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AD-A173 959

Permanent Magnet Variable Speed Constant Frequency Power Generation System

General Electric Company
Binghamton, New York 13902

March 1986

Final Report for Period of August 1978 to June 1984

Approved for Public Release—Distribution Unlimited

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The design, development, and aircraft installation of a 60-KVA permanent magnet starter-generator system is presented. The primary objective of this program was to advance the permanent magnet technology and demonstrate that a flexible, reliable, and low-cost starting means can be provided. The electrical system, developed under this program, obviates the use of large air ducts and complicated gearboxes, clutches, and torque converters. Eleven

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) systems were fabricated and flight qualification was completed. The starting capability was demonstrated at Syracuse Air National Guard base and at the General Electric Engine facility in Lynn, Massachusetts.

An A-10 aircraft was completely modified at Nellis Air Force base, and the permanent magnet starter-generator was installed. The planned flight test was deferred by Tactical Air Command and, thus, the aircraft was demodified and placed into regular operation.

FOREWORD

This final report was submitted by the Armament and Electrical Systems Department of General Electric Company under contract F33615-78-2200. The effort was sponsored by the Air Force Wright Aeronautical Laboratories, Air Force System Command, Wright Patterson Air Force Base, Ohio, under Project 2348, Task 234804, Work Unit 23480402, with Dr. W.U. Borger, AFWAL-POOC as Project Engineer. Messrs. R.C. Webb and C.H. Jennings, General Electric Company, were Program Managers and were responsible for the overall effort. Mr. G.P. Koerner was the Project Engineer on this program.

This report covers work performed during the period from August 1978 to June 1984, and was submitted to AFWAL in March 1985.

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Program Summary

1.1 OBJECTIVES

The objective of this program was to design, fabricate, demonstrate flightworthiness, and flight test a 60-KVA Variable Speed Constant Frequency (VSCF) Permanent Magnet (PM) electrical starter-generator system.

The realization of samarium cobalt, high-energy product permanent magnets (>20 million gauss-oersted), with excellent resistance to demagnetization, has allowed permanent magnets to be applied in high-powered electrical generating systems. The starter-generator, developed for this program, uses these high-energy samarium cobalt magnets in an all-metallic solid rotor.

Sufficient hardware was built to allow for flightworthiness testing, extensive laboratory testing—including paralleling operation—and demonstration of flight capability on two A-10 flight test aircraft. During the one-year flight test period, all 400-Hz power generation, with the exception of ground power and Auxiliary Power Unit (APU) generated power, and engine starting was to be accomplished with the equipment that was developed under this program.

This program was part of an overall Air Force effort to develop lightweight, low life-cycle cost airborne electrical systems, yielding high quality MIL-E-23001B, 400-Hz power, and provide flexible, reliable, low cost engine starting. The electrical starting system that was developed in this program for flight test negates the need for existing starting equipment such as complicated gearboxes, clutches, and torque converters. In addition, bulky and difficult to install items, such as large air ducts, are done away with. Moreover, since this device is also a generator, conventional hydromechanical type power systems (constant speed drives) are no longer required.

1.2 BACKGROUND

A majority of military airplanes use 400 Hz as their primary electrical power. This electrical power is generated from mechanical power that is extracted from the engine accessory gearbox, which has a variable speed due to changes in engine speed—typically two to one. A device that is located between the gearbox output and the 400-Hz power output terminal is necessary to produce the constant 400-Hz power. Most electrical systems, in use today, employ a hydromechanical transmission to drive a synchronous generator at constant speed.

With the advent of high power semiconductors in the late 1950s and early 1960s, it became technically feasible to manufacture aircraft electrical systems with solid-state converters that could accept the variable frequency output of the synchronous generators and could reconstruct the voltage wave electronically into a precise 400-Hz output. The conversion method, to be discussed, uses naturally commutated SCRs and is called a cycloconverter. The cycloconverter is a bidirectional, single stage converter. Two major features of cycloconverters are power flow, through a single semiconductor junction (giving high efficiency), and commutation by naturally occurring voltages. Naturally commutated converters are lighter, more efficient, and less subject to catastrophic commutation failures than are forced commutated converters. The cycloconverter with a synchronous generator forms a variable speed constant frequency system. A block diagram of this system is shown in Figure 1.

VSCF type power promises high reliability and maintainability, and it has demonstrated this capability in the industrial motor speed control industry where power conversion devices, similar to those used in VSCF systems, have become the standard. The application of VSCF type power equipment to aircraft electrical power generation had been delayed, for one reason or another, until 1972 when the equipment was called on to solve an A-4 electrical system problem.

The excellent results obtained in the A-4 program, coupled with the ever increasing high life-cycle costs of hydromechanical drives, prompted the Air Force to initiate a service test of a 60-KVA system. In August 1976, contract F0406-76-C-0902 was awarded to the Boeing Company to provide the engineering support for the 50-KVA system, conduct flightworthiness tests, install the system in three KC-135 aircraft, and monitor the service test program.

In addition to the A-4 program, the Navy recognized the inherent engine starting capability of the VSCF type power system. A study effort culminated in a contract (N00421-72-C-6579) to the General Electric Company in 1972 to construct a 60-KVA, wire-wound rotor VSCF starter-generator system for the A-6 aircraft. The results of the program showed that VSCF equipment can provide flexible engine starting systems.

During this same VSCF development period, the Air Force Materials Laboratory was leading the effort in the development of rare earth/transition metal permanent magnets.

In 1972 and 1973, permanent magnets with 20-million gauss-oersted magnetic energy products became commercially available. These magnets exhibited a demagnetization curve that is close to the ideal magnet curve and provide a high coercive force which overcomes the negative factors for the utilization of permanent magnets in high-power generators, see Figure 2.

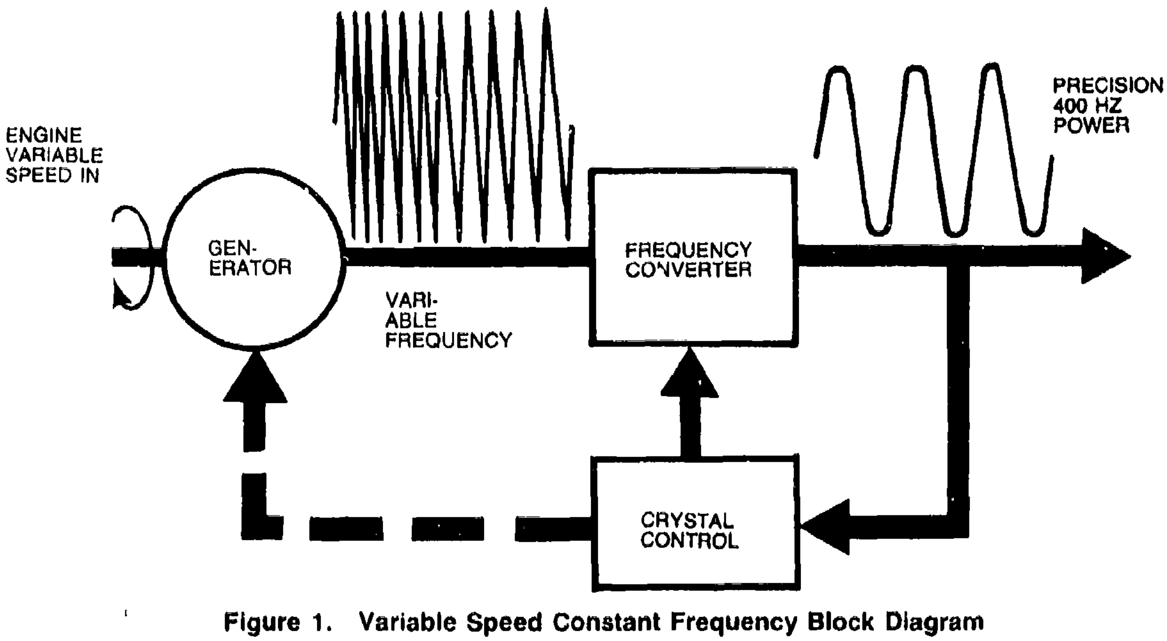

Figure 1. Variable Speed Constant Frequency Block Diagram

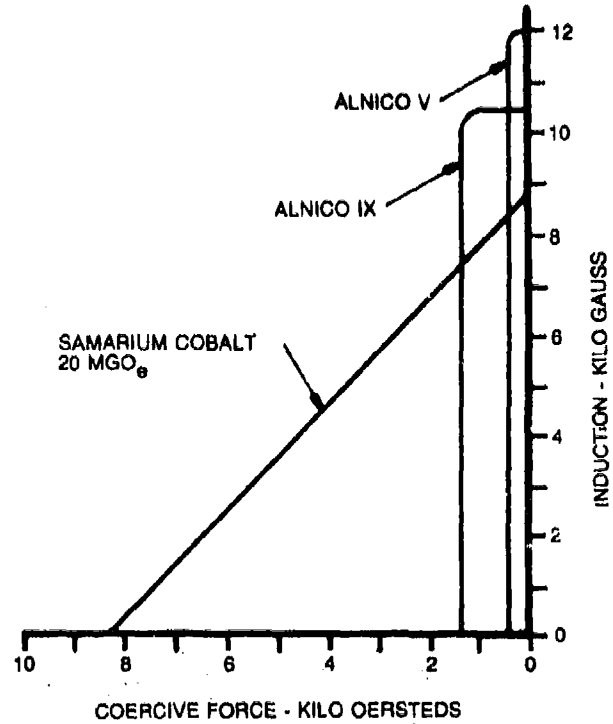

Figure 2. Magnet Comparison

It was clear, at this time, that permanent magnet VSCF systems were technically feasible and highly desirable from a reliability, weight, volume, and cost standpoint. Contract F33515-74-C-2037 was jointly awarded by the Air Force Materials Laboratory and the Air Force Aero Propulsion Laboratory to the General Electric Company to demonstrate a 150-KVA samarium cobalt VSCF starter-generator system. Testing was initiated in October 1976, and the program was completed in May 1978*.

The feasibility of applying samarium cobalt magnets was demonstrated on this program, and the VSCF system showed a significant improvement in generating efficiency over conventional electrical systems. The VSCF system also demonstrated the feasibility of performing electrical engine starting in the reverse power mode. Additional simplification in the engine auxiliary gearbox area and aircraft ducting can now be achieved by combining the engine starting and electrical power generation function into one system.

The 60-KVA Advanced Development Program (ADP) uses the design and experience gained on the 150-KVA PM VSCF program to transfer the PM VSCF system technology from laboratory status to flight line hardware.

*See final technical report AFAPL-TR-78-104.

1.3 OVERVIEW

The program schedule is shown in Table 1. Key events and accomplishments during the various phases are discussed below:

1.3.1 PHASE I—PRELIMINARY DESIGN

This phase was completed in the last two quarters of 1978. Initial design trade-offs were made in this phase, and it was decided that a nine-phase VSCF generator was a more optimized approach than a six-phase. The mock-up of the converter, made during this period, is shown in Figure 3.

TABLE 1
60-KVA ADP PROGRAM SCHEDULE

		1978		1979				1980				1981				1982				1983				1984			
PHASE	DESCRIPTION	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
I	Preliminary Design	▲	—	▲																							
II	Critical Design			▲	—	—	▲																				
III	Test Article Fab						▲	—	—	—	—	—	—	—	—	▲											
IV	Preliminary Qual Test														▲	—	—	—	—	—	—	—	▲				
V	Flight Article Fab											▲	—	—	—	—	—	—	—	—	—	—	—	▲			
VI	Installation on A/C																								▲		
VII	Flight Test																										
VIII	Test A/C Refurbish/Report																								▲	—	▲

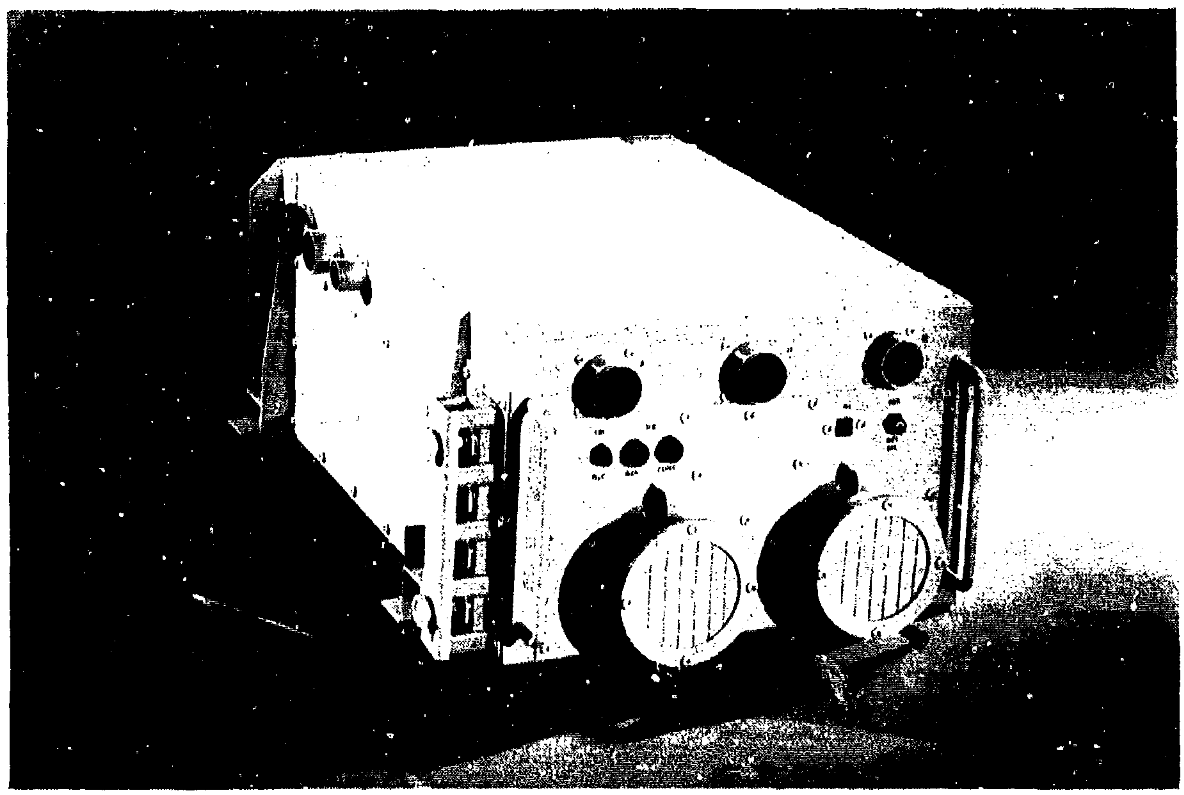

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Figure 3. Converter Mock-up

1.3.2 PHASE II—CRITICAL DESIGN

This phase was completed during the 1979 calendar year. In addition to designing a production system, a breadboard converter was built and tested, using the PM generator from the 150-KVA program. Series inductors were used with this machine to simulate the inductance that was expected with the production generator. A test setup was built in the development laboratory to facilitate start mode and parallel mode testing. A photo of the breadboard converter is shown in Figure 4.

1.3.3 PHASE III—TEST ARTICLE FABRICATION

This test was completed in the first quarter of 1982. The first of the three qualification converters and the qualification generator were fabricated in the fourth quarter of 1980. These units are shown in Figure 5.

All tests that were conducted prior to 1981 had used the 150-KVA PM machine. Because of speed limitations of this machine, the tests had been limited to about half of the designed maximum generator voltage and frequency. When the qualification generator was tested with the cycloconverter, it was discovered that SCR losses at top speed were higher than the predicted value. A third fan was then added to the converter, and the size of the SCR heat sink was increased. Also, the stator winding in the generator was changed to "short pitch" to lower the converter losses and reduce the SCR voltage stress. This change was incorporated in the fourth production generator.

1.3.4 PHASE IV—PRELIMINARY QUALIFICATION TEST

An extensive qualification test of the system was performed over a two-year period and was completed in December 1983. The schedule and sequence of the tests are given in Table 2.

The Electromagnetic Interference (EMI) test for radiated and conducted wire was run in the fourth quarter of 1981. Figure 6 shows the converter in the EMI test setup.

The generator vibration test began in December 1981. The generator passed the tests, except for a mysterious disconnect at a particular frequency. The generator was then disassembled and passed inspection. The test setup was adjusted, and the test was rerun successfully.

Water ingestion and humidity tests were completed with minimal problems.

Start filter vibration test uncovered some structural problems. Some parts inside the filter had to be redesigned. Tests were successfully completed with new parts installed in January 1983.

Current Transformer Assembly (CTA) vibration tests had minimal problems. These tests were run between October 1982 and November 1982.

The temperature/altitude tests uncovered some performance discrepancies with unbalanced loads. These discrepancies were in the areas of phase angles, harmonics, line-to-neutral, and line-to-line voltages. Some circuit improvements were incorporated to bring the voltage and harmonics within specification.

The preliminary qualification test report was submitted to the Air Force in September 1983, detailing all of the completed tests. After reviewing the report, the Air Force decided to add explosive atmosphere, converter air flow, and shock tests to the qualification program. These additional tests were all completed successfully, and the results were reported in January 1984.

1.3.5 PHASE V—FLIGHT ARTICLE FABRICATION

This phase was completed in March 1984. During this phase, eight (8) flight test converters, eight (8) generators, four (4) start filters, and 122 cable assemblies were built and tested. The final converter configuration is shown in Figure 7.

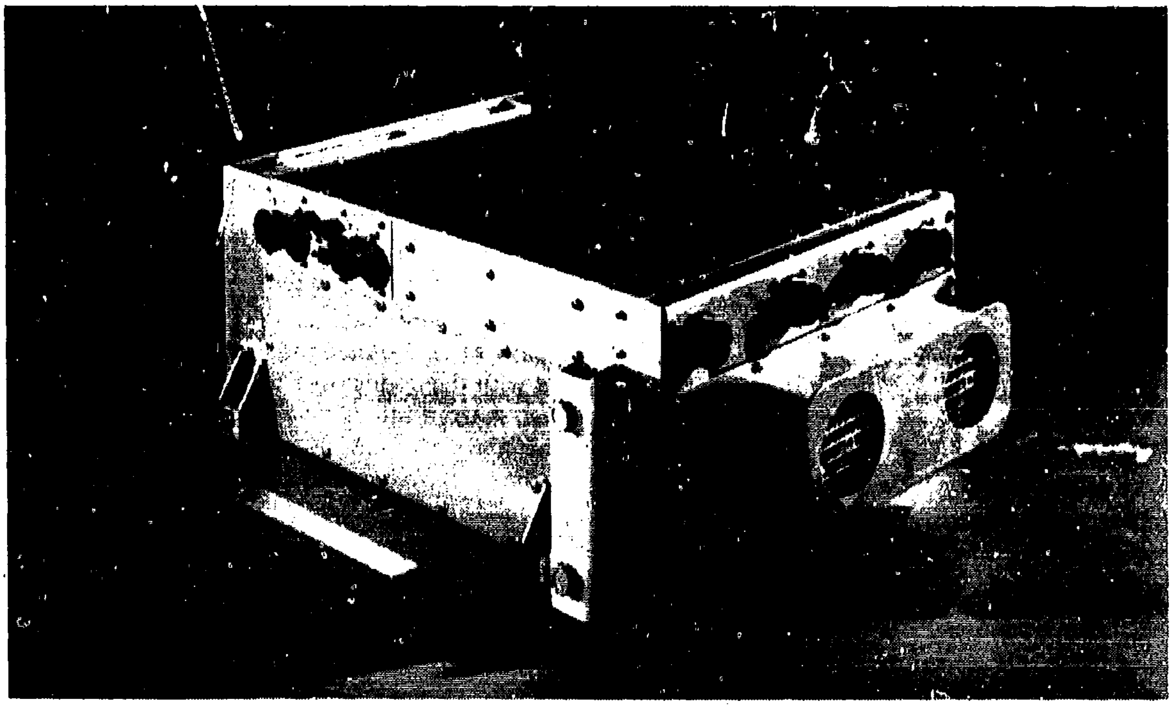


Figure 4. Converter Breadboard 28368-1

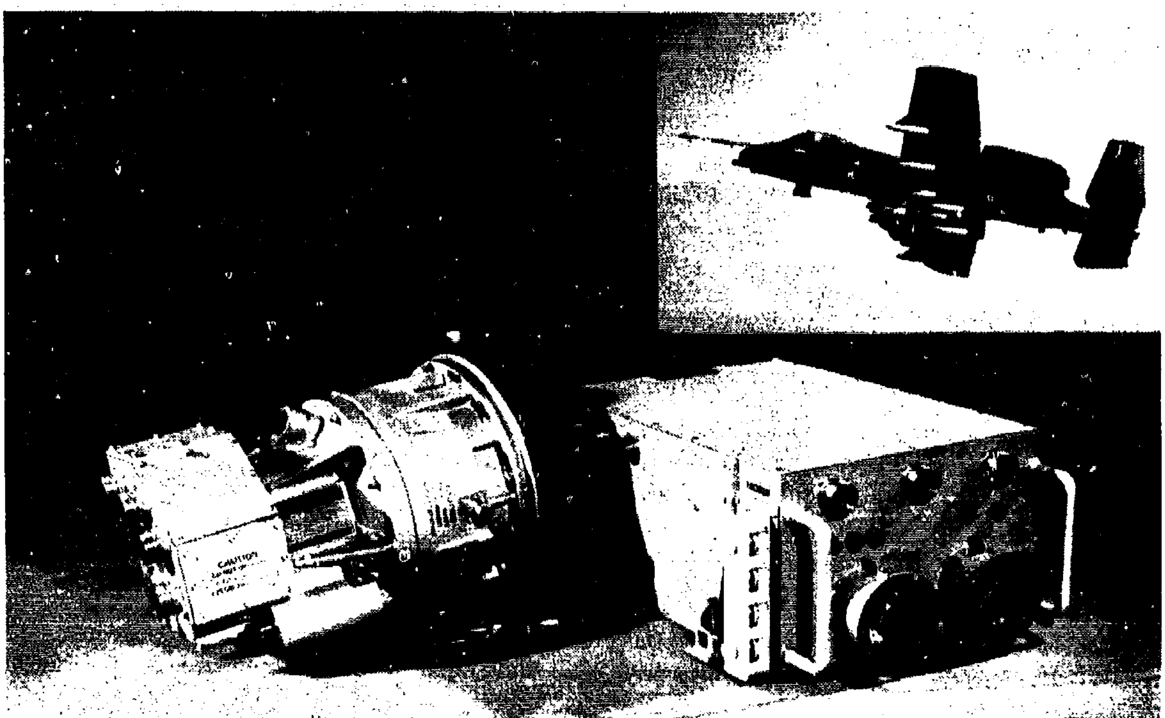
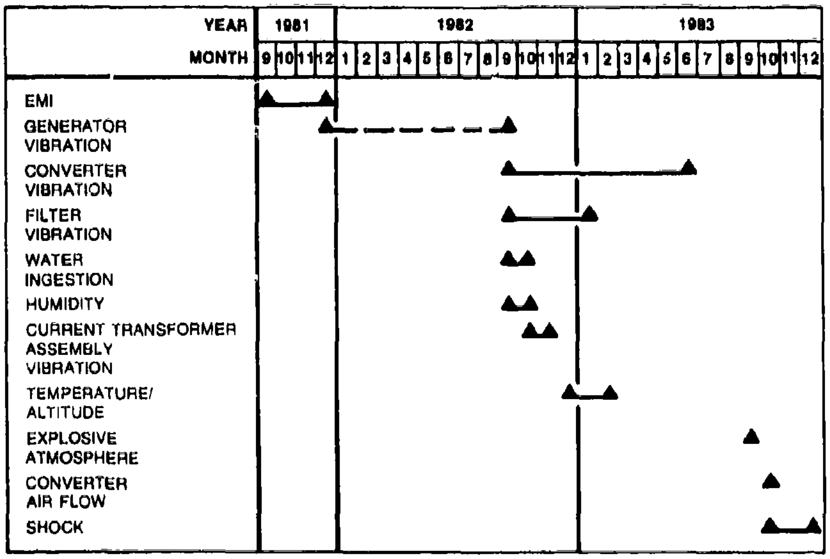


Figure 5. Initial Qualification Hardware 30067

TABLE 2
QUALIFICATION TEST SCHEDULE



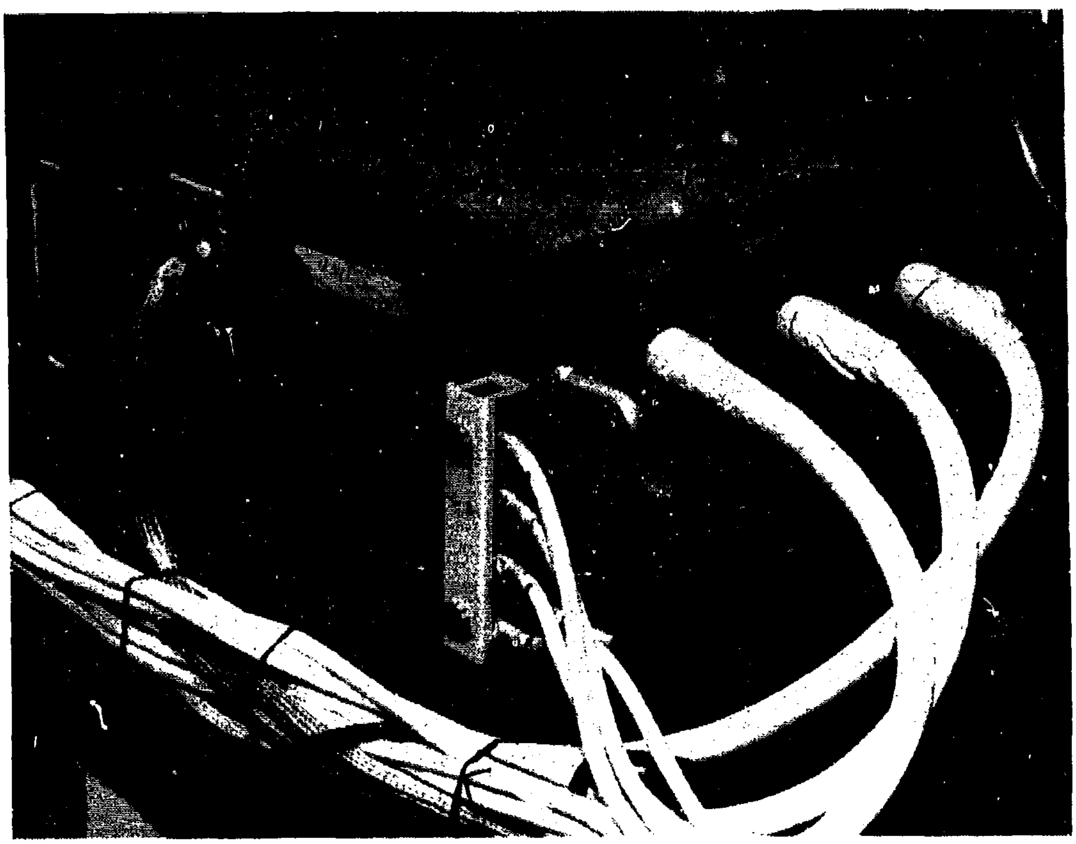


Figure 6. EMI Test Setup

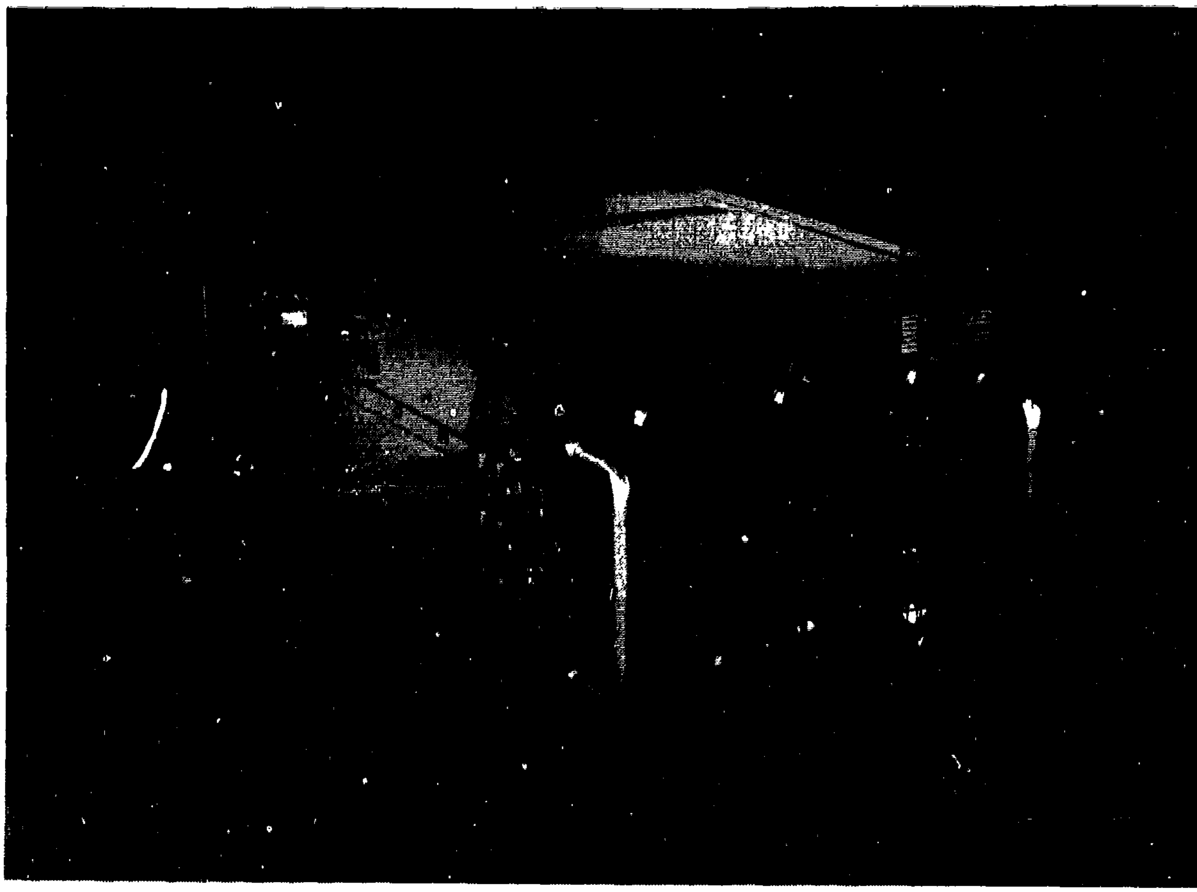


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Figure 7. 60-KVA Cycloconverter, Final Configuration

1.3.6 PHASE VI—INSTALLATION ON AIRCRAFT

During this phase, an A-10 aircraft (S/N 79-168) was modified, and the PM VSCF system was installed. This work was performed at Nellis Air Force Base during April and May 1984.

After the modification was completed, a full gamut of ground tests was conducted. This consisted of engine starts, motoring and generating operation, and bus switching. No problems were encountered during these tests.

1.3.7 PHASE VII—FLIGHT TEST

The flight test that was originally scheduled for one year on two aircraft did not take place.

1.3.8 PHASE VIII—TEST A/C REFURBISH/REPORT

The modified aircraft was demodified and refurbished in a five day period. The information presented herein constitutes the final report for the program.

1.4 CONCLUSIONS

This program, initiated in August 1978, was successfully completed in December 1984. During this period, design, development, fabrication, and flightworthiness demonstration and aircraft installation of a 60-KVA permanent magnet VSCF system were accomplished. Eight complete systems were built and extensively tested. This program advanced the state-of-the-art for aircraft starting systems and demonstrated that starting can be more efficiently accomplished electrically thereby eliminating complicated gearboxes, clutches, and large air ducts.

The modification of the A-10 aircraft at Nellis Air Force Base took slightly longer than the two-week period scheduled due mostly to aircraft compatibility problems. However, once these problems were resolved, the installation was completed successfully, and a significant amount of ground testing was conducted.

Based on the accomplishments of this program, the Air Force considers this PM starter-generator system fully demonstrated and suitable for incorporation in advanced aircrafts.

Section 2
Design

2.1 SYSTEM DESIGN

2.1.1 SYSTEM DESCRIPTION

The VSCF system, described by this report, consists of a cycloconverter with a synchronous generator that uses samarium cobalt magnets for its excitation. As part of its normal operation, the converter conditions the variable frequency and voltage delivered by the Permanent Magnet (PM) machine into precise frequency power. The cycloconverter is capable of reverse power flow, and the PM generator has the necessary excitation at standstill to make it possible to run the system as a brushless starter.

One channel is comprised of a nine-phase solid rotor PM generator and cycloconverter that are sized to start the TF-34 engine and deliver 60 KVA in the generating mode.

The size and actual weight of these assemblies are shown below:

		Size	Weight (Pounds)
Generator	Long	11.1 Inch	61.5 (Dry)
	Diameter	7.0 Inch	
Converter	Volume	2,750 $Inch^3$	79.9

The cycloconverter is forced air cooled, see Figure 8. All functions to control and protect the system during asynchronous, split synchronous, parallel, and starting are contained within the converter.

A generator photo is shown in Figure 9, and its description is shown in Table 3. Figure 10 shows the 60-KVA solid rotor next to a 60-KVA wire wound rotor. An adaptive gearbox is required for the flight test to match the TF-34 engine gearbox speed with the generator speed. This adaptive gearbox also contains an oil module that allows the generator to be designed as a shared oil machine. The gearbox and the generator have a total weight of 95.0 pounds.

Figure 8. 60-KVA Cycloconverter

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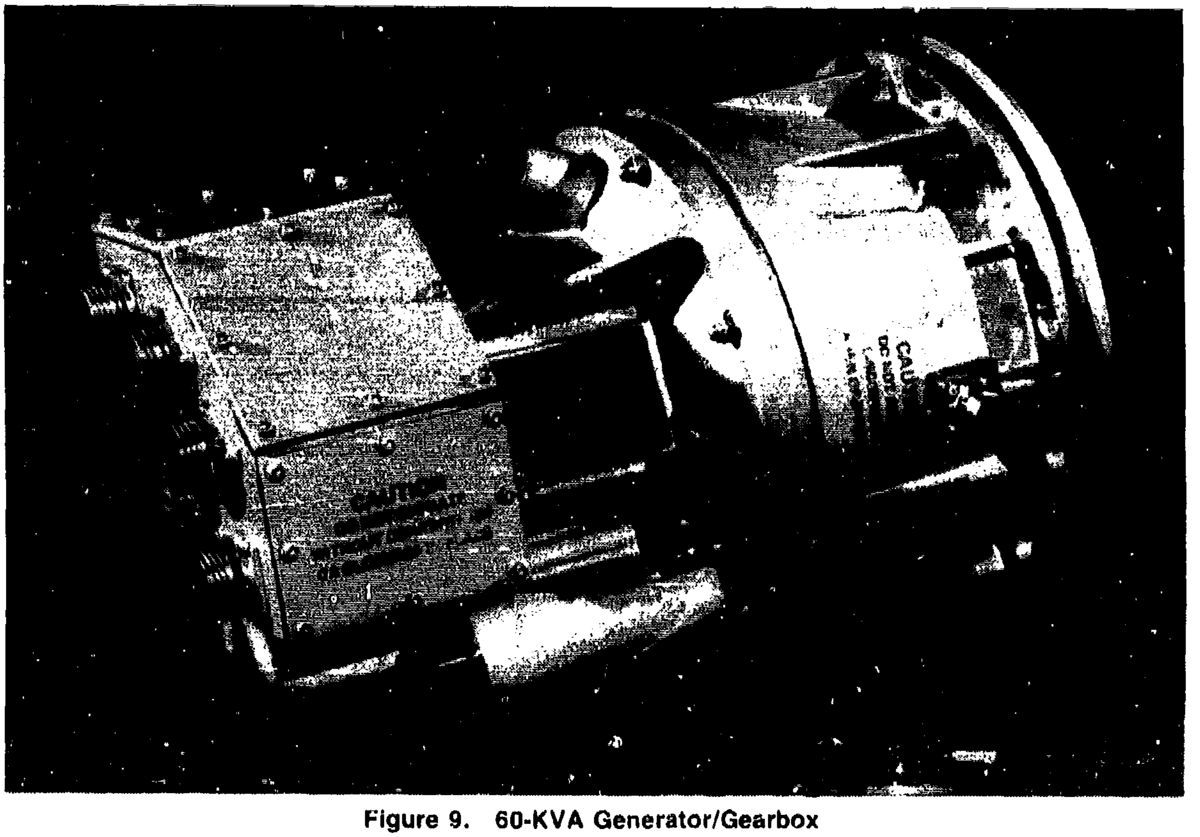


Figure 9. 60-KVA Generator/Gearbox

TABLE 3
60-KVA ADP GENERATOR DESCRIPTION

Speed	15 to 30 KRPM
Phases	9
Number of Poles	10
Magnets	20 MGO_e, Samarium Cobalt
Rotor Diameter	5.5 Inches
Stack Length	4.8 Inches
Stator OD	6.05 Inches
Slots	90
Air Gap	0.045 Inch
Number of Rotor Discs	4
Cooling	Shared Oil

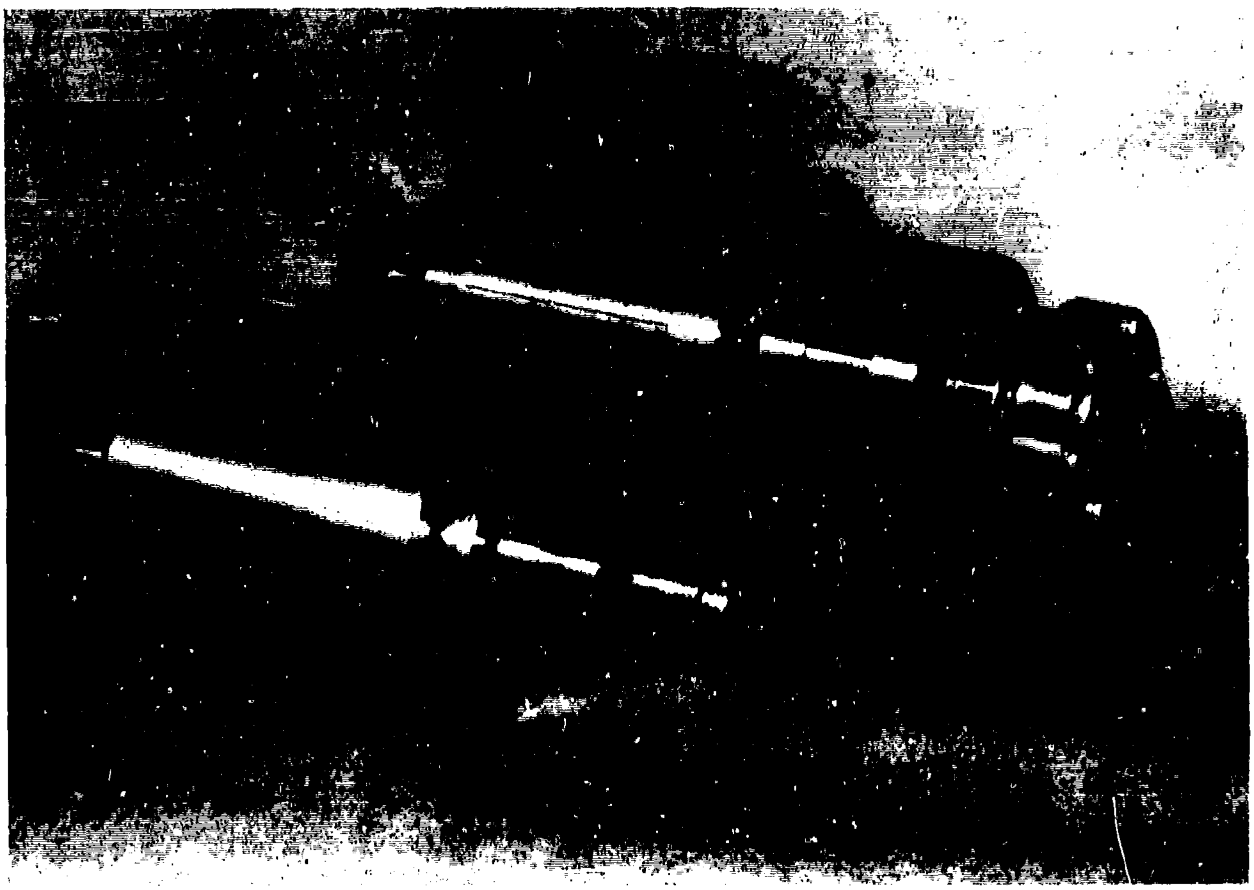


Figure 10. 60-KVA Permanent Magnet and Wire Wound Rotors

Shown in Figure 11 is a block diagram of the PM VSCF system. At the center is the main power path of the PM machine, the converter-filter, and the 400-Hz terminals. In the start mode the power flows from right to left. Four-hundred hertz power is converted to nine-phase variable frequency, variable voltage, which is phased by the position of the PM rotor. The PM machine then converts this electrical power to mechanical power.

In the generate mode, the system is a VSCF generator. Power flows from left to right. Three cycloconverters, functioning as linear amplifiers, reproduce 400-Hz sinusoidal reference waves at the power level required by the aircraft loads. The cycloconverters form sinusoidal output waves by the phase-controlling Silicon Controlled Rectifier (SCRs) so that the average voltages at the rectifier banks are the desired sine waves. The output waves are programmed on both positive and negative SCR banks throughout the cycle so that load current can flow in either direction with either voltage polarity. The power circuit remains unchanged, except for opening the contactors in the machine neutrals in the motoring mode. Nine-phase machines permit accurate programming and require only a light filter since ripple amplitude of a rectifier is minimal.

An Interphase Transformer (IPT) parallels three banks of three-phase commutating groups, which allows 120° conduction of the SCRs. Only one third of an output phase current is commutated, so this connection has very low source impedance. Leakage inductance of the IPTs and a shunt capacitor form a low-pass filter to smooth out the rectifier ripple.

Over the two to one speed range, the Permanent Magnet Generator (PMG) voltage varies with load and speed as shown in Figure 12. The voltage from no-load top speed to 2.0 per unit overload at minimum speed varies by approximately 2.5 to 1. Although this appears to impose a penalty on the converter, compared with a regulated machine system, the difference in transient withstanding is not as great. The required SCR voltage capability is only about 1.5 times that required for a regulated machine system, since the PM machine has no transients of its excitation system.

Converter systems with wound rotor machines must have their voltage regulator response limited by the generator voltage regulator response. The converter voltage must not recover before the generator voltage does when heavy reactive loads are applied because the load current cannot be commutated at full output voltage. The PM machine, which starts off at high voltage at light loads, dips almost immediately to the value set by the load current, but it does not go below the steady-state value.

The excess PM voltage at high speed or light load is rejected by phasing the SCRs in a narrow band, about 90°. Therefore, the time from the latest SCR firing until the end of the machine cycle does not significantly decrease as the speed goes up even though the period of the generator wave is decreasing. The SCRs for the PM system can have turn-off times that are twice that required for regulated machine systems.

Higher voltages also mean higher dv/dt during commutation or more snubber loss. Fortunately, here, too, the PM machine has a compensating characteristic. The solid surface of the shrink ring is an excellent damper for the commutating circuit, formed by the machine subtransient reactance, the SCRs, and the snubber capacitors. Instead of absorbing large losses in resistors in the converter, the damping loss is concentrated in the surface of the rotor where it can be removed by the generator cooling oil.

In the start or motoring mode, 400-Hz power is applied to the same terminals that provide the output in the generating mode. The only change of the power circuit is the disconnection of the machine neutrals from ground.

Logic level transformation of the converter functions now causes conversion of the 400-Hz power to variable voltage and frequency to drive the machine as a motor. The control strategy is to operate the system analogous to a brushless dc shunt machine. The armature is now stationary and the field rotating, in contrast to the rotating armature of a brush and commutator machine. This method of operation is chosen over synchronous motoring because a nearly optimum torque angle is always possible, and the hazard of loss of synchronism is eliminated.

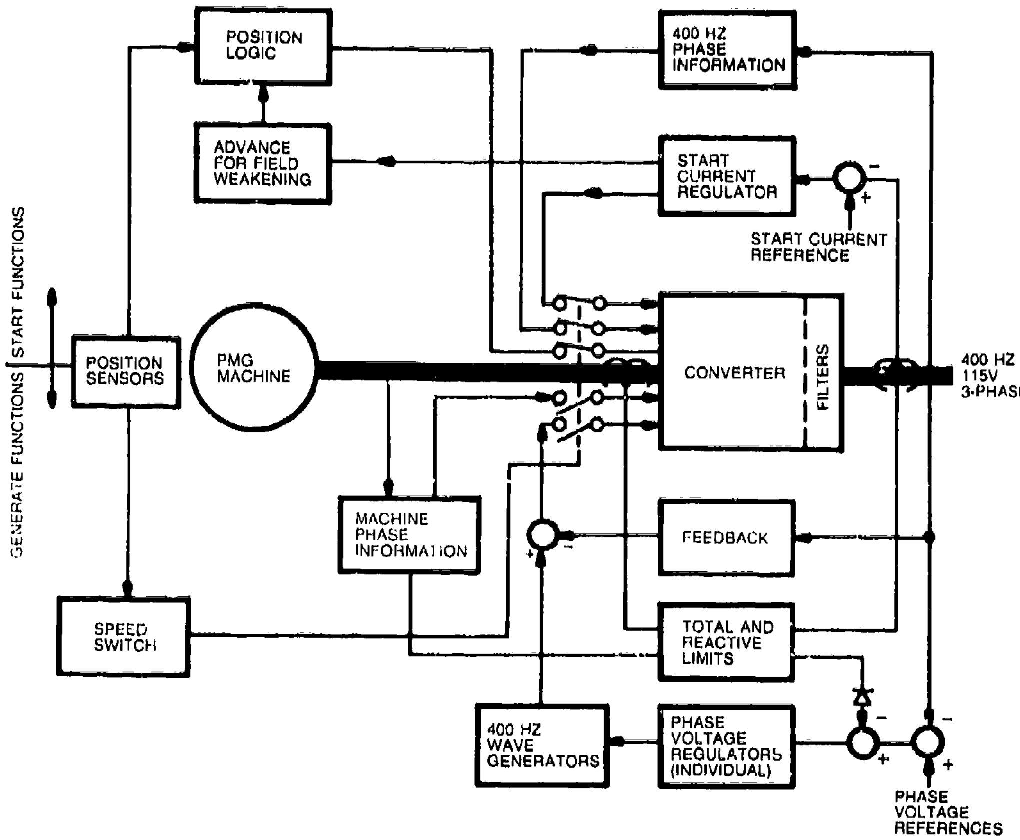


Figure 11. Permanent Magnet VSCF Block Diagram

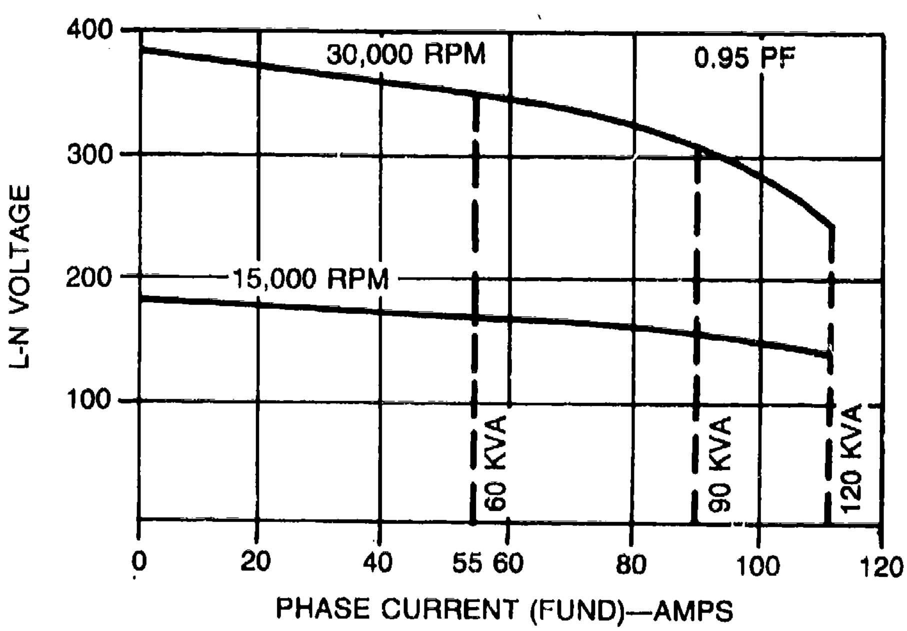


Figure 12. 60-KVA Starter-Generator Electrical Performance

The SCRs of the converter perform three functions simultaneously. First, the SCRs act as the commutator, switching currents in and out of armature (stator) windings. Feedback from the rotor position sensors replaces the geometric relationship of brush and commutator bar position. Second, the SCRs are phase controlled with respect to the 400-Hz power supply to control the current amplitude. Finally, at high motor speed, when the machine's back Electromotive Force (EMF) approaches the supply voltage, the SCR control takes over the function of field control. This is done by phase advancing the SCRs with respect to rotor position so that the machine draws more reactive current, which reduces the effective field and back EMF. More real power can then flow into the machine to maintain torque.

This system was designed to meet the application requirements of the A-10 aircraft. The A-10 presently uses two 30/40 KVA Constant Speed Drive (CSD) type electrical systems in a split-bus type arrangement. Engine starting is by means of air that is generated by the APU or from a ground power cart.

A modification package was developed to adapt the A-10 to an electrical starter-generator system while keeping the air starting system intact. The specified rating was 60 KVA to provide engine starting. The philosophy of the aircraft modification was to use as much of the existing airplane hardware and procedures as possible. The modification consisted of removing the CSD systems and installing the following:

- 2 Starter-Generators
- 2 Cycloconverters
- Current transformer assemblies
- Interconnecting cables
- Start filter
- Contactor assembly
- Start select switch
- Necessary air scoops and ducting

The air scoops and ducting were used for cooling the cycloconverters when they are mounted in the tail of the aircraft. The starter-generators were cooled by the air-to-oil heat exchangers on the TF-34 engines.

The current that is drawn by the starting system is a quasi-square wave and, therefore, distorts the voltage wave form of the source. The start filter was used to improve this wave shape.

The contactor assembly adds the start contactor and the tie start contactor. Integrating these contactors into the airplane bus structure made electric engine starting possible.

The resultant airplane bus structure, with the start filter and contactor assembly added, is shown in Figure 13.

The 60-KVA system is also capable of parallel operation and no break power transfers. These functions are not relevant to the A-10 and were meant to be demonstrated in the laboratory. The layout of the laboratory, used for development work and system demonstrations, is shown in Figure 14.

2.1.2 POWER CIRCUIT

The power circuit is slightly different from that of the earlier 150-KVA starter generator. Each machine three-phase winding is isolated from the other two. A three-pole contactor grounds the neutral of each three-phase generator winding during generate operation.

Figure 15 shows the generator and one output phase of the converter.

The SCRs are grouped in sets of three, which connect to a three-phase machine winding. The sets are then paralleled by interphase transformers. These IPTs permit current flow in each SCR for 120 machine degrees and divide the total output phase current equally between three SCRs at any instant. If all rectifiers were

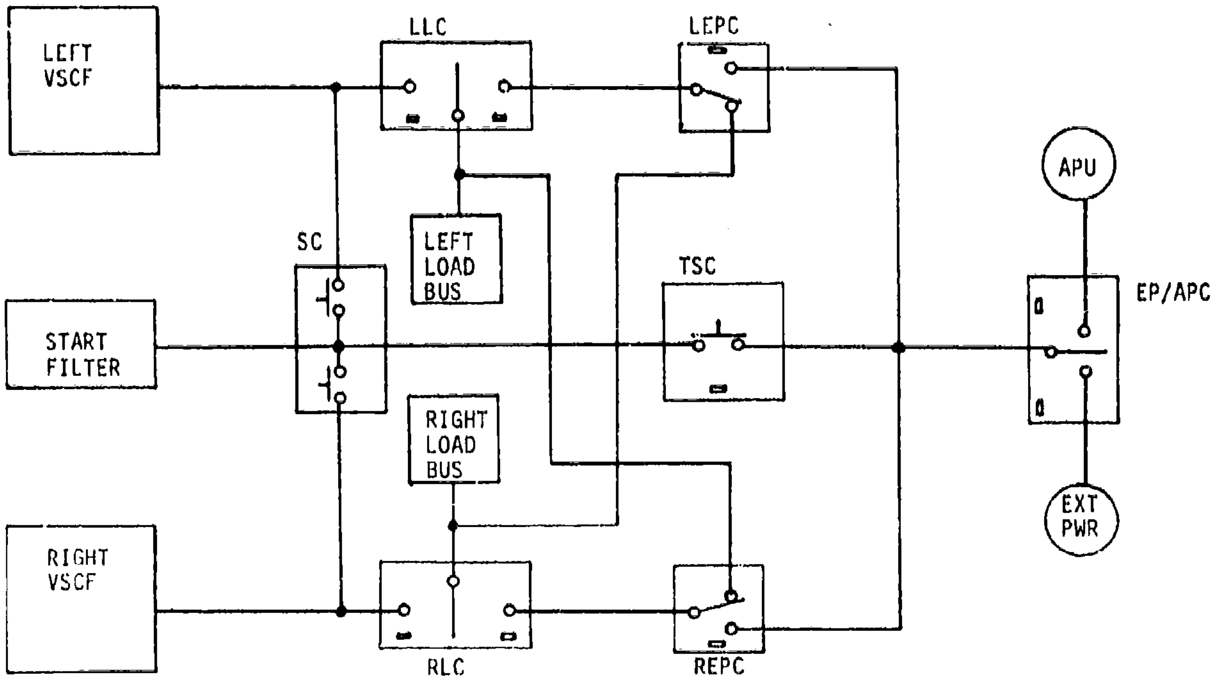


Figure 13. Airplane Bus Structure

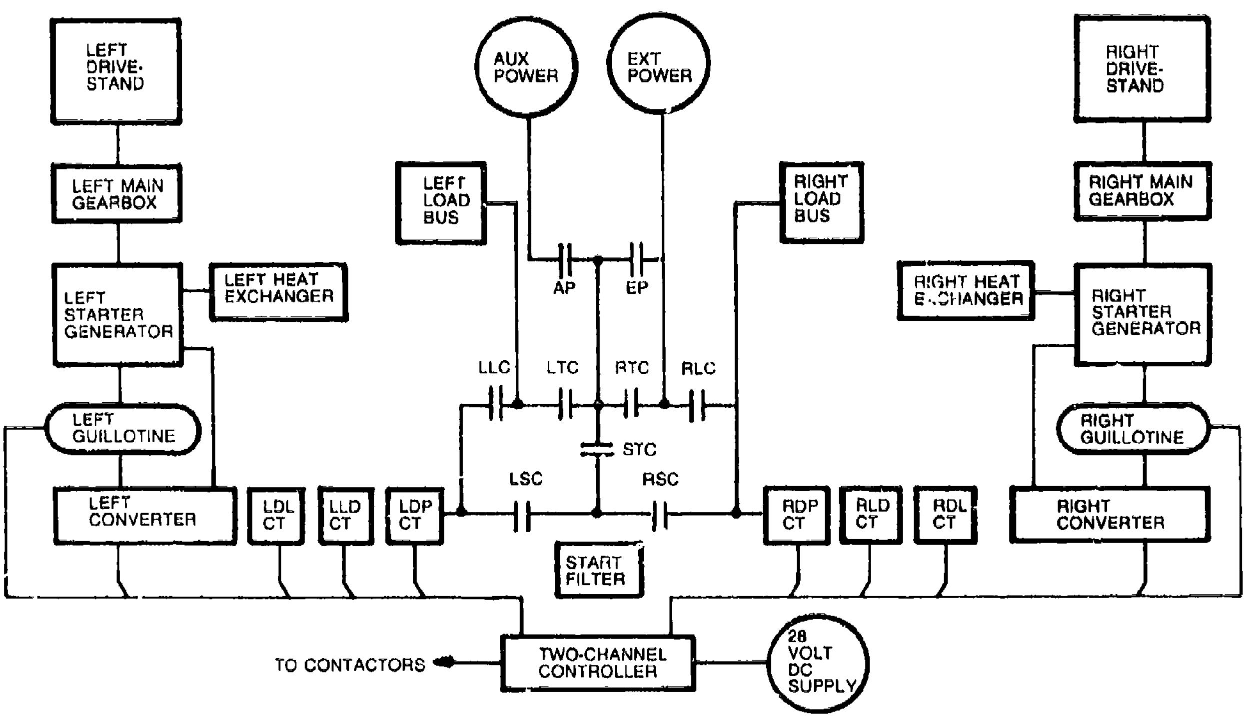


Figure 14. Laboratory Layout

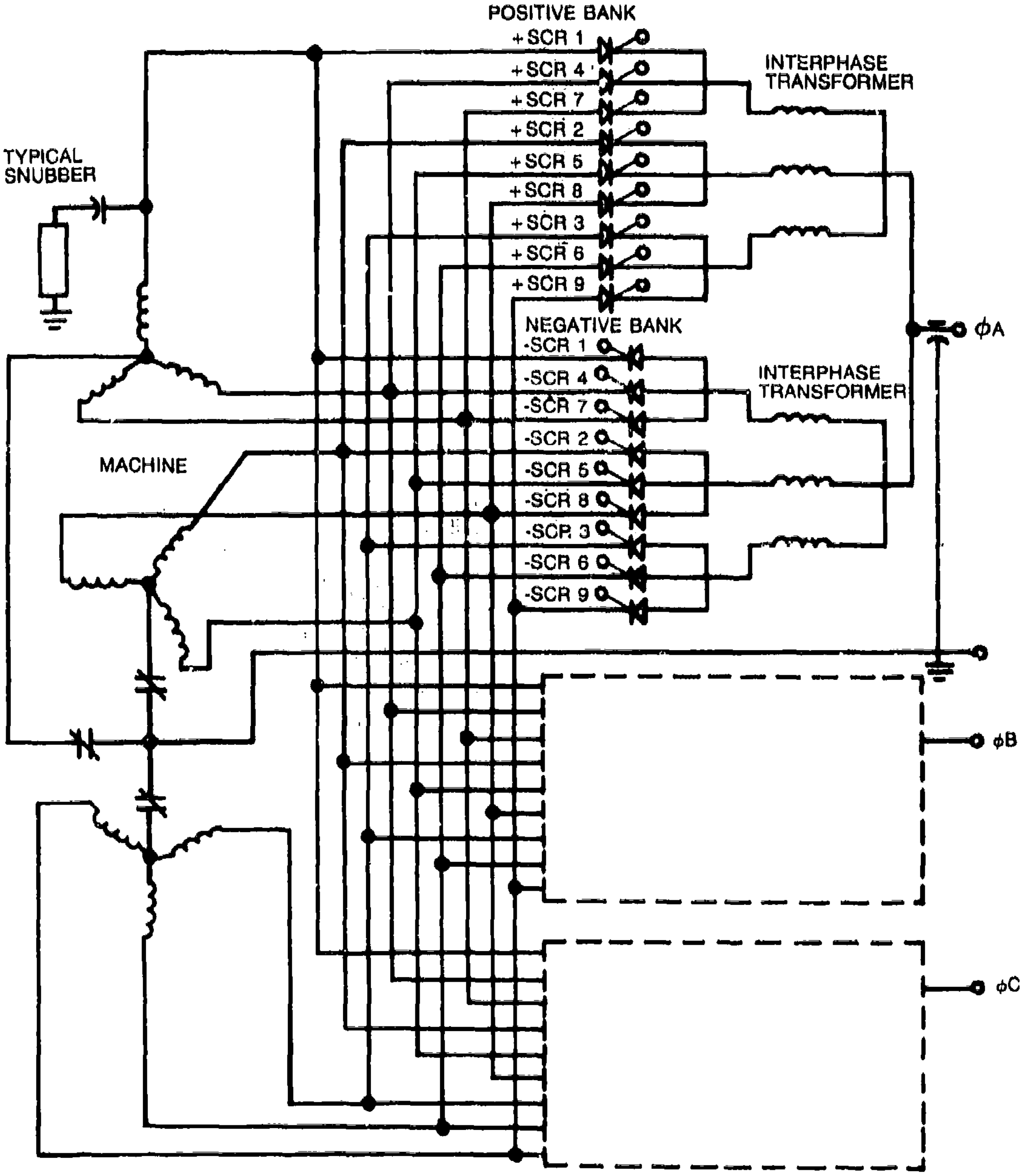


Figure 15. Power Circuit

tied together, the output current would flow in only one SCR at a time and for only 40°. The IPT, therefore, greatly eases the current requirements of the SCRs (and the generator). Equally important is that only 1/3 current must be switched or commutated from SCR to SCR at any instant.

2.1.2.1 Silicon Controlled Rectifiers (SCRs)

Neglecting the filter capacitor current, each SCR conducts 1/3 of the phase output current for 1/6 of the time. The SCR current at rated 60 KVA, 115 V is approximately 23.7 amps rms.

Maximum SCR voltage occurs at top speed, no load, which is no higher than for a wound rotor machine system. The difference is that the high voltage is always present at high speed rather than only transiently for wound rotor systems. This high voltage at high speed means that, from a commutation standpoint, long turnoff time SCRs may be used since the SCRs are never phased far from 90°.

The devices used are Westcode P0360 type rated at 1200 V, 40 amps average, 100 amps rms, and 30 μs turnoff time.

2.1.2.2 Interphase Transformers

The leakage inductance of the interphase transformers and the capacitor at the phase terminal form the filter that supresses the rectifier ripple and higher harmonics of the output wave. With a nine-phase machine and a base frequency of 1,250 Hz, the minimum rectifier ripple frequency is approximately 11 kHz. The IPT leakage inductance is about 16 μH, and the filter capacitor is 240 μf.

At high speed and/or light loads, excess machine voltage is rejected by phasing the SCRs. This maintains the 400-Hz output voltage but increases the rectifier ripple at each SCR bank. The IPT, which averages the three SCR banks, is designed to absorb this voltage.

In the selected IPT arrangement, shown in Figure 16, each functional IPT is actually three devices. This scheme lends itself to a higher copper content design with multiple short heat flow paths from the cores. Also, by arranging the windings as shown, the stray flux problem is minimized.

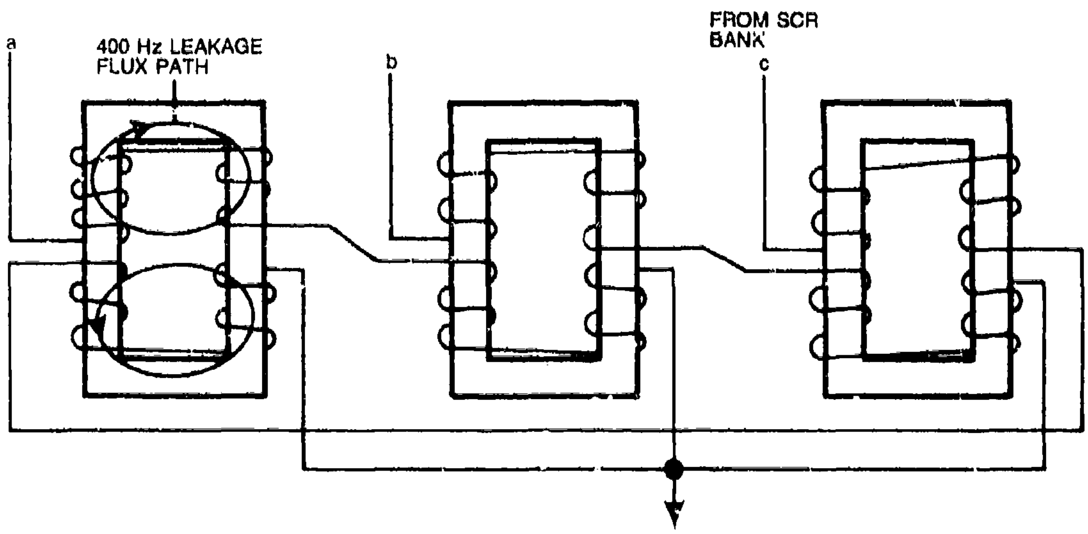


Figure 16. Equivalent Three-Leg IPT by Combining Three Two-Leg IPTs

To minimize iron losses, thin laminations are desirable, but a standard tape wound core has its laminations oriented so leakage flux of the IPT is perpendicular to the wide tape dimension. For the 60-KVA system, the IPTs were built with rectangular tape cores cut and reassembled as shown in Figure 17. The long legs were rotated so the leakage flux would not have to go through the width of the tape and, thus, cause eddy currents.

2.1.2.3 Filter Capacitor

The filter capacitor on each output phase is a 240- μf, feed-through type metalized film device. The filter capacitor's duty is not significantly different than for a regulated wound rotor machine system. Ripple current is constant with machine speed rather than decreasing with speed as in the wound rotor system. Packaging of the capacitor is unique for a feed-through cap in that both power terminations are on the same side. A cross section is shown in Figure 18.

2.1.2.4 Snubber Circuit

Commutation in the cycloconverter takes place by gating of the next SCR, which provides a more favorable current path than did the conducting SCR. Both SCRs conduct while the current decays in the old path, which transiently short circuits the two generator phases. Current does not stop in the old path when it reaches zero because the SCR does not block inverse voltage until the minority carriers are swept out. The SCR currents, as shown in Figure 19, have substantial reverse spikes. When the outgoing SCR does block, the voltage at the generator side of the SCRs recovers to the generator voltage. All other SCRs that are connected to these generator phases also experience this voltage change. The capacitance of the snubber limits the dv/dt, and the resistance limits both the capacitor discharge current and damps the RLC oscillation.

The commutating inductance in all machines leads to high losses. The solid rotor containment ring, however, makes the Q of the inductance of this type of permanent magnet machine particularly low, so the snubber resistor is sized by only capacitor discharge considerations.

While the snubber functions line-to-line, the physical snubber is connected in Wye to keep down the capacitor voltage and the resistor-to-chassis voltage.

Figure 20 shows the total snubber loss as a function of load and speed. Losses at light load are lower even with the higher machine voltage because reverse recovery currents are lower and because some of the commutations are completed before the snubber capacitor has time to completely discharge.

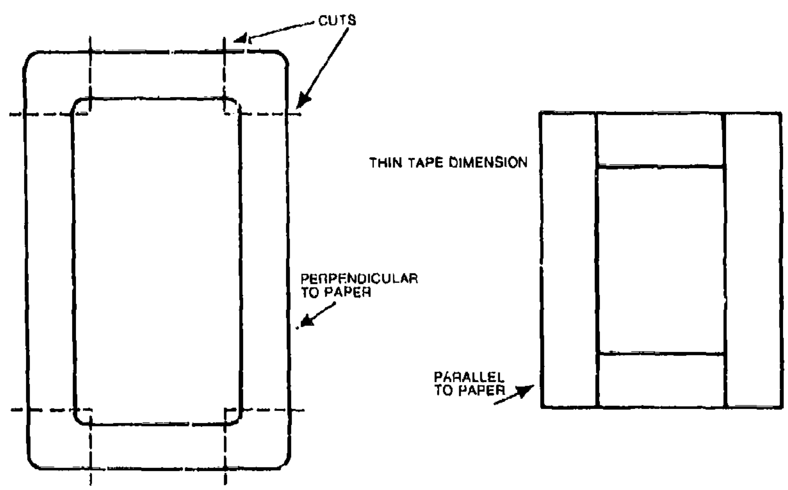


Figure 17. Construction of 60-KVA IPT from Tape Core

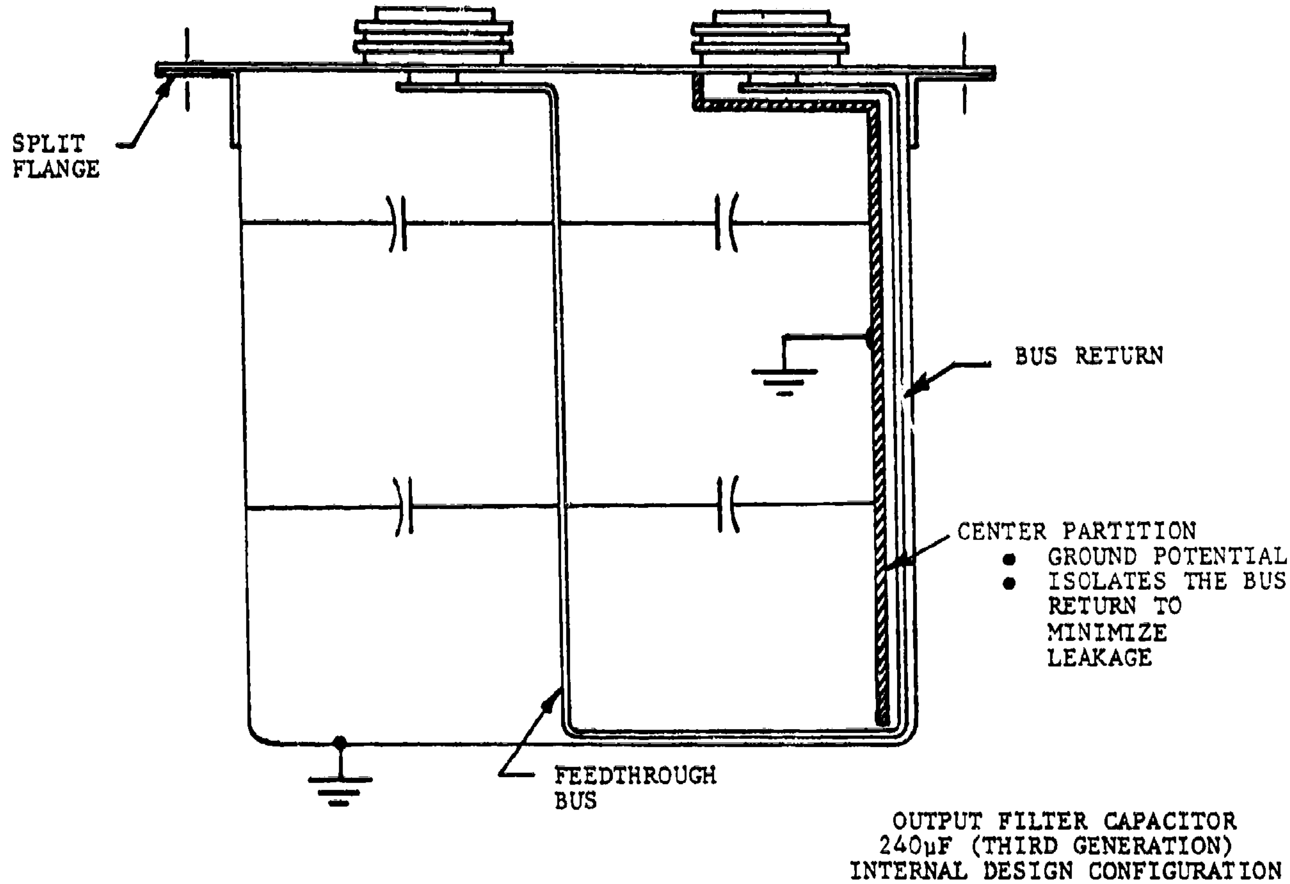
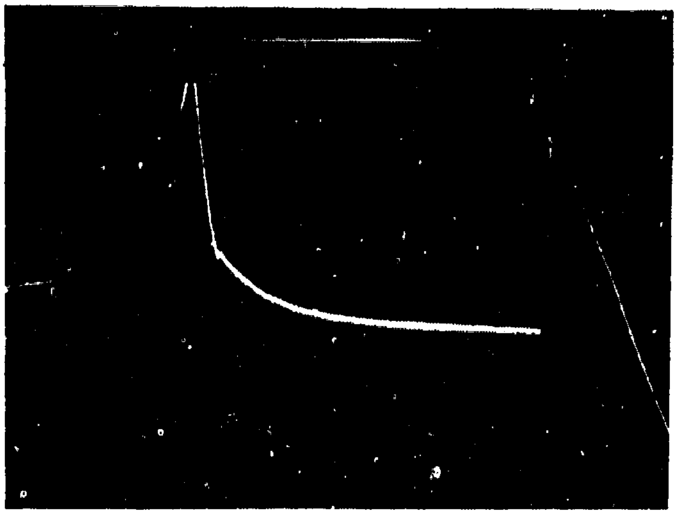


Figure 18. Output Filter Capacitor 240 μF (Third Generation) Internal Design Configuration

2 amps/cm
1,950 Hz



2 μsec/cm
60 KVA load

Figure 19. SCR Recovery Current

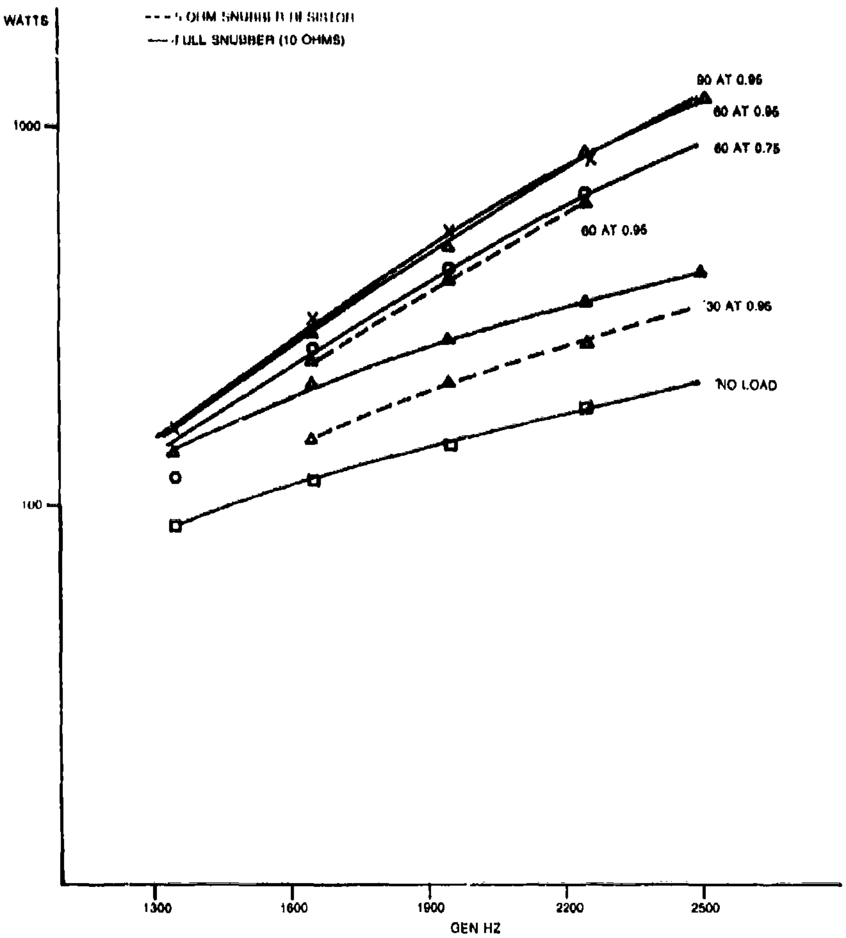


Figure 20. Snubber Losses—Short Pitch Machine, 0.12 MFD

2.1.3 GENERATE MODE CONTROL CIRCUITRY

2.1.3.1 Reference Wave Generator

The VSCF system in generate mode, basically, is three high-power amplifiers that reproduce three low-level, 400-Hz reference waves at 115 V and the power level required by the load. The reference wave generator develops the three-phase set of 400-Hz waves that are to be amplified. These reference waves have less than 1% total harmonics, are very accurately spaced 120° apart, and are individually amplitude controlled. A secondary function is to generate 400-Hz square waves that serve as discriminator references for the load division circuits.

For the 60-KVA system, the reference waves are stored in a Read Only Memory (ROM) that is repeatedly addressed by a counter. Each reference wave is not stored as sequence of multibit digital numbers; rather, the waves are stored in a pulse-width modulated mode. The advantage of this method is that the conversion to a smooth sine wave requires only a small RC filter rather than a full digital-to-analog converter. The amplitude of the reference waves is individually controlled by clipping the 1 bits stored in the ROM as required to satisfy the phase voltage regulator.

Only one-half cycle of each reference wave is stored in the ROM. Phase A reference is reversed by the lowest frequency bit of the counter. Phases B and C are reversed by "1's" stored in Bit 7 of the ROM at 60° and 120°.

2.1.3.2 Feedback and Mixers

The mixer circuit sums the 400-Hz reference signal and several feedback signals to develop the error voltage that goes to the modulator.

Figure 21 shows the signals of the mixer circuit. Feedback block G2 has very high low-frequency gain to suppress the dc voltage level of the output to a few millivolts. Block G3 senses the voltage at the rectifier banks. It is used to improve wave shape and to reduce the converter source impedance, thereby minimizing the voltage transients during load switching. This path has moderate gain at 400 Hz.

All three output phases are summed and filtered by band pass filters, tuned to 400 Hz and 1,200 Hz to minimize zero sequence and third harmonic voltages in the system output waves. The third harmonic feedback is also attenuated during overloads.

Since the third harmonic voltages of the three output phases tend to be indentical only with balanced loads, this feedback loses part of its value when the system load is unbalanced. A better arrangement is to detect the third harmonic in individual phases with a filter that has a notch at 400 Hz and rings up sharply at 1,200 Hz. This type transfer function, which can replace G4 as well as the third harmonic feedback, is easily attained with an active filter.

Block 4 feedback is used for wave shaping to suppress the lower harmonics of the 400-Hz output. Therefore, it has highest gain in the harmonic frequency region. During severe overloads or short circuits, this path tends to cause miscommutations. Most of this signal, therefore, is shunted to ground by a field effect transistor that acts as a variable resistor when the output current is above its rated load level.

The mixer also adds offset bias to the error voltage so that the output wave that is generated by the negative SCRs is more positive than the wave generated by the positive SCRs. This offset, or safety margin bias, which generates a dc voltage that opposes current flow from positive SCRs directly back through the negative SCRs, is shown in Figure 22.

2.1.3.3 Phase Voltage Regulators

The phase voltage regulators compare the converter output voltages, sensed at the point of regulation, with a dc voltage reference and adjust the reference wave amplitudes to regulate the converter output. The regulators sense the rectified average of the output rather than the rms value. The converter output voltage, measured by rms meters, varies slightly with load and speed. This variation is due to the change of wave shape. Experience has shown the regulation to be satisfactory even after allowing for wave shape effects, so the added cost of true rms sensing is not justified.

The converter terminal voltage is also sensed through resistors, which are sized so that the converter voltage will be limited just above the ultimate overvoltage trip level in the event of an opening of a sense wire to the point of regulation.

2.1.3.4 Beta Limit Circuit

In a phase-controlled rectifier, Beta is the angle from the firing of the SCR until the voltage reversal of the conducting SCR and the next SCR. The time that is represented by this angle must be sufficient to complete the commutation and for the SCR to recover its voltage-blocking ability.

The function of the Beta circuit is to detect current in the machine phases when it occurs at an angle where little time margin is left to complete the commutation and allow the SCR to regain its blocking ability. This

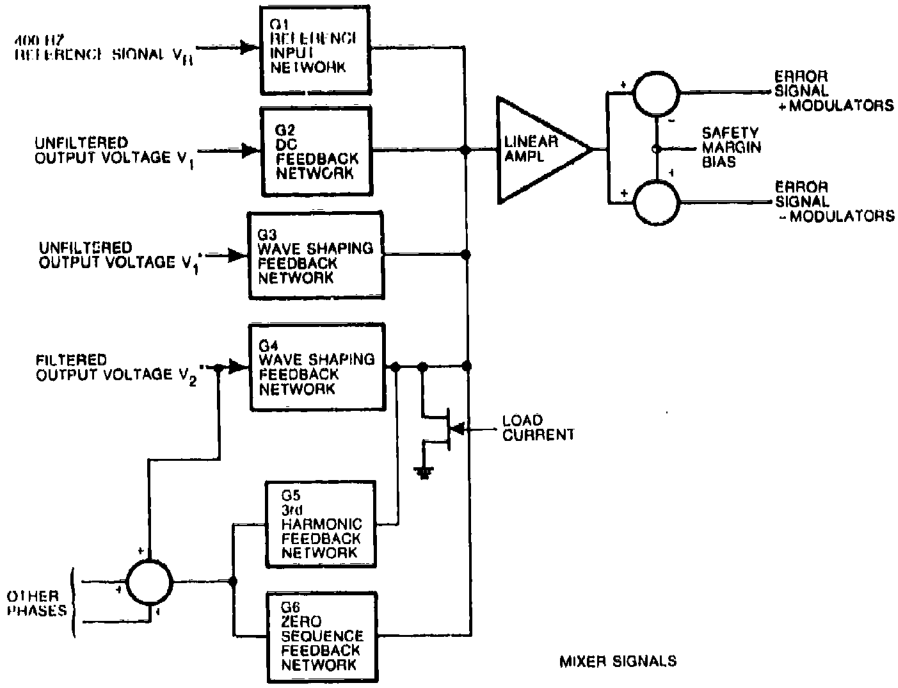


Figure 21. Mixer Signals

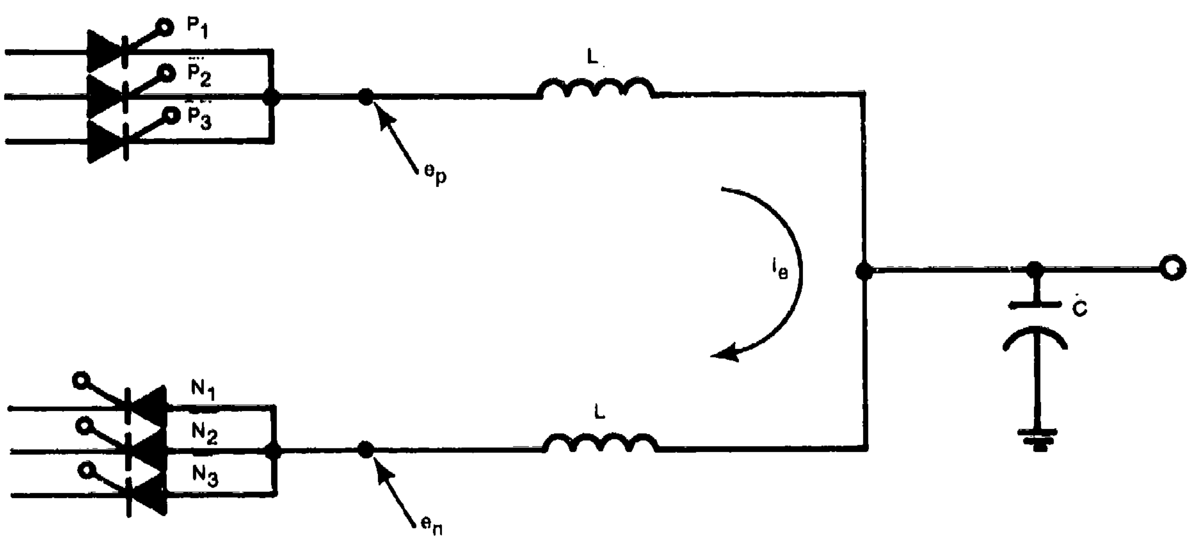


Figure 22. Circuit for Equalizing Current

function is mechanized by sampling the currents of three generator phases. The sampling period is established by the firing and blanking waves, and a reference is set in much the same way as a normal SCR firing is set. Figure 23 shows how the Phase 1, Beta gate is derived.

2.1.3.5 Firing and Blanking Wave Circuits

The basic SCR control is by the biased cosine method. In 60-Hz rectifier systems, the cosine firing waves are usually obtained by a phase-shifting transformer connected to the incoming utility power. In VSCF systems, the generator wave shape is an altered sine wave since each SCR commutation adds a notch to the wave.

It is necessary, therefore, to go back to the basic operation of a phase-controlled rectifier to derive suitable firing waves. Figure 24 shows the fundamental circuit of an SCR commutating off another SCR. AC voltage source e_1 is conducting, and source e_4 is to be switched in. These represent two phases of an ac machine, with L_c being commutating inductance.

Since the generated voltages are internal to the machine, they cannot be used to derive the control function directly. Terminal voltages and phase currents are used, as Figure 25 shows, to derive the firing waves for each set of 120° displaced machine phases.

Figure 26 shows a set of machine voltages, firing waves, and blanking waves for the idealized sine wave case. Comparators, whose inputs are connected to firing waves, derive the blanking waves. The blanking waves are fed to the modulators via tri-state CMOS logic gates. In the start mode, these gates are in the disabled or open circuit state.

Firing and blanking waves also go to the Beta circuit where they are used to establish the sampling periods for generator current, representing short SCR turnoff margins.

2.1.3.6 Modulators and SCR Gate Drive Circuits

The modulators determine the exact firing time for each SCR while in the generating mode. Figure 27 shows the operation of the modulator in the generating mode. The SCR firing can be controlled over a 180° interval, and the modulator is inhibited for the second 180° interval. The modulator delivers a train of pulses, starting at the firing angle and ending at the inhibit interval. Normally, only the first gate pulse is relevant because it triggers the SCR into conduction. The following train of pulses is added for insurance in case the SCR did not fire on the first pulse.

Figure 28 shows a modulator circuit. The Schmitt trigger Nand gate (U2) with RC feedback is a gated oscillator that runs when its second input is high. The invertor and transistor Q1 form a buffer to the output transistor Q2. Q1 never saturates because of its emitter resistor, and Q2 has fast turnoff via the reverse breakdown of Q1 emitter to base.

2.1.3.7 Frequency Control

The system is designed for parallel operation. It must be able to change frequency to synchronize with the system to which it is to be paralleled, and shift phase to divide load after the paralleling is accomplished. The chosen paralleling method is that of averaging the frequency references of the paralleled channels to establish the system frequency. The primary reference is a crystal oscillator. The secondary reference is a Voltage Controlled Oscillator (VCO) that drives the wave generator. The frequency control operates by counting the beat frequency between the crystal and voltage-controlled oscillators, determining which oscillator frequency is higher and converting the result into an analog voltage. This analog voltage is compared with synchronization and load division signals to set the frequency of the VCO and, therefore, of the system. This technique permits very high gains so that op amp offsets and other temperature and component shifts have little effect.

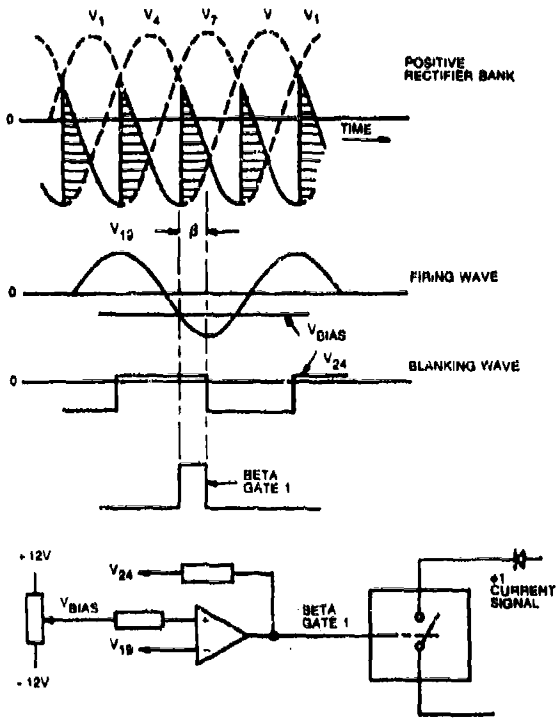


Figure 23. Derivation of Beta Gate Number 1

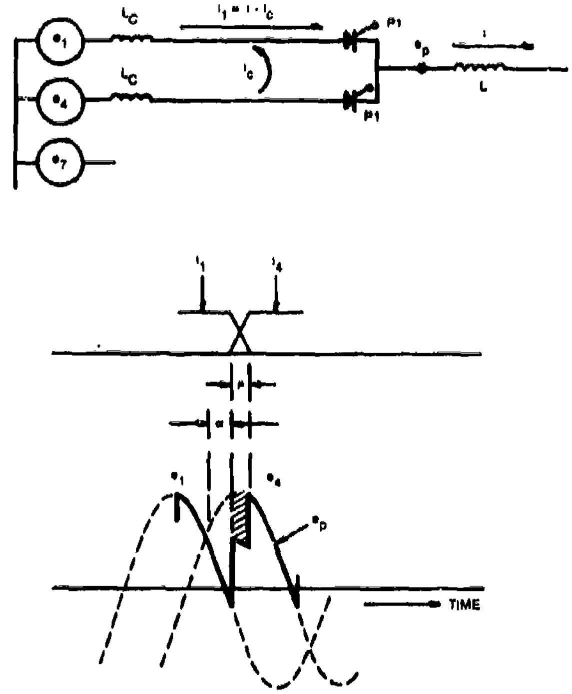


Figure 24. Commutation

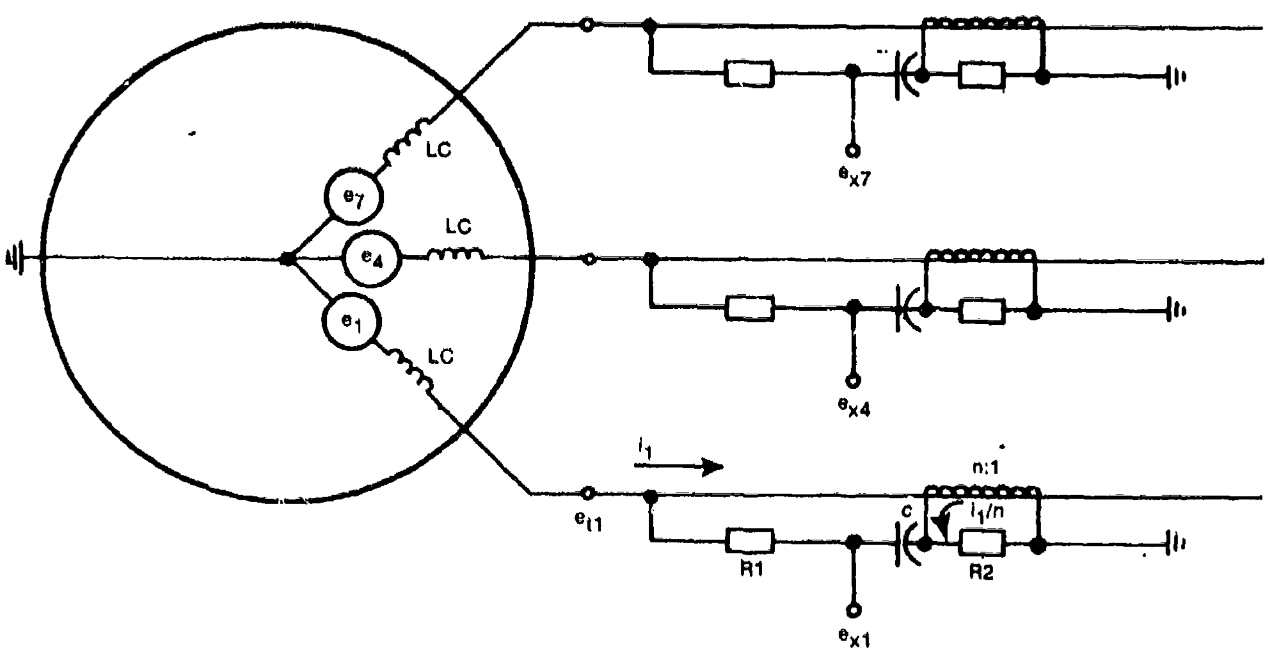


Figure 25. Circuit for Deriving Firing Waves

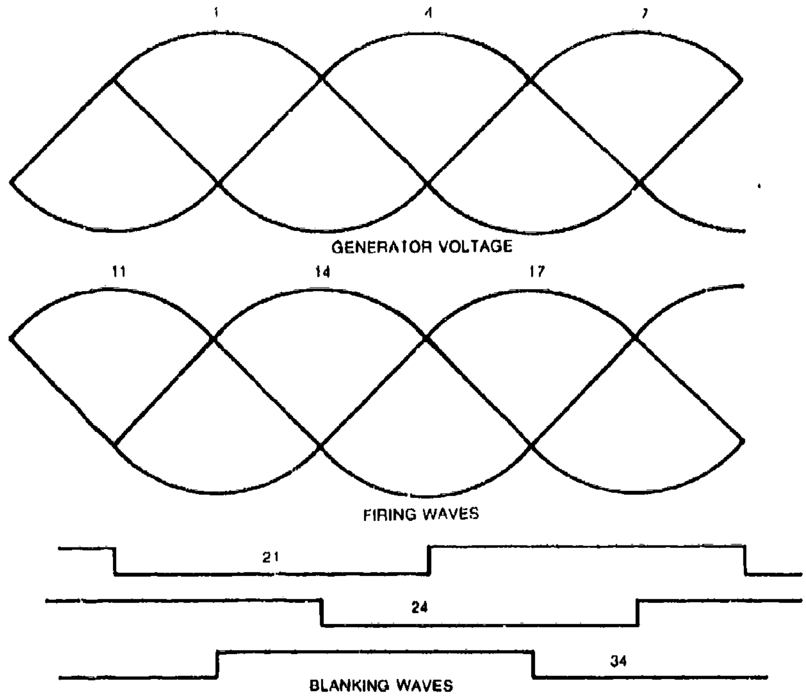


Figure 26. Machine Voltage, Firing and Blanking Waves

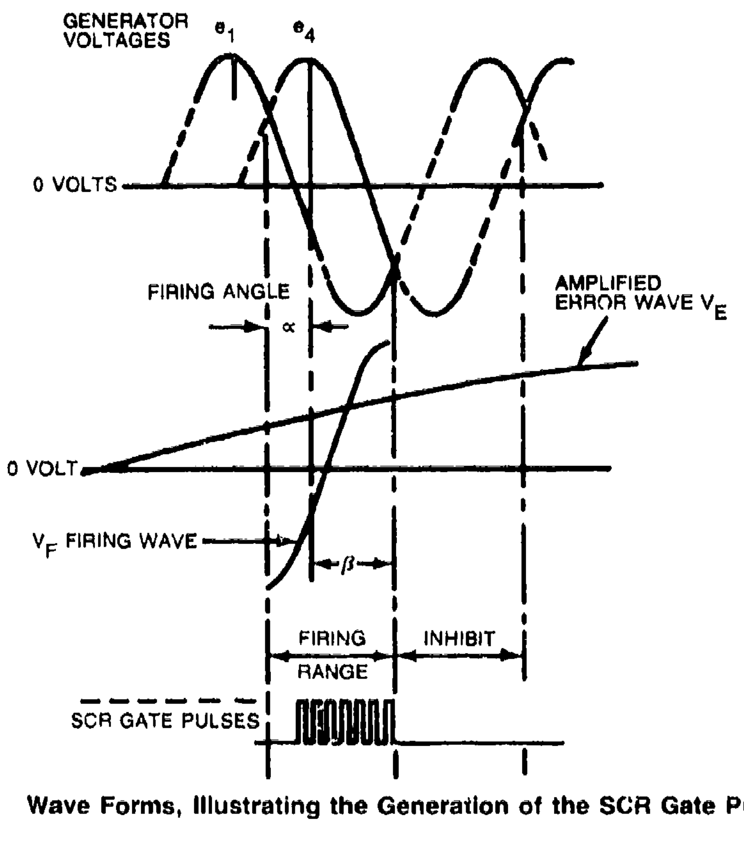


Figure 27. Wave Forms, Illustrating the Generation of the SCR Gate Pulses

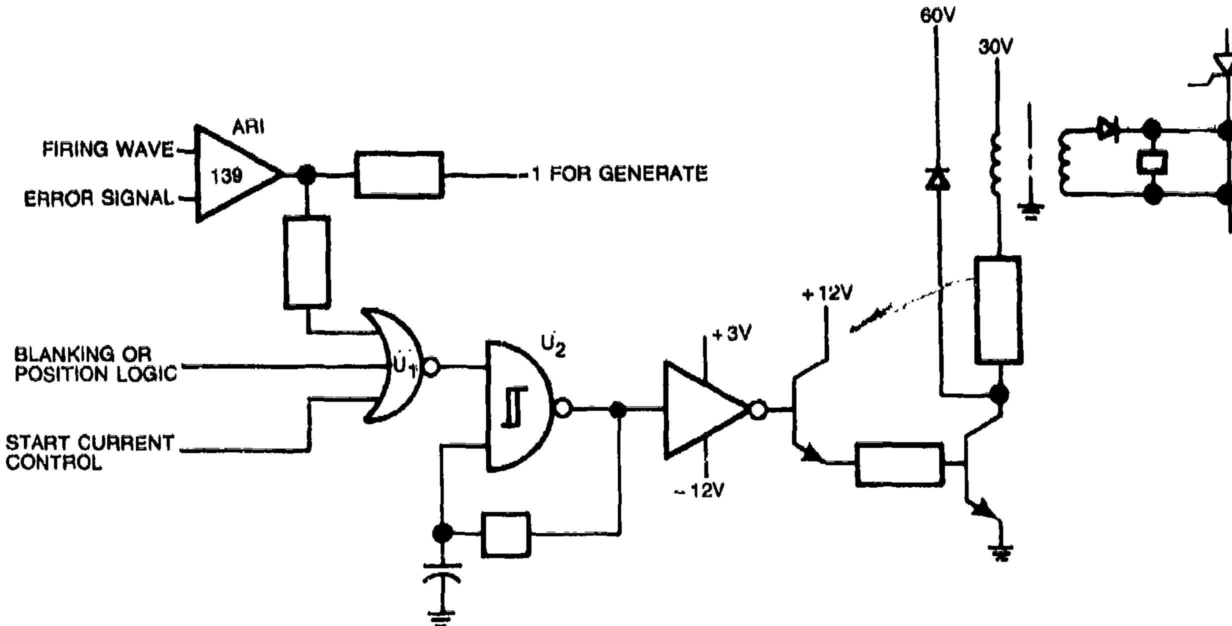


Figure 28. Modulator and Gate Drive Circuit

Since the comparison is between frequencies more than 100 times higher than the 400-Hz output, the frequency control loop response can be fast enough so that it has negligible effect on the stability of the load division loops.

2.1.3.8 Load Division

Parallel operation of VSCF systems is somewhat different from that of synchronous machines, although the fundamental rules apply. With synchronous machines operating in parallel, the circulating current, in phase with the voltage, provides the signal to control the speed of the prime movers or the phase of the generated voltage. The circulating current, at a right angle to the voltage, provides the signal to control the voltage regulators. Since the source impedance of the synchronous machine is largely inductive, the circulating current lags the phasor difference of generated voltage by about 90°.

In this cycloconverter system, the source impedance angle varies from about 60° at base speed to about 41° at top speed. The load division circuits, therefore, sense the component of circulating current at the angle of the source with respect to the terminal voltage. The phase or frequency bias circuit senses current at right angles to the source impedance angle.

The circulating current is measured by current transformer loops that compare the phase currents of the two systems. Phase discriminators then measure the components of this current. The references for these phase discriminators are derived in the reference wave generator. The discriminator references are 45° lagging for the voltage bias circuit and 45° leading for the frequency control bias. Before paralleling, the two systems are brought into synchronism by phase discriminators that look at the system terminal voltages.

2.1.3.9 Protection

The system contains the following protective circuits:

DC	=	DC Content
DH	=	High Frequency Feeder Fault
DL	=	Low Frequency Feeder Fault
GOC	=	Generator Overcurrent
GOT	=	Generator Overtemperature
LS	=	Load Share Error
OL	=	Overload
OV	=	Overvoltage
SOC	=	Start Overcurrent
SCO	=	Start Cutout
US	=	Underspeed
UV	=	Undervoltage
WD	=	Wave Form Distortion
WF	=	Wrong Frequency
WFB	=	Wrong Frequency Bias
ZV	=	Zero Sequence Voltage

The output of these circuits form the following protective functions, where "+" is OR and "·" is AND.

All SCRs On	=	DH + GOC
Disconnect	=	DH + GOC + GOT
Instant Trip	=	DH + GOC + OV + US + DC* + DL
5.12 Sec. Trip	=	UV** + WD + WFB + ZV + LS + DC*
0.16 Sec. Trip	=	WF
0.145 Sec. Trip	=	UV
Discontinue Start	=	SOC + SCO + DH
Generator Fail	=	GOT + DH
Converter Fail	=	START · SOC + TRIP · $\overline{OL}$ · (GOC + OV + DC + WF + UV + WD + WFB + ZV + LS)
*Instant DC Trip	=	DC · MLC Closed
5.12 Sec. DC Trip	=	DC · MLC Open
**0.145 Sec. UV Trip	=	$\overline{OL}$ · MLC Closed o Other System Not in Start Mode · UV
5.12 Sec. UV Trip	=	Any Other UV Condition

The protective circuitry and functions are described in the following text.

2.1.3.9.1 DC Content (DC)

This is a protection particular to VSCF systems, which is required because certain failure modes can result in large dc voltages in the output. The DC content circuit adds the three output terminal voltages and sends this signal through a low pass filter. The output of the low pass filter goes to a comparator. If the output of the low pass filter is high enough in either polarity, the comparator output goes from a logic 1 to a logic 0. Reaction time of the circuit is inversely proportional to DC voltage in the input. The ultimate trip point is less than 1.0 volt. The control logic will not allow the line contactor to close if a DC condition exists. In such a case, if the DC condition persists, the system would de-energize in 5.12 seconds. If a DC condition occurs after the Main Line Contactor (MLC) has closed, the system will de-energize and open the MLC instantaneously. DC protection is not active in the start mode.

2.1.3.9.2 High-Frequency Feeder Fault (DH)

This circuit protects the system if a short circuit should occur in the generator or in feeders between the generator and converter. There are current transformers in each of the nine generator neutrals in the machine and in each of the nine inputs to the converter. The circuit compares these two currents in each phase. If a difference of approximately 23 amps or more should exist, the output of the circuit will go from a logic 1 to a logic 0. This circuit is only enabled above generator frequencies of approximately 225 Hz. In start mode, when the generator is at very low speed, false DH trips may occur. For this reason $\overline{DH}$ is always a "1" below 225 Hz. If a DH condition should occur, the generator will disconnect and the line or start contactors will open immediately. Approximately 100 milliseconds later, the converter will go into All SCRs On mode.

2.1.3.9.3 Low-Frequency Feeder Fault (DL)

This circuit protects the system if a short circuit should occur between the converter output and the line contactor. The outputs of individual-phase current transformers in the converter and the Current Transformer Assembly (CTA) are compared. If a difference of more than 21 amps exists, the output of the DL circuit will go from a logic 1 to a logic 0. If a DL condition should occur, the converter will de-energize, and the line contactor will open immediately. DL protection is not active in start mode.

2.1.3.9.4 Generator Overcurrent (GOC)

This circuit protects the system if a serious fault should occur inside the converter. In effect, this circuit acts as a differential current protection by comparing the total generator current coming into the converter with the total 400-Hz current leaving the converter. If an abnormally high difference exists, this circuit first acts to clamp the phase voltage regulators. This GOC clamp is implemented so that the cycloconverter can recover from a commutation failure. If the converter does not recover within approximately 23 milliseconds, or there are repeated miscommutations, then the GOC output goes to a 0 then, immediately, the generator will be instructed to disconnect; the line contactor will open, and the converter will de-energize. Approximately 100 milliseconds later, the converter will go into All SCRs On mode.

2.1.3.9.5 Generator Overtemperature (GOT)

This circuit acts to prevent damage to the generator. A thermal switch in the gearbox measures oil temperature and will close at a temperature of approximately 175° C. A thermistor in the generator measures stator temperature. The termistor's resistance varies as a function of temperature and is part of a voltage divider in the converter. At a temperature of approximately 250° C, its resistance becomes low enough to cause a comparator to change state. When either the thermal switch closes or the comparator changes state, the output of the GOT circuit goes from a logic 1 to a logic 0. If GOT goes to 0, the generator is immediately instructed to disconnect. This will also shut down the converter when the generator goes through underspeed.

2.1.3.9.6 Load Share Error (LS)

This protection is only enabled when two converters are in parallel mode. Additional current transformers are placed in each of the output phases of both converters. The Current Transformer (CT) outputs in each phase are summed together. If the currents from the converters are balanced, there is no load share error signal. If the difference in currents in any phase reaches approximately 240 amps, the load share error signal becomes large enough to trip a comparator. When the comparator trips, the $\overline{LS}$ logic level goes from a 1 to a 0. This will cause the line contactor to open and the converter to de-energize if it persists for 5.12 seconds.

2.1.3.9.7 Overload (OL)

The overload circuit compares an analog signal, proportional to total load current, to a dc reference. If the total load on the converter exceeds approximately 90 KVA, a comparator will trip, causing the $\overline{OL}$ logic signal to go from a 1 to a 0. This will not trip the converter, but it has several other functions, which are:

1. If $\overline{OL}$ is a 0, and the converter is in generate mode, there will not be a converter fail flag if the converter trips.
2. If the converter trips when there is an overload, the contactor that allows another power source to pick up the load bus will be locked out.
3. If the converter is in parallel mode, senses an overload, and has one of the 5.12-second trip protective circuits go to a 0 for 2.56 seconds, then the paralleling bus tie contactor will open.

2.1.3.9.8 Overvoltage (OV)

This circuit senses the Point of Regulation (POR) voltage of each output phase. These voltages are rectified and filtered, then compared to a dc reference. If the POR voltage is above approximately 124.5 volts rms, a comparator will trip, causing the OV logic signal to go from a 1 to a 0. When $\overline{OV}$ goes to a logic 0, the converter will de-energize and open its line contactor immediately. Characteristics of the filter are such that trip time is inversely proportional to POR voltage magnitude. In parallel mode, a signal from the load division circuits is added to the rectified and filtered voltage signal. When the load division bias signal is positive, the OV trip is sped up. When it is negative, it is slowed down. In this way, only the faulty system would be tripped off.

2.1.3.9.9 Start Overcurrent (SOC)

This circuit is active only in start mode. It senses the 400-Hz current flowing into the converter. If this current exceeds approximately 400 amps rms, this circuit will first act to reduce the current called for by the start current regulator. If the 400-Hz current is not decreased sufficiently within approximately 20 milliseconds, the $\overline{SOC}$ logic signal will go from a 1 to a 0. This will de-energize the converter and terminate the start immediately.

2.1.3.9.10 Start Cutout (SCO) and Underspeed (US)

Start cutout and underspeed are speed switches. Start cutout is the logical inverse of underspeed, i.e. $SCO = \overline{US}$. This circuit operates by comparing the frequency of a blanking wave (a square wave whose frequency is the same as the generator frequency) to the frequency of a crystal-derived square wave.

At generator frequencies below the switch points, US = 1, and SCO = 0. Once the generator frequency exceeds the switch point, US = 0 and SCO = 1. This switch operates at two different frequencies, depending on whether the generator frequency is increasing or decreasing. This provides hysteresis to avoid cycling if the input speed wanders about the switch point. The switch operates at 1,347 Hz for increasing generator frequency and at 1,280 Hz for decreasing frequency. SCO = 0 is a qualifier for start mode operation. When the generator reaches 1,347 Hz in start mode, SCO goes to a 1 and the start is discontinued. US is a qualifier for generate mode operation. Whenever $\overline{US}$ is a 1, the converter may operate in generate mode if the generator switch is on and everything is normal. When the engine is shut down and generator speed goes below 1,280 Hz, US will cause the converter to de-energize and open the line contactor.

2.1.3.9.11 Undervoltage (UV)

This protection will operate to de-energize the converter and open the line contactor if any of the phase voltages at the point of regulation fall below 105 volts rms. If the MLC is closed, the other system is not in start mode, $\overline{OL}$ = 1, and an undervoltage condition exists, the converter will trip in approximately 145 milliseconds. If the above conditions are not satisfied and an undervoltage conditions exists, the converter will trip in approximately 5.12 seconds. This circuit rectifies and filters the sum of the three phase voltages and compares this signal to a dc reference. If the signal falls below the reference, a comparator will change state, causing the UV logic level to go from a 1 to a 0. When the converter is in start mode, the trip level is recalibrated to approximately 95 volts rms. In start mode the undervoltage protection is used to assure that the 400-Hz input power has high enough voltage for proper start operation. In the paralleling configuration, the 145-millisecond trip is not used. In parallel mode, a signal from the load division circuits is added to the rectified and filtered voltage signal. When the load division signal is positive, the trip level is effectively decreased; and when it is negative, it is effectively increased. In this way, only the faulty system would be tripped off if there were a converter problem.

2.1.3.9.12 Wave Form Distortion (WD)

The wave form distortion protection will de-energize the converter and open the line contactor if the total harmonic content in any of the three 400-Hz output waves exceeds approximately 8.6%. Each of the 400-Hz terminal voltages is fed through a twin-T filter that is tuned to 400 Hz and then compared to a dc reference. If the output of the twin-T exceeds the DC reference, a comparator changes state, causing $\overline{WD}$ to go from a logic 1 to a logic 0. If this condition persists for 5.12 seconds, the converter will trip. When the other converter is in start mode, harmonics tend to be higher than normal. Therefore, the DC reference is increased when the other converter is in start mode, yielding a trip level of approximately 13.4%.

2.1.3.9.13 Wrong Frequency (WF) and Wrong Frequency Bias (WFB)

These two protective circuits work together to de-energize the converter and open the line contactor if the output frequency of the converter should deviate beyond the limits of approximately 385–415 Hz. The output frequency of the converter is determined by a Phase-Locked Loop (PLL). The voltage input to the VCO portion of the PLL comes from the paralleling circuits. If the output frequency of the converter falls outside 385–415 Hz, the $\overline{WFB}$ logic level will go from a 1 to a 0. If the VCO voltage input is outside limits (greater than 1.2 volts for underfrequency and less than -1.2 volts for overfrequency), then the wrong frequency is caused by the paralleling circuitry and the WF protection will be inhibited, i.e., $\overline{WF}$ will remain a logic 1. However, if the VCO voltage input is not outside limits when the wrong frequency is sensed, then the paralleling circuitry is not the cause of the problem and $\overline{WF}$ will go from a logic 1 to a logic 0. If a $\overline{WF}$ = 0 condition should exist for 165 milliseconds, the converter will trip. If a $\overline{WFB}$ = 0 condition should exist for 2.56 seconds, the converter will go out of synchronization mode. If it remains for an additional 2.56 seconds, the converter will trip.

2.1.3.9.14 Zero Sequence Voltage (ZV)

This circuit will de-energize the converter and open the line contactor if a zero sequence voltage of approximately 5.0 volts rms should be present. The protective circuit looks at an analog signal from the ZV feedback and compares it to a dc reference. If the analog signal exceeds the dc reference, the comparator will change state, causing the ZV logic level to go from a 1 to a 0. If this condition remains for 5.12 seconds, the converter will trip.

2.1.3.9.15 All SCRs On

This circuit acts to limit or prevent damage to the generator if a serious fault should develop in the generator, high-frequency feeders, or converter power, because the generator is a permanent magnet machine and there is no way to turn off the excitation. The gearbox of the generator contains an electrically driven disconnect mechanism which, in effect, decouples the generator shaft from the drive pad. If a DH or GOC fault is sensed by the converter, the generator disconnect is actuated. Approximately 100 milliseconds later, all of the cycloconverter SCRs are fully turned on. This puts a passive, balanced nine-phase load on the generator. Now, all of the energy in the machine will be distributed evenly throughout all the generator windings, feeder cables, SCRs, and IPTs. Tests have shown that from top speed (30,000 rpm), the generator will stop in less than three seconds with this protection. If this protection were not in place, all the machine energy would be dissipated in the shorted phase, certainly burning the associated stator windings.

2.1.3.9.16 Failure Indicators

There are two passive failure indicators in the converter. Given a pulse of 28 vac, they will latch-on and can only be reset manually. The first of these is the generator failure indicator. If either a DH or GOT condition occurs, this failure indicator will trip. The other failure indicator is for converter failures. If the converter is in start mode and a SOC condition occurs, the indicator will trip. If the converter is in generate mode and trips, and at the instant of trip there is not an overload ($\overline{OL} = 1$), then any one of the following protections will cause a converter failure indicator: GOC, OV, DC, WF, UV, WD, WFB, ZV, or LS. If an overload is present, it is assumed that the problem lies in the load bus rather than the VSCF system, and DL does not cause a failure indicator to trip. SCO and US do not cause failure indicators, since this type of trip is normal operation.

2.1.3.10 Control Logic

The control logic uses discrete integrated CMOS circuitry that is wired into arrays to form logic functions. The original control logic configuration contained the necessary circuits to control paralleling and load division. Since the original control circuitry was designed, the requirements for paralleling and load division were deleted from the contract and additional requirements for the flight test—a 145-millisecond (UV) trip, bus tie lockout circuit, and start mode sequence control—were added.

In addition to the converter circuits, the logic also controls the line contactor, the bus tie contactor, the start contactor, and the generator disconnect. Control inputs to the logic are the Generator Switch (GCS), the Start Switch, Cross Start Mode, and a signal from the other converter, indicating that it is in start mode. A flow chart, showing how the logic works, is shown in Figure 29.

The converter will energize in generate mode when the generator reaches minimum speed ($\overline{US} = 1$), and the GCS switch is on. If the converter is in start mode, it will wait five seconds before energizing the generator. When the power quality becomes acceptable, the power ready latch is set. This, in turn, instructs the line contactor to close. The system will now supply any load that is on the bus until either the GCS switch is turned off, the generator goes underspeed, or one of the protections shuts off the converter. In all of these cases, the line contactor will open and the converter will de-energize.

The bus tie contactor enables the other VSCF or external power to pick up the load bus if the line contactor is not closed. The bus tie contactor and line contactor are actually part of the same contactor assembly. This contactor assembly has two coils and two sets of contacts. A mechanical interlock is used so only one side of the contactor can pick up at a time. The two sets of contacts are connected at the center and go to the load bus. The converter will always close the bus tie contactor when the line contactor is open unless the lockout latch has been activated. This occurs when the converter trips with an overload and prevents a fault from tripping both converters. The lockout latch will be reset when the line contactor is closed, and no overload is present.

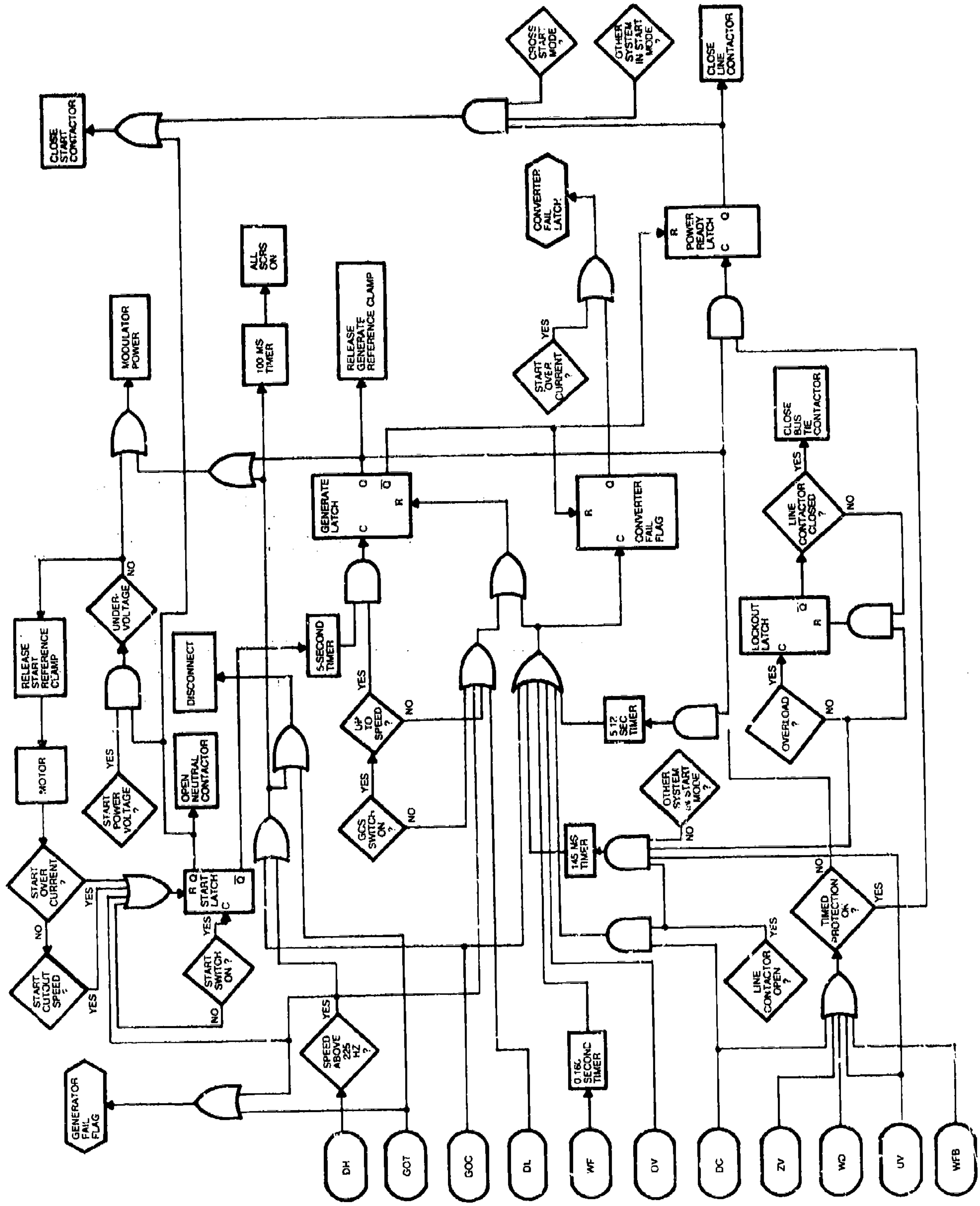


Figure 29. 60-KVA ADP Flight Test Logic

2.1.3.11 Power Supplies

The converter contains +25, +12, -12, and +8-volt dc power supplies. It is necessary to have these supplies all the time, even when the generator is not rotating because of the start mode capability of the converter.

A layout of the supplies is shown in Figure 30. An external 24-volt input is supplied to the converter. In the airplane, this is from the battery bus. In the laboratory, it is the shop supply. The other power supply input is phase 1 of the generator. The generator voltage (varying from 0 to 424 volts rms) is fed into a magnetic amplifier power supply whose output is 22–29 volts dc over the generator range of 1,170 Hz, 180 volts rms to 2,750 Hz, 424 volts rms; no load to 6 amps. The output of the mag amp supply and the 24-volt input are added together through diodes. The junction of these two diodes form the +25-vdc power supply. The +25 vdc powers the contactors, generator disconnect, relays, SCR drive circuits, and an inverter, the output of which is used for the +12 and -12 volt power supplies. The magnetic amplifer supply has a current foldback characteristic as shown in Figure 31.

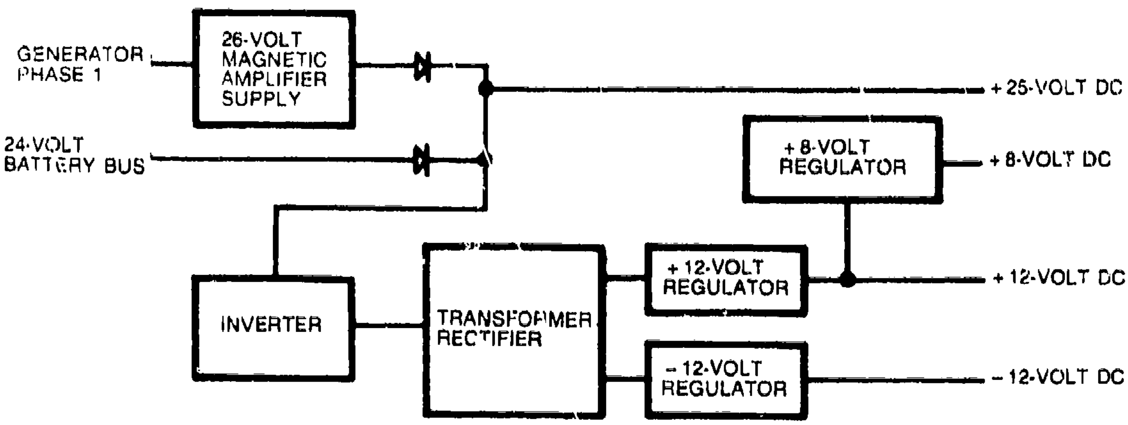


Figure 30. Power Supply Layout

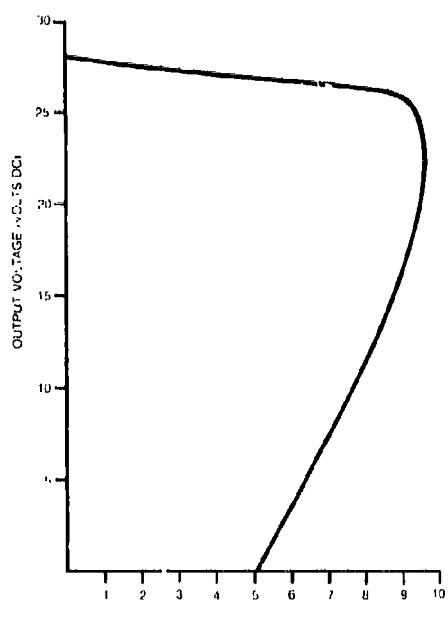


Figure 31. Magnetic Amplifier Foldback Characteristics

The inverter output goes through a center tapped transformer and is full wave rectified. The full wave rectifier outputs go to the +12 and -12 volt supplies. These supplies are transistor regulators, each good for approximately 1 amp. The +12 and -12 volt supplies power to all of the control circuits. The 8-vdc power supply is an integrated circuit regulator, powered from the +12 volt supply. The protection circuitry comparators use 8 vdc as this circuitry is more closely regulated than the +12 vdc and is capable of supplying approximately 150 milliamps.

2.1.4 START MODE CONTROL CIRCUITRY

During the start, 400-Hz ac is supplied to the system output terminals, and the converter supplies variable frequency power to the machine, which then delivers mechanical power at its shaft. The power circuit is unchanged, except for opening the contactors in the generator neutrals. Opening of the neutral increases the effective pulse number of each rectifier circuit from three to six and smooths both the machine and supply currents. The interphase transformers work in reverse of their normal mode to divide the incoming phase current between sets of machine phase windings and to force 120° (machine) conduction of the SCRs at high speeds, see Figure 32.

2.1.4.1 Mode of Operation

The system can provide start torque with the machine operating as a synchronous motor or as a brushless dc motor. A dc machine has dc current only in its field windings. Current in the armature winding is ac, with the commutator providing an inverter function of reversing current flow when a commutator bar rotates from one brush to another. The distinction between a synchronous machine and a dc machine, from the most basic standpoint, is that the angle between field flux and armature current is fixed in the dc machine by the geometric relationship of brushes to the field, while this angle in a synchronous machine varies as a function of power and excitation. Maximum power in a synchronous machine occurs when it is on the brink of slipping out of synchronism. Loss of synchronism results in drastic loss of torque and in large current pulsations. On the other hand, the dc machine cannot slip out of step because brush position controls the angle and, therefore, it is practical to operate at the optimum torque angle.

By operating the system as the equivalent of a brushless dc motor, maximum torque is obtained without danger of pole slip. Again, operation as a dc machine does not mean that there are dc currents other than in the field. A requirement for operation in this mode is that the rotor position must be known at all times. The position sensors are Hall devices that respond to flux density of the rotor. When the machine is rotating, rotor position can be determined by reconstructing the internal machine voltage by the same means as the firing waves for the generating mode are reconstructed.

Figure 33 shows the dc machine analogy for PMG machines. The SCRs in the converter provide the commutator function of switching current between the armature windings, which are now the stationary stator windings, as a function of field (rotor) position. These same SCRs simultaneously control the amplitude of current flow by phase control with respect to the incoming 400-Hz power.

Figure 11 shows the system block diagram for both start and generate functions. Basically, a current regulator replaces the generate mode phase voltage regulators, while the SCRs must be phase controlled with respect to both machine and 400-Hz voltages.

When the speed is high, the motoring machine voltage approaches that of the supply, so voltage starts to drop even with the SCRs fully advanced with respect to the input.

The machine voltage must be reduced by weakening the field just as is done with the conventional dc machine. Field weakening is accomplished by increasing armature reaction by further phase advancing the commutation. The field weakening is initiated by saturation of the supply phase advance circuit. With a PMG machine, indirect field weakening is the only choice.

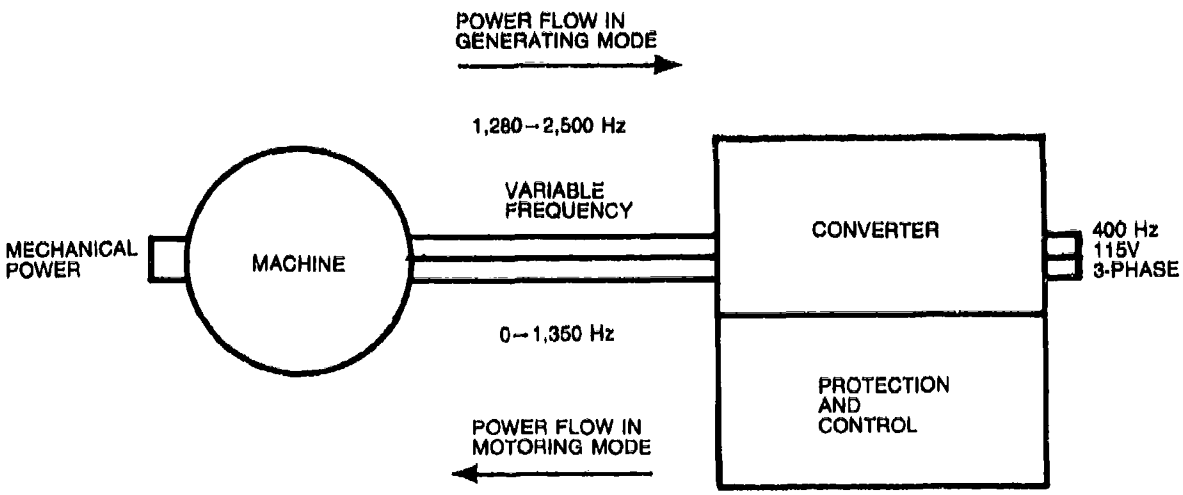


Figure 32. Power Flow

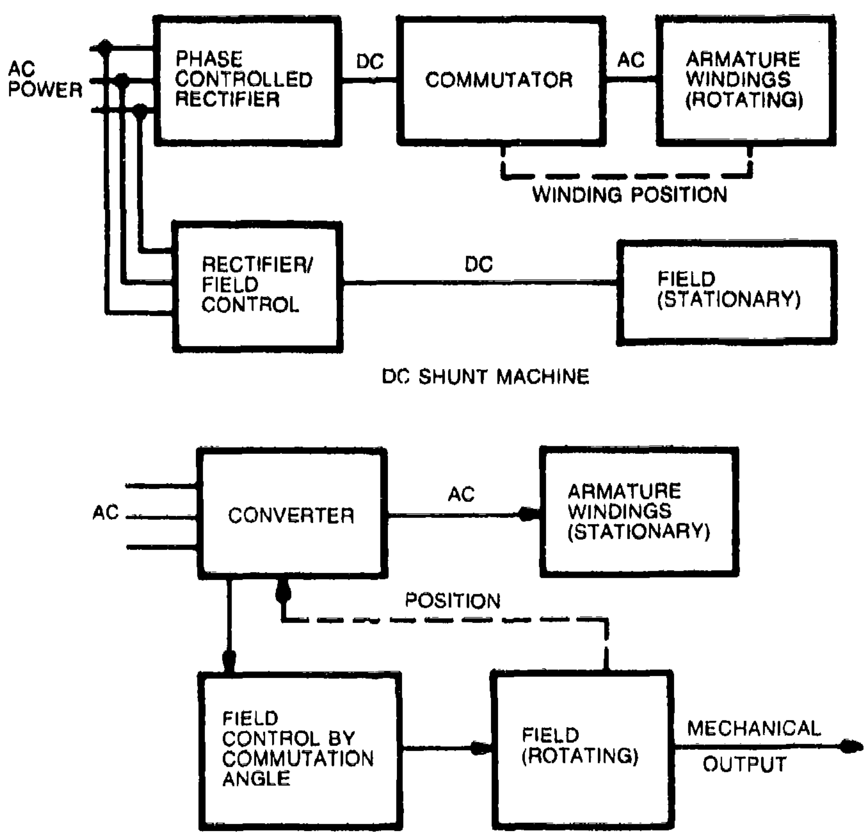


Figure 33. DC Machine Analogy in Start Mode

2.1.4.2 Commutation

Each SCR is phase controlled with respect to the incoming power to control voltage and current amplitude, and it is also gated with respect to rotor position so current will flow in the proper winding at the proper time. Each SCR may be commutated off by either the incoming supply voltage or by the back generated voltage of the machine. At standstill or low speeds, there are many cycles of the supply voltage for each cycle of the machine, and commutation can always be accomplished by the supply. At high speeds, there may be several machine cycles for each supply cycle so, in this region, commutation must be by the machine voltage.

2.1.4.3 Position Control Logic

No attempt is made to supply the machine with sinusoidal voltages, although this is possible at low speed. The voltage applied is the familiar quasi-sqaure wave, which has 120° constant voltage intervals spaced by 60° zero voltage intervals.

The nine-phase, quasi-square waves constitute 18,120° conduction intervals where groups of SCRs are to be fired. There are nine intervals of each polarity. These intervals are established by the position sensors, which report rotor position by means of Hall probes that sense leakage flux at the end of the rotor. Since only three probes are used, positions represented by the other six phases must be derived. One obvious possibility is to consider the outputs of the Hall probes as a micropower three-phase generator and to develop the intermediate angles by phasor addition. For reasonable accuracy, the outputs of all three probes must be equal, which requires the gain of the probes to be matched or their excitation to be individually adjusted. The method used is a phase-lock loop with a nine-stage ring counter to derive the nine phase positions. The loop includes three-phase discriminators, comparing the three sensor outputs with three of the counter stages.

In the three-phase mode, only each third stage in the ring is directly set by the position sensors. The remaining stages in the ring are clocked by the voltage-controlled oscillator, which is designed to have a minimum frequency. The stages, following those directly set, now lag by a fixed time or by an increasing phase angle as the motor speed increases. A gradual transition is made from the three-phase mode to the nine-phase mode so that, when the direct sets are disabled, a smooth transition is made to the phase-lock loop control.

The position logic is gradually advanced as the machine frequency increases from 150 to 400 Hz to optimize commutation.

At just above 800 Hz, the machine voltage approximates the supply so that the system current starts to drop even though the SCRs are fully advanced with respect to the 400-Hz supply. The unsatisfied current regulator, therefore, heads towards saturation and breaks over the zener that couples it to the position logic. Current flow through the zener advances the position logic, which shifts the machine current so that it is more reactive. This demagnetizes the machine, lowers its voltage, and permits more current to flow until the current regulator is satisfied.

2.1.4.4 Start Current Regulator

In start mode, the input current to the system is regulated. The same current transformers and rectifiers are used that sense output current in generating mode. The current is regulated by adjusting the advance of the SCR firing relative to the 400-Hz supply. The same biased cosine technique is used, as previously described, in the generating mode. Firing and blanking waves are derived from the 400-Hz waves, rather than the machine waves. The integration of the 400 Hz is available from the ac feedback filter used in the generating mode. All SCRs are equally advanced in this mode.

After fully advancing the SCRs, the current regulator controls the position logic, as previously described.

2.1.4.5 Start Mode Control Logic

If the generator speed is below the underspeed trip point and the start signal to the converter goes to a logic 1 (start switch on), the converter will go into start mode.

Immediately upon going into start mode, the following occurs: the neutral contactor opens, the start contactor closes, the UV protection is recalibrated, blanking wave control is switched over to the start position logic, and a start latch signal is sent to the other converter. The other converter then will recalibrate its wave form distortion protection and, if in cross-start mode, close its start contactor.

Approximately 18 milliseconds later, the modulator power to the SCRs will be turned on. Approximately 22 milliseconds after that, when the UV protection goes to a logic 1, the start current regulator clamp will be released.

Assuming that one of the protective circuits does not discontinue the start, it will proceed until either the start signal goes to a logic 0 (start switch off), or the generator attains the start cutout speed. Either of these events will reset the start latch. At this point, the start contactor will open, the start current clamp will be applied, and the UV protection trip limit will be normalized. Approximately 18 milliseconds later, the modulator power is removed. When the undervoltage protection goes low, the neutral contactor will open and the start latch signal to other converter will go low. The other converter then will open its start contactor and normalize its WD protection. At 5.12 seconds from the time the start latch is reset, the blanking waves are normalized to generating mode, and 0.32 seconds after that the converter will energize as a generating system if the generator control switch is on.

A diagram illustrating this timing can be seen in Figure 34.

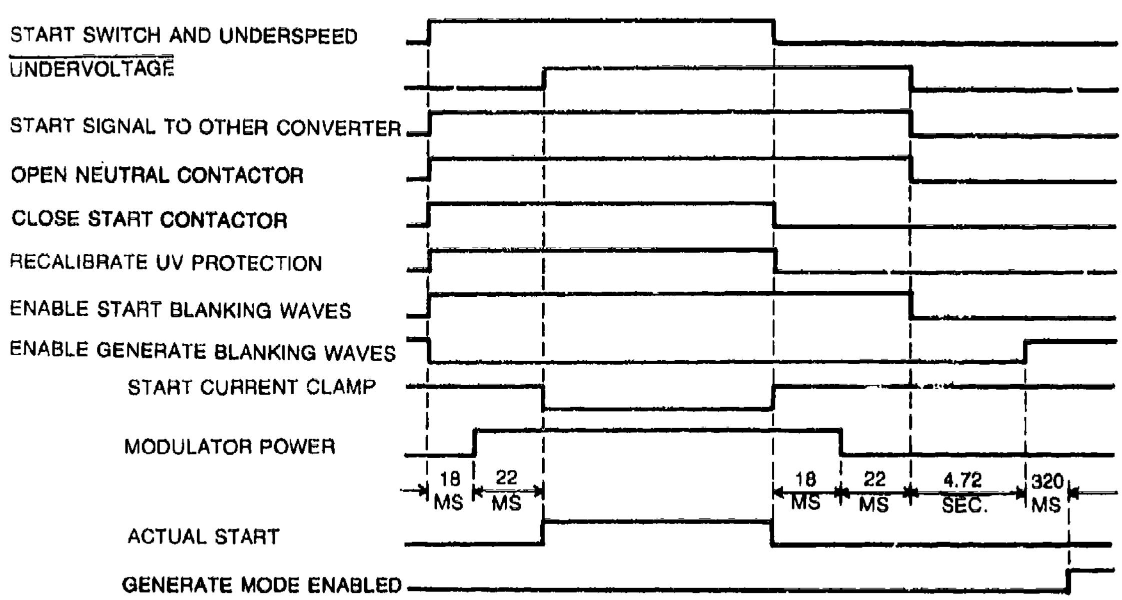


Figure 34. Start Mode Control Logic Timing

2.2 STARTER-GENERATOR DESCRIPTION

The starter-generator, developed for this contract, is an integral package that includes a 60-KVA variable speed, constant frequency permanent magnet generator, with starting capability through the use of the generator winding, and a self-contained lubricating and cooling oil pump and step-up gearbox. An outline of the generator/gearbox package, depicting general configuration and interface locations, is shown in Figure 35. A photo is shown in Figure 36.

A general description of the configuration, the function of the starter-generator/gearbox major components, and the salient features and characteristics are provided in the following sections so that the merits of the equipment delivered may be better understood.

2.2.1 STARTER-GENERATOR

The starter-generator is a permanent magnet machine with a nine-phase output winding and a permanent field, provided by rare earth magnets that are contained in an all-metallic rotor.

The starting capability is provided by application of power from the converter to the generator output windings. The generator, therefore, operates as a brushless dc motor. Sensors, which are used to detect the angular relationship between the rotor poles and phase windings, function as the commutator so that power is applied to the proper phase to produce torque for engine starting.

The generated voltage and power output to the converter is a function of speed. Therefore, the generator/gearbox capability was designed to deliver rated load and meet overload requirements at the 15,936 rpm base speed.

This starter-generator design is inherently more reliable than conventional wound rotor-type ac generators because the generator does not contain rotating windings, thus eliminating rotating rectifiers, and has one output winding. This design also has substantially fewer parts.

A layout/cross-sectional view of the generator, with identification of components as referenced and described, herein, is shown in Figure 37.

2.2.1.1 Frame and End Bell

The basic structure support is provided by the frame and end bell. Both of these members are high-strength aluminum sand castings of alloy C355. The drive-end bell also interfaces with the gearbox and supports two gearbox bearings. In addition, the generator frame contains the oil filter cavity and several oil passages, including the oil exit and inlet bases.

2.2.1.2 Rotor

The rotor is a 10-pole design with four 1.2-inch long sections to make the total field length. Each section or disk is constructed to contain the permanent magnets and the metallic members, and to provide the required magnetic paths and mechanical strength. The sections are aligned and assembled on the shaft to complete the rotor structure.

A radial cross-sectional view of the rotor, with component names, is shown in Figure 38. Descriptions of the component parts of the rotor are given in the following text.

- Shaft—The generator shaft material is a nonmagnetic, heat treatable material that has process capability to provide a yield strength of 125,000 psi. The shaft is hollow to minimize weight and provide for the flow of cooling oil inside.

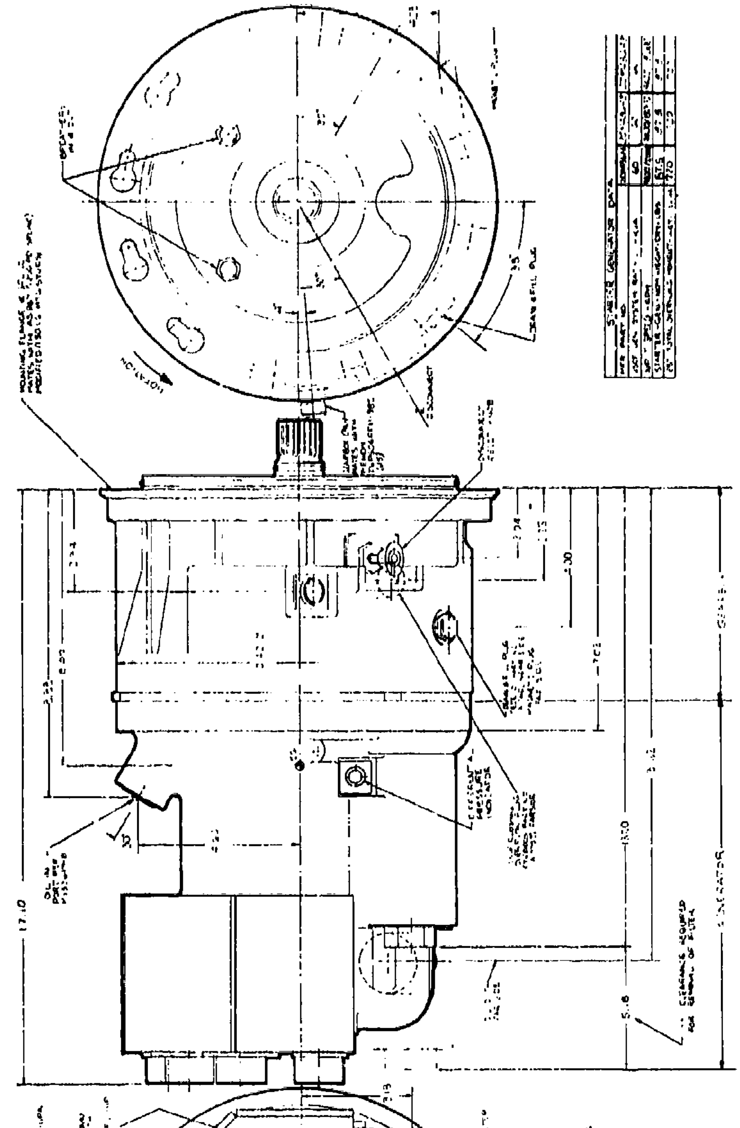


Figure 35. Starter-Generator Outline

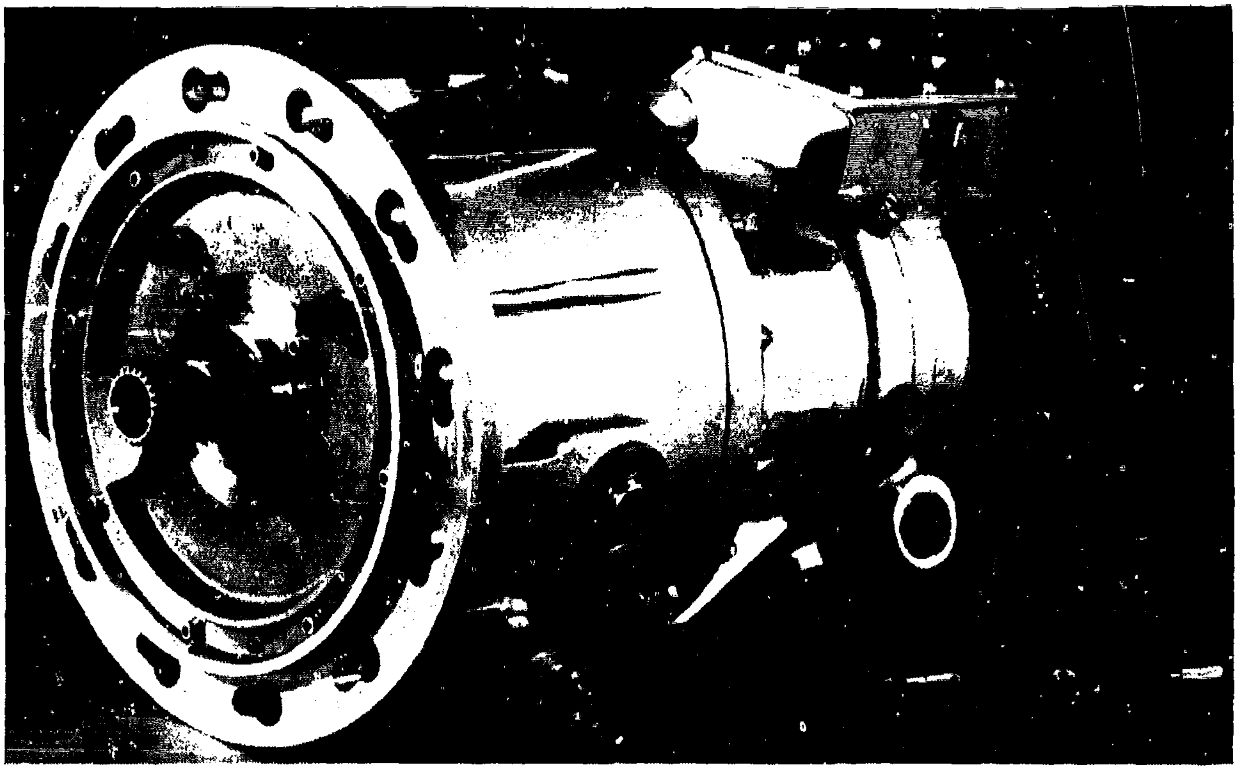


Figure 36. 60-KVA ADP Starter-Generator/Gearbox

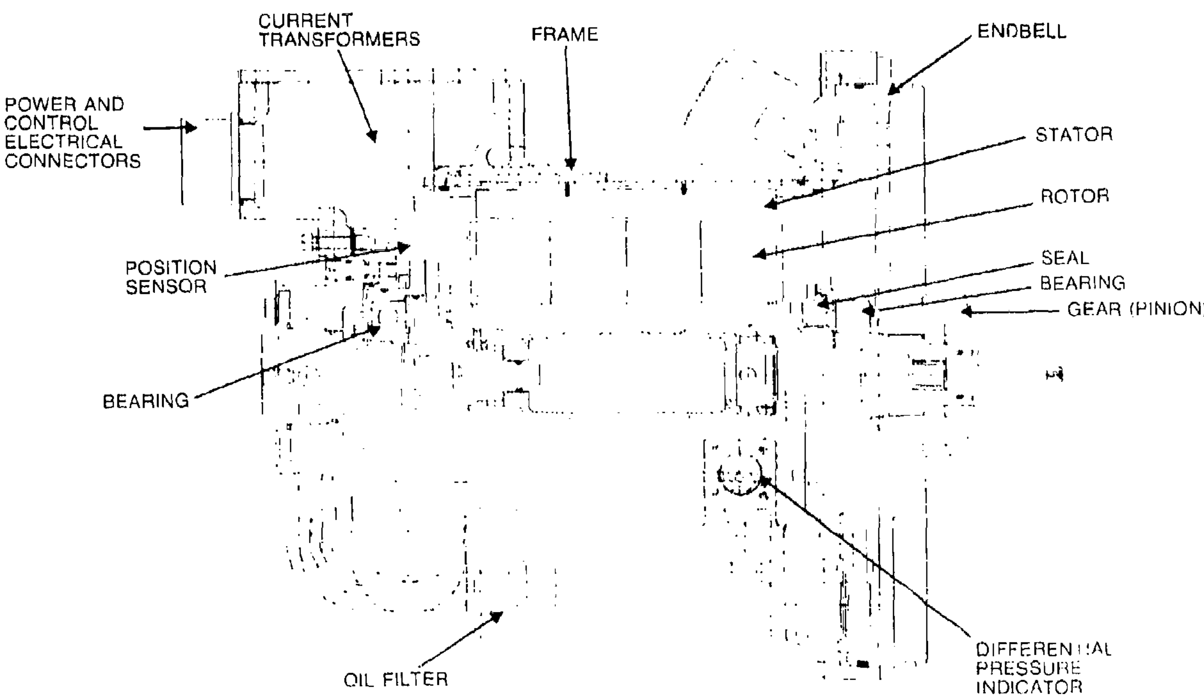


Figure 37. Generator Cross Section

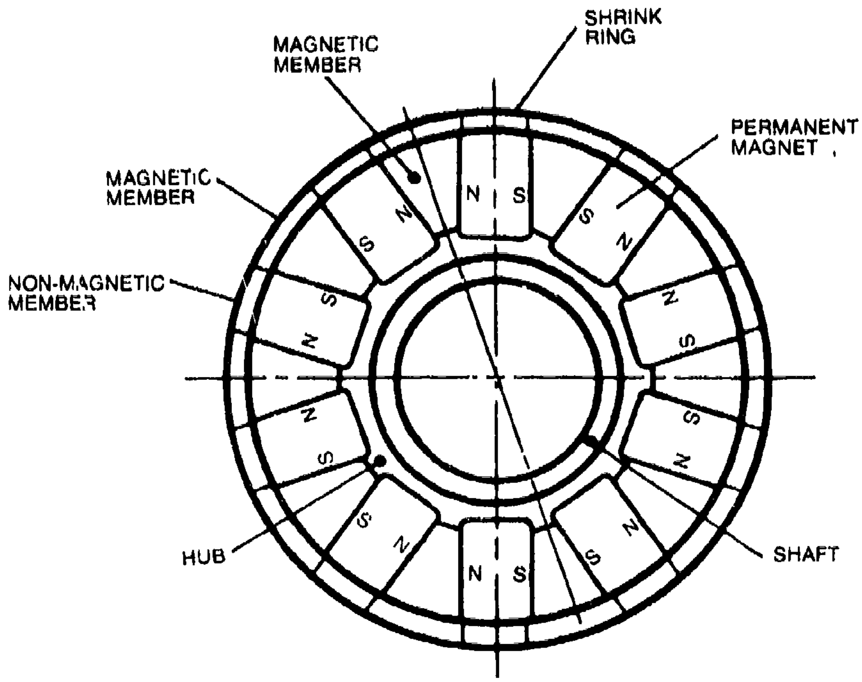


Figure 38. Rotor, Cross-Sectional View

- Hub—The hub material is heat treated to provide 125,000-psi yield strength properties. The hub provides the base or support for attachment of the spoke-configured magnetic members and the permanent magnets.
- Permanent Magnets—The permanent magnets are produced from fine particle, rare earth-samarium cobalt magnet alloy that is sintered, magnetic particle aligned, and heat treated to provide an energy product of not less than 20 x 10^6 gauss-oersted measured at room temperature. The magnets are assembled in the rotor structure in the fully magnetized condition.
- Magnetic Member Poles—The spoke-configured magnetic members are fabricated from 1018 steel and bonded to the hub by electron beam welding, see Figure 39.
- Shrink Ring—The shrink ring is a bimetallic member, consisting of a nonmagnetic heat-treatable material that is positioned over the permanent magnet in the rotor configuration, and a heat-treatable magnetic material that is located over the magnetic members.

2.2.1.3 Stator Wound

The stator is constructed with a wound laminated magnetic core and an outer aluminum shroud, see Figure 40. The laminated core is 4.75 inches in length, has 90 slots, and contains a nine-phase, multiple strand, round conductor winding. The stator slot is overhung to minimize the pole face losses.

- Stator Core—The stator core is constructed with 0.006-inch thick laminations of vanadium-cobalt steel that are stacked, aligned, and secured by bonding.
- Phase Winding—The phase coils are wound with round copper conductors. The strands are transposed in the end turns such that top positioned conductors, entering the slot, are transposed to a bottom position with respect to the slot in the end-turn region at the opposite end of the slot.

Figure 39. Rotor Segment Components CT3251-3

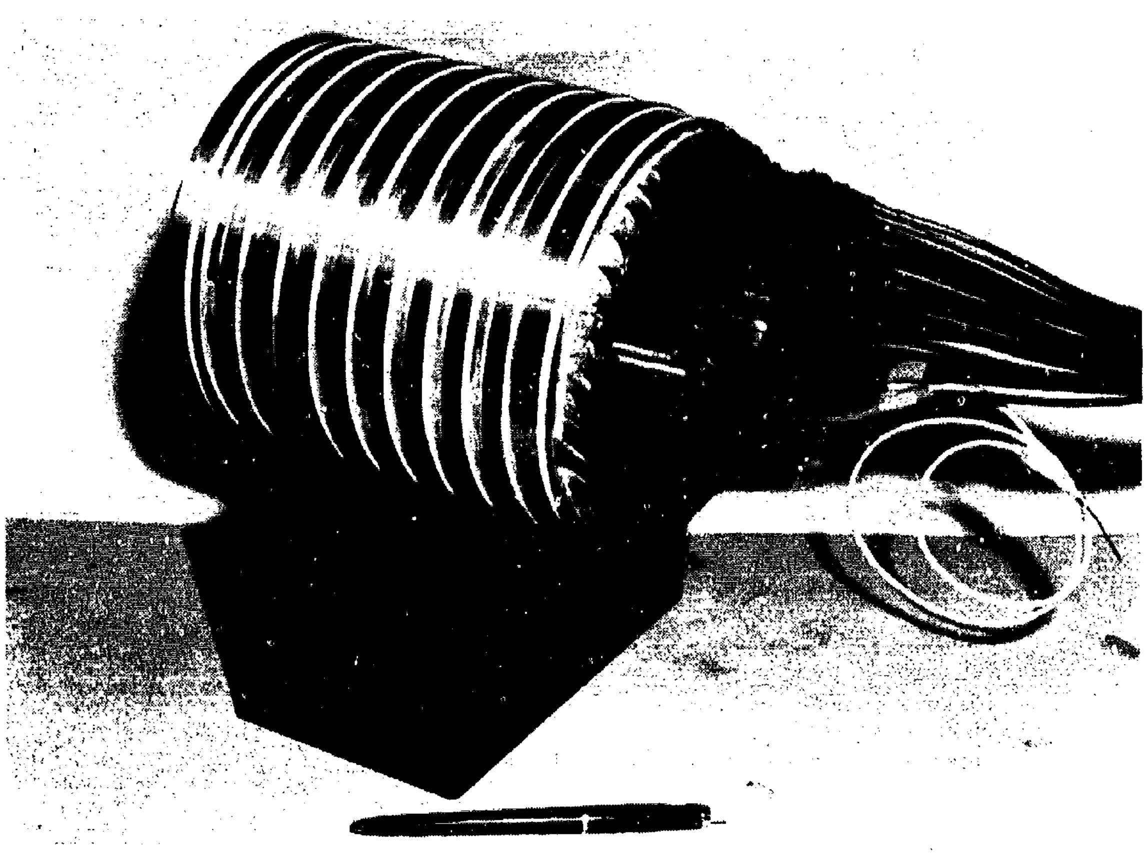


Figure 40. Stator Assembly CT3287-2

- Connections and Leads—The terminations of phase windings are brazed, with the connections of each phase made to a multiple wrap, polymide film insulated stranded copper cable.
- Stator Insulation—The stator slot ground insulation consists of slot liners to obtain good mechanical and electrical ground insulation. A phase separator was placed between the top and bottom conductors and extends out of the slot, see Figure 41.
- Cooling—Stator losses are conducted through the core, into the outer aluminum shroud, and then into the oil that flows in the grooves in the shroud.

2.2.1.4 Position Sensor

Three Hall effects elements are used to provide rotor position and speed sensing. Figure 42 shows the sensor assembly that contains the three Hall generators. The Hall generators are separated 120 electrical degrees and are positioned so as to detect the pole end-leakage flux of the permanent magnet rotor. Mounting screws permit circumferential adjustment, and the axial air gap with the end of the permanent magnet rotor is controlled by shims between the sensor assembly and frame. Also visible on Figure 42 are the ends of the copper rods that heat sink the Hall devices and magnetic cores to the generator frame. See Figure 37 for the location of the sensor assembly in the generator.

2.2.1.5 Bearings

The main generator bearings used are 107 size, deep groove, single row, single width, open type of radial Conrad construction. The bearing balls and rings are vacuum melted AISI M50 tool steel, heat stabilized, and manufactured to ABEC-7 precision tolerances. The ball retainers are outer ring, land piloted, machined bronze, and silver plated.

The lubrication and cooling of the bearings are provided by oil jets.

2.2.1.6 Seals

Dynamic shaft seals are provided on one side of the bearings to limit oil passage into the generator cavity. These are a circumferential type that seal directly on the outer diameter of seal runners, shrunk on the shaft.

All other seals are static O-rings, except for those at the connection box covers. An anerobic sealant is used under these cover plates.

2.2.2 GEARBOX

A cross section of the gearbox is shown in Figure 43. This provides several functions in one compact housing. It contains the power gearing that steps up the input rotation from the driving source to the generator rotational speed by 1.675 times. The gear train schematic is shown in Figure 44. This system, with the two-side idler gears or branches, keeps the input and output on the same centerline and reduces loading at the gear meshes. The gear reaction loads on the bearings on input and output shafts are also cancelled out by this arrangement. There is a shaft disconnect on the input side. The oil pumps and the system oil tank are also located in the gearbox.

There is a mechanical disconnect on the input gearshaft of the gearbox. When triggered by a 24 vdc, this mechanism decouples the driving torque, allowing the input shaft to continue to rotate free from the rest of the geartrain. Recoupling is accomplished by pulling a reset handle when at zero rpm.

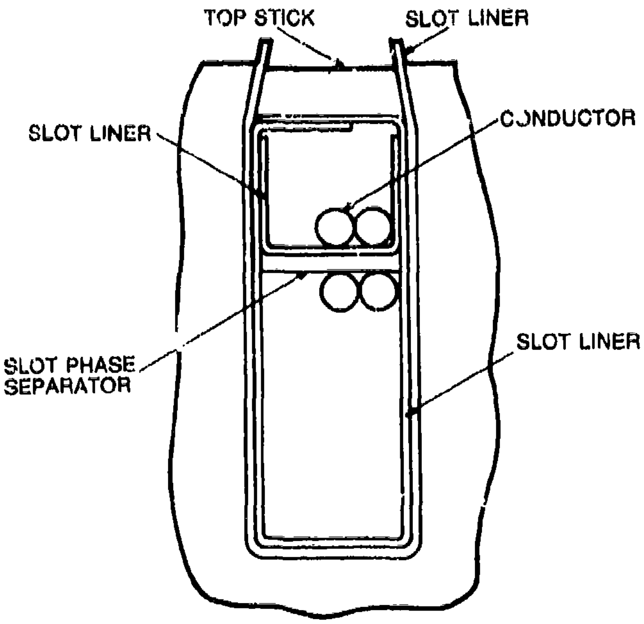


Figure 41. 60-KVA Starter-Generator Stator Winding

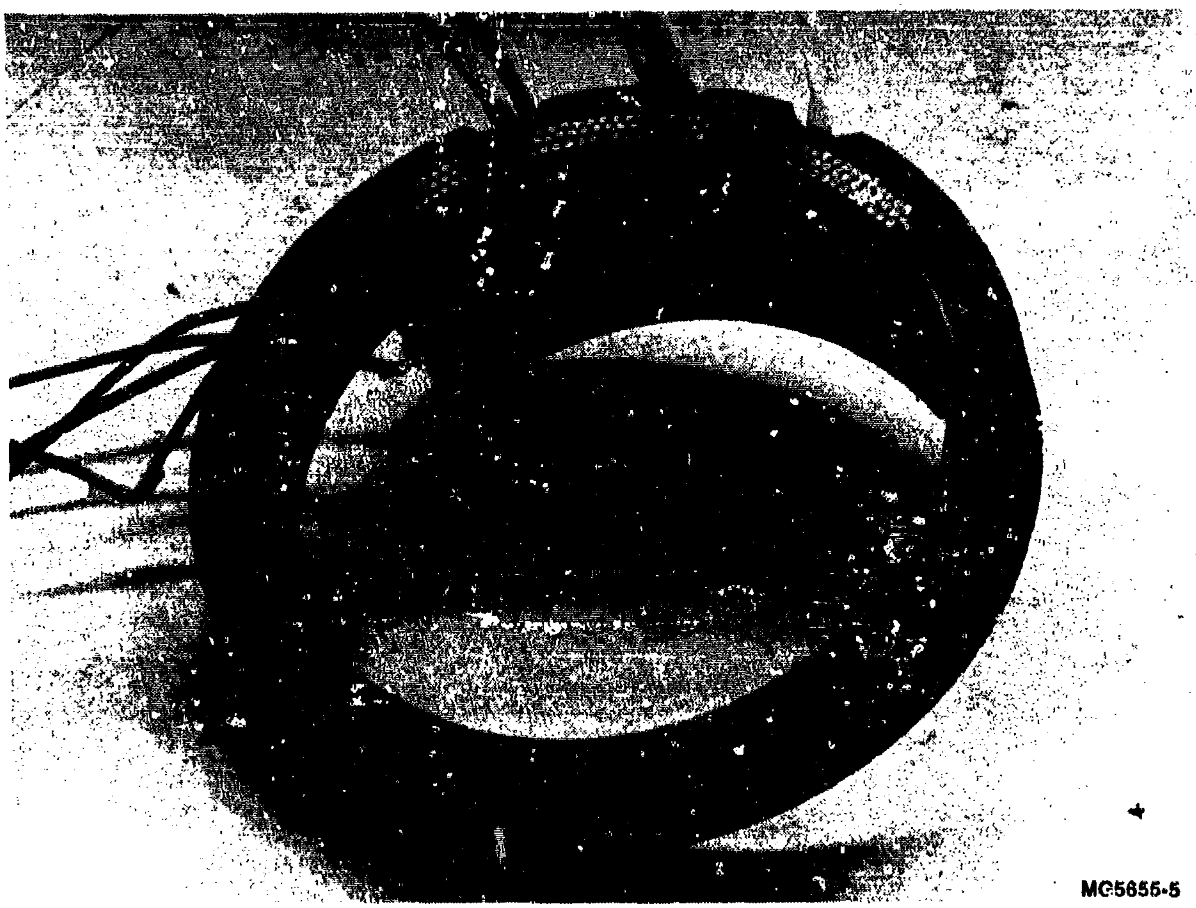


Figure 42. 60-KVA Permanent Magnet Starter-Generator Rotor Position Sensor Assembly

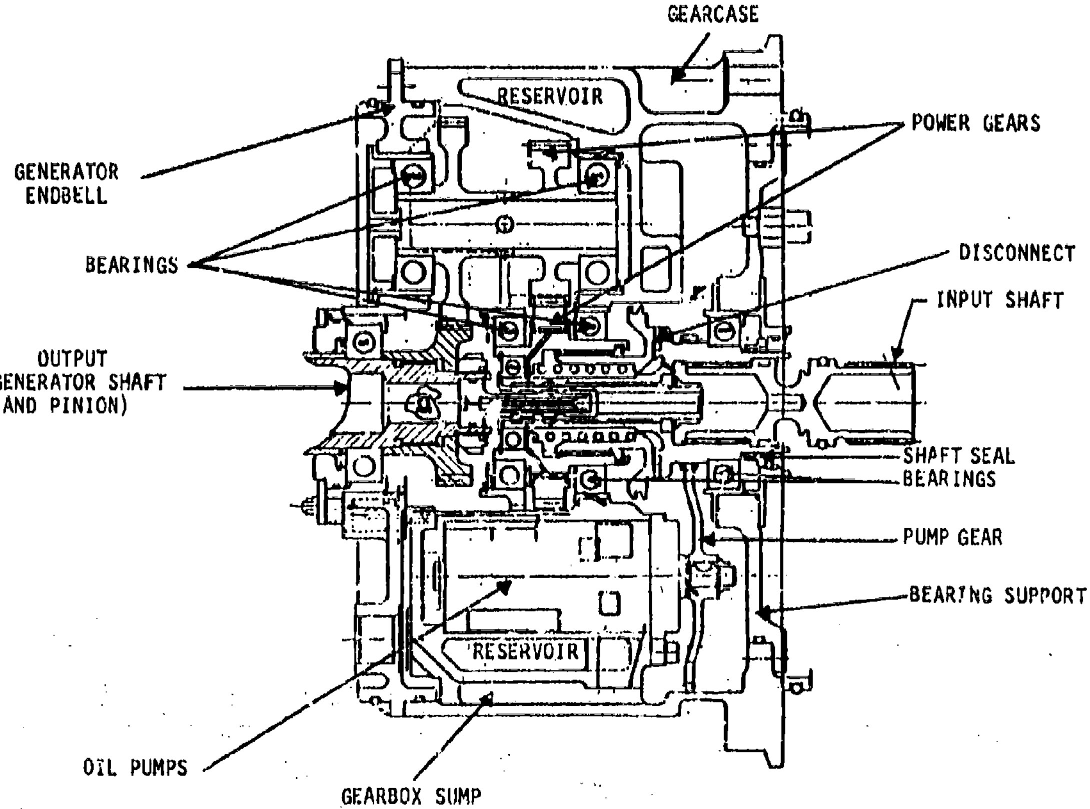


Figure 43. Gearbox Cross Section

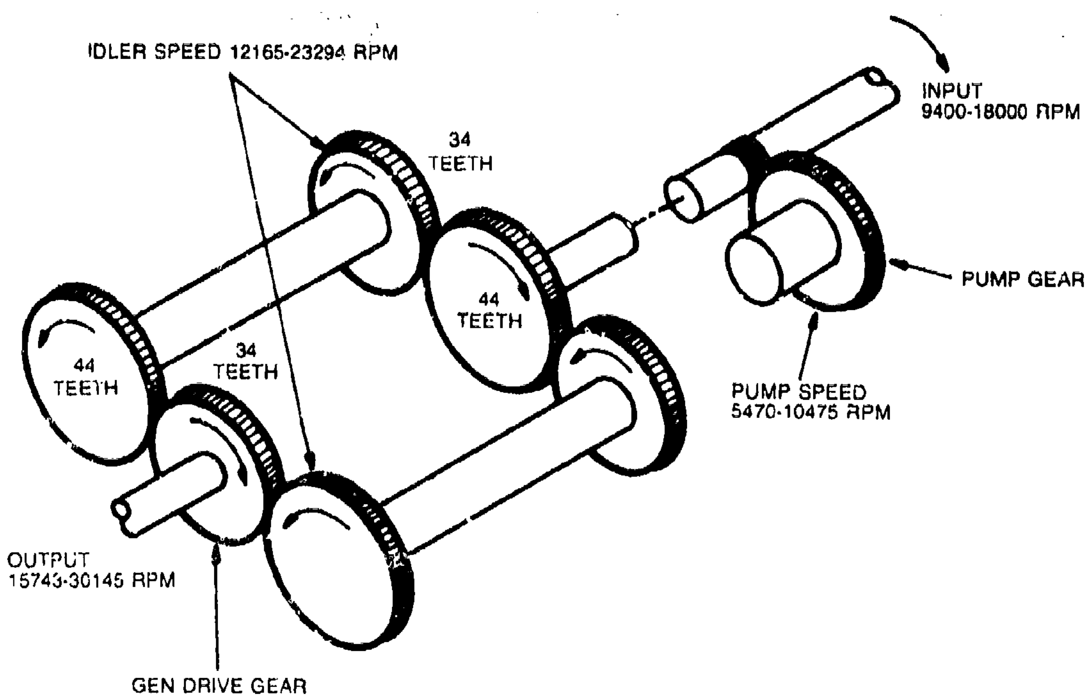


Figure 44. 60-KVA Starter-Generator Geartrain Schematic

2.2.2.1 Input Shaft

A stub shaft is used to transmit the torque from the drive pad into the gearbox. This shaft features a male spline on each end and a 4,000 + 250 in-lbs shear section. The input spline is also chrome plated by hand for wear and corrosion resistance, while the gearbox end spline connection is oil lubricated by the starter-generator oil system.

2.2.3 OIL SYSTEM

This system supplies oil to the gearbox and starter-generator for cooling and lubrication. Except for the external aircraft mounted heat exchanger, the complete system is contained in the gearbox and starter-generator. This system is designed to operate with either MIL-L-7808 or MIL-L-23699 aircraft turbine engine oil. The schematic of this system is shown in Figure 45. This diagram also shows various pressures and flows that occur in the system at maximum speed.

2.2.3.1 Pump

System pressures and scavenging are accomplished by a multiple element generator pump. Four separate pumps are built into one package.

The supply pump provides the basic pressure and flow for the system. It draws oil from the tank and pumps it to the filter. From the filter, it flows through the generator cooling circuits, to the external heat exchanger, and back into the starter-generator. At this point, a portion of the flow is diverted to the gearbox lube system, while the major portion is returned to the oil tank.

Scavenge pump 1 returns the gearbox lube oil to the tank from the pump in the bottom of the gearcase.

Scavenge pumps 2 and 3 pump any oil that might collect in the bottom of the starter-generator case into the oil tank. Each pump is dedicated to an end of the starter-generator case to provide positive case scavenging, regardless of attitude.

2.2.4 GENERATOR/GEARBOX WEIGHT

The breakdown of the generator weight is listed in Table 4 and that of the gearbox is listed in Table 5.

2.2.5 THERMAL ANALYSIS

2.2.5.1 Assumptions for Thermal Analysis

The thermal analysis was based on the following:

1. A thermal network as shown in Figure 46.
2. Cooling conditions: MIL-L-7808 Oil
   7 GPM Total Flow
   5 GPM Stator Flow
   1.65 GPM Rotor Flow
   50 PSI Pressured Drop
   120°C Inlet Temperature

2.2.5.2 1 PU Load Thermal Analysis—Steady State

At 60 KVA, 0.95 pf system load, and 30,000 rpm generator speed, the calculated hot spots were 241°C and 172°C in the winding and magnet, respectively.

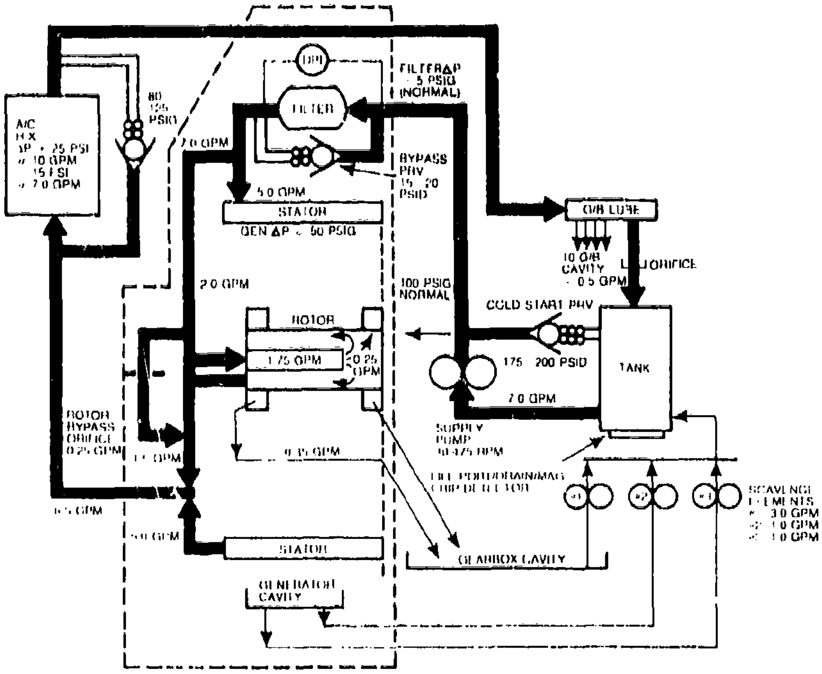


Figure 45. 60-KVA ADP Oil System Schematic

TABLE 4
GENERATOR WEIGHT BREAKDOWN

	Weight (Lbs.)
Rotor:	
Shrink Ring	6.3
Magnets	8.6
Poles	5.3
Hub	2.1
Shaft	5.9
Stator:	
Core	6.7
Copper	3.5
Insulation	0.5
Frame:	15.0
Bearings	0.7
Seals and Rings	1.4
Bearing Supports	1.5
Miscellaneous Hardware	4.0
Total Weight	61.5

TABLE 5
GEARBOX WEIGHT BREAKDOWN

	Weight (Lbs.)
Frame	20.3
Gears	5.2
Bearings	2.2
Disconnect	
Solenoid	0.4
Coupling	0.6
Body	0.4
Plunger	0.1
Shaft	0.9
Oil System	
Pumps	1.0
Pump Gear	0.3
Miscellaneous Hardware	2.1
Total Weight	33.5

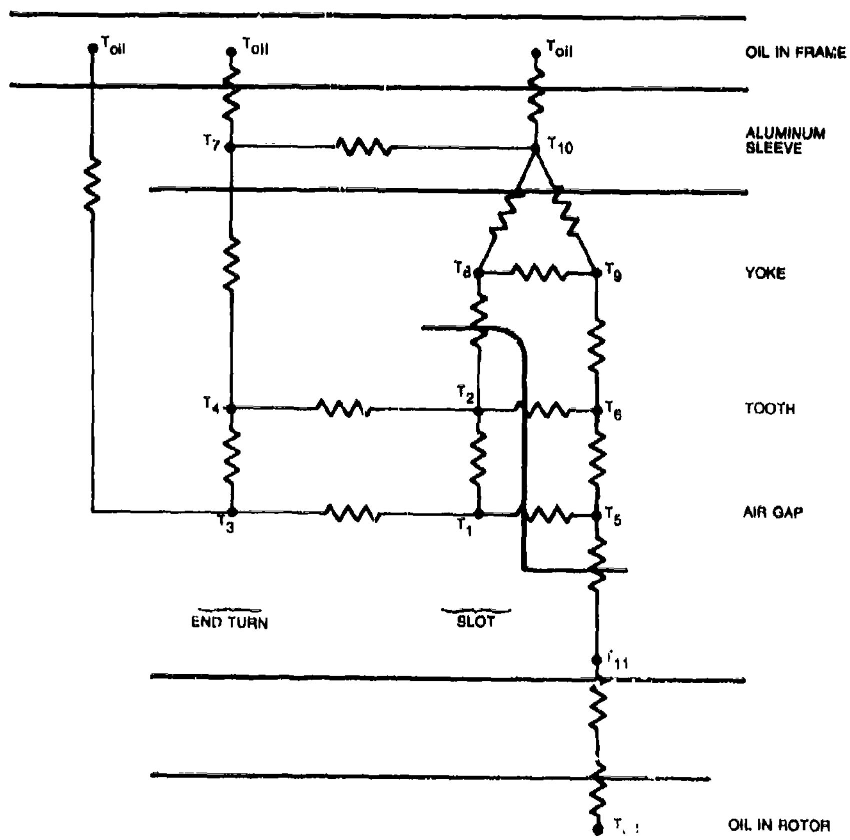


Figure 46. 60-KVA Starter-Generator Thermal Network

2.2.5.3 Transient Thermal Analysis

A transient analysis was made for the condition that represents application of 90-KVA system load after thermal stabilization at 60-KVA load. The results of this analysis are shown in Figure 47.

2.2.6 ELECTRICAL CHARACTERISTICS

2.2.6.1 Stator Winding

The generator has a balanced 9ϕ, 10-pole, distributed stator winding. The resistance per phase is 0.041 ohm at 25°C. The phases are spaced at 40 electrical degrees and connected in three sets of three-phase windings. Thus, phases 1-4-7, 2-5-8, and 3-6-9 are connected as three-phase windings and are each terminated at a separate connector on the unit.

2.2.6.2 Generator Open Circuit Voltage

2.2.6.2.1 Voltage Level

At 9,400 rpm input speed (15,743 rpm generator speed), the open circuit phase voltage is 201.5 volts.

2.2.6.2.2 Wave Shape and Harmonics

The voltage wave shape and harmonics analysis is shown in Figure 48.

2.2.6.3 Hall Generator Output

Figure 49 shows the position sensor Hall generator output. Typical output is 175 mV with 15 mA excitation.

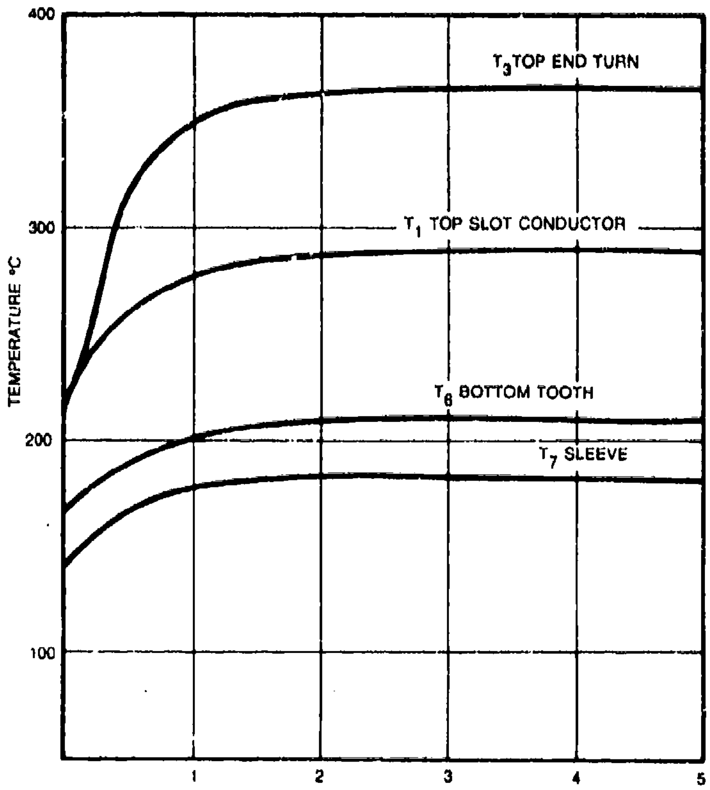
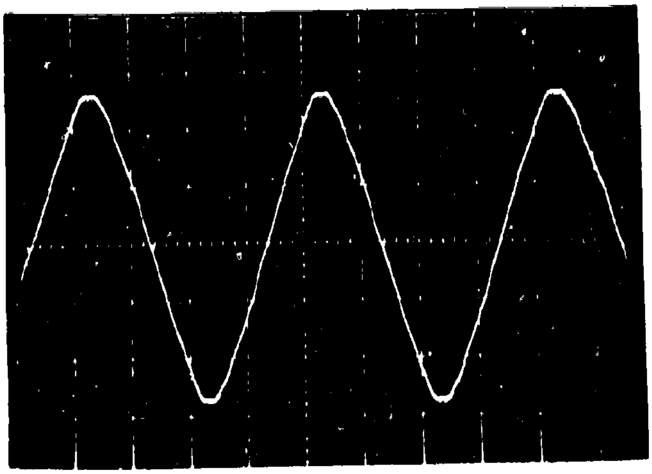
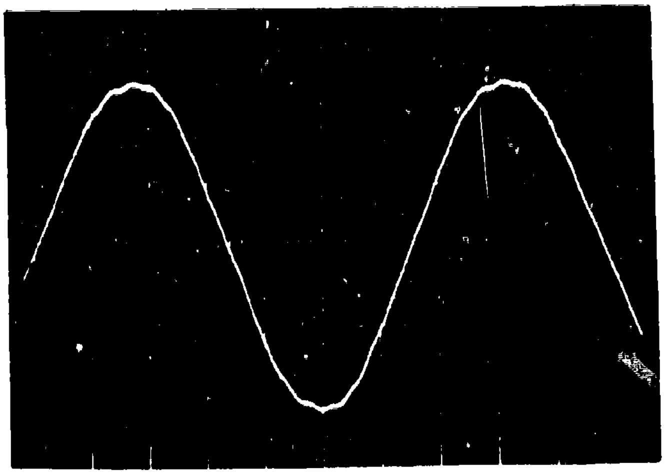


Figure 47. 60-KVA Starter-Generator Transient Thermal Analysis



	HARMONIC	%
L-N PHASE 1-N		
192 volts rms	1	100
	3	6.5
V = 100 V/cm	5	1.8
H = 0.2 ms/cm	7	0.2
Rotor rpm = 15,300	9	1.3
	11	0.3
	13	0.3
	15	0.2
	17	0.8
	19	0.2



WAVE SHAPE AND HARMONICS

L-L PHASE 1 - PHASE 4		
208 volts rms	1	100
	3	-
V = 100 V/cm	5	1.8
H = 0.2 ms/cm	7	-
Rotor rpm = 9,372	9	-
	11	0.3
	13	0.3
	15	-
	17	0.8
	19	0.4

Figure 48. Wave Shape and Harmonics

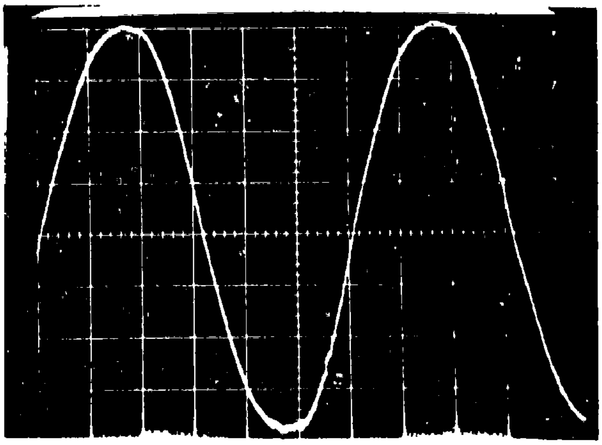


Figure 49. Hall Generator Output

2.3 CONVERTER DESIGN

2.3.1 DESCRIPTION

The 60-KVA ADP cycloconverter, see Figures 50 and 51, is a modular designed unit with a dip-brazed electrical chassis (A1), as shown in Figures 52 and 53. The chassis provides mounting for the following modules. See Figure 54 for module locations.

- Interphase Transformers, T1-T18
- Silicon Controlled Rectifier Modules, Z1-Z18
- Control Logic Boards, A2-A9
- Gate Drive Board, A10
- High-Frequency Current Transformer Assembly, A11
- High-Frequency Resistor Board, A-12
- IPT Resistor Board, A-13
- Transient Suppressor Capacitors, A-14
- Output Filter Capacitors, C1-C3
- Low-Frequency Current Transformer Assembly, T19
- Power Supply Module, PS1
- Air Blower, B1-B2
- Generator Power Connectors, J1-J3
- Converter Interface/Test Connectors, J4-J6

Carrying handles, mounting bolts, and covers complete the package.

2.3.1.1 Interphase Transformers, T1-T18

There are 18 IPTs, nine on each side of the converter, utilizing copper bus links as much as possible, see Figure 55. The IPT core is tape wound silicone-iron that has the four corners cut out, with two of the opposing legs flipped 90° to align the magnetic field and reduce stray flux leakage.

2.3.1.2 Silicon Controlled Rectifier Assembly, Z1-Z18

There are 18 SCR assemblies/modules mounted on a fin-stock, air-cooled cold plate and electrically isolated from this cold plate by Cotherm sheets, see Figures 56 and 57. Three C-148 type SCRs are soldered to each copper plate, which serves as a heat spreader and an electrically common anode. For noise immunity, each SCR has a gate to a cathode resistor bonded to it with RTV adhesive.

2.3.1.3 Control Logic Boards, A2-A9

All eight logic boards are double-sided glass epoxy with copper runs, see Figures 58 and 59. The boards are secured in the chassis by locking Birtcher guides and have aluminum stiffeners on them for improved vibration response. Each board has a MIL-C-55302 type box connector for ease of installation and are conformal coated for environmental protection from salt, fog, humidity, and moisture. Military quality components and parts are assembled and flow soldered to each board to ensure repeatable quality.

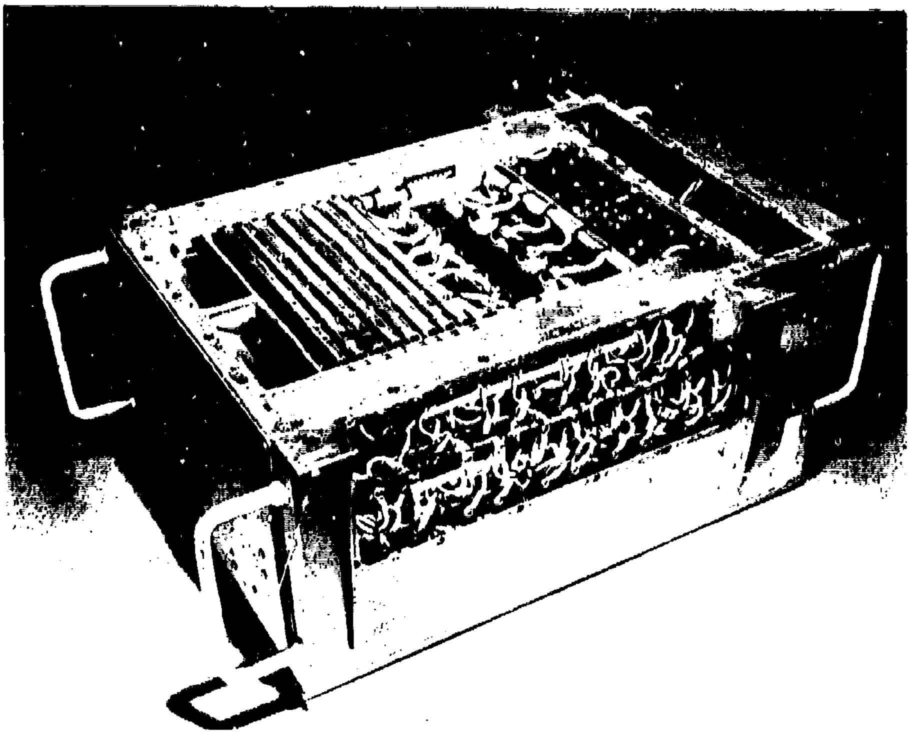


Figure 50. Cycloconverter (Bottom View) 32192

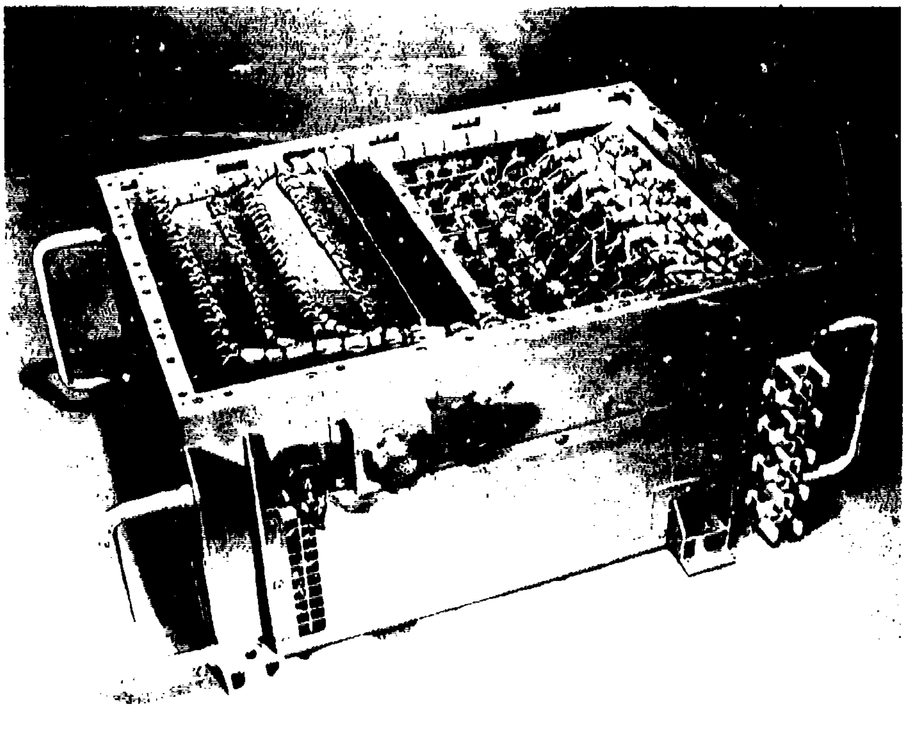


Figure 51. Cycloconverter (Top View) 32191

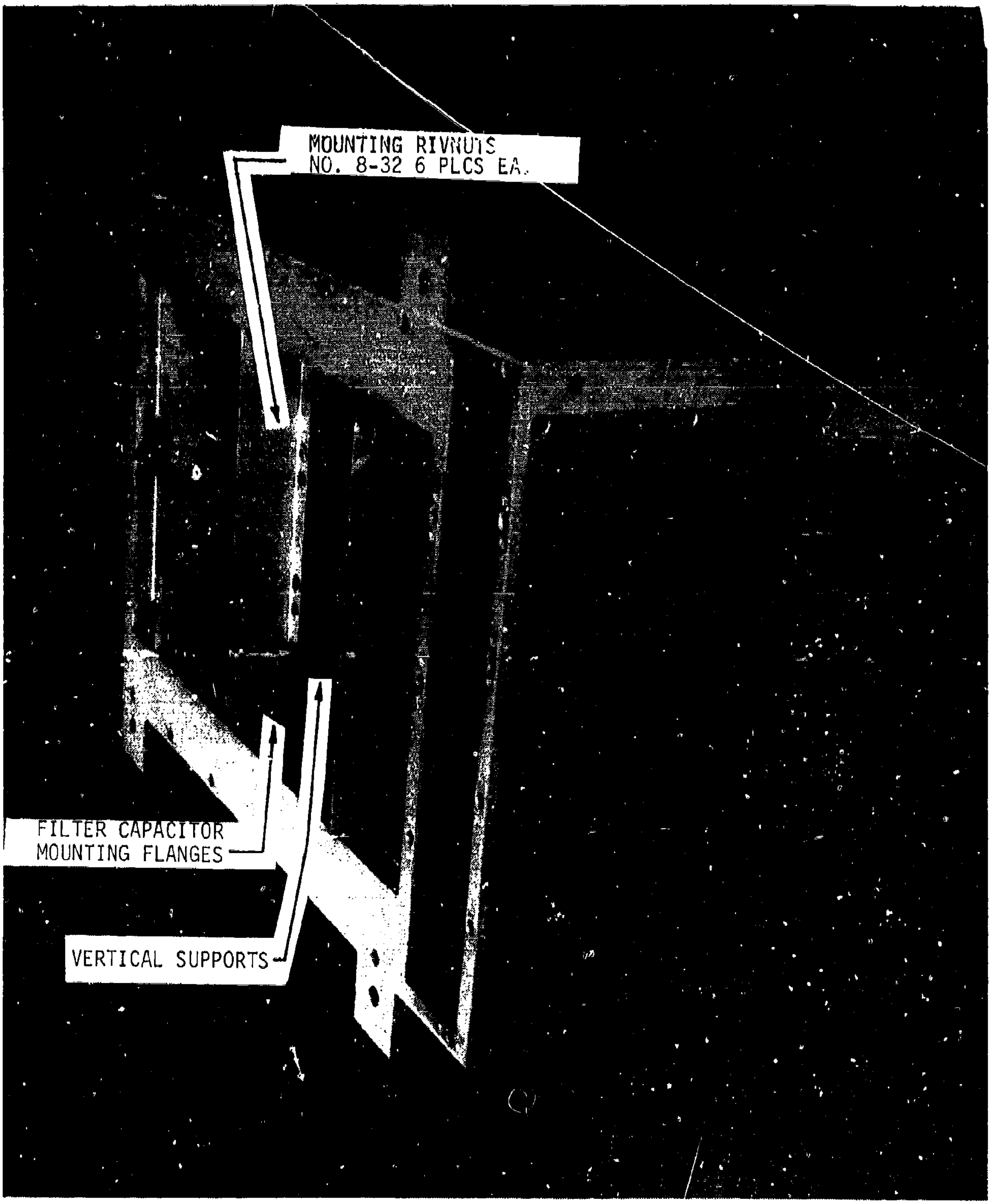


Figure 52. Dip-Brazed Chassis Original Configuration

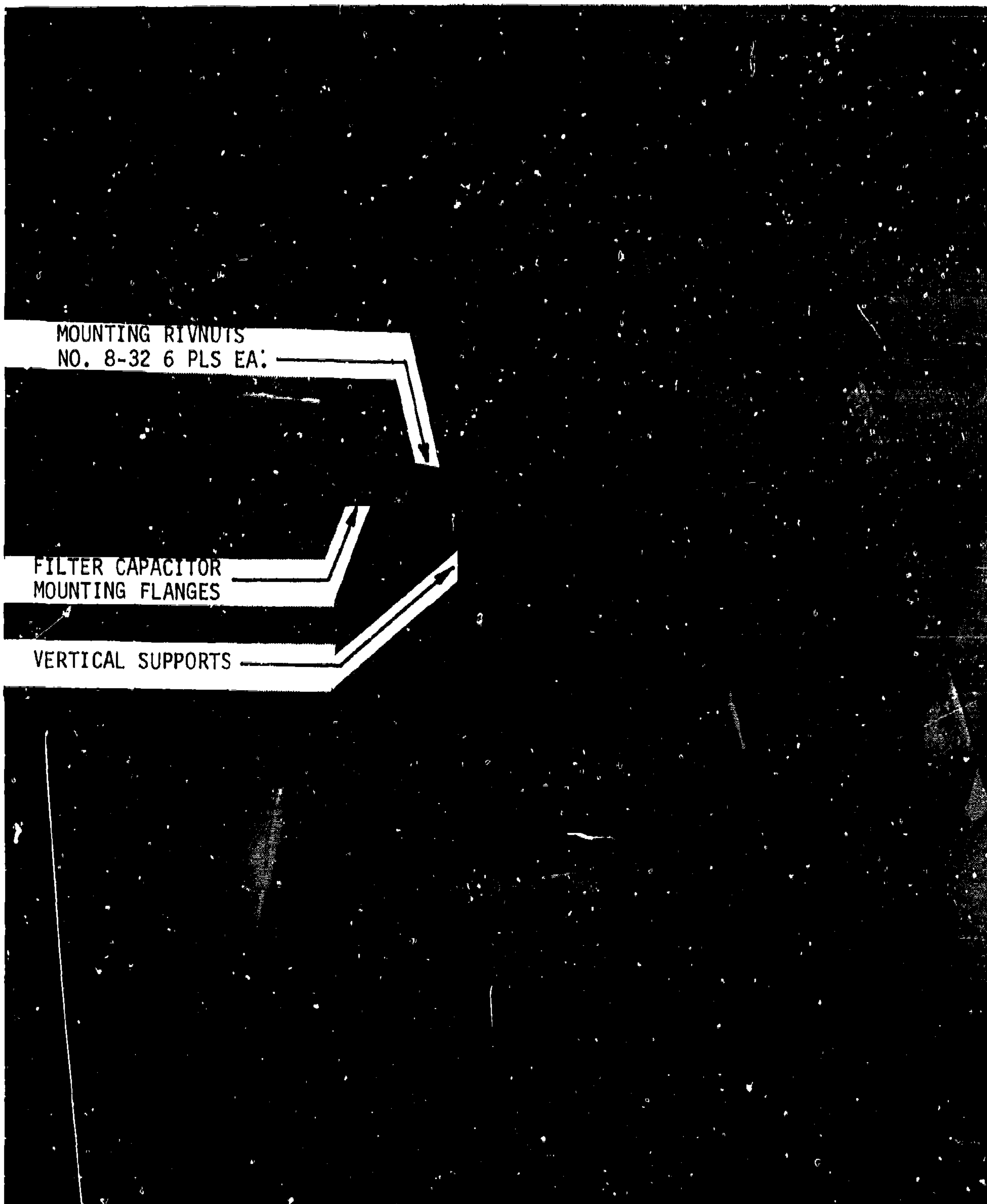


Figure 53. Dip-Brazed Chassis Original Configuration

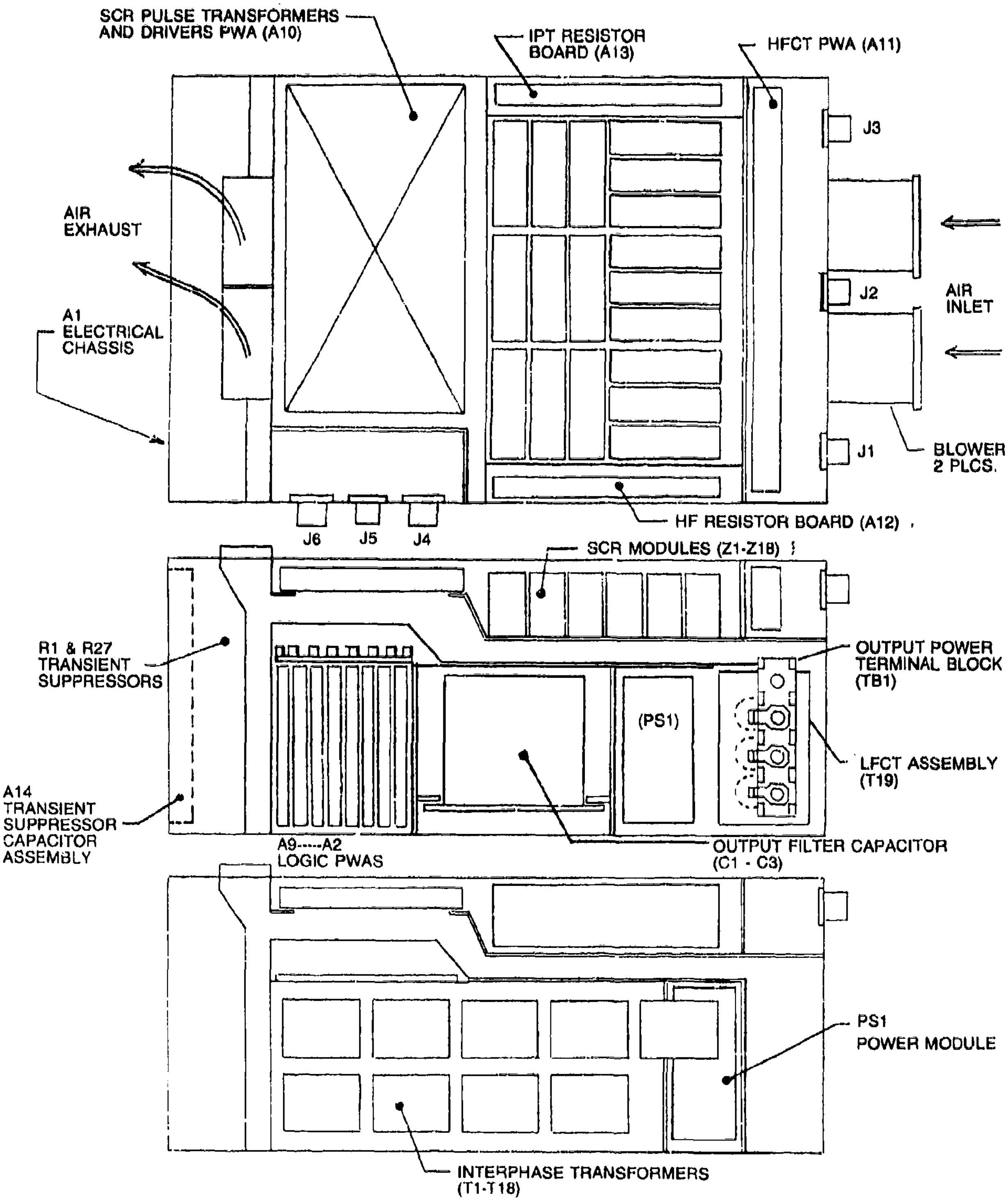


Figure 54. 60-KVA VSCF PMG Subassembly Location

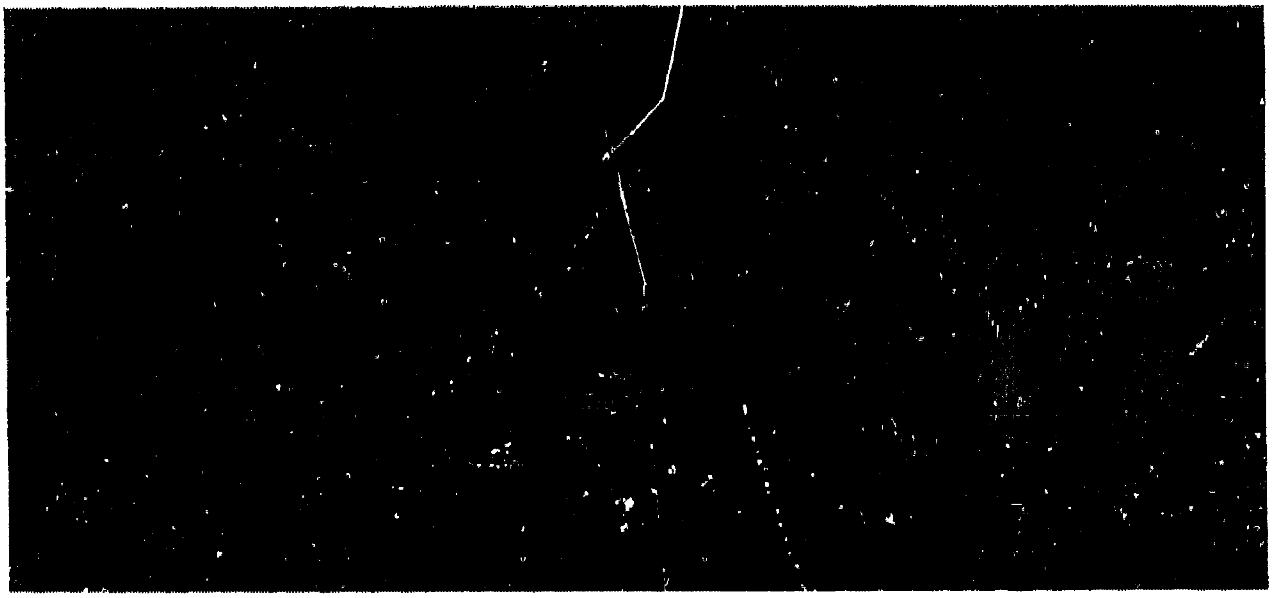


Figure 55. Interphase Transformer (IPT)

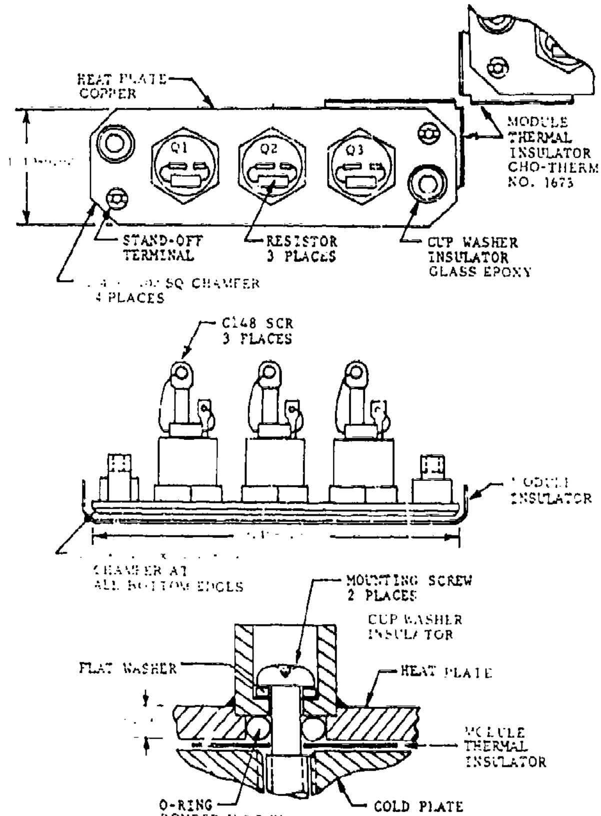
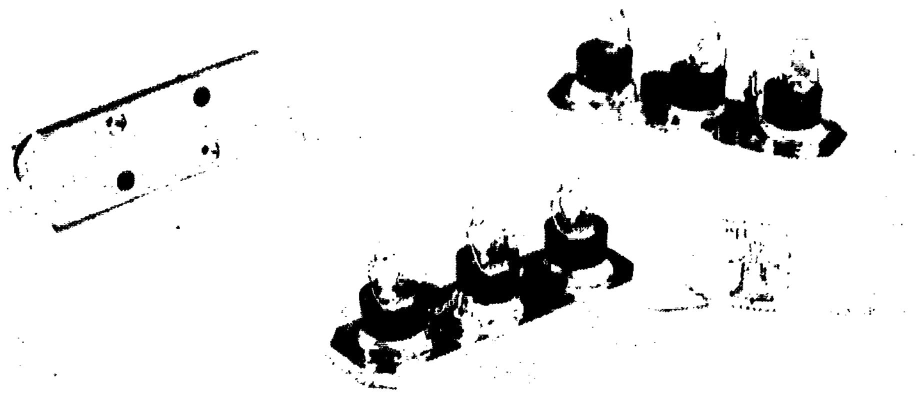
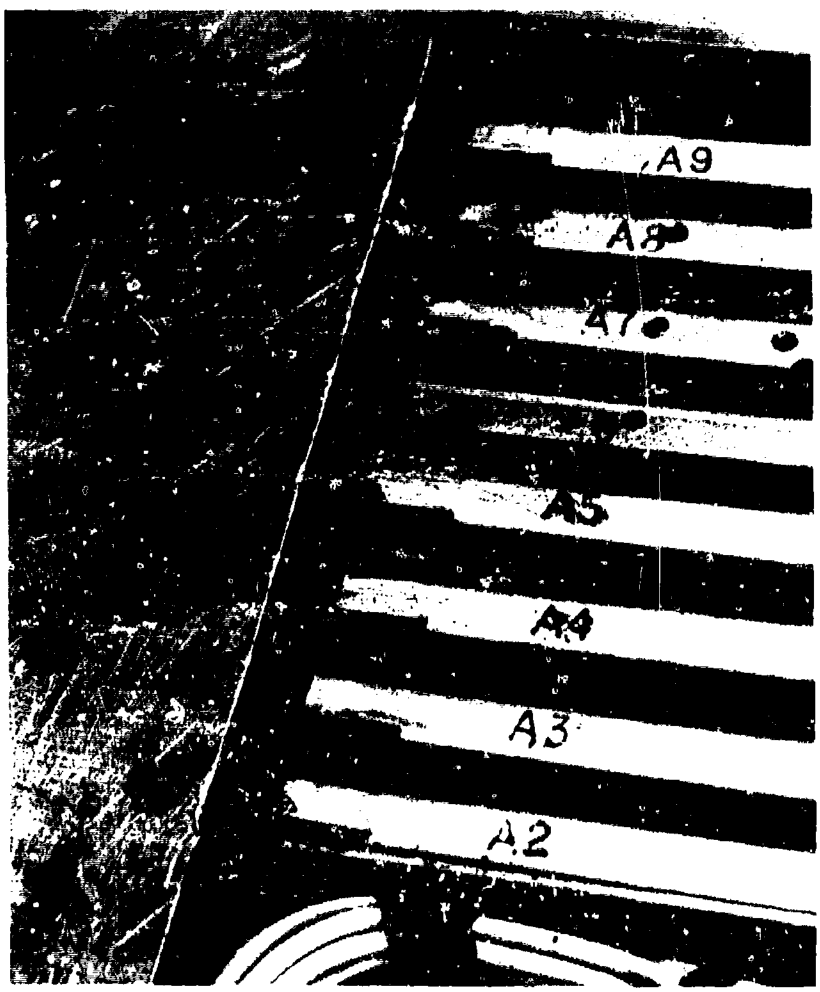


Figure 56. SCR Modules (Z1 Through Z18) Original Production Design



29657

Figure 57. SCR Module, Final Production Design



31532

Figure 58. Control Logic Board Installations

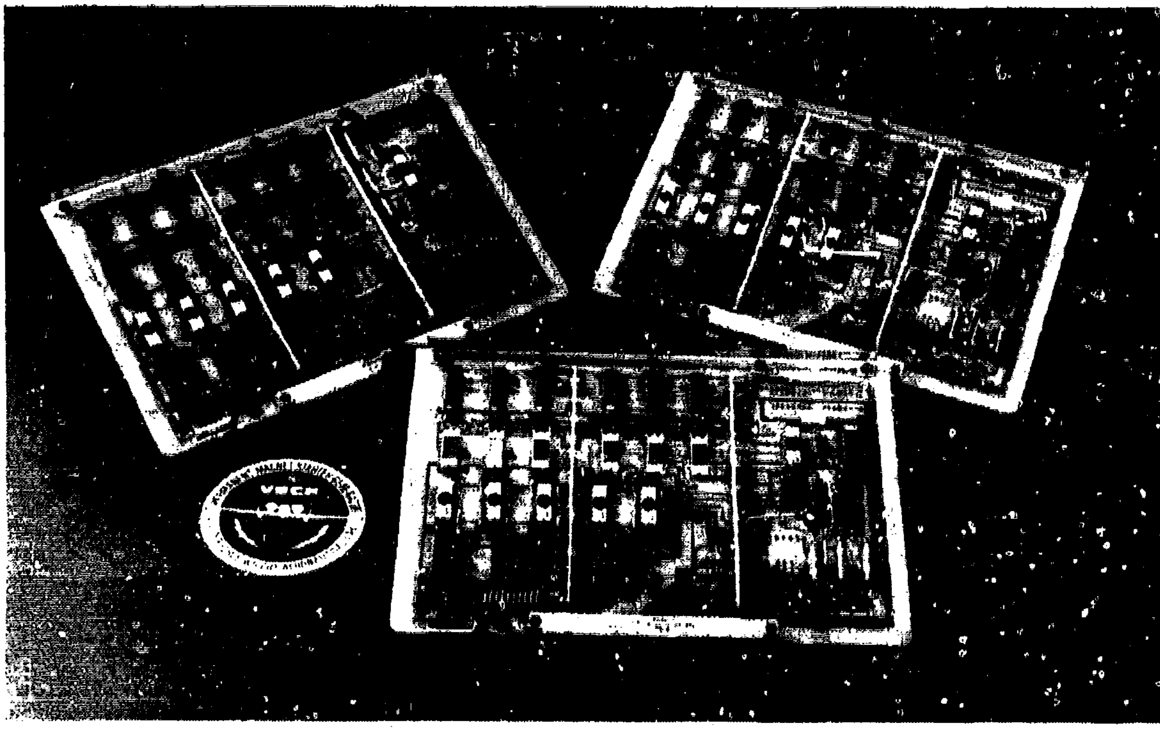


Figure 59. Control Logic Boards 29507

2.3.1.4 Gate Drive Board, A10

The gate drive board consists of 54 identical circuits that are flow soldered to a double-sided glass epoxy circuit board and conformal coated for environmental protection, see Figure 60. Wires from the gate drive board to each SCR are twisted pairs for EMI noise immunity. This board is hard mounted to the electrical chassis. The modulator signals, 28-volt signal, and ground connections all interface the A10 board via two 30-pin MIL-C-55302 connectors.

2.3.1.5 High-Frequency Current Transformer Assembly, A11

The A11 assembly consists of a double-sided printed circuit board with the torrodial current transformers, resistors, and diodes required for sensing current from the generator, see Figure 61. This board is also conformal coated for environmental protection and is hard mounted to the electrical chassis.

2.3.1.6 High-Frequency Resistor Board, A12

The A12 module is a double-sided printed circuit board with 18 metal film resistors, which is conformal coated for environmental protection, see Figure 62. This board is hard mounted to the electrical chassis with wire tie points to interface the chassis wire harness.

2.3.1.7 IPT Resistor Board, A13

The A13 board is a double-sided printed circuit board with 18 metal film resistors, which is conformal coated for environmental protection, see Figure 63. This board is hard mounted to the electrical chassis with wire tie points to interface the IPT wire harness.

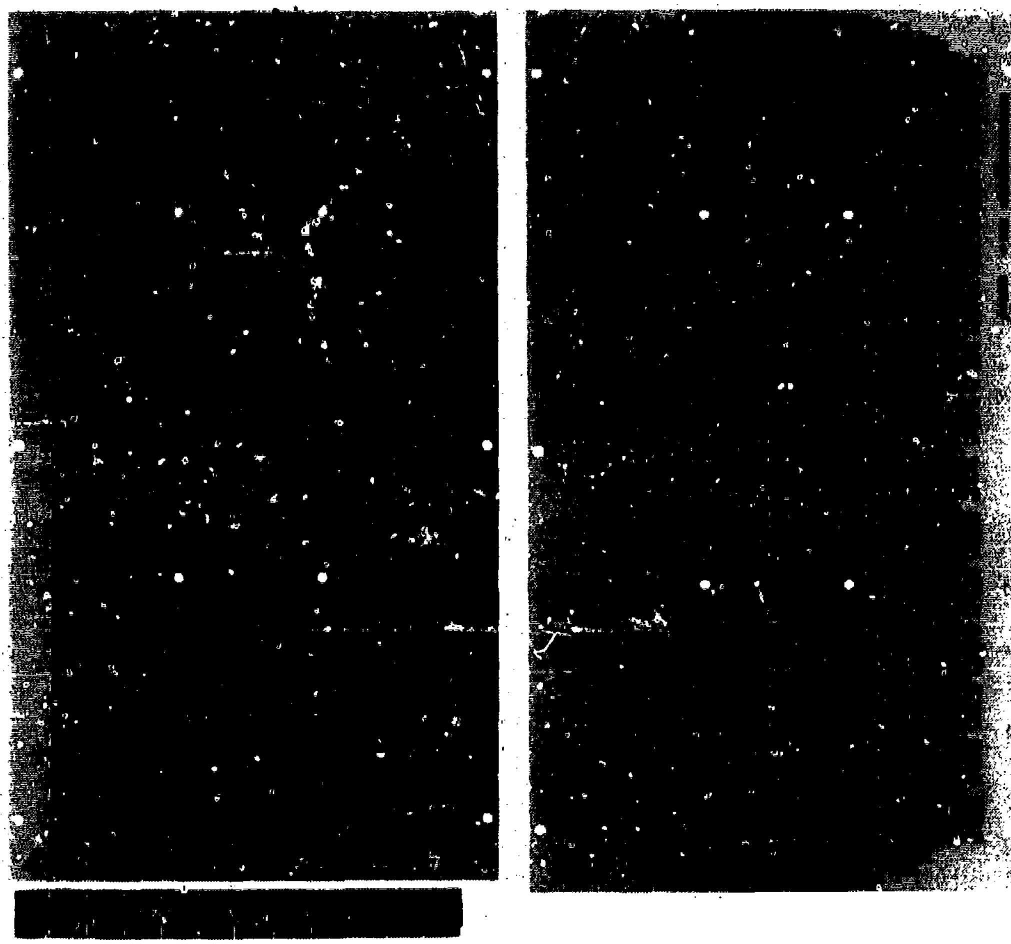


Figure 60. Gate Drive Board, A10 29512

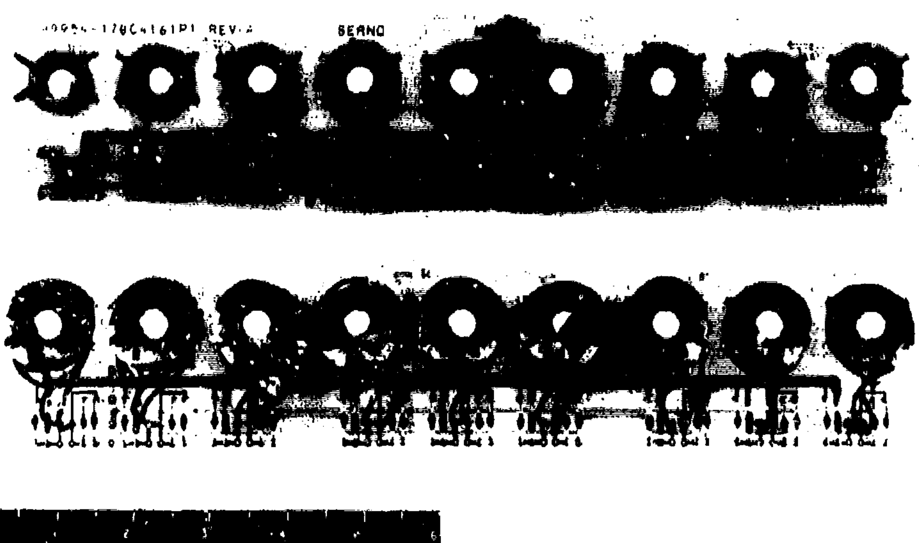
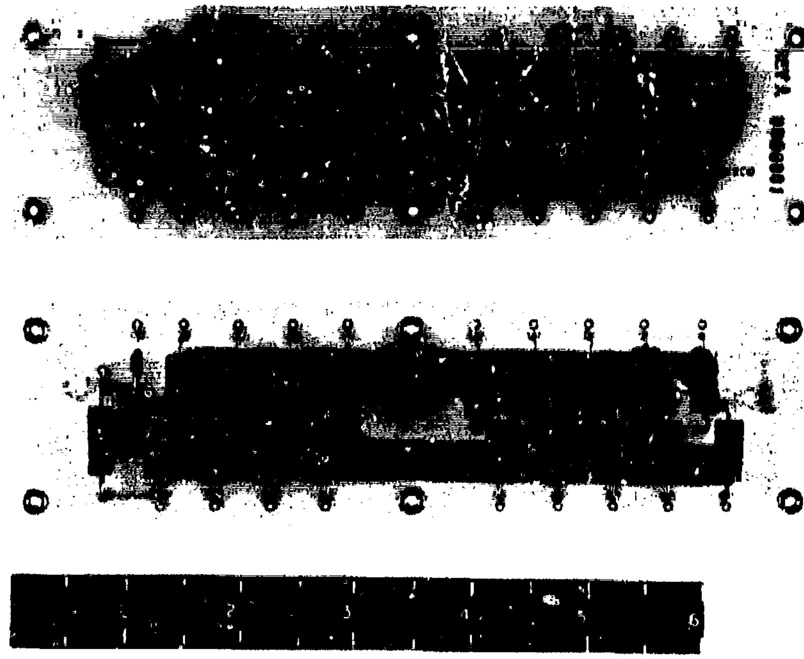
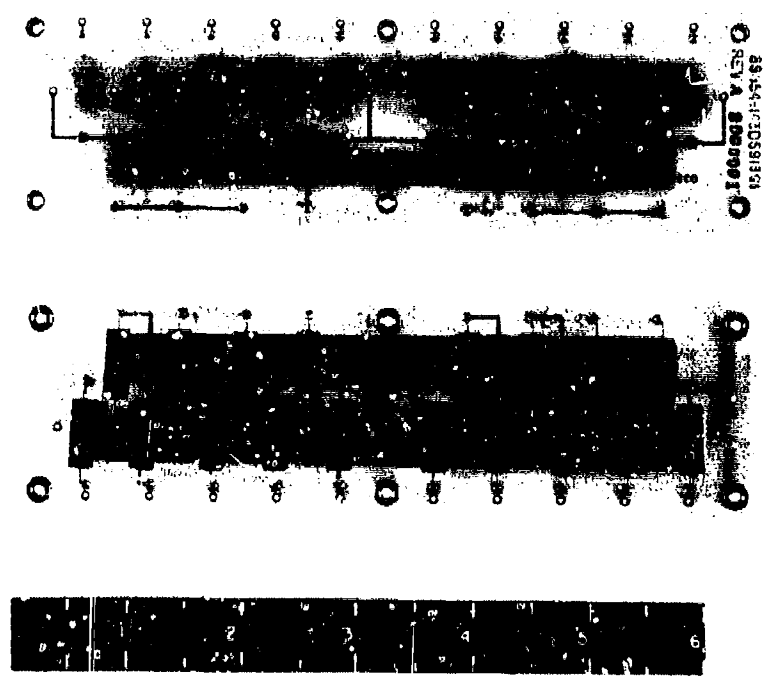


Figure 61. High-Frequency Current Transformer Assembly, A11 29523



29511

Figure 62. High-Frequency Resistor Board, A12



29509

Figure 63. IPT Resistor Board, A13

2.3.1.8 Transient Suppressor Capacitors, A14

The A14 capacitors are potted to the rear panel with RTV epoxy to reduce vibration failures associated with metal capacitor clips, see Figure 64. The capacitor leads are soldered to screw type stand-offs to provide electrical interface to the converter.

2.3.1.9 Output Filter Capacitors, C1-C3

Each filter capacitor is a 240 uF, polysolfone type enclosed in a can, see Figure 65. There are four terminals on the top, two for the input and two for the output of these feed-through type capacitors.

2.3.1.10 Low-Frequency Current Transformer Assembly, T19

This assembly combines the output terminal block with the load sensing and differential loop protection transformers in a watertight, sealed unit, see Figure 66. Copper links provide connection from the terminal block through the current transformers, and internal to the converter for the phase and ground terminations.

2.3.1.11 Power Supply Module, PS1

The power supply consists of a bent up aluminum chassis with power electronics, magnetics, and a double-sided printed circuit card mounted on it, see Figures 67 and 68. The chassis has rails on the side for Birtcher guide mounts and a MIL-C-24308 chassis connector that blind mates to the electrical chassis upon insertion of the power supply module. Plastic handles are provided for ease of insertion/removal of this module.

2.3.1.12 Air Blower, B1-B3

Each fan has a 3ϕ, 200-V, 400-Hz motor and is capable of delivering 100 cfm of air with a static pressure of 3.5 inches of water, see Figure 69.

2.3.1.13 Generator Power Connectors J1, J2, J3

These connectors carry the wild frequency nine-phase generator power and are MIL-C-38999, Series III type. They have 11 #12AWG pins in each connector, providing three pins per phase and six pins for the generator neutral total.

2.3.1.14 Converter Interface/Test Connectors J4, J5, J6

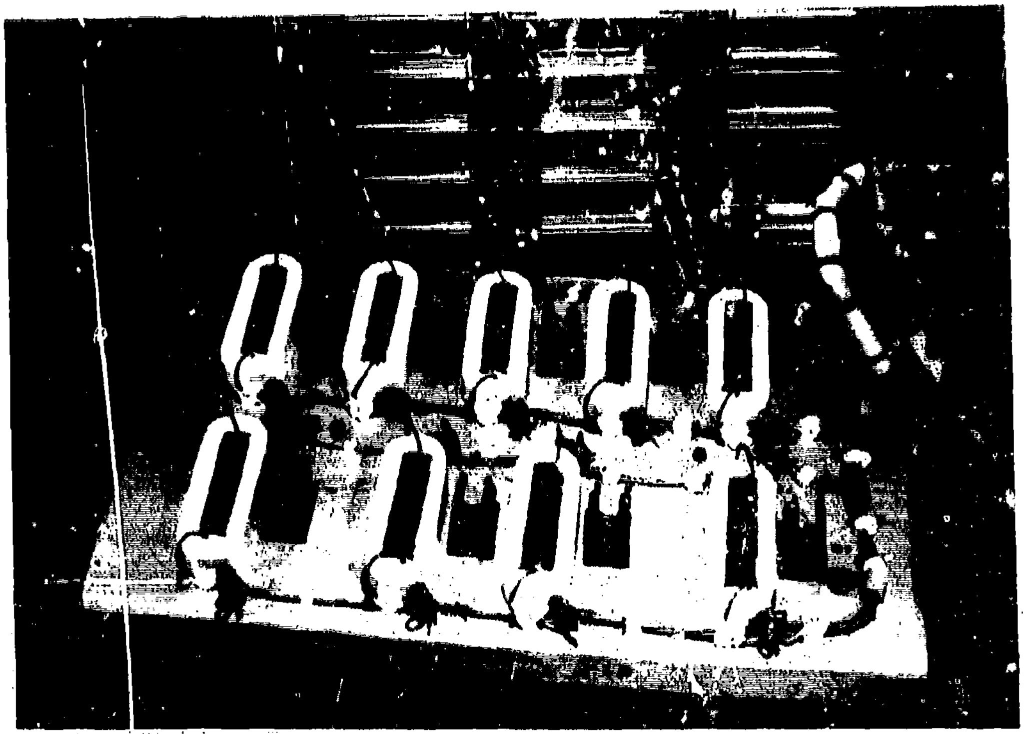
These connectors are all MIL-C-38999, Series I type, with J4 being the generator control and sensing connector. The aircraft interface connector, J5, is of the filter-pin type. The converter test connector, J6, is normally capped.

2.3.2 CONVERTER LOSSES

The converter losses as a function speed are given in Figure 70.

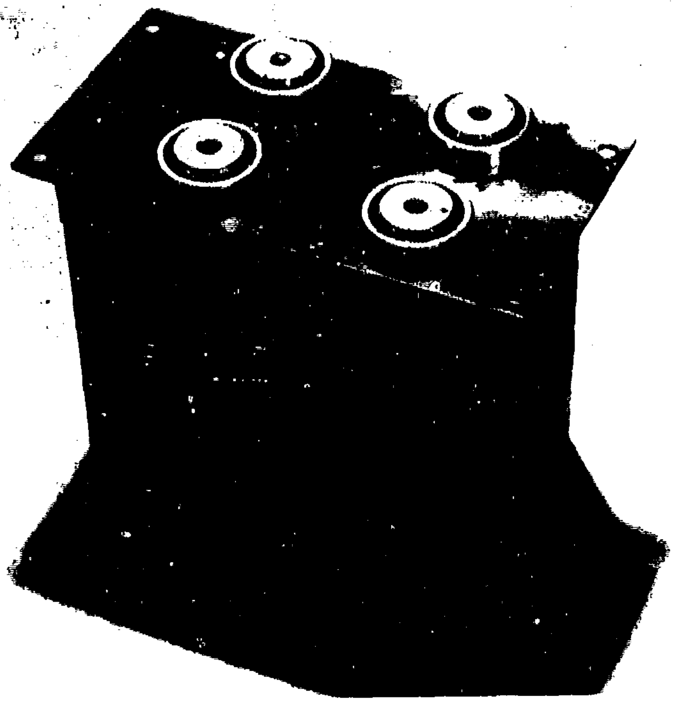
2.3.3 CONVERTER WEIGHT AND VOLUME

The weight breakdown for the converter is given in Table 6. The total converter volume was 2,750 in^3, with the outline dimensions shown in Figure 71.



32751

Figure 64. Transient Suppressor Capacitor Assembly, A14



32901

Figure 65. Output Filter Capacitor

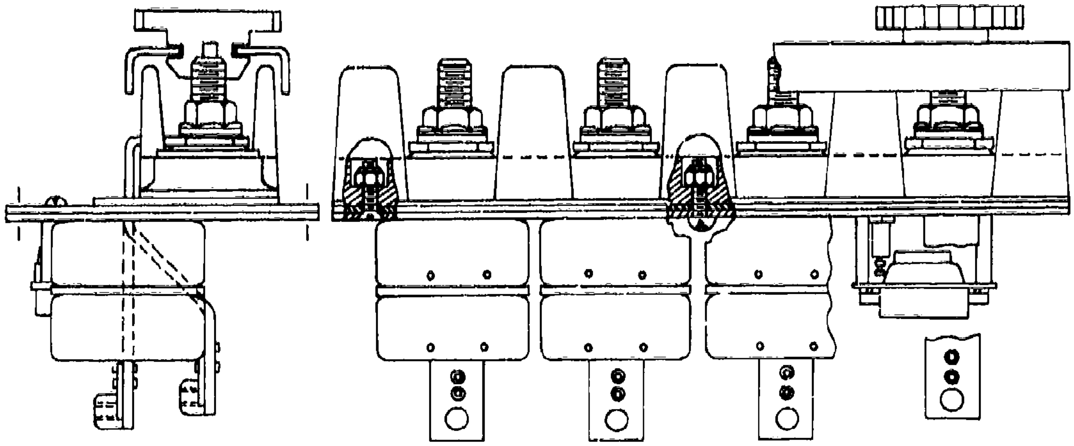


Figure 66. Low-Frequency Current Transformer Assembly

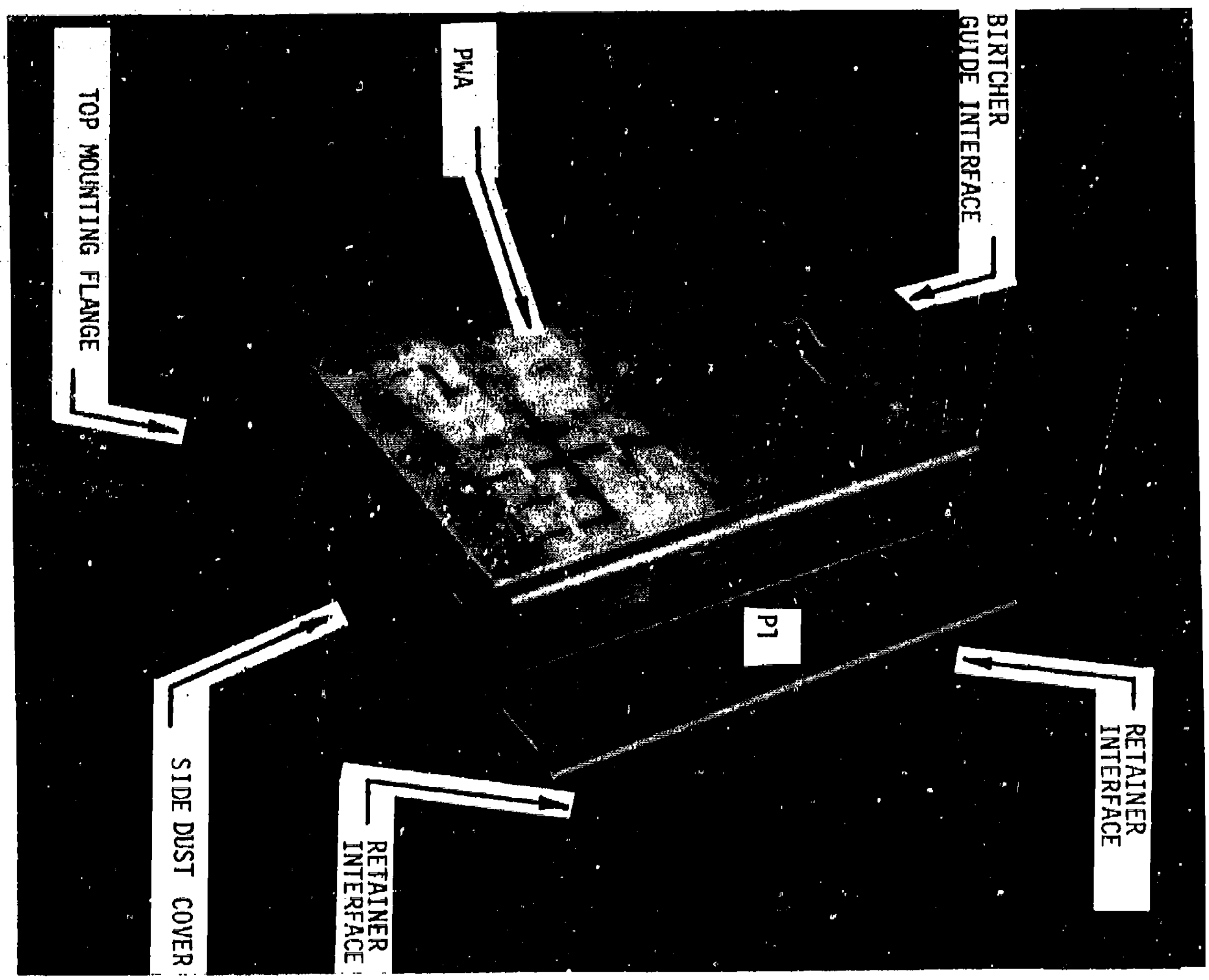
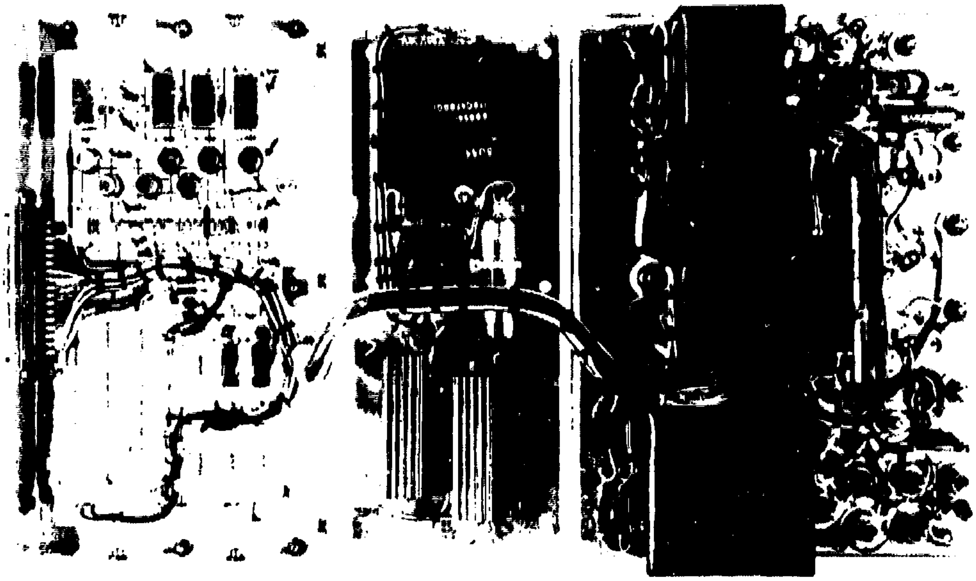
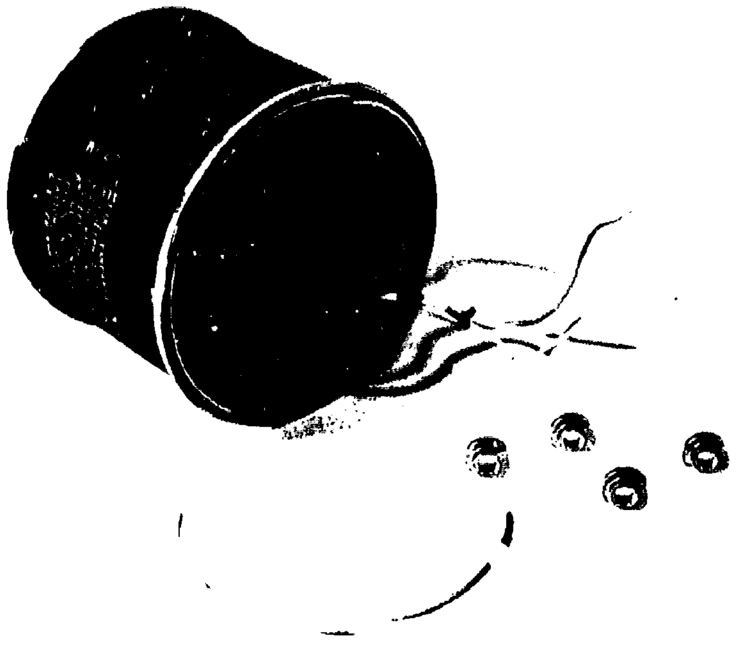


Figure 67. Logic Power Supply (PS1) Assembly



29817

Figure 68. Logic Power Supply Assembly



31590

Figure 69. Air Blower

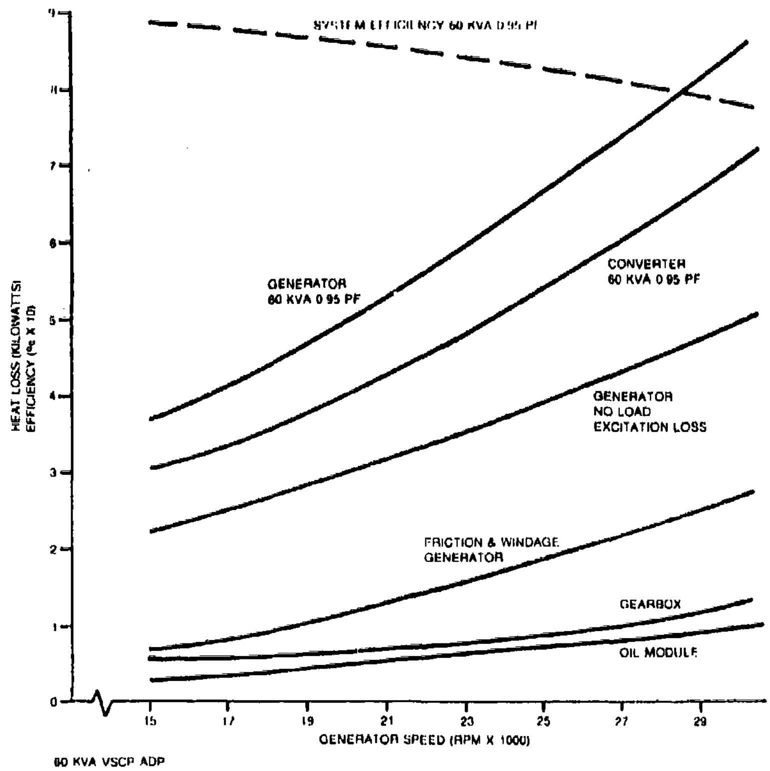


Figure 70. System Efficiency and Loss Breakdown Versus Generator Speed

TABLE 6
CONVERTER WEIGHT BREAKDOWN

	Weight (lbs.)
Logic Assemblies (A1 through A9)	5.462
MFCT (A10)	0.657
Pulse Transformers (A11)	1.819
Resistor Network Board (A12)	0.175
IPT Resistor Assembly (A13)	0.109
Power Supply (PS1)	1.226
Power Supply (PS2)	3.981
IPTs (T1 through T18)	14.400
LFCT Assembly (T19)	0.736
Filter Capacitors (C1 through C3)	15.980
SCR Module (Z1 through Z18)	3.996
Transient Suppressors	2.870
Chassis	10.036
Covers	4.270
Harnesses	4.500
Contactor	0.850
Electric Chassis	3.334
Blower Fans	2.700
Miscellaneous Hardware	2.799
Total Weight	79.900

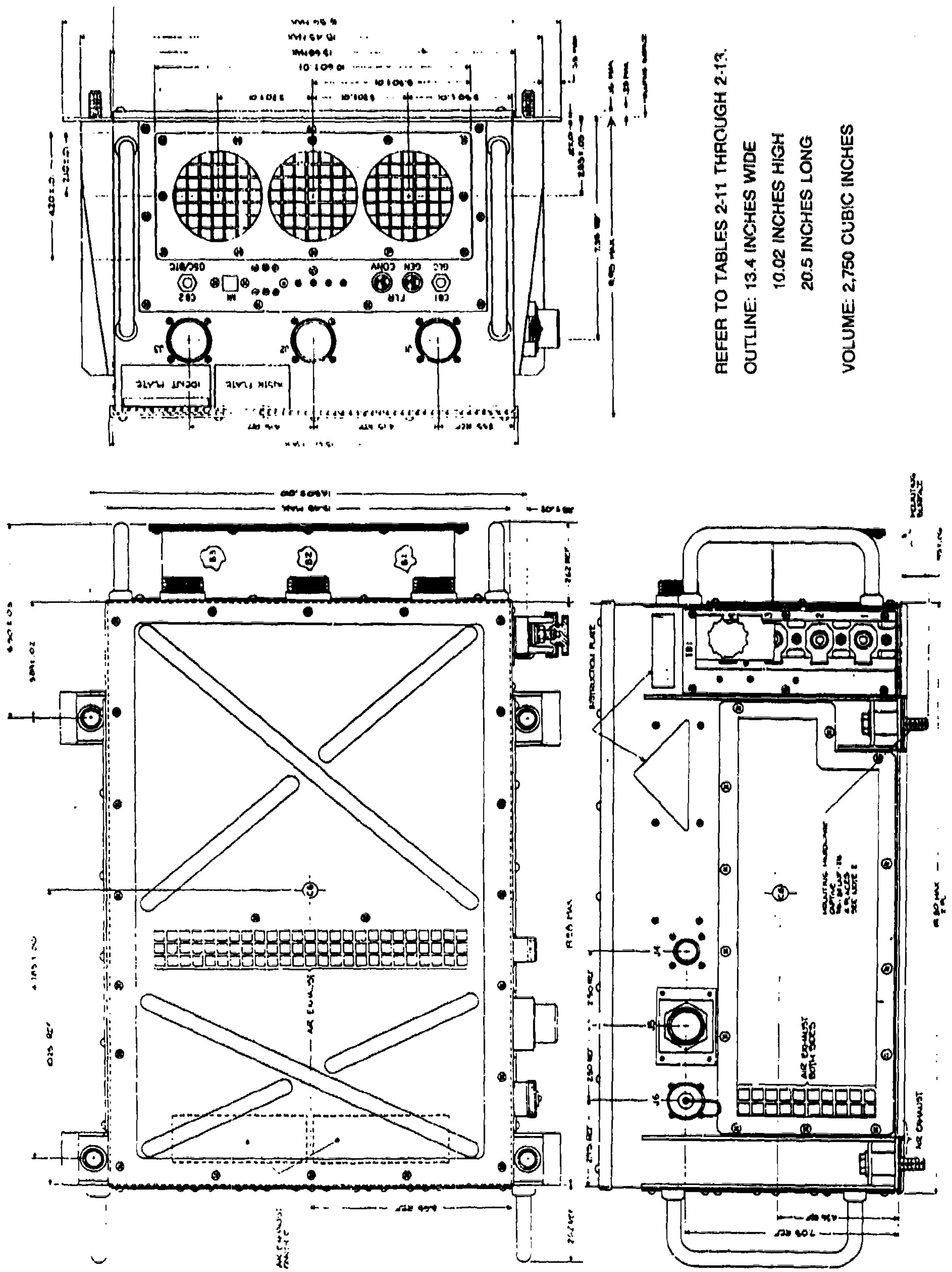


Figure 71. 60-KVA VSCF PMG ADP Converter, Outline Configuration After the Thermal Redesign: EMI and Vibration Qualification Test Design Modifications

2.3.4 AIR FLOW/THERMAL DESIGN

The SCRs and IPTs are the major heat generating elements in the converter. The size of the fan and the air-flow paths, shown in Figure 72 and 73, were determined to provide maximum cooling of the SCR heat-sink plate and the IPT banks.

2.3.4.1 Blower Selection

To ensure that the flow distribution is not affected by the operating differences between fans, several fans were evaluated, using the test setup shown in Figure 74, and fans with identical air displacement capabilities were selected.

2.3.4.2 Converter Operating Temperature

An extensive laboratory test was conducted to determine the temperatures of the SCRs, IPTs, and other electronic components in the converter under various operating conditions, which was based on a 30/40 KVA rating for a sea level, self ventilated mode.

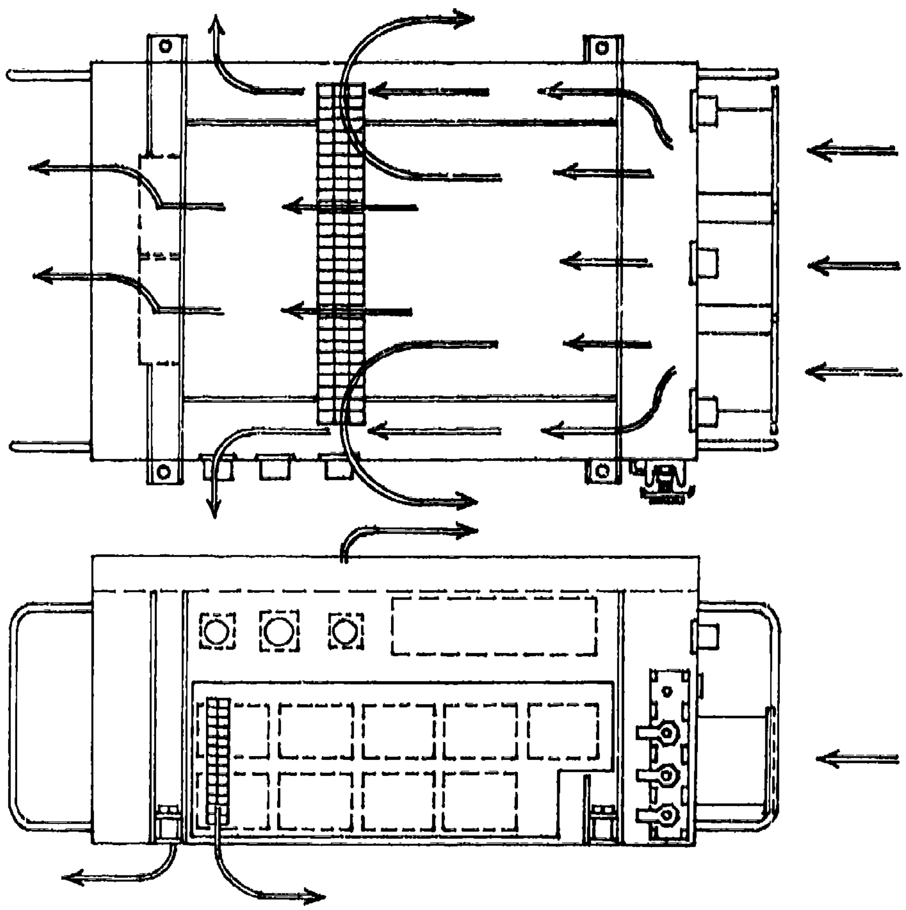


Figure 72. Converter Air Flow Paths, Final Three-Fan Air Flow Design

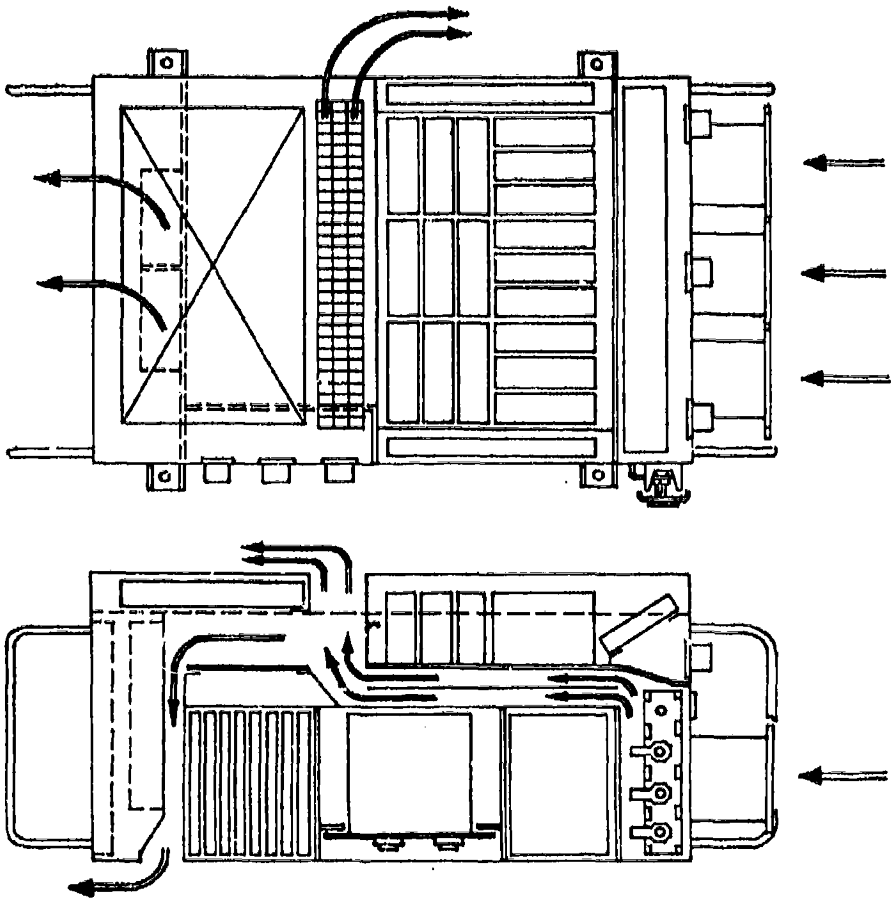


Figure 73. Converter Air Flow Paths, Final Three-Fan Air Flow Design

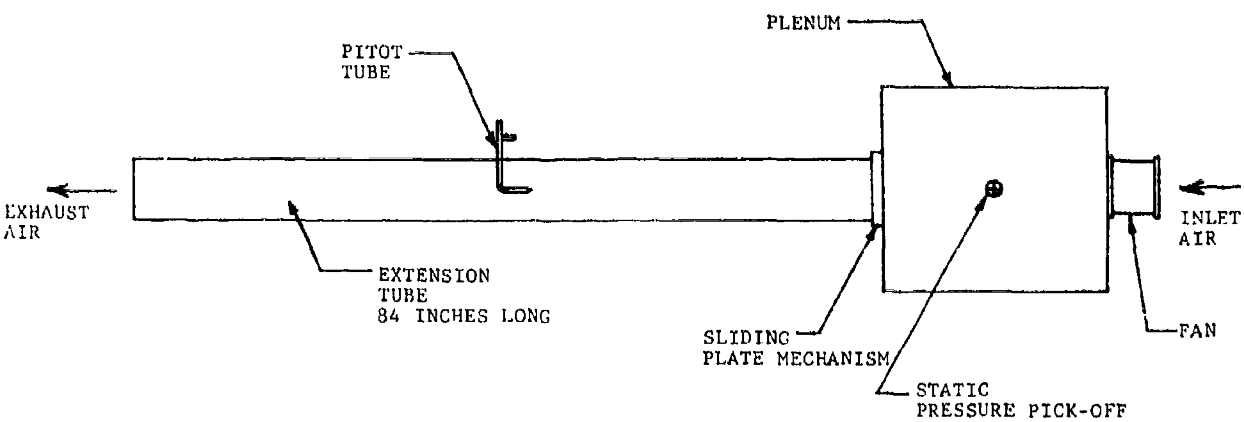


Figure 74. Blower Selection Test Setup

During this test, the converter was also operated in the worst-case conditions, and the stabilized temperatures were recorded.

Test results indicated that, at the continuous rated condition as well as the overload transients, the operating temperatures were within the acceptable levels.

The converter thermal design, therefore, was considered to be adequate in meeting the specification requirements of the 60-KVA Advanced Development Program.

2.3.4.2.1 Test Setup

Upon successful completion of alignment test, the converter was instrumented for thermal testing. Thermocouples were bonded into position, using a highly conductive material to ensure accuracy and consistency. The position of the thermocouples is shown in Figure 75 and 76 and listed in Table 7.

All tests were conducted in the laboratory environment. The temperatures were continuously monitored and recorded at one-minute intervals using a Data Requisition System.

2.3.4.2.2 Test Results

The steady-state temperatures, adjusted for 50°C maximum inlet cooling air, are listed in Table 8. It is apparent that the hot spots were in the T14 IPT coils but were well within the allowable limits.

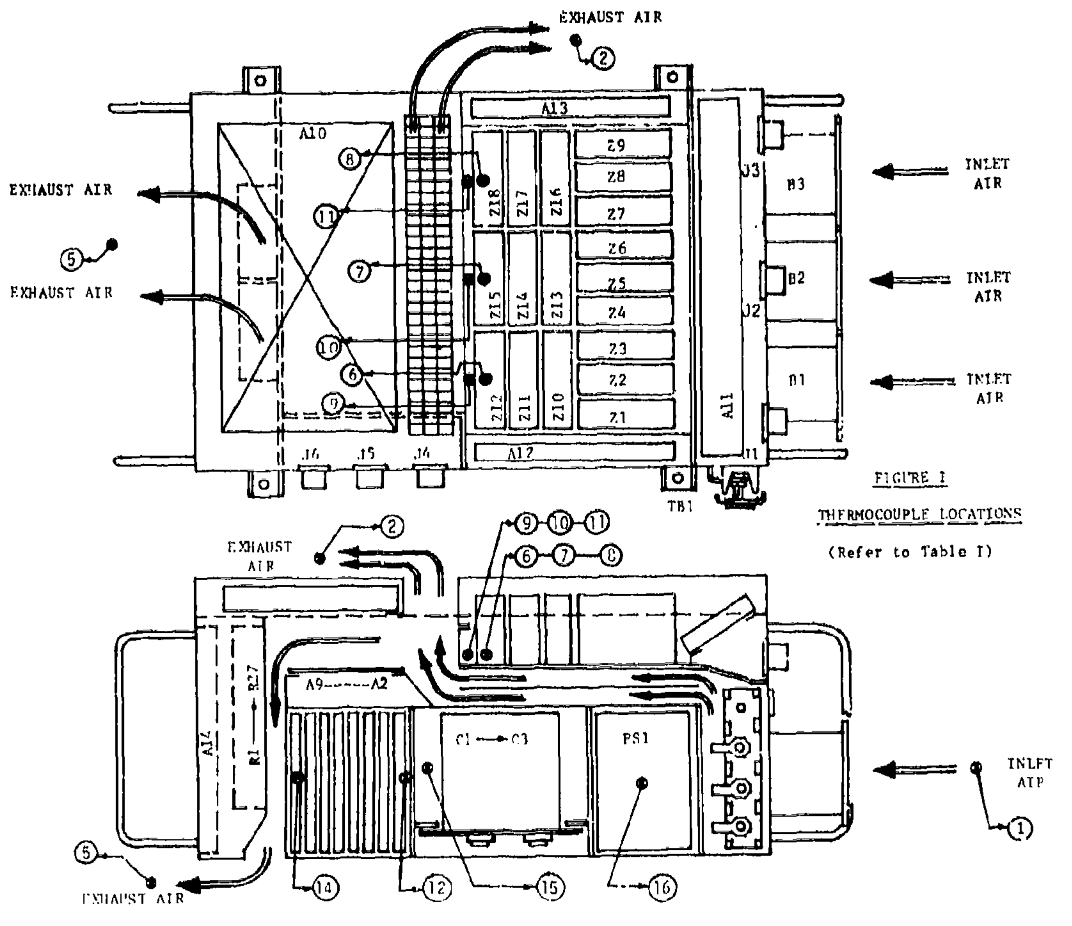


Figure 75. Laboratory Test, Thermocouple Locations

TABLE 7
THERMOCOUPLE LOCATIONS

Thermocouple Number	Description	Location
1	Air In	Centered Inside Inlet Plenum
2	Air Out	Top Cover—Cold Plate Exhaust
3	Air Out	Right Side Cover—T10 Through T18 Exhaust
4	Air Out	Left Side Cover—T1 Through T9 Exhaust
5	Air Out	Bottom Cover—A10 and TS Exhaust
6	SCR Heat Sink	Z12-Q2 Base
7	SCR Heat Sink	Z15-Q2 Base
8	SCR Heat Sink	Z18-Q2 Base
9	Cold Plate-SCR	Aft of Z12-Q2
10	Cold Plate-SCR	Aft of Z15-Q2
11	Cold Plate-SCR	Aft of Z18-Q2
12	A2 PWA Ambient	Center of Volume
13	T18 IPT Coil	Center—Between Coils
14	A9 PWA Ambient	Center Volume
15	C1, C2, C3 Ambient	Center—Aft Area
16	PS1 Internal Ambient	Center of Volume
17	T5 IPT Coil	Center—Between Coils
18	T9 IPT Coil	Center—Between Coils
19	T14 IPT Coil	Center—Between Coils

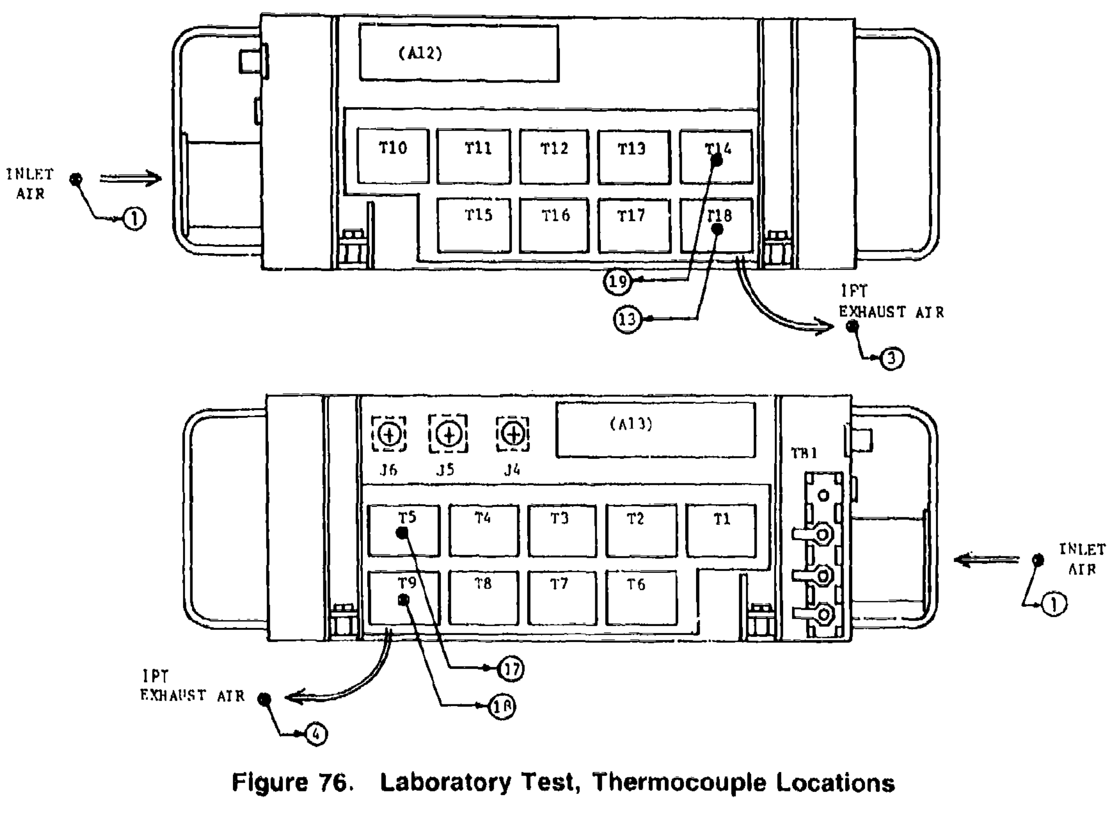


Figure 76. Laboratory Test, Thermocouple Locations

TABLE 8
TEMPERATURE PROFILES ADJUSTED FOR 50°C MAXIMUM INLET AIR

(TEMPERATURES IN °C)

TEST	OPERATING CONDITION	THERMOCOUPLE 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	60 KVA .95 PF 1350 HZ	50	64	76	81	67	79	79	82	74	73	75	63	150	63	61	53	165	150	158
2	60 KVA .95 PF 1650 HZ	50	64	80	84	70	81	80	87	75	74	79	61	156	62	59	51	182	153	163
3	60 KVA .95 PF 1950 HZ	50	66	84	88	73	82	83	93	76	76	83	62	160	65	60	52	195	158	169
4	40 KVA .95 PF 1350 HZ	50	59	64	68	61	69	69	71	66	65	67	58	96	59	58	53	109	102	105
5	40 KVA .95 PF 1650 HZ	50	60	67	72	64	70	71	75	67	66	70	59	101	61	58	53	119	107	112
6	40 KVA .95 PF 1950 HZ	50	62	72	77	68	74	74	82	69	69	75	59	110	61	58	53	135	117	123
7	40 KVA .95 PF 2250 HZ	50	63	73	78	69	75	75	85	71	70	77	60	112	63	58	54	140	120	126
8	40 KVA .95 PF 2500 HZ	50	65	78	82	73	79	79	95	73	74	84	59	123	63	58	54	157	129	135
9	45 KVA .95 PF 2500 HZ	50	67	81	85	75	81	81	98	75	76	88	60	130	64	59	54	168	137	142
*	60 KVA .95 PF 2500 HZ	50	80	95	101	84	99	99	103	92	91	93	78	187	78	76	66	218	187	181

* SCALED UPWARD FOR TOP SPEED OF 2500 HZ; REFER TO FIGURE IV.

2.4 START FILTER DESIGN

A photo of the start filter, designed for the A-10 application, is shown in Figure 77. Basically, the start filter has two functions. The first function is to act as a parallel, three-phase filter on the 400-Hz start tie bus. Without this filter, the 400-Hz harmonic content on the load bus would exceed the allowable 8% during start modes. The second function of the start filter is to modify the relay logic on the A-10 airplane to facilitate electric starting.

This is accomplished via a relay that is controlled by the pilot's start mode select switch located on the pilot's right console. When operated, this relay removes the air start valve from the starting system and allows the electric start system to operate.

The impedance of the start filter and the output capacitor, as a function of frequency, is shown in Figure 78.

Figure 77. Electric Start Filter

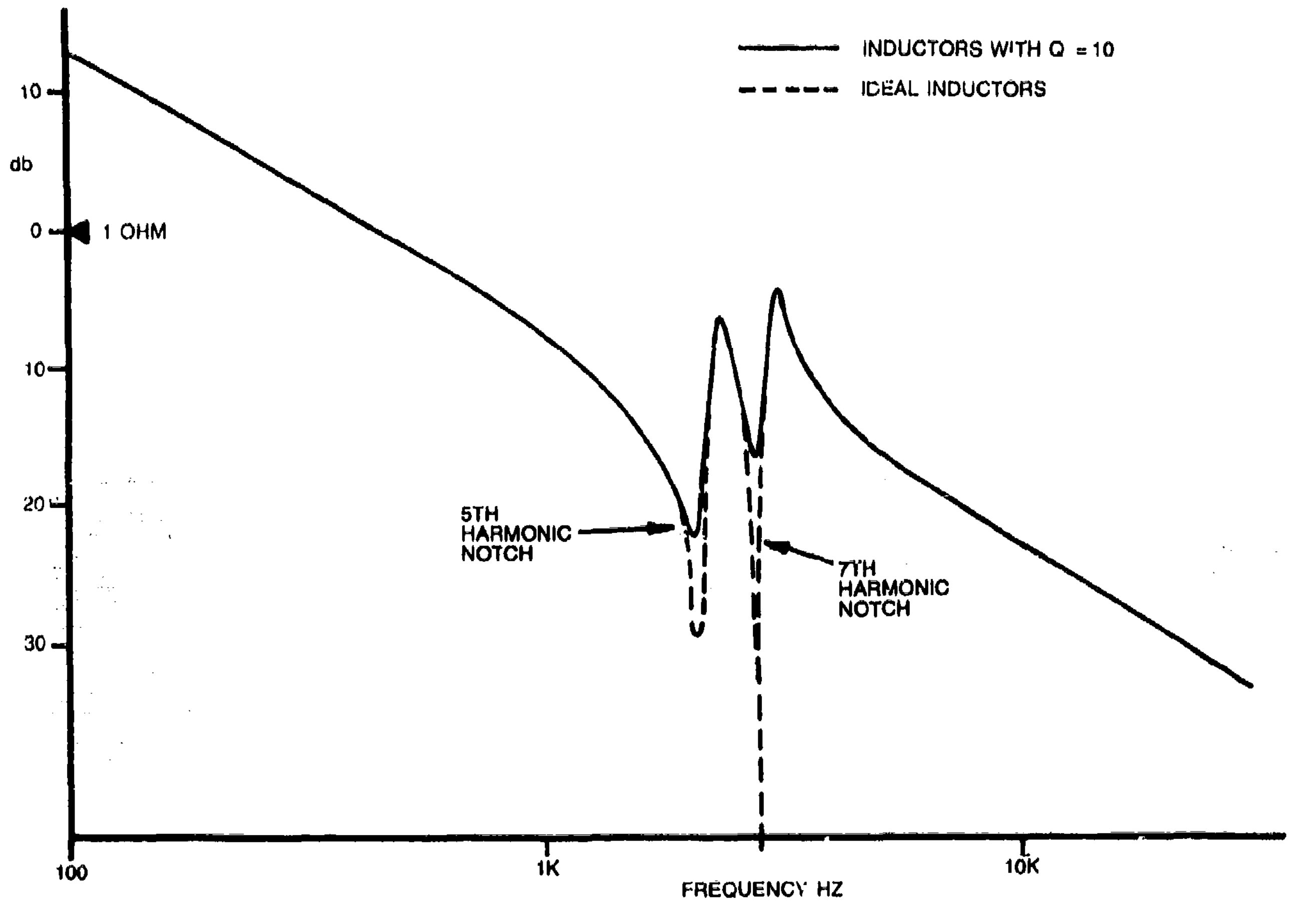


Figure 78. Impedance of Start Filter and Output Capacitor

Section 3
System Testing

3.1 PRODUCTION TESTING

3.1.1 CONVERTERS

When assembly of the converters was complete, an alignment test was performed. This test contained several circuit check-outs before any power was applied. When the converter was energized, it was brought up gradually to full power. Alignment test is meant to weed out most of the failures. Any failures that are not detected in the alignment test are caught in the acceptance test. The acceptance tests had government surveillance. Any failures found in acceptance tests were documented, and corrective action was taken, if appropriate. The acceptance test included an 80-hour burn-in test, which consisted of operation at temperatures between -55 °C and 50 °C, loads up to 40 KVA, and vibration.

3.1.2 GENERATORS

Upon completion, generators were required to pass a performance test that included a high-potential dielectric test and a 10 percent overspeed. Generators were then tested at the system level in the acceptance test discussed previously.

3.2 QUALIFICATION TESTING

A full description of the preflight qualification testing program can be found in the first and second qualification test reports, dated September 1983 and January 1984. What follows is a brief summary of each test.

3.2.1 GENERATOR VIBRATION

3.2.1.1 Specification Requirement

The following specifications were levied on the generator:

- MIL-E-23001/POP, paragraph 4.5.6
- MIL-STD-810B, Change 4, Method 514, Procedure I, at room temperature except

5-10 Hz	0.08 DA
10-15 Hz	± 0.41g
15-74 Hz	0.036 DA
75-500 Hz	± 10g

Resonances at ± 6.5g   Resonance dwell—30 minutes
Sinusoidal cycling—3 hours less dwells
Sweep time—15 minutes

- A-10 critical item specification 1605414001A, paragraph 3.2.5.9

3.2.1.2 Results

Based on the test/inspection data that were taken prior to, during, and after the generator vibration test, the 2CM436A1 starter-generator met the requirements which are outlined in the specification section 3.2.1.1, contained herein.

3.2.1.3 Discussion

The test plan included vibration in each of the three mutually perpendicular planes in the following orders: vertical, lateral, and longitudinal.

In these tests, the generator was run in the start mode with a 400-Hz supply hooked up to the converter. A photo of the test setup in the lateral plane is shown in Figure 79.

In the first test run, there was no load on the generator shaft for all three axes. For each plane, a resonance search was performed from 5 to 500 Hz with the level of vibration being 6.5 g maximum.

Following the resonance search, the generator was cycled in each of the three mutually perpendicular planes for three hours, less resonance dwell. No problems were observed in the vertical and lateral axes. After 1.5 hours into the longitudinal axis—at approximately 180-200 Hz on the sweep up in frequency—the generator gearbox disconnect operated. The disconnect operated at this point each time for the remainder of the longitudinal vibration test. The generator was disassembled and tested, and no problems were found.

Following examination in Erie, Pennsylvania, the generator longitudinal vibration test was rerun, using shaft loading. A 30-hp motor was used as the load. The disconnect did not trip during this retest.

3.2.2 CONVERTER VIBRATION

3.2.2.1 Specification Requirement

The following specifications were levied on the converter vibration testing:

- MIL-E-23001/POP, paragraph 4.5.7
- MIL-STD-810C, Method 514.2, Category b.2, Procedure IA, with spectral density per Figure 7 of MIL-E-23001/POP, as modified by Sp11N PO 0011, dated 15 December 1982, which gives levels of:
  - Design $0.034\ g^2/Hz$
  - Endurance $0.13\ g^2/Hz$

3.2.2.2 Results

Based on the test/inspection data that were taken prior to, during, and after the 3S2060DF141A1 converter was subjected to vibration testing, the vibration requirements were not fully met. The test consisted of vibration in each of the three mutually perpendicular axes for two hours of random vibration and one hour of gunfire vibration per axis. The test was conducted twice, due to failure modes noted in the first test.

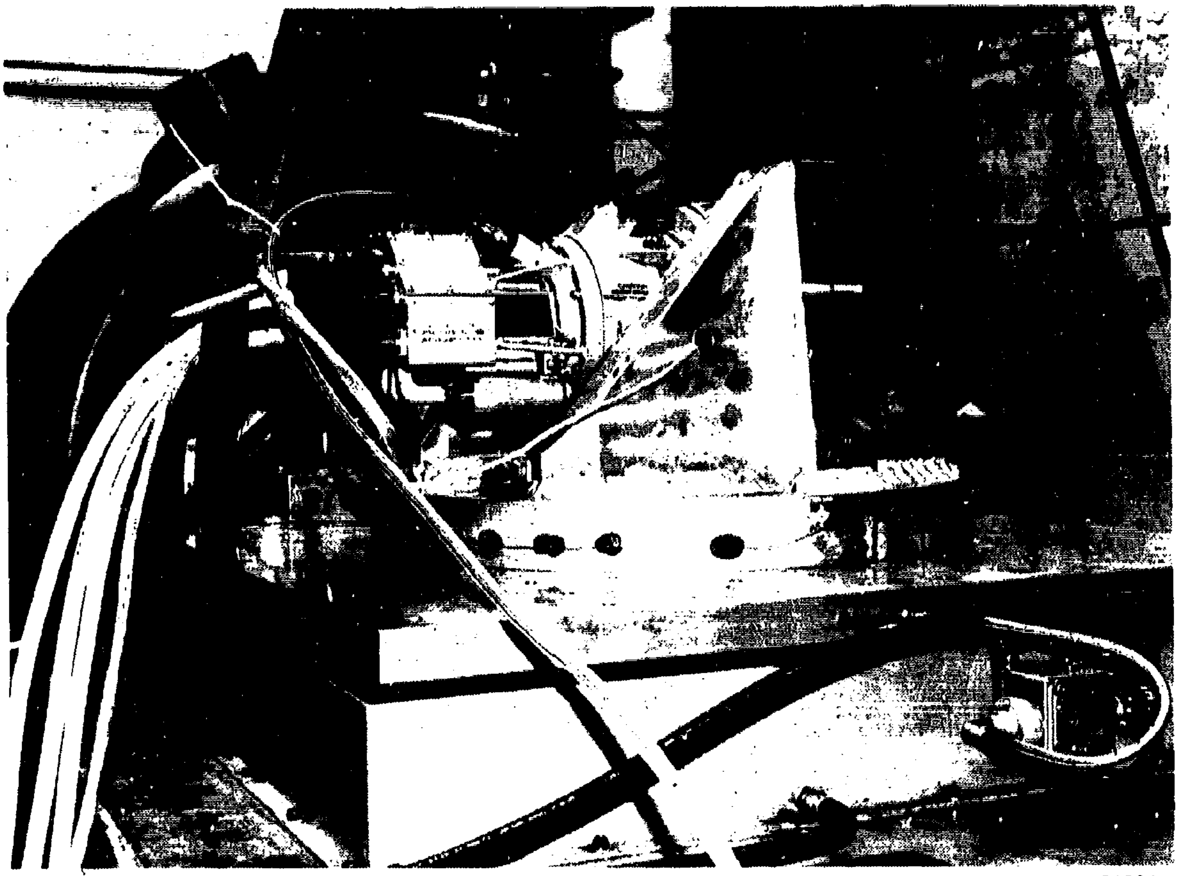


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Figure 79. Generator Vibration Test Setup

The list below shows corrective actions that were incorporated in the converter.

Vertical	**Ref. Facar**
New BIT Indicators	149420
M1 Mounting with Banding	151530
Picture Frame Support Bars	151550
Picture Frame Corner Pieces	151640
Longitudinal	
Picture Frame Corner Pieces	151640
Lateral	
Picture Frame Corner Pieces	151640

With the exception of the preceding list, all other items met the vibration requirements. The U.S. Air Force reviewed the results and approved the design for the flight test with the above changes incorporated.

3.2.3 START FILTER VIBRATION

3.2.3.1 Specification Requirement

The following specifications were levied on the electric start filter during vibration testing:

- MIL-STD-810C, Method 514.2, Category 10.2, Procedure 1A with spectral density as follows:
  - Design 0.01 g^2/Hz
  - Endurance 0.06 g^2/Hz

3.2.3.2 Results

Based on the test/inspection data that were taken prior to, during, and after vibration testing, the 937E332G1 electric start filter met the requirements of AES 14005, Rev. 03, paragraphs 4.2.3 and 3.4.

3.2.4 CURRENT TRANSFORMER ASSEMBLY (CTA) VIBRATION

3.2.4.1 Specification Requirement

The following specifications were levied on the CTA during vibration testing:

- MIL-STD-810C, Method 514.2, Category b.2, Procedure 1A with spectral densities as follows:
  - Design Random Vibration 0.034 g^2/Hz
  - Endurance Random Vibration 0.130 g^2/Hz
  - Design Gunfire Vibration 0.034 g^2/Hz
  - Endurance Gunfire Vibration 0.200 g^2/Hz

3.2.4.2 Results

Based on the test/inspection data that were taken prior to, during, and after vibration testing, the 143D6027G1 CTA met the vibration requirements.

3.2.5 WATER INGESTION

3.2.5.1 Specification Requirements

This test was conducted on the scoop, air ducts, and converters as mounted in the test aircraft. The converters were operated a minimum of ten consecutive hours. Both generators were operated at base speed. The converters were operating under no-load conditions. The air flow rate into the scoop was 400-600 cubic feet per minute. The air temperature was room ambient. The water was injected directly into the intake area of the scoop. The time periods in the following water injection table are consecutive time increments.

Time (minutes)	Water Injection Rate
10	600–700 ml/minute
240	0
30	200–700 ml/minute
150	0
30	200–240 ml/minute
90	0
10	600–700 ml/minute
40	0

3.2.5.2 Results

Based on the test/inspection data that were taken prior to, during, and after the water ingestion test, the 3S2060DF141A1 converter met the requirements outlined in the specification.

3.2.6 HUMIDITY

3.2.6.1 Specification Requirements

The following specifications were levied on the system:

- MIL-E-23001B, paragraph 4.5.7 as modified by MIL-E-23001/POP, paragraph 6.0
- MIL-E-81910, paragraph 4.4
- MIL-STD-810B, Method 507, Procedure II

3.2.6.2 Results

Based on the test/inspection data that were taken before and after the humidity cycle, the 3S2060DF141A1 converter met the specification requirements.

3.2.7 TEMPERATURE/ALTITUDE

3.2.7.1 Specification Requirements

The following specifications were levied on the system during the temperature/altitude testing:

- MIL-E-81910 (AS), paragraph 4.8
- MS33543 Curve II
- MIL-E-23001B (AS), paragraphs 4.5.4, 4.5.7, and 4.5.10 as modified by MIL-E-23001/POP, paragraph 6.0

3.2.7.2 Results

Based on the test/inspection data that were taken prior to, during, and after the temperature/altitude test, the system met the requirements, outlined in the specification, with the following modifications:

Line-to-Neutral Voltage	113.2–116.5
Line-to-Line Voltage	195–202
Voltage Phase Difference	120 ± 3°

Prior to beginning Temperature/Altitude (hereafter referred to as T/A), the 3S2060DF141A1 converter was subjected to a full ATP performance test. Following completion of this test, the generator/gearbox, converter, 143D6027G1 CTA, and cable assemblies were mounted in the same environmental chamber as shown in Figure 80. Thermocouples were also installed in the converter and generator (48 total) at critical component locations.

A total of nine tests was performed under various conditions as outlined in Table 9. For all tests where the converter was self-ventilated, the force air input adapter plate and T/A fixture were removed to allow sufficient air circulation. All self-ventilated tests were performed at sea level.

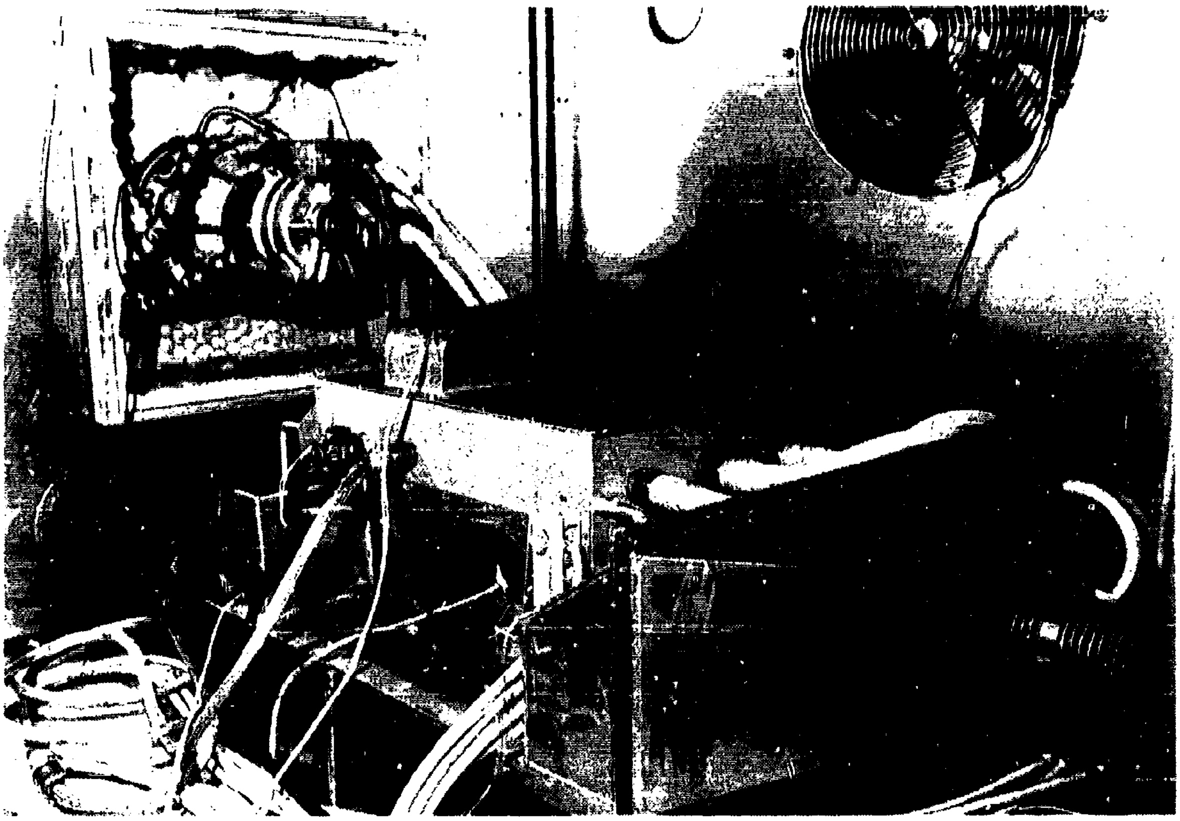

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Figure 80. Temperature/Altitude Test Setup

TABLE 9
TEMPERATURE/ALTITUDE TESTS

Procedure Paragraph Number	Name of Test	Gen Freq PM Hz	Chamber Altitude Feet	Chamber Temp. °C	Generator Oil Inlet Temp. °C	Converter Air Inlet Temp. °C	Converter Load	Converter Air Flow Rate Lb/Min
4.1.4.1	25°C, Sea Level	1,350	0	25	25*	25	40 at 0.95	Self-Ventilated
4.1.4.2	Low Temperature, Sea Level	1,350	0	-40	-40*	-40	40 at 0.75	Self-Ventilated
4.1.4.3	25°C, Sea Level	2,500	0	25	25*	25	40 at 0.95	Self-Ventilated
4.1.4.4	High Temperature, Sea Level	2,500	0	50	100	50	40 at 0.95	Self-Ventilated
4.1.4.5	High Temperature, Altitude	2,500	10K	34	100	34	40 at 0.95	9.4
4.1.4.6	High Temperature, Altitude	2,500	20K	18	80	18	40 at 0.95	7.4
4.1.4.7	High Temperature, Altitude	2,500	30K	0	60	0	40 at 0.95	6.0
4.1.4.8	High Temperature, Altitude	2,500	40K	-10	40	-10	40 at 0.95	5.4
4.1.4.9	25°C, Sea Level	1,350	0	25	25*	25	40 at 0.95	Self-Ventilated

*Temperature applies to start-up only.

3.2.8 ELECTROMAGNETIC INTERFERENCE (EMI)

3.2.8.1 Specification Requirements

The specifications levied on the system were as follows:

- MIL-E-81910, paragraph 4.5
- MIL-E-23001B, paragraph 4.5.7, as modified by MIL-E 23001/POP, paragraph 6.0
- Fairchild Spec. 160S414001A, Rev. 29, Dec. 1975, paragraph 3.3.2
- MIL-STD-461A, Notice 3
- MIL-STD-462, Notice 2

The RS02 radiated susceptibility specification called for 20 amps of 400-Hz current to be applied through wire wrapped around the control cable and converter case. The voltage spike, across five ohms through the control cable wire wrap, was also required as shown in Figure 81. The RS03 Notice 3 specification called for radiated fields as follows:

14 kHz to 35 MHz at 10 V/m

35 MHz to 10 GHz at 5 V/m

All tests were run at both top speed (30,000 rpm) and low speed (15,900 rpm) while the unit was supplying a 40 KVA at 0.75 power factor. RE01 was not conducted, since it is no longer required on the A-10 aircraft.

3.2.8.2 Results

A composite curve, showing the combined three-phase worst-case emissions and the specification for conducted and radiated noise, is shown in Figures 82 and 83. It is apparent that the specification was exceeded in the low-frequency range.

Rated susceptibility, RS02 and RS03, were performed successfully with no susceptibility observed on the system.

When all EMI testing was completed, the results were reviewed and accepted by the Air Force.

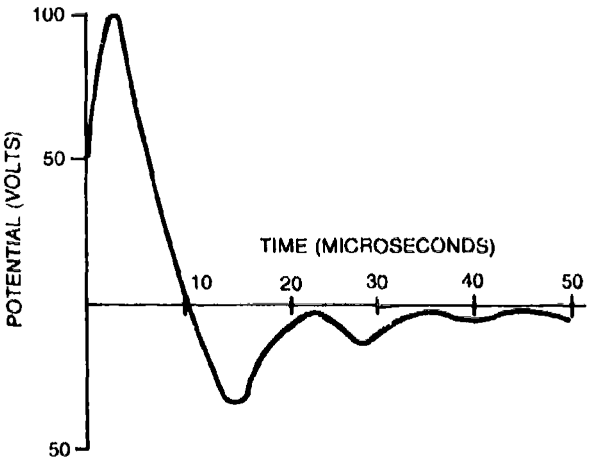

Figure 81. Voltage to Be Applied Across 10 Ohms for RSO2 Magnetic Induction Field Spike

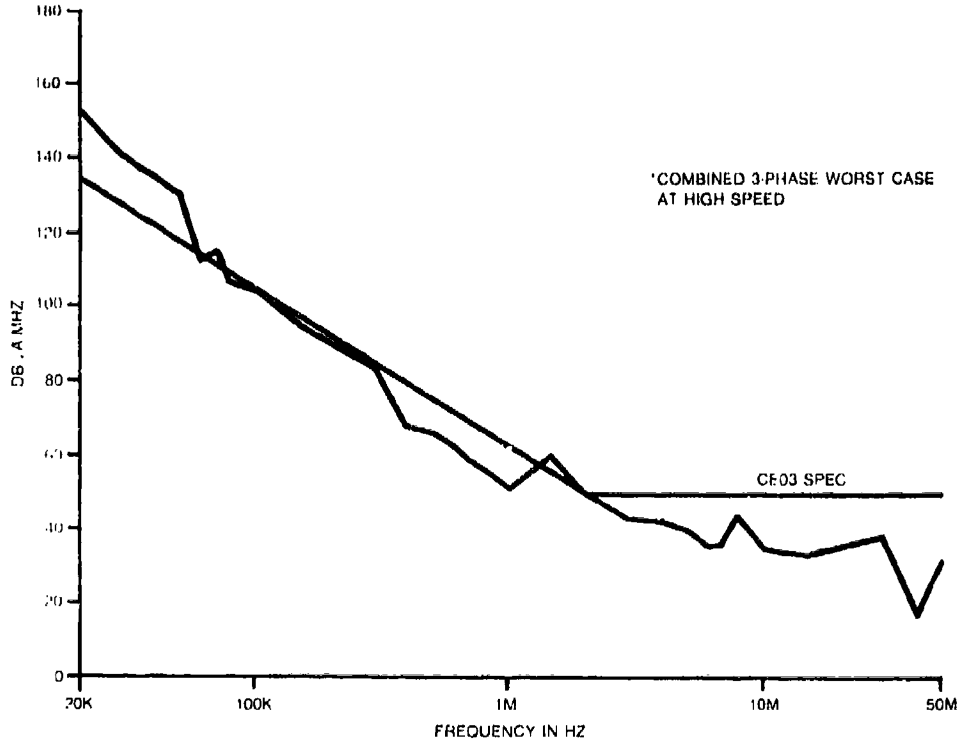

Figure 82. Conducted Emissions

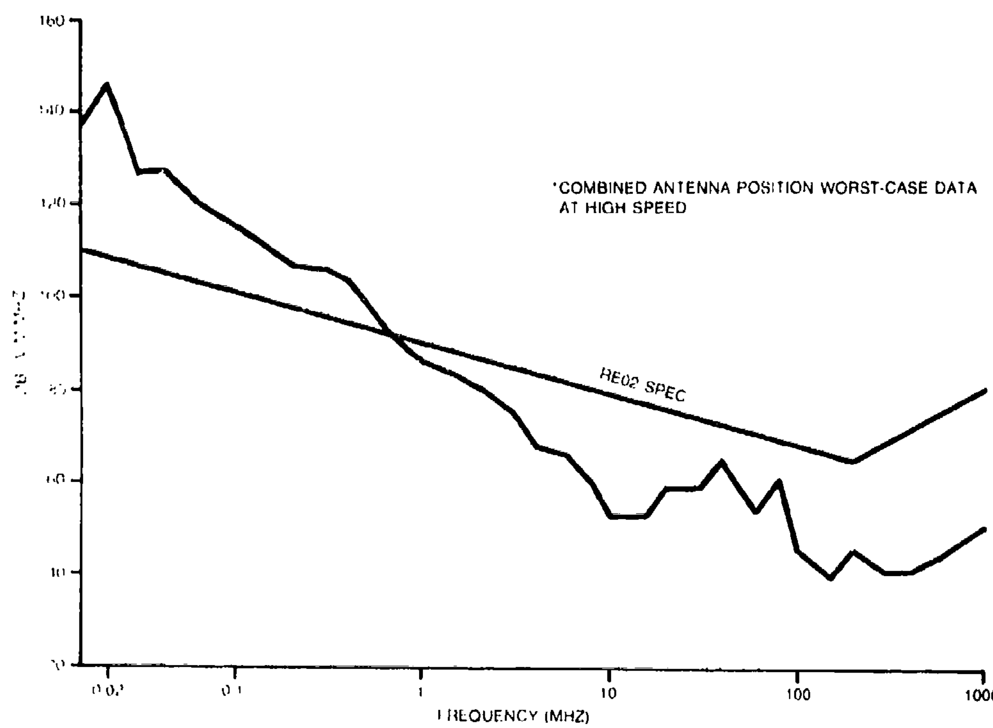

Figure 83. Radiated Noise

3.2.9 GENERATOR SHOCK

3.2.9.1 Specification Requirements

The following specifications were levied on the 2CM436A1 starter-generator during the shock test:

- MIL-STD-810C, Method 516, Procedure 1, with the following levels:

  Shock Pulse Amplitude ±15 g
  Shock Pulse Duration 11 ms

3.2.9.2 Results

Based on the test/inspection data that were taken prior to, during, and after the shock test, the 2CM436A1 starter-generator successfully met the requirements that were specified previously. A plot of the generator shock test setup is shown in Figure 84.

3.2.10 CONVERTER SHOCK

3.2.10.1 Specified Requirements

The following specifications were levied on the 3S2060DF141A1 converter during the shock test:

- MIL-STD-8106, Method 516, Procedure 1 with the following levels:

  Shock Pulse Amplitude ±15 g
  Shock Pulse Duration 11 ms

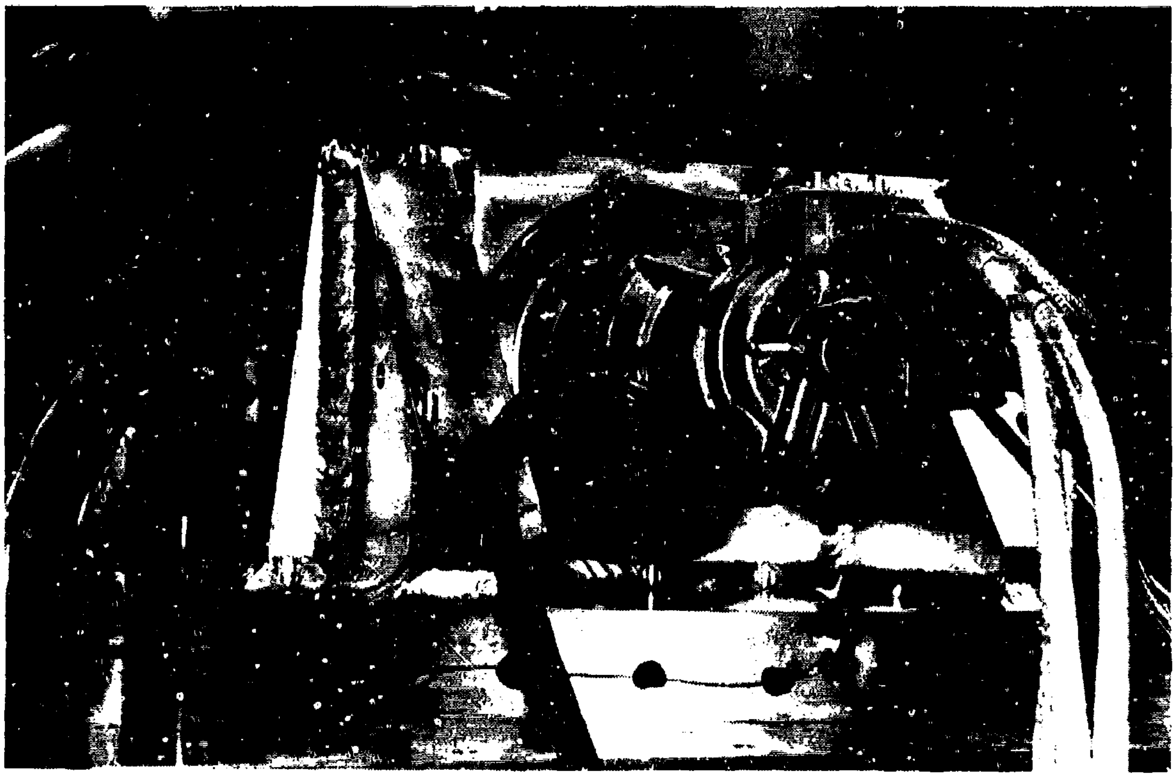

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Figure 84. Generator Shock Test Setup

3.2.10.2 Results

Based on the test/inspection data that were taken during and after the shock test, the 3S2060DF141A1 converter successfully met the shock test requirements as outlined previously. A photo of the test setup in the lateral plane is shown in Figure 85.

3.2.11 START FILTER SHOCK

3.2.11.1 Specification Requirements

The following specifications were levied on the electric start filter 937E332G1 during shock testing:

- MIL-STD-810C, Method 516, Procedure 1 with the following levels:

  Shock Pulse Amplitude ±15 g
  Shock Pulse Duration 11 ms

3.2.11.2 Results

Based on the test/inspection data that were taken prior to and after shock testing, the 937E332G1 electric start filter successfully met the requirements that were specified previously. A photo of the test setup is shown in Figure 86.

3.2.12 CTA SHOCK

3.2.12.1 Specification Requirements

The following specifications were levied on the CTA during shock testing:

- MIL-STD-810C, Method 516, Procedure 1 with the following levels:

  Shock Pulse Amplitude ±15 g
  Shock Pulse Duration 11 ms

3.2.12.2 Results

Based on the test/inspection data that were taken prior to and after the shock testing, the 143D6027G1 successfully met the shock test requirements that were specified previously. Also, electrical connections were made to verify operation at the completion of shock testing in each axis. A photo of the test setup in the longitudinal plane is shown in Figure 87.

3.2.13 EXPLOSIVE ATMOSPHERE TEST

3.2.13.1 Specification Requirements

The following specifications were levied on the converter and electric start filter during the explosive atmosphere testing:

- MIL-STD-810C, Method 511, Procedure 1
- Paragraphs 3.2 and 3.4, AES 14005, Rev. 03

3.2.13.2 Results

Based on the performance test data that were taken prior to and after the explosive atmosphere testing, and the fact that the operation of the 3S2060DF141A1 converter and 937E332G1 electric start filter did not cause the explosive atmosphere to ignite, the converter and electric start filter successfully met the explosive atmosphere test requirements.

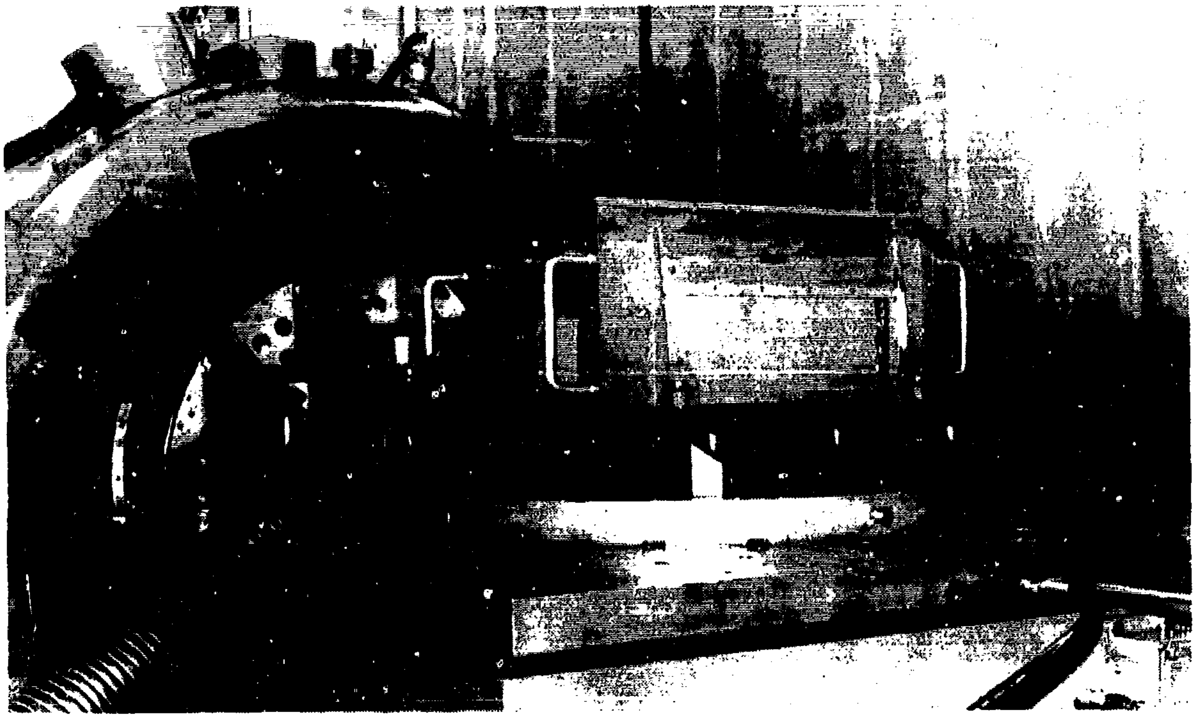

Figure 85. Converter Shock Test Setup 33829

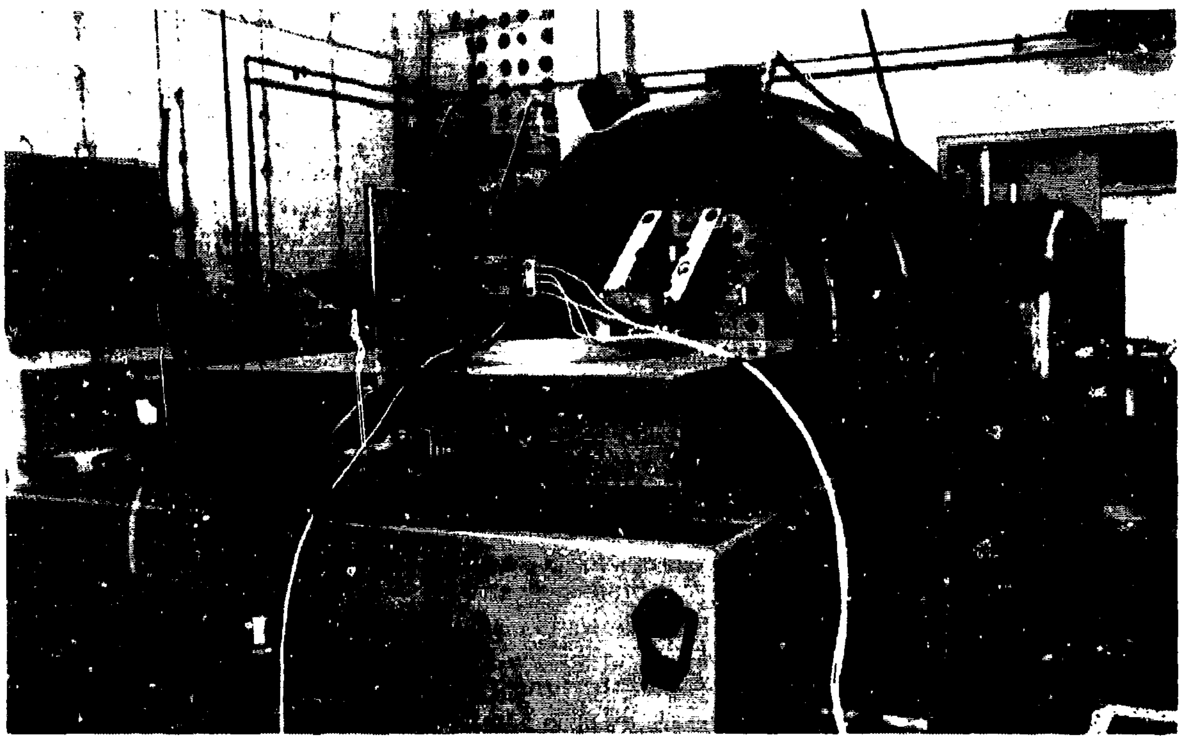

Figure 86. Start Filter Shock Test Setup 32251

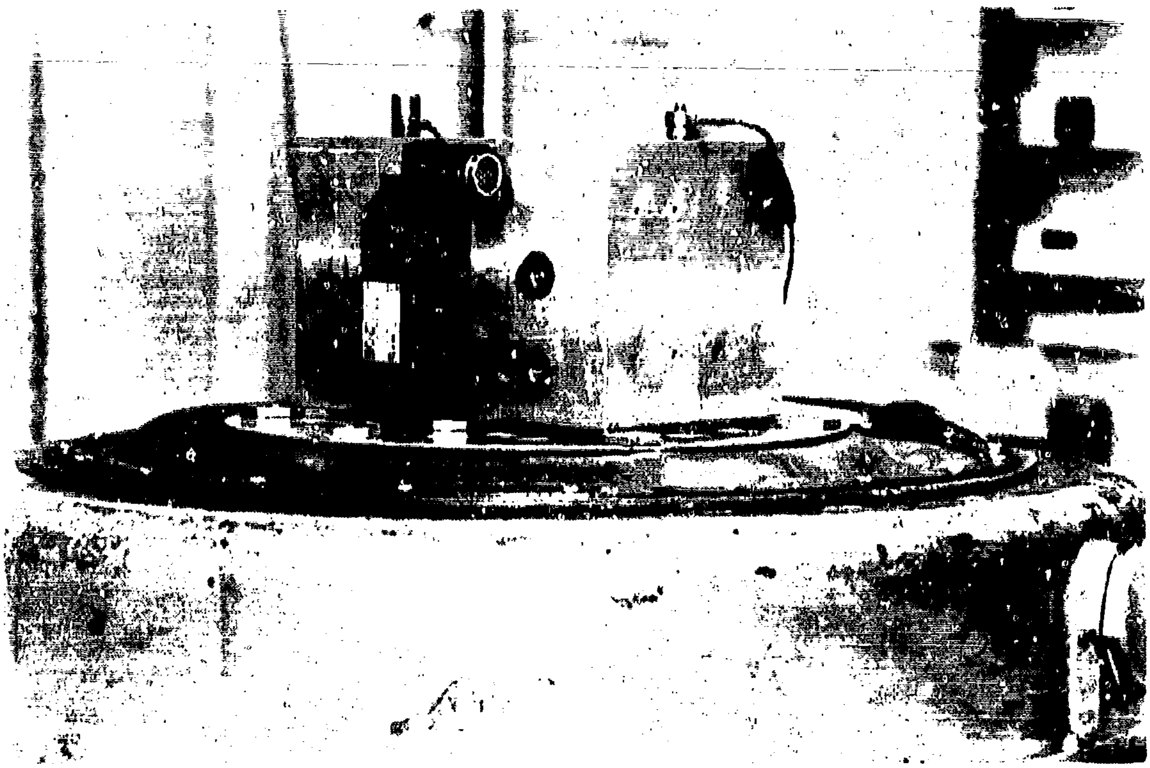

Figure 87. CTA Shock Test Setup 32466

3.2.14 AIR FLOW TEST

3.2.14.1 Specification Requirements

A mock-up was fabricated of the aft section of the A-10 aircraft. The mock-up simulated the aircraft fuselage from station 599.96 to station 678.80. All Class II modification equipment to be mounted in this area during the flight test was included in the mock-up. The mock-up was used to demonstrate the functional capability of the cooling system during both self-ventilated and ram air operation.

3.2.14.2 Results

The functional capability of the cooling system was successfully demonstrated. The results indicated that converter temperatures in the compartment, on the average, of only 10°F higher than in free air.

3.3 SYRACUSE AIR NATIONAL GUARD TEST

During October 1981, electrical starting of the TF-34 engine was demonstrated at the 174th Tactical Fighter Wing of the New York Air National Guard, Hancock Field, Syracuse, New York. The engine was mounted in a test stand that was used normally to determine the "health" of the engine after maintenance has been performed. A diagram of the engine test facility is shown in Figure 88. The power source was an AF A/M 32A-60 ground power cart. This cart is driven by a turbine and can supply air, 28 vdc, and 400-Hz power. The 400-Hz power supply is rated at 72 KVA at 0.8-1.0 pf lagging. Two separate carts were employed as the power supply during the start tests. One was equipped with a General Electric generator 2CM355C1 and regulator 3S020BR134B1. The second was equipped with a Bendix generator 28B94-111-A and regulator 20B82-10-A.

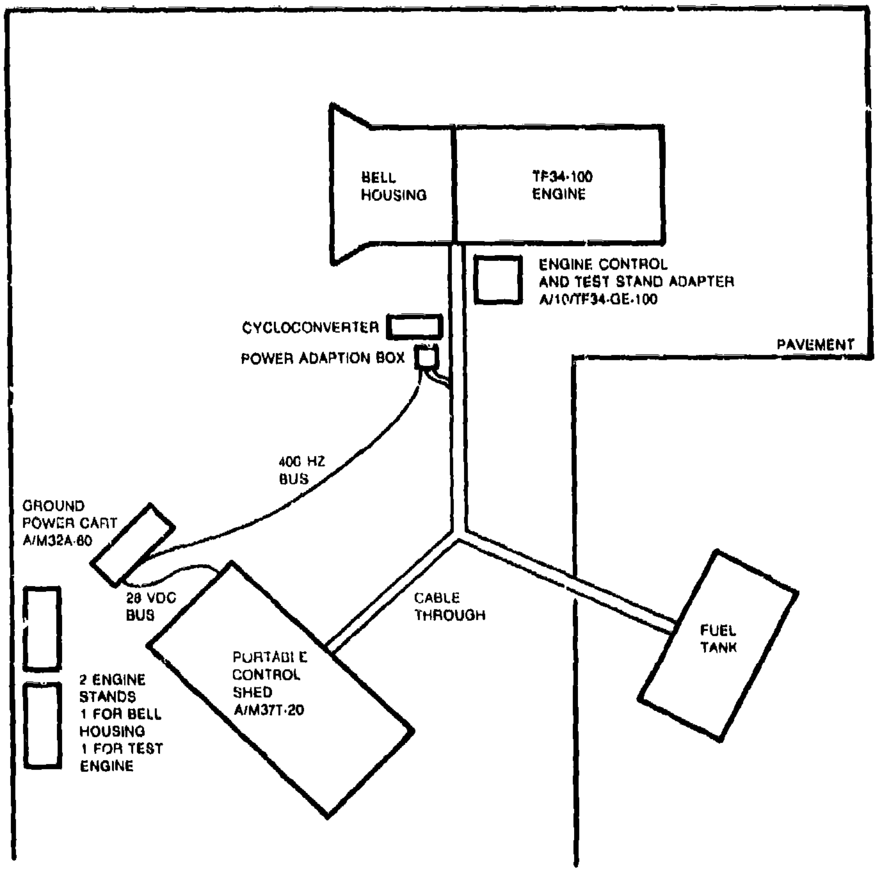

Figure 88. Syracuse Engine Test Cell

The initial engine starts were accomplished with the existing air turbine starter to ascertain engine and starter performance. The A/M-32A-60 power cart was used as an air source. The time to idle was approximately 30-35 seconds. The motoring speed (light off inhibited) was approximately 30%, or 5,400 rpm when reflected to the generator pad speed. Ambient temperature was between 45-50°F. A similar test was accomplished with the electrical starting system. Again, the A/M-32A-60 was employed as the power source—this time supplying electrical power. The time to idle speed was approximately 30 seconds. The motoring speed was approximately 32%, or 5,760 rpm as reflected to the generator pad. Figure 89 shows the envelope for the peak voltage and current during start. The voltage rise is believed to be precipitated by the leading power factor load (filter capacitors in both the harmonic traps and the converter). Distortion data were not recorded for the same period. Six electrical start tests were made during the Syracuse tests.

3.4 GE-LYNN ENGINE LIFE TEST

Early in 1982, GE-AESP (Aerospace Electrical Systems Programs, Binghamton, New York) was given the opportunity by GE-AEG (Aircraft Engine Group, Lynn, Massachusetts) to mount the 60-KVA starter-generator system on a TF34-100 engine Component Improvement Program (CIP) test. This test gave AESP the chance to get more test data and installation experience with the TF34-100 engine before the planned flight test at Nellis AFB.

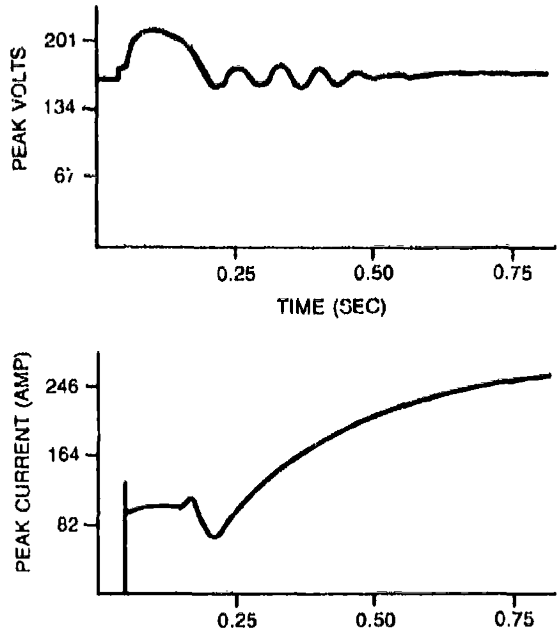

Figure 89. Voltage and Current Envelope—A/1132A-60A Ground Power Cart

A photograph of the engine test cell is shown in Figure 90. GE-Lynn normally used the Air Turbine Starter (ATS) to get the TF34 started and a six-phase generator to simulate the load of the 400-Hz generator. The installation plan called for removing the six-phase generator and installing the starter-generator. The ATS system would remain intact. AESP obtained an A/M32-60B 400-Hz ground power cart from the Air Force as the 400-Hz power source to start the engine. As a backup, a Hobart commercial 90-KVA cart was obtained. A portable, 30 KVA at 0.75 pf load bank was built by AESP to load the VSCF when the engine was running. Using an average system efficiency of 85% (top speed to idle), this amounted to a 45-hp load on the engine accessory gearbox. A diagram, showing a layout of the test cell and equipment, is shown in Figure 91. All interconnecting cables were supplied by AESP. Cable lengths and routing are shown in Figure 92.

GE-Lynn's test plan called for running AMT III R test cycles, as shown in Figure 93, to test the life of the engine with several design changes installed. The VSCF system would supply 30-KVA load whenever the engine was running. All engine starts would be done electrically. The ATS system served as a backup in the event that the electric start system malfunctioned during a start. This would allow the air starter to motor the engine and continue the CIP test, using the air system for starting until the AESP system could be repaired or replaced.

Testing first began on 31 March 1982, using the commercial ground power cart. Initially, an overfrequency problem was found with the commercial ground power cart, which tripped off the line after approximately 16 seconds of motoring. This condition was resolved by a simple adjustment to the ground power cart's control boards. After this adjustment to the commercial ground power cart, one five-minute motoring and two electric starts were accomplished successfuly. All measured parameters were within expectation.

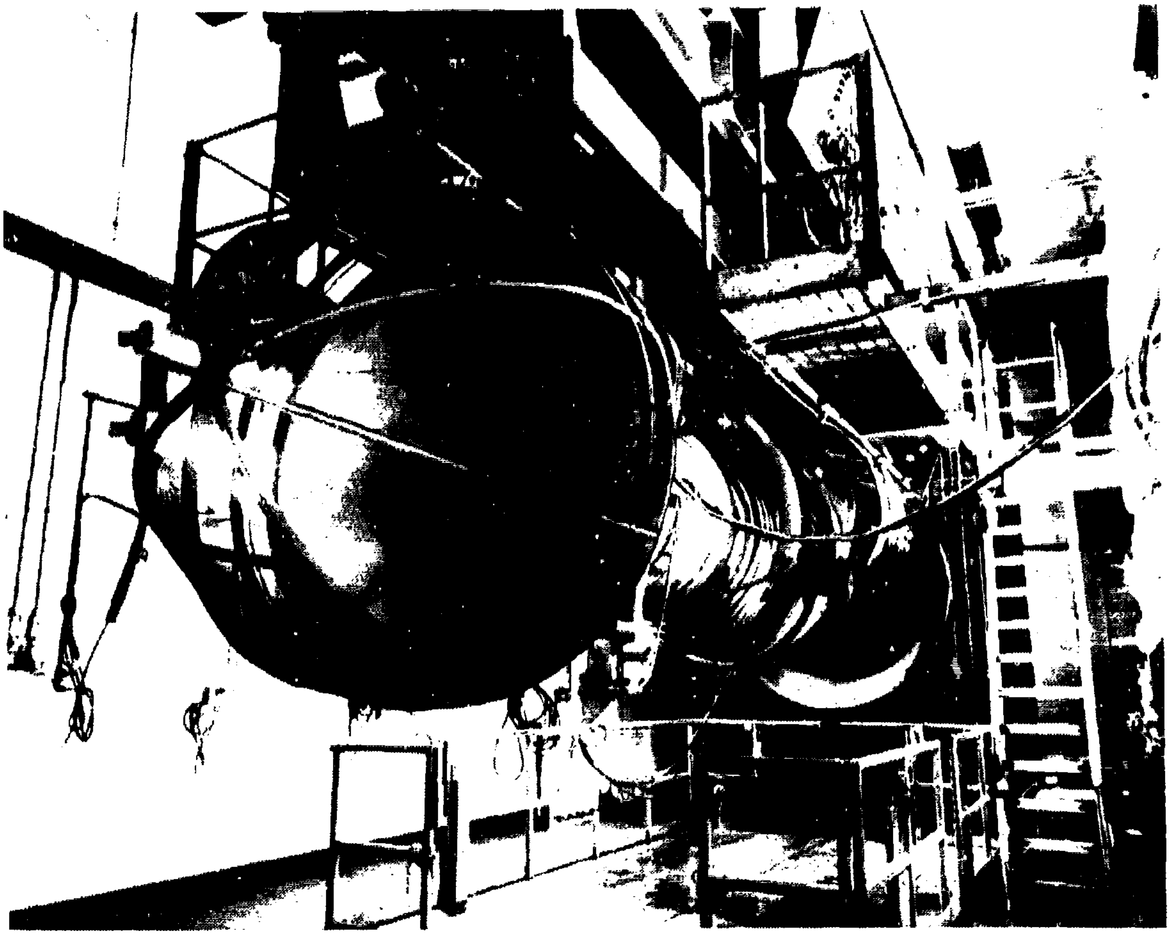

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Figure 90. Engine Test Cell

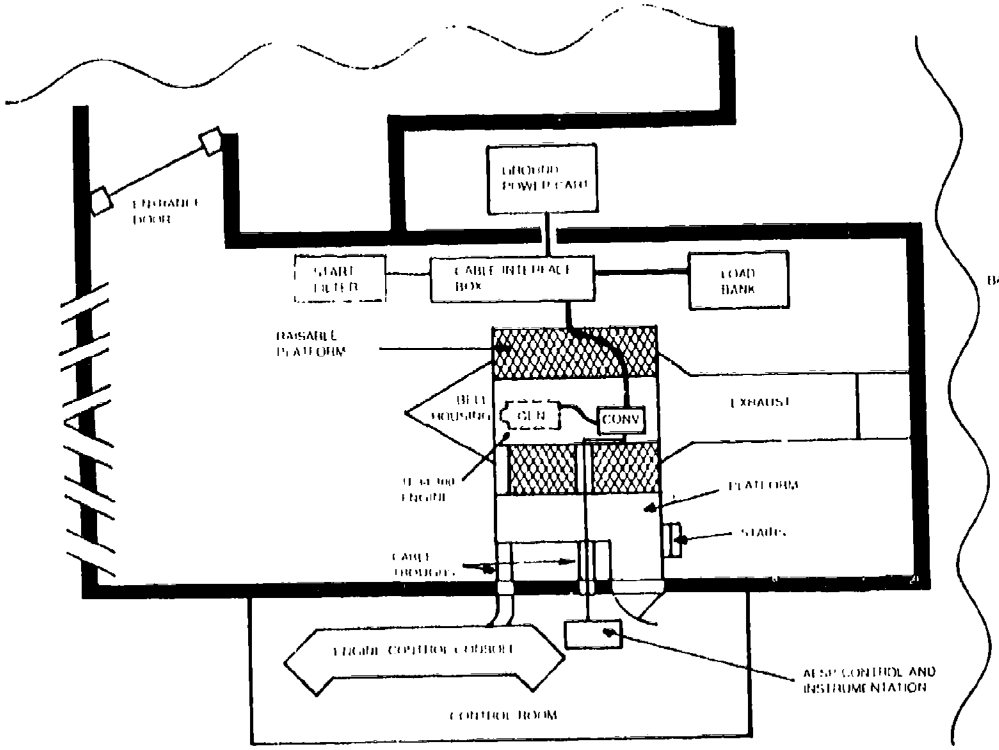


Figure 91. AEG Lynn Engine Test Cell

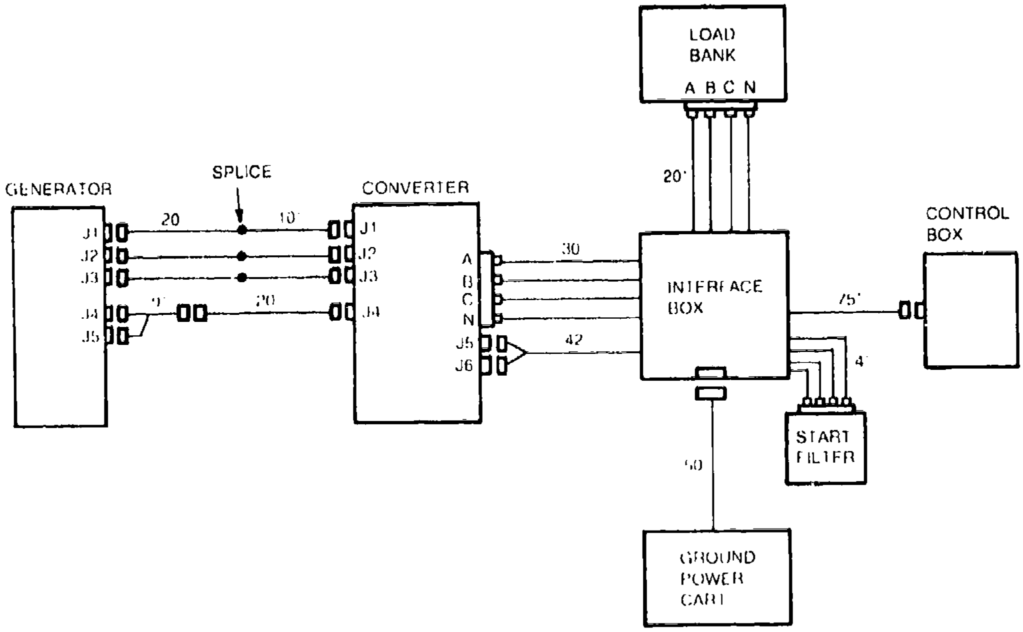


Figure 92. Cable Routing for Lynn Test

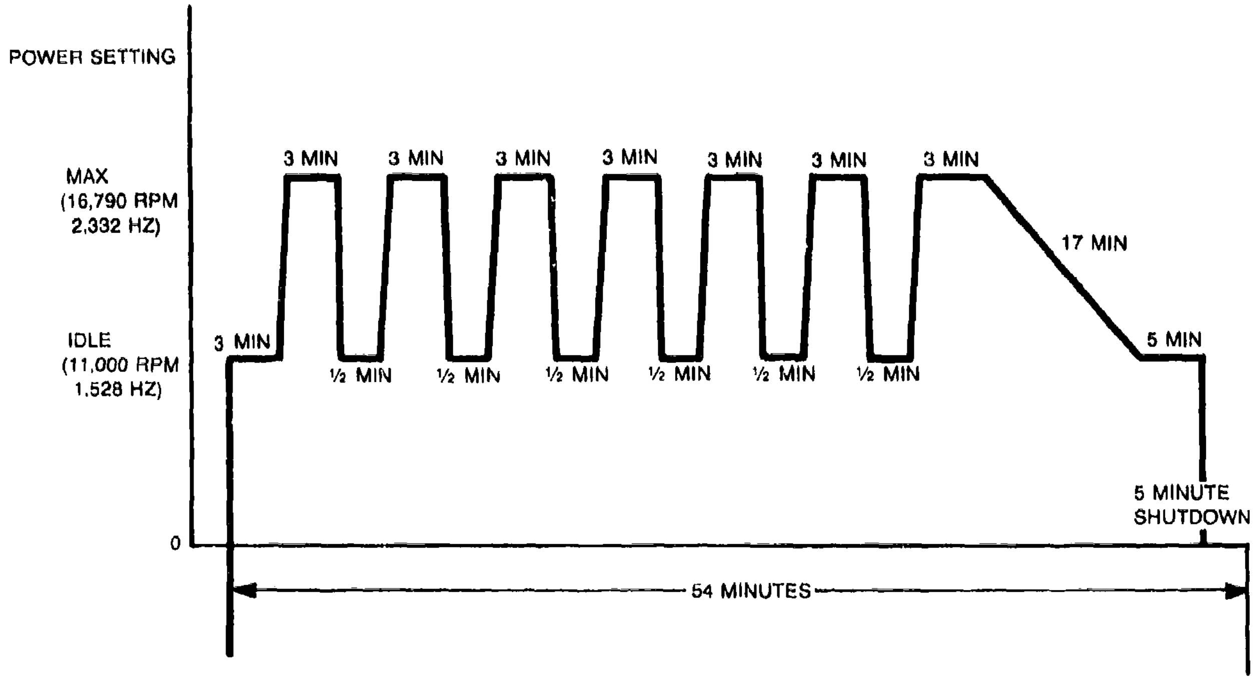


Figure 93. TF-34-100 Proposed AMT III R Factory Test Cycle

The start times for the two starts are listed below.

Start	AESP Starter Cutout (9,700 rpm) Secs.	AEG Idle (11,000 rpm) Secs.	Engine Ignition Secs.
First	27	34	
Second	22	27	9

The AEG requirement is to idle within 30 seconds. The first start time appears to be out of limits, but the time is normal as this was the first rollover of the engine in five days.

AEG test personnel provided information that the air starter time to idle varied, typically, between 20 to 35 seconds, depending upon engine condition, last rollover, and the air starter shutoff, which is turned off at 9,200 rpm but disengages at varies speed up to 10,000 rpm.

The motoring speed that was attained was 8,640 generator rpm (770 Hz), or 5,184 input rpm. Power quality data are shown in Table 10.

The test of the VSCF equipment at Lynn, Massachusetts, was completed on 15 May 1982, and the VSCF system was removed. The final status of the Lynn test was as follows:

Total cycles completed with VSCF	529
Number of electric starts	434
Converter hours at Lynn	432
VSCF failures	0

TABLE 10
60-KVA ADP VSCF DATA IN GENERATE MODE

2,332-Hz Generator Frequency (Maximum Test Speed)					
	Phase Voltage (Volts)	Phase Current (Amps)	Power (KW)	Harmonic Content (%)	Modulation (%)
A	114.9	84.2	7.12	1.32	0.18
B	115.1	86.1	7.28	1.51	0.18
C	115.0	85.9	7.17	1.67	0.15
Lynn Engine Test: 12 May 1982 Cycle 483 FSD Number 007 Converter, Generator Number 0012					

3.5 ALL SCRs ON PROTECTION TEST

On August 20, 1983, the All SCRs On protection test was run at speeds up to 26,580 rotor rpm. The test was successful, and stop times were less than expected.

3.5.1 TEST SETUP

The test was run in the GE 300-Horsepower Laboratory on station number 2. The engineering generator (serial 3) and one of the qualification converters (serial 7) were used. All SCRs On mode was accomplished by making the converter think it had a Generator Overcurrent (GOC) condition (GND-J6-17). Nine temperatures were monitored. A list of thermocouple locations is shown in Table 11. The data aquisition system was used to measure each thermocouple once a second. A light beam oscillograph was used to monitor ϕ4 current, ϕ9 current, ϕA IPT bank voltage (T6E3-T2E3), and ϕC IPT bank voltage (T18E3-T10E3). The oscillograph was run at 100 in/s. An oscilloscope was used to measure the magnitude and duration of the ϕ9 current. A digital milliohmeter was used to measure winding resistance of the generator after each test. Several modifications were made to the converter wiring to ensure that an adequate voltage was delivered to the disconnect coil. Guillotine contactors were in the circuit, but they were inhibited from opening.

TABLE 11
THERMOCOUPLE LOCATIONS

T1, T2, T3	Three thermocouples places on Stator end turns, 120° apart
T4	IPT #18 Coil
T5	IPT #9 Coil
T6	SCR Z12-Q2 Case
T7	Cold Plate Below Z12
T8	SCR Z18-Q2 Case
T9	Cold Plate Below Z18

3.5.2 TEST PROCEDURE

The converter was run at room ambient. The generator was run with as low an oil temperature as possible. The data acquisition system was programmed to take data for 30 seconds. The converter was not in generate mode at All SCRs On test inception. For each test, the sequence of events was:

1. Bring generator up to test frequency
2. Allow generator temperatures to stabilize about ten minutes
3. Start data collecting program on computer
4. Start oscilloscope trace
5. Start oscillograph trace
6. Induce GOC fault
7. Wait until rotor comes to rest
8. Take J2 connector off generator and make winding resistance measurements every 5 seconds up to 45 seconds after rotor rest

The drive stand was kept running for the whole test. This was to keep the oil system running in the generator. There was also an approximate 30-minute cool-down period between tests.

3.5.3 RESULTS

3.5.3.1 Test Results

Seven tests were run. A summary of test results is shown in Table 12. For each frequency, a table of temperature data is given, along with a plot of these temperatures as a function of time. Traces of the $\phi 9$ current are also shown in Figure 94.

3.5.3.2 Conclusion

The All SCRs On concept is proven feasible. Temperature rises are well within acceptable limits.

3.6 A-10 INSTALLATION AT NELLIS AFB

The following discussion briefly describes a Class II modification of the A-10, which took place at Nellis AFB in April and May of 1984. Two airplanes (S/N 79-168 and 79-170) were planned to be modified, flight tested for one year, and then demodified. However, after only one aircraft, number 168, had been modified and ground tested, Tactical Air Command (TAC) removed support of the flight test. The aircraft was then demodified and returned to service.

3.6.1 EQUIPMENT DESCRIPTION

The PM VSCF system, which was to have been flight tested, consisted of a starter-generator with an adaption gearbox unit (GE drawing number 194E930), a set of high-frequency cables, and a converter unit (GE drawing number 936E250) that are combined together to form one channel of the two-channel aircraft electrical system. The adaptation of this PM VSCF system to the A-10A aircraft for electric starting required that the following assemblies be added.

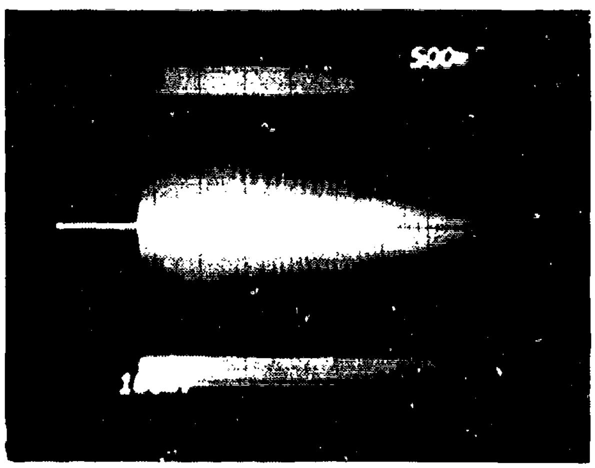
- Filter, electric start (GE drawing number 937E332)
- Start contactor assembly (GE drawing number 936E993)

TABLE 12
TEST SUMMARY

Test	Generator Frequency (Hz)	Insulation Rise (Measured °C)	Copper Rise (Estimated °C)	Generator* Current		Stop Time (Measured Sec.)
				Peak	RMS	
1	310	1.6	Insufficient Data	300	163	0.115
2	625	3.7	5.5	330	179	0.230
3	1,350	10.5	Insufficient Data	335	182	0.800
4	1,925	19.4	30	355	193	1.500
5	1,350	62.2	Insufficient Data	335	182	1.450 (Est.)
6	1,350	10.5	17.5	335	182	0.810
7	2,215	242+	Insufficient Data	360	196	1.750 (Est.)

*Peak current is average as a function of time.
RMS current calculations are based on a crest factor of 1.84.

ϕ9 current
2,215-Hz test



100 A/DIV
500 ms/DIV

Figure 94. ϕ9 Current, 2,215-Hz Test

3.6.1.1 Design Philosophy

The equipment, which was to have been flight tested, was designed to be configured and located on the airplane with the following goals in mind.

- Minimize changes in the cockpit
- Minimize changes in operation procedures
- Use as much existing hardware as possible
- Equipment other than the present IDG and its associated assemblies would not be removed during this flight test unless absolutely necessary
- Modifications must be removable to demodify the aircraft to its original condition at the end of the flight test

These goals are considered to have been met. Only one switch had been added to the cockpit area on the right pedestal which selects the mode of engine starting—air or electric. The engine start and generator control procedures and indications were identical to those of an unmodified A-10A. To mount the converters, minor structure modifications had been made in the aft tail section.

3.6.1.2 Starting Adaptation Hardware

The following equipment was added to adapt the basic channel hardware, described previously, with the existing aircraft ac bus structure to perform electric engine starting.

Figure 95 is a cable diagram of the existing A-10A bus structure. Figure 96 shows how the ac bus structure and was modified to perform electric starts.

3.6.1.2.1 Filter, Electrical Start (GE Drawing Number 937E332)

This assembly contains inductors and capacitors for each phase of a three-phase system, and it is located electrically so that only one assembly is required per aircraft. This assembly is used to filter out unwanted harmonics in the ac bus structure during starting to meet the total harmonic content required of MIL-STD-704A. During the initial portion of the start, the starter reflects itself as a pure inductive load until its back EMF builds up. This large inductance causes the power factor to drop briefly below 0.7 and, in turn, harmonic distortions above the limits contained within MIL-STD-704A may be experienced. Also included in this assembly is a relay that is controlled by the pilot's start mode select switch, located on the pilot's right console. When operated, this relay removes the air start valve from the starting system and allows the electric start system to operate.

The electric start filter assembly is a new unit and was mounted on the upper shelf behind access door F42, adjacent to the central air data computer (3113AT02).

3.6.1.2.2 Start Contactor Assembly

This is an assembly of two contactors that was added to incorporate electric starting into the ac bus structure. These two contactors, described in the following text, are attached to a mounting plate to form the assembly. This assembly mounts adjacent (forward) of the armament relay box (9413AK01), in the upper section, behind access door F40. Presently, no equipment is mounted in this area.

- **Contactor, Tie Start (TS)** (part number B301A Hartman)—This contactor provides ground power to the engine being started. In conjunction with this contactor's coil, interlocks are used to assure that it cannot be operated when APU power is in use or when the aircraft is airborne.

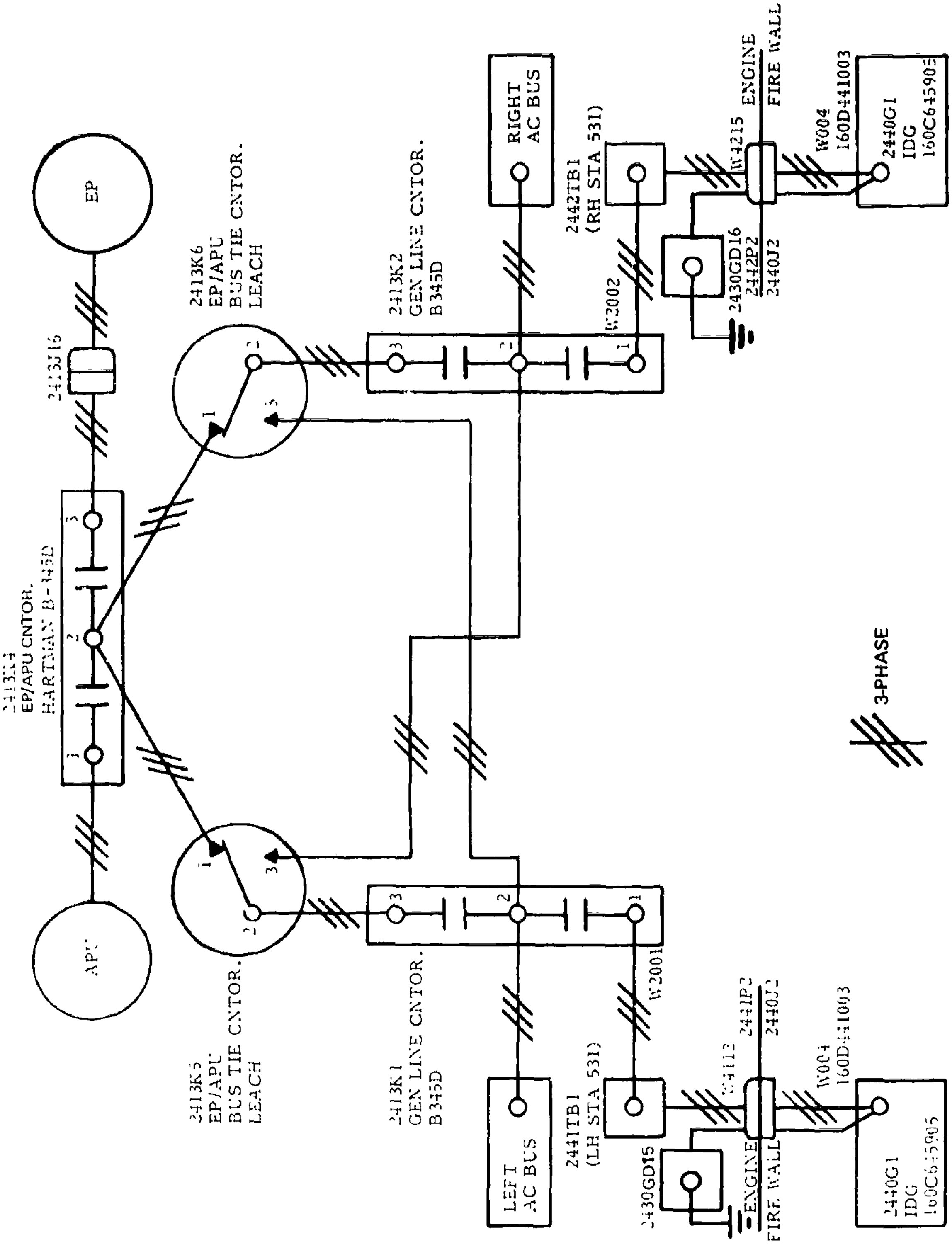


Figure 95. Cabie Diagram AC Bus Structure A-10A

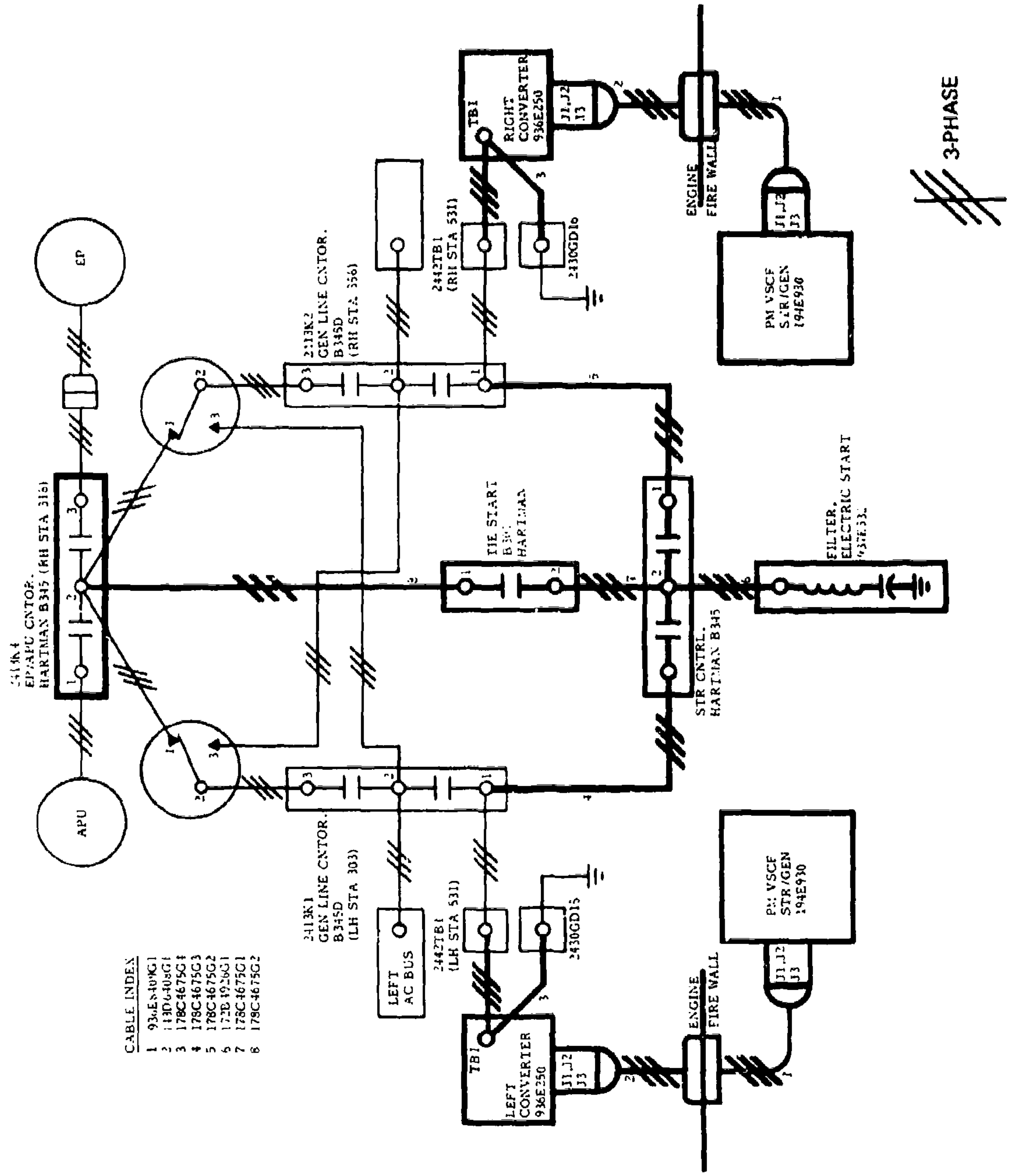


Figure 96. Cable Diagram AC Bus Structure Flight Test

- **Contactor, Start Control (SC)** (part number B345W Hartman)—This contactor controls start power to the engine being started. During ground power starts, only one side of the contactor can be operated. During cross-starts on the ground or in the air, both sides of the contactor may be operated simultaneously to transfer power from the operating bus side to the side being started.

  This contactor is the same model as the one used for the generator line contactor and the external power/auxiliary power contactor on the A-10A aircraft (B345D), except the mechanical interlock has been removed so that both sides can be operated simultaneously.

3.6.2 MODIFICATION DETAILS

3.6.2.1 Cockpit Modification

The cockpit right console has a blank panel removed and replaced with the engine starter select panel, GE part number 172B4923. Figure 97 shows this panel installed in the cockpit. Two orange wires were connected to this switch. One went to the essential circuit breaker panel in the cockpit. The other was routed out of the cockpit through a spare pin in an existing connector to the start filter. The cockpit bulkhead connectors are shown in Figure 98.

This start select switch provides control to select either the air or the electric start system. Switch position AIR did not alter the operation of the existing start system, while switch position ELECTRIC removed the air turbine starter solenoid, 8040L01, and armed the PM VSCF starter system. The start procedure and indications will remain the same when this switch is in either position.

3.6.2.2 Compartment F40 Modifications

The start contactor assembly was installed in the upper compartment area, as shown in Figures 99 (before) and 100 (after). Holes were drilled in the support bars and rivnuts were installed.

3.6.2.3 Compartment F42 Modifications

The start filter assembly was installed in the upper compartment area, as shown in Figures 101 (before) and 102 (after). Holes were drilled in the support bars and rivnuts were installed.

3.6.2.4 Compartment F12 Modifications

The present external power/auxiliary power contactor, part number Hartman B345D, identified as 2413K4, located on the upper equipment rack, right station 318, was removed, see Figure 103 for location.

A similar contactor was installed, using the same mounting and mounting hardware. The contactor that was installed is the basic Hartman B345D contactor, except an unused set of normally open contacts, pin E and pin X, were moved from the APU coil control side to the EP coil side. These contacts serve as interlocks to ensure that electric starts are not attempted with APU power on the ground or in the air. The existing A-10A APU generator is not sized to perform electric starts.

The right generator control unit (Westinghouse part number 946F992-2), identified as 2413G02, and located at right station 340, was removed, and its mounting area was left vacant, see Figure 102 for location of this modification. The mating generator control cable connector 2413P22, on cable W1316, had a jumper cable assembly (GE drawing number 178C4724) connected to it. The jumper cable was mounted on a bracket affixed to the frame where the Generator Converter Unit (GCU) has been mounted. The jumper cable assembly allows the existing W1316 aircraft cabling, going from station 340 to station 351, to be used. This jumper cable assembly ties the forward right ac bus control devices, which are the right generate line contactor connector 2413P23, the right current transformer assembly connector 2413P24, the cockpit generator control and annunciation connector 2413J10, and a ground point 2413GD26 to the aft fuselage mounted converter.

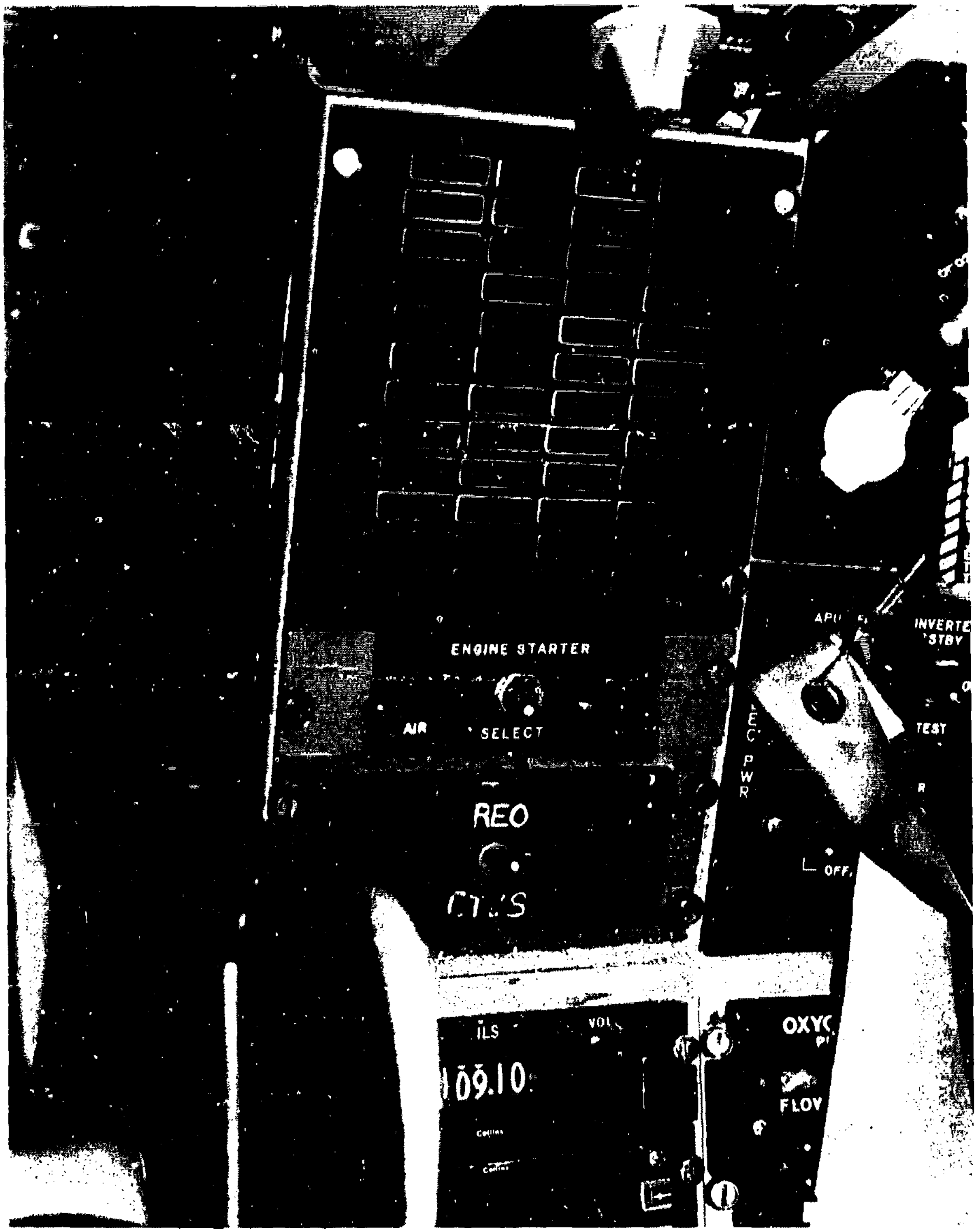


Figure 97. Engine Start Select Switch Installed in Cockpit

Figure 98. Wire Routing Through Cockpit Bulkhead Connectors

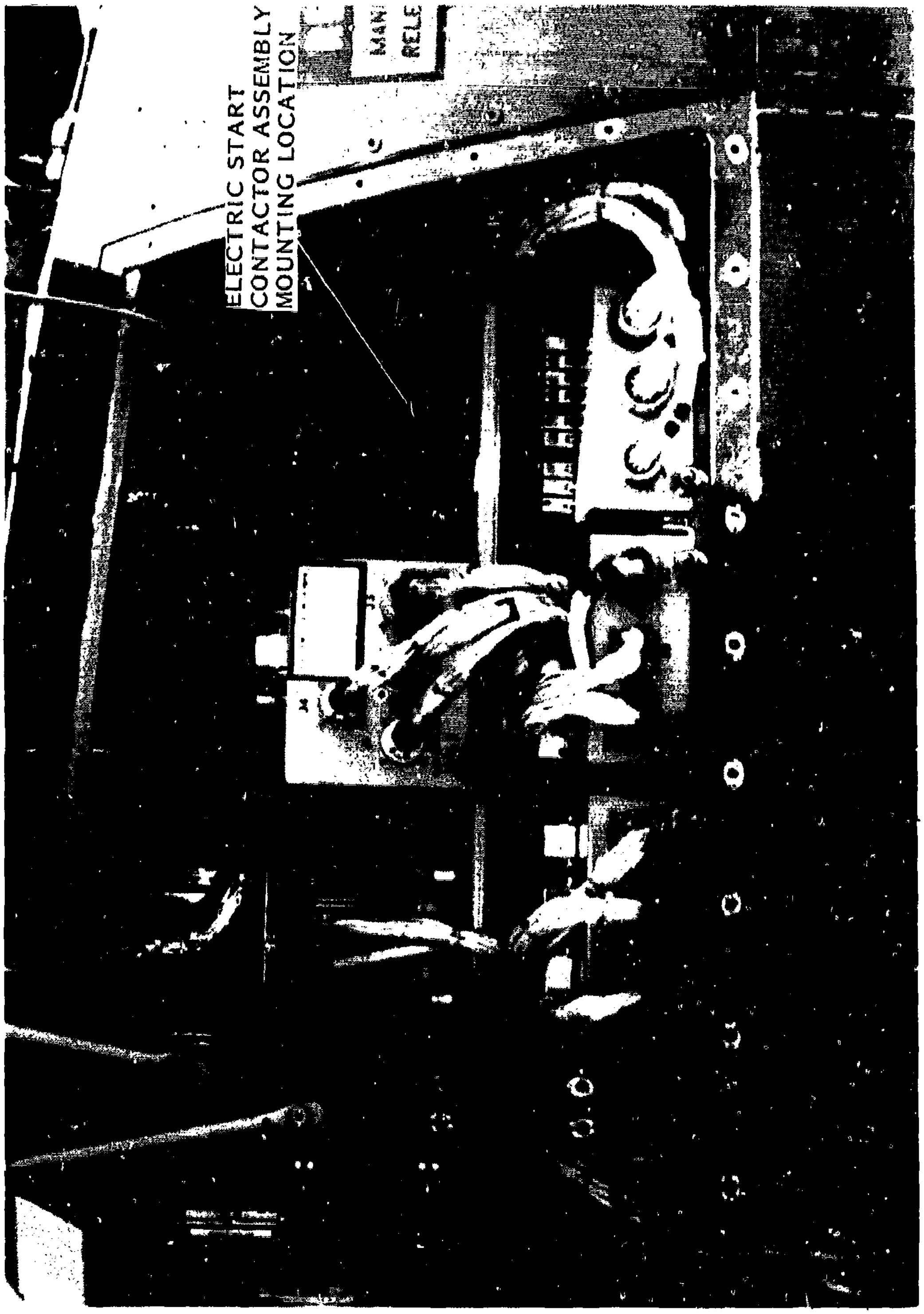


Figure 99. Compartment F40 Before Modification

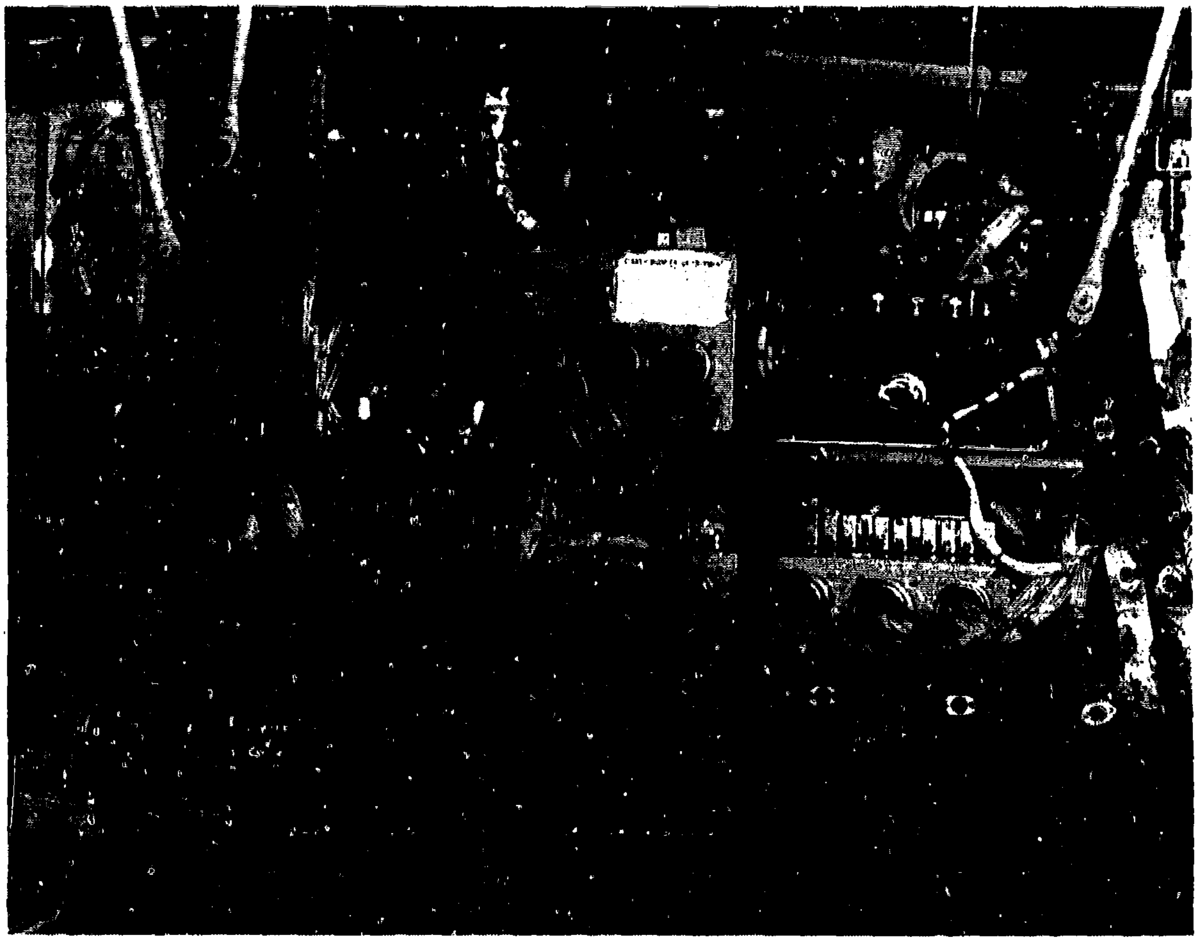


Figure 100. Compartment F40 with Start Contactor Assembly Installed

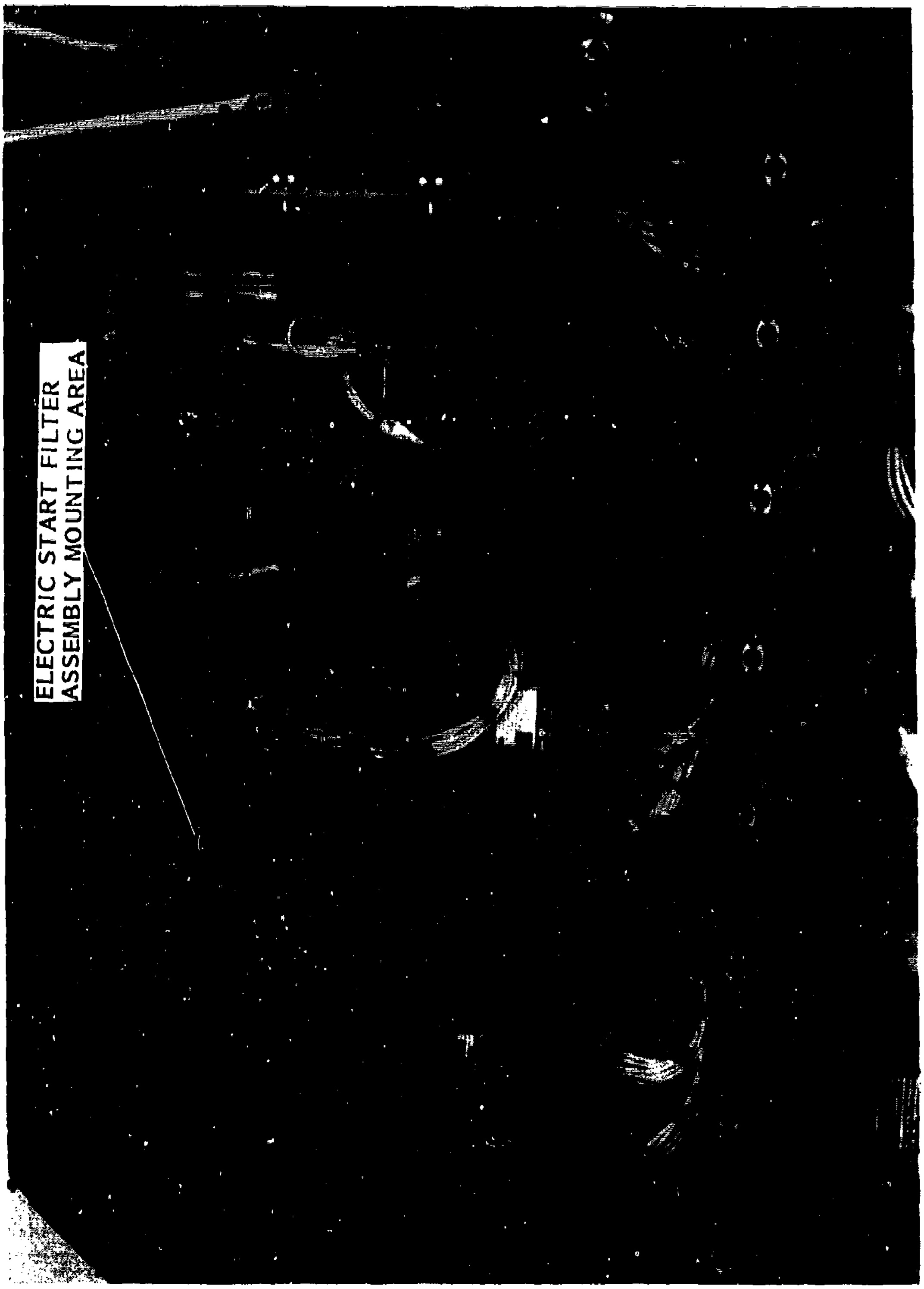


Figure 101. Compartment F42 Before Modification

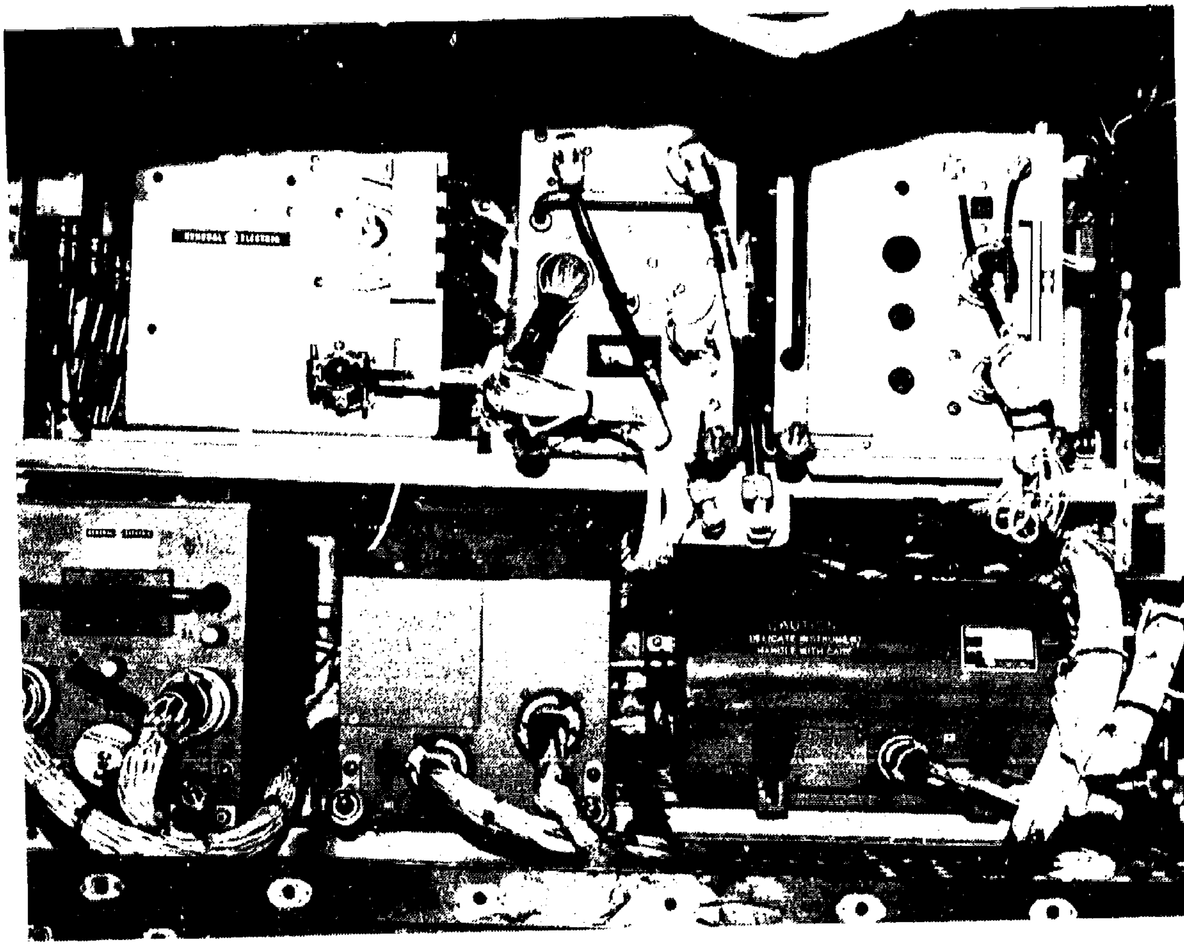


Figure 102. Compartment F42 with Start Filter Installed

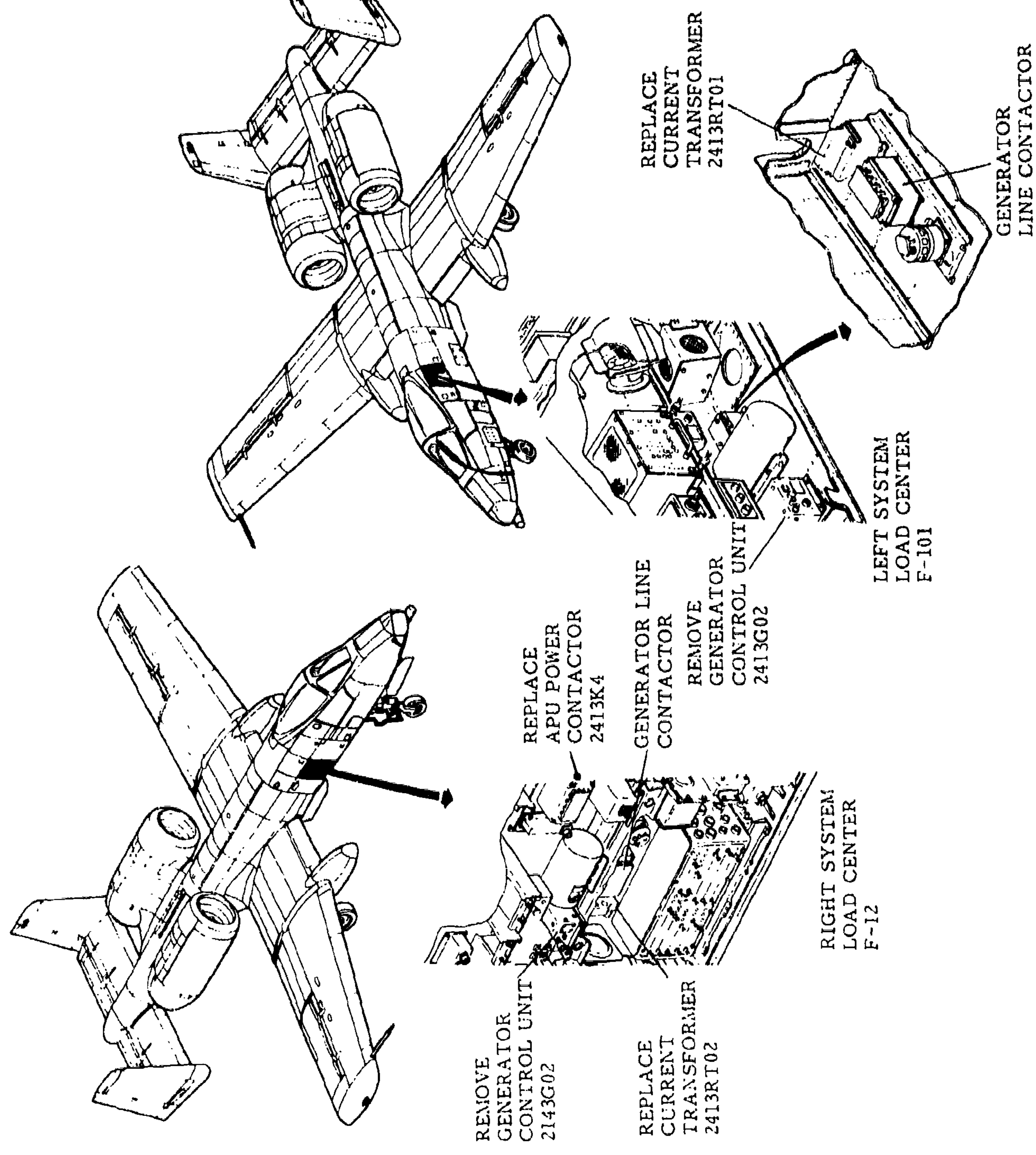


Figure 103. Generator Line Contactor Current Transformer and GCU Locations

One orange AWG #20 jumper wire was installed in the 2413P22 connector pin F* that goes to the right generator line contactor 2413K2, connector 2413P23 pin W. The pin W connection provides a ground logic signal, which is necessary for the converter bus control logic.

The system Current Transformer (CT) assembly (part number Westinghouse 943D668-1), identified as 2413RT02, was removed and replaced with current transformer assembly, GE part number 143D6052, see Figure 102 for location. These CT assemblies are physically interchangeable, thus the same mounting base and hardware were used.

The current transformer assembly was replaced for the flight test to assure proper feeder fault sensing for the flight test electrical system. The existing CT mating connector (2413P24) was connected to the flight test CT. Figure 104 is a photo that shows compartment F12 before the modification. Figure 105 is a photo of F12 after the modification, except the GCU jumper cable and bracket have not been installed.

3.6.2.5 Compartment F101 Modifications

The left generator control unit (Westinghouse part number 946F992-2), identified as 2413G01 and located at left station 290, was removed, and its associated mounting area was left vacant, see Figure 103 for location of this modification. The remade jumper cable assembly (see section 3.6.2.4 and Figure 106) was attached to the mating generator control unit cable connector 2413P14, on cable W1337. This connector assembly allows the existing W1337 generator control cable, going from station 290 to station 531, to be used during the flight test. This provided part of the cabling necessary to connect the flight test VSCF converter into the left ac bus control devices. These bus control device connectors are the left generate line contactor connector 2413P18, the left current transformer assembly connector 2413P16, the cockpit electric power panel control and annunciation connector 2413J14, and a ground point 2413GD56. The jumper assembly was mounted on a bracket affixed to the frame where the GCU had been mounted. These brackets were fabricated by GE at Nellis AFB.

One orange AWG #20 jumper wire was attached to pin F* of the 2413P14 connector. The signal is the same as discussed previously except, on the left side, pin F* goes to left generate control contactor 2413K1, connector 2413P18, pin W.

The left CT assembly (part number Westinghouse 943D668-1), identified as 2413RT01, was removed and replaced with current transformer assembly GE drawing number 143D6502, see Figure 103 for location. These CT assemblies are physically interchangeable; thus, the same mounting base and hardware may be used. The current transformer assembly was replaced to assure proper feeder fault sensing for the flight test electrical system. The new CT assembly was connected to the existing CT cable connector 2413P16. Figure 107 shows the new CT and the jumper cable bracket installed.

3.6.2.6 Video Tape Recorder (VTR) Relocation

The VTR was relocated to a forward mounting position behind access door F10. This location was selected because the Connecticut and Syracuse Air Guards have located their VTRs in this position. Wright Patterson, AFWAL P00S-2, submitted a separate Class II modification package, covering the VTR relocation for this flight test. The access to insert and remove the video tape deck in the new location is through access door F10.

The wiring that had been going aft to the VTR from the cockpit was cut and used for converter interface wiring. New wires were installed from the cockpit to the VTR in its new location.

The VTR remained in its new location and was not moved back during the demodification. Figure 108 is a photo of compartment F10, showing the new VTR location.

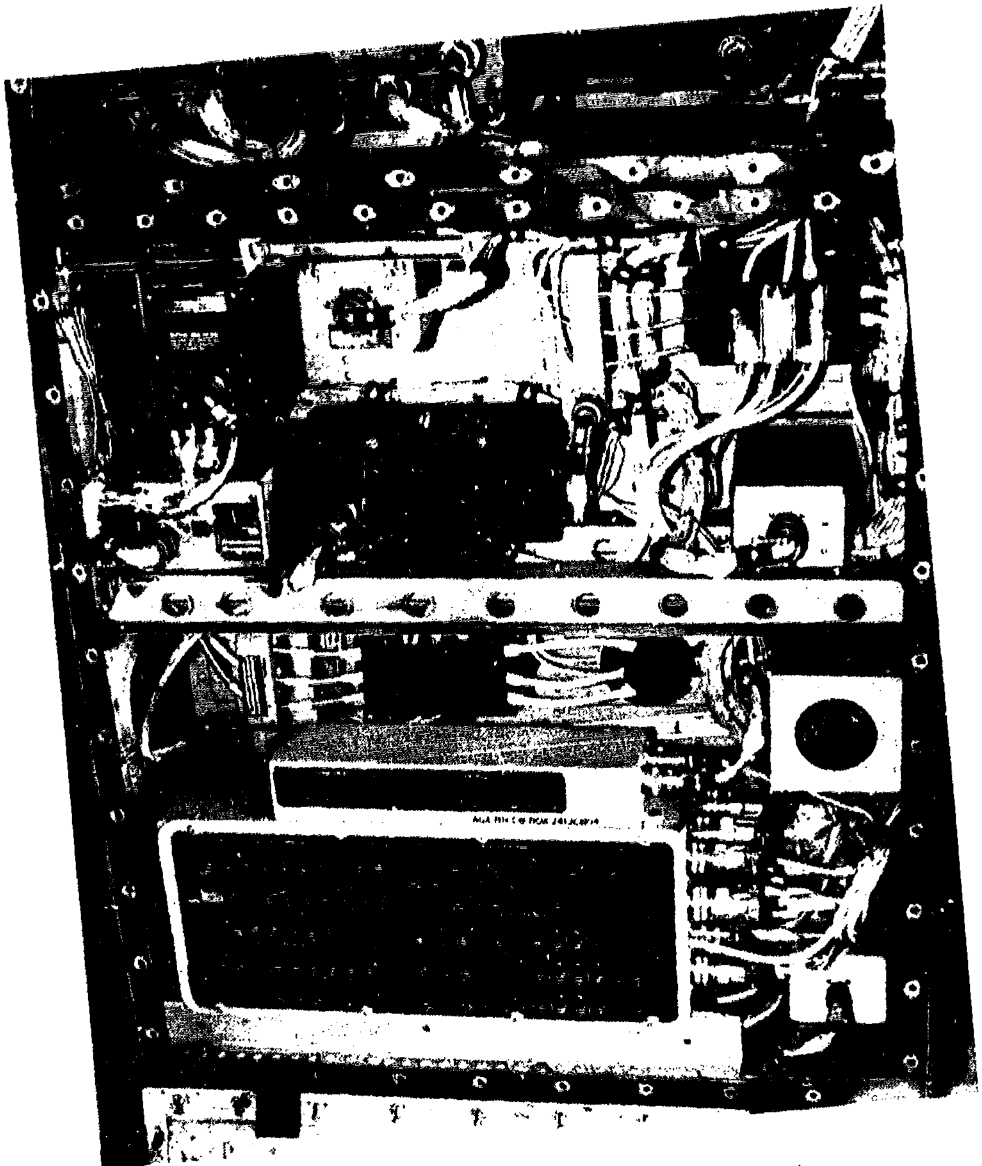


Figure 104. Compartment F12 Before Modification

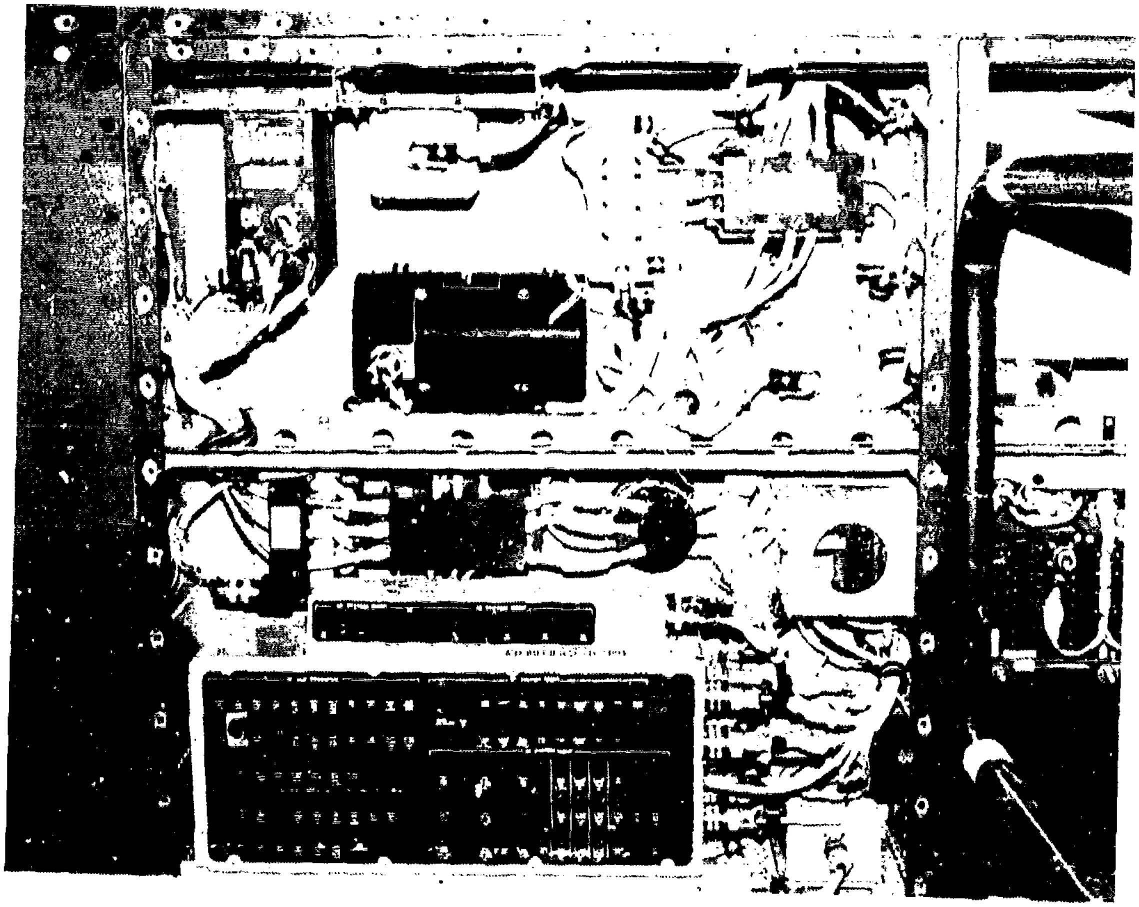


Figure 105. F12 with EP/AP Contactor and Right CTA Replaced

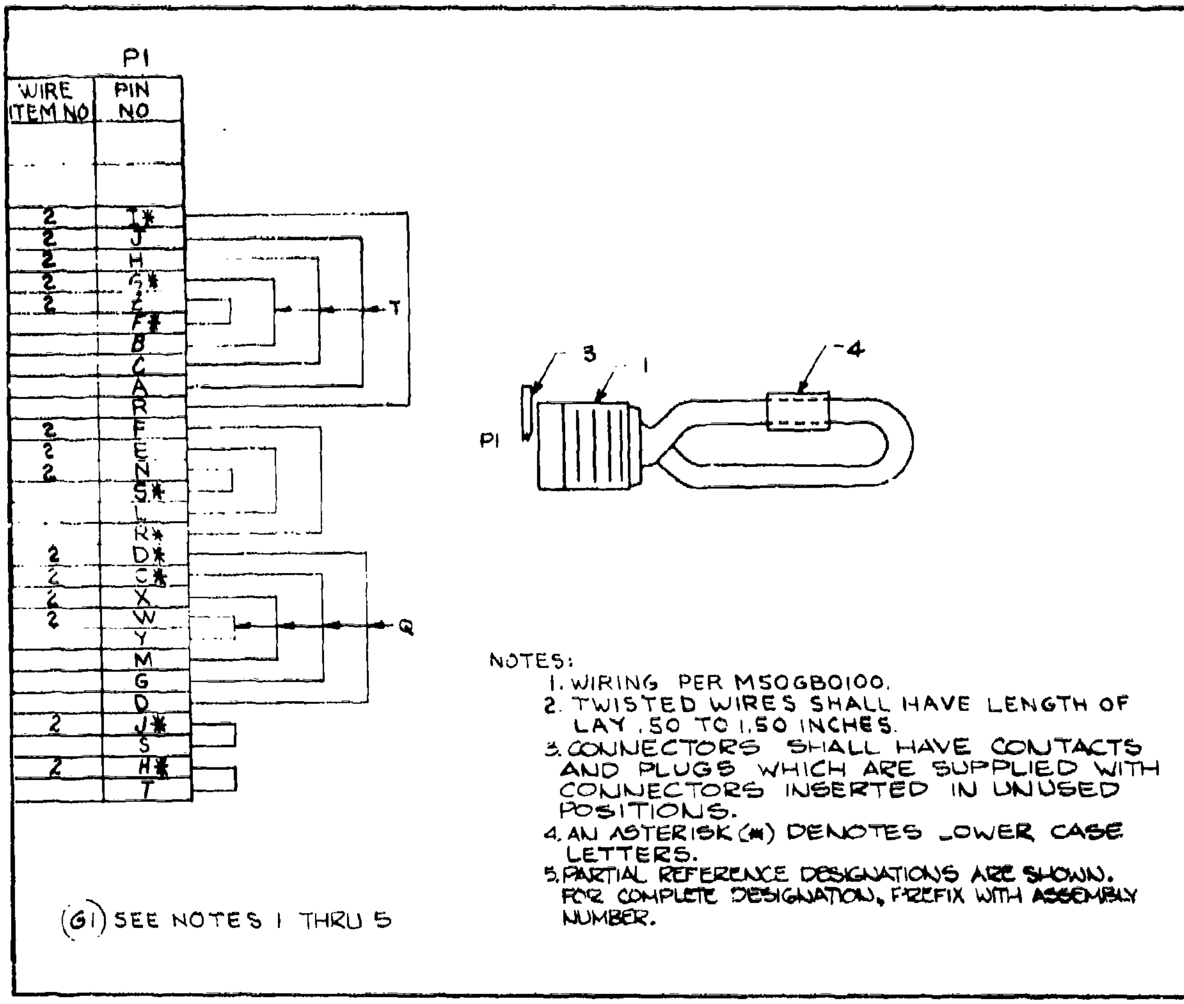


Figure 106. Jumper Cable Drawing

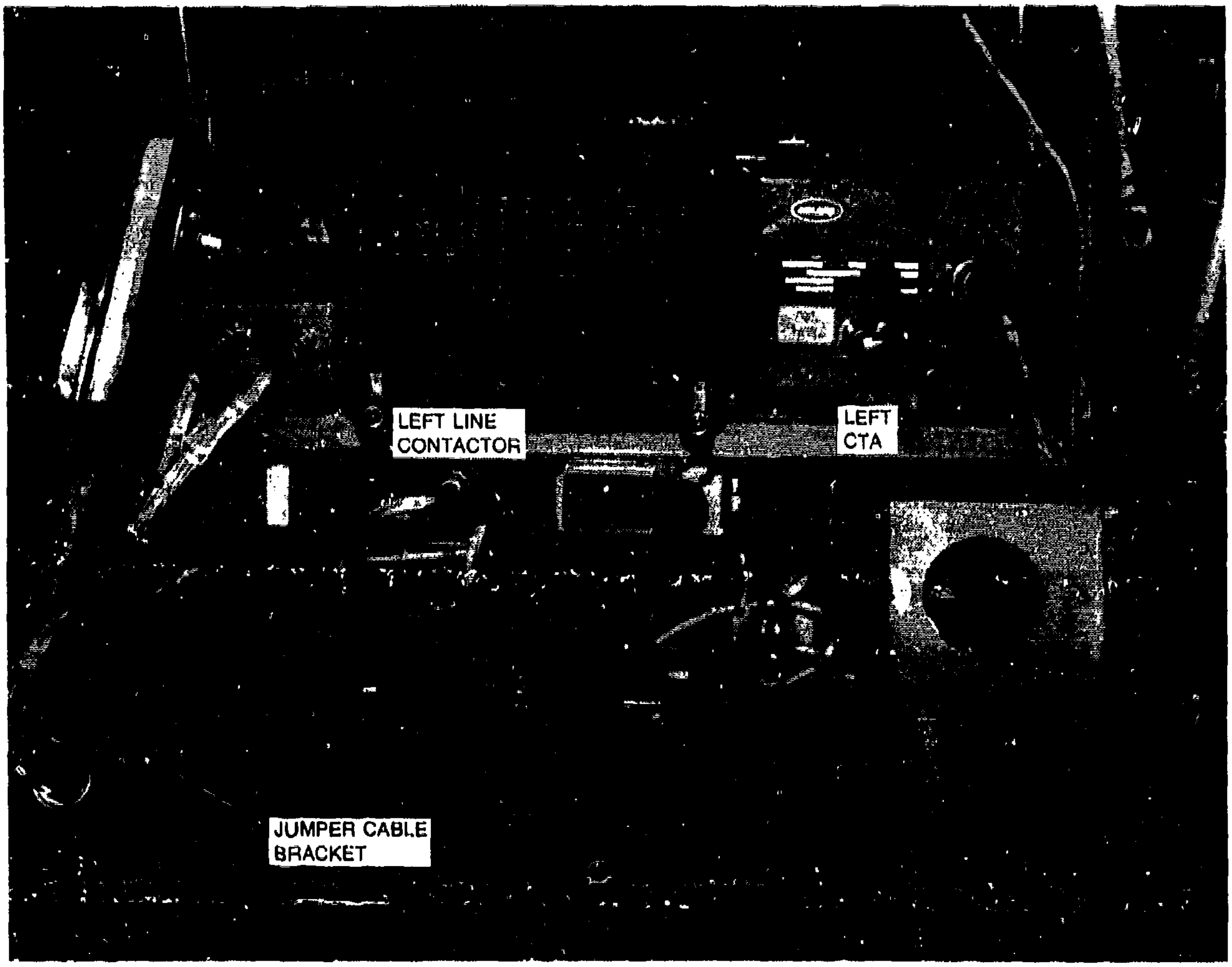


Figure 107. Compartment F101 During Modification

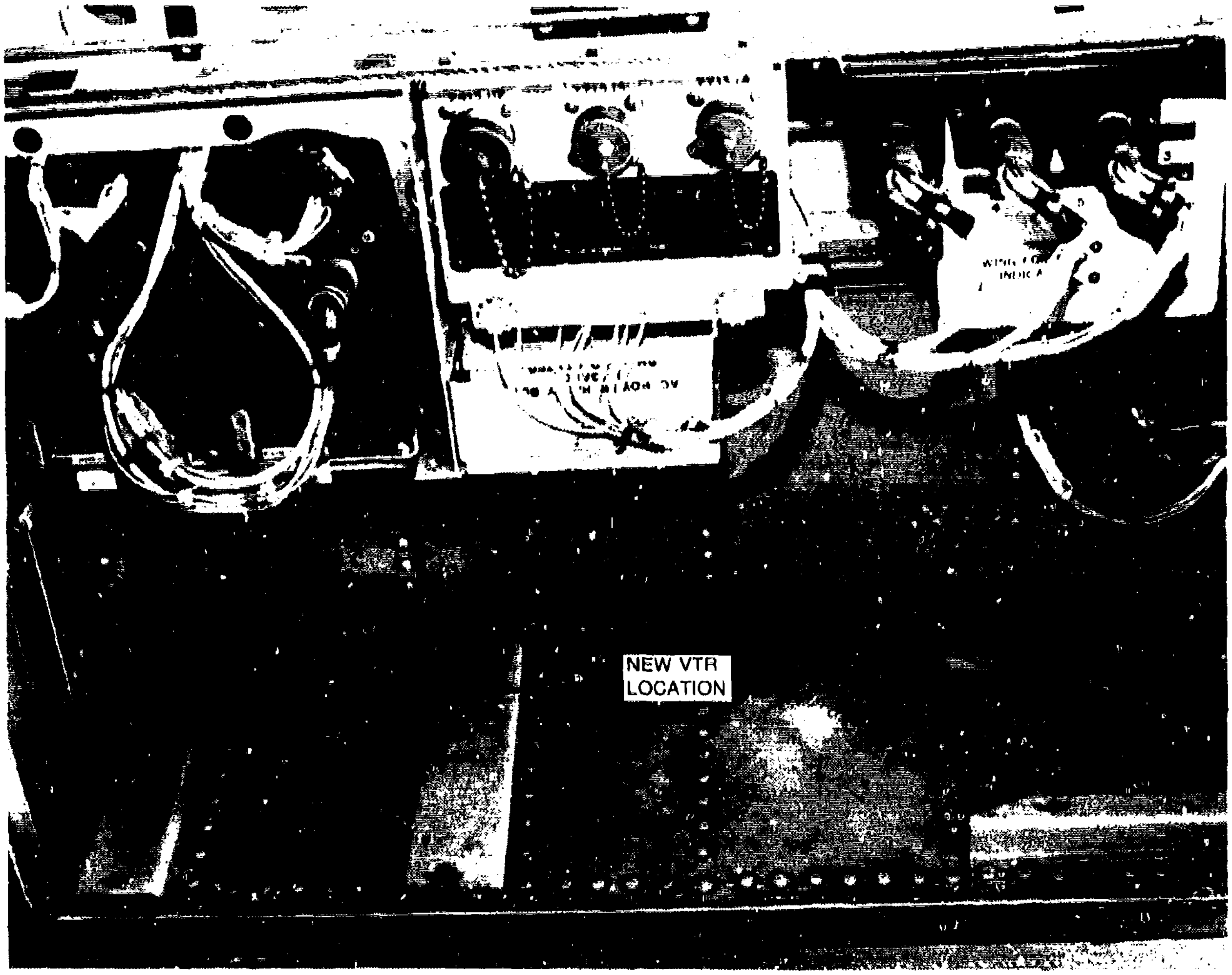


Figure 108. New VTR Location in Compartment F10

3.6.2.7 Converter Mounting

The converters were mounted in the aft position of the A-10A A/C fuselage between stations 639 and 659.

The rack that supports the converters is composed of longitudinal rails. These rails are attached to vertical supports which, in turn, are secured to the A/C formers, STA 639.38 (Fairchild drawing number 160D312009) at the forward end, and STA 659.08 (Fairchild drawing number 160D312010) at the aft end.

The modification to both formers is similar, with only geometrical differences in shape. Modification description of the STA 659 former follows the differences that are noted for the STA 639 former.

Details of the sheet-metal work and installation are in the modification document. Photos of this compartment are shown in Figures 109, 110, and 111.

3.6.2.8 Inlet and Exhaust Scoop Installation

3.6.2.8.1 Inlet Scoop

The inlet scoop is mounted in the hydraulic compartment access door, STA 599.96 to 619.68, F51 (Fairchild drawing 160D315004). The completed door is shown in Figure 112.

The throat opening of the scoop was designed to minimize the pressure drop to the converter under self-ventilated operating conditions on the ground.

- Modification of F51 door:
    1. Cutting a rectangular hole, approximately 7" x 3" with rounded corners, through the door skin.
    2. On the outer surface of the door skin, install the reinforcing doubler, centered over the scoop cutout. Bond the doubler to the skin, and secure it with fasteners that are common to the door skin and new doubler only (new locations).
    3. The scoop is attached to the door and new doubler by angles on the inside surface of the door. Bond the angles to the door, and secure them with fasteners through flange skin and doubler. The leading edge of the scoop is also attached to the doubler and door skin through the leading edge ramp (new locations).

3.6.2.8.2 Exhaust Scoop

The cooling air exhaust scoop is mounted to the aft fuselage lower door, STA 659.08 to 678.80, F57 (Fairchild drawing number 160D315005). A photo of the completed door is shown in Figure 113.

- Modification of F57 door:
    1. Cut a rectangular hole, approximately 3 7/8" x 16" with rounded corners, through the door skin. Note skin is chem-milled in cutout portion and, also, cutout does not extend through any door stiffeners.
    2. On the outer surface of the door skin, install the reinforcing doubler, centered over the scoop cutout. Bond the doubler to the skin, and secure it with fasteners that are common to the skin and new doubler only (mostly new locations, but also four existing stiffener locations).
    3. On the outer surface of the reinforcing doubler, install the exhaust scoop, centered over the opening. Bond the scoop flange to the doubler, and secure it with fasteners through flange skin and doubler (new locations).

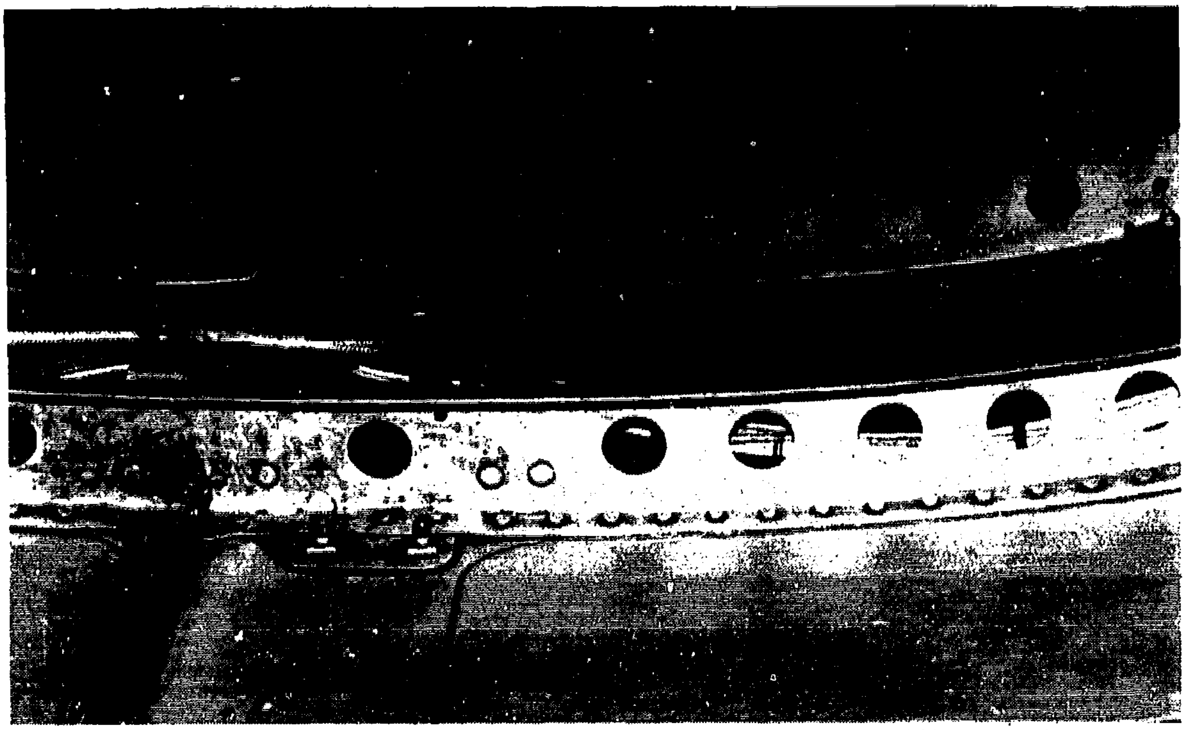


Figure 109. Back Compartment Before Modification, Showing Original VTR Location

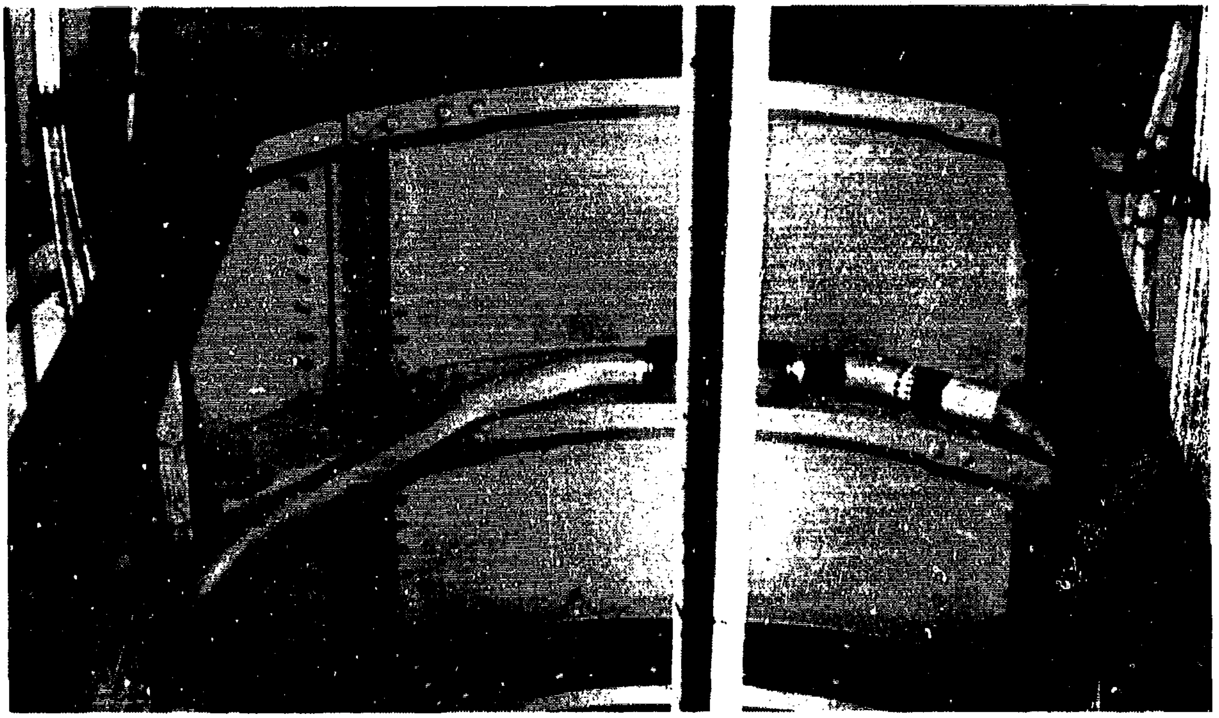


Figure 110. Back Compartment During Modification, Showing Back Support Bars in Place

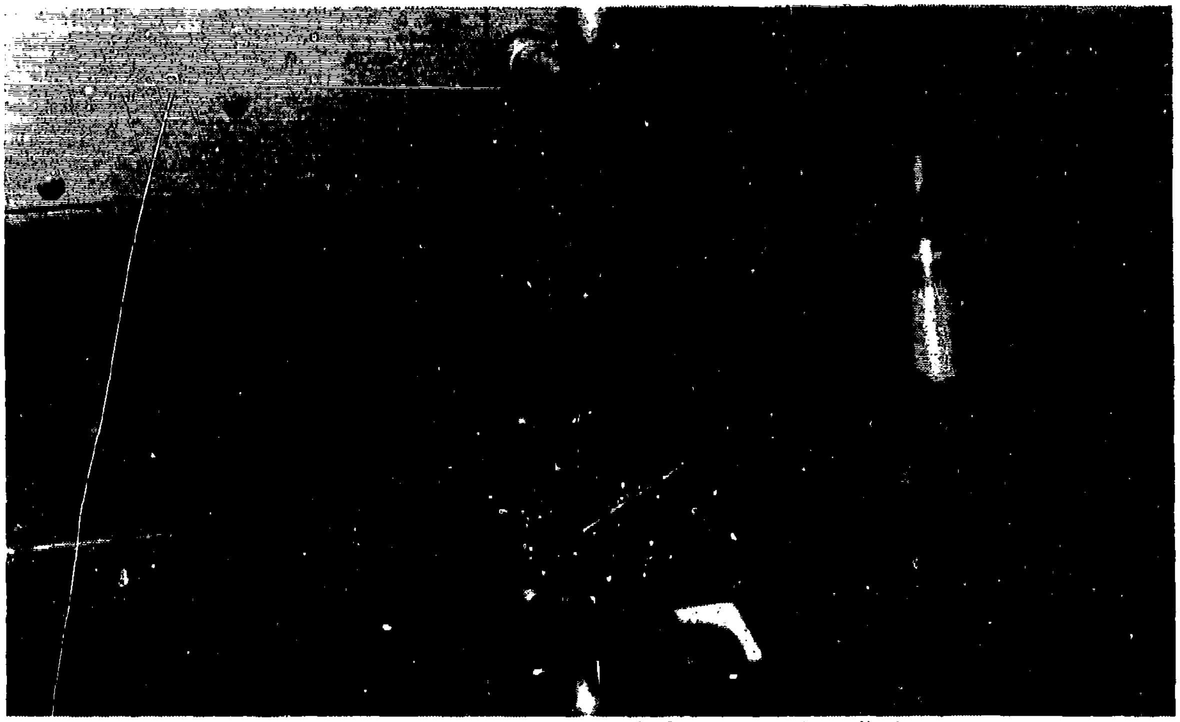


Figure 111. Completed Rock with Converters Installed

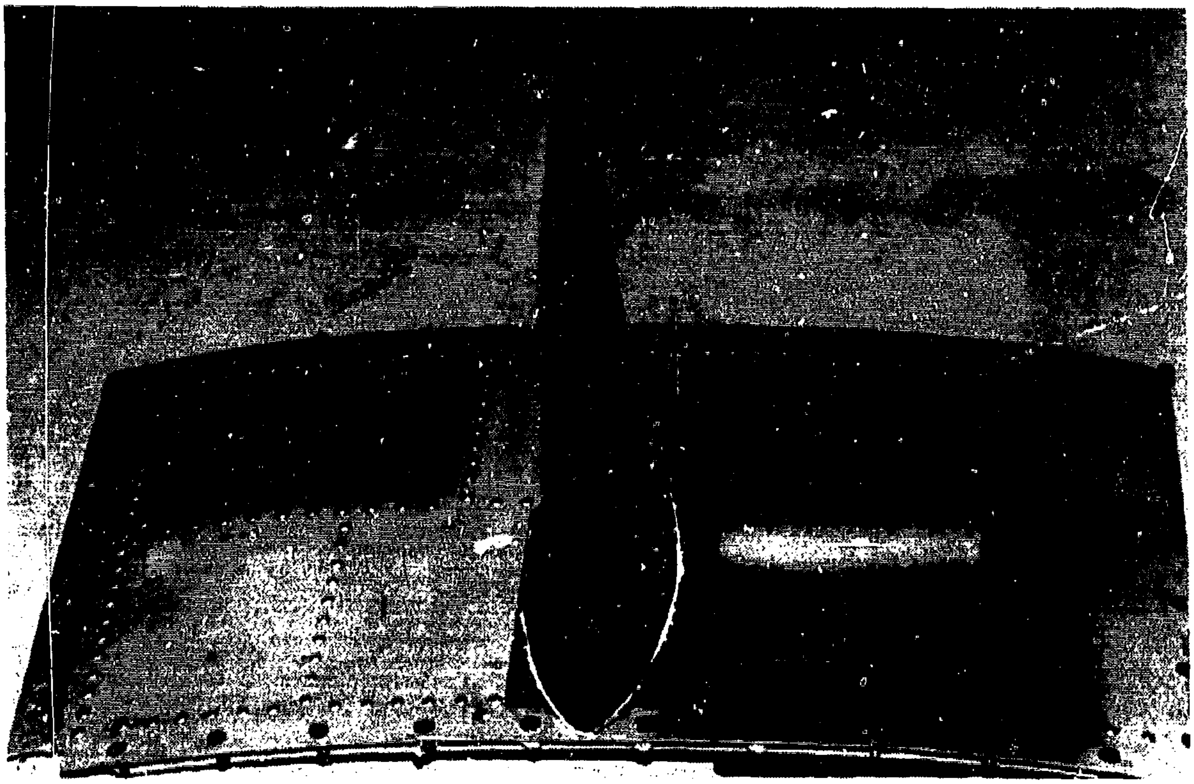


Figure 112. Modified F51 Door with Inlet Scoop

3.6.2.9 Inlet Duct Installation

The inlet duct interfaces the converter air inlet with a KISS-type rubber seal. The vertical portion of the inlet scoop slides inside the duct as the door closes and interfaces with the inlet duct, utilizing a rubber KISS-type seal. Both interfaces are shrouded to provide a guide for alignment. Support for the inlet duct is provided by two transverse members. These two transverse supports tie into the formers, just above the lower longeron, with NAS series steel bolts. A single-bolt connection is used at each end of the lateral supports, and one hole is slotted to allow for flex. A photo of the duct, installed in the A/C mock-up, is shown in Figure 114.

3.6.2.10 Starter-Generator Installation

The engine-driven Integrated Drive Generator (IDG) (Fairchild drawing number 160C645905) was removed on both engines and replaced with the PM VSCF starter-generator/gearbox package, using the same mounting and mounting hardware, see Figure 115 for IDG location.

The PM VSCF starter-generator unit is not identical to the IDG in form factor, but it was fit checked on A-10A aircraft at Nellis AFB before the modification.

Existing oil lines that go to the IDG heat exchanger were attached to the oil-in and oil-out ports on the starter-generator.

A photo of the IDG that is installed on the engine is shown in Figure 116. A photo of the engine with the IDG removed is shown in Figure 117. A photo of the VSCF starter-generator, installed on the engine, is shown in Figure 118.

3.6.2.11 Generator Power Cable Installation (Engine Mounted)

The right and left engine IDG power cable, (Fairchild drawing number 160D441003), identified as W4003, that goes from the IDG terminal block to the engine fire-wall area, was removed and replaced with cable assembly and junction box (GE drawing number 936E840, see Figure 119).

The cable assembly has three cables suspended from it, with each cable containing eleven AWG #12 wires. Both ends of these cables are terminated with eleven pin connectors, which are keyed to prevent connection to the wrong mating connector.

The suspended cable connectors were attached to the flight test starter-generator/gearbox connectors J1, J2, and J3. The engine fuel distributor overboard drain, 160B960382-1, interfered with the J2 cable. A bracket was fabricated and installed to relocate this line approximately two inches lower, see Figure 120.

The junction-box mounted connectors serve as the engine fire wall interface seal and as a quick-disconnect means of allowing engine removal from the pylon.

The routing of the cables was along the same path as the W4003 cable assembly that was removed. This path is over the engine thermocouple probes as seen in Figures 121 and 122. The existing cable tie points were used. Similar cable clamps (same basic NAS part number, except the size was changed) were used to mount the larger cable bundle. These three cables were routed through the IDG connector mounting hole in the engine pylon floor, and they were clamped inside the junction box to provide strain relief and to assure that the cables do not rub on the edges of this hole. Limited space in this area precludes the use of individual connector back-shell mounted cable clamps.

The IDG connector hole was not large enough to pass all three cables through with the connectors mounted. It was necessary, therefore, to install the generator connectors after the cables had been passed through the engine pylon floor, see Figure 123.

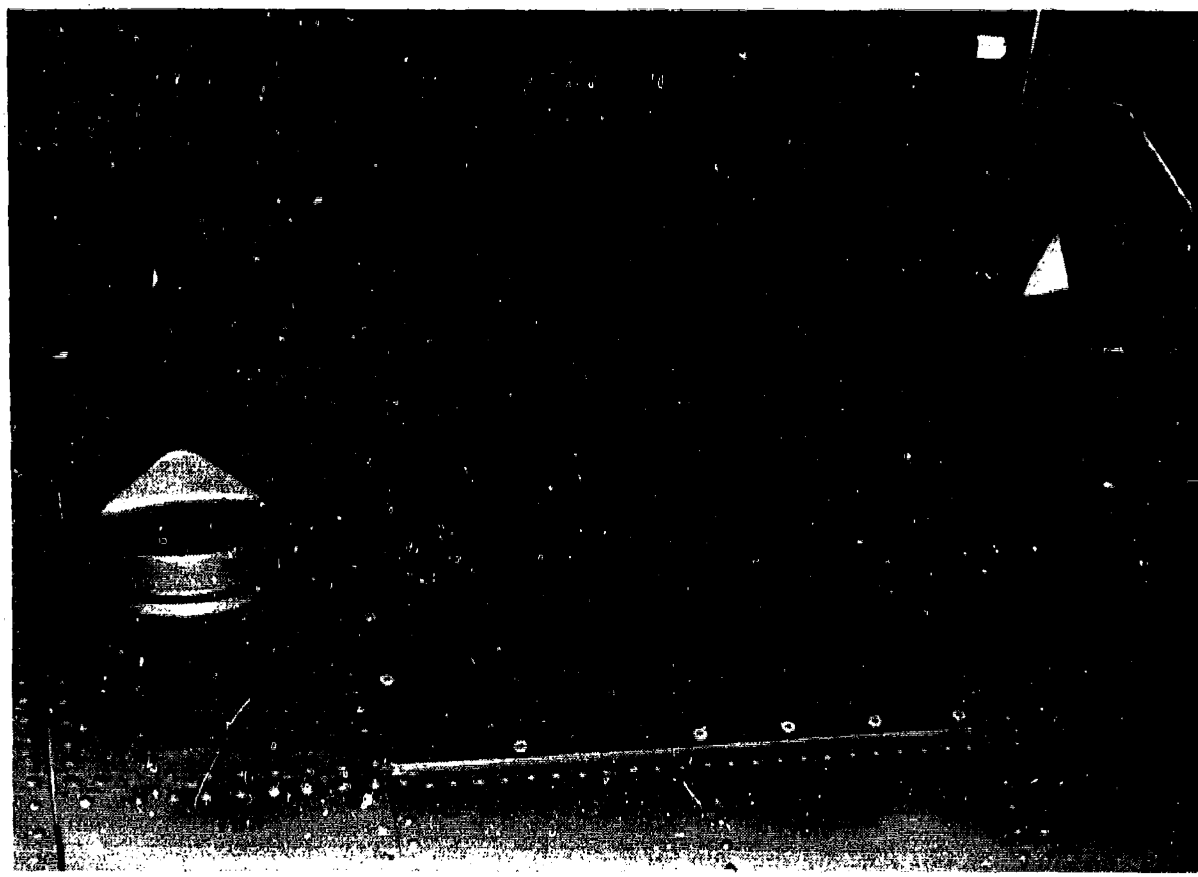


Figure 113. F57 Door with Exhaust Scoop In Place

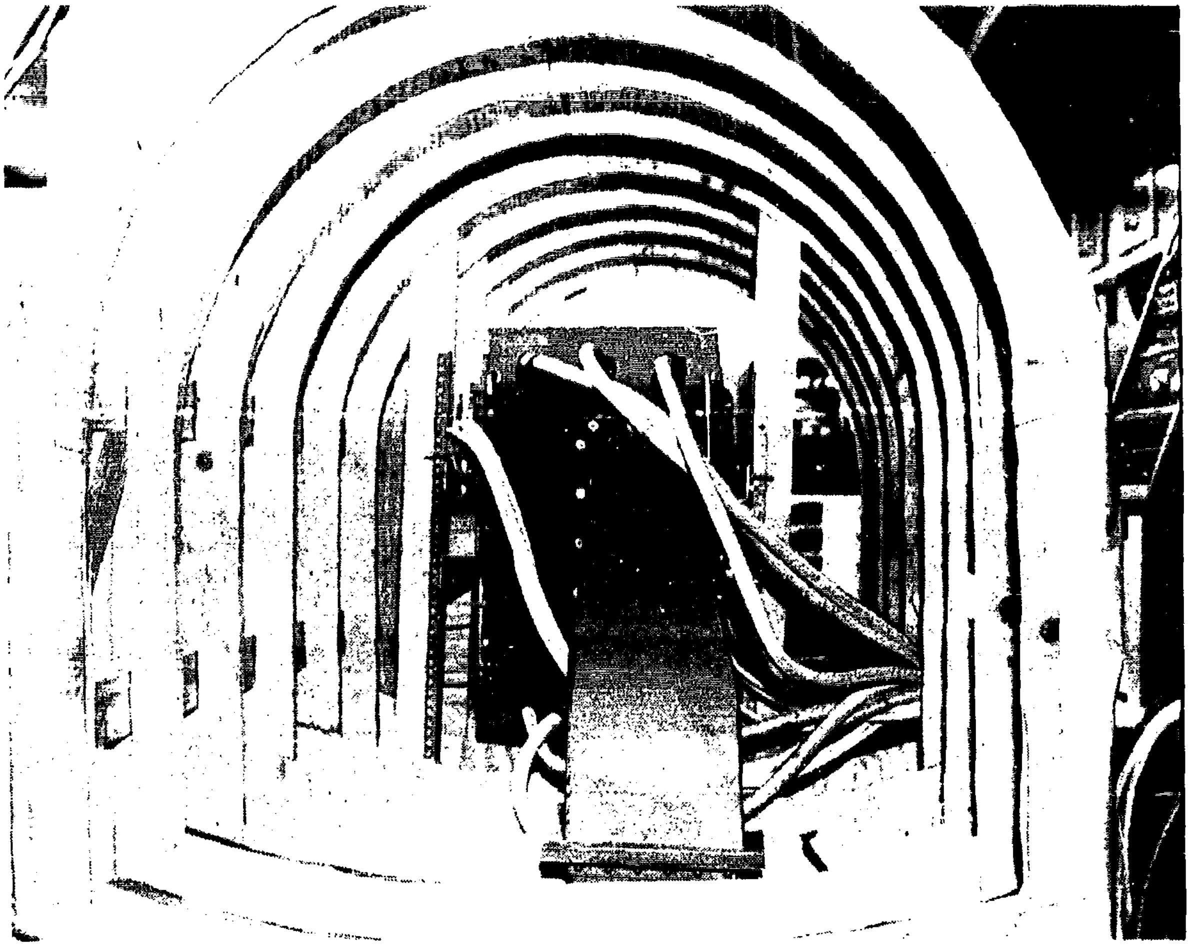


Figure 114. Inlet Duct Installed in Aircraft Mock-up

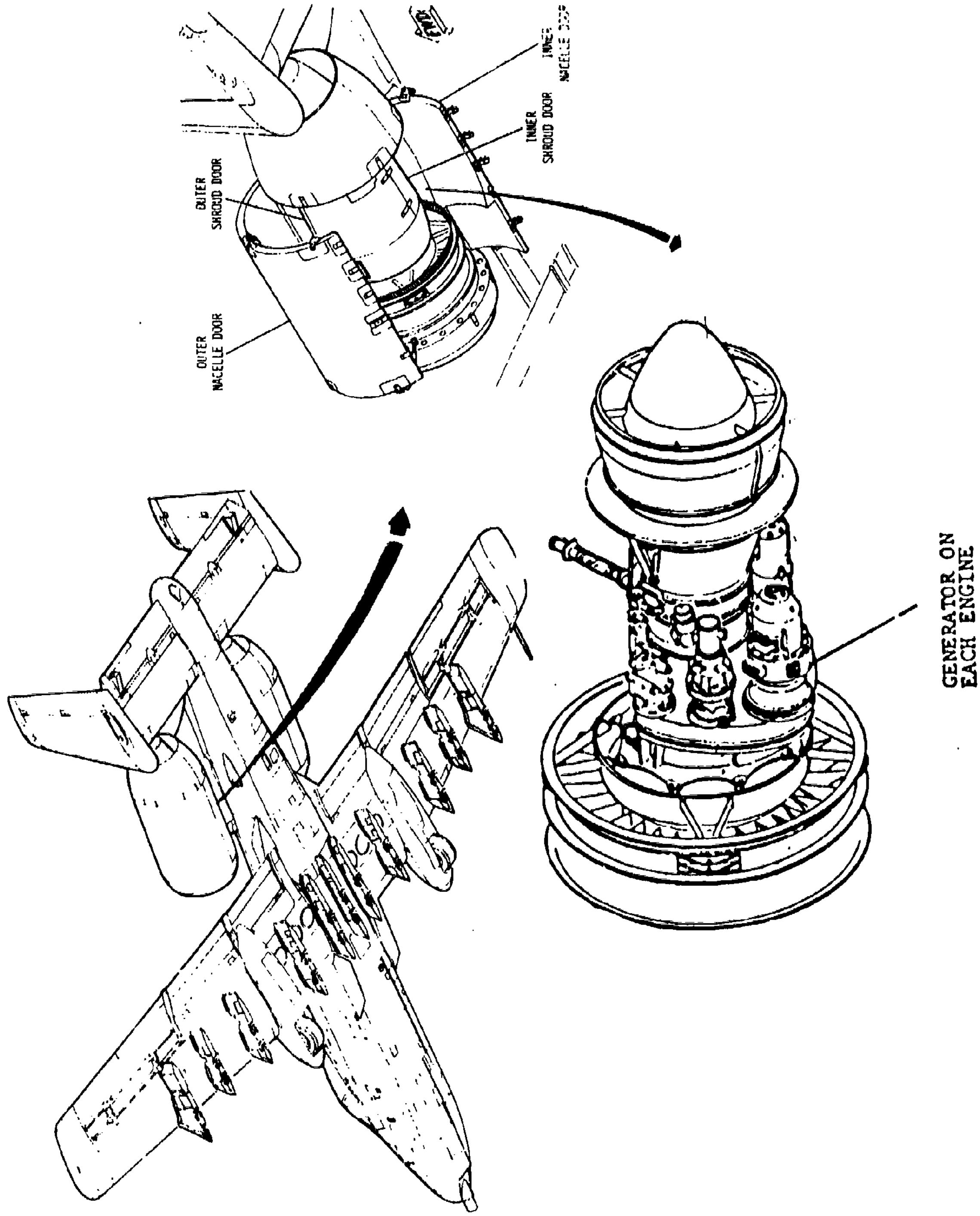


Figure 115. IDG Location

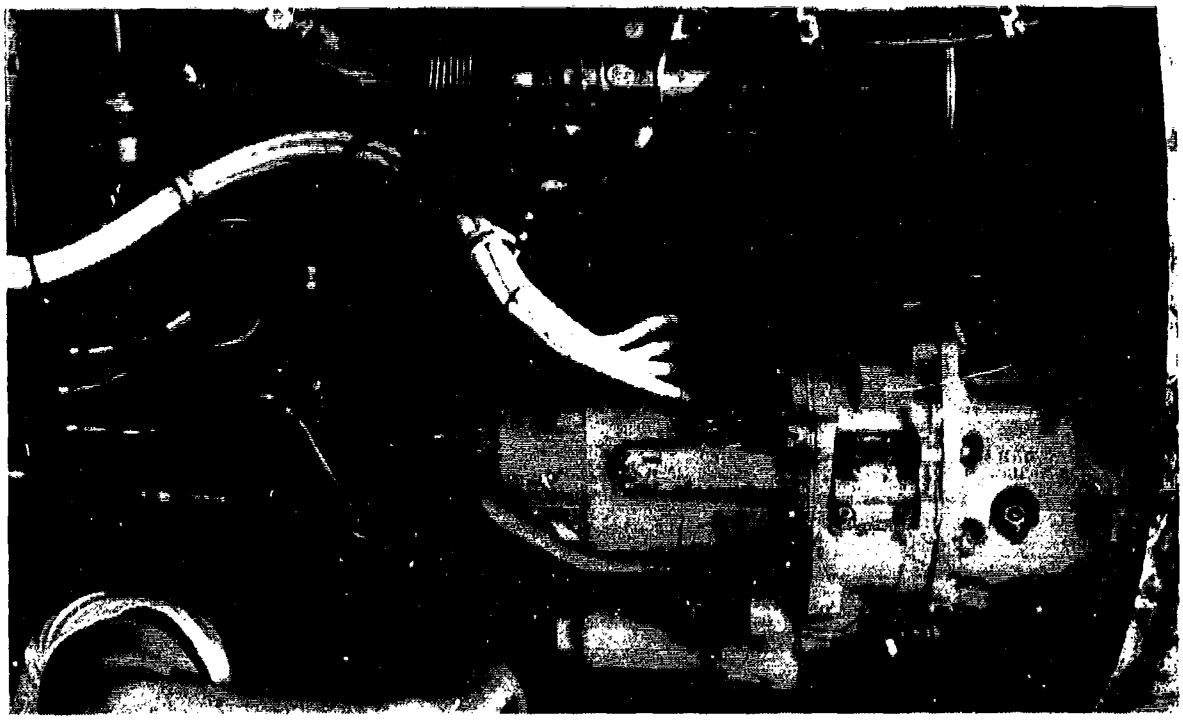


Figure 116. IDG Generator Installed on Engine

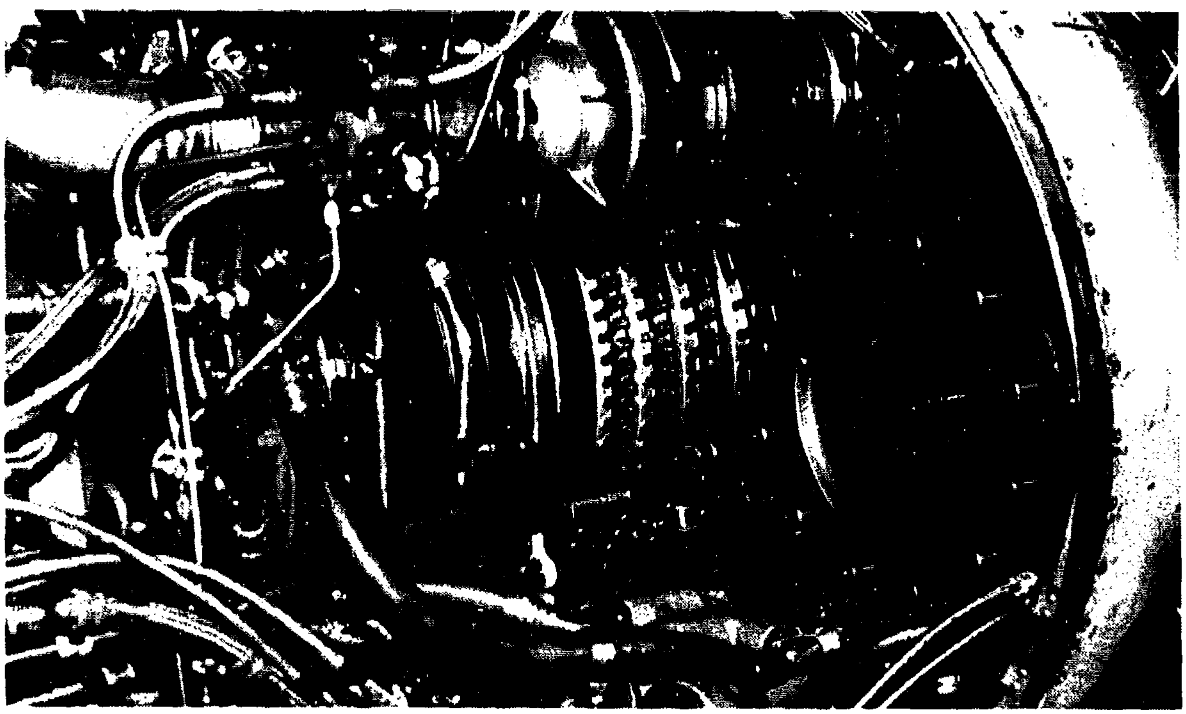


Figure 117. Engine with IDG Generator Removed

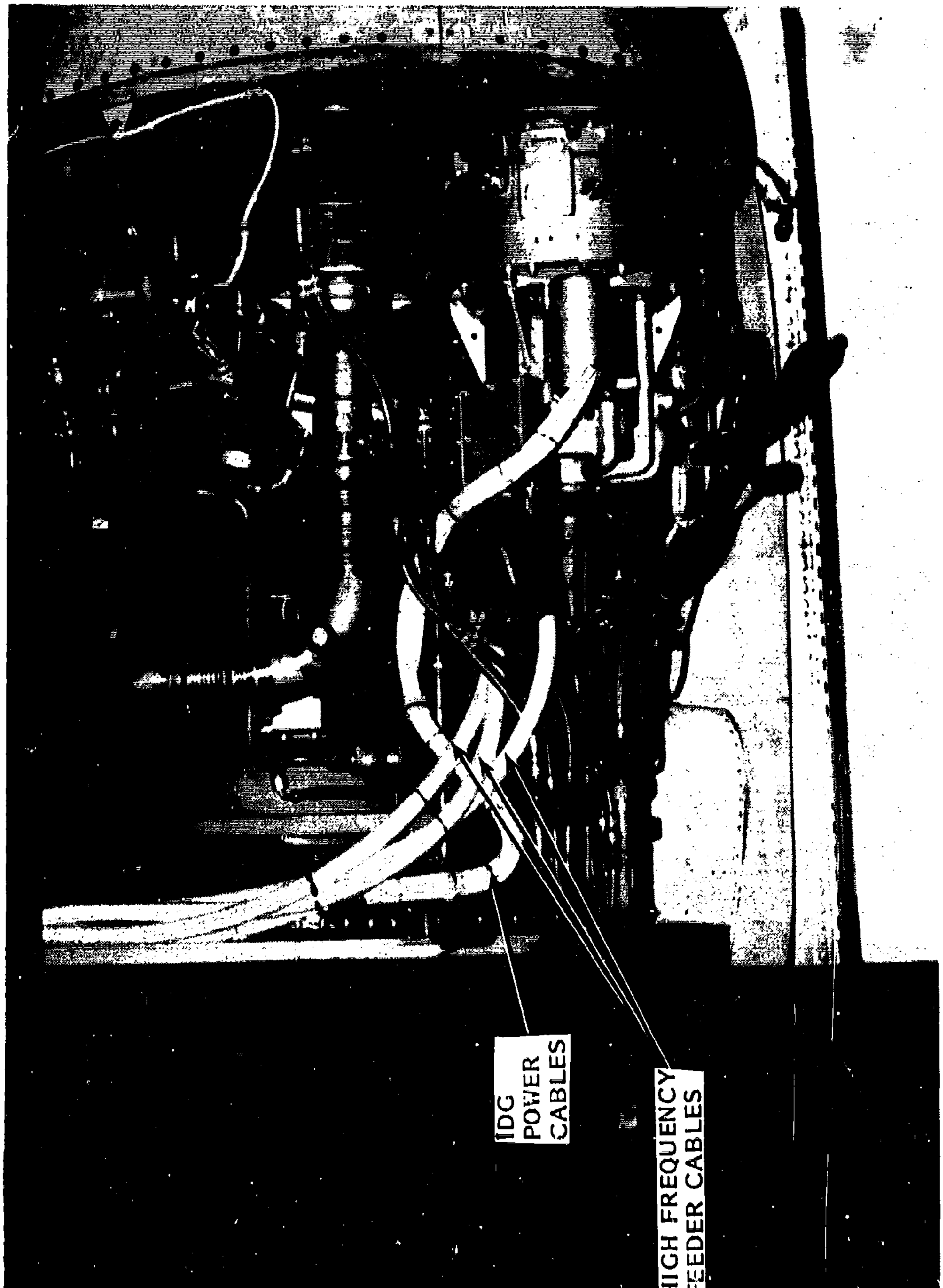


Figure 118. PM Generator/Gearbox Assembly Installed on TF-34-100 Engine

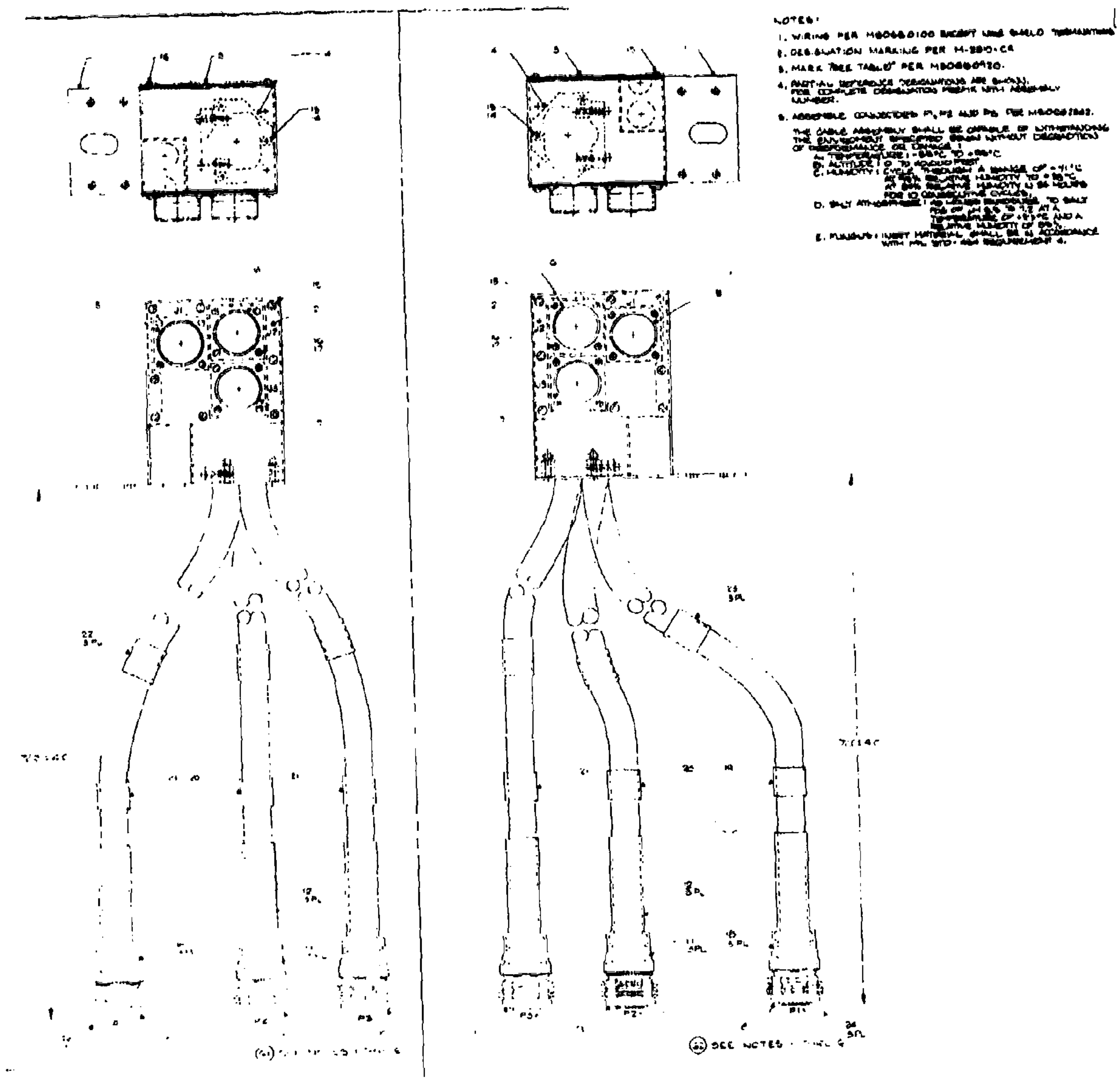


Figure 119. Engine Interface (Doghouse) Assembly

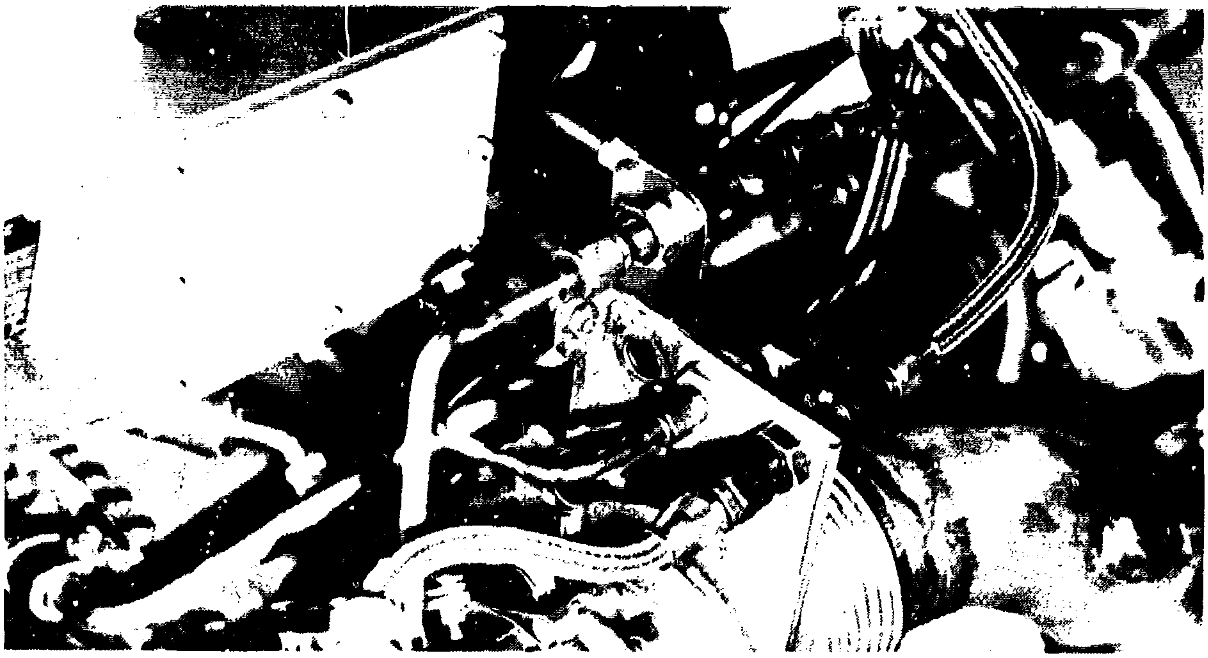


Figure 120. Bracket Fabricated to Relocate Drain Line

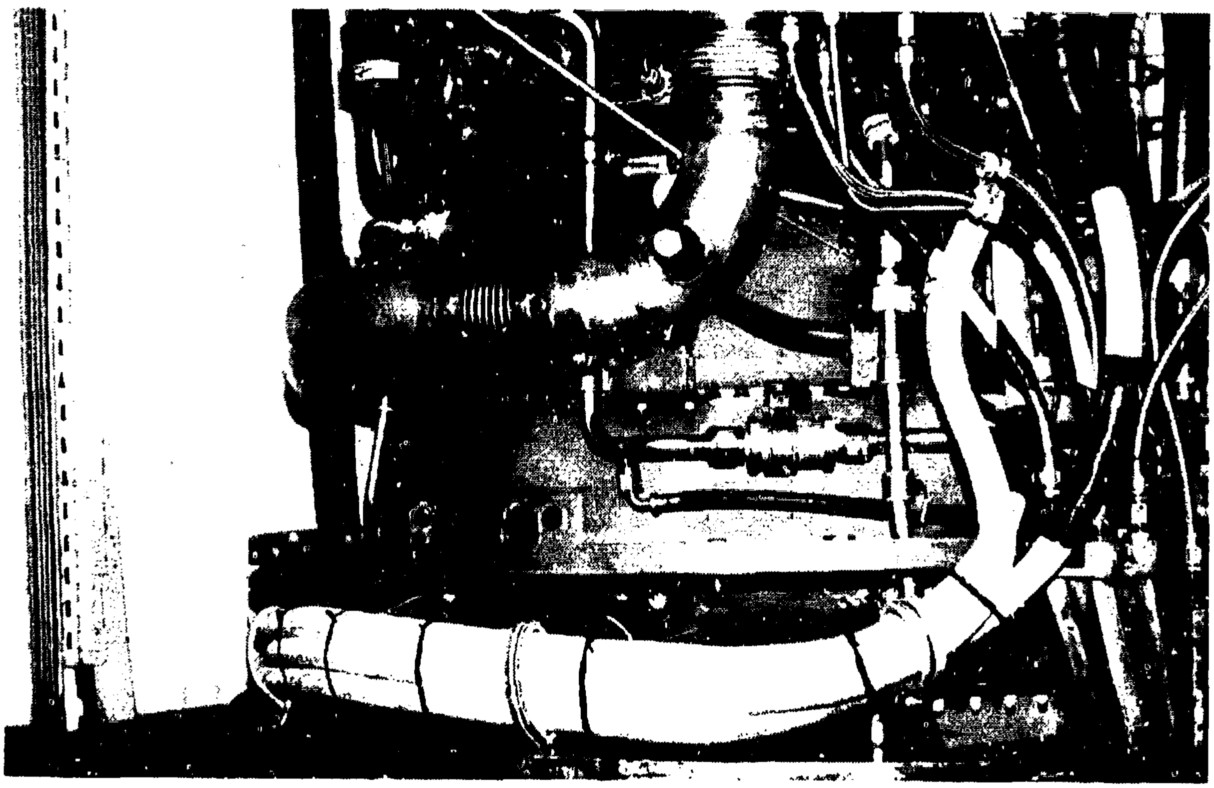


Figure 121. High-Frequency Feeder Cable Routing—Generator End

Figure 122. High-Frequency Feeder Cable Routing—Pylon End

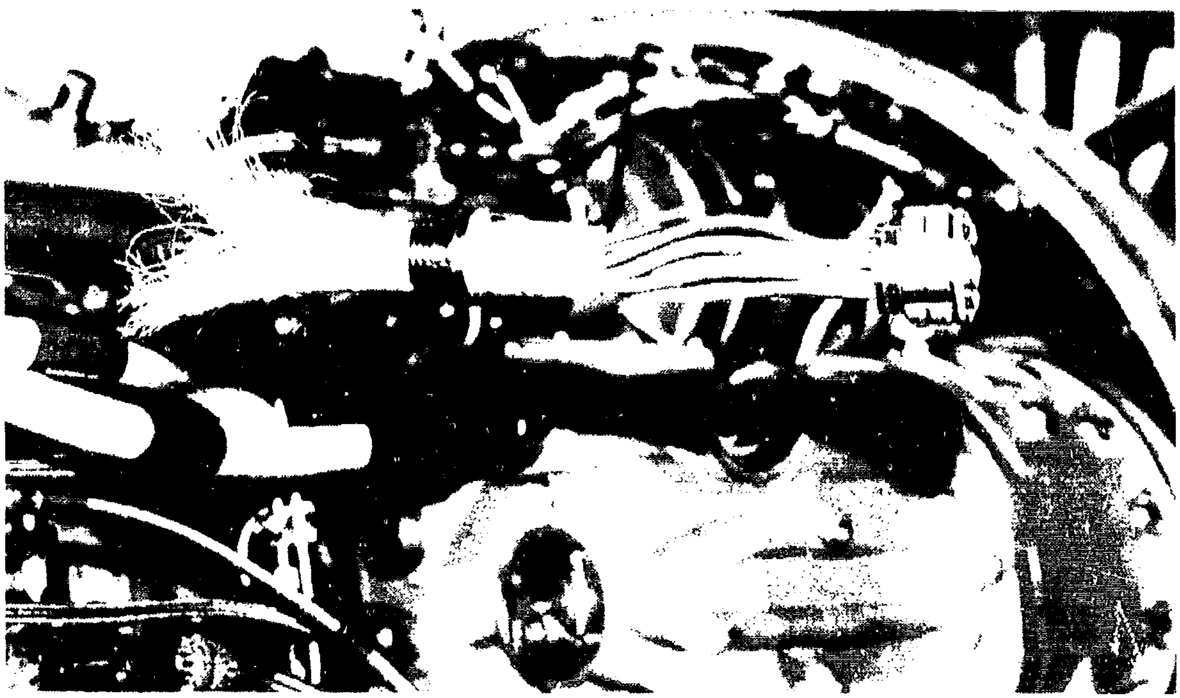


Figure 123. Generator Connector Installation

Removable covers enable the same junction box to be used on both the right and left engine. The junction box connectors face the fuselage to mate with the corresponding aircraft cable.

The junction box is mounted to the engine pylon floor, using the two aft IDG cable connector mounting holes and the four forward engine-hoist access cover mounting holes. The junction box has a floor that serves as a doubler plate to distribute the added load of the junction box.

The existing engine-hoist access plate, (Fairchild drawing number 160D960133) at nacelle station 202, was removed and replaced with an access cover (GE drawing number 172B4923) that attaches to the existing safety chain. The elongated mounting holes in this plate have been rotated 90° to allow removal with the junction box installed.

Clearance is provided in the junction box floor plate and in the lower wall area to clear the 14th-stage bleed fitting (not used on the A-10A) and the engine fire detector (Fairchild drawing number 160C960900-11). However, the engines had received the water-wash modification after the junction box was designed. The pylon floor with the water-wash modification is shown in Figure 124. In this configuration, the water-wash fitting, fire detector, 14th-stage bleed fitting cover plate retaining screw, and the pylon drain fitting screws all interfered with the junction box. The pylon floor on which the box is mounted is double metal, riveted together. Some of these rivets, which face up, also interfered with the box. The problem was solved by fabricating a new cover plate and following these instructions, see Figures 125 through 129.

- Remove 14th-stage bleed fitting hole cover plate.
- Remove water-wash fitting.
- Remove fire detector plug.
- Remove two screws from pylon drain fitting, which interfere, and replace with downward facing rivets.
- Drill hole to mount fire detector in original location.
- Remove any interfering upward facing rivets and reinstall facing down.
- Install new hole cover plate, using outboard screw from original hole cover plate and fire-detector plug in hole just drilled. The fire-detector plug requires an additional jam nut under the floor so that the fitting only protrudes 8-10 threads above upper nut for clearance. Apply RTV under new cover plate for sealing.
- Put rubber gasket around original IDG connector hole, under junction box.
- Fill unused IDG connector holes with RTV.
- Mount box, using six screws. A special apex (7/64" allen) is required for the two bottom screws.
- Drill hole in new engine-hoist cover plate for water-wash fitting.
- Install engine-hoist cover plate.
- Install water-wash fitting.

3.6.2.12 Generator Control Cable Installation (Engine Mounted)

The right and left engine IDG control cable was removed and replaced with cable assembly, GE drawing number 143D6413, see Figure 130 for location.

The same cable routing and cable tie points were used to mount this cable on the engine. The P1 connector for this cable uses the same part to enable mounting in the same location as the existing connector on the housing assembly. The P2 cable connector mates with the J4 connector on the aft end of the starter-generator assembly, and the P3 cable connector mates with the adaptive gearbox connector J1.

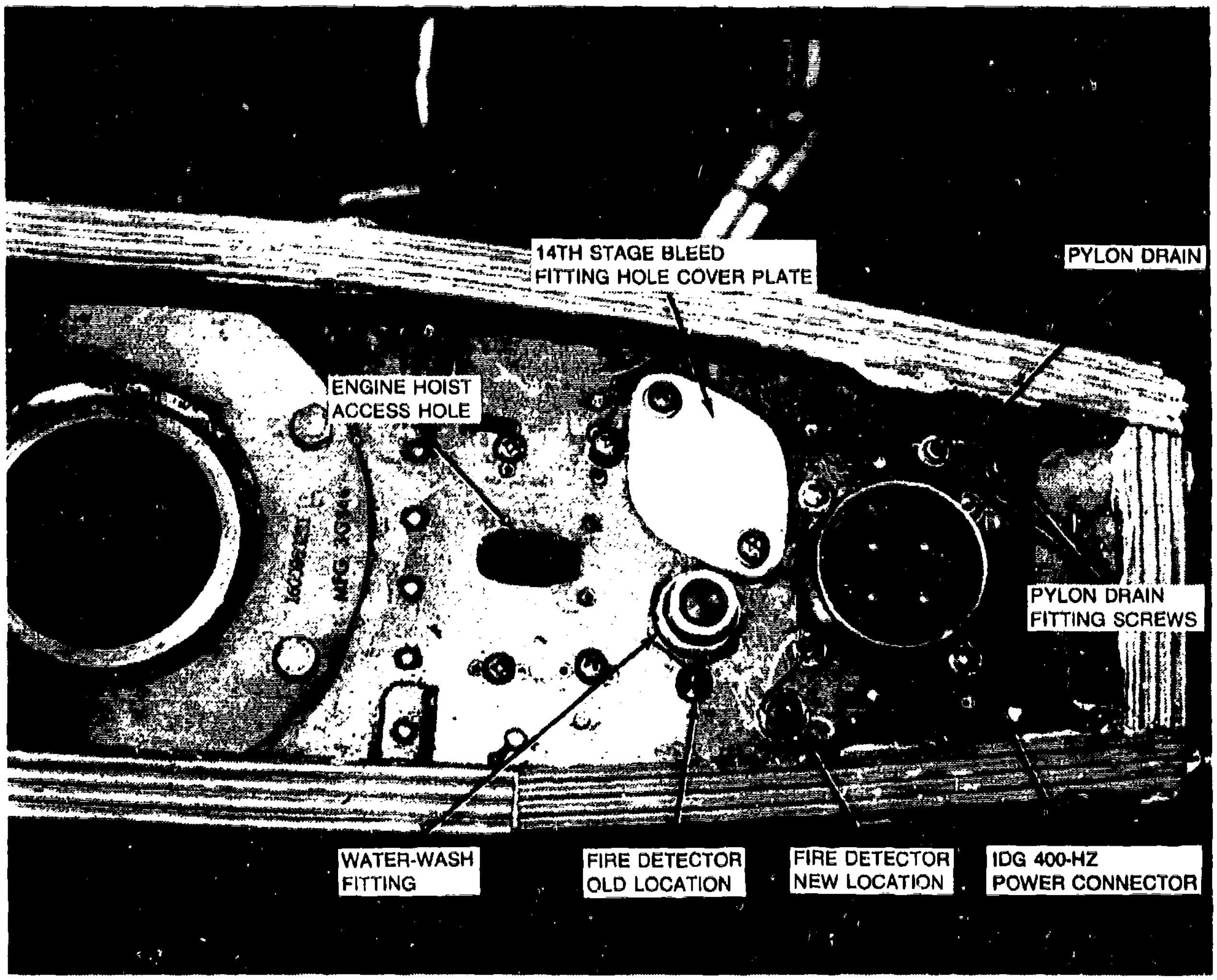


Figure 124. Pylon Floor with Water-Wash Modification Before GE Modification

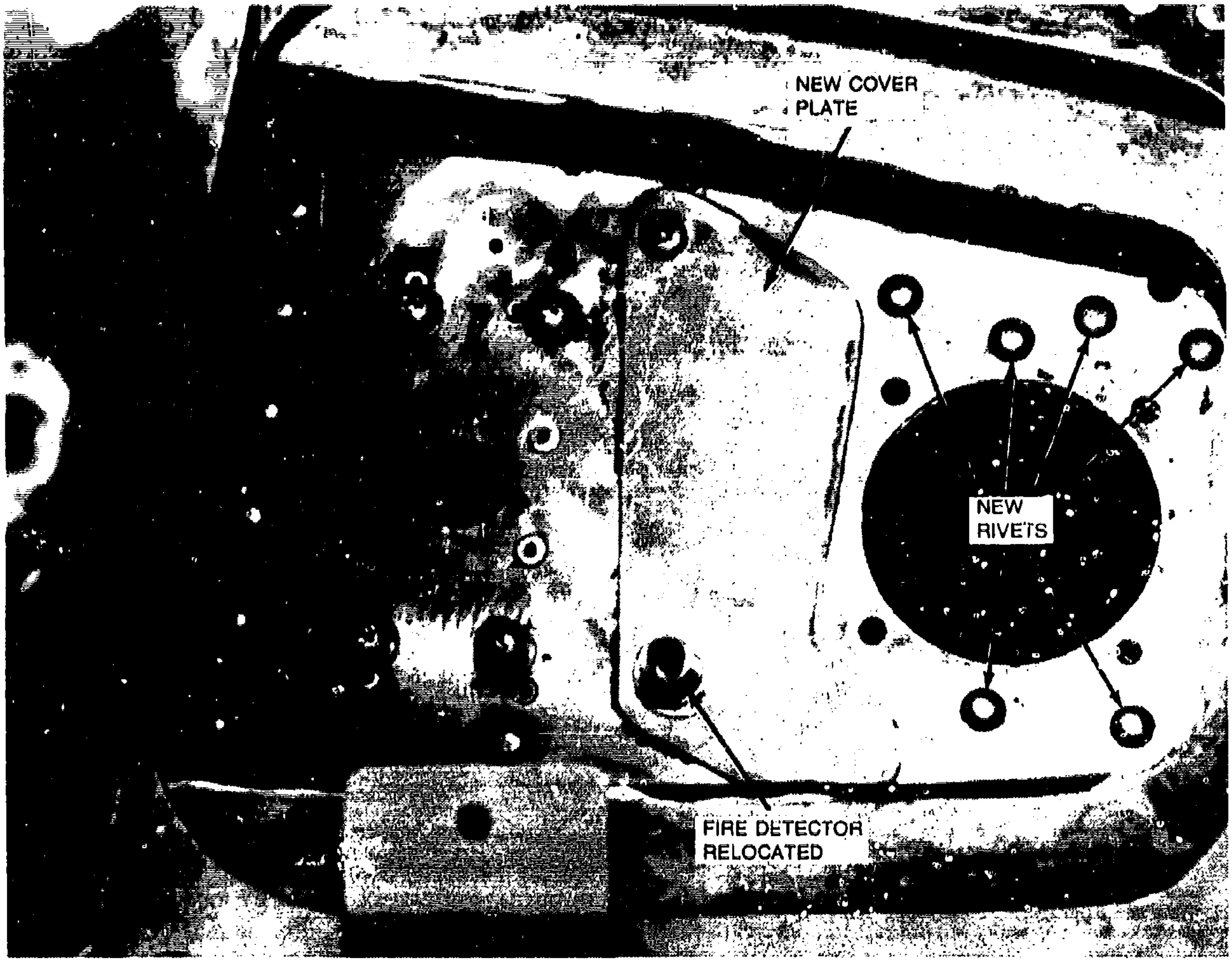


Figure 125. Pylon Floor After GE Modification

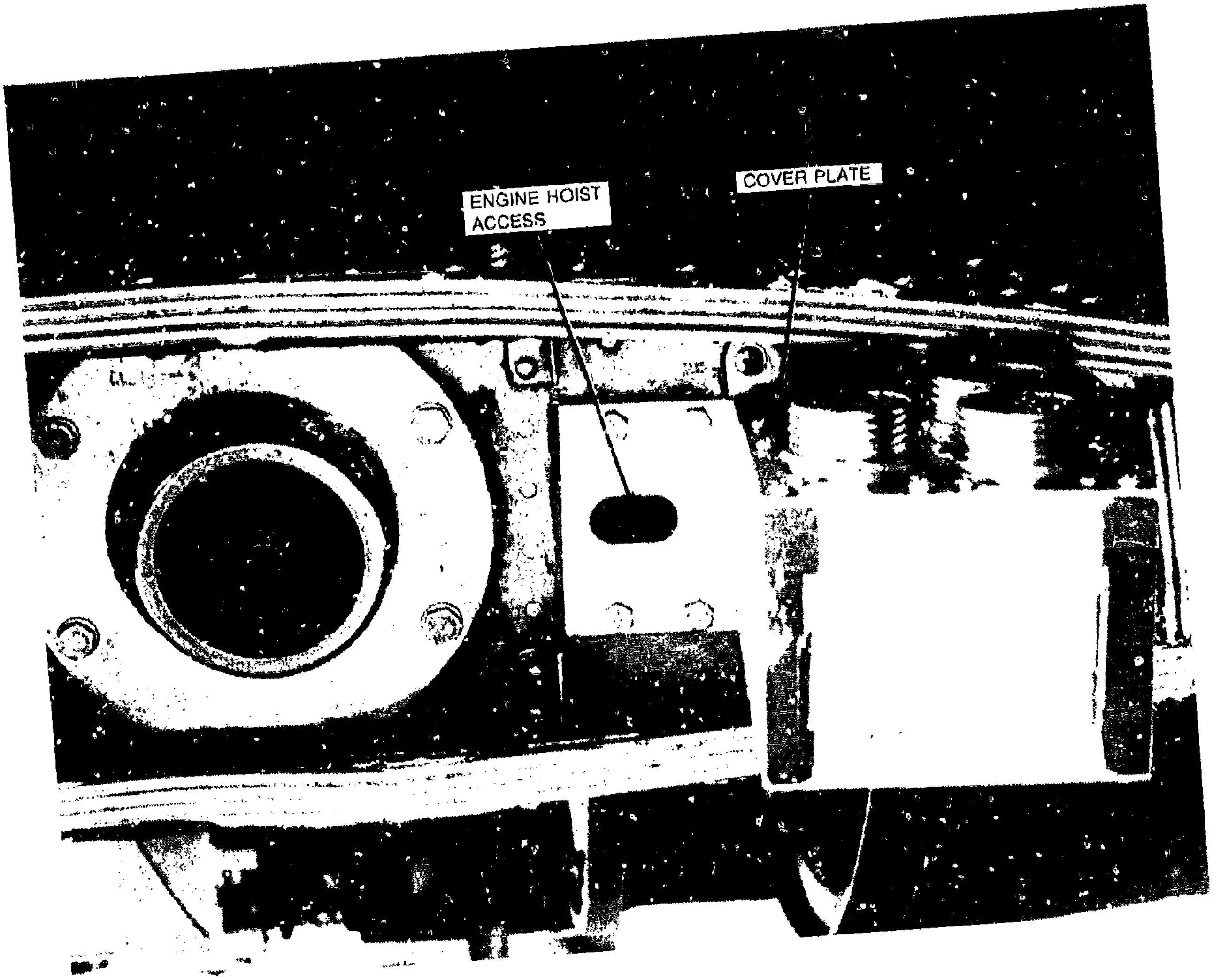


Figure 126. Junction Box Installed During Modification

Figure 127. Junction Box Installed During Modification with Engine-Hoist Cover Plate

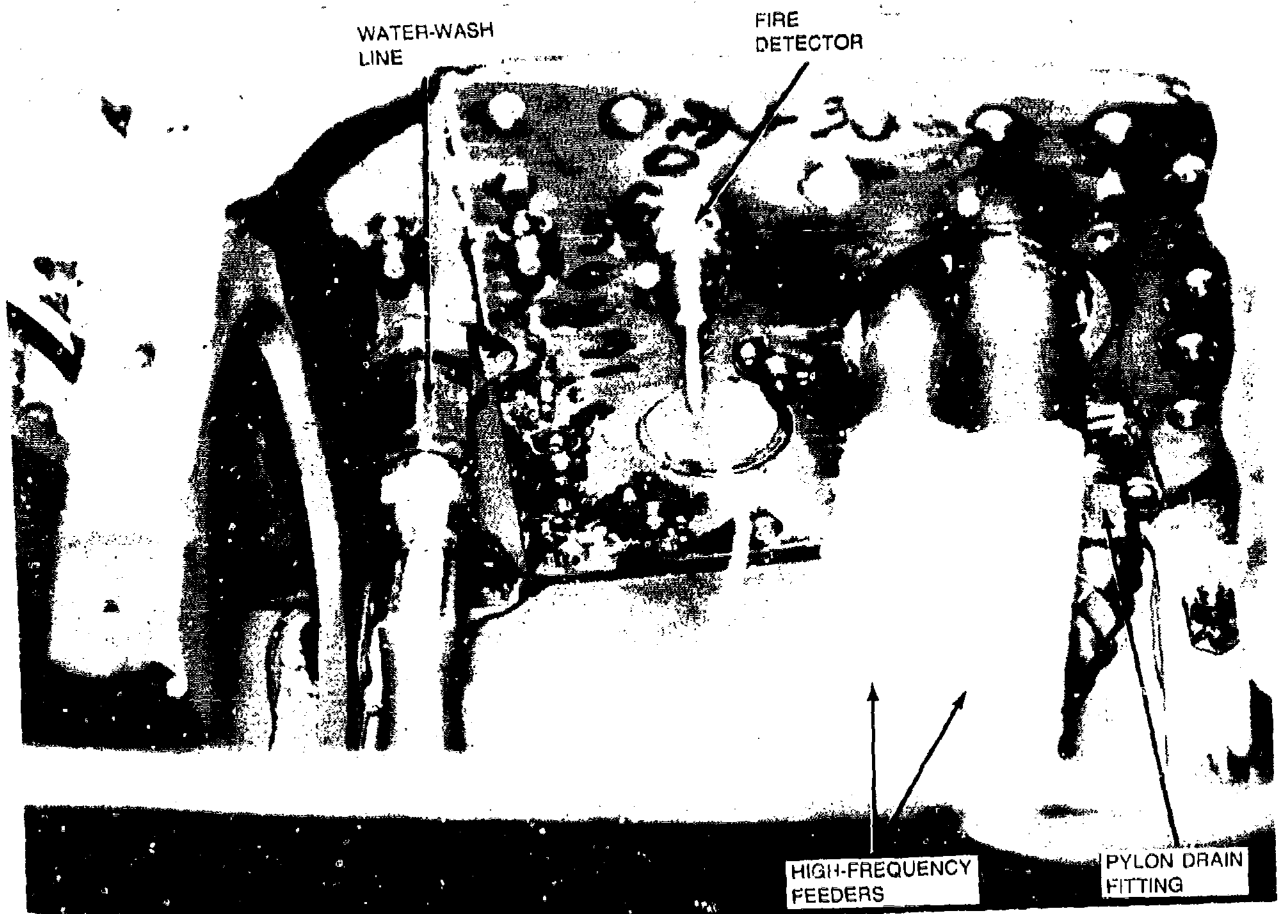


Figure 128. Pylon Floor—Bottom View After GE Modification

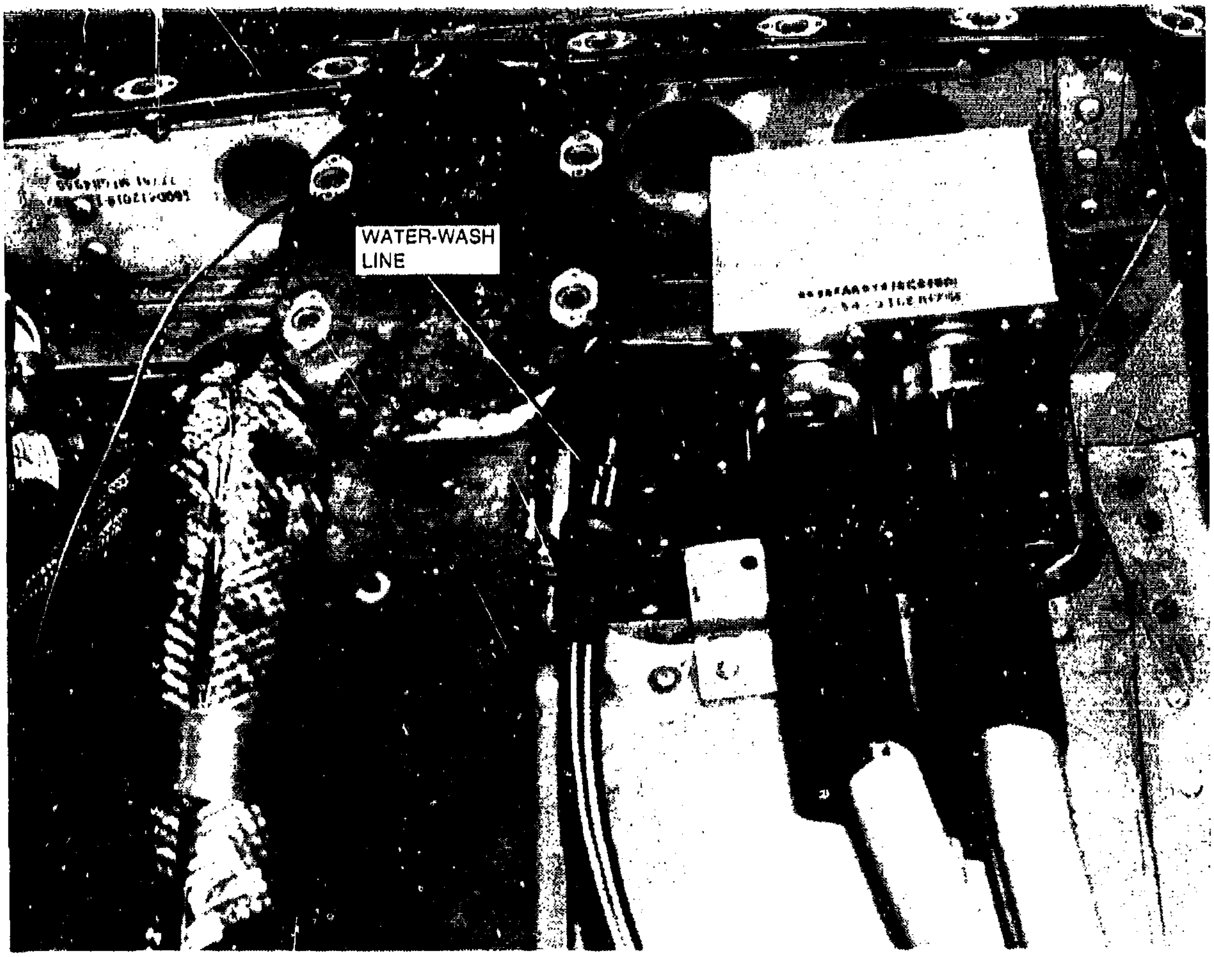


Figure 129. Completed Junction Box Installation

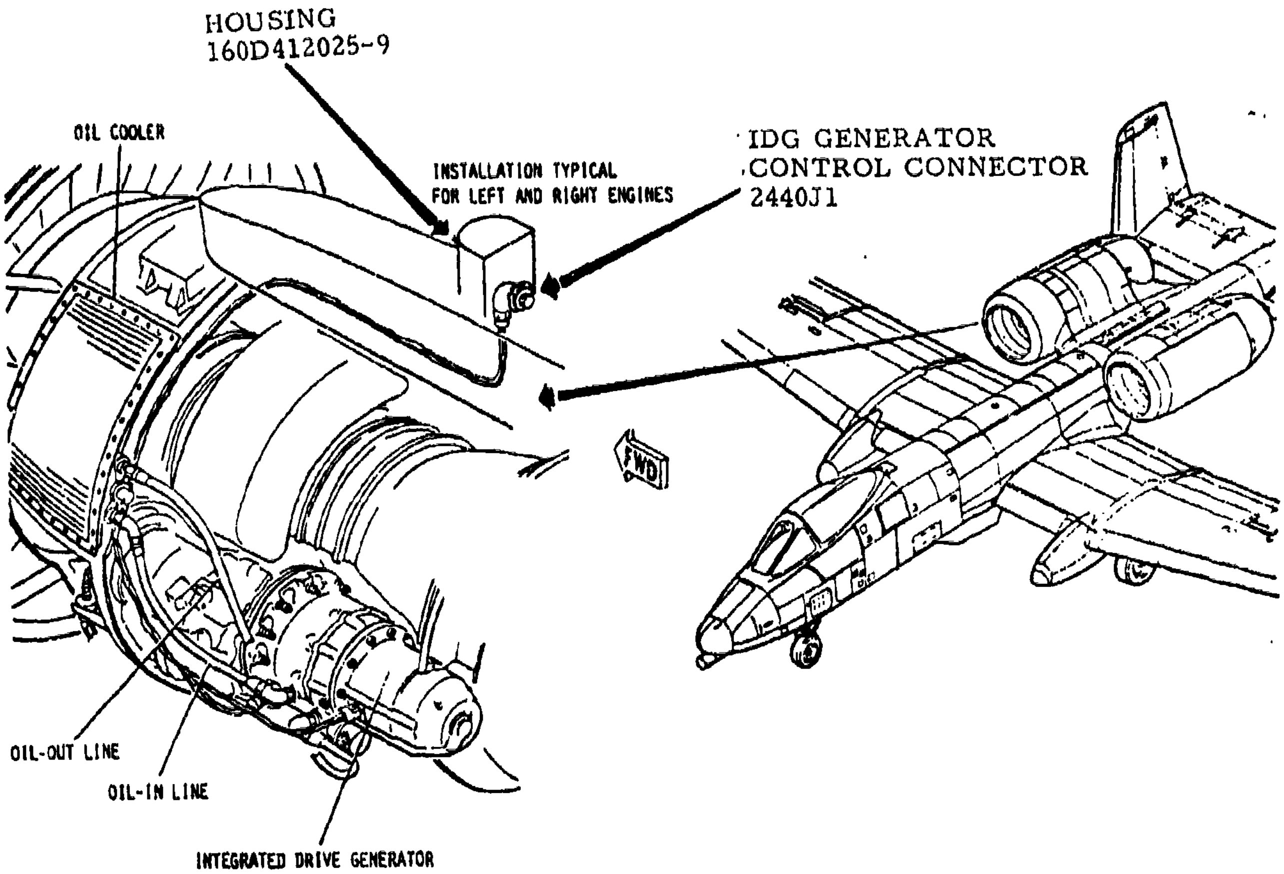


Figure 130. IDG Control Cable

3.6.2.13 Converter Power Cable Installation (Aircraft Mounted)

The 400-Hz ac bus cables that were attached to the pylon, as shown in Figure 131, were pulled back into the fuselage and run aft to the converter compartment where they were attached to GE cable assemblies mounted on a fabricated bracket, see Figure 132. These cable assemblies, in turn, were attached to the converter terminal blocks.

The high-frequency feeder cables (GE drawing 143DG408G1, G2, and G3) were installed to connect the cable junction box in the pylon to the VSCF converters that were mounted in the rear compartment. These cables were routed from the fuselage through the pylon cable port hole, forward of station 599.96, to the engine fire-wall mounted junction box, along the same path as the removed IDG power cables on both the right and left hand engine side. The same cable tie points were used, with larger cable clamps to accommodate the larger cable diameter. From this cable porthole back, numerous cable tie points were added to support these cables on both the right and left hand side.

3.6.2.14 Converter Interface Cable Installation

The IDG generator control cables, which go from the engine fire-wall disconnect area to aft fuselage station 531, had the pylon mounted sections relocated to the fuselage going to the converter.

Here they connected to adapter cables that went to the converter J5 connectors.

The cable routing was not changed from the fuselage cable porthole forward. Cable clamps were added from the fuselage porthole aft to the converters. This was accomplished on both the right and left hand sides.

The aircraft mounted generator control cables were connected to the engine fire-wall disconnect connectors in the pylons and wire routed to the converter J4 connectors. The cable routing from the fuselage cable porthole to the engine fire-wall area was not changed. Cable clamps were added from the fuselage cable porthole aft to the converters. This was accomplished for both right and left sides.

3.6.2.15 Cable Modifications—Electric Start

Power jumper cables, as identified and located in Figure 96, were installed to connect the start filter, tie start contactor, and start control contactors to the existing ac bus contactors.

Another cable assembly connected the start filter control connector, tie start contactor connector, and start contactor connector to each other and into the rest of the starting system with point-to-point wiring.

3.6.2.16 Modifications to Fuel and Engine Relay Box (Fairchild drawing 160D243006)

The fuel and engine relay box is located behind access door F38 on the right hand side of the aircraft, see Figure 133.

This box was modified by adding several jumper wires and moving several others. All modifications were done in orange. These changes were necessary to allow both air and electric starts.

3.6.2.17 Fixed and Variable Ballast Plates

Additional heavier ballast plates were installed to ensure that the airplane stayed within specified CG limits.

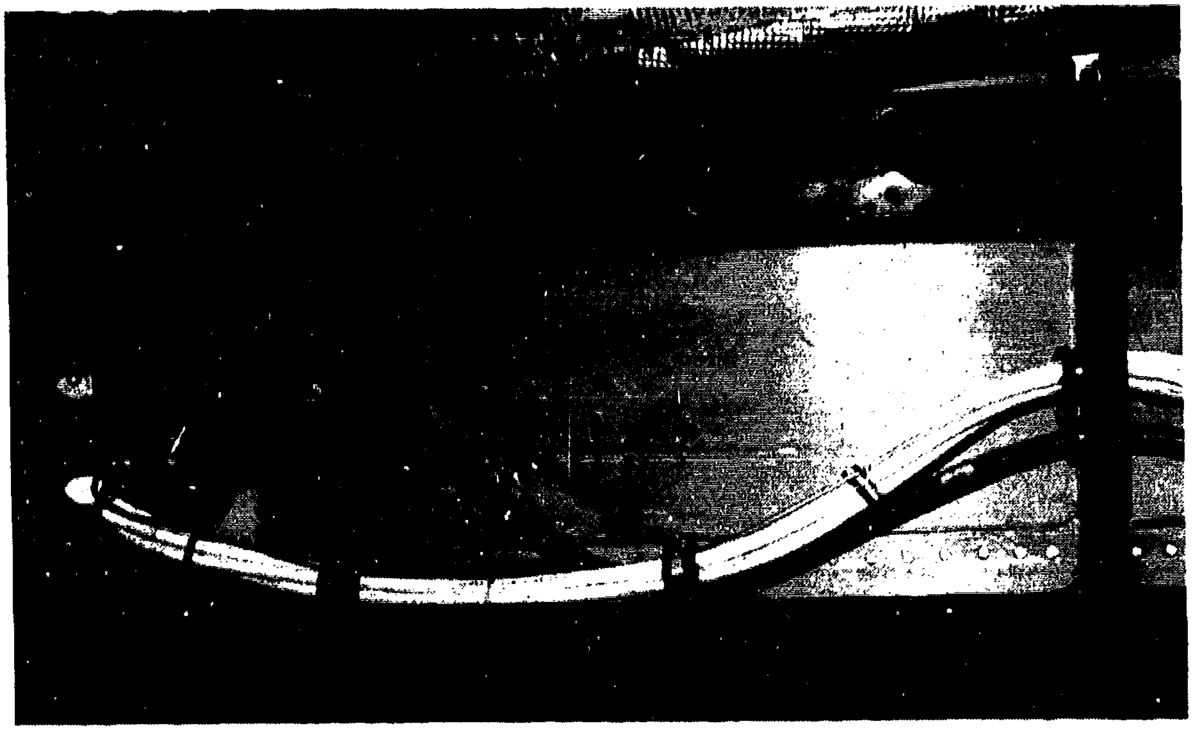


Figure 131. IDG 400-Hz Power Cable in Pylon

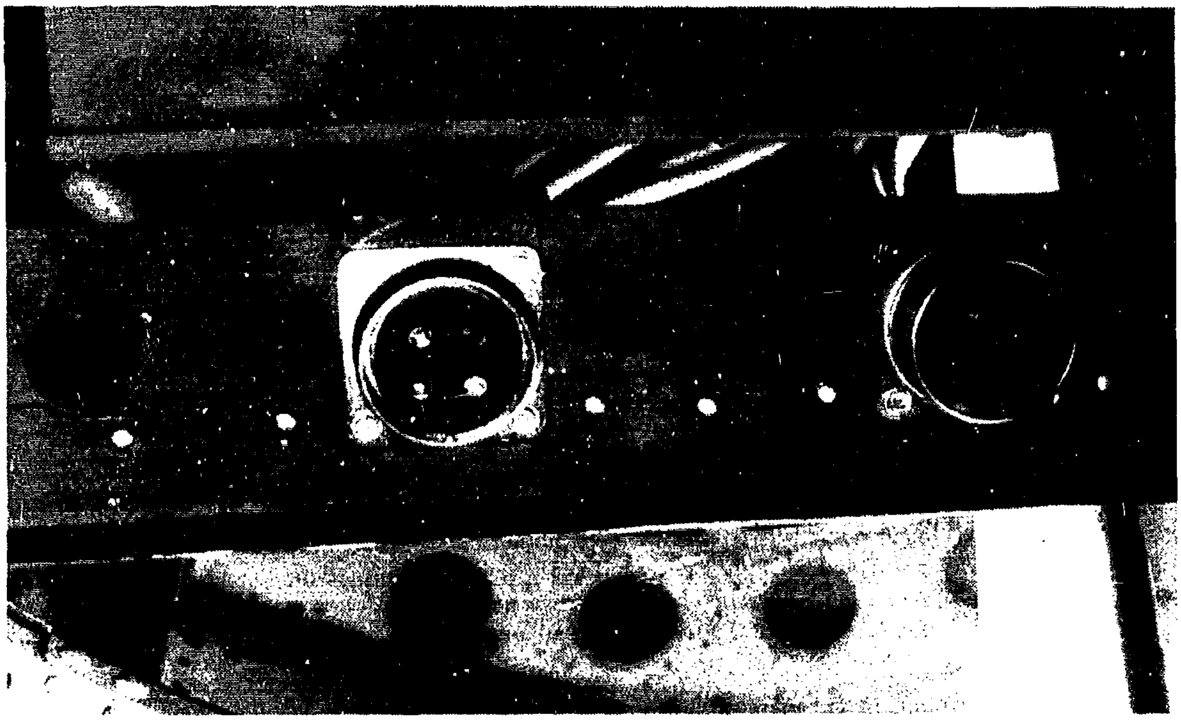


Figure 132. 400-Hz IDG Cable Adaptor, Cables Mounted on Supportive Bracket in Converter Compartment

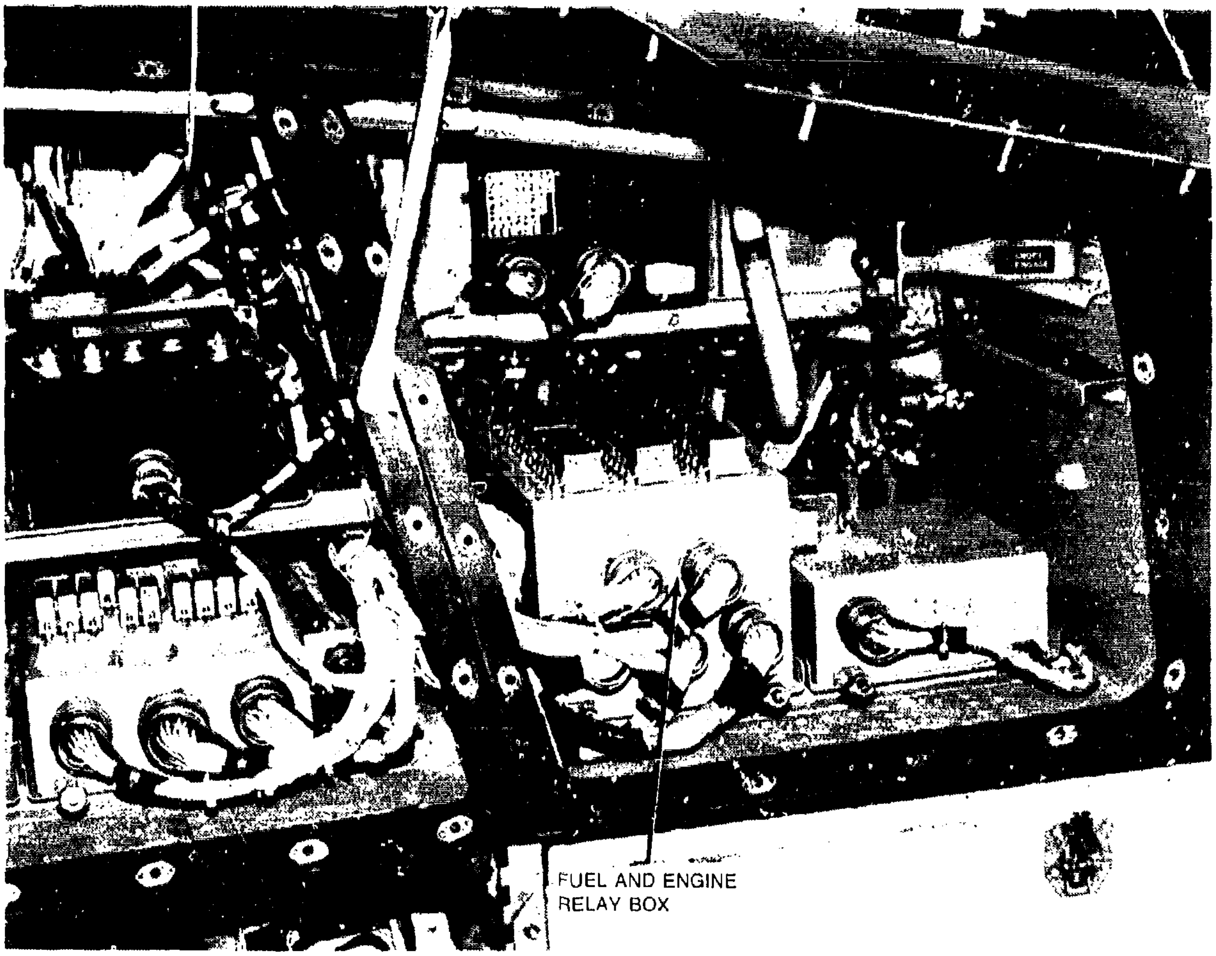


Figure 133. Fuel and Engine Relay Box Location

3.6.3 POWER, SUBSYSTEM COMPATIBILITY, AND ELECTRICAL LOAD ANALYSIS

The equipment that was built for the flight test replaced the existing IDG electrical power generation system, which had the following interfaces:

- Engine accessory gearbox for mechanical drive power input to the generator
- AC bus for electrical power extraction from the generator
- Engine mounted IDG heat exchanger for generator cooling and lubrication oil

In addition to generating electrical power, the GE equipment also performs the engine start function. This function is presently accomplished with the engine accessory gearbox mounted air starter. The air start system was to be left in place during the flight test. The ac bus structure was modified to supply the electrical power to the PM VSCF starter-generator system during electrical engine starts. The ac bus compatibility with electric engine starts was also considered.

The following paragraphs address the compatibility of the flight test equipment with the previously listed interfaces.

3.6.3.1 Engine Accessory Gearbox Interface

The flight test starter-generator/gearbox package was designed with the same mounting pad and spline interface as the present system to assure mounting compatibility with the engine accessory gearbox. The overhung moment for the flight test system is 776 in-lbs, which is within the mounting pad limit of 2,500 in-lbs, see Figure 134 for a summary of mounting interface details.

Figure 135 shows a comparison of generator system efficiencies. This figure indicates that the engine power extraction will be approximately 6% less during the flight test.

Figure 136 shows the engine drag torque curve for the TF-34-100 engine for various temperature conditions. The worst-case start condition is seen to occur at -40°C. The PM VSCF starter output torque is seen to be approximately 12% above the -40°C critical point at light off, which assures that electric starts can be accomplished under all engine temperature conditions.

Thus, it is concluded that the PM VSCF starter-generator system is compatible with the engine and engine accessory gearbox interface and will not compromise its operation.

	1 ENGINE	2 IDG GENERATOR	3 PM VSCF GEN/GEARBOX
Manufacturer	**General Electric**	**Sundstrand/ Westinghouse**	**General Electric**
Type	TF-34-100	SCD 160C645095	2CM436A1
Number of Units	2	2	2
Weight (Pounds)	-	76.50*	97.00
Center of Gravity (Inches)	-	9.17	8.00
Accessory Pad or Flange	Flange	Flange	Flange
Specification Drawing Number	AS 971A-8CS	AS 968-2	AS 968-2
Specification Type	Aerospace Standard	Aerospace Standard	Aerospace Standard
Diameter of Bolt Circle (Inches)	10.00	10.00	10.00
Min Drive Shaft RPM	9,400	9,400	9,400**
Max Drive Shaft RPM	18,000	18,000	18,000
Torque Rated (Lb/In)	1,050	560	640**
Max Accessory Weight (Pounds)	150	79.00*	97.00
Max Overhung Moment (Lb/In)	2,500	724.40	776

*Original IDG weight used in A-10A study. Current dry IDG weight is 79 pounds

**Value shown is for generate mode at 60 KVA. During electric start
Peak applied torque is 1,100 lb/in
Minimum drive speed – 0 to 9,200 rpm as starter

Figure 134. Generator Mounting and Drive Data (Ref. Figure 2, MIL-E-70168)

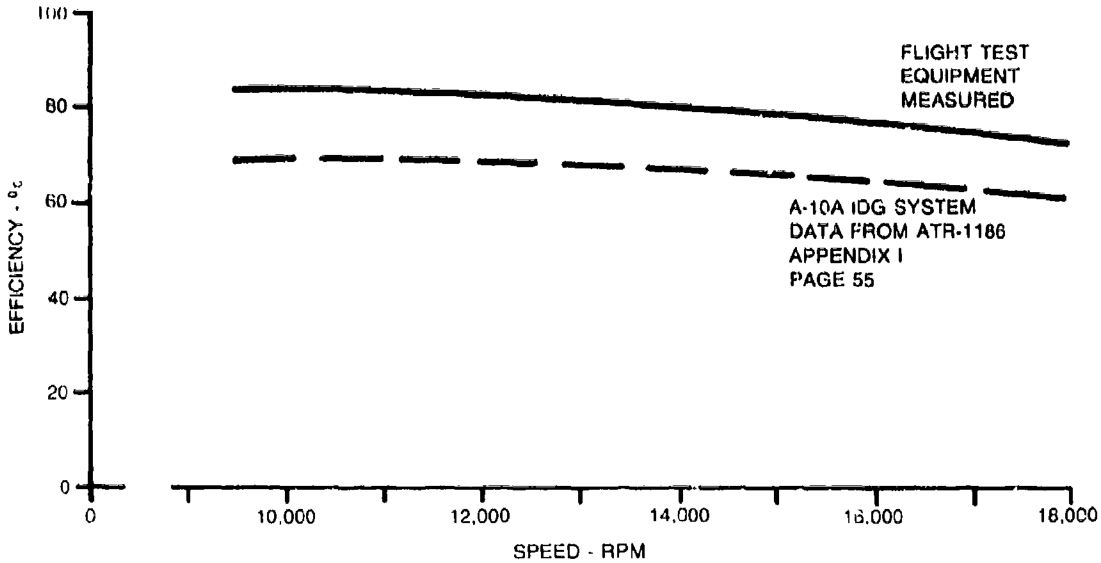


Figure 135. System Efficiency Comparison Flight Test Equipment Versus A-10A Equipment at 40-KVA, 0.90 PF

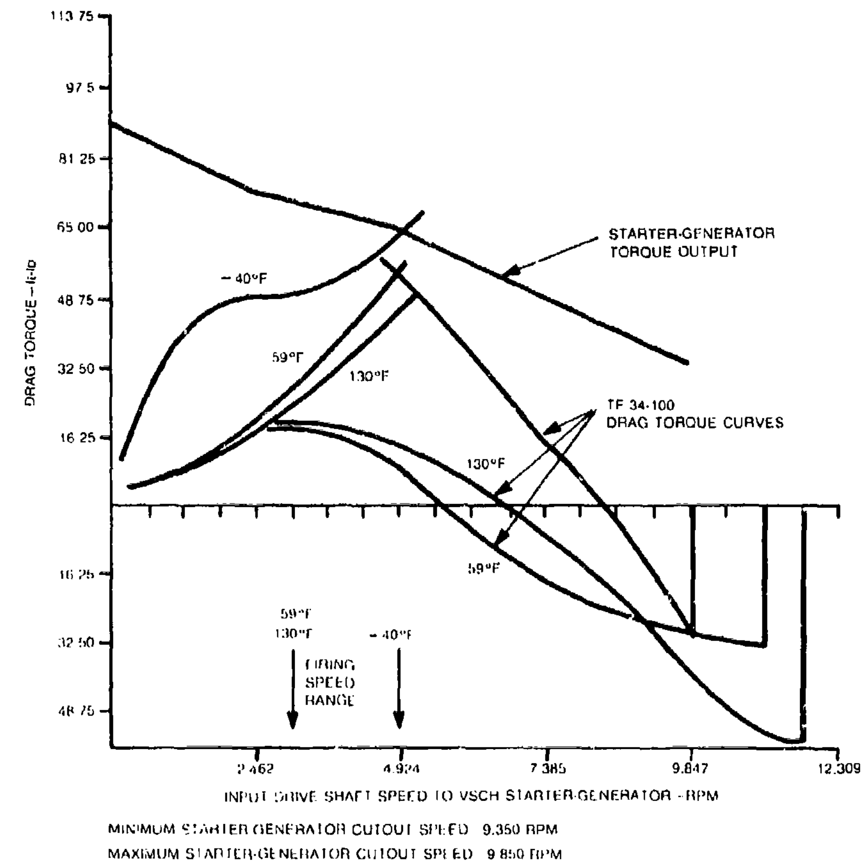


Figure 136. Electric Starter Performance with 60-KVA PM VSCF on TF-34-100 Engine

3.6.3.2 AC Bus Interface

The A-10A IDG system is rated at 30/40 KVA where the GE flight test equipment carried a full 60-KVA system rating, see Figure 137 power source output data for flight test equipment.

Thus, the ac power capability is above what is normally available on the aircraft.

The power quality requirements of the VSCF system are covered by MIL-E-23001B. This specification is written especially for solid-state conversion systems. In general, all the power quality requirements for the A-10A electrical system are met, and the following characteristics are held closer:

- Frequency regulation—400 ±1 Hz
- Shorter voltage transient
  - < 10 ms full load
  - < 30 ms overload (2 Pu)
- No amplitude modulation
- Lower dc content—< 50 mV

Thus, the power quality is better with the flight test hardware than on an unmodified A-10A. The existing ac bus structure was used.

Identification:		–	–	System
Item:		AC Generator	Cycloconverter	–
Number Units:		2	2	2
Rating:	(Name Plate)	–	–	60 KVA
Voltage:	(Base Speed) (Top Speed)	155 L-N 380 L-N	– –	115/200 115/200
Frequency:	(Base Speed) (Top Speed)	1,250 Hz 2,500 Hz	– –	400 Hz 400 Hz
Power Factor:		–	–	0.75 to 0.95
Configuration:		WYE	–	–
Manufacturer:		General Electric	General Electric	General Electric
Model Number:		2CM436A1	3S2060DF141A1	–
Interval Rating:		–	–	120 KVA–5 Sec. 90 KVA–5 Min.
Voltage Regulation:		–	–	±1 Volt
Frequency Regulation:		–	–	±1 Hz

Figure 137. Power Source Output Data (Ref. Figure 3, MIL-E-7016F)

Figure 138 shows the electric engine starting requirements. The possible and probable system peak currents were calculated from Table 13, listing power conditions, using paragraph 3.5.6.3 of MIL-E-7016F.

- Possible System Peak

	KVA	Current (Amps)
Starting system load	66.0	190.0
5-second start and warm-up	12.0	34.6
	78.0	224.6

- Probable System Peak

	KVA	Current (Amps)
Starting system load	66.0	190.0
5-minute start and warm-up	7.6	21.9
	73.6	211.9

As seen in Figure 138, the ground power cart selected, A/M 32A-60A, has sufficient capacity to perform electrical engine starts as well as supply power to the aircraft bus.

3.6.3.3 IDG Heat Exchanger Interface

The flight test starter-generator/gearbox package has been designed to interface with the existing IDG heat exchanger (Fairchild drawing number 160C433002, or 160C433005). Figure 139 is a comparison of the IDG system heat rejection versus the flight test equipment heat rejection at the 40-KVA, 0.90 pf load condition. As seen from this figure, the flight test equipment has a significantly lower heat rejection and, therefore, should not cause any interface problems.

3.6.4 MODIFICATION DIFFICULTIES

During the equipment installation and system verification, several problems were encountered most of which were attributable to incompatibility with the existing aircraft hardware. These problems and the corrective actions taken are discussed in the following sections.

3.6.4.1 Relay Logic

When the aircraft was first rolled out, it was discovered that the start mode was not functioning as designed. The source of this problem was found to be the aircraft relay logic, which failed to interact with the VSCF logic. A minor modification of the aircraft relay logic corrected this situation.

3.6.4.2 Generator Oil Leaks

Since the aircraft heat exchanger was mounted higher than the generator, oil would drain into and fill the generator cavity after the engine was shut down. On some generators, the oil leaked out via the Hall probe cover plates and the connector housing. This problem was rectified by effectively sealing these areas with gaskets.

3.6.4.3 False Generator Disconnect

During the system verification test the left generator started to disconnect. This problem was traced to a capacitor on one of the printed circuit boards. Failure analysis of the part and the board failed to reveal any discrepancy, and it was concluded that a sliver of wire or solder has caused a short. This problem did not occur after the converter was replaced.

3.6.4.4 Dead Load Bus

When the converter with the questionable capacitor was replaced, it was discovered that the left load bus would go dead when the left engine was mototed. This problem was found to be caused by an incorrect resistor on one of the circuit boards, resulting in a bus overload signal and opening of the Bus Tie contactor. This problem had not been discovered during acceptance tests since the laboratory bus structure was different from the aircraft bus structure due to the added paralleling capability. The replacement of the resistor eliminated this problem.

3.6.4.5 False Rudder Kicks

When the EMI susceptibility test was conducted, it was discovered that switching the right converter on or off sometimes caused a rudder kick of about five degrees. These rudder kicks were found to be caused by instructions from the Stability Augmentation System (SAS), which is powered from the right bus. It was found that the SAS could not stand power interruptions of more than 10 milliseconds duration. Although the specification for the 60-KVA system called for a transfer time of 100 milliseconds, the actual time was in the vicinity of 30 milliseconds, which was still in excess of the 10 milliseconds required by the SAS. Consequently, certain circuit changes had to be implemented which reduced the transfer time to about 3 milliseconds. While this fix was being incorporated in the flight hardware, Fairchild informed General Electric that the rudder kick was not a problem and should have been ignored.

3.6.5 TESTING PERFORMED

When the modification was complete, a point-to-point wiring check was performed. Then, with just battery power, generator disconnect operation and the status of several relays were checked. A full gamut of starts, including ground power, cross-starts, motors, generate mode operation, and bus switching, were tested successfully with no problems. Motoring for up to 15 minutes in duration was performed. Engine start times were approximately 23 seconds to generator start cutout and 25 seconds to idle. Full airplane loads were run on each system until steady-state temperatures were attained. Cross starts were done only from idle—approximately 63% core speed (about 1,600 Hz). The motoring speed that was attained was approximately 31% core speed (about 800 Hz). An EMI susceptibility test was successfully run where the VSCF systems acted as both source and victim.

None
Security Classification

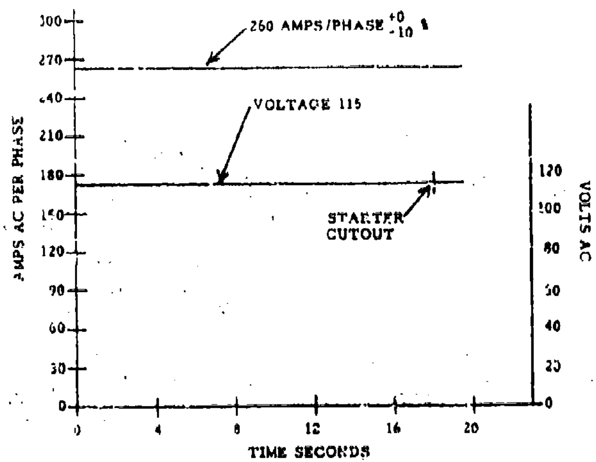
STARTER.

Manufacturer:	General Electric	Power Input (AMPS):	*260 Max
Model No.	2CM436A1	Volts, Maximum:	115 Vac (L-N)
MIL-Dwg No.:	--	Frequency:	400 Hz

Starting Bus Type:

Possible System Peak 294.6 Amps   Probable Sysem Peak 282 Amps

Starting Transient Curve=



Recommended Power Supply:	Ground Power	Airborne
Manufacturer:		N/A
Type:	A/M32A-60A	N/A
Rating:		N/A
KVA	75	N/A
Current Per Phase (AMPS)	217	N/A
Voltage	115	N/A
Interval	Continuous	N/A
Overload KVA	112.5 5 Minutes 150.0 5 Seconds	N/A
Overload AMPS	325.5 5 Minutes 434.0 5 Seconds	N/A

* Current limited to this value.

Figure 138. Electrical Requirements for Engine Starting (Figure 16, MIL-E-7016F)

TABLE 13
LOAD ANALYSIS CHART A-10A ELECTRICAL SYSTEM

	Channel						
	Left		Right		EP/APU		Time
	KVA	AMPS*	KVA	AMPS*	KVA	AMPS*	Interval
Ground Power	–	–	–	–	6.03	17.4	Continuous
AC Bus 4.18 KVA Fuel Pump 1.52 KVA Ignition 0.23 KVA DC Start Control 0.10 KVA							
Start and Warm-up	12.00	34.6	8.4	24.2	–	–	5 Seconds
Start and Warm-up	7.60	21.9	16.2	16.2	–	–	15 Minutes
Start and Warm-up	3 to(6)	17.3	3 to 6	17.3	–	–	Continuous
Cruise	3 to(6)	17.3	3 to 6	17.3	–	–	Continuous
Cruise Combat	13.12	37.9	16.9	48.8	–	–	15 Minutes
*3-Phase Current ◯-Worst Case							

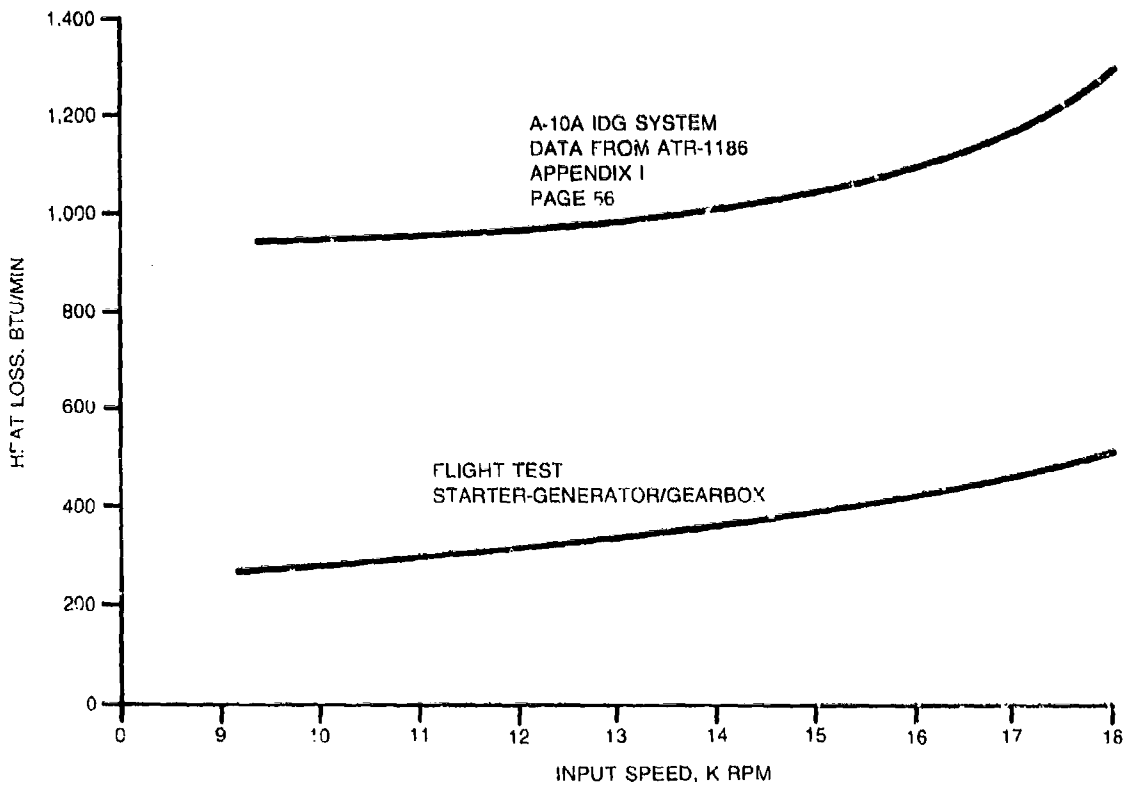


Figure 139. IDG Heat Exchanger Compatibility 40-KVA, 0.90 PF

*U.S.Government Printing Office: 1986 — 748-061/30528