ENGINEERING REPORT

PHASE I

CONTROLS PRELIMINARY DESIGN

FOR

BRAYTON ISOTOPE POWER SYSTEM (BIPS)

76-311937

August 20, 1976

AIRESARCH MANUFACTURING COMPANY OF ARIZONA

A DIVISION OF THE GARRETT CORPORATION
PHOENIX, ARIZONA

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76-311937

REPORT NO. 76-311937

TOTAL PAGES 289

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ATTACHMENTS:

REV	BY	APPROVED	DATE	PAGES AND/OR PARAGRAPHS AFFECTED
	WK		8-20-76	Initial Issue

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Definitions, Abbreviations, Terms and Symbols

The following is a list of definitions, abbreviations, terms, and symbols used herein.

<u>Abbreviation</u>	<u>Definition/Term</u>
ADC	Analog Digital Converter
ALU	Arithmetic Logic Unit
CMOS	Complimentary Metal Oxide Semi-conductor
LSI	Large Scale Integration
NPN	Negative-Positive-Negative (Transistor Construction and Function)
PNP	Positive-Negative-Positive (Transistor Construction and Function)
ROM	Read Only Memory
TTL	Transistor/Transistor Logic

<u>Symbol</u>	<u>Definition/Term</u>
N	Turbine Speed
°R	Degrees Rankine
T ₆	Turbine Inlet Temperature
Q _{IN}	Isotope Power Input (Heat source)

Other equations are defined in the appropriate sections herein. In addition Table B17331 Revision 1 following, provides a list of abbreviations and acronyms peculiar to the Brayton Isotope Power System (BIPS).

B17331 Rev 1
BIPS PROGRAM

ABBREVIATIONS AND ACRONYMS

A		E	
ABS	Auxiliary Battery System	ECS	Emergency Cooling System (for HSA)
ACS	Auxiliary Cooling System (for HSA)	EHS-D	Electrical Heat Source - Dynamic
ACS	Attitude Control System	EHS-S	Electrical Heat Source - Static
AEC	Atomic Energy Commission (now ERDA)	ELS	Eastern Launch Site
AEC PR	Atomic Energy Commission Procurement Regulation	EMS	Material Specification (AirResearch Term)
AIRPHX	AirResearch, Phoenix	EOM	End of Mission
AIRLA	AirResearch, Los Angeles	ESD	Electronic System Division (of Air Force Systems Command)
AFSCF	Air Force Satellite Control Facility	ET	External Expendable Tank
AM	Amplitude Modulation	EPS	Electrical Power System
AOA	Abort-Once-Around	ERDA	Energy Research and Development Administration (Formerly AEC)
ASE	Airborne Support Equipment	EVA	Extravehicular Activity
ARS	Atmospheric Revitalization Subsystem	F	
ATO	Abort-To-Orbit	F	Fahrenheit Degrees
ATCS	Active Thermal Control Subsystem	FBS	Flight Battery System Required for Start in Orbit
a/o	Atomic Percent	FIB	Fuel Impact Body
B		FM	Frequency Modulation
BCL	Battelle Columbus Laboratory	FMA	Failure Mode analysis
BOM	Beginning of Mission	FMEA	Failure Modes and Effects Analysis
BIPS	Brayton Isotope Power System	FMECA	Failure Modes, Effects and Criticality Analysis
BRU	Brayton Rotating Unit	FPR	Federal Procurement Regulation
C		fps	Feet per Second
C	Celsius (Centigrade) Degrees	FS	Flight System
CCAFS	Cape Canaveral Air Force Station	FSA	Fuel Sphere Assembly
CCD	Configuration Control Document	FSAR	Final Safety Analysis Report
CCTV	Closed Circuit Television	FSE	Flight Support Equipment
CFM	Cubic Feet per Minute	FSEC	Fairchild Space and Electronics Company
c.g. or CG	Center of Gravity	FUO	Follow-up Output
CO2	Carbon Dioxide	FT	Feet, Foot
CRT	Cathode Ray Tube	FWW	Food, Water and Waste Management
CSI	Control Servo Input	G	
D		g	Acceleration Due to Gravity
DAS	Data Acquisition System	GDS	Ground Demonstration System - PCS + EHS-S
db	Decibel	GE	General Electric, Valley Forge
DC	Direct Current	GET	Ground Elapsed Time
DCS	Demonstrator Cooling System	GFE	Government Furnished Equipment
Delta-V or ΔV	Velocity Change in Feet per Second	GMS	Gas Management System
DOD	Department of Defense	GMT	Greenwich Mean Time
DOD STS	Department of Defense Space Transportation System	GN2	Gaseous Nitrogen
E		GN&C	Guidance, Navigation and Control
EAI	Engineering Assembly Instructions	GSE	Ground Support Equipment
EAFB	Edwards Air Force Base	GTC	Ground Test Console (a STE/GSE item)
EPFS	Electrically Powered Flight System (PCS + EHS-D)		
ECLS	Environmental Control and Life Support		

ABBREVIATIONS AND ACRONYMS
(CONTD)

H		M	
HIP	Hot Isostatic Press	MECO	Main Engine Cut-Off
HS	Heat Source (Same as and replaced by IHS)	MHW	Multi-Hundred Watt (AEC/GE IHS Technology)
HSA	Heat Source Assembly (Does not include IHS or EHS. Does include HSHX, structure, insulation, ACS and ECS.)	MHZ	Megahertz
HRHX	Heat Rejection Heat Exchanger (Radiator simulator for GDS)	MM	Millimeters
HSHX	Heat Source Heat Exchanger	MMD	Mean Mission Duration
HSIS	Heat Source Insulation System	MOS	Mission Operation System
HSS	Heat Source Simulator (Same as and replaced by EHS)	MR	Milliradians
HTGR	High Temperature Gas Cooled Reactor	MSS	Mission Specialist Station
		MW	Molecular Weight
I		N	
IBFS	Isotope Brayton Flight System	NA	Not Applicable
IBGDS	Isotope Brayton Ground Demonstration System (PCS + EHS-S)	NASA LeRC	National Aeronautical and Space Administration Lewis Research Center
IHE	Isotope Handling Equipment	NRA	Nuclear Research and Applications, Division of ERDA (formerly SNS)
IHS	Isotope Heat Source		
IMU	Inertial Measurement Unit		
IUS	Interim Upper Stage		
IVA	Intra Vehicular Activity		
J		O	
JPL	Jet Propulsion Laboratory (Pasadena, California)	OBP	Orbiter Processing System
JFC	Johnson Space Center (Houston)	OHA	Operational Hazard Analysis
K		ORNL	Oak Ridge National Laboratory
KB	Keyboard	OMS	Orbital Maneuvering Subsystem
Kbaud	Code Elements per Second in 1000's		
Kbps	Bits per Second in 1000's		
KSC	Kennedy Space Center		
KW _e	Kilowatts Electrical		
KW _t	Kilowatts Thermal		
L		P	
LASL	Los Alamos Scientific Laboratory	PCL	Power Conversion Loop (Use of PCS preferred)
LCC	Launch Control Center	PCM	Pulse Code Modulation
LES 8/9	Lincoln Experimental Satellite (No. 8 and 9)	PCR	Payload Changeout Room
LF	Load Factor	PCS I	Power Conversion System (HSA + BRU + MBR + Heat Sink + Controls + Piping and structure)
LH2	Liquid Hydrogen	PCS II	Power Conversion System (HSA + BRU + MBR + Radiator + Controls + Piping and Structure)
LiOH	Lithium Hydroxide	PGHM	Payload Ground Handling Mechanism
LO2	Liquid Oxygen	PHA	Preliminary Hazard Analysis
LPS	Launch Processing System	PLC	Parasitic Load Control System
M		P/L	Payload
M	Meters	PLCC	Payload Control Center
MARSCOM	Materials Review and Selection Committee	PLH	Payload Handling
MBR	Mini-Brayton Recuperator	PLM	Payload Management
Mini-BRU	350 to 2100 Watts Electrical Brayton Rotating Unit	POP	Perpendicular to Orbit Plane
MCC	Mission Control Center	PSAR	Preliminary Safety Analysis Report
MDM	Multiplexer-Demultiplexer	PSC	Power Supply Console (for RHS)
		PSC	Procurement Specification (AiResearch Term)
		PSE	Peculiar Support Equipment
		PSS	Payload Specialist Station
		PSSR	Preliminary System Safety Review
		PICS	Plutonium Isotope Containment Shield
		Q	
		QA	Quality Assurance

BI7331 Rev 1
BIPS PROGRAM

ABBREVIATIONS AND ACRONYMS
(CONTD)

R

RCS Reaction Control System
RCS Radiator Cooling System
REM Roentgen Equivalent Man
RF Radio Frequency
RM Remote Manipulator
RMS Remote Manipulator System
RSS Root Sum Square
RTLS Return to Launch Site
RTG Radioisotope Thermoelectric Generator
RTS Remote Tracking Station

V

VAB Vehicle Assembly Building
VAFB Vandenberg Air Force Base
VDC Volts Direct Current
VHF Very High Frequency
VRE Voltage Regulator Exciter

W

w/o Percent by Weight

S

SAMSO Space and Missile System Organization
SNS Space Nuclear Systems (now NRA)
SMAB Solid Motor Assembly Buildup
SRB Solid Rocket Booster
SRM Solid Rocket Motor
SSP Space Shuttle Program
SSME Space Shuttle Main Engine
SSS Space Shuttle System
SSPP System Safety Program Plan
SSV Space Shuttle Vehicle
STDN/
TDRSS Space Tracking and Data Network/Tracking Data Relay Satellite System
STE Special Test Equipment
STS Space Transportation System
SURVSATCOM Air Force Survivable Communication Satellite (now AFSATCOM III)

T

TACB Temperature of Cabin
TBD To Be Defined
TDRS Tracking and Data Relay Satellite
TECO Thermo Electron Corporation
TES Teledyne Energy System (formerly Teledyne Isotopes)
TIT Turbine Inlet Temperature
TV Television

U

ULT Ultimate Loads
USAR Updated Safety Analysis Report

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PHASE I
CONTROLS PRELIMINARY DESIGN REPORT
FOR
BRAYTON ISOTOPE POWER SYSTEM (BIPS)

1. INTRODUCTION AND SUMMARY

This report presents the Phase I preliminary design and test results summary for the BIPS control system, conducted under Contract E(04-3)-1123.

1.1 Scope

Included are the design considerations and influencing factors, analysis of the NASA controls (basic concept) with recommended modifications, and a discussion of an alternate approach to the NASA control system. A synopsis of these areas is as follows:

- o Design Considerations - Section 2 provides a detailed discussion of factors influencing the reliability, performance, cost, and weight goals of this program. Various hypothetical control methods are discussed to provide background for later detailed circuit and component discussions.
- o NASA Control System - Section 3 presents results of analyses and tests performed on a NASA control system provided to AiResearch under Contract E(04-3)-1123. Included for this system are reliability, performance, and weight data.
- o Recommended Modifications - Section 4 presents AiResearch recommendations for changes to the basic NASA control system, considered applicable to improving reliability performance and weight.

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- o Alternate Control System (Digital Design) - Section 5 presents results of a BIPS control-system design program, undertaken independent of the basic NASA control system. A detail design is not available at this time, however, directions that this digital design should take, including optimized reliability, performance, cost, and weight are provided. In addition a supplementary digital design program is provided in this section.

1.2 Summary

This report provides background analyses of three control systems capable of controlling BIPS speed, output voltage, and start rate.

Conclusions of all functions considered are summarized herein.

1.2.1 Design Goals

The initial task accomplished was determination of minimum required control system design goals as follows:

- (a) Reliability - To ensure that the BIPS will meet a design goal reliability of 0.95 for five years, the BIPS control system requires a reliability of 0.99 minimum. All reasonable attempts will be made to maximize reliability to obtain this goal.
- (b) Performance - Beginning of Mission (BOM) available user power is established by contract at 1.3 Kw. Although End of Mission (EOM) power is not specified AiResearch has established a goal of maximization of EOM power.
- (c) Power Quality - MIL-STD-704B, modified for a 120 vdc system, has been selected as the power quality design

goal. This goal is defined in detail in AiResearch Specification SC-76-312008. A copy is presented in Appendix I herein.

- (d) Weight - The control system weight design goal is 15 lbs maximum.

1.2.2 Control System Block Diagram

The three systems considered for the BIPS control function are represented on block diagram, Figure 1-1.

A start inverter connected to the alternator output terminals, provides a conditioned three phase signal of the correct voltage and frequency to motor the alternator to 50 percent of rated speed. At 50 percent the unit is self-sustaining and accelerates to 100 percent rated speed.

Prior to reaching 100 percent speed, the alternator field is excited by the voltage regulator, producing an alternator three phase ac voltage. This voltage is full wave rectified to produce 120 volts dc to the user load.

Speed control is effected by a parasitic load in parallel with the user's load. When the speed sensor detects a speed greater than that programmed, parasitic load will increase, thus reducing unit speed. Reduction in speed below the programmed setpoint results in a corresponding parasitic load reduction.

The load sensor senses user load plus parasitic load and serves to keep total load constant. A change in user load causes the load sensor to produce an offsetting change in parasitic load so that total load on the system remains at a value determined by the speed sensor.

SIMPLIFIED BLOCK DIAGRAM

FIGURE 1-1

1.2.3 Performance

BIPS performance with the controls considered can best be understood by referring to the generalized performance curve on Figure 1-2. This figure shows general trends that can be expected from the BIPS. Output power versus rotor speed is presented as a function of input isotope power (Q_{IN}) and turbine inlet temperature (T_6). As shown, a reduction in speed results in an increase in output power, assuming Q_{IN} remains constant, with an accompanying increase in T_6 . The nominal BOM operating point is that point which lies at the intersection of the $Q_{IN} = 4.8$ Kw line, BOM input power, and $T_6 = 2060^\circ R$ line, maximum allowable turbine inlet temperature. This results in an output power of 1.3 Kw at 100 percent rotor speed (52,000 rpm).

The NASA and the NASA modified controls are constant speed controls and will maintain speed close to 100 percent for the entire mission life. Thus, at the end of seven years, the EOM operating point lies at the intersection of the $Q_{IN} = 4.5$ Kw line (EOM input isotope power) and the 99.7 percent rotor speed line (to account for control droop). This operating point yields an output power of slightly greater than 1.1 Kw at $T_6 = 1920^\circ R$.

Assuming a T_6 sensor were incorporated to maintain T_6 at $2060^\circ R$ for the entire mission, the operating point would move from the BOM operating point to the EOM Q_{IN} line along the $T_6 = 2060^\circ R$ line. This would result in an EOM output power of approximately 1200 watts at a rotor speed of slightly over 97 percent. Locating a temperature sensor capable of operating at $2060^\circ R$ for seven years in a vacuum, at the reliability levels required proved to be a major task and a compromise digital control was investigated. This control, maintains speed constant until output power has reduced to EOM power and then holds power constant at this level until EOM. The digital control advantages are as follows:

BIPS PERFORMANCE VERSUS TIME

FIGURE 1-2

- (a) EOM power is maximized.
- (b) Turbine inlet temperature is well below maximum allowable for most of the mission, ensuring long turbine life.
- (c) No additional sensors need be added.

Detailed performance maps are shown on Figures 1-3 through 1-5. These maps show effects of speed and load control tolerances on available output power for each system evaluated. Control system comparison data is presented in Table 1-1.

1.3 Overloads

Two types of overloads have been considered:

- (a) User Overload - In the event of a user overload, parasitic load will first go to zero in an effort to maintain constant speed/power. When this fails to shed sufficient load, output voltage will be reduced. This reduction in output voltage will reduce output power to a level that can be safely handled by the machine at or near full rated speed. An overload indication will be provided to the user.
- (b) BIPS Induced Overload - Certain BIPS system malfunctions may produce reduced output capability, resulting in overload conditions while user load remains within limits. The control will first determine the new output power capability, and then compute new speed and power references. A certain amount of communication with the user load will be required to allow reduction of user load on a least priority first basis.

BIPS PERFORMANCE
CONTROL LINE PLOT
(ALTERNATOR ROTATING GROUP INPUT POWER EFFICIENCY)

FIGURE 1-3

BIPS PERFORMANCE
CONTROL LINE PLOT
(ALTERNATOR MAGNETIC AND MECHANICAL EFFICIENCY)

FIGURE 1-4

FIGURE 1-5

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Other methods of handling overloads are available and are easily incorporated into the digital control system. Increased consideration will be given to overload conditions when flight system requirements are completely defined.

1.4 Conclusions

Because of the marked improvement in user power available at BOM and EOM, the digital control has been selected as the baseline for both the GDS and IBFS. However, due to the expected long lead time of this control, an interim control consisting of NASA circuits with AiResearch modifications will be used to initiate GDS testing, to maintain the schedule. The NASA interim control will be replaced by the digital control when available.

1.5 Start Inverter Tests

Laboratory tests have indicated that either synchronous or induction start inverters will accelerate the rotating group to self sustaining speed. Total energy required for each start configuration is comparable.

A comparison of input power required to accelerate the unit to 20,000 rpm appears in Table 1-2.

The synchronous start shows more promise of being able to start the unit directly from shuttle power supplies, while induction starting requires a voltage boost. The synchronous start mode will be the prime system pursued. Testing will continue using both methods until verification that sufficient power is not available on the shuttle for the induction start mode, and that synchronous starting is fully realizable.

NASA start inverter testing will be conducted at a later date to determine dc power required for this start method.

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	NASA CONTROL	NASA/AIRESEARCH CONTROL	DIGITAL CONTROL
PERFORMANCE			
BOM	1.095 KW	1.250 KW	1.300 KW
EOM	0.915 KW	1.060 KW	1.200 KW
POWER QUALITY	SC-76-312008	SC-76-312008	SC-76-312008
RELIABILITY	0.9916	>0.9916	0.9971

BIPS CONTROL SYSTEMS COMPARISON DATA

TABLE 1-1

START MODES

MODE	VOLTS	AMPS	SECONDS TO 20K RPM	APPARENT POWER (VA)		APPARENT ENERGY (VA-SECONDS)
				PEAK	AVG	
INDUCTION	30 L-N	37.5	2.0	1950	1950	3837
SYNCHRONOUS	25 DC	8.4 DC	9.5	750	210	3570

BIPS CONTROL SYSTEM TEST PROGRAM

TABLE 1-2

2. DESIGN CONSIDERATIONS

2.1 Power Characteristics

Initial BIPS Mini-BRU power output specifications required that a definitive specification be established for the Mini-BRU alternator design, consistent with system design goals. Specification SC-76-312008 satisfies this requirement. A copy is provided in Appendix I to this report. This specification provides BIPS initial design voltage and frequency limits, consistent with user power output criteria. The specification generally conforms with MIL-STD-704B, dated 17 July 1975. Standards specified in MIL-STD-704B were interpolated to establish the 120 vdc requirements defined in SC-76-312008. Upon subsequent BIPS testing this document will be updated, as applicable.

2.2 BIPS Operating Performance Characteristics

A complete discussion of factors influencing BIPS short and long term stability and output capability is presented in Appendix II. This discussion should be consulted to provide a background for topics discussed in later sections of this report. The most significant conclusions of this discussion are listed below:

- o A speed error of 1-percent results in approximately 3.5 percent (45 watts in the case of a 2-HSA system) reduction of output power.
- o If speed is held constant at 100 percent for the entire mission life, the EOM operating point will have a speed of 100 percent, turbine inlet temperature of 1900°R, and output power capability of 1.1 kW.

- o If T_6 is held constant at 2060°F for the entire mission life, the EOM operating point will have a speed of 97.5 percent, turbine inlet temperature of 2060°R, and output power capability of 1.2 kW.
- o Total load on the system must be maintained at or above the user load rating at all times, to enable handling of a step application of user load.
- o Parasitic load is applied to the system in response to speed and total load errors. The unit operating speed dictates total load to be applied. Parasitic load adjusts to cause total load (parasitic plus user) to be equal to this value.
- o Incorporating a load sensor into the system effectively eliminates load transients from consideration, thus eliminating temperature transients within the loop.

BIPS performance characteristics are shown on Figure 2-1. Steady-state operating points are determined by observing available user power output [kW(u)] versus percent speed (N) value as a function of heat source (Q_{IN}) thermal energy. As speed is increased, output power capability decreases. This results in a stable system, since if an incremental load is removed from the system, the speed will increase along a constant Q_{IN} line resulting in output capability reduction until capability matches the system reduced load. This results in the new operating point.

2.2.1 Transient Performance

Transient performance is determined by observing kW values versus percent speed (N percent) as a function of turbine inlet temperature

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BIPS PERFORMANCE CHARACTERISTICS

FIGURE 2-1

(T_6). Should speed be allowed to increase while holding T_6 constant output power capability will increase. If load remains constant the unit will accelerate to an even higher speed, increasing the accelerating power available until the unit runs away. A decrease in speed (while holding T_6 constant) results in a decrease in output power, and assuming constant load, will result in engine shutdown.

2.2.2 Speed Control

Figure 2-2 shows required action for a speed control system capable of controlling BIPS long term and transient speeds. The control line drawn represents total system load as a function of speed only. The $Q_{IN} = 4.8$ kW line crosses the control line at 100 percent speed, 1305 watts output, and $2060^\circ R$. This represents the steady-state system operating point, since the system output power capability at $Q_{IN} = 4.8$ kW equals applied total load. Output power capability for speed transients will remain on the $T_6 = 2060^\circ R$ line with power applied being a control line function.

When speed in this system drops to 99 percent, output power capability drops to 1265 kW, (the intersection of $T_6 = 2060^\circ R$ and $N = 99$ percent.) System load applied by the speed control will drop from 1305 to 1100 watts output, (the intersection of the control line and $N = 99$ percent). In this instance, the system is underloaded by 165 watts. This is sufficient power to accelerate back to the system design match point of $N = 100$ percent and 1305 watts output.

The BIPS control requirement equates to controlling speed while undergoing transient changes in output load, (user load), input power source decay (Isotope), and radiator effectiveness changes (orbital position). BIPS controls speed by varying power delivered to the BIPS parasitic load, to compensate for differences between available power and user load.

BIPS PERFORMANCE (WITH CONTROL)

FIGURE 2-2

2.2.2.1 Speed Control (Load Application)

Consider the speed control loop shown on Figure 2-3. Assume a system operating at 100 percent speed; the system control applies 1.3 kW parasitic load to cause T_6 to be 2060°R (T_6 for greatest efficiency/turbine wheel life combination). (See Figure 2-4). Parasitic load power, $P_{PL1} = P_{REF} - G_N \Delta N$. Total load power = $P_T = P_{REF} - G_N \Delta N + P_u$. With a user applied 1.3 kW system load, instantaneous total load would be 2.6 kW and unit speed decreases. As the speed decreases, T_6 may be considered constant and parasitic load will be removed according to control line slope, (200 watts/percent speed in this example). After a 6.5 percent decrease in speed, parasitic load power will go to zero and total system power load will then be the user load of 1.3 kW. However, at 94.5 percent speed and $T_6 = 2060^\circ\text{R}$, the system is not capable of providing 1.3 kW and unit speed will continue to decrease until shut-down occurs. The conclusion is that the system cannot be configured to operate at $N = 100$ percent, $T_6 = 2060^\circ\text{R}$ with zero user load, and instantaneously provide a 1.3 kW load using this control concept.

2.2.2.2 Speed Control (Load Removal)

The system is now configured to operate at the design point when 1.3 kW of user load is applied and that user load is suddenly removed. (Refer to Figure 2-5). At this point parasitic load is zero. The unit will accelerate due to the no-load condition. When $N = 106.5$ percent and $T_6 = 2060^\circ\text{R}$ output power is 1.54 kW. The match point for this condition will occur at $N = 108$ percent and a parasitic load power of 1.59 kW. Due to high unit speed, T_6 will not remain at 2060°R but will cool, resulting in a system output power loss. As speed reduces, parasitic load reduces at 200 watts/percent until the operating point returns to the steady-state operating point on the $Q_{IN} = 4.8$ kW line. This occurs at $N = 105.3$ percent, output power = 1.05 kW and $T_6 = 1700^\circ\text{R}$.

CONTROL SYSTEM LOOP

FIGURE 2-3

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OUTPUT POWER, KILOWATTS

BIPS PERFORMANCE WITH LOAD APPLICATION
(SPEED CONTROL ONLY)

BIPS PERFORMANCE WITH LOAD REMOVAL
AND REAPPLICATION (SPEED CONTROL)

FIGURE 2-5

With user load suddenly reapplied to the 1.3 kW system, speed would reduce along the $T_6 = 1700^\circ\text{R}$ line and would not reach a point capable of providing 1.3 kW. The unit would then shut down, thus making this design approach unacceptable.

The control line gain selected for these extreme examples is 200 watts/percent speed. Assuming the gain was lowered, this problem would be aggravated by exercising less control over the system. A higher gain is beneficial, but, only when combined with infinite gain would the system be capable of full load application and removal by the user. As noted in the dynamic analysis section, Appendix II, the system speed loop becomes unstable long before the speed gain can be raised to infinity.

2.2.2.3 Control System Minor Loop

One method of increasing stability is to incorporate a minor loop in the control system to keep total system load constant at a value required to maintain $T_6 = 2060^\circ\text{R}$, $N = 100$ percent, and output power capability at 1300 watts. This loop is shown on Figure 2-6.

2.2.2.4 Constant Power Loop

The changed control system map is shown on Figure 2-7, with multiple control lines. The system control line is a function of user load, and spacing between control lines is a function of power control loop gain. (G_p). The slope of these lines is a function of speed loop gain (G_N). The vertical spacing between user load = 1.3 kW and user load = 0 kW lines is $1.3 \text{ kW} \div (1 + G_p)$. Since the spacing shown is 50 watts, a G_p of 25 watts/watt has been assumed. The parasitic load power, P_{PL} , equals:

FIGURE 2-6

CONTROL SYSTEM LOOP
WITH POWER FEEDBACK

FIGURE 2-6

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BIPS PERFORMANCE WITH CONSTANT POWER LOOP

FIGURE 2-7

$$P_{PL} = \frac{G_P [(P_{REF} - G_N \Delta N) - P_u]}{1 + G_P}$$

G_P = Power Gain

P_{REF} = Design Point Output Power

G_N = Speed Loop Gain

$\Delta N = N_{REF} - N$

(N_{REF} = 100 percent)

P_u = User Load Power

Total load equals:

$$P_T = P_{PL} + P_u$$

$$P_T = \frac{P_u + G_P (P_{REF} - G_N \Delta N)}{1 + G_P}$$

2.2.4.1 Constant Power Loop (Load Removal)

See Figure 2-8 for an illustration of advantages of this control loop with a user load removal. The speed loop gain G_N , is the same as that considered previously (200 watts/percent speed). The power loop gain is 25 watts/watt. This figure shows the assumption of system operation at steady-state Point A. User load is 1.28 kW, parasitic load is 0.024 kW, and total load is 1.304 kW. Assuming the user removes all load, the power correcting loop will apply a total parasitic load of 1.254 kW in an attempt to maintain constant power. The instant after removing user load, and applying parasitic load, T_6 is equal to 2060°R and N = 100 percent. Since the system is capable of 1.304 kW at this operating point, and only 1.254 kW is applied, unit speed increases.

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BIPS PERFORMANCE WITH CONSTANT POWER LOOP
WITH LOAD REMOVAL

FIGURE 2-8

At Point B output power capability equals load applied and the system stabilizes at 100.23 percent as long as $T_6 = 2060^\circ\text{R}$. At the higher unit speed T_6 cools. Cooling of T_6 reduces output power capability and as shown on Figure 2-9, parasitic load is removed to match decreasing power capability and speed until the system reaches a final match point at C, where $T_6 = 2046^\circ\text{R}$, $N = 100.2$ percent, and power output = 0.295 kW.

2.2.2.4.2 Constant Power Loop (Load Application)

Figure 2-10 shows results after reapplication of 1.28 kW user load. Parasitic load readjusts to cause total system load to be on the $P_u = 1.28$ kW line. At 100.2 percent this results in a load of 1.345 kW. Since T_6 remains 2046°R , system power capability is 1.295 kW and system speed reduces. As speed drops, parasitic load is removed until a transient match point is reached at D. The system remains at this point as long as T_6 remains at 2046°R . At Point D output power is 1.282 kW, with 1.28 kW user load and 0.002 kW parasitic load and speed is 99.9 percent.

2.2.2.4.3 Steady-State (After Load Application)

At this reduced speed T_6 rises and, as shown on Figure 2-11, output power increases until a new steady-state matchpoint is reached at point E.

2.2.2.4.4 Overload

Maximum user load capability, when operating at point C shown on Figure 2-9, is 1.282 kW. Assuming a load greater, such as 1.29 kW, were applied, T_6 would be low enough to prevent the system reaching a matchpoint at 1.29 kW. This condition is shown on Figure 2-12. At point F, total system load capability is 1.29 kW, however load applied to the system is greater than 1.32 kW, therefore, system

BIPS PERFORMANCE STEADY STATE
FOLLOWING LOAD REMOVAL

FIGURE 2-9

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BIPS PERFORMANCE WITH CONSTANT POWER FEEDBACK
(LOAD APPLICATION)

FIGURE 2-10

BIPS PERFORMANCE STEADY STATE
AFTER LOAD APPLICATION

FIGURE 2-11

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BIPS PERFORMANCE (AT OVERLOAD)

FIGURE 2-12

speed continues to drop. At point G, total system load is 1.29 kW, consisting entirely of user load. Parasitic load has dropped to zero. System power capability at this point is less than 1.285 kW and system speed continues to drop. Since parasitic load is already zero, the load remains constant 1.29 kW. System speed continues to decrease at an accelerated rate until shutdown occurs.

2.2.2.5 Increased Power Loop Gain

The system effects, as a function of power loop gain, are shown on Figure 2-13. In this instance, power loop gain has increased to 50 watts/watt. Reconsidering the instance (Paragraph 2.2.2.3.1.4 above) of 1.29 kW user load application, the system now is capable of load handling. At this higher gain the system is capable of a user load change of zero to 1.293 kW. Assuming power loop gain could be increased to infinity, the $P_u = 1.3$ kW and $P_u = 0$ kW would be the same and the system would be capable of handling full load removal and application transients, with no changes in speed, total output power, or temperature T_6 .

2.2.3 Long Term Constant Speed Performance

With high gains in the speed and power loops, now consider system long term, steady-state performance. Shown on Figure 2-14, speed gain is 200 watts/percent and power gain is 25 watts/watt. At BOM, output power capability is 1.3 kW, $N = 100$ percent, and $T_6 = 2060^\circ\text{R}$. At EOM, isotope power input, Q_{IN} , has decayed to 4.53 kW. The steady-state operating point after seven years is shown as the intersection of control and $Q_{IN} = 4.53$ kW lines. This results in a power out capability of 1.135 kW, $N = 99.15$ percent, and $T_6 = 1950^\circ\text{R}$. Therefore, isotope decay alone reduces output power capability from 1.3 kW at BOM to 1.135 kW at EOM.

BIPS PERFORMANCE
INCREASED POWER LOOP GAIN

FIGURE 2-13

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BIPS PERFORMANCE
(LONG TERM CONSTANT SPEED)

FIGURE 2-14

2.2.3.1 Constant Temperature (T_6) Minor Loop

By incorporating a T_6 control loop, it is possible to shift control system load lines to the left (Figure 2-14) as T_6 decreases. With gains selected in accordance with the following configuration, system operation will change to point A (Figure 2-15) after seven years of operation. Nominal power output capability will be 1.21 kW, (compared to 1.125 kW without constant T_6); T_6 will be 2055°R, and speed will be 97.5. Unlike the previous system, steady-state operation (with constant Q_{IN}) with full customer load will vary by only fractions of a watt output, and a fraction of a degree T_6 from steady-state operation with no customer load. Only during and immediately after, application or removal of customer load will output speed and power vary as significantly as described for the previous system discussed above.

2.2.3.2 Temperature (T_6) Correction Loop

The T_6 correction loop is shown in Figure 2-16. The equation that satisfies this loop is:

$$1. \quad P_O = \frac{L_C}{1 + G_P} + \frac{G_P P_{REF} - G_N (N_{REF} - N) - G_T (T_{REF} - T_6)}{1 + G_P}$$

For this discussion, the following gains and reference values have been assigned:

$$\begin{aligned} G_P &= 25 \text{ watts/watt} \\ G_N &= 200 \text{ watts/percent} \\ G_T &= 0.4 \text{ percent/°R} \\ T_{REF} &= 2060^\circ\text{R} \\ N_{REF} &= 100 \text{ percent (52,000 rpm)} \end{aligned}$$

Engine characteristics can be closely approximated by the following equations and relationships.

BIPS PERFORMANCE
CONSTANT TEMPERATURE (T_6) MINOR LOOP

FIGURE 2-15

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BIPS SPEED LOOP WITH TEMPERATURE (T_6) CORRECTION

FIGURE 2-16

2. For $P_O = f(Q_{IN}, N)$:

$$P_O = 0.775 Q_{IN} - 47.5N + 2335$$

3. For $P_O = f, (N, T_6)$:

$$P_O = 36.3N + 1.25 T_6 - 4900$$

Steady-state operating points must satisfy equations 1, 2, and 3 simultaneously.

2.2.3.3 Long Term Steady State

For Figure 2-17, Equation 1 is plotted as a function of speed (N) with various assigned values of temperature (T_6). Equation 2 is plotted as a function on N with various assigned values of Q_{IN} , and Equation 3 is plotted as a function of N with various values of T_6 . By drawing a line through the intersections of like values of T_6 for Equations 1 and 3, a system steady-state operating line is constructed. Operating points are determined by observing the intersection of the appropriate Q_{IN} line (Equation 2) with the steady-state operating line (i.e., with $Q_{IN} = 4.6$ kW, $T_6 = 2056^\circ R$, $N = 97.15$, $P_O = 1.233$ kW).

Equation 1 was plotted with P_u (user load) = 0. For customer load equal to 1.3 kW, the steady-state operating line lies 0.4 watts and 0.2 degree R above the $P_u = 0$ customer line. Because of this small difference, all further steady-state operating line discussions will consider the $P_u = 1.3$ kW and $P_u = 0$ kW lines as the same.

2.2.3.3.1 Constant Temperature (T_6) Loop (Load Application)

Consider system behavior to a customer step load change. Refer to Figure 2-18, and consider a 1.22 kW load application. Assume Q_{IN} has decayed to 4.6 kW and 0 customer load before the change. At this

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BIPS LONG TERM PERFORMANCE

FIGURE 2-17

BIPS PERFORMANCE WITH CONSTANT T_6 LOOP
(LOAD APPLICATION)

FIGURE 2-18

operating point, the steady-state operating line essentially lies directly on $T_6 = 2056^\circ\text{R}$ and therefore only the T_6 line is shown. $N = 98.15$ percent, $T = 2056^\circ\text{R}$, $P_o = 1.23$ kW (all parasitic load).

When the 1.22 kW load is applied, parasitic load adjusts such that total system $P_o = 1.28$ kW. T_6 will not change immediately. that total system $P_o = 1.28$ kW. Also, T_6 will not change immediately. Since 1.28 kW is above system capability, at 98.15 percent and $T_6 = 2056^\circ\text{R}$, the unit speed decreases. As speed decreases, parasitic load is removed until a new match point is reached at $T_6 = 2056^\circ\text{R}$, $N = 97.86$ percent, $P_o = 1.223$ kW. Due to the lower operating speed, T_6 tends to rise toward the operating T_6 for $N = 97.86$ percent with $Q_{IN} = 4.6$ kW. As T_6 rises, the 1.22 kW load line shifts to the right to keep operation on the steady-state line. This shift continues until the 1.22 kW load, $Q_{IN} = 4.6$ kW, and the steady-state operating lines all cross at one point, (operating point). This is essentially the point prior to application of load, except that 1.22 kW of P_o is customer load and the remaining 0.013 kW is parasitic load. The left and right dashed control lines represent the final positions of the $P_u = 0$ kW control lines, respectively.

2.2.3.3.2 Constant Temperature (T_6) Loop (Load Removal)

Customer load removal at this point is essentially the opposite of load application. Transition to the new operating point is illustrated in Figure 2-19.

2.2.4 BIPS Operating Performance Characteristics Summary

BIPS operating performance characteristics summary is as follows:

- o Circuits will be incorporated to minimize effects of user load change on total system loads.

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BIPS PERFORMANCE WITH CONSTANT T_6 LOOP (LOAD REMOVAL)

FIGURE 2-19

- o A means will be incorporated to control system power to minimize the possibility of exceeding turbine inlet temperatures ($T_6 = 2060^\circ\text{R}$) over the long term.
- o Circuits will be incorporated to maximize system output power as a function of isotope decay.

2.2.5 Starting Characteristics

Two broad approaches for starting and accelerating the BIPS rotating group to optimum self-sustaining speed (approximately 26,000 rpm) have been considered and successfully demonstrated in the laboratory. These are synchronous motoring and induction motoring starting. The characteristics, advantages, and disadvantages of each starting approach are discussed herein.

2.2.5.1 Synchronous Starting

A ramped synchronous start was accomplished using an open loop variable input frequency signal, and a closed loop position feedback signal. The purpose of the open loop test was to demonstrate that a ramped synchronous start was feasible. Currents, voltages, and times required were of little importance technically since no attempt was made to optimize these starts in the time frame allowed. More meaningful data was accumulated using position feedback sensors on the rotor shaft. This data gave a good indication of the motoring capabilities under ideal conditions and provided design goals to be met for the ramped start.

2.2.5.1.1 Synchronous Start Inverter Fixture

A synchronous start inverter fixture was designed and fabricated to produce the conditioned signals required. The fixture is capable of providing open loop, ramped synchronous start with 60 degree

(mechanical) conduction angle and 90 degree conduction angle, and synchronous starts with shaft position feedback using 60 and 90 degrees conduction angles. A schematic of this fixture is shown on Drawing 306836.

2.2.5.1.1.1 Conduction Angle (60 Degrees)

Significance of the conduction angle is best understood by referring to Figure 2-20, wherein three inverter output, 60 degree conduction angle configurations, are shown. The output stages are driven so that each alternator armature phase is connected to the positive supply or ground for 60 mechanical degrees, with a 30 mechanical degree open circuit period between each. This figure also depicts the alternator phase rotation for these conditions. Note that for any time period, current flows from one phase to another with the third phase open.

2.2.5.1.1.2 Conduction Angle (90 Degrees)

The waveform for a 90 mechanical degree conduction angle and phase rotation is shown on Figure 2-21. In this configuration two phases are always shorted at the positive or ground leg and all current flows through the third leg.

For each configuration, dc current to the inverter remains constant. This occurs because the positive to ground leg resistance is constant.

2.2.5.1.1.3 Position Feedback

Position feedback was sensed using a system of light emitting diode/photo transistor couplers mounted on a manually rotatable disk with a light interrupter wheel on the rotating shaft. As the shaft rotated, the light sensors were interrupted at discrete angular

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OUTPUT STAGES

PHASE ROTATION - 60° CONDUCTION

PHASE VOLTAGES TO GROUND

SYNCHRONOUS START INVERTER -
60 DEGREE CONDUCTION ANGLE-OUTPUT

FIGURE 2-20

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PHASE ROTATION - 90° CONDUCTION

PHASE VOLTAGES TO GROUND

SYNCHRONOUS START INVERTER -
90 DEGREE CONDUCTION ANGLE-OUTPUT

FIGURE 2-21

positions. The light interruption causes the inverter driver transistors to switch and force rotation of the flux field created by armature current to lead the rotor at a fixed lead angle.

2.2.5.1.2 Synchronous Start Performance

Start tests were run using various field currents, inverter voltages, and lead and conduction angles to determine the optimum start condition consistent with alternator ratings and space shuttle power supplies. Experimental data plots are shown on Figures 2-22 through 2-29. In each instance approximately one amp of field current was required at low rpm to achieve a rotor lock in with the armature rotating field. In addition, a lead angle less than 50 to 60 degrees was required or the unit would not start or would tend to run backwards. In each instance the rotor would accelerate rapidly to a low speed value and run at this constant speed until field current was reduced. (During these tests, field current was reduced to zero.) With reduced field current the rotor would again accelerate at a rate dependent on the lead angle.

2.2.5.1.2.1 Composite Synchronous Start Performance Data

Figure 2-30 is a composite of several lead angle and field current settings required to produce the fastest start to 24,000 rpm. This figure shows, that assuming the unit were starting at 25 vdc inverter voltage, lead angle = 60 degrees and field current = 1 amp, and then field current at 10,000 rpm were dropped, with a subsequent lead angle change to 90 degrees between 14,000 and 18,000 rpm, the unit would accelerate to 24,000 rpm in 17 seconds with a peak power dissipation of 750 watts (less than one second), an average power of 210 watts, and a total energy of 3570 watt-seconds.

SYNCHRONOUS START PERFORMANCE

FIGURE 2-22

SYNCHRONOUS START PERFORMANCE

FIGURE 2-23

SYNCHRONOUS START PERFORMANCE

FIGURE 2-24

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SYNCHRONOUS START PERFORMANCE

FIGURE 2-25

SYNCHRONOUS START PERFORMANCE

FIGURE 2-26

SYNCHRONOUS START PERFORMANCE

FIGURE 2-27

SYNCHRONOUS START PERFORMANCE

FIGURE 2-28

SYNCHRONOUS START PERFORMANCE

FIGURE 2-29

OPTIMUM START PERFORMANCE

FIGURE 2-30

2.2.5.2 Synchronous Start Summary

The performance described above can only be achieved using shaft position sensors and feedback. The existing Mini-BRU alternator does not have position sensors installed and incorporation would involve an investigation of sensing techniques compatible with the limited space close to the shaft inside the Mini-BRU. In addition, sensor reliability would require investigation. In lieu of shaft position sensing, an open loop approach will be investigated, using a segmented ramped frequency input. If the acceleration rate of the input ramped frequency is kept less than the acceleration shown on Figure 2-30, the rotor should remain locked onto the rotating armature field. Signals from the monopoles could conceivably be used to trim the input frequency to assure lock on.

Parallel with this effort, availability of usable shaft position sensors will be investigated.

2.2.5.3 Induction Starting

Induction starting was accomplished by using an 80 kW aircraft generator attached to a variable speed drive shaft. This test setup allowed observation of acceleration times for various line to neutral voltages, field resistance, and frequencies. Test setup size prevented changing the frequency of the input waveform as the unit accelerated. This would probably have resulted in more efficient, faster start time, since the slip could have been optimized.

The start procedure used was to set alternator frequency and voltage, turn off the field, close the contactor to the Mini-BRU stator, and re-energize the alternator (power supply) field. This procedure, eliminated the initial kick that would have been present had the contactor been closed with the power supply alternator field energized.

2.2.5.3.1 Induction Start Data

Tables 2-1, 2-2, and 2-3 summarize data taken during induction starts. Since power factor has not yet been measured, it is impossible to determine at this time the real power required to provide such a start. However, it is apparent that voltage required for this supply is beyond that available from the space shuttle, assuming a bridge type inverter is used. A power converter would be required to provide 30 volts RMS line to neutral required for the minimum start time indicated in Table 2-2. A comparison of theoretical and actual currents required to start, as a function of frequency, is provided on Table 2-3.

2.2.5.4 Start Characteristics Summary

Data taken during synchronous and induction start tests of the Mini-BRU alternator indicate both methods described are workable. The induction start has the advantage of simplicity in circuit function, with the disadvantage associated with high current and voltage handling problems. The synchronous start offers the advantages of low voltage and current, with increased circuit complexity in the logic portion. Both approaches will be simultaneously tested and evaluated further.

2.3 BIPS Control System Dynamic Requirements

The BIPS control system dynamic requirements consist of the three main interacting elements (i.e., alternator, engine, and voltage regulator). Interactions, and the fact that non-linear operation is required, dictate that computer analysis be utilized to minimize the complex analyzing task. Toward this end two primary computer systems are being simultaneously pursued. These are as follows:

- (a) The NASA designed analog-pulse width modulated system

TABLE 2-1
BRAYTON ISOTOPE SYSTEM MINI-BRU MOTOR STARTING TEST

Speed N rpm	Input Frequency Hz	Field Resistor R _F Ohms	Voltage No Load Initial V rms		Thermocouple T _C No. 129, °F Initial Ending		Recording No.	Voltage Line-Neutral	Current Line	Start Time Second
9,000	300	300	100		90	118	1	30.0	47.5	0.6
7,860	262	100	100		91	-	2	30.0	36.3	0.6
8,300	302	50	92		92	-	3	30.0	37.5	0.6
8,840	302	200	100		92	100	4	30.0	45.0	0.7
8,980	302	150	100		95	100	5	30.0	37.5	0.63
8,820	302	100	100		128	-	6	30.0	37.5	0.7
8,820	300	100	90		97	-	7	28.5	34.5	0.8
0	300	100	80		101	110	8	26.0	37.8	No Start
8,820	300	100	110		98	-	9	33.0	36.0	0.55
8,820	300	100	115		130	132	10	37.8	34.0	0.40
①	-	-	-		-	-	-	-	-	-
12,000	400	100	100		94	105	11	33.0	37.5	1.4
11,900	400	200	100		94	112	12	33.5	37.5	1.4
12,000	400	300	100		95	110	13	33.5	37.5	1.4
12,000	400	α	100		98	-	14	33.5	37.5	1.3
0	400	300	90		94	-	15	30.0	37.5	No Start
12,000	400	300	110		95	-	16	35.0	39.5	1.2
12,000	400	300	120		95	110	17	37.5	42.0	1.1
0	400	300	0		79	-	18	-	-	No Start
0	400	300	100		87	-	19	-	-	No Start
12,000	400	300	130		85	108	② 20	39.0	47.0	0.88
Preset										
12,000	400	300	0	130	90	-	21	39.0	47.0	0.90
12,000	400	α	0	130	82	-	22	39.0	47.0	0.85
12,000	400	α	0	120	84	-	23	37.5	45.0	0.96
12,000	400	α	0	110	92	-	24	36.0	43.5	1.1
12,000	400	α	100	100	-	-	25	32.0	39.0	1.0
	400	α	0	100	85	-	26	32.0	39.0	No Start
0	500	300	100	100	84	-	27	33.0	30.0	No Start
0	500	300	110	110	83	84	28	39.0	34.0	No Start
0	500	300	0	110	83	87	29	36.0	35.5	No Start
0	500	300	0	120	87	86	30	35.0	37.5	No Start
15,000	500	300	0	120	85	94	31	42.0	46.0	1.67
15,000	500	α	120	120	80	93	32	41.0	39.0	1.68
15,000	500	300	130	130	86	96	33	42.0	42.0	1.48
③	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	90	110	-	-	-	-
15,000	500	300	0	130	100	110	34	30.0	40.0	1.4
15,000	500	α	130	130	-	-	35	-	40.0	1.5
18,000	600	300	130	130	98	110	36	33.0		
0	600	300	0	130	97	-	37	-		
	600	300	0	140	99	-	38	30.0		
18,000	600	α	0	140	98	108	39	30.0		
21,000	700	300	140	140	96	105	40	45.0	31.5	
0	700	300	0	140	96	100	41	32.0	30.0 33.0	No Start
0	700	α	0	140	-	102	42	-	-	No Start
0	700	α	0	150	98	102	43	30.0	37.0	No Start
21,000	700	α	150	150	98	105	44	38.0	39.5	2.5
24,000	800	α	150	150	98	106	45	40.0	30.0	3.35
24,000	800	300	150	150	96	-	46	-	-	3.5
24,000	800	300	140	140	97	-	47	40.0	30.0	3.88
0	800	300	130	130	96	100	48	-	-	No Start

- ① Cooled alternator at 400 Hz for 10 minutes
 ② Recorder paper speed changed from 16 mm/sec to 25 mm/sec
 ③ Recorder recalibration accomplished, 400 Hz
 ④ Re-calibration check at 400 Hz
 α Field resistor open circuit

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TABLE 2-2
INDUCTION START TEST DATA

Run No.	Time to Start sec	Speed rpm	Frequency Hz	Voltage Set*	Voltage Line-Neutral	Line Current (Ø) amps	Apparent Power $(V \cdot I \cdot \sqrt{3})$	Apparent Energy $(\sqrt{3} \cdot V \cdot I \cdot T)$
24	1.1	12,000	400	110	36	43.5	2712	2983
34	1.4	15,000	500	130	30	40.0	2078	2909
38-39	1.97	18,000	600	140	30	37.5	1948	3837

*Alternator open circuit set to voltage set, field turned off, contactor closed, then field turned on.

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TABLE 2-3

START CURRENTS
(CALCULATED VERSUS ACTUAL TEST)

Frequency, Hz	Voltage Line-Neutral	Current	
		Calculated	Test
400	36.0	66.7	43.5
500	30.0	42.9	40.0
600	30.0	35.34	37.5

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(b) The AiResearch alternate digital sample data system.

Appendix II presents a computer simulated design for the digital system. Included also is a digital system implementation method using a processor approach.

Analysis of the voltage regulator loop presented in Appendix II, indicates a loop gain of 10 to be adequate for accuracy, with ample stability margin. This gain is considered sufficient for application to any speed control selected. The actual computer numerical values found to be desirable are presented in Appendix II, for the specific systems considered.

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3. NASA CONTROL SYSTEM

3.1 General Description and Operation

The NASA Control System comprises the following major subsystems.

- o Starter Inverter
- o Three-Phase Alternator
- o Power Supply
- o Power Rectifier and Filter
- o Parasitic Load
- o Control Electronics (includes speed control, voltage regulator, carrier generator, and underspeed logic)

Major NASA control subsystem components operation and functional relationships are shown on Figure 3-1. The start inverter drives the alternator and turbine to a speed sufficient for turbine control. At this point the turbine drives the alternator, which provides input power to the power supply, rectifiers, and filter. Power supply output provides alternator field winding and control electronics power. Power filter output provides user load and parasitic load power. Turbine input power to the alternator remains constant, therefore, to maintain stable conditions, user and parasitic loads must dissipate all turbine energy. The voltage regulator and speed converter function to maintain system stability. The voltage regulator maintains a constant output voltage by controlling the alternator field current. The speed converter maintains a constant load (user plus parastic). A carrier generator provides the modulating rate for the voltage regulator and

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BIPS NASA CONTROL SYSTEM BLOCK DIAGRAM

FIGURE 3-1

and speed converter. The underspeed logic disconnects alternator output voltage at 90 percent turbine speed when system output load becomes excessive due to a fault.

3.2 NASA Control System Detailed Description

Refer to BIPS detailed block diagram, NASA Control System, Figure 3-2 and Schematic 306835 for discussion Paragraphs 3.2.1 through 3.2.2.8 below.

3.2.1 Starting

The alternator is started with a three-phase start inverter. The inverter energizes the stator windings, causing the alternator to perform as a motor generator, driving the turbine to a speed at which the heat source assumes turbine driving. At this point, the three-phase inverter is disconnected. The field windings are powered by an external +24 vdc source until the alternator speed generates sufficient voltage for the control system power supply to override the external 24 vdc source.

3.2.2 Operation

The three alternator output phases are connected to a rectifier and a power supply. Each phase is rectified by a full wave bridge, using diodes in a series parallel redundant configuration (see Figure 3-2). The multiple redundancy feature permits one to three diode failures without affecting operation, thereby providing exceptional reliability.

3.2.2.1 Rectifier Output

The rectifier output is connected to separate filters. The filters are parallel redundant and the capacitors are series fused.

BIPS DETAILED BLOCK DIAGRAM OF NASA CONTROL SYSTEM

FIGURE 3-2

[illegible]

QUANTITY REQ.	PART NO.	PART NO. OR IDENTIFYING NO.	ITEM	NOMENCLATURE OR DESCRIPTION	CODE	REMARKS AND SPECIFICATION	QTY.
← PART NUMBER			PARTS LIST				
			<div style="border: 1px solid black; padding: 5px;"> <p>SEARCH AREA MARKED AND COMPLEY OF RECORD 1. SEARCH AREA MARKED AND COMPLEY OF RECORD 2. SEARCH AREA MARKED AND COMPLEY OF RECORD 3. SEARCH AREA MARKED AND COMPLEY OF RECORD</p> </div>				
			<div style="border: 1px solid black; padding: 5px;"> <p>WIRING DIAGRAM SET SHIPS</p> <div style="border: 2px solid black; padding: 10px; text-align: center;"> <p>INFORMATION PRINT</p> </div> <p>THIS PRINT SET CONSISTS OF 1. INFORMATION PRINT 2. INFORMATION PRINT 3. INFORMATION PRINT</p> </div>				
REQ. NEED ASSY	USED ON	PLANT	DATE	TIME	BY	REMARKS AND SPEC.	
NEED TREATMENT	REMARKS AND SPEC.						
			<div style="border: 1px solid black; padding: 5px;"> <p>DATE 00000000</p> <p>TIME 000000</p> <p>BY 000000</p> <p>REMARKS AND SPEC.</p> </div>				
			<div style="border: 1px solid black; padding: 5px;"> <p>SCALE 1/1</p> <p>WT 1</p> <p>SHEET 1 OF 1</p> </div>

One filter output is connected to user load and provides the 120 vdc voltage regulator sample input. The second filter output is connected to parasitic loads.

3.2.2.2 Power Supply Input (+60 vdc)

The +60 vdc power supply input is half wave rectified with diodes in a series parallel redundancy arrangement. The associated filter capacitors are series redundant. The +60 vdc field output provides voltage source for the four alternator field coils.

3.2.2.3 Power Supply (+15 vdc)

Each alternator output phase provides input power for one +15 vdc supply. Each +15 vdc supply contains a four diode bridge allowing full wave rectification of each alternator input. The dc output of the rectifier is regulated with a resistor, transistor and zener diode circuit. The three +15 vdc supplies are separate and provide triple parallel redundant control voltage.

3.2.2.4 Carrier Oscillator

The carrier oscillator is a square wave generator operating at a frequency of 5.2 kHz. The carrier oscillator module contains two identical oscillators that are parallel redundant. The purpose of the carrier oscillator is to modulate the transistor switches that control generator field current and the transistor switches controlling current drawn by the parasitic load. Modulating in place of linearly regulating the transistor current, decreases the transistor's power dissipation, allowing the use of a smaller, less expensive transistor with greater reliability.

3.2.2.5 Voltage Regulation

Voltage regulation requirements are dictated by function of the generator speed and are controlled by the magnitude of current in the alternator field windings.

3.2.2.5.1 Voltage Regulator Pre-Amp

The voltage regulator pre-amp samples user load dc voltage, and compares this sample with a reference voltage. When user voltage is too high, the pre-amp output voltage is reduced. This reduction in pre-amp output causes the voltage regulator transistor switch drivers to reduce alternator field coil current, thereby lowering alternator output voltage. In addition, the voltage regulator pre-amp receives a frequency (speed) reference correction signal. Under overload conditions frequency decreases causing the output reference signal (speed buss) of the frequency to dc converter to decrease. When this reference signal is applied to the voltage regulator pre-amp, the result is the same as a regulator sensed overvoltage condition signal. This causes the voltage regulator pre-amp and drivers to decrease current in the alternator field windings. As a result, this feedback loop decreases voltage at reduced speeds while maintaining constant alternator power output.

When user load becomes excessive (beyond system capability), the speed of the alternator will decrease. Below 90 percent speed level, a high (+15 vdc) signal level from the underspeed logic module disables the voltage regulator pre-amp. This signal disconnects the field excitation current, thereby causing alternator output voltage to drop to zero. With the output voltage at zero, the alternator speed increases. When alternator speed exceeds 90 percent, the underspeed logic re-energizes the alternator field windings, and the system will assume normal operation.

3.2.2.5.1.1 Pre-Amp Voltage Regulator Module

The pre-amp voltage regulator module contains three identical pre-amp channels whose outputs are tied in a triple redundant arrangement. Should any channel fail, the control system would not be affected. The voltage regulator switch driver receives an input from the voltage regulator pre-amp and a square wave reference carrier input. The carrier input is then transformed into a triangular wave form by an integrator circuit (see Figure 3-2). The pre-amp dc output and triangular wave shape are summed to provide the modulating signal input for the voltage regulator switch drivers. The transistor switch receives a modulated input from the switch driver and opens and closes at the reference carrier rate. During the switch closed time, full current flows through the alternator field windings. When the switch is open, zero current flows through the alternator field windings. Lowering the pre-amp dc signal level, that is summed with the referenced carrier, causes the transistor on time switch period to become shorter and the off time period to become longer. The result is a field current reduction in the alternator, thereby lowering alternator output voltage. The voltage regulator input drives four amplifiers with common inputs (see Figure 3-2). Each amplifier drives a transistor switch. Each pair of switches is connected in series with the two pairs driving the generator field coils connected in parallel. The result is a series parallel redundancy configuration (similar to the rectifier).

3.2.2.6 Frequency to DC Converter Module

The frequency to dc converter module receives a frequency signal from the compressor, proportional to generator speed (rpm). This module converts the input frequency to a proportional dc level (frequency dc). This dc level then commands the parasitic load driver to increase or decrease the necessary load for controlling alternator speed. A monopole in the compressor provides a magnetic signal. This signal is half wave rectified and transformed to a square wave using a

capacitor balanced T network, transformed to a dc level inversely proportional to input frequency. The dc level is then amplified and inverted by an operational amplifier. The frequency to dc converter module is comprised of three separate triple redundant channels with separate monopoles (magnetic pickups). Each amplifier output provides inputs to two items. One output is the input of a 10K resistor. This output provides the input to underspeed logic module. The second output to a 10K resistor provides a secondary feedback loop, bypassing the amplifier. The output side of each 10K resistor (speed buss) is common with the other two, and feed two inputs. One inputs the voltage regulator pre-amp (for signal trims to the speed control reference); the second inputs the parasitic load driver.

3.2.2.7 Parasitic Load Driver

The parasitic load driver receives a carrier signal, that is integrated and added to the input (dc level) from the frequency to dc converter. When the frequency to dc converter dc level starts to increase (increasing frequency), the parasitic load driver increases the turn on to turn off time ratio on the loads. This effectively increases alternator load and decreases frequency. A low resistance adjustable resistor in series with the user load provides a voltage drop to measure user load current. The output voltage across this resistor is applied as an input to the frequency to dc converter amplifier. When user load current starts to exceed a predetermined amount, this signal causes the frequency to dc converter to reduce parasitic load and via the speed buss voltage regulator interface, reduces alternator output voltage. This loop produces only minor effects on the parasitic load used. Theory of operation is similar to the voltage regulator switch driver described previously. There are three separate loads on the parasitic load filter outputs. Each load is activated by a pair of switches in a series redundant arrangement for maximum reliability.

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3.2.2.8 Underfrequency Module

The underfrequency module receives speed information from the voltage to frequency converter module. When the underfrequency module detects an underspeed condition, a signal (approximately +15 vdc) is sent to voltage regulator to cut off alternator voltage. A minimum of two low speed signals are required for an alternator cutoff command to become operable.

3.3 Reliability, Performance, Cost, and Weight

Reliability, performance, cost, and weight are discussed in the following paragraphs.

3.3.1 Control System Reliability

This section presents the reliability assessment for control circuitry supplied to AiResearch by NASA. A computer program, PREDICTOR, was used to facilitate the many and varied reliability models for the electronic and electrical components. The program contains MIL-HDBK-217A, MIL-HDBK-217B, and RADC notebook, logic. MIL-HDBK-217B was used as the primary reference since latest accepted reliability models are provided therein. Redundancy, environment, duty cycle, failure rate, specifications, and/or changes thereto are easily handled. Based on circuitry shown on BIPS Control System (NASA) Schematic, Drawing 306835, the total control system failure rate is 0.19262 failures/million hours.

3.3.2 Control Subsystem Reliability

The control subsystem reliability assessments are as discussed in paragraphs 3.3.2.1 through 3.3.2.8 below..

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3.3.2.1 Alternator

The alternator is a modified Lundell (Rice) machine with a computed failure rate of 0.01070 failures/million hours.

3.3.2.2 Power Supplies

- o The power supplies incorporate extensive redundancy to enhance reliability. The computed failure rate of the rectifier section is 0.08983 failures/million hours.
- o The field control circuits also incorporate multiple redundant circuitry and have a computer failure rate of 0.01055 failures/million hours.
- o The electronic power supply is triple redundant with a computer failure rate of 1.657×10^{-7} failures/million hours.

3.3.2.3 Voltage Regulator Exciter

The voltage regulator exciter incorporates a triple input, double redundant and a double redundant output and has a computed failure rate for the circuitry of 0.0007 failures/million hours.

3.3.2.4 Carrier Generator

The carrier generator is double redundant with a computer failure rate of 0.00024 failures/million hours.

3.3.2.5 N Converter (Speed)

The speed carrier circuit incorporates a triple input (monopole) front end double redundant, and a triple redundant output. The computed failure rate for this circuit is 0.0702 failures/million hours.

3.3.2.6 Underspeed Circuits

Underspeed circuits are double redundant with triple circuits. The computed failure rate is 0.00015 failures/million hours.

3.3.2.7 Parasitic Bank

The parasitic heater element bank is double redundant with triple elements. The bank computer failure rate is 0.00023 failures/million hours.

3.3.2.8 Power Distribution

The power distribution system (cables, wiring, etc) are combined. In the combined condition these items have a computed failure rate of 0.01 failures/million hours.

3.3.3 Failure Modes and Effects Analysis (FMEA)

A FMEA was conducted on the control system at the major component level. Major component failure modes were determined. Table 3-1 presents a summary of the results. Note that some components were combined and a statement of failure modes and effects is presented. This FMEA is based on the system shown on Drawing 306835.

TABLE 3-1

BIPS CONTROL SYSTEM FAILURE MODES AND EFFECTS ANALYSIS (FMEA)

Component	Failure Mode	Probable Effect	*Effectivity
<u>Rectifier Circuit</u>			
Bridge Diode	Open	Up to two failures no effect (per leg). More than two, output voltage ripple increases.	2,3
Filter Coil	Open	One failure - increase of output voltage ripple. Two failures - loss of output voltage.	2,3
Filter Capacitor	Short	Failures tend to increase output voltage ripple.	3
<u>Alternator</u>			
Field Coil	Open	One failure - no effect. Two failures - loss of output power.	2.6
Stator Coil	Open	Loss of output power.	6
Connector	Dead Short to engine housing	Possible engine speed runaway because of loss of voltage (thus power) from alternator.	4,5
<u>Power Supplies</u>			
<u>Field Power Supply</u>			
Diode Bridge	Open	Up to two failures - no effect. More than two failures - loss of field excitation and output voltage.	2,6
External Supply Diode	Open	One failure - no effect two failures, loss of power to controls and field for low speed (start).	2,8
Filter Capacitor	Open	Failures increase ripple to field.	3

TABLE 3-1 (cont'd)

Component	Failure Mode	Probable Effect	*Effectivity
<u>Electronics Power Supply</u>			
Bridge Diode	Open	Up to two failures - no effect. More than two failures - depends on whether other two have failed in same circuit. (one can supply all power).	2,7
Zener Diode	Open	Loss of section or false signal output.	2,3
Misc. Resistor	Open	Loss of section or false signal output.	2,3
Filter Capacitor	Short	Loss of power supply	2,3
Series Pass Regulator Transistor	Short	Over voltage	2,3
<u>Carrier Generator</u>			
Oscillator Operational Amplifier	Saturated	Loss of oscillator section	2
Clipper Diodes	Open	Loss of carrier signal redundant.	2
Integrating Capacitor	Short	Carrier generator will not function	6
Misc. Resistor	Open	Loss of carrier signal or false signal output.	6
<u>Voltage Regulator</u>			
<u>Input</u>			
Amplifier	Saturated	Loss of regulator section.	2
Inhibit Transistor	Open	False regulator section output.	2
Clamping Zener	Open	False regulator section output.	2,5
Misc. Resistors	Open	Loss of signal or false signal.	2,5
Misc. Capacitors	Short	False regulator section output.	2

TABLE 3-1 (cont'd)

Component	Failure Mode	Probable Effect	*Effectivity
<u>Voltage Regulator</u>			
<u>Output</u>			
Comparator	Saturated	False regulator section output.	2
Darlington Driver (Transistors)	Open	Loss of regulator section.	2
Suppression Diode	Open	Up to two failures - no effect. More than two - may cause degradation of voltage regulation.	2,5
Clamping Zener	Open	False regulator section output.	2
Misc. Resistors	Open	Loss of regulator section output.	2
Misc. Capacitors	Short	Loss of section or false signal output.	2
<u>Speed Control</u>			
<u>Input</u>			
Clamping Network Transistor	Open	Loss of channel.	2
Level Shifter Transistor	Open	False channel signal.	2
Differential Amplifier	Saturated	False speed control signal.	2
Misc. Resistors	Open	Loss of channel or false signal output.	2
Misc. Capacitors	Shorted	Loss of channel or false signal output.	2
<u>Output</u>			
Carrier Level Comparator	Saturated	False channel output.	2
Darlington Driver Pair (Transistors)	Open	No output of speed channel (redundant).	2

TABLE 3-1 (cont'd)

Component	Failure Mode	Probable Effect	*Effectivity
Parasitic Load Suppression Diode	Open	No effect on speed control performance.	2
Misc. Diodes	Open	Loss of channel or false signal output.	2
Misc. Resistor	Open	Loss of channel or false signal output.	2
Misc. Capacitors	Short	Loss of channel or false signal output.	2
<u>Underspeed Voltage Cutoff</u>			
Undervoltage Comparator	Saturated	Loss of channel or false signal output.	2
Logic Gate	Random Output	Intermittent power at user bus.	2
Misc. Diodes	Open	Loss of channel or false signal output.	2
Misc. Resistors	Open	Loss of channel or false signal output.	2
Misc. Capacitors	Short	Loss of channel or false signal output.	2
<u>Parasitic Bank</u>			
Resistive Element	Open	Inherently redundant resistive element tolerates open at many points (redundant).	2
<u>Sensors</u>			
Monopole	Open	Loss of speed signal (redundant).	2
Current Shunt	Open	Loss of current signal (feeds redundant circuit).	2,3

TABLE 3-1 (cont'd)

Component	Failure Mode	Probable Effect	*Effectivity
<u>Miscellaneous</u> Power Supply Coils	Open	Loss of power to power supply.	2

*EFFECTIVITY

- 1 - Fails redundant circuit.
- 2 - Degrades performance slightly.
- 3 - Seriously degrades performance.
- 4 - Overstresses components.
- 5 - No user output under all conditions.
- 6 - No user output under certain conditions.
- 7 - No start

Review of the FMEA Table 3-1, indicates the only single point failure without redundancy is the alternator stator. All other components incorporate redundant features to the maximum degree possible within the constraints of performance, reliability, cost, and weight.

3.3.4 Performance

The analog-pulse width modulation system steady-state performance was primarily determined by laboratory data. A summary of laboratory testing is presented in Appendix IV. The change in speed experienced during a full load excursion was less than 250 rpm. This represents a speed droop of less than one half percent. The plot of the speed droop versus load (see Appendix IV) reflects control nonlinearity and that user current sensing (speed reset) does not fully compensate for changes in the user loads imposed. Speed loop gain and current (load reset) loop values were measured. These values were found to be lower than allowable, and still provide stability (see computer analysis, Appendix II). Assuming the higher gains are used in accordance with the computer analysis, further improvements in speed control accuracy with load changes will be possible.

3.3.4.1 Dynamic Performance

The analog-pulse width modulation system dynamic performance was established using two methods:

- (a) NASA control laboratory bench testing on the alternator
- (b) By system simulation on the analog and digital computers

Detailed laboratory results are described in Appendix II. The results are summarized in Table 3-2.

TABLE 3-2

DYNAMIC PERFORMANCE SUMMARY

<u>Test</u>	<u>Specification Requirement</u>	<u>Results</u>
Voltage Surge	55 - 210 volts (0.010 seconds or less)	120 volts - -4, +8 volts after filter
Voltage Spike	In accordance with MIL-E-6051	No spikes evident in test
Steady State	110 - 125 volts	120 $\pm$ 0.2 volts
Ripple Voltage	1.0 volts rms or less at 1000 Hz Approximately 0.2 volts rms at 5000 Hz or 2.5 volts peak	5.0 volts peak-to-peak

3.3.4.1.1 Voltage Surge

Table 3-2 shows large voltage surges (variations) for short duration (0.010 seconds) are allowable. Test results indicate no difficulty maintaining filtered output voltage within tolerance.

3.3.4.1.2 Voltage Spikes

Large voltage spikes are allowable by specification; however, no spikes in voltage were seen on the filtered output. No control problems as a result of spiking are anticipated.

3.3.4.1.3 Steady-State

Steady-state voltage tolerances present no problem. Voltage regulator gain may be lowered on the final design since the testing and calculations indicate a lower gain will meet required accuracy.

3.3.4.1.4 Ripple Voltage

Ripple voltage is 4-5 volts peak-to-peak after filtering. This value meets the 2.5 volt maximum peak voltage requirement. The RMS voltage/frequency spectrum allows one volt at 1000 Hz and approximately 0.2 volts at 5000 Hz. The frequency spectrum analysis was not performed during this test and this requirement will be evaluated after final filter selection.

3.3.4.2 Computer Analysis

Computer analysis (see Appendix II) shows control gains recommended for improved accuracy commensurate with stability. The modified NASA control design objective will allow sufficient adjustment to achieve these gains. The above testing indicates voltage specification

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compliance, is good. Adopting analysis recommendations are therefore certain to result in additional improvements in performance.

3.3.5 Cost

At this time the control system configured by NASA and/or modified by AiResearch does not contain any components that are prohibitive in cost to function relationships. No nonstandard or exotic components are contemplated. Engineering time and expenditures are expected to be commensurate with designing, building, and testing an engineering model* of the size and complexity required.

*An engineering model of a system is one that contains the flyable components but not necessarily all the hardware; such as:

(1) Envelope	(3) Subsystem Packages
(2) Housings	(4) Nuts, Bolts, Screws, etc.

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3.3.6 Weight Estimate - NASA Control System

The weight estimates are as follows:

	<u>Ground Demonstration System</u>	<u>Flight System</u>
o <u>Module 1</u>		
Starter Inverter	4.9 lbs	*
o <u>Module 2</u>		
(a) Current Transformers (3)	2.3 lbs.	
(b) User Load Filter	1.6 lbs	
(c) Parasitic Load Filter	1.5 lbs.	
(d) Rectifier	0.8 lbs.	
(e) Housing	<u>2.5 lbs.</u>	
Subtotal	8.7 lbs	
o <u>Module 3</u>		
(a) Speed Control	2.0 lbs.	
(b) Voltage Regulator	1.5 lbs.	
(c) Power Supply	0.7 lbs.	
(e) Housing	<u>1.8 lbs.</u>	
Subtotal	6.0 lbs.	
o <u>Module 4</u>		
(a) Parasitic Load	1.6 lbs.	
(b) Housing	<u>4.0 lbs.</u>	
Subtotal	5.6 lbs.	
Total Estimated	25.2 lbs.	

*The flight system weight objective is 10 lbs. The estimated component weights are not available at this time.

4. RECOMMENDED MODIFICATIONS

4.1 Power Supply (+60 vdc)/Voltage Regulator

The voltage regulator provides the excitation for the four alternator field windings. These windings are paralleled in two pairs and terminated at the power supply +60 vdc source. One pair of windings is capable of providing sufficient field excitation to maintain system operation.

At present, a short at the +60 vdc side in any winding would disable the system by removing all electronics control voltage and power to the alternator field windings. AiResearch recommends that each pair of field windings be fused separately and connected to a different +60 vdc line. These changes would prevent a single high side fault from disabling the system.

Should an accidental short occur on either field winding pairs low side, pair field windings would remain energized and alternator control output voltage would be lost. A modified circuit separating the high or +60 vdc lines and low side or transistor switch lines, with fuses and high side/low side switches, is recommended. (See modified schematic Drawing 306837, Modification A.)

Voltage output sensing to the voltage regulator is a single line. An open or short in this line would disable the system. The voltage sensing should consist of two or three lines with a series fuse in each line. This method would prevent a single fault from disabling the system. (See modified schematic Drawing 306837, Modification B.)

4.2 Carrier Generator

The carrier generator provides the voltage regulator reference wave form and the parasitic load drivers to pulse width modulate respective loads.

[illegible]

QUANTITY BIDD	QUANTITY REQD	PART NO OR IDENTIFYING NO	QTY	NONCLASSIFIED OR DESCRIPTION	CODE IDENT	MATERIAL AND SPECIFICATION	ITEM
PART NUMBER				PARTS LIST			
				AERONAUTICAL RESEARCH AND DEVELOPMENT COMPANY OF JAPAN, INC. 1-1-1, Yamanote-cho, Shinjyuku-ku, Tokyo 162, Japan			
MOD. REV. ASBY URG. ON HEAT TREATMENT PROCESS MATERIAL AND SPEC.				WIRING DIAGRAM SCHEMATIC, BIPS CONTROL SYSTEM (NASA)			
PARTS IDENT. USE PARTS IDENT. USE				BIP 99193 J SCALE ~ WT ~ SHEET / OF 1

The two carrier generators outputs are common at present. A short to either paralleled generator or an output line open or short would disable the system. AiResearch recommends the operational amplifiers utilize separate voltage regulator lines (one to each line) and the parasitic load driver (one to each line). (Drawing 306837, Modification C).

4.3 Parasitic Load

The parasitic load is in parallel with user load. Parasitic load changes inversely with user load in order to maintain a constant load on the alternator. A single line is shown connecting the parasitic filter output to the triple redundant parasitic load drivers. A short on the high side of this line disables the system. AiResearch recommends three separate fused lines to each load and driver. High side switching should also be considered in the event of a low side short. A low side short on one leg would limit amount of system user load provided. (See schematic Drawing 306837, Modification D.)

4.4 Digital Comparator

AiResearch recommends design and development of a digital comparator for establishing speed reference. AiResearch data indicates that a precision analog reference will drift out of tolerance limits during the long time span required. At present, the basic clock recommended for the digital comparator is a crystal controlled oscillator operating between one and two megahertz. The lower frequency was selected because most digital components operate reliably at or above this frequency. Crystals operating below this frequency are less reliable. These values permit a wide selection of components and component types.

4.5 Power Supply (+15 vdc)

The following power supply changes are recommended.

4.5.1 Parallel Redundant Reference Supplies (Added)

(a) Requirements

- o Output voltage 10 vdc +1 percent
- o Output current 5 ma - 10 ma
- o Input voltage 15 vdc +20 percent - 10 percent
- o Temperature range

(b) Application

- o Voltage regulator reference
- o Shutdown circuit reference
- o Speed converter (N reference)

4.6 Resistors

The following changes are recommended for resistors:

- (a) Where reference voltage is applied use of +2 percent metal film track (matched) within 25 parts per million per degree centigrade.
- (b) Replacement of all variable resistors with fixed resistors (value to be determined by test). Variable resistors are inherently unreliable (not allowed on some manned air/space programs).

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4.7 Summary

Further changes will be made to the AiRsearch digital approach to improve reliability and/or system performance, as further techniques and/or component changes are investigated.

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5. ALTERNATE APPROACH

In parallel with testing and analysing the NASA control system, an independent study was undertaken to determine the feasibility of a completely digital control system. Such a system would offer advantages of reduced drift in gains and set points, reduced power supply complexity, reduced parts count with associated reduction in interconnections, increased reliability, and the possibility of system implementation using advanced technology microprocessor techniques.

5.1 Block Diagram

A block diagram for the alternate digital BIPS control system is shown on Drawing SKP4639. Each subsystem and block is discussed below.

5.1.1 Start Inverter and Logic

The start inverter accelerates the BIPS rotating group to self-sustaining speed at a rate consistent with moderate loop temperature transients, minimum electrical energy consumption, and power levels consistent with alternator per unit rating.

Motoring to 26,000 rpm (50 percent N_e) is possible and has been demonstrated using either an induction or a synchronous start inverter. Determination of total energy consumed and total time will be established by additional testing. The inverter schematic currently in use for synchronous motoring tests at AiResearch is shown on Drawing 306836. The GDS inverter design will be similar to this inverter.

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ZONE	LTR	DESCRIPTION	DATE
A		REVISED LOGIC	9-23-75
B		REVISED LOGIC	3/18/76
C		REVISED LOGIC	6/17/76

QUANTITY REQD	FIND NO.	PART NO OR IDENTIFYING NO.	SYM	NOMENCLATURE OR DESCRIPTION	CODE IDENT	MATERIAL AND SPECIFICATION	ZONE
PART NUMBER				PARTS LIST			
				CONTRACT NO.	AIRSEARCH MANUFACTURING COMPANY OF ARIZONA A DIVISION OF THE GARRETT CORPORATION PHOENIX, ARIZONA		
				DATE	DWG TITLE		
				REVISED	BLOCK DIAGRAM BASIC IBFS CONTROL SYSTEM		
				RECD	SIZE		
				NEXT ASSY	D 99193		
				USED ON	SKP 4639		
				HEAT TREATMENT	SCALE		
				PROCESS	WT		
				NAME AND SPEC	SHEET / OF /		
					5-1A

5.1.2 Output Admittance Transducer

The output admittance transducer function is to monitor dc output voltage and total output current and to divide voltage into current to determine total load admittance. A multiplying type analog to digital converter will be used. The binary number appearing at the output represents the input voltage to reference voltage ratio, or E_{IN}/E_{REF} . When E_{REF} represents system output voltage (a fairly constant 120 vdc) and E_{IN} represents output current, then the device output represents load admittance.

Output voltage and current must be scaled and buffered before interfacing with the analog to digital converter (ADC). These circuits may require supply voltages other than the primary 10 vdc supply.

Attempts to approximate output admittance by determining I_O only while assuming E_O to be 120 volts have failed. E_O can differ significantly from the nominal 120 vdc during load transients, leading to erroneous Y_O measurements and possible instability in the constant power loop.

5.1.3 Speed Set

As discussed in Section 2 Design Considerations, certain advantages can be achieved by shifting the nominal operating speed reference to the left (decreased speed) to maintain T_6 high (approximately 2060°R). The speed set block accomplishes this by resetting speed as a function of either T_6 or total load.

5.1.3.1 T_6 Measurement Considerations

Resistance sensors, thermocouple/amplifiers, and a fluidic temperature sensor were investigated for use with the BIPS digital control system.

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To determine suitability of these sensors for the BIPS application, AiResearch conducted investigations into prospective qualified vendors and available technical literature. The summary of vendor responses is shown on Table 5-1. The summary of technical literature reviewed is shown on Table 5-2.

A review of temperature sensors and types available; thermocouple, resistance, thermal noise, optical, and thermistor, with a brief summary of capabilities is provided in Reference 7 of Table 5-2.

Resistance Sensors

The most likely candidates for a T_6 sensor that would meet the BIPS temperature (T_6) sensor requirements appear to be resistance type sensors. However, they would require custom design for the BIPS application.

A large permanent change in resistance of platinum wire sensors occurs during initial exposure to operating temperatures and requires up to 1000 hours to stabilize (see Table 5-2 reference 5). A burn-in time is required if this initial resistance change cannot be tolerated. A problem associated with using platinum resistance sensors is that wire size must be small in order to obtain reasonable resistance values at operating temperatures. This results in the need for closely controlled assembly procedures and use of extremely sensitive assemblies. When the sensor is subjected to vibration for long time periods, changes in element resistance or fine wire breakage may be expected. Some method of vibration dampening could be required to isolate the heat source assembly (HSA) exit pipe from long term vibration generated by the rotating engine alternator group.

For the GDS, an off-the-shelf resistance temperature sensor Model 118MB may be purchased from Rosemount or Simmonds Precision to determine feasibility of this sensor type.

TABLE 5-1

SUMMARY OF VENDOR RESPONSES FOR T₆ SENSOR DESIGN

Date	Response
2-9-76	Skurka suggested two possible designs that would meet the requirements. A platinum resistance sensing device having a rather low resistance or a thermocouple using platinum vs platinum rhodium or perhaps a more (5X) expensive material Platinel 2 developed by Englehart (now Simmonds Precision).
2-18-76	Gulton did not have a sensor meeting the requirements.
3-11-76	Thermo-Electric proposed platinum vs platinum-rhodium in an Inconel 600 sheath. Cautions us to check on nuclear radiation level at sensor location; sent drawing of proposed sensor.
3-15-76	Semco is not willing to select wire material for sensor. Recommends AiResearch make studies of data available on various wire materials, then select material for fabrication by Semco.
3-23-76	Omega proposed chromel-alumel in a stainless steel sheath with magnesium oxide insulation.
4-5-76	California Alloy Company uses platinum material for temperature sensors in a vacuum, however would not guarantee life or drift characteristics.
4-10-76	Leeds and Northrop cannot supply a suitable sensor because of the vacuum environment.
---	Kanthal Corporation - no response.
5-17-76	In a letter to F.H. Lucero, Drs. Thomas G. Kollie and R.L. Anderson, of ORNL, stated that the literature they reviewed indicated the longest reported test duration was 40,000 hours (4.6 years) at 1157°F for "R" type thermocouples (platinum-13% rhodium vs platinum). The reported drift was -3.6F and was attributed to oxidation of rhodium. Apparently this test was in air or some other oxidizing media. Dr. Kollie believes that 1700°F is above the temperatures for resistance thermometers. He also outlined requirements for a platinum-30% rhodium vs platinum-6%rhodium type B thermocouple that should last 10 years with a drift of 1.8°F

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TABLE 5-1 (CONTD)

SUMMARY OF VENDOR RESPONSES FOR T₆ SENSOR DESIGN

Date	Response
	per year (18°F total); but has some doubts about thermo-couple manufacturers being able to build a satisfactory unit. He estimates costs at \$4000 per yard of length for materials and \$20,000 for labor to build five units.
	Simmond Precision has promised a proposal for a resistance type temperature sensor the last part of May, 1976, but it has not been received.
5-27-76	Honeywell does not believe development of a temperature sensor to meet the requirements is economically feasible.
6-1-76	Rosemount offered a Mode 118 MB resistance temperature detector as the only model available for continuous service at 1700°F but did not comment on drift or life expectations.

TABLE 5-2
SUMMARY OF DOCUMENTS REVIEWED

SENSOR MATERIAL	WIRE DIA. INCH	TEMP RANGE OF	TEST TIME HOURS	DRIFT OF DURING TEST	ENVIRONMENT	INSULATION	CONTAMINATION	REF. NO.	CONCLUSIONS AND REMARKS
Plat-Rhod/Plat	.02	2294	3,700	(-)5.04 Ave. of 8 Units	2×10^{-8} Torr	Alumina	Iron from insulation	1	Concentration of iron impurities increased most at the thermocouple junction.
Plat-Rhod/Plat and Others	.02	1768	120	0	5×10^{-6} Torr or Less	Alumina	See Remarks	2	Contamination not conclusive but iron contamination could be expected for longer test times.
Tungsten/Rhenium Plat-Rhod/Plat	.02 .02	2420 2420	3,860 4,110	-28.26 - 8.46	5×10^{-6} Torr	Alumina	Iron & Silicon from insulation	3	Several failures encountered. Expected drift in 10,000 hrs is 41.4°F.
Chromel/Alumel Tungsten/Rhenium	.02 .02	2000 2000	10,000 10,000	-29&-11 - 5&-11	Inert Gas	Alumina Alumina	No contamination of the TC elements was detected.	4	Good information on fabrication techniques in this paper & a related paper (6).
Platinum	.00314	2012	3,000 ⁺	.045	"Filling Gas"	Fused silica & alumina	Kept clean by flushing with "filling gas"	5	Very stable under test conditions. 10 units tested, 4 had alumina insul. discs & 6 had fused silica discs. The alumina insul. was discontinued due to insul. leakage detected during a calibration check.
Chromel/Alumel Molybdenum	Not Specified	2000 2000	10,000 10,000	10	Inert Gas Inert Gas	Alumina Alumina		6	Actual vales of drift for C/A TC not presented-accuracy goal is $\pm 1\%$ ($\pm 20^\circ\text{F}$)
Platinum Noise Thermometer		Up to 1832 $T = \bar{V}/4kR\Delta f$	"Short time"	.018 to .036				7	Methods of measuring temps above 1000K are reviewed. "Resistance thermometers...most precise" "...where transmutation is troublesome the thermocouple Pt 5 Mo/Pt 0.1 Mo has been recommended..."

- 1) 6/69 NASA Tech. Note D-5287, "Thermal EMF Change for 85 Pt, 13Fh/Pt Thermocouples..."-A. J. Szanislo
- 2) 5/65 "Study of the Instability of Noble Metal Thermocouples in Vacuum..."-Walter, Ewing & Miller
- 3) 6/71 "Long Term Drift of Some Noble & Refractory Metal Thermocouples in Air, Argon & Vacuum"-G.E. Glawe & A.J. Szanislo
- 4) 2/65 PWAC-454 "Drift & Endurance Testing of C/A & Other Thermocouples at 1950 to 2000F"-S. Fanciullo
- 5) 6/71 "Stability of 25 ohm Platinum Thermometer Up to 1100°C"-S. Sawada and T. Mochizuki
- 6) 2/66 "High Temperature Thermometry at Canel"-P. Bliss and S. Fanciullo - Pratt & Whitney Aircraft
- 7) 6/72 "High Temperature Thermometry (A Review)"-R.E. Bedford, Div. of Physics, National Research Council of Canada

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5.1.3.1.1 Thermocouple/Amplifier Sensors

Conventional thermocouples do not appear to meet the BIPS T_6 requirements for one or more reasons as follows:

- o Excessive drift over required 7-10 year life.
- o Material contamination from impurities in insulation or conversion to other elements in radiation environments. Rhodium and rhenium are very susceptible to transmutation in neutron environments.
- o Materials not suitable for long term use in vacuums at the operating temperature.
- o Materials available are very sensitive to mechanical damage during assembly and operation.

Unproven thermocouples made from molybdenum vs columbium (niobium) have been proposed for low drift in nuclear environments (see Table 5-2 Reference 6), however little data is available to verify suitability for BIPS.

5.1.3.1.2 Fluidic Temperature Sensors

A fluidic temperature sensor was investigated for possible T_6 incorporation. Problems sometimes associated with fluidic sensors, including contamination due to particulate matter, seem nonexistent in the BIPS environment. This type sensor requires a source of high pressure gas which is available at the compressor discharge in the BIPS. Preliminary design data indicates a requirement of approximately 0.00083 lb/sec, or approximately 0.33 percent total flow for two HSA systems. Incorporating the sensor in series with the gas flow required to cool the BIPS bearings would provide the required flow with no performance degradation.

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Sensor output is a nominal 800 Hz at 2060°R and varies 0.4 Hz/°R around this operating point. The temperature transducer determines sensor output frequency, converts this output to a binary number representing T_6 , and transmits this data to the processor. Since this sensor is 100 percent digital with no mechanism for drift, drift over the seven-year mission would be negligible.

The fludic sensor requires a sampling tube to sense turbine inlet temperature. This tube must exit the plenum area from under thermal insulation and then route to a lower temperature area where the temperature limited frequency sensor is located. Calculations indicate that heat loss from the smallest usable sensing tube during the transition from hot to cold would equate to more than 30 watts electrical power, largely nullifying the gain in performance expected by using a T_6 sensor.

5.1.3.2 Y_o Set

After consideration of the uncertainties raised during the investigations discussed in paragraph 5.1.3.1, and considering the added complexity of a T_6 loop, it was decided to consider an alternate approach to set nominal speed.

Programed Speed Reduction

System isotope decay is predictable. Maintaining T_6 at 2060°R by allowing speed to decrease from 100 percent at BOM to 97.4 percent at EOM at a rate consistent with isotope decay is a viable solution. This could be accomplished using a time decreasing reference for speed, or programming the performance map into memory, to force increased power outputs at lower speeds. This design approach would yield performance comparable to that possible by measuring T_6 , except that any unforeseen degradation of system performance will result in a T_6 greater than the maximum allowable of 2060°R. Such a degradation

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could be brought about by a higher than expected loss of system inventory, degradation of the radiator, or loss of performance of any of the system components. Lines of constant temperature in Figure 5-1 will move down and to the right, resulting in the operating point lying on a temperature line greater than 2060°R . As discussed previously, a T_6 greater than the design point will result in reduced turbine life, making this approach unattractive.

5.1.3.2.1 Constant Speed/Constant Y_0

An alternate approach was conceived that yields optimum, guaranteed output power at BOM and EOM, yet with less than maximum allowable T_6 during the mission. Performance for this approach is shown on Figure 5-1. A speed gain of 580 Watt/percent and an infinite power gain have been assumed in this approach.

A BOM steady-state output power of 1.3 kW is available and will be provided at $N = 100$ percent and $T_6 = 2060^{\circ}\text{R}$. Prior to launch, T_6 will be measured and verified to be within proper limits.

During the mission the input isotope power decays. The speed loop, while attempting to maintain 100 percent, will reduce output power to compensate for input power decreases. When output power is reduced to a value corresponding to EOM power, no further power reduction is allowed and speed will then reset to maintain this power value until EOM.

To follow mission profile, refer to Figure 5-1. At BOM, point A, $N = 100$ and the speed reference is 100 percent. At point B, $3/4$ years into the mission, input isotope power has decreased to 4.67 kW. Speed has decreased, due to control droop, to 99.85 percent. Output power is 1.21 kW, exactly equal to EOM output power. T_6 has decreased to 1900°R . Any further reduction in average power will cause the control

BIPS MISSION PROFILE
PROGRAMMED SPEED REDUCTION

FIGURE 5-1

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line to shift to the left to maintain a system matchpoint at 1.21 kW. Theoretically, T_6 crosses the 2060°R line when $Q_{IN} = 4.531$ kW, seven years into the mission.

Figure 5-1 shows the most conservative approach for a control that will provide maximum power at BOM and EOM, with a sacrifice of power during the mission. The cooler T_6 experienced during the mission increases turbine life and reliability.

When maximum allowable power is required for long periods after BOM, the speed changes with time and output power can literally be shaped by reconfiguring the control system, assuming standard microcircuits are used, or with microprocessor reprogramming. Any operation at or below $T_6 = 2060^\circ\text{R}$ is permissible, and will result in an increase in reliability.

The worst case power loss using this approach occurs after 3.4 years. Refer to Figure 5-1. Note that with $Q_{IN} = 4.67$ kW, output power at 2060°R would be 1.26 kW, while output power using this design is 1.21 kW. This represents 50 watts of unusable power.

This system allows the power supply output to be specified in terms of maximum and minimum power and guarantees that power will be available regardless of T_6 .

5.1.4 Transducer/Governor

The digital speed control will be based on the three phase alternator output frequency. Control circuits count output frequency cycles for fixed time periods. From this data, appropriate parasitic loads will be applied and removed at a rate of 580 watts/percent speed. The use of alternator frequency to sense speed effectively increases reliability by eliminating an additional speed sensor for providing speed data.

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During startup, additional sensors may be required, since alternator output at low speeds is insufficient to drive speed converter circuits. At startup either monopole output signals or shaft position encoders will be used to provide speed information.

The selection of an acceleration speed sensor depends on control system requirements for motoring and acceleration control of the BIPS. At present it is not known if the final selected motoring design will be induction, synchronous, or a combination of both. Preliminary testing indicates the synchronous start provides the most motoring torque with the least power input. Assuming the synchronous start design is selected, a determination will be required if exact rotor position information must be provided the inverter circuits or if a programmed frequency ramp can be generated in order to reliably lock the rotor in and accelerate under all conditions.

If an induction start or programmed synchronous start is selected, the speed sensor design will likely incorporate a monopole in close proximity to compressor wheel blades and splitters.

If a synchronous start with fixed lead angle is selected, the speed sensor could be a monopole at the compressor with a fixed compressor index mark providing a position indicating pulse. This design depends on being able to motor the unit with a fixed ramp until sufficient monopole output signal pulse height is available to overcome electronic threshold limits.

If a synchronous start with constant or known lead angle is required from zero to maximum rpm, a rotor position sensor will be utilized.

5.1.5 Parasitic Load

The parasitic load circuit is shown in Drawing SKP4649. The load consists of six coarse power correcting load resistors (R_a)

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SKP4649 B

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through R_f) and one pulse width modulated resistor (R_t) for fine control. The power rating and admittance value of each resistor increases according to a 2-4-8 binary code from resistor to resistor. Total power dissipation of this load is 2880 Watts at 120 vdc. This value approximates maximum output Mini-BRU alternator capability. During normal operation, maximum single transistor current is 4 amps, resulting in low drive transistor power dissipation. Digital, binary encoded numbers representing desired parasitic load admittance can be used to drive parasitic load resistors directly. The maximum transistor current, load resistor values, admittance, and power dissipation at 120 vdc are shown on Table 5-3.

5.1.5.1 Parasitic Load Drivers

The parasitic load driver circuit is shown on Drawing SKP 4649. For the GDS high reliability transistors will be used to drive loads. For the FS, transistor quads (NPN-PNP) will be hybridized in separate packages. Since total dissipation per package should not exceed 8 Watts, a TO-3 package is sufficient. The load driver circuits (when off) will consume no power from the output, thus maximizing available power to user loads.

Any single transistor failure, open or shorted, has no effect on system operation. Assuming a transistor pair shorts or up to one of each complimentary pair fails open, there is no effect on system operation. Only when a transistor pair fails open or each complimentary pair shorts will any noticeable change in power occur. The worst case failure result would occur in the highest admittance load and would result in 480 Watts minimum parasitic load application for mission duration or until fault clearance. Dividing the load into smaller increments with a corresponding increase in driver transistor numbers will reduce failure effects.

TABLE 5-3

BIPS OUTPUT STAGES PARASITIC LOAD RESISTOR DATA

Load Resistor	No. In Parallel	Watts Per Resistor at 120 Vdc	Watts Per Parallel Combination at 120 Vdc	MHOS Per Resistor ($\times 10^{-3}$)	MHOS Per Parallel Combination ($\times 10^{-3}$)	Current Per Resistor (Current Per Transistor) at 120 Vdc	Current Per Parallel Combination at 120 Vdc
R_a	3	480	1440	33.3	100	4	12
R_b	2	360	720	25.0	50	3	6
R_c	1	360	360	25.0	25	3	3
R_d	1	180	180	12.5	12.5	1.5	1.5
R_e	1	90	90	6.25	6.25	0.75	0.75
R_f	1	45	45	3.125	3.125	0.375	0.375
R_t (trim)	1	45	45	3.125	3.125	0.375	0.375
Total	10	*	2880	*	200	*	24

*Sum Not Important.

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Solitron Devices Incorporated has stated that the transistor driver configuration is feasible and that hybridized power transistors with two NPN and two PNP chips in each package are available.

The BIPS-GDS and FS configuration requires 10 packages containing 40 driver transistors. Since current requirements for various transistors range from 375 milliamperes to 4 amperes, different part numbered transistors will be required. All transistors will be selected for reliability and maximum voltage capability as primary considerations.

5.1.6 Rectifier

The rectifier schematic is shown on Drawing SKP4649 attached. The rectifier is a common rectifier to user and parasitic loads. Average current flow through the rectifier remains constant throughout user load variations, due to parasitic load control action. Fuses F1 through F6 serve to reduce rectifier power dissipation. Should a diode short, excessive current flows through the associated fuse when the diode becomes reversed biased. When the fuse blows, a new diode is connected in the circuit. Assuming a diode opens, the parallel diode will accept full load current. This arrangement reduces total rectifier dissipation by a factor of two.

5.1.7 Filter

The filter schematic is shown on Figure 5-2. Three-phase alternator rectified output will have a basic ripple frequency six times the fundamental frequency (10,398 Hz), and unfiltered ripple voltage four percent of total dc output (4.8 volts rms). A low pass LC filter is proposed to reduce rectifier output ripple voltage to acceptable levels.

L_2 & C_2 IF REQUIRED FOR
SUPPRESSION AT PARASITIC LOAD

BIPS FILTER SCHEMATIC

FIGURE 5-2

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Ripple voltage attenuation calculations using a series input inductor (100 microhenries) shunted with a 50 microfarad capacitor indicate attenuation begins at a ripple frequency of 4500 Hz and reaches a value of 25 dB at the 10,398 Hz. Attenuation increases asymptotically at the higher frequencies. The 10,398 Hz ripple voltage would then be reduced by the low pass filter from approximately 4.8 volts rms to 0.28 volts rms (0.4 v peak). To effectively shunt high frequency harmonics, a small (0.01 mfd) bypass capacitor will be used at the rectifier output.

Locating the low pass filter at the parasitic and user load input side allows a nearly constant steady-state dc current component to flow in the filter inductor. An air gap in the magnetic core will be considered to prevent core saturation.

Should additional filtering be required, as a result of parasitic load element switching, an additional low pass filter will be incorporated in the parasitic load line. Oversize magnet wire will be used to increase inductor reliability and improve user load dc regulation. Silectron or equivalent magnetic core material with a maximum two mil lamination thickness is proposed to permit a high level of flux density to be used, and to minimize filter inductor(s) core losses.

Tantalum etched foil electrolytic capacitors for the low pass filter(s) are available with hermetically sealed cases. The tantalum etched foil electrolytic provides a compact unit with proven long life characteristics at temperatures to 125°C.

Polypropylene or paper high frequency bypass capacitors are recommended for the high pass filters.

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5.1.8 Current Transformers

Present AiResearch three HSA controls design requires redundant current transformers located on the alternator output leads. The current transformers are sized to provide alternator field excitation corresponding to the alternator output rating. Preliminary testing indicates a 0.7 ampere dc field current through each parallel field section is required to provide 16.3 amperes at 120 vdc output. Under hot field conditions, 20 field volts is required to provide 0.7 amperes per section.

Assuming 90 percent transformer efficiency, plus ac to dc conversion, and shunt regulator losses, a 22-volt ampere rating for each three-phase current transformer, at a three HSA power level, is required.

To minimize current transformer size and weight, superalloy magnetic material is proposed because of high permeability, and resulting low magnetizing current and core losses. Three separately wound primaries, on a single core with wye connected secondaries tapped to provide the optimum output current at either the two or three HSA power levels would be used. Preliminary estimates indicate the weight for the GDS, three-phase current transformer, is three pounds. Final FS design dimensions would be reduced by 20 percent.

5.1.9 Voltage Regulator (Output Stage)

Essential voltage regulator field drive elements are shown on Figure 5-3. The voltage regulator is a shunt regulator that pulse width modulates current in alternator field. Output voltage is converted from analog to digital in an ADC. This number is subtracted

VOLTAGE REGULATOR (OUTPUT STAGE)

FIGURE 5-3

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from a free running counter. As long as the difference is negative, current to the field is shunted. This results in a pulse width modulated signal whose period equals $2n/f_{osc}$.

5.1.10 Power Supplies

5.1.10.1 Field Power Supply

The field power supply is shown schematically on Figure 5-4. Power supply prime movers in order of decreasing authority are; output current, output voltage, and facility supply voltage. Only output current drive is shown on Figure 5-4.

Output current was selected as the primary field power supply source to ensure power during short circuited output periods.

Load corrections will be made in less than one millisecond after a user load change and will result in negligible field current interruptions during no load periods. In the event load is lost, output voltage will provide sufficient field drive power to ensure output terminal voltage when the load is reapplied. During start, field flashing is provided by shuttle power supplies.

Each field power supply is capable of providing sufficient current to maintain 120 vdc at the output terminals for all expected load conditions. Since the current transformers provide a constant current source, an opening in any field coil has little effect on output. This is true due to the constant total ampere turns. The three remaining coil currents increase to maintain the same value as that prior to failure. A shorted field will result in a lower voltage across the parallel fields. Output voltage current will clear the fault and the power supply will return to normal operation.

FIELD POWER SUPPLY

FIGURE 5-4

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5.1.10.2 Control Power Supply

The control power supply is required to operate over a system output voltage range of 80 to 140 volts. Because total output power at 80 volts is insufficient to limit speed (1280 Watts) and voltages of greater than 140 volts are not possible due to alternator characteristics, control system operation is limited to a range of 80-140 volts. The control system will be such that below 80 volts, full field current will be applied with zero parasitic load. This 80 volt value would most probably be a resultant of a short, with subsequent loss of real output power. Adding parasitic load would increase short circuit current and impede voltage buildup upon short clearance. In removing parasitic load, voltage will rise quickly after fault clearance followed by parasitic load application to control speed.

Assuming the control system incorporates a majority of digital CMOS circuits, the power supply requirements remain low. CMOS circuits operate properly with extremely small currents and require minimal power supply regulation. A power supply meeting these requirements is developed easily, using a switching regulator from a brute force dc voltage output supply. Assuming higher currents are required for transistor/transistor logic (TTL) and bipolar circuits, a more complex supply and regulator would be required with transformers to improve efficiency.

5.1.11 Load Control Circuits

A load control circuit schematic is shown on Drawing 306832. The schematic assumes fluidic temperature sensor use and includes speed control logic only.

The load control circuit monitors speed sensor outputs, T_6 transducer output, Y_0 transducer output, and parasitic load status.

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This circuit provides the parasitic load drivers a binary number indicating desired load admittance (since average voltage is constant, parasitic load power is proportional to admittance). This is accomplished using an arithmetic logic unit (ALU) to shift data, add and subtract in accordance with programmed load control memory circuit instructions. Calculation and data shifting is accomplished mainly with hardware; however, through microprocessor use, most calculations can be accomplished with software.

5.2 Component Selection

5.2.1 Control Microcircuits

Control microcircuits will be selected to the maximum extent possible from those identified in Specification MIL-M-38510 for Specification SS-STS-100 Vol. 3, identifying the Space Transportation System (STS) Interim Upper Stage (IUS) segment that references MIL-STD-454. Most microcircuits required are available from vendors at the required screening levels of MIL-STD-883. The ALU is not specified in MIL-M-38510; however, this unit is available from RCA at the required MIL-STD-883 screening level.

5.2.2 Analog to Digital Converters

The analog to digital converters are new devices not yet specified in MIL-M-38510. A survey is presently underway to determine future availability in accordance with MIL-STD-883 requirements.

5.2.3 CMOS Devices

Drawing 306832 shows the use of CMOS devices; however, the same functions can be achieved to a large degree with microcircuits defined in SAMSO-STD-73-4A, list of preferred parts for space and missile systems.

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5.3 System Loop Operation

System loop implementation is shown on Drawing 306830. Speed may be set by the thermocouple/amplifier combination, fluidic sensor, or as a function of output power.

5.3.1 Thermocouple/Amplifier

Assuming the thermocouple/amplifier is used, thermocouple voltage is amplified and subtracted from a reference voltage scaled to represent 2054.4°R . Resultant voltage is scaled, converted to a binary digital number, and added to a constant (1228). The resultant binary number provides a speed sensor input reference and sets unit operating speed point. A change in T_6 will cause C_N to increase at a rate corresponding to 0.44 percent/ $^{\circ}\text{R}$.

5.3.2 Fluidic Sensor

Assuming a fluidic sensor is used, output frequency is inputted to a counter. The counter counts total pulses for a fixed time interval (in this instance 14.25 seconds). A constant, C_T , is subtracted from the total count, leaving the remainder equal to C_N . The loop gain is identical to the thermocouple loop; 0.44 percent/ $^{\circ}\text{R}$.

5.3.3 Power Reset

Assuming speed is reset as a power function (preferred approach), the difference between measured Y_O required to hold speed, and Y_O required for EOM power is constantly measured. As long as the difference indicates long term average admittance is greater than referenced admittance, speed reference is 100 percent. When reference exceeds measured admittance, the difference is calculated and the resultant binary number is applied to the speed reference in a manner similar to temperature errors previously discussed.

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REVISIONS		DATE	APPROVED
ZONE	LTR	DESCRIPTION	

SPEED SENSOR

SPEED SET

LOAD ADMITTANCE DETECTOR

$$Y_{comm} = Y_{PL} + Y_n - Y_s - Y_0$$

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QUANTITY REQD	FIND NO	PART NO. OR IDENTIFYING NO.	SYM	NOMENCLATURE OR DESCRIPTION	CODE IDENT	MATERIAL AND SPECIFICATION	ZONE
PARTS LIST							
CONTRACT NO.				AIRSEARCH MANUFACTURING COMPANY OF ARIZONA A DIVISION OF THE GARRETT CORPORATION PHOENIX, ARIZONA			
DFT H. ROARK 5-6-76				DWC TITLE			
CHR. H. ROARK 5-6-76				BIPS SPEED CONTROL LOOP			
MFG				SIZE			
MTRL				D			
STRESS				99193			
AERO				306830			
APVD				SCALE			
DESIGN ACTIVITY APVD				WT			
OTHER ACTIVITY APVD				SHEET / OF			
				5-2A			

306830

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5.3.4 Speed Sensor Function

The speed sensor counts monopole pulses for a fixed time interval, subtracts C_N , and yields Y_N , a coded digital number equal to desired total system loads for existing T_6 and N conditions. The time interval for counting monopole pulses is 57.2 milliseconds.

The sensor gain is such that a one percent change in speed will result in sufficient change in admittance to cause output power change equal to 580 Watts at 120 vdc (i.e., power gain = 580 Watts/percent admittance gain = $580/\text{volts}^2/\text{percent} = 580/120 \text{ volts}^2/\text{percent} = 0.0402 \text{ mhos/percent}$).

5.3.5 Output Admittance Detector

The output admittance detector scales output voltage such that 120 vdc equals 7.5 volts into the ADC reference terminal and 1 ampere (I_{DC}) = 0.3128 volts into the input terminal. The resultant output binary number represents system total load admittance.

5.3.5.1 Data Processing

Speed sensor outputs, output admittance detector, and the parasitic load drivers last command are added and subtracted in accordance with the following equation to yield the new parasitic load command:

$$Y_{COMM} = Y_{PL} + Y_N - Y_O$$

where:

Y_{COMM} = new command to parasitic load

Y_N = speed sensor output (total desired admittance)

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Y_{PC} = existing parasitic load admittance

Y_O = user load admittance

Digital binary numbers generated by various sensors and transducers are ten bit numbers, where the first six bits represent the whole number and the last four bits represent the fraction to the nearest one sixteenth. To convert the binary number to actual admittance represented, the binary number is multiplied by 0.003125 mhos/bit. The greatest admittance possible is $(2^6 1/16)(0.003125) = (63.9375)(0.003125) = 0.1998$ mhos. Power at this admittance and 120 vdc = 2877.2 Watts (approximately maximum alternator available power). Minimum admittance possible is zero.

The parasitic resistors are weighted per bit exactly as the 10 bit binary numbers being control generated. Six resistors represent whole numbers, while the trim resistor, R_T , is pulse width modulated in one sixteenth increments to yield an average admittance equal to the binary number fractional portion.

As an example, take the following Y_{COMM} binary number:

0 0 1 0 1 0 . 0 1 1 0

The number is a 10 bit number with the decimal placed to indicate the first whole number six bits and the last four bits represent the fraction. Converting to base 10 is as follows:

$$\begin{aligned} 0 \times 2^5 &= 0 \\ 0 \times 2^4 &= 0 \\ 1 \times 2^3 &= 8 \\ 0 \times 2^2 &= 0 \\ 1 \times 2^1 &= 2 \end{aligned}$$

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$$\begin{array}{rcl}
 0 \times 2^0 & = & 0 \\
 0 \times 2^{-1} & = & 0 \\
 1 \times 2^{-2} & = & 0.25 \\
 1 \times 2^{-3} & = & 0.125 \\
 0 \times 2^{-4} & = & 0 \\
 \hline
 & & 10.375
 \end{array}$$

To determine total desired admittance, multiply by 0.003125 mhos.

$$(10.375)(0.003125) = 0.03242 \text{ mhos}$$

Assuming this binary number was used to drive the parasitic load directly, the results would be:

$$\begin{array}{rcl}
 0 \times Y_F & = 0 \times 0.1 & = 0.00000 \\
 0 \times Y_E & = 0 \times 0.05 & = 0.00000 \\
 1 \times Y_D & = 1 \times 0.025 & = 0.02500 \\
 0 \times Y_C & = 0 \times 0.0125 & = 0.00000 \\
 1 \times Y_B & = 1 \times 0.00625 & = 0.00625 \\
 0 \times Y_A & = 0 \times 0.003125 & = 0.00000 \\
 & & \hline
 & & 0.03125
 \end{array}$$

The fractional portion, 0110, is compared to a free-running counter operating from 0000 to 1111. When the counter is less than the fractional portion, the trim resistor is driven to on. When the counter is equal to or greater than the fractional portion, the trim resistor is off. Thus, the average trim resistor admittance equals:

$$\frac{\text{BINARY FRACTION}}{2^4} (Y_T)$$

For the example selected, 0110 equals $2^2 + 2^1 = 6$. Solving for the average admittance of the trim resistor is as follows:

$$(6/2^4)(0.003125) = 0.00117$$

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Summing the whole number and fractional calculations results provides a total average parasitic load admittance of:

$$0.03125 + 0.00117 = 0.03242$$

or the desired admittance calculation/results (exactly).

With admittance resolution of one sixteenth, it is possible for parasitic load drivers to apply an admittance up to one sixteenth (0.003125) = 1.95312×10^{-4} mhos low. The power error for this instance at 120 vdc output would be $V^2 Y = 2.8$ watts low. This would allow speed to increase until the parasitic load incremented up an additional 1.95312×10^{-4} mhos.

The speed sensor gain is 12.889 BITS/percent. Since an additional one sixteenth bit is the total required, the increase in speed will be:

$$\frac{0.0625 \text{ BITS}}{12.889 \text{ BITS/percent}} = 0.005 \text{ percent}$$

Therefore, maximum speed error due to parasitic load resolution is 0.005 percent.

5.4 Digital-Sample Data System Performance

The digital-sample data system controller transient performance was predicted by the system digital computer model. These computer results are shown in Appendix II. The systems investigated included a sample and multiply system. This system lacked stability. Several variations of the sample and add system are shown in Appendix II. The sampling period investigated was slow (one millisecond), resulting in large overshoots during step load transients. The major system disadvantage is that control has to wait one full sample period before a

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correction is possible. However, overshoots can be corrected by faster sampling and improved filters. These tradeoffs can be made during further evaluation of this concept. The computer results indicate that the system as presented originally can be filtered. However, the filter size becomes larger than desirable.

The control system response to transients is fast and well damped except for full to no load transients. This mode will require further investigation. No attempt was made during this preliminary analysis to optimize control gains or add dynamic compensation.

5.5 Supplementary Digital Approach Study

A supplementary digital study was performed by the Torrance Division of AiResearch on the BIPS Control System. This study verified that the digital approach is feasible and warrants further investigation in order to make an accurate comparison with the present analog system.

5.5.1 Digital Approach (BIPS System)

A block diagram is shown on Figure 5-5 of the BIPS Control System. The basic approach is to maintain a constant load on the alternator by holding the load admittance a constant. This is accomplished by dividing the output current by the output voltage and keeping this signal constant by adjusting parasitic load.

Over extended operation, as the heat source decreases, turbine speed will decrease. This speed decrease is sensed by the speed control, which reduces the parasitic load control set point as a speed error function. The result is a reduction in total load to maintain speed. This load reduction scale factor is 580 Watts/percent speed reduction.

Load Adjust 580 W/% Speed
Speed Adjust -0.06% Speed/Watt Below 1250 Watts

BIPS BLOCK DIAGRAM
(SUPPLEMENTARY DIGITAL APPROACH)

FIGURE 5-5

At approximately 1.9 years, the alternator output power will have reduced to 1250 Watts with a corresponding decrease in T_6 to 2020°R . At this point the load control circuit resets the speed control set point by 0.06 percent. The load control circuit will continue to decrease speed set point by 0.06 percent/Watt decrease in output power throughout the mission balance resulting in 1210 Watts and T_6 of 2060°R at EOM. Figure 5-6 shows T_6 , speed, and output power throughout mission life.

5.5.2 Digital System

A block diagram of the digital system is shown on Figure 5-7. Three microprocessors form the prime basis of this system. The microprocessors are large scale integrated (LSI) microcircuits, that control events sequencing and any computations required. The microprocessor program is a read only memory (ROM) that controls the processor sequence of events. The memory is in effect a read/write scratch pad that is used for temporary storage for comparison and computation.

5.5.2.1 Parasitic Load Output

The parasitic load output stores the load setting between computation cycles. Output to the field control stores the pulse width information between computational cycles.

5.5.2.2 Sensed Inputs

All the sensed inputs, output current (I_{OUT}), output voltage (E_{OUT}), and turbine speed (Speed), are triple redundant.

5.5.2.3 Microprocessor

Each microprocessor has access to all inputs by means of input selection logic. The microprocessor performs a majority selection on

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BIPS MISSION PROFILE - OUTPUT POWER

FIGURE 5-6

DIGITAL SYSTEM BLOCK DIAGRAM

FIGURE 5-7

each input function in order to disregard any single failure. When two failures occur on any input function, the out-of-range inputs are ignored. Therefore, in most situations, two out of three input malfunctions can be tolerated.

5.5.3 Reliability Analysis

Reliability analysis performed for this digital control is conservative in that only one failure for each group of three inputs is allowed for proper operation.

Parasitic load and field control circuits are such that any two failures will not disable these functions.

5.5.3.1 Mission Success

The parasitic load by microprocessor number 1 probability for successful operation is shown on Table 5-4. This probability [$P_S(D_{10})$] is 0.88196 for five years. The probability of successful operation of the parasitic load with all three microprocessors is shown in the following equation:

$$\begin{aligned}
 P_S(\text{Parasitic}) &= 1 - P_F \\
 &= 1 - [1 - P_S(D_{10})]^3 \\
 \text{since } P_S(D_{10}) &= P_S(D_{11}) = P_S(D_{12}) \\
 \text{and } P_F(D_{10}) &= 1 - P_S(D_{10}) \\
 \text{or } P_S(\text{Parasitic}) &= 1 - (1 - 0.88196)^3
 \end{aligned}$$

The field current control probability for successful operation is identical to the parasitic load control.

The overall probability for mission success is as follows:

$$\begin{aligned}
 P_S(\text{Mission}) &= P_S(\text{Parasitic}) P_S(\text{Field}) \\
 &= (0.99836)(0.99836) \\
 P_S(\text{Mission}) &= 0.99671
 \end{aligned}$$

TABLE 5-4

PROBABILITY OF SUCCESSFUL OPERATION
OF THE PARASITIC LOAD

For Microprocessor No. 1

D ₁	D ₂	D ₃	D ₄	D ₅	D ₆	D ₁₀	RESULT	PROBABILITY OF SUCCESS
1	1	1	1	1	1	1	Success	0.79880
1	1	1	1	1	0	1	Success	0.01298
1	1	1	1	0	1	1	Success	0.01298
1	1	0	1	1	1	1	Success	0.01405
1	1	0	1	1	0	1	Success	0.00023
1	1	0	1	0	1	1	Success	0.00023
1	1	0	0	1	1	1	Success	0.00023
1	0	1	1	1	1	1	Success	0.01405
1	0	1	1	1	0	1	Success	0.00023
1	0	1	1	0	1	1	Success	0.00023
1	0	1	0	1	1	1	Success	0.00023
0	1	1	1	1	1	1	Success	0.01405
0	1	1	1	1	0	1	Success	0.00023
0	1	1	1	0	1	1	Success	0.00023
0	1	1	0	1	1	1	Success	0.00023

$$P_S(D_{10}) = 0.88196$$

$$P_S(D_1) = P_S(D_2) = P_S(D_3) = 0.98272$$

$$P_S(D_4) = P_S(D_5) = P_S(D_6) = 0.98401$$

$$P_S(D_{10}) = 0.88339$$

For this analysis a number of common elements with the analog approach were not considered. These elements are field windings, stator windings, power rectifier and filter, and parasitic load.

5.5.3.2 Background Failure Rates

Table 5-5 shows the failure rates for this analysis.

5.5.3.3 Total System Failure Rates

When including total system components, failure rates are as follows:

	<u>Failure Rate/ Million Hours</u>
Digital Control	0.0374
Alternator	0.01700
Parasitic Load Bank	0.00023
Power Distribution System	<u>0.01000</u>
	0.06463

The total for a 5-year life cycle is 0.06463 failures/million hours or a reliability of 0.9971.

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TABLE 5-5

	Failure/ 10^6 Hrs	Probability of Success
1. I_{OUT} Amp	0.01446	0.99937
2. E_{OUT} Amp	0.01612	0.99929
3. +15 VDC Power	0.06717	0.99706
4. A to D Converter	0.04038	0.99823
5. Clock	0.25966	0.98868
6. Speed Input	0.00846	0.99963
7. Counter	0.03242	0.99858
8. Microprocessor*	2.82883	0.88339

*Includes Input Logic, Processor, Memory Program, Output, Clock,
and Power Supply.

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APPENDIX I

1. Specification for BIPS Electrical Power Output Characteristics, SC-76-312008.

SPECIFICATION

FOR
BRAYTON ISOTOPE POWER SYSTEM (BIPS)
ELECTRICAL OUTPUT POWER
CHARACTERISTICS

SC-76-312008

June 20, 1976

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SPECIFICATION

FOR
BRAYTON ISOTOPE POWER SYSTEM (BIPS)
ELECTRICAL OUTPUT POWER
CHARACTERISTICS

SC-76-312008

June 20, 1976

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REPORT NO. SC-76-312008

TOTAL PAGES 7

ATTACHMENTS:

REV	BY	APPROVED	DATE	PAGES AND/OR PARAGRAPHS AFFECTED
NC	WK	See Title Page	6-20-76	Initial Issue

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SPECIFICATION
FOR
BRAYTON ISOTOPE POWER SYSTEM (BIPS)
ELECTRICAL OUTPUT POWER CHARACTERISTICS

1. GENERAL

1.1 Scope

This specification defines the Brayton Isotope Power System (BIPS) standards and characteristics for electrical power generation, required to be maintained at utilizing equipments power-input terminals, during generation and distribution.

1.2 Purpose

The purpose of this specification is to provide voltage and frequency limits and conditions to be used as criteria for BIPS electrical power system performance.

2. REFERENCED DOCUMENTS

2.1

The issues of the following documents in effect on date of invitation for bids, form a part of this standard to the extent specified herein.

SPECIFICATIONS

Military

MIL-E-6051

Electromagnetic Compatibility
Requirements, Systems

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STANDARDS

Industry

DO-160	Environmental Conditions and Test Procedures for Airborne Electronic/Electrical Equipment Instruments;
IEEE STD-100-1972	IEEE Standard Dictionary of Electronic Terms

3. DEFINITIONS

3.1

Definitions of terms not explicitly treated are as shown in IEEE Standard Dictionary of Electrical and Electronic Terms.

3.2 DC Power Characteristics

The designation dc power characteristics applies to voltages in a direct-current, two-wire or ground return system.

3.2.1 Nominal dc Voltage

The nominal dc voltage magnitude is 120 volts.

3.3 Distortion

Distortion is the rms value of the superimposed alternating voltage.

3.3.1 Distortion Factor

The dc distortion factor is the ratio of dc distortion to average dc voltage.

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3.3.2 Distortion Spectrum

The distortion spectrum quantifies dc distortion in terms of the amplitude of each frequency component. The distortion spectrum includes the components resulting from amplitude and frequency modulation as well as harmonic and non-harmonic components of the ac waveform.

3.4 Electrical Power Characteristics

Electrical power characteristics include values and limits of voltage and frequency parameters, and include related characteristics pertinent to electro-magnetic compatibility requirements as well as those designated in ac and dc subcategories. These characteristics are representative of steady and transient states experienced in system operation during all phases of operation.

3.5 Electric Power System

The electric power system is that group of connected generation, distribution, protective and conversion equipments active in supplying electric power to utilization equipments.

3.6 Electromagnetic Compatibility

Electromagnetic compatibility is the capability of systems and associated equipment to perform at specified levels in the total electromagnetic environment.

3.7 Frequency

Frequency is equal to the reciprocal of the alternation period of the fundamental of ac voltage. The unit of frequency is the number of alternations per second of ac voltage and is designated Hertz (Hz.)

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3.8 Overvoltage and Undervoltage

Overvoltage and undervoltage are those voltages which exceed the combined steady state and surge limits and are usually terminated by the action of protective devices. Although generally short lived, these transients differ from surges in the sense that, if left unchecked, over and undervoltage would continue indefinitely at a fixed magnitude or until some breakdown in operation was precipitated. Overvoltage and undervoltage can exist indefinitely at values slightly exceeding steady state limits but within the trip limits of generator protection circuits. These transients are generally due to loss of regulator control, unbalance, or faults, i.e., causes other than those producing surge voltages.

3.9 Ripple Amplitude

Ripple amplitude is the maximum value of the difference between the average and instantaneous values of a pulsating unidirectional wave. (See 2.1, IEEE Standard.)

3.10 Steady State

A steady state condition of the characteristics is one in which the characteristic shows only negligible change throughout an arbitrarily long period of time.

3.11 Utilization Equipment

Utilization equipment is that which receives power from the electric power system. It may be an individual unit, a set of equipments or a complete subsystem receiving power through common equipment terminals or power converters.

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3.12 Voltage Surge

The voltage surge is defined as a transient departure of the peak values of voltage from the peak instantaneous value of steady state voltage, persisting for periods in excess of 500 microseconds, followed by recovery to within peak values corresponding to steady state. Surges are caused by load changes, switching or power interruptions elsewhere in the system, and are not expected to activate protective equipment.

3.13 Voltage Spike

Spike is a transient of total duration normally less than 500 microseconds and is superimposed on the otherwise unaltered instantaneous voltage. Spikes may be characterized in time domain in terms of voltage with parameters of duration, risetime and energy. Spikes may also be characterized equivalently in terms of Fourier component amplitudes as a function of frequency. Spikes are not expected to activate protective equipment.

3.14 Reference Ground

The primary spacecraft structure is reference ground for the dc electrical power system. In some instances, it may be possible to utilize the negative polarity wiring of the dc system as ground.

3.15 Power Sensitivity

Power sensitivity of utilization equipment is the ratio of incremental output changes to incremental input changes for specified output performance quantities and specified voltage or frequency input-power changes. (See IEEE STD, 2.1)

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4. GENERAL REQUIREMENTS

4.1 System Equipment Compatibility

The characteristics defined in this specification shall be maintained at the U/E terminals during operation of all expected combinations of power source, distribution and utilization equipment. BIPS operating modes outside the conditions defined herein specification will be permitted only when specifically authorized.

4.2 Power Interruption

Due to conditions of bus transfer, voltage may be between zero and steady state limits for a period no greater than fifty milliseconds, and within the limits of Figure 5-2 following this interruption. Interruptions resulting from overvoltage and undervoltage or over-current may be followed by bus transfer, or by power restoration delays as determined by the particular application. (See 5.1.3)

4.3 Conformance Tests

Tests for conformance of the electric system to the characteristics stipulated in this specification shall be defined as part of the procurement specifications to which this document is applicable, and shall be subject to approval of the procuring activity.

5. DIGITAL REQUIREMENTS

5.1 DC Power Characteristics

Dc power characteristics are those of a direct-current, two-wire or ground return system having a nominal voltage of 120 volts.

5.1.1 Steady State

5.1.1.1 DC Voltage Magnitude

The dc voltage shall be within 110 to 125 volts.

5.1.1.2 DC Distortion

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).

5.1.2 Transient

5.1.2.1 Voltage Surge

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

5.1.2.2 Voltage Spike

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

5.1.3 Overvoltage and Undervoltage

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).

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APPENDIX II
DYNAMIC ANALYSIS

APPENDIX II

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1. Introduction

This appendix presents the dynamic analysis performed on the engine control and power management system. This system analysis was conducted for the rectifier, filter, voltage regulator, engine rotating group, and the proposed control system, that regulates the listed components.

A previous BIPS system computer model included the heat source, recuperator, cooler, compressor, and turbine map descriptions. The results achieved were reported in AiResearch document 75-311279. This report presents transients around the loop during startup and load transient performance. The engine is modeled in detail, however, the alternator and electronic control are only functionally modeled, because the dynamics order of magnitudes are drastically different. The engine model examines a few hundred seconds of time, since the time constants or component response in this model are from approximately one second for pneumatics to 100 seconds for heat exchanger thermal response. The controls computer programs discussed herein examine only about 100 milliseconds during a single computer run. The program views electronic components time constants in microseconds, with attempts to predict voltage spikes and very high frequency closed loop stability.

The analysis was first performed with a digital computer using the Control Data Corp MIMIC simulation language. This method was selected for model checkout and for ease of computer access with no setup time required. (The analog computer requires re-setting potentiometers, changing program boards, etc. before a run.) The analog computer was selected for some electrical model final runs, because of ease of programming, gain changes are easily made, and time scaling allows viewing very high frequencies and affords cost (time) reduction. Both computers results are presented herein.

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2. DERIVATION OF EQUATIONS

The following are derivations of equations used in computer simulations. The model is generally linearized about the 52,000 engine rpm operating point. The 3 HSA power configuration was used since engine model experience indicated this configuration to be the "worst case" from a stability standpoint.

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2.1 Description of Mathematical Model for an Alternator

A simplified sketch of an alternator is shown below.

Figure - Ideal Alternator

Located upon the rotor or moving element is the field winding, f . Contained in the stator or stationary portion of the device are the 3 distributed windings, a , b and c . When a direct voltage is introduced upon the field winding and the rotor is turned an alternating voltage is induced in the three stator windings a , b and c . In the following section the mathematical relationships defining the voltage and current in the field and in each stator winding will be presented. To expedite

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analysis, the effects of saturation, hysteresis and eddy currents are neglected. It should be noted that in the following analysis only the field winding is assumed to exist on the rotor. In many devices damper or amortisseur circuits are constructed. Even if such circuits are not included in the device an additional equivalent circuit is formed by the bolts and iron in the rotor structure. Mathematically the addition of these extra rotor circuits complicates the analysis. Two additional voltage and flux linkage relationships are required for each amortisseur circuit considered. The addition of these equations does not present an insurmountable problem to the analysis. The main difficulty lies in obtaining the required physical constants in these equations. Physically these additional rotor circuits are observed to produce very fast decaying transient effects. For example in the short circuit of an alternator the effect of additional rotor circuits decay within a few cycles of the output of the device. For the mathematical development of the alternator including amortisseur circuits on the rotor see Concordia.²

Mathematical Description

The mathematical equations relating the applied voltage and input current for the field winding and each stator winding a, b and c are

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$$\begin{aligned} v_a &= r_a i_a + p \lambda_a \\ v_b &= r_b i_b + p \lambda_b \\ v_c &= r_c i_c + p \lambda_c \\ v_f &= r_f i_f + p \lambda_f \end{aligned} \quad (1)$$

where v is the applied voltage, i the input current, r the winding resistance, λ the flux linkage with the winding, and p the differential operator d/dt . The flux linkage expressions are

$$\begin{aligned} \lambda_a &= L_{aa} i_a + L_{ab} i_b + L_{ac} i_c + L_{af} i_f \\ \lambda_b &= L_{ba} i_a + L_{bb} i_b + L_{bc} i_c + L_{bf} i_f \\ \lambda_c &= L_{ca} i_a + L_{cb} i_b + L_{cc} i_c + L_{cf} i_f \\ \lambda_f &= L_{fa} i_a + L_{fb} i_b + L_{fc} i_c + L_{ff} i_f \end{aligned} \quad (2)$$

L in the previous equations represents inductance. Two like subscripts represents a self-inductance (that is an inductance with respect to a single winding) and two unlike subscripts denote a mutual inductance between the two windings concerned.

It should be noted that the flux linkage equations found in expression (2) could be substituted into equation (1) and the resulting equations solved for the three phase and field currents. A simpler result is found to occur however by a change of

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variables. The transformation employed is that of the three stator winding variables a , b and c into the direct and quadrature axis fixed to the rotor, see Figure-1. The transformation expressions for current are

$$i_d = \frac{2}{3} \left[\cos \theta i_a + \cos(\theta - 120^\circ) i_b + \cos(\theta + 120^\circ) i_c \right]$$

$$i_q = \frac{2}{3} \left[-\sin \theta i_a - \sin(\theta - 120^\circ) i_b - \sin(\theta + 120^\circ) i_c \right]$$

$$i_o = \frac{2}{3} \left[\frac{1}{2} i_a + \frac{1}{2} i_b + \frac{1}{2} i_c \right] \quad (3)$$

Where $\theta = \omega t$

$$i_a = \cos \theta i_d - \sin \theta i_q + i_o$$

$$i_b = \cos(\theta - 120^\circ) i_d - \sin(\theta - 120^\circ) i_q + i_o$$

$$i_c = \cos(\theta + 120^\circ) i_d - \sin(\theta + 120^\circ) i_q + i_o$$

Exactly the same transformations are made for the flux linkage λ and the applied voltage v . It should be noted that i_o is the zero-sequence current. In an ungrounded Y connection or under balanced 3-phase conditions, i_o is zero.

Utilizing the transformation described in equation (3) results in the following set of equations for voltage v and flux linkage λ .

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$$\begin{aligned} v_f &= r_f i_f + p \lambda_f \\ v_d &= -r_a i_d + p \lambda_d - \lambda_g \omega \\ v_g &= -r_a i_g + p \lambda_g + \lambda_d \omega \end{aligned} \quad (4)$$

$$\lambda_f = L_{ff} i_f - \frac{3}{2} L_{af} i_d$$

$$\lambda_d = L_{af} i_f - L_d i_d$$

$$\lambda_g = -L_g i_g$$

Note expressions for v_o and λ_o are omitted in the previous equation, since i_o is assumed to be equal to zero. The subscripts d and g represent the direct and quadrature axis variables respectively.

In order to complete the mathematical description of the device, the load which the alternator sees must be considered. Assuming the load is approximated by a balanced 3-phase Y-connected circuit having resistance r_L and inductance L_L in each phase,

The load equations are then

$$\begin{aligned} v_d &= r_L i_d + L_L p i_d - \omega L_L i_g \\ v_g &= r_L i_g + L_L p i_g + \omega L_L i_d \end{aligned} \quad (5)$$

Expressions (4) and (5) may be solved directly to yield a solution to the problem. A summary of the appropriate equations and a block diagram follow.

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$$\lambda_f = \frac{1}{p} (v_f - r_f i_f)$$

$$i_f = \frac{1}{L_{ff}} (\lambda_f + \frac{3}{2} L_{af} i_d)$$

$$\lambda_d = \frac{1}{p} (v_d + r_d i_d + \lambda_g \omega) \quad (6)$$

$$i_d = \frac{1}{L_d} (L_{af} i_f - \lambda_d)$$

$$\lambda_g = \frac{1}{p} (v_g + r_a i_g - \lambda_d \omega)$$

$$i_g = (-\frac{1}{L_g}) \lambda_g$$

and for the load

$$v_d = (r_L + L_L p) i_d - \omega L_L i_g \quad (7)$$

$$v_g = (r_L + L_L p) i_g + \omega L_L i_d$$

Drawing a block diagram of this set of equations produces (is shown on Figure A II-1)

BLOCK DIAGRAM OF ALTERNATOR MODEL

FIGURE A II-1

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A significant simplification can be made to the set of equations found in (6) by assuming

1. transformer voltages $p\lambda_g$ and $p\lambda_d$ are equal to zero
2. armature resistance is zero

Making these approximations reduces (4) to

$$\begin{aligned}\lambda_f &= \frac{1}{p} (v_f - r_f i_f) \\ i_f &= (\lambda_f + \frac{3}{2} L_{af} i_d) / L_{ff} \\ \lambda_d &= L_{af} i_f - L_d i_d\end{aligned}\quad (8)$$

$$\begin{aligned}v_g &= \lambda_d \omega \\ -\lambda_g &= L_g i_g \\ v_d &= -\lambda_g \omega\end{aligned}$$

The load expression is

$$i_d = \frac{1}{(r_L + L_L p)} (v_d + \omega L_L i_g)\quad (9)$$

$$i_g = \frac{1}{(r_L + L_L p)} (v_g - \omega L_L i_d)$$

Drawing a block diagram of equations (8) and (9) produces (as shown on Figure AII-2

NOMENCLATURE

V_f	Voltage on Field Winding
V_d	Voltage Generated in Direct Axis
V_q	Voltage Generated in Quadrature Axis
i_f	Field Current
i_d	Direct Axis Current
i_q	Quadrature Axis Current
λ_f	Field Flux Linkage
λ_d	Direct Axis Flux Linkage
λ_q	Quadrature Axis Flux Linkage
r_f	Resistance of Field Winding
r_L	Equivalent Load Resistance in Each Output Phase
L_{af}	Mutual Inductance Between Phase a and Field
L_{ff}	Self Inductance of Field Winding
L_d	Direct Axis Synchronous Inductance
L_q	Quadrature Axis Synchronous Inductance
L_L	Equivalent Load Inductance in Each Output Phase
X_L	Equivalent Load Reactance at Design Frequency

BLOCK DIAGRAM OF SIMPLIFIED ALTERNATOR MODEL

FIGURE A II-2

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The more simplified set of equations (that is equations (8) and (9) were used to model the Alighty BRU Alternator. The more complex form was not used since it appeared to offer no advantage over the simplified form. The block diagram of the more complex form also indicates an algebraic loop as well as using differentials.

A relatively simple description of the mathematics describing an alternator may be found in reference (1). A more thorough but difficult analysis including the effects of amortisseur circuits on the rotor is found in reference (2). In reference (3) is presented a more complex model of the alternator including a amortisseur circuit and saturation. This model was formulated for analogue computer use.

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Literature Cited

1. Fitzgerald, A. E., Electric Machinery, Mc Graw - Hill Book Co., Inc., New York, 1961, pp. 223 - 274.
2. Concordia, C., Synchronous Machines, John Wiley and Sons, Inc., New York, 1951, pp. 6 - 18.
3. Riaz, M., "Analogue Computer Representations of Synchronous Generators in Voltage - Regulation Studies," Journal of AIEE, December 1956, p. 1178.

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2.2 Sample Calculation of Input Data for Alternator Model

In order to Determine the Required Data for Simulation of an Alternator, the following Parameters are Required

R_a = armature resistance (ohms) *

R_f = field resistance (ohms)

X_d = direct axis synchronous reactance (ohms)

X_q = quadrature axis synchronous reactance (ohms)

X_l = armature leakage reactance (ohms)

X_{com} = equivalent reactance of rectifier (ohms) **

T_{fo} = open circuit field time constant (sec)

V_ϕ = alternator terminal voltage at operating point, line to neutral (volts)

I_ϕ = alternator terminal current at operating point, line to neutral (amps)

* not required for simplified model

** numerical value estimated to be $X_{com} = 2.5 X_l$

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Computation of Data for Alternator ModelArmature Resistance is given to be $r_a = .0938 \Omega$ Field Resistance for four coils in parallel is 14.58Ω

The equivalent circuit to the field is

$$V_f = (1.71 \text{ amps})(14.58 \Omega) = \underline{24.93 \text{ volts}}$$

Thus operating point for field is

$$\underline{r_f = 14.58 \Omega, \quad i_f = 1.71 \text{ amps}, \quad V_f = 24.93 \text{ volts}}$$

Compute L_{ff}

for open circuit conditions $r_L = \infty$ and thus $i_d = 0$. for this condition the field loop reduces to

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The transfer function for this loop is

$$\frac{i_f}{v_f} = \frac{1/r_f}{\frac{L_{ff}}{r_f} s + 1}$$

The open circuit time constant of the field is given as $\tau_{fo} = \frac{L_{ff}}{r_f} = .0397 \text{ sec}$

$$\text{Thus } L_{ff} = (.0397 \text{ sec})(14.58 \Omega) = .5788 \text{ Henry's}$$

Compute L_d and L_g

$$X_d = (1.046 \text{ per unit})(5.371 \Omega) = 5.618 \Omega$$

$$L_d = X_d / \omega = 5.618 \Omega / (1733 \times 2\pi) \text{ rad/sec}$$

$$L_d = 5.1595 \times 10^{-4} \text{ Henry's}$$

$$X_g = (.559 \text{ per unit})(5.371 \Omega) = 3.002 \Omega$$

$$L_g = X_g / \omega = 3.002 \Omega / 10,889 \text{ rad/sec}$$

$$L_g = 2.7573 \times 10^{-4} \text{ Henry's}$$

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Alternator Frequency

$$\omega = (1733)(2\pi) = 10,888.76 \text{ rad/sec}$$

Compute r_L , L_L , X_L

Consider Terminal Conditions at Alternator Exit for one phase $V_\phi = 66.23 \angle 0^\circ$ volts

$$\text{note p.f.} = \cos(34.57^\circ) = .8237$$

Following the Alternator Exit is a Voltage Drop Due to leakage and Rectifier Losses. Consider the Circuit

The Voltage Drop Across the Rectifier is

$$V_{rec} = V_\phi - j I_\phi (X_L + X_{com})$$

From the input data

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$$X_L = (.153 \text{ per unit}) (5.371 \Omega) = .8218 \Omega$$

$$X_{com} = 2.5 X_L = 2.0544 \Omega$$

Compute V_{rec}

$$V_{rec} = 67 - \left[(1 \angle 90^\circ) (12.27 \angle -34.57^\circ) (.8218 + 2.0544) \right] \quad 2.876 \Omega$$

$$V_{rec} = 67 - 35.29 \angle 55.43^\circ$$

$$V_{rec} = 67 - (20.02 + 29.05j)$$

$$V_{rec} = 46.98 - 29.06j$$

$$V_{rec} = 55.24 \angle -31.74^\circ$$

Note Since Z_R is Resistive loading the angle upon the previous result should be -34.57° , however result is close enough.

Compute Z_R

$$V_{rec} = I_\phi Z_R$$

$$\therefore Z_R = V_{rec} / I_\phi = \frac{55.24 \angle -31.74^\circ}{12.27 \angle -34.57^\circ}$$

$$Z_R = 4.502 \angle 2.83^\circ$$

$$Z_R = 4.497 \Omega + .222j$$

$$r_L = 4.497 \Omega$$

$$X_L = X_L + X_{com} + .222 = .8218 \Omega + 2.0544 \Omega + .222 \Omega$$

$$X_L = 3.098 \Omega$$

$$L_L = X_L / \omega = 3.098 / 19,888.76 = 2.845 \times 10^{-4} \text{ Henry's}$$

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Note the previous values of r_L and X_L could have been computed much more directly, however it was consider useful to illustrate the makeup of X_L and r_L . Check the results

$$V_\phi = I_\phi Z_L$$

$$V_\phi = (12.27 \angle -34.57^\circ)(4.497 + 3.098j)$$

$$V_\phi = (12.27 \angle -34.57^\circ)(5.46 \angle 34.56^\circ)$$

$$V_\phi = 67 \angle 0^\circ$$

Result Checks

Compute L_{af}

The following information may be found in more detail in "Electric Machinery" by Fitzgerald and Kingsley p. 234 - 238.

In Steady State the phasor voltage relationship is

$$E_f = V_\phi + r_a I_\phi + jX_d I_d + jX_q I_q$$

Where d and q refer to direct and quadrature components. Drawing the Vector Diagram

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The phasor sum of $V_\phi + r_a I_\phi + j I_\phi X_g$ locates the direction of the quadrature axis.

$$V_\phi = 67 \angle 0^\circ$$

$$r_a I_\phi \text{ neglect}$$

$$j I_\phi X_g = (1 \angle 90^\circ)(12.27 \angle -34.57^\circ)(3.002 \Omega) = 36.83 \angle 55.43^\circ$$

$$67 + (20.90 + 30.327j) = 87.90 + 30.327j$$

$$\delta = \tan^{-1}(30.327/87.90) = 19.04^\circ$$

$$\delta + \phi = 19.04^\circ + 34.57^\circ = 53.61^\circ$$

$$I_g = |I_\phi| \cos(53.61^\circ) = (12.27)(.5933) = 7.28 \text{ amps rms}$$

$$I_d = |I_\phi| \sin(53.61^\circ) = (12.27)(.805) = 9.877 \text{ amps rms}$$

Compute E_f Considering Phasor Diagram

$$E_f = V_\phi + r_a \overset{0}{\nearrow} I_\phi + j X_d I_d + j X_g I_g$$

$$E_f = 67 \angle -19.04^\circ + (5.618)(9.877) \angle 0^\circ + (3.002)(7.28) \angle 90^\circ$$

$$E_f = (63.33 - 21.85j) + 55.49 + 21.85j$$

$$E_f = 118.82 \text{ volts}$$

Note $E_f = \frac{\omega L_{af} i_f}{\sqrt{2}}$

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$$L_{af} = \frac{\sqrt{2} E_f}{\omega i_f} = \frac{(\sqrt{2}) (18.82)^{168.04}}{(10,888.76 \text{ rad/sec})(1.71 \text{ amps})}$$

$$L_{af} = 9.025 \times 10^{-3} \text{ Henry's}$$

Check

$$E_f = \frac{\omega L_{af} i_f}{\sqrt{2}} = \frac{(10,888.76)(9.025 \times 10^{-3})(1.71)}{\sqrt{2}} = 118.82 \text{ Volts}$$

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Summary of Data for Simulation

$$r_a = .0938 \Omega$$

$$r_f = 14.58 \Omega$$

$$L_{ff} = 0.5788 \text{ Henry's}$$

$$L_d = 5.1595 \times 10^{-4} \text{ Henry's}$$

$$L_g = 2.7573 \times 10^{-4} \text{ Henry's}$$

$$L_{af} = 9.025 \times 10^{-3} \text{ Henry's}$$

$$\omega = 10,889 \text{ rd/sec}$$

$$r_L = 4.497 \Omega$$

$$X_L = 3.098 \Omega$$

$$L_L = 2.845 \times 10^{-4} \text{ Henry's}$$

Consider Operating Point Inputs

$$V_f = 24.93 \text{ volts}$$

$$r_L = 4.497 \Omega$$

$$\omega = 10,889 \text{ rd/sec}$$

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Check Simulation Block Diagram to Insure Steady State Balance.

$$V_g = (i_f L_{af} - L_d i_d) \omega$$

$$V_g = \left[(1.712 \text{ amps})(9.025 \times 10^{-3}) - (5.1595 \times 10^{-4})(9.877) \sqrt{2} \right] 10,889$$

$$\underline{V_g = 89.57 \text{ volts peak}}$$

$$i_g = (V_g - X_L i_d) / r_L$$

$$i_g = \left[89.57 - (3.098)(13.968) \right] / 4.497$$

$$\underline{i_g = 10.295 \text{ amps peak}}$$

$$V_d = i_g L_g \omega$$

$$V_d = (10.295)(2.7573 \times 10^{-4})(10,889)$$

$$\underline{V_d = 30.91 \text{ volts peak}}$$

$$i_d = (V_d + X_L i_g) / r_L$$

$$i_d = \left[30.91 + (3.098)(10.295) \right] / 4.497$$

$$\underline{i_d = 13.966 \text{ amps peak}}$$

Draw Vector Diagram and Determine Power Factor

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$$V_p = 89.57 - j30.91 = \underline{94.75 \angle -19.03^\circ \text{ volts peak}}$$

$$I_p = 10.295 - j13.966 = \underline{17.35 \angle -53.60^\circ \text{ volts peak}}$$

Consider RMS values and Use Voltage Phasor as Reference Angle

$$V_p = 94.75/\sqrt{2} = \underline{67 \angle 0^\circ \text{ volts rms}}$$

$$I_p = 17.35/\sqrt{2} = \underline{12.27 \angle -34.57^\circ \text{ amps rms}}$$

Everything Checks

Note Input Variables to Simulation

V_f , ω and r_L

Output Variables

i_d , i_q , V_d and V_q

Phase Voltages of Stator Windings

$$i_a = i_d \cos \theta - i_q \sin \theta$$

$$i_b = i_d \cos (\theta - 120^\circ) - i_q \sin (\theta - 120^\circ)$$

$$i_c = i_d \cos (\theta + 120^\circ) - i_q \sin (\theta + 120^\circ)$$

$$V_a = V_d \cos \theta - V_q \sin \theta$$

$$V_b = V_d \cos (\theta - 120^\circ) - V_q \sin (\theta - 120^\circ)$$

$$V_c = V_d \cos (\theta + 120^\circ) - V_q \sin (\theta + 120^\circ)$$

$$\theta = \omega t \text{ where } \omega = 2\pi f$$

BLOCK DIAGRAM OF SIMPLIFIED ALTERNATOR

FIGURE A II-3

TABLE A II-1
ALTERNATOR PARAMETERS
REACTANCE AND RESISTANCE, FIELD TIME CONSTANT

(Based on Design Load of 6519 Volts Line to Neutral and 12.27 Amperes)

Base Impedance	Z_{Base} 5.371, Ohm
Resistances	
Armature at 360°F	R_A 0.0938 Ohm
Field at 350°F - 4 Control Fields in Parallel	R_{CF} 14.58 Ohm
Reactances	
Direct Axis Synchronous	X_D 1.046 per unit
Quadrature Axis Synchronous	X_Q 0.559 per unit
Armature Leakage	X_L 0.153 per unit
Field Leakage	X_F 0.280 per unit
Zero Sequence	X_0 0.066 per unit
Negative Sequence	X_2 0.197 per unit
Transient, Unsaturated	X_{DU} 0.433 per unit
Subtransient Direct*	X''_D 0.381 per unit
Subtransient Quadrature*	X''_Q 0.381 per unit
Field Time Constant (Hot) Short CCT (full current)	TPD 0.0145 seconds
Open CCT (no current)	TPDO 0.0397 seconds

*Estimated Value for Rice Rotor with no Damper Cage

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3 HSA Data at Design Point (Steady State Conditions) $E_{out} \text{ DC} = 119.87 \text{ volts}$ $I_{out} \text{ DC} = 15.9 \text{ amps}$ $R = 7.54 \Omega \quad \checkmark$ $\text{Power out} = 1.906 \text{ KW (net power)}$ } Output
of
rectifierConsider AC Input Quantities to Rectifier $V_{\phi} = 66.23 \text{ volts} \quad L-N \quad \text{rms}$ $I_{\phi} = 12.27 \text{ amps} \quad L-N \quad \text{rms}$ $p.f. = -.8234$

$$\text{Power in} = 3 [(66.23)(12.27)(.8234)] = 2.007 \text{ KW}$$

 $I_f = 1.71 \text{ amps total}$ $f = 1733 \text{ Hz at } 52,100 \text{ rpm}$

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2.3 Ideal Rectifier Description

Consider the Phase Voltages as seen at the input terminal of the rectifier. Shown below is a sketch of each of the 3 phases (with unity maximum amplitude)

An Ideal Rectifier Would Produce the following Terminal voltage (Note this is only true for the Rectifier Configuration Employed)

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The Average Value for the Output Wave Shape is

$$\bar{E}_{out} = 1.653$$

Compared to the Peak Value of each Phase Voltage.

*Note the Ideal Voltage Output from the rectifier is reduced by a approximately 3 volts due to diode voltage drop.

Sample Calculation of Rectifier Output Voltage

For the operating point the phase voltage and current at the the alternator exit is

$$V_{\phi} = 66.23 \text{ volts L-N rms}$$

$$I_{\phi} = 12.27 \text{ amps L-N rms}$$

$$p.f. = -.8234$$

Since the rectifier load is assumed to be resistive

$$|V_{rec}| = \sqrt{V_{\phi}^2 - [I_{\phi}(X_L + X_{com} + j.222)]^2}$$

$$|V_{rec}| = \sqrt{66.23^2 - [(12.27)(3.098\Omega)]^2}$$

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$$|V_{rec}| = 54.24 \text{ volts rms } L-N$$

Thus the Voltage Drop Across the Rectifier per Phase is 54.24 volts rms

$$|V_{rec}| = 54.24 \sqrt{2} = \underline{76.70 \text{ volts peak}}$$

The Average Voltage Output of the Ideal Rectifier:

$$V_{output} = (76.70)(1.653) = 126.79 \text{ volts}$$

Considering the voltage Drops Across the Diodes in the Rectifier

$$V_{DC} = 126.79 - 3 = \underline{123.79 \text{ volts DC}}$$

Note Actual Output Voltage is 119.87 volts
AND THUS CALCULATION IS Very Close

Consider Reflecting DC load Upon Output Side of Rectifier to compute load in each phase R_L

By considering conservation of Energy Across the Ideal Rectifier

$$\frac{[V_{rec}(1.653)]^2}{R_{DC}} = \frac{\left(\frac{V_{rec}}{\sqrt{2}}\right)^2}{R_L} \times 3$$

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Note V_{rec} in Previous Expression is in Peak.
 Simplifying this expression yields

$$\frac{(1.653)^2}{R_{DC}} = \frac{1.5}{R_L}$$

$$R_L = \frac{1.5}{(1.653)^2} \quad R_{DC} = 0.549 R_{DC}$$

Note the Previous Relationship is only approximate
 Since Diode Voltage Drops are Ignored. Check
 Results

$$R_L = 0.549 (7.54\Omega) = \underline{4.14\Omega}$$

previous calculation within section upon Sample
 Calculations of Input Data indicated $R_L = 4.497\Omega$

Compute I_{DC} and R_{DC}

Write Energy Equation Across the Rectifier

$$3 \times (\text{p.f.}) (V_\phi) (I_\phi) = V_{DC} I_{DC} + i_f^2 r_f + \text{losses}$$

Neglecting losses

$$I_{DC} = \frac{3 \times (\text{p.f.}) (V_\phi) (I_\phi) - i_f^2 r_f}{V_{DC}}$$

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Compute R_{DC}

$$R_{DC} = \frac{V_{DC}}{I_{DC}}$$

Consider Sample Calculation

$$I_{DC} = \frac{3 \times (.8234)(66.23 \text{ volts})(12.27 \text{ amps}) - (1.7 \text{ amps})^2(14.5)}{119.87 \text{ volts}}$$

$$I_{DC} = \frac{2007.39 - 42.63}{119.87} = 16.39 \text{ amps}$$

Actual steady state value is 15.90 amps

$$R_{DC} = \frac{V_{DC}}{I_{DC}} = \frac{119.87 \text{ volts}}{16.39 \text{ amps}} = 7.31 \Omega$$

Actual steady state value is 7.54 Ω

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TRACED BY	
CHECKED BY	
APPROVED BY	
UNIT NO.	

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PHASE CURRENT WHEN ON, = LOAD VOLTS $\div$ R_L

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ELECTRICAL ANGLE/VALUES

$$V_a = 1 \cos \theta$$

$$V_b = 1 \cos (\theta + 120^\circ)$$

$$V_c = 1 \cos (\theta - 120^\circ)$$

<u>θ</u>	<u>V_a</u>	<u>V_b</u>	<u>V_c</u>	<u>V_{reg}</u>
0°	1.0	-0.500	-0.500	1.5
5°	0.996	-0.574	-0.423	1.57
10°	0.985	-0.643	-0.342	1.63
15°	0.966	-0.707	-0.259	1.67
20°	0.940	-0.766	-0.174	1.71
25°	0.906	-0.819	-0.087	1.73
30°	0.866	-0.866	0.0	1.732
35°	0.819	-0.906	0.087	1.73
40°	0.766	-0.940	0.174	1.71
45°	0.709	-0.966	0.259	1.67
50°	0.643	-0.984	0.342	1.63
55°	0.574	-0.996	0.423	1.57
60°	0.500	-1.0	0.500	<u>1.50</u>
65°	0.423	-0.996	0.574	1.57
70°	0.347	-0.984	0.643	1.63
75°	0.259	-0.966	0.707	1.67
80°	0.174	-0.940	0.766	1.71
85°	0.087	-0.906	0.819	1.73
90°	0.0	-0.866	0.866	1.73

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2.4 Brayton Cycle Model

The model of the engine cycle (i.e., rotating unit, heat exchangers) is a linear representation derived for a 3 HSA unit. The 3 HSA design was chosen for this evaluation as previous computer runs using program BRTDYN indicated this was the worst case for system stability. The partial derivatives used in the linearized description were derived by finite difference techniques on performance programs.

Schematic Figure AII-4 depicts the linear model and the partials are summarized:

ENGINE BLOCK DIAGRAM

FIGURE AII-4

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SYSTEM PARTIALS

$$\left. \frac{\partial Q}{\partial N_{BRU}} \right|_{T_6} = - \frac{7.0346}{N_{BRU}^2} \left[-2.34425 T_6 + 1657.932 \right]$$

$$\left. \frac{\partial Q}{\partial T_6} \right|_{N_{BRU}} = \frac{7.0346 (-2.34425)}{N_{BRU}} + \frac{7.0346 (.04225)}{520}$$

$$\Delta Q_{BRU} = \left. \frac{\partial Q_{BRU}}{\partial T_6} \right|_{N_{BRU}} \Delta T_6 + \left. \frac{\partial Q_{BRU}}{\partial N_{BRU}} \right|_{T_6} \Delta N_{BRU}$$

$$\Delta Q_{BRU} = J_{BRU} \frac{dw_{BRU}}{dt}$$

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VOLTAGE REGULATOR TRANSFER FUNCTION *

Reference Drawing of Computer Diagram 306833

$$L_{ff} = 0.5788 \text{ h}$$

$$r_f = 14.58 \text{ } \Omega$$

Transfer Function of Inner Loop

$$\frac{i_f}{V_f} = \frac{\frac{1}{.5788 s}}{1 + \frac{1}{.5788 s} 14.58}$$

$$\frac{i_f}{V_f} = \frac{0.068}{0.0396 s + 1}$$

* Note: The λ_f feedback loop is not included for simplicity for this approximate calculation.

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If gain of voltage regulator $G_2 = 10$

$$\frac{i_f}{I_{err}} = \frac{\frac{10 \times .068}{.0395 + 1}}{1 + \frac{.68}{.0395 + 1}}$$

$$\frac{i_f}{I_{err}} = \frac{0.404}{.0235 + 1}$$

If gain $G_2 = 100.$

$$\frac{i_f}{I_{err}} = \frac{\frac{100 \times .068}{.0395 + 1}}{1 + \frac{6.8}{.0395 + 1}}$$

$$\frac{i_f}{I_{err}} = \frac{0.87}{.005065 + 1}$$

DATE May 1976PREPARED BY B. Minshall

CHECKED BY _____

CALC. NO. _____

MODEL BIPS

PART NO. _____

Voltage Regulator Accuracy Requirement -

$$V_{DC} = 120 \pm 2.5$$

Using this as the accuracy criteria
Repeating Drawg 306833-

VOLTAGE REGULATOR

$$G_1 = 1.0$$

$$L_{ff} = 0.57 \text{ h}$$

$$I_f = 14.58 \text{ A}$$

$$\frac{\partial V_{DC}}{\partial I_f} = 25.64$$

from alternator
predicted perfo

Find G_2 necessary for accuracy -

$$\Delta V_{DC} = \frac{\partial V_{DC}}{\partial I_f} \Delta I_f$$

$$2.5 = 25.64 \Delta I_f$$

$0.1 = \Delta I_f$ This is then the allowable
variation in field current to
hold output voltage variation
to 2.5 volts

The gain of I_{err} to V_{DC} in the
forward loop is unity. The

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 PART NO. _____

remaining term in the forward loop is $\frac{I_f}{I_{err}}$

For accuracy the 2.5 volt DC error must be multiplied by sufficient forward gain to produce a change in I_f of 0.1 amps. OR

$$\frac{\partial I_f}{\partial I_{err}} \geq \frac{0.1}{2.5} = 0.04$$

The previous pages indicate that if the gain $G_2 = 10$, $\frac{\partial I_f}{\partial I_{err}} = 0.404$ which is 10 times higher than the gain required for accuracy. There is a possibility that the current feed back loop may be able to be removed altogether since the gain is 0.068 open loop on field current. However, a higher gain would be desirable if the feedback is removed.

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3. Digital Computer Analysis

A digital computer program was created for operation on the Control Data Corporation Model 6400 digital computer. The program was written using the Control Data MIMIC simulation language.

The equations used in the simulation are as derived in Appendix II Section 2. These derivations results are shown on block diagram shown in Drawing 306833. The control system modeled was of two basic configurations that will be described in detail and shown schematically on the following pages.

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3.1 Digital System

The digital computer runs were all made using the same user load profile imposed as a disturbance on the system. This load profile is shown on Figure AII-5.

The digital control system is shown on Figure AII-6 herein. This system operates as described in the main body of this report. The general system objective is to maintain the alternator load constant by sensing load and changing parasitic load as necessary to hold total load constant. The load is sensed by using phase current and dc voltage. Any error in resistance (mhos in this case) causes resistors to be added or subtracted in the parasitic load. The system is thus basically a sample data system with a sampling interval of one millisecond as previously noted. This is then the maximum time between parasitic load corrections. The simulation results are shown and identified as run numbers in the 100 series plots herein. Several computer runs were made to investigate this type of system. A sample and multiply system was modeled and discarded because of stability problems. The remaining systems are sample and add configurations. A variable time increment scheme was investigated wherein sampling interval was reduced from 10 milliseconds to one millisecond whenever the voltage error exceeded a predetermined tolerance band. This scheme was discarded because of being more complicated than required. Various sizes of trim load switching were tried. One important advantage of the digital scheme is the small resistance requiring switched in and out to trim speed.

LOAD PROFILE

FIGURE A II-5

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DIGITAL CONTROL SYSTEM

FIGURE A II-6

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3.1.1 Dynamics

The primary dynamics problem associated with this control scheme is that at a sample rate of one millisecond, the control system can obviously take up to one millisecond to respond to a change in user load. The user load can change and requires up to a full millisecond before the control realizes the change occurred. A large voltage spike which is of short duration is the result, as the control system is fast and accurate, after sensing the load change and the resulting control mhos error. The solution to the voltage spikes is not difficult and can be pursued along one of two lines:

- (a) Reducing sample interval. For example, the sample frequency could be increased from 1000 Hz to 5000 Hz. This provides improvement in two ways: first by reducing the spike size due to faster correction, and second by making spike filtering easier at low amplitude, high frequency.
- (b) Filtration of the output. This method is demonstrated to a limited degree by computer data provided. The result is that a filter can be designed to smooth output noise.

The final solution to the problem will depend upon the filter size required and the possibility that all power need not be filtered to the same degree. The alternative of increasing sampling frequency against filtering will require further evaluation.

3.1.2 100 Series Digital Computer Plots

Digital computer plots and explanations and interpretations are presented in paragraphs 3.1.2.1 through 3.1.2.5 below. During the

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computer runs it was found that filter element within the closed loop caused stability problems, due to a lag in the sensed voltage regulator parameter. Second order filters with break frequencies up to 250 Hz were tried within the analysis. Higher frequency filters were not considered since these can not be expected to accomplish the filtration required. The sensing of dc voltage prior to filtering solved the stability problem since this method removed lag from the closed loop. The filter is then in the output only and not in the control loop. This represents a modification of the block diagram 306833.

3.1.2.1 Computer Results - Run No. 105

This run shows the system previously described, except for a filter added external to the closed dc voltage loop described above. The filter is at 250 Hz break frequency and is a second order, with a damping ratio of 0.3.

The plot shows an initial transient due to all initial conditions not being at steady state. After the initial transient, output power (POUT) remains nearly constant at nearly 2200 Watts and power takes only momentary pulses at the points where user load is being changed. This is accomplished by the admittance sensing loop which controls total power. Speed accelerates during the initial transient to 40 rpm over the 52,000 rpm set point (DELNB) and then returns towards the zero error point. Power ripple can be seen at the basic one millisecond sampling frequency, however, it does not affect speed because of rotating engine inertia. A system cycling is seen between 95 and 110 milliseconds. This power cycling of about 200 Watts feeds through to speed to approximately one rpm. It is not known whether or not this is a limit cycle or if the cycling would stop. Further investigation would be desirable and difference gains could be run to investigate stability.

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Voltage is on the next plot and VERR is voltage error based on 120 volts, unfiltered. The variable VDCF is dc voltage filtered. (Note VERR = 120 - VDC and low voltage shows on this plot as a positive error.) The filtered voltage still follows these variations in dc voltage and overshoots exceed 20 volts. This is not an acceptable filter, and a lower break frequency is indicated as described in following plot. Field voltage (VF2) is seen to cycle at the sample frequency. Field current is also excited at this frequency.

The last plot is of parasitic load, as measured in mhos (XMHBIN) and total load measured in mhos (MHOMES). The lag of one millisecond in changing load can be seen in this plot and the resulting overshoot and undershoot in total load at the switch points is shown.

3.1.2.2 Computer Results - Run No. 106

This computer run is the same as previous run, except the filter was changed to a second order of 0.3 damping at a break frequency of 25 Hz. This slower filter is seen to remove one millisecond noise as well as spikes. The filtered voltage (VDCF) total accuracy is shown on this plot as 92 to 128 volts. The major portion of deviation from 120 volts resulted during initial transient. Thereafter transient voltage remained between 114 and 126 volts with spikes very well filter dampened. This filter may be sufficient; longer computer runs would allow this filter to stabilize close to 120 volts. The filter response to spikes is small. (Recall VERR positive means a low voltage).

3.1.2.3 Computer Results - Run No. 108

This run is similar to runs 105 and 106, except the filter on dc output (VDCF) is a second order with a 2.5 Hz break frequency and 0.3 damping ratio. Filtered voltage ranges from 120 to 116, however the most disturbance is caused by the initial transient. Assuming

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the initial conditions were proper, the voltage would remain within the desired accuracy for 120 volts. The voltage spikes make no discernible impression on the dc voltage. This is a filter design extreme and should not be required.

3.1.2.4 Computer Results - Run No. 102

This run is included to demonstrate the instability resulting from placing a filter within the closed loop. The filter used on this run was a second order with a break frequency of 25 Hz.

3.1.2.5 Summary Plot Nomenclature

The identification nomenclature on the plots are correlated with computer diagram drawing 306833.

Plot Abbreviations

VF2	- alternator field voltage (volts)
IF	- alternator field current (amps)
DELNB	- rotating speed error (rpm)
POUT	- total output power (kW)
VERR	- dc voltage filtered (volts)
VDCF	- dc voltage filtered (volts)
XMHBIN	- amount of binary load applied (mhos)
MHOMES	- total load (mohs)

KEY

VERR — 1
VDCCF — 2

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BIPS CONTROL SYSTEM - RUN NO. 105

KEY
XMHBIN 1
MHOMES 2
05/25/76

BIPS CONTROL SYSTEM - RUN NO. 105

KEY

DELNB —▲— 1
POUT —+— 2

05/24/76

BIPS CONTROL SYSTEM - RUN NO. 106

KEY

VERR — 1
VDCE — 2

05/24/76

BIPS CONTROL SYSTEM - RUN NO. 106

BIPS CONTROL SYSTEM - RUN NO. 106

KEY

VF2 —◆— 1
IF —+— 2

05/24/76

KEY
 XMHBIN — 1
 MHOMES — 2
 05/24/76

BIPS CONTROL SYSTEM - RUN NO. 106

KEY
DELNB —▲— 1
POUT —+— 2
05/26/76

BIPS CONTROL SYSTEM - RUN NO. 108

KEY

VERR —▲— 1
VDCF —+— 2

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BIPS CONTROL SYSTEM - RUN NO. 108

KEY

VF2 — 1
IF — 2

05/26/76

BIPS CONTROL SYSTEM - RUN NO. 108

KEY
XMHBIN — 1
MHOMES — 2

05/26/76

BIPS CONTROL SYSTEM - RUN NO. 108

KEY

DELNB — 1
POUT — 2

05/21/76

BIPS CONTROL SYSTEM - RUN NO. 102

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KEY

VERR. —▲— 1

05/21/76

BIPS CONTROL SYSTEM - RUN NO. 102

KEY

VF2 —▲— 1
IF —+— 2

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BIPS CONTROL SYSTEM - RUN NO. 102

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BIPS CONTROL SYSTEM - RUN NO. 102

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3.2 Analog System

The NASA system was modeled as a proportional system to improve the run time required on the digital computer. In reality the NASA system consists of a 5000 Hz carrier frequency for a pulse width modulation system. This high frequency pulse width modulation concept is much faster than the loop response and aside from the high frequency ripple should not affect the system results. The digital simulation of the high frequency triangular carrier wave slows the digital program operation to a degree that it is impractical. For this reason the proportional model was used. The detailed triangular simulation can be made on the analog computer. The analog control system schematic is shown on Figure AII-7. The basic control varies parasitic load as a function of speed and speed is reset as a load function, sensed by dc current.

3.2.1 200 Series Digital Computer Plots

Program plots results from this system are numbered in the 200 series. These plots follow discussion, paragraph 3.2.2.5. The variable XMHBIN was zero during these runs and was not used. During all digital computer runs, basic control loop investigation was conducted. No filters are in the loop.

3.2.1.1 Computer Results -Run No. 202

This plot presents the control, using the speed control loop only (no current reset of speed). The plot indicates that the loop has stability problems with the rather low speed gain of 580 watts/percent speed. The voltage regulator gain (G2) is 100 during this run and as determined using the analog computer, this gain influences stability. Note that output power (POUT) varies greatly and speed does not control very closely.

3.2.1.2 Computer Results - Run No. 203

This run is similar to the previous run, except that current speed reset was added and the speed loop gain was set at 100 watts/

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SENSED
PARAMETERS

NASA CONTROL SYSTEM

FIGURE A II-7

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percent speed. The current gain was one percent speed/ampere (100 Watts/ampere). Note that speed does not hold well at all, however the control is attempting to hold power constant. Power does not control because of control low gain. Voltage spikes of long duration also are shown.

3.2.1.3 Computer Results - Run No. 207

On this run the current speed reset gain was increased coupled with a speed loop gain increase. These become 170 Watts/percent speed and 4 percent speed/ampere (680 Watts/ampere). Power regulation was improved and voltage error considerably reduced. Some field instability or noise is evident in the voltage plot. Computer runs attempted at higher current reset gains were time limited due to high frequency noise that caused the program run time to be lengthened.

3.2.1.4 Computer Results - Run No. 209

This is the same as Run No. 202, except that a current feedback loop was added. Speed gain is 580 Watts/percent speed and current gain is one percent speed/ampere (580 Watts/ampere). The loop that was unstable in Run 202 is now stable due to current feedback and power regulation. The voltage spikes were also more reasonable.

3.2.1.5 Computer Results - Run No. 211

This run was with even higher gain to improve control accuracy. The speed gain is 1160 Watts/percent speed and the current gain is one percent speed/ampere (1160 Watts/ampere). The voltage spikes are less than 26 volts amplitude and no more than 3 milliseconds wide. Such voltage variations should be removable by filters, since the spikes are similar to those seen with the digital control which appear to be receptive to filtering. The power output (POUT) is controlled reasonably well, aside from spikes between 2000 and 2200 Watts.

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This control scheme was run with higher gains, however difficulty was encountered with computer time limiting. This is caused by high frequency noise or instability slowing the run, as integration sub-routines decrease time intervals in an attempt to follow up and down cycles. The runs at the higher gains indicate further improvement in accuracy and reduced voltage spikes during the time printed out. The results indicated general best stability regimes are verified by analog computer runs. Investigations of the higher gains are shown in paragraph 4 Appendix II, following. It should be noted that all digital computer runs made did not contain a loop filter. The analog results demonstrated how much higher gains can be run when a loop filter is added to remove high frequency noise.

KEY

DELNB $\blacktriangle$ 1
POUT $+$ 2

05/15/76

BIPS CONTROL SYSTEM - RUN NO. 202

BIPS CONTROL SYSTEM - RUN NO. 202

BIPS CONTROL SYSTEM - RUN NO. 202

KEY

VF2 Δ 1
IF + 2

05/15/76

KEY
 XMHBIN — 1
 MHOMES — 2
 05/15/76

BIPS CONTROL SYSTEM - RUN NO. 202

BIPS CONTROL SYSTEM - RUN NO. 203

05/19/76

KEY

VERR 1

05/19/76

BIRS CONTROL SYSTEM - RUN NO. 203

KEY

VF2 — 1
IF — 2

05/19/76

BIPS CONTROL SYSTEM - RUN NO. 203

KEY

XMHBIN — 1
MHOMES — 2

05/19/76

BIPS CONTROL SYSTEM - RUN NO. 203

KEY

DELNB —▲— 1
POUT —+— 2

05/24/76

BIPS CONTROL SYSTEM — RUN NO. 207

KEY

VERR $\blacktriangle$ 1
05/24/76

BIPS CONTROL SYSTEM - RUN NO. 207

KEY

VF2 $\triangle$ 1
IF $+$ 2

05/24/76

BIPS CONTROL SYSTEM - RUN NO. 207

KEY

XMHBIN — 1
MHOMES — 2

05/24/76

BIPS CONTROL SYSTEM - RUN NO. 207

KEY

DELNB —▲— 1
POUT —+— 2

05/25/76

BIPS CONTROL SYSTEM - RUN NO. 209

KEY
VERR — 1
05/25/76

BIPS CONTROL SYSTEM - RUN NO. 209

KEY

XMHBIN — 1
MHOMES — 2

05/25/76

BIPS CONTROL SYSTEM - RUN NO. 209

KEY

DELNB $\blacktriangle$ 1
POUT $+$ 2

05/26/76

BIPS CONTROL SYSTEM - RUN NO. 211

05/26/76

BIPS CONTROL SYSTEM - RUN NO. 211

KEY

VF2 —▲ 1
IF —+ 2

05/26/76

BIPS CONTROL SYSTEM - RUN NO. 211

KEY

XMHBIN — 1
MHOMES — 2

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BIPS CONTROL SYSTEM - RUN NO. 211

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4. ANALOG COMPUTER ANALYSIS

The analog control system (NASA control) was simulated on the AiResearch analog computer. This computer consists of two Electronic Associates Inc. (EAI) Model 680 Analog Consoles slaved together to allow solution of problems of this magnitude. The facility also includes a Model 8800 Strip Chart Recorder. This allows simulation using up to 81 amplifiers and 24 multipliers.

The simulation of the NASA control is shown on computer diagram Drawing 306973. This analysis uses the same alternator and engine described in Appendix II Introduction.

Several computer runs were made utilizing the unique analog computer ability to make runs in rapid succession and to make changes in gains and system schemes.

The results of the analog computer runs agreed well with the conclusions drawn using the digital computer model in terms of stability and size of voltage spikes. The reason for digital runs high frequency noise can be seen during these runs. Similar gains were run herein, with the loop filter in. A significant improvement is shown. Computer plots are shown following paragraph 5.4 herein.

4.1 Analog Computer Results - Run No. 1

This is a plot of full load and one half load transients for the following system:

Speed Gain	= 1100 watts/percent speed
Current Gain	= 1100 watts/amp
Voltage Regulator Gain	= 30
No filter

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These results are similar to digital results except that voltage regulator noise can be seen because no filter is used.

4.2 Analog Computer Results - Run No. 2

This is the same system as in Run No. 1, however, a dc voltage filter was added. The filter is a first order lag with a time constant of 0.15 milliseconds. This filter reduces the loop noise or oscillation considerably.

4.3 Analog Computer Results - Run No. 3

This is the same as Run No. 1, except that voltage regulator gain was reduced to 10. This gain was previously calculated to be sufficient for regulator accuracy. The noise seen on field voltage was observed to be of a lessor magnitude than in Run No. 1 conducted with a voltage regulator gain of 30. The noise shown on Run No. 3A is at approximately 60,000 Hz and was generated by computer amplifiers. At a voltage regulator gain of 100, oscillation becomes severe. This gain can be run with only slight noise on the digital computer, reference (see Run No. 211). This disagreement may be due to analog computer amplifier generated noise, however, digital and analog program conclusions agree in that both allow a required gain of 10 be used without difficulty.

4.4 Analog Computer Results - Runs No. 4 and No. 5

These runs are at the desired voltage regulator gain value of 10. The control loop for this run was subsequently increased to:

Speed Gain = 2300 Watts/percent speed
Current Gain = 2300 Watts/ampere

With this gain Run No. 4 was conducted without the first order lag

[illegible]

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filter and Run No. 5 is with the loop filter. The resulting system shows good voltage regulation with small voltage spikes. The maximum spike on full load change was approximately 10 volts.

Subsequent computer runs indicated that a system with a voltage regulator gain of 10 and with a loop filter can operate with stability using gains as high as 40.

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5. CONCLUSIONS

5.1 Voltage Regulator

The voltage regulator function is similar for the NASA analog and the digital control circuits. The loop gain of this element must be sufficient to control steady-state voltage to within the desired tolerance of ± 2.5 volts. Calculations presented in this appendix indicate a gain of 10 is more than sufficient to accomplish this accuracy. Higher gains result in a somewhat more accurate control, however these gains reduce speed and field voltage loop stability. Calculations indicate that when the gain (G_2) is raised from 10 to 100, closed loop gain changes from 0.404 to 0.87, a factor of two. Since a gain change of two is generally not significant (in terms of changing phase margin and stability), the overall loop stability is not overly sensitive to this parameter. The closed voltage regulator loop does see the factor of 10 change, and thus has more dramatic stability effects on this minor loop.

The loop gain seen in the calculations, also reduce the field time constant. As gain (G_2) changes from 10 to 100, the linear system time constant changes and is divided by one plus the loop gain, causing a change from 0.023 seconds to 0.005 seconds. The stator (L_L/r_L) time constant is a magnitude of two decades faster than 0.005 seconds, therefore the field time constant shift does not cause a large change in speed loop stability.

As shown on computer runs, the higher gain regulator tends to saturate field voltage and consequently field current rises with the field time constant. The field time constant shown on computer plots then does not represent the time constant that was computed previously as being associated with gain (G_2). The reason is that the computed time constants are for a linear system and would be

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valid for small perturbations. The disturbances as shown on Figure AII-5 are of one half load and full load size and cause field voltage saturation and the resulting nonlinear and slower field current reaction.

Computations indicate a regulator gain (G_2) of 10 is sufficient for accuracy. The possibility of removing the current feedback loop does exist and can be investigated on the BIPS-GDS control system. The computer results also indicate the gain of 10 provides stability in the voltage regulator loop.

5.2 Analog Control

The NASA analog type of control system appears to be fast, accurate, and stable during loading step inputs, when run with the allowable gains. The voltage regulator gain of 10 is sufficient for voltage accuracy and presents no stability difficulty, without the first order filter. An output voltage filter can be added to reduce voltage spikes. The speed gain of 1100 to 2300 Watts/percent speed and a similar current gain, yield fast response with small overshoots. This system also provides considerable stability margin. Further system modifications can be investigated, including output filtering and investigation of lead-lag compensation. Investigation to date has progressed to a point that assures a satisfactory design can be accomplished.

5.3 Digital Control

The digital sample data system was investigated with indication that this control is also a viable alternative for engine and power management control. The digital system investigation was not pursued to the extent that the analog-pulse width modulating system was, since this system was considered a backup design.

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5.4 Summary

The schemes presented will be refined prior to GDS testing. This analysis was conducted to provide basic feasibility and refinements. Dynamic compensation may prove to be desirable and reduce power dc filter size. Work on systems refinement will continue with these basic computer programs used to evaluate new concepts.

RUN NO. 1

BIPS ANALOG CONTROL SYSTEM
 SPEED GAIN = 1100 WATTS/PERCENT SPEED
 CURRENT GAIN = 1100 WATTS/AMP
 VOLTAGE REGULATOR GAIN = 30
 FILTER NOT IN LOOP

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RUN NO 2

BIPS ANALOG CONTROL SYSTEM
 SPEED GAIN=1100 WATTS/PERCENT SPEED
 CURRENT GAIN=1100 WATTS/AMP
 VOLTAGE REGULATOR GAIN=30
 FILTER IN LOOP

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RUN NO 3

BIPS ANALOG CONTROL SYSTEM
 SPEED GAIN=1100 WATTS/PERCENTSPEED
 CURRENT GAIN=1100 WATTS/AMP
 VOLTAGE REGULATOR GAIN=10
 FILTER NOT IN LOOP

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0.001 sec.

105 %

100 %

BRU SPEED 95 %
-0.25-

USER LOAD-MHOS

0-
200-

D.C. VOLTS

0-
50-

TOTAL LOAD RESISTANCE OHMS

0-
40-

PHASE CURRENT-AMPS.

0-
5-

TOTAL LOAD-KW.

0-
5-

FIELD VOLTS

0-

RUN NO. 3A

BIPS ANALOG CONTROL SYSTEM
SPEED GAIN=1100 WATTS/PERCENT SPEED
CURRENT GAIN=1100 WATTS/AMP
VOLTAGE REGULATOR GAIN=10
FILTER NOT IN LOOP

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RUN NO. 4

BIPS ANALOG CONTROL SYSTEM
 SPEED GAIN=2300 WATTS/PERCENT SPEED
 CURRENT GAIN=2300 WATTS/AMP
 VOLTAGE REGULATOR GAIN=10
 FILTER NOT IN LOOP

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RUN NO 5

BIPS ANALOG CONTROL SYSTEM
 SPEED GAIN=2300 WATTS/PERCENT SPEED
 CURRENT GAIN=2300 WATTS/AMP
 VOLTAGE REGULATOR GAIN=10
 FILTER IN LOOP

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RUN NO. 6

BIPS ANALOG CONTROL SYSTEM
 SPEED GAIN=4600 WATTS/PERCENT SPEED
 CURRENT GAIN=4600 WATTS/AMP
 VOLTAGE REGULATOR GAIN=10
 FILTER IN LOOP

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APPENDIX III

RELIABILITY ANALYSIS

Page

Presented on the following pages is the reliability program summary data for the NASA control shown on Drawing 306835. 1 - 44

LEVEL 4. POWER DISTRIBUTION

POWER DISTRIBUTION

STRESS RATIO OR TN	ITEM FAILURE RATE	BASE FAILURE RATE	QTY	TOTAL FAILURE RATE	DT C.	RL	CSR	RATING	STYLE
0.30	0.01000	0.01000	1	0.01000	0.	0.0	0.0	0.0	DISTRIBU
TOTAL PARTS FR / MILLION HRS. AT 25 C.				1	0.01000				
MTBF IN HOURS				100000128.					

LEVEL 4. POWER DISTRIBUTION
PART TYPE CONTRIBUTIONS

	QTY	FP	%
POWER DISTRIBUTION	1	0.01000	100.00
	-----	-----	-----
	1	0.01000	100.00

111

LEVEL 6. ALTERNATOR COILS

	STRESS RATIO OR TN	ITEM FAILURE RATE	BASE FAILURE RATE	QTY	TOTAL FAILURE RATE	DT C.	PI	CSR RATING	STYI F
TRANSFORMER									
I-R= 0.0027 PI-E= 1.00 PI-F= 4.00		0.00266	0.01063	2	0.02126	5.	0.20	0.	
CONNECTOR									
I-B= 0.0017 PI-E= 1.00 PI-P= 1.00 PI-CY 0.0100	0.23	0.00169	0.01166	2	0.02332	0.	0.20	0.	

 TOTAL PARTS 4
 FR / MILLION HRS. AT 25 C. 0.04459
 2 UNITS, 1 REQ.
 (OPERATIONAL REDUNDANCY)

REDUNDANCY K-FACTOR 0.00ADJ. FAILURE RATE 0.00009

MTRF IN HOURS 11507490800.

LEVEL 6. ALTERNATOR COILS
PART TYPE CONTRIBUTIONS

	QTY	FR	%
68 COILS. MTL-T-15305	2	0.02126	47.69
92 CONNECTORS	2	0.02332	52.31
	4	0.04459	100.00

LEVEL 6, ALTERNATOR STATOR ASSEMBLY

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TRANSFORMER, AP=FILTER, OU=UPPER
L-R= 0.0027 PI-F= 1.00 PT-F= 4.00

STRESS RATIO OR TN	ITEM FAILURE RATE	BASE FAILURE RATE	QTY	TOTAL FAILURE RATE	DT C.	RL	CSR	RATING	STYI F
	0.00266	0.01063	1	0.01063	5.	0.20	0.		
TOTAL PARTS			1						
FR / MILLION HRS. AT 25 C.				0.01063					
MTRF IN HOURS				94051552.0					

LEVEL 4. ALTERNATOR STATOR ASSEMBLY
PART TYPE CONTRIBUTIONS

	QTY	FR	%
68 COILS, MTL-T-15305	1	0.01063	100.00
	-----	-----	-----
	1	0.01063	100.00

LEVEL 4, ALTERNATOR STATOR CONNECTOR

CONNECTOR	STRESS RATIO OR TN	ITEM FAILURE RATE	BASE FAILURE RATE	QTY	TOTAL FAILURE RATE	DT C.	RI	CSR RATING	STYLE
L-B= 0.0019 PI-E= 1.00 PI-P= 1.00 PI-CY 0.0100	0.23	0.00186	0.00001	2	0.00001	0.	0.20	0.	
2 ITEMS, 1 REQ. (OPER. REDUNDANCY)									

 TOTAL PARTS
 FR / MILLION HRS. AT 25 C. 0.00001
 4 UNITS. 4 REQ.
 (OPERATIONAL REDUNDANCY)

MTRF IN HOURS 163214262000.

LEVEL 6, ALTERNATOR STATOR CONNECTOR
PART TYPE CONTRIBUTIONS

	QTY	FR	%
92 CONNECTORS	2	0.00001	100.00
	-----	-----	-----
	2	0.00001	100.00

	NO. OF PARTS	FAILURE RATE	QTY	TOTAL FAILURE RATE
LEVEL 4. ALTERNATOR				
43800. HRS. LIFE CYCLE				
LEVEL 5. ALTERNATOR COILS	4	MISSION 0.0001	2	MISSION 0.0001 *
2 UNITS, 1 REQ. (OPER. REDUNDANCY)				
LEVEL 6. ALTERNATOR STATOR ASSEMBLY	1	0.0106	1	0.0106
LEVEL 6. ALTERNATOR STATOR CONNECTOR	2	0.0000	4	0.0000
	-----		-----	
TOTAL PARTS	17			0.0107

* MEANS REDUNDANCY F.R. USED.

TOTAL FAILURE RATE 0.0107

MTRF IN HOURS 93235824.0

LEVEL 4, ALTERNATOR
PART TYPE CONTRIBUTIONS

	QTY	FR	%
68 COILS, MIL-T-15305	5	0.01072	51.44
92 CONNECTORS	12	0.00012	0.55
111 POWER DISTRIBUTION	1	0.01000	48.01
	-----	-----	-----
	18	0.02083	100.00

LEVEL 4. PARASITIC BANK

	STRESS RATIO OR TN	ITEM FAILURE RATE	BASE FAILURE RATE	QTY	TOTAL FAILURE RATE	DT C.	RI	CSR	RATING	STYLE
PARASITIC BANK	0.30	1.00000	0.04197	2	0.04197	0.	0.0	0.	BANK	
2 ITEMS, 1 REQ. (OPFR. REDUNDANCY)										

TOTAL PARTS				2						
FR / MILLION HRS. AT 25 C.					0.04197					
3 UNITS, 2 REQ.										
(OPERATIONAL REDUNDANCY)										
REDUNDANCY K-FACTOR	0.01ADJ.	FAILURE RATE			0.00023					
MTRF IN HOURS					4334075900.					

LEVEL 4, PARASITIC BANK
PART TYPE CONTRIBUTIONS

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PARASITIC BANK

QTY	FR	%
2	0.04197	100.00

2	0.04197	100.00

LEVEL 8. RECTIFIER SECTION

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	STRESS RATIO OR TN	ITEM FAILURE RATE	BASE FAILURE RATE	QTY	TOTAL FAILURE RATE	DT C.	RL	CSR	RATING	STYLE
D1,D2,D3,D4,DIODE	0.10	0.00705	0.00000	4	0.00000	0.		0.20	150.	DIODE
L-B= 0.0134 PI-E= 1.00 PI-Q= 5.00 PI-A= 1.5000 PI-C= 1.00										
PI-S 0.7000										
4 ITEMS, 2 REQ. (OPER. REDUNDANCY)										
D5,D6,D7,D8,DIODE	0.10	0.00705	0.00000	4	0.00000	0.		0.20	150.	DIODE
L-B= 0.0134 PI-E= 1.00 PI-Q= 5.00 PI-A= 1.5000 PI-C= 1.00										
PI-S 0.7000										
4 ITEMS, 2 REQ. (OPER. REDUNDANCY)										
D9,D10,D11,D12,DIODE	0.10	0.00705	0.00000	4	0.00000	0.		0.20	150.	DIODE
L-B= 0.0134 PI-E= 1.00 PI-Q= 5.00 PI-A= 1.5000 PI-C= 1.00										
PI-S 0.7000										
4 ITEMS, 2 REQ. (OPER. REDUNDANCY)										
D13,D14,D15,D16,DIODE	0.10	0.00705	0.00000	4	0.00000	0.		0.20	150.	DIODE
L-B= 0.0134 PI-E= 1.00 PI-Q= 5.00 PI-A= 1.5000 PI-C= 1.00										
PI-S 0.7000										
4 ITEMS, 2 REQ. (OPER. REDUNDANCY)										
D17,D18,D19,D20,DIODE	0.10	0.00705	0.00000	4	0.00000	0.		0.20	150.	DIODE
L-B= 0.0134 PI-E= 1.00 PI-Q= 5.00 PI-A= 1.5000 PI-C= 1.00										
PI-S 0.7000										
4 ITEMS, 2 REQ. (OPER. REDUNDANCY)										
D21,D22,D23,D24,DIODE	0.10	0.00705	0.00000	4	0.00000	0.		0.20	150.	DIODE
L-B= 0.0134 PI-E= 1.00 PI-Q= 5.00 PI-A= 1.5000 PI-C= 1.00										
PI-S 0.7000										
4 ITEMS, 2 REQ. (OPER. REDUNDANCY)										
C1,C2,C3,CSR13	0.20	0.00029	0.00000	3	0.00000	0.		0.20	0.	CSR13
L-B= 0.0041 PI-E= 1.00 PI-Q= 1.00 PI-SR 0.0700										
3 ITEMS, 2 REQ. (OPER. REDUNDANCY)										
C6,C7,C8,CSR13	0.20	0.00029	0.00000	3	0.00000	0.		0.20	0.	CSR13
L-B= 0.0041 PI-E= 1.00 PI-Q= 1.00 PI-SR 0.0700										
3 ITEMS, 2 REQ. (OPER. REDUNDANCY)										
L1,COIL		0.01123	0.04492	1	0.04492	50.		0.20	0.	L1
L-B= 0.0112 PI-F= 1.00 PI-F= 4.00										
L2,COIL		0.01123	0.04492	1	0.04492	50.		0.20	0.	L2
L-B= 0.0112 PI-E= 1.00 PI-F= 4.00										

TOTAL PARTS 32
FR / MILLION HRS. AT 25 C. 0.08983
MTRF IN HOURS 11131527.0

LEVEL 8, RECTIFIER SECTION
PART TYPE CONTRIBUTIONS

		QTY	FR	%
32	C, CS, MTL-C-26655 OR 39003	6	0.00000	0.00
54	DIODES, SILICON	24	0.00000	0.00
72	TRANSFORMERS, MIL-T-21038	2	0.08983	100.00
		-----	-----	-----
		32	0.08983	100.00

LEVEL 8. FIELD POWER SUPPLY

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	STRESS RATIO OR TM	ITEM FAILURE RATE	BASE FAILURE RATE	QTY	TOTAL FAILURE RATE	DT C.	RI	CSR RATING	STYLE
D1,D2,D3,D4,DIODE		0.10	0.00705						
L-B= 0.0134 PI-E= 1.00 PI-Q= 5.00 PI-A= 1.5000 PI-C= 1.00			0.00000	4	0.00000	0.	0.20	150.	DIODE
PI-S 0.7000									
4 ITEMS, 2 REQ. (NPR. REDUNDANCY)									
C1,C2,C3,C4,CSP13	0.20	0.00029	0.00029	4	0.00114	0.	0.20	0.	CSR13
I-B= 0.0041 PI-E= 1.00 PI-Q= 1.00 PI-SR 0.0700									
D1,D2,DIODE	0.10	0.00470	0.00470	2	0.00940	0.	0.20	150.	DIODE
I-B= 0.0134 PI-E= 1.00 PI-Q= 5.00 PI-A= 1.0000 PI-C= 1.00									
PI-S 0.7000									

TOTAL PARTS 10
FR / MILLION HRS. AT 25 C. 0.01055
MTRF IN HOURS 94800544.0

LEVEL 8, FIELD POWER SUPPLY
PART TYPE CONTRIBUTIONS

		QTY	FR	%
32	C, CS, MTL-C-26655 OR 39003	4	0.00114	10.85
54	DIODES, SILICON	6	0.00940	89.15
		-----	-----	-----
		10	0.01055	100.00

LEVEL 4. ELECTRONICS POWER SUPPLY

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	STRESS RATIO OR TN	ITEM FAILURE RATE	BASE FAILURE RATE	QTY	TOTAL FAILURE RATE	DT C.	RI	CSP	RATING	STYLE
D1,D2,D3,D4,DIODE		0.10	0.00705							
L-B= 0.0134 PI-E= 1.00 PI-Q= 5.00 PI-A= 1.5000 PI-C= 1.00			0.00000	4	0.00000	0.		0.20	150.	DIODE
PI-S 0.7000										
4 ITEMS, 2 REQ. (OPER. REDUNDANCY)										
D5,D6,7FNER		0.01767	0.01767	2	0.03534	0.		0.20	175.	D6
L-B= 0.0353 PI-E= 1.00 PI-Q= 5.00										
R1,RNR60F	0.20	0.00171	0.00171	1	0.00171	0.	M	0.20	0.	RNR60F
L-B= 0.0017 PI-E= 1.00 PI-Q= 1.00 PI-P= 1.0000										
R2,RNR60F	0.20	0.00171	0.00171	1	0.00171	0.	M	0.20	0.	RNR60F
L-B= 0.0017 PI-E= 1.00 PI-Q= 1.00 PI-R= 1.0000										
Q1,NPN		0.00548	0.00548	1	0.00548	10.		0.20	175.	NPN
L-B= 0.0509 PI-E= 1.00 PI-Q= 2.00 PI-A= 1.5000 PI-C= 1.00										
PI-S 0.3000										

TOTAL PARTS 9
FR / MILLION HRS. AT 25 C. 0.04425
3 UNITS. 1 REQ.
(OPERATIONAL REDUNDANCY)

REDUNDANCY K-FACTOR 0.00ADJ. FAILURE RATE 0.00000

MTRF IN HOURS 6034694340000.

LEVEL 8, ELECTRONICS POWER SUPPLY
PART TYPE CONTRIBUTIONS

		QTY	FR	%
43	R, RN, MTL-P10509 OR 55182, FIXED FILM	2	0.00342	7.73
54	DIODES, SILICON	4	0.00000	0.00
57	DIODES, SILICON, 7FNER	2	0.03534	79.88
61	TRANSISTORS, NPN, SILICON	1	0.00548	12.39
		-----	-----	-----
		9	0.04425	100.00

	NO. OF PARTS	FAILURE RATE	QTY	TOTAL FAILURE RATE
LEVEL 6, POWER SUPPLIES				
43A00. HRS. LIFE CYCLE		MISSION		MISSION
LEVEL 8, RECTIFIER SECTION	32	0.0898	1	0.0898
LEVEL 8, FIELD POWER SUPPLY	10	0.0105	1	0.0105
LEVEL 8, ELECTRONICS POWER SUPPLY	9	0.0000	3	0.0000 *
3 UNITS, 1 REQ. (OPER. REDUNDANCY)				

TOTAL PARTS	-----	-----
49		0.1004

* MEANS REDUNDANCY F.R. USED.

TOTAL FAILURE RATE 0.1004

MTRF IN HOURS 9961800.00

BLANK

					STRESS RATIO OR TH	ITEM FAILURE RATE	BASE FAILURE RATE	QTY	TOTAL FAILURE RATE	DT C.	RI	CSR	PATING	STYLE
R1, RNR60F					0.20	0.00171	0.00188	1	0.00188	0.	M	0.20	0.	RNR60F
I-B= 0.0017 PI-F=	1.00	PI-Q=	1.00	PI-R= 1.1000										
R2, RNR60F					0.20	0.00171	0.00171	1	0.00171	0.	M	0.20	0.	RNR60F
I-R= 0.0017 PI-F=	1.00	PI-Q=	1.00	PI-R= 1.0000										
R3, RNR60F					0.20	0.00171	0.00171	1	0.00171	0.	M	0.20	0.	RNR60F
L-B= 0.0017 PI-F=	1.00	PI-Q=	1.00	PI-R= 1.0000										
R4, RNR60F					0.20	0.00171	0.00171	1	0.00171	0.	M	0.20	0.	RNR60F
L-B= 0.0017 PI-F=	1.00	PI-Q=	1.00	PI-R= 1.0000										
R5, RNR60F					0.20	0.00171	0.00171	1	0.00171	0.	M	0.20	0.	RNR60F
L-B= 0.0017 PI-F=	1.00	PI-Q=	1.00	PI-R= 1.0000										
R6, RNR60F					0.20	0.00171	0.00171	1	0.00171	0.	M	0.20	0.	RNR60F
I-B= 0.0017 PI-F=	1.00	PI-Q=	1.00	PI-R= 1.0000										
R7, RNR60F					0.20	0.00171	0.00171	1	0.00171	0.	M	0.20	0.	RNR60F
L-B= 0.0017 PI-F=	1.00	PI-Q=	1.00	PI-R= 1.0000										
R8, RNR60F					0.20	0.00171	0.00171	1	0.00171	0.	M	0.20	0.	RNR60F
L-B= 0.0017 PI-E=	1.00	PI-Q=	1.00	PI-R= 1.0000										
R9, RNR60F					0.20	0.00171	0.00171	1	0.00171	0.	M	0.20	0.	RNR60F
L-B= 0.0017 PI-F=	1.00	PI-Q=	1.00	PI-R= 1.0000										
R10, RNR60F					0.20	0.00171	0.00188	1	0.00188	0.	M	0.20	0.	RNR60F
L-B= 0.0017 PI-F=	1.00	PI-Q=	1.00	PI-R= 1.1000										
C1, CSP13					0.20	0.00029	0.00029	1	0.00029	0.		0.20	0.	CSP13
I-B= 0.0041 PI-F=	1.00	PI-Q=	1.00	PI-SR 0.0700										
C2, CSP13					0.20	0.00029	0.00029	1	0.00029	0.		0.20	0.	CSP13
I-B= 0.0041 PI-E=	1.00	PI-Q=	1.00	PI-SR 0.0700										
D1, DIODE					0.10	0.00470	0.00470	1	0.00470	0.		0.20	150.	DIODE
I-B= 0.0134 PI-E=	1.00	PI-Q=	5.00	PI-A= 1.0000 PI-C= 1.00										
PT-S 0.7000														
D2, ZENER						0.01767	0.01767	1	0.01767	0.		0.20	175.	D2
L-B= 0.0353 PI-E=	1.00	PI-Q=	5.00											
Q1, PNP						0.00338	0.00338	1	0.00338	0.		0.20	175.	PNP
I-B= 0.0804 PI-E=	1.00	PI-Q=	2.00	PI-A= 0.7000 PI-C= 1.00										
PT-S 0.3000														
71, ANALOG IC,						0.00150	0.01501	1	0.01501	0.		0.0	0.	71
I-B= 0.0015 PI-E=	0.20	PI-Q=	10.00	C1= 0.0016 PI-L= 1.00										
PT-T 0.2422 C2=	0.01													

TOTAL PARTS ----- 16
 FR / MILLION HRS. AT 25 C. 0.05877
 3 UNITS, 2 PRQ.
 (OPERATIONAL REDUNDANCY)

REDUNDANCY K-FACTOR 0.01ADJ. FAILURE RATE 0.00045
 MTRF IN HOURS 2212839680.

LEVEL 8, VOLTAGE REGULATOR FRONT END
PART TYPE CONTRIBUTIONS

		QTY	FR	%
32	C, CS, MTL-C-26655 OR 39003	2	0.00057	0.97
43	R, RN, MTL-R10509 OR 55182, FIXED FILM	10	0.01744	29.67
54	DIODES, SILICON	1	0.00470	8.00
57	DIODES, SILICON, ZENER	1	0.01767	30.07
60	TRANSISTORS, PNP, SILICON	1	0.00338	5.75
98	ANALOG IC	1	0.01501	25.53
		-----	-----	-----
		16	0.05877	100.00

LFVFL R. VOLTAGE REGULATOR BACK END

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	STRESS RATIO OR TM	ITEM FAILURE RATE	BASIS FAILURE RATE	QTY	TOTAL FAILURE RATE	DT C.	RI	CSR	RATING	STYLE
P1,P2, RNR60E	0.20	0.00171	0.00171	2	0.00342	0.	M	0.20	0.	RNR60E
L-B= 0.0017 PI-F= 1.00 PI-Q= 1.00 PI-R= 1.0000	0.20	0.00171	0.00171	1	0.00171	0.	M	0.20	0.	RNR60E
R3, RNP60F	0.20	0.00171	0.00171	1	0.00171	0.	M	0.20	0.	RNR60E
L-B= 0.0017 PI-F= 1.00 PI-Q= 1.00 PI-R= 1.0000	0.20	0.00171	0.00171	1	0.00171	0.	M	0.20	0.	RNR60E
R4, RNR60F	0.20	0.00171	0.00171	1	0.00171	0.	M	0.20	0.	RNR60E
L-B= 0.0017 PI-F= 1.00 PI-Q= 1.00 PI-R= 1.0000	0.20	0.00171	0.00171	1	0.00171	0.	M	0.20	0.	RNR60E
R5, RNR60E	0.20	0.00171	0.00171	1	0.00171	0.	M	0.20	0.	RNR60E
L-B= 0.0017 PI-F= 1.00 PI-Q= 1.00 PI-R= 1.0000	0.20	0.00171	0.00171	1	0.00171	0.	M	0.20	0.	RNR60E
R5, RNR60E	0.20	0.00171	0.00171	1	0.00171	0.	M	0.20	0.	RNR60E
L-B= 0.0017 PI-F= 1.00 PI-Q= 1.00 PI-R= 1.0000	0.20	0.00171	0.00171	1	0.00171	0.	M	0.20	0.	RNR60E
R6, RNR60F	0.20	0.00171	0.00171	1	0.00171	0.	M	0.20	0.	RNR60E
L-B= 0.0017 PI-F= 1.00 PI-Q= 1.00 PI-R= 1.0000	0.20	0.00171	0.00171	1	0.00171	0.	M	0.20	0.	RNR60E
R7, RNR60E	0.20	0.00171	0.00171	1	0.00171	0.	M	0.20	0.	RNR60E
L-B= 0.0017 PI-E= 1.00 PI-Q= 1.00 PI-R= 1.0000	0.20	0.00171	0.00171	1	0.00171	0.	M	0.20	0.	RNR60E
R8, RNR60E	0.20	0.00171	0.00171	1	0.00171	0.	M	0.20	0.	RNR60E
L-B= 0.0017 PI-F= 1.00 PI-Q= 1.00 PI-R= 1.0000	0.20	0.00171	0.00171	2	0.00342	0.	M	0.20	0.	RNR60E
R9, R10, RNR60E	0.20	0.00171	0.00171	1	0.00171	0.	M	0.20	0.	RNR60E
L-B= 0.0017 PI-E= 1.00 PI-Q= 1.00 PI-R= 1.0000	0.20	0.00171	0.00171	1	0.00171	0.	M	0.20	0.	RNR60E
R11, RNR60E	0.20	0.00171	0.00171	1	0.00171	0.	M	0.20	0.	RNR60E
L-B= 0.0017 PI-E= 1.00 PI-Q= 1.00 PI-R= 1.0000	0.20	0.00171	0.00171	1	0.00171	0.	M	0.20	0.	RNR60E
R12, RNR60E	0.20	0.00171	0.00171	1	0.00171	0.	M	0.20	0.	RNR60E
L-B= 0.0017 PI-E= 1.00 PI-Q= 1.00 PI-R= 1.0000	0.20	0.00171	0.00171	1	0.00171	0.	M	0.20	0.	RNR60E
R13, RNR60E	0.20	0.00171	0.00171	1	0.00171	0.	M	0.20	0.	RNR60E
L-B= 0.0017 PI-E= 1.00 PI-Q= 1.00 PI-R= 1.0000	0.20	0.00029	0.00029	1	0.00029	0.		0.20	0.	CSR13
C1, CSR13	0.20	0.00029	0.00029	1	0.00029	0.		0.20	0.	CSR13
L-B= 0.0041 PI-E= 1.00 PI-Q= 1.00 PI-SR 0.0700	0.20	0.00029	0.00029	1	0.00029	0.		0.20	0.	CSR13
C2, CSR13	0.20	0.00029	0.00029	1	0.00029	0.		0.20	0.	CSR13
L-B= 0.0041 PI-E= 1.00 PI-Q= 1.00 PI-SR 0.0700	0.20	0.00029	0.00029	1	0.00029	0.		0.20	0.	CSR13
C3, CSR13	0.20	0.00029	0.00029	2	0.00057	0.		0.20	0.	CSR13
L-B= 0.0041 PI-E= 1.00 PI-Q= 1.00 PI-SR 0.0700	0.20	0.00029	0.00029	1	0.00029	0.		0.20	0.	CSR13
C4, C5, CSR13	0.20	0.00029	0.00029	1	0.00029	0.		0.20	0.	CSR13
L-B= 0.0041 PI-F= 1.00 PI-Q= 1.00 PI-SR 0.0700	0.20	0.00029	0.00029	1	0.00029	0.		0.20	0.	CSR13
C6, CSR13	0.20	0.00029	0.00029	1	0.00029	0.		0.20	0.	CSR13
L-B= 0.0041 PI-E= 1.00 PI-Q= 1.00 PI-SR 0.0700	0.20	0.00029	0.00029	1	0.00029	0.		0.20	0.	CSR13
C7, CSR13	0.20	0.00029	0.00029	1	0.00029	0.		0.20	0.	CSR13
L-B= 0.0041 PI-E= 1.00 PI-Q= 1.00 PI-SR 0.0700	0.20	0.00029	0.00029	1	0.00029	0.		0.20	0.	CSR13
C8, CSR13	0.20	0.00029	0.00029	1	0.00029	0.		0.20	0.	CSR13
L-B= 0.0041 PI-E= 1.00 PI-Q= 1.00 PI-SR 0.0700	0.20	0.00029	0.00029	1	0.00029	0.		0.20	0.	CSR13
C9, CSR13	0.20	0.00029	0.00029	1	0.00029	0.		0.20	0.	CSR13
L-B= 0.0041 PI-F= 1.00 PI-Q= 1.00 PI-SR 0.0700	0.20	0.00029	0.00029	1	0.00029	0.		0.20	0.	CSR13
C10, CSR13	0.10	0.00470	0.00470	1	0.00470	0.		0.20	150.	D100E
L-B= 0.0134 PI-F= 1.00 PI-Q= 5.00 PI-A= 1.0000 PI-C= 1.00										
PI-S 0.7000										

LEVEL R, VOLTAGE REGULATOR BACK END
CONTINUED

	STRESS RATIO OR TN	ITEM FAILURE RATE	BASE FAILURE RATE	QTY	TOTAL FAILURE RATE	DT C.	RL	CSP	RATING	STYLE
D2, ZENER		0.01767	0.01767	1	0.01767	0.		0.20	175.	D2
L-B= 0.0353 PI-E= 1.00 PI-Q= 5.00										
D3, D4, D5, D6, DIODE	0.10	0.00705	0.00000	4	0.00000	0.		0.20	150.	DIODE
L-B= 0.0134 PI-E= 1.00 PI-Q= 5.00 PI-A= 1.5000 PI-C= 1.00										
PI-S 0.7000										
4 ITEMS, 2 REQ. (NPER. REDUNDANCY)										
Q1, Q3, NPN		0.00256	0.00256	2	0.00512	10.		0.20	175.	NPN
L-B= 0.0609 PI-E= 1.00 PI-Q= 2.00 PI-A= 0.7000 PI-C= 1.00										
PI-S 0.3000										
Q2, Q4, NPN		0.00256	0.00256	2	0.00512	10.		0.20	175.	NPN
L-B= 0.0609 PI-E= 1.00 PI-Q= 2.00 PI-A= 0.7000 PI-C= 1.00										
PI-S 0.3000										
Z1, Z2, ANALOG IC,		0.00150	0.01501	1	0.01501	0.		0.0	0.	72
L-B= 0.0015 PI-E= 0.20 PI-Q= 10.00 C1= 0.0016 PI-L= 1.00										
PI-T 0.2422 C2= 0.01										

TOTAL PARTS 35
FR / MILLION HRS. AT 25 C. 0.07441
2 UNITS, 1 REQ.
(OPERATIONAL REDUNDANCY)
REDUNDANCY K-FACTOR 0.00ADJ. FAILURE RATE 0.00024
MTRF IN HOURS 4136440580.

LEVEL 2. VOLTAGE REGULATOR BACK END
PART TYPE CONTRIBUTIONS

		QTY	FR	%
32	C, CS, MII-C-26655 OR 39003	10	0.00286	3.85
43	R, RN, MII-R10509 OR 55182, FIXED FILM	14	0.02394	32.17
54	DIODES, SILICON	5	0.00470	6.32
57	DIODES, SILICON, ZENER	1	0.01767	23.75
61	TRANSISTORS, NPN, SILICON	4	0.01023	13.75
98	ANALOG IC	1	0.01501	20.17
		-----	-----	-----
		35	0.07441	100.00

	NO. OF PARTS	FAILURE RATE	QTY	TOTAL FAILURE RATE
LEVEL A, VOLTAGE REGULATOR EXCITER				
43800. HRS. LIFE CYCLE				
LEVEL A, VOLTAGE REGULATOR FRONT END	16	0.0005	3	0.0005 *
3 UNITS, 2 REQ. (OPER. REDUNDANCY)				
LEVEL A, VOLTAGE REGULATOR BACK END	35	0.0002	2	0.0002 *
2 UNITS, 1 REQ. (OPER. REDUNDANCY)				
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TOTAL PARTS	118			0.0007

* MEANS REDUNDANCY F.R. USED.

TOTAL FAILURE RATE 0.0007

MTRF IN HOURS *****

LEVEL R. MONOPOLE CONDITIONING

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	STRESS RATIO OR TN	ITEM FAILURE RATE	BASE FAILURE RATE	QTY	TOTAL FAILURE RATE	DT C.	RL	CSR RATING	STYLE
MONOPOLES	0.30	3.56999	3.56999	1	3.56999	0.	0.0	0.	MONOPOLE
R1,R2,RNR60E	0.20	0.00171	0.00171	2	0.00342	0.	M 0.20	0.	RNR60E
L-B= 0.0017 PI-E= 1.00 PI-Q= 1.00 PI-R= 1.0000									
C1,C2,C3,C4,CSR13	0.20	0.00029	0.00000	4	0.00000	0.	0.20	0.	CSR13
L-B= 0.0041 PI-E= 1.00 PI-Q= 1.00 PI-SR 0.0700									
4 ITEMS, 2 REQ. (OPER. REDUNDANCY)									

TOTAL PARTS 7
FR / MILLION HRS. AT 25 C. 3.57341
3 UNITS, 1 REQ.
(OPERATIONAL REDUNDANCY)
REDUNDANCY K-FACTOR 0.02ADJ. FAILURE RATE 0.06954
MTBF IN HOURS 14380466.0

BLANK

LEVEL R, MONOPOLE CONDITIONING
PART TYPE CONTRIBUTIONS

		QTY	FR	%
32	C, CS, MTL-C-26655 OR 39003	4	0.00000	0.00
43	R, RN, MTL-R10509 OR 55182, FIXED FILM	2	0.00342	0.10
101	MONOPOLES	1	3.56999	99.90
		-----	-----	-----
		7	3.57341	100.00

LEVEL 4, SPEED CONTROL FRONT END

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				STRESS RATIO OR TM	ITEM FAILURE RATE	BASE FAILURE RATE	QTY	TOTAL FAILURE RATE	DT C.	RL	CSR RATING	STYLE
R1, RNR60F				0.20	0.00171	0.00188	1	0.00188	0.	M	0.20	0. RNR60F
L-B= 0.0017 PI-F= 1.00 PI-Q= 1.00 PI-R= 1.1000												
R2, RNR60F				0.20	0.00171	0.00171	1	0.00171	0.	M	0.20	0. RNR60F
I-B= 0.0017 PI-E= 1.00 PI-Q= 1.00 PI-R= 1.0000												
R3, RNR60F				0.20	0.00171	0.00171	1	0.00171	0.	M	0.20	0. RNR60F
L-B= 0.0017 PI-F= 1.00 PI-Q= 1.00 PI-R= 1.0000												
R4, RNR60F				0.20	0.00171	0.00171	1	0.00171	0.	M	0.20	0. RNR60F
L-B= 0.0017 PI-F= 1.00 PI-Q= 1.00 PI-R= 1.0000												
R5, RNR60F				0.20	0.00171	0.00171	1	0.00171	0.	M	0.20	0. RNR60F
I-B= 0.0017 PI-E= 1.00 PI-Q= 1.00 PI-R= 1.0000												
R6, RNR60F				0.20	0.00171	0.00171	1	0.00171	0.	M	0.20	0. RNR60F
L-B= 0.0017 PI-F= 1.00 PI-Q= 1.00 PI-R= 1.0000												
R7, RNR60F				0.20	0.00171	0.00171	1	0.00171	0.	M	0.20	0. RNR60F
I-B= 0.0017 PI-E= 1.00 PI-Q= 1.00 PI-R= 1.0000												
R8, RNR60F				0.20	0.00171	0.00171	1	0.00171	0.	M	0.20	0. RNR60F
L-B= 0.0017 PI-E= 1.00 PI-Q= 1.00 PI-R= 1.0000												
R9, RNR60F				0.20	0.00171	0.00171	1	0.00171	0.	M	0.20	0. RNR60F
L-B= 0.0017 PI-E= 1.00 PI-Q= 1.00 PI-R= 1.0000												
R10, RNR60F				0.20	0.00171	0.00171	1	0.00171	0.	M	0.20	0. RNR60F
I-B= 0.0017 PI-E= 1.00 PI-Q= 1.00 PI-R= 1.0000												
R11, RNR60F				0.20	0.00171	0.00171	1	0.00171	0.	M	0.20	0. RNR60F
L-B= 0.0017 PI-E= 1.00 PI-Q= 1.00 PI-R= 1.0000												
R12, RNR60F				0.20	0.00171	0.00171	1	0.00171	0.	M	0.20	0. RNR60F
L-B= 0.0017 PI-E= 1.00 PI-Q= 1.00 PI-R= 1.0000												
R13, RNR60F				0.20	0.00171	0.00171	1	0.00171	0.	M	0.20	0. RNR60F
L-B= 0.0017 PI-F= 1.00 PI-Q= 1.00 PI-R= 1.0000												
R13, RNR60F				0.20	0.00171	0.00171	1	0.00171	0.	M	0.20	0. RNR60F
I-B= 0.0017 PI-F= 1.00 PI-Q= 1.00 PI-R= 1.0000												
C1, CSR13				0.20	0.00029	0.00029	1	0.00029	0.		0.20	0. CSR13
L-B= 0.0041 PI-E= 1.00 PI-Q= 1.00 PI-SR 0.0700												
C2, CSR13				0.20	0.00029	0.00029	1	0.00029	0.		0.20	0. CSR13
I-B= 0.0041 PI-F= 1.00 PI-Q= 1.00 PI-SR 0.0700												
C3, CSR13				0.20	0.00029	0.00029	1	0.00029	0.		0.20	0. CSR13
L-B= 0.0041 PI-E= 1.00 PI-Q= 1.00 PI-SR 0.0700												
C4, CSR13				0.20	0.00029	0.00029	1	0.00029	0.		0.20	0. CSR13
I-B= 0.0041 PI-F= 1.00 PI-Q= 1.00 PI-SR 0.0700												
C5, CSR13				0.20	0.00029	0.00029	1	0.00029	0.		0.20	0. CSR13
L-B= 0.0041 PI-E= 1.00 PI-Q= 1.00 PI-SR 0.0700												
C6, CSR13				0.20	0.00029	0.00029	1	0.00029	0.		0.20	0. CSR13
I-B= 0.0041 PI-F= 1.00 PI-Q= 1.00 PI-SR 0.0700												
C6, C7, CSR13				0.20	0.00029	0.00029	2	0.00057	0.		0.20	0. CSR13
L-B= 0.0041 PI-E= 1.00 PI-Q= 1.00 PI-SR 0.0700												
Q1, NPN					0.00492	0.00492	5	0.02459	0.		0.20	175. NPN
I-B= 0.0546 PI-F= 1.00 PI-Q= 2.00 PI-A= 1.5000 PI-C= 1.00												
PI-S 0.3000												

LEVEL R, SPEED CONTROL FRONT END
CONTINUED

	STRESS RATIO OR TN	ITEM FAILURE RATE	BASE FAILURE RATE	QTY	TOTAL FAILURE RATE	DT C.	RL	CSR RATING	STYLE
Q2, PNP		0.00507	0.00507	1	0.00507	0.	0.20	175.	PAP
I-B= 0.0804 PI-E= 1.00 PI-Q= 2.00 PI-A= 1.5000 PI-C= 0.70									
PI-S 0.3000									
71, ANALOG IC,		0.00150	0.01501	1	0.01501	0.	0.0	0.	71
I-B= 0.0015 PI-E= 0.20 PI-Q= 10.00 C1= 0.0016 PI-L= 1.00									
PI-T 0.2422 C2= 0.01									

29

TOTAL PARTS
FR / MILLION HRS. AT 25 C. 0.07106

3 UNITS, 2 REQ.
(OPERATIONAL REDUNDANCY)

REDUNDANCY K-FACTOR 0.01ADJ. FAILURE RATE 0.00066

MTBF IN HOURS 1515156480.

LEVEL 8, SPEED CONTROL FRONT END
PART TYPE CONTRIBUTIONS

		QTY	FP	%
32	C, CS, MTL-C-26655 OR 39003	8	0.00229	3.22
43	R, RN, MTL-P10509 OR 55182, FIXED FILM	14	0.02411	33.93
60	TRANSISTORS, PNP, SILICON	1	0.00507	7.13
61	TRANSISTORS, NPN, SILICON	5	0.02459	34.60
98	ANALOG IC	1	0.01501	21.12
		-----	-----	-----
		29	0.07106	100.00

						STRESS RATIO OR TN	ITEM FAILURE RATE	BASF FAILURE RATE	QTY	TOTAL FAILURE RATE	DT C.	RI	CSR RATING	STYLE
R1, RNR60E						0.20	0.00171	0.00188	1	0.00188	0.	M	0.20	0. RNR60E
L-B= 0.0017 PI-E=	1.00	PI-Q=	1.00	PI-R=	1.1000									
R2, RNR60E						0.20	0.00171	0.00171	1	0.00171	0.	M	0.20	0. RNR60E
L-B= 0.0017 PI-F=	1.00	PI-Q=	1.00	PI-R=	1.0000									
R3, RNR60E						0.20	0.00171	0.00171	1	0.00171	0.	M	0.20	0. RNR60E
L-B= 0.0017 PI-E=	1.00	PI-Q=	1.00	PI-R=	1.0000									
R4, R5, RNR60E						0.20	0.00171	0.00171	2	0.00342	0.	M	0.20	0. RNR60E
L-B= 0.0017 PI-F=	1.00	PI-Q=	1.00	PI-R=	1.0000									
R6, RNR60E						0.20	0.00171	0.00171	1	0.00171	0.	M	0.20	0. RNR60E
L-B= 0.0017 PI-F=	1.00	PI-Q=	1.00	PI-R=	1.0000									
R7, RNR60E						0.20	0.00171	0.00171	1	0.00171	0.	M	0.20	0. RNR60E
L-B= 0.0017 PI-E=	1.00	PI-Q=	1.00	PI-R=	1.0000									
R8, RNR60E						0.20	0.00171	0.00188	1	0.00188	0.	M	0.20	0. RNR60E
L-B= 0.0017 PI-F=	1.00	PI-Q=	1.00	PI-R=	1.1000									
R9, RNR60E						0.20	0.00171	0.00171	1	0.00171	0.	M	0.20	0. RNR60E
L-B= 0.0017 PI-E=	1.00	PI-Q=	1.00	PI-R=	1.0000									
R10, RNR60E						0.20	0.00171	0.00171	1	0.00171	0.	M	0.20	0. RNR60E
L-B= 0.0017 PI-F=	1.00	PI-Q=	1.00	PI-R=	1.0000									
R11, R12, RNR60E						0.20	0.00171	0.00171	2	0.00342	0.	M	0.20	0. RNR60E
L-B= 0.0017 PI-E=	1.00	PI-Q=	1.00	PI-R=	1.0000									
R13, RNR60E						0.20	0.00171	0.00171	1	0.00171	0.	M	0.20	0. RNR60E
L-B= 0.0017 PI-F=	1.00	PI-Q=	1.00	PI-R=	1.0000									
R14, RNR60E						0.20	0.00171	0.00171	1	0.00171	0.	M	0.20	0. RNR60E
L-B= 0.0017 PI-E=	1.00	PI-Q=	1.00	PI-R=	1.0000									
R15, RNR60E						0.20	0.00171	0.00171	1	0.00171	0.	M	0.20	0. RNR60E
L-B= 0.0017 PI-F=	1.00	PI-Q=	1.00	PI-R=	1.0000									
R15, RNR60E						0.20	0.00171	0.00171	1	0.00171	0.	M	0.20	0. RNR60E
L-B= 0.0017 PI-E=	1.00	PI-Q=	1.00	PI-R=	1.0000									
R15, RNR60E						0.20	0.00171	0.00171	1	0.00171	0.	M	0.20	0. RNR60E
L-B= 0.0017 PI-F=	1.00	PI-Q=	1.00	PI-R=	1.0000									
C1, CSR13						0.20	0.00029	0.00029	1	0.00029	0.		0.20	0. CSR13
L-B= 0.0041 PI-E=	1.00	PI-Q=	1.00	PI-R=	0.0700									
C2, CSR13						0.20	0.00029	0.00029	1	0.00029	0.		0.20	0. CSR13
L-B= 0.0041 PI-F=	1.00	PI-Q=	1.00	PI-R=	0.0700									
C2, CSR13						0.20	0.00029	0.00029	1	0.00029	0.		0.20	0. CSR13
L-B= 0.0041 PI-E=	1.00	PI-Q=	1.00	PI-R=	0.0700									
C4, C5, CSR13						0.20	0.00029	0.00029	2	0.00057	0.		0.20	0. CSR13
L-B= 0.0041 PI-F=	1.00	PI-Q=	1.00	PI-R=	0.0700									
C6, CSR13						0.20	0.00029	0.00029	1	0.00029	0.		0.20	0. CSR13
L-B= 0.0041 PI-E=	1.00	PI-Q=	1.00	PI-R=	0.0700									
C7, CSR13						0.20	0.00029	0.00029	1	0.00029	0.		0.20	0. CSR13
L-B= 0.0041 PI-F=	1.00	PI-Q=	1.00	PI-R=	0.0700									
C7, CSR13						0.20	0.00029	0.00029	1	0.00029	0.		0.20	0. CSR13
L-B= 0.0041 PI-E=	1.00	PI-Q=	1.00	PI-R=	0.0700									

LEVEL 8, SPEED CONTROL BACK END
CONTINUED

						STRESS RATIO OR TM	ITEM FAILURE RATE	BASE FAILURE RATE	QTY	TOTAL FAILURE RATE	DT C.	RI	CSR RATING	STYLE
C8, CSP13						0.20	0.00029	0.00029	1	0.00029	0.	0.20	0.	CSP13
L-B= 0.0041	PI-E=	1.00	PI-Q=	1.00	PI-SP 0.0700									
C9, CSP13						0.20	0.00029	0.00029	1	0.00029	0.	0.20	0.	CSP13
L-B= 0.0041	PI-F=	1.00	PI-Q=	1.00	PI-SR 0.0700									
D1, 7ENF2,							0.01767	0.01767	1	0.01767	0.	0.20	175.	D1
L-B= 0.0353	PI-F=	1.00	PI-Q=	5.00										
D2, DIODE						0.10	0.00470	0.00470	1	0.00470	0.	0.20	150.	DIODE
L-B= 0.0134	PI-E=	1.00	PI-Q=	5.00	PI-A= 1.0000 PI-C= 1.00									
PI-S 0.7000														
D3, DIODE						0.10	0.00470	0.00470	1	0.00470	0.	0.20	150.	DIODE
L-B= 0.0134	PI-E=	1.00	PI-Q=	5.00	PI-A= 1.0000 PI-C= 1.00									
PI-S 0.7000														
Q1, Q3, NPN							0.00256	0.00256	2	0.00512	10.	0.20	175.	NPN
L-B= 0.0609	PI-E=	1.00	PI-Q=	2.00	PI-A= 0.7000 PI-C= 1.00									
PI-S 0.3000														
Q5, NPN							0.00229	0.00229	1	0.00229	0.	0.20	175.	NPN
L-B= 0.0546	PI-E=	1.00	PI-Q=	2.00	PI-A= 0.7000 PI-C= 1.00									
PI-S 0.3000														
Q6, Q7, NPN							0.00256	0.00256	2	0.00512	10.	0.20	175.	NPN
L-B= 0.0609	PI-E=	1.00	PI-Q=	2.00	PI-A= 0.7000 PI-C= 1.00									
PI-S 0.3000														
Z1, 72, ANALOG IC,							0.00150	0.01501	1	0.01501	0.	0.0	0.	72
L-B= 0.0015	PI-E=	0.20	PI-Q=	10.00	C1= 0.0016 PI-L= 1.00									
PI-T 0.2422	C2=	0.01												

TOTAL PARTS
FR / MILLION HRS. AT 25 C.
3 UNITS, 1 REQ.
(OPERATIONAL REDUNDANCY)

REDUNDANCY K-FACTOR 0.00ADJ. FAILURE RATE 0.00000

MTRF IN HOURS 799364022000.

LEVEL A, SPEED CONTROL BACK END
PART TYPE CONTRIBUTIONS

		QTY	FR	%
32	C, CS, MTL-C-26655 OR 39003	10	0.00286	3.29
43	R, RN, MII-R10509 OR 55182, FIXED FILM	17	0.02941	33.85
54	DIODES, SILICON	2	0.00940	10.82
57	DIODES, SILICON, ZENER	1	0.01767	20.34
61	TRANSISTORS, NPN, SILICON	5	0.01253	14.42
98	ANALOG IC	1	0.01501	17.27

		36	0.08688	100.00

	NO. OF PARTS	FAILURE RATE	QTY	TOTAL FAILURE RATE
LEVEL 6, SPEED CONTROL				
43800. HRS. LIFE CYCLE				
LEVEL 8, MONOPOLE CONDITIONING	7	0.0695	3	0.0695 *
3 UNITS, 1 REQ. (OPER. REDUNDANCY)				
LEVEL 8, SPEED CONTROL FRONT END	29	0.0007	3	0.0007 *
3 UNITS, 2 REQ. (OPER. REDUNDANCY)				
LEVEL 8, SPEED CONTROL BACK END	36	0.0000	3	0.0000 *
3 UNITS, 1 REQ. (OPER. REDUNDANCY)				
	-----			-----
TOTAL PARTS	216			0.0702

* MEANS REDUNDANCY F.R. USED.

TOTAL FAILURE RATE 0.0702

MTRF IN HOURS 14245033.0

	STRESS RATIO OP TN	ITEM FAILURE RATE	BASE FAILURE RATE	QTY	TOTAL FAILURE RATE	DT C.	RI	CSR RATING	STYLE
R1,R2,RNR60E									
L-B= 0.0017 PI-E= 1.00 PT-Q= 1.00 PI-R= 1.0000	0.20	0.00171	0.00171	2	0.00342	0.	M	0.20	0. RNR60E
R3,R4, RNR60E									
L-B= 0.0017 PI-E= 1.00 PT-Q= 1.00 PI-R= 1.0000	0.20	0.00171	0.00171	2	0.00342	0.	M	0.20	0. RNR60E
R3,R4,RNR60F									
L-B= 0.0017 PI-E= 1.00 PT-Q= 1.00 PI-R= 1.0000	0.20	0.00171	0.00171	2	0.00342	0.	M	0.20	0. RNR60F
R5,R6,RNR60E									
L-B= 0.0017 PI-E= 1.00 PT-Q= 1.00 PI-R= 1.0000	0.20	0.00171	0.00171	2	0.00342	0.	M	0.20	0. RNR60E
R7,R8,RNR60E									
L-B= 0.0017 PI-E= 1.00 PT-Q= 1.00 PI-R= 1.0000	0.20	0.00171	0.00171	2	0.00342	0.	M	0.20	0. RNR60E
R9,R10, RNR60F									
L-B= 0.0017 PI-E= 1.00 PT-Q= 1.00 PI-R= 1.0000	0.20	0.00171	0.00171	2	0.00342	0.	M	0.20	0. RNR60F
C1,C2,CSR13									
L-B= 0.0041 PI-E= 1.00 PT-Q= 1.00 PI-SR 0.0700	0.20	0.00029	0.00029	2	0.00057	0.		0.20	0. CSR13
D1,D2,D3,D4,DIODE									
L-B= 0.0134 PI-F= 1.00 PT-Q= 5.00 PI-A= 1.0000 PI-C= 1.00	0.10	0.00470	0.00470	4	0.01881	0.		0.20	150. DIODE
PT-S 0.7000									
Z1, ANALOG IC,									
L-B= 0.0034 PI-E= 0.20 PT-Q= 10.00 C1= 0.0044 PI-L= 1.00		0.00336	0.03358	1	0.03358	10.		0.0	0. 71
PT-T 0.2422 C2= 0.01									

TOTAL PARTS 19
FR / MILLION HRS. AT 25 C. 0.07348
2 UNITS, 1 REQ.
(OPERATIONAL REDUNDANCY)

REDUNDANCY K-FACTOR 0.00ADJ. FAILURE RATE 0.00024

MTRF IN HOURS 4242156290.

BLANK

LEVEL 4, CARRIER GENERATOR
PART TYPE CONTRIBUTIONS

		QTY	FR	%
32	C, CS, MTL-C-26655 OR 39003	2	0.00057	0.78
43	R, RN, MII-R10509 OR 55182, FIXED FILM	12	0.02052	27.92
54	DIODES, SILICON	4	0.01881	25.60
98	ANALOG IC	1	0.03358	45.70
		-----	-----	-----
		19	0.07348	100.00

LFVFL 6, OVERLOAD CUTOFF

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	STRESS RATIO OR T _N	ITEM FAILURE RATE	BASE FAILURE RATE	QTY	TOTAL FAILURE RATE	DT C.	RL	CSR	RATING	STYLE
R1, RNR60F		0.20	0.00171	0.00171	1	0.00171	0.	M	0.20	0. RNR60F
L-B= 0.0017 PI-F= 1.00 PI-Q= 1.00 PI-R= 1.0000										
R2, RNR60F		0.20	0.00171	0.00171	1	0.00171	0.	M	0.20	0. RNR60F
L-B= 0.0017 PI-E= 1.00 PI-Q= 1.00 PI-R= 1.0000										
R2, RNR60E		0.20	0.00171	0.00171	1	0.00171	0.	M	0.20	0. RNR60E
L-B= 0.0017 PI-F= 1.00 PI-Q= 1.00 PI-R= 1.0000										
R4, RNR60E		0.20	0.00171	0.00171	1	0.00171	0.	M	0.20	0. RNR60E
L-B= 0.0017 PI-F= 1.00 PI-Q= 1.00 PI-R= 1.0000										
R5, RNR60F		0.20	0.00171	0.00171	1	0.00171	0.	M	0.20	0. RNR60F
L-B= 0.0017 PI-E= 1.00 PI-Q= 1.00 PI-R= 1.0000										
R6, RNR60E		0.20	0.00171	0.00171	1	0.00171	0.	M	0.20	0. RNR60E
L-B= 0.0017 PI-F= 1.00 PI-Q= 1.00 PI-R= 1.0000										
D1, DIODE		0.10	0.00470	0.00470	1	0.00470	0.		0.20	150. DIODE
L-B= 0.0134 PI-E= 1.00 PI-Q= 5.00 PI-A= 1.0000 PI-C= 1.00										
PI-S 0.7000										
Z1, DIGITAL IC,			0.00184	0.01836	1	0.01836	0.	0.0		0. 71
L-B= 0.0018 PI-E= 0.20 PI-Q= 10.00 C1= 0.0033 PI-L= 1.00										
PI-T 0.1686 C2= 0.01										

TOTAL PARTS 8
FR / MILLION HRS. AT 25 C. 0.03332
3 UNITS. 2 REQ.
(OPERATIONAL REDUNDANCY)

REDUNDANCY K-FACTOR 0.00ADJ. FAILURE RATE 0.00015

MTBF IN HOURS 6872817660.

LEVEL 6, OVERLOAD CUTOFF
PART TYPE CONTRIBUTIONS

		QTY	FR	%
43	R, RN, MIL-R10509 OR 56182, FIXED FILM	6	0.01026	30.79
54	DIODES, SILICON	1	0.00470	14.11
99	DIGITAL IC	1	0.01836	55.10
		-----	-----	-----
		8	0.03332	100.00

BLANK

	NO. OF PARTS	FAILURE RATE	QTY	TOTAL FAILURE RATE
LEVEL 4. CONTROLS				
43800. HRS. LIFE CYCLE				
LEVEL 4, POWER SUPPLIES	69	0.1004	1	0.1004
LEVEL 4, VOLTAGE REGULATOR EXCITER	118	0.0007	1	0.0007
LEVEL 4, SPEED CONTROL	216	0.0702	1	0.0702
LEVEL 4, CARRIER GENERATOR	19	0.0002	2	0.0002 *
2 UNITS, 1 REQ. (OPER. REDUNDANCY)				
LEVEL 4, OVERLOAD CUTOFF	8	0.0001	3	0.0001 *
3 UNITS, 2 REQ. (OPER. REDUNDANCY)				
	-----			-----
TOTAL PARTS	465			0.1717

* MEANS REDUNDANCY F.R. USED.

TOTAL FAILURE RATE 0.1717

MTRF IN HOURS 5825531.00

LEVEL 4, CONTROLS
PART TYPE CONTRIBUTIONS

		QTY	FR	%
32	C, CS, MTL-C-26655 OR 39003	106	0.00124	0.37
43	R, RN, MTL-R10509 OR 55182, FIXED FILM	205	0.00170	0.51
54	DIODES, SILICON	72	0.00973	2.90
57	DIODES, SILICON, ZENER	14	0.00052	0.16
60	TRANSISTORS, PNP, SILICON	6	0.00022	0.07
61	TRANSISTORS, NPN, SILICON	41	0.00075	0.22
68	COILS, MTL-T-15305	5	0.01072	3.20
72	TRANSFORMERS, MIL-T-2103A	2	0.08983	26.80
92	CONNECTORS	12	0.00012	0.03
98	ANALOG IC	13	0.00108	0.32
99	DIGITAL IC	3	0.00024	0.07
101	MONOPOLES	3	0.20842	62.17
102	PARASITIC BANK	6	0.00069	0.21
111	POWER DISTRIBUTION	1	0.01000	2.98
		-----	-----	-----
		489	0.33525	100.00

APPENDIX IV
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NASA Control Test	1 - 9

1. NASA CONTROL TEST (USING AIR TURBINE DRIVEN GENERATOR)

1.1 Test System Components

The following components were used to conduct the NASA control tests.

- o Adjustable air pressure regulator supply for air turbine.
- o Air turbine drive (lab equipment).
- o Mini-BRU alternator assembly, P/N 2045425-1.
- o NASA speed and voltage control breadboard.
- o User and parasitic load bank.
- o User load bank control.

1.2 Speed Control Open Loop Gains

The NASA Analog Control System has two speed control loops controlling speed by application of alternator parasitic load; they are: an outer loop controlling as a function of BRU speed whose gain is $\frac{\delta P_P}{\delta N_{BRU}}$, and an inner loop controlling as a function of user current

$$\frac{\delta P_P}{\delta I_U}.$$

1.3 BRU Speed Parasitic Load Control

Determination of $\frac{\delta P_P}{\delta N_{BRU}}$ was accomplished using an open loop bench and system tests with the air turbine driven alternator. System test data obtained did not appear as consistent as the bench test data due to transistor switch noise and differences in the three channels speed set point. Therefore bench test data was used in determining

$$\frac{\delta P_P}{\delta N_{BRU}}.$$

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1.4 Bench Test for Determination of $\frac{\partial P}{\partial N}_{BRU}$

A sine wave was introduced into the three-speed converter channels at the monopole input. On-off ratio was measured at the collector of the switching transistor to one parasitic load. Gain for each channel is:

SPEED INPUT o/o N	LOAD RESISTOR ON RATIO
	$\frac{\text{On Time}}{(\text{On} + \text{Off}) \text{ Time}}$
99.27%	0.238
101.21%	0.857

$$\frac{\partial P}{\partial N}_{BRU} = \frac{0.857 - 0.238}{101.21 - 99.27\%} \times \frac{(120)^2}{1} = 353 \text{ watts/percent N}$$

Total gain with three channels is 1059 watts/percent speed (N).

1.5 User Current Parasitic Load Control

User current parasitic load control gain is determined by user load sensor ($\partial V_U / \partial I_U$) gain. Speed signal reset gain of the speed converter ($\partial N_{BRU} / \partial V_U$), and the parasitic load power versus speed gain ($\partial P / \partial N_{BRU}$).

The speed signal reset gain was determined using an open loop bench test (see Figure AIV-1). A millivolt signal was introduced at the "shunt" line and a speed signal sine wave was introduced at the monopole speed input. Speed reset was measured as a function of the shunt millivolt signal. Speed signal reset gain is 0.0387 percent N/millivolt.

User load sensor gain is set by a user load sensor resistor adjustable tap. The gain was measured with the tap set as received from NASA. The measured gain at this point was 1.6 millivolts/ampere.

PARASITIC LOAD CONTROL GAIN TEST BLOCK DIAGRAM

FIGURE A IV-1

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The user current parasitic load gain ($\partial P_P / \partial I_U$) is:

$$\frac{\partial V_U}{\partial I_U} (X) \frac{\partial N_{BRU}}{\partial V_U} (X) \frac{\partial P_P}{\partial N_{BRU}} = \frac{\partial P_P}{\partial I_U}$$

$$\begin{aligned} \text{One channel: } 1.6 \frac{\text{millivolts}}{\text{ampere}} (X) 0.387 \frac{N\%}{\text{millivolts}} (X) 353 \frac{\text{watts}}{\%N} \\ = 21.86 \frac{\text{watts}}{\text{ampere}} \end{aligned}$$

$$\text{Three channels: } \frac{\partial P_P}{\partial I_U} = 65.57 \frac{\text{watts}}{\text{ampere}}$$

1.6 Voltage Regulator Gain

Voltage regulator gain was measured by an open loop bench test. A variable dc power supply was connected to the dc buss. The on-off ratio to the field was measured at the field drive transistor collectors. Gain was determined by the difference of time on-off to user voltage ratio. Gain was determined to be 2 amperes/volts. Regulator gain is adequate, as shown on Figure AIV-2.

1.7 Ripple Noise On User Buss

User buss ripple is 4 volts peak-to-peak from zero to full user load and is predominately a 1400 Hz, repetitive wave. The 1400 Hz is considered caused by user filter ringing. The user filter, when considered as a second order filter, has a damping ratio (at full load) of 0.06 and a ω_n of 1300 Hz. The same ringing was also observed on the analog computer with the NASA filter programmed as the user buss filter. Therefore, the ripple value will depend on the final filter design selected.

VOLTAGE REGULATION

FIGURE A IV-2

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1.8 Closed Loop Speed Control Test

Speed control as a function of user load is shown on Figure AIV-3. Total speed deviation is 0.5 percent. Total power set point at 100 percent speed is 1650 watts. The power set point is set in each of 3-speed control channels with each controlling a separate parasitic load resistor. Any two channels are capable of applying alternator full rated load. Control range of each channel is approximately 2 percent of 100 percent speed. On Figure AIV-3, Curve A, the power decreases rapidly after 1600 watts and went to overspeed when more than an 1800 watt load was applied. In Curve B, the alternator went to overspeed when an 1800 watt load was applied. These power levels exceed the 2 HSA requirements with margin.

1.9 Voltage Regulation

Output voltage as a function of user load is shown on Figure AIV-2. Voltage regulation is within ± 0.1 percent from 0 to 1650 watts.

1.10 Transient Response

User voltage transient response measured at the user buss with application of 0 to 800 watt user load transient is 1.5 volts. Transient response for the 800 to 0 watt load transient is 8 volts. Figure AIV-4 shows a trace of transient response. Ringing on load removal is considered to be caused by filter ringing.

1.11 Power Transistor and Diode Temperatures

The power transistor and diode temperatures are as follows:

- o Voltage regulator driver transistors - 105°F at 77°F room temperature

BRU SPEED DROOP

FIGURE A IV-3

USER VOLTAGE TRANSIENT RESPONSE

FIGURE A IV-4

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- o Parasitic driver transistors - 117°F at 77°F room temperature
- o Power rectifiers - 93°F at 13 amperes load current at 77°F room temperature

1.12 General Observations

The following general observations were noted:

- o Circuit cards were constructed with carbon resistors throughout, causing some temperature drift. For example, the speed buss drifted 1.2 volts during a one minute warm up.
- o Difficulty was encountered in setting the power level/speed set point on the three-speed channels.
- o Discrepancies were noted between schematic diagrams and the wired breadboard control. Example: a 0.5 uf capacitor and 22K ohm resistor in feedback series around the VR preamp is shown with the 22K resistor connected to a common buss to the field drivers, forming a lag-lead (0.5 second lag). This would cause an instability. In reality, the 22K ohm resistor is connected to the output of the 741 operational amplifier.