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CRUISE MISSILE POWER SYSTEM

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Aeropropulsion Laboratory
Air Force Wright Aeronautical Laboratories
Air Force System Command
Wright-Patterson Air Force Base, Ohio 45433-6563

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The program was for design and development of an exploratory advanced generator and control unit which would have an improved energy density over present day components. This generator was to be applied to cruise missiles which might be operational in the next 10 to 20 years with higher power loads. Loads were analyzed for future cruise missile missions. The prototype generator and control unit were fabricated and tested to verify the design and the analysis. Concepts reviewed were: mounting the generator and control unit internally on the engine rotor shaft and on the accessory pad, as in the

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present cruise missile. Because of cooling difficulties, the generator of the size selected could not be integrated in the shaft of any conceived engine size. Thus, the provision is for accessory pad mounting. The weight of the generator and control unit is 27.75 pounds and 227 cubic inches for a 5kW rating.

FOREWORD

This technical report covers work performed under Contract F33615-81-C-2057 with the Aeropropulsion Laboratory, Air Force Wright Aeronautical Laboratory, Air Force Systems Command, Wright Patterson Air Force Base, Ohio. The work was performed by the Electrical Power Systems Technology Organization in the Boeing Aerospace Company. Work described herein covers the period from September 1981 - October 1984.

Included in this document is the description of the design, analysis, fabrication, and test of an advanced generator and control unit for an undefined future cruise missile. The generator will not be flight qualified because the cooling design was required to be modified in order to obtain data on the parameters for the cooling effectiveness.

The Boeing Program Manager was Sidney W. Silverman, and the technical leaders were Joseph M. Voss for Tasks I and II, and William G. Dunbar for Task III.

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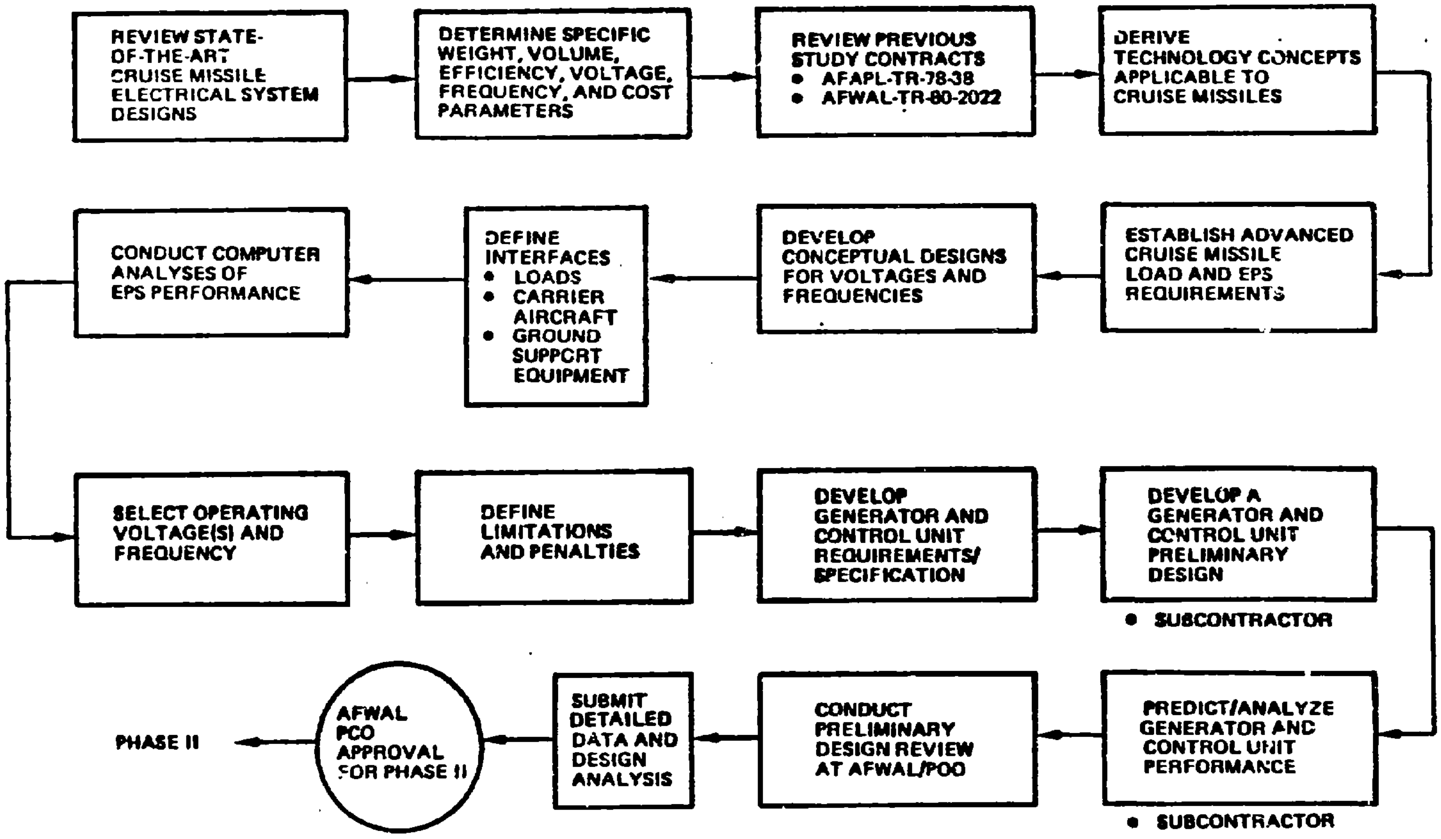
SECTION I
INTRODUCTION

This program was undertaken to develop an advanced generator and control unit for application to advanced cruise missiles. The objective of the development work was to improve the energy density (weight and volume) over the present state-of-the-art of missile generators and controls. Although an advanced cruise missile was not identified for application, the size of the generator was to be established by estimating what loads might be anticipated in future cruise missiles. Present day cruise missiles are in the range of 3.5kW and may be mounted in different locations in different missiles.

The AGM-86B, Boeing Air-Launched Cruise Missile, has the 3.5kW generator mounted on the engine accessory pad where it is cooled by ram air. For the advanced cruise missile the application of samarium cobalt magnetics and a miniaturized semiconductor electronic controller, plus mounting of the generator within the engine shaft and eliminating the accessory pad would be an approach for reduction of electrical system per unit weight and volume, if all the parameters could be achieved simultaneously.

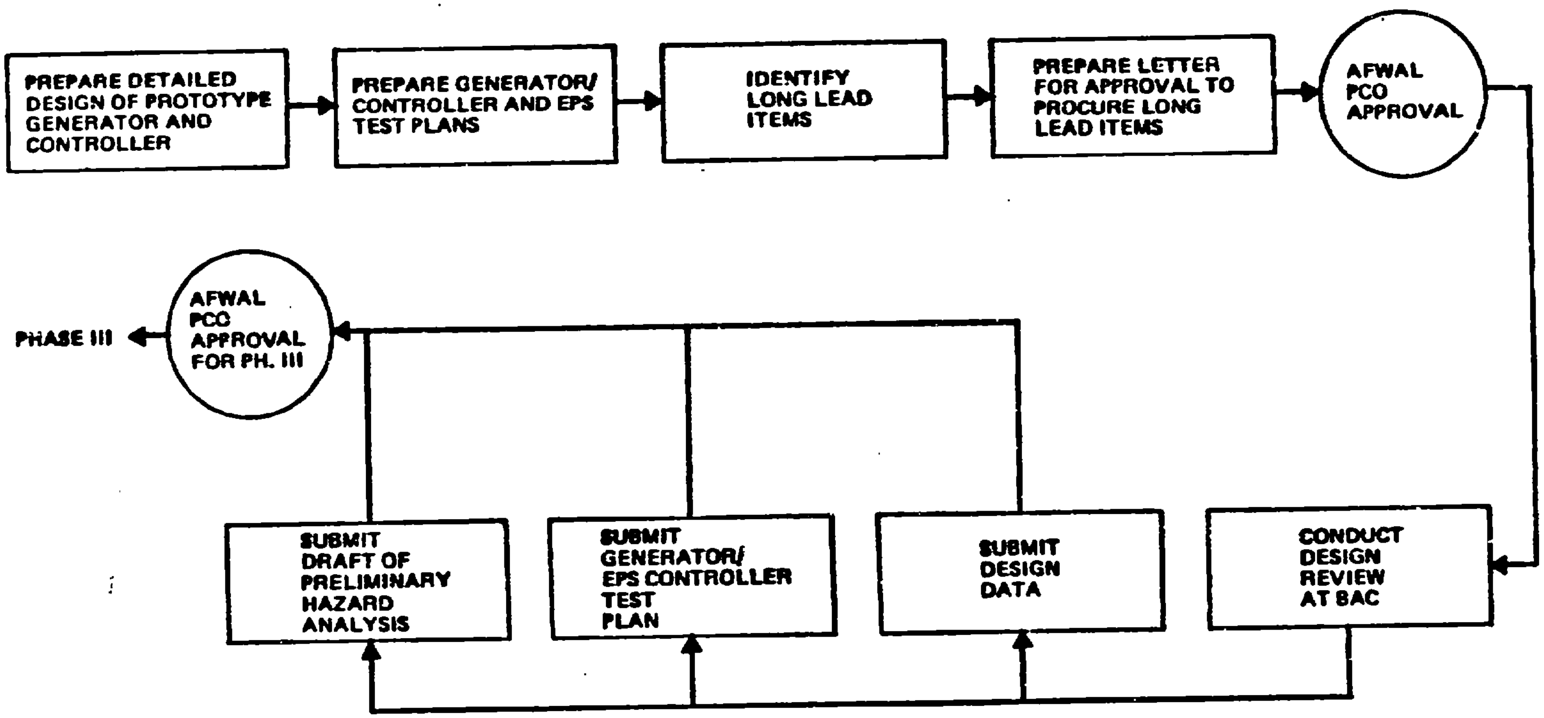
To determine the generator rating, a detailed survey was made of analyses of cruise missile operations and loads which might be used in advanced cruise missiles. Some scenarios of future cruise missile operations included sensors which are not used presently. These sensors were for penetration aids to assist the cruise missile in reaching its target. The power for the sensor is in the range of 1kW, which then increases the total missile load to about 5kW. This value is appreciably larger than other cruise missile generators and influences the selection of the generator and the location within the vehicle.

The attached sketches 1, 2, and 3 show the program logic diagrams which were followed in conducting the work. After the load had been determined, conceptual designs of generators and controls were traded in order to narrow down to the most likely candidate. The generator selected was applied to potential installations in a hypothetical cruise missile. Although the shaft-mounted generator was attractive because of the deletion of the accessory drive pad on the engine, the analysis showed that the cooling of the shaft-mounted generator was not achievable because the air

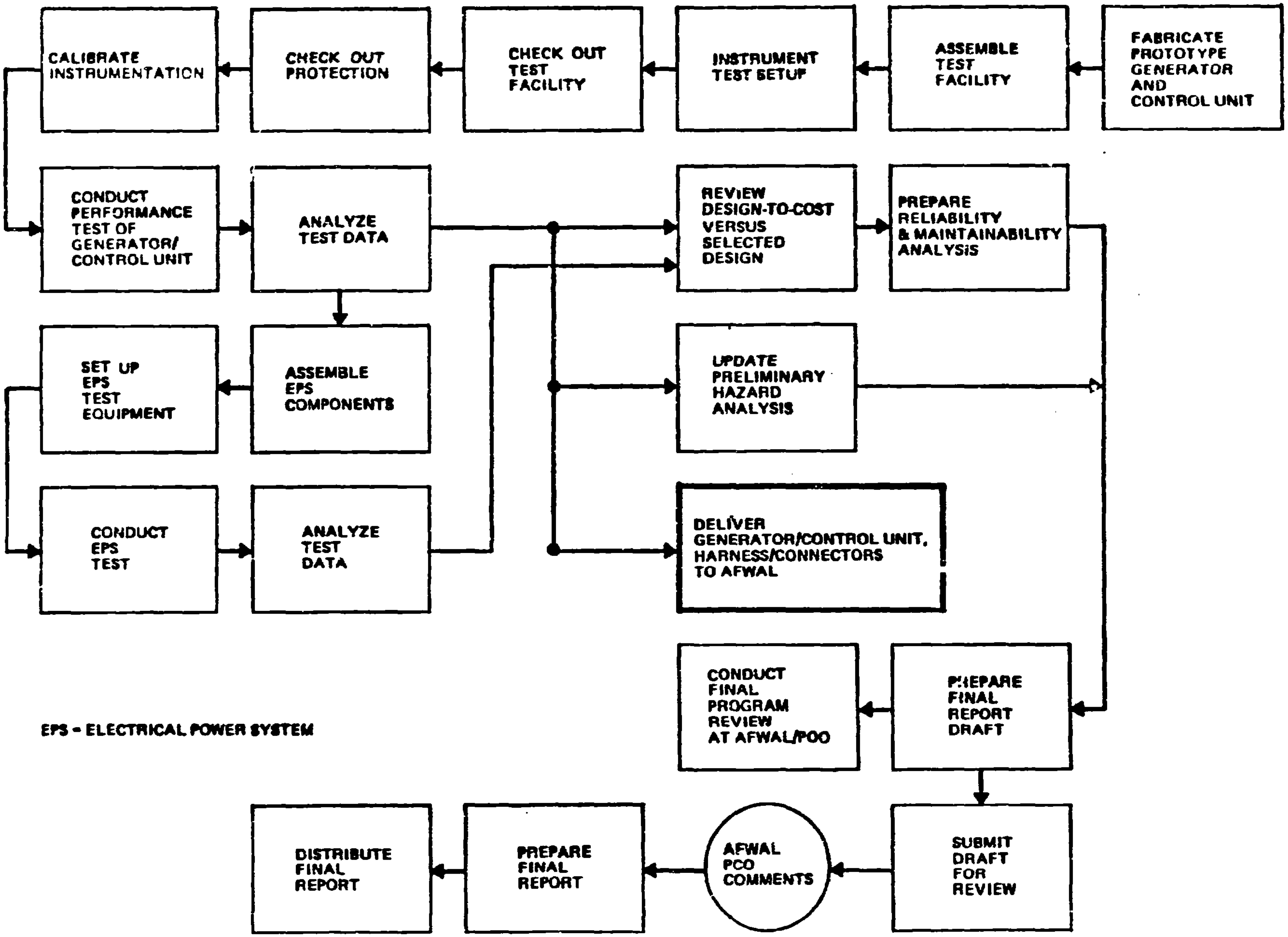


EPS - ELECTRICAL POWER SYSTEM

Sketch 1: Phase I Logic Diagram



Sketch 2: Phase II Logic Diagram



Sketch 3: Phase III Logic Diagram

and oil temperatures in the vicinity were too high. Thus, the design dictated that the generator was to be mounted on the accessory pad, similar to the AGM-86B cruise missile. The design proceeded from that point and was fabricated accordingly. At this point the generator and control unit have an improved per unit weight and volume when compared with present-day cruise missile generators and control units.

SECTION II
BACKGROUND

This program was undertaken to develop an improved energy density (weight and volume) generator and control unit for the next generation cruise missile. At the inception of the analysis to select the concept with which to proceed, the application to a realistic cruise missile engine was not addressed because it was felt that an engine could be developed to include the high-energy-density generator and control unit which would result from this contract. As the program proceeded the studies of advanced cruise missile mission profiles were analyzed to establish potential load profiles for arriving at the maximum power level. Thus, a 5-kilowatt rating was established for the generator. This resulted when all the sensors and control equipment were identified which would be included in the various scenarios to overcome the threat.

To establish the cruise missile environment (altitude, temperature, and speed), the study reviewed reports fo subsonic and supersonic flights and the launching and operating altitudes. The studies showed that the altitude would be low and the missile would be terrain-following, and the speed would be subsonic, similar to present-day cruise missiles. Fuel consumption and range had optimized that profile.

The next analysis was of the temperature of the oil available for generator cooling. This, too, was unsatisfactory because the oil was already warm when it reached the generator located in the shaft. In addition, it was decided with the USAF contract manager that some engine design concept should be addressed so that the generator might be applied in the future. Our investigation resulted in the identification of an advanced cruise engine design which was being conceptually formulated. The shaft on this engine was of too small a diameter to accommodate the 5kW generator. Reviews with the engine designer were held concerning larger diameter shafts. To increase the shaft diameter to accommodate a 5kW generator was not under consideration unless such a design requirement would be formulated by the USAF. There was no such requirement defined at this time, so reversion to an accessory mounted generator was accomplished. An additional penalty would also have resulted if the generator would have been mounted in the engine shaft and the accessory pad deleted. The accessory pad mounted fuel pump would then have to be provided with a drive, which would be the pump driven by an electric motor. The additional drive motor load would increase the total power requirement to more than 5kW, thereby further complicating the problem.

Next to be considered was the generator speed and voltage, and the type of generator. A high-speed generator and a high-voltage generator would result in a smaller, lighter machine. At high voltage, the lower current would also improve the controller design because it would not have to accommodate processing the higher current as in a lower voltage machine. The higher voltage originally selected was 75V, but when the installation was considered for a host vehicle, it was determined that 75 volts was not available from the host vehicle. Addition of a converter to match the 28-volt line available from the carrier aircraft would add to the generator and controller weight. We could not require a converter to be added to the carrier aircraft for just this type of missile since other missiles are also carried by the same aircraft.

As a result, the 28-Vdc generator design was selected. The 44,000 RPM generator speed was determined by the availability of a high speed bearing which would meet this application. A higher speed bearing was considered originally, but was found to not have the long life operation capability.

A design was selected for cooling the generator and the electronics contained in the generator housing. Because of the intricacy of the cooling passages, uncertainties surface as to whether the cooling fan and the passages would operate as analyzed. In order to avoid a needless cost of fabricating an improper cooling system, the decision was made to simulate the fan cooling by substituting a cylindrical disk to mass load the shaft and to force air through the generator passages to cool the electronics. The results of the test would be used to verify whether the complex cooling analysis was essentially correct. If the results matched the prediction, then the analysis method could be used to design the actual cooling fan in a subsequent fabrication.

Because of the speed range of the generator during flight, the voltage range would also be large, thereby necessitating that the regulator process a large amount of current for a wound rotor generator. The trade-off then resulted in a homopolar inductor alternator which supplies a heavy current but its regulator only processes the current to control the field. This amounts to about 4.5% of the total load current. Also, a samarium cobalt (SmCo) generator was shown to be heavier than a homopolar machine.

SmCo magnets were used in the homopolar inductor alternator to provide excitation for the starting current until the generator field current started.

The generator and control unit are designed with the diodes placed in the generator cooling passages. The remainder of the control electronics is on a circuit board engineering model with discrete components. There was no attempt made to package the controller in a flight configuration.

SECTION III
PRELIMINARY DESIGN

1. CANDIDATE ELECTRIC POWER SYSTEMS

Five candidate electric power systems considered were for the baseline system:

- A 28-Vdc system such as employed on ALCM-B
- A variable speed, variable frequency system drawing power directly from an engine-mounted ac generator.
- A hybrid system where a portion of the power is supplied at 28 Vdc (rectified generator power) or another dc voltage, and the remainder directly from an engine-driven ac generator.
- A 270-V and 100-Vdc system.
- A 115-V, 3-phase, 400-Hz system such as is available from the B52 airplane, or a 230-V, 3-phase, 400-Hz system available on the B1-B airplane.

The primary considerations in the baseline selection were the effect of the choice on the load and carrier aircraft interfaces. All missile loads except for 15W required for the flight control electronics timer are operating at various dc voltages. These vary from 20 Vdc for the servo motors and the IR defense load to ±15 V and +5 V for various avionic equipment. The pitostatic heater could employ either ac or dc power of up to 220 V. However its volume restricts the design to two heating elements. This eliminates the possibility of using a balanced 3-phase heating element. Airplane power is available at either 115 V, 3 phase, 400 Hz or nominal 28 Vdc for the case of the B52 and 230 V, 3 phase, 400 Hz or nominal 28 Vdc in the case of the B1-B carrier.

An analysis of the design drivers of the proposed ALCM-C missile indicates the lack of space for mounting additional equipment and the need to reduce power dissipation so as to facilitate denser avionic and payload packaging. There is therefore a need to select a power system that would facilitate through minor redesign a reduction of power consumption of each of the avionic and payload boxes.

A basic constraint is the need to supply most missile loads from a set of batteries for up to 23 seconds following missile launch and for smooth power transfer from battery to generator power. This is best accomplished with a dc distribution system, where the dc generator gradually takes over from the thermal batteries the supply of power to all loads.

The use of an ac power distribution system would shift the task of power rectification to each of the power users. This would increase both the size of each avionic box and its dissipation, and increase the number of wires of the distribution system.

The use of dc power other than 28 Vdc does entail a carrier aircraft penalty. This means that alternate dc voltages need be generated within the missile.

2. SYSTEM REQUIREMENTS AND CONSTRAINTS

The length and shape of the AGM-86B missile is determined by the spatial constraints of the B-52 rotary launcher. When carried on a future B-1B, the missile could be on either a rotary launcher or pylon. Information available suggests that no additional space can be expected in future cruise missiles. The limited space for mounting additional avionic equipment suggests that a design solution be sought that will not cause avionic hardware volume or dissipation to grow. Other important system constraints are the requirements to:

- Use established reliability parts
- Meet a ten-year storage life without maintenance
- Meet EMP and radiation hardening requirements.

It is postulated that a future cruise missile will operate over an altitude of 0-45,000 feet, and at mach nos. of 0.5-0.65.

a. Secondary Power System Rating

A survey was made of equipment considered needed for future cruise missile missions. The assumption was made that the primary missile flying mode will be at low altitude, since studies had previously shown this was the optimum altitude for cruise missiles. Defensive avionics considered as potentially necessary for such a mission in the future were identified. The experience gained on ALCM-B (AGM-86B) led to design changes as reflected in the modifications proposed for ALCM-C.

Flight experience with the AGM-86B missile led to the elimination in the proposed ALCM-C missile of the requirement for the engine inlet heater. Power requirements for the two air data sensor (pitot) heaters has increased from 300 W/unit to 500 W/unit. The inrush current to these heaters is twice rated current for less than 0.2 second. The requirement for a fuel pump has also been eliminated in favor of a fuel demand system and bladders in the fuel tank. The revised free flight power demand is 3712 W as shown in Table 1.

The air vehicle specification requires an electrical system capability at least 33% greater than the maximum continuous power demand. This dictates a generator and control unit capacity of 3712 x 1.33 = 5 kW.

TABLE 1. LOAD POWER DEMAND

	POWER DEMAND, WATTS		
LOAD	NOMINAL	PEAK	DURATION
Inertial Navigation Element	400		
Missile radar altimeter	40		
Flight control electronics	94		
Pitot heater	1000	2000*,	0.2 sec
Servo motors	336	750*	0.01 sec
Fuel control actuator	48		
Instrumentation or warhead	184		
Hammot	10		
Advanced guidance	250		
Terminal defense	250		
IR defense	1100		
Total	3712		

*The generator does not experience the two peak loads simultaneously. The battery carries the servo motor peak load while the heater load occurs.

b. Power System Bus Configuration

The AGM-86B bus configuration was evaluated to determine whether it could be improved in a future system. The intent of the separate "pulse load" and "constant load" buses is to decouple such sensitive loads as the computer in the inertial navigation equipment from heavy pulse load activity during the first several seconds of free-flight on the pulse load bus. Review of the bus voltages and generator current traces at a resolution of 2 cm/sec from a typical instrumented flight shows a constant load bus variation of less than ± 0.36 V once the generator shares in the supply of power to this bus. The data suggest that this bus architecture is satisfactory. It has therefore been adopted as a baseline for this study.

c. System Voltage

An increase in system bus voltage to either 135 or 270 Vdc need be accompanied by development of established reliability (ER) capacitors that meet a 10 year non-operating life requirement. The most volume efficient is the non-solid ER tantalum capacitor military type M39006/22, available at voltages of up to 125 Vdc. On AGM-86B these are derated to 60% of rated voltage. Tantalum foil, polypropylene and polysulfone are available at higher operating voltages, but not in the established reliability category.

The calculated reliability for the 28 V AGM-86B battery is P = 0.999,998,6. A battery operating at 270 Vdc will have a reliability of P = 0.999,986,6 higher than the allocated P = 0.999.

The constant load (C.L.) and pulse load (P.L.) launch requirements for the postulated power system are shown in Table 2.

TABLE 2. LAUNCH POWER REQUIREMENTS

LOAD EQUIPMENT	OPERATING TIME	LOAD IN WATTS C.L. BUS	 P.L. BUS
Inertial Navigation Element	Cont.	250	
Missile radar altimeter	Cont.	40	
Eight squibs 1/event	100 ms		280
Flight control electronics	Cont.	94	
Fuel Control Actuator	Cont.	48	
Hammot	Cont	10	
Power Switch Unit	1 sec	13	
EBW firing module	5 sec	3	
Instrumentation	Cont.	98	
Advanced guidance	Cont.	250	
Servo motors	10 ms/cont.	—	1500/336*
Total		806	1780/336

*Peak/nominal value

d. Generator and Control Unit (G&CU) Mounting Options

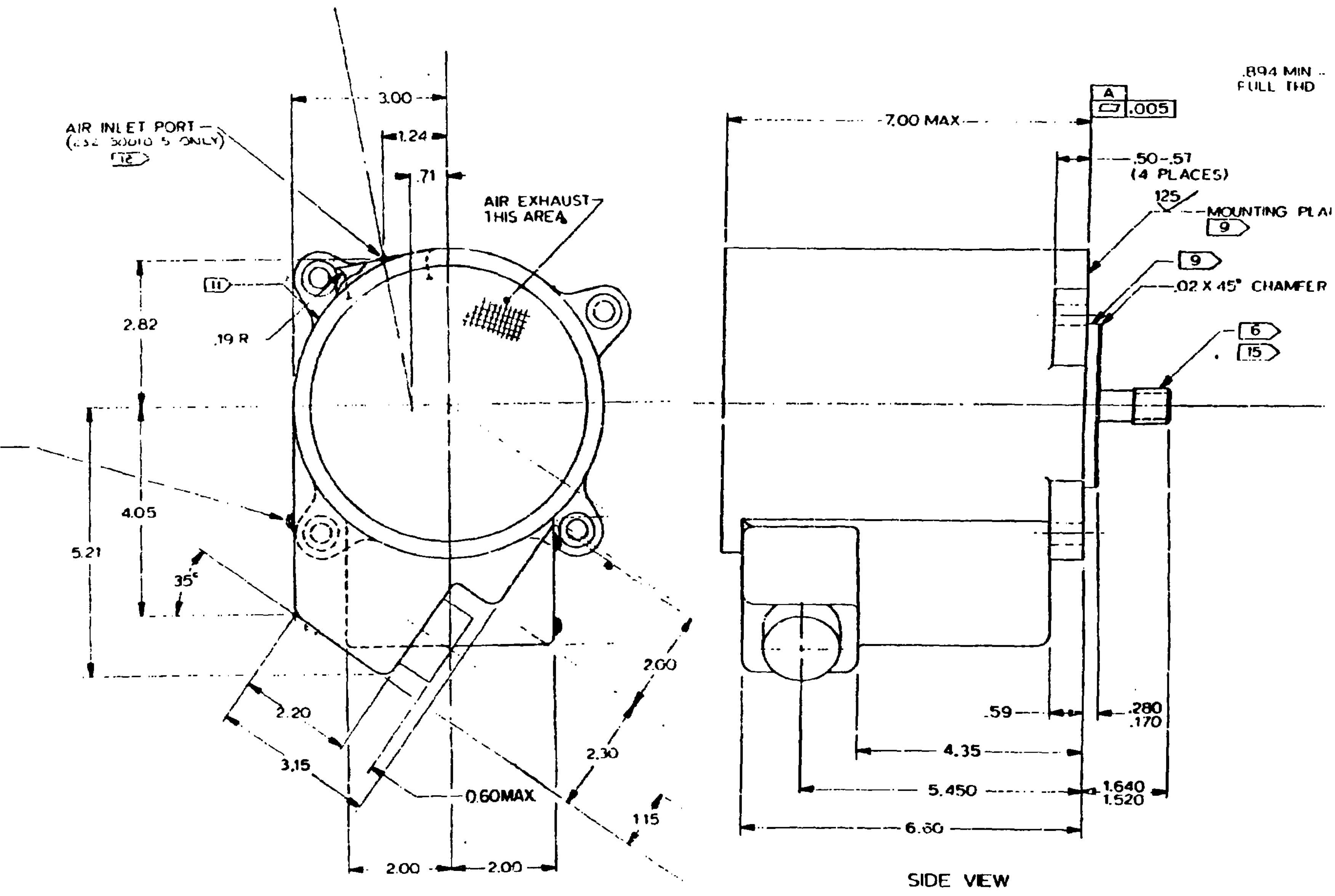
Three mounting options were initially considered:

1) Pad Mounting.

A G&CU mounted on the present AGM-86B engine pad fitting within the envelope shown in Figure 1. This envelope approximates the space taken up by the present AGM-86B generator. The input speed to be selected will be proportional to the advanced engine high speed shaft speed range of 48,500 to 65,000 RPM. The control unit can alternatively be mounted against the missile skin using a 10 x 10-inch footprint.

2) Internal Mounting on the Low-Speed Shaft of the Williams International Modified 14A6 Engine.

A generator mounted inside the missile engine within the space shown in Figure 2. The rotor is fitted onto the shaft and the stator is bolted to the aluminum



10 Figure 1 Drive Mounting

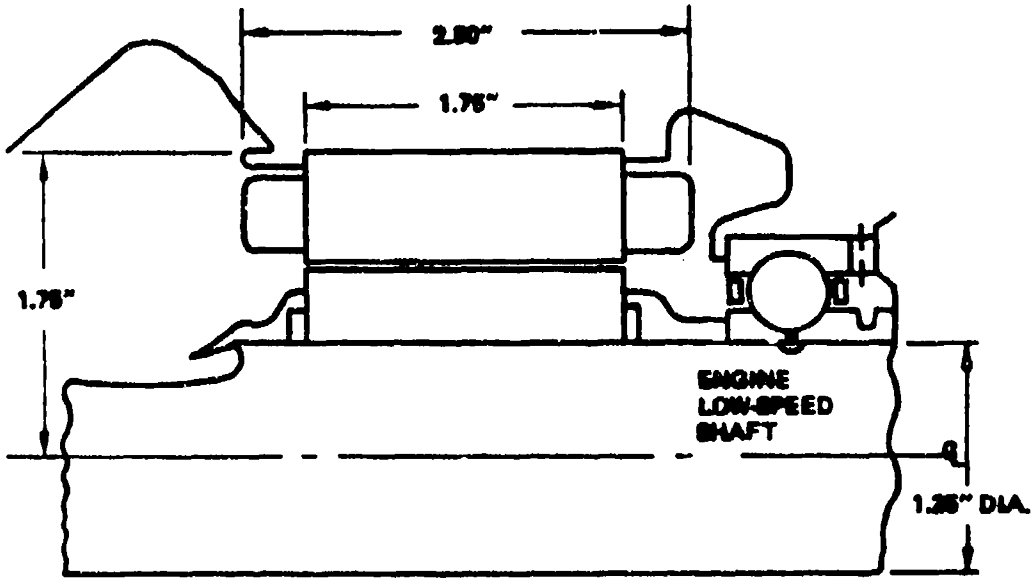


Figure 2. Space Allocation for Internally Mounted Generator, Modified 14A6 Engine

housing. The generator shaft speed will vary from 18,400 to 35,300 RPM. The control unit may be mounted against the missile skin as shown in Figure 3.

3) Internal Mounting in a Recuperative Engine

In a future engine such as the Williams International Model WR-50, the generator could be mounted inside the engine housing as shown in Figure 4. The generator in this installation is supported by bearings interior to the engine. The engine idle speed is 64,000 RPM and maximum speed is 84,000 RPM.

Because of the uncertainty as to whether the recuperative engine will be the prime candidate for a future cruise missile engine design of this option was not carried beyond the sizing of a generator.

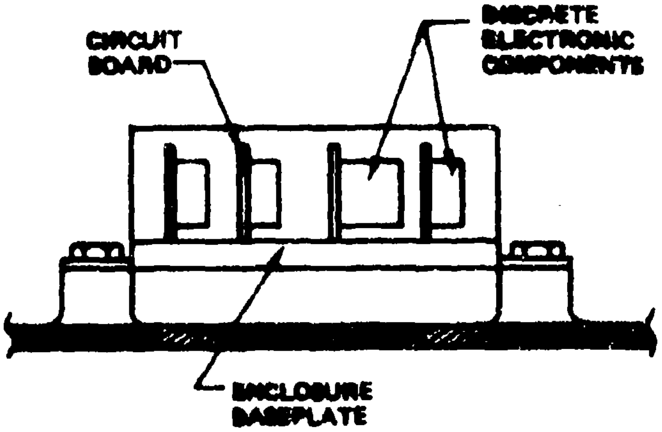
e. G&CU Cooling

For Option I oil, fuel, and air cooling were considered for the generator as well as missile skin cooling for the control unit should it be mounted separately as for Option II. Oil cooling of the pad-mounted G&CU was rejected, because the engine oil system cannot take on additional heat load. Fuel is used for oil cooling (to reduce engine oil consumption) after leaving the engine pumps. It is estimated to reach 300°F when available for control unit cooling, i.e., excessive for electronic parts, which themselves need to be maintained at ca. 212°F.

Ram air is available from a 2-inch-diameter inlet to provide air for temperature sensing near the engine inlet. The maximum air temperature is 160°F near sea-level. A 0.25" gap is maintained between this air duct and the generator air scoop to assure adequate air flow past the temperature sensing coils, part of which enters the nearby missile cavity. Unpressurized air is thus available to the G&CU at this maximum temperature that can be drawn by a fan on the generator shaft.

Engine bleed air temperature on a hot day is available at 350°F to act as a heat sink when blowing over the aluminum structure that holds the stator in Option II.

Three possible heat sinks have been considered for the control unit for Option II (and Option I if separate from generator): the engine, the fuel tank and the missile's rear skin.



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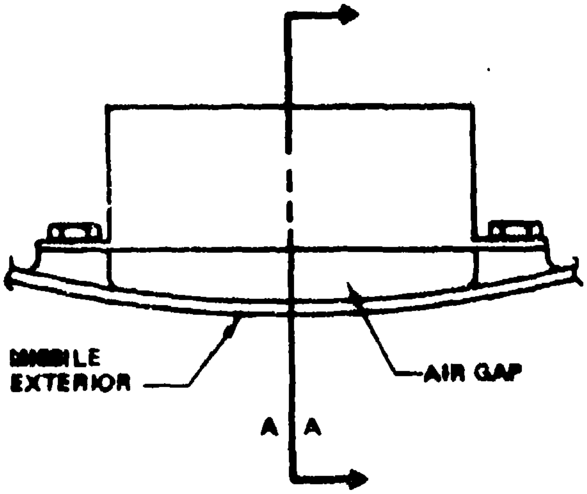

Figure 3. Control Unit Mounted to Missile Skin

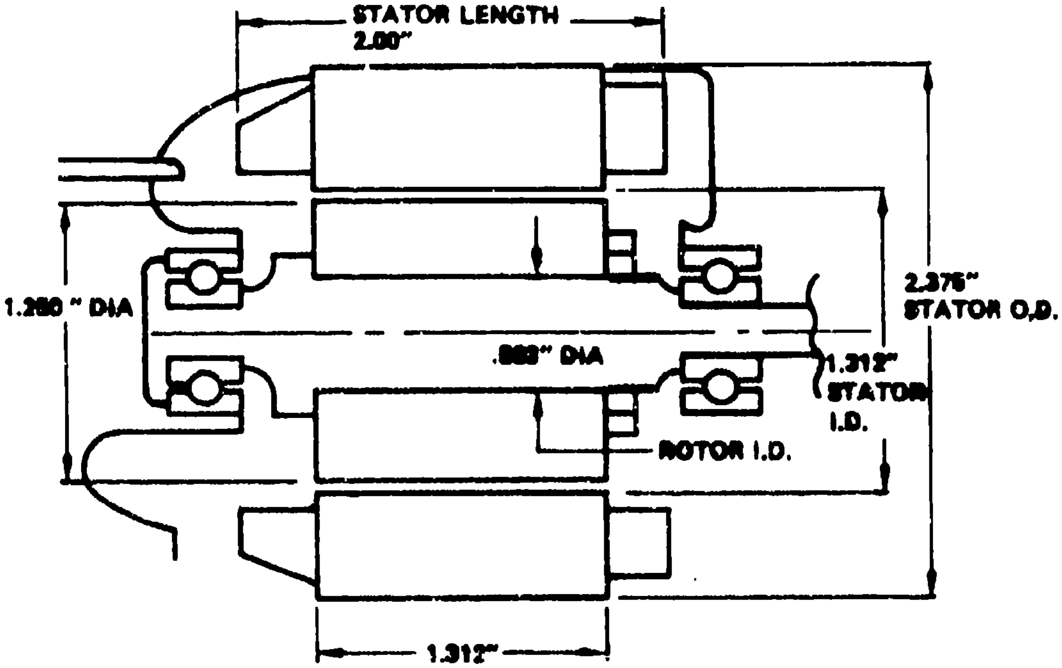

Figure 4. Space Allocation for Internally Mounted Generator WR-50 Engine

The engine was considered first since mounting in this location would reduce electrical lead length, and put the control unit in close proximity to the engine's pump-to-combustor fuel line, which was considered a potential heat sink. Mounting to the engine was rejected however, due to three factors:

- Vibration levels would be high, requiring shock isolators.
- Advance versions of the missile engine are expected to operate at a case temperature of 325 °F.
- The fuel, as mentioned above, must be used for oil cooling first.

The fuel tank has also been rejected as a control unit heat sink based on fuel temperature limits. The AGM-68B specification requires fuel delivery to the engine at or below 160 °F, a point now approached in long-duration flights.

Mounting of the control unit in one or more boxes on the rear skin is possible. Heat sink temperatures on a hot day, when the missile is in a high speed, low altitude flight are estimated at 170-172 °F.

The suggested 10 x 10 inch footprint is based on the fact that the GM-86B aft body section is a casting having vertical stiffening ribs positioned approximately 10 inches apart. One method of providing a heat conduction path would be to cast bolting bosses into the missile and bolt the enclosure in place as shown in Figure 3. Previous packaging experience indicates that using six 5/16-inch-diameter attachment bolts, a bolting boss-to-enclosure baseplate thermal conductance of 9.6 W/°F is achieved. This figure suggests the need for several flat boxes to handle the total expected dissipation. The use of aft section air is not considered practical because the compartment air is presently at 200 °F, and expected to rise to 220 °F when using the advanced engine proposed for ALCM-C. The use of ram air at 160 °F that is drawn by a fan mounted in the control unit is a practical alternative.

The generator in Option III, would be operating in an oil mist. The estimated maximum gear box temperature is 350 °F.

3. TRADE STUDIES

a. Generator and Control Unit (G&CU) Design Characteristics

Trade study parameters were selected that are in consonance with the system requirements and constraints.

- A G&CU demand of 5 kW continuous rating was postulated, providing a 30% overload capability for 2 minutes. The overload requirement was added to take care of future peak loads such as heaters, servo motors, and IR defense.

- A regulation of ±3% was initially postulated for the G&CU as a level that is readily achievable, and one that will meet the constraint that avionic and payload size and dissipation not be penalized.

- Sensitivity of G&CU weight, volume and dissipation were determined for nominal voltages of 28, 100, and 270 Vdc.

- A generator shaft speed ratio of 1.36 was assumed for the pad mounted generator, Option I, slightly wider than the 1.34 speed ratio for the AGM-86B pad to accommodate other engines proposed on the ALCM-L program. This speed ratio (r) covers the case of internal mounting in a recuperative engine r = 1.31. A generator shaft speed ratio of r = 1.91 was postulated for the case of an internally mounted generator mounted on the low-speed shaft of the Williams International 14A6 engine, option II.

- The nominal generator shaft speed for Option I, pad mounting, was left open to determine the highest speed beyond which weight saving diminishes and technical risk is excessive.

Three types of G&CU's were selected that appeared to potentially reduce specific weight and volume, meeting or approaching the study design goal of 14 lbs and 200 cu. inch.

- A combination permanent magnet generator and switching regulator shown in Figure 5.

- A combination permanent magnet generator and SCR (thyristor) phase-regulator, shown in Figure 6.

- A homopolar alternator whose output is rectified and regulated, shown in Figure 7.

The design/analysis approach was to select suitable components for the above systems, and determine the size, weight, power loss, and relative reliability for these systems. From these data the optimum configuration was selected based on size, weight and power.

1) Study Results

- The SCR regulator/PMG, as shown in Tables 3 and 4, is heavier than the other two candidate systems at 28 Vdc. It is due to the large peak currents that have to be handled by the SCR's and alternator.

- The 270 Vdc system presents no significant weight or volume advantages with respect to a 100 Vdc system.

- Speed sensitivity data, illustrated in Tables 5 and 6, plus fan and bearing limitations, suggest a top speed of 65,000 RPM translating to a minimum speed 48,500 RPM, i.e., a speed ratio of 1:1 with respect to the high speed shaft of the Williams International 14A6 engine.

- The internally mounted PMG systems are larger and heavier than the pad mounted system. This is primarily due to the lower speed, as shown in Tables 3 and 4. A homopolar generator will not fit into the space allocated for it, per Figure 7. A PM generator that will fit the allocated space will carry 5 kW continuous, but only 6 kW for 2 minutes rather than the required 6.5 kW. In order to take full advantage of the saving in volume, weight, and engine cost that elimination of the generator pad entails, it is necessary to supply an additional 600 W power for the engine accessories that are presently mounted on the other pad-side. The gear box weight is 9.3 lbs, the volume is 1 cu. ft, and the cost saving, in eliminating the gear box is estimated by Williams at about 20% of engine cost. Against that must be weighed the development and production costs of electronic engine controls.

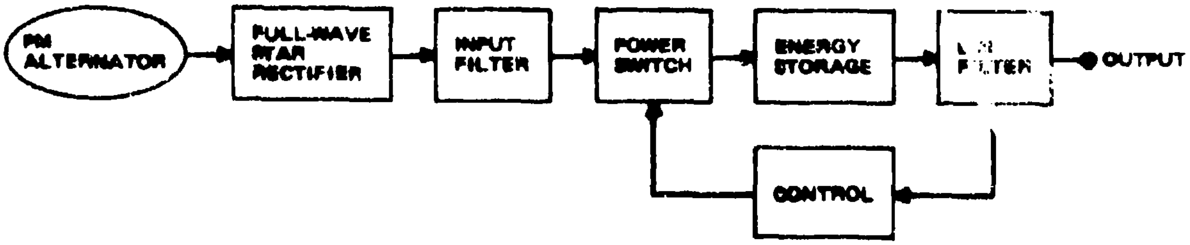

Figure 5. Switching Regulator/PMG, Block Diagram

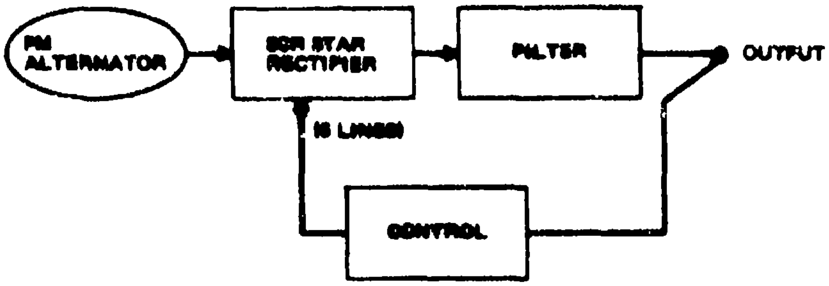

Figure 6. SCR Controller/PMG, Block Diagram

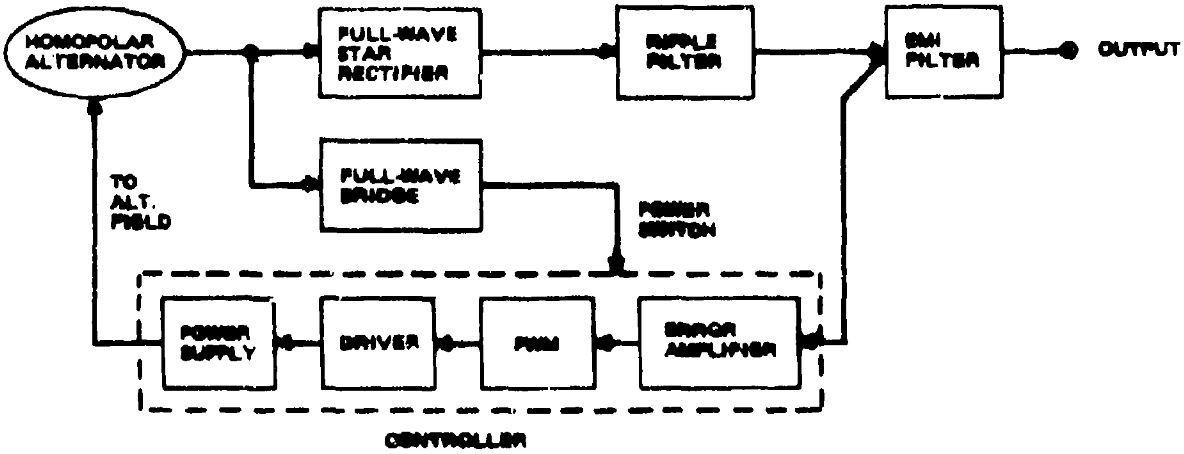

Figure 7. Homopolar Alternator/Regulator, Block Diagram

TABLE 3. SUMMARY OF SYSTEM WEIGHTS

Speed Ratio	System Type	Weight, lbs at output voltage of: 28	100	270 Vdc
1.36	SW	21.9	18.7	17.7
1.36	HP	18.6	15.4	15.6
1.36	SCR	26.9	17.9	18.1
1.91	SW	24.6	21.7	22.4
1.91	HP	18.3	15.1	15.3
1.91	SCR	27.9	18.9	18.9

TABLE 4. SUMMARY OF SYSTEM VOLUMES

Speed Ratio	System Type	Volume in cu. inches at output voltage of: 28	100	270 Vdc
1.36	SW	414	256	271
1.36	HP	265	128	164
1.36	SCR	384	330	284
1.91	SW	599	464	337
1.91	HP	269	132	167
1.91	SCR	399	345	299

SW = Switching Regulator/PMG
HP = Homopolar Generator
SCR = SCR Regulator/PMG

TABLE 5. ALTERNATOR CHARACTERISTICS, SWITCHING REGULATOR/PMG

Output		Min.					Max.
V	I	Speed	O.D.	Length	Volume	Weight	Losses
V	A	KRPM	In.	In.	Cu. In.	Lbs.	Watts
28	232	30.0	3.1	2.9	34	6.5	485
100	65	30.0	3.1	2.9	34	6.5	508
100	65	44.0	2.8	2.9	28	5.4	510
100	65	44.0	2.5	3.6	27	5.4	530
270	24	30.0	3.1	2.9	34	6.5	485
270	24	44.0	2.5	3.6	27	5.4	500
270	24	44.0	2.8	2.9	28	5.4	485

Condition: External mounting, speed ratio = 1.36

TABLE 6. ALTERNATOR CHARACTERISTICS, HOMOPOLAR GENERATOR

Output		Min.					Max.
V	I	Speed	O.D.	Length	Volume	Weight	Losses
V	A	KRPM	In.	In.	Cu. In.	Lbs.	Watts
28	232	18.4	4.4	5.0	90	12.3	1500
28	232	50.0	3.7	5.8	62	10.8	1120
100	65	18.4	4.4	5.0	90	12.3	1500
100	65	50.0	3.7	5.8	62	10.8	1120
270	24	18.4	4.4	5.0	90	12.3	1500
270	24	50.0	3.7	5.8	62	10.8	1120

Condition: External mounting, speed ratio = 1.36

2) Carrier Aircraft Interface

The carrier aircraft presently provides single phase ac power for avionics heating, and two separate sources of 28 Vdc, one to the constant load bus, the other to the pulse load bus. The dc checkout power demand consists of:

Inertial Navigation Element	250 W
Advanced Guidance	250 W
Total Continuous	500 W

with other loads such as Flight Control Electronics being checked out sequentially when checkout of advanced guidance has been completed. The peak load during checkout occurs for 200 ms when the two servo motors are powered in locked position P = 1500 W, total P = 2000 W.

Operation of the missile at a voltage higher than 28 Vdc requires that the carrier aircraft ac power be converted to the desired dc bus voltage. Full wave rectification of the 115-V 3-phase, 400-Hz power provides an output of 270 Vdc. However this output is floating with respect to ac and dc ground necessitating a transformer ahead of the rectifier to provide a common missile and aircraft ground. This 400 Hz, 3 phase transformer alone weighs 6.2 lbs (based on 80 W/lb design). The total converter is estimated to weigh 12 lbs.

An alternative power converter is a 3-phase half-wave rectifier and filter, providing an output of 133 Vdc. While the negative of this converter is common to aircraft ac and dc ground, its larger 1200 Hz ripple, as compared to the full-wave rectifier requires a filter that is sized for the peak 2000 W load. The converter is estimated to weigh 4.4 lbs.

The estimated weight of the power system elements providing an assessment of the merits of operating at a voltage higher than 28 Vdc are shown in Table 7. The Homopolar generator was chosen for this comparison because of its lower weight as compared to the other candidate generators.

TABLE 7. SYSTEM ELEMENTS WEIGHT ANALYSIS

SYSTEM ELEMENT	SYSTEM WEIGHT, LBS		
System Voltage, V	28	135	270
G&CU	18.6	15.4	15.6
Umbilical	4.5	4.5	4.5
Thermal battery	8.0	8.6	8.9
Separation Switch	5.5	5.5	5.5
Power Dist. J-box	2.5	2.1	2.1
Wire harness	25.6	23.1	21.8
Converter	—	4.4	12.0
	64.7	63.1	70.4

The weight advantage of a 135 Vdc system is negligible, not justifying the addition of a converter.

The 28-Vdc homopolar generator power loss is 1750 W of which 1120 W is dissipated in the generator and 630 W in the regulator.

The homopolar generator was chosen for the baseline design because not only its weight and volume are close to the design goal, but it is also more capable as compared to a switching regulator/PMG, of handling the pulsating loads such as the IR defense load. The homopolar generator will fit into the present space allocated for the AGM 86-B generator.

The basis for the weight and volume estimates are shown in Tables 8 and 9. The effect of speed on alternator weight is shown in Figure 8.

The estimated reliability of the respective choices are shown in Table 10.

TABLE 8. SYSTEM WEIGHT, HOMOPOLAR GENERATOR

COMPONENT	COMPONENT WEIGHT, LBS AT OUTPUT VOLTAGE Vdc			
	28	100	270	28(1)
Rectifier	2.5	0.3	0.1	2.0
Ripple/EMI Filter	3.6	3.1	6.9	1.5
Control Card	0.6	0.6	0.6	0.6
Wire, Case, Etc.	0.5	0.4	0.3	2.5
Subtotals	7.4	4.4	4.7	6.6
Packing Factor	0.95	0.95	0.95	0.95
Regulator	7.8	4.6	4.9	6.9
Alternator	10.8	10.8	10.8	10.8
System Total	18.6	15.4	15.7	17.7

Condition: Speed Ratio 1.36, minimum speed = 50,000 RPM

TABLE 9. SYSTEM VOLUME, HOMOPOLAR GENERATOR

COMPONENT	COMPONENT WEIGHT, LBS AT OUTPUT VOLTAGE Vdc			
	28	100	270	28(1)
Rectifier	70	4.2	2.9	30
Ripple/EMI Filter	19	18	38	20
Control Card	5.7	5.7	5.7	6
Wire, Case, Etc.	7.0	5.0	5.0	10
Subtotals	102	33	51	66
Packing Factor	0.5	0.5	0.5	0.5
Regulator	203	66	102	122
Alternator	62	62	62	62
System Total	265	128	164	182

Condition: Speed ratio 1.36, minimum speed = 50,000 RPM

(1) Further development of weight and volume estimates based on meeting ripple requirements at up to full load, but not during overload.

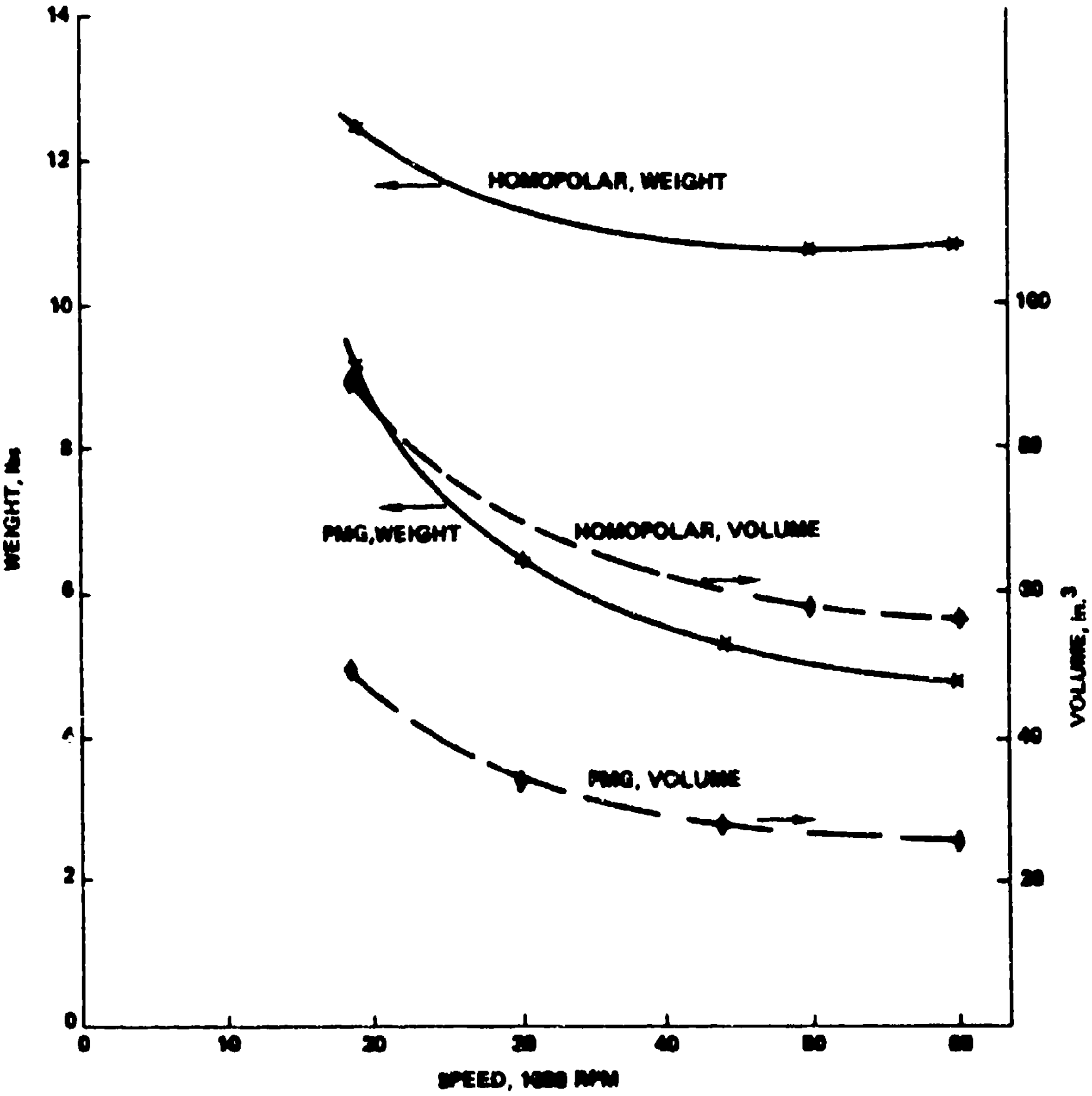

Figure 8. Effect of Speed on Alternator Weight, Volume

TABLE 10. SYSTEM RELIABILITY

Item	MTBF, Hrs
Switching Regulator	35,000
PMG - Internal	200,000*
PMG - External	30,000
Homopolar Regulator	40,000
Homopolar Generator	30,000

*The increaed MTBF is due to the absence of bearing that are provided by the engine.

b. Significant Design Features

1) Permanent Magnet Generator/Switching Regulator

The permanent-magnet generator consists of 6 magnets located on the rotor which is rotated in proximity of stator coils permanently fixed on 9 pole teeth, as shown in Figure 6. The magnets are cemented onto the rotor hub with an epoxy compound. A retaining ring is heat shrunk over the magnets/poles with a final machining of the retaining sleeve to meet the alternator radial gap requirements. The total airgap is 70 mil, of which the retaining ring occupies 45 mils and the active airgap 25 mils. Concentricity is maintained to ±5 mil.

The windings are connected in a 6 phase star configuration so as to reduce rectification losses from 2 to 1 volt.

The switching regulator package consists of a rectangular aluminum extrusion heat sink which was 4 x 6 x 2 inches for a previous 50 A unit design. MOSFETs are mounted directly to the exterior of the aluminum heat sinks. All control and logic circuitry is contained on a single PC board.

2) Homopolar Generator

The proposed homopolar generator will have two stator stacks for each rotor core each shifted 30 electrical degrees from the other. This will increase the ripple frequency over what the power control unit would see if one stack was used. This technique reduces the rectified ripple voltage.

Starting - Self starting will be obtained through the use of residual magnetism in the stator stack laminations. Because the residual magnetism cannot be relied upon for self-starting over long periods of storage, Sm-Co permanent magnets will be securely fastened to the rotor. This will provide sufficient output in the stator coils to energize the field coil and allow self-starting. These magnets will be symmetrically located 90 mechanical degrees apart on each end of the rotor and mechanically supported by an Inconel 718 sleeve to withstand the high rotational speeds.

c. Load Sensitivity To Input Voltage

The relevant design/performance requirements that impact the size, weight and dissipation of the converter section of the load utilization equipment are:

- Polarity protection - typically provided by a diode in series with the input terminal.
- Conducted interference requirement of MIL-STD-461 typically implemented with a single or dual stage filter section.
- Provision for normal aircraft source dropout of 20-ms duration when in captive flight in a B-52 carrier. This requirement is eliminated for future cruise missiles carried by B-1B airplanes.
- EMP protection typically provided by the input filter or when necessary by the transient suppressor.
- Operate under input power quality requirements specified by MIL-STD-704A.

A typical avionic load includes a switching regulator whose output produces the requisite +5, ±15 Vdc typically required for analog and digital circuits. An increase in nominal input voltage will reduce the dissipation in the series diode and the switching transistor. The reduction in dissipation for a 200 W converter operating at switching frequency of 20 kHz, is 13 W when the input voltage is 135 Vdc.

The size of the filter capacitor will remain invariant as the same energy need be stored regardless of input voltage. The magnetic elements are sized by the level of power processed which remains invariant. The converter size and weight is therefore expected to remain the same or decrease modestly.

A slightly higher power savings results from increasing the input voltage to the servo motors. The latter consists of two Darlington transistors that control motor current each dropping approximately 2V. The input filter accounts for another 1V drop. The AGM-86B motor is currently limited to 31A. At an average power demand of 168 W/unit the average dissipation is:

Average P(diss.) = (168/28)(5) = 30 W
Peak P(diss.) = (31)(5) = 155 W.

At a nominal input voltage of 135 Vdc, I(avg) = 124A

Average P(diss.) = (124)(5) = 6.2 W
Peak P(diss.) = (6.4)(5) = 32 W

A reduction of 14% in power demand is indicated @ 135 V, and 16% @ 270 Vdc.

4. BASELINE DESIGN REQUIREMENTS

The key G&CU requirements and their source are listed below.

The load analysis plus air vehicle margin requirements dictate that the G&CU:

- Deliver continuous power of 5.0 kW at 28 Vdc.

- Withstand a 2-minute overload of 1.3 pu of rating.

- Provide the above power at a steady-state regulation of 28-30 Vdc.

Engine characteristics dictate that G&CU deliver the above power and regulation:

- Over a speed range of 48,500-64,8000 RPM and a transient range of 47,000-66,000 RPM recovering to within steady limits within 2 seconds.

- Meet requirements after withstanding a 5-minute overspeed at 73,100 RPM.
- Withstand shaft acceleration and deceleration of 10,000 RPM/sec.
- Produce vibration levels lower than those in figure 3 of the system specification.
- Operate with an engine/generator interface temperature of 300°F.

System requirements dictate the G&CU to:

- Operate at an altitude range of 0-45,000 ft.
- Meet a 10-year storage life requirement.
- Meet an MTBF of 5240 hours.
- Be designed using electronic components procured to MIL-STD Established Reliability Specifications.
- Meet EMP and radiation hardening requirements.
- Weight = 18 lbs, volume = 220 cu. in.

Other requirements are detailed in the accompanying system specification.

5. IMPACT ON SYSTEM COMPONENTS

a. Thermal Battery

The present AGM-86B battery is a $Ca/CaCrO_4$ type. The Li/FeS_2 battery has found increasing application in missiles because of its higher energy density. The Li/FeS_2 meets the ignition and temperature requirements of AGM-86B. This battery has the further advantage of a lower (1/2) cell impedance which provides performance advantages for operation under pulsed load conditions such occur on the pulse load bus. A weight analysis of a proposed alternative to the AGM-86B battery indicates that 40% of the battery weight is represented by the enclosure and connectors required for a hermetic design that is compatible with an explosive atmosphere and a 10 year life. The total battery weight meeting AGM-86B requirements was comparable to the 9.5 pounds of the present battery.

In estimating the weight and volume of a 135 Vdc and 270 Vdc Li/FeS_2 battery a separate stack was postulated for a third 28-Vdc squib battery supplying 10A.

Estimated unit cost of a Li/FeS_2 varied between \$1500 - \$2,000. Development costs were estimated at \$200,000. The present AGM-86B battery production costs are \$4,500.

b. Separation Switch

The design of the switch will be unaffected by the identified additional loads. Its rotary switch design may need to be modified to handle such higher bus voltages as 135 or 270 Vdc. In such a case a separate battery would be provided to service the 10A squib circuit leaving these circuits unchanged.

c. Power Distribution and Cabling

The effects of an increase in bus voltage to 135 V on cable weight was examined. The components that make up the total weight of each wiring harness are:

- wire
- shield
- jacket
- connector
- backshell

For the purpose of this analysis, the weight of the wire was the only parameter varied, based on constant current density. That is, temperature and voltage drop were held constant. A new wire size was chosen in each case that is the next larger size. The results are shown in Table 11.

TABLE 11. CABLING WEIGHT SAVING

WIRE RUN	AGM-86B SYSTEM		135 VDC SYSTEM
	Cable Wt lbs	Actual Wt lbs	Cable Wt
W1	0.65	0.73	0.53
W2	1.14	1.40	0.81
W3	5.79	4.70	2.50
W5	2.23	1.99	1.79
Total	9.81	8.82	5.70

Net saving is 3 pounds, or 12% of the total cabling weight of 25 lbs.

d. Umbilical Enclosure Assembly

The specification for the umbilical enclosure assembly was reviewed to determine what modifications are required in its design to accommodate the additional loads.

The pin functions that need to be changed are:

o A pair of #20 pins are presently used for the positive (and negative) side of the temperature probe heater. The two wires from the enclosure connector are spliced to a #16 wire. These four pins can be used for the terminal defense load in a similar fashion. The current of the former load was 10.7A, the latter 8.9A.

o A single #20 wire presently supplies power to the countermeasure load. Its current demand is 3.2A. The advance guidance load whose demand is 8.9A would require a connector change.

The umbilical and connector contacts are designed to withstand a dielectric withstanding voltage of 500 V RMS minimum under combined temperature-humidity-altitude conditions specified for AGM-86B. It could thus be used at a higher bus voltage.

e. Power Distribution Junction Box

The power distribution junction box serves to couple the generator constant load battery and pulse load battery to their respective buses. It also houses the diodes that couple the main bus and batteries to the constant load bus and pulse load bus respectively. The 5 x 6.2 x 2-inch box presently does not have space for a separate defense bus, hence need be enlarged by approximately 20%.

f. Flight Control Actuator

The present flight control actuator consists of an H bridge, i.e. 4 darlington transistor pairs, and a torque motor. A reliable brush system is provided using relatively large brushes (of 30% copper) with a high-altitude impregnation and heavy (3 psi) brush springs.

The substitution of a brushless motor would facilitate the use of more copper in the stator, thereby reducing the dissipation in the motor by approximately 1/3 (40W). This will reduce its maximum operating temperature, now 425°F. A brushless motor will require position sensors which are difficult to mount, and stabilize in the small volume available for the motor (1.8-inch dia). The controller will require 2 more transistors and additional logic, increasing its volume by ca. 30% from the present 131 cu. inch. The controller is mounted near the engine in a crowded location. The choice between the two design approaches depends in part on future configuration constraints.

Because of commutator bar spacing limitations, it is desirable to limit the voltage between bars to 10 V. The present motor has 9 bar segments between brushes. It can thus operate at 85 Vdc. At operating voltages higher than 90 V, the brushless motor design approach is the proper choice.

6. SYSTEM PHYSICAL CHARACTERISTICS

The advanced secondary power system is rated at 5 kW. It consists of the same elements as those of the AGM-86B secondary power system. Table 12 below summarizes the physical characteristics.

TABLE 12. PHYSICAL CHARACTERISTICS

ELEMENT	WEIGHT lbs	VOLUME cu. in.
1. Gen. & Control Unit	18	220
2. Thermal Battery	9.5	75
3. Separation Switch	5.5	60
4. Power Distribution J-Box	2.5	85
5. Umbilical Enclosure	4.5	210
6. Wire Harness and Connectors	25.6	---
TOTAL	65.6	

7. STUDY RESULTS

The study results lead to the following conclusions:

- The power requirements of future cruise missiles are expected to rise such as to dictate a 5-kW generator and control unit, or a 5.7-kW unit if electronic fuel control of future missile engines is included.

- Volume for additional hardware on a larger generator is at a premium in cruise missiles hence volume minimization ranks on a par with weight minimization in future designs. The design goal should be to fit the generator either inside the engine or inside the present AGM-86B generator envelope.

- A bus voltage of 28 Vdc, i.e., the present voltage, is the best choice to reduce G&CU specific weight and volume.

- The generator and control unit (G&CU) that comes closest to the weight and volume goals set for the study is a homopolar generator mounted on the present generator pad, geared to the high-speed shaft, operating at a nominal speed of 60,000 RPM. It will fit into the present AGM-68B generator envelope.

- Control unit cooling is best handled through passive cooling if the unit is separate. Oil or fuel cooling is not possible because of their elevated temperatures. Generator cooling cannot be accomplished by using engine oil because the latter cannot receive additional heat load. This leaves air cooling of the generator, employing the ram air used to measure engine inlet temperature as the best option.

- Internal mounting of the generator inside a missile engine is of potential system benefit inasmuch as it will free about 1 cu. ft. of space by eliminating the engine/generator and pump pad. Additional studies to define the thermal and structural interfaces are recommended to enable design of such a generator.

- No new technology was identified that would reduce the weight or volume of the umbilical connector or the separation switch.

SECTION IV

ADVANCED DC GENERATOR SPECIFICATION

A specification was written for a prototype dc generator based on the design analysis reported in section III.

1. SCOPE

1.1 This specification establishes the requirements for the performance and design of a 30 V homopolar, direct current, engine driven generator and associated voltage regulators herein referred to as generator.

2. APPLICABLE DOCUMENTS

Pertinent documents referenced in Boeing generator envelope 232-30010, Generator Direct Current, para. 2.1 and 2.2

Abbreviations:
NA: Not applicable
TBA: To be added.
p.u.: Per Unit

3. REQUIREMENTS

a. Item Definition. The generator is a self-excited, brushless, air-cooled, 5 kW machine that provides 30 Vdc power at the generator terminals.

1) Interface Definition.

a) Generator Mounting Pad. The generator shall be mounted directly to a power take-off pad on the missile jet engine. The generator shall provide a flange and pilot circle to match the engine pad shown on Boeing drawing 232-30011. The power take-off pad maximum continuous operating temperature is 300°F.

b) Regulator Mounting. The regulator shall be mounted on or built as a integral part of the generator.

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c) Mechanical Interface. The generator shall be mechanically coupled to the engine drive by means of a drive shaft. The drive shaft shall mate with the spline of the engine drive. Shaft size shall be that shown in Boeing drawing 232-30011.

d) Electrical Interface. An electrical receptacle in accordance with MIL-C-38999 shall be provided on the generator to interface with the plug on the missile electrical cable. The wiring between the generator and regulator shall be determined by the supplier. The electrical receptacle shall mate with MS27467T21B11P.

b. Characteristics

1) Performance. The generator shall have a continuous rating of 5 kW for the speed and voltage levels specified in 1 a(1)(b) and 1 b(1)(c).

a) Two minute overload. The generator shall withstand a 2 minute overload of 1.3 per unit (pu) at full voltage

b) Rated speed. The generator shall be designed for a nominal rated speed of 60,000 RPM. The generator steady-state speed will range between 48,500 and 64,800 RPM. The generator transient speed will range between 47,000 and 66,000 RPM recovering to within steady-state limits within 2 seconds.

Overspeed. The generator shall meet the requirements of this specification after withstanding 5 minutes of continuous 73,100 RPM overspeed operation at no load, after reaching temperature stability at rated load.

Acceleration/Deceleration. The generator shall withstand a shaft acceleration of 10,000 RPM per second from zero RPM to 60,000 RPM, and a deceleration of 10,000 RPM/s from 60,000 RPM to stop.

Vibration. The generator shall not produce vibration levels that exceed those of figure 9.

c) Voltage Control. The point of regulation shall be at the generator terminals inside the generator housing.

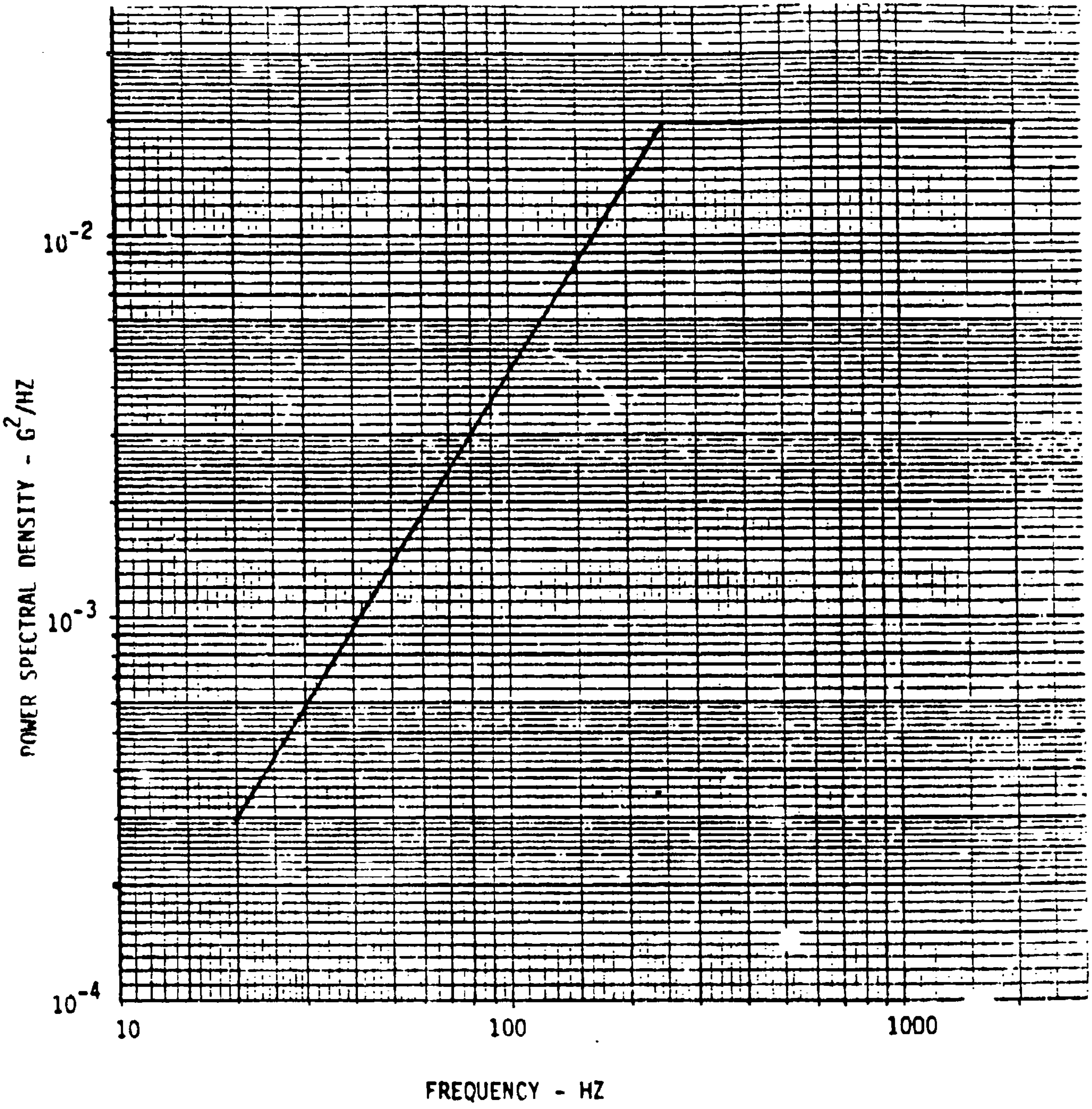

Figure 9. Generator Vibration Limits

Voltage Regulation. When operating between 48,500 RPM and 64,800 RPM from 0.02 pu to full load and over the full temperature range, the output voltage shall be maintained between 30 and 32 V at the point of regulation. When, at the same operating conditions and carrying 1.3 pu load, the respective voltages shall remain within 28-32 Vdc.

Voltage Transient. When switching loads from 0.1 pu to 0.85 pu and down to 0.1 pu, and for generator speeds between 48,500 and 64,800 RPM the generator voltage shall remain within 0.8 and 1.2 pu terminal voltage and recover to within steady-state limits in 0.1 second. (30 V=1.0 pu)

Voltage Regulation During Speed Change. The generator shall not exceed the limits of 30-32 Vdc respectively at the point of regulation when the speed varies between 48,500 and 64,800 RPM. The maximum speed change will be 10,000 RPM/s.

d) Voltage Ripple. When operating between 48,500 and 64,800 RPM from 0.1 pu to full load, the peak ripple voltage shall not exceed the dc average voltage by more than 1.5 V for either polarity. The frequency characteristics of the ripple shall be in accordance with figure 7 of MIL-Std-704.

e) Efficiency. The minimum efficiency at maximum rated speed shall be 76% at 5 kW when both outputs are at full load.

f) Startup and Windmilling. The generator shall be capable of voltage buildup with resistive loads (heaters) having an equivalent resistance of 0.8 ohms across the 30 Vdc terminal. The generator control shall be designed to limit the load reflected back to the engine power take off (PTO) from exceeding the curve of figure 10. A voltage regulator turn-on inhibit circuit may be necessary to limit the PTO loads during engine start. If a turn-on inhibit circuit is used, the inhibit circuit shall not switch the voltage regulator off before the speed declines to 20,000 RPM during generator coast down when the engine is shut down. The generator shall withstand engine windmilling for up to 15 minutes. The generator windmilling speed will be 8000 RPM.

g) Generator Excitation Power. The generator shall be self excited.

2) Physical Characteristics.

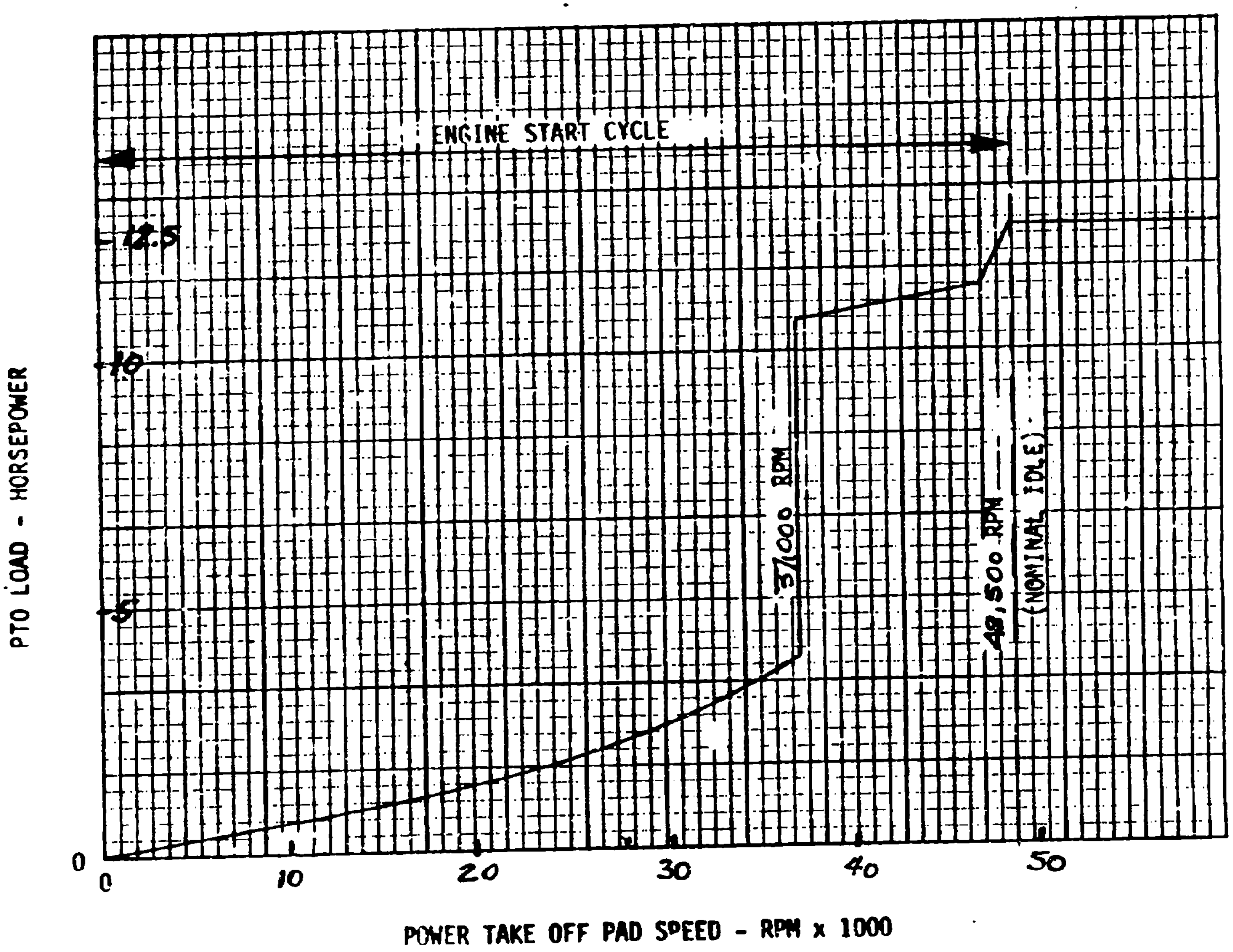

Figure 10. Engine Power Take Off Pad Load Limits During Start Cycle

a) Weight. The generator shall weigh less than 18 lbs.

b) Overhung Moment. The overhung moment shall not exceed 93-inch lbs.

c) Envelope Dimensions. (The generator shall fit within the envelope of the generator defined by Boeing dwg 232-30011).

d) Direction of Rotation. The direction of rotation shall be as shown in Boeing dwg 232-30011 and shall be clearly marked on the generator.

e) Cooling. The generator shall be air cooled. A fan shall be an integral part of the generator to provide self cooling. No ram air or forced air cooling will be provided through the generator. Cooling air will be provided to the 2-inch-dia. air inlet of the generator. The fan shall draw the cooling air through the generator. The temperature of the cooling air provided at the air inlet to the generator is shown in figure 11.

f) Lubrication. The generator, when assembled for testing, and the control unit fan shall be permanently lubricated.

g) Resistance to Liquids. The generator insulation, finishes and materials shall be resistant to the deleterious effects of MIL-L-7808 oil, MIL-H-5606 oil, and jet engine fuel in accordance with MIL-P-87107 (USAF).

3) Reliability. The generator shall meet or exceed the following minimum requirements.

a) Flight Mean Time Between Failure (MTBF). The unit shall be shown by analysis to have a minimum MTBF of 5240 hours while operating within the captive and free-flight environment specified in paragraph 3.2.5 and with the load and speed levels specified in paragraphs 3.2.1.1 and 3.2.1.2.

b) Useful Life. The G&CU shall be designed for a useful life of ten years including operating and storage times in the environment specified herein. For this purpose, useful life is defined as the calendar time that the item is to be in the USAF inventory. During the 10 years useful life, the generator will experience 45 on-off cycles and 100 cumulative hours of operation.

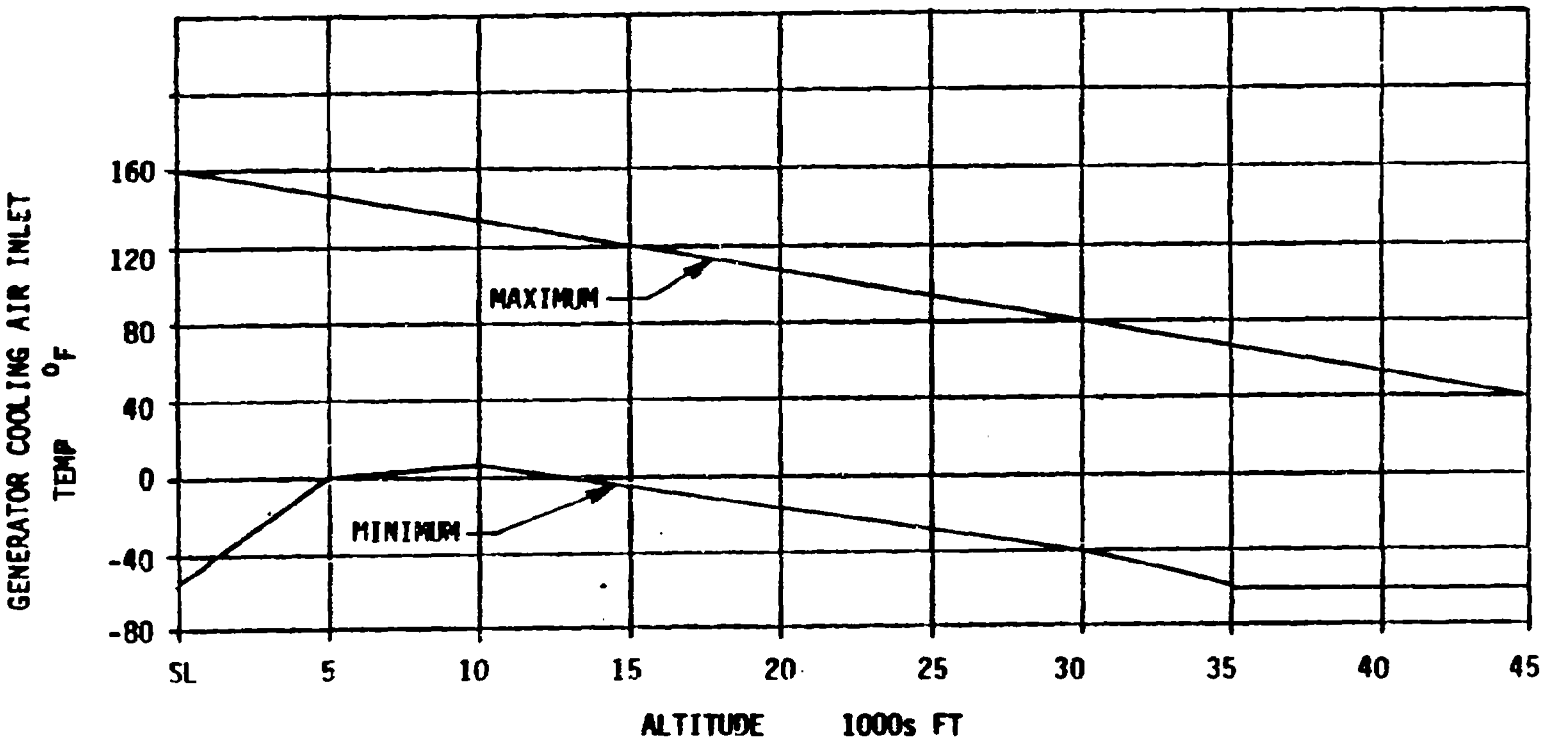

Figure 11. Generator Cooling Air Temperature

4) Maintainability. The G&CU shall require no scheduled or preventive maintenance during its useful life.

5) Environmental Conditions.

a) Non-operating Environment. Ground Operation, Short Term Storage and Transit, and Long Term Storage Modes:

During the ground operation mode, the G&CU are part of an unprotected, fully assembled air vehicle. This mode includes periods of transporting between sheltered storage and maintenance areas, unprotected holding time before, during, and after carrier installation, and time on the operational flight line including aircraft engine runup and taxi conditions.

Short-term storage and transit conditions relate to worldwide shipment and temporary non-operational storage of equipment. Transit or shipment is base-to-base by any means of transportation. Short term storage is considered to mean storage of equipment in a non-operational condition while in transit and in an unprotected area (loading, docks, etc.). Packaging containers may be used to protect the generator against other environments.

Long-term storage conditions related to sheltered but uncontrolled storage of equipment. The generator and regulator may be stored as components or as part of a fully assembled air vehicle.

Captive Flight Mode: During this mode, the generator is installed as part of a fully assembled air vehicle attached to a carrier aircraft which is taking off, airborne or landing.

Natural Environment. The generator shall be capable of operating after exposure to the natural environments shown in Table 13. In addition, the generator shall be capable of operation after exposure to the following environments during captive flight:

Thermal. -54 °C to +71 °C (-65 °F to +160 °F).

TABLE 13. NATURAL ENVIRONMENT

ENVIRONMENT CONDITION	LIMITS
High Temperature	+160 °F *
Low Temperature	-65 °F *
High Humidity (Relative at 80°F)	100%
Low Humidity (Relative at 125°F)	5%
Penetration and Abrasion: Sand and Dust	Per MIL-STD-810C, Method 510.1
Atmospheric Pressure	15.4 psia maximum 1.68 psia maximum
Salt Fog	Per MIL-STD-810C, Method 50.1

Natural environments are as specified in MIL-STD-210 except where noted by an asterisk (*).

Pressure. Ambient pressure from 15.4 to 1.69 pounds per square inch absolute (psia) changing at a rate of 0.50 psi per second.

Thermal Shock. -65°F to 160°F changing at a rate of 6° per second.

Induced Environment (Non-operating). The generator shall be capable of operation after exposure to the induced environments specified in the subsequent subparagraphs.

Mechanical Shock. The generator shall be designed to withstand three shocks in each direction in three axes (18 total) for each of the following design conditions:

Free Flight (ejection)	18 g peak 0.010 to 0.015-second duration half sine pulse shape
Captive Flight	(values enveloped by Free Flight)
Ground Handling and Transportation	(values enveloped by Free Flight)

The generator shall be designed to withstand the bench-handling shock test of MIL-STD-810, Method 516.2, Procedure V.

Acceleration. The generator shall withstand the levels defined by the area within the closed figures shown in Figure 12.

Vibration. The vibration environment for the generator during non-operating conditions (captive carry) is the random vibration level of Figure 13. Exposure time for the generator is 4 hours per axis.

Acoustic. Ground Operation and Captive Flight Mode: As shown in Figure 14.

Survivability/Vulnerability. NA

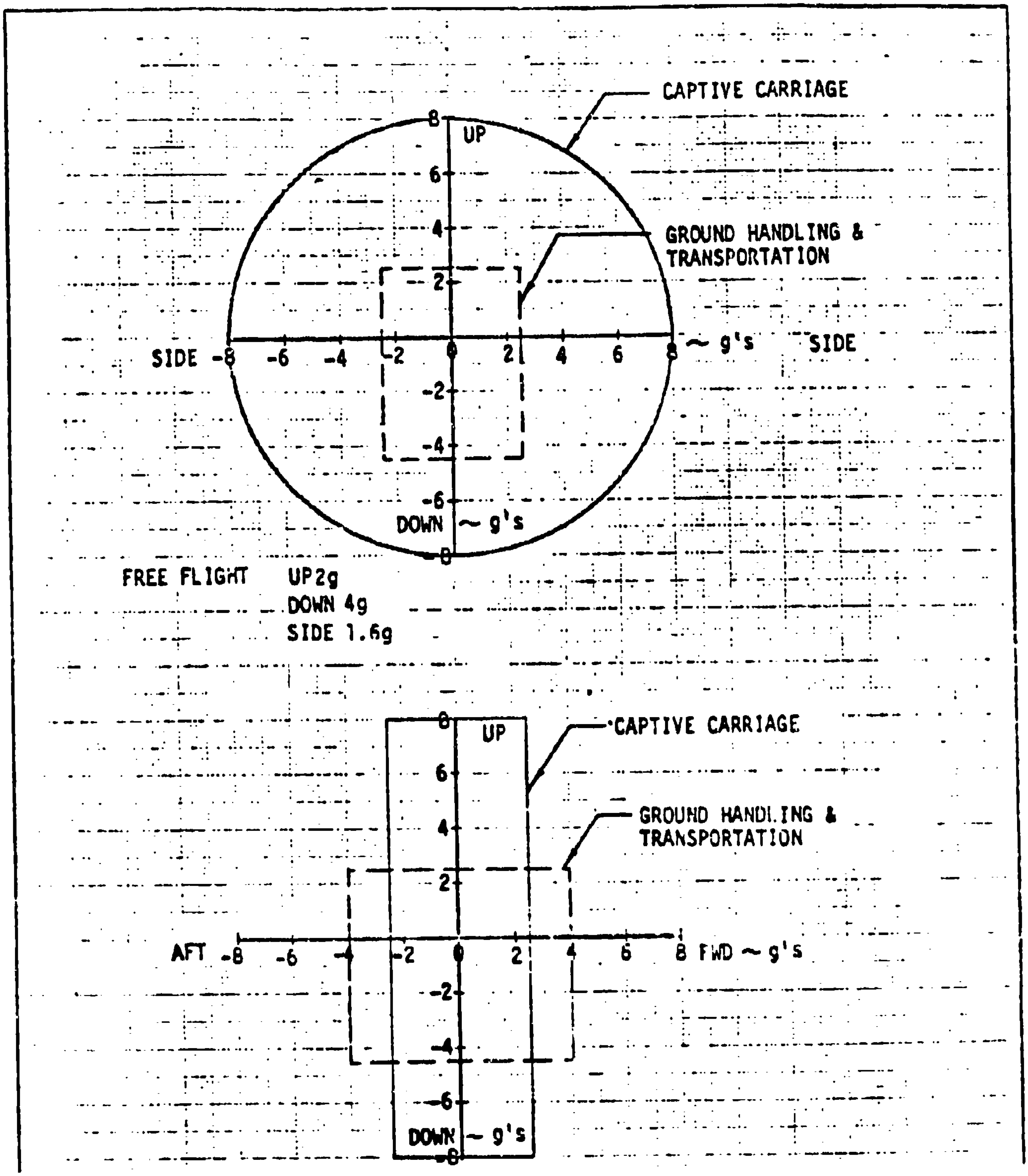

Figure 12. Acceleration Design Limit Load Factors

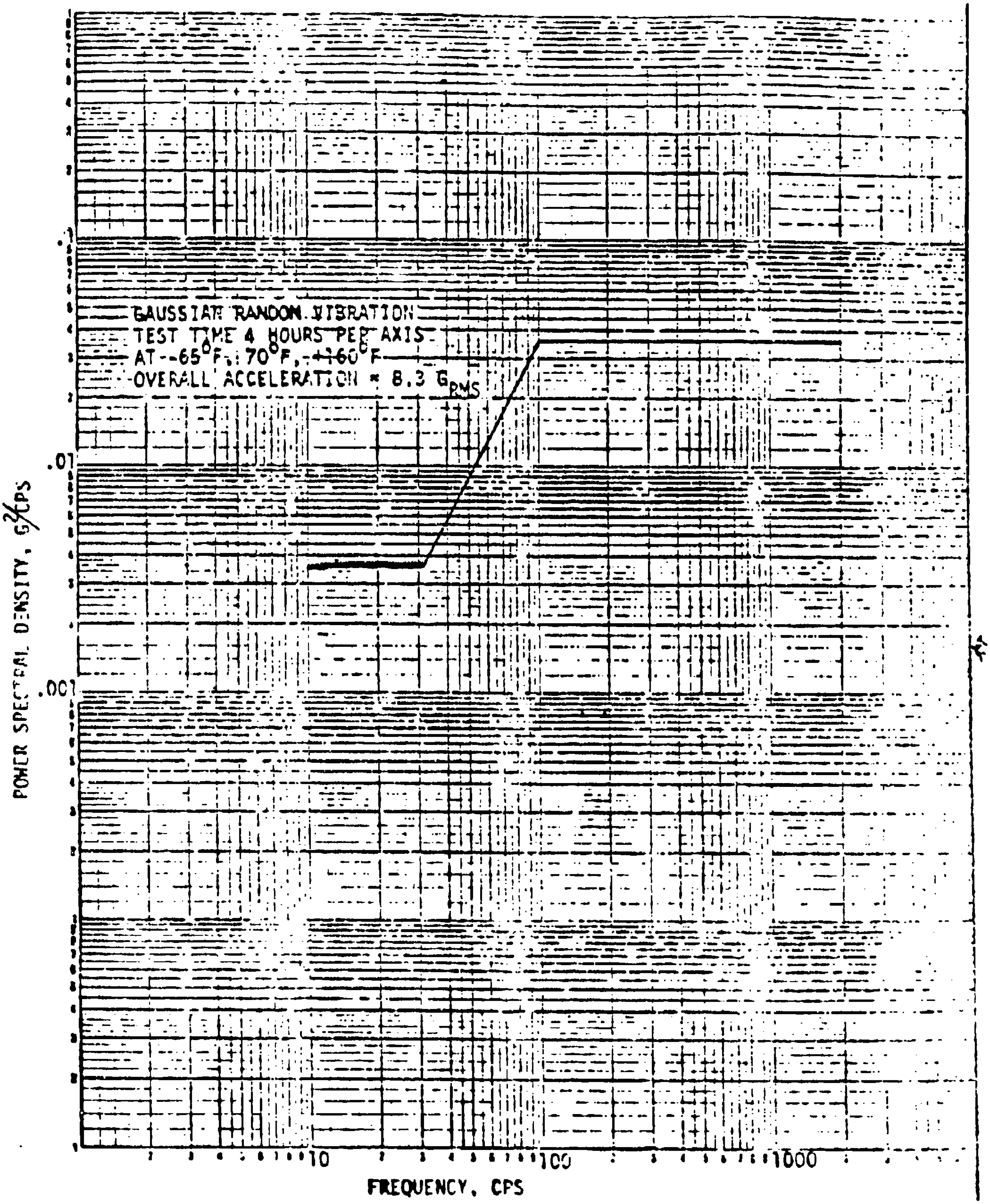

Figure 13. Random Vibration Spectrum

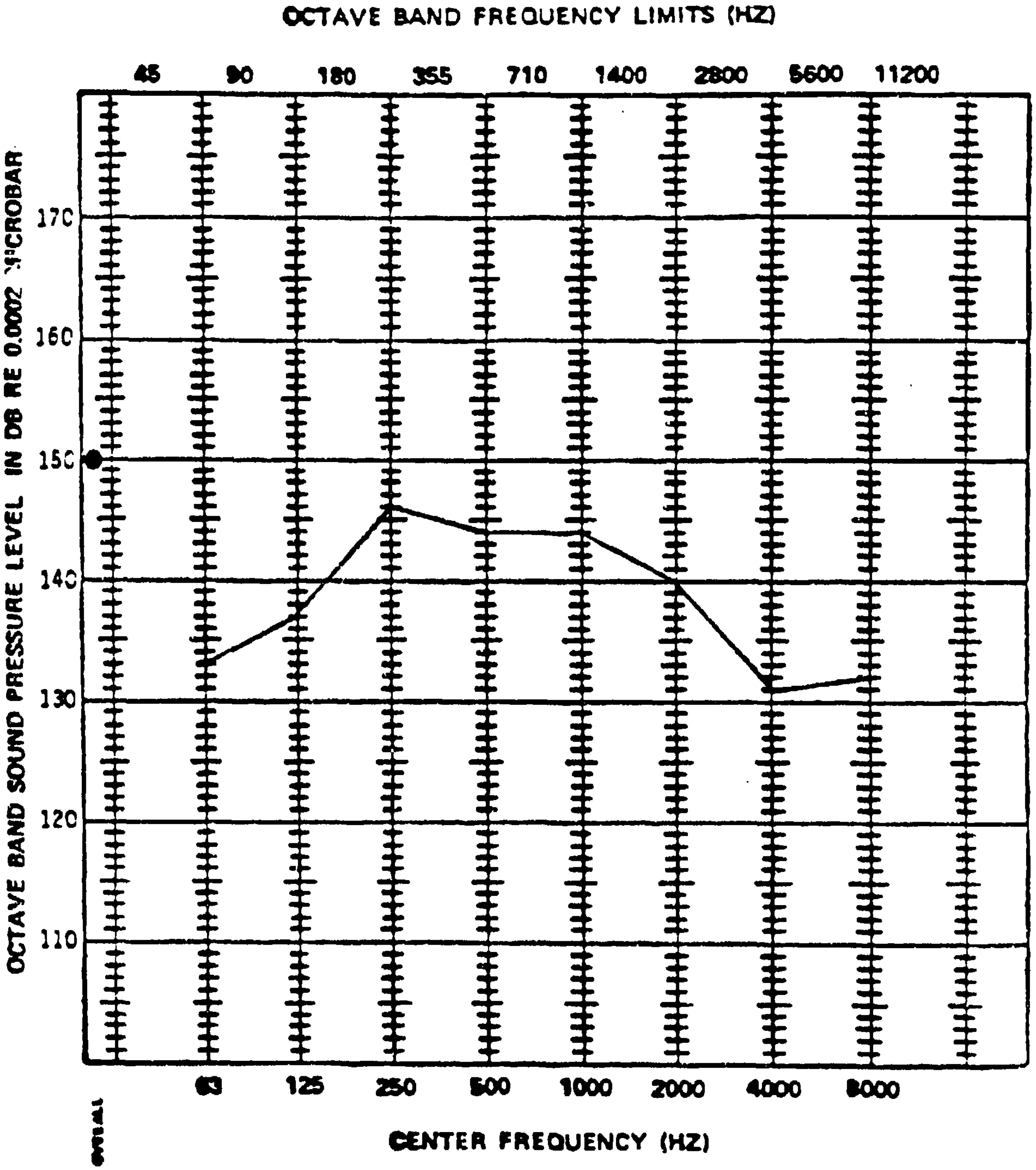

Figure 14. Acoustic Environment

b) Operating Environment. The generator shall meet the reuqirements of this specification during exposure to the following environments:

Temperature. During air vehicle free flight, the ambient temperature environment will be as shown in Figure 15.

Pressure. Ambient pressure from 15.4 to 2.72 pounds per square inch absolute (psia) changing at a rage of 0.3 psi per second.

Humidity. No additional requirements beyond those specified in 3 b(2)(e), Table 13.

Thermal Shock. No additonal requirements beyond those specified in 3 b(5)(a).

Mechanical Shock. No additional requirements beyond those specified.

Acceleration. Per limits of Figure 12.

Vibration. The generator shall be capable of meeting performance requirements while subjected to the following vibration environments:

A low frequency random vibration spectrum of Figure 16 for 1 hour per axis and the sinusoidal vibration spectrum of Figure 17.

Survivability/Vulnerability. NA

Explosive Atmosphere. The item shall not cause ignition of an ambient-explosive gaseous mixture with air when operating in such an atmosphere.

6) Transportability. The generator shall be packaged in accordance with Section 4, Preparation for Delivery , and shall be transportable by common air or surface carriers.

c. Design and Construction.

1) Materials, Processes and Parts. The selection and application of materials and processes shall follow the guidelines of Chapter 7 of AFSC DH 1-2. All parts,

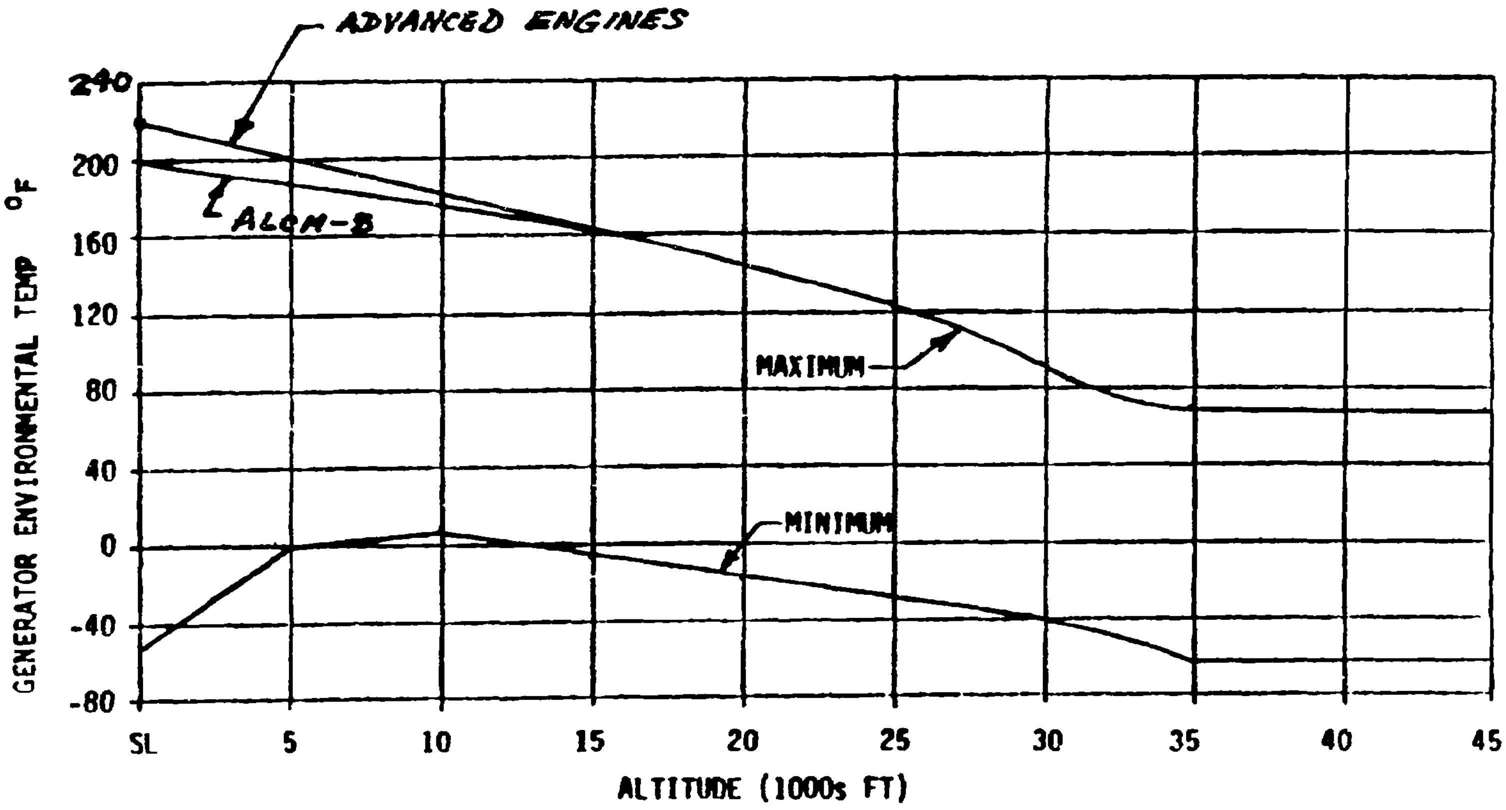

Figure 15. Generator Environmental Temperature

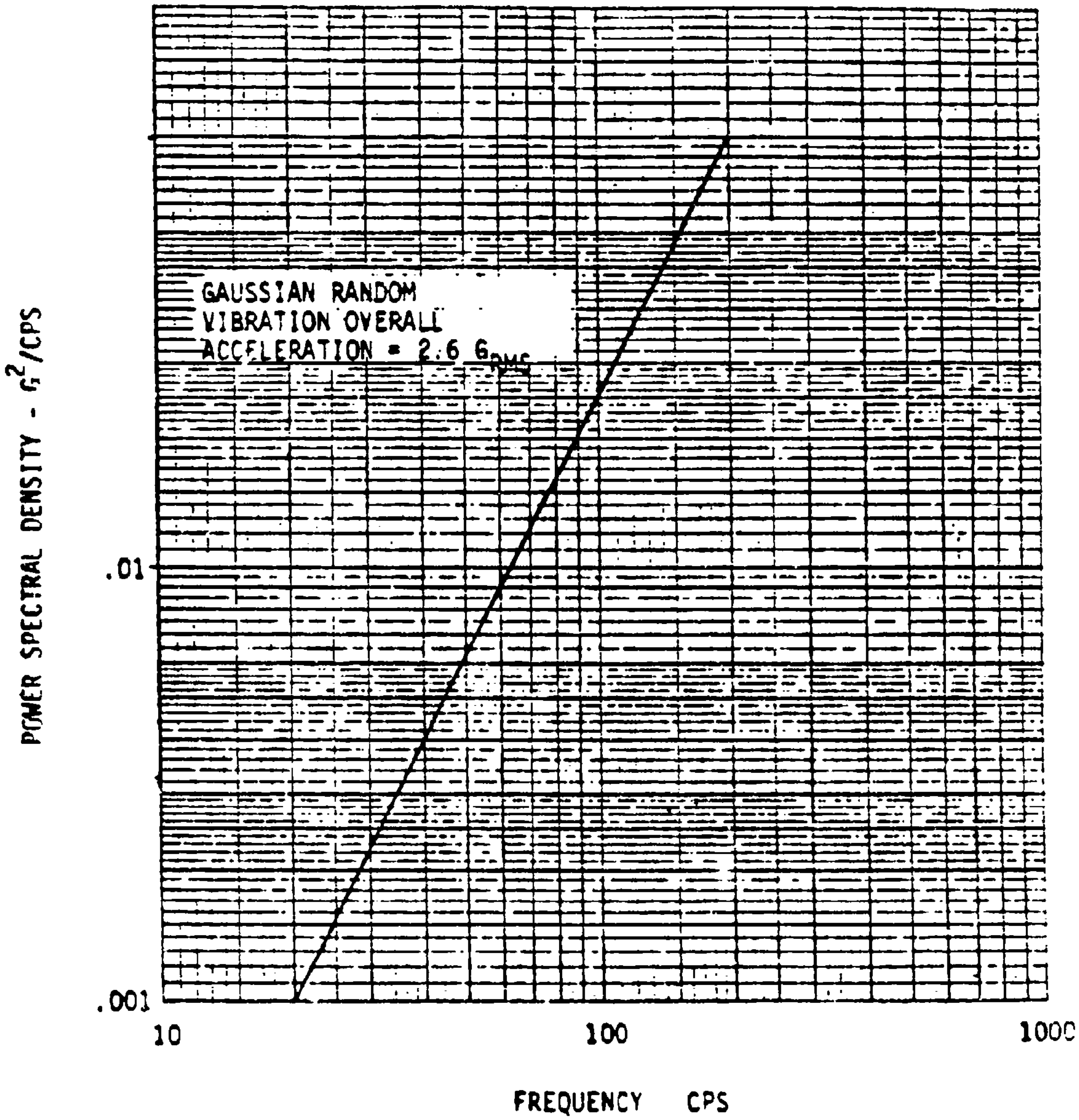

Figure 16. Generator Random Vibration Environment

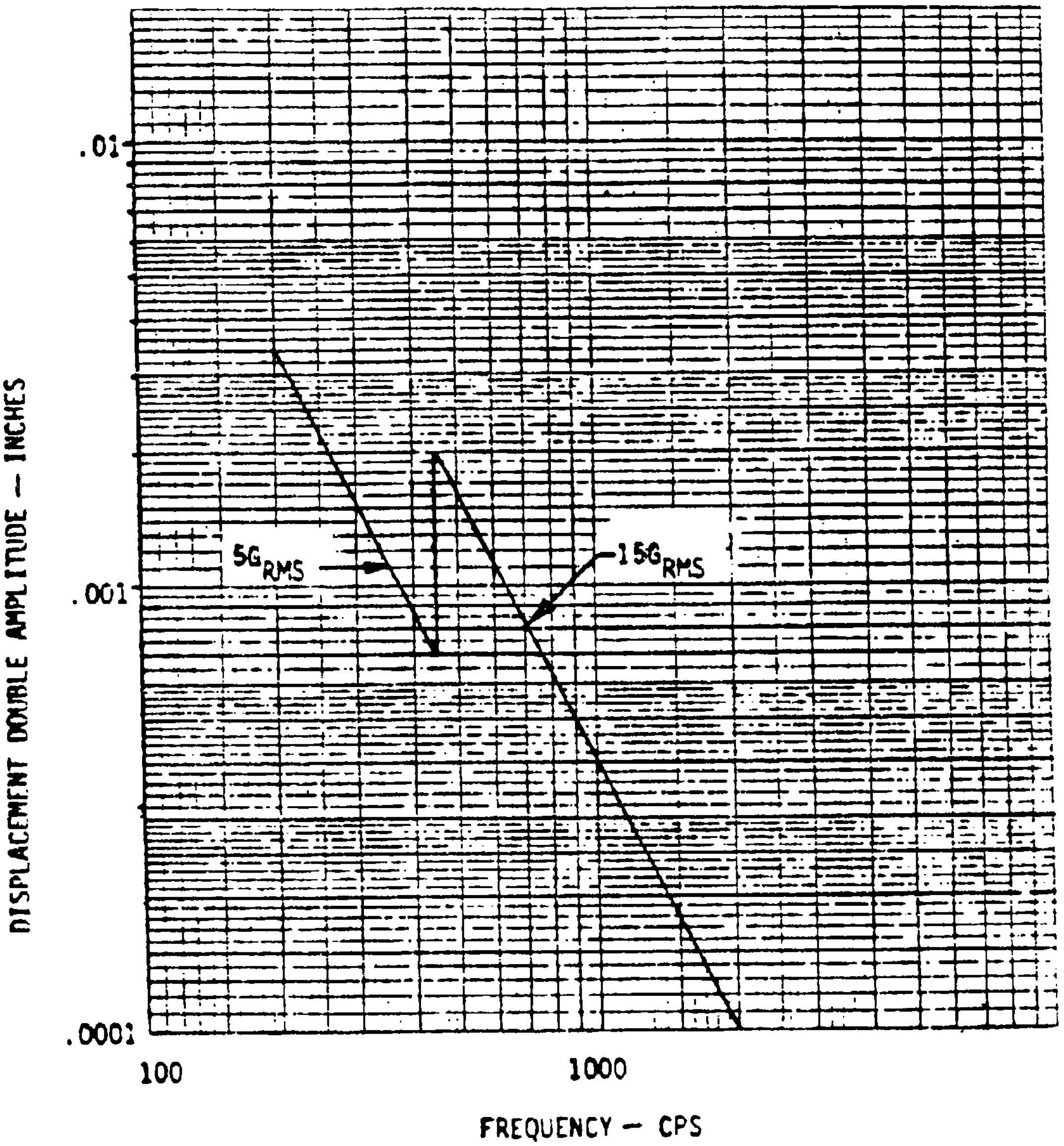

Figure 17. Generator Sinusoidal Vibration Environment

including spares, shall be finished so as to provide protection from corrosion when coupled with a minimum control program. The order of precedence of specifications and standards shall be in accordance with MIL-STD-143 unless otherwise specified herein. Common MS or AN parts such as screws, bolts and nuts, shall be used in preference to equivalent commercial parts wherever practical. If such commercial parts are used, they shall be replaceable by equivalent MS or AN parts without alteration. All low alloy, high-strength steel parts (over 220,000 psi) located in corrosive environments, shall require suitable anodic protection, e.g., cadmium plating, either by vacuum deposit or by an approved process, non-embrittling to high strength steels. All cadmium plated steel fasteners shall be as specified in QQ-P-416 Type II, Class 2. Screw threads shall confirm with MIL-S-7742 or MIL-S-8879. Duplicate parts differing only in thread form are not permitted. Fastener design and selection shall conform to all the requirements of MIL-STD-1515, MIL-BUL-147, and AFSC DH 1-2, Chapter 4, except as noted below. Fasteners and joint allowable loads for fasteners listed in MIL-STD-1515, MIL-BUL-147 shall be in accordance with MIL-HDBK-5, Chapter 8. When selecting fasteners, items which best suit the design shall be selected in the following order of precedence:

- MS Code 11
- MS other codes
- AN
- NAS
- Other industry standards (AS, etc.)
- Company specifications.

All screw recesses (internal drives) for flush head, flat head, pan head, or domed head screws shall conform to MS-33750, Hi-Torque Recess, or MS-9006, Cross Recess. MS-33750 shall apply when the screw is made of material having an ultimate tensile strength (UTS) in excess of 150 KSI, or a hardness greater than Rockwell C32 or equivalent, and is of a number 10 size or greater. When the above conditions do not apply, MS-9006 may be used. Materials and processes for electronic equipment shall be per MIL-E-8189.

a) Selection of Electrical/Electronic Parts. Selection of electrical and electronic parts used in equipment supplied to this specification shall be made from section I of Boeing document D232-10327-1, ALCM part selection list. Part candidate shall satisfy one of the two following requirements:

- o The part shall be a standard part for missile electronic equipment as defined in MIL-E-8189.
- o The part shall be equivalent to or better than similar standard parts. There shall be no standard part suitable for the application. The request shall be accompanied by nonstandard part justification on DESC Form 344 and sufficient data to demonstrate the unsuitability of similar standard parts.

In addition, electrical electronic parts shall meet the following requirements:

- o Microelectronic circuit devices shall satisfy the general requirements of MIL-M-38510 and the specific requirements of reliability class B.
- o Transistors and diodes shall be selected to MIL-STD-701 and procured to MIL-S-19500, JANTX or JANTX quality.
- o Resistors shall be procured to Established Reliability (ER) military specifications.
- o Capacitors shall be selected to MIL-STD-198 and procured to Established Reliability (ER) military specifications.
- o Relays and coils shall be procured to Established Reliability (ER) military specifications.
- o No potted connectors shall be used.
- o No plastic encapsulated devices shall be used.

Derating of Electrical/Electronic Parts. Equipment design shall provide for stress derating of electrical/electronic parts to the requirements defined by the part design. In no event shall any part be stressed or applied beyond the part manufacturer's published ratings for any parameter.

2) Electromagnetic Radiation. The generator shall comply with the EMC control requirements and test limits for CE03 narrow band only, RE02, RS03, and RE 04 of MIL-STD-461, notice 3 for class A equipment. The generator shall be designed to withstand the E-field environment of 20 V/m between 10 kHz to 20 GHz external to the unit.

3) Electrical Bonding. The generator electrical bonding design shall be in accordance with the class R electrical bonding requirement of MIL-B-5087, amendment 2. The frame structure of the generator shall be so assembled that there is a continuous, low impedance path from the anti-drive end to the face of the mounting flange. The direct current resistance from anti-drive end to mounting flange shall not exceed 1 mohm. The area normally covered by mounting nuts shall be free from any insulating type of surface treatment.

4) Nameplates and Product Marking. A nameplate of a permanent and legible nature shall be affixed to the exterior of the generator. The nameplate shall provide the information required per MIL-STD-130. In addition the nameplate shall bear the following data:

Speed	RPM
Rotation	CCW or ARROW
Output	86 Vdc, 28 VDC
Rating	5 KW

5) Workmanship

Workmanship shall be in accordance with high grade manufacturing practices for aircraft and missile accessories and equipment. The units shall be free from dirt, sand, metal chips, machining compounds, and other foreign matter. All machined surfaces shall have a smooth finish and all details of manufacture, including the preparation of parts and accessories, shall be in accordance with good practice for high quality electric equipment. Particular attention shall be given to neatness and thoroughness of soldering, wiring, impregnation of coils, marking of parts, plating, coatings, riveting, clearance between soldered connections, and ruggedness. Burrs, sharp edges, and resin flash that might crumble shall be removed. Equipment workmanship shall be in accordance with the applicable portions of MIL-STD-454.

6) Safety.

a) Electrical Safety. All electrical conductors shall be protected against condensate by location or insulation. Uninsulated conductors or connections shall be located or covered so that accidental contact or grounding is prevented.

b) Personnel Safety. Provisions for personnel safety shall be inaccordance with MIL-STD-454, Requirement I.

c) Factors of Safety. The unit shall be designed to sustain design limit loads without experiencing detrimental deformations or stresses in excess of the yield strength of the structural material. Design limit load is defined as the maximum load resulting from exposure to the shock and vibration environments specified herein. The unit shall be designed to sustain ultimate loads without failure. Ultimate load is defined as the limit load times the design ultimate factor of safety. For free-flight loading conditions, the minimum factor of safety shall be equal to 1.0 for limit loads and 1.25 for ultimate loads. For captive flight, ground operation, and ejection conditions, the minimum design ultimate factor shall be 1.50. For thermal conditions, the minimum design factor shall be 1.0 for all cases.

In addition to the above factors of safety a fitting factor of 1.15 and/or a casting factor of 2.0 shall be applied where applicable.

d. Documentation.

Documentation for the unit shall consist of drawings and specifications prepared and maintained in accordance with MIL-D-1000, MIL-S-83490, MIL-STD-100, MIL-STD-483 (USAF) and MIL-STD-490.

4. PREPARATION FOR DELIVERY

(See apendix C, section 5 of Boeing specification 232-30010)

SECTION V

PROTOTYPE GENERATOR AND CONTROL UNIT DESIGN

1. DESIGN SUMMARY

The generator/control unit was redesigned after the design analysis review to one which did not require adding a converter. The requirement for such a converter could not be imposed on the host airplane, but would have to be incorporated in the missile and be allocated as part of the generator/control unit. Thus, the design of the generator/control unit was modified to produce a 30 V dc output. To accomplish this it was necessary to increase the previously selected speed so as to reduce the generator size and weight. At the 30 V output rating for a 5 kW generator, the current would be of the order of 167 amperes. This led to a trade off which resulted in the selection of a homopolar generator design. Homopolar machines are characterized by high current output at (relatively) low voltage. Their use is essentially confined to those applications. To reduce the generator size significantly, the speed was raised to a nominal value of 60,000 rpm with peaks up to 75,000 rpm. This then imposed a requirement for bearings which could operate at such speeds for the flight period. The generator designers investigated the availability of high-speed bearings and found that the projected life of available bearings was inadequate for the requirement. Hence, the nominal speed was reduced to 40,200 rpm with peaks up to 55,000 rpm. The designers were then able to select a suitable bearing which is available, and would be compatible with the engine shaft speeds.

The other major factor was a fan design and cooling of the control electronics. For this design, a fan consultant was retained. The consultant analyzed the cooling requirements and conducted a trade-off study which resulted in the selection of a single fan at the aft (downstream) end of the generator where the air exits from the generator housing.

a. Generator Fan, Cooling Design. Design of the fan and the cooling passages to keep the regulator transistors and rotor within the required temperature regime was carried out by a trade-off of four concepts to select one. The competitive concepts included single or double fans at the aft end of the generator to pull the air through, as well as fans at the front end to push the cooling air over the control electronics and the rotor. Analysis showed that a single fan at the aft end of the generator was optimum. To verify the selection it is necessary either to test a full scale prototype or a simulation of the fan. Because of complexity of fan design, the uncertainty of high speed fan analyses, and the attendant cost of such designs, a simulation model was selected in order to evaluate the analysis results. In order to be an acceptable fan simulator, it must provide shaft loading similar to an operational fan. Thus, the simulator must be a mass to stress-load the shaft and must provide a thrust on the same shaft bearing as would the designed fan. Since the simulator cannot pull the cooling air throught the generator, the air flow temperature and the pressure will be simulated by forcing air through the generator passages in a test facility in which the air can be controlled. With suitable instrumentation, the measurements of temperature pressure, air flow, and flow rates can be made and compared with the analysis prediction. Corrections to the analysis can then be made so that a correct fan can be designed.

1) Cooling. The following specifications were used in the analysis and design of the cooling system.

- Power generated is 5 kW.
- The exterior dimensions were limited to 6 in. diameter and 7 inches length.
- Rotor speed: 50,000 rpm. (The initial rotor speed was set at 60,000 rpm, but was later reduced).
- Heat sources and quantities were:

  Rotor: 300 watts electrical,
  200 watts air friction,
  Stator: 310 watts electrical,
  Electronic modules: 420 watts electrical,
  Inductors, misc.: 44.5 watts.

Other specifications included a limitation on the inlet air duct location and size, and the design operating flight envelope conditions. The initial design point was at 50,000 ft., hot day, with higher than ambient temperature inlet. This was later changed to 20,000 ft. altitude and 29°F.

a) Configuration Selection. Although the original main objective was to determine feasibility and preliminary design numbers of the cooling fan, it was first necessary to determine the flow and pressure drop of the cooling air. It was therefore necessary to design the cooling passages and calculate the flow velocities. Four cooling configurations were analysed as shown in figure 18. Fan arrangements included both one and two fans. The final selected configuration included one axial flow fan and three cooling paths.

Figure 18 shows the four cooling configurations analyzed. Operating conditions specified were:

20,000 ft. altitude
Temperature: 20^{o}F
(Pressure: 7.183 psia).

The approximate fan power for cooling for each configuration are:

Configuration (Fig 14)	Fan Power (Watts)
S1	545
S2	359
D1	492
D2	328

For the desired alternator-generator efficiency, 350 Watts was the limit of consumed fan power. From this requirement, configurations S1 and D1 were eliminated. The S2 configuration was selected for these reasons:

- o The rotor of D1 or D2 would have to be lengthened to allow sufficient flowing area for the air to move radially inward at the location midway between the ends of the rotor.
- o The additional pressure drop required for the radially inward flow in configuration D1 or D2 was not taken into account.
- o Substantial pressure drop was anticipated for configuration D2 in the outer annulus, because of electronic components and wiring (Figure 19).

b) Heat Transfer. A short computer program was generated for analyzing the heat transfer flow area, the surface area for cooling electronic components, and the outer surface of the stator iron core. The nature of the cooling passages are shown in

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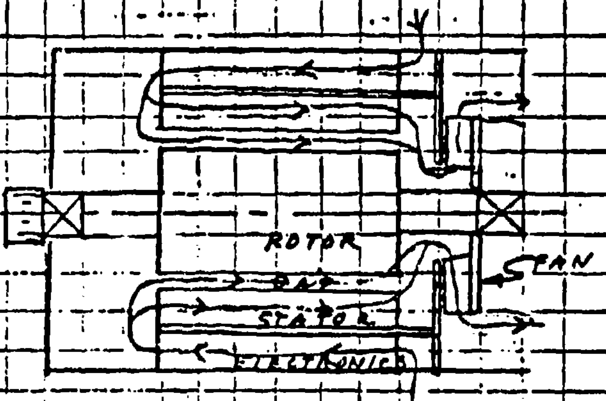
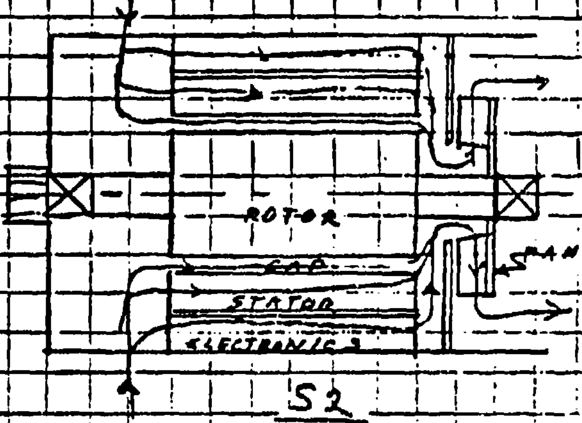
COMPANY: Simmonds
PROJECT: Generator Cooling DATE: PAGE:
SUBJECT: One vs Two Fans

Single Fan Configurations

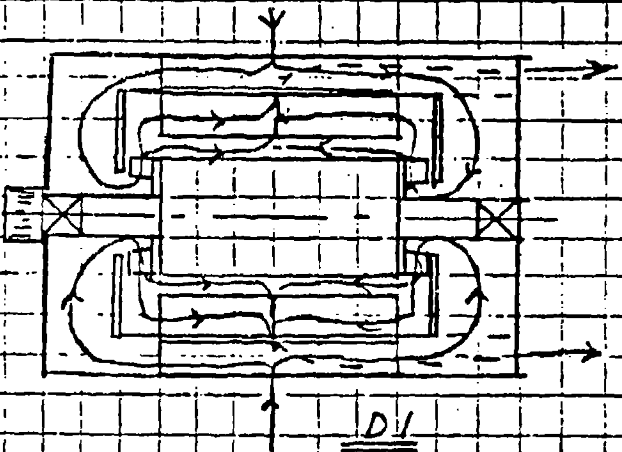


S1

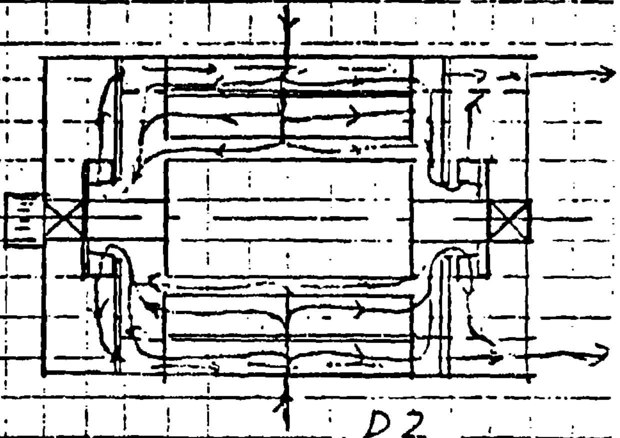


S2

Double Fan Configurations



D1



D2

Compare at: 20,000 feet, ARDC Std. Hot
p = 7.183 psia
T = 29 °F
RPM = 50,000

Figure 18. Fan Configuration

figures 19 and 20. Heat transfer and pressure drop data were obtained from reference 1.

Data from reference 2 were used to determine heat transfer between the rotor and stator. Figure 21 (reference 2) was used for the smooth portion of the shaft. For the laminated and slotted areas, figure 22 was used.

Table 14 is a summary of heat transfer and pressure drop in the cooling paths. Velocity in the cooling passages of the electrical components was determined to satisfy the cooling requirement. Then pressure drop was calculated. To this head loss, three additional head losses were added to account for (a) inlet piping losses, (b) entering losses, and (c) exit losses. The required fan head rise was thus determined.

Stator-rotor flow area was then adjusted to produce the same pressure drop for the required flow. A flow restriction should be added at the fan end of the rotor. The configuration with the restriction is shown in figure 20. The flow restrictor is shown oriented so as to direct the air flow against the stator coil open passages. This approach will cool the stator coil, the stator, and take some of the swirl out of the flow through the gap cooling air. Smoothing the flow in this manner will help to improve fan performance and pressure rise.

c) Metal Temperature. From the heat transfer calculations described, and summaries in table 14, average wall temperatures were determined. The method used yields conservative results, so that we can assume that if the metal temperatues calculated are not excessive, then safe limits are being observed. The method used is as follows:

- o The inlet air, outlet air, and average air temperature are known from design specifications and heat transfer calculations.
- o Average wall temperature is known.
- o Add (T(Avg. wall) - T(Avg. air)) to the inlet air temp and outlet air temperature. The values obtained will be the approximate wall temperature at the inlet and exit. Heat-transfer coefficient is assumed to be constant along the cooling path.
- o Conduction from higher to lower temperature in the walls is not calculated. However, because of this conduction effect, the metal temperature at the hot end will be lower than calculated, and temperature at the cold end will be

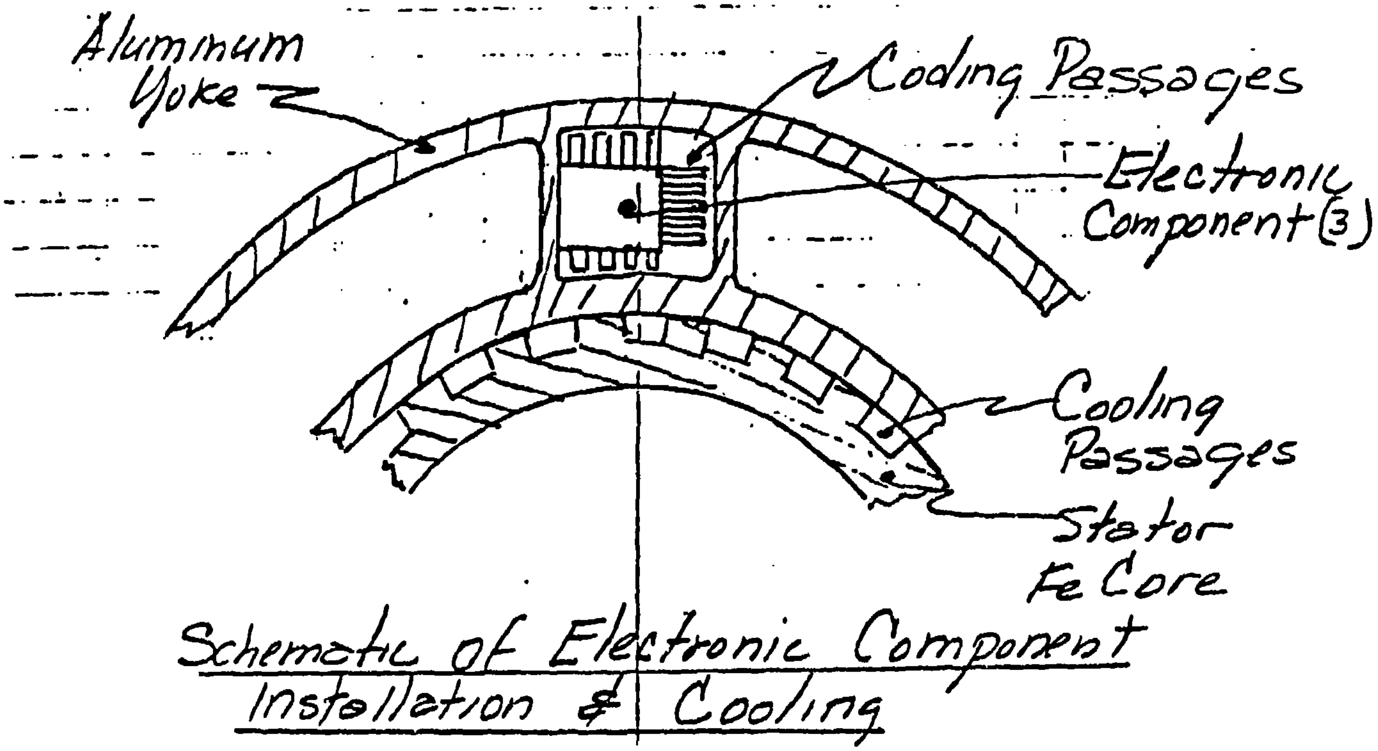


Figure 19. Schematic of Electronic Installation and Cooling

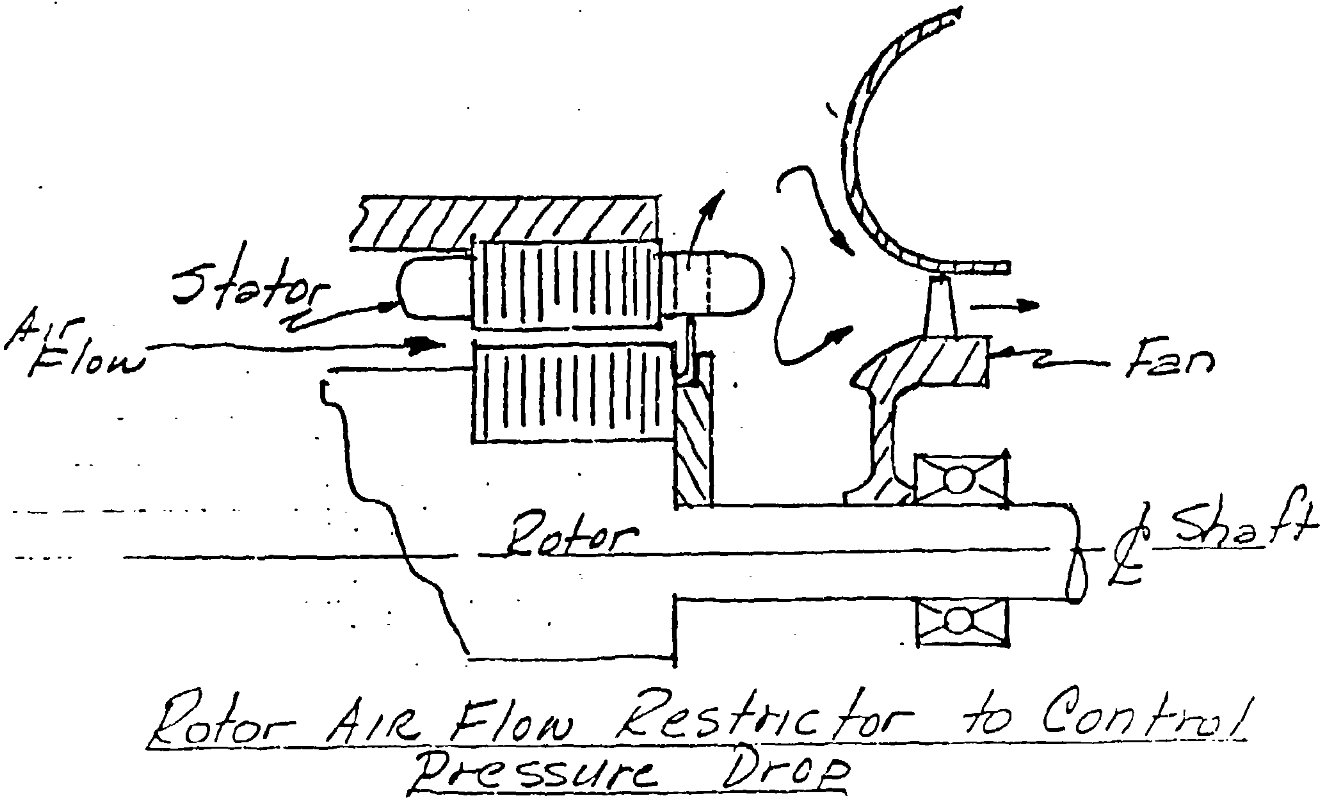


Figure 20. Rotor Air Flow Restrictor to Control Pressure Drop

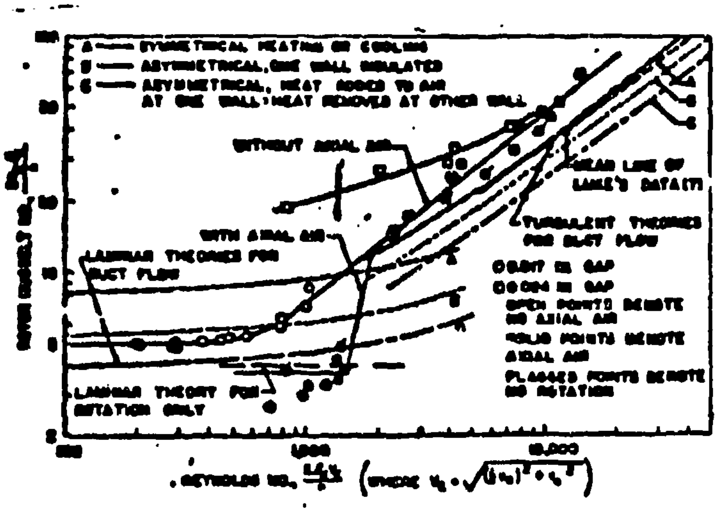


Figure 21. Air Gap Heat Transfer (Smooth Surfaces) Heat Transfer Between Transfer Tetween Rotor Surface and Air

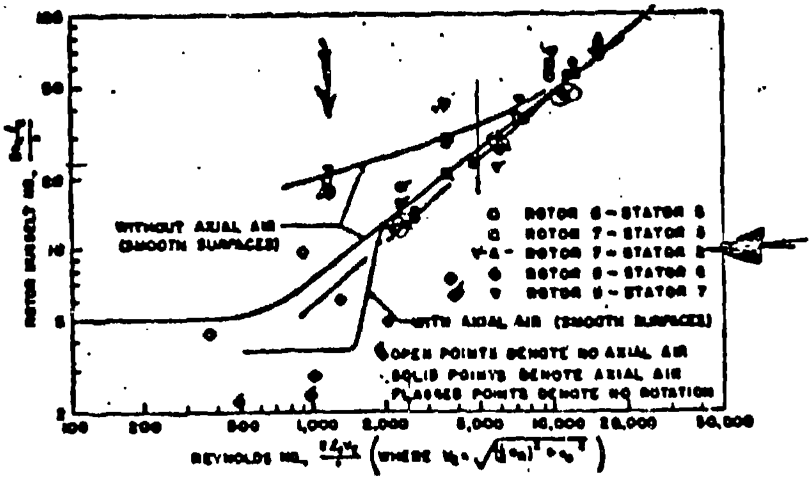


Figure 22. Air Gap Heat Transfer (Slotted Surfaces) Heat Transfer Between Rotor Surface and Air

Table 14. Heat Transfer and Pressure Drop

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COMPANY: Simmonds

PROJECT: Generator Cooling (Phase II) DATE: 3/18/83 PAGE: 16

SUBJECT: Summary Sheet of Cooling

20,000 feet altitude, P = 7.183 psia, T = 29 °F

	Heat Dissipated (Watts)	Average Wall Temp. (°F)	Air Out Temp. (°F)	Air Flow (lb/hr.)	$h_{req'd}$ (BTU/hr ft² °F)	$h_{calc.}$ (BTU/hr ft² °F)	V_a (ft/sec.)	$\frac{V_a^2}{2g}$ (ft)	Pumping Power (Watts)
Electronics	420	195	78	121.9	17.7	18.0	136.1	287.7	91.9
Inductors	25			7.0					5.3
Rect. & Trans.	19.5			7.0					5.3
Cavity wgd	—			9.0					6.8
Stator	*310	200	94	67.8	13.3	15.5	126.7	249.1	51.1
Rotor	590	299	99	120.1	42/13.1	42/13.1	96.6/36.7	144.9	90.6
Totals	1364.5			332.8					251

$$\text{Watts pumping power} = \frac{\overset{\text{lb/hr}\searrow}{W_t} \times \overset{\text{Total head drop}}{1200} \times 746}{60 \times 33{,}000 \times \underset{\uparrow \text{ Assumed fan efficiency}}{0.6}} = 0.754 \times W_t$$

* Required from estimate of distribution of dissipated heat = 220 watts. 90 watts were added because of unknown nature of heat flow from stator copper coils.

somewhat higher than calculated. Average temperature will not be exceeded. Therefore, the values calculated will be conservative.

Using the preceding method of determining wall temperatures, the following results were obtained:

	T(Wall in)	T(Wall avg.)	T(Wall out)	
Electronics	170.5 °F	195. °F	219.5 °F	(1)
Stator	167.5	200.	232.5	
Rotor	264.	299.	334.	(2)

Note (1) This value is above the required 212 °F, but it is very likely that metal conduction will reduce temperature to less than 212 °F. If this does not occur, then further temperature reduction can be obtained by a small increase in air flow.

Note (2) This temperature is less than the 450 °F limit for the rotor, but higher than the limit for the bearing. It is expected that conduction into the fan disc and convection into the cooling air, via the fan blades, will reduce the temperature to less than 334 °F.

d) Fan Design. By means of an existing fan design computer program, a number of fan designs were investigated. The process of arriving at a usable design was as follows:

- o From a rotor speed specification, a tip diameter of 3 inches was found to be a maximum value. This produces a tip speed of 654.5 ft./sec.
- o By varying the blade root (inside) diameter and axial velocity, fan efficiency was then calculated. With an inside diameter of 2.25 inches (blade height 3/8 inch) the total/static efficiency was 0.61.
- o By adding a fan stator (aerodynamic flow straightener) to the blade design of (b), the total/static efficiency was increased 0.71.

A Clark "Y" airfoil configuration was selected as the best alternate for this application, for these reasons:

- It has a flat pressure surface, which is simpler to manufacture and to establish blade angle.
- A 10-percent-thick airfoil has good stall margin and it's relative thinness is agreeable with the tip mach number of 0.58.

A preliminary design sketch of the fan is shown in figure 23. The fan stator (turning vanes) were not used because of space limitations and additional complexity.

For setting the blades, the isolated airfoil method was used (reference 3) without cascade interference correction. Lift coefficient at the root was chosen as 1.0, and at the tip (for a constant chord of 0.522 inch) was 0.72 (See figure 24).

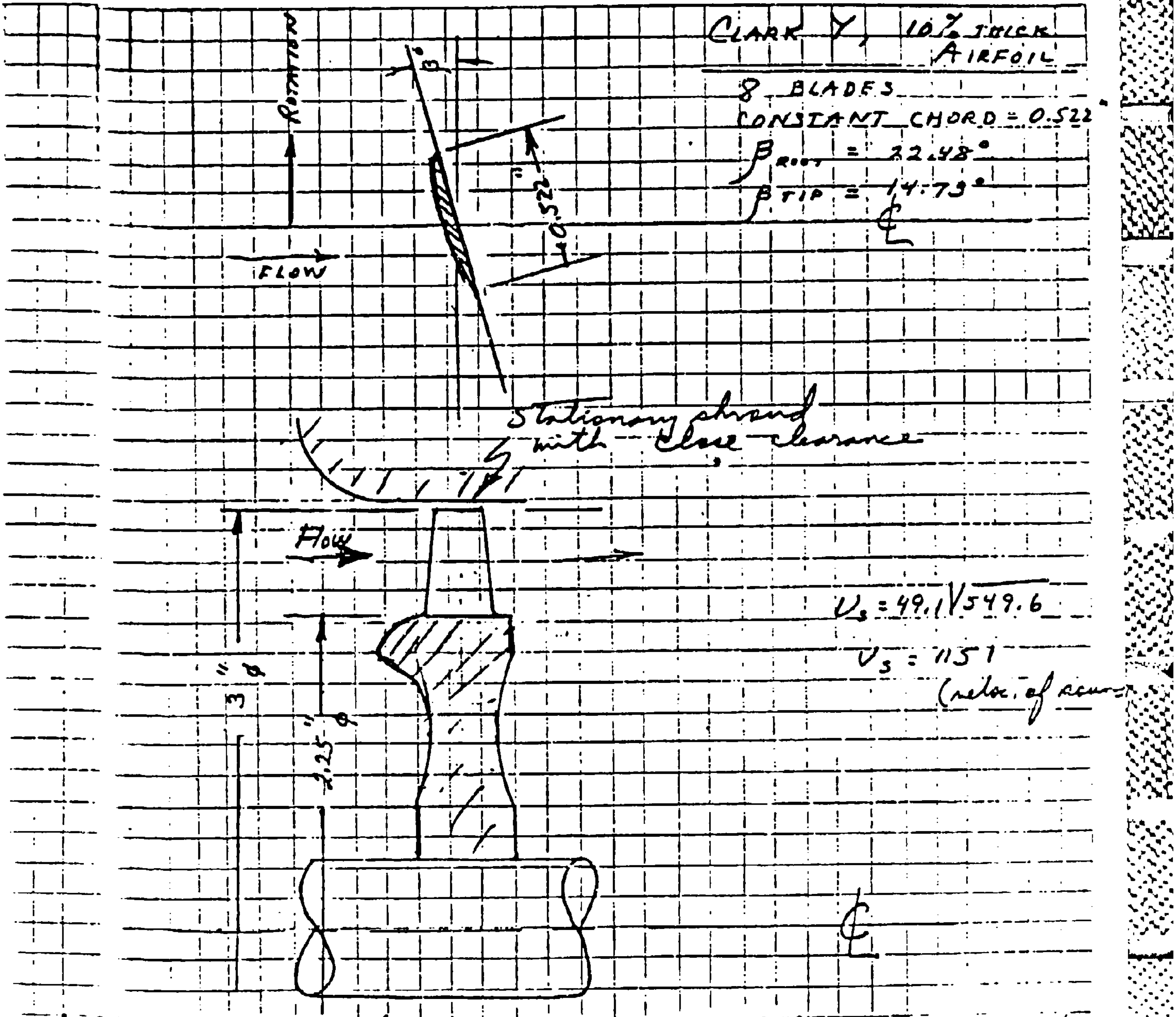
As noted in the notes of figure 23, the fan design is not conservative, because of the stringent design conditions stipulated under which it must operate. The design is considered as a possible one, with some risk involved. Further analysis is recommended before a detailed hardware design is started.

e) Stress Analysis of Fan Rotor. Calculations were made to determine maximum stresses in the fan blade and rotor disc. The conditions used were:

Speed: 50,000 rpm
Inlet Pressure: 14.7 psia
Inlet Temperature: -60 °F

These conditions were used because the fan will be operated at sea level conditions during test, and the resultant stresses will be near the maximum.

- Blade stresses (at root)
  Centrifugal stress = 3492 psi
  Shear stress = 26 psi
  Bending stress = 797 psi
  Thrust per blade = 0.506 pound
  (Does not include disc thrust which may be 3.8 pounds maximum).
- Disc stresses. Stresses were calculated for these two configurations:



Note: Although this design is possible, there is risky as it has been designed. Relative approach Mach # 0.58, which is high for a fan design. Also, blade loading combined with the high stagger (flat angle) is risky. Before a detailed design is made, it must be looked at more closely.

Figure 23. Preliminary Fan Design

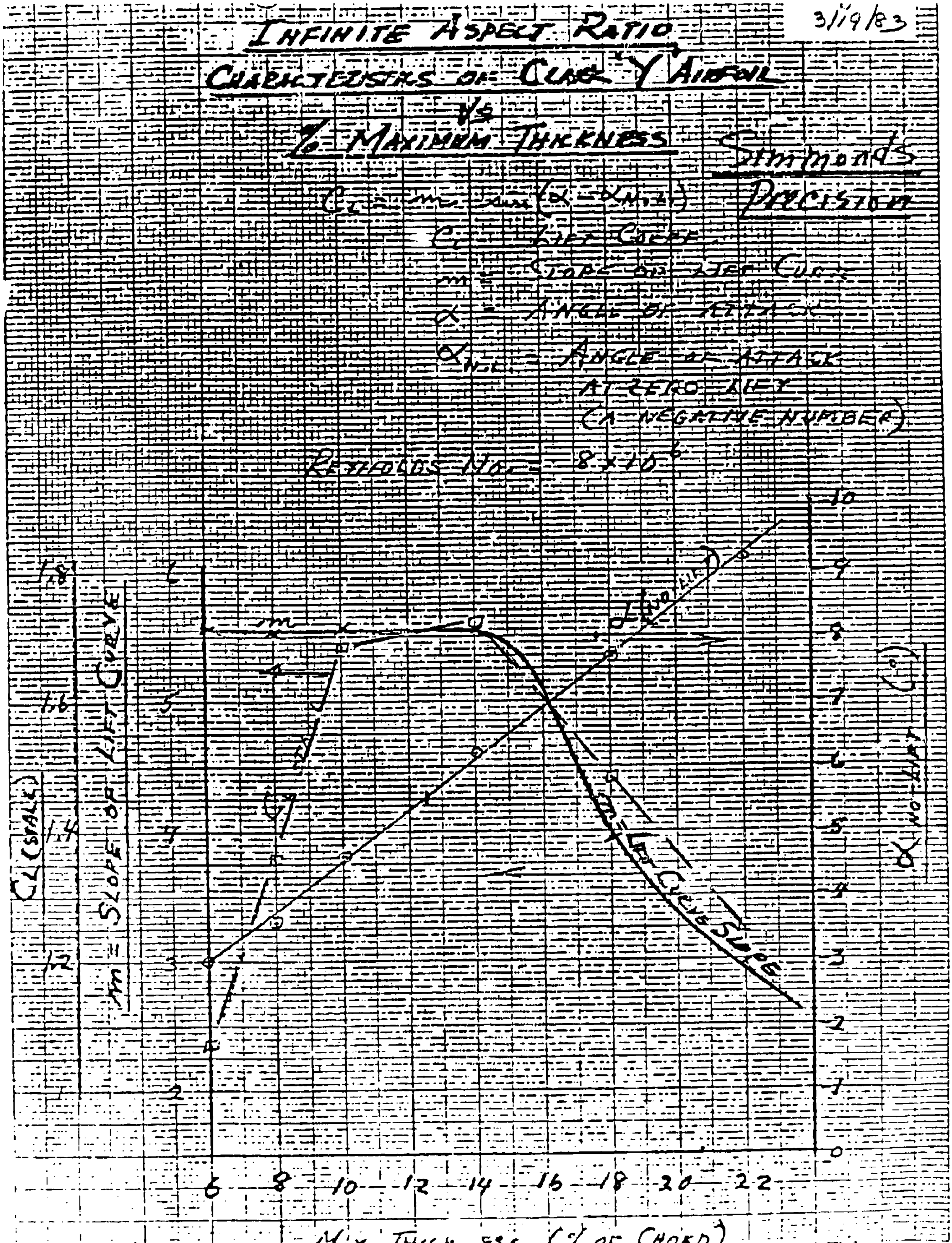


Figure 24. Infinite Aspect Ratio Characteristics of Clark Y Airfoil Versus Percent Maximum Thickness

Results were tabulated on page 3 of Boeing Generator Envelope 232-30010, where:

S_T = Tangential stress of disc alone
S_T = Added tangential stress due to blade pull (70.75 pounds per blade)
S_T = Total tangential stress
S_T = Total radial stress

For the disc, the mean tangential stress is 4493 psi and for the ring, it is 7853 psi. Because the stress levels are low, deflections were not calculated.

The disc width at the bore should be increased, primarily to provide a more stable support on the shaft. It will also reduce the local stress and provide better heat transfer out of the shaft.

f) Recheck of Deflections of Fan Disc and Ring. As a second check on the disc and ring deflection, even with low stresses, the following method was used:

- o Calculating the ring stresses with the pull of the blades.
- o Calculating the stresses of the disc alone.
- o Adding to the disc a varying amount of rim pull (outward).
- o Adding to the ring a varying amount of rim pull (inward).
- o Equating the total tangential stresses at the 7/8-inch radius which resulted from steps 3 and 4.
- o Recalculating the stresses in each with this equated tangential stress at the 7/8" radius.

Results are shown in figure 25. We have tabulated the most significant stresses and compared them with those stresses previously calculated:

	Previous Calculation		New Calculation	
	Disc	Ring	Disc	Ring
Mean Tangential Stress (psi)	4493	7583	7688	4679
Max. Bore Stress (psi)	7501	--	12253	--

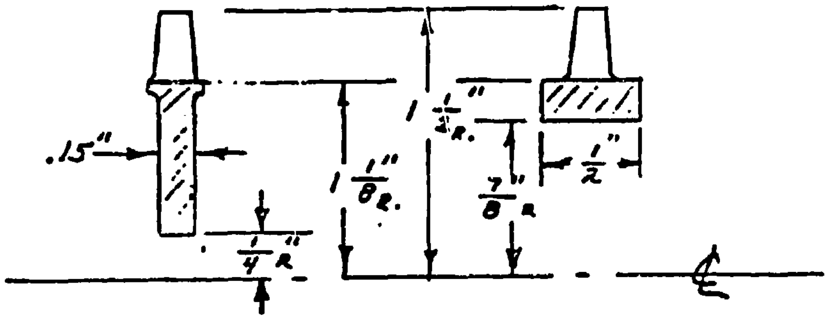


Figure 25. Fan Disc and Ring Dimensions

A further analysis should be made to equate radial stresses and also calculate the stresses due to the bending moment imposed at the outer rim of the disc.

g) Summary and Recommendations for the Fan and Rotor.

- There are no problems with steady state stresses at 50,000 rpm.
- At 65,000 rpm, the significant stresses will be 1.69 times those at 50,000 rpm. A high quality aluminum casting which is solution treated and aged should be satisfactory, as long as good design practice is used to minimize stress concentrations.
- The main concern from a stress standpoint should be blade vibration, because the endurance limit of aluminum is quite low. If natural frequencies are not coincident with the many potential excitation frequencies, there should be no problem.
- As previously stated, there is some aerodynamic risk with this design. Before building such a fan, even for a test, it should be looked at more closely. It is likely that the chord (particularly at the root) should be increased and that the blade setting procedure should be given more attention to adjust for the cascade interference effect.

b. Self-Starting. To provide the self-starting, permanent magnets were added to the rotor. The regulator can then bootstrap the electrical output to full power. Modifications were made to the regulator circuit board to accommodate the self-starting.

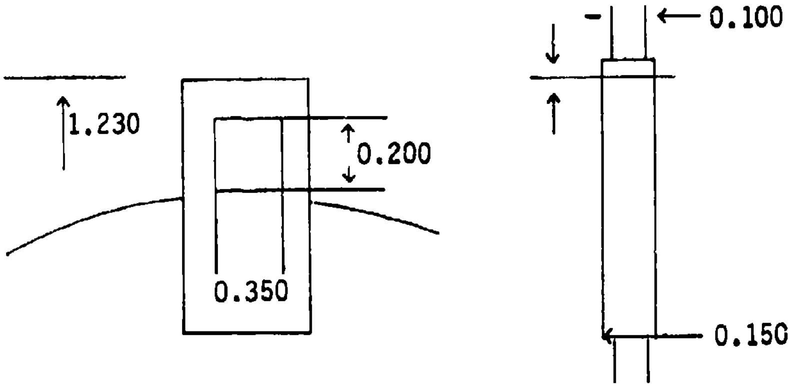
For self-starting, twelve (12) permanent magnets, six (6) at each end of the rotor are used. The magnet characteristics and size are determined such that the voltage generated is more than 15 volts DC at 30600 rpm.

The permanent magnet section is designed using an alternator computer program, print-out of main characteristics show that the neutral to line open circuit voltage per phase at 30,600 rpm is 7.9 volts RMS and the optimum power per phase is 66.9 watts. 7.9 voltas RMS line to neutral converts to about 16.0 volts DC, this is above the minimum needed to turn the system on.

This analysis assumes that the stator covers approximately 0.11 inch of the permanent magnet part as indicated by the resistance and reactance values. The maximum Flux density in the stator tooth is calculated to be 0.69 tesla. The additional core loss of 2.4 watts is not enough to change the overall [illegible] calculations.

The output of the permanent magnet section is only 3.9% of the total power output. Therefore, the impact of the permanent magnets on the control of the homopolar field for regulation will be unimportant. Calculations and sketches of the permanent magnet rotor are given below.

Starting Magnet/and Plate



Magnet = 0.300 x 0.250 x 0.100 Density = 0.290 #/ft^3
End Plate = 30 Stainless σ_y = 35,000 psi

1) Magnet Load

radius of CG = $\left\{ (1/2)\ (2.230)\ -\ .06)\ +\ \left[(1/2)(2.230 - 0.060 - 0.200) \right] \right\}^{1/2}$

= 0.995

weight = ρV = (.29 #/ft^3) (.2") (.25") (.1") = 1.45 lbs.

load = MWr = $\frac{1.45\ -\ 3.66}{3.06\ \#/ft^3} - \frac{2\pi}{60} \times 61000)^2\ (.955) = 146$ lbs

2) Assume Pure Shear Failure

Area = 2. (.100) (.06) + (.250) (.06) = .027 in^2

τ = F/# = (146 lbs.)/(.027 in^2)

= 5400 psi

3) Pure Tension

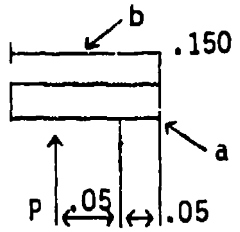
$$\text{Area} = (.390)\ (.050) + (.390 - 250)\ (.100) = 0.335 \text{ in}^2$$

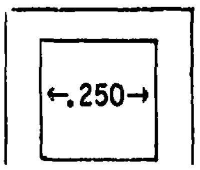
$$\sigma = P/A = (146 \text{ lbs})/(.0335 \text{ in}^2)$$

$$= 4400 \text{ psi}$$

4) Bending

Assume load from magnet acts in center of magnet.





$$I = \Sigma \frac{bh^3}{12} = \frac{(.390 - .250)\ (.150)^3}{12} + \frac{(.250)\ (.050)^3}{12}$$

$$= \underline{3.99 \text{ E-5} + 2.604 \text{ E-6}} = \underline{4.198 \text{ E-5 in } \#}$$

$$\left[\text{Neglects parallel axis theorem}\right] \quad \sigma = \frac{Mc}{I}$$

$$M = (146 \text{ lb})\ \left(.05 + \frac{.05}{2}\right) = 11 \text{ in lb}$$

$$\sigma = \frac{(11 \text{ in lb})\ (.05/2)^2}{(4.198 \text{ E-5})} = 65000 \text{ psi}$$

Section is thicker, I would be greater and stresses less.

For shaft diam of 0.450, backiron thickness of 0.525, and 0.0. of 2.230 (in), for 6-pole rotor, tooth width is .389, and tooth height is .365 (in). Rotor speed is 61,000 rpm, backiron stress is 15,721 psi, factor of safety = 2.23.

c. Yoke Losses. The homopolar power loss calculations assume that the yoke and the shaft carry a fixed flux created by a DC current. Although there is a pulsating flux created in the stator laminations due to the rotor paddles moving from stator slot to stator tooth, the fluxuations decrease to 0 at yoke and shaft.

The argument is made by averaging the air gap around the rotor as the rotor turns. The air gap is nearly constant. Thus, though there is localized flux changes, those changes are summed and cancelled by the time the flux enters the yoke and shaft.

Hence, the assumption that there will not be any losses in the yoke due to pulsating flux. This remains true so long as the stator core is not saturated and this is one of our design criteria.

The individual losses that are calculated by the computer program are as follows:

- Field conductor losses.
- Stator conductor losses.
- Pole face losses.
- Stator core losses.
- Stator tooth losses.
- Windage losses.
- Miscellaneous load losses.

A comparison of test data and calculated results on three alternators showed a maximum difference of 0.7% on overall efficiency. From this it can be concluded that the yoke losses, if any, is less than .07%.

d. Alternator Design Margins. The alternator is designed to meet the overload output requirements at minimum speed and maximum temperature.

For a homopolar alternator, the maximum output at a given speed is determined by the flux density in various components and the current density in armature and field conductors. So long as there is no saturation at full load, the machine will have overload capability, assuming also that there is no overheating. As the parts start to saturate they require increasingly large ampere turns, thus limiting the output. In the proposed design at full load and maximum speed, the flux density in shaft and yoke are

1.4 tesla and 1.33 tesla, respectively. During 130% overload, other conditions remaining the same, the above flux densities become 1.52 tesla and 1.45 tesla. The other parts like rotor poles, stator tooth, and core have lower flux densities, mainly to limit the overall losses. The current density in the field during overload condition is 6800 amps per square inch.

Assuming a limit of 1.6 tesla for flux density in the shaft and yoke, the design has a margin of 5.2 to 10%.

e. Housing. The housing was designed to give sufficient cooling to the regulator electronics to allow for the heat transfer required in paragraph IV, 1a 1(b). A cast housing was selected over a machined housing because of the intricacy of the passages.

f. Spline Selection. A review was made of spline endings on the alternator shaft end for coupling with the drive motor. The design selected is one that is found in machines available from industry.

g. Printed Circuit Board Vibration Analysis.

1) Calculated Natural Frequency. The board was modeled as a simple beam with clamped edges loaded by a uniformly distributed load. There were concentrated loads, however these were typically mounted near the edges. Since their effect would be lessened due to the clamped edges, the effect of the concentrated loads were included in the distributed load. Plate stiffness, D, was substituted for beam stiffness, EI, in the frequency equation. The board was NEMA G-10 laminate, .060-inch thick. The frequency equation for a simple beam with fixed ends was used to estimate the fundamental frequency of the board.

$$f_i = \frac{\lambda_i^2}{2\pi L^2}\left(\frac{EIg}{m}\right)^{1/2}$$

$\lambda_1 = 4.730$

f_i = i^{th} mode critical freq. (Hz)

$E = 2.2 \times 10^6$ (psi)

$\nu = .12$

m = weight/unit Length (Lb$_f$/in) = .315 [illegible]

$g = 386$ in/s^2

$D = \frac{Ebh^3}{12(1-\nu^2)} = 181$ Lb-in^2

b = board width = 4.5 in

h = board thickness = .060 in

L = board Length = 2.37 in

f_1 = 300 Hz

2) Calculation of Max. Single Amplitude Deflection. Calculations from "Vibration Analysis for Electronic Equipment" by Dave Steinberg. The max. single amplitude deflection:

$$Y_o = \frac{(386)(G)(Q)}{4 \pi f^2}$$

Q = Transmissibility $\approx (f_n)^{1/2}$

f = Harmonic frequency (Hz)

G = Input acceleration in G's = 5 (per CDRL13)

Yo = .0094"

As per above reference, a design goal for maximum deflection is:

Yo_{max} = (.003) (b)

b = Board length between supports

Yo_{max} = .0071"

The operating amplitude was shown to be greater than the maximum recommended value. This dilemna could be solved using board stiffeners or some method to reduce transmissibility from the case to the board. Ultimately, testing of a prototype piece will determine the extent of modification.

h. Generator.

1) Bearing Load Analysis, Calculation of Radial Loads

Radial load = (shaft assy weight) + (imbalance force) x 1/2

Shaft Assy = 2.55 Lb_f

Imbalance force = mr w^2 Total imbalance = .001 in. oz.

$$= \frac{(.001 \text{ in/oz})(60900 \frac{\pi}{30} \frac{1}{5})^2}{386 \text{ in/s}^2} \frac{1 \text{ Lbf}}{16 \text{ oz}}$$

$$= 6.59 \text{ Lbf}$$

Radial load = 1/2 (2.55 + 6.59) = 4.57 Lb_f

2) Bearing Load Analysis, Calculation of Thrust Loads

Thrust load = fan reaction + bearing preload.

Preload = 10 Lb_f (per catalogue)

Fan reaction = 4.05 Lb_f (blades) + 3.8 Lb_f (disk) (per consultants 3/25/83)

= 7.85 Lb_f

Thrust load = 17.85 Lb (use full value due to uncertainty).

3) Bearing Load Analysis, Bearing Feasibility.

The bearing selected for this application, based on load and speed requirements, was the Barden #100FFTX1K5. It was chosen with flexseals to insure against contamination of, and try to retard oxidation of, the grease. Exxon Andok 260 (Barden Code G-29) grease should be used because of its high dN and temperature capabilities (dN = 600,000; max. op. temp. = 300 °F).

Bearing life (L_{10}) calculation was based on Barden catalogue #ST2, pp. E-17 thru E-20 (see attached). The equation is:

$L_{10} = L_{1000} \times (A_1) \times (A_2) \times (1000/N)$; where

L_{1000} = Bearing life in thousands of hours at 1000 rpm

N = Brg speed in rpm

A_1 and A_2 are life modifying factors which take into account lubricant viscosity, radial and thrust loads and bearing material. This formula assumes adequate lubrication throughout the temperature range and life which the bearing must endure. For this bearing and load conditions:

Radial load R = 4.57 Lb_f

Thrust load T = 17.9 Lb_f

Load Rating C = 660 Lb_f

Contact Angle = 12.8°

No. of balls n = 7

C_p = .72

L_{1000} = 210,000 hours

A_1 = 1.00

Viscosity of grease at 280°F; V = 5.8 cSt U = 20

$A_2 = 1.22$

$L_{10} = A_1 A_2 L_{1000} \times 10^3/N$

$= (1.00)\ (1.22)\ (210{,}000)\ (10^3)/(50000)$

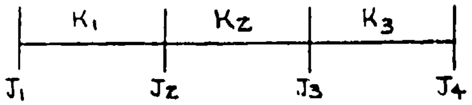
$= \underline{5100 \text{ hours}}$

The bearing life is controlled by the grease. Maximum speed must be limited to 60,000 rpm due to the dN value for this grease; this is only 900 rpm shy of the ratioed value of max. speed from CDRL13. The rotor temperature must be controlled to about 260°F (currently 300°F) to keep the viscosity of the grease sufficient to assure a hydrodynamic film.

The 10 year life, however, is the limiting requirement. Typical greases will oxidize when exposed to air. The flexseals will reduce this exposure, but the twice/year running of the unit will adversely affect life of the grease. The shelf life of petroleum grease in an unsealed environment is on the order of 2 years. Synthetic greases, which are more oxidation resistant, cannot handle dN values greater than 200,000 (20,000 rpm).

4) Critical Shaft Speed Analysis

a) Calculated Torsional Natural Frequency. The torsional frequency was calculated using Holzer's method as outlined in "Mechanical Vibrations" by Tse, Morse, Hinkle. The discrete masses are: The fan, the two rotor stacks, and the center section of the shaft. Stiffnesses were calculated using shaft dimensions and material properties (SAE4620).



J_1 = 8.10E-5 Lb_f-s^2-in (fan)

$J_2 = J_4$ = 7.58E-4 Lb_f-s^2-in (stack)

J_3 = 8.02E-4 Lb_f-s^2-in (center of shaft)

K_1 = 6.74E6 in-Lb/rad

$K_2 = K_3$ = 3.69E7 in-Lb/rad

First mode 209000 rad/sec
2000000 RPM

b) First Mode Lateral Natural Frequency. Lateral rotor dynamics were analyzed using an in-house finite element method program. Assuming infinite bearing stiffness, the first mode critical frequency was 102000 RPM (1700 Hz).

c) First 3 Modes, Including Effects of Bearing Stiffness. Using the bearing stiffness of 263,000 Lb_f/in (as per Barden), the running critical speed first mode was 1130 Hz (67600 RPM). 110% of overspeed; 135% of nominal. Static Brg stiffness was assumed over the speed range. Frequencies for modes 1, 2, and 3 were plotted as a function of bearing stiffness.

d) Conclusion. The shaft assembly was shown to be dynamically sound, from a vibrations standpoint. Rotor lamination integrity also was checked with classical methods. Two assumptions were: 1) the most likely failure mode is tensile (hoop) failure in the rotor back iron, and 2) the tensile stress is evenly distributed across the back iron. The analysis was based on the superposition of the stresses caused by the centrifugal forces due to the back iron and the poles. The lamination was also analyzed to assure that the tooth would not pull out of the back iron.

Fan assembly integrity was analyzed by modeling the hub as a disk-ring-fan assembly. Artificial loads were applied to the discrete parts to assure continuity of the solid unit and stresses were computed from the superposition of all applied loads. The same answers resulted for equating stresses at the junction.

Fan blade dynamics were investigated using a Campbell diagram and results showed no problems should be anticipated in this area.

i. Overhung Moment Analysis. An overhung moment analysis for the generator flange mount is shown in table 15.

TABLE 15. OVERHUNG MOMENTS

Item	Weight (lb)	CG (in. from -A-)	OM (in-lb)
End Cap	1.74	0.22	0.38
End Cap	2.10	6.46	13.57
Housing	1.70	3.45	5.87
Box	0.44	3.60	1.58
Rotor	2.41	3.14	7.57
Stator & Yoke	6.25	3.20	20.00
Inductor, L1	0.8	5.03	4.02
Inductor, L2	0.7	2.50	1.75
Connector	0.26	5.45	1.42
Capacitor	0.01	3.80	0.04
Bearing	0.06	0.10	0.006
Bearing	0.06	6.50	0.39
Rectifiers (6)	0.25	3.20	0.80
Fan	0.14	5.85	0.82
PCB	0.75	3.15	2.36
Field Coil	0.71	3.20	2.27

Total Weight = 18.4 lb.

Total Overhung Moment = 62.8 in-lb.

j. Thermal Analysis. A cooling system has been developed for the alternator-regulator. However, due to the severe system requirements and the need to further define the operating environment, the fan design, and the analysis is not complete for a production machine. The air inlet temperature and system efficiency restrictions over the specified flight profile simply cannot be met with the present alternator/regulator design. This report is intended to analyze the application and provide data to support additional concessions necessary to develop a sound design.

The layout shown in figure 26 represents the system developed to analyze the cooling of the alternator and the electronics. The package dimensions represent the minimum

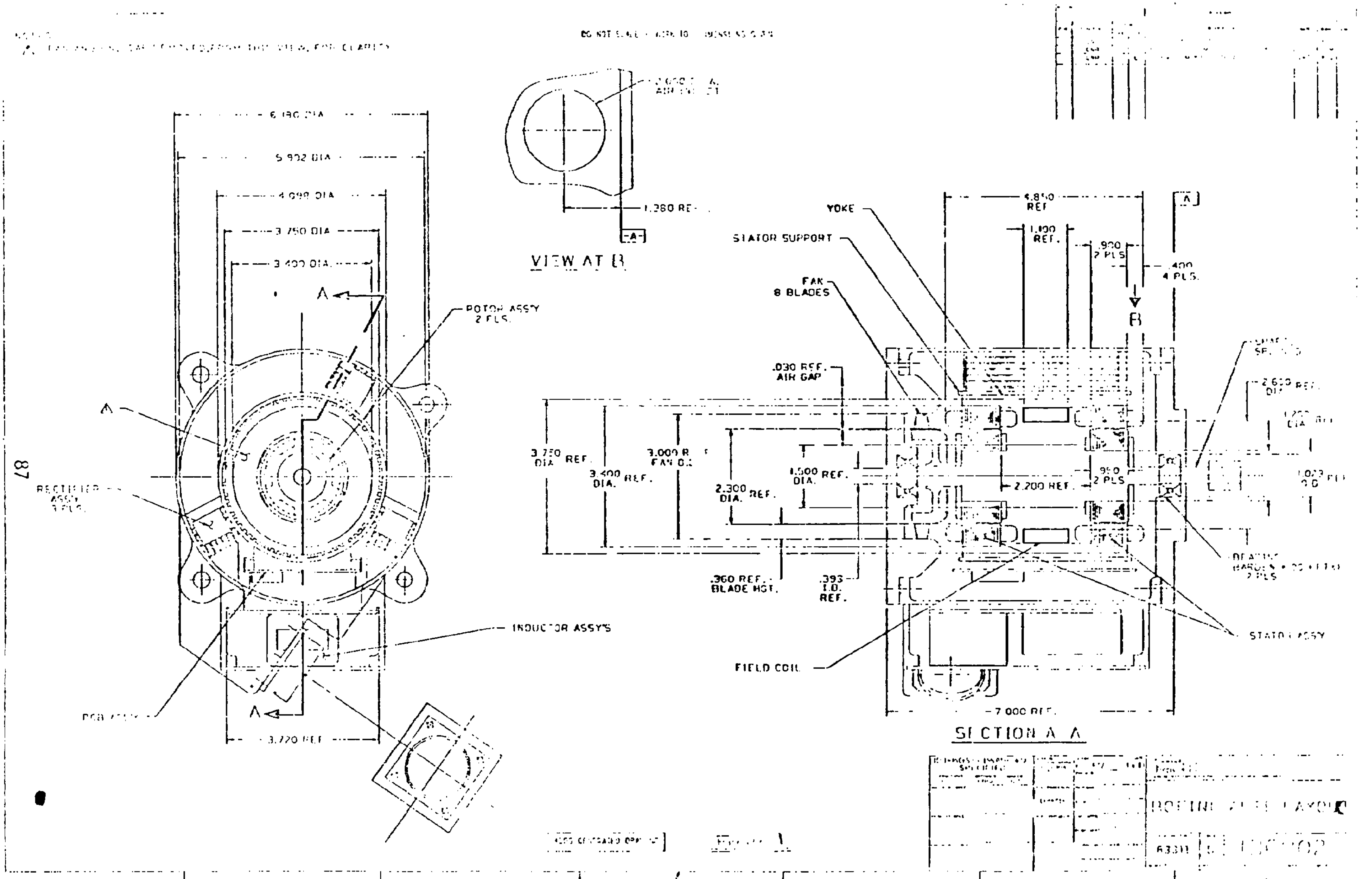


Figure 26. Alternator Layout

to locate the major system components. With the exception of the 6.180" O.D., this package conforms to the requirements of CDRL 13. However, because wiring and mounting details have not been addressed at this time, further dimensional relief will be required.

The initial study was performed for a magnetic design developed at a nominal speed of 60,000 rpm and magnetic losses of 865 watts (table 16). Due to bearing limitations, this was later revised to a nominal speed of 50,000 rpm and magnetic losses were reduced to 830 watts. (Table 17, note that thermal analysis is limited to nominal speed only.) The initial study was based on the cooling air temperature profile specified in section IV 3 b (5) figure 15. It was a result of this study that revealed the problem between air inlet temperature, altitude and system efficiency which has yet to be resolved. Boeing responded with relief in efficiency to 71% at standard atmospheric temperatures and a reduction in power from 5 kW to 3.5 kW at altitudes over 20,000 feet. Even with these concessions, it was still necessary to reduce the air inlet temperature at 20,000 feet from 110 °F to 29 °F. The 29 °F design point was chosen for two reasons:

- Represents Naval Air Environment High Temperature Operations (MIL-STD-210B, para. 4.2.3.2.2).
- 29 °F is the maximum inlet air temperature capable of meeting CDRL 13 concessions noted above.

1) Heat Transfer Analysis of Optimum Design Condition. Figure 27 is a graph of the results of a parametric study performed to determine the system cooling requirements. Using 29 °F at 20,000 feet altitude as the optimum design point, it depicts system efficiencies for standard atmospheric temperatures at other altitudes and maximum load conditions. Figure 28 shows the effect of using the 110 °F inlet air temperature on system efficiency. Mass flow rates, densities, head losses and efficiencies were used to generate the graphs shown in figure 27. A typical computer printout for each of the cooling paths at sea level and 59 °F is included.

2) Critical Components and Maximum Operating Temperatures. The critical components and their respective maximum operating temperatures have been identified in table 18.

TABLE 16. ALTERNATOR LOSSES AT 60,000 RPM

	FULL LOAD WATTS	OVERLOAD (2 MIN) WATTS
Field	44	62
Windage	210	210
Stator Tooth	40	48
Stator Core	16	20
Pole Face	407	548
Stator Copper	122	246
Misc. Load	25	25
Total	864	1159
	865 watts	1160 watts

Above numbers are arrived at using homopolar program except for pole face and misc. losses. Pole face losses are assumed to be 60% of computed values.

TABLE 17. ALTERNATOR LOSSES AT 50,000 RPM

Losses	3.5 KW Watts	Full Load At 50 K Watts	Overload At 54 K Watts
Field	42	59	79
Windage	198	198	223
Stator Iron	68	68	75
Pole Face	259	299	415
Stator Copper	125	178	359
Misc.	25	25	25
Total	717	827	1176

Field Current - 4.0 amps per full load at 50 K RPM
4.4 amps per overload at 54 K RPM

Electronics at 5 KW 440 watts losses, full load
3.5 KW 310 watts losses, full load

30 System

50,000 RPM - 100% Speed
61,000 RPM - Overspeed
3.75 0 Over Yoke

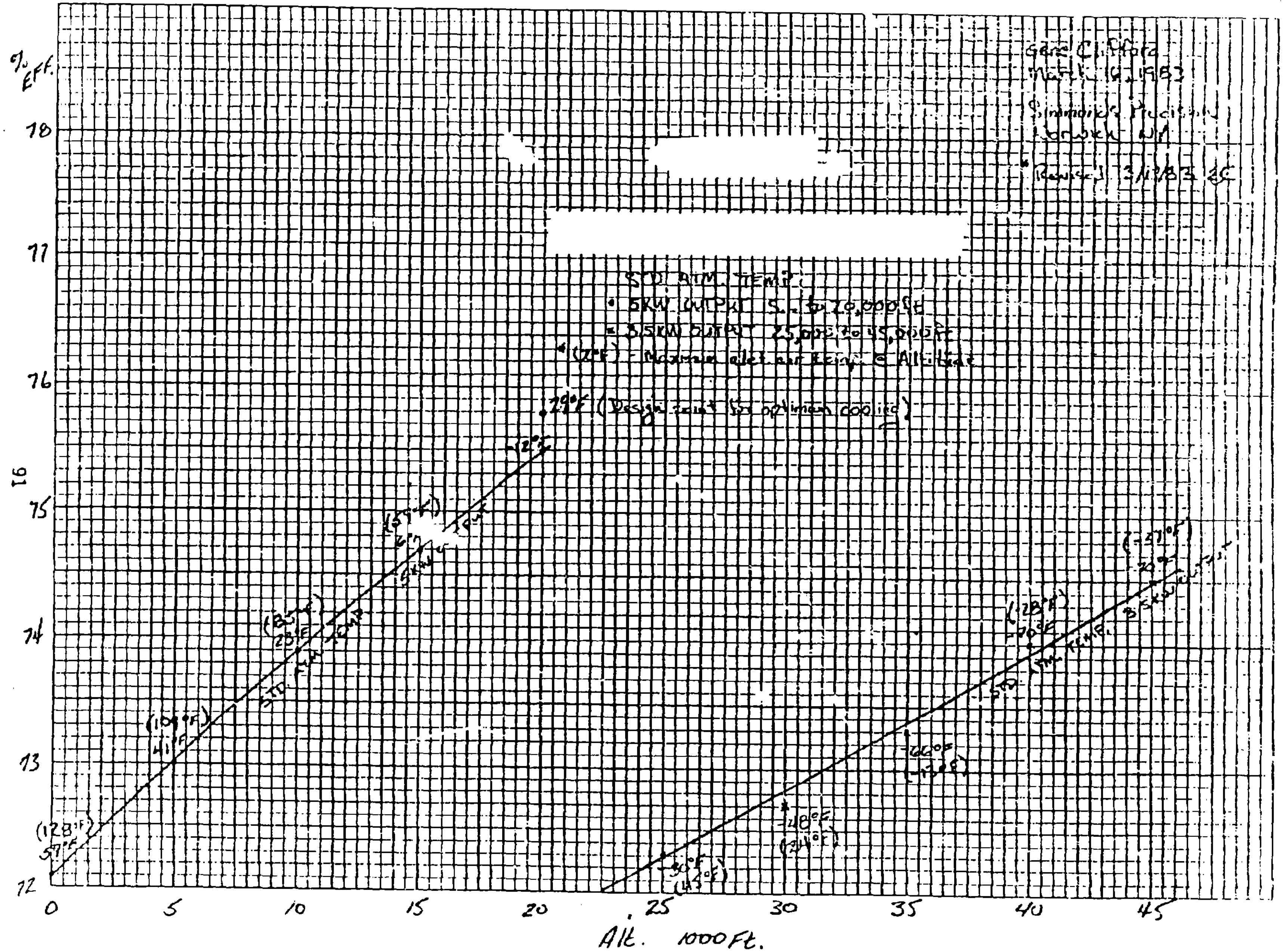


Figure 27. System Efficiency vs. Altitude

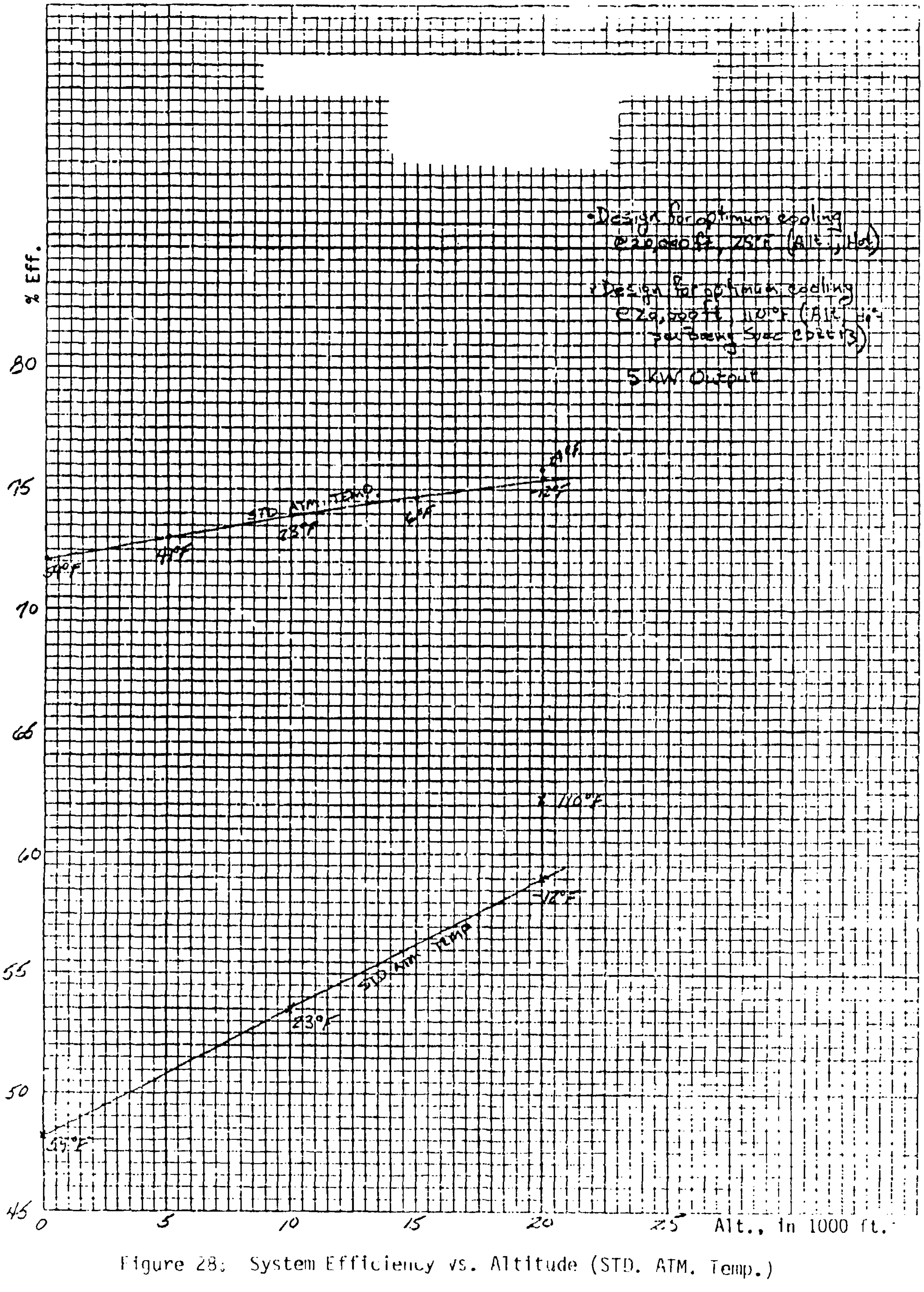


Figure 28: System Efficiency vs. Altitude (STD. ATM. Temp.)

TABLE 18. COMPONENT MAXIMUM OPERATING TEMPERATURES

	Max. Oper. Temp.	Limiting Factors
Rotor	450 °F	potting compound
Stator	450 °F	potting compound
Bearings	280 °F	lubrication
Rectifiers (case temp.)	212 °F	junction temperature
PCB	212 °F	component junction temperature
Inductors	330 °F	potting compound

For location of components, see figure 29.

3) Extreme Operating Conditions for Critical Components. Various wall temperatures at air inlet, outlet, and their averages are shown in table 19.

TABLE 19. WALL TEMPERATURES

	T (Wall in)	T (Wall avg.)	T (Wall out)
Rotor	264 °F	299 °F	334 °F
Stator	167.5 °F	200 °F	232.5 °F
Rectifiers	171 °F	195 °F	220 °F

From these, other critical components can be estimated as follows:

Bearing, Front	264 °F	Lower than rotor at air inlet
Bearing, Rear	334 °F	Lower than rotor at air inlet
PCB	200 °F	Lower than stator wall average
Inductors	300 °F	Additional losses in inductors will result in a T of much less than 100 °F over stator wall average.

4) Evaluation of Operating Margins.

Rotor - The maximum rotor temperature is well within operating range.

Stator - The maximum stator temperature is well within operating range.

Front Bearing - Assuming that the mounting pad temperature is below 260 °F, front bearing should be within the 260 °F design goal.

Rear Bearing - The rear bearing will require further analysis to more precisely predict its maximum operating temperature. However, because the fan is located between the rotor and the bearing, it should provide excellent heat sinking and isolate the bearing from the 334 °F rotor temperature.

Rectifiers - The thermal design was developed to specifically address the rectifiers. They have been identified as the most critical component. The importance of maintaining the wall temperature at 212 °F may be relieved once the thermal characteristics of the custom rectifiers have been defined. In the meantime, however, the predicted T wall out of 220 °F can be reduced by a slight increase in air flow or rectifier fin surface area.

PCB & Inductors: Although these components do generate some heat and have a limited operating temperature range, they do not appear to be a cause for concern. By bleeding a small amount of cooling air through the lower compartment, sufficient convection cooling can be maintained.

k. Weight Analysis. The weight analysis for the generator and control unit is given in this section. At the 5 kW rating, the energy density is 23.1 lbs/5 kW = 4.62 lbs per kW. This compares with the present ALCM generator and control unit weighing 17.1 lbs and rated at 3 kW, for a density of 5.7 lbs per kW.

A summation of the calculated weights are shown in table 20.

TABLE 20 WEIGHT ANALYSIS

Item	Weight (lb)	Material
End Cap	1.74	Aluminum
End Cap	2.10	Aluminum
Housing	1.70	Aluminum
Box	0.44	Aluminum
Rotor	2.41	Shaft - AISI 4620
		Laminations - Magnesil - N
Stator & Yoke	6.25	Yoke - Electrical Iron
		Laminations - Magnesil - N
		Winding - HML magnet wire
Inductor L1	0.8	Core - Iron
Inductor L2	0.7	Windings - Copper Strip
Connector	0.26	
Capacitor	0.01	MIL-C-39006/9D
Bearings	0.12	Borden 100FFTX1
Rectifiers	0.25	
Fan	0.14	Aluminum
PCB	0.75	NEMA G-10 & components
Field Coil	0.71	HML magnet wire
Total	18.4 lbs.	

Items missing: Wiring
Mounting screws
Inlet & outlet screens
Misc. ducting

2. PERFORMANCE

The performance requirements are defined in the system specification outlined in Section IV. The transient regulation analysis of the generator and control unit as designed is given in this section.

a. Preliminary Transient Regulation Analysis. The generator-regulator is divided into four blocks for analysis as shown in figure 29. Transient response of each block is considered separately.

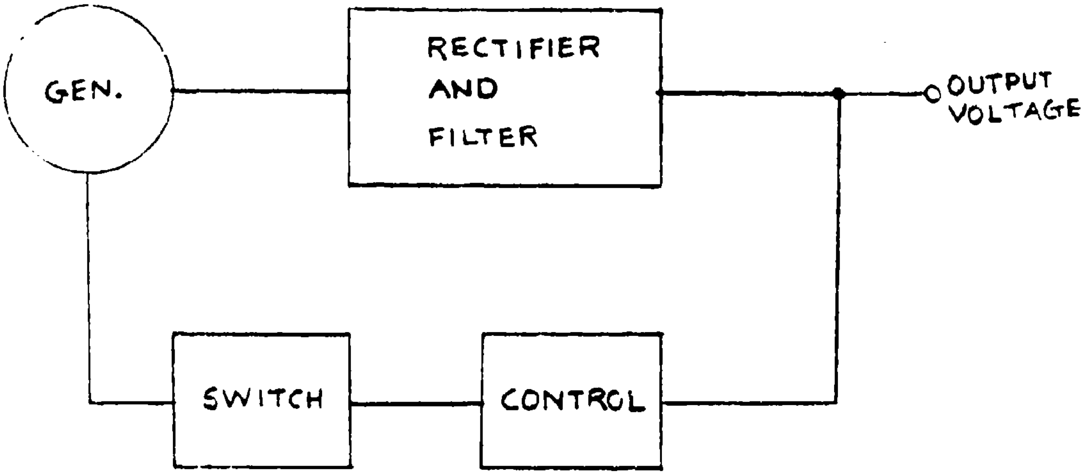


FIGURE 29. GENERATOR AND CONTROL UNIT BLOCK DIAGRAM

1) Generator: The transient response of the generator, when switching loads from no load to full load, is 50 msec, as determined from the computer program used for homopolar alternator design.

Therefore, the transient response of the generator when switching loads from 10% to 85% and down to 10% of full load will be approximately 35 msec each (A).

The change in the generator voltage when switching loads from no load to full load is 40% of the nominal voltage, using the same computer program.

As a result, the change in the generator voltage when switching loads from 10% to 85% is 30% using linear approximation.

The generator-regulator output voltage is 30 to 32 VDC by specification, resulting in a generator-regulator nominal output voltage of 31 VDC.

Therefore, the change in the voltage when switching loads from 10% to 85% and down to 10% of full loads is

$31 (\pm 0.30) = \pm 9.3$ V or approximately ±10 VDC (B).

The resulting transient voltage range is 21 to 41 VDC.

For 31 VDC (nominal), the transient voltage range per Boeing Specification CDRL 13 is 24.8 to 37.2 V.

Assuming the transient response curve of the generator to be exponential, figure 30.

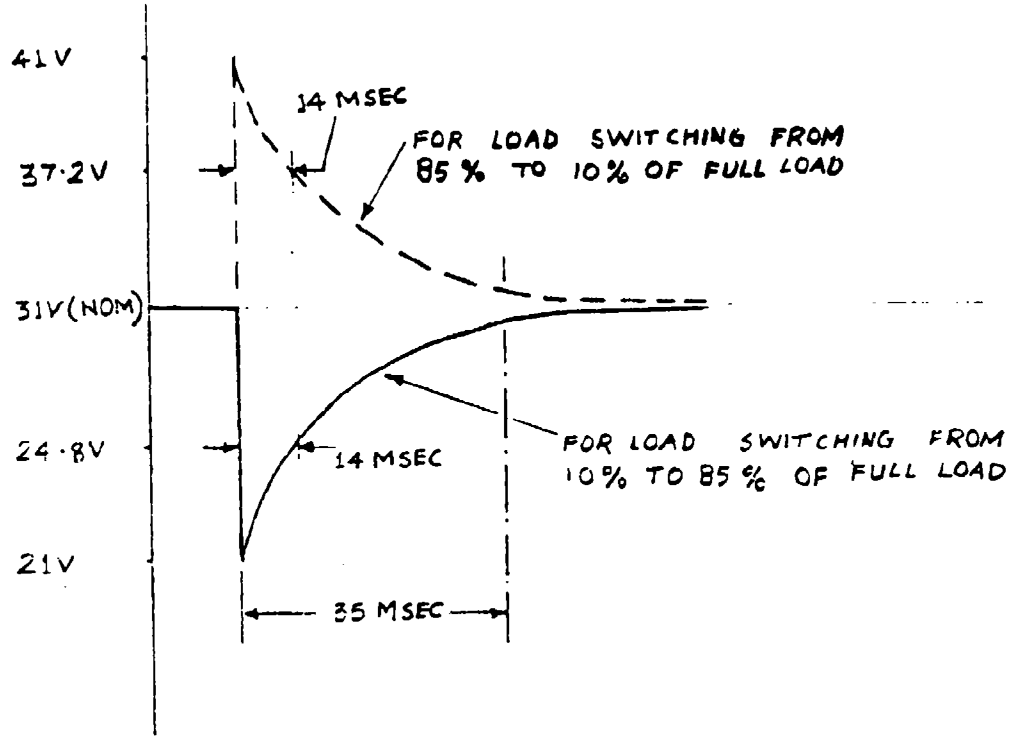


FIGURE 30. GENERATOR TRANSIENT VOLTAGE CURVE

For Load switching from 10% to 85% of full load

$$V = 21 + 10(1 - e^{-\alpha} {}_1{}^{t} \qquad (1)$$

Using conditions (A) and (B), α can be determined.

Assuming in 35 msec, the voltage will settle down to 30.5 VDC approx. 98% of nominal voltage (4 time constants) .

$$30.5 = 21 + 10 (1 - e^{-\alpha}{}_1 {}^{\times 0.035}$$

$$\alpha_1 = 86$$

Now the time required to reach 24.8 VDC can be determined

$$24.8 = 21 + 10(1 - e^{-86 \times t})$$

$$t = 14 \text{ msec}$$

This means that the transient voltage will be within the transient voltage range in 14 msec.

For load switching from 85% to 10% of full load:

$$V = 31 + 10e^{-\alpha_2 t} \qquad (2)$$

Assuming a 35 msec voltage settling time to 31.5 VDC (approx. within 2% of nominal voltage).

α_2 can be determined using condition (A) and (B).

$$31.5 = 31 + 10e^{-\alpha_2 \times 0.035}$$

$$\alpha_2 = 86$$

Now the time required to reach 37.2 VDC can be determined

$$37.2 = 31 + 10e^{-86t}$$

$$t = 14 \text{ msec}$$

This means that the transient voltage will be within the 14 msec range.

2) Rectifiers and Filter. A block diagram of the rectifiers and filter is shown in figure 31.

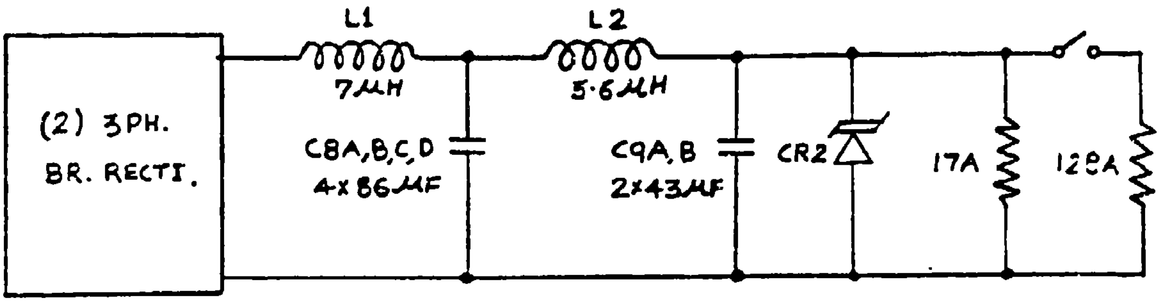


FIGURE 31. RECTIFIERS AND FILTER BLOCK DIAGRAM

Full Load Current I_{FL} = 167A
10% of I_{FL} = 17A
85% of I_{FL} = 142A

At 85% of I_{FL} energy stored in L2= $\frac{L2I^2}{2}$

$$= \frac{5.6 \times 10^{-6} \times (142)^2}{2}$$

$$= 5.65 \times 10^{-2} J.$$

At 10% of I_{FL} energy stored in L2= $\frac{5.6 \times 10^{-6} \times (17)^2}{2}$

$$= 8.1 \times 10^{-4} J.$$

Change in stored energy $\frac{\Delta LI^2}{2} = (5.65 \times 10^{-2} - 8.1 \times 10^{-4})J.$

$$= 5.57 \times 10^{-2} J.$$

Since capacitors C8A, B, C, D are very large in value compared to C9A, B, the change in stored energy will be dissipated in capacitors C9A, B.

$$\frac{\Delta LI^2}{2} = \frac{CV^2}{2}$$

$$V = \sqrt{\frac{\Delta LI^2}{2} \times \frac{2}{C}} = \sqrt{\frac{5.57 \times 10^{-2} \times 2}{86 \times 10^{-6}}} = 36V$$

Since there is a 10% minimum load on the output, the actual spike will be less than 36 V. If we assume at least a 10% reduction in the spike due to 10% load, then V = 32 V.

$$\text{Resonant frequency } f = \frac{1}{2\pi\sqrt{L_2 C_q}}$$

$$= \frac{1}{2\pi\sqrt{5{\cdot}60 \times 10^{-6} \times 86 \times 10^{-6}}} = 7.25 \text{ KHz}$$

Duration of Spike = 1/2 x 1/f

= 68.9 usec or approximately 70 usec.

Therefore, there will be a 32V spike for a duration of 70 usec on top of the 31 VDC nominal voltage. This will be clipped off somewhat by the transzorb, CR2.

3) Control. Transient response of the control section will be less than 1 msec.

4) Switch. Because of fast switching transistors, transient response of the switch will be less than 5 usec.

5) Conclusion. The transient voltage regulation will be dominated by the transient voltage response time of the generator. The transient voltage amplitude will be out of specification limits for approximately 14 msec and then fall within the specification range, and will settle down to steady state range in under 100 msec which is within the CDRL 13 specification requirements.

b. Worst Case Regulation. The worst case regulation due to change in load, speed and temperature for the generator-regulator is determined below.

1) Approach. A worst case regulation analysis has been performed on the generator-regulator considering the impact of the following conditions:

a. Load variation of 167 amps to 17 amps (100% to 10% load).
b. Speed variation between 40,400 rpm and 54,000 rpm.
c. Temperature variation of -55°C to +71°C.

The generator-regulator is divided into functional blocks in order to perform the analysis. The worst case temperature effect has been considered for each block while the worst case load and speed effects have been considered for the overall transfer function of the complete generator-regulator.

2) Worst Case Analysis:

Full load current I_O = 167A

10% full load current I_{O10} = 17A

TABLE 21. GENERATOR LOAD CHARACTERISTIC

% LOAD	0	25	50	100	130
Field Current At 40400 RPM	2.67A	2.75A	2.95A	3.70A	4.40A
Field Current At 50,000 RPM	2.15A	2.25A	2.49A	3.30A	4.00A
Field Current At 54,000 RPM	1.99A	2.09A	2.35A	3.20A	3.83A

Field Coil Resistance @ 120°C = 7.68 OHMS

From the Data: Field Current at 10% Load	2.702A @ 40,400 RPM
	2.19A @ 50,000 RPM
	2.03A @ 54,000 RPM

% Change in field current at 40,400 RPM when load is changed from 100% to 10% =

$$\frac{3.70 - 2.702}{3.70} = 27\% \text{ say } 30\%$$

% Change in field current when speed is changed from 40,500 RPM to 54,000 RPM at full load = $\frac{3.70 - 3.20}{3.70} = 13.5\% \text{ say } 15\%$

Field voltage will change direct proportional to field current change so for worst case:

Field voltage will change 30% due to change in load

Field voltage will change 15% due to change in speed.

Above changes in field voltage will be considered in calculating regulation using overall transfer function of the regulator, figure 32.

REGULATOR:

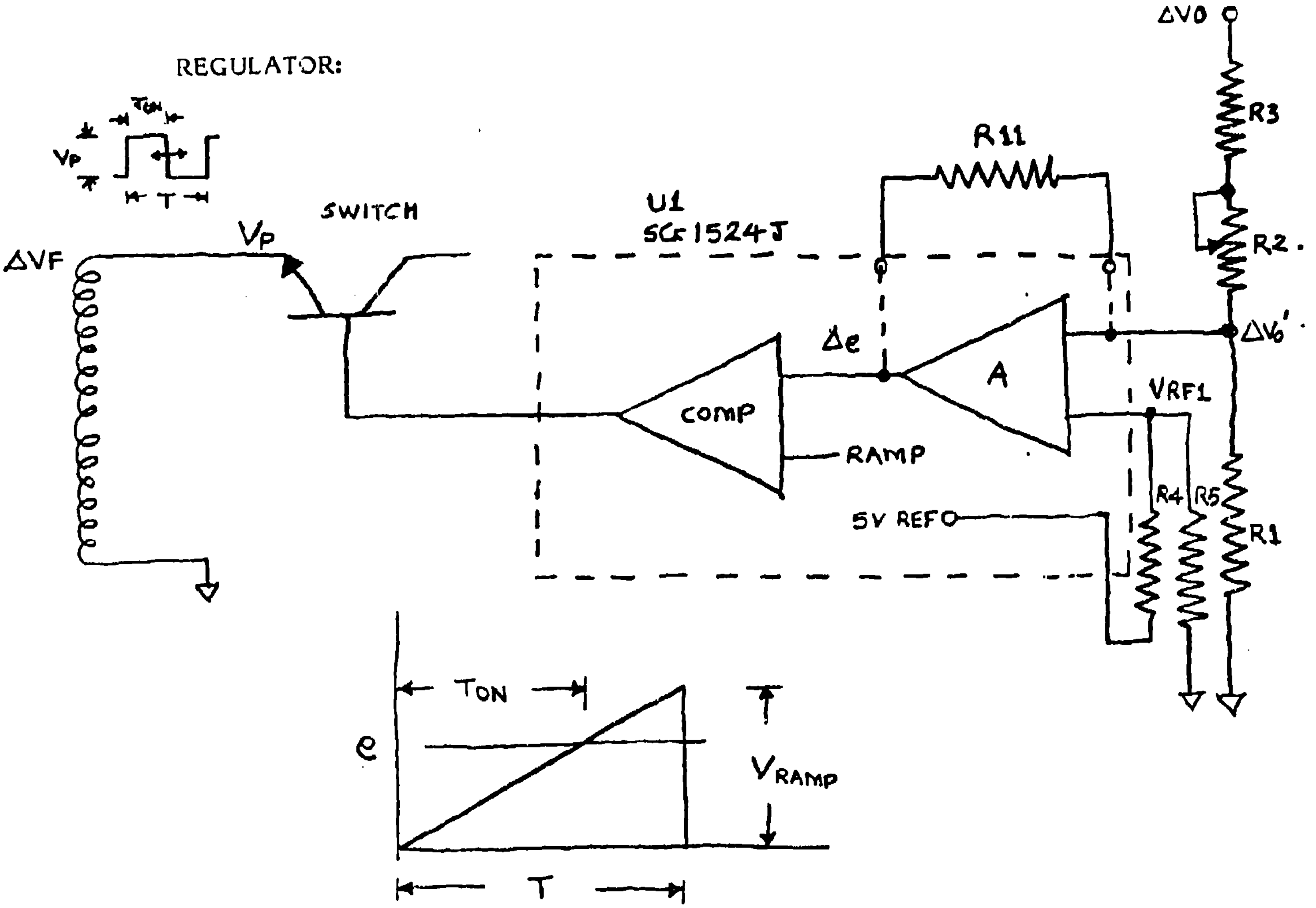


FIGURE 32. REGULATOR SKETCH

DATA: R1 = 2.87 K; R2 = 10 K; R3 = 28 K; R11 = 100 K; R4,R5 = 4.99 K

R3'= R3 + R2/5 = 28 + 5 = 33 K

Λ_{op} = 72 db (MIN)

= 80 db (TYP)

Vramp = 3.5 V TYP

Temp. stability of ramp voltage is 2%

Switching frequency = 30 kHz; Period T = 33 sec

VRF1 = 5.0 = 2.5 V (NOM)

Temp. stability of 5 V ref is 1%.

R4 and R5 are RNC type resistors having low temp. coefficient. Change in resistance of R4 and R5 due to temp. will have negligible effect on VRF1 because of partial cancellation of temp. coefficients.

$$\text{Sense Voltage Factor} = \frac{R1}{R_1 + R_3'} = \frac{2{\cdot}87}{2{\cdot}87 + 33} = 0{\cdot}08$$

Change in resistance of R1 and R3' due to temperature will be partially cancelled because of resistor ratio so temp. will have a minimum effect on the sense voltage factor.

VO = Change in output voltage

VF = Change in field voltage

$$\text{Now } V_F = \frac{Ton}{T} \times Vp$$

$$\Delta V_F = \frac{Vp}{T} \times \Delta \, Ton \qquad (1)$$

$$\Delta V_O = \frac{R_1}{R_1 + R_3} \, \Delta \quad Vo \qquad (2)$$

ACL, closed loop gain of OP Amp = $-\frac{R11}{R1N}$, where R1N = R1$||$R3 = 2.64K

$$ACL = -\frac{100}{2.64} = 37.87 \text{ Say } 37 \qquad (3)$$

Because of negative feedback, closed loop gain is independent of open loop gain of OP AMP, so variation in open loop gain has negligible effect on closed loop gain.

$$\text{Now} \Delta e = ACL \times \Delta V_O \qquad (4)$$

$$\alpha = \text{Slope of Ramp} = \frac{Vramp}{T} \qquad (5)$$

Δ Ton is directly proportional to Δe

$$\Delta \, Ton = \frac{\Delta e}{\alpha} \qquad (6)$$

Substituting EQNS. 2, 4, 5, and 6 in EQN gives,

$$V_F = \frac{V_P}{T} \times A_{CL} \times \frac{R_1}{R_1 + R_3'} \Delta V_0 \times \frac{T}{V_{RAMP}}$$

$$V_0 = \frac{V_{RAMP}}{V_P} \times \frac{R_1 + R_3'}{R_1} \times \frac{1}{A_{CL}} \times \Delta V_F \qquad (7)$$

Now $V_P = V_0$ - Drop in Switch

Drop in Switch = 1 V (TYP)
= 1.5 V (MAX)
= 2.0 V (MAX) Over Temp. Range

From EQN. 7 it's apparent that the change in output voltage will be maximum when V_{RAMP} is maximum and V_P is minimum.

Now $V_{P(MIN)}$ = V_0 - Drop in Switch (MAX)
= 30 - 2
= 28 V

$V_{RAMP(MAX)}$ = 1.02 x 3.5

Substituting values of all parameters in EQN. 7

$$\Delta V_0 = \frac{1.02 \times 3.5}{28} \times \frac{1}{0.08} \times \frac{1}{37} \times \Delta V_F$$

$$0.0431 \times \Delta V_F$$

Since temp. stability of 5 V ref is 1%, V_0 will increase by 1% over temp. as the sense voltage is being compared with reference voltage.

$$\Delta V_0 = 1.01 \times 0.0431 \times \Delta V_F$$

$$= 0.04351 \times \Delta V_F$$

$$\text{i.e.} \quad \Delta V_0 = \frac{\Delta V_F}{23} \qquad (8)$$

EQN. 8 suggests that output voltage will change 1:23 to the change in field voltage.

Worst case regulation calculation:

Full load output voltage = 30 V DC

Duty Cycle = 50%

Field voltage $V_F = 0.5 \times 30 = 15$ V

Worst case change in V_F due to load $= 0.30 \times 15 = 4.5$ V

Worst case change in V_F due to speed $= 0.15 \times 15 = 2.5$ V

So total change in $V_F = 4.5 + 2.5 = 7$ V = V_o

Total change in output voltage = = 0.305 = V_o

% Regulation = = 1.015% say 2%

So worst case regulation will be 2% which is less than 6.67% Boeing limit.

3. FINAL DESIGN

A complete set of drawings and a drawing tree were developed for a 30 V, 5 kW generator and control unit (G&CU). The latter consists of a rectifier assembly, regulator, and filter. The G&CU is cooled with ram air routed over the generator components via a duct over the rectifier assembly and the magnetic parts. Baffles direct part of the available air over the regulator circuit board and filter components. The rectifier assembly is mounted on the generator periphery, and the regulator/filter in a recess off the generator. The production generator will have a fan that draws the air over the aforementioned parts. The prototype generator will have a fan substitute that duplicates the mass of the eventual fan. Prototype machine tests will be run to determine fan requirements and to verify the analysis by forcing air over the generator from an external source to simulate fan operation.

4. TEST PLAN

Included with this technical report are the plans for tests of a production generator and control machine. This test plan is more complete than the test plan used for the prototype test unit. The prototype test plan shown in section VI is to determine whether the generator and control unit was fabricated and assembled as per the drawings, and whether it will perform as analyzed.

a. Objective. The test is intended to demonstrate G&CU performance when suppling a missile-like load, at the temperature and pressure range that a future cruise missile is likely to operate.

b. Approach. The generator is designed to be mounted on the engine accessory pad. The spline shaft of the generator will be coupled to the engine high-speed shaft, thus experiencing an 1.34:1 speed variation between engine idle and cruise conditions. Generator overspeed will be proportional to engine overspeed.

c. Mechanical Compatibility. The generator will experience a transmitted vibration envelope such as that specified for F107-WR-103 Williams International Engine, at its accessory pad. The generator's own vibration contribution must be under that shown in figure 3 of the system specification.

The generator will be tested to show its capability to withstand the engine vibration, and limit its own contribution to that permitted.

d. Thermal Compatibility. The generator will be cooled with ram air routed through an engine mounted duct. The air is first used to sense engine inlet temperature. A fan, mounted on the generator, is necessary to derive the required air flow from that available at the exhaust of the aforementioned engine duct. Because advance cruise missiles are expected to be designed to have a low radar cross-section, the ram air duct will be expected to have only partial pressure recovery most of which is lost in the duct. The generator can, therefore, count on only static pressure at a given altitude for cooling. The generator will be tested to demonstrate that it can draw an adequate amount of air under the aforementioned interface conditions while maintaining the temperature of its electronic (and other) components within specified limits.

e. Power Quality. It is assumed that future cruise missiles will have their avionic loads checked out prior to launch, by the missile carrier, using airplane power. This implies the continued use, as in ALCM-B, of a thermal battery that supports the power bus during the transition from airplane to on-board missile generator power. It follows that inrush currents demanded by those loads that are already on the bus, when the generator is spun-up by the missile engine, are supplied by the battery. The generator will supply inrush current and peak current to those loads that are turned-on following generator spin-up. The inrush current of such major loads as Flight Control Electronics and heaters will be simulated, and these connected to the G&CU in a periodic fashion simulating the expected load profile.

The generator will be tested at the lowest speed to demonstrate capability under worst case thermal conditions, and at the highest speed to demonstrate maximum dissipation and vibration characteristics.

The generator will have received selected non-operating tests prior to system testing to demonstrate its structural integrity while in captive flight.

The sequence of tests will be governed by the test equipment usage and expected stress sequence in captive and free-flight.

In order to prevent damage to the G&CU by the test facility, protection will be employed at the facility interface. The protection will be automated and will include control of overspeed, overcurrent, excessive vibration loss of coolant, and excessive coolant temperature.

f. Test Sequence.

1) Vibration Characteristics. The generator shall be operated at minimum, nominal, and maximum speed, at minimum load, and again at maximum load. Inlet temperature shall be the maximum specified for sea-level conditions. The generator shall meet the vibration limits shown in figure 3 of the system specification. The generator drive shall have unloaded vibration characteristics within the limits shown in figure 9 of the system specification.

2) G&CU Cooling.

o The generator shall be operated at minimum speed, maximum altitude, humidity, and temperature for a period of 1 hour at full-load after having stabilized its internal temperatures within ±10 ^{o}F. The test shall demonstrate that key regulator, rectifier, and generator components remain below their maximum allowable temperatures.

- The generator shall be operated at minimum speed, and at maximum sea-level temperature and pressure. After thermal stabilization, operate the generator for 1 hour at full-load to demonstrate performance when the G&CU experiences maximum internal dissipation.

3) Load Takeover from Battery Power. The missile secondary power system will be simulated with a Pb-Acid battery that has the voltage and source impedance of the missile thermal battery. Thermal battery voltage decay will be simulated by the Pb-Acid battery with a progressive by-pass of its two top cells. The load-assumption of the generator in a cruise missile will be simulated by accelerating the generator at a rate specified, for the 14A6 Williams International propulsion engine per their specification 24235WR9511 dated March 15, 1982, "Prime Item Development Specification For The F107 Cruise Missile Turbofan Engines." The power bus will be loaded with the specified initial missile load (see figure 1). The test will demonstrate the generator capability to support the bus voltage during transition from battery to generator power within power quality limits specified for the ALCM-B missile (Boeing doc. M232-10602-1).

4) Peak-Power-Handling Capability. The generator will be subjected to the load profile shown in figure 1 of the system specification to simulate periodic changes in missile elevon position and the application and removal of electronic countermeasure loads. The test will be performed at maximum cruise altitude and temperature, and minimum generator speed so as to demonstrate the capability of the generator to meet transient voltage and efficiency requirements. The load bank will be designed to simulate typical input filters required to meet avionics-conducted interference requirements. These inductors and capacitors will cause the expected load inrush current to be drawn by the postulated loads.

5) Instrumentation. Instrumentation shall be provided to measure and record the following data:

Time
Speed
Voltage
Current
Vibration

Coolant Flow Rate
Coolant In and Out Temperatures

g. Description of Tests. The following section defines all tests which will be performed on the generator/regulator. The following should be noted:

- Testing at environmental conditions shall be performed in a non-operating mode only. Operational environmental tests cannot be conducted due to limitations of the air supply used to simulate the cooling fan in the generator/regulator.
- The unit shall be calibrated prior to and at the completion of each of the tests specified in the sections (3.1 Operating and 3.2 Non-operating). The calibration will be in accordance with acceptance test procedure with the exception that the vibration screening will not be performed. Following the completion of all tests, the unit will also be subjected to First Article Inspection and a final calibration prior to shipment to Boeing.

1) Operational Test. The generator/regulator shall be operated at 100% speed and full rated load to verify system integrity at ambient air pressure, temperature, and humidity only.

a) Cooling. Cooling air shall be provided from a compressor, to simulate the fan. Temperature and airflow must be monitored to ensure sufficient cooling and to verify the validity of the system cooling method.

- Instrumentation - Airflow. The condition of the air, both upstream and downstream of the generator/regulator, shall be monitored. Measurements of volumetric flow rate, pressure, and temperature are required upstream. Pressure and temperature are required downstream of the generator/regulator. Sufficient pressure information to determine pressure drop across the generator/regulator (pumping loss) must be obtained.
- Instrumentation - Thermal. The temperature of the following components or areas shall be monitored: stator coils, center of each stack; rectifiers BR2 & BR3, surface temp. near exit and entrance; bearing outer races; rectifier BR1; transistor Q1; inductor assembly L1 and L2.

b) Efficiency. The efficiency of the generator/regulator shall be determined using the following method. Power to the generator/regulator shall be calculated by measuring input torque and speed. Output power from the regulator shall be directly measured at full load and light load conditions.

2) Non-Operational Environment Tests.

a) Vibration. The generator/regulator shall be subjected to the random vibration level of figure 33 in each of three axes. Exposure time for generator/regulator is 4 hours per axis.

b) Thermal Shock. The generator/regulator shall be subjected to a thermal shock of -65 °F to +150 °F. Transition time between temperature extremes shall be less than 30 seconds.

h. Test Documentation. Prior to start of tests, a complete test procedure will be prepared detailing the individual steps involved, the procedures, test setups (including test speeds, loads, etc.), equipment, etc. and submitted to Boeing for approval. At the completion of the above testing, a complete test report (as specified in the test procedure) will be prepared and submitted for approval.

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1. Kays and London, Compact Heat Exchangers, McGraw-Hill, 1964.
2. Gazely, Carl Jr., "Heat Transfer Characteristics of the Rotational and Axial Flow Between Concentric Cylinders," ASME Trans., Jan. 1958.
3. Wallis, R.A., Axial Flow Fans, Academic Press, 1961.

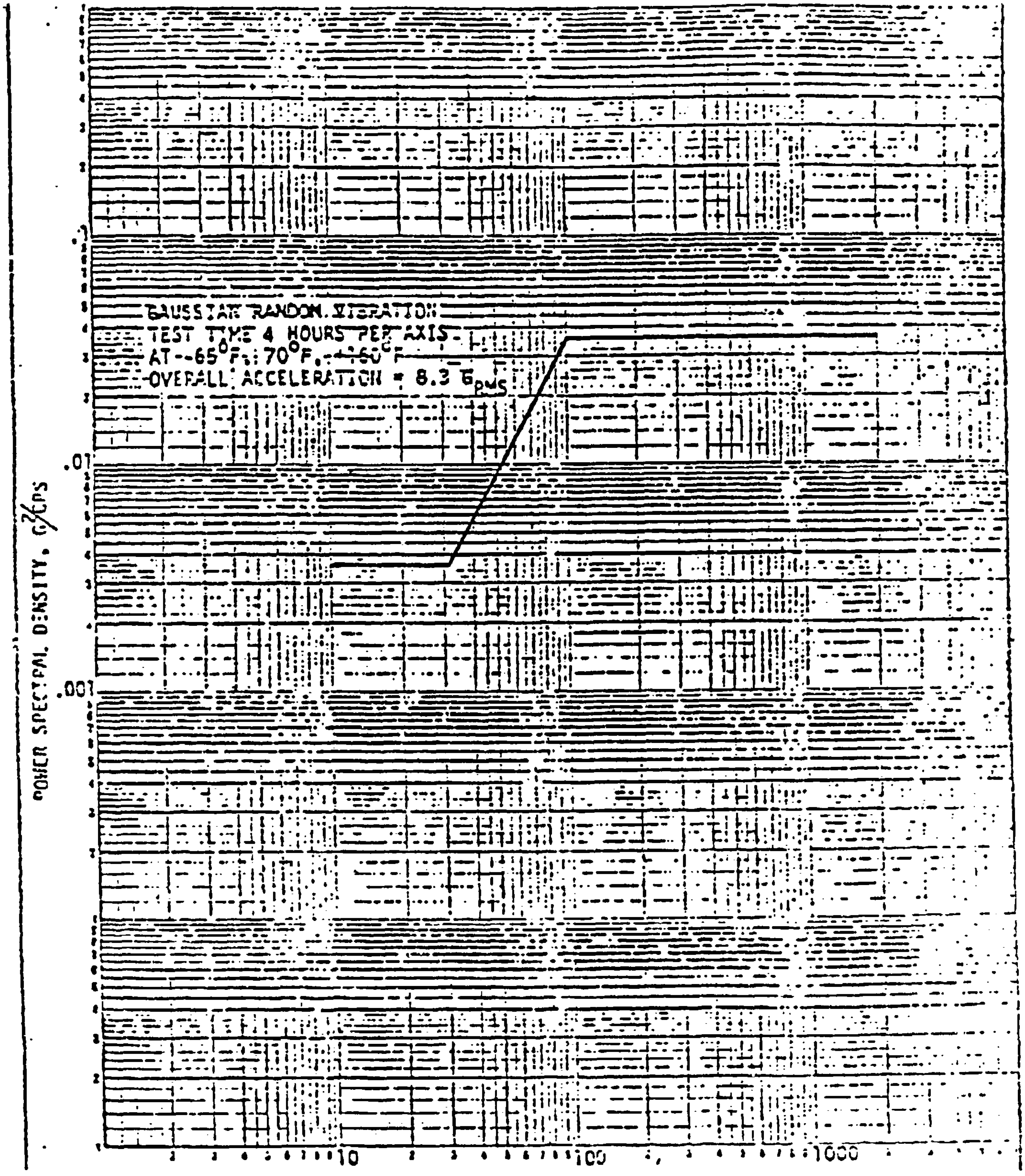

Figure 33. Random Vibration Spectrum

SECTION VI
FABRICATION AND TEST

1. FABRICATION

Work accomplished and reported in sections III, IV, and V on the design and analyses for the generator and control unit was done by Simmonds Precision, Inc. Fabrication and testing was contracted to HTL Electro Kinetics to meet the time schedule for test and evaluation.

a. Drawings. The majority of the Simmonds Precision, Inc. drawings were unchanged. The drawings that were changed did not influence weight, size, or function. Typical changes were dimension compatibility between the detail and assembly drawing, alignment of air flow paths, and the location of thermocouples. Two new detail drawings have been added to the drawing tree; 1) the magnet polarity and installation on the rotor and 2) the coil connections. With these changes, fabrication was undertaken.

b. Assembly. Once the drawings were completed and approved for manufacture, HTL Electro Kinetics started fabrication of parts and assemblies to the schedule shown in figure 34.

During manufacture, drawings were found to have incompatible dimensions, the drawings were red-lined and fabrication continued on schedule.

All the machine parts were fabricated per print. Two stationary parts, namely an end bell and housing, each have a tool chatter mark on them. Both marks will be enclosed by the framework of the machine. A third small machine error appears on the rotating shaft. The key slot has a tool slip on one end. It does not effect either the locations or the stability of the key. In keeping with the schedule, these workmanship errors were noted on the red-lined drawings and the parts used in the prototype machine.

With the acceptance of the three workmanship errors, all machine shop work was completed. All parts fit and were assembled into a working machine. The prototype machine was readied for test and evaluation for the:

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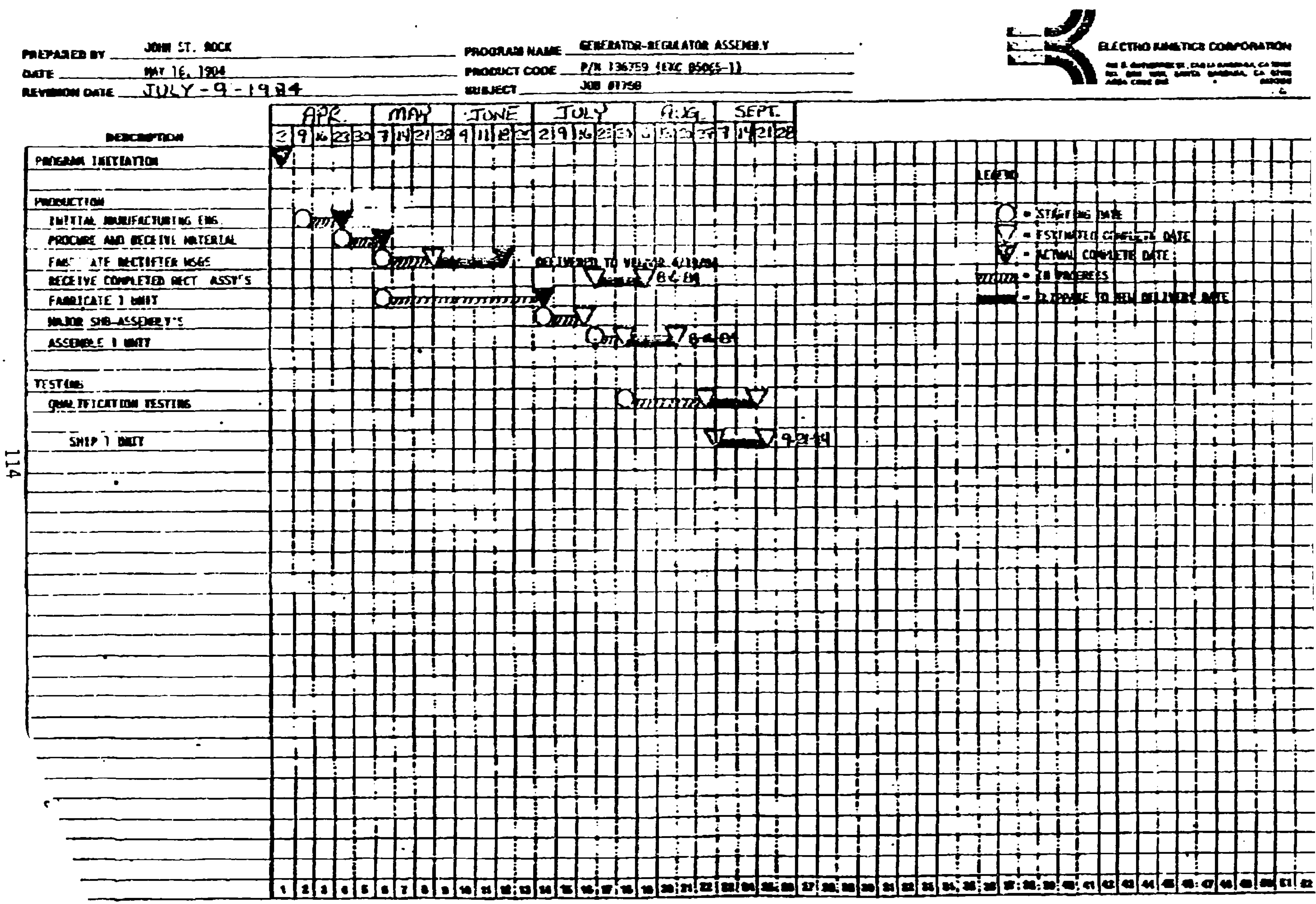


PREPARED BY JOHN ST. ROCK
DATE MAY 16, 1984
REVISION DATE JULY-9-1984

PROGRAM NAME GENERATOR-REGULATOR ASSEMBLY
PRODUCT CODE P/N 136759 (EKC 85065-1)
SUBJECT JOB #1758

Figure 34. Generator-Regulator Assembly

- Acceptance Test Procedure for the generator and control unit.
- Specification Compliance Test Procedure for the generator and control unit.

2. ACCEPTANCE TEST PROCEDURE

a. Scope. This document establishes the Acceptance Test Procedure (ATP) for HTL/Electro Kinetics build-to-print Generator/Control.

b. Test Requirements. The following tests shall be conducted on the Generator/Control. A data sheet shall be initiated and a reproducible shall be furnished to Boeing company. The original data sheet shall be on file and become a permanent record in the HTL/Electrokinetic Company Quality Control Department.

- Inspection
- Voltage Regulation
- Overload
- Voltage Transient
- Ripple Voltage
- Start-Up and Windmilling
- Overspeed

1) Test Conditions.

- Temperature:
  Room ambient (23 ± 10°C).
- Humidity:
  Room ambient 10 to 90 percent.
- Atmospheric Pressure:
  Sea Level (28.5 inches of mercury).
- Current, Voltage, and Power:
  All instrumentation accuracy shall be within ±1%.
- Cooling Air:
  As supplied by blower TFX4C118 at room ambient temperature.
- Load: ±5%
- Speed: ±2%

2) Test Equipment and Instruments. Test instruments will be periodically calibrated against certified standard traceable to the National Bureau of Standard. See table 22 for equipment list.

TABLE 22. TEST EQUIPMENT LIST

The equipment listed, or an equivalent, shall be used for Acceptance Testing.

EQUIPMENT DESCRIPTION	MANUFACTURER & MODEL NUMBER
Test Loadbank	United Mfg. Co. Type A-1
Thermocouple Meter	Omega 199
Thermocouples	Omega Copper / Constantan
Drive Stand	U.S. Motors
A.C. Peak Voltmeter	B & K Precision, Dynascan Corp. 2426
Oscillograph (strip chart)	CEC 5-124A
D.C. Voltmeter	Fluke 8010A
Frequency Counter	Systron Donner 6250
Ammeter	Fluke 8010A
Shunt	Simpson 250 Amp
Mounting Fixture	HTL/EKC
High-Speed Gearbox	HTL/EKC

c) Test Procedure.

1) Inspection. In addition to complete "in-process" inspections, the Generator/Control will be examined to determine conformance to the top assembly drawing with respect to finish and workmanship, envelope dimensions, nameplate data and weight. Results shall be recorded on data sheets.

2) Voltage Regulation.

o Mount the Generator/Control to the high-speed drive stand and connect the output to the load bank. Connect the cooling-air blower and the thermocouple leads. See figure 35 for test set up. Turn on cooling-air blower and set the flow for maximum.

NOTE: Thermocouples are installed during the manufacturing process. Connect to the thermocouple meter, the thermocouples for Stator #1, BA2 and L1 only.

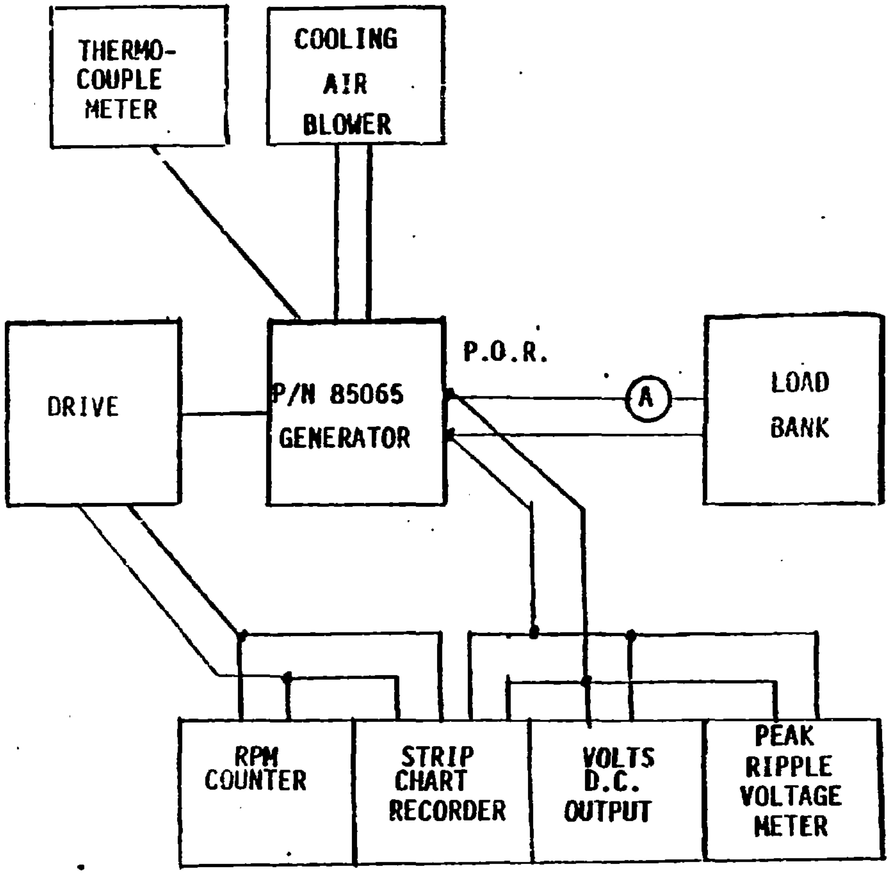


Figure 35. Test Set-Up

- o Operate the Generator at 40200 RPM and apply a load of 3.22 DC amperes. Voltage must be between 30 and 32 VDC. Record on data sheet the voltage, amperes, and ripple voltage.
- o Apply a load of 16.1 DC amperes and record on data sheet the voltage, amperes, and ripple voltage.
- o Apply a load of 80.5 DC amperes and record on data sheet the voltage, amperes, and ripple voltage.
- o Apply a load of 161 DC amperes and record on data sheet the voltage, amperes, and ripple voltage.
- o Operate the Generator at 55000 RPM and repeat 2 through 5 above.

3) Overload.

- o With the Generator/Control set up as in 4.2.1, operate the Generator at 40200 RPM and apply a load of 209 DC amperes and maintain for 2 to 3 seconds. Remove load. Record the DC voltage and amperes on data sheet for the overload condition. Voltage must be between 28-32 VDC.

- o Increase Generator speed to 55000 RPM and repeat step 1 above.

4) Voltage Transient.

- o With the Generator/Control set up as in 4.2.1 operate the Generator at 40200 RPM and apply a load of 16.1 amperes. Start the strip chart recorder and apply and remove an additional load of 120.7 amperes maintaining the 16.1 ampere load. Stop the recorder and from the recording verify that the peak transient voltages remained within the limits of 24 to 36 VDC and recovered to within the steady state limits of 30 to 32 VDC in 0.1 second. Record the transient voltages and time on the data sheet.

- o Operate the Generator at 55000 RPM and repeat step 1 above.

5) Ripple Voltage. During the test for voltage regulation, Paragraph 4.3, the ripple voltage shall be measured and recorded. The peak ripple shall not exceed the DC average voltage by more than 1.5 volts for either polarity. An oscilloscope or a peak reading voltmeter shall be used to measure the ripple voltage.

6) Start-up.

- o Set up the Generator/Control as in 2,c,2). Connect one channel of a strip chart recorder to the drive stand RPM output. Connect one channel of the recorder to the Generator/Control DC output. See figure 35. Apply a load of 0.8 OHMS to the Generator/Control output.
- o With the chart recorder running, start the drive stand and bring the Generator speed up slowly to 25000 RPM. Note that the output comes on above 20000 RPM.
- o Slowly reduce speed and note that the output shuts off below 20000 RPM. Stop the drive.
- o From the chart recording verify that the Generator/Control output comes on line above 20000 RPM and drops out below 20000 RPM. Record on data sheet the results.

7) Overspeed.

- o With the Generator/Control set up as in 2.,C),2), operate the generator at 40200 RPM and apply a load of 161 DC amperes. Maintain this condition until temperature stability has been reached. Record on data sheet the DC voltage and stabilized temperatures. Voltage must be between 30 and 32 VDC.
- o Remove the load and increase the Generator speed to 60500 RPM and maintain for 5 minutes ± 5 seconds. Record on data sheet the DC voltage at the beginning and end of the 5 minute run. Voltage readings for reference only.
- o Decrease generator speed to 40200 RPM and apply a load of 161 DC amperes recording voltage on data sheet. Voltage must be between 30 and 32 VDC.

d. Test Data Sheets. Test data sheets shall be completed during the test. Sample copies are shown in table 23.

3. SPECIFICATION COMPLIANCE TEST PROCEDURE

a. Scope. This document describes the test procedures and requirements for HTL Electro Kinetics build-to-print generator/control unit.

TABLE 23. ACCEPTANCE TEST DATA SHEET
GENERATOR/CONTROL
P/N 85065

TEST NO.

S/N ________
TEST BY ________
Q.A. ________
DATE ________

c1) INSPECTION

Dimensions ______ (✓) if ok
Finish and Workmanship ______ (✓) if ok
Nameplate Data ______ (✓) if ok
Weight ______ Weight

c2) VOLTAGE REGULATION

c5) RIPPLE

RPM	VOLTS DC	LOAD AMPS DC	PEAK RIPPLE +	PEAK RIPPLE -	VOLT LIMIT	RIPPLE LIMIT
40200		3.22			30-32 volts DC	1.5 volts peak +/-
40200		16.1				
40200		80.5				
40200		161				
55000		3.22				
55000		16.1				
55000		80.5				
55000		161				

c3) OVERLOAD

RPM	VOLTS DC	LOAD AMPS DC	VOLTAGE LIMIT
40200		209	28-32 VDC
55000		209	

TABLE 23. ACCEPTANCE TEST DATA SHEET (Cont.)

c4) VOLTAGE TRANSIENT

RPM	VOLTS DC	LOAD AMPS DC	PEAK VOLTS	TRANSIENT RECOVERY TIME SEC.	LIMITS
40200		16.1	X	X	Transient 24-36 VDC Peak Steady State 30-32 VDC 0.1 Sec. to Steady State
Apply 40200		16.1 + 120.7			
Remove 40200		16.1			
55000		16.1	X	X	
Apply 55000		16.1 + 120.7			
Remove 55000		16.1			

c6) START-UP

4.6.2 Output ON ______________ RPM Above 20000 RPM
4.6.3 Output OFF ______________ RPM Below 20000 RPM

c7) OVERSPEED

RPM	VOLTS DC	LOAD AMPS DC	TIME MIN.	VOLT LIMIT	STABILIZED TEMPERATURE #1 STATOR	BR2	L1
40200		161		30-32 VDC at Rated Load & RPM			
60500		0	0				
60500		0	5				
40200		161					

b. Applicable Documents. Applicable sections of the following documents are referenced herein and have been used in the preparation of this Compliance Verification Test Plan.

c. General Requirements.

1) Test Conditions. Unless otherwise specified herein measurements and tests shall be made at standard ambient conditions. Standard ambient conditions are:

Temperature	23° ± 10°C (73° ± 18°F)
Relative Humidity	50 percent ± 30 percent
Atmospheric Pressure	725 + 50 mm. Hg. (28.5 + 2.0 in. Hg.)

2) Instrumentation. Test instruments shall be calibrated periodically against certified standards as required by MIL-STD-45662. Instrument accuracy shall be at least 0.5% for the unit to be measured, except that current, temperature and air flow may be ± 2% or better.

d. Compliance Verification Tests. The verification tests are categorized as Operational and Non-Operational Environmental Tests. The following should be noted:

- Testing at environmental conditions shall be performed in a non operating mode only. Operational environmental tests cannot be conducted due to limitations of the air supply used to simulate the cooling fan in the generator/regulator.
- The unit shall be calibrated prior to and at the completion of each of the tests specified in the sections. The calibration will be in accordance with Acceptance Test Procedure. Following the completion of all tests, the unit will also be subjected to First Article Inspection and a final calibration prior to shipment.

1) Operational Tests.

a) Cooling Requirement. The generator/regulator shall be operated at 100% speed and full rated load to verify system integrity at ambient air pressure, temperature, and humidity. The generator/regulator shall be operated at the above conditions until temperature of the monitored components stabilize. Stabilization is attained when the area of largest mass changes no more than 3.0°C per hour. Care shall be taken not to exceed the maximum temperature ratings of any of the components. Components to monitor and maximum temperature are as follows:

COMPONENT MONITORED	MAX. TEMP.
Stator coils, center of each stack	450°F (232°C)
Rectifiers BR2 and BR3, surface temperature near exit and entrance	212°F (100°C)
Bearing outer races	280°F (138°C)
Rectifier BR1	212°F (100°C)
Transistor Q1	212°F (100°C)
Inductor assembly L1 and L2	330°F (166°C)

Thermocouples shall be installed during the manufacturing process.

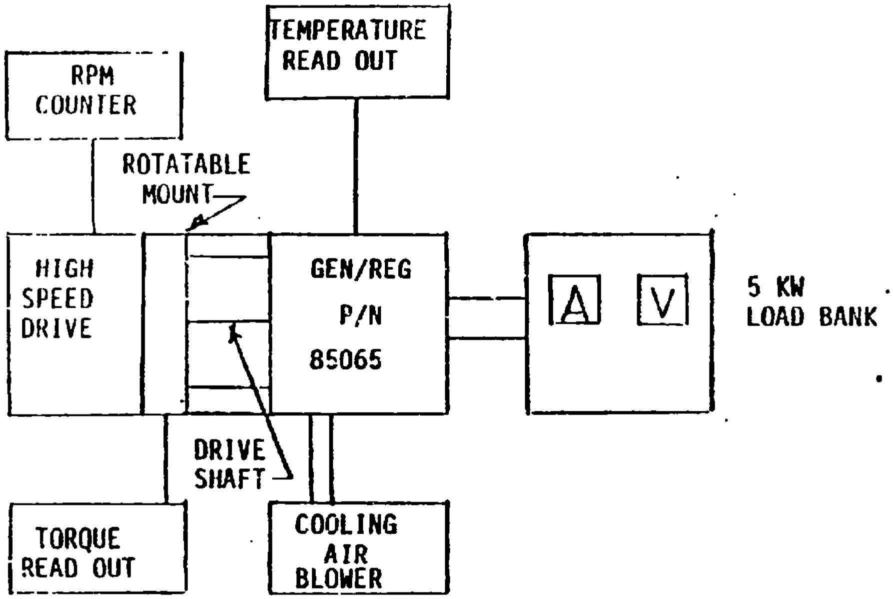
Cooling air shall be provided from a compressor, to simulate the fan. Temperature and airflow shall be monitored to ensure sufficient cooling and to verify the validity of the system cooling method.

The condition of the air, both at the inlet and outlet of the generator/regulator, shall be monitored. Measurements of volumetric flow rate, pressure, and temperature are required at the inlet. Pressure and temperature shall be monitored at the outlet of the generator/regulator. Sufficient data shall be obtained to determine the pressure drop across the generator/regulator and minimum air flow requirements.

2) Procedure.

Mount the generator/regulator to the high speed drive stand. Reference figure 36 for test set up.

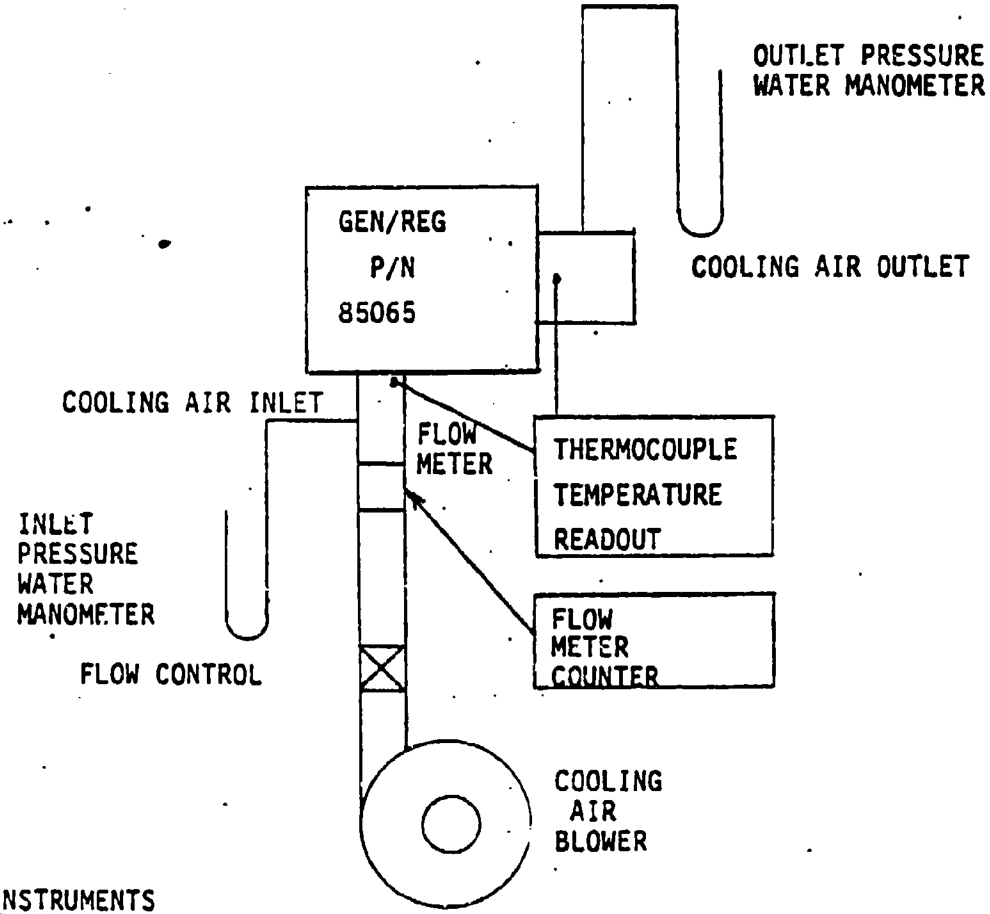
- o Connect the thermocouples to the temperature readout.
- o Connect the DC output to the load bank and the necessary meters.
- o Connect the cooling air supply to the generator/regulator air input and connect the exhaust duct to the generator/regulator cooling air outlet. See figure 37 for cooling air instrumentation requirements and test set up.



INSTRUMENTS

Temp. Read Out: Omega #175
Counter: Simpson 7026
Torque Read Out: Lebow #7525
Loadbank: EKC
High Speed Drive: EKC

Figure 36. Test Set-Up



INSTRUMENTS

Flow Meter: Cox GL3-150
Flow Counter: Simpson 7026
Temp. Read Out: Omega #175
Thermocouples: Copper Constantan
Manometers: Dwyer 36-W/M

Figure 37. Test Set-Up and Instrumentation

- o With all instrumentation properly set up turn on cooling air blower and adjust for maximum flow. Record on data sheet the inlet and outlet temperatures, pressure and inlet flow rate.
- o Operate the generator/regulator at rated speed (60,000 ± 600 RPM) and apply a load of 5,000 ± 50 W. (30VDC at 166.6 ADC.) Record volts and amps on data sheet.
- o Monitor and record on data sheet the temperatures of all components listed below until stabilization, not to exceed rating of 3d1)a).

  Rectifiers BR2 and BR3
  Bearing outer races
  Rectifier BR1
  Transistor Q1
  Inductors L1 and L2
  Cooling air inlet and exhaust
  Cooling air inlet and exhaust pressure
  Cooling air flow CFM
- o Reduce air flow until component(s) with the maximum temperature reaches the maximum rated temperature and stabilizes. Record all data. This establishes the minimum air flow required to cool the hottest component to within its rating.

a) Efficiency Requirement. The generator/regulator efficiency shall be 51% or greater at 60,000 ± 600 RPM with a load of 5,000 ± 50 watts (30 VDC at 166.6 amperes). The test procedure is as follows:

- o Mount the generator/regulator to the drive stand and connect test equipment per paragraph 3d1)a).
- o Calibrate the torque measuring load cell.
- o Turn on cooling air blower and adjust for maximum flow.
- o Operate the generator/regulator at 60,000 ± 600 RPM and apply a 5,000 ± 50 watt load (30 VDC at 166.6 amperes).
- o Record the RPM, volts DC, amps DC, and resulting drive torque.
- o Reduce the load to 2,500 ± 250 watts (30 VDC at 83.33 amperes) and record the RPM, volts DC, amps DC, and torque.
- o Compute the efficiency for each load. Minimum of 51% at 5 kW load is required.

b) Non-Operational Thermal Shock Requirement. The generator/regulator shall be subjected to a thermal shock of -65° to +150°F. Transition time between temperature extremes shall be less than 30 seconds. The following procedure shall be followed.

- o Place the generator/regulator in a temperature chamber set at -65 +5 °F and allow to stabilize for 2 hours.
- o Remove the generator/regulator from the chamber, and within 30 seconds, place in a temperature chamber set at +150 °F and allow to stabilize for 2 hours.
- o Remove the generator/regulator from the chamber and allow to stabilize at room ambient for 2 hours.
- o Perform an ATP per the acceptance test procedure, noting that there is no degradation of performance.

c) Non-Operational Vibration. No vibration testing will be conducted at this time since the existing design is an electrical performance prototype configuration.

d) Data Sheets. Test data sheets shall be completed during the test. Sample data sheets are attached in table 24.

4. FINAL ASSEMBLY

The generator and control unit were assembled as specified in the drawing tree. A gear box was manufactured to increase the speed of the generator from that of the drive stand to 60,000 rpm.

a. Generator Assembly. Photographs of the generator control unit electronics assembly are shown in Figures 38 and 39. The power inductors connector and solid-state filter devices are shown in Figure 38. The final assembly of the electronic, including the printed circuit board, is shown in Figure 39.

Assembly of the generator is shown in the photographs of Figures 40, 41, and 42. In Figures 40 and 41 are shown all the electrical parts for the assembly with the stator coils installed in the main frame. All the wiring, rectifiers assemblies, and stator are shown assembled in the main frame in Figure 42. The rotor was carefully inserted into the assembly after the drive end bell, covers, and the gear box were all assembled.

TABLE 24. SPECIFICATION COMPLIANCE DATA SHEET

DATE ____________

TEST BY ____________

Q.A. ____________

S/N ____________

			TEMPERATURES °C												INLET	OUT	
RPM	VOLTS DC	AMPS DC	STAT 1	STAT 2	BR2	BR3	FRT BGR	REAR BGR	BR1	Q1	L1	L2	INLET	OUTLET	IN. H2O	IN. H2O	FLOW CFM

TABLE 24. SPECIFICATION COMPLIANCE DATA SHEET (Cont.)

DATE ____________

TEST BY ____________

Q.A. ____________

S/N ____________

RPM	DC VOLTS	DC AMPS	TORQUE IN.OZ.	% EFFICIENCY

Para. 4.2.1 Thermal Shock

1. Stabilize at -65^{+0}_{-5} °F for two hours (✓) if done ____________
2. Within 30 seconds stabilize at $+150^{+0}_{-5}$ °F for two hours. (✓) if done ____________
3. Stabilize at room ambient for two hours. (✓) if done ____________
4. Perform an ATP per ER 14/87. These shall be no degradation of performance. (✓) if okay ____________

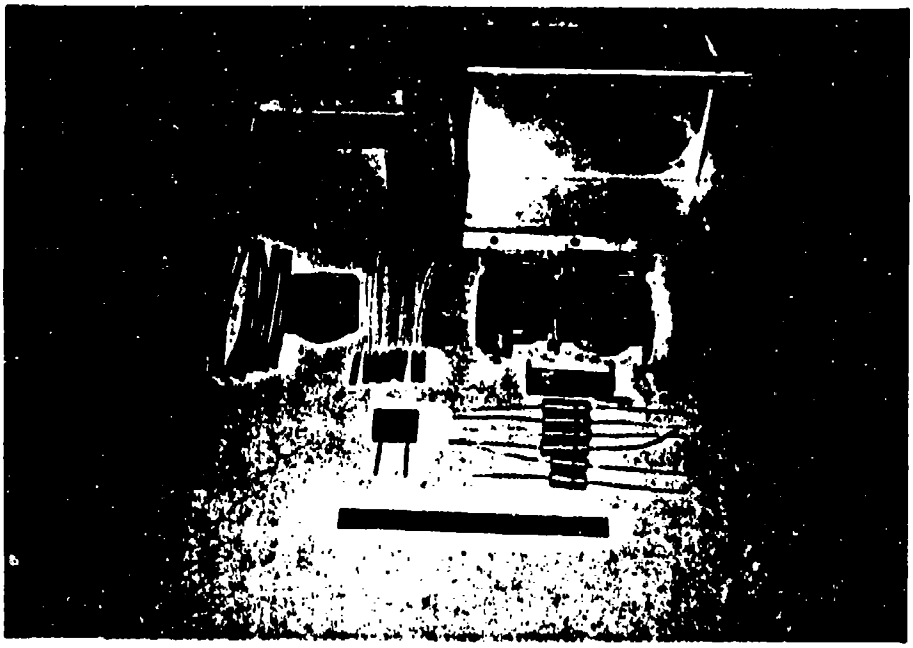


Figure 38. Inductor Assembly

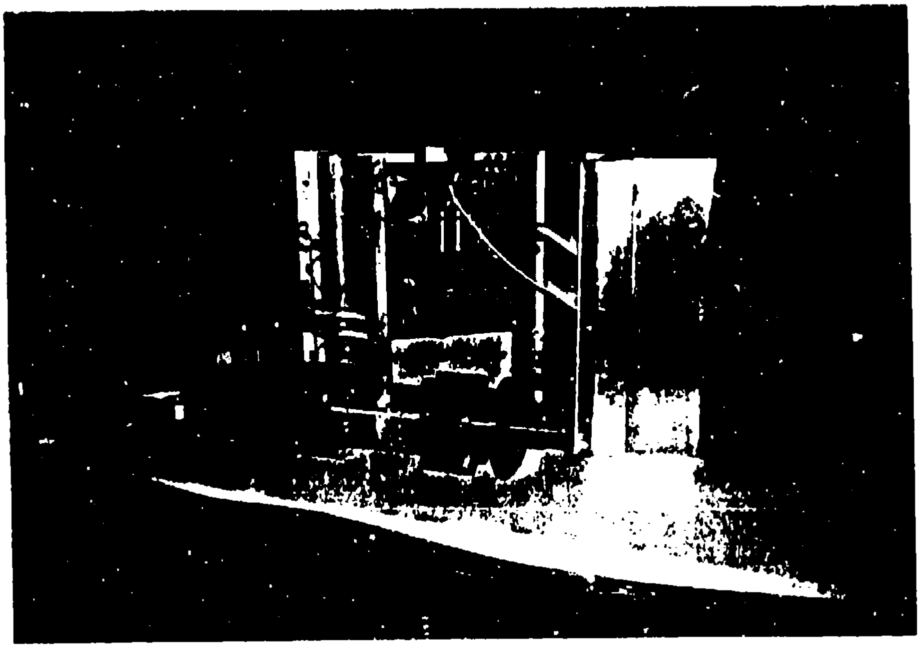


Figure 39. Printed Circuit Board

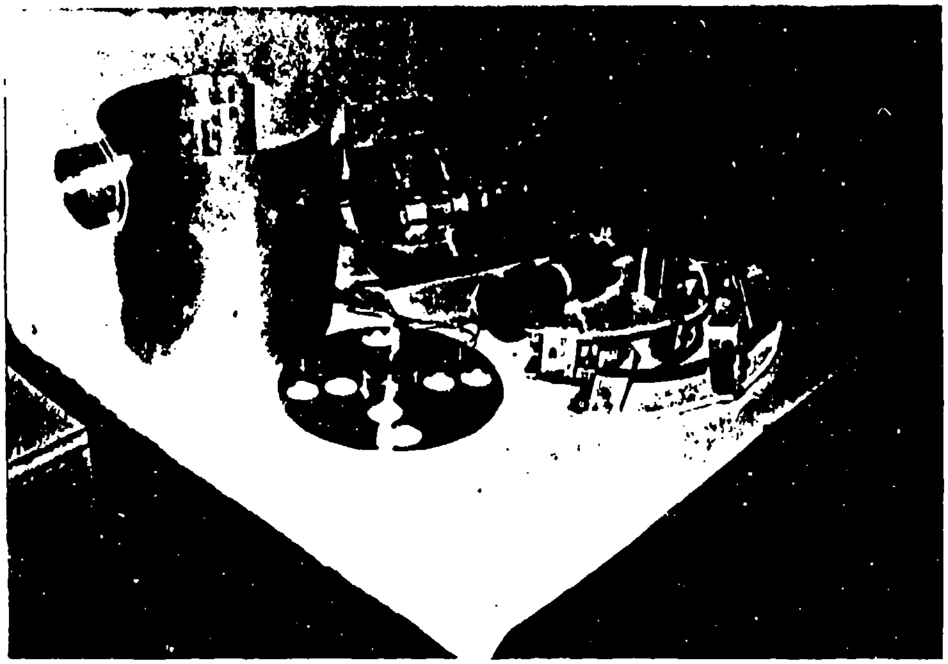


Figure 40. Generator Parts Showing Stator Coils Installed

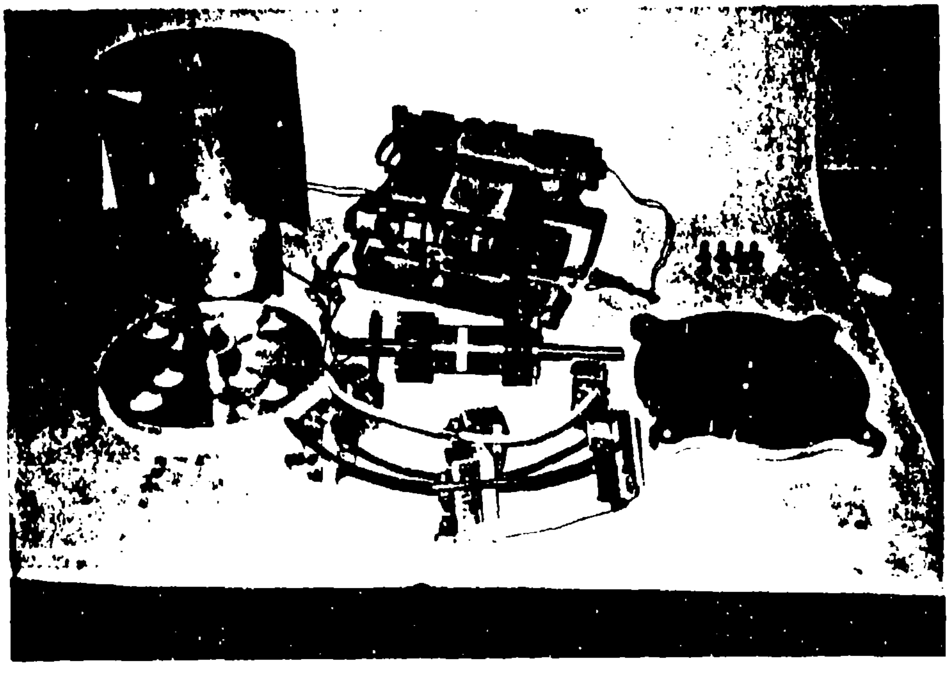


Figure 41. Generator Mainframe Assembly and Parts

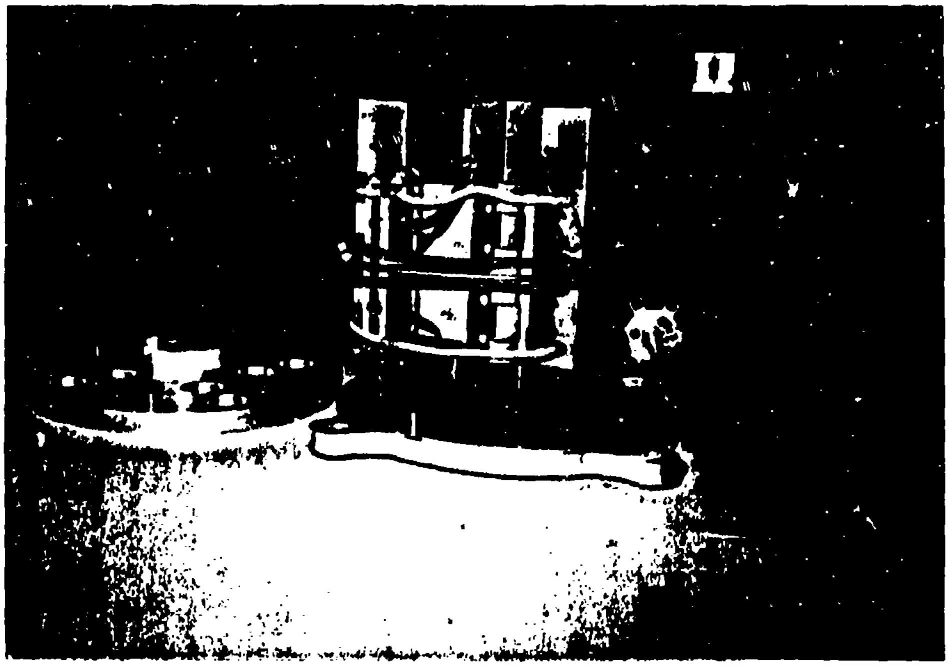


Figure 42. Mainframe Final Assembly

b. Gear Box. All the parts of the gear box are shown in Figures 43 and 44. When the small parts were assembled the gear box appeared as shown in Figure 45 before installing the drive gear and input enclosure. The gear box final assembly with a cooling oil circulating pump installed, is shown in Figure 46. The gear box has a speed ratio is 5.57:1.

The weight of the assembled generator and control unit is 27.75#.

c. Thermocouple Installation. During final assembly thermocouple were embedded in the windings and attached to the critical components to comply with the requirements outlined in the specification compliance test procedure of paragraph 3 above. The location of these thermocouples are shown in Table 25.

TABLE 25. THERMOCOUPLE LOCATIONS

THERMOCOUPLE NUMBER	SYMBOL	LOCATION
0	Ambient	Room Ambient Tempered
1	BR3 (-)	Negative Bridge Rectifier 3
2	BR3 (+)	Positive Bridge Rectifier 3
3	DE Bearing	Drive End Bearing
4	AD E Bearing	Anti-drive Bearing
10	BR1	Bridge Rectifier 1
11	L1	inductor 1
12	L2	Inductor 2
13	Q1	Transistor 1
14	S1	Stator 1
15	S2	Stator 2
16	BR2 (-)	Negative Bridge Rectifier 2
17	BR2 (+)	Positive Bridge Rectifier 2
18	Air Outlet	
19	Air Inlet	

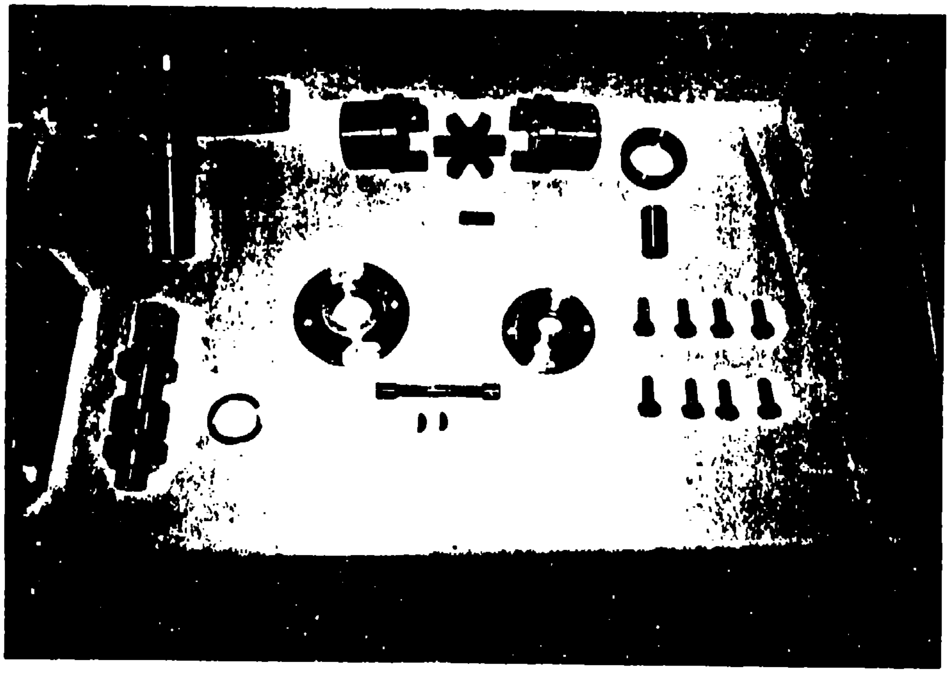


Figure 43. Gear Box Internal Parts

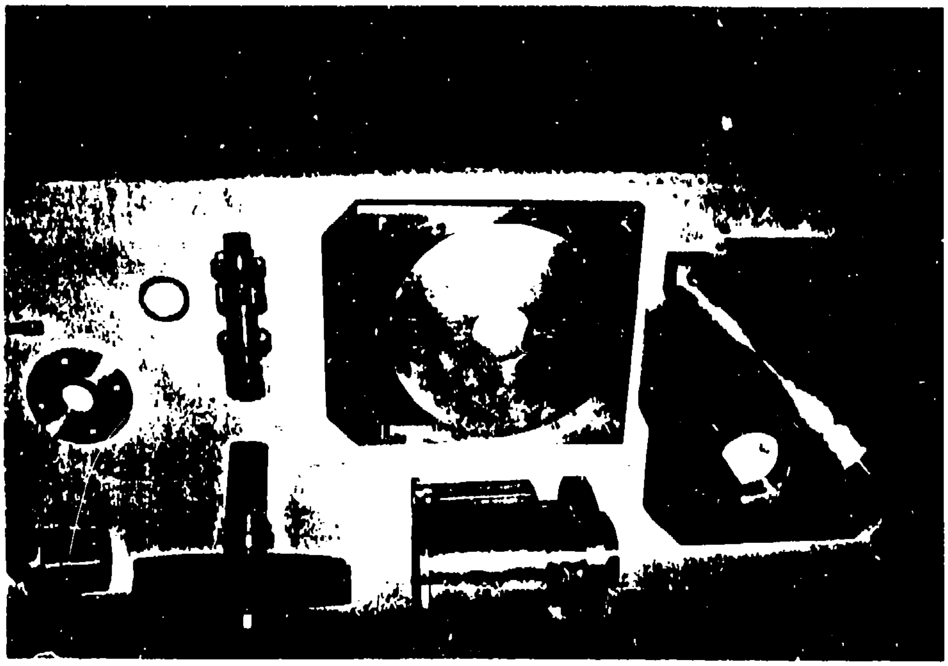


Figure 44. Gear Box Structural Parts

Figure 45. Parts Assembly

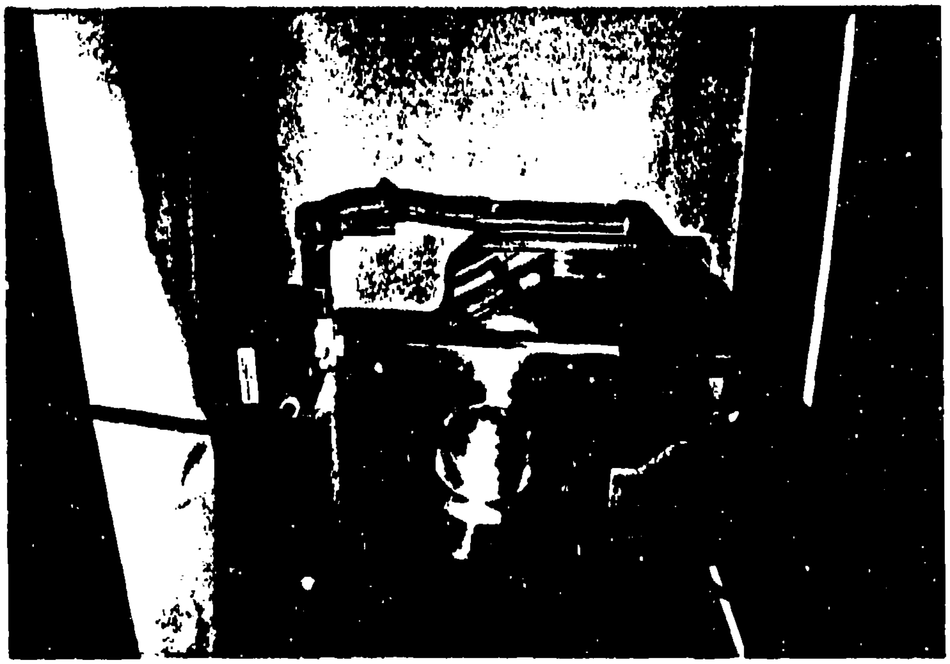


Figure 46. Gear Box Final Assembly

5. TEST PREPARATION

The rotor of the generator was measured across the six poles. This measurement was made to determine rotor expansion, if any, caused by high speed operation. The initial and post operating dimensions are shown in Table 26.

TABLE 26. ROTOR TOOTH OUTSIDE DIMENSIONS

MEASUREMENT NUMBER	INITIAL	POST TEST
Drive End		
1	2.2317	2.2316
2	2.2316	2.2318
3	2.2308	2.2298*
Anti Drive End		
1	2.2310	2.2316
2	2.2313	2.2318
3	2.2314	2.2107*

* Rotor dimensions #3 were shortened due to the rotor rubbing the stator at high speed.

The generator and control unit assembly was mated to the gear box and then mounted on the test stand as shown in Figure 47. All thermocouples were connected to the proper electronic monitors and the generator output connected to the load bank as shown in Figure 48. The unit was inspected, the test monitor and the test operators were prepared for the test.

6. TEST RESULTS

Structural design inadequacies were rapidly discovered in the test program. During the initial start, the drive stand and gear box came up to 12,000 rpm very rapidly. Since the motor turned very slowly, it was apparent the generator drive shaft key or shaft had sheared. An inspection of the generator showed the drive shaft key sheared. A meeting of engineering personnel was convened and it was decided to replace the 1/2-inch-dia x 1/16-inch-thick key with a 1/2-inch-dia x 1/8-inch-thick key. The

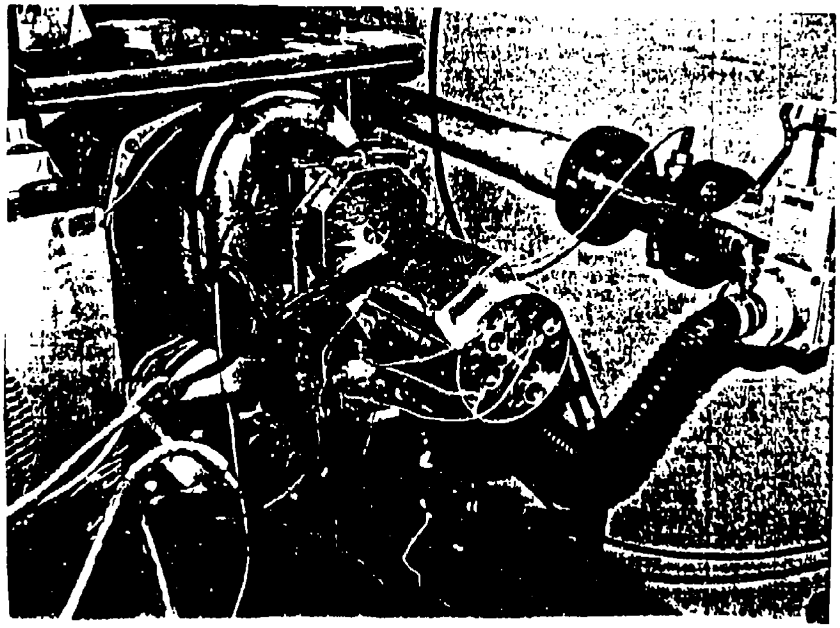


Figure 47. G&CU Test Assembly

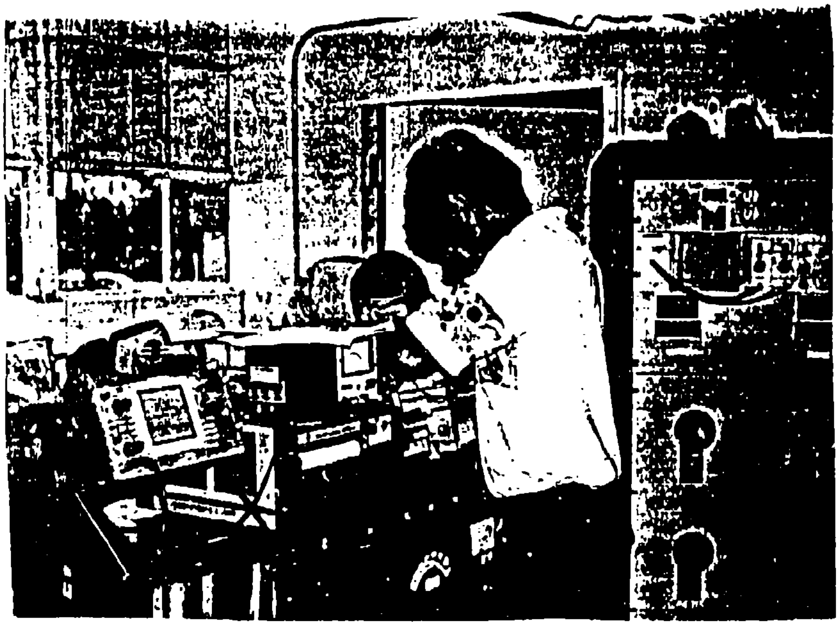


Figure 48. Test Control Panel and Electronics

generator shaft and rotor were removed and new keyways machined into the shaft and coupling. The generator was reassembled and readied for the second test.

Following a visual inspection of the G and CU, the unit was reassembled and readied for test. The machine was started and brought up to 20,000 rpm. At that time the generator control unit provided very low voltage. As the operating speed was slowly increased, the voltage did increase to 2 to 5 volts at 25,000 rpm. This implied that the control did not operate properly due to a design deficiency or a malfunction.

It was decided to increase the speed to 44,000 rpm to determine the stability of the machine at full speed. The generator speed was increased from 25,000 rpm toward 44,000 rpm. During the speed increase the machine appeared to operate as specified. At 39,000 rpm the rotor made contact with the stator, causing mechanical damage to the generator, and the test was discontinued. A photograph of the failed rotor is shown in figure 49.

A post test inspection and analysis was made of the damaged generator and control unit. The following was observed:

a. Control Unit. The control unit was disconnected and removed from the generator for bench testing. Some of the operational amplifier units had been overstressed or the adjustments had changed with time and temperature. The control unit may require redesign for proper long term operation, depending on the exact cause of the failure.

b. Generator Diagnosis. A visual inspection of the generator revealed that the rotor, stator, shaft, and bearings had been damaged severely. The shaft was bent, the bearings were destroyed, three sectors of the rotor were damaged, and both ends of the stator iron was damaged. Four magnets appear to be damaged or loosened from their seatings but the stator winding appears in good shape. The shaft was bent in the direction of the damaged sectors.

From this visual observation it appears that the damage/malfunction resulted from the rotor mating contact with the stator. Two possible causes for the damage/malfunction were investigated: 1) elastic expansion, and 2) vibration.

Elastic and thermal expansion can both be eliminated. At 50,000 rpm the tangential stress was calculated to be 7,688 psi; at 65,000 rpm the value is 1.69 times that at 50,000, or 12,993 psi. Both values are within the elastic limit of aluminum and steel. Likewise, the machine had operated but a few minutes with very small temperature rise indicated within the windings or stator. Both thermal and elastic expansion can be ruled out as a cause for the malfunction/damage.

Vibration was the most probable cause of the malfunction/damage. During design, an analysis was made for the first vibration mode, and was calculated to be 1,130 Hz (67,880 rpm), which included the bearing stiffness. This calculation implied that the shaft assembly would be dynamically sound at the speeds below 67,800 rpm.

The shaft assembly was dynamically balanced at 2,500 rpm using a Hoffman Co., Type HL-14.1 test instrument. The unbalance for the two ends of the shaft were 0.0001-inch and 0.0002-inch. At this slow speed the shaft assembly appeared mechanically sound. As speed is increased this slight amount of unbalance flexes the shaft and causes the first vibration mode to occur at a lower frequency; in this case 39,000 rpm. Thus the damage/malfunction.

In several discussions with HTL engineering, it has been concluded that the shaft had inadequate stiffness. If the unit is to be redesigned, the shaft/armature assembly must be modeled and a stiffer shaft designed for the machine. A flexible shaft will result in greater vibration magnitude and ultimate destruction, as occurred in this case.

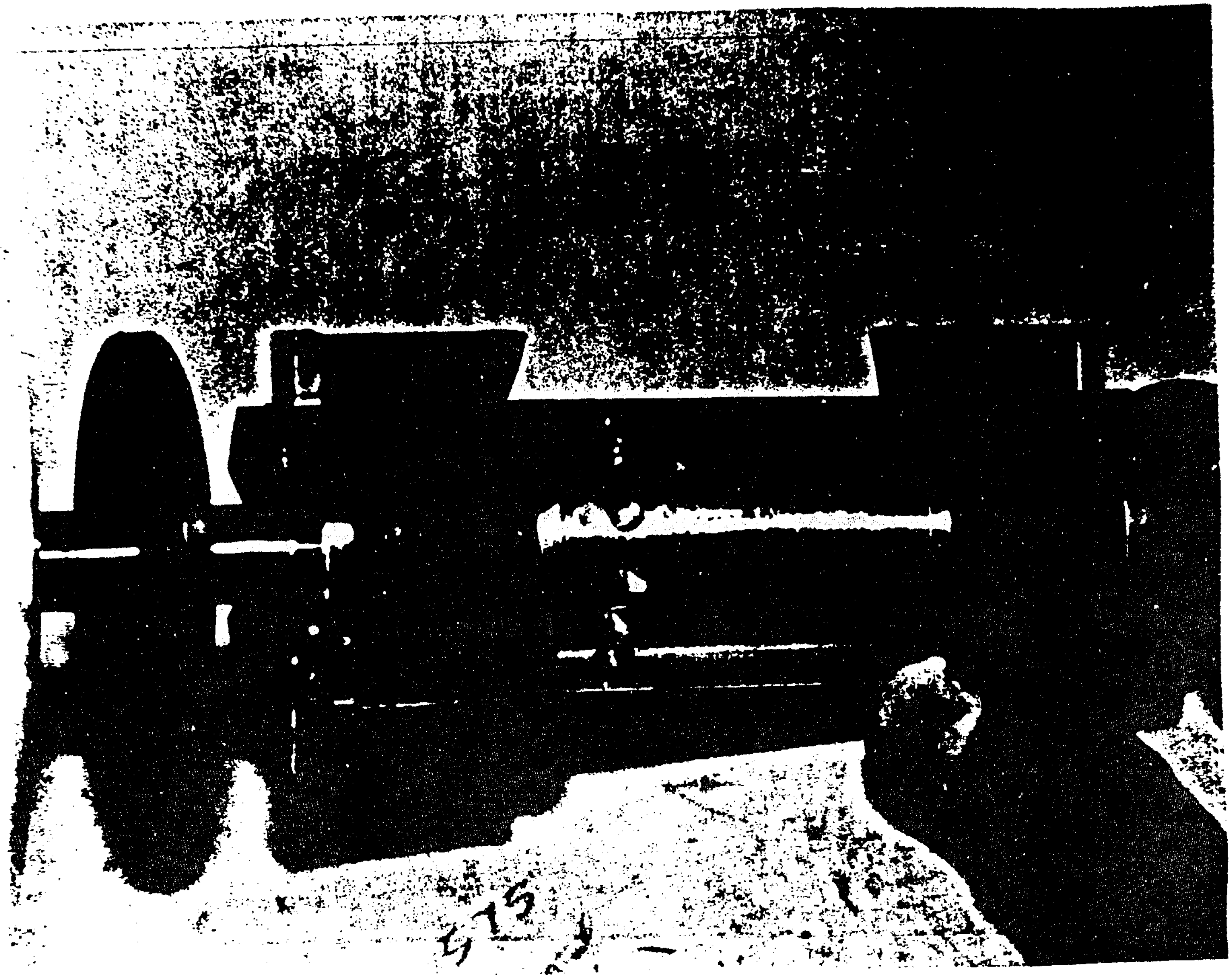


Figure 49. Post Test Rotor Failure

SECTION VII
CONCLUSIONS

The design, analysis, fabrication, and test of a high speed generator and control unit for an advanced version of the ALCM have been shown in the preceding sections. Although the machine failed to achieve the desired high speed requirements, significant results and conclusions are drawn.

- The generator shaft should be analyzed. It appears the shaft is much too small for the operational speeds specified. If the shaft is too small and led to the design failure, a new shaft should be designed for the machine that will tolerate the vibration and speed.
- The air gap has a nominal spacing of 0.005 inch. The elastic expansion of the rotor at high speed may be greater than the air gap spacing. An analysis of rotor expansion should be determined.
- The rotor laminations should have heavier laminations or fixtures on the inboard and outboard of each rotor to prevent lamination feathering.
- The control unit should be analyzed for parasitic oscillations and functional operation.
- The rotation of the machine must be checked for correct output polarity.

SECTION VIII
RECOMMENDATIONS

The following recommendations have been identified to warrant further work on the high speed generator and control unit.

- Design a new shaft and bearings for the unit.
- Modify the end bells to accommodate the new bearings.
- Increase the air gap by decreasing the rotor diameter.
- Measure the maximum rotor diameter optically at full speed to assure the rotor will not hit the stator.
- Check the machine polarity to the rectifier.
- Mount the rectifier, filter, and control unit in a separate or attached package.
- Analyze and redesign the control circuit electronics as required.
- Design a fan for the unit.

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