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LONG PULSE HOMOPOLAR GENERATOR

Edward A. Knoth
David P. Bauer

IAP Research, Inc.
2763 Culver Avenue
Dayton OH 45429-3723

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The objective of this program was to develop a lightweight, long pulse homopolar generator. The generator is designed to deliver 250 kW at 10 kA for pulses greater than 10 seconds.

This report reviews the truncated drum (rotor) design and the testing performed. The main design features, such as active excitation coil cooling, of the generator components are reviewed.

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INTRODUCTION

Air Force pulse power applications continue to increase in number. Pulse power applications require very high levels of power (typically megawatts) in relatively long pulses (a few seconds to several minutes). A repetitive electromagnetic gun is an example of this type of application. Average power on the order of 40 MW is required.[1] Energy storage systems sized to meet this requirement would be impractically large. We proposed an alternative concept involving a non-air-breathing turbine and a "long pulse" homopolar generator (HPG).[2]

The long pulse power system concept is illustrated in Figure 1. As configured for an electric gun system, it would consist of a non-air-breathing turbine, high current homopolar generator, an energy storage coil, and a repetitive switch. The turbine and generator produce the required high current and high average power, while the energy storage coil and switch compress the energy further to provide repetitive, high current pulses at power levels 2 to 3 orders of magnitude above the average power level. This system has very attractive characteristics for many pulse power applications involving either very long pulses or bursts of pulses lasting for seconds or more.

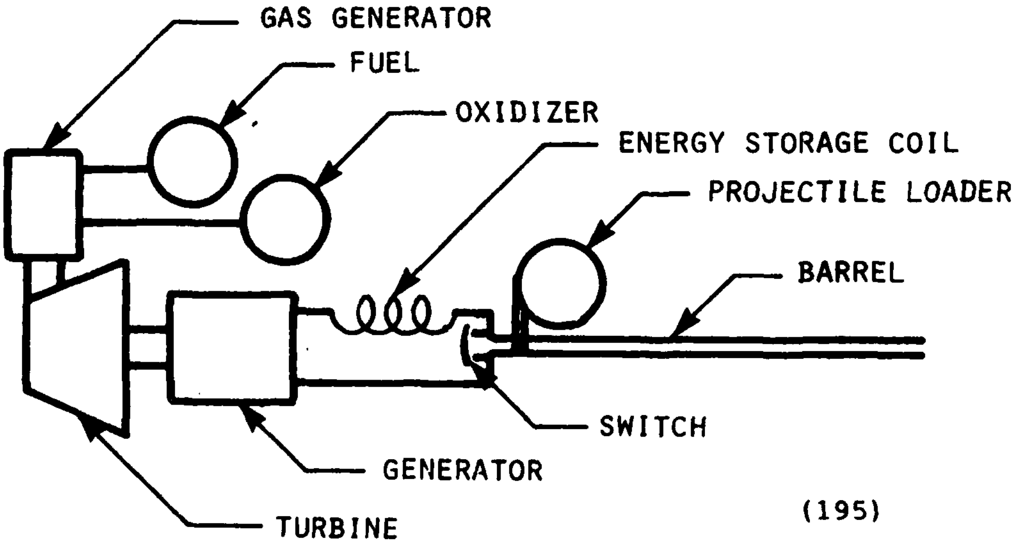

Figure 1. Pulse power system for "long pulses".

The major components of this power system concept are at varying stages of development. The Air Force is continuing the development of high power turbines, inductive energy storage, and opening switches to meet the high power, long pulse requirements. This report describes the characteristics of a scaled homopolar generator designed to operate with the other components of a long pulse, high current power system. This program was the first effort by the Air Force to design and build such a generator.

Most high current homopolar generators built to date are energy storage devices. Energy is stored rotationally and delivered in a single, high current pulse to a load. Discharge times for these machines are less than 1 second.

The objective of this program was to develop a lightweight, long pulse homopolar generator. The generator, shown in Figure 2, was designed to deliver 250 kW at 10 kA for a pulse length of 5 seconds.

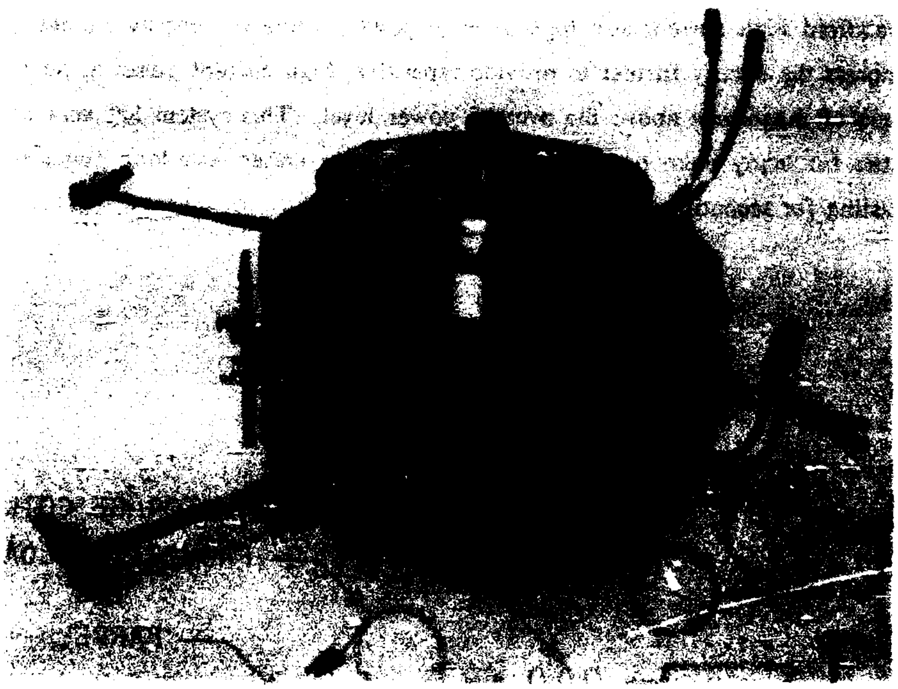

Figure 2. Our long pulse HPG.

The program began with the evaluation of alternate geometries for generator construction. Single, double, and tapered disk and several shell rotor configurations were considered. This report focuses on the truncated drum HPG configuration which was built.

This report has three remaining sections. Section 2 describes the design of the HPG and its components. Section 3 reviews the component and HPG assembly testing. Section 4 presents the conclusions.

SECTION 2

HPG DESIGN

The homopolar generator (HPG), shown in Figure 3, is a truncated drum (rotor) design. The rotor rotates in a radial magnetic field producing a voltage potential between the brush tracks. The magnetic flux is generated by toroidal excitation coils placed in the stator. The stator (or backiron) completes the magnetic circuit. An air operated brush actuation system completes the electrical circuit.

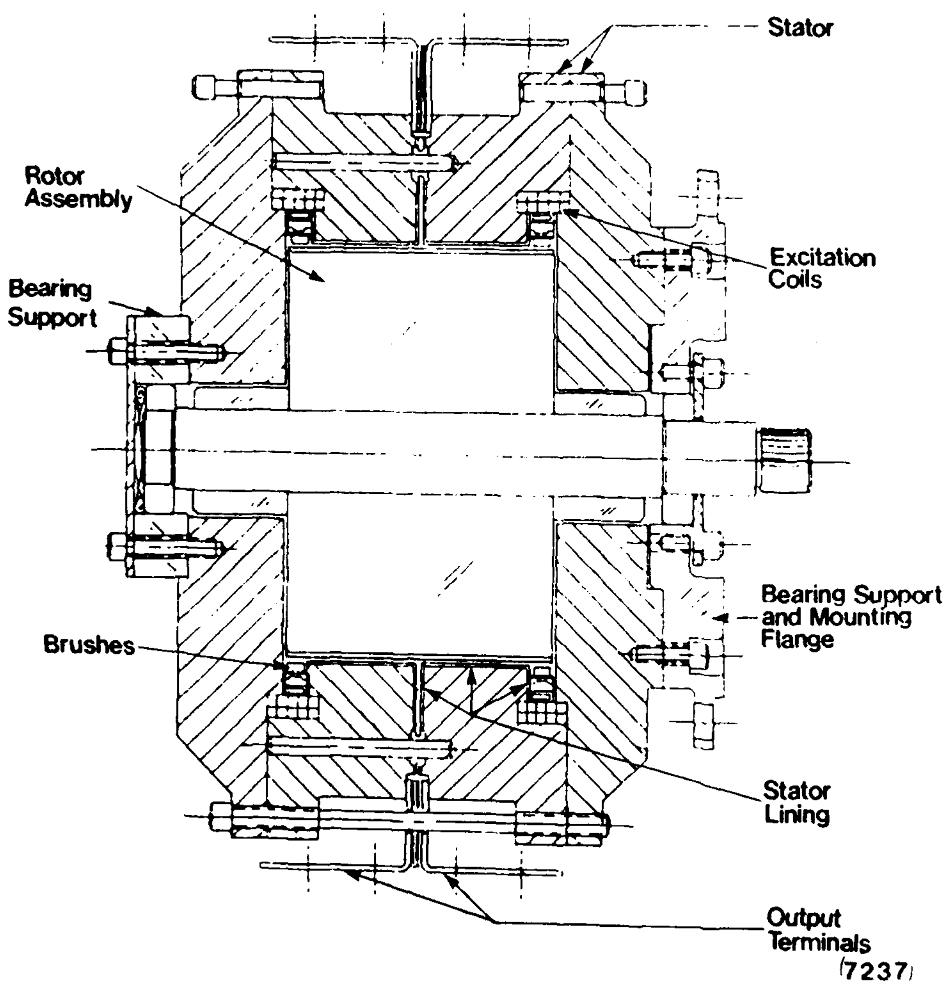

Figure 3. The homopolar generator.

Table 1 lists some of the HPG design specifications. The following subsections will review the magnetic analysis performed and the main design features of the generator components.

Table 1

HPG Specifications

Parameter	Value	Units
Output Voltage	30	V
Output Current	10	kA
HPG Overall Size		
Diameter	370	mm
Length	340	mm
Weight	190	kg
Excitation		
Magnetic Flux Density	1.5	T
Current	820	A
Water Supply Pressure	550	kPa
Rotor		
Rotational Speed	19,100	rpm
Diameter	200	mm
Length	132	mm
Weight (about)	40	kg
Brush Supply Pressure	275	kPa

2.1 Magnetic Finite Element Analysis

Magnetic Finite Element Analysis (MFEA) was performed in conjunction with HPG component design. Magnetic analysis enabled us to analyze the effects of device geometry and materials on the flux distribution. The leakage magnetic flux densities in the current collection and rotor bearing areas were of particular interest in the HPG design.

Figure 4 indicates that some radial flux passes through the current collection brushes. Figure 5 shows an expanded plot of the finite element model in the current collection region. The magnitude and direction of the flux density in each element near the brush-rotor interface is superimposed on Figure 5. The average radial component of magnetic flux passing through the brush face is 0.159 T. The voltage gradient across the brush due to this flux is given by:

$$V' = Bv \tag{1}$$

where V' = the voltage gradient

B = the magnetic flux density, and

v = the sliding velocity at the interface.

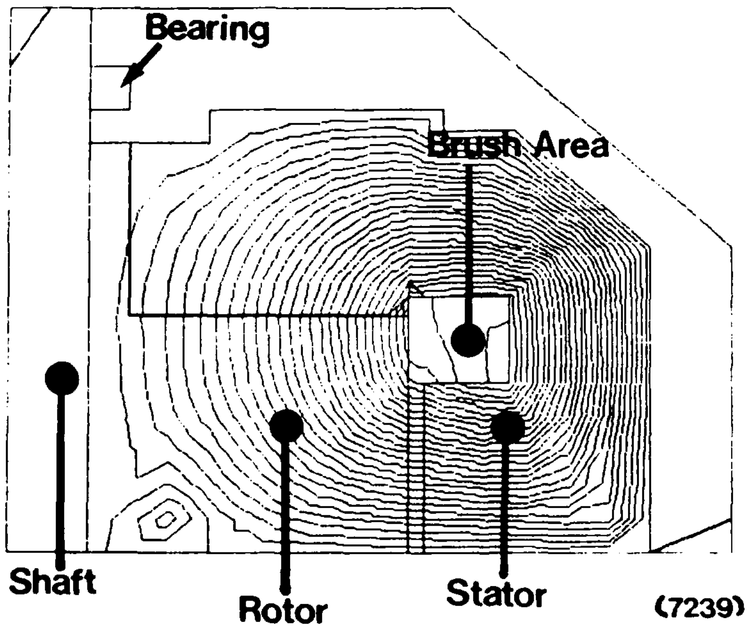

Figure 4. HPG flux distribution.

For a rotor tip speed of 200 m/s, the brush voltage is 31.9 V/m. According to work done by Marshall[4], voltage gradients on brushes cause a nonuniform current distribution and therefore nonuniform heating within the brushes. Based on experiments with copper-graphite brushes operating at a current density of 6.5 MA/m², an acceptable voltage gradient on the brush face is 40 V/m. Therefore, the level of magnetic flux density in the brush area is acceptable and will not cause excessive brush heating.

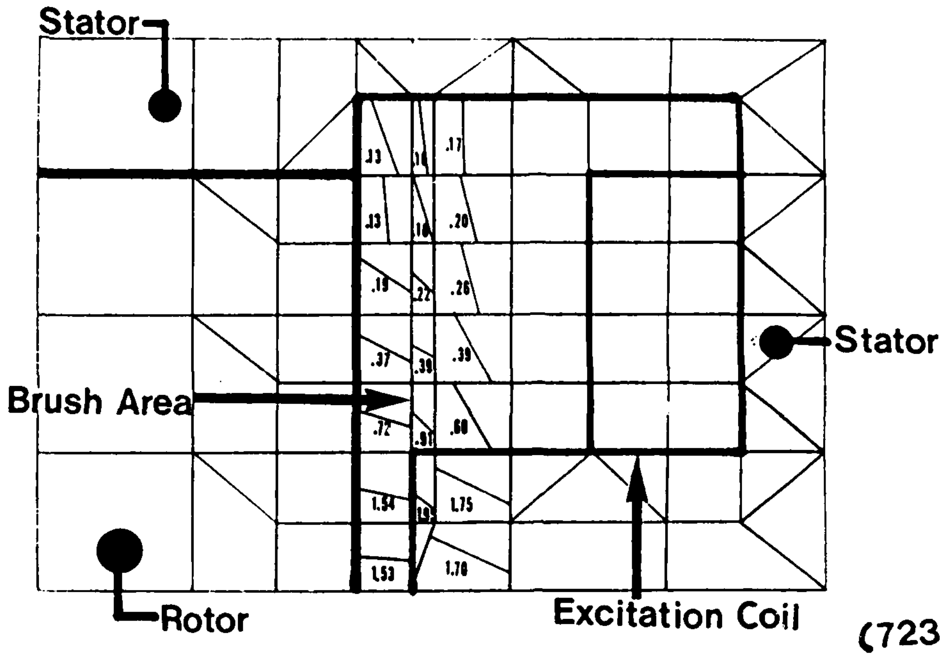

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Figure 5. Magnetic flux density in current collection region.

Figure 4 indicates that the magnetic flux density in the bearing area is very low. The results show that bearing flux density is about 0.008 T. The bearing functions like a drum type HPG with the predominant voltage axial along the inner race. The voltage generated can be calculated as:

$$V_b = Blv_b, \tag{2}$$

where V_b = the bearing voltage,
l = the inner race thickness (0.015 m), and
v_b = the inner race surface speed (40 m/s).

The bearing generated voltage is about 5 mV. The upper limit of acceptable bearing voltage has been established as 50 to 100 mV[5]. Therefore, the level of magnetic flux density present in the bearing location does not present a problem to bearing operation.

2.2 Components

The HPG consists of rotating and stationary components. The rotating components include the rotor assembly and bearings. The stationary components consist of the stator, excitation coils, and current collection system. The HPG's rotor assembly and bearings, stator, excitation coils, and current collection system will be discussed in the following subsections.

2.2.1 *Rotor Assembly and Bearings*

The rotor assembly, shown in Figure 6, can be divided into two parts: the rotor and the conducting sleeve. Deep-groove ball bearings support the rotor. The rotor, conducting sleeve, and bearings will be discussed in the following subsections.

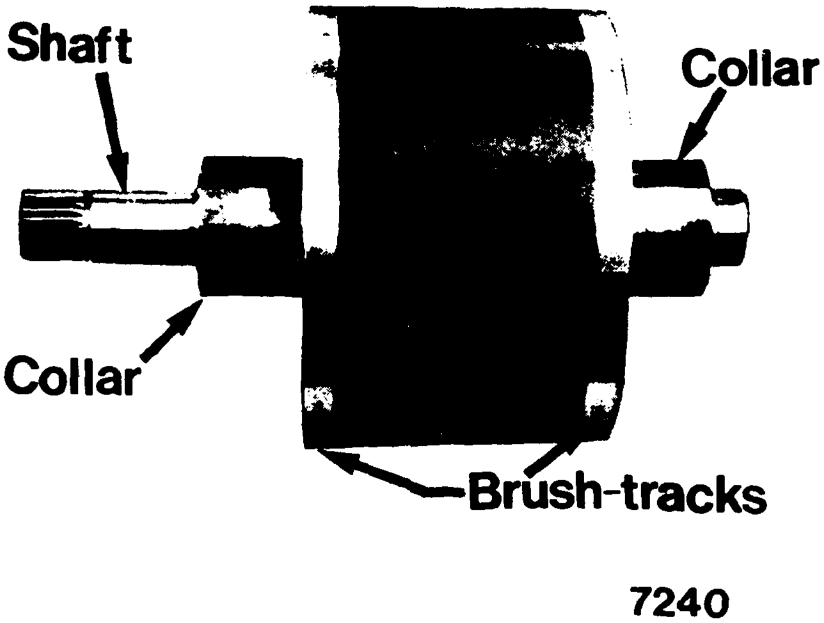


Figure 6. HPG rotor assembly.

2.2.1.1 Rotor

The rotor consists of four individual parts: the shaft, the core, and the two shaft collars. A nonmagnetic shaft material, 303 stainless steel, was chosen to reduce the magnetic flux density in the bearing locations. Power is transferred to the shaft through a standard AN-4182 external spline. A 475 N-m shear section is located directly behind the input spline to protect the drive system and torque transducer.

The rotor core is made from 4340 steel. A shrink fitting procedure was used to insert the oversized shaft into the rotor core. The rotor was heated to 177° C in an oven while the shaft was cooled to -196° C by submerging it in liquid nitrogen (LN_2). The interference fit of 0.10 mm is sized to transmit the required torque at design conditions.

The two shaft collars were made from 1020 steel. The collars were pressed onto the shaft (interference of 0.06 mm) until they contacted the rotor core. These collars stiffen the shaft and place the natural frequency of the rotor assembly beyond the operating range.

2.2.1.2 Conducting Sleeve

The conducting sleeve is made from extruded 6061-T6 aluminum tube. The sleeve is insulated from the rotor core by two layers of 56 μm thick Kapton film. A shrink fitting procedure is also used to slip the sleeve onto the rotor core. The sleeve to core interference (including insulation) is 0.51 mm.

The outer surface of the sleeve contains two brush tracks, one at each end. Silver plating is used to prevent aluminum oxide from forming at the brush interface. The surface between the brush tracks is hard anodized to prevent arcing from the sleeve surface to the current collection system.

A sleeve thickness of 4.2 mm was chosen to keep the excitation power requirements below 10,000 A-T. Figure 7 shows the flux density obtained from a specified level of excitation for several thicknesses of rotor conductor. Although the design level flux density is 1.5 T, we selected 1.65 T as the flux density attainable at an excitation of 10,000 A-T to allow for some margin in excitation performance.

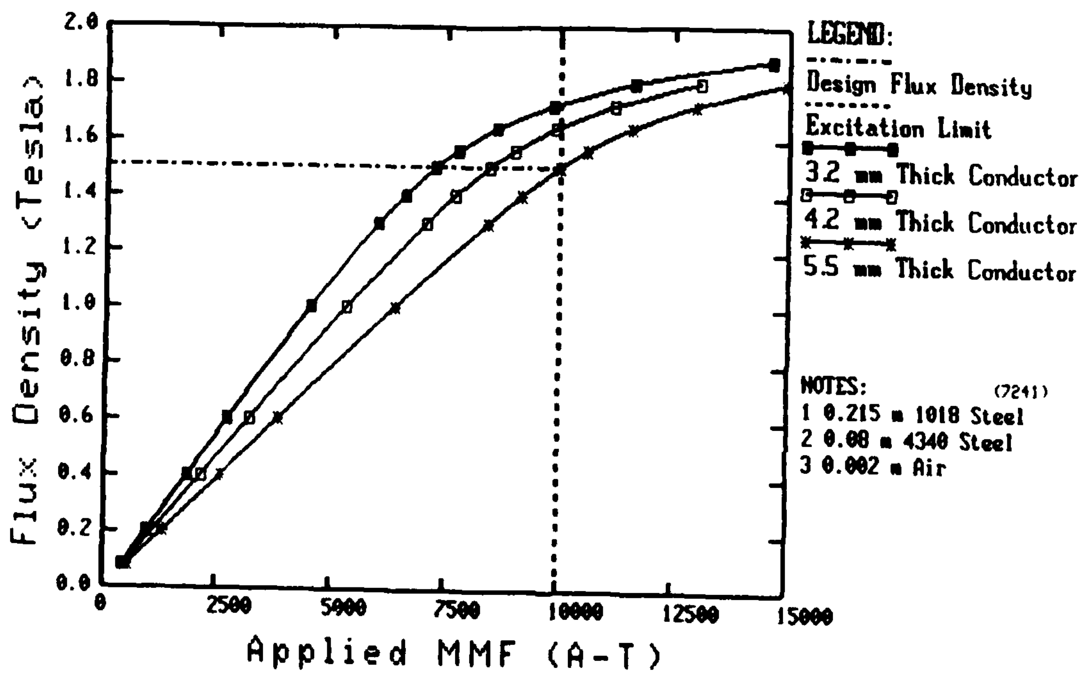


Figure 7. Excitation current requirements limit sleeve thickness.

2.2.1.3 Bearings

Deep-groove ball bearings were selected because they can support radial and thrust loads. Rotor weight determines the radial load. Thrust load is dependent on the rotor to end stator air gaps and generator excitation. A peak thrust load of approximately 9 kN is expected at maximum excitation.

We purchased two P/N 107FFT-G6 bearings from The Barden Corporation. The selected bearings are made from SAE 52100 bearing steel, prelubricated with Exxon Andok C grease, and permanently sealed.

2.2.2 Stator

The stator (or housing) serves two purposes. First, the stator provides a low reluctance path for the excitation magnetic flux. Second, the stator functions as the HPG's housing. The stator provides location plus support for the excitation coils, current collection system, and rotor assembly.

The stator is divided into four parts as shown in Figure 8. Most of the stator is made from 1020 steel. The bearing and mounting inserts, located in the end stators, are made from 303 stainless steel to keep the magnetic flux density low in the bearing locations.

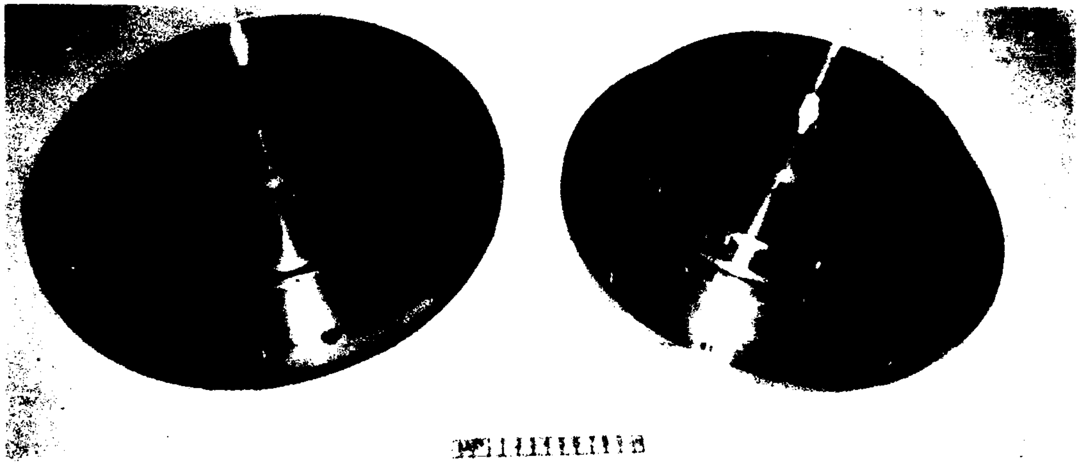
2.2.3 Excitation Coils

The excitation coils provide the magnetic flux needed by the HPG to convert mechanical energy into electrical energy. The coils are made from commercially available 3/16 inch square copper tubing. The tubing was wrapped around a 118.8 mm radius cylinder forming two layers with 5 turns each.

The voltage created by the generator is dependent on the excitation current level. Figure 9 shows how generator voltage increases with increasing excitation current. The excitation current must be approximately 820 A to operate the generator at the design voltage of 30 V. Excitation current level is regulated by a 16 V, 1000 A DC power supply.

The heat generated by the excitation coils is removed by water passing through the coils. Figure 10 shows the supply pressure needed to keep the water temperature rise below 60° C. The supply pressure required to drive the water through the coils at the design current is 550 kPa.

(a) Center Stators



(b) End Stators

Figure 8. HPG stator (housing).

2.2.4 Current Collection System

The current collection system can be divided into two systems: brush actuation and return conductor. The brush actuation system contacts silver-plated brush tracks at each end of the conducting sleeve to complete the electrical circuit shown in Figure 11. The return conductor system connects the brush actuation system to the load. The brush actuation and return conductor systems will be discussed in the following subsections.

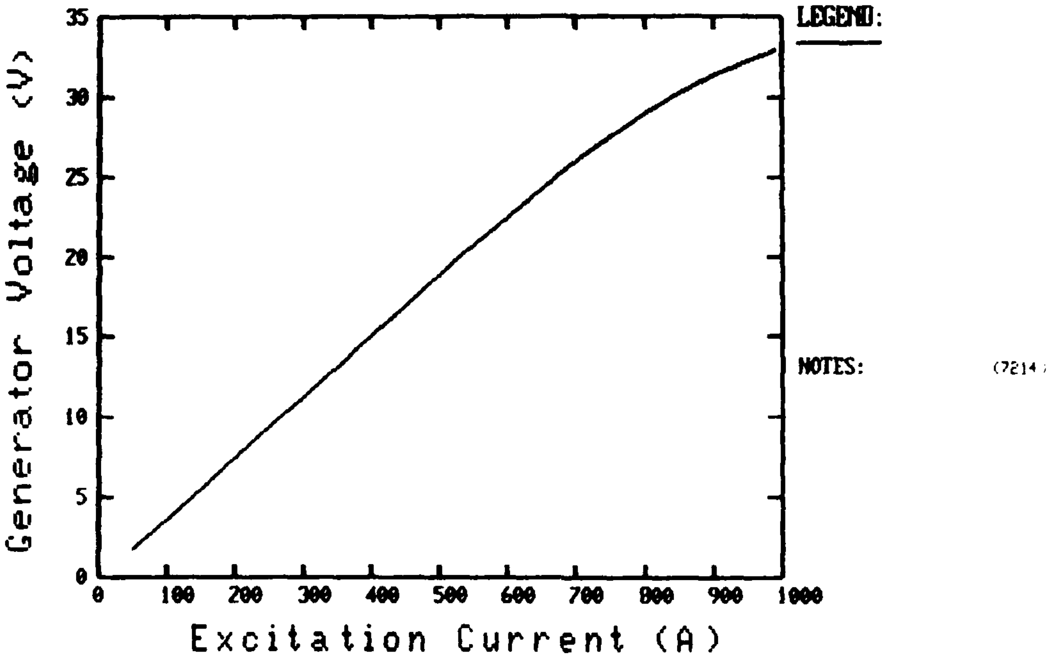


Figure 9. Generator voltage is dependent on excitation current.

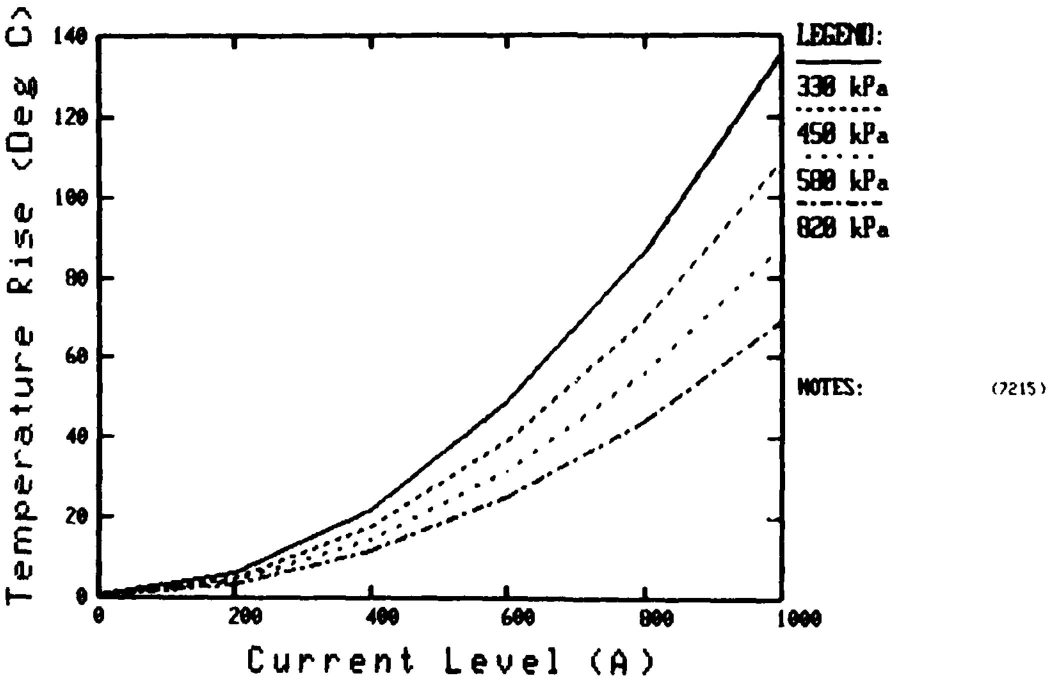


Figure 10. Water is used to cool the excitation coils.

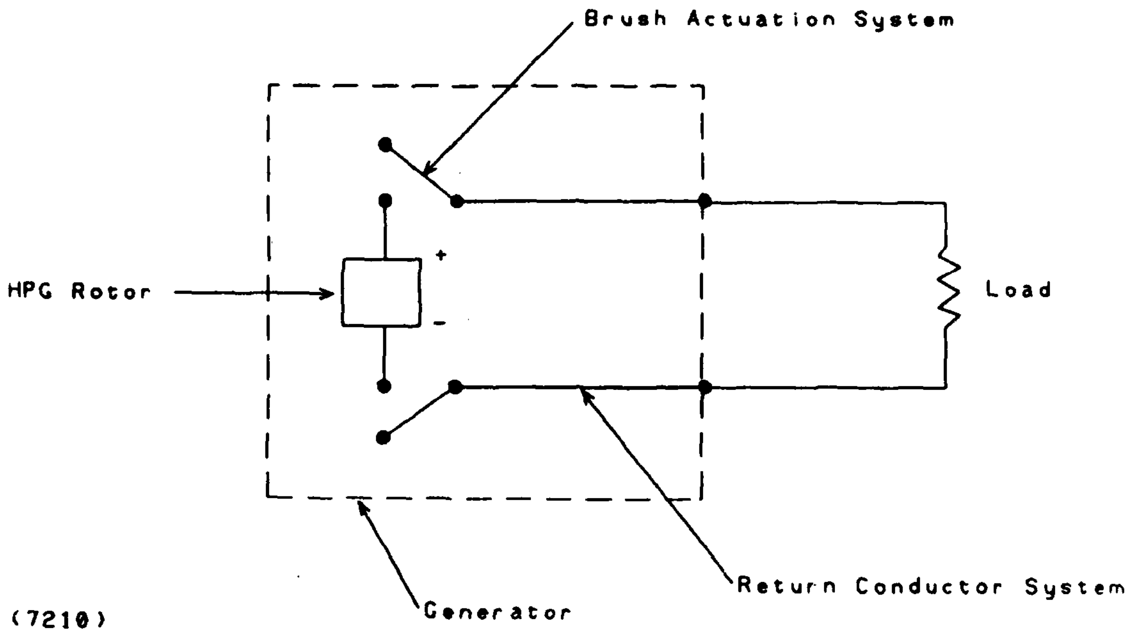


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Figure 11. HPG electrical circuit.

2.2.4.1 Brush Actuation System

The brush actuation system is shown in Figure 12. The brushes are 1 cm square blocks of CM1S (copper-graphite) material. Each brush is 5.08 mm thick, radially. Brush straps connect the brushes to the air supply manifold. The brush straps are made from 16 pieces of 12.7 mm x 76 μm (1/2 inch X 0.003 inch) thick copper foil soldered at each end. Pistons are used to load the brushes onto the rotor surface. The pistons are located in the air supply manifold. The manifold is made from 6.35 mm x 12.7 mm (1/4 inch X 1/2 inch) rectangular copper tubing with 40 copper piston cylinders soldered to the inner diameter.

The brush straps were made from foil to decrease the strap stiffness and to increase the current carrying cross-sectional area. After testing is complete, the brush straps function as a weak spring to deactuate the brushes.

2.2.4.2 Return Conductor System

Two parts form the return conductor system. They are the stator lining and the output terminals. The C-shaped stator linings snap around the inner diameter of the center stators. Screws fasten the brush actuation system to the linings. The L-shaped output terminals connect the load cables to the stator linings.

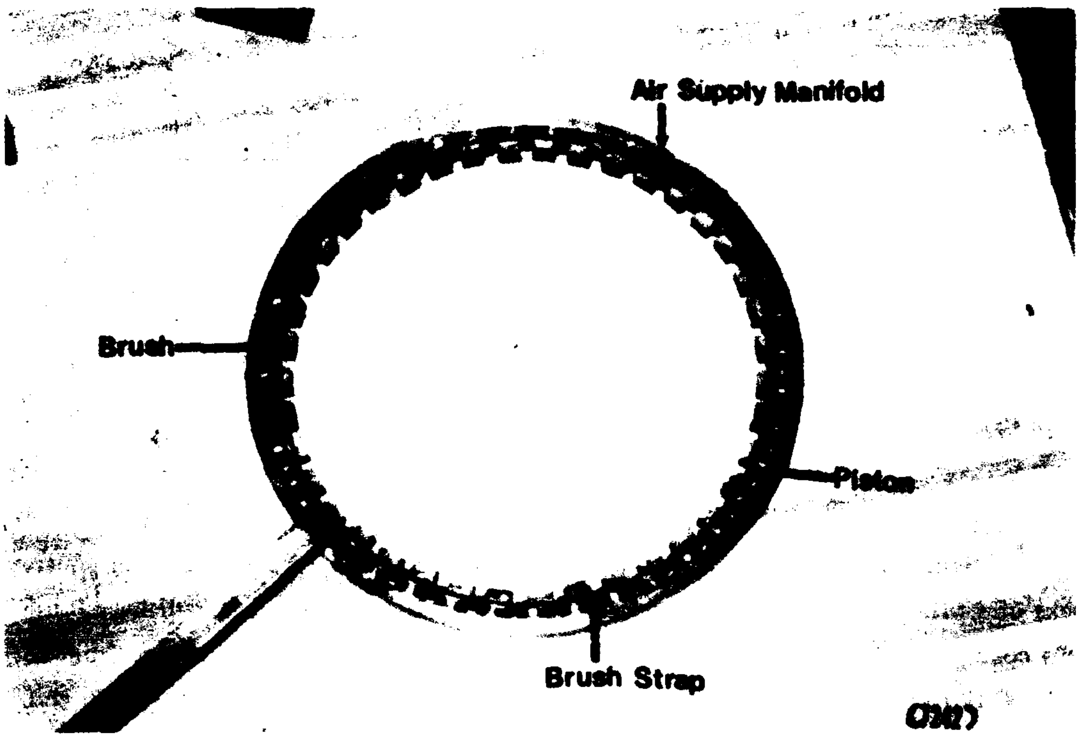

Figure 12. HPG brush actuation system.

The stator linings are shown in Figure 13. They were made from 1.02 mm (0.040 inch) copper sheet. The linings are adiabatically sized to keep their temperature rise below 10° C during a current pulse. Varnish was used to electrically insulate and join the linings and center stators.

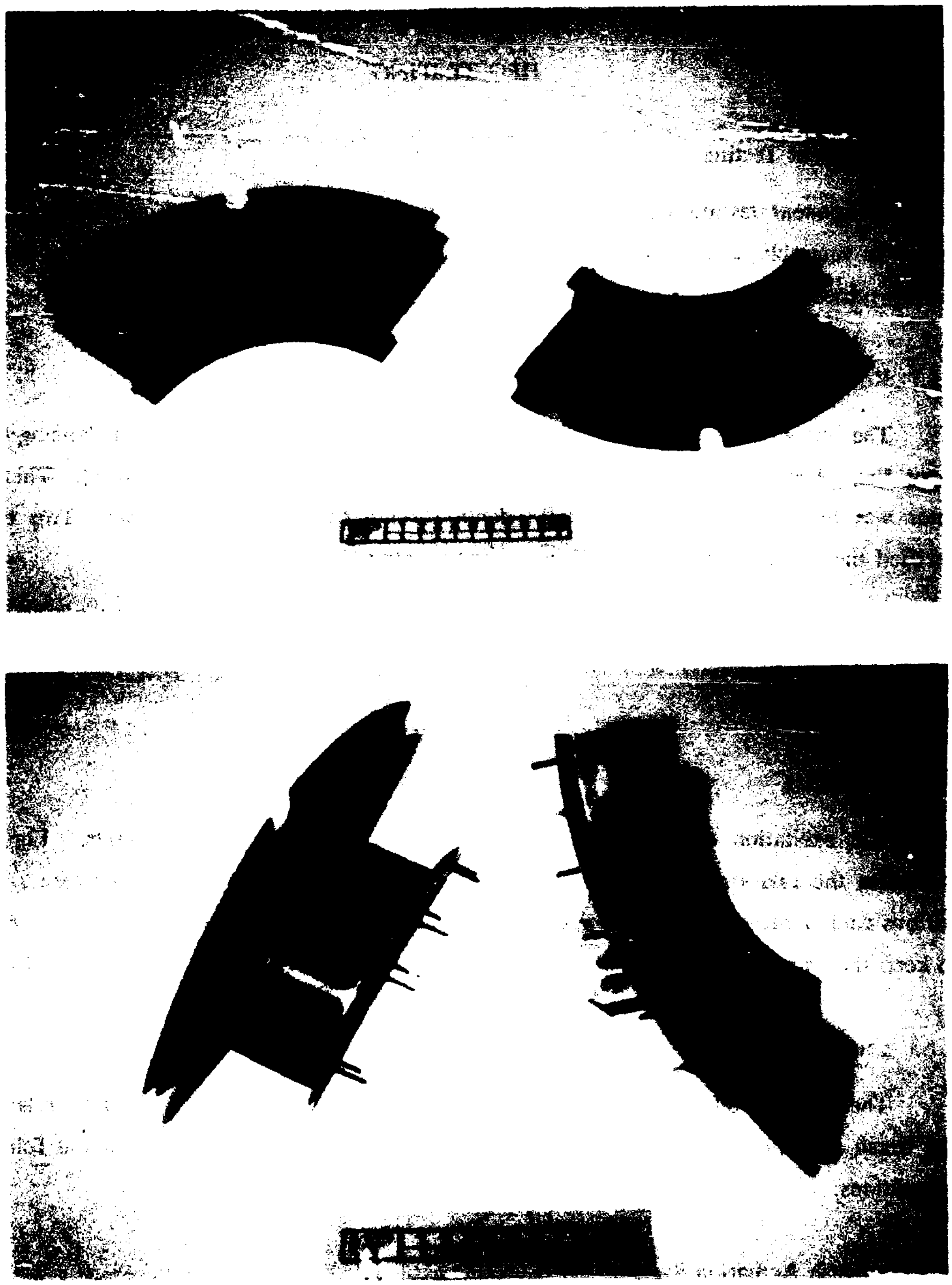

Figure 13. HPG stator linings.

SECTION 3

HPG TESTING

3.1 Component Testing

Component testing was performed prior to HPG assembly. The tests performed on the rotor assembly, excitation coils, and current collection system are discussed in the following subsections.

3.1.1 Rotor Assembly

The rotor assembly shown in Figure 14 was spin tested by The Balancing Company, Inc. The rotor was held at 19,000 rpm for 30 seconds (design condition). Then, the rotor was held at 21,000 rpm for 60 seconds (design condition +10 percent). This testing verified the mechanical integrity of the rotor assembly.

The rotor assembly passed a voltage standoff test. A 35 V potential was placed across the sleeve-to-core insulation. This insulation prevents ground loops from passing current through the bearings.

3.1.2 Excitation

The excitation coils were tested to verify coolant supply requirements. Figure 15 illustrates the relationship between excitation current level and water temperature rise for various supply pressures. A water supply pressure of 550 kPa (80 psig) or greater is needed to keep the water from boiling at the exit.

3.1.3 Current Collection System

The current collection system was tested prior to HPG assembly. The tests relating to the brush actuation system and return conductor system will be discussed in the following subsections.

3.1.3.1 Brush Actuation System

Load tests were conducted on the left and right brush actuation systems. Supply pressure was varied from 275 to 410 kPa (25 to 45 psig). A load cell was used to measure individual brush loads. The average brush load versus supply pressure is illustrated in Figure 16.

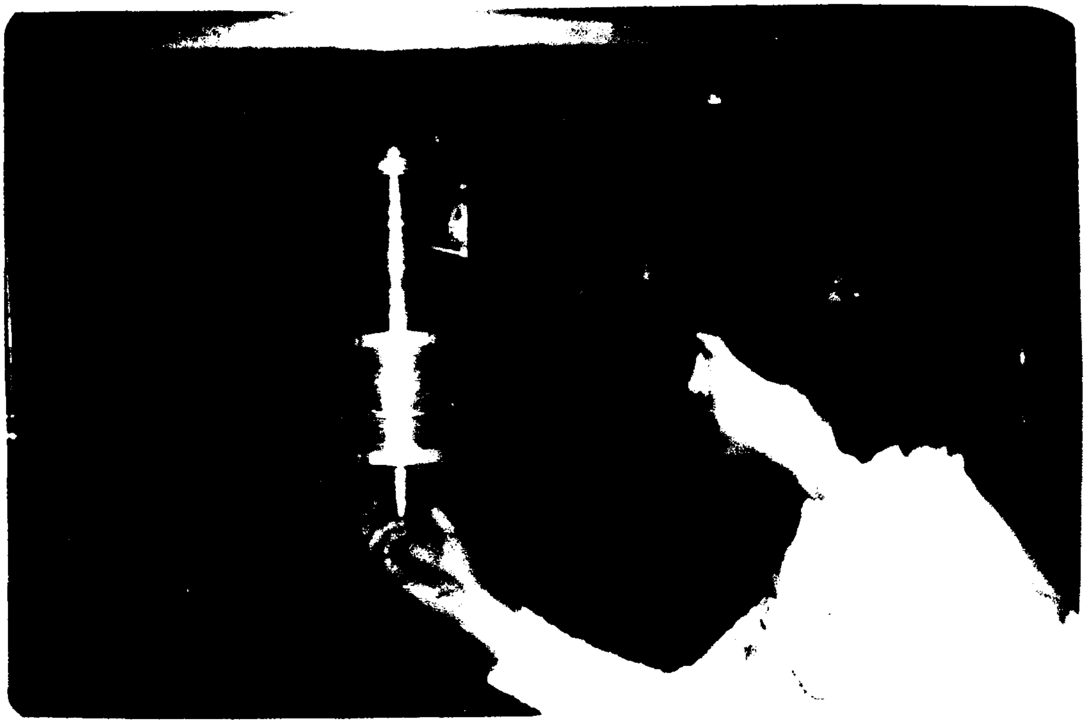

Figure 14. Rotor assembly in test fixture.

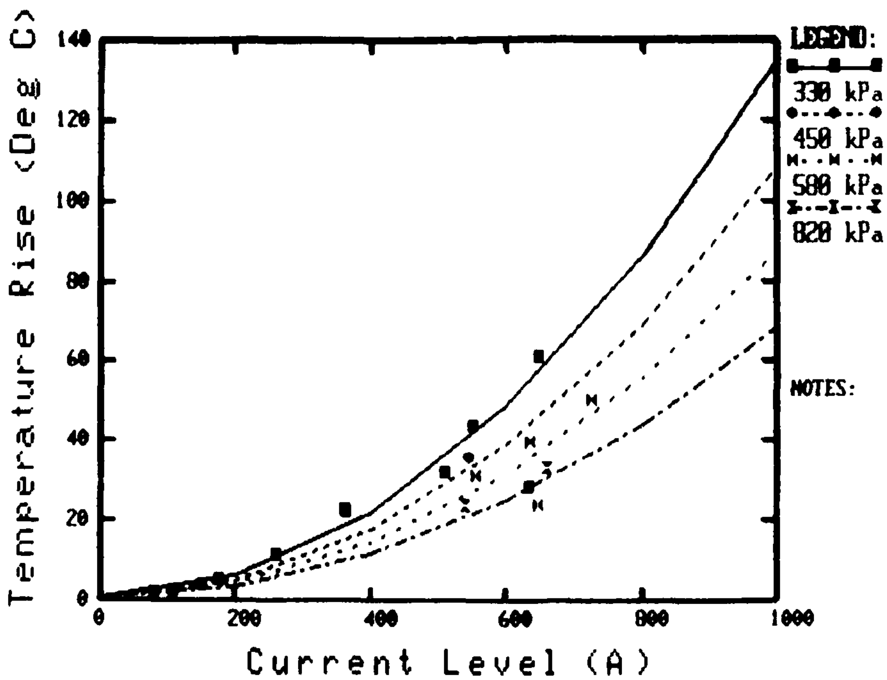

Figure 15. Supply pressure of 550 kPa is required.

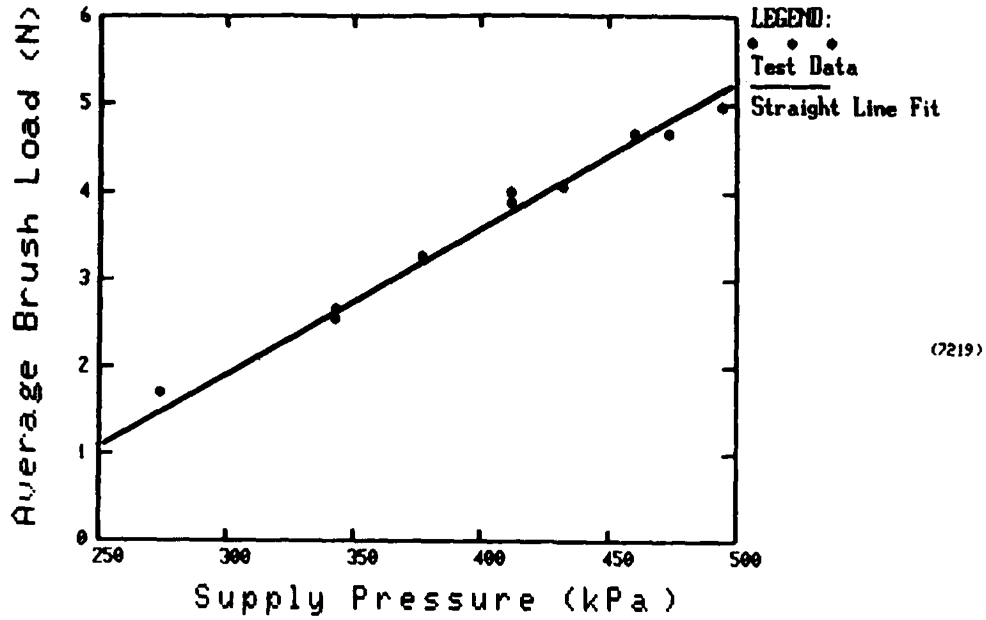

Figure 16. Brush load is linear with supply pressure.

The air flow rate required to operate the brushes at a given supply pressure is shown in Figure 17. An air supply pressure of 275 kPa (25 psig) is required at the design current level of 10,000 A.

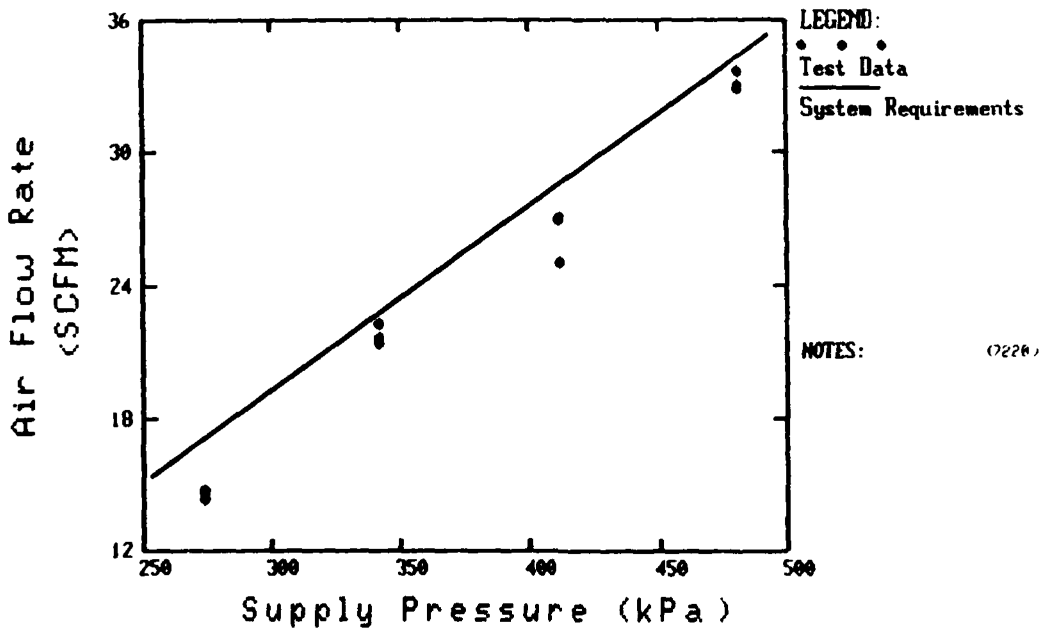

Figure 17. Air flow rate is dependent on supply pressure.

3.1.3.2 Return Conductor System

Two tests were performed on the stator linings. One test measured the temperature rise of the solder joints versus current and time. The other test verified that the linings were insulated from the stator.

Figure 18 illustrates the relationship between stator lining joint temperature rise, current, and operating time. A stator lining temperature rise of approximately 7° C can be expected during peak current testing. Each lining will conduct 2500 A.

A Hewlett-Packard high resistance meter, Model 4329A, measured the resistance between the stator linings and the stator. The resistance values ranged from 340 to 3500 MΩ. Therefore, the linings were effectively insulated from the stator.

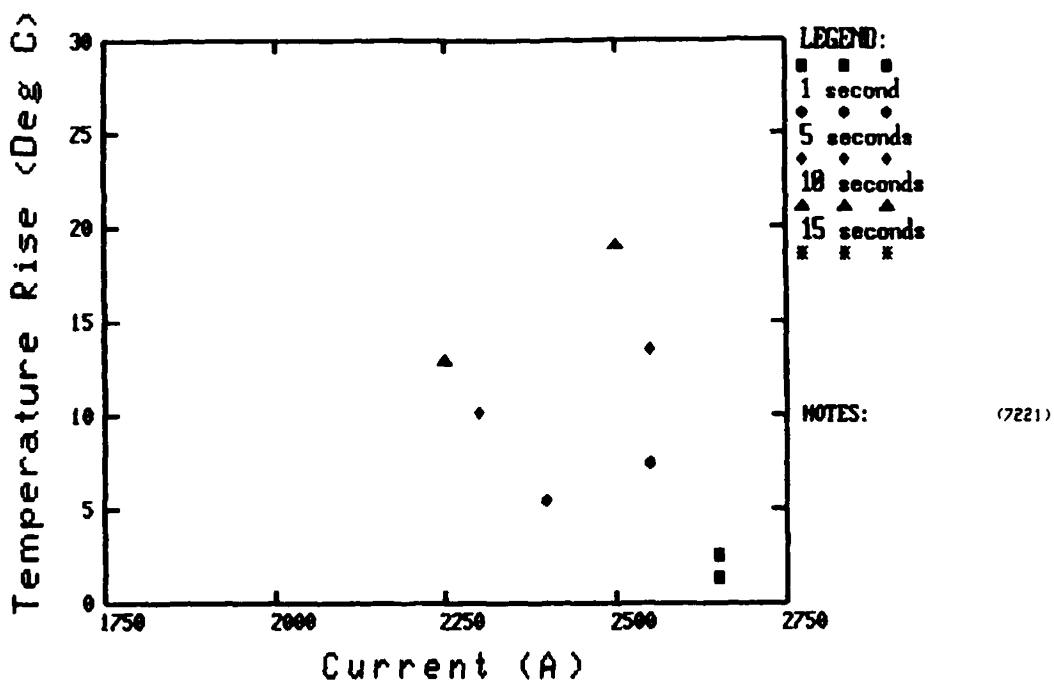

Figure 18. Stator linings will remain cool during testing.

3.2 HPG Assembly Testing

HPG testing included torque and mechanical testing. Overspeed and thermal stresses caused a rotor sleeve failure during the mechanical testing. This failure precluded final brush friction, voltage, and current testing during this program. The following subsections discuss the torque and mechanical tests performed on the HPG.

3.2.1 Torque Testing

Torque tests were performed on the HPG after assembly. The tests measured the breakaway torque of the bearings and the coefficient of friction of the brushes. The breakaway torque ranges from 0.68 to 0.90 N-m (6 to 8 in-lbf). Figure 19 shows the torque required to overcome brush friction. The measured static coefficient of friction was 0.23.

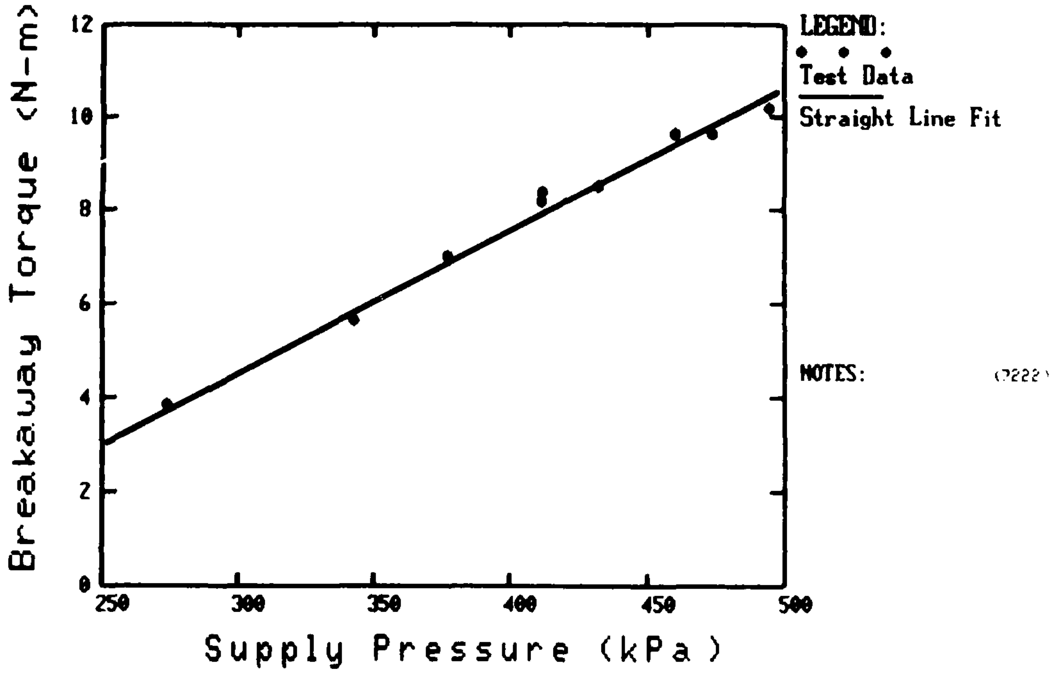

Figure 19. Brush frictions increase with supply pressure.

3.2.2 Mechanical Testing

On June 8, 1987 mechanical testing was started. Five tests were to be performed. The first four would take the generator to 20,000 rpm in 5,000 rpm increments. The fifth test would take the generator to 21,010 rpm, a 10 percent overspeed condition.

Table 2 contains temperature data for the last three tests. TLBR is the temperature of one brush on the left brush actuation system. TLBRG and TRBRG represent the left and right bearing temperatures, respectively. This data indicates the bearings were operating satisfactorily before and after the generator sleeve failure. The temperatures listed are steady-state values.

Table 2

Temperature Data

Test No.	3	4	5
Speed, rpm	14,228	20,371	21,198
TLBR, °C	65	80	37>468*
TLBRG, °C	29	30	28/35*
TRBRG, °C	24	26	28/119*

*Data shown is following generator failure.

In addition to temperatures, generator torque and vibration were measured. The torque and vibration signals indicated that the generator was operating smoothly.

During the fifth test on June 10, 1987 the generator failed. The generator reached a speed of 21,549 rpm before settling to 21,198 rpm. The generator was at speed for approximately 4 seconds prior to a sudden torque increase. The increase in torque slowed the rotor to 19,753 rpm. The motor was delivering maximum power.

The operator requested the motor to shut down at a rate of 2000 rpm/s. The motor control did a good job regulating the deceleration considering what was going on inside the generator. At 8,541 rpm the generator was brought to a stop in 0.280 second or 20 revolutions. This sudden stop was caused by friction welding of the input spline's rotor collar to the right end plate.

After disassembling and examining the HPG, the following sequence of events was formulated. The aluminum sleeve while subjected to a speed of 2220 rad/s continued to expand due to frictional heating caused by dragging brushes. This expansion continued until the sleeve contacted a stator lining. The large increase in brush temperature following the torque excursion indicates that failure occurred near this location. This contact initiated the torque excursion. The increase in power consumption was used to melt away a section of the sleeve resulting in an unbalanced rotor. The rotor unbalance was responsible for bending the shaft and friction welding the rotor collar to the end stator. Figure 20 shows a before and after view of the rotor assembly.

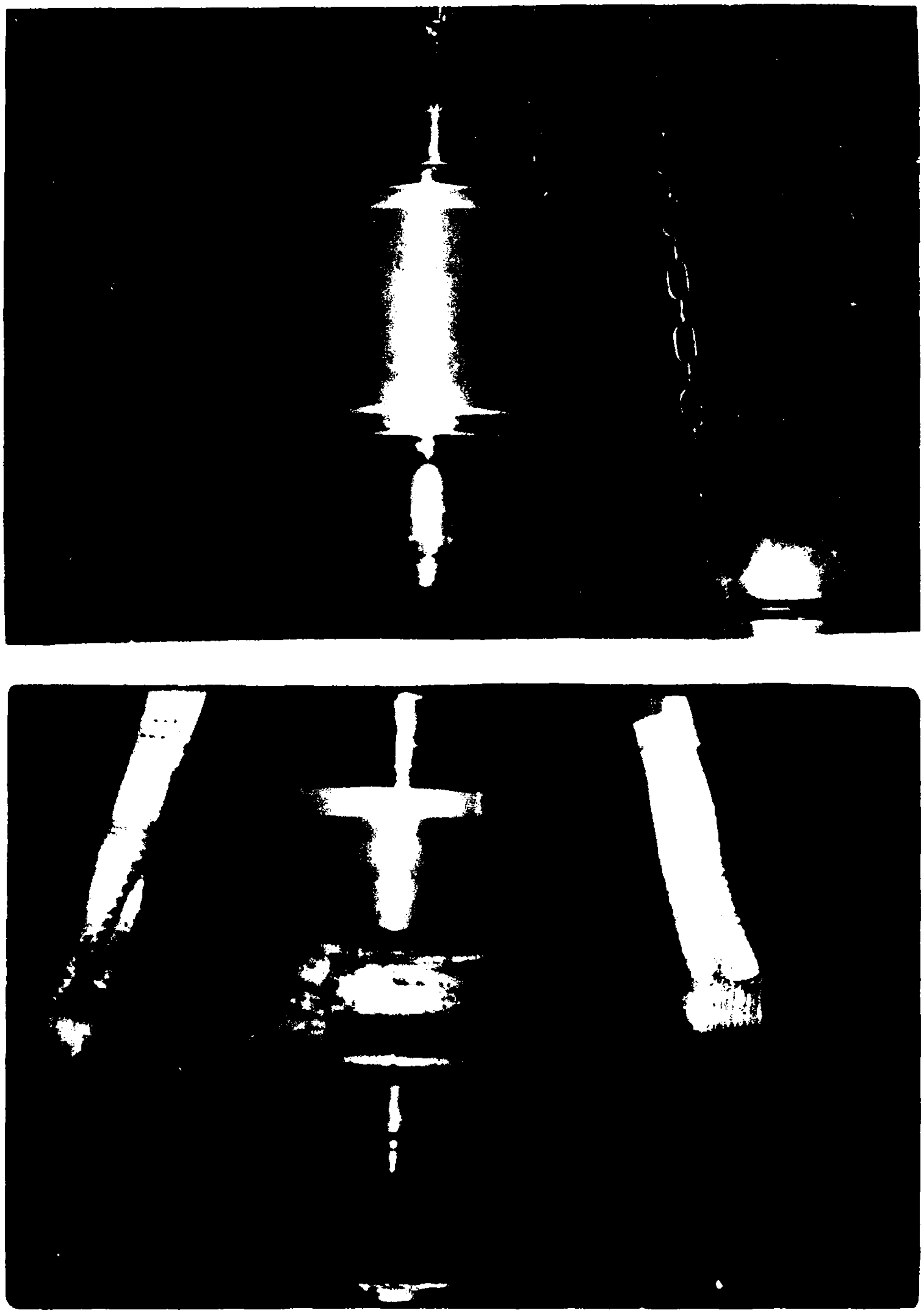

Figure 20. HPG rotor before and after testing.

SECTION 4

CONCLUSIONS

The HPG is designed to deliver 250 kW at 10 kA for a pulse length greater than 10 seconds. We are rebuilding this generator for future government testing.

The generator developed by this program has a compact design which is scalable to larger machines. Many of the features required for continuous operation are present. These features include water cooled excitation coils and air cooled brushes.

The test plan for this program was flawed. The generator was placed at high risk before most of the performance data was obtained. Future test plans will be sequenced to perform high risk tests at the end of a test program.

*U.S.Government Printing Office: 1989 — 648-056/04191