection of NASA-BRU after 21,208 hours operation disclosed no structural defects or surface deterioration.</p>	30	30

SYSTEM/ SUBSYSTEM	COMMENTS	FAILURE RATE X 10 ⁻⁹	
		ALLOCATED	ESTIMATED
Compressor (Mini-BRU), includes ra- dial wheel (impeller) diffuser, and shroud	<p>Very conservative design - like the turbine, the small diameter results in low tip speed and, hence, low stress.</p> <p>Blade Stress - Impeller is understressed by factor of >5 to 1 (Max stress occurs in discharge region; calculated to be 10 ksi @ 120% speed. Standard practice calls for stress not to exceed 1/2 yield stress at tip region; impeller is SS410 with yield strength of 99 ksi @ 100°F).</p> <p>Disk Stress - Burst margin at 62,400 rpm (120% speed) = 3.83</p> <p>Blade vibration - if $\frac{\text{Fundamental Freq}}{\text{Rotational Freq}} > 4.5$, design is satisfactory Fundamental mode occurs at 27,977 cps $\frac{27,977 \text{ cps} \times 60 \text{ sec/min}}{52,000 \text{ rpm}} = 32.3$ Hence, blade vibration should be no problem.</p> <p>Deflection - Computer calculations show axial deflection (flowering) at the exducer to be 0.0015" and max axial displacement at the inducer to be 0.00038. (Radial displacements are generally smaller and less significant.) Tests have confirmed that interference is not a problem.</p> <p>Creep - Because of low temperature, creep is of no concern</p> <p>Low temperature operation, conservative design, and absence of credible failure modes suggest that failure rate is order of magnitude less than that estimated for turbine.</p> <p>Allocation - 30×10^{-9} failures/hr Predicted - 3×10^{-9} failures/hr.</p>	30	3

SYSTEM/ SUBSYSTEM	COMMENTS	FAILURE RATE X 10 ⁻⁹	
		ALLOCATED	ESTIMATED
Alternator (Mini-BRU) Includes rotor, stator, and electrical connecting lines	<p>Alternator is simple Rice 4-pole Brushless design</p> <p><u>Rotor</u> contains no windings</p> <p>Min. burst speed is twice design stress</p> <p>Development rotor was spun to 134,000 rpm with no growth detected (normal operating speed is 52,000 rpm). Each production rotor will be spun to 88,000 rpm.</p> <p><u>Stator</u> - Redundancy of field coils/excitation circuits assures that single point failure will not result in loss of alternator output.</p> <ul style="list-style-type: none"> - Close control of assembly process will ensure high quality of power windings. - Off-Gassing tests will confirm integrity of potting and insulating materials at operating temperature. - Tests are scheduled to verify calculated temperature distribution in stator. <p>Estimated failure rate of alternator was calculated (by modeling the alternator as field and stator coils and associated connectors) and found to be 5×10^{-9}.</p> <p>Allocation - 30×10^{-9} (includes connecting lines and terminals)</p>	30	5
Tie Bolt (Mini-BRU)	<p>Creep - Max. temperature is well out of range of concern</p> <p>Low Cycle Fatigue - Life calculated to be 10^5 cycles</p> <p>Load Relaxation - Minimum tie bolt load is approximately 4 times load required to prevent separation of the rotor.</p> <p>Tie-bolt stretch and load values will be measured to confirm calculated values.</p> <p>Relatively low operating temperature and high temperature alloys assures that creep is not a problem.</p> <p>Allocation - 10×10^{-9} Failures/hr</p>	10	10

SYSTEM/ SUBSYSTEM	COMMENTS	FAILURE RATE X 10 ⁻⁹	
		ALLOCATED	ESTIMATED
Foil Bearings (Mini-BRU)	<p>Two (2) Foil (Gas) Journal Bearings and one (1) Foil (Gas) Thrust Bearing support rotating group.</p> <p>Unlike ball bearings, a gas bearing has no moving parts in direct contact and consequently has theoretically infinite life. However, in actual practice, repeated start/stop cycles may reduce the coating, thereby increasing friction, until point is reached where loss of restart capability results. This mechanism of high starting torque is primary failure mode of a gas bearing. (However, many start/stop cycles are required to effect wear. In one laboratory test, 30,000 cycles failed to produce degradation of coating. After 40,000 cycles bare metal was exposed and starting torque had increased, but bearings were still operable.)</p> <p>Flight system will experience maximum of 10 start/stop cycles, hence coating wear is expected to be essentially zero.</p> <p>(Pivoted pad bearings in NASA BRU showed no discernible wear after 64 start/stop cycles and 21,208 operating hours.)</p> <p>AiResearch has accumulated following experience with foil bearings in air cycle machines (ACM) installed in DC-10 aircraft (3 machines in each aircraft):</p> <p>8,955,120 hours accumulated through February 1976</p> <p>Foil Journal Bearing MTBF - 456,164 hours F.R. = 2.192×10^{-6}</p> <p>Foil Thrust Bearing MTBF - 149,252 hours F.R. = 6.700×10^{-6}</p> <p>NOTE: Many of these failures are not primary bearing failures. In most instances, something else fails first. For example, ingestion of a foreign object results in damage to turbine. The resulting imbalance causes bearing failure.</p> <p>These DC-10 bearings operate in an open cycle machine in a relatively dirty environment. They are subjected to shock and vibration of aircraft operation. In airline operation, machines average one start/stop cycle for every 2 operating hours. ACM bearings are mass-produced and do not undergo 100% inspection.</p> <p>In contrast, the Mini-BRU Foil Bearings will operate in a closed cycle with clean gas as lubricant. Shock and vibration will be restricted to launch; engine will operate in zero-G space environment, at stable operating temperature, and will undergo minimal start/stop cycles. Finally, the bearings will have undergone many critical quality assurance inspections during fab and assembly.</p> <p>In view of these considerations, it is estimated that the Mini-BRU foil bearings will have failure rates at least two orders of magnitude better than the open cycle commercial aircraft experience. On this premise, the estimated failure rate becomes:</p>

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SYSTEM/ SUBSYSTEM	COMMENTS	FAILURE RATE X 10 ⁻⁹	
		ALLOCATED	ESTIMATED
Foil Bearings (Mini-BRU) (Contd)	<div> <div>2 Journal Bearings @ 2.192x10⁻⁸</div> <div>1 Thrust Bearing</div> <div> <div>4.384x10⁻⁸</div> <div>6.700x10⁻⁸</div> <div>Total- 11.084x10⁻⁸ failures/hr</div> </div> </div> <p>Past experience provides confidence that Mini-BRU bearings are, in fact, much better than this failure rate.</p>	114	110

SYSTEM/ SUBSYSTEM	COMMENTS	FAILURE RATE X 10 ⁻⁹	
		ALLOCATED	ESTIMATED
Structural Integrity (Mini-BRU)	<p>The Mini-BRU is structurally sound. The turbine plenum is the only component subject to question. C-103 was selected for the turbine plenum because of its excellent weldability, high temperature strength, and its fabricability. Adequacy of the present design is dependent upon the authentication of columbium alloy C-103 creep rupture data.</p> <p>An extensive materials testing program is already underway to develop a fundamental data base to permit:</p> <ul style="list-style-type: none">(a) An early determination of the limitations of using refractory alloys in a contaminating environment(b) An estimate of the permissible impurity concentrations in the system(c) An assessment of the oxidation/reduction reactions between C-103 and superalloys(d) A determination of methods (e.g., gettering, barriers, or substitution of other alloys) to avoid or to minimize the possibly damaging effects of impurities. <p>This test program is being conducted by NASA LeRC, ORNL, and BCL. It will either confirm the integrity of the existing plenum design or will provide data necessary for modifying the design so as to assure the long term life of the system.</p> <p style="text-align: center;">Allocation for structure - 15×10^{-9}</p>	15	15
	Mini-BRU Total	229	173

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SYSTEM/ SUBSYSTEM	COMMENTS	FAILURE RATE X 10 ⁻⁹	
		ALLOCATED	ESTIMATED
Recuperator (MBR)	<p>Primary failure mode of Heat Exchanger is low cycle fatigue. Sub modules (1/2 stack height + 1/2 flow length) of the MBR have undergone accelerated low cycle fatigue tests. The basic design has been modified to strengthen areas where leakage may occur after repeated start-up cycles.</p> <p>A prototype (first article, production quality) MBR will be subjected to repeated start/stop thermal cycles to verify cyclic life. The test cycle will be modeled to fit the startup transient(s) identified as being the most realistic and will include the transient ramp, a hold at design temperature and pressure for creep relaxation, the cool-down transient, and hold at ambient temperature. The prototype heat exchanger will be tested until a failure occurs or 200 cycles is reached. (Working fluid leakage, either internal or external, constitutes failure.)*</p> <p>Since flight system will experience maximum of 10 start/stop cycles, test is expected to demonstrate the design far exceeds cyclic life requirement. Once startup is accomplished MBR reaches and remains at constant temperature and pressure. The MBR has evolved from the experience gained from earlier generation recuperators developed for and extensively tested in the Navy's CCPS 40-1 engine and the NASA BRU program.</p> <p>Estimated failure rate 0.125×10^{-6} equates to $R=0.995$ @ 5 years. (RADC Nonelectronic Reliability Notebook lists ground heat exchangers with $F.R.=1.242 \times 10^{-6}$ hours. High quality space equipment can be expected to show at least an order of magnitude improvement.)</p> <p>* The thermal cycling may be restricted to 50 cycles in order to preserve the prototype for use as a spare MBR for GDS. Even so, this will subject the MBR to five times the expected life time thermal cycles.</p>	125	125

SYSTEM/ SUBSYSTEM	COMMENTS	FAILURE RATE X 10 ⁻⁹	
		ALLOCATED	ESTIMATED
Heat Source Assembly (HSA)	<p>Adequacy of Heat Source Heat Exchanger (HSHX) design is dependent upon:</p> <ul style="list-style-type: none">(a) Authentication of columbium alloy C-103 creep rupture data (including contamination effects)(b) Demonstration of the fabrication (diffusion welding) process and inspection techniques to assure the integrity of the HSHX. <p>Materials test program described in connection with the structural integrity of the Mini-BRU also applies to (a) above.</p> <p>HSA developer (GE) has programmed a series of trial parts to be diffusion welded. The assemblies will then be evaluated to determine that the fabrication method has been successful. The diffusion welding will utilize an autoclave at 2800°F and 15,000 psi. Ultrasonic inspection will detect unbonded fin segments as short as 0.050 inches (using calibrated known effects model). Other NDT methods are being considered as a means of detecting partial bonds. (It is to be noted that the outer cylinder of the HSHX is not in itself a pressure vessel. Its strength is dependent upon the integrity of the welded C-103 fins. While some debonding can be tolerated, debonding of adjacent fins will probably propagate, with hoop stress eventually causing rupture of the outer cylinder. The point is made that other designs are possible should the proposed design prove unfeasible. If need be, the outer cylinder can be increased in thickness in order to act as a pressure vessel, thus eliminating the diffusion welding of the fins. Alternatively, by increasing the number of fins one can retain the present wall thickness and safely tolerate multiple unbonding of fins. It has been shown that the latter course would result in a smaller weight penalty. Finally there are alternate designs available as back-up should the planned diffusion welding of the HSHX prove deficient.)</p> <p style="text-align: center;">Allocation - 0.125×10^{-6} (for 2 HSAs)</p> <p>(Weld integrity is included in "Loop Containment" allocation)</p>	125	125

SYSTEM/ SUBSYSTEM	COMMENTS	FAILURE RATE X 10 ⁻⁹	
		ALLOCATED	ESTIMATED
Space Radiator (BIPS)	<p>Radiator design is in an early conceptual stage. However, the design is based on AIRPHX experience gained under Air Force Contract AF33(657)-11721 to investigate closed-Brayton cycle components. A prototype radiator (3 feet in diameter and 4 feet long) was successfully tested in a space environment. Heat rejection performance exceeded predicted by 10 percent.</p> <p>Design consists of extruded aluminum (or beryllium) tubing forming the inlet and outlet headers with 32 finned tubes comprising the radiated surfaces.</p> <p>Each tube is protected against penetration by meteoroids. Radiator will be designed to NASA specification SP8013; sizing of components will provide probability of ≥ 0.99 that radiator survives micrometeoroids for 7-year mission. (F.R. = 0.164×10^{-6}).</p> <p>Surface coating will be selected for superior radiation heat transfer as well as resistance to degradation by solar or nuclear radiation.</p> <p>Emissivity coating will be selected in order to provide overall reliability of 0.99 for 5 years (i.e., R = 0.99 that radiator survives micrometeoroids and that emissivity loss does not adversely affect system performance.)</p> <p>Allocation 0.229×10^{-6} failures/hr.</p>	229	229

SYSTEM/ SUBSYSTEM	COMMENTS	FAILURE RATE X 10^{-9}	
		ALLOCATED	ESTIMATED
Controls (BIPS)	<p>A NASA LeRC electronic control system has been selected as the base-line design. This design has been analyzed using a computer program which utilizes logic derived from MIL-HDBK-217B data. Resistors and capacitors of highest known reliability values were used for the analysis. Upper quality, screened (MIL-STD-883C) and JANTXV semi-conductors were used wherever possible. Inherently redundant parasitic load resistor networks were incorporated. Special circuitry for paralleling monopole signals for redundancy was used to enhance the system reliability.</p> <p>Latest analysis indicates a reliability of 0.985 at 5 years.</p> <p>Through use of redundancy and component derating, there exists complete confidence that the goal of $R = 0.99$ at 5 years will be met or exceeded.</p> <p>Allocation: 0.229×10^{-6} failures/hr.</p>	229	229

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SYSTEM/ SUBSYSTEM	COMMENTS	FAILURE RATE X 10 ⁻⁹									
		ALLOCATED	ESTIMATED								
Loop Containment (BIPS Joint Integrity)	<p>System contains a large number of weld joints which must retain the working fluid. High reliability will result from high quality welding techniques and 100% inspection of welds. Components will be leak checked both separately and as a part of the integrated system. There are no seals in the system.</p> <p>A study performed by GE for JPL in 1974 calculated the total failure rate of all joints in the flight system, the failure of any one of which would result in loss of working fluid, to be 58.4x10⁻⁹ failures per hour which equated to R = 0.9974 @ 5 yrs. The GE report placed a high confidence level on this reliability estimate since it resulted from accumulated welding experience.</p> <p>AIRPHX has recalculated the earlier analysis using the up-to-date system configuration. Revised total failure rate is 110.1x10⁻⁹ failures/hr. which equates to 0.9952 @ 5 years.</p> <p>Increased confidence in the system's ability to retain the working fluid can also be gained from a review of the maximum allowable leakage rates of the components.</p> <p>NASA LeRC-developed components, used in the GDS, have specific maximum contractual leakage rates as follows:</p> <table><tr><td><u>Component</u></td><td><u>Rate (Standard CC He/Sec)</u></td></tr><tr><td>*Mini-BRU, each joint</td><td>1 x 10⁻¹⁰</td></tr><tr><td>MBR</td><td>1 x 10⁻⁷</td></tr><tr><td>HSA</td><td>1 x 10⁻⁹</td></tr></table> <p>*Since the Mini-BRU has 40 joints that could lose working fluid to space vacuum, the total maximum leakage rate through joint welds is 4.0x10⁻⁹. In addition, the Mini-BRU contains 12 hermetic connectors used for feed through of electrical and monitoring leads. Each connector may leak at the rate of 2x10⁻⁹ resulting in a total leakage rate through the connectors of 2.4x10⁻⁸. This, added to the joint leakage, results in a Mini-BRU total max leakage rate of 2.80x10⁻⁸.</p>	<u>Component</u>	<u>Rate (Standard CC He/Sec)</u>	*Mini-BRU, each joint	1 x 10 ⁻¹⁰	MBR	1 x 10 ⁻⁷	HSA	1 x 10 ⁻⁹	100	110
<u>Component</u>	<u>Rate (Standard CC He/Sec)</u>										
*Mini-BRU, each joint	1 x 10 ⁻¹⁰										
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HSA	1 x 10 ⁻⁹

SYSTEM/ SUBSYSTEM	COMMENTS	FAILURE RATE X 10 ⁻⁹															
		ALLOCATED	ESTIMATED														
Loop Containment (Contd)	<p>FS hardware can be expected to meet or exceed existing estimates of leak tightness. However, assuming that all FS components and joints leak at the maximum rates estimated for GDS components, the total loss rate is calculated as:</p> <table><thead><tr><th><u>Component</u></th><th><u>Rate (Standard cc He/Sec)</u></th></tr></thead><tbody><tr><td>Mini-BRU</td><td>2.80 x 10⁻⁸</td></tr><tr><td>MBR</td><td>1 x 10⁻⁷</td></tr><tr><td>2 HSA at 1 x 10⁻⁹</td><td>2 x 10⁻⁹</td></tr><tr><td>Space Radiator</td><td>1 x 10⁻⁹</td></tr><tr><td>Duct Welds (46)</td><td>4.6 x 10⁻⁹</td></tr><tr><td>Bellows (19 with 2 welds each)</td><td>3.8 x 10⁻⁹</td></tr></tbody></table> <p>Based on these rates the system total leakage rate is 1.394 x 10⁻⁷ standard cc He/sec. Since the allowable MBR leakage rate is 72 percent of the total, it may prove feasible to allow only a 1 x 10⁻⁹ standard cc/sec of He leakage rate in the FS MBR.</p> <p>A constant maximum leakage rate for five years will result in 21.98 standard cc total loss. This loss equates to only 0.0145 percent of inventory, since the FS contains 1.16 pounds (150,079 standard cc) of Xe/He (MW - 83.8) gas at standard conditions. The resultant effects of this loss are negligible.</p> <p>It is recognized that leakage rates do not normally remain constant, but rather, tend to grow with time. However, this is not considered a problem because the FS can tolerate leakage rates exceeding two orders of magnitude greater than the above noted maximum rate.</p>	<u>Component</u>	<u>Rate (Standard cc He/Sec)</u>	Mini-BRU	2.80 x 10 ⁻⁸	MBR	1 x 10 ⁻⁷	2 HSA at 1 x 10 ⁻⁹	2 x 10 ⁻⁹	Space Radiator	1 x 10 ⁻⁹	Duct Welds (46)	4.6 x 10 ⁻⁹	Bellows (19 with 2 welds each)	3.8 x 10 ⁻⁹		
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SYSTEM/ SUBSYSTEM	COMMENTS	FAILURE RATE X 10 ⁻⁹	
		ALLOCATED	ESTIMATED
Loop Containment (Contd)	<p>For example, assume the total working fluid loss after 5 years will be as high percentage wise as the thermal input reduction resulting from radioisotope decay. (Although technically impractical to achieve, this would represent an ideal condition because the turbine inlet temperature and system efficiency would remain constant.)</p> <p>It is estimated that thermal input will degrade to 96.13 percent after 5-years. An equivalent reduction in working fluid is 0.0387 x 150,079 cc, which equates to 5808 standard cc. This computes to a constant system loss of 3.68×10^{-5} standard cc He/sec, which is 264 times greater than the assumed 1.394×10^{-7} maximum rate. From this, it is obvious that the FS can tolerate an average maximum leakage rate exceeding 3×10^{-5} standard cc He/sec.</p> <p>The FS control system will compensate for thermal input, and working fluid decreases. This is accomplished by altering engine speed to maintain a constant turbine inlet temperature (T_6).</p>

SYSTEM/ SUBSYSTEM	COMMENTS	FAILURE RATE X 10 ⁻⁹	
		ALLOCATED	ESTIMATED
Ducting and Bellows (BIPS)	<p>Components comprising the BIPS are interconnected with ~ 287 in. of ducts and bellows. Duct sizes are 1.5 in, 1.6 in, and 2.5 in. OD; wall thickness ranges from 0.035 in. to 0.060 in. Temperatures range from 60°F to 1600°F; internal pressures range from 45 to 67 psia. Materials are Hastelloy-X, Stainless Steel (CRES), Beryllium, and Columbium Alloy C-103. Ducts formed from seamless tubing. The 19 bellows will be designed to compensate for centerline misalignment due to thermal expansion and lateral deflection.</p> <p>Zero stress at operating temperature.</p> <p>Bellows formed of seamless tubing.</p> <p>Two-ply design has been adopted. A two-ply bellows is superior to a single ply bellows because the length is shorter, the stiffness is less (lower flange loads), and, most importantly, it provides double containment. Bellows design criteria provides for short time proof pressures of 1.5 times the working pressure and burst pressures of 2.5 times the working pressure.</p> <p>The high temperature C-103 bellows will incorporate an inner sacrificial sleeve which will provide protection against contaminants in the loop.</p> <p>An accelerated test to demonstrate bellows reliability has been recommended.</p> <p>Allocation - 0.134×10^{-6} failures/hr. (Weld integrity is included in "Loop Containment" allocation)</p>	134	134