THE SIX PHASE RECTIFIER AS A POWER SOURCE FOR OPERATING DC MOTORS

by

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I. Introduction

There exists in various industries today applications for electric motors where the characteristics of alternating current machines are not satisfactory, and therefore, where the use of direct current machines is desirable if not absolutely necessary. Applications requiring a wide range of speed control fall into this category. Synchronous machines are absolutely constant speed devices, and, in general, induction motors are relatively constant speed machines, except those of the wound rotor type, the speed of which can be controlled by adding resistance in series with the rotor winding. This latter method of speed control would be unsatisfactory in many applications because the speed fluctuations under varying conditions when the rotor resistance was high might be too great, and because the efficiency of the machine is very much decreased when resistance is added to the rotor circuit.

Since the power available in practically any location that one could mention in the United States will almost invariably be in the form of alternating current, the problem of how best to convert this power into the direct current form is paramount in any application which must have direct current for its successful and satisfactory operation. In general, there are two methods for converting large quantities of alternating current energy into direct current energy. They are:

(1) the use of rotating machinery such as a motor generator set or a rotary converter,

(2) the use of any of the various types of mercury arc rectifiers available on the market today.

Many factors enter into such a choice.[1] A few of these considerations are purchase price, cost of installation, cost of maintenance, dependability, weight, vibrations set up by the equipment, noise, efficiency, and allowable ripple voltage present in the output.

Purchase price and installation cost must be considered together. The purchase price of the rectifier is higher in the lower voltage classes. Above 500 volts this trend changes, the rectifier being cheaper, especially in the larger power ratings. However, the installation cost is somewhat greater for the rotating machine because of the more massive foundation necessary. The cost varies somewhat, depending on the type of installation and the location, but this high installation cost of the rotating machine sometimes gives a decided advantage to the rectifier, especially on units of 250 volts or more.

The cost of maintenance has proved to be cheaper on the rectifier because it has no rotating parts. However when repairs are needed, more experienced personnel is needed to repair a rectifier, and the availability of such personnel on short notice might be an important consideration.

In the larger power and voltage ratings, the rectifier is a lighter piece of equipment, sets up no vibration, and produces very little noise compared to an equally rated rotating machine.

Below 250 volts the efficiency of the rectifier is inferior to the rotary converter but better than motor generator efficiency down to about half that rating. Above this voltage the rectifier has a better efficiency. This is especially true at light and intermediate loads, an important consideration in applications where peak power is used only a small percentage of the time.

The amount of ripple allowable in the output of a power converter depends upon the application. The two main applications of DC power today are electrolytic refining and driving DC motors. In the former application the ripple voltage is for the most part entirely acceptable, having no undesirable effect on the device utilizing the energy; however, in the latter application, driving DC motors, the question of what effect the ripple has on the DC motor performance is perhaps the main consideration in the minds of many engineers who may strongly prefer rotating machines to rectifiers. Information concerning this matter is not readily available to most engineers today. It is the purpose of this investigation to study these effects using a six phase rectifier, and to determine how disadvantageous rectifier operation is, compared to DC generator operation, from the points of view of temperature rise, efficiency, and commutation.

II. A Review of the Literature

Although there is to be found throughout the literature many articles dealing with various aspects of mercury arc rectification, surprisingly few references are made to the very important aspect of deleterious effects in DC motors caused by rectifier output ripple. Most authors have confined themselves to descriptions of applications, advantages of rectifiers over rotating machines, the problem of arc back, the problem of communication interference caused by rectifiers, comparisons of various types of rectifier circuits, and mathematical analyses of rectifier wave forms, efficiency, losses, and voltage regulation. The few pertinent references which could be found are described below.

Siegfried[2] states that rectifier operation may cause motor armature current pulsations so that the peak armature current may be very much larger than the average current, resulting in greater heating in the motor. No data for actual operating conditions of a motor are given. A chart is given showing the ratio of effective current to average current for several cases of discontinuous conduction likely to be incurred in practice with a single phase full wave rectifier. Mention is made of possible added losses in the iron which may come about because of field current pulsations, and Siegfried suggests that a partial solution to this problem would be to use laminated pole pieces and a laminated yoke. Siegfried also states that additional vibrations set up by the current pulsations will require that better grades of insulation be used to avoid chafing from mechanical stresses, and the additional voltage stresses will surely necessitate better insulation. Siegfried's paper limits the discussion to single phase operation, and, therefore, the writer does not feel that this paper presents a true picture of the problem as it appears today in industry.

Dalton,[3] an engineer for the General Electric Company, Schenectady, New York, in a discussion of Siegfried's paper states that Siegfried's presentation is very pessimistic because actual practice shows current pulsations to be very much smaller than suggested in that paper. Dalton admits that single tube operation can cause heating as much as three times normal in small motors, but two tube operation rarely gives heating in excess of twice normal. Rectifiers with three or more tubes give added losses which are often negligible, and since polyphase rectifiers are very much more common in practice than single phase rectifiers, Siegfried's statements are not too significant.

Marti and Winograd[4] give a very brief statement of their beliefs in a rather lengthy paper they wrote in 1927, devoted almost entirely to other aspects of rectifier application.

> ...extensive tests have been carried out to determine the effect of the undulations in the wave upon the load connected to a rectifier. For this purpose shunt wound and series wound motors were connected, first to a battery, then to a rectifier fed, respectively, by a single phase, a three phase, and a six phase a-c source. With six phase operation no difference in efficiency as compared to operation from a battery could be noticed in the case of either motor; nor did the undulations have any effect upon commutation.

DeWolfe[5] of the General Electric Company investigated this problem and has found that

> Serious problems may arise in the operation of a d-c motor from rectified alternating current particularly when a single phase rectifier is used... Experience has shown that careful design allows the realization of the many advantages of the rectifier type d-c motor drive.

This paper gives no actual figures, but merely states the causes of additional heating.

The most pertinent article the writer could find was written by Smith and Schmidt[6] of the Westinghouse Company. They state that the losses are greater in the current carrying parts of the motor when operated from a rectifier because of increased eddy current loss, increased effective resistance caused by skin effect, and because the effective value of the current will be greater than the average or torque producing components of current; losses in the flux carrying parts of the machine will be increased because of increased hysteresis and eddy current loss resulting from flux pulsations. They mention that the presence of a series field will accentuate the iron loss effects. Delayed firing angle on the rectifier will also accentuate all the additional heating effects. Commutation will be worse because commutating pole flux pulsations will not be proportional to, nor will they be in phase with, armature current pulsations. Extensive data in the form of charts are given. In analyzing this data they state that

> Examination of the data...shows that at full voltage the 6-phase rectifier power supply does not appreciably affect the temperature rise, but the 3-phase rectifier power supply resulted in a 10 to 20 per cent increase in temperature rise. At 25 per cent voltage, where much greater ripple currents exist, the temperature rise was from 10 to 20 per cent greater than normal with a 6-phase rectifier but was from 35 to 120 per cent greater with a 3-phase rectifier.

With reference to commutation they state that, "...the 6-phase rectifier has practically no adverse effects on the commutation characteristics of this motor even at reduced voltages."

In comparing 3-phase rectifiers with DC generator sources, they state that, "A comparison between performances with a generator supply and with a 3-phase rectifier...shows a definite inferiority of performance with 3-phase rectifier power..." In conclusion they state that

> It appears that no derating due to increased temperature rise is indicated for operation on 6-phase rectifiers at full voltage. Some slight derating might be required if extended operation at low voltages were contemplated... When operating from a 3-phase rectifier delivering full voltage, a certain amount of derating would be necessary in order to maintain rated temperature rise. When operating at 25 per cent voltage on a 3-phase rectifier, considerable derating would be necessary to prevent overheating of the motor...No discernable lessening of commutation ability appears to result when a 6-phase rectifier is used.

Wright[7] states that

> The ripple voltage of a three phase half wave rectifier unit is large enough to cause overheating of rotating machinery; however, most power rectifiers are six or twelve phase and usually incorporate some type of smoothing reactor; thus the ripple is reduced to such a low value that its heating effects are negligible.

The only other references pertaining to heating in rotating machinery resulting from rectifier operation were two articles discussing AC generator operation. Although this topic is not directly applicable to the problem discussed here, it is remotely related, and the writer believes it might throw light on opinions held by persons experienced with rectifier equipment.

Ross and Batchelor[8] discuss this problem, stating that, "Heating in generators will be very small for 12 phase and negligible for larger numbers of phases. Derating is necessary for less than 6 phases."

Evans[9] in a similar paper says, "Generators supplying rectifiers are subjected to increased heating because of harmonics, particularly local heating in the rotors...the problem is negligible for rectifiers of more than 12 phases or where the rectifiers are a small part of the total load."

This last statement seems most pertinent to the writer since, even though a motor would probably get all its power either from a rectifier or from a DC generator, not both simultaneously, an AC generator would most likely be supplying a variety of loads, which fact would tend to minimize the adverse effects of the rectifier partial load. It should be remembered that armature reaction in a synchronous machine is very much more pronounced than in a DC machine. This fact is probably the reason Evans found excessive heating in the rotor.

III. Equipment

The DC motor tested was a compound motor, the name plate data of which is given below.

Variable Speed	Westinghouse	Compound Wound
15 H. P.	Type SK DC Motor	RPM 1200
115 Volts	Continuous Rating 50°C Rise	Style 399564
113 Amps		Serial 4549222

This machine will hereinafter be referred to as the test machine or test motor.

It was necessary to use another DC motor of equal rating in conjunction with the test machine in order to successfully carry out the experimentation. This machine will be called the auxiliary motor. Its name plate data is as follows:

Variable Speed	Westinghouse	Compound Wound
15 H. P.	Type SK DC Motor	RPM 1200
115 Volts	Continuous Rating 50°C Rise	Style 399564
113 Amps		Serial 4546389

Two synchronous generators were used to load the two motors just described. The name plate data from these two machines is given here.

<u>Generator Loading the Test Motor</u>

15 KVA	Westinghouse	Cycles 60
220 Volts	A. C. Generator	RPM 1200
39.4 Amps		Excitation Amps 12.8
80% P.F.		Excitation Volts 125
3 Phase		Serial 4549224

<u>Generator Loading the Auxiliary Motor</u>

15 KVA	Westinghouse	Cycles 60
220 Volts	A. C. Generator	RPM 1200
39.4 Amps		Excitation Amps 12.8
80% P.F.		Excitation Volts 125
3 Phase		Serial 4548391

The rectifier supplying power to the motors was a six phase ignitron rectifier which had originally been a three phase unit at the time of manufacture. It has been converted to six phase operation by the manufacturer, using a delta to double wye transformer bank with an interphase transformer. This conversion approximately doubled the rated power output, so there are now several inaccuracies on the name plate data which is tabulated below.

Output	Westinghouse	Input
KW 18.75	Ignitron Rectifier	60 Cycles
Volts DC 250	Serial Number	230 Volts
Amps DC 75	20-23P 125	3 Phase

Since the rectifier was rated at 250 volts and the test machine was rated at 115 volts, the problem of how to use the two pieces of equipment together arose. How this problem was solved is described later under "Test Procedure"; but, having solved the problem, it was thought that the simplest method of changing over from rectifier operation to DC generator operation was to merely change the input power leads from the rectifier terminals to a 250 volt DC generator, rather than to use a 125 volt generator. If the latter arrangement had been used, changes in the test circuit would have been necessary every time the conversion from rectifier input to DC generator input had been made. Also, 250 volts were necessary to excite the two alternators. Since no 250 volt generators were available, two 125 volt machines were used. These two machines were driven by induction motors. The data on all these machines are given below.

<u>Generator No. 1</u>

Type RC 30	Direct Current Generator	Form A 44
Comp. Wound	Model 72370	Amps 160
Volts 125/125		Speed 1800
20 KW		No. 1230854
	Continuous 50°C	
	General Electric Company	

Motor Driving Generator No. 1

Type AHI 4 15M 1800 P.F. 0.8 12 KW Speed 1800 15 KVA	Alternating Current Generator No. 4026925	Form C 39 Amps 220 Volts Cycles 60

60°C Rise Continuous
General Electric Company

Generator No. 2

Type RC 30 Comp. Wound Volts 125/125 20 KW	Direct Current Generator Model No. 72370	Form A 44 Amps 160 Speed 1800 No. 1354204

Continuous 50°C
General Electric Company

Motor Driving Generator No. 2

Type AHI 4 15M 1800 P.F. 0.8 12 KW Speed 1800	Alternating Current Generator No. 4026924	Form C 39 Amps 220 Volts Cycles 60

60°C Rise Continuous
General Electric Company

Eleven copper-constantan thermocouples were used to measure temperatures. The voltages from these thermocouples were measured using a No. 7651 Leeds and Northrup potentiometer, a Rubicon spotlight galvanometer, and an Eplab standard cell. Information concerning this equipment together with a list of meters and other items used is given below.

Potentiometer

Leeds and Northrup Co.
Philadelphia
727142
Made in U.S.A.

Standard Cell

Eplab Students' Cell
149227
The Eppley Laboratory, Inc.
Newport, R.I.
Made in U.S.A.

Galvanometer

Cat. No. 34244
Ser. No. 7618
Sensitivity 0.018 microamperes/mm
Resistance 197 ohms
Period 20 sec.
C.D.R.X. 600 ohms
Date 2-3-47
Rubicon Company
Philadelphia

Tachometer

Associated Research Corporation
Model 21
Made in U.S.A.
Chicago, Illinois

Current Transformer

Weston Current Transformer
Model 461 No. 12818 Type 1 Cap. 5va
Freq. 25 - 133 Line Volts 2500

Wattmeter

Weston Electrical Instrument Corp.
Model 432 No. 7551
Max Volts 400/200 Max Amps 7.5

Wattmeter

Weston A.C. and D.C. Wattmeter, Model 310
Form 1 No. 3653
Normal Current 50/100 amps
Normal Voltage 150/300
Maximum Current 75/150
Maximum Voltage 250/450

AC Ammeter

Weston Electrical Instrument Corp.
Model 433 No. 67607
25 - 500 Cycles
Full Scale 5 Amps

AC Ammeter

Weston Electrical Instrument Corp.
Model 155 No. 32124
Full Scale 150 Amps

AC Voltmeter

Weston Electrical Instrument Corp.
Model 433 No. 76924
25 - 125 Cycles
Full Scale 150/300 Volts

DC Ammeter

Weston Electrical Instrument Corp.
Model 430 No. 22411
Full Scale 3/15/30 Amps

DC Millivolt Meter

Weston
Model 250 No. 150580
Full Scale 50 Millivolts

200 Amp 50 Millivolt Shunt

DC Voltmeter

Weston DC Voltmeter Model 45
Serial No. 39912
Full Scale 3/15/150 Volts

3 Loading Rheostats

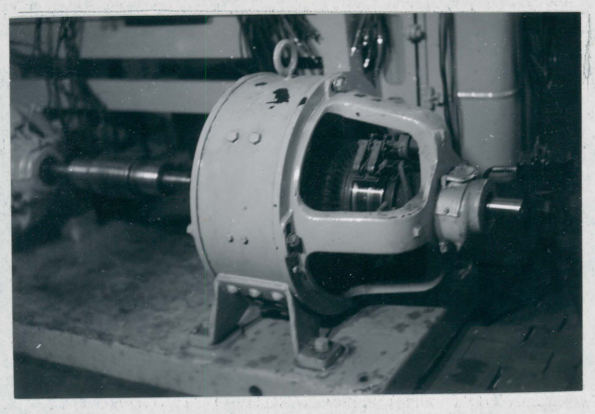
3 Phase Throw-Over Board

Shunt Field Rheostat

Potentiometer Rheostat

DuMont Cathode Ray Oscillograph

Photographs of the test motor, the rectifier, the load, and the temperature measuring equipment are shown in Figures 1, 2, 3, 4, and 5.



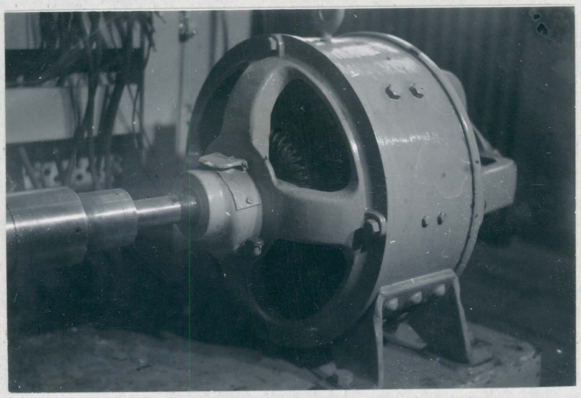


Figure 1. Two views of the test motor.

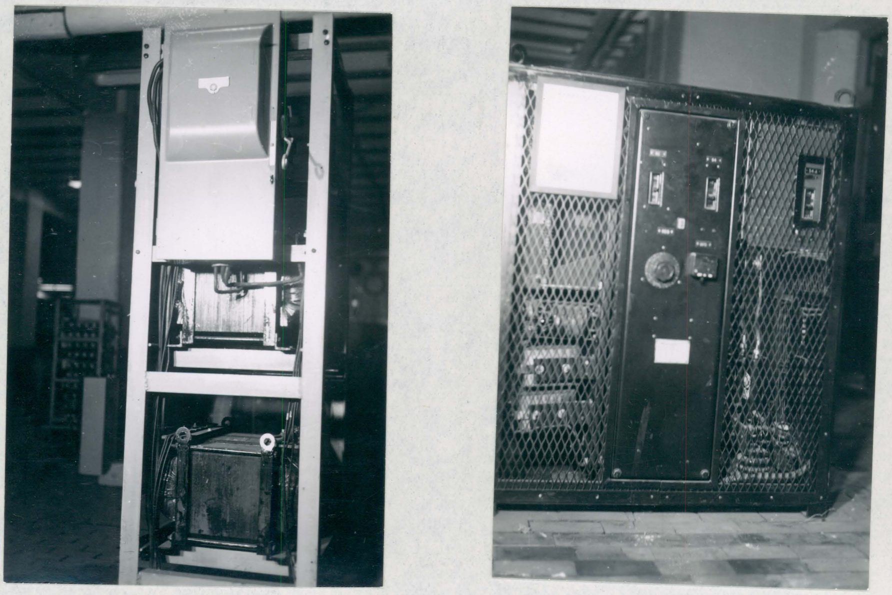


Figure 2. Westinghouse ignitron rectifier and transformer bank.

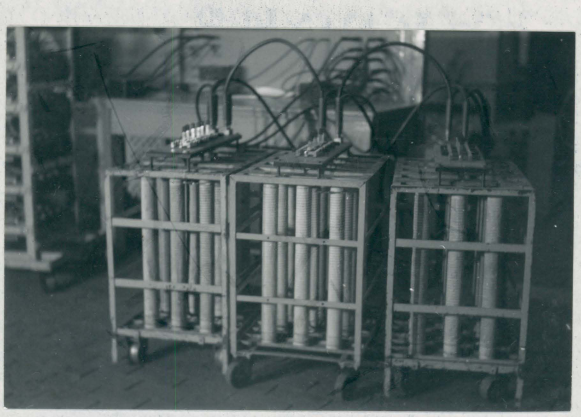


Figure 3. The three phase resistive load for the alternators.

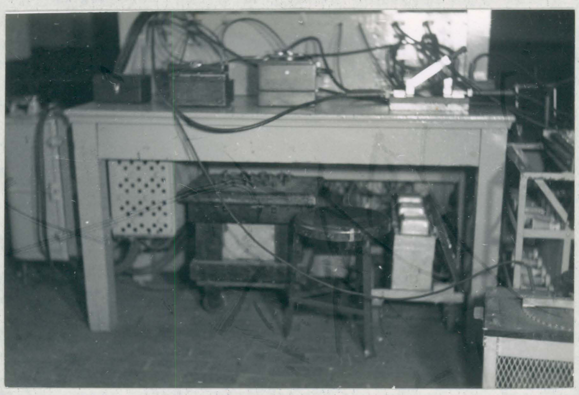


Figure 4. A view of the metering and switching arrangement of the test machine.

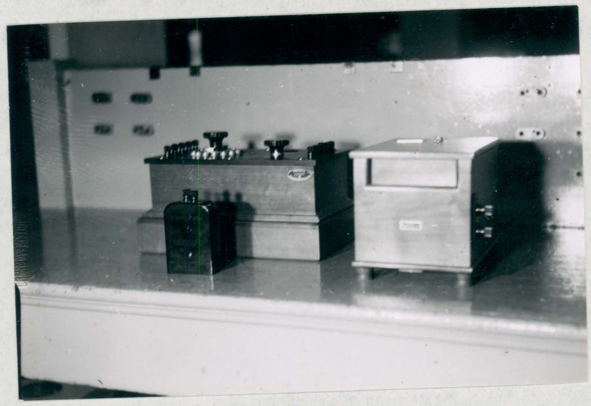


Figure 5. Rubicon spotlight galvanometer, Leeds and Northrup potentiometer, and Eplab standard cell.

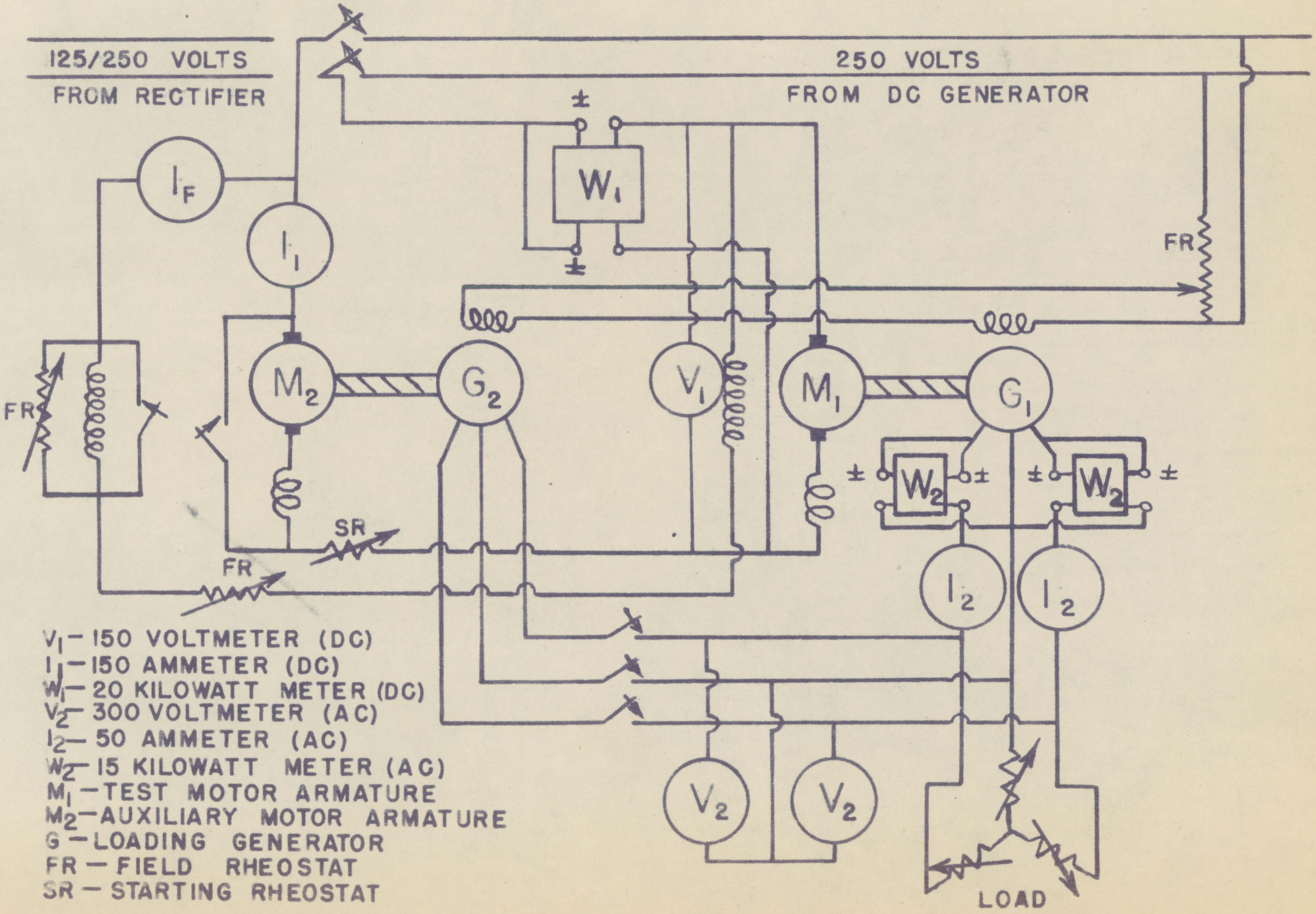
IV. Test Procedure

Preliminary Considerations and Circuit Arrangements

The first problem which was encountered resulted from the fact that the six phase rectifier to be used was a 250 volt unit whereas the DC motor to be tested was a 115 volt machine. Later, it was found that this fact was advantageous. The voltage of the rectifier could be controlled by changing the firing angle of the tubes, and, therefore, could be brought down to 125 volts. However, to run the tests under these conditions seemed undesirable since the harmonic content of the rectifier is very much greater if the firing angle is delayed sufficiently to give 125 volts output.[10] To allow this condition to prevail seemed to impose an unfair disadvantage on the rectifier, since the results were to be compared with DC generator operation.

To solve this problem, two DC motors, as nearly identical as possible were used together. The armatures were connected in series, and the shunt fields were connected in series. The complete circuit diagram of the connections is shown in Figure 6. Under certain conditions described below, the machines could be made to divide the voltage equally, and conditions for a 125 volt rectifier with one DC motor would be assimilated. Then, if it were desired to study the effect of using the rectifier with a decreased voltage setting, this could be done by simply using one DC motor alone, and the only factor which could possibly have changed would be the per cent ripple voltage, since input voltage to the test machine would again be 125 volts as before. It is seen, then, that the large difference in voltage ratings between the rectifier unit and the

FIGURE 6
WIRING DIAGRAM OF APPARATUS TESTED



V_1 — 150 VOLTMETER (DC)
I_1 — 150 AMMETER (DC)
W_1 — 20 KILOWATT METER (DC)
V_2 — 300 VOLTMETER (AC)
I_2 — 50 AMMETER (AC)
W_2 — 15 KILOWATT METER (AC)
M_1 — TEST MOTOR ARMATURE
M_2 — AUXILIARY MOTOR ARMATURE
G — LOADING GENERATOR
FR — FIELD RHEOSTAT
SR — STARTING RHEOSTAT

test motor, which at first seemed like a problem, became, instead, a rather fortunate condition, making it possible to study more thoroughly effects which might be encountered in industry under various conditions.

It has been stated previously that the two DC motors could be made to divide the input voltage under certain conditions. These conditions will now be discussed. Since the shunt field currents of the two machines are equal, the field fluxes are equal. Therefore, the back emf's and the terminal voltages will be equal only if the machines are running at equal speeds and if the armature currents are equal. The latter condition is satisfied since the armatures are connected in series. Several other minor considerations are necessary in order that the equality of back emf's be realized. For example, the brushes would have to be set the same on both machines so that the effect of armature reaction would not change the field flux more on one machine than the other; and, of course, it is rather obvious that the two machines should have identical construction, rating, etc., in order to carry out the tests successfully.

So the problem was to find a method of assuring that the speeds of the two machines would always be equal. Whether they would be equal or not depends entirely on the method of loading. Prony brake loads would be wholly unsatisfactory because as soon as some small disturbing influence occurred which caused the one machine to slow down slightly, the armature current would not rise by an amount to be expected under normal constant voltage DC motor operation because of the existance of the other armature in series with it, which, by hypothesis has not been slowed down. Therefore, the torque developed in the first machine would not be increased enough to bring it back up to speed, and the probable result would be that the one machine would stop and the other machine would have the whole 250 volts impressed on its armature. Its speed, of course, would have doubled with such a condition. Indeed, even at no load it was found difficult if not impossible to even start the two machines so that the speeds would increase together. Usually either one machine or the other would begin to rotate and come up to speed, and the other would not even move at all.

Since it was desired to study temperature rise, the proposed tests would necessarily be of rather long duration, probably four hours each. It is seen, therefore, that the speed stability problem had to be solved in a foolproof manner because it did not seem practical to construct any arrangement where it would be absolutely necessary to stand vigil during every minute of every test. Perhaps loading with self excited shunt generators would have provided a stable system since any decrease in speed would cause the generator to drop part of its load, allowing the motor to come back up to speed. However, it was realized that if the loads were AC synchronous generators tied in parallel, the speeds would always be exactly the same. This latter method was used to conduct the tests.

Several methods could have been used to load these two parallel alternators. Loading them into the three phase power lines in the laboratory would have been much more economical than using a resistance load. This was an important consideration, realizing the amount of energy which would be fed into the DC motors by the time the experimentation would be complete. However, this imposed the condition that the whole series of tests would have to be run at a constant speed of 1200 r.p.m. It was desired to note any differences which might exist between speed regulation of the motor when the change was made from rectifier operation to DC generator operation, and this could not have been studied with the constant speed restriction. Also, it would have been necessary to vary the shunt field current in the motors to vary the load, but it was desired to keep this current constant throughout the experimentation to limit the possibilities of changing any conditions whatsoever which might influence the results. Certainly varying the field current in a DC motor changes some of its losses because the flux density in the armature would change.

These considerations were minor problems which perhaps could have been solved. The main reason for not loading the generators into the AC power lines was that a DC shunt motor has an exceedingly flat speed-load characteristic. The brushes on a DC machine are usually set to minimize sparking, and when this is done, the armature reaction is demagnetizing. This tends to cause the motor to have a very flat speed-load characteristic or perhaps even a slightly rising one. If the characteristic is rising by even a very small amount, a condition of instability exists when the constant speed restriction is imposed. As soon as a small load is placed on the machine, it tends to increase its speed, but cannot, so more load is put on it, and immediately the load increases beyond bounds. In other words the larger the armature current becomes, the weaker the field flux becomes. This causes the back emf to drop off and a still larger armature current results. If the characteristic is only slightly drooping, it will be found that very minute changes in shunt field current vary the load by large amounts, so precise conditions would be difficult to attain and maintain.

Another possible undesirable effect which might have come about if the alternators had been loaded into the AC power lines would have occurred any time the power system frequency changed slightly. This frequency is changing continually by small amounts, and it is conceivable that this amount could be large enough to change the load considerably on the motor if it had a very flat speed characteristic because its speed would have to be proportional to the frequency of the AC power lines in the laboratory. Since all of the results of the experimentation are to be a comparison between rectifier and DC generator operation, exact conditions must be maintained.

In light of all these factors it was decided that the only satisfactory load for the alternators would be a three phase resistive load.

One other connection shown on the wiring diagram, Figure 6, should be explained at this time. The variable resistor shunted across the shunt field of one of the DC motors is for the purpose of intentionally making the shunt field currents in the two machines unequal. Until this time, the hypothesis has been that these two currents were equal so that with equal speeds the input voltage would be divided equally between the two armatures. This condition was postulated to simplify the description of how the voltage division could at least be controlled. It was found that the circuits used gave considerable voltage regulation for one reason or another (line drop, rectifier transformer regulation, over compounded generators, etc.) so that it did not prove possible to maintain a 250 volt input under all load conditions. If the voltage across the test machine had been allowed to vary, the results might have been in error to some extent, and the conclusions drawn might have been less significant than if strict control of voltage had been maintained. The shunting resistor caused the shunt field current in that machine to be less than the current in the test machine with a resulting decrease in back emf in the first machine. Therefore, if the input voltage decreased, it was always possible to bring the test motor armature voltage back up to 125 volts, which was used throughout the experimentation, simply by using the proper value of shunting resistance across the other shunt field. The net result was a greater torque developed in the test machine because of its greater flux density; therefore, the alternators were not loaded equally.

There is only one possible error that could have been introduced by using this expedient.[11] The assumption was later made that the alternators were operating at unity power factor. Under the conditions specified above, even though the resulting voltage and current from the two machines are obviously at unity power factor since the load is a pure resistance, nevertheless, neither machine would operate at unity power factor. This is true since the power outputs are unequal while the field excitations are equal. This statement can be seen to be true by observing the vector diagrams of Figure 7. The assumption is made that the synchronous impedances can be represented by pure reactances. In the first case, the alternators are loaded equally. In the second case, the one machine is being "pushed" harder than the other, so its generated voltage vector moves ahead a small amount. The net result is that it is now slightly under excited, whereas

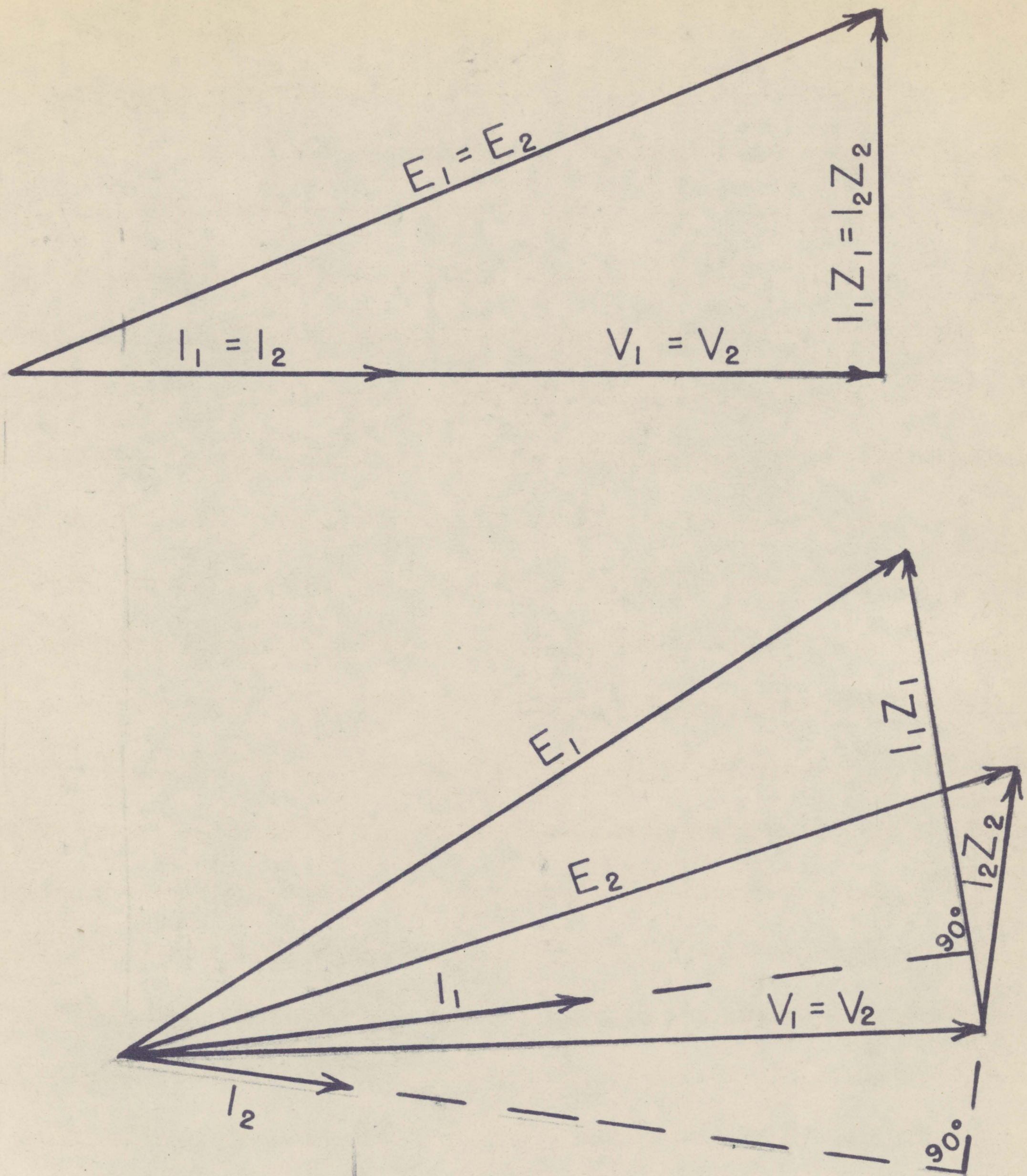


FIGURE 7
VECTOR DIAGRAMS OF
TWO SYNCHRONOUS GENERATORS
IN PARALLEL

the other machine is now over excited to supply to the first machine the necessary vars to cause the resultant output to be at unity power factor, which by hypothesis must be true. The efficiency test calculations were made on the assumption of unity power factor alternator load, but it will be shown later in the discussion of these calculations that the error is entirely negligible.

Before any test runs were made it was desired to inspect the commutator and brush settings on the two DC motors and to make such adjustments as would seem necessary for optimum operating conditions. The commutators were thoroughly cleaned by removing all dirt from the surface and from between the commutator segments. On a DC motor the best commutation will occur when the brushes are set slightly off the no load electrical neutral in a direction opposite to the rotation. This causes the armature reaction to be demagnetizing tending to make the speed regulation of the motor to droop less than in the case where armature reaction is negligible. In some cases the regulation may be negative. The motor used gave a very small positive speed regulation with the brush setting used. It was found possible to limit the sparking to an amount practically invisible with 125% load even with the worst possible conditions of ripple input voltage used throughout the experimentation.

Temperature Rise Tests

The first type of test conducted was a load test to determine the temperature rise at various points on the machine. Every test that was made using rectifier input of 250 volts was duplicated using DC generator input with 250 volts and was again repeated using 125 volts rectifier input. This latter arrangement gave the worst possible conditions of per cent ripple voltage that would ever be encountered in almost any practical application except in cases of extremely poor engineering, for it does not seem likely that a rectifier of a given voltage rating would be installed where it was expected to be operated at half voltage continuously.

Tests were made at 50% load, 100% load, and 125% load. It is necessary to specify at this time what is meant by a certain per cent load. Apparently, the only fair way to compare the rectifier with the DC generator as an energy source is to make two tests with equal motor output power, not equal motor input power. It did not prove convenient during this part of the experimentation to calculate the power output of the motor, so the following scheme was used to establish equality of conditions between tests. The alternator fields were always excited from the DC generators whether the DC motors were operated from rectifier or DC generator, and every test was made by adjusting the alternator fields so that their terminal voltage would be 220 volts. This assured that the losses in the alternator were always identical with a previous run so long as the output power was the same as in a previous run. Likewise mechanical power output of the motor was identical with mechanical power of a previous run if the output of the alternator was identical with a previous run. In this way the runs were standardized, so to speak. It was realized that a run with the rectifier might have been called equivalent to a run with the DC generators merely if the motor armature current had been the same in the two cases. However, the RMS current in the armature using the rectifier might have to be larger than with the DC generators because some of the current would be alternating current components which contribute little or nothing to the mechanical torque. The result, if appreciable, would reflect favorably upon the rectifier. This effect was eliminated as explained above.

All runs were of 4 hours duration except the 125% load runs which were of one and one-half hours duration. The temperature readings for the 50% and 100% load runs were taken every half hour except the armature and commutator temperatures which were taken every hour. The "American Standards for Rotating Electrical Machinery"[12] states that it is standard procedure to shut down the machine on tests of this sort every hour to take these temperatures when absolutely necessary, if the shut down time is not over one minute. On the 125% load tests readings were taken every 15 minutes except the armature and commutator temperatures, which were taken every half hour. The machine was tested under every condition mentioned above as a shunt machine; the tests were all repeated using a cumulative compound connection. This made a total of 18 runs that were made.

Every effort possible was made to maintain the room temperature constant throughout each run. When this condition could not be maintained within two or three degrees centigrade, the test was repeated.

The tests were purposely arranged in a more or less random order. For example, all the shunt motor runs were not made in succession; all the rectifier input tests were not made in succession; all the 100% load runs were not made in succession. The purpose of this procedure was to eliminate the possibility of any random influences affecting the results, which might accumulate over a period of several weeks, such as poor thermocouple contact or change in ambient temperature or humidity caused by seasonal fluctuations, etc. It was possible that such influences might radically effect the conclusions to be drawn.

The temperatures were measured with copper constantan thermocouples using a melting ice reference. These thermocouples give voltages in the order of four milli-volts over the temperature range encountered. To measure this magnitude of voltage accurately without loading the circuits, a Leeds and Northrup potentiometer was used in conjunction with a spot-light galvanometer as a null indicator. A standard cell was used to calibrate the potentiometer. A schematic diagram of the switching arrangement used to measure quickly the ten temperatures and a diagram of the potentiometer is shown in Figures 8 and 9.

A calibration for a copper constantan thermocouple was gotten from the A. E. Knowleton Standard Handbook for Electrical Engineers,[13] and this calibration was checked against the thermocouples actually used. The calibration chart is shown in Figure 10. It is sufficiently linear that linear interpolation between the points 0°, 25°, 49°, 72°, and 94° centigrade was made when the voltage temperature conversions were calculated.

The choice of just what parts of the machine on which temperature rise would be measured was an important matter. Any adverse effects which rectifier operation had would probably be more apparent at some points than others. The following list shows the locations tested.

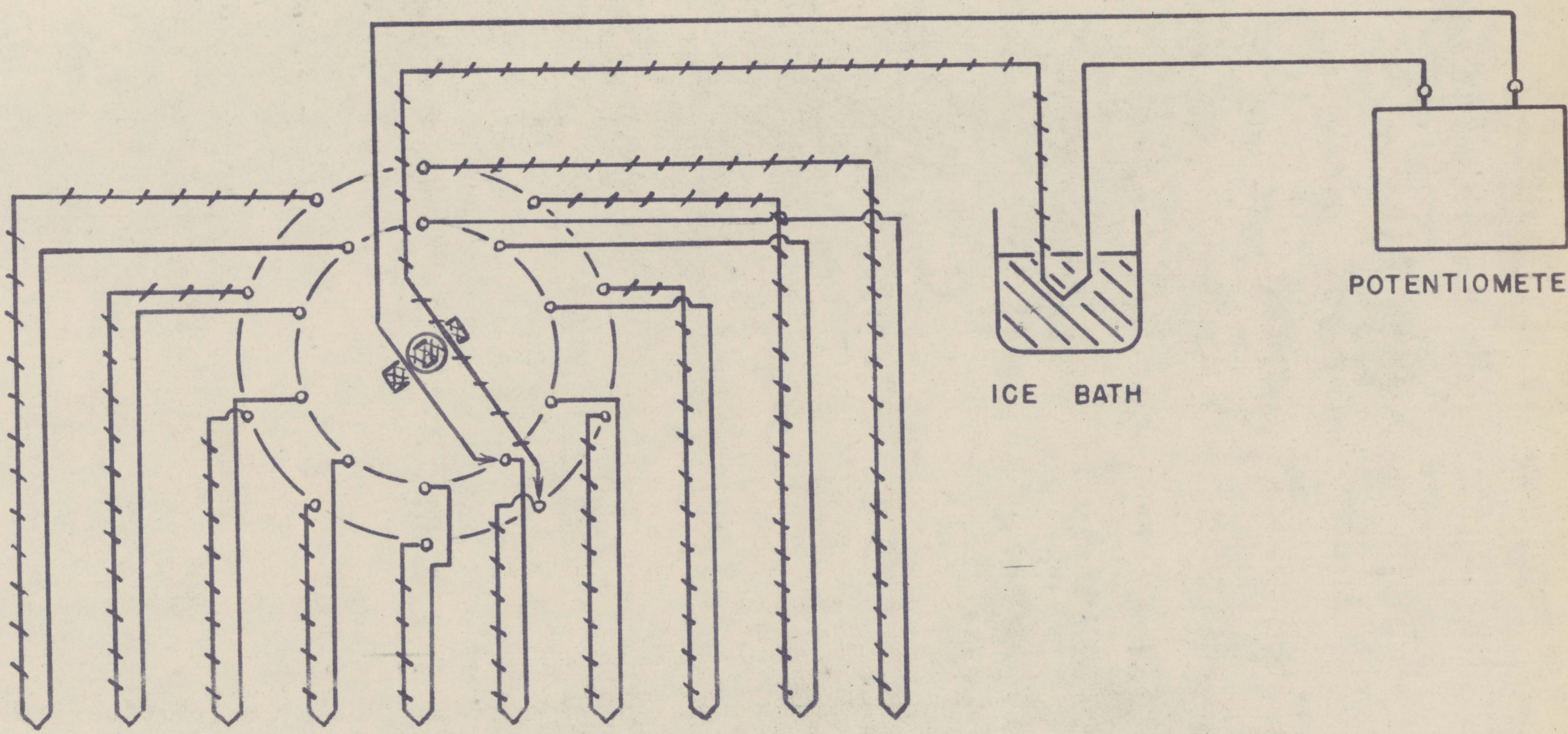
Table 1

Locations on Motor where Temperature was Measured

One point on the yoke of the machine

The leading tip of two of the four field poles

The trailing tip of two of the four field poles



CONSTANTAN
ALL OTHER CONNECTIONS COPPER

FIGURE 8
SWITCHING ARRANGEMENT
OF THE
THERMOCOUPLES

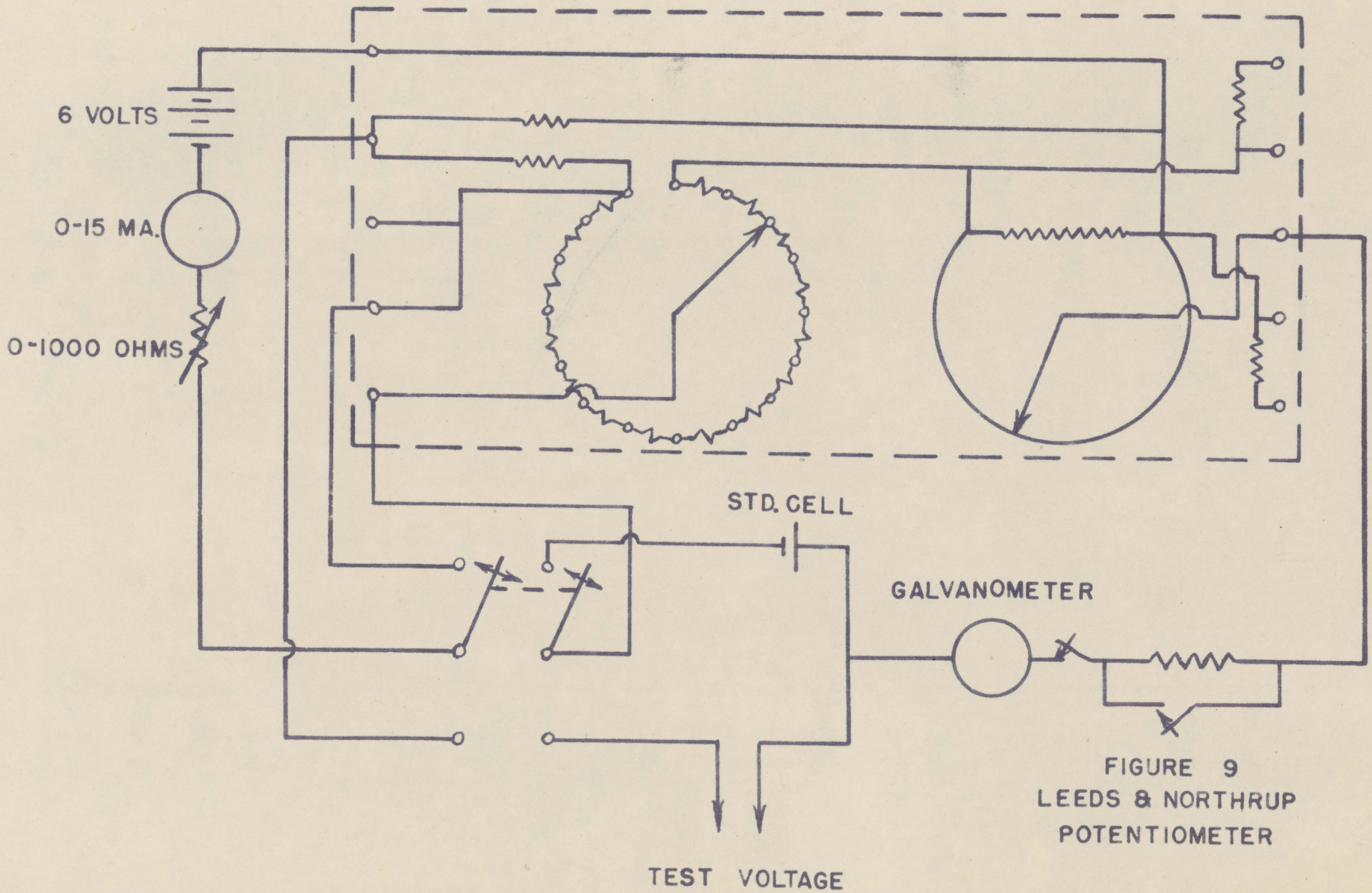


FIGURE 9
LEEDS & NORTHRUP
POTENTIOMETER

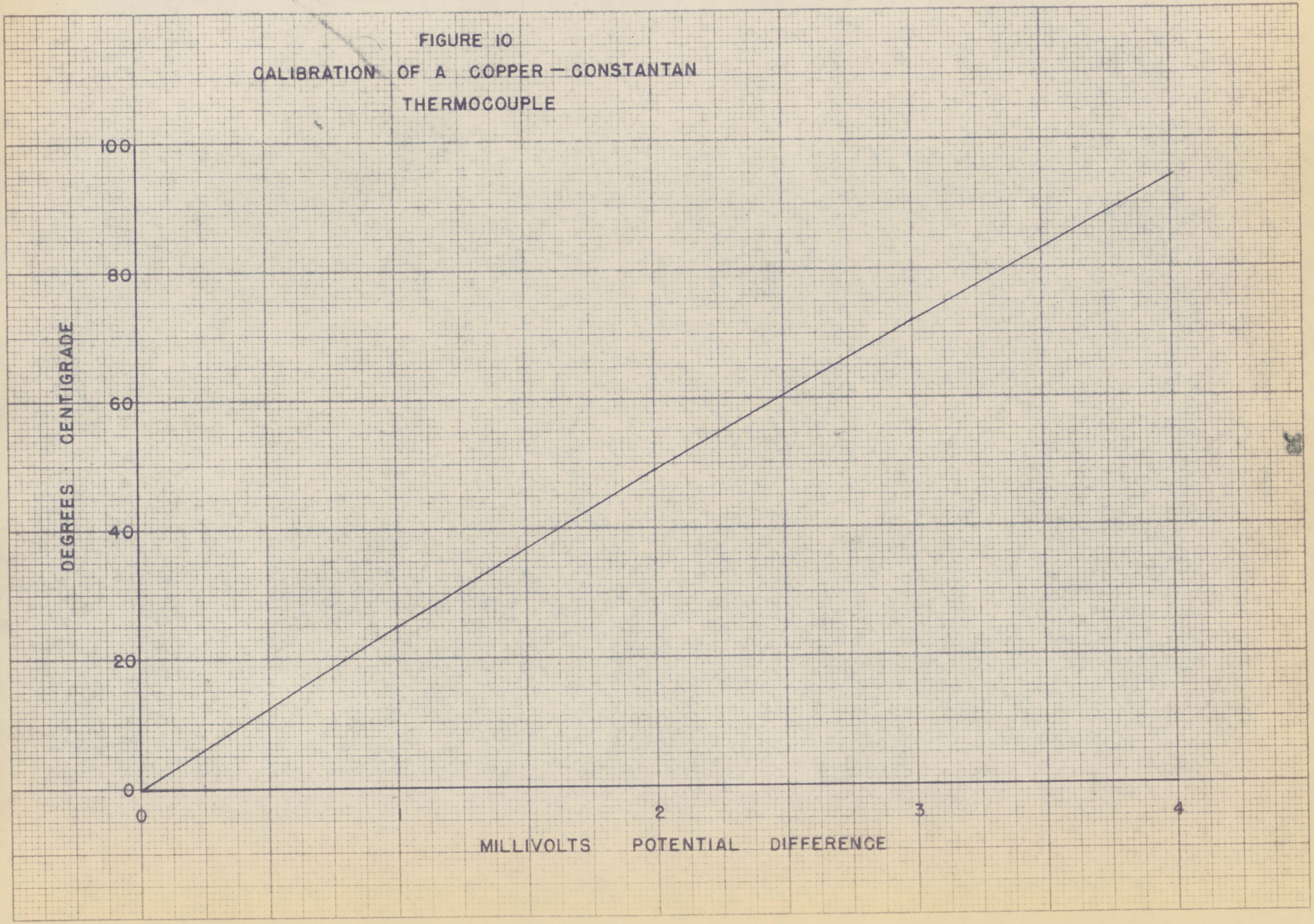


FIGURE 10
CALIBRATION OF A COPPER — CONSTANTAN
THERMOCOUPLE
DEGREES CENTIGRADE
0
20
40
60
80
100
0
1
2
3
4
MILLIVOLTS POTENTIAL DIFFERENCE

The face of both commutating poles

The winding of one field pole

The surface of the armature

The surface of the commutator

The results of a thesis[14] similar to this one employing a three phase rectifier showed that considerable overheating would occur at any point which had armature current passing through it. It was desired to investigate such possible effects using the six phase rectifier.

The results of these tests are shown in the section devoted to discussion of results.

Efficiency Tests

The second type of test to be conducted was an efficieny test. To carry out this type of test was a rather involved procedure because no direct method of measuring motor output was available. It was necessary to load the machine, measure motor input power with a wattmeter, measure alternator output power by the two wattmeter method, calculate the alternator losses for each point in the tests, and thereby calculate the power output and efficiency of the motor. A description of how the alternator losses were determined is given below. The efficiency test was made over the range from no load to 125% rated load for the motor, repeating the test three times, once for each of the three types of input used in the temperature test, namely, DC generator, rectifier with full voltage, and rectifier with decreased voltage. Again the second DC motor was used to assure a constant voltage across the armature of the test machine.

To get the data for motor input vs. alternator output was obviously a simple matter. Calculating the losses of the alternator was rather complicated however, and just how this was done will now be explained. To make calculations of this sort on a machine from calibration tests always involves certain approximations and errors, but the following method is reasonably accurate. Any errors, if not too large, are of little consequence since it is a comparison between rectifier and DC generator which is desired. The tests were conducted so that any such errors would be consistent between runs.

One of the first things that becomes apparent about the losses of an alternator[15] is that its iron loss due to the main field flux is almost wholly determined by two factors, speed and terminal voltage. Varying the field current on a synchronous generator connected to constant voltage lines, for example, will not change the iron losses much, although the power factor will vary, thereby changing the armature current and armature copper loss. This fact, which at first is not at all obvious, comes about because the armature reaction causes the total field flux which threads the armature winding to remain relatively constant even though the field current is varied, so long as the terminal voltage remains constant. The vector diagram in Figure 11 shows this phenomenon. Vector V represents the terminal voltage. Vector E represents the voltage that would be induced in the armature if the load current were zero and is, therefore, a measure of the magnetomotive force of the field winding. Vector $I_a X_r$ represents the voltage drop due to flux loss by armature reaction. Therefore vector E_g might be thought to represent the actual voltage induced in the armature. However, this is not a measure of the armature iron loss because the flux loss is greater than the amount lost

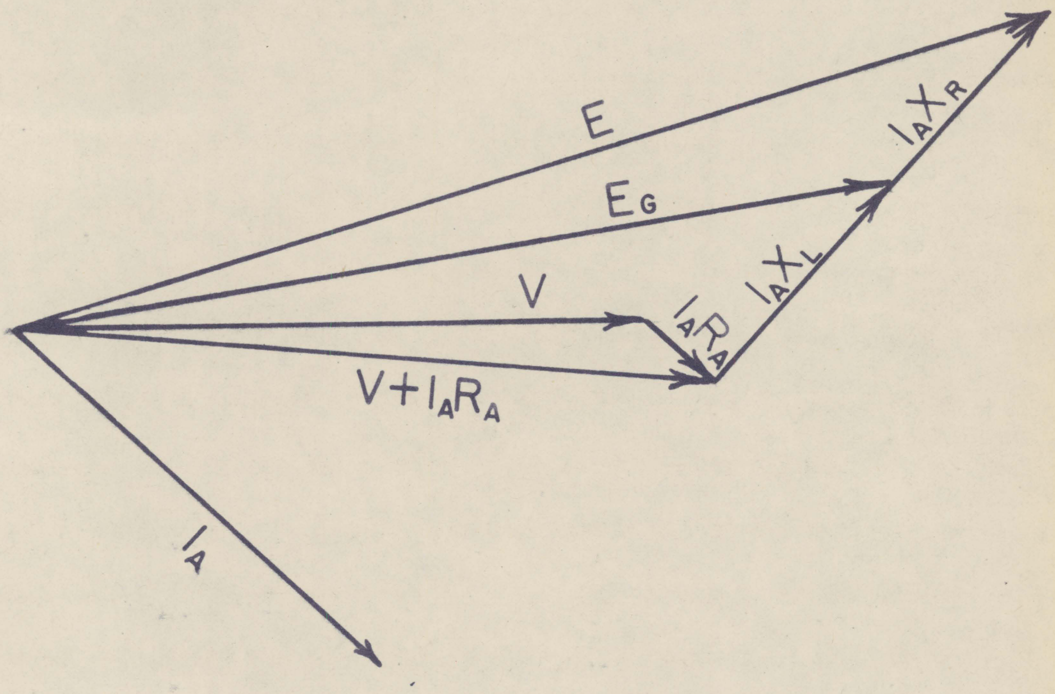


FIGURE II
VECTOR DIAGRAM
OF A
SYNCHRONOUS GENERATOR

from armature reaction. Leakage reactance causes another drop, vector I_aX_l, of the same nature as drop I_aX_r, so the vector $V \neq I_aR_a$ is found to be the measure of iron loss. The problem is further simplified by the fact that all tests were made at unity power factor, or nearly so, as explained under "Test Procedure," so $V \neq I_aR_a$ is an arithmetic addition. It was foreseen that keeping the terminal voltage at 220 volts throughout all tests would again simplify calculations, and this was done, varying field current as load was added, so that the terminal voltage was always 220 volts. So it is seen that the loading was done in such a way that the iron loss in the alternator was, for all practical purposes, dependent only upon speed, and this loss could be measured easily by test.

The first job in calibrating the alternator was to run a no load test on the driving motor with the alternator uncoupled. Motor shunt field current throughout the calibration procedure was maintained constant so that friction, windage, hysteresis, and eddy current losses for the motor would be functions of speed alone. Speed was varied by changing the armature voltage. Measuring armature input power vs. speed and subtracting from this the armature $I_a^2R_a$ loss gave a graph of motor friction, windage, hysteresis, and eddy current losses vs. speed for the motor which was used subsequently.

Next, the alternator was connected and driven at various speed with excitation sufficient in each case to give 220 volts output at no load. Measuring motor armature input power vs. speed and subtracting from this the various motor losses previously determined gave a graph of alternator friction, windage, hysteresis, and eddy current losses vs. speed.

The only other alternator loss to determine was the stray load and armature I^2R loss which was assumed to be dependent upon armature current only. The test was similar to a short circuit test on a transformer. The machine was short circuited and driven at various speeds, each time with sufficient excitation to give rated current in the armature. Motor armature input power vs. speed was recorded. By subtracting the motor losses as in the previous test, alternator friction, windage, armature copper, and stray load loss were determined. Apparently the friction and windage losses had to be separated from this, since they were to be taken into account by the previous tests, so another run was made with no excitation and with the armature circuit open.

The "equivalent" or "apparent" armature resistance could now be calculated using the relationship:

$$\text{Armature copper and stray load loss} = I_a^2 R_a.$$

This resistance was found to be relatively independent of speed and armature current, and a mean value from all the readings was computed and found to be 0.127 ohms per phase.

The field losses of the alternator did not have to be taken into account because they were not supplied by the motor, and they contributed nothing to the alternator power output.

The results of these tests are shown on Figures 12 and 13, and from these graphs the efficiency of the motor for all the points in the efficiency tests was calculated. The results of the efficiency tests are shown in the section devoted to discussion of results.

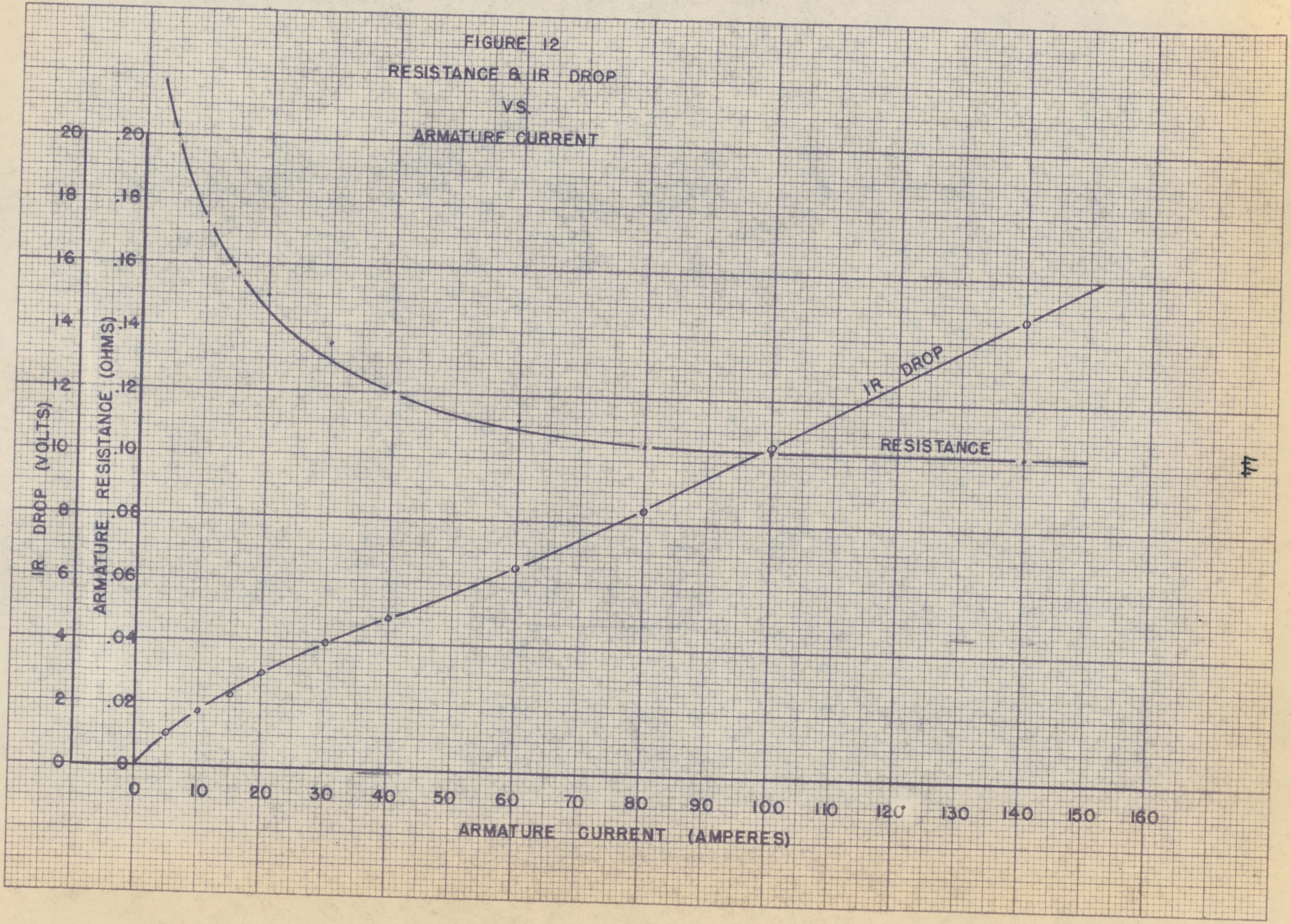


FIGURE 12
RESISTANCE & IR DROP
VS.
ARMATURE CURRENT

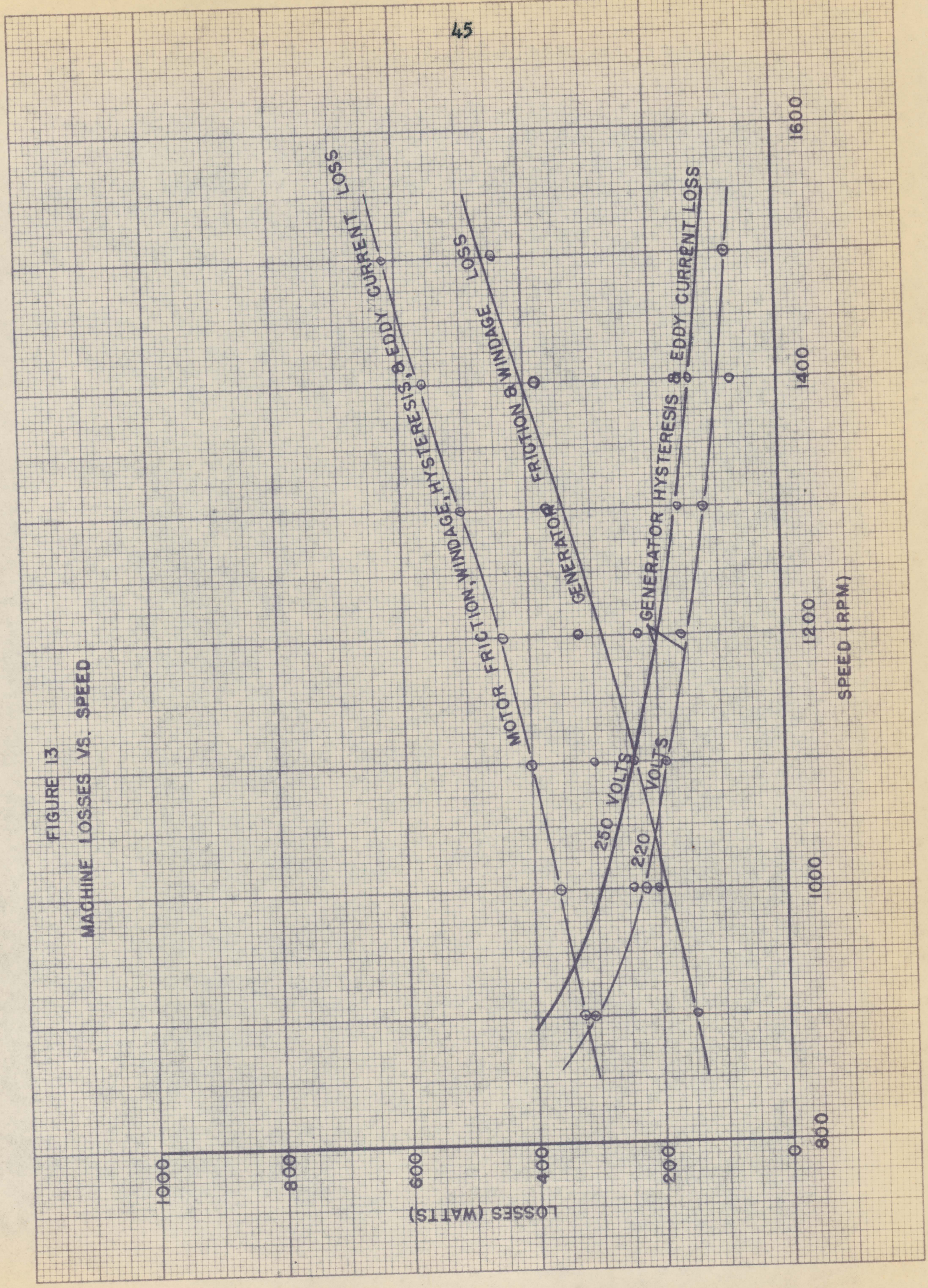


FIGURE 13

MACHINE LOSSES VS. SPEED

Voltage and Current Wave Forms

The voltage and current wave forms of the rectifier under various conditions were observed on an oscillograph and photographed. Since and ordinary oscillograph would not show the DC component of the quantity being observed, special measures were taken to show a zero axis so that a comparison between the ripple component and the DC component could be made in each case. This was done very simply, as described below, using an electronic switch.

The electronic switch used was provided with two input channels, A and B, and one pair of output terminals which were connected directly to the oscillograph. The electronic switch fed the oscillograph first, with the input to channel A, and second, with the input to channel B, alternating between the two signals at a frequency determined by a dial setting. The instrument was also equipped with a balance which provided a means of adjusting the relative vertical positions of the two signals. This arrangement was used feeding the rectifier wave into channel A and feeding no signal at all into channel B. Signal B then appeared as a straight line on the oscillograph. Using the balance adjustment, signal B could then be used as a base line.

Certain calibrations, however, were necessary in order to know where to place the base line. Feeding 60 cycle voltage or current into the circuit and observing the resulting pattern on the oscillograph gave a means of finding the sensitivity in inches per volt or inches per ampere. Knowing this sensitivity, the base line could simply be placed properly by observation, knowing the value of the DC voltage or current actually present.

Observing voltages was done by placing a resistive voltage dividing network across the power lines, tapping off a signal of magnitude suitable for the electronic switch. Current wave forms were observed by placing a very small resistance in series with the current. It was assumed that this resistance did not affect appreciably the wave form being observed.

Photographs of the input voltage and armature current at light and heavy load were taken for rectifier output voltages equal to one half rated voltage and full voltage. These photographs are shown in the section devoted to discussion of results.

Harmonic analyses of these same voltages and currents were made using a wave analyzer. This information is included in the section devoted to discussion of results, comparing the data with information which can be obtained visually from the photographs of the wave forms.

A Study of the Commutation

Photographs of the commutation were taken in order to make a comparison between the commutating ability of the motor when using the DC generator source and when using the rectifier source. The amount of sparking at the commutator is important, of course, because this sparking can cause the temperature rise of the commutator to be excessive and because it can cause pitting of the commutator.

Since it had been observed that the commutation was not much worse with rectifier input than with DC generator input, much care was necessary in the preparation of these photographs in order that a visual comparison would be possible. In developing the negatives, care was taken to make the development time the same for all the exposures. Exposure time on the camera was in all cases one second. In making the prints, exposure time with every negative was made identical by using a time delay relay, the normally closed contacts of which were placed in series with the printer light bulb. When the power switch was closed, both relay and light bulb were energized. The relay served to de-energize the light bulb at the proper time. This arrangement proved very useful in making all the photographs shown in this thesis, making it a simple matter to produce five identical prints of each negative.

These commutation photographs are shown in the section devoted to discussion of results.

V. Discussion of Results

A knowledge of the true comparison between rectifiers and DC generators as power sources for operating DC motors has always been important when selecting AC to DC conversion equipment for a new installation. As discussed in the introduction, many factors influence such a choice. The matter of comparing purchase price and installation cost would presumably present no problem to the prospective buyer since prices would of course be readily available from the manufacturer; also, there seems to be abundant information concerning the efficiency to be expected from various types of converting equipment. Probably the consideration of motor performance to be expected when operated from a rectifier has been the most questionable matter in the minds of many persons faced with making such a choice because very little quantitative data is available. It is generally accepted that a rectifier can hardly be expected to perform more satisfactorily than the rotating machine in this regard, so the questions remain to be answered, "How much worse is the performance with rectifiers compared to operation with rotating machine sources?" and "Does this margin overshadow the advantages which might be derived from rectifier operation?"

Factors Affecting the Heating in a DC Motor

Various machine characteristics will cause the motor to have additional heating because of the input voltage ripple of a rectifier. Since an alternating component of current will be present in the field winding, there will be a variation of the field flux not present when using a continuous current. These variations will cause additional hysteresis and eddy current losses in the field poles and yoke. This effect may be more pronounced at certain places in the magnetic circuit since, for example, the leading pole tip of a loaded motor has a more dense magnetic flux than the trailing pole tip. It does not seem likely that the armature iron would be heated much more from this cause since the pulsations of flux would certainly be very small compared to the complete reversal of flux that the armature iron experiences every time it moves 180 electrical degrees. The heating in the field winding could be increased, however, since the r.m.s. value of the current would be greater than the average value.

Pulsations of the armature current are likely to produce more pronounced effects than pulsations of field current for several reasons. The per cent armature ripple current will be greater than the per cent shunt field ripple current because the shunt field winding, having a much larger number of tuns, will present a much larger inductive effect than the armature will present. In addition the armature circuit is represented by a practically constant back e.m.f. in series with a very small resistance and an inductance, and this back e.m.f., while limiting direct components of armature current, is not effective in limiting alternating components in the armature. Therefore, the ratio of "apparent DC resistance" to total AC impedance may not be nearly so favorable to that found in the field cirucit, where there is a large resistance to both AC and DC components of current. "Apparent DC armature resistance" is to be interpreted as DC armature circuit voltage divided by DC armature current, being a quantity much larger than the actual armature circuit resistance measured with the machine at stand still. This quantity will include a fictitious resistance which would absorb an amount of power equal to the power developed in the armature. It is non-existent to alternating components of armature current.

It is seen, therefore, that the pulsations of armature current may be quite pronounced when compared to the pulsations in the field circuit. It is conceivable that the armature current might even be intermittent, passing through zero for appreciable lengths of time while the rectifier voltage wave was at its smaller values. This possibility can be understood perhaps more clearly when it is realized that small changes in armature input voltage produce large changes in armature current if the back e.m.f. stays constant. Just how pronounced the pulsations will be depends upon the amount of inductance in the armature circuit. This effect will be more pronounced at light loads since the direct component of armature current will be small.

These pulsations can increase the heating in the motor in several ways. For a given amount of torque the direct component of armature current must be a certain value whether the total current is pulsating or continuous. Therefore, the r.m.s. value of the armature current will be greater for a given horsepower output when using a rectifier than when using a rotating machine as a source. This obviously produces more heating in the armature copper. More heating in the armature iron, especially in the armature teeth, can occur because the pulsations of armature current produce additional hysteresis and eddy current losses in the iron adjacent to the conductors. Another influence that the pulsating armature current can have is to increase the effective winding resistance due to skin effect.

Compound and series machines can be adversely affected to a greater degree than shunt machines because the highly pulsating armature current is passed through the series field. This increases any of the several effects on increased iron losses as discussed previously; however, the series field may cause the armature current pulsations to be smaller than with shunt motor operation.

Commutation can be adversely affected by input ripple for several reasons. Because of the variation in the field flux there will be set up in the armature conductors being commutated short circuit currents due to transformer action. Apparently, from Lenz's law, these currents will tend to oppose the changes in flux just as current in the short circuited secondary of a current transformer tends to make the flux very small. The conditions are somewhat similar to the effect of equalizer connections on a lap winding, where short circuit currents in the winding tend to alter the flux in each pole so that the proper voltage is induced in each path. The currents set up by this transformer action may or may not be large enough to influence the armature ohmic losses appreciably, but their influence relative to commutation results from the fact that actual current in the conductors being commutated is no longer proportional to the commutating pole current. Hence, the commutating pole is no longer as effective in armature conductor current reversal as when field flux pulsations do not exist. Unfortunately, changing the number of turns on the commutating pole winding will not help this condition because it will be noted that the ratio of armature conductor current to commutating pole winding current is changing during the field flux cycle.

Other influences can adversely effect commutation when the armature current is pulsating. There will be hysteresis loss in the commutating pole which means that the commutating pole flux will not be in phase with the commutating pole winding current. Therefore, even if the transformer action explained above were negligible, still the commutation would be adversely affected. This hysteresis loss can also overheat the commutating pole.

In any DC machine one limit of commutation at heavy load will be commutating pole saturation, causing the flux to be no longer proportional to current. Since the peak value of current in a pulsating wave is more than its average, it would seem that commutation difficulties would start to occur at ligher loads due to commutating pole saturation than if the current were continuous.

This summarizes briefly the principle sources of additional heating that will occur to some extent when a machine is operated from a rectifier instead of a rotating machine. Just how much influence each effect has may be rather difficult to measure accurately and fortunately may be of little consequence except to the design engineer who strives to alter the construction of a machine to make it more suitable for rectifier operation. The purpose of this investigation is to measure by test the overall effects on the machine by subjecting it to actual operation under various conditions.

A Comparison of the Heating in the Motor Under Various Conditions

A comparison of the temperature rise tests is difficult to make with a casual glance at the curves of temperature rise vs. time. If the results of the three types of power sources, namely, DC generator, rectifier with full voltage, and rectifier with decreased voltage, had been widely divergent, small experimental errors would have been insignificant in the interpretation of results. However a casual glance will show the observer that a 5°C change in almost any one of the graphs could change one's opinion as to which type of power input caused the motor to heat up the most. One might conclude as a rough first approximation that no matter which of the three types of input were used, the temperature rise would be the same within about 5°C. However, detailed study of the graphs will give a more complete picture than this.

Before the finer points of comparison can be made, however, certain inherent errors of experimentation should be discussed. It was found humanly impossible with the conditions existing in the laboratory to control the initial conditions within the bounds necessary to assure accuracy within 5°C every time. In order for a run to be a valid indication the temperature of the room would have to stay constant for several hours before the run started so that the machine temperature at all points would be the same as room temperature at the beginning of the run. What is even more important, the room temperature would have to stay constant for the four hour duration of the run. In order to approach this ideal it was found necessary to open doors and windows on some days to keep the room temperature down, whereas on other days this procedure was unnecessary. Opening a window could cause circulation of air through the motor which could alter the results 5°C even though the room temperature was maintained constant. Humidity conditions could also change the results. No readings of humidity were taken, and no control of humidity was possible. It follows, then, that interpretations must be in terms of trends rather than absolute values of some particular set of runs. It should be realized that one could not expect to duplicate any particular run by setting up the original equipment and expect to get results to check closer than perhaps $5^{o}C$ on the average. One cannot conclude, for example, that, just because the curve for yoke temperature using rectifier input was lower than with DC generator input voltage when the load was 100% rated value, it necessarily follows that motors run cooler at full load when operated from rectifiers than when operated from DC generators; neither should one conclude that such an absurd indication throws unfavorable light on the experimental work.

It can surely be stated that the expected results should be that DC generator input will give the coolest operation, rectifier input with full voltage should give hotter operation, and rectifier input with decreased voltage should give the hottest operation. With this in mind discrepancies can be weighed more intelligently and trends will be more apparent.

The most obvious trend is shown by the fact that, on almost every graph, the rectifier with decreased voltage caused the motor to run the hottest when the load was 125% rated. This was also true on most of the 100% rated runs with the compound motor. On the remaining graphs there was no such definite trend shown by the rectifier with decreased voltage, this type of connection many times giving the intermediate value of temperature and sometimes the lowest. The writer does not believe that this latter statement can be used to imply that the compound motor gave more adverse performance than the shunt motor gave when rectifier input was used because a comparison of DC generator runs with rectifier full voltage runs shows no such trend.

Another noteworthy trend can be seen by comparing all the results obtained at the commutator and armature. It would seem that these locations might be the most important points to observe for they will usually be the hottest parts of the machine. These parts are the ones most likely to be overheated by the phenomena being studied. The most striking thing about these graphs is that, in general, the three types of input give closer checks on the temperature rise than are found at any other point on the machine. These graphs should be considered to be more dependable than the other graphs because each time that a reading was taken, it was necessary to place the thermocouple on the test spot after the machine was shunt down, and therefore better contact than in some other rather inaccessible spots was assured.

It can be stated at this point that the results which can be interpreted by mere observation of the curves seem to indicate that the rectifier, even with decreased voltage, is only slightly inferior to DC generator operation from the point of view of heating effects. Quantitatively, the only other means of comparing the three types of input using these graphs is to average the temperature rises over the 10 points of the machine tested for each of the 18 conditions used. These results are given in Table 2.

Table 2

Average Temperature Rise of the Motor

Shunt Motor

	DC Generator Input	Rectifier Input With Full Voltage	Rectifier Input With Decreased Voltage
50% Load	21.85	20.45	22.15
100% Load	36.80	36.90	35.15
125% Load	40.45	43.40	44.55

Compound Motor

	DC Generator Input	Rectifier Input With Full Voltage	Rectifier Input With Decreased Voltage
50% Load	21.20	20.15	24.35
100% Load	38.90	35.00	43.50
125% Load	46.25	43.75	48.90

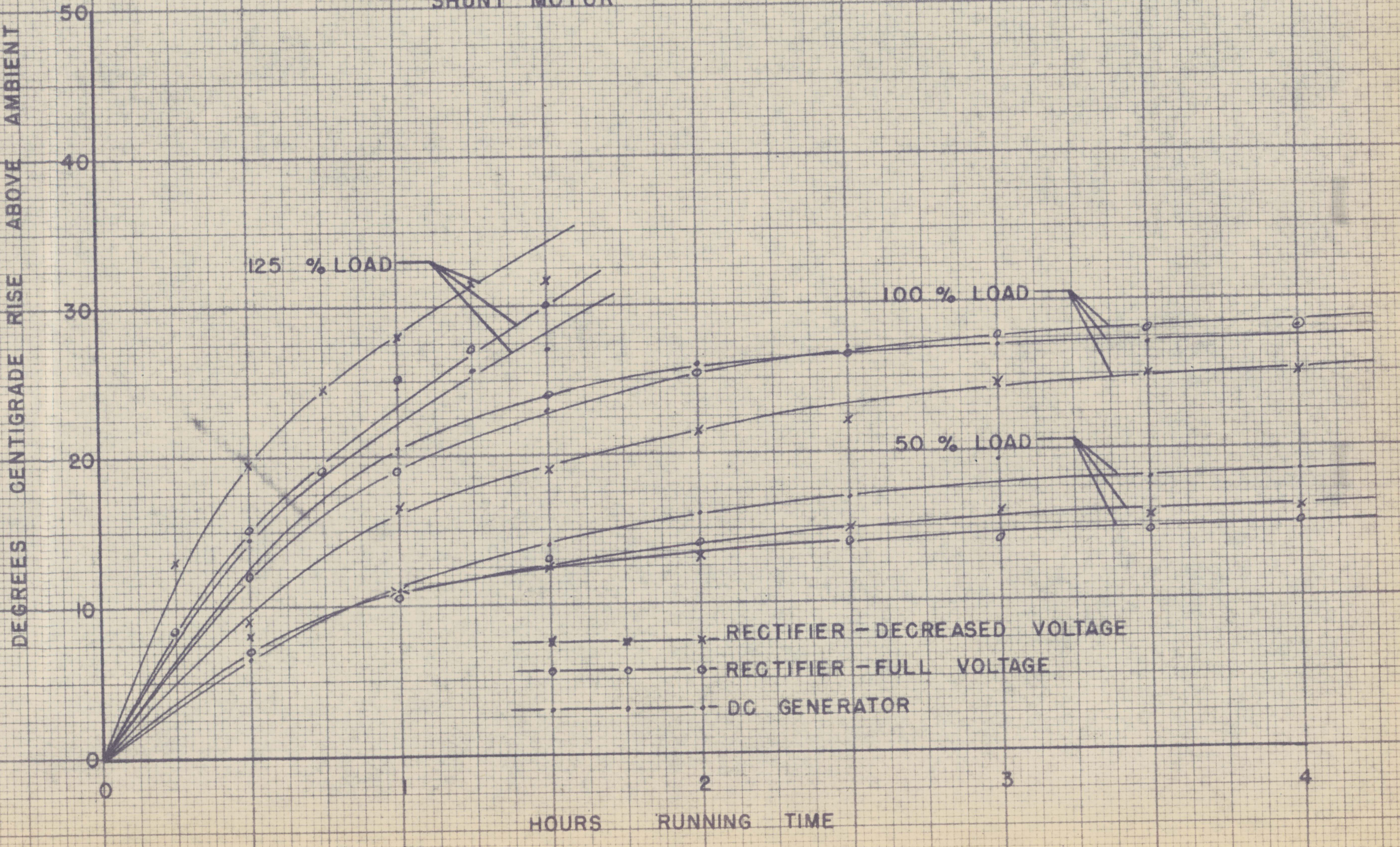
It is easily seen that the average temperature rise for any given value of load was independent of the type of input used within five degress except for one condition; namely, when the compound motor was run with 100% load using the rectifier with decreased voltage. Considering all the possibilities for experimental error as discussed under "Test Procedure," it seems reasonable to weigh this value lightly, especially since the 125% load run showed no such decided trend. Careful study of the table shows that the contrast between shunt and compound operation is greater than the contrast between DC generator input and rectifier input.

FIGURE 14

TEMPERATURE RISE VS. RUNNING TIME

YOKE

SHUNT MOTOR



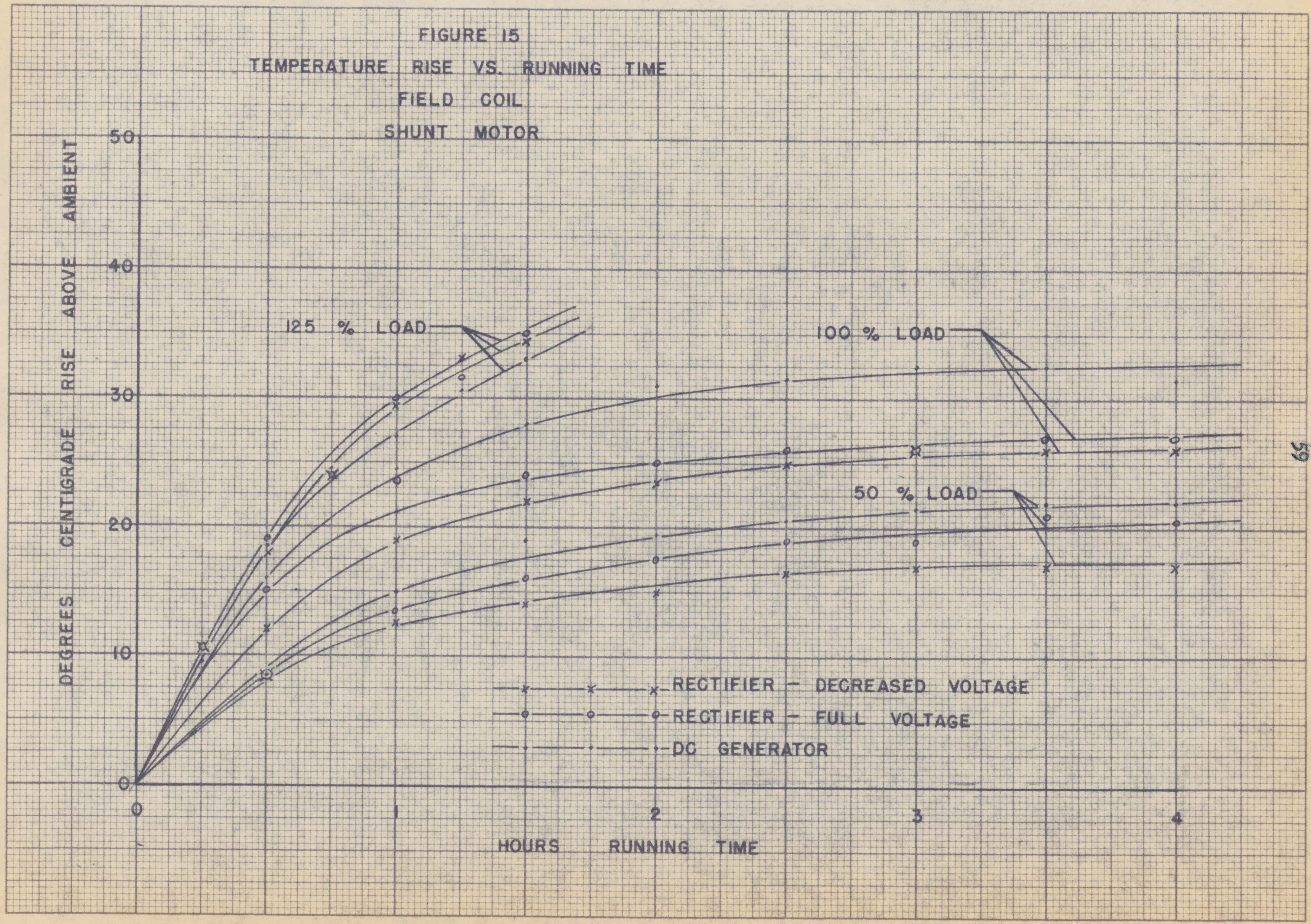


FIGURE 15
TEMPERATURE RISE VS. RUNNING TIME
FIELD COIL
SHUNT MOTOR
DEGREES CENTIGRADE RISE ABOVE AMBIENT
0
10
20
30
40
50
125 % LOAD
100 % LOAD
50 % LOAD
RECTIFIER - DECREASED VOLTAGE
RECTIFIER - FULL VOLTAGE
DC GENERATOR
0
1
2
3
4
HOURS RUNNING TIME

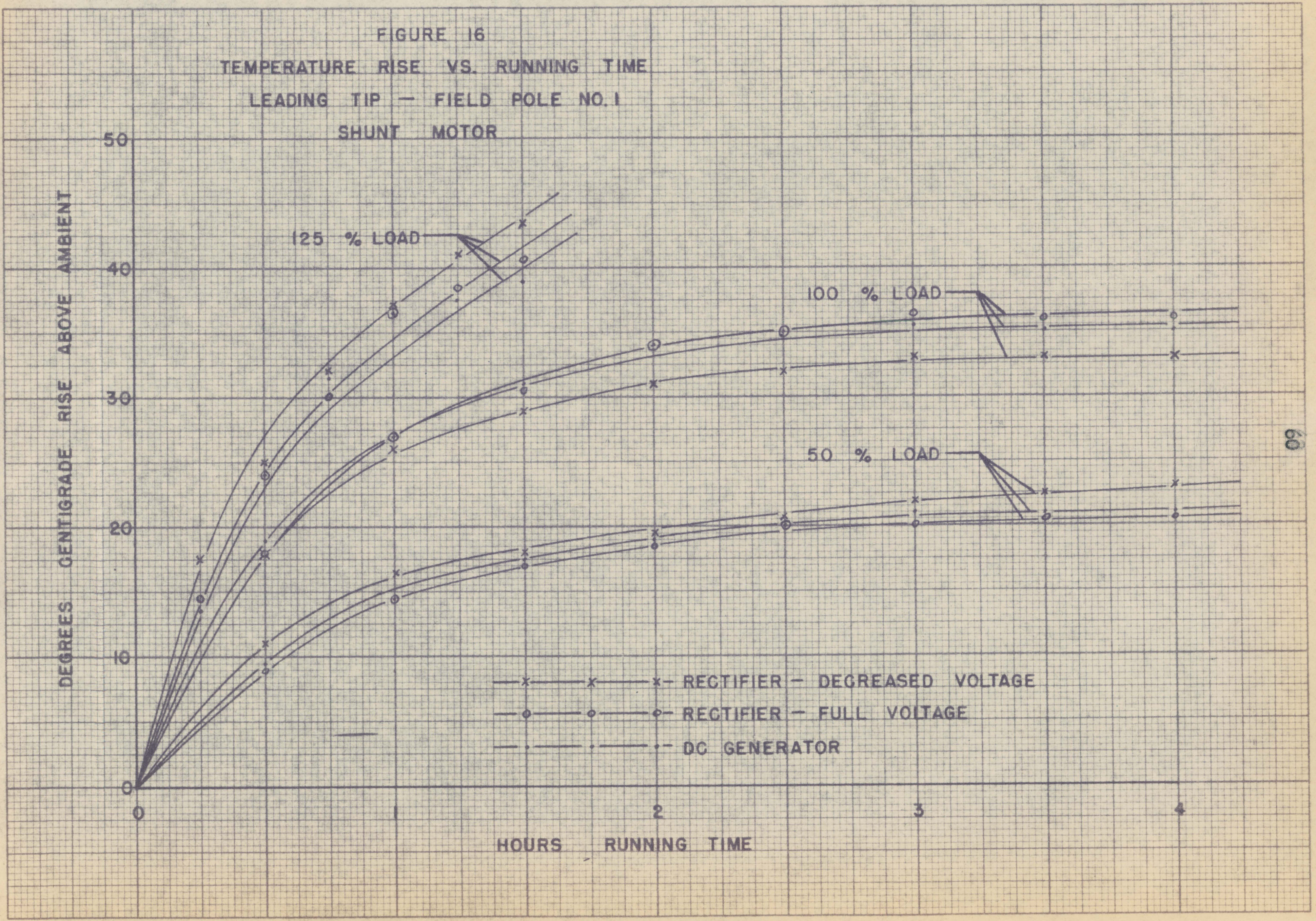


FIGURE 16
TEMPERATURE RISE VS. RUNNING TIME
LEADING TIP – FIELD POLE NO. 1
SHUNT MOTOR

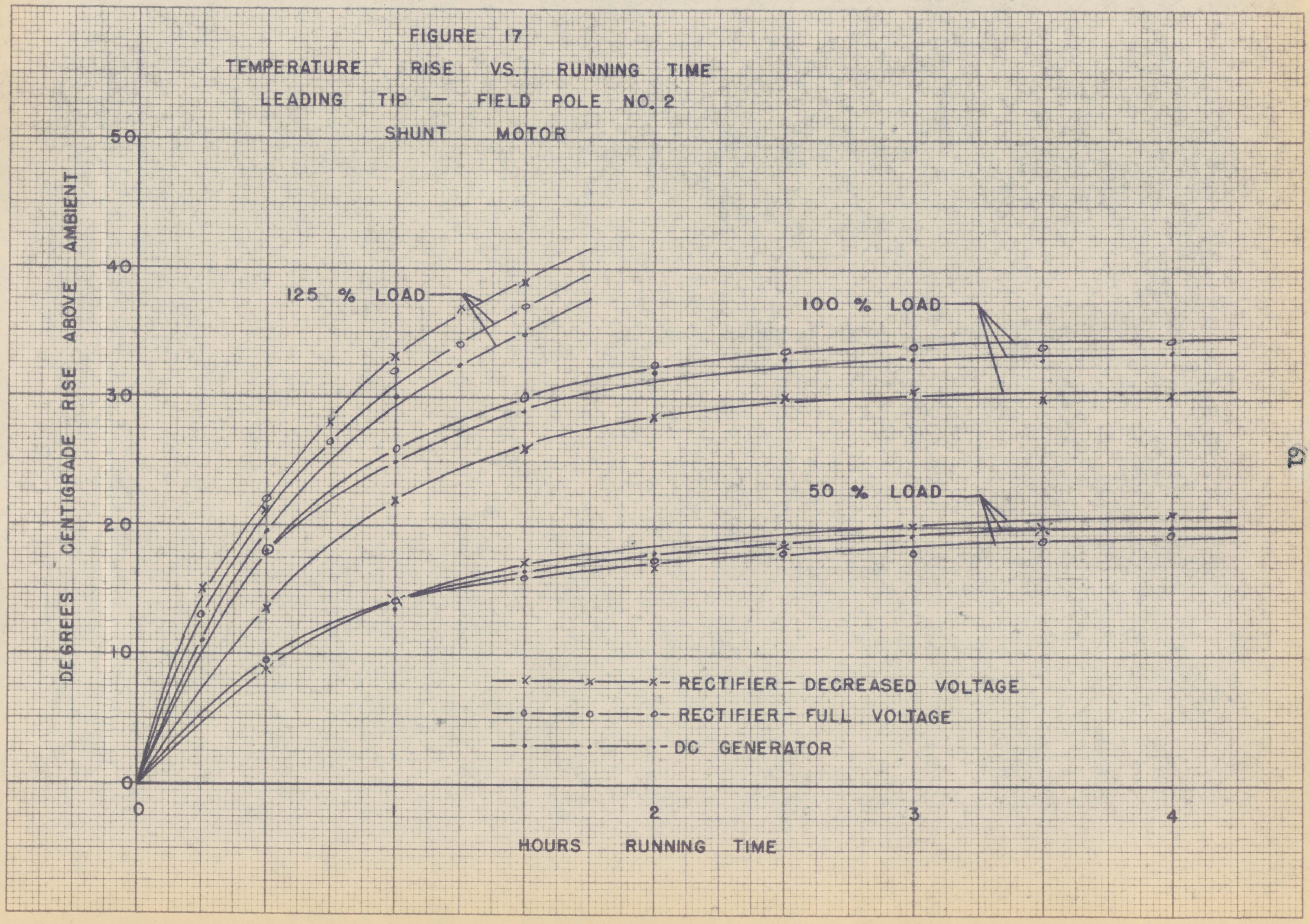


FIGURE 17
TEMPERATURE RISE VS. RUNNING TIME
LEADING TIP — FIELD POLE NO. 2
SHUNT MOTOR
125 % LOAD
100 % LOAD
50 % LOAD
RECTIFIER — DECREASED VOLTAGE
RECTIFIER — FULL VOLTAGE
DC GENERATOR
DEGREES CENTIGRADE RISE ABOVE AMBIENT
HOURS RUNNING TIME
0
10
20
30
40
50
1
2
3
4

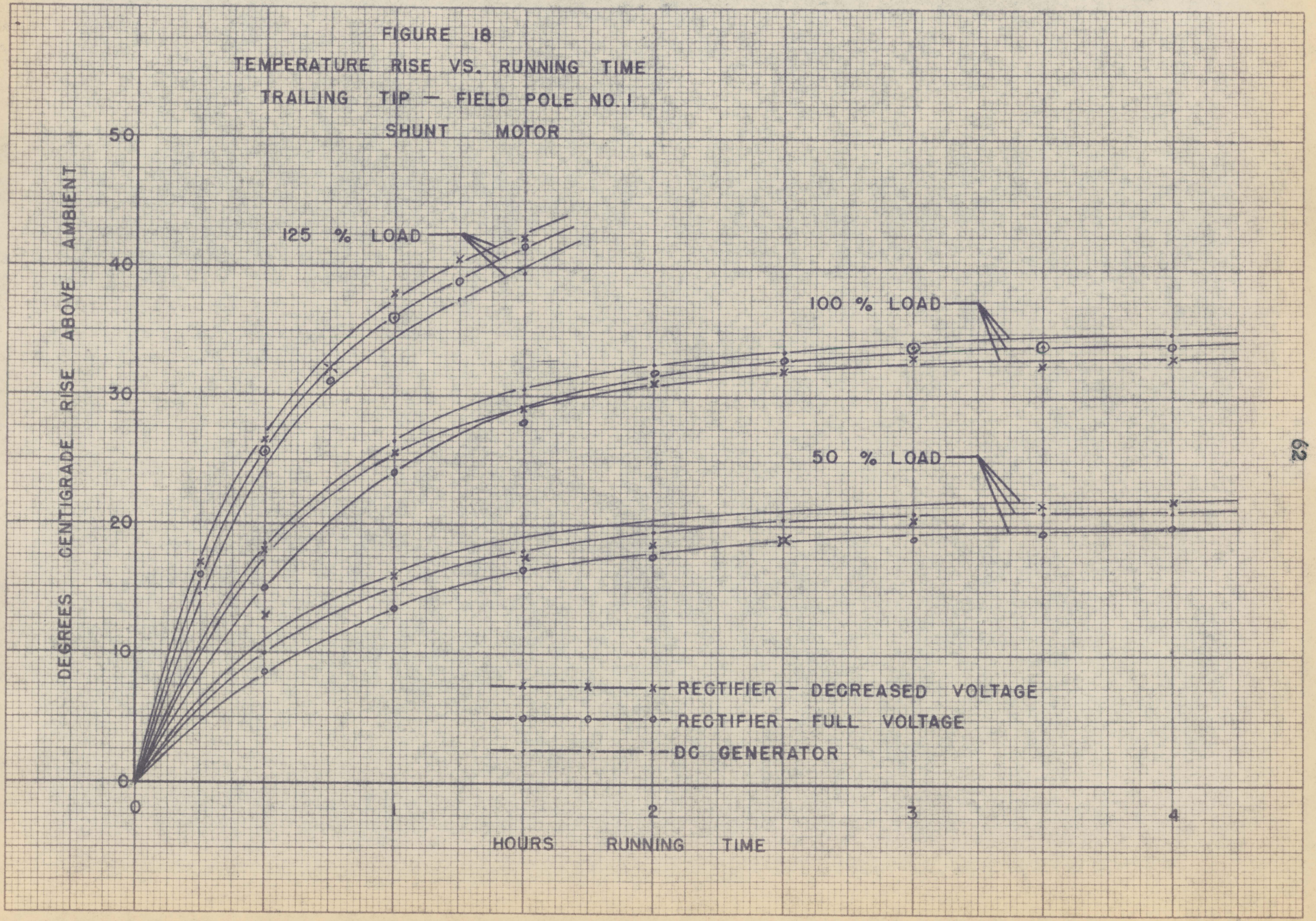


FIGURE 18
TEMPERATURE RISE VS. RUNNING TIME
TRAILING TIP — FIELD POLE NO. 1
SHUNT MOTOR
125 % LOAD
100 % LOAD
50 % LOAD
RECTIFIER — DECREASED VOLTAGE
RECTIFIER — FULL VOLTAGE
DC GENERATOR
DEGREES CENTIGRADE RISE ABOVE AMBIENT
0
10
20
30
40
50
0
1
2
3
4
HOURS RUNNING TIME

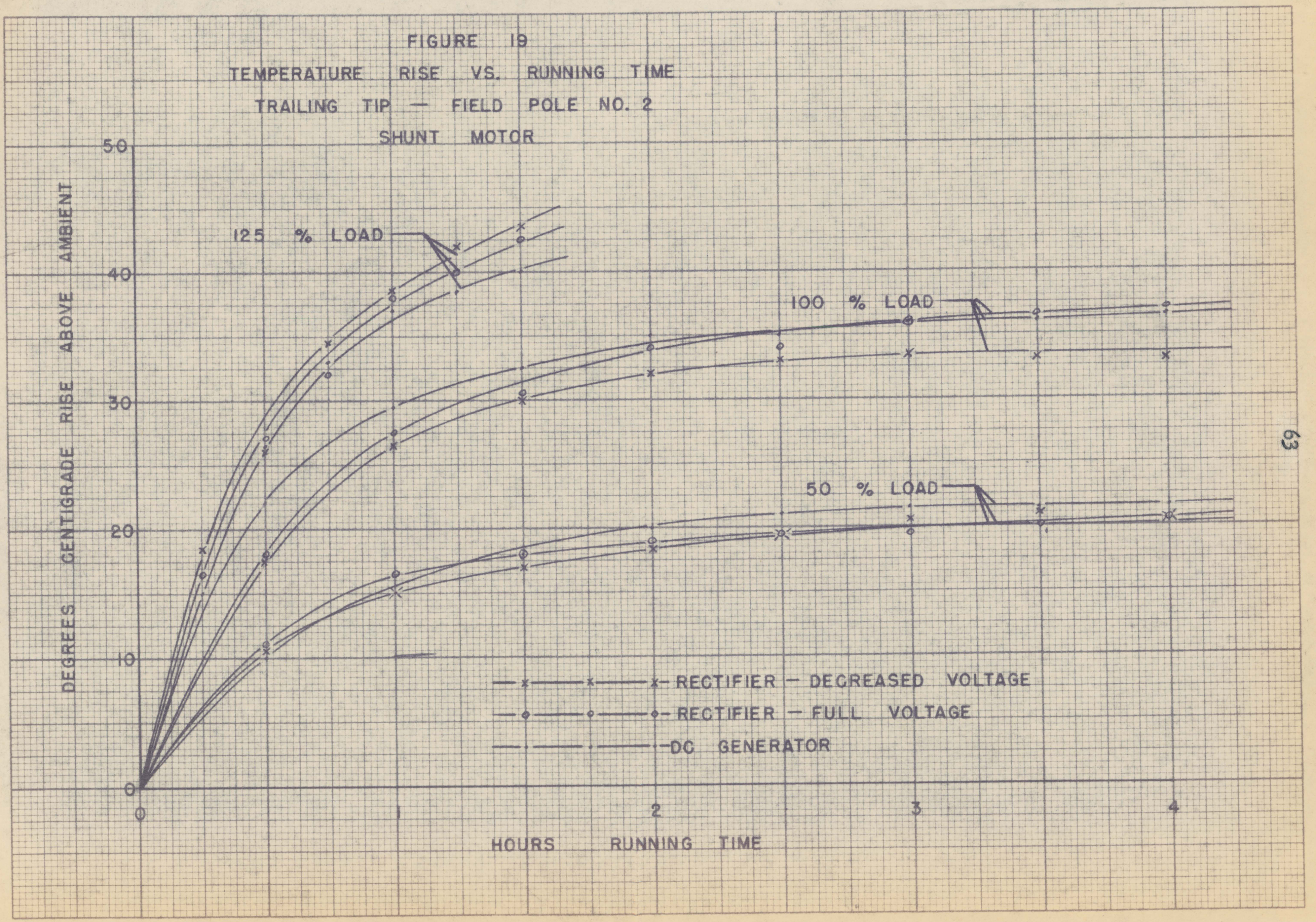


FIGURE 19
TEMPERATURE RISE VS. RUNNING TIME
TRAILING TIP — FIELD POLE NO. 2
SHUNT MOTOR
125 % LOAD
100 % LOAD
50 % LOAD
RECTIFIER — DECREASED VOLTAGE
RECTIFIER — FULL VOLTAGE
DC GENERATOR
DEGREES CENTIGRADE RISE ABOVE AMBIENT
HOURS RUNNING TIME
0
10
20
30
40
50
0
1
2
3
4

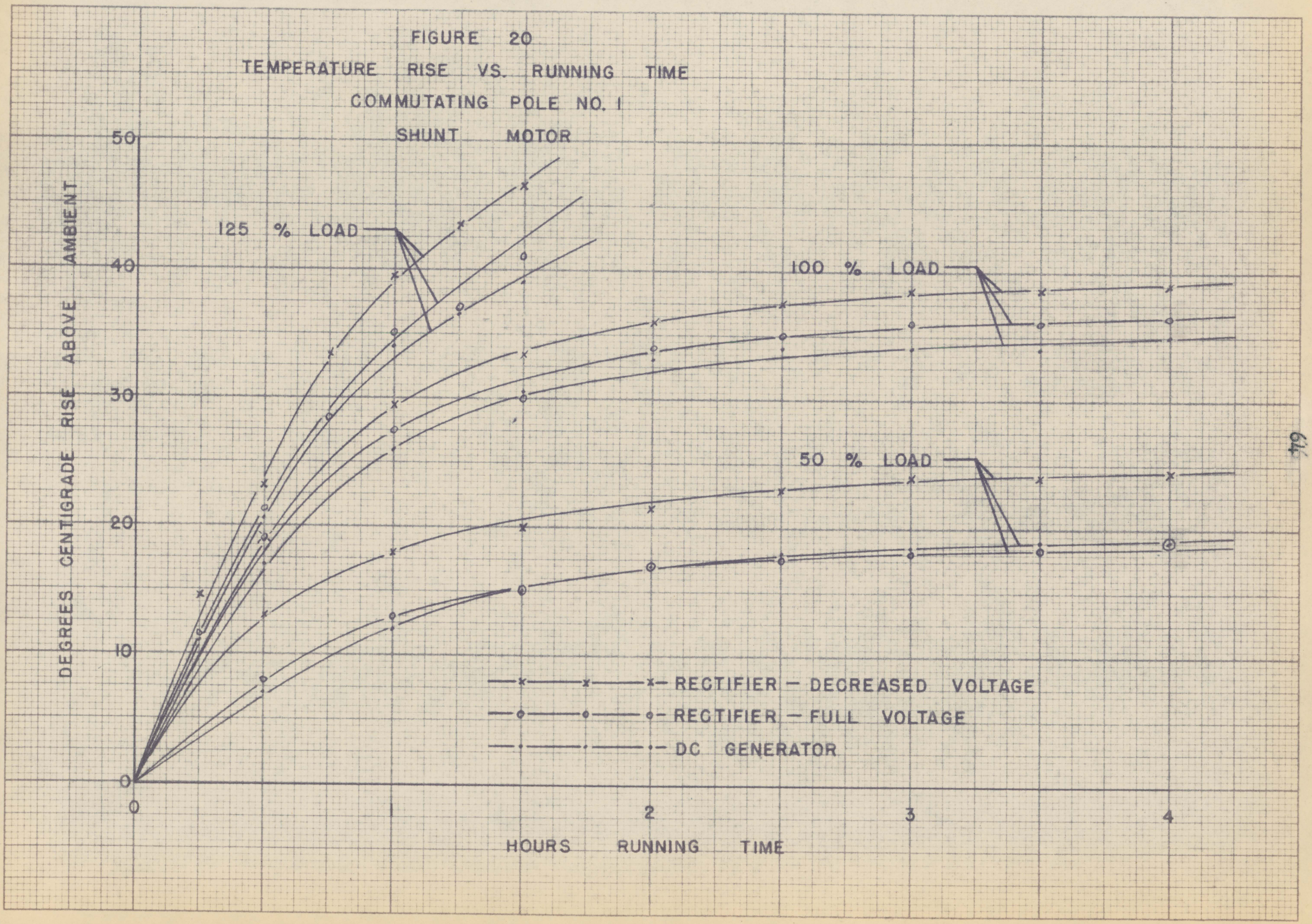


FIGURE 20
TEMPERATURE RISE VS. RUNNING TIME
COMMUTATING POLE NO. 1
SHUNT MOTOR

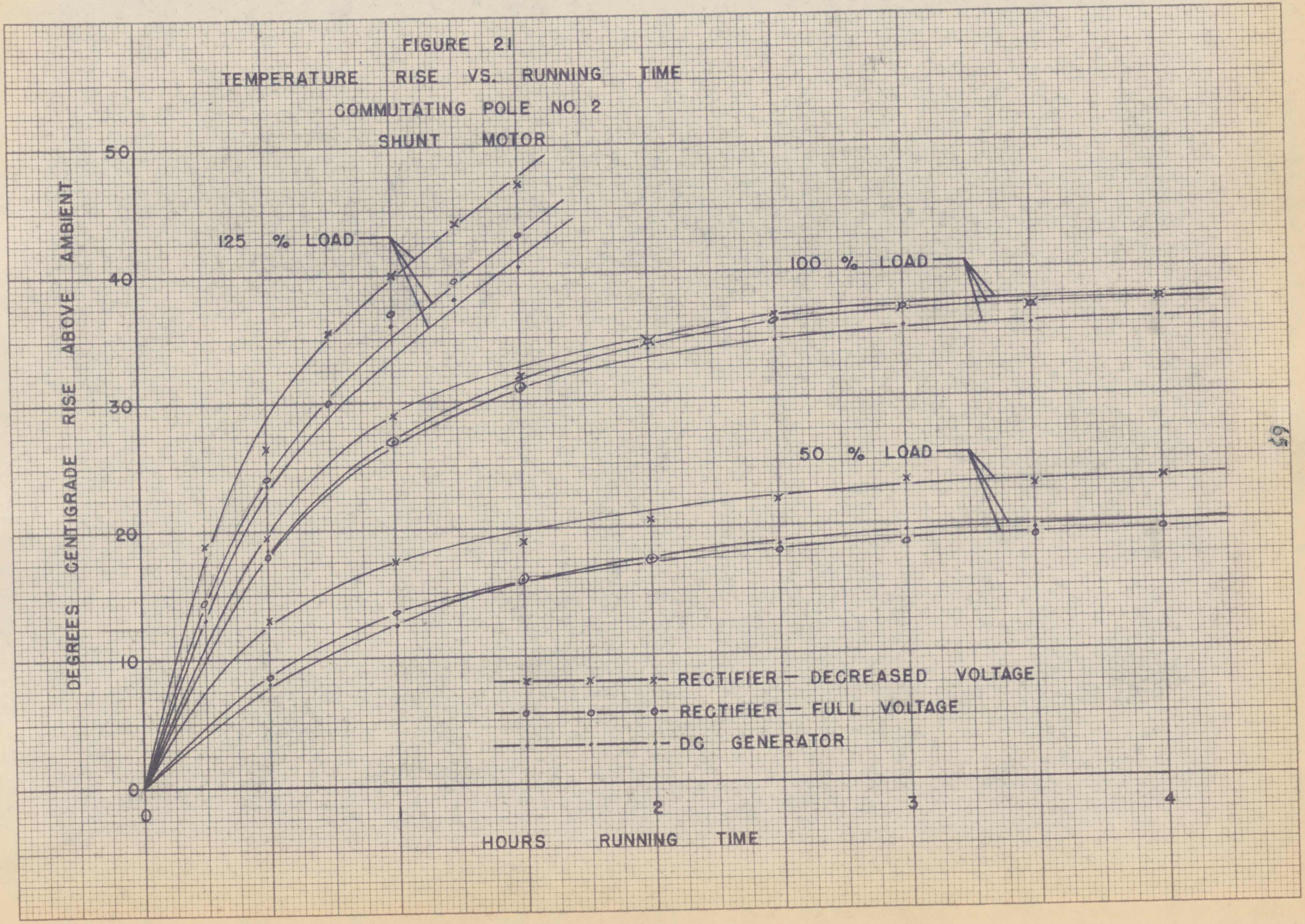


FIGURE 21
TEMPERATURE RISE VS. RUNNING TIME
COMMUTATING POLE NO. 2
SHUNT MOTOR
125 % LOAD
100 % LOAD
50 % LOAD
DEGREES CENTIGRADE RISE ABOVE AMBIENT
0
10
20
30
40
50
0
2
3
4
HOURS RUNNING TIME
RECTIFIER — DECREASED VOLTAGE
RECTIFIER — FULL VOLTAGE
DC GENERATOR

FIGURE 22
TEMPERATURE RISE VS. RUNNING TIME
ARMATURE
SHUNT MOTOR

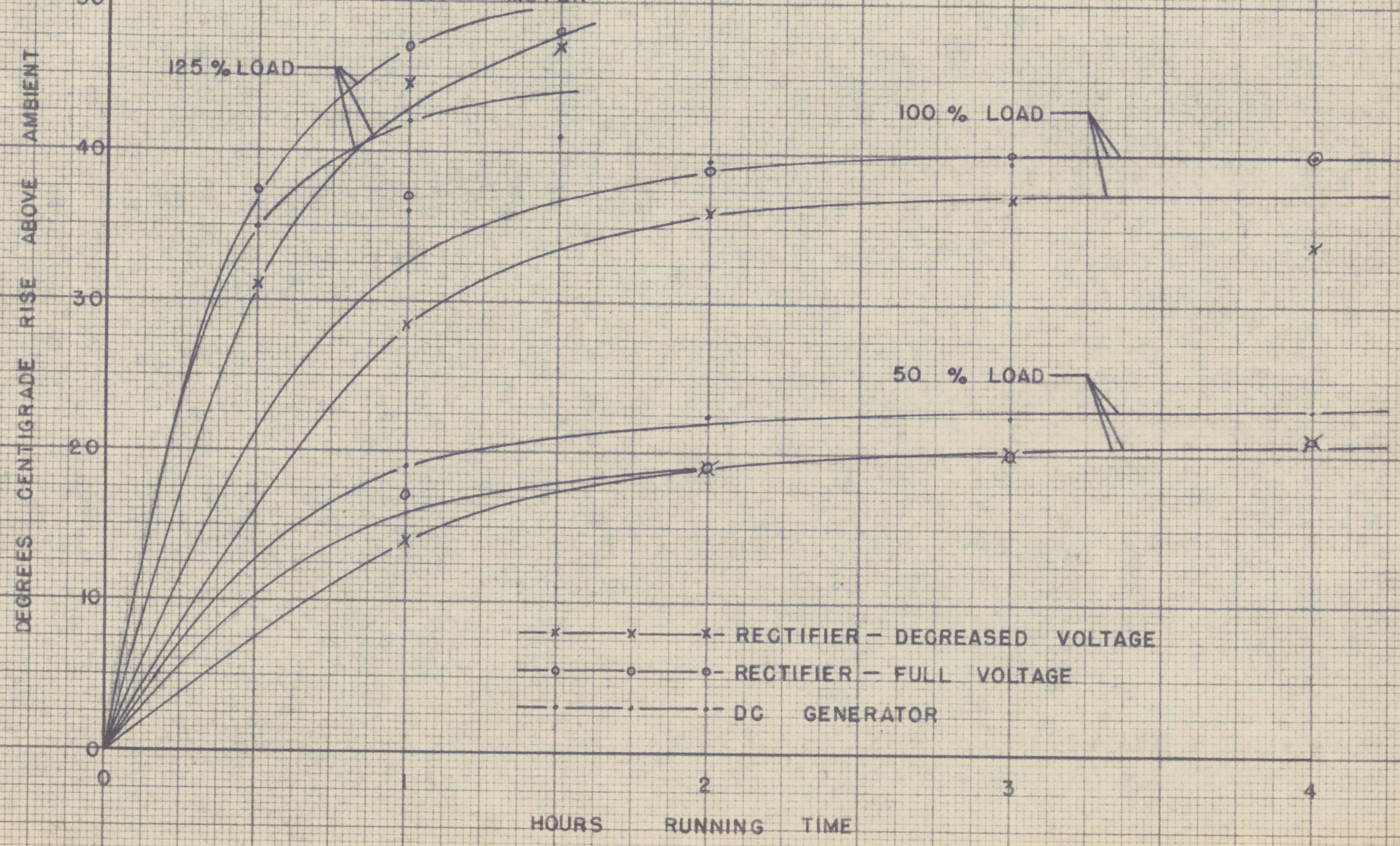


FIGURE 23

TEMPERATURE RISE VS. RUNNING TIME

COMMUTATOR

SHUNT MOTOR

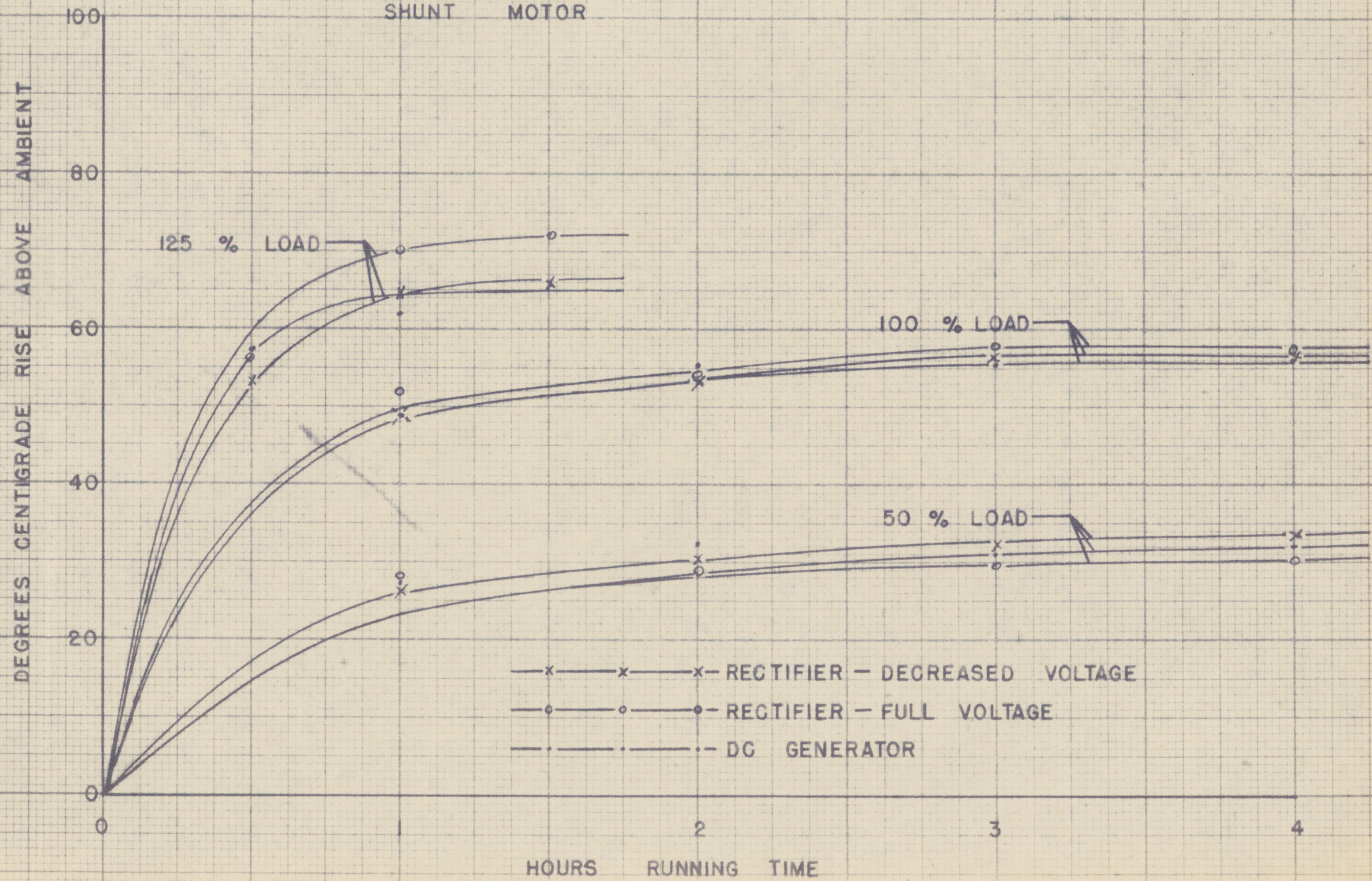
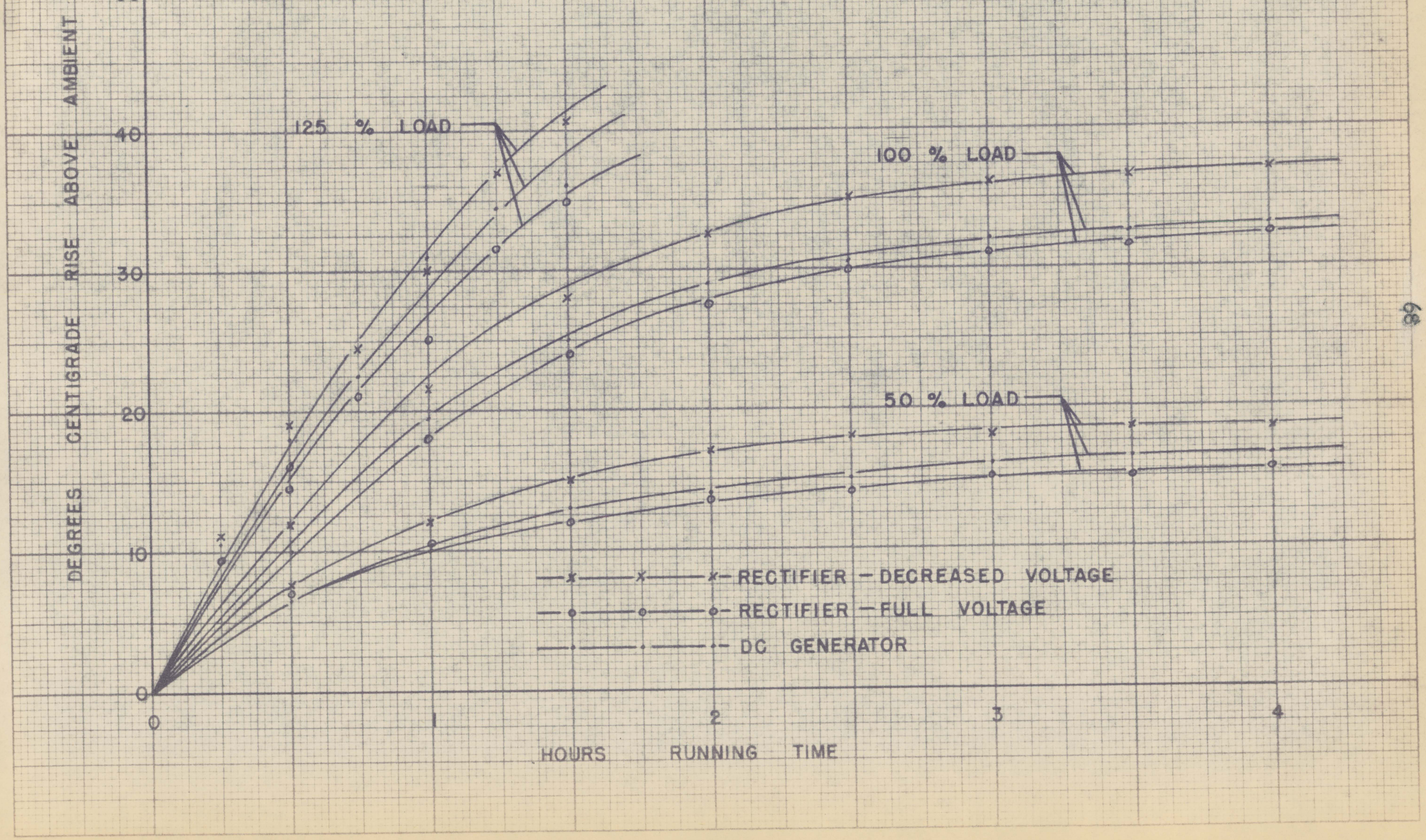


FIGURE 24

TEMPERATURE RISE VS. RUNNING TIME

YOKE

COMPOUND MOTOR



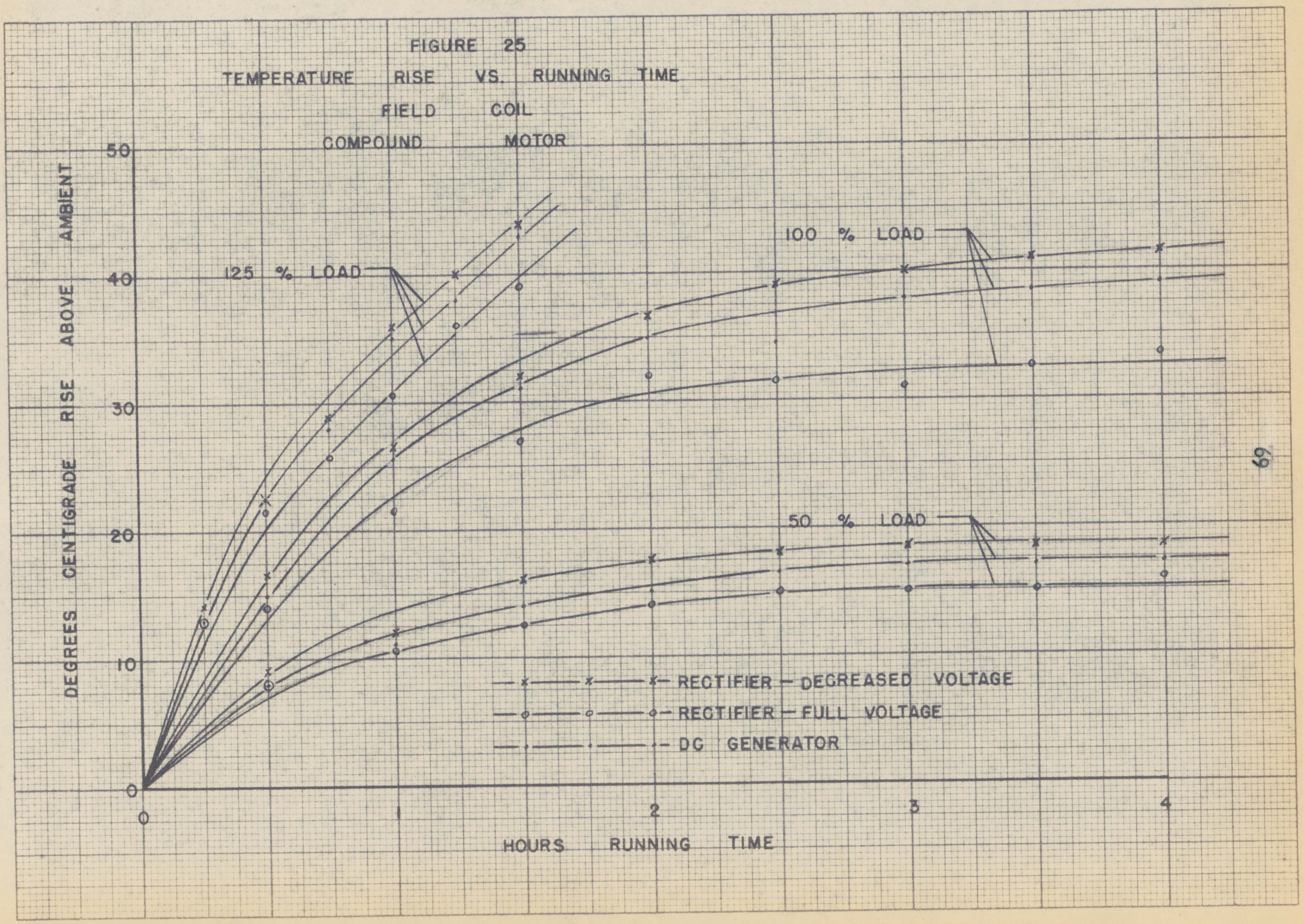


FIGURE 25
TEMPERATURE RISE VS. RUNNING TIME
FIELD COIL
COMPOUND MOTOR

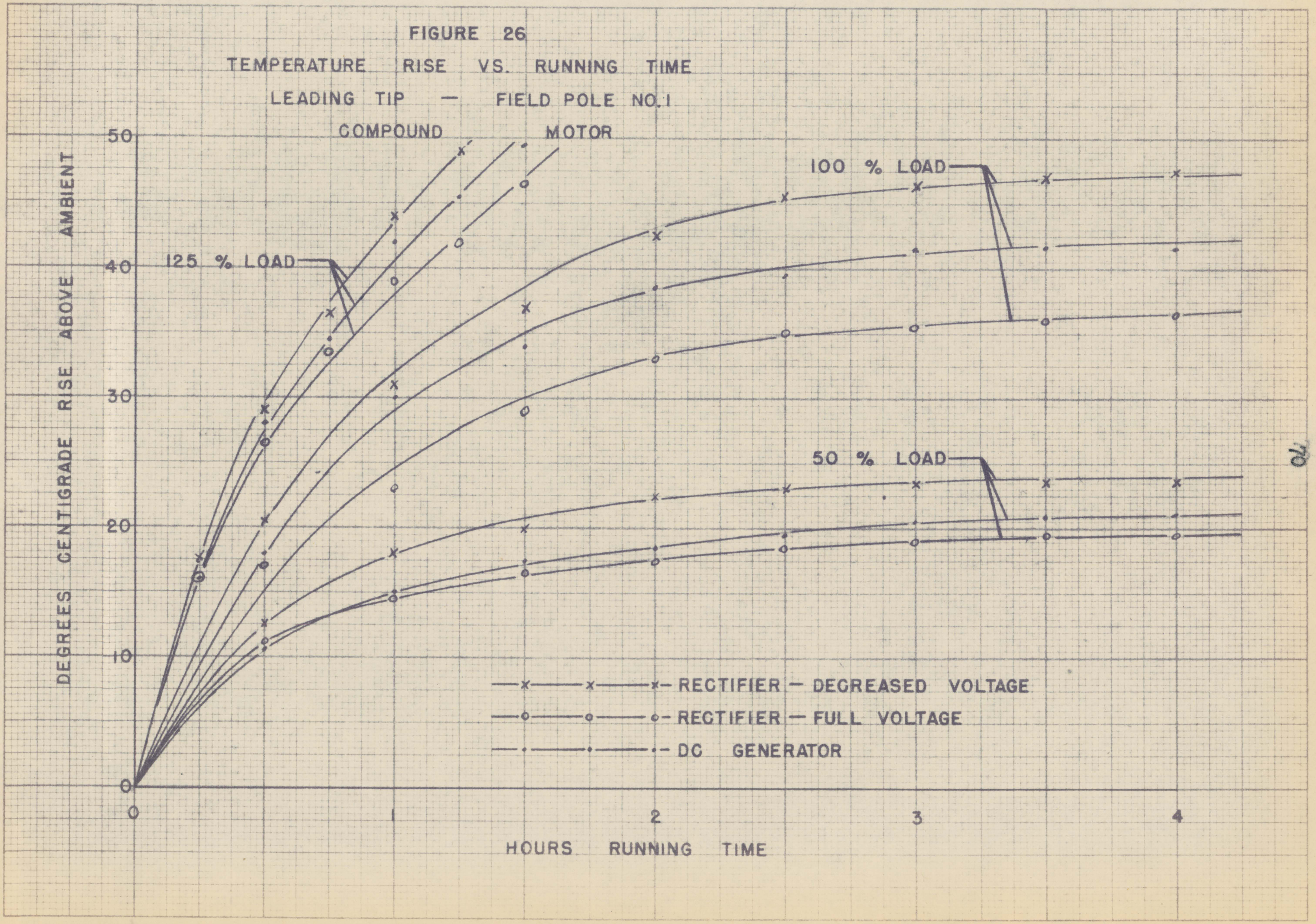


FIGURE 26
TEMPERATURE RISE VS. RUNNING TIME
LEADING TIP — FIELD POLE NO.1
COMPOUND MOTOR
125 % LOAD
100 % LOAD
50 % LOAD
RECTIFIER — DECREASED VOLTAGE
RECTIFIER — FULL VOLTAGE
DC GENERATOR
DEGREES CENTIGRADE RISE ABOVE AMBIENT
HOURS RUNNING TIME
0
10
20
30
40
50
0
1
2
3
4

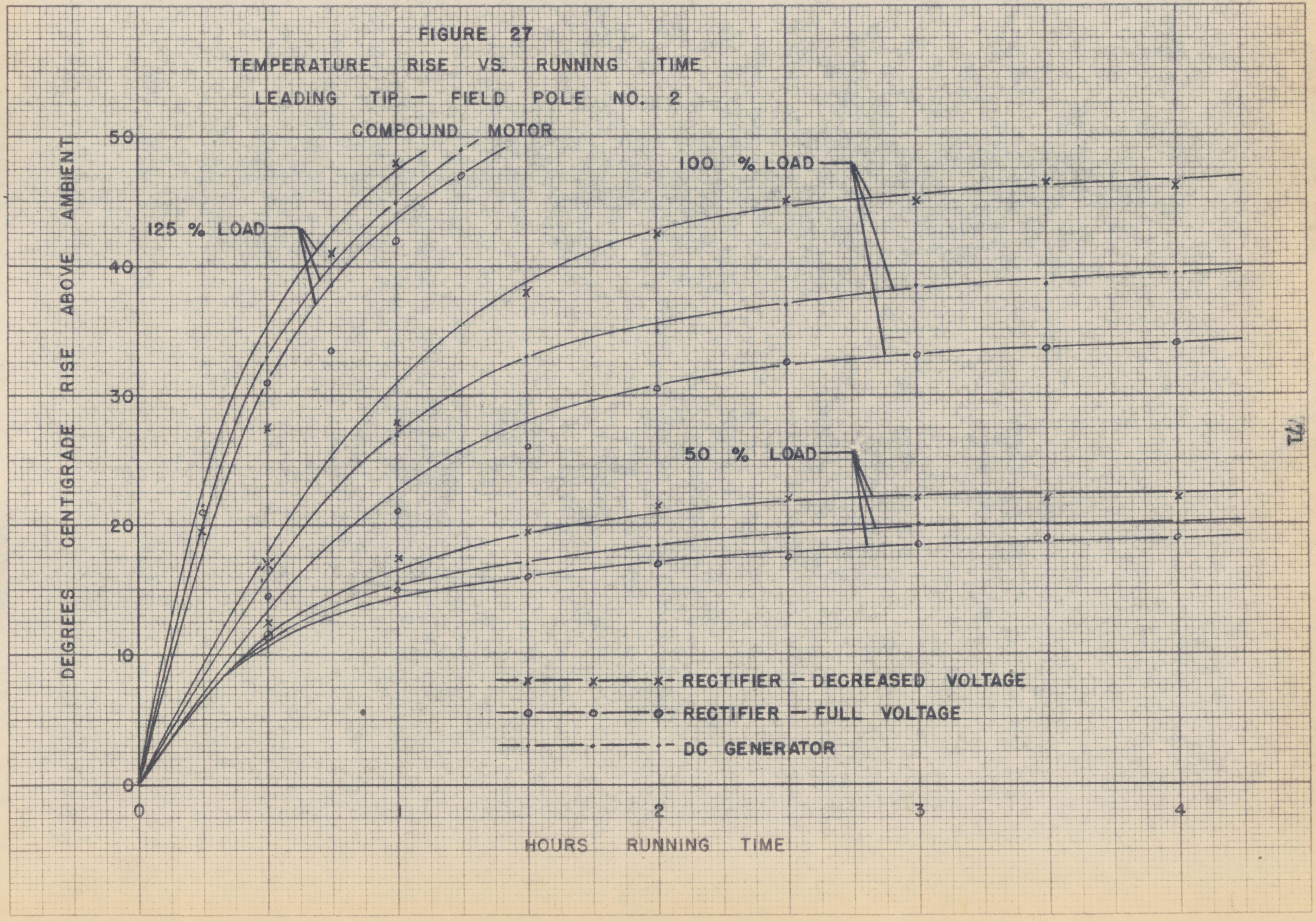


FIGURE 27
TEMPERATURE RISE VS. RUNNING TIME
LEADING TIP — FIELD POLE NO. 2
COMPOUND MOTOR
125 % LOAD
100 % LOAD
50 % LOAD
DEGREES CENTIGRADE RISE ABOVE AMBIENT
0
10
20
30
40
50
0
1
2
3
4
HOURS RUNNING TIME
RECTIFIER — DECREASED VOLTAGE
RECTIFIER — FULL VOLTAGE
DC GENERATOR

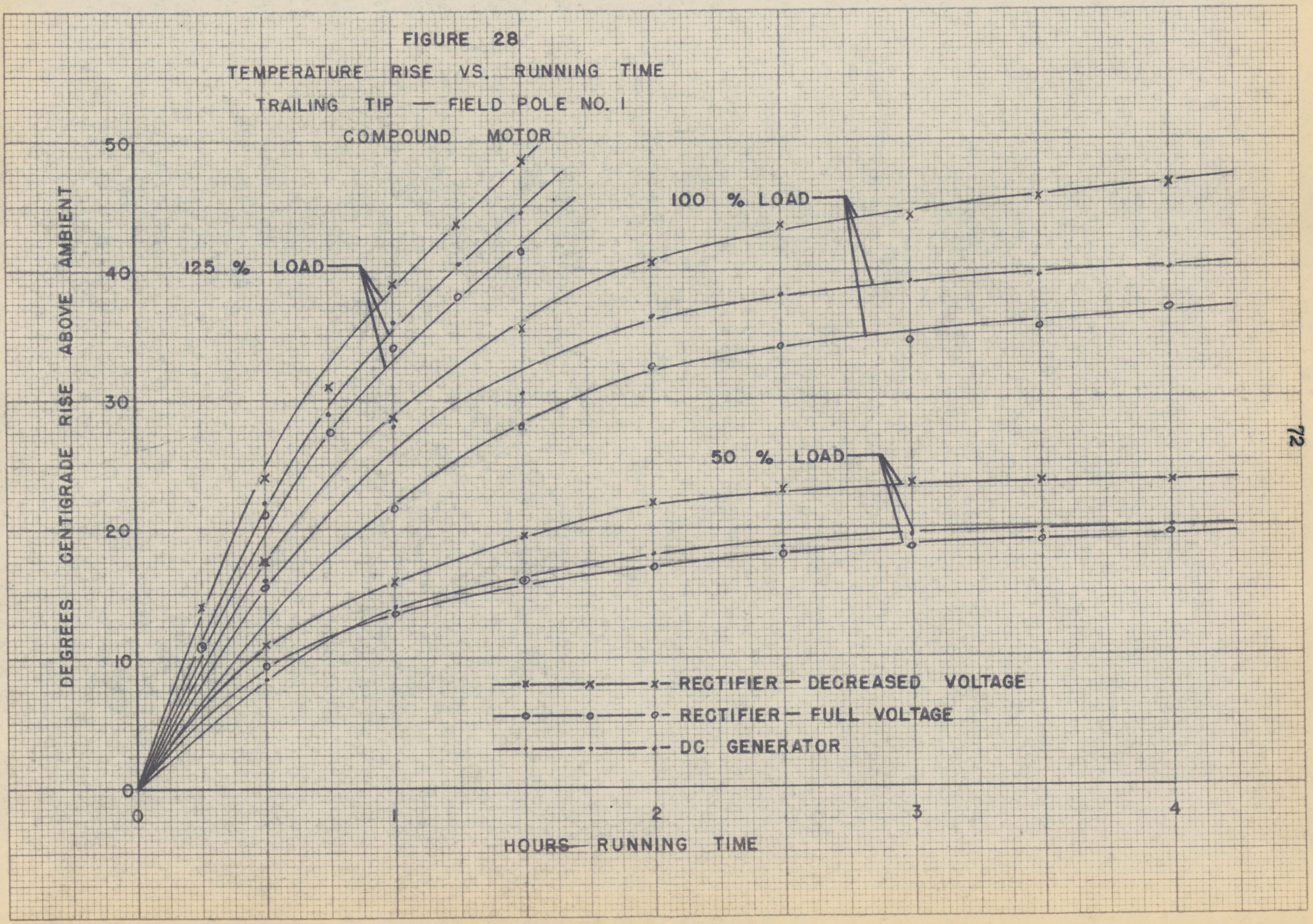


FIGURE 28

TEMPERATURE RISE VS. RUNNING TIME

TRAILING TIP — FIELD POLE NO. 1

COMPOUND MOTOR

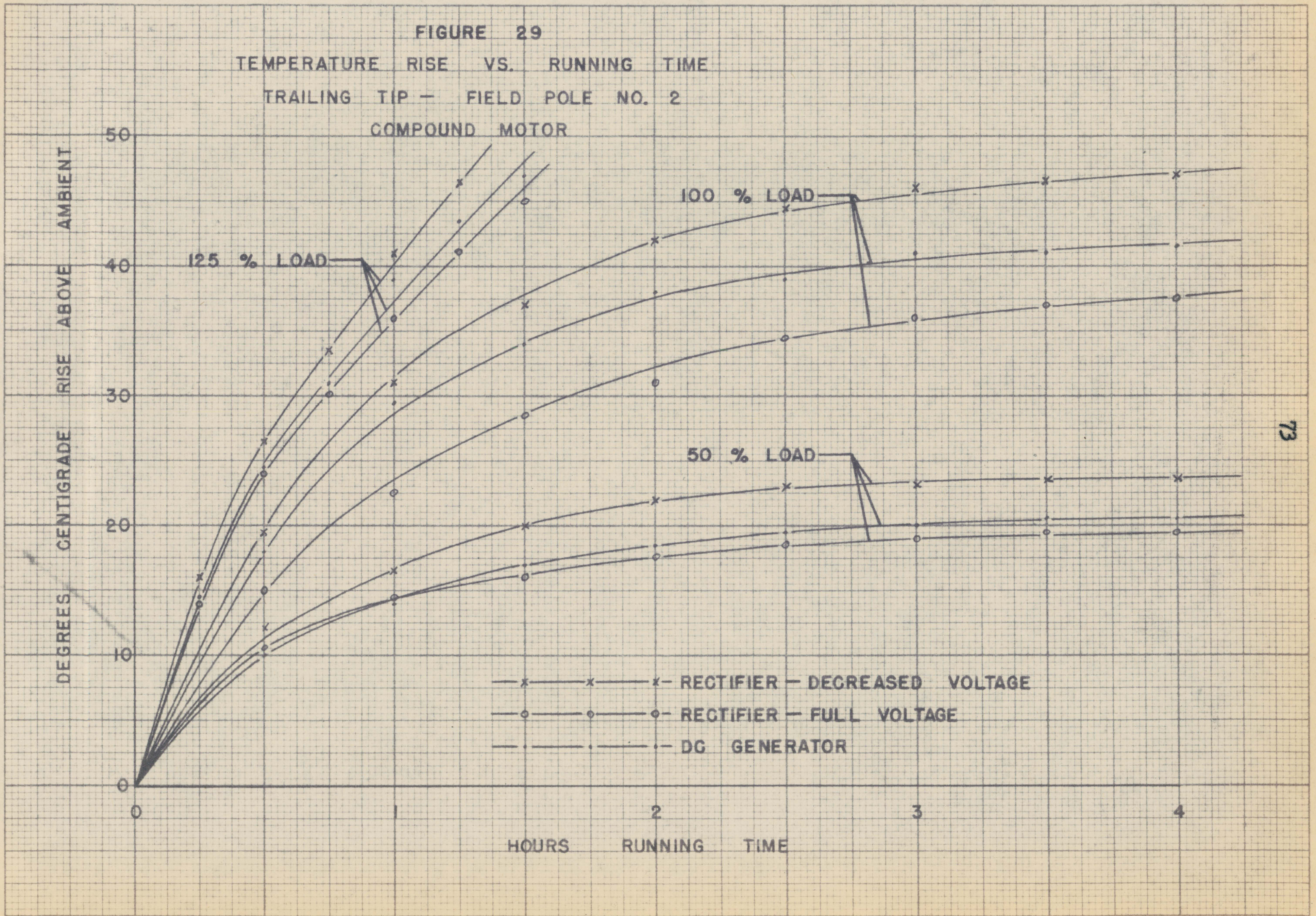


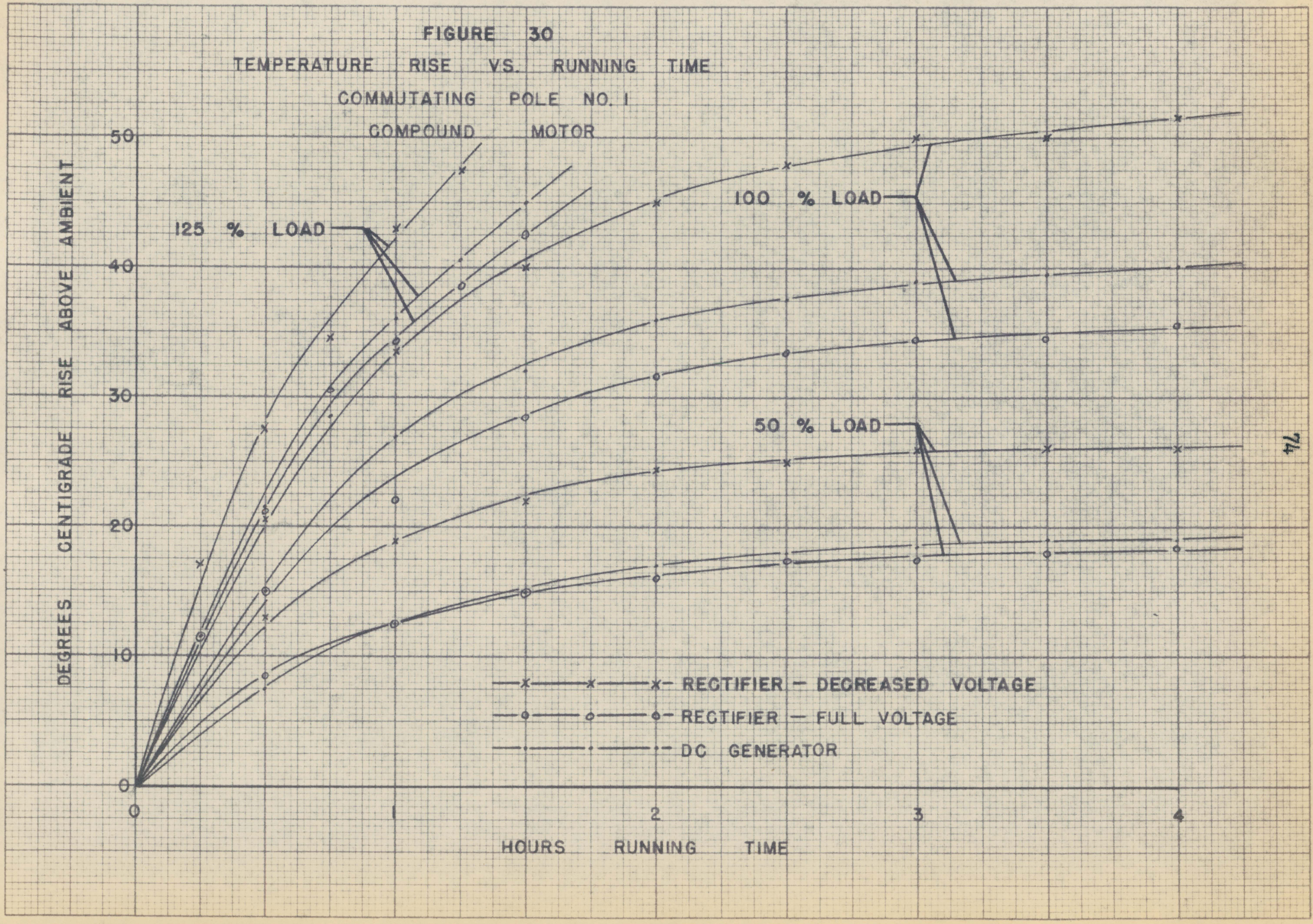
FIGURE 29
TEMPERATURE RISE VS. RUNNING TIME
TRAILING TIP — FIELD POLE NO. 2
COMPOUND MOTOR
125 % LOAD
100 % LOAD
50 % LOAD
RECTIFIER — DECREASED VOLTAGE
RECTIFIER — FULL VOLTAGE
DC GENERATOR
DEGREES CENTIGRADE RISE ABOVE AMBIENT
HOURS RUNNING TIME
0
10
20
30
40
50
1
2
3
4

FIGURE 30

TEMPERATURE RISE VS. RUNNING TIME

COMMUTATING POLE NO. I

COMPOUND MOTOR



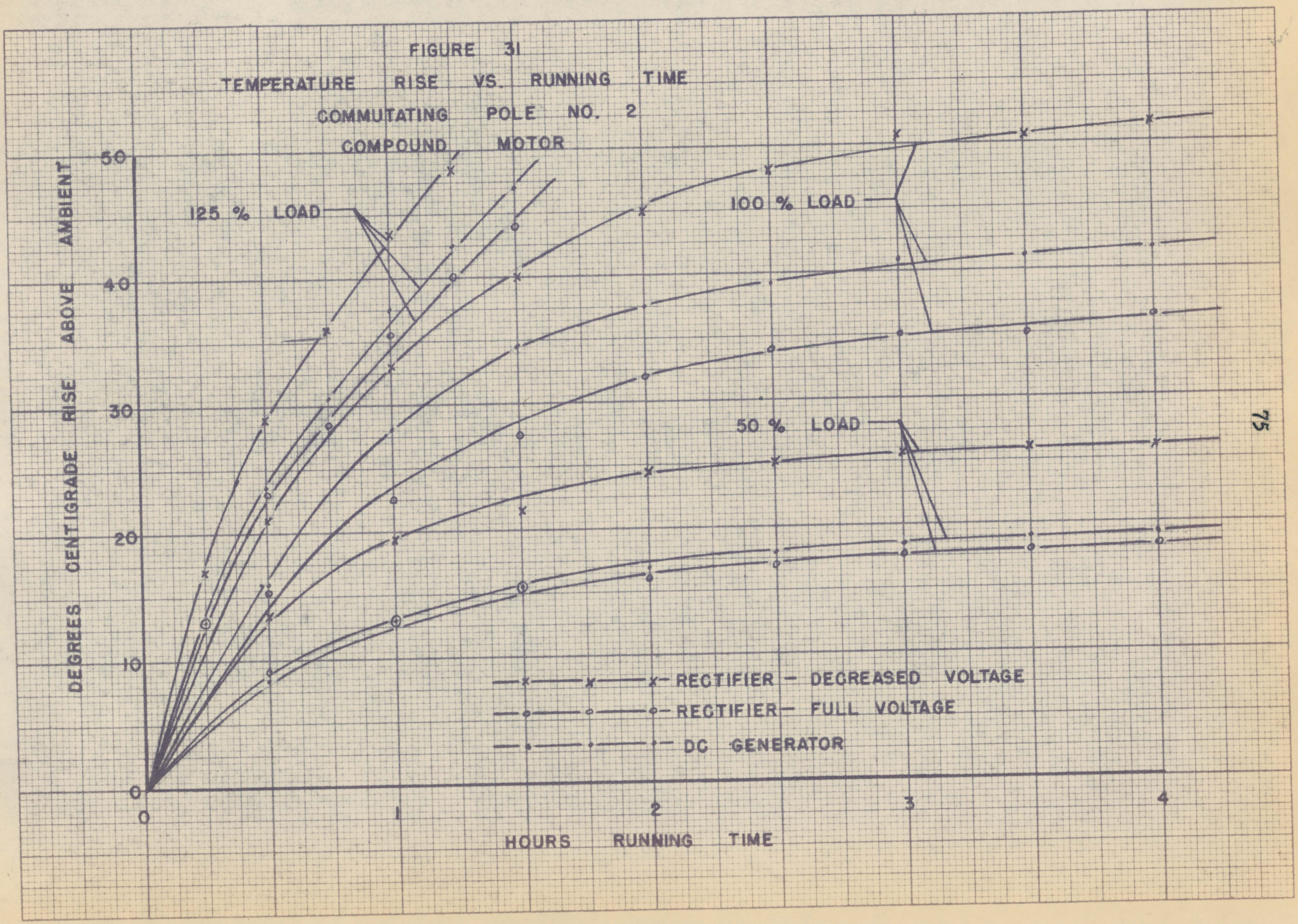
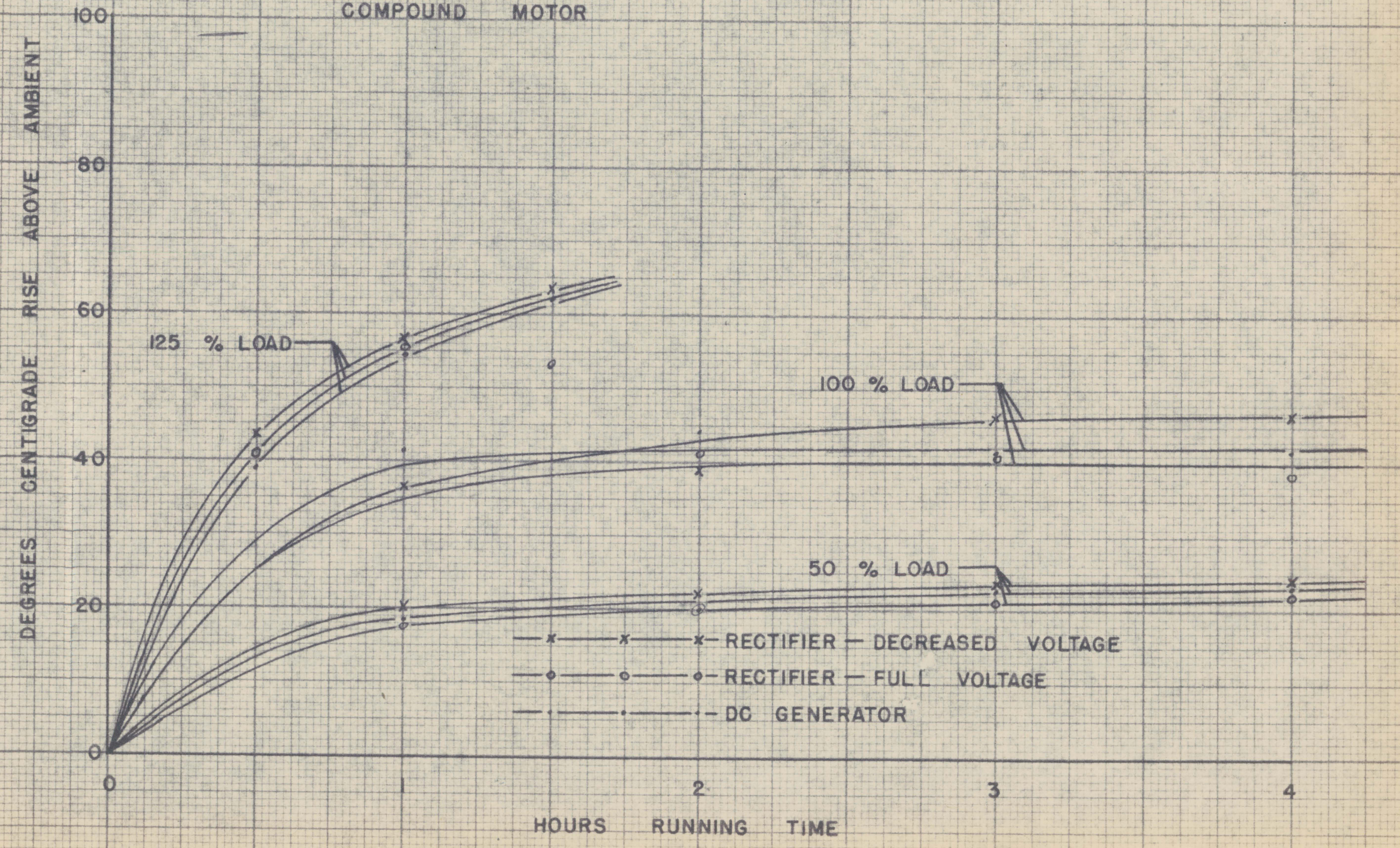


FIGURE 31
TEMPERATURE RISE VS. RUNNING TIME
COMMUTATING POLE NO. 2
COMPOUND MOTOR
125 % LOAD
100 % LOAD
50 % LOAD
DEGREES CENTIGRADE RISE ABOVE AMBIENT
50
40
30
20
10
0
1
2
3
4
HOURS RUNNING TIME
RECTIFIER — DECREASED VOLTAGE
RECTIFIER — FULL VOLTAGE
DC GENERATOR

FIGURE 32
TEMPERATURE RISE VS. RUNNING TIME
ARMATURE
COMPOUND MOTOR



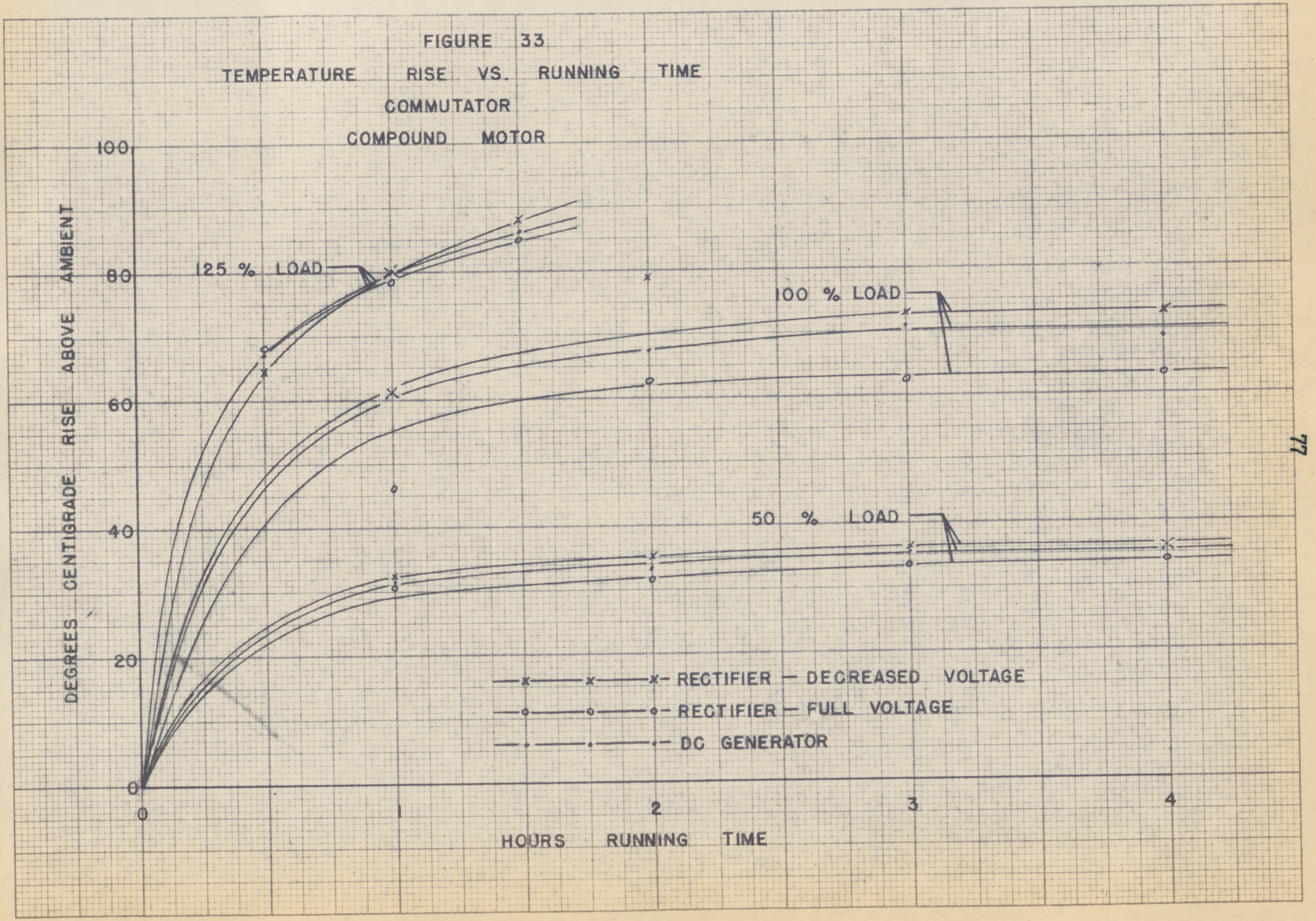


FIGURE 33
TEMPERATURE RISE VS. RUNNING TIME
COMMUTATOR
COMPOUND MOTOR
125 % LOAD
100 % LOAD
50 % LOAD
RECTIFIER — DECREASED VOLTAGE
RECTIFIER — FULL VOLTAGE
DC GENERATOR
DEGREES CENTIGRADE RISE ABOVE AMBIENT
HOURS RUNNING TIME
0
20
40
60
80
100
1
2
3
4

A Comparison of the Efficiency in the DC Motor Under Various Conditions

The results of the efficiency tests are shown in Figures 34 and 35. It is seen that they are very much more concise than the results of the temperature runs, and relative performance can be quickly judged by observation. It is immediately seen that for any particular value of power output the efficiency is almost exactly the same no matter which type of power source is used.

It should be noted that the method used for determining these graphs, as outlined in the "Test Procedure" section, is a method which, if not acceptable for the most exacting applications, gives results that are dependable in this case, since any errors in the method are consistent throughout the tests. Note that not one single point digresses from a smooth curve.

FIGURE 34

EFFICIENCY VS. K.W. OUTPUT

SHUNT MOTOR

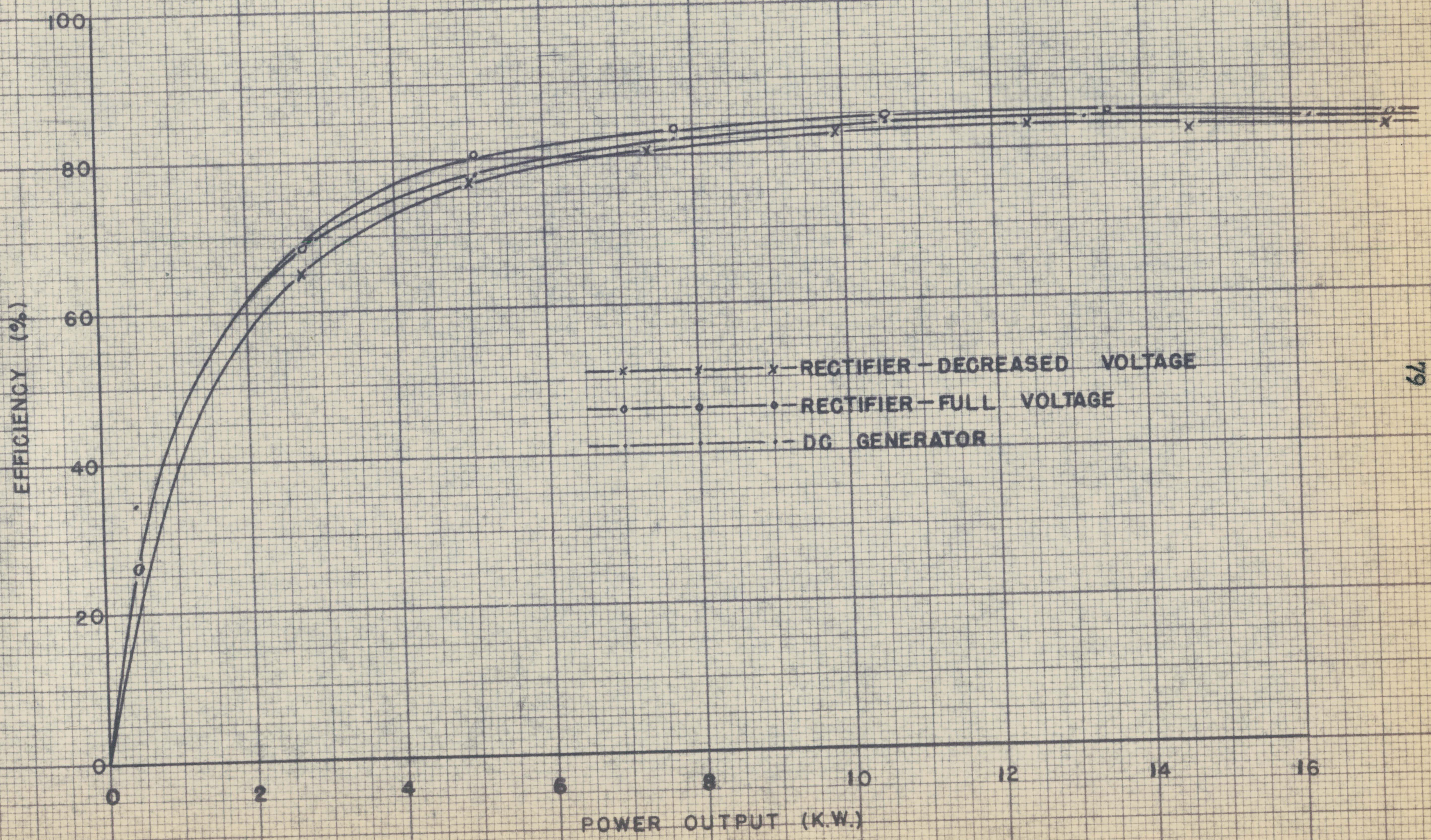
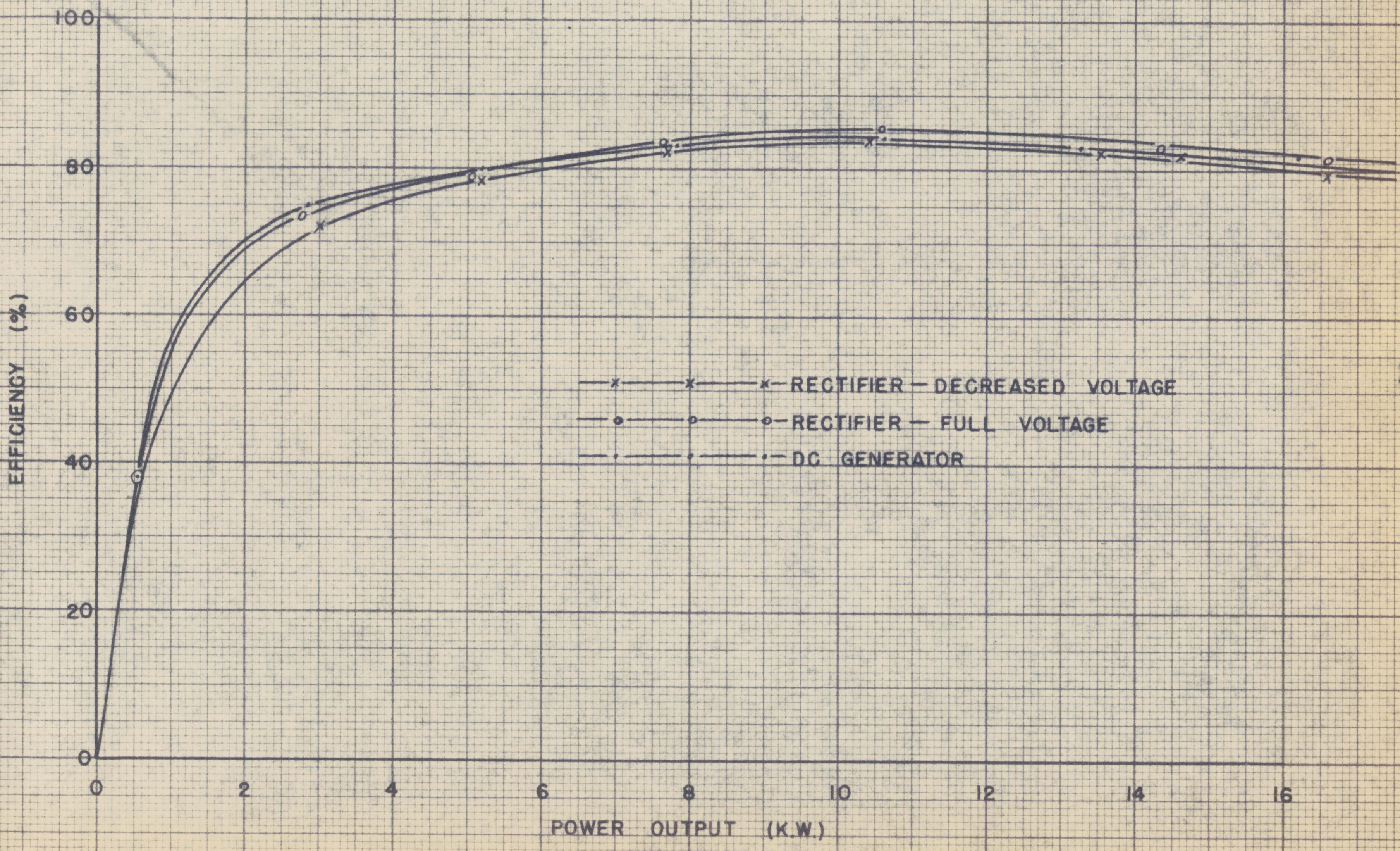


FIGURE 35

EFFICIENCY VS. K.W. OUTPUT

COMPOUND MOTOR



Analysis of the Input Ripple

Oscillograms of the output voltage of the rectifier are shown in Figures 36 and 37. Armature current wave forms are shown in Figures 38, 39, 40, and 41. These figures show that the current wave form at 125% load have considerably smaller ripple factors than the voltage wave forms have; these figures also show that the amount of current ripple is relatively independent of load except that at very light load the ripple may become more jagged and hence, contain larger amounts of higher frequency harmonics, notable, twelfth harmonic. Notice the intermittent nature of the current at light load when using rectifier input with decreased voltage.

Since the magnitude of the ripple is relatively independent of load, the per cent ripple current at light loads is large; however, this fact is of little consequence, since it is the magnitude of the ripple, not the per cent ripple, which governs the amount of increased heating.

Table 3 shows harmonic analyses of these various quantities, verifying experimentally the facts stated above, which are gotten from visual observation of the oscillograms.

Table 3

Harmonic Analyses of Voltage and Current Wave Forms

	Full Voltage			
	DC	360cps	720cps	1080cps
Input Voltage	123	15.0	6.5	4.0
Armature Current Heavy Load	115	7.6	1.8	0.7
Armature Current Light Load	16	12.6	2.7	1.3

Half Voltage

	DC	360cps	720cps	1080cps
Input Voltage	125	42.0	18.0	15.0
Armature Current Heavy Load	115	21.0	4.3	2.6
Armature Current Light Load	16	11.7	8.2	2.4

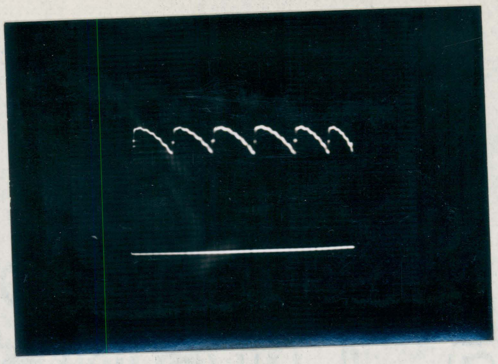


Figure 36. Rectifier output voltage wave form with full voltage.

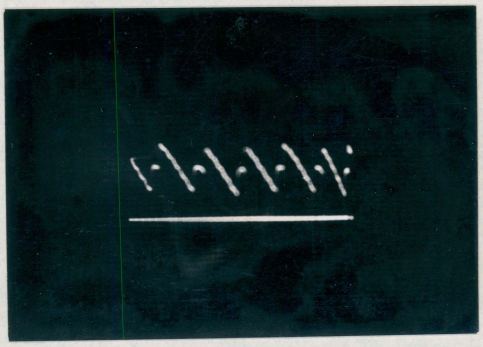


Figure 37. Rectifier output voltage wave form with half voltage.

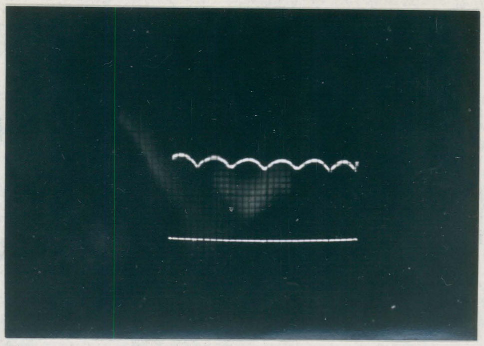


Figure 38. Motor armature current at 125% rated load with rectifier adjusted to full voltage.

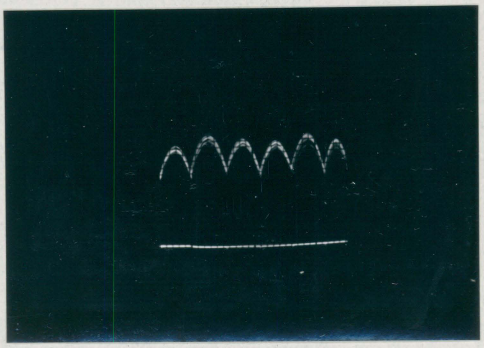


Figure 39. Motor armature current at 125% rated load with rectifier adjusted to half voltage.

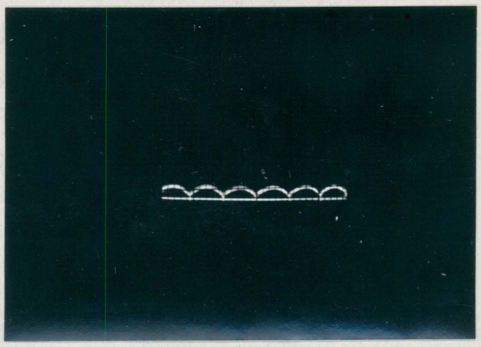


Figure 40. Motor armature current at light load with rectifier adjusted to full voltage.

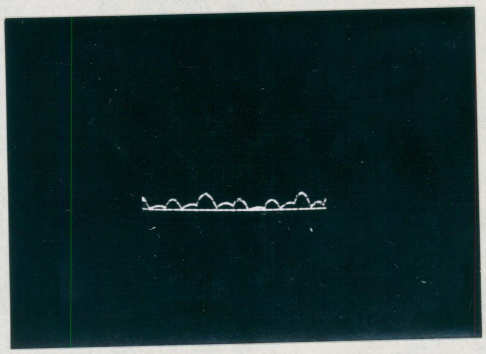
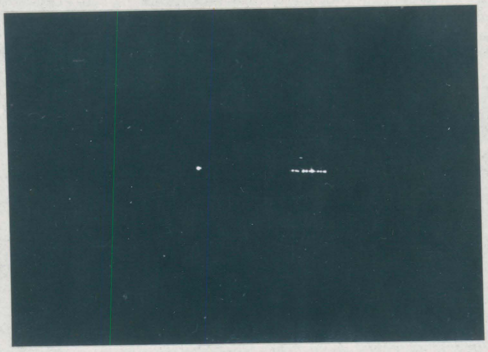


Figure 41. Motor armature current at light load with rectifier adjusted to half voltage.

Photographs of the Commutation

Photographs of the commutation under various conditions are shown in Figures 42 and 43. These photographs are visual checks on the relative performance of the motor with rectifier and DC generator input. Conclusions can be drawn by observing the relative width and brightness of the lines. It was simply stated under "Test Procedure" that the commutation of the machine was excellent for even the worst condition of ripple. The writer believes these photographs can at least illustrate that commutation was not much worse with rectifier input than it was with DC generator input. Notice that one experiences difficulty detecting any difference in the width of the lines.

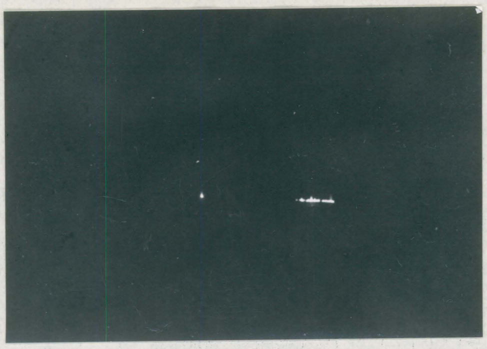
Rectifier--half voltage



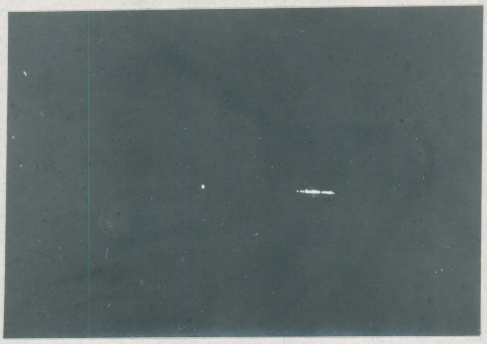
Rectifier--full voltage

DC generator

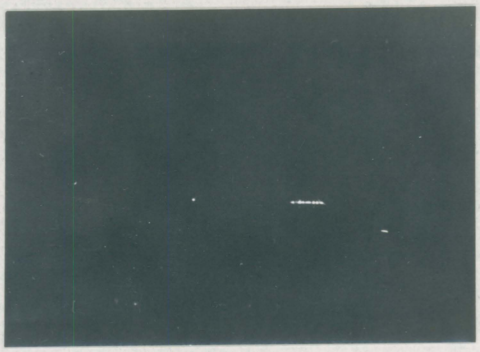
Figure 42. Commutation of the shunt motor for the various types of input.



Rectifier--half voltage



Rectifier--full voltage



DC generator

Figure 43. Commutation of the compound motor for the various types of input.

VI. Summary and Conclusions

It can definitely be stated that the results of the experiments show that almost no appreciable adverse effects on the test motor result from six phase rectifier operation. The efficiency was unaffected by rectifier operation. The temperature rise with rectifier operation was roughly within 5°C of that obtained with DC generator input. The commutation was not adversely affected when using the rectifier. These statements apply even when the rectifier is operated at half voltage, a condition giving very much more ripple than the full voltage ripple.

These results apply to tests conducted using only one machine. Much work could yet be done to determine whether or not various size machines would behave differently. Perhaps a much larger machine or a much smaller machine might respond more adversely to rectifier operation for one reason or another. Perhaps a series motor would give prohibitive heating at rated load since the highly pulsating armature current supplies all the field excitation; or perhaps the choking effect of the series field would cause the series motor to operate just as satisfactorily as the shunt and compound motors did in this work.

An interesting and most significant fact concerning the results of this work is that the conclusions to be drawn are very much in contrast to the conclusions of a thesis[14] by Mr. T. L. Phillips. His work was similar to the work done in this thesis except that a three phase rectifier was used. Phillips found decided increases in temperature and decided decreases in efficiency when using a three phase rectifier. This difference can be explained by studying the harmonic analysis of rectifier voltage wave forms for various numbers of phases. This analysis[16] shows that the ripple factor for the nth harmonic is equal to $2/(n^2 - 1)$, where n can be only multiples of the number of phases. Therefore, the first harmonic present in the six phase rectifier is only 0.228 times as large as the first harmonic present in the three phase rectifier and is of twice the frequency, so is more effectively choked out. Also note that every harmonic present in the six phase rectifier is also present in the three phase rectifier. Therefore, the results of this thesis are not inconsistent with the results of Phillips' work.

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