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DEVELOPMENT OF AN ALTERNATING-CURRENT VOLTAGE MONITOR, EXPANDED SCALE, FOR SPACECRAFT INSTRUMENTATION SYSTEMS

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DEVELOPMENT OF AN ALTERNATING-CURRENT VOLTAGE MONITOR, EXPANDED SCALE, FOR SPACECRAFT INSTRUMENTATION SYSTEMS

PART 1 - INTRODUCTION

The purpose of this document is to present a discussion of the development of the alternating-current (AC) voltage monitor with an expanded scale, Engineered Magnetics Model EMSE-124, and a description of the circuit and its operation. Using standard components, this device combines small size, light weight, and low power consumption with excellent stability, linearity, and low noise under extreme environmental conditions. This is presently being used in Apollo/Lunar Module Spacecraft Instrumentation Systems.

1. DESCRIPTION

The EMSE-124 voltage monitor is a miniature expanded-scale AC-to-DC voltage converter of conventional-component, welded-module construction. It is contained in a 4.6-cubic-inch case. The unit was developed for NASA by Gulton Industries, Engineered Magnetics Division, under NASA Contract NAS 9-2524. The voltage monitor has been evaluated by the Instrumentation and Electronic Systems Division (IESD) of the Manned Spacecraft Center and has met all the performance specifications listed in Table 1 and the Environmental Specifications of the IESD listed in Appendix A (based on Environmental Specification IESD 19-1B developed by MSC). A schematic and instructions for connecting the unit are shown in Figure 1.

TABLE 1. SPECIFICATIONS OF THE EMSE-124 VOLTAGE MONITOR

Function	Value
Input supply voltage	28 VDC nominal (24 to 32 VDC)
Input supply ripple	4 V p-p maximum (DC to 2 KHz square wave)
Input transient	±15 V, 20 msec base width, 8 msec rise time
Feedback to input supply	30 mV p-p maximum with source impedance 1 ohm
Input supply polarity reversal	Unit internally protected
Input supply undervoltage	To 22 VDC with 10-percent maximum degraded unit performance
AC supply voltage	115/200 V, 3 phase, 400 or 800 Hz ±10 percent ungrounded wye (for calibration only)
Input signal	0 to 150 V rms, 400 to 3200 Hz ±10 percent
Input impedance	50 000 ohms or greater, 400 to 3200 Hz ±10 ±10 percent
Output signal	0 to +5 V
Output impedance	1000 ohms or less
Conversion gain	Adjustable from 0 (lower limit) to +5 V (upper limit) for the following inputs; 20 V rms lower limit and 30 V rms upper limit, to 100 V rms lower limit and 150 V rms upper limit (selected by jumpers)
Frequency response	Gain within ±1 percent of the DC value from DC to 10 Hz
Output signal ripple	25 mV p-p, DC to 15 MHz

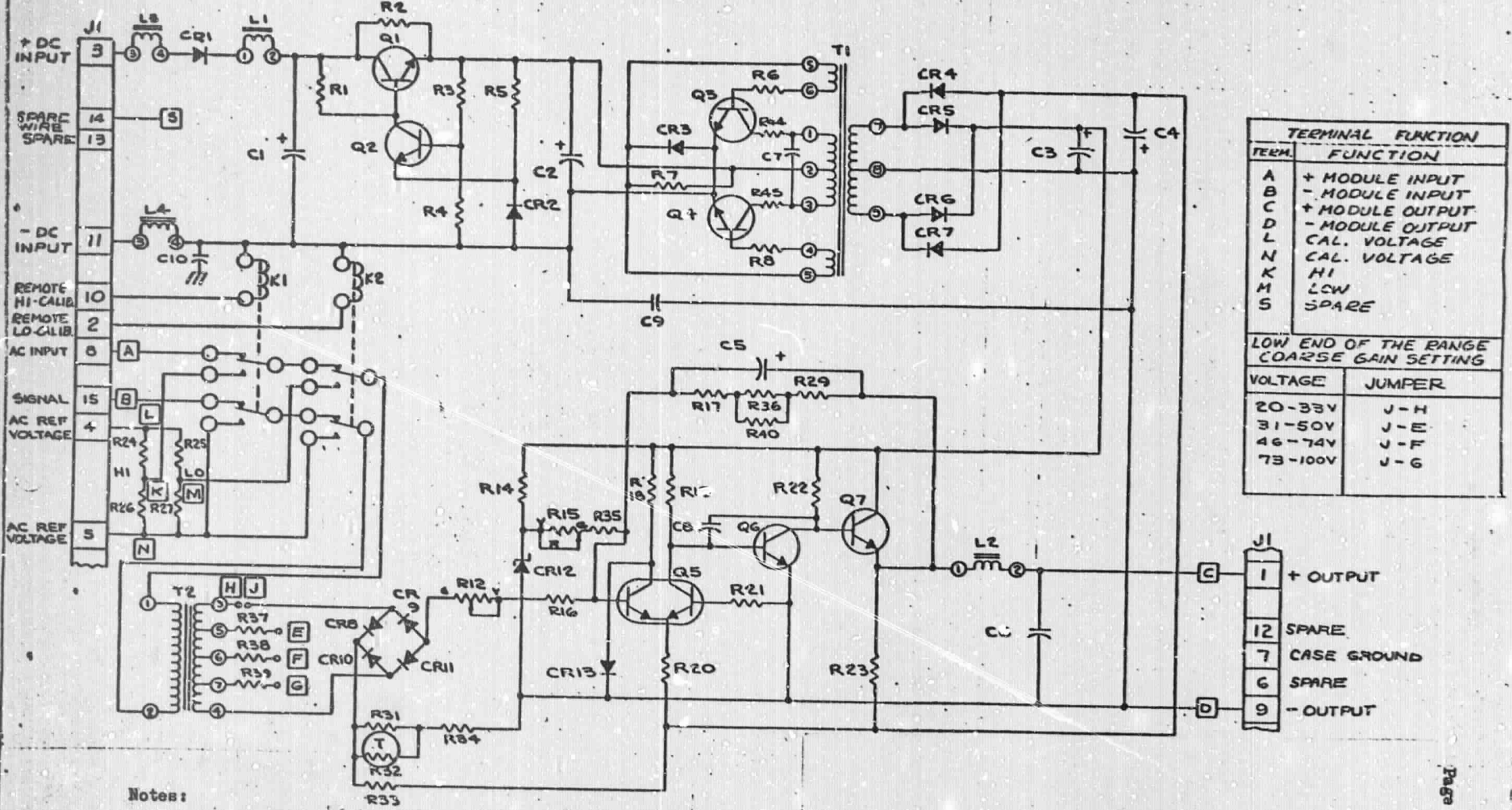
TABLE 1. SPECIFICATIONS OF THE EMSE-124 VOLTAGE MONITOR (CONT'D)

Function	Value
Warmup time	15 minutes maximum
Linearity	±12.5 mV of a straight line between 0 (lower limit) and +5 V (upper limit)
Conversion gain stability	0.75 percent maximum
Power consumption	50-mA maximum with DC input supply voltage, 1-mA maximum with AC supply voltage
Common-mode rejection	100 dB or more for balanced or unbalanced input lines (400 ohms maximum resistance) for frequencies from DC to 1000 Hz and voltages of +5 to -5 V
Weight	6 ounces maximum
Volume	4.6 cubic inches

2. GENERAL

The Development Flight Instrumentation Systems for the LM program was allotted a minimum of weight, power and volume when compared to the numbers and characteristics of the measurements required to be transmitted.

Many components used on previous programs did not meet the requirements of the LM program because of their size, weight, power and environmental limitations. The AC voltage monitor fell into this category thus making it necessary to completely redesign this component.



TERMINAL FUNCTION	
TERM.	FUNCTION
A	+ MODULE INPUT
B	- MODULE INPUT
C	+ MODULE OUTPUT
D	- MODULE OUTPUT
L	CAL. VOLTAGE
N	CAL. VOLTAGE
K	HI
M	LOW
S	SPARE

LOW END OF THE RANGE COARSE GAIN SETTING	
VOLTAGE	JUMPER
20-33V	J-H
31-50V	J-E
46-74V	J-F
73-100V	J-G

Notes:

1. Last component designator used: C10 CR13, J1, K2, L4, Q7, R45, T2.
2. Not used component designators: R9, 10, 11, 13, 26, 30, 41, 42, 43.
3. Letters in squares ([A]) Denote Terminal Function.

POT	FUNCTION
R15	ZERO CONTROL
R12	FINE CONTROL

Figure 1. Schematic Diagram of AC Voltage Monitor

DEVELOPMENT OF AN ALTERNATING-CURRENT VOLTAGE MONITOR, EXPANDED SCALE, FOR SPACECRAFT INSTRUMENTATION SYSTEMS

PART 2 - ALTERNATING-CURRENT VOLTAGE MONITOR

1. GENERAL

The EMSE-124 expanded-scale AC voltage monitor provides a 0- to 5-VDC analog output which is zero at two-thirds full-scale AC signal input and plus 5 VDC at full-scale AC signal input. Range adjustment permits the 0-VDC output to be generated for any input from 20 to 100 V (the corresponding 5-VDC output points are 30 to 150 V) at frequencies of 400 to 3200 Hz. Accuracy specification of the unit is such that an AC voltage can be monitored to 0.25 percent of its full-scale value. A functional block diagram of the unit is shown in Figure 2.

The DC-to-DC converter is of routine design consisting of a series regulator and a saturating transformer oscillator and rectifier. The converter isolates the output from the DC bus which supplies power to the unit and regulates the positive and negative DC voltages for the operational amplifier.

The input AC signal voltage is transformer-coupled to a four-diode rectifier. Taps on the secondary of the input transformer, in conjunction with a 50-kilo-ohm potentiometer, are used to meet the gain-range requirements. Compensation was needed because temperature change produced fluctuation in the rectifier diode voltage drop and winding resistance in the input transformer.

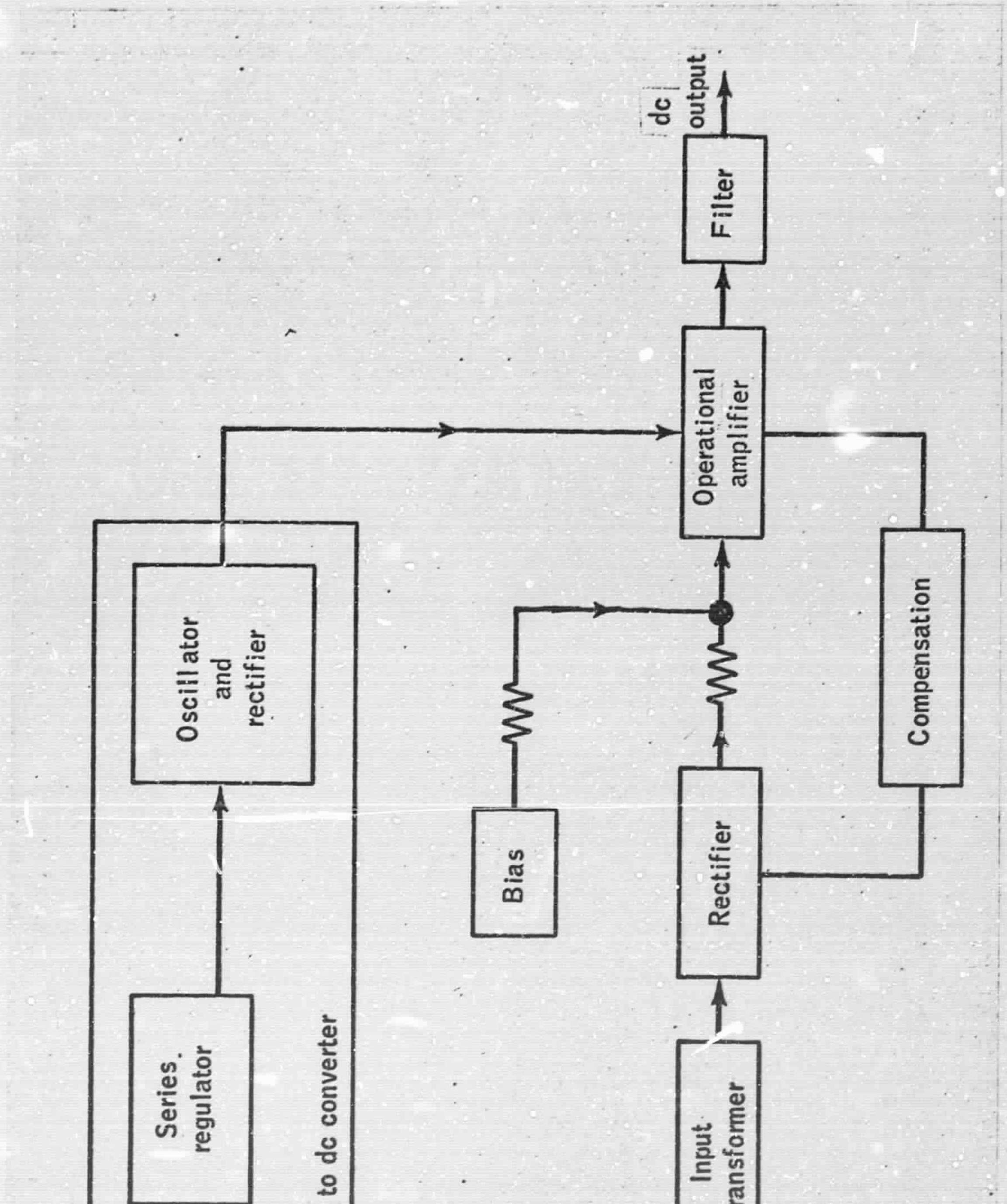


Figure 2. Functional Block Diagram of AC Voltage Monitor

The full-wave rectified AC output is connected to the summing junction of the operational amplifier where a bias current (opposite in polarity to the rectified AC voltage) is added to get 0.00-VDC output at the desired value of the AC input. Shunt capacity across the amplifier feedback resistor provides filtering. The operational amplifier provides the necessary power gain to achieve low-output impedance. A two-pole filter provides the remainder of the desired output ripple reduction and calibration-checking relays and a terminal board permit calibration and coarse-gain selection.

2. DESIGN CONSIDERATIONS AND CIRCUIT OPERATION

The large input transformer is necessary to maintain 150 V at 360 Hz. The transformer has a turns ratio of 1:1 for a 20- to 30-V input and taps for use with higher-level inputs. The output of the transformer is rectified and the pulsating DC is applied through a variable "summing resistor" to the input of the operational amplifier. The only important sources of error are found in the input transformer and rectifier.

2.1 Amplifier Error Analysis

Errors in the transformer-rectifier are introduced because both the series copper resistance and the diode forward drop are appreciable and temperature-sensitive. To facilitate correction of these errors, the circuit was arranged so that the input current is constant for any output, regardless of transformer tap or potentiometer setting. Thus, the input impedance is minimum at the 20- to 30-V setting and higher for greater inputs. The "constant" current feature results in easy compensation for diode instability because one compensation is correct for all ranges. Copper resistance change is 0.5 percent of full-scale input in the most extreme case and is compensated to appear the same for all conditions of gain adjustment. The constant current provision results in a temperature dependence which is not related to gain setting. These errors are present in the rectified input before scale expansion and must, therefore, be reduced to less than the specification of 0.25 percent of full-scale input.

2.2 Operational Amplifier

A simplified circuit diagram of the operational amplifier is shown in Figure 3.

The feedback resistor (R_f) is adjusted for the proper value of conversion gain. A small capacitor across the feedback resistor keeps the amplifier in its linear region, despite the large pulsations present, and helps to reduce the output ripple.

The two basic equations which govern the design are as follows:

a. The loop gain on the amplifier must be much greater than one to establish linearity and independence of transistor parameters. In the design, AB equals 5000 which shows an 0.02 percent gain departure from the ratio of the resistors, and an 0.0033-percent maximum temperature dependence. Because these errors are introduced after the scale expansion, their importance is relative to a 0.75-percent specification, hence negligible.

b. The second equation is $\frac{E_{in}}{R_{in}} + \frac{E_{bias}}{R_b} = \frac{E_{out}}{R_f}$.

For 0.00 VDC, $\frac{E_{in}}{R_{in}} = \frac{E_{bias}}{R_b}$;

Therefore, $E_{bias} = \frac{R_b(E_{in})}{R_{in}}$.

By adjusting R_b, the scale expansion is determined, that is, the voltage above which the output voltage rises with the input

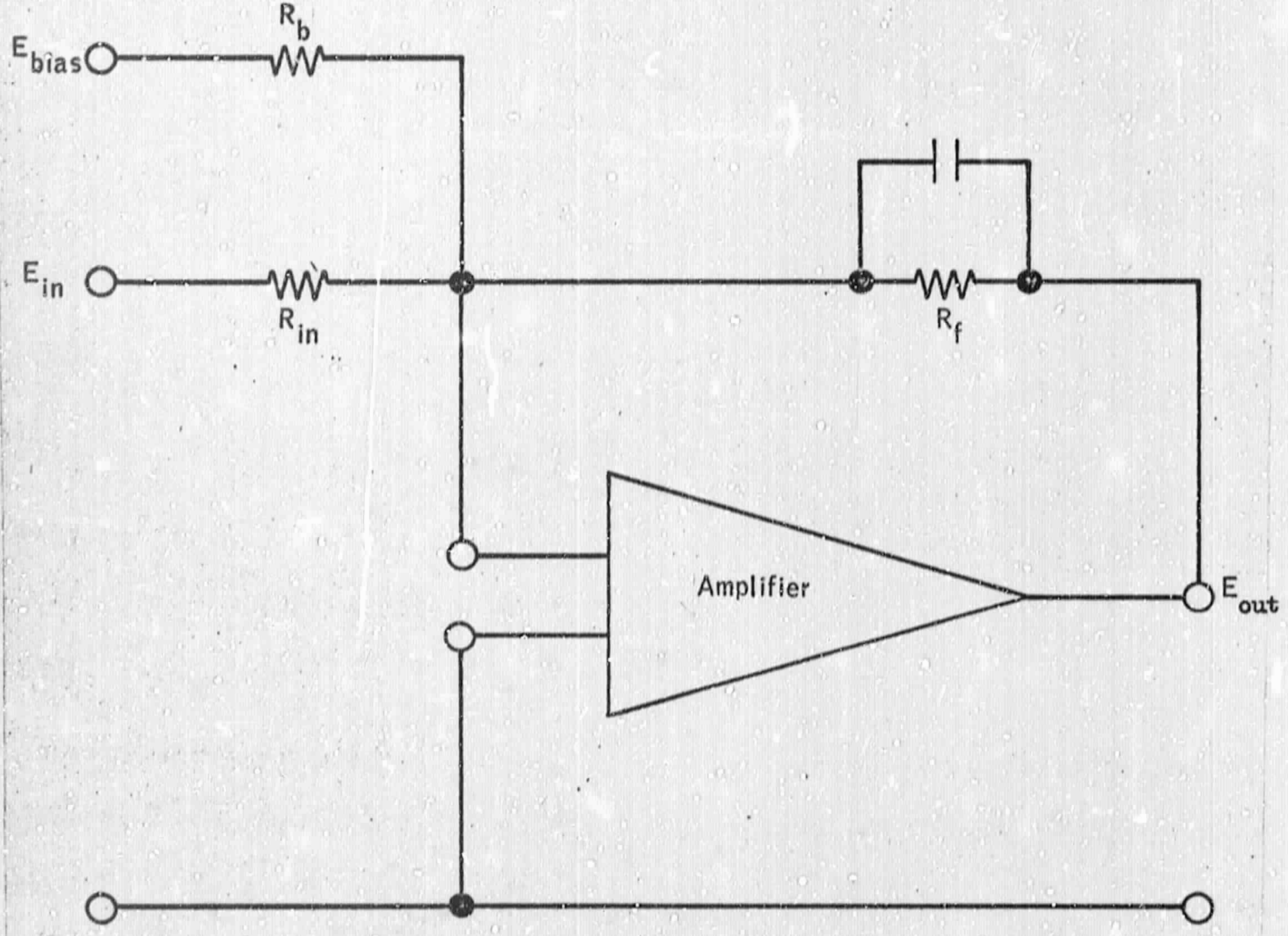


Figure 3. Simplified Circuit of Operational Amplifier

voltage. The conversion gain is the ratio of the feedback resistor to the input resistance.

$$-\frac{(E_{in} + F_{in})}{R_{in}} + \frac{E_{bias}}{R_b} = \frac{E_{out} + E_{out}}{R_f}$$

Since $E_{out} = 0$

when $\frac{E_{in}}{R_{in}} = \frac{E_{bias}}{R_b}$,

therefore, $E_{out} = \frac{R_f(E_{in})}{R_{in}}$

above $E_{in} = \frac{R_{in}}{R_b} E_{bias}$.

There is an emitter-follower stage at the output of the operational amplifier for low output impedance.

3. PACKAGING AND MECHANICAL CONSIDERATIONS

Although most internal wiring is resistance-welded, some interconnections are made of stranded copper wire. Solid coating of the finished unit protects it from severe environmental conditions. The glass bead and silicone rubber coating is light in weight, moisture resistant, and able to withstand thermal shock conditions. Welded-module construction permits more components to be placed in a small space and is easy to manufacture and test.

4. ELECTROMAGNETIC INTERFERENCE (EMI) CONTROL PLAN

The EMSE-124 AC voltage monitor is designed to minimize effects of electrointerference. The following design considerations assure compliance with interference requirements.

For minimum conducted and radiated interference:

- Careful component selection and design will reduce transistor and diode switching which causes current spikes.
- Minimize wire length to prevent capacitance coupling caused by fast-switching voltages.
- No shielding is used for this purpose.
- Utilize inductance-capacitance (L-C) networks for suppression of the remaining interference.

Audio susceptibility is reduced by series L and series regulator at power input.

5. DESIGN AND TEST PROBLEMS

5.1 Temperature Fluctuation

Temperature fluctuation caused packaging difficulty. The compensation discussed previously is dependent on the equality of temperatures of the temperature-sensitive and compensating components. Temperature fluctuation made test duplication impossible. A certain amount of apparent "nonrepeat" was caused by the relatively long thermal time constant of the potted assembly. Apparent nonrepeat was also caused by meter uncertainties. The package design was revised to reduce temperature fluctuation.

Efforts were made to evaluate the precision with which measurements could be made. It could not be determined whether inaccuracies of amplitude measurements were attributable to the measuring instrument or to the unit.

Note

> Amplitude fluctuation at the time of measurement could complicate the measurement or appear as instability of the unit.

For example, 0.1 percent of instability or nonrepeat in the AC amplitude measurement at a 30-V root-mean-square (rms) level would indicate a 17-mV change at the output. A change of 17-mV is 45 percent of the gain stability limit. This type of change commonly occurs during the temperature stability testing. More than 10 percent of the allowable gain stability limit or 0.02 percent of the AC reading was undesirable for use as the possible measurement error.

5.2 AC Source Considerations

Initially, a Hewlett-Packard oscillator Model 200CD was used as an AC source. A Non-Linear Systems Model 125B AC-to-DC converter in conjunction with a Model 481 digital voltmeter was used to measure the AC input signal. Because the Hewlett-Packard Model 200DC amplitude stability (1-minute duration) was completely inadequate, it was replaced by a Hewlett-Packard Model 651A oscillator which has ±0.1-percent amplitude stability for a period of 17 hours. Because this model has almost no amplitude fluctuation during a 1/2 to 1 minute period (the time required to take a reading), the Hewlett-Packard Model 651A oscillator was considered adequate.

5.3 Voltmeter Evaluation

Two AC voltmeters were evaluated at 20 V AC and 400 Hz.

a. The Non-Linear Systems AC voltmeter (consisting of an AC-to-DC converter, Model 125B, and a digital voltmeter, Model 481) has a four-digit display. Because the last digit consists of a minimum of 10 millivolt steps, it displays 0.05 percent of 20-V rms uncertainty. The specified stability of the AC-to-DC converter in conjunction with the digital voltmeter is 0.37 percent of the reading. The evaluated stability at 20 V AC and 400 Hz, wher checked with a Holt Model 613R AC standard, was 0.15 percent. Thus, the instrument did not meet stability requirements.

b. The Ballantine-true rms voltmeter, Model 350, has a four-digit display, and a resolution of 0.05 percent of 20 V rms. Readings were taken every 15 minutes for 6 hours on a Holt Model 613R AC standard. The meter met the Holt short-term stability standard of 0.05 percent. The sensitivity of the Ballantine's null of the second voltmeter at 400 Hz is not well defined.

5.4 EMSE-124 AC Voltage Monitor

The Ballantine was found suitable for initial setting of the EMSE-124 AC voltage monitor. The tolerance for the initial setting of the voltage monitor includes the instability and uncertainty of the null setting existing in the Ballantine. This uncertainty could not be tolerated during temperature stability tests where the tight gain specification prohibits any measurement error.

An EMSE-124 AC voltage monitor was to be used as a reference or input measuring device during temperature stability testing, if it met the requirements of sensitivity, resolution, and stability.

The sensitivity and resolution of the EMSE-124 AC voltage monitor was determined by changing the amplitude of the AC input signal and measuring the DC output. A 2-mV change in the AC signal registered a 1-mV change at the output. The resolution of the EMSE-124 AC voltage monitor is limited by the instrument used to measure the output. A Fluke differential voltmeter with a resolution of 0.001 percent of 20 V rms was the measuring instrument.

Evaluation of the monitor's absolute stability presented an intricate problem because the stability figure sought was better than the stability or resolution of available AC measuring instruments.

Three EMSE-124 AC voltage monitor units were monitored with the Ballantine; readings were taken several times a day during a 100-hour test. The EMSE-124 AC voltage monitor units were as stable as the Ballantine. Drift during the allowable 15-minute warmup period was less than 5 mV. Thus, the stability and resolution of the EMSE-124 AC voltage monitor was better than any AC instruments available at Engineered Magnetics.

To improve accuracy, an EMSE-124 AC voltage monitor unit was used during the acceptance-testing of other EMSE-124 AC voltage monitor units as a reference for AC measurements used in conjunction with the Ballantine voltmeter.

Temperature transient performance was checked because temperature compensation was required. A test was conducted and data recorded. The rate of temperature change was 20 degrees F per minute. The change in output voltage was 20 mV during temperature transient.

Package size limitations posed a design difficulty. A thin-wall case became necessary despite the use of space-saving welded interconnects in modular construction. The case is thickened at the corners around the mounting holes for adequate rigidity. Two of these corners also serve as a backing against which the gasket behind the removable cover plate is compressed. This compressible gasket seals the terminal-board area against moisture. The terminal-board carries printed wiring to interconnect some of its pins. The printed wiring is double-sized for increased reliability.

With a thin-wall case it is not feasible to use an O-ring against humidity penetration. The unit was sealed with a bonding-type silicone rubber coating. This compound is used to form a sealing gasket which adheres to the bulk case and to the case interfaces at the connector and the corners and the edges of the package. The coating material, Emerson & Cuming ECCO-SIL 4640, is a lightweight silicone rubber mixture containing glass microballoons.

6. CONCLUDING REMARKS

Electrical tests indicate that the EMSE-124 meets required specifications. In all of the tests, the measured values were less than the maximum allowable deviation. Figure 4 is a graphic presentation of the average test values obtained from five units.

Test results indicate that this unit is virtually insensitive to the mechanical environment levels (vibration, shock, and acceleration) imposed by the specification.

The drift characteristics measured during temperature, altitude, oxygen and humidity, and salt fog environments were within specification requirements.

Performance tests for electromagnetic interference indicate that the design complies with the requirements of MIL-I-2600, MSC-EMI-10A, and MSC/IESD 19-3.

In reducing weight by 70 percent and volume by 75 percent, the design of the EMSE-124 represents a significant improvement over previous devices of this type.

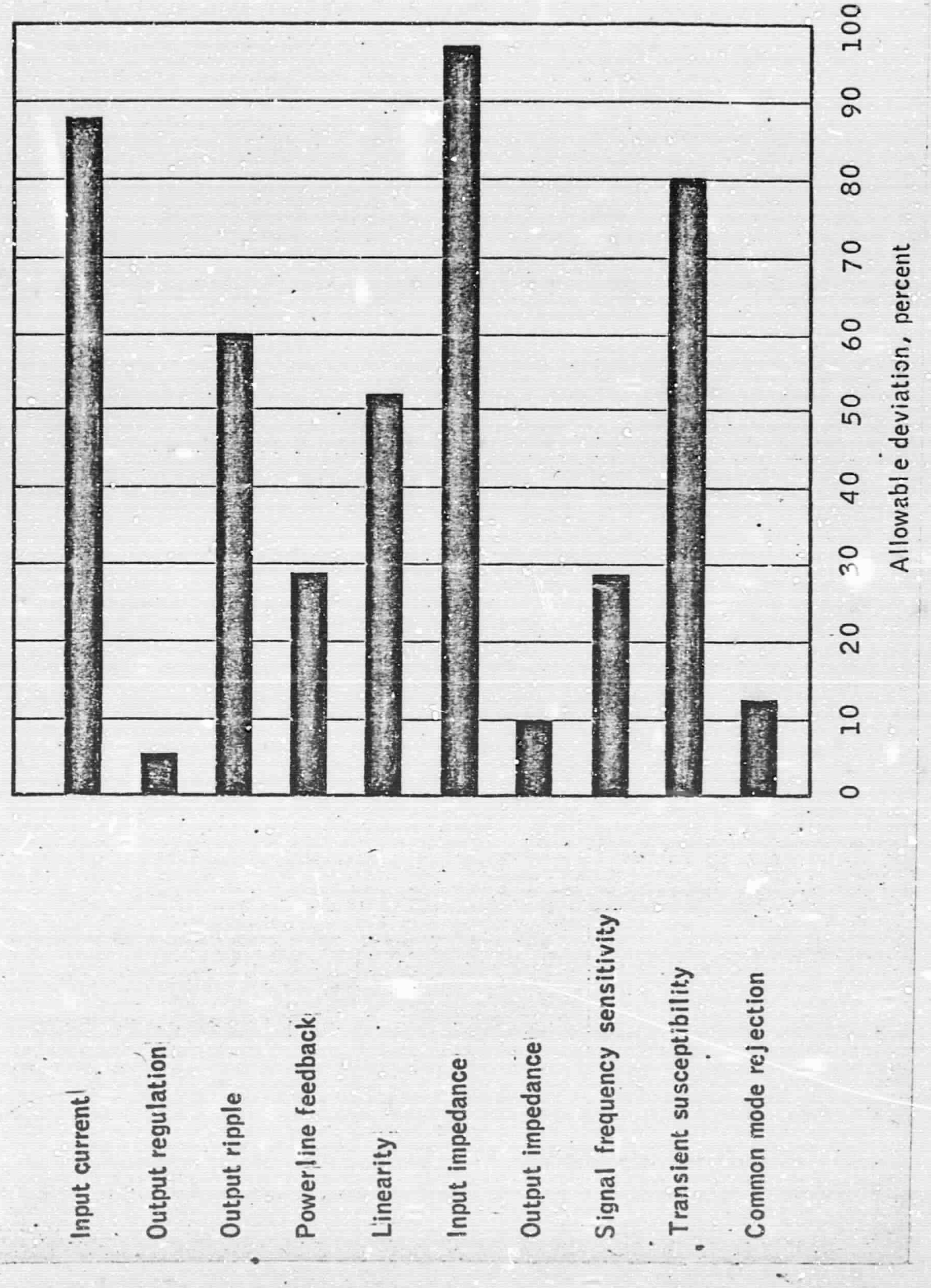


Figure 4. Average Test Values From Five Units

APPENDIX A

Environmental Specifications

APPENDIX A - ENVIRONMENTAL SPECIFICATIONS

The information contained in this appendix is based on Environmental Specification MSC/IESD 19-1B (April 1, 1965), developed by MSC.

1. SCOPE

This specification covers:

- Vibration
- Acceleration
- Acoustics
- Temperature
- Humidity
- Vacuum
- Shock
- Salt Fog
- Oxygen
- Sand and Dust
- Fungus
- Hazardous Gases
- Electrical Requirements

Note

Conduct tests in sequence listed if facilities permit.

2. REQUIREMENTS

2.1 Vibration (random and sinusoidal to be used sequentially)

Random and sinusoidal motion shall be applied sequentially along each of three mutually perpendicular axes for 36 minutes. Random spectra are referenced to a log-log plot and held to a ±30 percent power spectral density. The component shall be operative and monitored throughout test.

12.3g root mean square (rms) for 5 minutes

10 cps, 0.01 g^2/cps

10-75 cps, linear increase to 0.14 g^2/cps

75-200 cps, constant 0.14 g^2/cps

200-2000 cps, linear decrease to 0.05 g^2/cps

5g rms for 25 minutes

10 cps, 0.0017 g^2/cps

10-75 cps, linear increase to 0.023 g^2/cps

75-200 cps, constant 0.023 g^2/cps

200-2000 cps, linear decrease 0.0082 g^2/cps

Sinusoidal motion shall be swept logarithmically from 5 cps to 2 kc to 5 cps in 6 minutes in each of the three mutually perpendicular axes. The component shall be operative and monitored thoughout the test.

5-10 cps, constant 0.20 in double amplitude (D.A.)

10-26 cps, constant ±1g

26-56 cps, constant 0.03 in D.A.

56-2000 cps, constant ±5g

2.2 Acceleration

The component shall be subjected to 20g for a time duration of 10 minutes minimum in each direction of three mutually perpendicular axes including whatever time is required to make a functional test. The component is not to be subjected to greater than 20g while increasing or decreasing to test level. The component shall be monitored at all times.

2.3 Acoustic Noise

Components shall be subjected to 165 ±1 dB random noise referenced to 0.0002 dynes/cm^2 for a period of 15 minutes. Octave bands (center frequencies) will be held to ±3 dB. Components shall be monitored at all times.

Octave Band, cps	Sound Pressure Level, dB
22.4 to 45	157
45 to 90	160
90 to 180	159
180 to 355	158
355 to 710	156

Octave Band, cps	Sound Pressure Level, dB
710 to 1400	151
1400 to 2800	145
2800 to 5600	139
5600 to 11200	133

Overall 165 dB

2.4 Temperature (at atmospheric pressure, -65° to +160°F)

The following steps shall be followed during the 5-day temperature cycle. The component shall be mounted in the chamber in a manner which ensures adequate circulation around all surfaces.

a. Reduce temperature to -65°F and soak for 4 hours ±15 minutes. The component shall be in a deenergized condition. No operational check is required.

b. Increase temperature to 100 ±5°F in 30 ±10 minutes. Energize and soak for 4 hours Conduct an operational test. Record time, temperature, and data; deenergize equipment.

c. Increase temperature to 160 ±5°F in 15 ±5 minutes and soak for 24 ±1 hours. Energize components during the last 30 minutes; conduct an operational test. Record time, temperature, and data; deenergize component.

d. Decrease temperature to 0 ±5°F in 15 ±5 minutes and soak for 24 ±1 hours. Energize component during the last 30 minutes; conduct an operational test. Record time, temperature, and data; deenergize equipment.

e. Continue cycling as in steps c and d except with component energized during the last 36 hours. Conduct an operational check at room ambient temperature at conclusion. Record temperature, time, and data. The Time-Temperature table for energizing is as follows:

Hours	4	4	24	24	24	24	24
Temp, °F	-65	+100	+160	0	+160	0	+160
Energized	no	yes	30 min	30 min	30 min	12 hr	yes

2.5 Humidity

One hundred percent humidity including condensation for 5 days in a temperature range of 80 to 160°F. Temperature cycling shall be maintained as in MIL-STD-810 (USAF) Method 507. The component shall be operative during last 30 minutes.

2.6 Altitude

a. Stratosphere-ionosphere environments

Ambient pressure to 100,000 + 10,000 feet or -0 feet, equivalent pressure in 2.5 + 0 minutes or -0.5 minute; continue to 200,000 + 50,000 feet or -0 feet, and hold for 30 minutes. The component shall be operative.

b. Deep space environment

Nominal 5 days at 1 X 10^{-6} mm Hg pressure or less for 5 days. The components shall be operative 2 hours each 24-hour period.

2.7 Shock

Shock impulses at 30g for 11 ±1 msec. There shall be 3 shocks in each direction of three mutually perpendicular axes for a total of 18 shock impulses. Shock input will be a saw-toothed waveform with 10 ±1-msec rise and 1 ±1-msec decay time. The component shall be operating during test.

2.8 Salt Fog

As in MIL-STD-810 (USAF) Method 509 (equivalent to spray or 5-percent salt solution in water for 50 hours).

2.9 Oxygen Atmosphere

One hundred percent atmosphere at 5 PSIA for not less than 5 days. The component shall be operative 10 minutes each 24-hour period.

2.10 Sand and Dust

Sand and dust are such as encountered in desert and ocean beach areas (equivalent to 140-mesh silica flour with a particle velocity up to 500 feet per minute) and as described in MIL-STD-810 (USAF) Method 510.

2.11 Fungus

The fungus test will be conducted as specified in MIL-STD-810 (USAF) Method 508 on components containing nutrient materials. Whenever possible, fungus resistant materials as defined in MIL-E-5400 should be used.

2.12 Hazardous Gases

In the event of a short circuit, the nonmetallic materials shall not give off products that are deleterious to the astronaut at the temperature at which the material fuses.

At low pressure and/or high temperatures, there shall be no outgassing containing nauseous, toxic, or harmful components such as carbon dioxide, carbon monoxide, hydrogen sulfide, sulfur dioxide, methane, indole, skatole, mercaptans, ozone, and similar compounds which shall result in decreased performance capabilities of the astronaut.

2.13 Electrical Requirements

Operating voltage shall be 28 ±4 VDC. No damage will occur to the component with a constant input voltage of 37 VDC for 10 minutes. The component output data shall not vary over ±1 percent during application of four-volt peak-to-peak ripple (DC to 2 KC square wave), imposed on the 28-V bus. The component shall operate with less than 10-percent performance degradation with the input voltage between 22 and 24 VDC.

The transient susceptibility test shall be performed as described in this paragraph. The components shall survive a minimum of 10 negative 28-V pulses and 10 positive 15-V pulses with a rise time of

8 msec or less, a time base of 20 msec, and at a random pulse repetition frequency. This pulse will be applied to the input bus with the component operating at 28 VDC.

Feedback ripple shall be measured across a 1-ohm resistance inserted in series with the power source and will be less than the following values:

a. 30 mV peak-to-peak for any component drawing less than 1 ampere of current at 28 V

b. 100 mV peak-to-peak for a component drawing between 1 to 3.5 ampere of current at 28 V

c. 150 mV peak-to-peak for a component drawing between 3.5 to 8 ampere of current at 28 V

Reverse polarity of input power for 10 minutes shall not damage component. Isolation resistance between primary power input and signal output shall exceed 20 M-ohm at 100 VDC.

2.14 Design and Testing

Components shall be designed and tested in accordance with MIL-I-26600/MSC-EMI-10A.