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ARMY GAS-COOLED REACTOR SYSTEMS PROGRAM

Alternator Final Design Report

June 1964

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ARMY GAS-COOLED REACTOR SYSTEMS PROGRAM

ALTERNATOR FINAL DESIGN REPORT

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ARMY GAS-COOLED REACTOR SYSTEMS PROGRAM

ALTERNATOR FINAL DESIGN REPORT*

ABSTRACT

The development and testing of a demonstration brushless alternator for the ML-1 mobile nuclear power plant is described. The brushless concept was selected after it became apparent that a conventional power generator could not satisfy the ML-1 weight and size requirements.

The demonstration alternator fabricated and tested under this program did not meet all performance specifications; the efficiency was low and the unit could not be operated for significant periods of time without overheating. However, a large body of useful data was accumulated during the extensive development program. Of special interest are data on the rotor and stator design, the cooling requirements and on the distribution of eddy current losses. Analysis of the data indicates that a brushless alternator, only slightly larger and heavier than was specified for the ML-1, could be developed with a modest additional effort.

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ARMY GAS-COOLED REACTOR SYSTEMS PROGRAM

ALTERNATOR FINAL DESIGN REPORT

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ARMY GAS-COOLED REACTOR SYSTEMS PROGRAM

ALTERNATOR FINAL DESIGN REPORT

I. INTRODUCTION

This report describes the design, development and testing of a demonstration alternator for the ML-1, a compact, transportable nuclear power plant being developed for the USAEC under the Army Gas-Cooled Reactor Systems Program (AGCRSP). The goal of the AGCRSP is to develop plans and specifications for a mobile nuclear power plant for military use (the ML-1A).

The ML-1 plant operates as a conventional Brayton closed-cycle gas-turbine plant, using a nuclear reactor as the heat source and oxygenated nitrogen (0.5 vol% O₂, 99.5 vol% N₂) as the reactor coolant and power plant working fluid. The coolant gas enters the reactor at 800°F and leaves at 1200°F. The reactor transfers 3.0 Mw(t) to the gas. Energy is extracted from the hot gas in a turbine-compressor/gear-box set to which an alternator is directly coupled. The net output of the plant is 330 kw(e) at 100°F ambient temperature.

The power plant consists of two major skid-mounted packages (reactor skid and power conversion skid) and a control cab skid. The power conversion skid includes the turbine-compressor set, recuperator, precooler, electrical switchgear and the alternator.

The principal characteristics of the ML-1 are given in Table 1. Additional information about the ML-1 and the AGCRSP is given in Appendix A.

An investigation of the characteristics of commercially available alternators revealed that none of the available units satisfied the requirements for the ML-1. As a consequence, the development of a unique machine was undertaken. As indicated in this report, this development had not been completed at the time the program was discontinued; tests of the demonstration alternator revealed certain deficiencies which could probably be corrected by

continued development and testing. However, the experience gained in this development program has advanced the state-of-the-art of brushless alternator technology, particularly in the areas of rotor and stator design, eddy current formation and distribution, and heat transfer analysis and internal cooling design.

TABLE 1 - PRINCIPAL MILITARY CHARACTERISTICS OF THE ML-1 POWER PLANT

Electrical output	300-500 kw, 2,400/4,160 v, 3 phase, 50-60 cycle at ambient temperatures ranging from -65 to 100°F
Overall weight	Approximately 40 ton total; 15 ton maximum package weight
Design lifetime	10,000 hr between reactor fuel changes; 50,000 hr for entire plant
Radiation	15 mr/hr at 25 ft in forward direction 24 hr after shutdown
Transport	M-172, M-172A trailers; rail; barge; C-130, C-124 and C-133 aircraft
Size	As dictated by transport
Environment	Conformance with military shock, vibration, temperature and environmental specifications
Field procedure requirements	Installation time: 12 hr Preparation for relocation: 6 hr

II. DESIGN

A. DESIGN CRITERIA

The detailed design criteria for the ML-1 alternator are included in the alternator specifications presented as Appendix B. The major design criteria are discussed in this section. The size and weight requirements were the most severe limitations imposed on the alternator design:

- Length - 30 in.
- Width - 36 in.
- Height - 36 in.
- Weight - 2,900 lb

The unit had to be capable of continuous operation for at least 10,000 hr without maintenance and the design lifetime of the machine was specified as 50,000 operating hr. The required outputs under alternate conditions were:

- Capacity at full load (wye connected): 400 kw, 2400/41600 volts, 3 phase, 60 cycles at 0.8 power factor.
- Capacity at full load (delta connected): 400 kw, 2400 volts, 3 phase, 60 cycles at 0.8 power factor.
- Minimum of 83% of rated full load when generating 50 cycle power.

A radical departure from standard generator configurations was necessary to achieve the required power output within the specified dimensions and weight. A compact, light-weight, brushless alternator was the concept selected for this application.

B. CONCEPTUAL DESIGN

The basic concept of the brushless alternator involves, as the name implies, the development of magnetic flux in the field iron without the requirement for a rotating field coil and the associated brushes or other devices to conduct the exciting current from the stationary to the rotating parts.

The flux path is basically axial (as opposed to the predominantly radial flux paths in a conventional alternator) and the current is generated by sweeping the "doughnut"-shaped armature winding with the rotating axial flux field induced in the rotor (field iron). The configuration of the magnetic material in the rotor is selected to produce optimum current in the armature.

The flux path in the machine is shown schematically in Figure 1. The excitation current is applied to the stationary field coil to develop the flux field which envelopes the (magnetic) drive end housing. The flux path is from the housing across an air gap into the rotor hub, and axially along the magnetic portion of the shaft to the north pole of the rotor (field iron). The flux then passes through the stationary armature and back to the south pole of the rotor, crossing the air gap between the armature and the rotor twice. The configuration of the south pole is such that the flux is evenly distributed for passage across the air gap between the rotor and the field coil housing, completing the magnetic circuit. The space between the north and south poles of the rotor is filled with non-magnetic material so that the final configuration of this part is a smooth-surfaced right cylinder.

Figure 2 shows a typical configuration for the alternator. Note that the field coil extends into the rotor and adjoins on two sides the magnetic material of the drive end housing. The air gap between the housing and the rotor (shown in Figure 2 between item 17 and items 11, 12, 20 and 23) is a homopolar air gap. By definition, a homopolar air gap results when the air gap is traversed by magnetic flux of unchanging direction (as is generated by direct current). Since the direction of the flux does not change, the surfaces adjoining the air gap assume and maintain constant polarities. In contrast, the air gap between the rotor and the armature (stator) - shown in Figure 2 between items 11 and 12 and item 27 - is a heteropolar air gap. A heteropolar air gap results when the air gap is traversed by flux which periodically reverses direction. Such a condition occurs between the rotor and stator because, although the polarities of the north and the south poles of the rotor remain individually constant, a given portion of the air gap is alternately adjoined by the north and the south pole as a result of the rotation of the rotor. Figure 3 presents an isometric representation of rotor laminations and the distribution of magnetic masses in the laminations.

The principal problems in the design of the brushless alternator involved (1) minimizing the flux losses in the homopolar and heteropolar air gaps so that the desired power output could be developed in the armature without excessive heating of the stator and, (2) properly distributing the masses of magnetic material in the rotor to produce the optimum flux path required to generate current of the desired characteristics in the armature.

Theoretically; the brushless alternator more closely resembles a smooth rotor machine than a salient pole alternator. In salient pole machines, the principal flux leakage path is through the air between adjacent pole tips and is a function of polar arc and polar pitch. The ratio of leakage flux to total flux is less in a smooth rotor (and brushless) alternator than in a salient pole machine because the interpolar region is filled with electrically conductive non-magnetic material. Despite the similarity between smooth-rotor and brushless alternators, the differences are sufficient to require significant modification of the standard smooth-rotor design formulae for adaptation to a brushless machine design.

FIGURE 1. FLUX PATH IN TYPICAL BRUSHLESS ALTERNATOR

The conceptual design for the rotor of the brushless alternator specified the use of nine 0.75-in. thick laminations. Eight of the nine laminations were composed of two pieces of USS Cor-Ten steel welded to a non-magnetic spacer of AISI Type 304 stainless steel. The varying configurations of the magnetic masses within the laminations are shown in Figure 3. Six laminations contribute mass to both poles; the remaining three contain only parts of the south pole (which includes the flux distribution ring). The flux path in the north pole can be divided into three parts (Figure 1): (1) An axial path along the shaft; (2) A radial path through the lamination; and, (3) An axial path in the peripheral portion of the pole. The area of the axial path in the peripheral portion of the north pole was taken as equal to the projection of that portion of the pole which faced the stator (armature). The radial path in the north pole structure was found by summation of the areas (in terms of mass through which the flux travels) of the path in each of the laminations. To simplify this calculation, the component masses of the north pole were shaped so that the area of the path at each given radius was constant in a given lamination. The dimensions of the magnetic portion of some of the laminations was established by stress considerations and are greater than needed to satisfy magnetic requirements. The area of the axial flux path along the shaft is equal to about 1.7 times the area of the radial flux path. The flux path through the south pole is axial and is the summation of the effective areas of each south pole lamination. The area of the flux path through the rotor hub was specified as 160 sq in. with a total path length of 4.5 in. All of the active flux and all of the leakage flux passes through this area. The areas of the radial north pole flux path and the axial south pole flux path were each specified at 108 sq in. with a path length of 8.5 in. All of the active flux and half of the leakage flux passes through these areas. The total flux in the north and south poles was considered to be equal to the flux at the heteropolar gap plus the leakage flux between the poles. The total flux in the field housing was considered to be equal to the flux in the rotor hub plus the leakage flux across the homopolar gap.

The direct-axis synchronous reactance for the alternator was calculated by the same techniques used for conventional (brush-equipped) alternators. The calculation of armature reaction reactance, however, differed from that used for conventional machines in that the total (homopolar and heteropolar) air gap was considered. The calculational technique used to determine the quadrature-axis synchronous reactance in a conventional machine was used for the brushless alternator since the permeances involved are the same (armature to pole-tip to opposite pole-tip to armature, including two heteropolar air gaps). The brushless alternator was treated as a smooth-rotor machine for the calculation of direct-axis subtransient reactance except that no provision was made to include the effect of damper windings since these do not exist in the brushless concept. The quadrature-axis subtransient reactance was considered to be equal to the direct-axis subtransient reactance since the interpolar material of the rotor provides a good path for induced currents.

The calculation of the no-load saturation curve for the brushless alternator conceptual design considered the fact that slot width-to-tooth width ratio varied across the armature with the result that the apparent reluctance of the air gap also varied. Although it would have been possible to select a particular portion of the armature surface and treat it as a weighted mean configuration, the absence of any corollary data based on previous

- 1 STATOR PIN (8)
- 2 ROTOR CAVITY
- 3 DIAPHRAGM (TO CONTAIN STATOR COOLANT)
- 4 STARTER MOTOR (OMITTED FROM DRAWING)
- 5 LAMINATED STATOR CORE
- 6 STATOR CAVITY
- 7 STATOR COOLANT CONNECTION
- 8 COOLANT PASSAGE IN BOTTOM OF COIL SLOT
- 9 AXIAL CROSS-SECTION OF COIL SLOT SHOWING FIVE-TURN COILS
- 10 RADIAL CROSS-SECTION OF FIVE-TURN COIL IN COIL SLOT
- 11 NON-MAGNETIC INTERPOLAR MATERIAL (ROTOR)
- 12 FLUX DISTRIBUTION RING, PART OF S POLE
- 13 LAMINATED RING INSERTED IN DRIVE END HOUSING
- 14 FIELD COIL COOLANT PASSAGE
- 15 LAMINATED RING INSTALLED ON DRIVE END HOUSING
- 16 FIELD COIL
- 17 DRIVE END HOUSING (MAGNETIC)
- 18 NON-MAGNETIC PORTION OF ROTOR SHAFT
- 19 MAGNETIC PORTION OF ROTOR SHAFT
- 20 ROTOR HUB (MAGNETIC)
- 21 N POLE
- 22 FIELD COIL BOBBIN
- 23 S POLE
- 24 ALUMINUM CASE
- 25 PRESSURE CONNECTION
- 26 HOMOPOLAR AIR GAP
- 27 HETEROPOLAR AIR GAP

FIGURE 2. TYPICAL CONFIGURATION FOR A BRUSHLESS ALTERNATOR

FIGURE 3. ARRANGEMENT OF MATERIALS IN LAMINATED ROTOR OF DEVELOPMENTAL BRUSHLESS ALTERNATOR

experience could have resulted in the introduction of significant errors into the calculation. Consequently, a more conservative procedure was followed in which the armature was divided into concentric rings and the magnetic circuit associated with each ring calculated separately. The overall characteristic of the design configuration was then determined graphically. The no-load saturation curve for the conceptual design brushless alternator is shown in Figure 4.

The open circuit and short circuit characteristics of the conceptual, brushless alternator with a 25/36 pitch and a 2/3 pitch are shown in Figures 5 and 6, respectively. The detailed design calculations for the conceptual design are presented in Appendix C.

C. DESIGN AND FABRICATION OF DEVELOPMENTAL ALTERNATOR

The design of the developmental model of the brushless alternator was completed, based on the theoretical configuration developed in the conceptual design phase (but with a 23/24 pitch). The design and fabrication procedures are summarized below.

1. Stator (Armature)

The stator core was fabricated by wrapping Armco Steel Corporation M-6 electrical steel coil (0.012-in. thick) on a 17-in. OD right circular cylinder of 1/4-in. thick AISI Type 304 L stainless steel 13-in. long. The M-6 sheet was wrapped continuously until the diameter was 30 in., at which point the end of the sheet was tapered and welded and the assembly enclosed in a 30-in. ID right circular cylinder of Type 304 L stainless steel 13 in. long. This finished configuration is shown in Figure 7a. Eight type 304 L stainless steel pins were inserted radially through the yoke to prevent shifting of the laminations. In subsequent machining operations the length of the core was reduced to 12 in. and the back (away from the rotor) surface was recessed on a 47° 30' angle to provide space for the start motor mounting assembly. The machined configuration is also shown in Figure 7b. The core was then slotted to accommodate the armature windings. Seventy-two equally spaced slots 0.433-in. wide and 2.1 in. deep were milled in the flat face of the core. The slotted configuration is shown in Figure 8.

The armature winding was fabricated from seventy-two separate coils (each consisting of five copper bars) 0.144-in. thick and 2.58-in. wide. Each bar was covered with 0.010 in. of insulation and the bundle of five bars ("five-turn coils") enclosed in 0.040 in. of insulation. The configuration of the coils is best understood by reference to Figure 9; the short, straight portions of each coil are placed in two slots that are approximately 120° apart. The coils are placed in such a manner that one straight portion of any given coil is uppermost in one slot and at the bottom of the other slot. The two coils in each slot are secured by a slot wedge (refer to Figure 2). The ends of the coils are connected and comprise the armature winding. The armature winding is tapped at six places to provide a three-phase output. The installation of the coils in the slotted yoke completed the fabrication of the stator assembly.

FIGURE 4. NO-LOAD SATURATION CURVES FOR ALTERNATIVE CONCEPTS OF BRUSHLESS ALTERNATOR

FIGURE 5. BRUSHLESS ALTERNATOR OPEN AND SHORT CIRCUIT CHARACTERISTICS, 25/36 PITCH

FIGURE 6. BRUSHLESS ALTERNATOR OPEN AND SHORT CIRCUIT CHARACTERISTICS, 2/3 PITCH

Figure 7a.

Figure 7b.

FIGURE 7. STATOR ASSEMBLY

FIGURE 8. COIL SLOTS IN STATOR, DEVELOPMENTAL ALTERNATOR

FIGURE 9. ARMATURE COIL CONFIGURATION

2. Rotor

The rotor was fabricated from nine laminations; three were discs 30 in. in diameter, three were discs 28.4 in. in diameter and three were rings with an outside diameter of 28.4 in. and an inside diameter of 23 in. The discs were fabricated from irregularly shaped sections of 1 in. thick USS Cor-Ten material welded to and separated by non-magnetic sections of AISI Type 304 stainless steel. Figure 10 shows the configuration of the Cor-Ten sections for the No. 1 rotor disc; note the chamfer provided for subsequent welding of the three parts. The three rings were fabricated from 1-in. thick Cor-Ten material to serve as flux distribution rings for the south pole. The completed rotor assembly is shown in Figure 11 (also refer to Figure 3).

3. Field Coil

The field coil consisted of No. 11 square copper wire insulated with epoxy. The wire was wound on a coil form, or bobbin, and installed in the field coil housing. The configuration of the housing was such that the field coil extended into the space inside the three outer (away from the armature) laminations of the rotor.

A cross-sectional view of the developmental alternator is shown in Figure 12. Figure 13 shows the several parts of the alternator prior to assembly. The rotor is shown on the left with the side facing the armature exposed (up). The stator is shown to the right of the rotor; the recessed face is on top. The field coil is shown in the center foreground behind the array of bearings and miscellaneous parts. The drive end housing is on the stand in the right center of the photograph; the field coil support protrudes upward. The diaphragm which separates the stator from the rotor areas is shown at the right with the face matching the stator exposed. The alternator case, standing on end, is shown behind the diaphragm.

D. TESTING AND MODIFICATION OF THE DEVELOPMENTAL ALTERNATOR

During static testing of the developmental alternator, it was observed that the load on the thrust bearing was significantly greater than anticipated. Investigations revealed that this situation was the result of approximately 16% more flux leakage than predicted. The thrust bearing was replaced with a new unit with suitable performance characteristics before the dynamic tests.

The initial no-load dynamic tests revealed that the voltage induced in the armature was only approximately 50% of the design value and that the generated voltage at constant field current was proportional to the rotor speed (Figure 14). Search coils were used to measure the flux in the machine in the static condition. These investigations revealed that sufficient flux existed in the non-rotating condition to develop 90 to 95% of design voltage. On the basis of this data, it was concluded that the cross sectional area of the flux distribution ring was too small and, as a consequence, non-uniform flux distribution existed in the homopolar gap. This non-uniformity resulted in the development of eddy currents in the drive end housing and canceled, in part, the flux field generated by the field coil, reducing the usable flux available for power generation. An attempt was made to minimize the eddy

FIGURE 10. TYPICAL ROTOR DISC ASSEMBLY, DEVELOPMENTAL ALTERNATOR

FIGURE 11. ROTOR, DEVELOPMENTAL ALTERNATOR

FIGURE 12. DEVELOPMENTAL ALTERNATOR CROSS-SECTION VIEW

FIGURE 13. ALTERNATOR COMPONENTS

FIGURE 14. NO-LOAD PERFORMANCE OF DEVELOPMENTAL ALTERNATOR

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currents in the drive end housing by installing laminated rings in the housing adjacent to the homopolar air gap.

No-load dynamic tests of the machine with the modified drive end housing did not reveal any significant change from the earlier findings; the induced voltage was still approximately 50% of the design value and proportional to rotor speed. Further investigations led to the conclusion that the stainless steel pins in the stator were producing eddy currents which were responsible for the observed performance. These pins were removed and replaced with laminated magnetic material without structural rigidity. No-load tests with the modified stator indicated that the machine would produce 90% of the design no-load voltage and that the effect of rotor speed on the induced voltage had been eliminated (see Figure 15). During static tests it was possible to operate with a smaller air gap than in dynamic tests; the effect of a diminished air gap is also shown in Figure 15.

The rotor shaft was modified to minimize end leakage flux. In the original concept, the rotor shaft was entirely made of magnetic material, the modified shaft was a composite of magnetic and non-magnetic materials as shown in Figure 2.

Dynamic load tests of the machine were attempted but the results indicated that performance was significantly poorer than predicted. Evaluation of the substandard performance indicated that a magnetic short-circuit in the rotor was the probable cause. The machine was disassembled and the rotor was checked. This investigation revealed that the permeability of the AISI Type 304 stainless steel used to separate the pole pieces in the rotor laminations was approximately 4.0 as opposed to the specified value of 1.02. It was concluded that the change in permeability of the material was the result of heat generated in the laminations during the welding of the Cor-Ten parts to the stainless steel parts. (See Appendix D for a discussion of this subject.)

A replacement rotor was designed and fabricated. AISI Type 310 stainless steel was specified as the non-magnetic material and the distribution of the magnetic material masses in the rotor was altered slightly. A thicker flux distribution ring was provided and the drive end housing was modified to accommodate the new, longer rotor.

The machine was reassembled with the new rotor and no-load dynamic tests were performed. Table 2 summarizes the results of these tests and indicates that the specified 2400 volt output was attained at acceptable field excitation levels. However, load tests at unity and 0.8 power factors revealed that the machine would not generate the specified output (Table 3).

TABLE 2 - NO-LOAD SATURATION DATA - MODIFIED ROTOR

Field current, amperes	7.5	9	12.3	15.3	18.3	20.5	25	30.3
Field voltage, volts	60	70	100	125	160	180	220	280
Output voltage, volts/phase to neutral								
Phase A	1360	1540	1920	2120	2280	2340	2440	2480
Phase B	1360	1540	1920	2120	2280	2340	2440	2480
Phase C	1360	1540	1920	2120	2280	2340	2440	2480

FIGURE 15. NO-LOAD PERFORMANCE OF DEVELOPMENTAL ALTERNATOR AFTER STATOR PIN MODIFICATION

11-2-64-1289

TABLE 3 - LOAD TEST PERFORMANCE DATA - MODIFIED ROTOR

(1.0 and 0.8 Power Factor)

Field current, amperes	23.6	25.2	26.8	26.4	29.2	33.5	31	26.8	28.8
Field voltage, volts	200	210	225	230	260	315	285	245	260
Power factor	1.0	1.0	1.0	1.0	1.0	0.8	1.0	0.8	0.8
Output power, kw									
Phase A	4	18	36	44	58	20	72	10	14
Phase B	4	16	35.2	40	60	18	68	9	12.8
Phase C	4	18	35.3	44	58	18	68	10	14
Total, kw	12	52	106.4	128	176	56	208	29	40.8
Output current, amperes									
Phase A	4.0	6.0	12.0	20	24	8	30	4	6
Phase B	4.0	6.0	12.0	20	24	8	30	4	6
Phase C	4.0	6.0	12.0	16	23.2	8	26	4	6
Output voltage, volts									
Phase A	2400	2390	2390	2390	2390	2400	2390	2390	2390
Phase B	2420	2400	2400	2410	2400	2400	2400	2400	2400
Phase C	2420	2420	2400	2410	2410	2420	2400	2400	2400

An alternate set of armature coils was fabricated that was physically interchangeable with the original coils. The new coils consisted of six copper bars each ("six-turn coils"). No-load tests with these coils indicated a significant improvement over the performance with the five-turn coils (Table 4). Load tests revealed that the modified machine developed design power at unity power factor (Table 5) but was deficient (as indicated by the data in Table 6) at 0.8 power factor. These results are shown graphically in Figure 16.

TABLE 4 - NO-LOAD SATURATION DATA - SIX-TURN STATOR

Field current, amperes	0.75	16.5	44
Field voltage, volts	55	135	368
Output voltage, volts/phase to neutral			
Phase A	1600	2394	2858
Phase B	1600	2400	2860
Phase C	1600	2400	2858

FIGURE 16. LOAD TEST PERFORMANCE - SIX - TURN STATOR

TABLE 5 - LOAD TEST PERFORMANCE DATA - SIX-TURN STATOR-UNITY POWER FACTOR

Field current, amperes	18	21	25.5	36
Field voltage, volts	152	176	222	325
Output power, kw				
Phase A	34	68	102	134.5
Phase B	33	67	101	133
Phase C	33.2	67.4	100.8	132.8
Total	100.2	202.4	303.8	400.3
Output current, amperes				
Phase A	15.2	28	41	55
Phase B	15.2	28	41.6	55
Phase C	14.8	28	41.5	55
Output voltage, volts				
Phase A	2408	2408	2400	2398
Phase B	2410	2408	2410	2404
Phase C	2410	2406	2408	2406
Power factor	0.91	1.000	1.00	1.00

TABLE 6 - LOAD TEST PERFORMANCE DATA - SIX-TURN STATOR - 0.8 POWER FACTOR

Field current, amperes	16	20	26	34	48
Field voltage, volts	145	170	220	305	450
Output power, kw					
Phase A	--	16	35	52	68
Phase B	--	17	34	53	66
Phase C	--	18	34	50.4	67.2
Total, kw		51	103	155.4	201.2
Output current, amperes					
Phase A	--	10	20	28.8	35.2
Phase B	--	12	20	28.8	35.6
Phase C	--	10	18	26.7	35.5
Output voltage, volts					
Phase A	2288	2410	2400	2400	2368
Phase B	2392	2410	2406	2412	2374
Phase C	2390	2404	2406	2404	2374
Power factor	--	0.662	0.74	0.8	0.8

During load testing, it was observed that the combined losses due to resistance and reactance in the end turns of the armature windings required the dissipation of approximately 13 kw of heat from the stator. The original concept contemplated the removal of this heat by flooding the stator portion of the alternator with transformer oil and the transfer of the heat through the oil to the water-cooled case. The testing demonstrated that the heat transfer properties of the oil were inadequate and, after experimentation with other materials, aluminum oxide was added to the transformer oil to improve the heat transfer. This solution was adequate for continued testing but was not considered a satisfactory permanent solution to the problem.

The original concept had expected that conductive heat transfer to the field coil housing would provide adequate cooling for the field winding. During testing of the developmental machine, it was observed that the insulation on the individual conductors in the coil prevented adequate heat transfer. The coil was modified so that the square wires were wound on an oil-cooled bobbin. This arrangement removed sufficient heat to permit developmental testing but was not considered a permanent solution to the problem.

E. DESIGN AND CONDUCT OF ROTOR MODEL TESTS

Evaluation of the testing of the developmental alternator revealed that the machine did not produce the required power output with either the original or the modified rotor because of insufficient working flux. It was concluded that excessive interpolar leakage and non-uniform flux distribution across the homopolar gap were probably the principal factors contributing to this substandard performance.

A wooden scale mock-up of the rotor was fabricated to investigate the possibility of magnetic short circuits in the rotor. This investigation revealed one definite magnetic short circuit and several probable high leakage paths. At this point it became apparent that redesign of the rotor would be required.

The objectives of the rotor redesign were to obtain:

- Maximum useful flux at the heteropolar air gap between the rotor and the stator
- Minimum leakage flux between the poles in the rotor
- Most effective distribution of the magnetic material in the rotor and a uniform degree of saturation
- Uniform flux distribution at the homopolar air gap

The geometry of the rotor was considered to be the largest contributing factor to interpolar leakage because the outer (south) pole must almost encircle the inner (north) pole to ensure uniform flux transfer across the homopolar air gap and thus prevent the induction of high circulating currents in the stationary components of the field structure. Accurate predictions of leakage paths and flux distribution were extremely difficult because of the complex geometry of the poles. It was decided therefore, to fabricate quarter-

scale models of two rotors (one with a geometry similar to that used in the developmental machine and one with a larger diameter at the field coil end) and to test these models to develop the data required for the redesign of the rotor. SAE 1010 hot-rolled steel was selected as the magnetic material for the rotor models. Specimens of this material were analyzed chemically to confirm that the constituents were in accordance with the specification. The results of this analysis is presented in Table 7.

TABLE 7 - CHEMICAL ANALYSIS OF SAE 1010 STEEL FOR ROTOR MODELS

<u>Element</u>	<u>Quantity by Analysis, %</u>
Iron	97.877
Nickel	1.25
Manganese	0.043
Copper	0.61
Carbon	0.22

The magnetic properties of the SAE 1010 steel were determined from tests conducted on a ring 3/16-in. thick by 4-in. OD by 3-in. ID. A distributed excitation winding was placed on one side of the ring and a distributed search coil winding was placed on the opposite side. The flux detected by the search coil was measured for several values of excitation current. The measured magnetic properties of this material agreed quite well with the data published by steel suppliers (Figure 17).

The relationship of the critical design parameters of the quarter-scale models to the corresponding parameters of the full-size unit are presented in Table 8.

TABLE 8 - RELATIONSHIP BETWEEN FULL-SIZE AND MODEL ROTORS

<u>Parameter</u>	<u>Ratio</u>
Air gap length	1 : 4
Air gap area	1 : 16
Flux lines	1 : 16
Ampere turns	1 : 4
Material volume	1 : 64

The design of the models specified the use of 14 laminations each 3/16 in. thick and a flux distribution ring (9/16 in. thick). Nine of the laminations included both north and south pole material; five of the laminations included only south pole material in an effort to optimize the distribution of flux at the flux distribution ring. No non-magnetic spacer material was provided since it was not required for structural rigidity and the performance difference between stainless steel and air was considered to be acceptable for the tests planned. The field coil winding was wrapped around the simulated rotor hub immediately adjacent to the ninth lamination. The hub included

FIGURE 17. MAGNETIC PROPERTIES OF SAE 1010 HOT ROLLED STEEL

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a yoke to support the field coil and to provide a flux return path from the flux distribution ring. A dummy stator was provided; the air gap between the stator and the rotor pole faces was simulated by the insertion of non-metallic plates of various sizes. The diameter of the first four laminations of the large diameter model was reduced to match the diameter of the existing stator. The full-scale equivalent dimensions of the two rotors are presented in Table 9; views of the assembled large (32 in. equivalent) rotor model are shown in Figures 18 and 19.

TABLE 9 - FULL-SCALE EQUIVALENT DIMENSIONS OF ROTOR MODELS

<u>Lamination No.</u>	<u>Rotor Model 1 Diameter, in.</u>	<u>Rotor Model 2* Diameter, in.</u>
1	30.0	30.0
2	30.0	30.5
3	30.0	31.5
4	30.0	32.0
5	30.0	32.0
6	30.0	32.0
7	30.0	32.0
8	30.0	32.0
9	30.0	32.0
10	30.0	32.0
11	29.6	32.0
12	29.2	32.0
13	28.8	32.0
14	28.4	32.0

*The so-called "large rotor" model.

The rotor models were instrumented for the test as follows:

- A ten-turn search coil was wrapped around the field coil to measure the flux generated by the field winding.
- A ten-turn search coil was wrapped around the stator ring along the quadrature axis (bisecting the interpolar region) to measure the flux in the stator.
- A single-turn search coil was wrapped around each north pole lamination.

The output of the search coils was applied to a Sensitive Research Instrument Company Model FM flux meter. This meter measured the integral of the ampere-seconds of current applied at the terminals and was calibrated to within $\pm 3\%$ by applying a known current for measured time

FIGURE 18. SIDE VIEW OF ASSEMBLED ROTOR MODEL WITH DUMMY STATOR

11.2-64-1292

FIGURE 19. THREE-QUARTER VIEW OF ASSEMBLED ROTOR MODEL
SHOWING POLE FACES

intervals. The flux distribution in the homopolar gap was measured with a FW Bell Inc. Model 120 Gauss meter. This is a Hall-effect type instrument which measures flux density directly when the instrument probe is inserted in a flux field.

The field current was supplied by a variable d.c. supply through a polarity reversing switch. The field current was measured with a Weston Type 316 millivolt meter and a 100 ampere/50 millivolt shunt. A schematic diagram of the test setup is shown in Figure 20 and a photograph of the equipment is presented in Figure 21.

Calculations were performed to determine the relationship between the air gap (actually, non-magnetic material) between the pole faces and the dummy stator in the rotor model and the load effect that such an air gap would have on a full-scale machine. The gaps were calculated so that, at rated flux (in ampere turns) for a given load, the number of ampere turns across the model gap was equal to one-fourth the calculated sum of ampere turns across the full-scale alternator heteropolar gap plus the ampere turns required to compensate for armature reaction reactance. The results of this calculation are shown in Table 10.

TABLE 10 - RELATIONSHIP BETWEEN ROTOR MODEL AIR GAPS AND LOAD OF
FULL-SCALE ALTERNATOR MODELS

<u>Rotor Model Gap, in.</u>	<u>Simulated Load</u>
0.080	No load
0.163	400 kw, 0.9 pf, lagging
0.175	400 kw, 0.8 pf, lagging
0.190	450 kw, 0.8 pf, lagging

The following data were taken at several values of field current during each test run:

- Total flux, as indicated by the field flux search coil
- Stator flux, as indicated by the stator flux search coil
- North pole lamination flux, as indicated by the search coil on each north pole lamination
- Homopolar air gap flux distribution, as determined with the Gauss meter

In addition, the polarity of the field coil current was reversed at each test point to cancel out the effects of hysteresis in the test configuration.

The results of the tests performed with the (larger) rotor test model 2 are shown in Figure 22. Figure 23 presents similar test results for the rotor test model 1 and compares the findings with those for model 2. These curves show that the ratio of stator flux to the total field flux varies

CALIBRATING
RESISTOR

STATOR FLUX

SEARCH COIL

DUMMY STATOR

AIR GAP

POLE FLUX

SEARCH COIL

ONE-QUARTER
SCALE ROTOR

FIELD COIL

FIELD FLUX
SEARCH COIL

FLUX METER

REVERSING
SWITCH

50 mv
SHUNT

MILLIVOLT
METER

VARIABLE dc
POWER SUPPLY

FIGURE 20. SCHEMATIC TEST SETUP FOR MODEL ROTOR TESTS

FIGURE 21. ROTOR MODEL TEST SETUP

FIGURE 22. ROTOR MODEL 2 TEST RESULTS

FIGURE 23. ROTOR MODEL 1 TEST RESULTS

from about 0.43 to 0.52 ampere turns for the full range of simulated loads at rated voltage. Since comparable ratios were obtained in tests of both rotors, it is apparent that neither configuration was superior in this characteristic. Figures 24, 25 and 26 show the variation in the north pole lamination flux with various air gaps as a function of the field current. In these curves, lamination nine is nearest the field coil and lamination one is the pole surface. All the curves indicate a fairly uniform loss in flux from the field coil to the pole lamination, confirming the absence of any localized high leakage path. The flux density distribution in the homopolar air gap at selected pole face-to-stator air gaps and field currents is shown in Figure 27. These values were determined from Gauss meter measurements made during the test of model 2. At near the rated field excitation (24 amperes) the flux distribution in the no-load (0.080 in. air gap) varies about 3.5 kilogauss. However, at full load condition (0.175 in. air gap) the variation is only about one kilogauss.

The predicted performance of the full scale alternator rotor based on the results of the rotor model tests is summarized in Table 11.

TABLE 11 - PREDICTED PERFORMANCE OF FULL-SCALE ALTERNATOR
BASED ON TESTS OF ROTOR MODELS

<u>Rotor Model</u>	<u>Full-Size Equivalent, in. OD</u>	<u>Percent of Required Flux Produced at Rated Field Current</u>	
		<u>400 kw, 0.8 pf</u>	<u>400 kw, 0.9 pf</u>
1	30/28.4	92.5	100.5
2	30/32	101.0	113.0

F. DESIGN AND FABRICATION OF DEMONSTRATION ALTERNATOR

The design of the demonstration model of the brushless alternator was based on the developmental model, modified as indicated by the results of the rotor model tests and the test experience with the developmental unit. The design and the fabrication procedures are described in the sections which follow. The completed assembly is shown in Figure 28.

1. Stator

The stator core for the demonstration alternator was fabricated in the same fashion as that for the developmental unit. The outside diameter of the core was increased to 30-1/2 in. and the finished length was increased to 12-1/2 in. to increase the mass of the assembly to eliminate the possibility of saturation. The slots to accommodate the stator winding were modified to provide a channel for the circulation of oil coolant at the bottom of each slot. A five-turn coil, essentially identical with the one used in the developmental alternator, was provided for the stator. Although the data from the rotor test work had indicated superior performance with a six-turn stator coil, the five-turn coil was used to minimize armature reaction reactance. The coil insulation was modified to accommodate the improved stator cooling concept which involved direct cooling of the coils with OC-11 turbine oil. Selection of the insulation material and the final specification for the coil are described in Appendixes E and F respectively.

FIGURE 24. ROTOR MODEL 2 TEST RESULTS (NO AIR GAP)

FIGURE 25. ROTOR MODEL 2 TEST RESULTS (0.080 in. AIR GAP)

FIGURE 26. ROTOR MODEL 2 TEST RESULTS (0.250 in. AIR GAP)

FIGURE 27. AIR GAP FLUX DENSITY DISTRIBUTION IN THE HOMOPOLAR AIR GAP (FIELD CURRENT)

11.2-64-1299

- 1 STATOR PIN (8)
- 2 ROTOR CAVITY
- 3 DIAPHRAGM (TO CONTAIN STATOR COOLANT)
- 4 STARTER MOTOR (OMITTED FROM DRAWING)
- 5 LAMINATED STATOR CORE
- 6 STATOR CAVITY
- 7 STATOR COOLANT CONNECTION
- 8 COOLANT PASSAGE IN BOTTOM OF COIL SLOT
- 9 AXIAL CROSS-SECTION OF COIL SLOT SHOWING FIVE-TURN COILS
- 10 RADIAL CROSS-SECTION OF FIVE-TURN COIL IN COIL SLOT
- 11 NON-MAGNETIC INTERPOLAR MATERIAL (ROTOR)
- 12 FLUX DISTRIBUTION RING, PART OF S POLE
- 13 LAMINATED RING INSERTED IN DRIVE END HOUSING
- 14 FIELD COIL COOLANT PASSAGE
- 15 LAMINATED RING INSTALLED ON DRIVE END HOUSING
- 16 FIELD COIL
- 17 DRIVE END HOUSING (MAGNETIC)
- 18 NON-MAGNETIC PORTION OF ROTOR SHAFT
- 19 MAGNETIC PORTION OF ROTOR SHAFT
- 20 ROTOR HUB (MAGNETIC)
- 21 N POLE
- 22 FIELD COIL BOBBIN
- 23 S POLE
- 24 ALUMINUM CASE
- 25 PRESSURE CONNECTION
- 26 HOMOPOLAR AIR GAP
- 27 HETEROPOLAR AIR GAP

FIGURE 28. DEMONSTRATION ALTERNATOR ASSEMBLY

The stator core was annealed after winding to eliminate internal stresses and the completed core assembly was immersed in epoxy resin and baked to provide the rigidity required for the slot machining. The completed assembly is shown in Figure 29.

2. Rotor

The configuration of the magnetic masses within the rotor for the demonstration alternator differed significantly from that of the developmental unit (Figure 30). The rotor was fabricated from thirteen, 3/4 in. thick laminations and a 2-1/4 in. flux distribution ring. Eight laminations contained both north and south pole material and five laminations only south pole material; the flux distribution ring was homogeneously magnetic. The overall length of the rotor was increased to 12 in., the diameter at the pole face was increased to 30 in., and that at the field coil housing to 32 in. The magnetic material (north pole, south pole, and distribution ring) in the rotor was USS Cor-Ten and the non-magnetic (interpolar) material was low-permeability AISI Type 310 stainless steel. The face of the pole lamination was slotted to reduce eddy current losses.

The original concept specified welding of the magnetic and non-magnetic sections of each lamination and assembly of the laminations into the final rotor by peripheral welds at the interfaces between laminations. During fabrication, it was observed that the peripheral welds warped the laminations, causing air gaps up to 0.03-in. wide. This condition was considered intolerable because these added air gaps increased the reluctance in the path of the useful flux. Tests were conducted with four full-scale laminations to develop a brazing technique for joining the laminations with a copper-silver eutectic alloy. Although, in the final assembly of the rotor, the laminations appeared to adhere well, separation occurred in subsequent tests. As a consequence, 24-5/8 in. diameter axial dowel pins were installed to provide the required integrity in the assembly. The pins were fabricated from AISI Type 310 (non-magnetic) stainless steel since they passed through both magnetic and non-magnetic materials in the rotor. The completed rotor assembly (before pinning) is shown in Figure 31.

3. Field Coil

The configuration of the field coil for the demonstration alternator was altered significantly from that used in the developmental unit. As shown in Figure 32, square copper tubing was installed between the pairs of windings to remove heat generated in the coil. The ribbon type coil wire was wound so that one side of each winding was in contact with the cooling surface. The entire assembly was then wrapped in glass cloth and dipped in a silicon-based resin. The completed field coil assembly with the drive end housing is shown in Figure 33.

FIGURE 29. STATOR DEMONSTRATION ALTERNATOR

FIGURE 30. ARRANGEMENT OF MATERIALS IN LAMINATED ROTOR OF DEMONSTRATION ALTERNATOR

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FIGURE 31. ROTOR OF DEMONSTRATION ALTERNATOR

APPENDIX F

ML-1 ALTERNATOR STATOR COIL SPECIFICATIONS

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APPENDIX F

ML-1 ALTERNATOR STATOR COIL SPECIFICATIONS

1. SCOPE

This specification describes form-wound stator coils for the ML-1 500-kva alternator.

2. REQUIREMENTS

2.1 General Description - Slot-sized coils of high quality construction are required. Acceptable workmanship and material is evidenced by:

2.1.1 Relative absence of voids

2.1.2 Accuracy of slot section dimensions

2.1.3 Taping uniformly spaced and of even build

2.1.4 Controlled curing of impregnants

2.1.5 Ease of installing coils in stator, without unusual stress, deformation, or abrasion

2.1.6 Flexibility sufficient to permit normal installation of the throw coil without damage to insulation from bending

2.2 Dimensions and Quantity - The coil dimensions are specified in AGC Drawing No. 083431-1. The number of coils required is 74 (including 2 spares).

2.3 Materials - Coil construction materials are specified in Table 2.3.1.

2.4 Construction -

2.4.1 General - Over-all insulation requirements for the coils are specified in Table 2.4.1.

TABLE 2.3.1 - MATERIALS

<u>Application</u>	<u>Description</u>
Magnet Wire	0.144 in. by 0.258 in. copper; Anaconda Double Silotex (DX); copper OFHC soft annealed
Insultating Tape	Mica paper composite; General Electric 77866 Mica-mat tape; 0.0057-in.-thick, 1/2-in.-wide
Impregnant and Coatings	Solventless epoxy resin; General Electric 74011 epoxy resin
Leads Insulation	Inner wrapping - General Electric 77866 Mica-mat tape; 0.0057-in.-thick, 1/2-in.-wide. Outer wrapping - Hess Goldsmith B weave fiberglass tape, untreated; 0.003-in.-thick, 1/2-in.-wide
Outer Protective Tape	Hess Goldsmith B weave fiberglass tape, untreated; 0.003-in.-thick, 1/2-in.-wide

TABLE 2.4.1 - CONSTRUCTION COIL MAJOR GROUND INSULATION

<u>Coil Designation</u>	<u>Slot Section</u>	<u>End Turns</u>	<u>Leads Insulation</u>
Phase	Five applications of mica tape, half-lapped (See NOTE 1 below)	Stator inside diameter coil end turns - Five applications of mica tape, half-lapped. Stator inside diameter coil end turns - Three applications of mica tape, half-lapped.	Five applications of mica tape, half-lapped.
Non-phase	Five applications of mica tape, half-lapped (See NOTE 1 below)	Two applications of mica tape, half-lapped	Five applications of mica tape, half-lapped.

NOTE 1: If Option 3, Article 1.2 of Part II is selected, slot section of coil will have five half-laps and one BUTT application of MICA tape.

Lead insulation of all coils shall extend 4 in. along the end turn from the point where the lead leaves the coil.

The major ground insulation (General Electric 77866 Mica-mat) tape shall be wrapped on the coil with the glass cloth to the outside.

2.4.2 Coil Construction Procedure

2.4.2.1 Wind coil on shuttle and form. Metal bands and/or sacrifice tape may be used to hold conductors in position during forming. Either untreated fiberglass sleeving or one butt lap of untreated glass tape shall be used to enclose the second inside turn at each knuckle.

2.4.2.2 Press coil slot section to align individual conductors. Metal bands on slot sections of coil shall be removed prior to pressing operation.

2.4.2.3 Test each coil per Article 3.1.

All metal bands shall be removed from the coils prior to testing.

2.4.2.4 Remove sacrifice tape and heat coil in oven for one hour at 300°F.

2.4.2.5 Remove coil from oven and immediately brush on General Electric 74011 epoxy resin to entire coil, including leads. Special care should be taken during the brushing operation to insure a good fill of resin between strands.

2.4.2.6 Air dry until coil is non-tacky.

2.4.2.7 Apply two half laps of G.E. 77866 Mica-mat tape to entire coil, including leads.

2.4.2.8 Phase Coils: Apply three additional half laps of G.E. 77866 tape to coil slot sections, coil end turns corresponding to stator outside diameter, and coil leads. Apply additional one-half lap of G.E. 77866 tape to coil end turns corresponding to stator inside diameter.

If Option 3, Article 1.2 of Part II (Procedures and Methods for Preparing Stator; Installing, Connecting and Curing Coils; and Installing of Winding Thermocouples; Miscellaneous Notes - ML-1 500 KVA Alternator), is selected apply one additional butt lap of G.E. 77866 tape to slot section of coil.

Non-phase coils: Apply three additional half laps of G.E. 77866 tape to slot sections of coils and leads. The slot insulation shall extend a minimum of 2 in. beyond the end of the slot, as measured along the coil end turns, to provide for maximum creepage protection.

2.4.2.9 Apply outer wrap of 0.003-in.-thick untreated fiberglass tape, one-half lapped, to entire coil.

2.4.2.10 Heat coil to 300°F for 15 minutes. Remove coil from oven and immediately brush on G.E. 74011 resin to entire coil, including leads.

2.4.2.11 Partially cure - 15 minutes at 300°F.

2.4.2.12 Remove coil from oven and immediately brush on another coating of 74011 resin to entire coil, including leads.

2.4.2.13 Repeat Step 11.

3. TESTS

3.1 Coil Turns Insulation - Each coil shall be tested at 3000 volts (Refer to Procedure 3, Article 2.4.2) with a Surge Comparison Tester, using the Two-Coil Method. Coils showing either leakage or breakdown shall be rejected.

PROCEDURES AND METHODS FOR PREPARING STATOR: INSTALLING, CONNECTING AND
CURING COILS: INSTALLING OF WINDING THERMOCOUPLES: AND MISCELLANEOUS NOTES
ML-1 500 KVA ALTERNATOR

1. STATOR PREPARATIONS

1.1 Finish of Slots - Edges of all slots shall be filed down to a 1/32-in. radius. Following this, the entire stator shall be cleaned thoroughly with a suitable solvent (e.g., acetone, xylene, etc.) to remove metal particles.

1.2 Insulation of Slots - One of the following three options shall be used in order to provide additional scuff protection for the slot sections of the coils during insertion.

Option 1: Install a single slot liner of General Electric 77520 flexible mica plate. Liner shall extend beyond the end of the slot on both sides to the point where the coil end turn bends 90°, in order to provide for maximum creepage protection.

Option 2: Apply one wrapping of General Electric 77520 flexible mica plate to slot section of finished coil and secure with a suitable tape (tape must be compatible with various materials used in coil). Wrapping shall be applied so that maximum creepage protection is provided (See Option 1 above).

Option 3: Apply one additional butt lap of General Electric 77866 mica-mat tape to slot section of both phase and non-phase coils during coil construction, per Article 2.4.2, Procedure 8, Part I, ML-1 Alternator Stator Coil Specifications.

This additional insulation shall extend a minimum of 2 in. beyond the end of the slot, as measured along the coil end turns, to provide for maximum creepage protection.

1.3 Insulation of Stator Core - Insulate inside diameter and outside diameter of stator core with one layer of General Electric 77866 Mica-mat flexible sheet. Adhesive tapes used to secure mica sheet to core shall be compatible with all materials used in the insulation system.

2. INSTALLATION OF COILS IN STATOR

2.1 Insert one 1/32-in.-thick NEMA Grade G-3 phenolic/glass spacer (P/N 083432-1) in the bottom of each slot. A similar spacer shall be used to separate the top and bottom coils in each slot.

2.2 Install partially cured coils in slots. Apply General Electric 74011 epoxy resin to slots following insertion of coils (apply to coil top sides only) to provide a good fill of resin between coils, and between coils and iron. No resin shall be permitted to enter cooling oil ducts located in the bottom of the stator slots.

2.3 Drive the slot wedge (P/N 072204-1) into position immediately after applying 74011 resin to top coil.

3. WINDING CONNECTIONS

3.1 Form, insulate and partially cure phase group connection assemblies prior to connection in the winding. The assemblies shall be insulated with the same type and quantities of materials as specified for the coil leads, per Tables 2.4.1 and 2.3.1, Part I, M1-1 Alternator Stator Coil Specifications. The curing procedures shall conform to those specified in Coil Construction Procedure, Article 2.4.2 of the same specification.

3.2 In preparing the coil leads and phase group connection assemblies for brazing, special care should be taken to prevent notching or grooving of the copper conductors. (Notches in copper conductors may cause conductor failure in service due to fatigue failure.)

3.3 Braze coil stub connections, main leads, and phase group connections with Handy and Harmon Sil-Fos brazing material. Lap joints shall meet the following criteria:

3.3.1. Two conductors to be brazed together shall be overlapped a minimum distance of three times the thickness of the thinner member. For example, in joining two conductors each with dimensions of 0.144 in. by 0.258 in., the overlap distance would be 3×0.144 in. or 0.432 in. This would then provide a joint area of 0.432 in. by 0.258 in.

3.3.2 During the brazing operation, the brazing material should flow between the conductors being joined by capillary action; thus providing a continuous filling of brazing material between the conductors. Clips may be used to hold the conductors in place during the brazing operation.

3.4 Brazed joints shall be insulated with the same type and number of layers of insulation as specified for the coil leads, per Tables 2.4.1 and 2.3.1, Part I, ML-1 Alternator Stator Coil Specification. Two brushings of General Electric 74011 resin shall be applied to the insulated joints.

3.5 Main Leads: After the silicone rubber flexible lead cables are connected, an outer wrapping (one half lap) of untreated fiberglass tape shall be applied to the straight section of the cables. This is in addition to insulation applied to cable joints per Article 3.4 above. Two applications of General Electric 74011 epoxy resin shall then be made to provide a continuous coating to the glass tape.

4. FINAL CURING OF STATOR

General Electric 74011 epoxy resin shall be sprayed over the entire winding, including the tops of the wedges. Ascertain that the cooling oil ducts are free of resin. The stator shall then be cured in an oven as follows:

1 hour at 150°C (302°F)
plus 1 hour at 180°C (356°F)
plus 1 hour at 200°C (392°F)

NOTE: The time for the stator to reach the curing temperature should be added to the above curing time. (See data sheet for General Electric 74001 epoxy resin included in Part I, ML-1 Alternator Stator Coil Specifications).

5. INSTALLATION OF THERMOCOUPLES

5.1 Chromel/alumel thermocouples furnished by Aerojet-General Corporation shall be installed in the stator as indicated below:

<u>Thermocouple No.</u>	<u>Location</u>
1	In contact with bottom surface of bottom coil, center of slot 1 (Slot 1 should be a slot in which a phase coil is located.)
2	In contact with bottom surface of top coil, center of slot 2.
3	In contact with top surface of top coil, center of slot 3.

<u>Thermocouple No.</u>	<u>Location</u>
4	In contact with end turn of slot 1 phase coil, inside bore
5	In contact with the stator iron, top of tooth, slot 2, center of core
6	In contact with the stator iron, bottom of tooth, slot 3 center of core
7 - 12	Correspond to 1-6 except about 180 mechanical degrees away (slots 25, 26 and 27).

NOTES:

1. Thermocouple junctions shall be in close contact with insulated phase coils and iron to ensure that they will monitor the proper temperature.
2. The thermocouples shall be properly insulated from all parts of the winding to eliminate the possibility of personnel coming into contact with 4160 volts.

6. TESTS

Following final curing, stator winding shall be a-c high potential tested at 6 kv for one minute.

7. SUMMARY OF INSULATING MATERIALS SPECIFIED IN PART II

Fiberglass tape	Hess Goldsmith B weave fiberglass tape, untreated; 0.003-in.-thick, 1/2 in. wide
Impregnating resin	General Electric 74011 solventless epoxy resin
Mica tape	General Electric 77866 Mica-mat, 0.0057-in. thick, 1/2 in. wide
Wedge and spacer	NEMA-ASTM Grade G-3 natural laminate of fine weave continuous filament fiberglass cloth bonded with phenolic resin
Flexible Mica Sheet	General Electric 77866 Mica-mat flexible sheet
Brazing material	Handy and Harmon Sil-Fos
Thermocouples	Leeds and Northrop chromel/alumel, #28, asbestos/fiberglass insulation, Type 28-58-1
Main leads	1/C, 4 AWG, 133/35 stranding, copper conductor silicone rubber insulation with silicone impregnated outer braid

FIGURE 32. DETAIL OF FIELD COIL ASSEMBLY

FIGURE 33. DEMONSTRATION ALTERNATOR FIELD COIL AND DRIVE
END HOUSING

G. TEST OF THE DEMONSTRATION ALTERNATOR

The demonstration alternator was tested to evaluate the performance of the machine. Tests in this series were identified, typically, as D196-LE-41. In the discussion which follows, the tests are referred to by the last two digits only although some of the graphical and tabular presentations of data may include the entire identification.

In general, all of the tests were conducted by driving the alternator at rated speed with a prime mover, exciting the field with a variable-output power supply and absorbing the alternator output in an inductive load bank. Some modifications made to the machine during the conduct of the tests are described in chronological sequence in the summary of tests which appears below. Only the test data is reported in this section; the evaluation of the data is discussed in Section III.

Test 41 was conducted to develop the no-load saturation curve of the machine before pinning the rotor. The alternator was driven at constant speed and the field current was varied from 5 to 22 amperes. The open circuit voltage at the "A" phase stator terminals was recorded as being typical for all three phases. The no-load saturation curve developed during this test is shown in Figure 34.

Test 42 was run to develop the short circuit saturation curve for the machine. In this case, the armature windings were short-circuited by ammeters and armature current data were plotted as a function of field current (Figure 34).

Test 43 was conducted to establish the load saturation (field compounding) characteristics of the machine. In this test the total armature power was determined for varying field currents at three selected power factors as controlled by the inductive load bank (Figure 35); five-turn stator coils were used but one curve applicable to the six-turn stator coils is included for comparison.

Test 44 was initiated to establish the steady state temperatures in the machine during full-load operation. The test was aborted after 9 minutes when the brazed rotor laminations separated and damaged the diaphragm between the stator cavity and the rotor cavity. The machine was disassembled and the diaphragm was replaced. At that same time, the rotor was pinned (see Section II-F-2).

Tests 45 and 46 were run to repeat tests 41 and 42 (no-load saturation curve and short-circuit saturation curve) with the pinned rotor (Figure 36).

Test 47 repeated test 43 to determine the load characteristics of the machine at various power factors. No simulation of a six-turn stator was tested. The results are shown in Figure 37.

Test 48 repeated the work of test 47 except that capacitors rated to produce 45 KVAR were installed across each output phase. These tests were limited to 150 minutes each by excessive machine temperatures (Figure 37).

FIGURE 34. NO-LOAD AND SHORT CIRCUIT SATURATION TESTS, BEFORE PINNING ROTOR DEMONSTRATION ALTERNATOR

11.2-64-1305

FIGURE 35. LOAD CHARACTERISTICS AT 0.8, 0.9 AND 1.0 POWER FACTORS, DEMONSTRATION ALTERNATOR

FIGURE 36. NO-LOAD AND SHORT CIRCUIT SATURATION TESTS, AFTER PINNING ROTOR DEMONSTRATION ALTERNATOR

11.2-64-1307

*SEE TEXT FOR THE NOTE

FIGURE 37. LOAD CHARACTERISTICS AT 0.8, 0.9 AND 1.0 POWER FACTORS, DEMONSTRATION ALTERNATOR

Test 49 was conducted to evaluate the eddy current formation in the drive end housing. The potential at selected positions on the exposed surface of the drive end housing (Figure 38) was measured as a function of the field current. The results of the test are shown in Figure 39.

Test 50 was conducted to determine the steady state temperatures in the machine as sensed by thermocouples positioned as shown in Figure 38. The machine was loaded to 300 kw and thermocouple data taken periodically to evaluate the temperature rise. After 75 minutes of operation, temperatures in the stator had reached approximately 250°F and were still rising. The load was then reduced to 200 kw but the test was terminated after an additional 15 minutes of operation during which the stator temperatures continued to increase. The results of this test are shown in Figure 40.

Tests 51 and 52 were run to verify the stator temperature data developed in test 50. In both cases the stator temperature stabilized after approximately 120 minutes of operation at 200 kw; in test 51 the equilibrium temperature was 280°F but in test 52 the temperature stabilized at 250°F (Figure 41).

Following these tests, the coolant flow path in the stator was altered. Originally the coolant entered at the top of the case and was drained out at the bottom. With this arrangement it was possible for the coolant to flow around the stator but not flow through the coolant slots. The flow path was altered by injecting the coolant at the center of the stator thus forcing it to flow radially outward through the coolant passages.

Following the modification, tests 53 and 54 were run to evaluate the effect of the change. The stator temperature stabilized after approximately 60 minutes of operation at 240°F (Figure 41). Based on these data it was concluded that the modification had been successful and that the design of the stator cooling system was satisfactory.

Tests 55, 56 and 57 were run to provide data concerning the power loss in the machine. The results of these tests are presented in Table 12.

TABLE 12 - POWER LOSS IN THE DEMONSTRATION ALTERNATOR

<u>Test No.</u>	<u>Power In, kw</u>	<u>Power Out, kw</u>	<u>Power Loss, kw</u>
D196-LE-55	475	380	95
D196-LE-56	461	372	85
D196-LE-57	249	192	57
D196-LE-58*	456	376	80
D196-LE-59*	464	374	90
D196-LE-61*	482	402	80

*Laminations in drive end housing.

The input power values shown were derived from the input torque at a given speed by the expression:

FIGURE 38. TEST HOOKUP FOR TEST D196-LE-49 AND THERMOCOUPLE LOCATION FOR TESTS D196-LE-50 THROUGH-59

FIGURE 39. POTENTIAL VARIATIONS IN FIELD COIL HOUSING, DEMONSTRATION ALTERNATOR

FIGURE 40. HEAT RUN, DEMONSTRATION ALTERNATOR

FIGURE 41. STATOR WINDING AREA TEMPERATURES, DEMONSTRATION ALTERNATOR

$$\frac{\text{Torque} \times \text{rpm}}{5250} \times 746 = \text{Input Power}$$

As indicated in this table, the power loss was quite high and, as discussed in Section III, only a portion of the loss could be accounted for. Consequently, the drive end housing was modified by the insertion of axial laminations (i.e., a laminated plate) in the surface opposite the rotor flux distribution ring. The purpose of this modification was to minimize the eddy currents produced by the non-uniform flux emanating from the rotor.

Test 58 repeated tests 55, 56 and 57 to evaluate the effects of the laminations in the drive end housing. This test was discontinued after 60 minutes of operation when a lead in the field coil shorted to ground. After repair of the field coil, test 59 was run to repeat test 58. The data from these two tests are also shown in Table 12.

Test 60 was run to develop a no-load saturation curve for the machine with laminations in the drive end housing and with capacitors installed across the armature terminals. The results of this test are shown in Figure 42.

Test 61 was run to repeat tests 58 and 59; the data is shown in Table 12.

Test 62 was run to permit further investigation of the potential differences in the drive end housing. After 110 minutes of test operation, the laminations in the housing were pulled into the rotor by the magnetic field and the test was discontinued. The laminated plate was removed and replaced with a solid plate.

Test 63 was run to develop no-load saturation curves for the machine with solid drive end housing and with and without capacitors across the armature terminals. The results of this test are shown in Figure 43.

FIGURE 42. NO-LOAD SATURATION TEST, DEMONSTRATION ALTERNATOR, WITH LAMINATIONS

FIGURE 43. NO-LOAD SATURATION TEST, DEMONSTRATION ALTERNATOR, LAMINATIONS REMOVED

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III. EVALUATION OF THE DEMONSTRATION ALTERNATOR

A. TEST RESULTS

As indicated by the test data, the demonstration alternator was capable of generating 400 kw at 0.8 power factor (with capacitors installed in parallel with the load bank), but unable to meet design output-requirements.

In both static and dynamic tests, the rotor pole flux that enveloped a given location of the drive end housing at any one instant varied as a function of the geometry of the magnetic mass opposite that location. The greatest flux density was associated with the configuration at the 90° position of the rotor; the least density, with the configuration at the 180° position of the rotor. (Position of the rotor refers to the arbitrary axes system shown in Figure 19, used to designate a specific axial cross-section of the magnetic mass within the rotor.) The flux wave form in the homopolar air gap was investigated during test 55 with a search coil. The test setup is shown in Figure 44a and the waveform obtained in Figure 44b. This waveform does not represent the actual flux distribution in terms of voltage amplitudes, but shows variation of flux about a mean d-c level. The high frequency spikes superimposed on the main envelope are caused by instantaneous variations of air gap reluctance brought about by the passage of axial steel pins in the rotor.

During test 49, while the alternator was producing 395 kw, the voltage variations at a point near the rotor shaft on the external face of the drive end housing were measured. The wave form representing these variations is shown in Figure 44c. Because the voltages were measured at a point close to the center of the drive end housing, they can be taken as an index of flux distribution throughout the entire drive end housing.

The coolant flow through the stator was found to be adequate on the basis of heat balance tests (56 and 57) in which the stator winding temperature stabilized at 275°F, while generating 400 kw at 0.8 power factor and 70°F ambient temperature. However, the flux leakage into and around the drive end housing resulted in high rotor and field coil temperatures. Incorporation of laminations in the drive end housing to alleviate this situation resulted in only a slight reduction of losses ascribed to this heat generation. The

44a. Test Hookup Eddy Current Effect Across Homopolar Air Gap - Demonstration Alternator

44b. Flux at Homopolar Gap - Test 55

44c. Voltage at Field Coil Housing - Test 49

FIGURE 44. WAVE FORM INVESTIGATIONS

test data did not permit any conclusive evaluation of the effectiveness of laminations in the drive end housing; but there was no significant performance improvement (Table 12).

During rotor model tests, a correlation was established between air gap density and maximum/minimum flux differential in the drive end housing. In the demonstration alternator a large flux differential caused an imbalanced magnetic pull in an axial direction which resulted in a magnetic couple acting on the rotor and exerted an imbalanced radial force on the rotor bearings. During tests with laminations in the drive end housing (58 through 62) there were indications that these lamination aggravated the magnetic pull. In test 62 the laminations were pulled free of the driven end housing and into the rotor. Imbalanced forces and the concomitant wear on rotor bearings limited the tests to short duration runs.

B. ANALYSIS

The currents that result from the magnetomotive forces along the various paths in the demonstration alternator cannot be regarded relative to their source and location alone. Currents induced in the stator end of the case, the rotor end of the case, and the drive end housing interact to some degree. The extent and the nature of this interaction is difficult to ascertain due to the random nature of the currents. The average total loss experienced during tests (see Table 12) was 86 kw; where calculations were practicable, an attempt was made to allocate portions of this total loss to discrete parts or functions of the alternator.

1. Drive End Housing

Because of the three-dimensional nature of the flux distribution in the drive end housing and the random nature of the flux paths, calculation of losses in the driven end housing is impractical, if not impossible. The uneven flux distribution was attributed to two factors:

- Reluctance in the "wrap-around portion" of the south pole material was too high to support uniform flux distribution across the homopolar air gap.
- Interpolar flux leakage existed along the 0° - 180° axis.

Absolutely uniform flux across an air gap is only achieved in the theoretical case where the permeabilities of both rotor and field iron equal infinity. Ampere's circuital law states that as permeability decreases, the flux distribution can no longer be uniform unless the magnetomotive force across all points of the gap is equal. This essentially requires that the integral of magnetomotive force along any path through the pole iron, from stator gap to drive end housing, be constant. The rotor model tests indicated that such was not the case for the developmental alternator. At low gap densities the difference between maximum and minimum flux was about 10%. This difference increased to 40% as the magnetomotive force was increased. The 10% value at low gap densities was probably due to the difference in interpolar leakage flux; the increase to 40% is almost certainly due to saturation of the wrap-around portion of the south pole. The test data and the results of the

loss calculations (Section III-2) show that the loss associated with this uneven flux distribution amounts to approximately 57.5 kw. The damping effects of the currents generated in the drive end housing can be shown to be in opposition to the main (working) flux. The number of full load ampere turns were predicted on the basis of the rotor model tests, but proved to be inadequate. During tests on the demonstration alternator it proved to be necessary to install load capacitors to obtain design output. At power factors of less than 1.00, a back-electromotive force (and therefore magnetomotive force) is created with consequent degradation of output power. When, through the use of capacitors the power factor is changed from 0.8 to 0.9, reactive power is introduced which decreases the effect of the opposition by the electromotive force created in the stator.

2. Aluminum Case

The distribution of the flux generated by the stator windings in the alternator case is susceptible of analysis, although the random nature of the paths within the aluminum material complicates such an analysis. The magnetomotive force generated by the stator outer-end windings caused eddy currents in the stator end of the case. The interpolar leakage flux in the rotor enveloped the rotor end of the case and rotated with the rotor, causing eddy currents in the rotor end of the case. Analysis of the losses associated with the interpolar leakage flux is impractical because of the interaction between the resultant eddy currents and the flux distribution in the drive end housing and the homopolar air gap.

3. Friction and Windage

The friction and windage in the demonstration alternator was estimated by measuring the power delivered by the prime mover under no-load and subtracting this value from the power delivered by the prime mover while driving the alternator. Both measurements were performed at rated alternator speeds. The loss due to friction and windage derived from these measurements was 10.25 kw.

4. Stator Copper

The loss in the stator copper was calculated. This loss is a function of the stator current and the effective resistance of the stator. Resistance of any substance of uniform cross-section is proportional to the length of the material in which the current is flowing and inversely proportional to the cross-sectional area. The resistance value varies with temperature and, depending on the configuration of the cross-section, normally requires correction by application of an appropriate rounding factor.

The basic relationship is expressed by:

$$R = \rho \frac{L}{A} \quad (1)$$

where: R is the resistance in ohms,

ρ is the resistivity of copper, 0.68×10^{-6} ohms/in. at 20°C ,

L is the length of the conductor, in this case 10,560 in./phase, and

A is the cross-sectional area of the conductor, in this case 0.0372 sq in.

Substituting in Equation 1:

$$R = 0.68 \times 10^{-6} \left(\frac{10560}{0.0372} \right) = 0.1923 \text{ ohms per phase at } 20^{\circ}\text{C}$$

To derive the value at the operating temperature of 125°C , the following expression is used:

$$R_T = R_O \left[1 + \alpha_O (T - T_O) \right] \quad (2)$$

where: R_T is the resistance in ohms at 125°C ,

R_O is the resistance in ohms at 20°C ,

α is the temperature coefficient of resistivity of copper, in this case $0.00382 \text{ ohms}/^{\circ}\text{C}$,

T is the operating temperature, 125°C , and

T_O is 20°C .

Substituting in Equation 2:

$$R_T = 0.1923 \left[1 + 0.00382 (125 - 20) \right] = 0.2731 \text{ ohms per phase at } 125^{\circ}\text{C}.$$

The cross-sectional configuration of the conductor is such that a rounding factor 95% must be applied.

Consequently, $0.2731/0.95 = 0.287 \text{ ohms per phase at } 125^{\circ}\text{C}$.

The total stator copper loss can now be calculated from the following expression:

$$W = 3 (I^2 R) \quad (3)$$

where: W is the stator copper loss in watts,

I is the stator current per phase in amperes, 69.5, and

R is the resistance per phase at the operating temperature in ohms, 0.287.

Substituting in Equation 3:

$$W = 3(69.5^2 \times 0.287) = 4158 \text{ watts}.$$

5. Stator Core

The stator core loss was estimated from an experimental correlation between the magnetic flux produced in the stator and the loss of flux per pound of stator core material. This correlation was developed by surrounding the bare stator core with a test winding through which a 60 cps current was made to flow. The derived correlation is shown in Figure 45.

Data from earlier stator tests have indicated that the average mean flux density in the stator core teeth was 110 kilolines sq in. and that the corresponding value for the rest of the stator was 112 kilolines sq in. The weight of core material in the stator teeth is 160 lb and the weight of material other than the teeth is 986 lb. From Figure 45, the loss in the teeth is 4.25 watt/lb while that in the rest of the stator is 4.55 watt/lb if a conversion factor of one kiloline/sq in. $\times 0.155$ = one kilogauss is used. The total stator core loss is then $(160 \times 4.25) + (986 \times 4.55) = 5.166$ watt.

6. Rotor Pole Face

The rotor pole face loss was calculated by the method of W. J. Gibbs*. This method discusses losses due to eddy currents, hysteresis and pulsations, and demonstrates that only the losses due to eddy currents are important. Although the brushless alternator rotor has a grooved pole face, the losses must be first calculated as if the face were ungrooved and the value thus obtained subsequently modified to compensate for the grooves.

The eddy current loss in the ungrooved rotor is given by:

$$P_e = 5.9 \lambda \beta_2 B_m N_a H \times 10^{-10} \quad (4)$$

where: P_e is the loss in watt/sq cm,

λ is the armature slot pitch in cm, 2.60,

β_2 is the flux oscillation factor, from Figure 30 of Gibbs' work = 0.1,

B_m is the average flux density in the pole face, from test data = 9500 gauss,

N_a is the number of stator slots, 72, and

H is the magnetic field strength in Oersteds.

The value of H must be found from the expression:

$$H \sqrt{\mu} = 1.81 \lambda \beta_2 B_m (nN_a)^{1/2} \times 10^{-6} \quad (5)$$

*W. J. Gibbs, "Tooth-Ripple Losses in Unwound Pole Shoes," Institution of Electrical Engineers, V. 94, Part II, 1947

FIGURE 45. TEST RESULTS: CORE FLUX LOSS MEASUREMENTS

where: ρ is the resistivity of the core material in ohm/cm,
 μ is the permeability of the core material in e.m.u.,
 n is the rotor speed, 3600 rpm,
 and the other terms are as defined in Equation 4.

Substituting in Equation 5:

$$H \sqrt{\rho \mu} = (1.81)(2.60)(0.1)(9500) \left[(3600)(72) \right]^{1/2} (10^{-6}) \\ = 2.27.$$

From Figure 5 of Gibbs' work, when $H \sqrt{\rho \mu} = 2.27$, $H = 22$.

Substituting in Equation 4:

$$P_e = (5.9)(2.60)(0.1)(9500)(3600)(72)(22)(10^{-10}) \\ = 8.3 \text{ watts/cm}^2.$$

Since the pole face area for the ungrooved rotor is 2230 sq cm, the total pole face loss for the ungrooved rotor is then $8.3 \times 2230 = 17,800$ watts.

The grooving of the rotor face decreases the surface area subjected to the oscillating flux, and increases the length and the associated resistance of the eddy current paths. To obtain a value for $H \sqrt{\rho \mu}$ which considers the groove configuration, it is necessary to determine the value of ρ_{eff}/ρ by the following expression:

$$\frac{\rho_{\text{eff}}}{\rho} = 1 \times \frac{0.263 \lambda b (2d + w)}{l(2d + w + 0.263 \lambda)} \quad (6)$$

where: ρ_{eff} is the effective resistivity of the grooved rotor face in ohms/cm,

ρ is the resistivity of the rotor face material without grooves in ohm/cm,

b is the number of grooves in the pole face, 32,

d is the depth of the grooves in cm, 0.762,

w is the width of the grooves in cm, 0.152, and

λ is the armature slot pitch in cm.

Substituting in Equation 6:

$$\frac{\rho_{\text{eff}}}{\rho} = 1 \times \frac{(0.263)(2.60)(32) \left[(2) \left[(0.762) + (0.152) \right] \right]}{(16.61) \left[\left[(2)(0.762) \right] + (0.152) + \left[(0.263)(2.60) \right] \right]} \\ \frac{\rho_{\text{eff}}}{\rho} = 1.93.$$

To obtain a value for $H\sqrt{\rho\mu}$ for the grooved rotor face, the following expression is used:

$$H\sqrt{\rho\mu}_g = \frac{H\sqrt{\rho\mu}_{ug}}{\frac{P_{eff}}{\rho}} \quad (7)$$

where the subscripts "g" and "ug" represent the values for the grooved and ungrooved rotor faces, respectively.

Substituting in Equation 7:

$$H\sqrt{\rho\mu}_g = \frac{2.27}{1.93} = 1.63.$$

Referring to Figure 5 of Gibbs' paper yields a value of 11 for H in this case so that the total polar face loss for the grooved rotor is $\frac{11}{22} \times 17,800 = 8900$ watts.

7. Summary

The measured and calculable losses in the machine are as follows:

Friction and windage loss	10.25 kw
Stator copper loss	4.16 kw
Stator core loss	5.17 kw
Rotor pole face loss	<u>8.90 kw</u>
Total	28.48 kw

The average measured losses in tests 55 through 59 and 61 were 81 kw. The unaccounted for 52.5 kw is assumed to be associated with the field coil housing and metallic case losses which are not calculable.

C. RECOMMENDED ACTION

Based on the analyses conducted to date, it appears that the modifications described below will reduce the losses attributed to the drive end housing by at least 40%, will eliminate the magnetic couple on the rotor and probably eliminate the need for capacitors to correct the power factor. However, additional analysis and model testing should be undertaken to confirm the tentative conclusions.

The rotor must be modified to reduce the reluctance of the "wrap-around" portion of the rotor south pole. This is probably the only effective way of equalizing the flux distribution at the homopolar gap. The optimum way to decrease the reluctance is to increase the diameter of the rotor in the wrap-around section. This, in turn, will increase the size of the alternator beyond that specified in the design criteria.

In addition, the stainless steel pins in the rotor should be replaced with composite pins which provide magnetic material for the portion of the pin passing through the magnetic part of the rotor and non-magnetic material for that portion which passes through the non-magnetic (stainless steel) part of the rotor.

The aluminum alternator case should be replaced with a plastic case to eliminate stator and rotor eddy current losses. This modification will require the addition of a heat exchanger capable of absorbing about 20 kw of energy (the sum of the polar face and friction and windage losses) formerly dissipated in the metallic case.

APPENDIX A

AGCRSP BACKGROUND INFORMATION

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APPENDIX A

AGCRSP BACKGROUND INFORMATION

This background of the Army Gas-Cooled Reactor Systems Program includes a short history of the Program, a description of the ML-1 power plant, and a selected bibliography.

A. HISTORY

The purpose of the Army Gas-Cooled Reactor Systems Program (AGCRSP) is to develop a mobile nuclear power plant for military field use. The current primary goal of the Program is the fabrication and test operation of a demonstration model of such a plant.

In 1955, at the request of the USAEC Division of Reactor Development, the Oak Ridge School of Reactor Technology performed a study which established the feasibility of the concept of a mobile, closed-cycle, gas-cooled nuclear power plant. Following this work, the Corps of Engineers Nuclear Power Field Office authorized the Sanderson and Porter Company to evaluate power conversion equipment and to prepare a conceptual design for the projected plant. At the conclusion of the Sanderson and Porter work, responsibility for development of the power conversion equipment for the plant was assigned to the Corps of Engineers and the development of the reactor was assigned to the USAEC.

As a result of the above arrangement, parallel programs were undertaken as follows:

- 1) The Corps of Engineers directed the Stratos Division of Fairchild Engine and Aircraft Corporation to develop a turbine-compressor set suitable for use in the projected plant. The construction of a test facility (GTTF) to evaluate the power conversion equipment was assigned to Aerojet-General Corporation. (The design of the facility was completed by Sanderson-Porter.)
- 2) Under the direction of the USAEC, Aerojet studied the feasibility of several concepts for the reactor to be incorporated in the power plant. The water-moderated concept was selected as the basis for development because of the modest extrapolation of technology required. Aerojet was

awarded the contract for the design and testing of a reactor based on this concept. At the same time, Aerojet was assigned responsibility for the design and construction of a test facility (GCRE) at NRTS.

Aerojet was designated as systems contractor and performance specifications for the demonstration power plant were evolved in June 1959. Fabrication of the reactor skid was completed in April of 1961, fabrication of the power conversion skid was completed in June 1962, and the power plant first operated as a unit (ML-1) in September 1962. Following a modification and checkout, the ML-1 power plant operated successfully for 101 hours in February and March 1963.

B. THE ML-1

The ML-1 is a closed cycle, gas-cooled nuclear power plant developed under the AGCRSP to demonstrate the feasibility of such a plant for military field use. During the design and construction, every reasonable effort was made to incorporate features into the plant which would be directly usable in the design of a field unit. However, since evaluation of the performance of the plant was a major requirement for the ML-1, a significant amount of additional instrumentation was provided. The physical arrangement of the equipment is such that the "prototype" components are easily identified as the:

- 1) Reactor Skid - a 15 ton unit containing the nuclear reactor and associated shielding and controls;
- 2) Power Conversion Skid - a 15 ton unit containing the power conversion equipment; and,
- 3) Control Cab - a 2-1/2 ton unit containing all the instruments and controls for operation of the field plant.

The ML-1 reactor consists of a calandria-type pressure vessel with appropriate inlet and exit gas ducts and plenums. Sixty-one pin-type BeO-UO₂ fuel elements are located in the tubes of the calandria. The demineralized water moderator surrounds the calandria and the six semaphore-type control rods operate in the moderator spaces between the calandria tubes. The entire reactor structure is supported inside a nine-foot diameter tank which contains heavy metal shields to permit relocation of the reactor within 24 hours after shutdown from extended operation, and a drainable (borated water) shield to attenuate radiation during reactor operation.

The plant working fluid (99.5 vol% nitrogen, 0.5 vol% oxygen) enters the reactor at 800°F and approximately 300 psia. The gas is heated to 1200°F in a single pass over the hot surfaces of the fuel elements. The moderator water is maintained at a temperature of 180°F; energy deposited in the moderator is removed in an water-to-air heat exchanger mounted on top of the power conversion skid. Provision is made for circulation, filtration and demineralization of the moderator water and for circulation and cooling (by exchange with the moderator water) of the shield water.

The hot gas leaving the reactor is expanded in a gas turbine which drives the compressor and alternator. The gas leaving the turbine passes through a regenerative heat exchanger (recuperator), through the system heat sink (air-to-air precooler) and to the compressor suction. The compressor discharges through the recuperator to the reactor inlet, thus completing the closed (modified Brayton) cycle. A lubrication system (including provision for recovery and removal of lubricating oil from the working fluid which leaks past the turbine compressor seals), the electrical switch gear, and miscellaneous power conversion hardware are mounted on the power conversion skid. An a-c, two-speed motor is coupled to the turbine compressor shaft to provide starting power to the set.

The following auxiliary systems are provided for the ML-1:

- 1) A deoxygenation system which removes dissolved oxygen from a bypass stream to maintain the moderator system oxygen content below 0.7 ppm.
- 2) An emergency cooling system which automatically injects a supply of coolant gas into the reactor in the event of a complete stoppage of working fluid flow.
- 3) A working fluid makeup system to compensate for normal leakage and to provide for initial charging of the system.
- 4) Waste gas storage facilities to accommodate the charge of radioactive gas in the loop in the event of an emergency.

C. BACKGROUND BIBLIOGRAPHY

The following bibliography provides information on sources of additional background to the material presented in this report. These documents trace the technical evolution of the AGCRSP from inception but do not, in general, document programmatic decisions. Such activity may be inferred from the technical approaches pursued and from the general background information presented in the reports.

The following reports were published by Aerojet-General Nucleonics, San Ramon, California under the Army Gas-Cooled Reactor Systems Program.

<u>DOCUMENT NO.</u>	<u>TITLE</u>	<u>CLASSIFICATION</u>
IDO-28505	<u>GCRE Semiannual Report, 1 November 1956 Through 30 June 1957, 20 February 1958</u>	CRD
IDO-28506	<u>GCRE-I Hazards Summary Report, December 1958, with three addenda, March 1959, February 1960, May 1960</u>	U
IDO-28519	<u>GCRE Semiannual Progress Report, 1 July Through 31 December 1957, 26 June 1958</u>	CRD
IDO-28526	<u>GCRE Semiannual Progress Report, 1 January Through 30 June 1958, 17 October 1958</u>	CRD

Report No. AGN TM-406

DOCUMENT NO.	TITLE	CLASSIFICATION
IDO-28533	<u>AGCRSP Semiannual Progress Report, 1 July Through 31 December 1958, 28 February 1959</u>	CRD
IDO-28537	<u>Preliminary Hazards Summary Report for the ML-1 Nuclear Power Plant, 22 April 1959</u>	U
IDO-28542	<u>AGCRSP Semiannual Progress Report, 1 January Through 30 June 1958, July 1958</u>	U
IDO-28549	<u>AGCRSP Semiannual Progress Report, 1 July Through 31 December 1959, 22 December 1959</u>	U
IDO-28550	<u>The ML-1 Design Report, 16 May 1960</u>	U
IDO-28555	<u>ML-1 Transportability Studies, 23 March 1960</u>	U
IDO-28558	<u>AGCRSP Semiannual Progress Report, 1 January Through 30 June 1960, 11 July 1960</u>	U
IDO-28560	<u>Final Hazards Summary Report for the ML-1 Nuclear Power Plant, with four supplements, 5 August 1960</u>	U
IDO-28567	<u>AGCRSP Semiannual Progress Report, 1 July Through 31 December 1960, 17 December 1960</u>	U
IDO-28573	<u>AGCRSP Semiannual Progress Report, 1 January Through 30 June 1961, 10 August 1961</u>	U
IDO-28581	<u>AGCRSP Semiannual Progress Report, 1 July Through 31 December 1961, 31 January 1962</u>	U
IDO-28590	<u>AGCRSP Semiannual Progress Report, 1 January Through 30 June 1962, 24 August 1962</u>	U
IDO-28597	<u>AGCRSP, Study of the GCRE Tube Bundle Failure, 14 December 1962</u>	U
IDO-28602	<u>AGCRSP Semiannual Progress Report, 1 July Through 31 December 1962, 22 February 1963</u>	U
IDO-28607	<u>AGCRSP Quarterly Progress Report, 1 January Through 31 March 1963, 15 May 1963</u>	U
IDO-28612	<u>AGCRSP Quarterly Progress Report, 1 April Through 30 June 1963, 15 August 1963</u>	U
IDO-28617	<u>AGCRSP Quarterly Progress Report, 1 July Through 30 September 1963, 15 November 1963</u>	U

Report No. AGN TM-406

<u>DOCUMENT NO.</u>	<u>TITLE</u>	<u>CLASSIFICATION</u>
IDO-28621	<u>AGCRSP Quarterly Progress Report, 1 October Through 31 December 1963, 27 January 1964</u>	U
IDO-28626	<u>AGCRSP Quarterly Progress Report, 1 January Through 31 March 1964, 15 May 1964</u>	U
IDO-28629	<u>AGCRSP Quarterly Progress Report, 1 April Through 30 June 1964, 27 May 1964</u>	U

APPENDIX B

EXTRACT FROM ALTERNATOR SPECIFICATIONS

(AGC-60003; MLS-45; 10 Feb 60)

APPENDIX B

EXTRACT FROM ALTERNATOR SPECIFICATIONS

(AGC-60003; MLS-45; 10 Feb 60)

III. REQUIREMENTS

III.1 General

The major components of the system are the heater, turbine-compressor, gear box, generator, precooler and recuperator. Heat is supplied to the system by a heater, the working fluid passing to a turbine, thence through the low pressure side of the recuperator, a precooler, a compressor, the high pressure side of the recuperator and back to the heater. A small amount of the high-pressure working fluid is bypassed from compressor discharge to precooler inlet for turbine-compressor control purpose. The output of the turbine is coupled through a gear box to a generator which is located in line with the turbine and gear box.

For the purpose of this specification, the generator, exciter and regulator shall be considered as a unit, hereinafter referred to as the generator unless otherwise noted.

III.2 Operating Conditions

III-2.1 General

The generator must be capable of operating at full design capacity as defined in Paragraph III-3.2.1 under any possible combination of operating conditions, as listed in Paragraphs III-2.2.1, III-2.2.2, III-2.3.1 and III-2.3.2. It must withstand conditions in transit as listed in Paragraph III-2.2.2 without loss of serviceability. This unit shall be designed for continuous operation without maintenance for at least 10,000 hours. During such periods of maintenance free operation, the unit will be started and stopped approximately twice a week. The generator shall be designed for a

life expectancy of no less than 50,000 operating hours with overhaul periods at intervals of 10,000 hours. During these overhauls, no major parts (Shaft-Rotor Assembly, Stator with its windings, the Field Coil and the Housings) shall require replacement.

Starting of the turbine-compressor set shall be accomplished either by motorizing the generator or by providing a starting motor.

III-2.2 External Conditions

III-2.2.1 While Running

Inclination to Horizontal: 15° max. Ambient temperatures during operation at sea level: -65 to 100°F at full load.

Blowing snow-sand-dust:

Snow Crystals: 1-3 mm dia.

Sand Particles: 0.18-0.30 mm dia.

Dust Particles: 0.0001 - 0.01 mm dia.

Marine Atmosphere and Salt Spray

Radiation:

Gamma	4.0×10^7	$\frac{\text{Mev}}{\text{cm}^2/\text{sec}}$
(3-5 Mev)		

Fast Neutron	2.0×10^5	$\frac{\text{Mev}}{\text{cm}^2/\text{sec}}$
(3-5 Mev)		

Altitude: 200 feet below sea level to 8,000 feet above sea level

Pressure: Ambient corresponding to altitudes

Humidity: Corresponding to 30% to precipitation at ambient temperatures

III-2.2.2 While Shut Down

Inclination to Horizontal: No limit

Ambient temperatures for storage and transit: -65 to 155°F

Blowing sand-snow-dust:

Snow Crystals: 1-3 mm dia.

Sand Particles: 0.18-0.30 mm dia.

Dust Particles: .0001-.01 mm dia.

Marine Atmosphere and Salt Spray

Shock Loads: The alternator shall be capable of with-

standing any combination of the following shock loads without loss of serviceability:

Horizontal (Transverse to axis of set): 5.0 G's

Horizontal (Parallel to axis of set): 5.0 G's

Vertical: 5.0 G's

Shock Duration: 0.12 sec.

Humidity: Humidity during storage will vary from 30% to precipitation at ambient temperature conditions for storage.

III-2.3 System Conditions

III-2.3.1 While Running

The generator shall be subject to instantaneous fluctuations in load from no-load to full-load and back to no-load, and must operate occasionally at 125% rated speed for periods not to exceed 1 minute.

All windings and the entire magnetic circuit of the generator including rotor and stator will be exposed to an atmosphere of air or nitrogen gas. The air will contain undesirable contaminant maximums as listed:

Water Vapor	0-40 ppm
Hydrocarbons	0-160 ppm
Ammonia	0-10 ppm

The nitrogen will have the following composition:

<u>Component</u>	<u>Relative Amount</u>
Nitrogen	99 + mole per cent
Oxygen	1720 - 6000 ppm
Carbon Monoxide	0 - 640 ppm
Carbon Dioxide	0 - 640 ppm
Hydrogen	0 - 10 ppm
Water Vapor	0 - 40 ppm
Hydrocarbons	0 - 160 ppm
Ammonia	0 - 10 ppm
All Others	0 - 10 ppm

Internal generator pressure will be 20 to 25 psia during normal operation.

Starting procedures require that the entire gas loop be sealed off from atmosphere, evacuated to 3 psia, purged and finally pressurized to 100 psia at 100°F ambient temperature with the reference nitrogen atmosphere. The nitrogen gas will be circulated through a dessicator for drying. When satisfactorily dried, the gas loop will be raised gradually in temperature until operating temperatures are reached. When operating temperatures are reached, pressures in the gas loop will be raised to maximum operating pressures. During starting, the turbine-compressor set, gear train, and generator must be rotated by the generator or starting motor at approximately 1/3 of rated speed.

III-2.3.2 While Shut Down

Internal generator pressure will be 200 psia max.

Internal general temperature will not exceed the maximum operating temperature, 250°F.

III-3 Design

III-3.1 General

The unit described in this purchase specification shall be of the general configuration defined in Paragraph III-3.3.1....

The size and weight of this generator are of prime importance. The object of this specification is to obtain a compact unit of minimum weight and high reliability. Accessibility for maintenance, and minimum maintenance are major requirements. The generator unit will be assembled by flange mounting to the turbine-compressor set.... The turbine-compressor set will employ integral gear reduction having a 3600 rpm output. Coupling of the output of the turbine-compressor set with the generator shall be accomplished in a minimum space, with a minimum number of components, and maximum reliability. Since the generator will be canned, provision shall be made to circulate nitrogen within the generator casing and to design the generator casing interior and exterior for efficient heat transfer. Selection of material such as lubricants, and insulation where required by the design must be adequate for 50,000 hour lifetime in the radiation field of Paragraph III-2.2.1. Semiconductor devices must be incorporated in plug-in units for

quick replacement. (Note: The shock that the generator will be subject to is defined in Paragraph III-2.2.2.)

III-3.2 Electrical

III-3.2.1 Capacity

Under conditions specified in III-2.1, III-2.2, and III-2.3, the generator shall be capable of delivering at full load, 400 kw at 0.8 power factor, at either 2400, or 4160 volts, 3 phase, 4 wire (wye connected) or 2400 volts, 3 phase, 3 wire (delta connected) at 60 cycles; and 83% minimum of rated full load at 50 cycles. Six terminals, two for each phase, shall be provided....

III-3.2.2 Output Characteristics

III-3.2.2.1 Voltage Regulation

At any constant load from no load to full load and at rated power factor, the regulator, at stable operating conditions, shall not permit the average rms generator terminal voltage to vary more than $\pm 1\%$ from the average of the no load and the full load average rms generator terminal voltages. This does not include the allowable voltage deviation for constant load conditions. The stable operating condition is defined as that condition where, with a constant load, the instantaneous rms generator voltage does not vary more than $\pm 0.5\%$ from its average rms value.

Following any sudden change in load from stable operating condition by any increment equal to or less than 50% of rated load at rated power factor, the maximum transient voltage dip shall not exceed 15% of rated generator terminal voltage and the regulator shall re-establish stable operating conditions within a 3 second period. The average variation of instantaneous rms terminal voltage during this 3 second period shall not exceed 4% of rated rms generator terminal voltage. Generator is defined as in Paragraph III-1.

III-3.2.2.1.1 Remote Voltage Control

The voltage regulator shall be infinitely adjustable over a range to provide a $\pm 10\%$ change in average rms rated terminal voltage output. The adjustment will be made by means of a variac type auto transformer... located in the control cab 500 feet from the voltage

regulator. The control voltage shall not exceed 200 volts rms.

III-3.2.2.2 Voltage Balance

Voltage variation between rms line-to-neutral voltages under the condition of a symmetrical, 3 phase, 0.8 power factor full load shall not be in excess of 5% of rated rms generator line-to-neutral voltage between any two phases. Voltage variation between rms line-to-line voltages under the condition of a symmetrical 3 phase, 0.8 power factor full load shall not be in excess of 5% of rated rms generator line-to-line voltage between any two phases.

III-3.2.2.3 Wave Shape

The maximum deviation of the line-to-neutral voltage waveform from a true sine wave shall not exceed 5% for no load or a symmetrical 3 phase, 0.8 power factor full load. Maximum deviation of the line-to-line voltage waveform from a true sine wave shall not exceed 5% for no load or a symmetrical 3 phase, 0.8 power factor full load. The rms of all harmonics shall be less than 5.0% and that of any one harmonic less than 2% at full rated load.

III-3.2.3 Efficiency

Generator efficiencies at rated power factor considering all electrical and mechanical losses shall be:

Full load	94%
3/4 load	93.5%
1/2 load	93%
1/4 load	90.5%

Losses to be included shall comprise:

1. Core losses
2. Friction and windage
3. I^2R (Stator and field)
4. Stray load loss
5. Exciter and regulator losses

The required efficiencies are to be achieved after the generator has attained its stabilized temperature for each of the specified loads.

III-3.2.4 Starting

Capability to accelerate the generator, gear train, and turbine-compressor set to starting speeds of $1/4$, $1/3$ and $1/2$ of normal full load operating speed must be provided. Normal full load operating speed (3600 rpm) per III-3.1. Starting must be accomplished with no more than 30 kw, 480 V, 30, 50/60 cps, input power.... Continuous cranking capability is required....

III-3.2.4.1 Motorizing

If the generator is designed to be motorized and provide a starting capability, the above specified starting speeds must be met. Selection of speeds specified in Paragraph III-3.2.4 during operation of the generator as a motor shall be made by reconnecting to appropriate power transformer taps.... Design of the generator for motorizing shall be such as to make the maximum horsepower available without compromising the generator performance or compactness.

III-3.2.4.2 Starting Motor

If a starting motor is provided, it shall, in addition to the above requirements, be incorporated as an integrally sealed part of the generator design and drive the "uncoupled" end of the generator shaft. During continuous cranking, the stabilized temperature of the starting motor shall remain within a safe operating range. The starting motor design shall be such as to accomplish rapid removal and installation in order to match the starting requirements with a redesigned motor in event the initial design is not satisfactory.

III-3.2.5 Parallel Operation

The generator shall be capable of operation successfully in parallel with other generators of modern design provided that the governors of the prime movers operate satisfactorily in parallel. A current signal from the same transformers which supply the power control meters will be utilized to control the generator output voltage for parallel operation. The current transformers... will have an ASA Standard accuracy of 0.3 B-2 (ASA C57.13) and shall be driving an instrument burden which may vary from 0 to 50 voltamperes.

III-3.2.6 Fault Current

The generator shall be designed to withstand all forces resulting from any 3 phase fault current which may be produced by a 3 phase short circuit at its terminals. The general neutral will be grounded... through a reactor of such value as to limit the fault current in the windings to the subtransient current under 3 phase fault conditions.

The generator shall be designed to withstand for a period of two (2) minutes without injurious heating, a 3 phase overload current of 200% of normal 3 phase full load current.

III-3.2.6.1 Field Forcing

Provision shall be made for forcing the field supply to the generator, during a fault, through the use of current transformers on the generator output. The current transformers shall, at the occurrence of a fault, increase the field excitation so that the steady state fault current, with a 3 phase, zero impedance short circuit at the plant output terminals, will be at least 3 times rated current.

III-3.2.6.2 Short Circuit Data

The following maximum values shall be established during fabrication:

- a. Asymmetrical d-c transient short circuit current.
- b. Subtransient, transient and steady state rms symmetrical short circuit current (balanced 3 ϕ , line-to-line, and line-to-ground).
- c. Instantaneous voltage surge, due to field forcing during short circuit conditions, immediately after the short is cleared.
- d. Value of zero sequence required in generator neutral to protect the generator when subjected to a direct line to ground short for 0.15 sec.

III-3.2.7 Reactances

Synchronous - direct axis	1.0 max.
Transient - direct axis	.25 max.
Sub-transient - direct axis	.20 max.
Negative sequence	.10 max.

III-3.2.8 Insulation

All associated equipment except for the generator field windings shall be capable of withstanding a continuous 60 cycle test voltage of twice the highest rated value of the terminal voltage plus 1000 volts.

The generator field windings shall be capable of withstanding a continuous test voltage of ten (10) times excitation voltage, but in no case less than 2500 volts.

III-3.2.8.1 Generator

The insulation of the generator not including the exciter and voltage regulator shall be Class H, Per MIL-I-3505B capable of operating under the conditions of maximum radiation, temperature and pressure imposed by Paragraphs III-2.2 and III-2.3. The generator insulation shall be capable of withstanding explosive decompression of the generator casing from 300 psia to atmospheric with no harmful effect on the operation of the unit. No replacement of insulation or of insulated conductors shall be necessary during the first 50,000 hours of operation..

III-3.2.8.2 Static Exciter and Regulator

The insulation of the static exciter and regulator shall be capable of operating under the conditions of maximum radiation, temperature and humidity imposed by Paragraphs III-2.2 and III-2.3. Where protection against mechanical damage and/or particulate matter cannot be afforded by the design of the immediate containing housing of the exciter and regulator, the unprotected components must be capable of providing unbroken service for the first 50,000 hours of operation.

III-3.2.8.2.1 Input Power to Exciter

The exciter and regulator shall be designed to operate from 480 volts, 3Ø, 50/60 cps power. During startup, the power will be supplied from a separate source. After the generator is in operation, the excitation power will be supplied from the generator output through a transformer and contactor....

III-3.2.8.2.2 Field Current Measurement

Provision shall be made for connection of a shunt in series with the field windings to enable field current measurement.... The shunt shall be suitable for a 0 to 50 millivolt meter.

III-3.2.8.3 Pressure Tight Bushings

All electrical leads passing through the generator casing shall be sparkplug-type, pressure tight, insulated bushings. No gas leakage shall be detectable using a helium mass spectrometer and pressurizing the casing interior with helium to 350 psia.

The bushings shall be suitably protected against mechanical damage in such a manner that damage to the generator casing will occur before the bushings are damaged. The bushings may be made easily replaceable but the pressure tight seal shall be designed so as not to require inspection more often than once each 10,000 hours of continuous operation..

The insulation employed in the bushings shall be capable of operating under the conditions of maximum radiation, temperature, voltage and humidity imposed by Paragraphs III-2.2, III-2.3 and III-3.2.8.

III-3.2.9 Radio Interference

The generator shall conform to the requirements established in MIL-I-11683b - Radio Interference Suppression.

III-3.3 Mechanical

III-3.3.1 Size and Weight

The generator envelope and weight shall be within the following maximums:

Length - 30 in.
Width - 36 in.
Height - 36 in.
Weight - 2900 lb

The above are desired maximums which include voltage regulator, exciter, and starting motor and should be decreased whenever possible. The mounting provisions shall be within the above defined envelope.

III-3.3.2 Critical Frequencies of Parallel Operation

III-3.3.2.1 Design Characteristics

The design characteristics of the generator when operating in parallel, shall be such as to keep allowable power interchanges below any amount which would cause the temperature rise specified in Paragraph III-3.3.5.2 to be exceeded.

III-3.3.2.2 Oscillatory Frequencies

The natural and undamped oscillatory frequencies of the generator will differ at least by 25% from the generator rated full speed, half speed and double speed.

III-3.3.3 Vibratory Effects on the Structural and Dynamic Integrity

III-3.3.3.1 Dynamic Characteristics

The dynamic characteristics of the generator and its components shall be compatible with the total requirements of the power plant's entire rotating system in order to preserve and maintain the dynamic stability and structural integrity from the mechanical effects of lateral and torsional oscillations. The critical speed shall be at least 145% of the speed at rated load.

III-3.3.4 Moment of Inertia

The moment of inertia of the assembled rotating parts of the generator referred to the axis of the turbine-compressor set shaft shall, when combined with the turbine-compressor and gearbox inertia, be a minimum of 2.0 ft-lb-sec^2 . The contribution of the turbine-compressor and gearbox will not exceed 1.25 ft-lb-sec^2

1.

III-3.3.5 Frame Design

III-3.3.5.1 Pressure Vessel

The generator, with the exception of the exciter and regulator, shall be wholly contained within a pressure tight can which is flanged at one end to mount to the output shaft end of the t-c set. The generator can shall be capable of withstanding a maximum internal proof pressure of 400 psia, 250°F reference gas (Paragraph III-2.3.1) with all items which will pierce the pressure vessel wall in place for this test. The can shall also be capable of withstanding a pressure of 5 mm Hg without any deformation.

All welded joints shall be helium leak tested under the above conditions of pressure and temperature. Acceptable gross leakage of 0.01 micron cubic feet per hour and no single leak of greater than 0.005 micron cubic feet per hour....

III-3.3.5.1.1 Gas Leakage

There shall be no leakage of gas detectable by helium mass spectrometer when the generator is assembled to the rest of the system and the system pressurized with helium to 350 psia at 250°F.

III-3.3.5.2 Cooling

Provisions shall be made to maintain the internal maximum component temperature of the generator no higher than 250°F under sea level conditions. Ambient air at 100°F may be assumed during generator operation to be flowing past the can at 15 mph....

III-3.3.5.3 Bearings

The generator shall be of two-bearing design employing pressure-lubricated journals supplied from a central lubrication system which also supplies the turbine and gearbox.

III-3.3.5.4 Lubrication System

III-3.3.5.5 Support

The Seller shall provide support to meet the requirements of AGN specification control drawings number P-408811 and P-408809. The generator and its supports shall be designed to carry the

imposed load as stated on AGN drawing number P-408811, the weight of the turbine-compressor set with its piping loads plus its own weight. During transportation, the supports shall be capable of withstanding shock loading from the combined generator and turbine as defined in Paragraph III-2.2.2.

III-3.3.5.6 Handling

Provisions for lifting and handling, such as lugs or eye-bolts, shall be included in the general design of the generator. These lugs or eye-bolts shall be located within the envelope defined in Paragraph III-3.3.1.

III-3.3.6 Instrumentation

III-3.3.6.1 Temperatures

Iron-constantan, chromel-constantan, or copper constantan thermocouples shall be installed to sense each bearing temperature, lube oil inlet and outlet temperatures, and the winding hot spot temperature.... The thermocouples shall be of proven design capable of operating for the life of the generator with only routine maintenance requiring simple tools. Wherever possible, the sensing elements shall be easily accessible. The accuracy and range of the bearing and lube oil thermocouples shall be $\pm 1\%$ over the range of 50° to 200°F . The accuracy and range of the winding of the thermocouples shall be $\pm 1\%$ over the range of 200°F to 300°F . A certificate signed by a responsible officer of the thermocouple vendor stating that the thermocouple wire has been calibrated at the end points and middle of the above stated ranges and is so shown to conform to the requirements of ISA Specification RP1.1-7 shall be obtained.... The leads of the thermocouples shall be brought to an easily accessible, dust-tight, moisture-proof junction box and terminated on test points of the same material as the thermocouple wire. The thermocouples shall not be grounded at the mounting or junction box. Grounding will be accomplished.... at the indicating instrument.

III-3.3.7 Surface Preparation

Stainless steel and nonferrous surfaces shall be painted. All exterior surfaces shall receive the Seller's standard prime and finish painting except for color. Machined or threaded exposed surfaces subject to atmospheric corrosion during shipment and subsequent storage shall be coated with an easily removed rust preventative. External surfaces shall be lusterless olive drab enamel, Fed. Std. 595, Color No. 34087.

APPENDIX C

DESIGN CALCULATIONS FOR THE BRUSHLESS ALTERNATOR

This appendix presents the conceptual design calculations completed for the ML-1 brushless alternator. The analytical techniques developed in this work were used, with only minor revision, in all subsequent engineering calculations.

The appendixes referred to in the summary were design drawings; this information has been included in the main body of this report and, consequently, these drawings are omitted from this appendix.

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WORK ORDER 0202-56-182

ML-1 Alternator Electrical Design Analysis

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2. Armature Calculations	Pages 1 - 41
3. Field Form	Pages 13 - 18
4. Rotor Calculations	Pages 42 - 79
5. Field Leakage	Pages 69 - 78
6. Inactive Air Gaps & D.E. Housing	Pages 80 - 87
7. Machine No Load Saturation	Pages 88 - 98
8. Reactances & Time Constants	Pages 99 - 132
9. Open Circuit & Short Circuit Curves	Pages 133 - 136
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References

I Design of Electrical Apparatus

*John H. Kuhlman, John Wiley & Sons Inc.
Second Edition, 1946*

*II Calculation of Synchronous Machine
Constants*

*L.A. Kilgore, AIEE Trans. Vol. 50
Dec. 1931 p. 1201-1214*

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SUBJECT 500 KVA Alternator BY W. Halliday

WORK ORDER 0202-56-102

I Armature (See Appendix B For Construction)

Item	Value	See Pages:
1. Material	.014 Armco M-6	35 & 39
2. Outside Diam.	30 in.	1 & 2
3. Inside Diam.	17 in.	1 & 2
4. Air Gap Area	480 in. ²	5 to 12
5. Air Gap Length	.200 in.	
6. Slot Constant	1.113 - 1.218	19 to 21
7. Slot Length	6.5 in.	1 & 2
8. Slot Dimensions	.437 wide x 2.10 deep	1 to 4
9. No. of Slots	72	1
10. Tooth Pitch	.742 - 1.309 in.	1 & 21
11. Stacking Factor	.97	32
12. Yoke Depth	3.35 in. - 9.35 in.	2
13. Air Gap Flux		
No Load	8,700 K.L. per Pole	91-95 & 134
Full Load	9,480 K.L. per Pole	91-95 & 134
14. Tooth Density		
No Load	87 - 97 K.L.	37, 40 & 41
Full Load	100 - 102 K.L.	37, 40 & 41

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I Armature (cont.)

Item	Value	See Pages:
15 Yoke Density		
No Load	95-120 K.L.	26-41
Full Load	110-125 K.L.	26-41
16 Armature & Air Gap Open Circuit Excit.	4000 A.T. per pole	41
17 Slots per Pole per Phase	12	
18 Winding	2 Layer Y or Δ	
19. Circuits per phase	1	
20. Coil Throw	Slots 1-25	
21. Pitch	$\frac{2}{3}$	
22. Pitch Factor	K_p	
Fundamental	.866	
3 rd Harmonic	0	
5 th " "	-.866	
7 th " "	.866	
23 Distribution Factor	K_d	
Fundamental	.955	
3 rd Harmonic	.636	
5 th Harmonic	.191	
7 th Harmonic	-.136	

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I Armature (Cont.)

Item	Value	See Pages
24 Conductors		
Per Slot	10	4
Dimensions	144 x .258	4
In series per phase	240	
Total	720	
25 Length per Turn	88 in.	106
of Conductor	7.33 ft.	138
26 Resistance per Phase	.246 Ω (D.C.)	138
@ 75°C	.32 Ω (A.C.)	106
27 Per Unit Resistance	.009	106 &
Drop		109
28 Per Unit Reactance	.135	109
Drop		
29 Per Unit Impedance	.1353	109
Drop		
30 Armature Reaction	7,753	114 - 116
Eq. Fld. A.T. per pole		

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SUBJECT 500 KVA Alternator BY AM Halliday

WORK ORDER 0202-56-182

II Rotor (See Appendix C for Construction)

<u>Item</u>	<u>Value</u>	<u>See Pages</u>
1. Material	U.S.S. Cor Ten & 304 Stainless	66
2. Outside Diam.	30 in.	42-53
3. Pole Pitch	22 in to 45 in.	42-53
4. Pole Arc (Effective)	72.4 %	13-18
5. Active Air Gap	.200	
6. Total Air Gap (Effective per pole)	.605	99

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SUBJECT 500 KVA Alternator BY W. HallidayWORK ORDER 2202-56-182III Reactances & Time Constants

Item	Value	See Pages
1. Synchronous Reactance	$X_d = 1.229$	99-120
	$X_g = 1.30$	121-122
2. Transient Reactance	$X_d' = .281$	123
	$X_g' = .74$	125
3. Subtransient Reactance	$X_d'' = .174$	124
	$X_g'' = .18$	125
4. Negative Sequence Reactance	$X_2 = .177$	126
5. Zero Sequence Reactance	$X_0 = .054$	127
6. Armature Time Constant	$T_a = .052 \text{ sec.}$	128
7. Open Circuit Time Constant	$T_{d0} = 1.61 \text{ sec.}$	129
8. Transient Time Constant	$T_d' = .368$	130
9. Displacement Angle & Synchronizing Power	$\delta_0 = 30.25^\circ$	131
	$P_r = 800 \text{ K.W.}$	132

**ARMATURE
SECTION B-B**

FIG B
WTHALL/DY
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SUBJECT 500 KVA Alternator BY W. Hallidy

WORK ORDER 0202-56-182

FIG. C Isometric View of One Armature Lamination

SLOT CONFIG

FIG. 3
 DRAWING
 0000-56-100

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SUBJECT 500 KVA Alternator by L. M. HallidyWORK ORDER 0202-56-182

NO-LOAD SATURATION CURVE

The technique for calculating the No-Load Saturation Curve must take into account the fact that the slot width to tooth width ratio varies across the length of the stator face, with the result that the apparent reluctance of the air gap varies across the length of the stator face & that the teeth in different sections of the stator become saturated at different air gap flux densities.

Obviously, one could pick a particular portion of the stator face & call it the weighted mean configuration. But without previous experience, one could be in serious error in a machine of this size. A safe procedure would be to break the air gap into several concentric rings & calculate the characteristics of the magnetic circuit associated with each ring. Then, the characteristics of the total machine could be found by graphical means.

In the following analysis, the stator will be broken into consecutive rings with 0.5 inch difference between inner & outer radii. The No Load Saturation Curve will be calculated for the magnetic circuit associated with each ring from one pole face to the other pole face. The remainder of the magnetic circuit (poles, yoke & shaft) will be treated as an entity.

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SUBJECT 500 KVA Alternator BY W. HallidayWORK ORDER 0202-56-182Air Gap Characteristics

Curve I shows the area of the air gap between "r" (variable) & the inner edge of the armature (where $r = 8.5$ in.). The curve also shows the area of the slot opening, & the area of the teeth.

$$\text{Area}_{A.G.} = \text{Area}_r - \text{Area}_{8.5}$$

$$A_{A.G.} = A_r - A_{8.5}$$

where: $\text{Area}_{A.G.}$ = Air Gap Area

Area_r = Area of circle with radius r

$\text{Area}_{8.5}$ = Area of circle with radius = 8.5

$$(\text{Area}_{8.5} = 226.980 \text{ in.}^2)$$

$$\begin{aligned} \text{Area}_{\text{slot}} = A_s &= \text{No. of slots} \times \text{Slot width} \times (r - 8.5) \\ &= 72 \times .437 \times (r - 8.5) \end{aligned}$$

$$A_T = \text{Area of teeth} = A_{A.G.} - A_s$$

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Air Gap Characteristics (cont.)

Area of Air Gap, Slot Opening, & Tooth Width between Two concentric circles of radius "r" & radius 8.5

r (IN.)	A _r IN. ²	A _{A.G.} IN. ²	A _S IN. ²	A _T IN. ²
9.0	254.469	27.489	15.732	11.757
9.5	283.529	56.549	31.464	25.085
10.0	314.159	87.179	47.196	39.983
10.5	346.361	119.381	62.928	56.453
11.0	380.133	153.153	78.660	74.493
11.5	415.476	188.496	94.392	94.104
12.0	452.389	225.409	110.124	115.285
12.5	490.874	263.894	125.856	138.038
13.0	530.929	303.949	141.588	162.361
13.5	572.555	345.575	157.320	188.255
14.0	615.752	388.772	173.052	215.720
14.5	660.520	433.540	188.784	244.756
15.0	706.858	479.878	204.516	275.362

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AREA (IN.²)

480

440

400

360

320

280

240

200

160

120

80

40

0

8

9

10

11

12

13

14

15

"r" IN.

$A_{A.G.}$, A_T & A_S vs. "r"

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CURVE I
WALLIDY
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$A_{A.G.}$

A_T

A_S

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SUBJECT 500 KVA Alternator BY W. M. Lilly

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Air Gap Characteristics (cont.)

Curve II shows the incremental area of the air gap, slot opening & tooth width between r & $r+0.5$ IN.

$$\Delta A_{AG} = A_{AG}(r+0.5) - A_{AG}(r)$$

r IN	ΔA_{AG} IN ²	ΔA_S IN ²	ΔA_T IN ²
8.5	27.489	15.732	11.757
9.0	29.060	" "	13.328
9.5	30.630	" "	14.898
10.0	32.202	" "	16.470
10.5	33.772	" "	18.040
11.0	35.343	" "	19.611
11.5	36.913	" "	21.181
12.0	38.485	" "	22.753
12.5	40.055	" "	24.323
13.0	41.626	" "	25.894
13.5	43.197	" "	27.465
14.0	44.768	" "	29.036
14.5	46.338	" "	30.605
15.0	.	.	.

$\Delta A_{A.G.}, \Delta A_T \text{ \& } \Delta A_S$ vs. "r"

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CURVE II
W. HALLIDY
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ACTIVE $\Delta A_{A.G.}$ & ΔA_T PER POLE

If we multiply the $\Delta A_{A.G.}$ & ΔA_T in Curve II by $\frac{1}{2}$ the polar span, we can then plot Curve II A for use in future computations.

Using Fig E or Fig. A:

r	ϕ°	$\frac{\phi}{180^\circ}$	ACTIVE $\Delta A_{A.G.}$	ACTIVE $\Delta A_{A.T.}$
8.5	62	.378	10.39	4.44
9.0	62	.378	10.99	5.04
9.5	62	.378	11.59	5.62
10.0	62	.378	12.18	6.22
10.5	62	.378	12.74	6.81
11.0	62	.378	13.33	7.41
11.5	62	.378	13.94	7.99
12.0	66.1	.367	14.11	8.35
12.5	64.3	.357	14.30	8.68
13.0	62.9	.349	14.52	9.04
13.5	61.5	.342	14.78	9.39
14.0	60.2	.335	15.00	9.73
14.5	58.9	.327	15.13	10.00
15.0	58.0	.322		

This gives us the area of the air gap actually carrying Flux, & also gives us the area of the teeth that are carrying Flux

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Analysis of Wave Form

For that portion of the armature at a given radius "r", it can be considered that the Flux distribution Factor (F_d) is equal to the per unit pole span, since the air gap is constant & relatively small & thus the Field form is essentially a rectangle.

Using a point midway between the two poles as the reference or 0° point, it can be said that negligible Flux exists at points 7.5° & 15° from the reference point.

At 22.5° from the reference point, the per unit value of the air gap Flux in respect to the maximum Flux at the center of the poles is equal to the per unit value of the Flux contributed by the portion of the stator lying between $r = 8.5$ & $r = 11.6$ inches.

The same thing can be said for the point 30° from the reference point, except that the portion of the stator to be considered lies between $r = 8.5$ & $r = 14.0$ inches.

Since the total air gap Flux is essentially limited by the area of the teeth, the ratio of the teeth area is considered

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Analysis of Wave Form (cont.)

From the data on Curve II A, we find:

1. Total tooth area opposite one pole between
 $r = 8.5$ & $r = 11.6$ in. = 35.54 in.²
2. Total tooth area as above except between
 $r = 8.5$ & $r = 14.0$ in. = 78.97 in.²
3. Total tooth area as above except between
 $r = 8.5$ & $r = 15.0$ in. = 98.70 in.²

Then, the per unit value of Flux at:

1. $22.5^\circ = \frac{35.54}{98.70} = .360$
2. $30^\circ = \frac{78.97}{98.70} = .800$

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CURVE II B
WHA/ldy
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FIELD FORM

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SUBJECT 500 KVA Alternator BY W HallidayWORK ORDER 0202-56-182Wave Form Analysis (cont.)

The Flux density at the center of the pole is considered to have a value of 100. Values of Flux density are read off for every 7.5 electrical degrees, starting at a point midway between the two poles.

The equations used for the maximum value of the various harmonics of the Flux wave are:

$$(1) B_1 = \frac{1}{6} [B_{7.5} \sin 7.5^\circ + B_{15} \sin 15^\circ + B_{22.5} \sin 22.5^\circ + \dots \\ \frac{1}{2} B_{90} \sin 90^\circ]$$

$$(2) B_3 = \frac{1}{6} [B_{7.5} \sin(3 \times 7.5^\circ) + B_{15} \sin(3 \times 15^\circ) + B_{22.5} \sin(3 \times 22.5^\circ) + \\ \dots \frac{1}{2} B_{90} \sin(3 \times 90^\circ)]$$

$$(3) B_5 = \frac{1}{6} [B_{7.5} \sin(5 \times 7.5^\circ) + B_{15} \sin(5 \times 15^\circ) + B_{22.5} \sin(5 \times 22.5^\circ) + \\ \dots \frac{1}{2} B_{90} \sin(5 \times 90^\circ)]$$

$$(4) B_7 = \frac{1}{6} [B_{7.5} \sin(7 \times 7.5^\circ) + B_{15} \sin(7 \times 15^\circ) + B_{22.5} \sin(7 \times 22.5^\circ) + \\ \dots \frac{1}{2} B_{90} \sin(7 \times 90^\circ)]$$

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Wave Form Analysis (cont.)

X Elect. Deg.	B _x % Flux Density	SIN X	SIN 3X	SIN 5X	SIN 7X	B _x × SIN X	B _x × SIN 3X	B _x × SIN 5X	B _x × SIN 7X
7.5	0.	.130	.383	.609	.793	0.	0.	0.	0.
15.0	0.	.259	.707	.966	.966	0.	0.	0.	0.
22.5	36.0	.383	.924	.924	.383	13.8	33.3	33.3	13.8
30.0	80.0	.500	1.000	.500	-.500	40.0	80.0	40.0	-40.0
37.5	100.0	.609	.924	-.130	-.991	60.9	92.4	-13.0	-99.1
45.0	100.0	.707	.707	-.707	-.707	70.7	70.7	-70.7	-70.7
52.5	100.0	.793	.383	-.991	.130	79.3	38.3	-99.1	13.0
60.0	100.0	.866	0.000	-.866	.866	86.6	0.	-86.6	86.6
67.5	100.0	.924	-.383	-.383	.924	92.4	-38.3	-38.3	92.4
75.0	100.0	.966	-.707	.259	.259	96.6	-70.7	25.9	25.9
82.5	100.0	.991	-.924	.793	-.609	99.1	-92.4	79.3	-60.9
90.0	100.0	.500	-.500	.500	-.500	50.0	-50.0	50.0	-50.0
Total						689.4	+63.3	-79.2	-89.0
$\frac{1}{6}$ Total						+114.9	+10.55	-13.20	-14.83

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SUBJECT 500 KVA Alternator BY W HallidyWORK ORDER 0202-56-182*Wave Form Analysis (cont.)*

1. The average value of the Flux wave =
- B_A

$$B_A = \frac{2}{\pi} (B_1 + \frac{1}{3} B_3 + \frac{1}{5} B_5 + \frac{1}{7} B_7)$$

$$= \frac{2}{\pi} (114.9 + \frac{1}{3} \times 10.55 + \frac{1}{5} \times -13.2 + \frac{1}{7} \times -14.83)$$

$$B_A = 72.4$$

2. The effective value of the Flux wave =
- B_e

$$B_e = \sqrt{\frac{1}{2} (B_1^2 + B_3^2 + B_5^2 + B_7^2)}$$

$$= \sqrt{\frac{1}{2} (114.9^2 + 10.55^2 + 13.2^2 + 14.83^2)}$$

$$B_e = 82.82$$

3. The Flux distribution Factor =
- $F_d = .724$

$$4 \text{ The Form Factor} = F_b = \frac{B_e}{B_A} = \frac{82.82}{72.4} = 1.15$$

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Slot Constant (Carter's Coefficient)

$$K = \frac{t_1 (5\delta + w_s)}{t_1 (5\delta + w_s) - w_s^2}$$

Where: $t_1 = \text{Tooth Pitch} = \frac{2\pi r}{S}$

$S = \text{Number of Slots} = 72$

$r = \text{radius} = \text{Variable From } 8.5 - 15.0 \text{ IN.}$

$\delta = \text{air gap length} = .200$

$w_s = \text{Slot width} = .437$

$$(5\delta + w_s) = 1.437$$

$$w_s^2 = .191$$

$$\frac{2\pi}{S} = .0873$$

$$\frac{2\pi}{S} \times (5\delta + w_s) = .1254$$

Then:

$$K = \frac{r \times \frac{2\pi}{S} \times (5\delta + w_s)}{r \times \frac{2\pi}{S} \times (5\delta + w_s) - w_s^2}$$

$$K = \frac{r \times .1254}{r \times .1254 - .191}$$

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Slot Constant (cont.)

r (in.)	$r \times .1254$	$r \times .1254 - .191$	K	$z_1 = \frac{2\pi r}{5}$ (in.)
8.5	1.066	.875	1.218	.742
9.0	1.128	.937	1.203	.787
9.5	1.192	1.001	1.190	
10.0	1.254	1.063	1.180	.875
10.5	1.318	1.127	1.168	
11.0	1.380	1.189	1.161	.961
11.5	1.443	1.252	1.152	
12.0	1.506	1.315	1.143	1.047
12.5	1.569	1.378	1.138	
13.0	1.630	1.439	1.133	1.134
13.5	1.693	1.502	1.129	
14.0	1.756	1.565	1.122	1.222
14.5	1.820	1.629	1.118	
15.0	1.881	1.690	1.113	1.309

TOOTH PITCH & SLOT CONSTANT vs. T''

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 CURVE III
 6THALLIBY
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Air Gap Line

If we use:

$$A.T.A.G. = \beta_{A.G.} \times \frac{\delta K}{3.2} ,$$

$$\text{we can plot } \frac{\delta K}{3.2} = .0625 K$$

$$\text{when: } \delta = .200$$

We can also plot A.T.A.G. For $\beta_{A.G.} = 50,000 \text{ lines/in.}^2$

by:

$$A.T.A.G. = 3,125 K$$

This is plotted on Curve IV

CURVE IV

W. HALLIDY

0202-56-182

 $A_{T.A.G.}$ vs. T for $P_{A.G.} = 50 \text{ K.I./in}^2$ Angeit General
CORPORATION $A_{T.A.G.}$ for $P_{A.G.} = 5 \times 10^4 \text{ lines/in}^2$ $\frac{\delta K}{3.2}$

.077

.076

.075

.074

.073

.072

.071

.070

.069

8

9

10

11

12

13

14

15

 $T \text{ (in)}$

3800

3700

3600

3500

3450

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Air Gap Line Stator Sections

Curve IV gives us the excitation required by any particular section of the stator for a Flux density: $B_{A.G.} = 50 \text{ K.L./in.}^2$

Multiplying values of $A_{A.G.}$ found on Curve II A by 5×10^4 gives us Φ/pole for $B_{A.G.} = 50 \text{ K.L./in.}^2$

Using the above, we can draw Curve V showing the air gap line for each section of the air gap area lying between (r) & $(r+0.5 \text{ in.})$

Sample Calculation for section of stator lying between $r = 10.0$ & $r = 10.5$

From curve IV, the excitation required at $r = 10.25 \text{ in.}$ equals 3666 A.T./pole

From curve II A, the area of the air gap spanned by one pole between the pole & the section of the stator lying between $r = 10 \text{ in.}$ & $r = 10.5 \text{ in.}$ equals 12.18 in.^2

$$\Phi/\text{pole} = 12.18 \text{ in.}^2 \times 5 \times 10^4 \text{ lines/in.}^2 = 609 \text{ K.L./pole}$$

AIR GAP LINES - STATOR SECTIONS

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Yoke Depth & Flux Density as a Function of Tooth Area & Flux Density.

Since there is no chamfer on the pole tips, & because the air gap (.200 in.) is small compared to the pole pitch (27 in. to 47 in.), we can consider that only the teeth directly opposite the pole face carry Flux.

If we consider one lamination (Fig. C), we can say that the active tooth area per pole equals

$$A_T = \frac{1}{2} \times \text{Polar Span} \times [\pi D - \text{No. of Slots} \times \text{Slot Width}]$$

$$= \frac{1}{2} \times \text{Polar Span} \times [\pi D - 72 \times .437]$$

$$A_T = \frac{1}{2} \times \text{Polar Span} \times [\pi D - 31.66]$$

Since there are two parallel paths in the yoke, a yoke depth equal in value to $\frac{1}{2} A_T$ would result in a Flux density in the yoke equal to the tooth Flux density.

This can be plotted as shown in Curve VI

The ratio of the actual Yoke depth to $\frac{1}{2} A_T$ will show the ratio of the yoke Flux density to the tooth density:

$$\frac{\frac{1}{2} A_T}{\text{Yoke Depth}} = \frac{B_y}{B_T}$$

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r	Polar Span	.5 x Polar Span	πD	$\pi D-31.7$	$A_{t...}$	Yoke Depth for $B_y = B_t$
8.5	.756	.378	53.4	21.7	8.20	4.1
9.0	.756	.378	56.6	24.9	9.41	4.71
9.5	.756	.378	59.7	28.0	10.59	5.29
10.0	.756	.378	62.8	31.1	11.75	5.87
10.5	.756	.378	66.0	34.3	12.97	6.48
11.0	.756	.378	69.1	37.4	14.12	7.06
11.5	.756	.378	72.2	40.5	15.30	7.65
12.0	.734	.367	75.4	43.7	16.05	8.03
12.5	.714	.357	78.5	46.8	16.70	8.35
13.0	.699	.349	81.6	49.9	17.40	8.70
13.5	.681	.340	84.8	53.1	18.08	9.04
14.0	.668	.334	87.9	56.2	18.77	9.38
14.5	.655	.327	91.1	59.4	19.40	9.70
15.0	.645	.322	94.2	62.5	20.1	10.05

To calculate the actual ratio of $\frac{B_y}{B_t}$, we merely take the ratio of the actual

yoke depth to the yoke depth required for $B_y = B_t$.

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CURVE VI
WHALLIDY
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Magnetization Curve - Teeth & Yoke

An examination of the poly directional characteristics of M-6 steel shows that the lowest saturation level & the highest excitation requirements are encountered when the flux is travelling at an angle between 40° to 60° to the direction of orientation of the steel.

From the geometry, we can see that the width of the path for flux flowing at an angle of 60° is equal to:

$$\begin{aligned} A_{60^\circ} &= \sec 60^\circ \times A_y \\ &= 2.0 \times A_y \end{aligned}$$

At the worst condition, where $A_y = \frac{A_T}{1.250}$, we see that:

$$A_{60^\circ} = 1.6 A_T$$

$$B_{60^\circ} = \frac{B_T}{1.6}$$

Thus, when $B_T = 107.5 \text{ K.L./in.}^2$, $B_{60^\circ} = 67 \text{ K.L./in.}^2$ with an excitation requirement of 4 A.T./in.

We can also see that $A_{40^\circ} = \sec 40^\circ \times A_y = 1.3 \times A_y$

$$A_{40^\circ} = 1.04 A_T$$

$$B_{40^\circ} = \frac{B_T}{1.04} = 103 \text{ K.L./in.}^2 \text{ when } B_T = 107.5 \text{ K.L./in.}^2$$

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Using the data published by Armco showing the polydirectional characteristics of M-6, we can show:

For section where:

$$\frac{B_y}{B_T} = 1.250$$

$$B_{40} = \frac{B_T}{1.04}$$

$$\frac{B_y}{B_T} = 1.100$$

$$B_{40} = \frac{B_T}{1.18}$$

B_{40} (K.L./IN ²)	A.T. ₄₀ (PER IN)	B_T (K.L./IN ²)	A.T. _T (PER IN)	B_{40} (K.L./IN ²)	A.T. ₄₀ (PER IN)	B_T (K.L./IN ²)	A.T. _T (PER IN)
60	2.4	62.5	3.7	60	2.4	70.8	4.2
65	2.65	67.5	4.0	65	2.65	76.6	4.9
70	3.31	72.7	4.3	70	3.31	82.5	7.2
75	4.10	78.0	5.2	75	4.10	88.5	26.5
80	8.30	83.0	7.5	80	8.30	94.4	58.
85	30.0	88.5	27	85	30.0	100	105.
90	51.0	93.5	58	90	51.0	106	117.
95	97.0	98.7	90	95	97.0	112	260.
100	145	104	145	100	145		
105	200	109	210	105	200		

It is obvious that we can neglect the excitation of the Transition zone except for that part of the zone that lies at 40° to the direction of orientation in that part of the stator where $\frac{B_y}{B_T} = 1.225 - 1.250$.

As a good approximation, we can include the excitation requirements of the 40° zone by assuming a tooth length of 3.0 in. effective instead of the 2.1 in. actual.

DIAGRAM SHOWING HYPOTHETICAL
FLUX TUBES IN TRANSITION FROM
TEETH TO YOKE

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SUBJECT 500 KVA Alternator BY W. Halliday WORK ORDER 0202-56-182*Magnetization Curve - Teeth & Yoke*

In order to plot the excitation requirements of the teeth & yoke, we will calculate the flux per pole of each 0.5 in wide section of the stator for different values of B_f .

To do this, we must multiply the incremental tooth area (Curve II) by the lamination or stacking factor. Since the laminations will be wound with a minimum of 20 p.s.i. pressure between laminations, we will use a stacking factor of 0.97 (Armco Data)

In the following table, A_T = Tooth Area from Curve II ; & $A_{T_1} = 0.97 A_T$ = Tooth iron area

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SUBJECT 500 KVA Alternator BY W HallidayWORK ORDER 0202-56-182 Φ /POLE PER SECTION (K.L.) YS BT

$\S 14.5-15$ $A_I = 9.70$	679	703	728	752	776	801	825	849	874	897	922	946	970	995	1019	1043	1067		
$\S 14-14.5$ $A_I = 9.44$	661	685	708	732	756	779	803	826	850	874	897	921	944	969	992	1017	1042		
$\S 13.5-14$ $A_I = 9.10$	637	660	683	705	728	751	774	796	819	841	864	887	910	933	956	979	1002		
$\S 13-13.5$ $A_I = 8.76$	612	634	656	678	700	722	744	766	788	810	832	854	876	898	920	941	963		
$\S 12.5-13$ $A_I = 8.41$	589	610	631	652	673	694	715	736	757	778	799	820	841	862	883	905	927		
$\S 12-12.5$ $A_I = 8.09$	566	586	606	626	646	667	687	708	728	749	769	789	809	830	849	870	891		
$\S 11.5-12$ $A_I = 7.75$	543	562	581	601	620	639	659	678	697	717	736	756	775	795	814	834	854		
$\S 11-11.5$ $A_I = 7.18$	503	521	538	556	574	592	610	628	646	664	682	700	718	736	755	772	799		
$\S 10.5-11$ $A_I = 6.61$	463	479	496	512	529	545	562	579	595	611	628	644	661	678	694	711	728		
$\S 10-10.5$ $A_I = 6.03$	422	438	453	468	483	498	514	529	544	559	574	589	604	619	634	649	664		
$\S 9.5-10$ $A_I = 5.45$	382	395	408	423	436	450	464	477	491	504	518	531	545	559	572	586	600		
$\S 9-9.5$ $A_I = 4.88$	342	354	366	378	390	403	415	427	439	451	464	475	488	500	512	525	538		
$\S 8.5-9$ $A_I = 4.30$	301	311	322	333	344	355	366	376	387	398	408	419	430	441	451	462	473		
B_T (K.L./IN ²)	60	65	70	72.5	75	77.5	80	82.5	85	87.5	90	92.5	95	97.5	100	102.5	105	107.5	110.0

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SUBJECT 500 KVA Alternator BY W. Halliday

WORK ORDER 0202-56-182

Magnetization Curve - Teeth & Yoke

Teeth Excitation

Length of Path equals 3" per pole

<i>BT</i>	<i>A.T./IN.</i>	<i>A.T._T (per pole)</i>
60	3.7	11.1
65	3.8	11.4
70	4.1	12.3
72.5	4.3	12.9
75	4.6	13.8
77.5	5.0	15.0
80	5.7	17.1
82.5	7.2	21.6
85	11.5	34.5
87.5	22	66
90	34	102
92.5	47	141
95	62	186
97.5	80	240
100	105	315
102.5	130	390
105	160	480
107.5	200	600
110.0	250	750

Magnetization Curve - Teeth & Yoke

For a particular Flux density in the yoke of a particular section of the stator, the Flux per pole crossing the air gap is found by considering:

$$\Phi/\text{pole} = A_{T.I.} \times B_T \quad \text{where: } A_{T.I.} = \text{Tooth Iron Area} \\ B_T = \text{Tooth Flux density}$$

$$B_T = \frac{B_y}{\left(\frac{B_y}{B_T}\right)} \quad \text{where: } \frac{B_y}{B_T} \text{ is Found on Curve VI}$$

$$\text{Then: } \Phi/\text{pole} = A_{T.I.} \times \frac{B_y}{\left(\frac{B_y}{B_T}\right)}$$

or:

$$\Phi/\text{pole} = B_y \times \frac{A_{T.I.}}{\left(\frac{B_y}{B_T}\right)}$$

In the following table, we shall represent $\frac{A_{T.I.}}{\left(\frac{B_y}{B_T}\right)}$ by the symbol A_I'

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Φ/pole per section (K.L.) vs. By

§14.5-15 $A_I' = 8.90$	801	824	846	868	890	913	935	957	979	1002	1024	1046	1068	1090	1112	1135	1158			
§14-14.5 $A_I' = 8.54$	769	790	811	833	854	875	896	918	940	961	983	1004	1025	1046	1068	1089	1110			
§13.5-14 $A_I' = 8.09$	728	749	769	789	809	830	850	870	891	911	931	951	971	991	1011	1031	1051			
§13-13.5 $A_I' = 7.56$	680	699	718	737	756	775	793	812	831	850	869	888	906	925	945	964	982			
§12.5-13 $A_I' = 7.17$	645	663	681	699	717	735	753	770	788	806	824	842	860	878	896	914	932			
§12-12.5 $A_I' = 6.74$	606	623	640	657	674	691	708	725	742	759	775	792	809	826	843	860	876			
§11.5-12 $A_I' = 6.29$	566	582	597	613	629	645	660	676	692	708	723	739	755	771	786	802	818			
§11-11.5 $A_I' = 5.76$	518	533	547	561	576	590	604	619	633	648	662	676	691	705	720	734	749			
§10.5-11 $A_I' = 5.31$	478	491	504	518	531	544	557	570	584	597	610	624	636	650	663	676	690			
§10-10.5 $A_I' = 4.85$	437	449	461	473	485	497	510	522	534	546	558	570	582	594	606	618	630			
§9.5-10 $A_I' = 4.41$	397	408	419	430	441	452	463	474	485	496	507	518	529	540	551	562	573			
§9-9.5 $A_I' = 3.96$	356	366	376	386	396	406	416	425	435	445	455	465	475	485	495	505	515			
§8.5-9 $A_I' = 3.51$	316	325	333	342	351	360	369	378	386	395	403	412	421	430	439	448	457			
$B_y (K.L./IN^2)$	75	80	85	90	92.5	95	97.5	100	102.5	105	107.5	110	112.5	115	117.5	120	122.5	125	127.5	130

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SUBJECT 500 KVA Alternator BY W HallidayWORK ORDER 0202-56-182

Magnetization Curve - Teeth & Yoke

Yoke A.T./POLE vs. B_y Assumed path length = $.7\pi = .7\pi r \text{ total} = .35\pi r / \text{pole}$

§ 14.5-15 $L = 16.21 \text{ IN}$	8.1	9.4	10.2	11.4	12.6	14.4	16.9	19.8	24.2	30.0	39.6	57.6	94.0	178	284	441	665	1015	1478	2140	2985	4050
§ 14-14.5 $L = 15.68 \text{ IN}$	7.8	9.1	9.9	11.0	12.2	14.0	16.3	19.1	23.2	29.0	38.2	55.6	91.0	172.	274.	426.	642.	979.	1430.	2070.	2880.	3920.
§ 13.5-14 $L = 15.12 \text{ IN}$														166	265	411	620	945	1380	2000	2780	3780
§ 13-13.5 $L = 14.59 \text{ IN}$														160	255	396	598	911	1330	1930	2680	3640
§ 12.5-13 $L = 14.02 \text{ IN}$														154	246	382	575	875	1280	1850	2580	3500
§ 12-12.5 $L = 13.49$														148	236	366	552	842	1230	1780	2480	3370
§ 11.5-12 $L = 12.93$														142	226	352	530	808	1180	1710	2380	3230
§ 11-11.5 $L = 12.38$														136	217	337	507	774	1130	1630	2280	3100
§ 10.5-11 $L = 11.82$														130	207	322	485	740	1080	1560	2180	2960
§ 10-10.5 $L = 11.29$														124	198	307	463	705	1030	1490	2080	2820
§ 9.5-10 $L = 10.72$														118	188	292	440	670	980	1420	1980	2680
§ 9-9.5 $L = 10.18$														112	178	276	417	635	925	1340	1870	2540
§ 8.5-9 $L = 9.64$														106	169	262	395	600	876	1270	1770	2410
A.T./IN.	.50	.58	.63	.70	.78	.89	1.04	1.22	1.48	1.85	2.44	3.55	5.80	11.0	17.5	27.2	41.0	62.5	91.0	132.	184.	250.
B_y (K.L.)	75.	80.	82.5	85.	87.5	90	92.5	95	97.5	100	102.5	105.	107.5	110.	112.5	115.	117.5	120.	122.5	125.	127.5	130.

MAGNETIZATION CURVE
ARMATURE & AIR GAP SECTIONS

41 OF 183
CURVE VIII B
WHALLIDY
0202-56-182

MAGNETIZATION CURVE
ARMATURE & AIR GAP

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SUBJECT 500 KVA Alternator BY W HallidyWORK ORDER 0202-56-182Field Structure- Rotor

The rotor portion of the field structure is composed of 9 laminations 0.75 in. thick. Six of the nine laminations are composed of two pieces of U.S.S. Cor-Ten steel welded to a non-magnetic spacer of type 304 stainless steel. These six laminations are shown in Fig. E through J.

Two of the laminations are as shown in Fig. K, & one is as shown in Fig. L.

For convenience, the laminations are numbered I through IX, with lamination I being the lamination closest to the armature, & lamination IX being the one farthest from the armature, as shown in Fig. M.

Fig M' shows a cross-section of the pole labelled "N" for means of identification. The flux tubes shown in Fig M' are only approximate & are shown merely for the sake of estimating the length of path.

The Flux path in the "N" pole can be broken down into three sections. One is an axial path in the outer or peripheral portion of the "N" pole. The area of this section is taken as being equal to the axial projection of portion of the "N" pole facing the stator. This can be taken as $\frac{1}{2}$ the area of the air gap times the polar span:

$$A = \frac{1}{2} A_{A.G.} \times \text{Polar Span}$$

$$= \frac{1}{2} \times 480 \text{ in.}^2 \times .722$$

$$A = 173.3 \text{ in.}^2$$

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SUBJECT 500 KVA Alternator BY W HallidyWORK ORDER 0202-56-182Field Structure - Rotor (cont.)

Another path section is the axial path about the shaft. On the following pages, it will be seen that this area is equal to approximately 1.7 Times the area of the radial Flux path. Since the area of the radial Flux path equals 108.4 in^2 , the area of the axial Flux path about the shaft equals 184.3 in^2 , or rather, the equivalent of 184.3 in^2 .

The area of the radial path in the "N" pole structure is found by adding the areas of the path in each of the laminations I through II. In order to simplify the calculations of the areas, the laminations were purposely shaped so that the area at any particular radius is a constant for any particular lamination.

In rotor lamination II, the "N" pole structure subtends an angle of 126° at a radius of 9.5 in . The area for Flux travelling radially is equal to the area of a segment of a cylinder with radius $r = 9.5 \text{ in}$, & length $L = 0.75 \text{ in}$.

$$A = 2\pi r L \times \frac{\theta}{360^\circ} = \pi r L \times \frac{\theta}{180}$$

$$A = 2\pi \times 9.5 \times 0.75 \times \frac{126}{360} = 15.669 \text{ in}^2$$

Rewriting the equation, we get:

$$\theta = A \times \frac{180}{\pi r L}, \text{ or, for lam. II, } \theta = \frac{1197.0}{r}$$

210°
150°200°
160°190°
170°

180°

170°
190°160°
150°

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Pages

ROTOR LAMINATION I

FIG. E
W. HALLIDY
0202-56-182220°
140°230°
130°240°
120°250°
110°260°
100°270°
90°280°
80°290°
70°300°
60°310°
50°320°
40°140°
220°130°
230°120°
240°110°
250°100°
260°90°
270°80°
280°70°
290°60°
300°50°
310°40°
320°

Aerojet-General Corporation

359-31G
44-31111-1K&E POLAR CO-ORDINATE
KEUFFEL & ESSER CO.

NOTE: 1. LAMINATION THICKNESS = 0.075 IN.
 2. POINTS MARKED + DEFINE BOUNDARY FOR AREA = 13.195 IN.²
 FOR FLUX TRAVELLING RADIALLY IN POLE "N"

330°
-30°340°
-20°350°
-10°

0

+10°
350°+20°
340°+30°
330°

210°
150°

200°
160°

190°
170°

180°

170°
190°

160°

150°

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ROTOR LAMINATION II

FIG. A
W. HALLIDY
0202-56-182

NOTE: 1. LAMINATION THICKNESS = 0.75 INCHES
2. POINTS MARKED + DEFINE BOUNDARY FOR AREA = 15.67 IN² FOR FLUX TRAVELLING RADIALLY IN POLE "N"

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359.31G

POLAR CO-ORDINATE
KEIFFEL & ESSER CO.

210°
150°200°
160°190°
170°

180°

170°
190°160°
200°

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ROTOR LAMINATION III

FIG. 6

W. HALLIDY

0202-56-182

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359-31G

POLAR CO-ORDINATE
KLUFFEL & BESSER CO.

210°
150°

200°
160°

190°
170°

180°

170°
190°

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ROTOR LAMINATION IV

FIG H
W. HALLIDY
0202-56-182

NOTE: 1. LAMINATION THICKNESS = 0.25 INCHES
2. POINTS MARKED + DEFINE BOUNDARY FOR AREA = 19.462 IN.²
FOR FLUX TRAVELLING RADIALLY

330°
30°

340°
20°

350°
10°

0

10°
350°

20°
340°

30°
330°

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POLAR CO-ORDINATE
KEUFFEL & ESSER CO.

210°
150°200°
160°190°
170°

180°

170°
190°

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ROTOR LAMINATION V

FIG. I
W. HALLIDY
0202-56-182

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359-31G
MADE IN U.S.A.K&E POLAR CO-ORDINATE
KEUFFEL & ESSER CO.

FIG. J
W. HALLIDY
0262-56-182

ROTOR LAMINATION VII

NOTE: 1. LAMINATION THICKNESS = 0.05 IN.
2. POINTS MARKED + DEFINE BOUNDARY FOR AREA 21.277 IN.²
FOR FLUX TRAVELLING RADIALLY

210°
150°

200°
160°

190°
170°

180°

170°
190°

Page 160°
200° 50 of 163210 Pages

FIG. K
W. MALLIDY
0202-56-182

ROTOR LAMINATION VII & VIII

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359-31G

POLAR CO-ORDINATE
KEUFFEL & ESSER CO.

210°
150°

200°
160°

190°
170°

180°

170°
190°

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ROTOR LAMINATION IX

FIG. 1

W. HALLIDY

0202-56-182

220°
140°

230°
130°

240°
120°

250°
110°

260°
100°

270°
90°

280°
80°

290°
70°

300°
60°

310°
50°

320°
40°

140°
220°

130°
230°

120°
240°

110°
250°

100°
260°

90°
270°

80°
280°

70°
290°

60°
300°

50°
310°

40°
320°

330°
30°

340°
20°

350°
10°

0

10°
350°

20°
340°

30°
330°

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359-31G

POLAR CO-ORDINATE
KEUFFEL & ESSER CO.

K-E

SECTION C-C

FIG. 14
WHALLIDY
0202-56-182

FIG. M'
WPAALIDY
0202-56-102

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SUBJECT 500 KVA Alternator BY W. HallidayWORK ORDER 0202-56-182ROTOR LAMINATION CONFIGURATION - "N" pole radial flux path.

The original rotor lamination configuration was laid out on the basis of a stator core having an I.D. of 16 inches & on the basis of a polar span of 70%. For various reasons such as existing tooling, need for end turn space, need for reduction of harmonics, etc., the stator I.D. was changed to 17 inches & the polar span was changed to the one shown in Fig. E.

It was not felt necessary to change the configuration of the magnetic portion of the first rotor lamination to conform to the revised stator I.D. of 17 inches since there would be no reduction in weight.

The angle θ subtended by the arc within the two pole edges of the pole marked N (Fig. E) in the case of the original polar span of 126° (70%) equals 126° at a radius of 8 inches. Thus, the area available for flux travelling radially equals $\pi r l \times \frac{\theta}{180^\circ}$.

Thus, in rotor lamination I, the area at a radius of 8 in:

$$A = \pi r l \times \frac{\theta}{180^\circ} = \pi \times 8 \times .75 \times \frac{126}{180} = \pi \times 8 \times .75 \times .70$$

$$A = 13.195 \text{ in.}^2$$

We can then rewrite the equation as:

$$r\theta = \frac{13.195 \times 180}{\pi \times .75}, \text{ or: } \theta = \frac{1008}{r}$$

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SUBJECT 500 KVA Alternator BY W. HallidyWORK ORDER 0202-56-182

ROTOR LAMINATION CONFIGURATION (cont.)

FOR POLE MARKED "N" IN FIG. E THROUGH J
Radial Flux path

(1.) ROTOR LAMINATION I $A = 13.195 \text{ in.}^2$

$$\theta = \frac{1008.0}{r}$$

(2.) ROTOR LAMINATION II

$$r = 9.5 \text{ in.} \quad \theta = 126^\circ$$

$$A = \pi r l \times \frac{\theta}{180} = \pi r l \times \frac{126}{180} = \pi \times 9.5 \times .75 \times .70$$

$$A = 15.669 \text{ in.}^2$$

$$\theta = \frac{1197.0}{r}$$

(3.) ROTOR LAMINATION III

$$r = 10.6 \text{ in.} \quad \theta = 126^\circ$$

$$A = 17.482 \text{ in.}^2$$

$$\theta = \frac{1335.6}{r}$$

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ROTOR LAMINATION CONFIGURATION (cont.)

FOR POLE MARKED "N" (cont.)
Radial Flux path

(4) ROTOR LAMINATION IV

$$r = 11.8 \text{ in.} \quad \theta = 126^\circ$$

$$A = 19.462 \text{ in.}^2$$

$$\theta = \frac{1487.8}{r}$$

(5) ROTOR LAMINATION V & VI

$$r = 12.9 \text{ in.} \quad \theta = 126^\circ$$

$$A = 21.277 \text{ in.}^2$$

$$\theta = \frac{1625.4}{r}$$

$$(6) \text{ TOTAL AREA} = 13.20$$

$$15.67$$

$$17.48$$

$$19.46$$

$$21.27$$

$$\underline{21.28}$$

$$108.36 \text{ in.}^2$$

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ROTOR LAMINATION CONFIGURATION (cont.)

FOR POLE MARKED "N" (cont.)
Radial Flux path

LAMINATION: I II III IV V & VI

r	θ°	θ°	θ°	θ°	θ°
3.0	336				
3.5	288	342			
4.0	256	299	334		
4.5	224	266	297	330	
5.0	202	240	268	298	325
5.5	183	218	243	270	296
6.0	168	200	222	248	271
6.5	155	184	206	229	250
7.0	144	171	191	212	232
7.5	134.5	160	178	198	217
8.0	126.0	150	167	186	203
8.5		141	157	175	191
9.0		133	148	165	181
9.5		126	141	157	171
10.0			134	149	163
10.5			127	142	155
11.0				135	148
11.5				129	141
12.0					135
12.5					130

ROTOR LAMINATION CONFIGURATION (cont.) & Axial Flux Path

The rotor shaft material is picked for minimum permeability consistent with strength, etc. in order to minimize end turn leakage reactance in the armature. Thus, to calculate the area required in pole "N" for Flux Travelling axially about the & of the rotor laminations, we will use only 20% of the area of the shaft as available for carrying Flux

The area of the shaft equals:

$$A = \pi r^2 = \pi \times 2.75^2 = \pi \times 7.5625$$

$$A = 23.76 \text{ in.}^2$$

$$.20 \times A = 4.75 \text{ in.}^2 \quad \& \quad .80 A = 19.01$$

(1.) Lamination VI

Since all of the Flux for the "N" poles enters Lamination VI, the area required is:

$$A = 108.36 + 19.01 = 127.37 \text{ in.}^2$$

Then, the minimum radius for pole "N" is

$$r = \sqrt{\frac{127.37}{\pi}} = 6.37 \text{ in.}$$

The actual minimum radius is 7.90 in. (Fig. J.)

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Rotor Lamination Config. (cont.) & Axial Flux path

(1.) Lamination VI (cont.)

Another way to look at it is this: The area of "N" pole available for carrying Flux equals:

$$A = \pi (r_o^2 - r_i^2) = \pi (7.90^2 - 2.75^2)$$

$$A = 172.13 \text{ in.}^2$$

The area of shaft available for carrying Flux is:

$$A = 4.75 \text{ in.}^2$$

Then the total area available is:

$$A = 172.13 \text{ in.}^2 + 4.75 \text{ in.}^2 = 177.05 \text{ in.}^2 = 177 \text{ in.}^2$$

The area required to equal the area of the radial Flux path is:

$$A = 108.4 \text{ in.}^2$$

$$\text{The ratio of } \frac{172.13}{108.4} = 1.59 \approx 1.6$$

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SUBJECT 500 KVA Alternator BY W Hallidy WORK ORDER 0202-56-182Rotor Lamination Config. (cont.) $\oint$ axial flux path

(2.) Lamination V

$$\text{Available area} = \pi (r_o^2 - r_i^2) = \pi (7.25^2 - 2.75^2)$$

$$A = 141.5 \text{ in.}^2$$

The area of shaft available for carrying flux equals:

$$A = 4.75 \text{ in.}^2$$

The total available area equals

$$A = 141.5 \text{ in.}^2 + 4.75 \text{ in.}^2 = 146.25 \text{ in.}^2$$

The required area equals:

$$A = 108.4 \text{ in.}^2 - 21.3 \text{ in.}^2$$

$$A = 87.1 \text{ in.}^2$$

$$\text{The ratio of } \frac{146.3}{87.1} = 1.67$$

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SUBJECT 500 KVA Alternator BY W. HallidayWORK ORDER 0202-56-182Rotor Lamination Config. (cont.) $\oint$ axial flux path(3.) Lamination IV

In a similar fashion:

Total available area equals:

$$A = \pi(r_o^2 - r_i^2) + 4.75 \text{ in.}^2 = \pi(6.40^2 - 2.75^2) + 4.75 \text{ in.}^2$$

$$A = 109.75 \text{ in.}^2$$

Total required area equals:

$$A = 87.1 - 21.3 = 65.8 \text{ in.}^2$$

$$\text{The ratio of } \frac{109.75}{65.8} = 1.67$$

(4.) Lamination III

Total available area equals:

$$A = \pi(6.1^2 - 2.75^2) + 4.75 \text{ in.}^2$$

$$A = 97.8 \text{ in.}^2$$

Total required area equals: $A = 72$

$$A = 65.8 - 19.5$$

$$A = 46.3 \text{ in.}^2$$

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Rotor Lamination Config. (cont.) & axial flux path

(4) Lamination III (cont.)

$$\frac{97.8}{46.3} = 2.1$$

(5) Lamination II

$$\text{Total Available Area} = \pi(6.0^2 - 2.75^2) + 4.75 \text{ in.}^2$$

$$A = 94.0 \text{ in.}^2$$

$$\text{Required Area} = 46.3 \text{ in.}^2 - 17.5 \text{ in.}^2 = 28.8 \text{ in.}^2$$

$$\text{Ratio } \frac{94.0}{28.8} = 3.26$$

(6) Lamination I

$$\text{Total available area} = \pi(5.0^2 - 2.75^2) + 4.75 \text{ in.}^2$$

$$A = 59.3 \text{ in.}^2$$

$$\text{Required area} = 28.8 \text{ in.}^2 - 15.7 \text{ in.}^2 = 13.1 \text{ in.}^2$$

$$\text{Ratio } \frac{59.3}{13.1} = 4.5$$

Note: The radii of laminations I, II, & III were determined by stress-strength requirements & not by magnetic requirements, which is the reason for the excess area.

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ROTOR LAMINATION CONFIGURATION (cont.)

"S" pole

The flux travels axially in the "S" poles of the rotor laminations.

(1) LAMINATION I

$$\text{Area} = .5 \times .722 \times A_{A.G.} = 173.3 \text{ in.}^2$$

(2) Lamination II

$$\begin{aligned} \text{Area} &= \frac{1}{2} \times .7 \times \pi (r_o^2 - r_i^2) \\ &= .35 \times \pi (15^2 - 9.5^2) \\ &= 148.4 \text{ in.}^2 \end{aligned}$$

(3) For lamination III, we take the area of the portion of lamination III that is in contact with lamination IV

$$\begin{aligned} \text{Area} &= \frac{147^\circ}{360^\circ} \times \pi (r_o^2 - r_i^2) \\ &= .408 \times \pi (14.2^2 - 10.5^2) \\ A &= 117 \text{ in.}^2 \end{aligned}$$

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ROTOR LAMINATION CONFIGURATION (cont.) "S" pole

- (4.) For lamination IV, we take the area of the portion of lamination IV in contact with lamination V

$$\text{Area} = \frac{166^\circ}{360^\circ} \times \pi(14.2^2 - 11.0^2)$$

$$A = 117 \text{ in.}^2$$

- (5.) For laminations I, VI, VII & VIII, the area is:

$$A = \frac{183}{360} \times \pi(14.2^2 - 11.5^2)$$

$$A = 111 \text{ in.}^2$$

6. For lamination IX, the area is

$$A = \pi(14.2^2 - 11.5^2)$$

$$A = 215 \text{ in.}^2 \text{ for the air gap side, \&}$$

$$A = 111 \text{ in.}^2 \text{ for the side touching lamination } \underline{\text{VIII}}$$

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WORK ORDER 0202-56-182*ROTOR LAMINATION CONFIGURATION (cont.)*

In order to get a fairly accurate magnetization curve for the rotor without going into unwarranted refinement, we will make two magnetization curves for the rotor. One will be for the portions where the area is equal to 108.4 in.^2 to 117 in.^2 , & we will draw the curve as though the area in these portions were all equal to 108.4 in.^2 . These portions are: the radial flux path in the N poles, with a length of path equal to 4.0 inches (Fig. M'); & the "S" poles of laminations III - VIII, with a length of path equal to 4.5 in.

The other curve will be for the portions where the area equals 148 in.^2 to 173 in.^2 . This curve will be drawn as though the area in these portions were all equal to 160 in.^2 . The combined total length of path of these areas is 6.75 in.

It is felt that the "joint gaps" can be neglected without introducing any noticeable error in the final magnetization curve of the total machine

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Rotor Magnetization Curve Data

Φ / Pole (K.L.)	Area = 108.4 in. ² Length = 8.50 in.			Area = 160 in. ² Length = 6.75 in.			Combined	
	β (K.L.)	A.T./ in.	A.T.	β (K.L.)	A.T./ in.	A.T.	A.T. Total	A.T./ Pole
1000	9.22	5.2	44.1	6.25	4.1	26.6	70.7	35.4
2000	18.44	7.7	65.4	12.50	6.3	42.5	107.9	54.0
3000	27.66	9.6	81.6	18.75	7.8	52.6	134.2	67.1
4000	36.9	11.6	98.6	25.00	9.2	62.0	160.6	80.3
5000	46.1	14.0	119.0	31.25	10.5	70.8	189.8	94.9
6000	55.4	17.0	144.6	37.50	11.8	79.6	224.2	112.
7000	64.6	21.5	182.8	43.75	13.2	89.2	272.0	136.
8000	73.8	28.0	238.	50.00	15.0	102.2	340.2	170.
9000	83.0	40.0	340.	56.25	17.3	116.8	454.8	227.
10000	92.2	60.0	510.	62.50	20.5	138.2	648.2	324.
11000	101.4	95.0	806.	68.75	24.8	167.4	973.4	487.
12000	110.8	172.	1462.	75.00	29.5	199.0	1661.	831.
13000	119.8	330.	2810.	81.25	37.0	249.6	3060.	1530.
14000	129.1	730	6200.	87.50	48.3	326.0	6526.	3263.
15000				93.75	64.0	431		
16000				100.00	89.0	601		
17000				106.00	126.0	851		
18000				113.0	200.0	1350		

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ROTOR MAGNETIZATION CURVE

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 FIG M"
 WTHALLIDY
 0202-56-182

SECTION C"-C"
 INTERPOLAR SPACE

Field Leakage

Section C"-C" (Fig. M") shows the interpolar space for that portion of the rotor between $\theta = -70^\circ$ & $\theta = +70^\circ$ (Fig E through L). An approximate equipotential line is drawn to aid in estimating the interpolar gap length. The surface of the cone shown approximates the configuration of the equipotential line & is used to compute the air gap area.

The area of a Frustum of a cone is:

$$A = \pi (r_1 + r_2) \sqrt{h^2 + (r_1 - r_2)^2}$$

The area for leakage in Fig. M" is:

$$\begin{aligned} A &= \frac{140^\circ}{360^\circ} \times \pi \times (10.0 + 6.5) \sqrt{5.0^2 + (10.0 - 6.5)^2} \\ &= \frac{140}{360} \times \pi \times 16.5 \sqrt{5.0^2 + 3.5^2} \\ &= \frac{140}{360} \times \pi \times 16.5 \sqrt{25 + 12.25} \end{aligned}$$

$$A = 123 \text{ in.}^2$$

The average interpolar gap length is taken as 2.25 in., & the permeability of fully annealed Type 304 stainless steel is taken as 1.02

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Field Leakage (cont.)

$$A.T. = \frac{B\delta}{3.2 \times 1.02} =$$

$$B = A.T. \times \frac{3.2 \times 1.02}{\delta}$$

For a potential difference of 20,000 A.T. between the two poles:

$$B = \frac{20,000 \times 3.2 \times 1.02}{\delta}$$

$$B = \frac{6.528 \times 10^4}{\delta} \text{ lines/in}^2$$

$$B = \frac{65.28}{\delta} \text{ K.L./in}^2$$

$$\phi = B \times \text{Area}$$

$$\phi = \text{Area} \times \frac{65.28}{\delta} \text{ K.L.}$$

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SUBJECT 500 KVA Alternator BY W HallidayWORK ORDER 0202-56-182*Field Leakage (cont.)**Thus:*

$$\Phi_{L1} = 123 \times \frac{65.28}{2.25} \text{ K.L.} = 3,560 \text{ K.L.}$$

$\Phi_{L1} = 3,560 \text{ K.L.}$ for a potential difference of
 20,000 ampere turns between poles

The area of the interpolar gap for that portion of the rotor between $\theta = +70^\circ$ & $\theta = +92^\circ$ can be computed by computing the area of $\frac{22}{360}$ of the surface of a cylinder with $r = 9.5 \text{ in.}$ & $L = 4 \times .75 \text{ in.} = 3 \text{ in.}$ Since the poles are symmetrical, the total area is:

$$A = 2 \times \frac{22}{360} \times 2\pi r L$$

$$= 2 \times \frac{22}{360} \times 2\pi \times 9.5 \times 3.0$$

$$A = \frac{88}{360} \times \pi \times 28.5$$

$$A = 22.0 \text{ in.}^2$$

We will take the length of gap as: $L = 2.0 \text{ in.} = \delta$

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Field Leakage (cont.)

$$\phi_{L2} = \text{Area} \times \frac{65.28}{\delta} \text{ K.L.}$$

$$= 22.0 \times \frac{65.28}{2.0} \text{ K.L.}$$

$$\phi_{L2} = 718 \text{ K.L.}$$

The area for leakage between the "N" pole of lamination VI & the "S" pole of lamination IX is taken as:

$$A = \frac{140}{360} \times \pi (r_o^2 - r_i^2)$$

$$A = .389 \pi (14.2^2 - 11.5^2) = .389 \pi (201.64 - 132.25)$$

$$A = .389 \pi \times 69.4 = 84.7 \text{ in.}^2$$

$$A = 85.0 \text{ in.}^2$$

$$\delta = 1.5 \text{ in.}$$

$$\phi_{L3} = \text{Area} \times \frac{65.28}{\delta} = 85.0 \times \frac{65.28}{1.5}$$

$$\phi_{L3} = 3480 \text{ K.L.}$$

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SUBJECT 500 KVA Alternator BY W. HallidayWORK ORDER 0202-56-182*Field Leakage (cont.)*

The saturation flux level of Curve X is determined by the portions of the rotor field structure where the area equals 108.4 in.². There are two such sections: one is the radial flux path in pole "N" & the other is the axial flux path in pole "S".

An examination of the leakage flux paths assumed shows that only ϕ_{L1} & $0.75 \times \phi_{L2}$ pass through the axial flux path of pole "S", & that only ϕ_{L2} & ϕ_{L3} pass through the radial flux path of pole "S". All of the leakage flux passes through the rotor hub, or the axial flux path about the ϕ of pole "N".

Only the active flux passes through the axial flux path in the peripheral portion of pole "N" which has an area of 173 in.². Since the active flux will equal approximately 9,300 K.L./pole, the excitation requirement of this portion of the magnetic circuit is only 80 ampere turns total. For this reason, we will neglect this portion of the magnetic circuit in future computations.

Assuming that the potential difference between the two poles is 20,000 A.T.:

$$\phi_{L1} + 0.75 \phi_{L2} = 3,560 + 538 \text{ K.L.}$$

$$\phi_{L1} + 0.75 \phi_{L2} = 4,098 \text{ K.L.}$$

$$\phi_{L2} + \phi_{L3} = 718 + 3480 \text{ K.L.}$$

$$\phi_{L2} + \phi_{L3} = 4198 \text{ K.L.}$$

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Field Leakage (cont.)

Since the two quantities are practically equal, we can say that the rotor magnetic circuit is made up of two parts:

1. The rotor hub with an area of 160 in.^2 & a path length of 4.5 in. ; through which passes all of the active flux per pole & all of the leakage flux.
2. The "N" pole radial path & the "S" pole axial path with an area of 108.4 in.^2 & a path length of 8.5 in. total. All of the active flux passes through this combined section, as well as, effectively, $\frac{1}{2}$ of the leakage flux

An equivalent electrical circuit is shown below where $I_T = I_A + I_L = 9,300 + 8,300 = 17,600$

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SUBJECT 500 KVA Alternator BY W HallidyWORK ORDER 0202-S6-182*Field Leakage (cont.)**Obviously, the circuit can be redrawn as follows:*

Curve XI will show Φ_L (ROTOR HUB) & Φ_L ("N" & "S" POLE)

Curve XII will show the magnetization curve of the "N" pole radial path & the "S" pole axial path. Area = 108.4 in.² Length = 8.5 in.

Curve XIII will show the magnetization curve of the rotor hub. Area = 160 in.² Length = 4.5 in.

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SUBJECT 500 KVA Alternator BY W Hallidy WORK ORDER 0202-56-182*Field Leakage (cont.)*

$$\Phi_{LT} = \Phi_{L1} + \Phi_{L2} + \Phi_{L3} = 3480 + 718 + 3560 = 7,760 \text{ K.L.}$$

$$\Phi_{LT} = 7,760 \text{ K.L.} = \Phi_L (\text{ROTOR HUB})$$

$$\begin{aligned} \Phi_L (\text{N} \& \text{S} \text{ POLES}) &= \frac{1}{2} \left[\Phi_L (\text{N} \text{ POLE}) + \Phi_L (\text{S} \text{ POLE}) \right] \\ &= \frac{1}{2} \left[(3480 + 718) + (3560 + 0.75 \times 718) \right] \\ &= \frac{1}{2} \left[4198 + 4098 \right] \end{aligned}$$

$$\Phi_L (\text{N} \& \text{S} \text{ POLE}) = 4150 \text{ K.L.}$$

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ROTOR MAGNETIZATION

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CURVE XII
WMA110Y
0202-56-182

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ROTOR HUB AIR GAP (cont.)

The area between the field coil bobbin & the rotor is:

$$A = \pi(r_1^2 - r_2^2) \quad \text{where } r_1 = 7.4$$

$$r_2 = 6.1$$

$$A = \pi(54.76 - 37.21)$$

$$A = 55.1 \text{ in.}^2$$

$$\beta = \frac{3.2 \text{ A.T.}}{\delta}$$

$$\text{where } \delta = .400$$

$$\text{A.T.} = 4000$$

$$\beta = \frac{3.2 \times 4 \times 10^3}{4 \times 10^{-1}}$$

$$\beta = 3.2 \times 10^4 \text{ lines/in}^2$$

$$\phi = \beta \times A = 3.2 \times 10^4 \times 5.51 \times 10^1$$

$$\phi = 1.76 \times 10^6 = 1.76 \times 10^3 \text{ K.L.}$$

The total flux crossing the rotor hub air gap:

$$\phi = 8.91 + 1.76 \times 10^3 \text{ K.L.}$$

$$\phi = 10.67 \times 10^3 \text{ K.L. per pole For 2000 A.T./pole}$$

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ROTOR HUB AIR GAP

The area of the rotor hub air gap in the conical portion is:

$$A = \pi(r_1 + r_2) \sqrt{h^2 + (r_1 - r_2)^2} \quad \text{where} \quad \begin{aligned} r_1 &= 6.1 \\ r_2 &= 3.2 \\ h &= 5.2 \end{aligned}$$

$$A = \pi \times 9.3 \sqrt{35.45} = \pi \times 9.3 \times 5.95$$

$$A = 174 \text{ in.}^2$$

$$\beta = \frac{3.2 \text{ A.T.}}{\delta} \quad \text{where} \quad \begin{aligned} \delta &= .250 \\ \text{A.T.} &= 4000 \end{aligned}$$

$$\beta = \frac{3.2 \times 4 \times 10^3}{2.5 \times 10^{-1}}$$

$$\beta = 5.1 \times 10^4 \text{ lines/in}^2$$

$$\phi = \beta \times A = 5.1 \times 10^4 \times 1.74 \times 10^2$$

$$\phi = 8.91 \times 10^6$$

$$\phi = 8,910 \text{ K.L.}$$

ROTOR HUB AIR GAP

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CURVE XIII

WHALLIDY

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Rotor - D.E. Housing Air Gap

The area of the Rotor - D.E. Housing Gap is:

$$A = \pi (r_1^2 - r_2^2) \quad \text{where } r_1 = 14.2$$

$$r_2 = 11.5$$

$$A = \pi (14.2^2 - 11.5^2)$$

$$A = 215 \text{ in.}^2$$

$$\beta = \frac{3.2 \times \text{A.T.}}{\delta}$$

$$\text{where } \delta = .500$$

$$\text{A.T.} = 1 \times 10^4$$

$$\beta = \frac{3.2 \times 1 \times 10^4}{5 \times 10^{-1}}$$

$$\beta = 6.4 \times 10^4$$

$$\phi = \beta \times A$$

$$= 6.4 \times 10^4 \times 2.15 \times 10^2$$

$$\phi = 13.77 \times 10^6 \text{ lines}$$

$$\phi = 13,770 \text{ K.L. for } 5000 \text{ A.T./POLE}$$

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CURVE XIV
WHALLIDY
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ROTOR - D.E. HOUSING AIR GAP

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D. E. HOUSING

Fig N indicates how the D.E. Housing was designed. The envelope for 140 in.² area, was drawn first. Then the configuration of the housing was adjusted to stay just outside of the envelope.

The material will be U.S.S. Cor Ten steel. The magnetization curve for the D.E. Housing is shown on curve XV. The length of path is assumed to be 6.0 in.

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FIG N
WHALLIDY
0202-56-182

D.E. HOUSING CONFIGURATION

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MAGNETIZATION CURVE
D.E. HOUSING

B7.0 F 183
CURVE XII
WMA410Y
02.02-56-182

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SUBJECT 500 KVA Alternator BY W HallidyWORK ORDER 0202-56-182NO LOAD SATURATION CURVE

In order to find the excitation requirement for the total machine, we add:

1.	A.T./POLE	Stator & Air Gap	Curve <u>VIII B</u>
2.	A.T./POLE	"N" & "S" Poles	Curve <u>XII</u>
3.	A.T./POLE	Rotor Hub	Curve <u>XII</u>
4.	" "	Rotor - D.E. H's'g. Air Gap	Curve <u>XIV</u>
5.	" "	Rotor Hub Air Gap	Curve <u>XIII</u>
6.	" "	D.E. Housing	Curve <u>XV</u>

The total Flux in the "N" & "S" poles is equal to the air gap Flux for the stator plus the leakage Flux for the "N" & "S" poles, Curve XI.

The total Flux in 3, 4, 5 & 6 above is equal to the stator air gap flux plus the Hub leakage Flux, Curve XI.

We will plot the result as Generated Voltage vs. Excitation for a $\frac{25}{36}$ pitch machine & also for a $\frac{2}{3}$ pitch machine (Curves XVI & XVII).

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AIR GAP Φ (K.L.)	A.T./POLE Stator CURVE VIII B	Φ _L "N.E.S." (K.L.) CURVE XI	Φ _T "N.E.S." (K.L.)	A.T./POLE "N.E.S." CURVE XII	Φ _L HUB (K.L.) CURVE XI	Φ _T /POLE HUB (K.L.)	A.T./POLE HUB CURVE XII	A.T./POLE Rotor-DE. CURVE XIV	A.T./POLE HUB A.G. CURVE XIII	A.T./POLE D.E. MS9. CURVE XV	A.T./POLE TOTAL
1000	430										
2000	850	350	2350	38	650	2650	18	960	500	26	2392
3000	1270	520	3520	48	970	3970	21	1440	750	30	3559
4000	1680	690	4690	56	1290	5290	24	1930	1000	37	4727
4,500	1890	780	5280	62	1450	5950	26	2180	1130	40	5328
5,000	2100	870	5870	70	1620	6620	29	2400	1250	44	5893
5,500	2310	970	6470	80	1810	7310	32	2630	1370	48	6470
6,000	2520	1050	7050	95	1960	7960	37	2890	1500	52	7094
6,500	2730	1130	7630	115	2110	8610	40	3140	1630	57	7712
7,000	2950	1230	8230	138	2290	9290	44	3380	1760	62	8334
7,500	3200	1330	8830	166	2480	9980	48	3630	1890	80	9014
8,000	3480	1450	9450	207	2700	10,700	53	3880	2020	100	9740
8,500	3830	1580	10080	266	2950	11450	60	4160	2160	120	10596
9,000	4270	1770	10770	365	3300	12300	72	4470	2320	150	11647
9,500	4930	2030	11530	540	3780	13280	87	4830	2510	210	13104
9,750	5420	2250	12000	730	4190	13,940	110	5050	2620	275	14205
10,000	6120	2530	12,530	1050	4710	14,710	140	5350	2780	360	15800
10,250	7150	2960	13,210	1650	5510	15,760	192	5720	2980	580	18272
10,500	8860	3,660	14160	3300	6840	17,340	338	6280	3260	1390	23428

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Pitch Factor k_p $\frac{25}{36}$ Pitch

$$k_{p_m} = \sin \frac{m \cdot a}{2} \quad \text{where: } m = \text{harmonic}$$

$a = \text{angle, in electrical degrees, spanned by coil}$

$$a = 25 \times 5^\circ = 125^\circ$$

$$k_{p_1} = \sin \frac{1 \times 125^\circ}{2} = \sin 62.5^\circ = .887$$

$$k_{p_3} = \sin \frac{3 \times 125^\circ}{2} = \sin 187.5^\circ = -.131$$

$$k_{p_5} = \sin \frac{5 \times 125^\circ}{2} = \sin 312.5^\circ = -.737$$

$$k_{p_7} = \sin \frac{7 \times 125^\circ}{2} = \sin 77.5^\circ = .976$$

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Generated Voltage $\frac{25}{36}$ Pitch 60 cycle

$$E_G = \frac{P \phi Z N}{60 a \times 10^8} \times k_b \times k_p \times F_b$$

where: P = Number of Poles = 2

ϕ = Flux per Pole, (Lines)

Z = Total number of Inductors = 720

N = Speed = 3600 r.p.m.

a = Number of paths (or phases) = 3

k_b = Distribution Factor = .955

k_p = Pitch Factor = .887

F_b = Form Factor = 1.16

$$E_G = \phi \frac{P Z N}{60 a \times 10^8} \times k_b \times k_p \times F_b$$

$$= \phi \times \frac{2 \times 720 \times 3600}{60 \times 3 \times 10^8} \times .955 \times .887 \times 1.16$$

$$\underline{\underline{E_G = \phi \times 2.830 \times 10^{-4} \text{ VOLTS}}}$$

Per Unit Voltage:

$$E_G (\text{p.u.}) = \phi \times \frac{2.83 \times 10^{-4}}{2400}$$

$$\underline{\underline{E_{G(\text{p.u.})} = \phi \times 1.18 \times 10^{-7} \text{ per unit volts}}}$$

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SUBJECT 500 KVA Alternator BY W Halliday WORK ORDER 0202-56-182Generated Voltage $\frac{2}{3}$ Pitch 60 cycle

$$k_p = \text{Pitch Factor} = .866$$

$$E_G = \phi \times 2.83 \times 10^{-4} \times \frac{.866}{.887}$$

$$\underline{E_G = \phi \times 2.763 \times 10^{-4} \text{ VOLTS}}$$

$$E_{G(p.u.)} = \phi \times 1.18 \times 10^{-7} \times \frac{.866}{.887}$$

$$\underline{E_{G(p.u.)} = \phi \times 1.15 \times 10^{-7} \text{ per unit volts}}$$

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SUBJECT 500 KVA Alternator BY W HallidyWORK ORDER 0202-56-102Generated Voltage $\frac{25}{36}$ Pitch 50 cycle

$$E_G = \phi \times 2.83 \times 10^{-4} \times \frac{3000}{3600}$$

$$E_G = \phi \times 2.36 \times 10^{-4} \text{ VOLTS}$$

$$E_{G(p.u.)} = \phi \times 1.18 \times 10^{-7} \times \frac{3000}{3600}$$

$$E_{G(p.u.)} = \phi \times .983 \times 10^{-7} \text{ per unit volts (2400 V. = 1.0 p.u.)}$$

$$E_{G(p.u.)} = \phi \times .983 \times 10^{-7} \times \frac{6}{5}$$

$$E_{G(p.u.)} = \phi \times 1.18 \times 10^{-7} \text{ per unit volts (2000 V = 1.0 p.u.)}$$

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SUBJECT 500 KVA Alternator BY W Halliday WORK ORDER 0202-56-182

Generated Voltage $\frac{2}{3}$ pitch 50 cycle

$$E_G = \phi \times 2.763 \times 10^{-4} \times \frac{3000}{3600}$$

$$E_G = \phi \times 2.302 \times 10^{-4} \text{ VOLTS}$$

$$E_{G(p.u.)} = \phi \times 1.15 \times 10^{-7} \times \frac{3000}{3600}$$

$$E_{G(p.u.)} = \phi \times .96 \times 10^{-7} \text{ per unit volts (2400v. = 1.0 p.u.)}$$

$$E_{G(p.u.)} = \phi \times .96 \times 10^{-7} \times \frac{6}{5}$$

$$E_{G(p.u.)} = \phi \times 1.15 \times 10^{-7} \text{ per unit volts (2000v. = 1.0 p.u.)}$$

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SUBJECT 500 KVA Alternator BY W. HallidayWORK ORDER 0202-56-1822400 V. = 1.0 P.U.

ϕ (LINES)	A.T.	60 Cycle		50 cycle	
		$\frac{25}{36}$ Pitch	$\frac{2}{3}$ Pitch	$\frac{25}{36}$ Pitch	$\frac{2}{3}$ Pitch
Air Gap ϕ per Pole	(per pole)	$\phi \times 1.18 \times 10^{-7}$ Per Unit Volts	$\phi \times 1.15 \times 10^{-7}$ Per Unit Volts	$\phi \times .983 \times 10^{-7}$ P.U. Volts	$\phi \times .960 \times 10^{-7}$ P.U. Volts
2000 $\times 10^3$	2392	.236	.230	.1966	.192
3000	3559	.354	.345	.2949	.288
4000	4727	.472	.460	.3932	.384
4,500	5328	.531	.5175	.4424	.432
5000	5893	.590	.575	.4915	.480
5,500	6470	.649	.6325	.5407	.528
6000	7094	.708	.690	.5898	.576
6,500	7712	.767	.7475	.6390	.624
7000	8334	.826	.805	.6881	.672
7500	9014	.885	.8625	.7373	.720
8000	9740	.944	.920	.7864	.768
8500	10596	1.003	.9775	.8356	.816
9000	11,647	1.062	1.035	.8847	.864
9500	13,104	1.121	1.0925	.9339	.912
9750	14,205	1.1505	1.1213	.9584	.936
10000	15,800	1.180	1.150	.9830	.960
10250	18,272	1.2095	1.1788	1.0076	.984
10500	23,428	1.239	1.2075	1.0322	1.008

9705/183
CURVE TEL
WTHAL10Y
0202-56-102

NO LOAD SATURATION CURVE

50 CYCLE

2400 V. = 1.0 P.U.

96 of 153
CURVE 1
UNITS
0202-55-102

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SUBJECT 500 KVA Alternator BY W HallidyWORK ORDER 0202-56-1A2

Direct Axis Synchronous Reactance & Impedance

The direct axis synchronous reactance is considered to be composed of armature leakage reactance (X_L) and armature reaction reactance (X_{ad}). Calculation of the armature leakage reaction X_L is straightforward. Calculation of the armature reaction reactance X_{ad} must, obviously, consider the total air gap, active & inactive, & not just the active air gap between the pole face & the armature.

The biggest difference between this machine & "brush-type" machines is the fact that the inter-polar leakage flux can not be neglected. The equations used by the authors with whom the writer is familiar do not take into account that the slope of the air gap line will change markedly during short circuit operation.

On pages 103 to 111, we have calculated X_L & X_{ad} using equations that have been found to be quite accurate on conventional machines. In calculating X_{ad} , we have used the total effective air gap.

Shown below are the calculated values of X_d for a $2/3$ pitch machine

1. Considering total effective air gap = .605 in.

$$X_d = .934$$

2. Considering only the effective active air gap = .230 in.

$$X_d = 2.2363$$

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SUBJECT 500 KVA Alternator BY W Hallidy WORK ORDER 0202-56-182Direct Axis Synchronous Reactance & Impedance (cont.)

Since the resistance of the armature windings is negligibly small, we can consider that synchronous reactance & synchronous impedance are equal.

Again, in a conventional machine, interpolar leakage flux has no effect on the determination of synchronous impedance (Z_d). Thus the ampere turns of field mmf required during short circuit operation is the sum of the ampere turns required to generate the voltage required to overcome the armature's internal impedance drop plus the equivalent ampere turns per pole of opposing m.m.f. due to armature reaction.

It is felt that, in the case of our machine, we must add one more component of m.m.f.: the additional ampere turns required by the leakage flux crossing the two inactive air gaps

Calculating the synchronous impedance neglecting the leakage flux, we get:

$$Z_d = .898$$

Including the leakage flux, we get:

$$Z_d = 1.229 \quad (\text{pages } \quad \text{to } \quad)$$

The latter is considered the correct value for the synchronous impedance

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SUBJECT 500 KVA Alternator BY W HallidyWORK ORDER 0202-56-1B2Direct Axis Synchronous Reactance & Impedance (cont.)

Per the A.S.A. definition, (page), the direct axis synchronous impedance is the ratio of the field ampere turns for short circuit operation to the field ampere turns for 1.0 p.u. volts on the air gap line

Per the A.S.A. definition, (page), the unsaturated direct axis synchronous reactance is the ratio of the air gap line open circuit voltage that would be induced by the ampere turns for short circuit to the short circuit current.

For the $\frac{2}{3}$ pitch machine,

$$X_d = \frac{1.229 \text{ p.u. volts}}{1.0 \text{ p.u. amps}} = 1.229 \Omega \quad \text{unsaturated}$$

$$X_d = \frac{1.07 \text{ p.u. volts}}{1.0 \text{ p.u. amps}} = 1.07 \Omega \quad \text{saturated}$$

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Synchronous Reactance, Synchronous Impedance &
Short Circuit Ratio

Tabulating the results on the following
pages, we have:

	$\frac{25}{36}$ Pitch	$\frac{2}{3}$ Pitch
1. $X_D = X_L + X_{a.d.}$ (effective air gap = .230)	2.340	2.236
2. $X_D = X_L + X_{a.d.}$ (effective air gap = .605)	.913	.934
3. $X_D = \frac{P.U. \text{ volts}}{P.U. \text{ amps}}$ (Neglecting leakage Flux)	.939	.898
* 4. $X_D = \frac{P.U. \text{ volts}}{P.U. \text{ amps}}$ (including leakage Flux)	Unsat.: 1.288 Sat.: 1.111	Unsat.: 1.229 Sat.: 1.07
* 5. $Z_D = \frac{A.T.s}{A.T.a.g.}$ (including leakage Flux)	1.288	1.229
* 6. S.C. R. (including leakage Flux)	.817	.878

* Considered as the values to use

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SUBJECT 500 KVA Alternator BY W. HallidayWORK ORDER 0202-56-182

Armature Leakage Reactance $\frac{25}{36}$ Pitch 60 cycle

$$X_L = \frac{2.0 F l m N^2}{S_s \times 10^7} \left[K_s \left(\frac{d_1}{3w_s} + \frac{d_2}{w_s} \right) + \frac{0.3(3P-1) \cdot D \cdot S_s}{p^2 l} + \frac{0.266 D \cdot k_p^2 \cdot k_d^2}{S_s \cdot \delta \cdot k} + \frac{0.319 D \cdot k_p^2 \cdot k_d^2 \cdot S_s \cdot K_b}{p^2 \cdot \delta \cdot k} \right]$$

where: F = Frequency (c.p.s.) = 60 c.p.s.
 l = length of armature = 6.5 in.
 m = number of phases = 3
 N = number of series conductors per phase = 240
 S_s = number of stator slots = 72
 K_s = Factor = 0.77
 d_1 = 1.790 (Fig. D)
 d_2 = 0.230 (Fig. D)
 w_s = slot width = .437 in.
 P = per unit pitch = .695
 D = Armature diameter = 23.5 in. (Average Diam.)
 p = number of poles
 k_p = pitch factor = .887
 k_d = distribution factor = .955
 δ = air gap = .200
 k = Carter's coefficient = 1.150
 K_b = Belt Leakage Constant = .0016

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SUBJECT 500 KVA Alternator BY W HallidyWORK ORDER 0202-56-182

Armature Leakage Reactance $\frac{25}{36}$ Pitch 60 cycle

$$(1.) \quad K_s \left(\frac{d_1}{3w_s} + \frac{d_2}{w_s} \right) = 0.77 \times \left(\frac{1.790}{3 \times .437} + \frac{.230}{.437} \right) = 1.458$$

$$(2.) \quad \frac{0.3(3P-1) D \times S_s}{p^2 l} = \frac{0.3(3 \times .695 - 1) \times 23.5 \times 72}{4 \times 6.5} = 21.18$$

This is the end connection leakage reactance.

The end connections on the I.D. of the stator are surrounded by the shaft iron & the stator iron. The stator iron is heavily saturated, & the shaft iron has been picked for relatively low permeability. On the O.D. of the stator, the stator iron is moderately saturated, & the housing is aluminum.

At both the I.D. & the O.D., there is a considerable air gap between the end connections & the iron.

Considering the above, we will multiply the end connection leakage reactance by a factor of 1.15

$$\frac{X_e}{\left(\frac{2.0 \text{ FlmN}^2}{S_s \times 10^7} \right)} = 21.18 \times 1.15 = 24.36$$

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SUBJECT 500 KVA Alternator BY W Hallidy WORK ORDER 0202-56-182Armature Leakage Reactance $\frac{25}{36}$ Pitch 60 cycle

$$(3.) \frac{0.266 D k_p^2 k_d^2}{S_s \times \delta \times k} = \frac{0.266 \times 23.5 \times .887^2 \times .955^2}{72 \times .200 \times 1.150}$$

$$= .271$$

$$(4.) \frac{0.319 D k_p^2 k_d^2 S_s k_b}{p^2 \delta k} = \frac{0.319 \times 23.5 \times .887^2 \times .955^2 \times 72 \times .0016}{4 \times .2 \times 1.150}$$

$$= .674$$

$$(5.) \frac{2.0 F l m N^2}{S_s \times 10^9} = \frac{2.0 \times 60 \times 6.5 \times 3 \times 240^2}{72 \times 10^9} = .187$$

$$(6.) X_L = .187 \times (1.458 + 24.36 + .271 + .674) = 5.005$$

$$X_L = 5.0 \Omega$$

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Armature Leakage Reactance $\frac{25}{26}$ pitch 60 cycle

The per unit reactance drop:

$$\frac{X_L \times I}{E} = \frac{5.0 \times 69.3}{2400} = .1444 \text{ p.u. volts}$$

The per unit resistance drop

$$\frac{R \times I}{E} = \frac{.32 \times 69.3}{2400} = .00925 \text{ per unit volts}$$

$$\text{The per unit impedance drop} = \sqrt{.1444^2 + .00925^2}$$

$$= .1447 \text{ p.u. v.}$$

Note: A layout has indicated that the mean turn length of a coil is 88 in.

Total length of conductor per phase is:

$$120 \text{ Turns} \times \frac{88 \text{ in.}}{\text{turn}} \times \frac{1 \text{ Ft}}{12 \text{ in}} = 880 \text{ Ft. per phase}$$

The hot resistance at 75°C = .280 Ω per 1000 Ft.

$$\text{The a.c. resistance} = 1.3 \times \frac{.280 \Omega}{1000 \text{ Ft.}} \times 880 \text{ Ft.} = .32 \Omega$$

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Armature Leakage Reactance $\frac{25}{36}$ Pitch 50 cycle

$$\text{At 50 cycles, } X_L = 5.0 \Omega \times \frac{5}{6} = 4.167 \Omega$$

The per unit reactance drop:

$$\frac{X_L I}{E} = \frac{4.167 \times 69.3}{2000} = .1444 \text{ p.u. volts}$$

The per unit resistance drop

$$\frac{R \times I}{E} = \frac{.32 \times 69.3}{2000} = .00925 \times \frac{6}{5} = .0111 \text{ p.u. volts}$$

$$\text{P.U. Impedance Drop} = .1448 \text{ p.u. volts}$$

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SUBJECT 500 KVA Alternator BY W Halliday WORK ORDER 0202-56-182Armature Leakage Reactance $\frac{2}{3}$ pitch

The constants that are changed for a $\frac{2}{3}$ pitch winding are:

$$K_s = \text{Factor} = 0.75$$

$$P = \text{Per Unit Pitch} = 0.667$$

$$k_p = \text{Pitch Factor} = .866$$

$$K_b = \text{Belt Leakage Constant} = .0021$$

$$(1.) \quad K_s \left(\frac{d_1}{3w_s} + \frac{d_2}{w_s} \right) = 1.458 \times \frac{0.75}{0.77} = 1.420$$

$$(2.) \quad \frac{0.3 (3P-1) \times D \times S_s}{p^2 l} = 21.18 \times \frac{(3 \times 0.667 - 1)}{(3 \times 0.695 - 1)}$$

$$= 21.18 \times \frac{1.001}{1.085} = 19.54$$

$$= 19.54$$

$$\frac{X_e}{\left(\frac{2.0 \text{ FLm N}^2}{S_s \times 10^7} \right)} = 19.54 \times 1.15 = 22.47$$

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SUBJECT 500 KVA Alternator BY W. HallidayWORK ORDER 0202-56-182Armature Leakage Reactance $\frac{2}{3}$ Ditch

$$3. \frac{0.266 D k_p^2 + k_d^2}{S_s \times \delta \times k} = .271 \times \frac{.866^2}{.887^2} = .260$$

$$4. \frac{0.319 D k_p^2 + k_d^2 \cdot S_s \cdot K_b}{p^2 \delta k} = 0.674 \times \frac{.866^2}{.887^2} \times \frac{.0021}{.0016}$$

$$= 0.848$$

$$X_L = .187 \times (1.420 + 22.47 + .260 + .848) = 4.67 \Omega$$

$$\text{The per unit reactance drop} = .1444 \times \frac{4.67}{5.0} = .1350$$

$$\text{The per unit impedance drop} = \sqrt{.135^2 + .00925^2}$$

$$= .1353 \text{ p.u. volts}$$

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Direct Axis Synchronous Reactance X_d

* "The direct-axis synchronous reactance is the ratio of the fundamental component of reactive armature voltage, due to the fundamental direct-axis component of armature current, to this component of current under balanced steady-state conditions and at rated frequency"

* A.S.A. C42.10, 1957

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SYNCHRONOUS REACTANCE

METHOD I

 $\frac{2}{3}$ pitch

$$X_{ad} = X_m \times \frac{I}{E} \times A_d$$

$$X_m = \frac{6.38 \times F \times l_g \times m \times N^2 \times k_p^2 \times k_d^2 \times D}{p^2 \times \delta_{eff} \times 10^8}$$

$$A_d = K_a \times A_i \quad \text{where } K_a = \text{demagnetizing factor} = .835$$

$$A_i = \frac{B_i}{B_{a.g.}} = 1.16$$

$$X_{ad} = \frac{6.38 F l_g m N^2 k_p^2 k_d^2 D}{p^2 \delta_{eff} \times 10^8} \times \frac{I}{E} \times K_a \times A_i$$

where: F = Frequency = 60 c.p.s. l_g = Armature length = 6.5 in. m = number of phases = 3 N = series inductors per phase = 240 k_p = pitch factor = .866 k_d = distribution factor = .955 p = poles = 2 δ_{eff} = effective air gap length = .605 in. δ_{eff} is taken as $\frac{1}{2}$ of the total air gap length:

$$\delta_{eff} = \frac{1}{2} (2(\delta_{air\ gap} \times R) + \delta_{rotor\ hub} + \delta_{rotor-D.E. NSg.})$$

$$= \frac{1}{2} (2[.200 \times 1.15] + .250 + .500)$$

$$\delta_{eff} = .605 \text{ in}$$

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SYNCHRONOUS REACTANCE METHOD I (cont.) $\frac{2}{3}$ pitch

$$X_{ad} = \frac{6.38 \times 60 \times 6.5 \times 3 \times 240^2 \times .866^2 \times .955^2 \times 23.5}{2^2 \times .605 \times 10^8} \times \frac{69.3}{2400} \times .835 \times 1.16$$

$$X_{ad} = .7987$$

$$X_d = X_{ad} + X_L$$

$$= .7987 + .1353$$

$$X_d = .934$$

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SUBJECT 500 KVA AlternatorBY W. HallidyWORK ORDER 0202-56-182Synchronous Impedance:

* "The per unit direct-axis synchronous impedance equals the ratio of the field current at rated armature current on sustained symmetrical short circuit to the field current at normal open circuit voltage on the air-gap line."

* A.S.A. C42.10, 1957

The A.T. per pole of field excitation required on sustained symmetrical short circuit is:

$$A.T._S = A.T._{I_2} + A.T._{a.f.} + A.T._{\phi_L}$$

where:

$A.T._{I_2}$ = Ampere turns required to circulate through the entire magnetic circuit the flux required to generate the voltage required to overcome the armature impedance drop $I\bar{Z}_a$. This is found from the open circuit saturation curve

$A.T._{a.f.}$ = Equivalent field ampere turns per pole of armature reaction

$A.T._{\phi_L}$ = Ampere turns required to circulate the additional leakage flux due to $2 \times A.T._{a.f.}$ potential difference between the poles

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SUBJECT 500 KVA Alternator BY W HallidayWORK ORDER 0202-56-182

Armature Reaction $\frac{25}{36}$ Pitch

The equivalent field ampere turns per pole of armature reaction:

$$A.T_{a.f} = K_a \times \frac{0.45 m N I k_p k_d}{p}$$

where $m = \text{number of phases} = 3$
 $N = \text{number of series inductors per phase} = 240$
 $I = \text{armature phase current} = 69.3$
 $k_p = \text{pitch factor} = .887$
 $k_d = \text{distribution factor} = .955$
 $p = \text{number of poles}$
 $K_a = \text{Armature reaction factor}$

$$K_a = \frac{\pi F_d + \sin \pi F_d}{4 \sin \frac{\pi}{2} F_d} \quad \text{where: } F_d = \text{Flux distribution factor} = .722$$

$$K_a = \frac{\pi \times .722 + \sin(180 \times .722)}{4 \sin(90 \times .722)}$$

$$K_a = .835$$

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SUBJECT 500 KVA Alternator BY W HallidyWORK ORDER 0202-56-182Armature Reaction (cont.) $\frac{25}{36}$ Pitch

$$A.T_{a.f.} = K_a \times \frac{0.45 \cdot m \cdot N \cdot k_p \cdot k_d}{p} \times I$$

$$= .835 \times \frac{0.45 \times 3 \times 240 \times .887 \times .955}{2} \times I$$

$$A.T_{a.f.} = 114.58 \times I$$

$$A.T_{a.f.} = 114.58 \times 55.44 = 6352.3 @ .8 p.u. I$$

$$A.T_{a.f.} = 114.58 \times 69.3 = 7940.4 @ 1.0 p.u. I$$

$$A.T_{a.f.} = 114.58 \times 86.625 = 9925.5 @ 1.25 p.u. I$$

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SUBJECT 500 KVA Alternator BY W Halliday WORK ORDER 0202-56-182Armature Reaction $\frac{2}{3}$ Pitch

$$A.T_{a.f.} = 114.58 \times I \times \frac{.866}{.887} = 111.87 I$$

$$A.T_{a.f.} = 111.87 \times 55.44 = 6202.1 @ 0.8 p.u. I$$

$$A.T_{a.f.} = 111.87 \times 69.3 = 7752.6 @ 1.0 p.u. I$$

$$A.T_{a.f.} = 111.87 \times 86.625 = 9690.8 @ 1.25 p.u. I$$

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SUBJECT 500 KVA Alternator BY W. HallidayWORK ORDER 0202-56-182Synchronous Impedance (cont.) $\frac{25}{36}$ Pitch

$$1. \quad A.T._{I_2} = A.T. \text{ For } .145 \text{ p.u. volts} = 1,450 \text{ A.T. per pole}$$

$$2. \quad A.T._{a.f.} = 7,940 \text{ A.T. per pole}$$

$2 \times A.T._{a.f.} = 15,880 \text{ A.T. additional potential difference between poles}$

$\phi_{L_1} = 6,130 \text{ K.L. additional leakage Flux (Curve II)}$
in the rotor hub, drive end housing & two inactive air gaps

Additional A.T. For $\phi_{L_1} =$

25	For the rotor hub
35	For the drive end housing
1150	For the rotor hub air gap
<u>2225</u>	For the rotor-D.E. H's, air gap
3,435	

$\phi_{L_2} = 3,260 \text{ K.L. additional leakage Flux in the rotor}$
"N" & "S" poles

Additional A.T. For $\phi_{L_2} = 15 \text{ a.t. For the rotor poles}$

$$3. \quad A.T._{\phi_L} = 3,450 \text{ a.t. per pole}$$

$$A.T._S = 1,450 + 7,940 + 3,450$$

$$A.T._S = 12,840 \text{ a.t. per pole}$$

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SUBJECT 500 KVA Alternator BY W Hallidy WORK ORDER 0202-56-182

Synchronous Impedance (cont.) $\frac{25}{36}$ Pitch

The direct-axis synchronous impedance:

$$Z_d = \frac{12,840}{10,000} = 1.284$$

The Short Circuit Ratio:

$$SCR = \frac{10,500}{12,840} = .817$$

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SUBJECT 500 KVA Alternator BY W HallidyWORK ORDER 0202-56-182Synchronous Impedance $\frac{2}{3}$ pitch

$$A.T._s = A.T._{I_2} + A.T._{a.f.} + A.T._{\phi_2}$$

$$A.T._{I_2} \text{ For } .135 \text{ p.u. volts} = 1,400 \text{ a.t. per pole}$$

$$A.T._{a.f.} = 7750 \text{ a.t. per pole}$$

$$2 \times A.T._{a.f.} = 15,500 \text{ a.t.}$$

$$\phi_{L1} = 6000 \text{ K.L.}$$

$$\phi_{L2} = 3,200 \text{ K.L.}$$

$$\text{Additional A.T.} = 70 \text{ a.t. per pole for iron paths}$$

$$= 1125 \text{ a.t. for Hub air gap}$$

$$= 2180 \text{ a.t. for Rotor-D.F. Hsg Gap}$$

$$3,375$$

$$A.T._{\phi_2} = 3,375 \text{ a.t. per pole}$$

$$A.T._s = 1,400 + 7,750 + 3,375$$

$$A.T._s = 12,525$$

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Direct Axis Synchronous Impedance $\frac{2}{3}$ Pitch (cont.)

$$Z_d = \frac{12,525}{10,200} = 1.229$$

$$SCR = \frac{11,000}{12,525} = .878$$

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Quadrature Axis Synchronous Reactance X_q $\frac{2}{3}$ Pitch

$$1. \quad X_q = X_L + X_{AQ}$$

$$2. \quad X_{AQ} = X_{AD} \times \frac{A_{q1}}{A_{d1}}$$

$$3. \quad A_{q1} = \frac{4\psi + 1}{5} - \frac{\sin \psi \pi}{\pi}$$

where: ψ = per unit polar
embrace
= .722

$$A_{q1} = \frac{4 \times .722 + 1}{5} - \frac{\sin(.722 \times \pi)}{\pi}$$

$$A_{q1} = .537$$

$$4. \quad A_{d1} = .835 \times 1.16 = .968$$

$$5. \quad \frac{A_{q1}}{A_{d1}} = \frac{.537}{.968} = .555$$

6. From (1) & (2) above:

$$X_q = X_L + X_{AD} \times \frac{A_{q1}}{A_{d1}}$$

Since $X_{AD} = X_D - X_L$

$$7. \quad X_q = X_L + (X_D - X_L) \frac{A_{q1}}{A_{d1}}$$

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Quadrature Axis Synchronous Reactance X_q (cont.) $\frac{2}{3}$ Pitch

$$\begin{aligned}
 8. \quad X_q &= X_L + (X_D - X_L) \frac{A_{q1}}{A_{D1}} \\
 &= .135 + (X_D - .135) .555 \\
 &= .135 + .555 X_D - .075 \\
 &= .060 + .555 X_D
 \end{aligned}$$

The quadrature axis involves the permeances encountered in a path from the armature through the active air gap to the pole tip, across the pole to the opposite pole tip, & then through the active air gap to the armature. Thus, the quadrature axis calculations should consider this machine as a conventional machine with a .230 effective air gap. Therefore, we will use the X_D calculated for a machine with an effective air gap of .230 in.

$$X_D = 2.24$$

$$\begin{aligned}
 X_q &= .060 + .555 X_D \\
 &= .060 + 1.24
 \end{aligned}$$

$$X_q = 1.30$$

Transient Reactance - Direct Axis X_d'

$$X_{du}' = X_L + X_{ad} - \frac{X_{ad}^2}{X_F + X_{ad}} = \text{Unsaturated transient reactance}$$

where: X_L = Armature leakage reactance
 X_{ad} = Reactance of armature reaction
 X_F = Field leakage reactance

We have said that we consider $X_d = Z_d = X_L + X_{ad} + X_F$

$$X_d = 1.229 = X_L + X_{ad} + X_F = .135 + .799 + X_F$$

From which $X_F = .295$

2. Then:

$$X_{du}' = .135 + .799 - \frac{.799^2}{.295 + .799}$$

$$= .934 - .583$$

$$X_{du}' = .351$$

3. We will consider the saturated transient reactance equals $.8 X_{du}'$

$$X_d' = .8 \times .351$$

$$X_d' = .281$$

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SUBJECT 500 KVA Alternator BY W HallidyWORK ORDER 0202-J6-182Subtransient Reactance - Direct Axis X_d''

The construction of the rotor of the subject machine is more nearly like that of a solid-cylindrical-rotor machine than it is like a salient pole machine in that there are no damper windings, but the polar material is such that there will be large damping currents during subtransient conditions, i.e., the polar material forms a good damper winding.

Since $X_d'' = X_L + X_{Dd}$, where X_{Dd} = Damper winding reactance

We say: $X_d'' = .135 + X_{Dd}$.

Instead of attempting to calculate X_{Dd} , we will consider a solid-cylindrical rotor machine whose reactances are very nearly the same as those in our machine. This is safe to do since the two large inactive gaps in our machine should not enter into a consideration of subtransient conditions.

From this comparison, we get:

$$X_d'' = .174$$

*Transient & Subtransient Reactances -
Quadrature Axis X_q' & X_q''*

In a solid-cylindrical-rotor machine, X_q' more nearly equals X_q'' instead of being equal to X_q . The reason is that the interpolar iron forms a good path for induced currents in the quadrature axis, whereas there are no windings or circuits in the quadrature axis of a typical salient pole machine.

For this reason, we will consider X_q'' as approximately equal to X_d'' , & X_q' lying between X_q & X_d'

$$\begin{aligned} \text{So: } X_q' &= \frac{1}{2} (X_q + X_d') \\ &= \frac{1}{2} (1.30 + .281) \end{aligned}$$

$$X_q' = .74$$

$$X_q'' \approx X_d''$$

$$X_q'' = .18$$

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Negative Sequence Reactance X_2

The negative sequence reactance is the average of X_d'' & X_q''

$$\begin{aligned} X_2 &= \frac{1}{2} (X_d'' + X_q'') \\ &= \frac{1}{2} (.174 + .180) \end{aligned}$$

$$X_2 = .177$$

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Zero Sequence Reactance X_0

For a $\frac{2}{3}$ pitch machine, we can use:

$$X_0 = .4 \times X_L$$

$$= .4 \times .135$$

$$X_0 = .054$$

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SUBJECT 500 KVA Alternator BY W HallidayWORK ORDER 0202-56-182Armature Time Constant T_a

$$T_a = \frac{1}{2\pi f} \times \frac{X_2}{r_a}$$

where: f = Frequency = 60 c.p.s.
 X_2 = Negative sequence
 reactance = .177 p.u.
 r_a = armature resistance
 = .0093 p.u.

$$T_a = \frac{1}{2\pi \times 60} \times \frac{.177}{.0093}$$

$$T_a = .052 \text{ sec.}$$

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SUBJECT 500 KVA Alternator BY W HallidyWORK ORDER 0202-56-182Open Circuit Time Constant (T_{do}')

1. $T_{do}' = \frac{L_F}{R_F}$ where: L_F = Self Inductance of Field
 R_F = Resistance of Field coil

2. $L_F = \frac{N \Phi}{I} \times 10^{-8}$ where: N = No. of Turns
 Φ = Total Flux through center of coil (lines)
 I = Current in coil

3. $L_F = \frac{1,681 \times 12.3 \times 10^6}{\frac{22,000 NI (TOTAL)}{1681 N}} = \frac{1681 \times 12.3 \times 10^6}{13.09} \times 10^{-8}$

 $L_F = 15.8$ Henries

4. @ $20^\circ C$ $T_{do}' = \frac{15.8}{8.08} = 1.96$ sec.

@ $75^\circ C$ $T_{do}' = \frac{15.8}{9.83} = 1.61$ sec.

@ $121^\circ C$ $T_{do}' = \frac{15.8}{11.29} = 1.40$ sec.

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SUBJECT 500 KVA Alternator BY W. HallidyWORK ORDER 0202-56-182Transient Time Constant T_d'

$$T_d' = \frac{x_d'}{x_d} \times T_{d0}$$

$$T_d' = \frac{.281}{1.23} \times 1.61$$

$$T_d' = .368$$

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SUBJECT 500 KVA Alternator BY W. HallidayWORK ORDER 0202-56-182Displacement Angle δ

$$1. \quad \delta = \sin^{-1} \frac{X_g \cos \theta}{\sqrt{1 + X_g^2 + 2X_g \sin \theta}}$$

$$= \sin^{-1} \frac{1.30 \times 0.8}{\sqrt{1 + 1.30^2 + 2 \times 1.30 \times 0.6}}$$

$$= \sin^{-1} \frac{1.04}{2.062}$$

$$= \sin^{-1} .504$$

$$\delta = 30.25^\circ$$

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SUBJECT 500 KVA Alternator BY W HallidyWORK ORDER 0202-56-182Synchronizing Power P_r

$$1. \quad P_r = \frac{57.3}{\delta} \times \text{Shaft K.W.}$$

$$\text{Shaft K.W.} = \frac{\text{Output K.W.}}{\text{EFF}}$$

$$= \frac{400 \text{ K.W.}}{.946}$$

$$\text{Shaft K.W.} = 423 \text{ K.W.}$$

$$2. \quad P_r = \frac{57.3 \times 423}{30.25}$$

$$P_r = 800 \text{ K.W.}$$

OPEN & SHORT CIRCUIT CHARACTERISTICS
25/36 PITCH

CURVE ID
WHAAL/DY

13306183

CURVE XX
WMAALIDY

137 24 15

VECTOR CONSTRUCTION 25/36 PITCH

VECTOR CONSTRUCTION $2/3$ PITCH

CURVE **XI** B
WM/ALLIDY
0202-56-1/82

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Field Coil Design

$$1. \text{ #11 Square with Heavy Epoxy: } .0962 \times .0962 \text{ (Max.)}$$

$$2. \frac{4.0 \text{ in}}{.0962 \text{ in.}} = 41.58 \text{ Turns per layer} \\ = 41.58 \text{ layers}$$

$$3. 41 \times 41 = 1681 \text{ Turns}$$

$$4. 1681 \text{ Turns} \times 1.5 \frac{\text{Ft.}}{\text{Turn}} \times \pi = 4.71 \frac{\text{Ft.}}{\text{T}} \times 1681 \text{ T} \\ = 7.922 \text{ M Ft.}$$

$$5. 7.922 \text{ M Ft.} \times 1.02 \frac{\Omega}{\text{M Ft.}} @ 20^\circ\text{C} = 8.08 \Omega @ 20^\circ\text{C}$$

$$6. \frac{45,000 \text{ NI}}{1681 \text{ T}} = 26.77 \text{ amps}$$

$$7. 26.77 \text{ amps} \times 8.08 \Omega = 216.3 \text{ V.} @ 20^\circ\text{C}$$

$$8. (26.77 \text{ amps})^2 \times 8.08 \Omega = 5.79 \text{ K.W.} @ 20^\circ\text{C}$$

$$9. 1.216 \times 8.08 \Omega = 9.825 \Omega @ 75^\circ\text{C}$$

$$10. 26.77 \text{ amps} \times 9.825 \Omega = 263.0 \text{ V.} @ 75^\circ\text{C}$$

$$11. (26.77 \text{ amps})^2 \times 9.825 \Omega = 7.041 \text{ K.W.} @ 75^\circ\text{C}$$

$$12. 1.397 \times 8.08 \Omega = 11.29 \Omega @ 121^\circ\text{C}$$

$$13. 11.29 \Omega \times 26.77 \text{ amps} = 302.2 \text{ V.} @ 121^\circ\text{C}$$

$$14. (26.77 \text{ amps})^2 \times 11.29 \Omega = 8.089 \text{ K.W.} @ 121^\circ\text{C}$$

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SUBJECT 500 KVA Alternator BY W HallidyWORK ORDER 0202-56-182*Losses:**A. Armature I^2R*

1. Mean turn length per coil = 88 in. = 7.33 Ft.
2. Five Turns per coil = 36.65 Ft. per coil
3. 120 Turns per phase = 880 Ft. per phase

$R @ 75^\circ C = .280 \Omega \text{ per M Ft.}$

$$R_{\text{per phase}} = \frac{.280 \Omega}{\text{M Ft.}} \times .88 \text{ M Ft.} = .2464 \Omega / \text{phase}$$

B. Stray Load Losses

Stray Load Losses are taken as 30% of the armature I^2R losses

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SUBJECT 500 KVA Alternator BY W HallidayWORK ORDER 0202-56-1B2

Losses

Armature I^2R & Stray Load Losses

Load	Armature I^2R (watts)		Stray Load (watts)	
	0.8 p.f.	1.0 p.f.	0.8 p.f.	1.0 p.f.
0	0	0		
1/4	223	142	267	267
2/4	891	568	534	534
3/4	2008	1280	801	801
4/4	3560	2280	1068	1068
5/4	5,560	3560	1335	1335

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Field Coil Losses

I 0.8 p.f. ($\frac{3}{4}$ load = 400 K.W.)

Load	A.T./pole	I_F	I_F^2	$I_F^2 R_F$ 20°C	$I_F^2 R_F$ 75°C	$I_F^2 R_F$ 121°C
0	10,200	12.2	148.8	1202.3	1462.7	1679.9
$\frac{1}{4}$	13,060	15.5	240.3	1941.6	2362.1	2713.0
$\frac{2}{4}$	16,100	19.2	368.6	2978.3	3623.3	4161.5
$\frac{3}{4}$	19,250	22.9	524.4	4237.1	5154.8	5920.4
$\frac{4}{4}$	22,700	26.9	723.6	5846.7	7113.0	8169.4
$\frac{5}{4}$	26,700	31.7	1004.9	8119.9	9878.0	11345.0

II 1.0 p.f.

0	10,200	12.2	148.8	1202.	1463	1680
$\frac{1}{4}$	10,750	12.8	163.8	1323.	1609	1849
$\frac{2}{4}$	11,650	13.9	193.2	1562	1898	2162
$\frac{3}{4}$	13,150	15.6	243.4	1968	2392	2745
$\frac{4}{4}$	15,000	17.8	316.8	2562	3118	3578
$\frac{5}{4}$	16,800	20.0	400.0	3235	3930	4518
$\frac{6}{4}$	18,700	22.2	492.8	3980	4845	5558

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SUBJECT 500 KVA Alternator BY W. HallidayWORK ORDER 0202-56-182LossesArmature Core Losses at $E_g = 1.1$ p.u. voltsA. Teeth

1. Average tooth density $B_T = 115$ K.L./in²

From Armco data on core loss at right angles to direction of orientation of Armco M-6:

2. Core loss @ $B = 115$ K.L./in² = 2.8 watts/pound
3. Weight of teeth = 155 lbs.
4. Core loss in teeth = 434 watts

B. Yoke

1. Average Yoke density = 117.5 K.L./in²

From Armco data on core loss in direction of orientation:

2. Core loss = 1.25 watts/pound @ $B = 117.5$ K.L./in²
3. Weight of Yoke = 904 lbs
4. Core loss in Yoke = 1,130 watts

C Armature core loss = 434 + 1,130 watts
= 1,564 watts

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SUBJECT 500 KVA Alternator BY W HallidyWORK ORDER 0202-56-1B2*Pole Face Losses:*

A plot was made of the flux distribution in the air gap using a scale of 1 inch = .1 inch. The results are shown in Fig. O & Fig. P.

Electrically conductive paper, a voltage dividing network & a microammeter were used. The results are considered to be quite accurate.

Using the empirical relationships cited by Langsdorf & by Kuhlmann, we have taken the pole face losses as 3.0 K.W. Total for an air gap of .200 in, or an air gap to slot opening ratio of 1:2.18

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FIG D
W Halliday
0202-56-182

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FIG. P
Wmallydy
0202-56-102

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Bearing Losses

as calculated by:

W.C. Dunn
Sr. Engineer
P.E. Div.
A.G.N.

Ref: 1. Machine Design 2-9-56 Pp 119-128
2. Marks Handbook Sect. 8

I check on Laminar Flow Region.

$$N_T = \frac{V \times 77.4 \times 10^3}{(m)^{1.5} \times D^2}$$

where: V = Viscosity in centistokes
= 12.56

$$m = 1000 \times \frac{\text{diametrical clearance}}{\text{bearing diameter}}$$

 D = Bearing diameter

$$N_T = \frac{12.56 \times 77.4 \times 10^3}{\left(1000 \times \frac{.006}{4.0}\right)^{1.5} \times 4^2}$$

$$N_T = 33,100 \text{ r.p.m.}$$

Therefore, with 4" diam. bearing @ 3600 r.p.m.,
oil flow is laminar

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Bearing Losses (cont.)

$$II \quad A = \frac{132}{\eta} (1000 m)^2 \cdot \frac{P_{avg.}}{z N}$$

$$\text{where: } m = \frac{\text{diametrical clearance}}{\text{Bearing Diameter}} = .0015$$

 $P_{avg.}$ = Average bearing pressure z = Oil viscosity = 10.2 centipoise @ 165°F

$$N = \text{RPM} = 3600$$

$$\text{From Fig 3 ref (1)} \quad \eta = 0.48$$

$$A = \frac{132}{0.48} (1.5)^2 \cdot \frac{31.2}{10.2 \times 3600}$$

$$A = 0.527, \text{ From which } \epsilon = .075 \text{ From Fig. 4, ref (1)}$$

$$\text{For } \epsilon = .075, \eta = .36 \neq A = .722, \text{ From which } \epsilon = 0.1$$

$$\text{For } \epsilon = 0.1, \eta = .39 \neq A = .667, \text{ From which } \epsilon = .077$$

$$\text{Let } \epsilon = 0.076$$

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Bearing Losses (cont.)

$$\text{III} \quad F = K_f \mu N r \frac{l}{m} \quad \text{where } K_f = 0.6 \quad \text{Ref. (2)}$$

$$F = \frac{0.6 \times 10.2 \times 1.45 \times 10^{-2} \times 3600 \times 2 \times 4}{.0015}$$

$$F = 17 \text{ lb.}$$

$$\text{IV} \quad \text{Friction H.P.} = \frac{FV}{33,000} = \frac{17 \times 3600 \pi \times 4}{33,000 \times 12}$$

$$\text{H.P.} = 1.94 \quad \text{for } 4" \text{ bearing}$$

V Similarly, Mr. Dunn calculated .77 h.p. loss in the 3" bearing

$$\text{VI} \quad \text{Total bearing loss} = 1.94 \text{ h.p.} + .77 \text{ h.p.}$$

$$\text{Bearing loss} = 2.71 \text{ h.p.} \times .746 \frac{\text{K.W.}}{\text{h.p.}}$$

$$= 2.02 \text{ K.W.}$$

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SUBJECT 500 KVA Alternator BY W. HallidyWORK ORDER 0202-56-182

Windage Losses as calculated by: W. C. Dunn
Sr. Engineer
P.E. Div.
A.G.N.

Reference: (1) Jet Propulsion & Gas Turbine - Zucrow
Pg 420

(2) Fluid Mechanics - Binder

I Disc Friction Ref. (1)

$$h_{Pr} = K_1 \left(\frac{\mu}{100} \right)^3 \frac{D^2}{v}$$

where: $K_1 = 0.0607$

$D = 2.5 \text{ Ft.}$

$\mu = \frac{3600}{60} \times \pi D = 470 \text{ F.p.s.}$

$v = \frac{1}{.07274} \times \frac{860}{528} = 22.4 \frac{\text{Ft}^3}{\text{lb.}}$

$$h_{Pr} = 0.0607 \left(\frac{470}{100} \right)^3 \times \frac{(2.5)^2}{22.4}$$

$$h_{Pr} = 1.76 \text{ h.p.}$$

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Windage Losses (cont.)

II Edge Friction Ref (2)

$$Re = \frac{\rho V L}{\mu} \quad \text{where} \quad \rho = .07274 \times \frac{528}{860} = .0447$$

$$V = 470 \text{ F.P.S.}$$

$$L = \pi D = 7.85 \text{ Ft.}$$

$$\mu = .022 \times .000672 \frac{\#}{\text{Sec. Ft.}}$$

$$Re = \frac{.0447 \times 470 \times 7.85}{.022 \times .000672} = 1.115 \times 10^7$$

From which $C_f = .003$

$$\text{Drag Force} = C_f \frac{\rho V^2}{2} S \quad \rho = \frac{.0447}{9} \frac{\text{slug}}{\text{ft}^3}$$

$$S = \pi D L = 7.85$$

$$\text{Drag Force} = .003 \times \frac{.0447}{32.2} \times \frac{(470)^2}{2} \times 7.85$$

$$= 3.63 \#$$

$$\text{H.P. drag} = \frac{3.63 \# \times 15 \text{ in.} \times 3600 \text{ r.p.m.}}{63,000}$$

$$= 3.12 \text{ h.p.}$$

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Windage Losses (cont.)

III Total Loss = $3.12 \text{ h.p.} + 1.76 \text{ h.p.}$
 $= 4.88 \text{ h.p.}$
 $= 3.64 \text{ K.W.}$

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SUBJECT 500 KVA AlternatorBY Wm HallidayWORK ORDER 0202-56-102

Summation of losses

0.0 P.F.60 cycle 75°C

	LOAD					
	0	1/4	2/4	3/4	4/4	5/4
A. Armature I^2R (K.W.)	0	.223	.891	2.008	3.560	5.560
B Stray Load	0	.267	.534	.801	1.068	1.335
C Field I^2R (variable)	0	.899	2.460	3.692	5.650	8.915
C' Field I^2R (Fixed)	1.463	1.463	1.463	1.463	1.463	1.463
D Regulator (variable)	0	.100	.200	.300	.400	.500
D' Regulator (Fixed)	.600	.600	.600	.600	.600	.600
E Armature Core	1.565	1.565	1.565	1.565	1.565	1.565
F Pole Face	3.000	3.000	3.000	3.000	3.000	3.000
G Bearing	2.020	2.020	2.020	2.020	2.020	2.020
H. Windage	3.640	3.640	3.640	3.640	3.640	3.640
Variable Losses (K.W.)	0	1.49	3.79	6.80	10.68	15.81
Fixed Losses (K.W.)	12.29	12.29	12.29	12.29	12.29	12.29
Total Losses (K.W.)	12.29	13.78	16.08	19.09	22.97	28.10
Output (K.W.)	0	100	200	300	400	500
Input (K.W.)	12.29	113.78	216.08	319.09	422.97	528.10
Efficiency %	0	87.9	92.6	94.0	94.6	94.7

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SUBJECT 500 KVA Alternator BY W Hallidy WORK ORDER 0202-56-182Axial Forces on Rotor

The axial gaps in this machine result in the production of axial forces due to the magnetic pull. The Air Gaps were arranged on the assumption that we wanted 0 resultant force at 1/2 load, 0.8 P.F.

On the following three pages, the components of force are calculated. If we assign a minus sign to forces acting toward the Motor End Housing, & a plus sign to forces acting toward the Drive End Housing, our calculations show:

1. No Load

$$F_R = +8,500 + 5,100 - 12,100 = +1,500 \text{ lbs.}$$

2. Full Load 500 KVA 0.8 p.f.

$$F_R = 12,100 + 7,250 - 14,470 = +4,880 \text{ lbs}$$

The actual forces to be measured in tests will probably differ from the calculated values by enough to even possibly change the signs from plus to minus on F_R . This is because we have tried to be pessimistic on the calculation of total leakage flux. Also, in the case of the Rotor - D.E. Housing Air Gap, the area value used is too small by the leakage factor, resulting in higher forces calculated than would be calculated with a true flux path area.

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Axial Forces on Rotor (cont.)

Therefore, we will use the results of our calculations merely as a guide to the relative values of the force components. During the test phase, we will measure the necessary parameters (leakage flux, force components, etc.) & adjust the areas, angles, etc. so that $F_R = 0$ at $\frac{1}{2}$ load.

Adjusting the effective area of the Rotor-D.E. Housing gap is expected to be an easy matter, since the design was purposely made this way.

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Axial Forces on Rotor

I Stator - Rotor Air Gap Pull

$$A. F = \frac{\Phi_T^2}{A} \times \frac{1}{7.213 \times 10^7} = \frac{\Phi_T^2}{A} \times 1.39 \times 10^{-8}$$

$$B. \text{ At "no load" } \quad \Phi_T = 17.38 \times 10^6 \text{ lines}$$

$$A = .722 \times 480 = 346.6 \text{ in}^2$$

$$F = \frac{(1.74 \times 10^7)^2}{3.47 \times 10^2} \times 1.39 \times 10^{-8}$$

$$F = 12,100 \text{ lbs. Total pull}$$

C At 500 K.V.A., 0.8 p.f.

$$\Phi_T = 1.90 \times 10^7 \text{ lines}$$

$$F = \frac{(1.90 \times 10^7)^2}{3.47 \times 10^2} \times 1.39 \times 10^{-8}$$

$$F = 14,470 \text{ lbs.}$$

D At 20 p.u. short circuit

$$\Phi_T = 7.04 \times 10^6 \text{ lines}$$

$$F = \frac{(7.04 \times 10^6)^2}{3.47 \times 10^2} \times 1.39 \times 10^{-8}$$

$$F = 1,986 \text{ lbs.}$$

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Axial Forces on Rotor

II Rotor - D.E. Housing Air Gap Pull

A. "No Load"

$$\Phi_T = 1.15 \times 10^7 \text{ lines}$$

$$A = 215 \text{ in}^2$$

$$F = \frac{(1.15 \times 10^7)^2}{2.15 \times 10^2} \times 1.39 \times 10^{-8}$$

$$F = 8,500 \text{ lbs}$$

B 500 KVA, 0.8 p.f.

$$\Phi_T = 1.37 \times 10^7$$

$$F = \frac{(1.37 \times 10^7)^2}{2.15 \times 10^2} \times 1.39 \times 10^{-8}$$

$$F = 12,100 \text{ lbs}$$

C At 3.0 p.u. short circuit $\Phi_T = 2.5 \times 10^7 \text{ lines}$

$$F = \frac{(2.5 \times 10^7)^2}{2.15 \times 10^2} \times 1.39 \times 10^{-8}$$

$$F = 40,400 \text{ # pull}$$

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Axial Forces on Rotor

III Rotor Hub Air Gap

A No Load

$$\phi_T = 1.15 \times 10^7 \text{ lines}$$

$$A = 1.80 \times 10^2 \text{ in}^2$$

$$F = \frac{(1.15 \times 10^7)^2}{1.8 \times 10^2} \times 1.39 \times 10^{-8} \times \cos 60^\circ$$

$$F = 5,100 \text{ lbs}$$

B 500 KVA, 0.8 p.f. $\phi_T = 1.37 \times 10^7$

$$F = \frac{(1.37 \times 10^7)^2}{1.8 \times 10^2} \times 1.39 \times 10^{-8} \times 0.5$$

$$F = 7,250 \#$$

C. 3.0 p.u. short Circuit $\phi_T = 2.5 \times 10^7 \text{ lines}$

$$F = \frac{(2.5 \times 10^7)^2}{1.8 \times 10^2} \times 1.39 \times 10^{-8} \times 0.5$$

$$F = 21,200 \#$$

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Weight - Armature Core

A. Yoke

Volume of Yoke equals:

(1.) (Volume of cylinder with $r = 15$ in. & $h = 9.35$ in.)

(2.) - (Volume of Frustum of cone with $r_1 = 15$ in., $r_2 = 8.5$ in &
 $h = 6.0$ in.)

(3.) - (Volume of cylinder with $r = 8.5$ in. & $h = 3.35$ in.)

$$(1.) \text{ Vol.} = \pi r^2 h = \pi \times 15^2 \times 9.35 = \pi \times 225 \times 9.35 = 6609 \text{ in.}^3$$

$$\text{Vol.} = 6,609 \text{ in.}^3$$

$$(2.) \text{ Vol.} = \pi \times \frac{h}{3} (r_1^2 + r_1 r_2 + r_2^2) = \pi \times \frac{6.0}{3} (15^2 + 15 \times 8.5 + 8.5^2)$$

$$= \pi \times 2.0 (225 + 97.5 + 72.25) = \pi \times 2 \times 394.75$$

$$\text{Vol.} = 2480.3 \text{ in.}^3$$

$$(3.) \text{ Vol.} = \pi r^2 h = \pi \times 8.5^2 \times 3.35 = \pi \times 72.25 \times 3.35$$

$$\text{Vol.} = 760.38 \text{ in.}^3$$

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Weight - Armature Core (cont.)

A. Yoke (cont.)

$$\begin{array}{r} (2.) + (3.) = 2480.3 \\ + 760.4 \\ \hline 3240.7 \text{ in.}^3 \end{array}$$

$$\begin{array}{r} (1.) - [(2.) + (3.)] \quad 6,609.0 \\ - 3240.7 \\ \hline 3368.3 \text{ in.}^3 \end{array}$$

$$(4.) \text{ Volume of Yoke} = 3368.3 \text{ in.}^3$$

$$(5.) \text{ Volume of iron in yoke} = \text{Stacking Factor} \times \text{Volume of Yoke}$$

$$= .97 \times 3368.3 \text{ in.}^3$$

$$\text{Volume of iron in yoke} = 3267.2 \text{ in.}^3$$

$$(6.) \text{ Weight of yoke} = \text{Density} \times \text{Volume of iron.}$$

$$\text{Density of Armco M-6} =$$

$$7.655 \text{ grams/cm.}^3 \times .03613 = .2766 \text{ lbs./in.}^3$$

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Weight - Armature Core (cont.)

A. Yoke (cont.)

$$\begin{aligned} (6.) \text{ Weight of Yoke} &= .2766 \frac{\text{lbs.}}{\text{in.}^3} \times 3267 \text{ in.}^3 \\ &= 903.7 \text{ lbs.} \end{aligned}$$

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SUBJECT 500 KVA Alternator BY W Hallidy

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Weight - Armature Core (cont.)

B. Teeth

Volume of teeth equals:

(1.) (Volume of hollow cylinder with $r_1 = 15.0$ in,
 $r_2 = 8.5$ in. & $h = 2.10$ in.)

(2.) - (Volume of 72 slots 2.10 in. deep, .437 in. wide,
& 6.5 in. long)

$$(1.) \text{ Vol.} = \pi h (r_1^2 - r_2^2) = \pi \times 6.5 (15^2 - 8.5^2)$$

$$= \pi \times 6.5 \times (225 - 72.25) = \pi \times 2.1 \times 152.75$$

$$\text{Vol.} = 1007.5 \text{ in.}^3$$

$$(2.) \text{ Vol.} = 72 \times 2.1 \times .437 \times 6.5$$

$$\text{Vol.} = 429.48 \text{ in.}^3$$

$$(3.) \quad (1.) - (2.) \quad \begin{array}{r} 1007.5 \\ - 429.5 \\ \hline 578.0 \text{ in.}^3 \end{array}$$

$$\text{Vol. of teeth} = 578.0 \text{ in.}^3$$

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Weight - Armature Core (cont.)

B. Teeth (cont.)

(4.) Weight of teeth = Density × Stacking Factor × Volume of teeth

$$= .2766 \frac{\text{lbs}}{\text{in.}^3} \times .97 \times 578 \text{ in.}^3$$

$$= .2766 \frac{\text{lbs}}{\text{in.}^3} \times 560.67 \text{ in.}^3$$

Weight of teeth = 155.17 lbs.

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Volume of inner ring equals:

(1.) (Volume of hollow cylinder with $r_1 = 8.50$ in.,
 $r_2 = 8.24$ in. & $h = 5.45$ in.)(2.) - (Volume of 72 slots 2.10 in. deep, .437 wide
& .26 in. long)

$$(1.) \text{ Vol.} = \pi h (r_1^2 - r_2^2) = \pi \times 5.45 (8.50^2 - 8.24^2)$$

$$= \pi \times 5.45 (72.25 - 67.90) = \pi \times 5.45 \times 4.35$$

$$\text{Vol.} = 74.48 \text{ in.}^3$$

$$(2.) \text{ Vol.} = 72 \times 2.10 \times .437 \times .260$$

$$\text{Vol.} = 17.18 \text{ in.}^3$$

$$(3.) \quad (1.) - (2.) \quad \begin{array}{r} 74.48 \\ - 17.18 \\ \hline 57.3 \end{array}$$

$$\text{Vol. of inner ring} = 57.3 \text{ in.}^3$$

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Weight - Armature Core (cont.)

C. Inner Ring (cont.)

$$\begin{aligned} (4.) \text{ Weight of inner ring} &= \text{Density} \times \text{Volume} \\ &= .287 \frac{\text{lb}}{\text{in}^3} \times 57.3 \text{ in}^3 \end{aligned}$$

$$\text{Weight of inner ring} = 16.45 \text{ lb}$$

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Weight Armature Core (cont.)

D Outer Ring

Volume of outer ring equals:

- (1.) Volume of hollow cylinder with $r_1 = 15.25$ in.,
 $r_2 = 15.0$ in. & $h = 11.44$ in

minus

- (2.) Volume of 72 slots 2.10 in deep, .437 wide
& .25 long

$$(1.) Vol = \pi h (r_1^2 - r_2^2) = \pi \times 11.44 (232.56 - 225)$$

$$Vol. = 271.7 \text{ in.}^3$$

$$(2.) Vol. = 17.18 \text{ in.}^3$$

$$(3.) (1.) - (2.) = 271.7 - 17.2 \text{ in.}^3$$

$$Vol. \text{ of outer ring} = 254.5 \text{ in.}^3$$

$$(4.) \text{ Weight of outer ring} = 254.5 \text{ in.}^3 \times .287 \frac{\#}{\text{in.}^3}$$

$$\text{Weight} = 73.04 \#$$

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Weight - Armature Core

E. Bosses (8)

Volume of 1 boss equals (1.) - (2.) - (3.)

(1.) Volume of Solid 1.5 in. x 2.75 in. x 2.5 in.

$$\text{Vol.} = 10.31 \text{ in.}^3$$

(2.) Volume of Triangular solid 1.5 thick x 1.9 x 2.15

$$\text{Vol.} = 1.5 \times \frac{1}{2} (1.9 \times 2.15)$$

$$\text{Vol.} = 3.06 \text{ in.}^3$$

(3.) Volume of Tapped hole .450 D x 1.38 deep

$$\text{Vol.} = \pi \frac{d^2}{4} h = \pi \times \frac{(.45)^2}{4} \times 1.38$$

$$\text{Vol.} = .22 \text{ in.}^3$$

4. Volume of 1 boss equals: 10.31 - 3.06 - .22

$$\text{Vol. equals } 7.03 \text{ in.}^3$$

$$\text{Weight of one boss equals: } 7.03 \text{ in.}^3 \times .287 \frac{\#}{\text{in.}^3} = 2.02 \#$$

$$\text{Weight of 8 bosses} = 16.16 \#$$

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SUBJECT 500 KVA Alternator BY W HallidyWORK ORDER 0202-56-102Weight Armature Copper

1. The mean turn length per coil is 88 in.
2. There are 5 turns per coil, 24 coils per phase.

$$5 \times 24 \times 88 = 10,560 \text{ in. per phase}$$

$$\frac{10,560 \text{ in.} \times \frac{1 \text{ ft.}}{12 \text{ in.}} = 880 \text{ Ft. per phase}$$

3. There are 3 phases, so:

$$3 \times 880 \text{ Ft.} = 2,640 \text{ Ft of conductor}$$

4. The weight of the insulated conductor is
144 lbs per thousand feet

5. Weight of armature copper:

$$\text{Weight} = \frac{144 \text{ lbs}}{1000 \text{ Ft.}} \times 2.64 \text{ thousand feet}$$

$$\text{Weight} = 380.2 \text{ \#}$$

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Weight Wound Armature

The weight of the wound armature equals the sum of:

A. Yoke	903.7 lbs.
B. Teeth	155.2 lbs.
C. Inner Ring	16.5
D. Outer Ring	73.0
E. 8 Bosses	16.2
F. Copper	380.2
G. Wedges, Varnish	10.0

Total 1554.8 lbs

We will call the weight: 1555. lbs.

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SUBJECT 500 KVA Alternator BY W HallidyWORK ORDER 0202-56-182Weight - Rotor Discs

The volume of rotor disc #1 equals (1.) - (2.)

(1.) Volume of disc with $r = 15.0$ in. & $h = .75$ in

$$\text{Vol.} = \pi r^2 h = \pi \times 225 \times .75$$

$$\text{Vol.} = 530.1 \text{ in}^3$$

(2.) Volume of hole with $D = 5.5$ in. & $h = .75$ in.

$$\text{Vol.} = \pi \frac{D^2}{4} h = \pi \times 30.25 \times .75 \times \frac{1}{4}$$

$$\text{Vol.} = \frac{71.3}{4} \text{ in}^3 = 17.83 \text{ in}^3$$

(3.) Volume of disc = (1.) - (2.)

$$= 530.1 - 17.8$$

$$\text{Vol.} = 512.3 \text{ in}^3$$

$$4. \text{ Weight} = 512.3 \text{ in}^3 \times .287 \frac{\#}{\text{in}^3}$$

$$\text{Weight} = 147.0 \#$$

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Weight - Rotor Discs

The volume of rotor disc #4 equals (1.) - (2.)

(1.) Volume of disc with $r = 14.2$ in. & $h = .75$ in

$$\text{Vol.} = \pi r^2 h = \pi \times 201.64 \times .75$$

$$\text{Vol.} = 475.1 \text{ in.}^3$$

(2.) Volume of hole with $D = 5.5$ in. & $h = .75$ in

$$\text{Vol.} = \frac{71.3}{4} \text{ in.}^3 = 17.8 \text{ in.}^3$$

(3.) Volume of disc = (1.) - (2.)

$$= 475.1 - 17.8$$

$$\text{Vol.} = 457.3 \text{ in.}^3$$

$$4. \text{ Weight} = 457.3 \text{ in.}^3 \times .287 \frac{\#}{\text{in.}^3}$$

$$\text{Weight} = 131.2 \#$$

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The volume of rotor disc #7 equals the volume of a hollow cylinder with:

$$r_1 = 14.2 \text{ in.}$$

$$r_2 = 11.5 \text{ in.}$$

$$h = .75 \text{ in.}$$

$$\begin{aligned} 1. \quad \text{Vol.} &= \pi h (r_1^2 - r_2^2) \\ &= \pi \times .75 (201.64 - 132.25) \end{aligned}$$

$$\text{Vol.} = 163.5 \text{ in.}^3$$

$$2. \quad \text{Weight} = 163.5 \text{ in.}^3 \times .287 \frac{\#}{\text{in.}^3}$$

$$\text{Weight} = 46.92 \#$$

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Weight - Rotor spacer

Volume of rotor spacer = (1.) - (2.)

(1) Volume of Frustum of cone with

$$r_1 = 5.94$$

$$r_2 = 3.16$$

$$h = 4.81$$

$$Vol = \frac{1}{3} h \pi (r_1^2 + r_1 r_2 + r_2^2) = \frac{1}{3} \pi \times 4.81 (35.29 + 18.77 + 9.99)$$

$$Vol. = \frac{967.9}{3} \text{ in.}^3 = 322.6 \text{ in.}^3$$

2. Volume of cylinder with $r = 2.75$ & $h = 4.81$

$$Vol. = \pi r^2 h = \pi \times 7.56 \times 4.81 = 114.2 \text{ in.}^3$$

3. Volume of spacer = $322.6 - 114.2 \text{ in.}^3$

$$Vol. = 208.4 \text{ in.}^3$$

$$4 \text{ Weight} = 208.4 \text{ in.}^3 \times .287 \frac{\text{lb}}{\text{in.}^3}$$

$$\text{Weight} = 59.81 \text{ lbs.}$$

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SUBJECT 500 KVA Alternator BY W. HallidayWORK ORDER 0202-56-182Weight - Shaft

The volume of the shaft equals: (1.) + (2.) + (3.) + (4.)
+ (5.) + (6.) + (7.) + (8.)
- (9.) - (10.) - (11.)

(1.) Volume of cylinder with $r = 2.0$ & $h = 4.22$

$$\text{Vol.} = \pi r^2 h = \pi \times 4.0 \times 4.22 = 53.03 \text{ in.}^3$$

(2.) Volume of cylinder with $r = 2.55$ & $h = 1.4$

$$\text{Vol.} = \pi r^2 h = \pi \times 6.5025 \times 1.40 = 28.60 \text{ in.}^3$$

(3.) Volume of cylinder with $r = 3.16$ & $h = .5$

$$\text{Vol.} = \pi r^2 h = \pi \times 9.986 \times .5 = 15.69 \text{ in.}^3$$

(4.) Volume of cylinder with $r = 2.75$ & $h = 10.47$

$$\text{Vol.} = \pi r^2 h = \pi \times 7.563 \times 10.47 = 248.8 \text{ in.}^3$$

(5.) Volume of Frustum of cone with $r_1 = 2.5$, $r_2 = 2.125$ & $h = 3.59$

$$\text{Vol.} = \frac{1}{3} \pi h (r_1^2 + r_1 r_2 + r_2^2) = \frac{1}{3} \pi \times 3.59 \times (6.25 + 5.32 + 4.53)$$

$$\text{Vol.} = \frac{181.6}{3} \text{ in.}^3 = 60.53 \text{ in.}^3$$

(6.) Volume of cylinder with $r = 2.0$ & $h = 1.06$

$$\text{Vol.} = \pi r^2 h = \pi \times 4 \times 1.06 = 13.32 \text{ in.}^3$$

(7.) Volume of cylinder with $r = 1.5$ & $h = 3.26$

$$\text{Vol.} = \pi r^2 h = \pi \times 2.25 \times 3.26 = 23.04 \text{ in.}^3$$

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Weight - shaft (cont.)

(8.) Volume of cylinder with $r = 1.125$ & $h = 1.49$

$$Vol = \pi r^2 h = \pi \times 1.26 \times 1.49 = 5.90 \text{ in}^3$$

(9.) Volume of hole with $r = .33$ & $h = 1.80$

$$Vol = \pi r^2 h = \pi \times .1089 \times 1.80 = .62 \text{ in}^3$$

(10.) Volume of hole with $r = 1.33$ & $h = 2.62$

$$Vol. = \pi r^2 h = \pi \times 1.77 \times 2.62 = 14.57 \text{ in}^3$$

(11.) Volume of hole with $r = .43$ & $h = 1.90$

$$Vol. = \pi r^2 h = \pi \times .185 \times 1.90 = 1.10 \text{ in}^3$$

Total Volume of shaft equals $448.9 \text{ in}^3 - 16.3 \text{ in}^3$

$$Vol. = 432.6 \text{ in}^3$$

$$Weight = 432.6 \text{ in}^3 \times .287 \frac{\text{lb}}{\text{in}^3} = 124.2 \text{ lbs.}$$

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Weight - Rotor Assy.

Rotor Disc	1	147.0
"	2	147.0
"	3	147.0
"	4	131.2
"	5	131.2
"	6	131.2
"	7	46.9
"	8	46.9
"	9	46.9
Rotor Spacer		59.8
Shaft		124.2
Nut		3.6

Total 1162.9 lbs

Call Rotor Assy. weight = 1163 lbs

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Weight Drive End Housing (including bearing, & seal)

The configuration of the D.E. Housing will be approximated with a series of hollow cylinders & cones. It is estimated that the volume computed will be accurate within 5%

The volume of the D.E. Housing equals (1.) + (2.) + (3.) + (4.) + (5.) + (6.) - (7.) - (8.)

(1.) Volume of hollow cylinder with: $r_1 = 14.25$, $r_2 = 13.38$ & $h = .95$

$$\text{Vol.} = \pi (r_1^2 - r_2^2) h = \pi (203.06 - 179.03) \times .95 = \underline{\underline{71.72 \text{ in.}^3}}$$

(2.) Vol. of hollow cylinder with: $r_1 = 13.38$, $r_2 = 13.0$, & $h = 1.7$

$$\text{Vol.} = \pi (r_1^2 - r_2^2) h = \pi (179.03 - 169) \times 1.7 = \underline{\underline{53.57 \text{ in.}^3}}$$

(3.) Vol. of hollow cylinder with $r_1 = 13.0$, $r_2 = 11.5$, & $h = 3.25$

$$\text{Vol.} = \pi (r_1^2 - r_2^2) h = \pi (169 - 132.25) \times 3.25 = \underline{\underline{375.2 \text{ in.}^3}}$$

(4.) Vol of hollow cylinder with $r_1 = 11.5$, $r_2 = 3.0$ & $h = 1.52$

$$\text{Vol.} = \pi (r_1^2 - r_2^2) h = \pi (132.25 - 9.0) \times 1.52 = \underline{\underline{588.8 \text{ in.}^3}}$$

(5.) Vol of Frustum of cone with $r_1 = 13.0$, $r_2 = 3.0$ & $h = 3.0$

$$\text{Vol.} = \frac{1}{3} \pi h (r_1^2 + r_1 r_2 + r_2^2) = \frac{1}{3} \pi \times 3 (169 + 39 + 9) = \underline{\underline{681.7 \text{ in.}^3}}$$

(6.) Vol. of cylinder with $r = 7.0$ & $h = 4.0$

$$\text{Vol.} = \pi r^2 h = \pi \times 49 \times 4 = \underline{\underline{615.8 \text{ in.}^3}}$$

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Weight - Field Coil 4x4 coil

4.33 (Thousand Feet) of #8 square heavy epoxy

$$\text{Weight} = 4.33 \text{ M Ft.} \times 60.87 \frac{\text{#}}{\text{M Ft.}} = 263.6 \text{ lbs.}$$

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Weight - Drive End Housing (cont.)

(7.) Volume of cylindrical hole with $r = 3.0$ & $h = 3.0$

$$\text{Vol.} = \pi r^2 h = \pi \times 9 \times 3 = \underline{\underline{84.82 \text{ in.}^3}}$$

8. Volume of Frustum of cone with $r_1 = 6.0$, $r_2 = 3.7$ & $h = 4.0$

$$\begin{aligned} \text{Vol.} &= \frac{1}{3} \pi h (r_1^2 + r_1 r_2 + r_2^2) = \frac{1}{3} \pi \times 4.0 (36 + 22.2 + 13.69) \\ &= \underline{\underline{301.2 \text{ in.}^3}} \end{aligned}$$

$$\begin{aligned} \text{Volume of D.E. Housing} &= 2386.79 \text{ in.}^3 - 385.62 \text{ in.}^3 \\ &= 2001.17 \text{ in.}^3 \end{aligned}$$

$$\text{Call Vol. of D.E. Housing} = 2000 \text{ in.}^3$$

$$\text{Weight} = 2000 \text{ in.}^3 \times .287 \frac{\text{**}}{\text{in.}^3} = 574 \text{ **}$$

$$\text{Weight} = 574 \text{ **}$$

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The configuration of the Motor End Housing will be approximated by a group of cones & cylinders.

$$\text{Vol.} = (1.) + (2.) + (3.) - (4.) - (5.)$$

(1.) Vol. of Frustum of cone with $r_1 = 15.9$, $r_2 = 11.0$, & $h = 4.5$

$$\text{Vol.} = \frac{1}{3} \pi h (r_1^2 + r_1 r_2 + r_2^2) = \frac{1}{3} \pi \times 4.5 (252.81 + 174.9 + 121.0)$$

$$\text{Vol.} = \underline{\underline{2585.6 \text{ in.}^3}}$$

$$\underline{\underline{2586 \text{ in.}^3}}$$

(2.) Vol. of Cylinder with $r = 15.9$, $h = .75$

$$\text{Vol.} = \pi r^2 h = \pi \times 252.81 \times .75 = \underline{\underline{595.7 \text{ in.}^3}}$$

(3.) Vol. of hollow cylinder with $r_1 = 19.5$, $r_2 = 15.9$, & $h = 1.55$

$$\text{Vol.} = \pi (r_1^2 - r_2^2) h = \pi (380.25 - 252.81) 1.55 = \underline{\underline{624.6 \text{ in.}^3}}$$

(4.) Vol. of cylinder with $r = 3.75$ & $h = 1.75$

$$\text{Vol.} = \pi r^2 h = \pi \times 14.06 \times 1.75 = \underline{\underline{77.30 \text{ in.}^3}}$$

(5.) Vol. of Frustum of cone with $r_1 = 15.9$, $r_2 = 12.0$, $h = 3.5$

$$\text{Vol.} = \frac{1}{3} \pi h (r_1^2 + r_1 r_2 + r_2^2) = \frac{1}{3} \pi \times 3.5 (252.81 + 190.8 + 144)$$

$$= \underline{\underline{2215.2 \text{ in.}^3}}$$

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Weight - Motor End Housing

$$\text{Vol.} = 3806 \text{ in.}^3 - 2293 \text{ in.}^3 = 1,513 \text{ in.}^3$$

$$\text{Weight} = 1513 \text{ in.}^3 \times .098 \frac{\text{#}}{\text{in.}^3} = 148.3 \text{ #}$$

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Weight Outer Housing

The configuration of the outer housing will be approximated by a group of cones & cylinders

$$\text{Vol.} = (1.) + (2.) + (3.) + (4.) - (5.)$$

(1.) Vol. of hollow cylinder with $r_1 = 19.5$, $r_2 = 18.53$ & $h = 2.0$

$$\text{Vol.} = \pi(r_1^2 - r_2^2)h = \pi(380.25 - 343.35)2.0 = \underline{\underline{231.8 \text{ in.}^3}}$$

(2.) Vol. of hollow cylinder with $r_1 = 18.53$, $r_2 = 18.0$ & $h = 12.2$

$$\text{Vol.} = \pi(r_1^2 - r_2^2)h = \pi(343.35 - 324)12.2 = \underline{\underline{741.6 \text{ in.}^3}}$$

(3.) Vol. of Frustum of cone with $r_1 = 18.9$, $r_2 = 15.65$ & $h = 6.6$

$$\text{Vol.} = \frac{1}{3}\pi h(r_1^2 + r_1 r_2 + r_2^2) = \frac{1}{3}\pi \cdot 6.6(357.21 + 295.8 + 245.0) = \underline{\underline{6206.6 \text{ in.}^3}}$$

(4.) Vol. of hollow cylinder with $r_1 = 16.0$, $r_2 = 14.25$ & $h = 2.4$

$$\text{Vol.} = \pi r_1^2 h - \pi r_2^2 h = \pi(256 - 203.1)2.4 = \underline{\underline{399.6 \text{ in.}^3}}$$

(5.) Vol. of Frustum of cone with $r_1 = 18.0$, $r_2 = 14.85$ & $h = 6.6$

$$\text{Vol.} = \frac{\pi}{3}h(r_1^2 + r_1 r_2 + r_2^2) = \frac{1}{3}\pi \cdot 6.6(324 + 267.3 + 220.5) = \underline{\underline{5610.7 \text{ in.}^3}}$$

$$\text{Vol.} = 7579 \text{ in.}^3 - 5610 \text{ in.}^3 = 1969 \text{ in.}^3$$

$$\text{Weight} = 1969 \text{ in.}^3 \times .098 \frac{\text{lb}}{\text{in.}^3} = 193 \text{ lbs.}$$

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Weight - Supports & Lifting eyes

*The weight of the supports & lifting eyes
has been calculated by the structures designers
as:*

Weight = 16.4 lbs.

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SUBJECT 500 KVA Alternator BY W HallidyWORK ORDER 0202-56-182

Summation of Weights:

I Armature

1555 lbs.

A. Core

1164.6 lbs

1. Yoke	903.7 lbs.
2. Teeth	155.2 lbs.
3. Inner Ring	16.5 lbs.
4. Outer Ring	73.0 lbs.
5. 8 Bosses	16.2 lbs

B Copper

380.2 lbs

C. Varnish, wedges, etc.

10.2 lbs

II Rotor Assy.

1163 lbs.

A. Rotor Discs (Total)

975.3 lbs.

1. Discs 1-3 ea.	147.0 lbs
2. Discs 4-6 ea	131.2 lbs
3. Discs 7-9 ea	46.9 lbs

B Rotor Spacer

59.8 lbs.

C. Shaft

124.2 lbs.

III Field Coil

264 lbs.

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SUBJECT 500 KVA Alternator BY W HallidayWORK ORDER 0202-56-182*Summation of Weights (cont.)*

<u>IV</u>	Drive End Housing (includes bearing & seal)	574 lbs.
<u>V</u>	Motor End Housing	148 lbs.
<u>VI</u>	Outer Housing	193 lbs.
<u>VII</u>	Supports	16 lbs.
<u>VIII</u>	Motor End Bearing & Seal	17 lbs.
<u>IX</u>	Transformer Oil & Diaphragm	30 lbs.
Total		3960 lbs.

Note: Calculation of items I - III are considered accurate within $\pm 3\%$

Calculation of items IV - IX are considered accurate within $\pm 10\%$

Thus:	Minimum weight	3775
	Maximum weight	4145
	Nominal weight	3960

APPENDIX D

NON-MAGNETIC MATERIALS TESTS

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APPENDIX D
NON-MAGNETIC MATERIALS TESTS

The stainless steel in the rotor of the developmental alternator was found to have a considerably higher permeability than that specified. Tests showed that this was not due to incorrect handling of the AISI Type 304 stainless steel during fabrication. Permeability tests before and after the rotor components had been subjected to heat, in accordance with the manufacturer's recommendations, disclosed that the permeability ranged from 2.0 to 4.0, significantly greater than the 1.02 maximum quoted in the steel manufacturer's catalog. It was discovered, however, that the manufacturer obtained this value by subjecting the material to 1950°F for eight hours followed by water quenching. Steel company metallurgists stated that heat generated by welding could account for the increase in permeability to 4.0.

Low permeability of the steel used as interpolar material is of major importance to proper functioning of the alternator. This low permeability could not be restored in the finished rotor by the heat treatment and water quench process because of the danger of shaft warpage and/or other distortion of the rotor.

An investigation was conducted into the characteristics of various materials which might be suitable for use between the poles. The following conclusions were reached:

- The general 18-8 class of stainless steel is considered an austenitic material (and therefore of low permeability) because of the maximum (claimed) permeability figure of 1.02. Figure D-1 shows the variation in structure caused by variation of the chrome-nickel ratio

in Fe-Cr-Ni alloys containing 0.10% carbon, 0.90% manganese and 3% silicon.

- Certain impurities found in 18-8 class stainless steel favor the formation of austenite, while other impurities favor the formation of ferrite (with the associated increase in permeability).
- Chemical analysis of production heats of 18-8 class stainless steel were obtained from all the major steel manufacturers. AISI Type 304 stainless steel is generally considered to have the most advantageous composition to ensure low permeability. The chemical analyses of ten heats of Type 304 stainless steel, however, indicated chrome and nickel contents comparable to those found in the material of the development rotor (Figure D-2). Although not generally considered to be less permeable than Type 304 stainless steel, chemical analyses of production heats of Type 310 stainless steel revealed the latter material to be uniformly more austenitic. Type 310 stainless steel was tested for permeability in the as-received condition, during the rough form cutting, and after welding. The permeability values obtained were all below 1.01, indicating the probability that the permeability of the Type 310 stainless steel in the finished rotor would not exceed the design parameter for interpolar permeability of 1.2.

FIGURE D-1. EFFECT OF CHROMIUM - NICKEL RATIOS

FIGURE D-2. EFFECT OF CHROMIUM - NICKEL EQUIVALENTS

11.2-64-1317

APPENDIX E

RESULTS OF ML-1 STATOR INSULATION TESTS

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APPENDIX E
RESULTS OF ML-1 STATOR INSULATION TESTS

Tests were conducted to determine the most effective insulating materials for the ML-1 alternator stator. The following candidate materials were screened:

1) Magnet Wire:

- a) Anaconda "Silotex" DX glass served wire, bare conductor OFHC copper, 0.144 x 0.258 in.
- b) Anaconda heavy epoxy magnet wire, AWG 18
- c) Anaconda heavy "Formex" magnet wire, AWG 18

2) Mica-tape:

- a) General Electric 77866 "Mica-mat" tape, 0.0057 in. thick, 1/2 in. wide
- b) General Electric 77878 "Mica-mat" semi-cured tape, 0.009 in. thick, 1/2 in. wide

3) Varnish and resin:

- a) Dolph BC-325 varnish
- b) General Electric 74011 solventless epoxy resin

4) Sleeveings:

- a) Bently Harris "Acryl-A" sleeving
- b) L. Frank Markel "Polytube" sleeving

5) Wedge and Spacer:

- a) NEMA-ASTM Grade G-3 natural laminate of fine weave continuous filament fiberglass cloth bonded with phenolic resin
- b) NEMA-ASTM Grade G-5 melamine glass laminate

6) Fiberglass tape:

- a) Hess Goldsmith B weave, Code 562 fiberglass tape, untreated, 0.005 in. thick, 3/4 in. wide.

Three insulation systems were tested:

TABLE E-1 - CANDIDATE INSULATION SYSTEMS

<u>Component</u>	<u>System "A"</u>	<u>System "B"</u>	<u>System "C"</u>
Magnet Wire	Anaconda "Silotex" DX, 0.144 in. x 0.258 in. OFHC annealed copper	Same as for System "A"	Same as for System "A"
Major ground insulation, slot section and end turn	General Electric 77878 "Mica-mat" tape, 0.009 in. thick, 1/2 in. wide	General Electric 77866 "Mica-mat" tape, 0.0057 in. thick, 1/2 in. wide	Same as for System "B"
Outer wrapping	Hess Goldsmith B weave Code 562 fiberglass tape, 0.005 in. thick, 3/4 in. wide	Same as for System "A"	Same as for System "A"
Varnish or resin	General Electric 74011 solventless epoxy resin	Dolph BC-325 varnish	General Electric 74011 solventless epoxy resin

Four tests were run in this evaluation:

1) Test I:

Purpose: To determine the compatibility of the insulating materials with OC-11 turbine oil.

Procedure: Small samples of materials were immersed in OC-11 oil held at 250°F continuously for 1 month. Additional samples were held at the same temperature in air for comparison. Following the test, all samples were microscopically examined for evidences of deterioration.

Results: Summarized in Table E-2 on page E-5.

Conclusions:

- a) "Formex" wire, a wire that is frequently used in commercial transformers, is not compatible with OC-11 oil and should not be used in the ML-1 system.
- b) Both mica tapes were slightly affected by OC-11 oil; however, the changes observed are probably not significant when the tapes are applied as a coil wrapping.

TABLE E-2 - COMPATIBILITY OF INSULATING
MATERIALS WITH OC-11 TURBINE OIL (TEST 1)

Sample		Chemical	Comments
No.	Description	Compatibility Rating (1)	
1-A-1	Anaconda Silotex DX wire	1	No changes noted
1-A-2	Anaconda heavy epoxy wire	1	No changes noted
1-A-3	Anaconda heavy formex wire	3	Formex coating changed to black color and was slightly softened; film flaked off when wire was wrapped around 0.25 in. mandrel
1-B-1	G.E. 77866 "Mica-mat" tape	2	Composite tended to delaminate; no evidence of chemical attack on mica, glass or Mylar components
1-B-2	G.E. 77878 "Mica-mat" tape	2	Fiberglass and mica paper were found to be brittle; brownish deposit was noted throughout composite
1-C-1	Dolph BC-325 varnish	1	Varnish film had darkened where immersed in oil; varnish film was hard, glossy and flaked off when copper shim was flexed
1-C-2	G.E. 74011 resin	1	Varnish film was hard and glossy; film was brittle in thick section
1-D-1	L. Frank Markel Polytube sleeving	1	Tubing was rigid as a result of thermalizing
1-D-2	Bently Harris Acryl-A sleeving	1	Good condition
1-E-1	Phenolic glass laminate	1	Color changed to dark brown
1-E-2	Melamine glass laminate	1	No changes noted
1-F-1	Hess Goldsmith untreated glass tape	1	Glass tape was stained brown

(1) Rating System: 1 = good; 2 = fair; 3 = poor; based on microscopic examination of samples.

2) Test II:

Purpose: To determine the compatibility of various material combinations held in air at elevated temperature.

Procedure: Samples were sealed in stainless steel capsules and held at 311°F continuously for 1 month. Prior to sealing, the capsules and samples were dried. Following the test, the samples were microscopically examined for evidences of deterioration.

Results: Summarized in Table E-3 on page E-7.

Conclusions: All material combinations were found to be compatible.

3) Test III:

Purpose: To determine the resistance of insulating materials to hydrolysis at elevated temperature.

Procedure: Samples were sealed in stainless steel capsules with 1/2 ml of distilled water. Additional samples were sealed in capsules without water as controls. Following the test, microscopic examinations of the samples were made.

Results: Summarized in Table E-4 on page E-8.

Conclusions: Formex wire, Polytube sleeving and melamine glass laminate all badly deteriorated as a result of hydrolysis. Consequently none of these materials should be used in the ML-1 system.

4) Test IV:

Purpose: To determine the compatibility of insulating materials when exposed to a mixture of OC-11 oil and moisture at elevated temperature.

Procedure: Samples were sealed in stainless steel capsules with OC-11 oil and 1/2 ml of distilled water and held at 311°F continuously for 1 month (Test IV-A). In addition, coil samples representing three insulation systems were individually sealed in similar capsules with OC-11 oil and 1/2 ml of distilled water, and held at 250°F continuously for 1 month (Test IV-B).

Results: Summarized in Table E-5 and E-6 on pages E-9 and E-10.

Conclusions:

a) Anaconda Silotex D wire, Dolph BC-325 varnish and Polytube sleeving were found to be badly deteriorated. Consequently, these materials were eliminated from further consideration.

b) Insulation System C, which was used in the new ML-1 alternator stator, and insulation System A were both found to be satisfactory. Insulation System B was eliminated from further consideration.

TABLE E-3 - COMPATIBILITY OF VARIOUS INSULATING MATERIAL
COMBINATIONS IN AIR AT ELEVATED TEMPERATURE
(TEST II)

<u>No.</u>	<u>Description</u>	<u>Comments</u>
2-A-1/D-1	Anaconda "Silotex" DX wire, L. Frank Markel "Polytube" sleeving	No changes were noted for wire; sleeving was rigid as a result of thermal aging, sleeving had changed color to dark brown, coating on sleeving was glossy
2-A-1/D-2	Anaconda "Silotex" DX wire, Bentley Harris "Acryl-A" sleeving	No changes were noted for wire; sleeving was glossy, and color changed to dark brown, sleeving had fair flexibility
2-A-2/D-1	Anaconda heavy epoxy wire, L. Frank Markel "Polytube" sleeving	Wire coating was brittle, glossy and had changed to black color; sleeving was rigid, glossy and it's color had changed to dark brown
2-A-2/D-2	Anaconda heavy epoxy wire, Bentley Harris "Acryl-A" sleeving	Sleeving had fair flexibility, sleeving coating had changed to brown color; wire coating was glossy, hard and brittle-color changed to dark brown color
2-A-3/D-1	Anaconda heavy "Formex" wire, L. Frank Markel "Polytube" sleeving	Sleeving was rigid, glossy and had changed to dark brown color; wire film was glossy, brittle and had changed to black color
2-B-1/C-1	G.E. 77866 "Mica-mat" tape, Dolph BC-325 varnish	Varnish applied to tape was glossy, brittle and had changed to dark brown color; mica tape in good condition
2-B-1/C-2	G.E. 77866 "Mica-mat" tape, G.E. 74011 resin	Varnish applied to tape had changed to black color; mica composite was brittle but mica paper was intact
2-A-1/B-1	Anaconda "Silotex" DX wire, G.E. 77866 "Mica-mat" tape	Mica tape slightly less flexible and had changed to brown color; no changes in wire were noted
2-A-1/B-2	Anaconda "Silotex" DX wire, G.E. 77878 "Mica-mat" tape	Mica tape was brittle and well bonded to wire
2-A-2/B-1	Anaconda heavy epoxy wire, G.E. 77866 "Mica-mat" tape	Mica tape slightly less flexible; wire coating was glossy, brittle and had changed to black color
2-A-2/B-2	Anaconda heavy epoxy wire, G.E. 77878 "Mica-mat" tape	Mica tape was brittle and well bonded to wire
2-A-3/B-1	Anaconda heavy "Formex" wire, G.E. 77866 "Mica-mat" tape	Mica tape slightly less flexible; wire coating was glossy, brittle and had changed to black color
2-A-3/B-2	Anaconda heavy "Formex" wire, G.E. 77878 "Mica-mat" tape	Mica tape was brittle; wire coating was glossy, brittle and had changed to black color
2-D-1/C-1	L. Frank Markel "Polytube" sleeving, Dolph BC-325 varnish	Sleeving was glossy, rigid and had changed to dark brown color
2-D-1/C-2	L. Frank Markel "Polytube" sleeving, G.E. 74011 epoxy resin	Same note as for Sample 2-D-1/C-1
2-D-2/C-1	Bentley Harris "Acryl-A" sleeving Dolph BC-325 varnish	Same note as for Sample 2-D-1/C-1
2-D-2/C-2	Bentley Harris "Acryl-A" sleeving G.E. 74011 epoxy resin	Sleeving had fair flexibility, was glossy and had changed to dark brown color
2-A-1/C-1	Anaconda Silotex DX wire, Dolph BC-325 varnish	Wire in good condition, varnish was glossy and had changed to dark brown color
2-A-1/C-2	Anaconda Silotex DX wire, G.E. 74011 epoxy resin	Same notes as for Sample 2-A-1/C-1
2-A-2/C-1	Anaconda heavy epoxy wire, Dolph BC-325 varnish	Varnish coating was glossy, brittle and had changed to dark brown color
2-A-2/C-2	Anaconda heavy epoxy wire, G.E. 74011 epoxy resin	Same notes as for Sample 2-A-2/C-1
2-A-3/C-1	Anaconda heavy "Formex" wire, Dolph BC-325 varnish	Same notes as for Sample 2-A-2/C-1
2-A-3/C-2	Anaconda heavy "Formex" wire, G.E. 74011 epoxy resin	Same notes as for Sample 2-A-2/C-1

TABLE E-4 - RESISTANCE OF VARIOUS MATERIALS
TO HYDROLYSIS AT ELEVATED TEMPERATURE
(TEST III)

<u>No.</u>	<u>Description</u>	<u>Resistance To Hydrolysis (1)</u>	<u>Comments</u>
3-A-1	Anaconda Silotex DX Wire	2	Outer serving of fiberglass was unraveled; silicone resin appeared to still be present, however, it was darker in color
3-A-2	Anaconda heavy epoxy wire	1	Wire coating was glossy, brittle and had changed to black color
3-A-3	Anaconda heavy Formex wire	3	About 50% of wire coating was in charred condition; film was very brittle and discolored
3-B-1	G.E. 77866 "Mica-mat" tape	2	Mylar backing decomposed to white powder, mica paper and fiberglass back in good condition; some of polyester binder had lost binder property
3-B-2	G.E. 77878 "Mica-mat" tape	1	Composite was rigid and brittle, mica paper in good condition, binder was intact but had changed to dark brown color
3-C-1	Dolph RC-325 varnish	1	Varnish film was glossy, brittle and hard
3-C-2	G.E. 74011 resin	1	Varnish film was glossy, brittle and hard
3-D-1	L. Frank Markel "Polytube" sleeving	3	Coating flowed and became tacky; coating changed to dark brown color
3-D-2	Bentley Harris "Acryl-A" sleeving	2	Sleeving was rigid; coating had less glossiness-color changed to black
3-E-1	Phenolic glass laminate	1	Laminate changed to brown/black color; binder in excellent condition
3-E-2	Melamine glass laminate	3	Melamine binder disintegrated into yellow powder
3-F-1	Hess Goldsmith untreated glass tape	1	Tape was slightly less flexible; tape was stained brown

(1) Rating System: 1 = good; 2 = fair; 3 = poor; based on microscopic examination of samples.

TABLE E-5 - COMPATIBILITY OF INSULATING MATERIALS WITH
OC-11 OIL AND MOISTURE AT ELEVATED TEMPERATURE
(TEST IV-A)

<u>No.</u>	<u>Description</u>	<u>Chemical Compatibility Rating (1)</u>	<u>Comments</u>
4-A-1	Anaconda Silotex DX wire	3	Outer glass serving unraveled; silicone binder lost binding property; wire flexibility was poor
4-A-2	Anaconda heavy epoxy wire	1	Wire coating was glossy and had changed to dark brown color; film flexibility was good
4-A-3	Anaconda heavy formex wire	2	Wire coating was glossy and hard; film color had changed to black
4-B-1	G.E. 77866 "Mica-mat" tape	2	Mylar backing had decomposed; mica paper and fiberglass cloth were in good condition; polyester binder had dissolved
4-B-2	G.E. 77878 "Mica-mat" tape	1	Composite was rigid and brittle; epoxy binder and mica paper were intact
4-C-1	Dolph BC-325 varnish	3	Varnish disintegrated and mixed with oil
4-C-2	G.E. 74011 resin	2	Varnish film was glossy, slightly brittle and color had changed to dark brown
4-D-1	L. Frank Markel "Polytube" sleeving	3	Sleeving coating had softened and mixed with oil
4-D-2	Bentley Harris "Acryl-A" sleeving	2	Sleeving coating had softened
4-E-1	Phenolic glass laminate	1	Changed to brown/black color
4-E-2	Melamine glass laminate	1	Good condition
4-F-1	Hess Goldsmith untreated glass tape	1	Fiberglass tape stained brown

(1) Rating System: 1 = good; 2 = fair; 3 = poor; based on microscopic examination of samples.

TABLE E-6 - COMPATIBILITY OF COIL SAMPLES WITH OC-11OIL AND MOISTURE AT ELEVATED TEMPERATURE

(TEST IV-B)

<u>No.</u>	<u>Description</u>	<u>Chemical Compatibility Rating (1)</u>	<u>Comments</u>
A-1	Insulation system A-control sample (exposed only to temperature)	---	Coil sample extremely rigid; epoxy coating on glass slightly weak due to thermal aging effect; mica paper in good condition but had wrinkled during wrapping
B-1	Insulation system B-control sample (exposed only to temperature)	---	Tape appeared to be slightly softened by solvent evaporation
C-1	Insulation system C-control sample (exposed only to temperature)	---	Good condition
A-2	Insulation system A	1	Epoxy resin showed good resistance to oil; no evidence of hydrolysis action-overall coil good condition
B-2	Insulation system B	2	Varnish on wire strands had degraded badly; mica tape in good condition; however, binder dissolved out; outer wrapping coating in good condition
C-2	Insulation system C	1	No evidence of hydrolysis action; epoxy coating resisted oil well; mica tape in good condition (Mylar, glass and mica paper intact) but binder appeared to have dissolved out; epoxy coating on wire strands in good condition
	Lead cable - silicone, rubber flexible cable	---	Silicone rubber in good condition; outer braid loosened and showed effects of degradation of the binder

(1) Rating System: 1 = good; 2 = fair; 3 = poor; based on microscopic examination of samples.

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The information herein is regarded as preliminary and subject to further checking, verification and analysis.

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