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COMPARISON OF METHODS OF
PARALLEL OPERATION OF AIRCRAFT GENERATORS
IN AN ELECTRICAL SYSTEM.

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By Bruce G. Bingham

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Approved by:

L. R. Larson - Head, Systems and Applied Research Section

Dr. Wayne C. Hall
Superintendent, Electricity Division

Commodore H. A. Schade
Director, Naval Research Laboratory

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ABSTRACT

In accordance with Project Directive TED No. NRL 31E70, a complete four-generator aircraft electrical system was set up in the laboratory, and tests were made on each of four paralleling systems. Most of the tests were conducted with the circuits duplicating the electrical system installed in the PB4Y-2 airplane. Other tests were conducted on some of the factors involved in the design of any system of voltage regulation and paralleling. For these tests, several components of the PB4Y-2 circuits were independently varied, to determine their effect on the system as a whole.

The results of the paralleling systems tests for steady-state loading show that the Compensating Coil System gives the best voltage regulation, and that the Standard Navy System and the two Army Systems have very similar characteristics in this respect. The Standard Navy System, however, gives the best load division results; although for operating conditions it is very little better than the Compensating Coil System. The two Army systems showed comparatively poor load division. In shock loading tests, the Standard Navy System showed qualitatively best results from an overall performance standpoint.

The results of the tests involving design factors are lengthy and somewhat inconclusive, so they are not presented here.

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AUTHORIZATION

1. The work done on this project was authorized by reference (a).

DEFINITIONS

2. Efficiency of Paralleling - This term has an "overall" meaning, and no way has been found to express it by means of one "percentage." Its value can only be judged by a comparison of the relevant factors involved. Some of these are:

(A) Voltage Regulation - Defined, for these tests, as the difference between the no-load voltage and the full load voltage, divided by the full load voltage and expressed in per cent; all voltages were measured at the bus. Obviously, the lower the percentage of voltage regulation, the better the system.

(B) Load Division - The way in which the load is divided among the several machines of a multi-generator system. The superior system will be the one which comes closest to completely equalizing the load among the generators, hence making available the rated power of all the generators. This characteristic can be measured in various ways, as follows:

1. Range - The difference between the maximum and minimum machine currents for any particular load condition. It has been computed here by taking the range and expressing it as a percentage of the load at 1/4, 1/2, 3/4 and full load.

$$R \% = \frac{I_{\max} - I_{\min}}{I_{\text{load}}} \times 100$$

I_{\max} = max. generator current
 I_{\min} = min. generator current
 I_{load} = total system load.

2. Average Deviation - The average of the differences between individual generator currents and one-fourth of the system load is taken and expressed as a percentage of the load on the machines:

$$\text{Average Deviation} = \frac{I_{1\text{Diff}} + I_{2\text{Diff}} + I_{3\text{Diff}} + I_{4\text{Diff}}}{4 \times I_{\text{load}}} \times 100$$

3. Standard Deviation - A more accurate measure of the differences between the individual machine currents and their arithmetic mean. It has been computed by the root-mean-square method, and also expressed as a percentage of the load on the machines.

$$\text{Standard Deviation} = \sqrt{\frac{I_{1\text{Diff}}^2 + I_{2\text{Diff}}^2 + I_{3\text{Diff}}^2 + I_{4\text{Diff}}^2}{4}} \times \frac{100}{I_{\text{load}}}$$

(C) Stability - That characteristic of a system which enables it to develop restoring forces between the elements thereof equal to, or greater than, any disturbing forces, resulting in the return of the system to a state of equilibrium. Since there is no doubt as to the steady-state stability of the systems under study, and probably no measurable differences, no attempt was made to evaluate this characteristic. A measure of the transient stability, however, is easily determined from oscillograms taken when the system was shock-loaded. The measures used are those of the time taken for the system (bus) voltage to recover to within ten per cent of its pre-shock-load value. This is similar to the criterion used as a specification for voltage regulators in AN-R-1a.

(D) Stiffness - That characteristic of an electrical system which measures the ability to maintain terminal voltage with increase in load. It is measured in terms of $\frac{\Delta E}{\Delta I}$, where ΔE is the drop in voltage due to an increase in the load, ΔI . Since this ratio is, in effect, the slope of the VOLTAGE REGULATION curve, it will be seen that, for a given set of conditions, the system which results in the lowest values for STIFFNESS has the best REGULATION and is to be preferred over other systems with higher values of STIFFNESS. The measurement of ΔE and ΔI are straightforward for the steady-state tests. For shock-loading, the following method was used:

$$\frac{E_{\text{pre-shock}} - E_{\text{min shock}}}{I_{\text{shock max}} - I_{\text{pre-shock}}} \times 100$$

$E_{\text{min shock}}$ and $I_{\text{shock max}}$ did not necessarily occur at the same time, but were, perhaps, as much as 0.03 second apart; however, these values were used, due to lack of any other standard way of selecting ΔE and ΔI . (These values are susceptible to the response characteristics of the oscillograph elements used for their determination.)

3. In presenting the computed values of these various factors; space-saving averages over speed or load range have been used. It was not merely assumed, however, that the averages would be completely consistent with all individual values. Each condition was examined and plotted, in order to justify this method of presentation.

INTRODUCTION

4. The primary objective of this project was an evaluation and resulting comparison of four methods of paralleling and regulating the generator voltage of a multi-generator D.C. electrical system. The four systems are:

(A) Standard Navy System (Figure 4) - This system applies a portion of the voltage drop across the series field of the generator to the equalizing coil of the carbon pile regulator. A potentiometer for adjusting irregularities between generators is necessary. The regulation point is at the generator terminals for the system used in this analysis.

(B) Compensating Coil System (Figure 5) - This system is the same as the Standard Navy System, except that a third coil has been added to the regulator. This coil also uses a portion of the series field drop (proportional to the load current) and a variable resistor (set proportional to the positive generator lead resistance, or as desired,) so that its effect on the carbon pile is proportional to the IR drop in the positive generator lead. This arrangement is equivalent to regulation at the bus. The equalizing coil voltage is obtained in the same manner as in the Standard Navy System.

(C) Army I System (Figure 6) - This system uses the drop across a fixed, accurate resistance or shunt in the negative lead of the generator. The drop across this shunt, due to load current, is applied to the equalizing coil, where it is balanced against the equalizing currents of the other generators in the system by means of the equalizing bus.

(D) Army II System (Figure 7) - This system is the same as the Army I System, except that the shunt which provides the equalizing voltage is placed in the positive generator lead, instead of in the negative lead.

5. The evaluation of these systems can be accomplished only by an examination of the various factors which affect satisfactory operation of an aircraft electrical system. These factors are numerous, but a few may be named: voltage regulation, load division, stability, stiffness, serviceability, reliability, flexibility and ease of operation. Only the first four of these factors are considered in this report. Since it might be expected that the various systems would react differently to various types of loading, an effort was made to cover the speed and load ranges for both steady-state and transient or shock loading.

6. In addition to an evaluation of the four systems, some tests were made to determine the effect of variation of the following components in any system:

- Regulator lead lengths or wire sizes
- Location of the regulation point
- Number of batteries
- Inclusion of a stabilizing transformer.

These changes were made on the Standard Navy System (as shown on Figure 4); hence, conclusions are strictly applicable only to that system. Generally speaking, however, they may also be applied to the other systems, since the components studied are common to all.

CIRCUITS, EQUIPMENT AND INSTRUMENTS

7. (A) Circuits - The wiring circuit of the PB4Y-2 airplane was used as a basis for the laboratory mockup. This airplane is a four-engine craft with four direct connected, 300-ampere, D.C. generators, and a network bus system which extends throughout the fuselage and inboard wing panels. The extensive bus network of the aircraft (Figure 1) was

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reduced to an equivalent network (Figure 2), with wire sizes and lengths modified for facilitating hookup. Similarly, the voltage regulator and reverse current relay leads (Figure 3) were modified (Figure 4). The changes in the hookup necessary to construct the Compensating Coil (Figure 5) and the two Army Systems (Figures 6 and 7) were made on this simplified circuit. The changes necessary to test for variations in regulator lead length were also made on this modified circuit (Figure 4). These changes involved the lead from Lt on the regulator to the regulation point (RP₁ at the reverse current cutout; RP₂ at the junctions of #1 and #2 generator leads and #3 and #4 generator leads; RP₃ at the central bus).

(B) Equipment and Instruments - The electrical system components used during the tests were:

Generators - General Electric Type 2CM73B7
Voltage Regulators - Eclipse (Bendix) Type 1042,
Model 9, Style A
Reverse Current Relays - General Electric
Model 3GTR72C1A
Current Relays (Battery) - Eclipse (Bendix)
Type 987, Model 3, Style A
Stabilizing Transformers - Westinghouse Type AVT-12
Batteries - 24-Volt, 34 Ampere-hour, AN-3150
Inverters - Jack & Heintz, 2500 Volt-ampere, AN #3186-1

Other equipment included:

Variable drive stands - 50 horsepower
Blowers, Manometers.

(C) Instrumentation - Instrumentation was as follows:

4 Weston Voltmeters, Model 45, 1/4 of 1% accuracy
5 Weston Ammeters, Model 45, 1/4 of 1% accuracy
6 Weston 50-Millivolt shunts
1 Strobotac General Radio, Type 631-B
1 Consolidated Oscillograph (Recording)

The voltmeters were connected to a gang-switch so that the voltage at several points in the system could be read with each voltmeter.

EXPERIMENTAL PROCEDURE

8. General - The generators were mounted on the vari-drive stands to obtain a speed range of 4000 to 8000 r.p.m. Tachometer generators and their respective r.p.m. meters were connected to give continuous readings of the generator speeds, but changes in speed between runs were made on the individual drives with the aid of the more accurate Strobotac. This speed setting was accomplished as accurately as possible, in order to eliminate any variation in load division between generators due to

difference in r.p.m.

9. Standard Conditions - Ram air pressure equivalent to 6 inches of water was maintained at all times on the generator. For all runs, the system was warmed up by at least 30 minutes of running, primarily to heat up the regulators and allow them to stabilize. No attempt was made, however, to measure or control temperatures throughout the system, and these would naturally vary throughout a series of tests, due to differences in running time and loading. Check runs showed, however, that variations in the voltage drop of the leads was negligible between ambient and hot conditions. The generators are known to have relatively invariable characteristics in this respect. Further consideration shows that even if variations due to temperature were appreciable, the only possible effect, over the short period of time necessary to take a set of readings, would be a slight raising or lowering of whole plotted curves, with little effect on the slopes or differences between points on these curves. It also seems reasonable to assume that, as long as all the respective components of the system are at nearly identical temperatures, load division will be unaffected by small temperature differences between runs. In addition to the check runs above, several complete Standard Navy System runs were made during the testing period in order to insure that no radical variations had occurred in any of the system components during this time.

10. Steady-State Loading - Loading for the steady-state runs was accomplished with resistance banks tied directly across the equivalent bus. Readings were taken within a few seconds after applications of the various loads. The following conditions of speed and loading were used as test points:

Speed - 4000, 4500, 6000, 8000 r.p.m.
Loading - 300, 600, 900, 1200 amperes

All the combinations of these speed and loading conditions were applied to each of the four systems, and to the Standard Navy System with various lead lengths and regulation points.

11. Shock Loading - The load for determining system response to transient loading consisted of three 2-1/2 KVA inverters connected across the equivalent bus and started in parallel (peak starting current around 2000 amperes). Tests were made on the four systems and on the Standard Navy System with stabilizing transformer attached, at 4500 and 6000 r.p.m. Pre-shock, steady-state loading with the resistance banks to 300 and 900 amperes, as well as the no-load condition, were used. All combinations were tested without batteries and with two and four batteries attached. The procedure was to connect the batteries to the bus, then apply the steady-state load, and allow the system to stabilize and the battery charging current to drop below 10 amperes. With the oscillograph running, the inverters were thrown on the line and allowed to reach normal running speed (a matter of about two seconds). The voltages of the four generators and the bus, and the currents of the four generators, the batteries

and the load were recorded. From the resulting oscillograms, it is possible to find the voltage drop at the generator terminals and on the bus, due to the sudden application of the load and the time for recovery of the voltage to within 10 per cent of its pre-shock load value. The division of the load between the generators and batteries can be measured, and the various factors involved in judging the efficiency of paralleling of the systems determined.

EXPERIMENTAL OBSERVATIONS

12. Steady-State Loading.

(A) TABLE I gives the computed values of VOLTAGE REGULATION for the various systems.

TABLE I
VOLTAGE REGULATION AT BUS IN PER CENT

GENERATOR R.P.M.	4000	4500	6000	8000
Standard Navy	16.01	13.04	9.92	9.33
Compensating Coil	12.0	6.44	1.77	1.39
Army I	21.0	12.04	8.4	7.43
Army II	16.5	14.5	10.58	9.95

A sample calculation of VOLTAGE REGULATION for the Standard Navy System, at 4000 r.p.m., follows:

$$\frac{28.2 - 24.3}{24.3} \times 100 = 16.01\%$$

An examination of the figures shows that the Compensating Coil System gives the best overall regulation. The other three systems have approximately similar characteristics, which are shown best comparatively by plotting as in PLATE I. The VOLTAGE REGULATION data for all conditions are plotted in the Appendix, PLATES XII - XXI.

(B) TABLE II gives the calculated values of the RANGE of DEVIATION in LOAD DIVISION. It can be seen from these figures, and from the plotted curves on PLATE I, that the Standard Navy System gives the best LOAD DIVISION when it is measured in this manner, since minimum range is desired.

TABLE II
RANGE IN PER CENT OF LOAD

	1/4 LOAD	1/2 LOAD	3/4 LOAD	FULL LOAD
Standard Navy	3.5	1.91	1.2	1.06
Compensating Coil	5.08	2.33	1.76	1.31
Army I	10.6	6.8	5.2	4.02
Army II	8.42	4.3	3.24	2.75

A sample calculation of RANGE for Standard Navy System at 1/2 load follows:

$$\frac{158-137}{583} \times 100 = \begin{array}{l} 3.60\% \text{ (4000 r.p.m.)} \\ 1.80\% \text{ (4500 r.p.m.)} \\ 0.66\% \text{ (6000 r.p.m.)} \\ \underline{1.60\% \text{ (8000 r.p.m.)}} \\ 7.66 \end{array}$$

$$\text{Range (average)} = \frac{7.66}{4} = 1.91\%$$

(C) The LOAD DIVISION as measured by the AVERAGE DEVIATION is given in TABLE III and plotted on PLATE II. Minimum deviation is the desired condition, and this is accomplished best by the Standard Navy System, with the Compensating Coil System not far behind. The two Army systems have from two to three times the amount of deviation of the Standard Navy and Compensating Coil Systems.

TABLE III
AVERAGE DEVIATION IN PER CENT OF LOAD

	1/4 LOAD	1/2 LOAD	3/4 LOAD	FULL LOAD
Standard Navy	1.15	0.62	0.36	0.34
Compensating Coil	1.67	0.73	0.53	0.43
Army I	3.54	2.2	1.74	1.35
Army II	3.35	1.72	1.24	0.99

A sample calculation of AVERAGE DEVIATION for the Compensating Coil System at 3/4 load follows:

$$\begin{array}{r} \frac{(10 + 1 + 4 + 5) \times 100}{4 \times 920} = 0.816\% \text{ (4000 r.p.m.)} \\ \phantom{\frac{(10 + 1 + 4 + 5) \times 100}{4 \times 920} = } 0.556\% \text{ (4500 r.p.m.)} \\ \phantom{\frac{(10 + 1 + 4 + 5) \times 100}{4 \times 920} = } 0.174\% \text{ (6000 r.p.m.)} \\ \phantom{\frac{(10 + 1 + 4 + 5) \times 100}{4 \times 920} = } \underline{0.574\%} \text{ (8000 r.p.m.)} \\ \phantom{\frac{(10 + 1 + 4 + 5) \times 100}{4 \times 920} = } 2.120 \end{array}$$

$$\text{Average Deviation} = \frac{2.12}{4} = 0.53 \%$$

These data are presented in different form in TABLE IV, where the AVERAGE DEVIATION in amperes for the four test speeds is given.

TABLE IV
AVERAGE DEVIATION IN AMPERES

GENERATOR R.P.M.	4000	4500	6000	8000
Standard Navy	6.75	4.13	1.13	2.63
Compensating Coil	7.8	5.25	2.06	4.25
Army I	13.5	10.5	16.7	15.3
Army II	13.7	15.0	5.8	8.06

A sample calculation of AVERAGE DEVIATION for the Compensating Coil System at 8000 r.p.m. follows:

$$\begin{array}{r} \frac{(2 + 5 + 6 + 4)}{4} = 4.25 \text{ amperes (1/4 load)} \\ \phantom{\frac{(2 + 5 + 6 + 4)}{4} = } 3.50 \text{ amperes (1/2 load)} \\ \phantom{\frac{(2 + 5 + 6 + 4)}{4} = } 5.00 \text{ amperes (3/4 load)} \\ \phantom{\frac{(2 + 5 + 6 + 4)}{4} = } \underline{4.25} \text{ amperes (Full load)} \\ \phantom{\frac{(2 + 5 + 6 + 4)}{4} = } 17.0 \end{array}$$

$$\text{Average Deviation} = \frac{17.0}{4} = 4.25 \text{ amperes.}$$

This form of presentation bears out the conclusions of the former method. Since the spread of these values is sufficient to give significant results, the STANDARD DEVIATIONS for steady state loading conditions is not presented, although they were computed and bear out the AVERAGE DEVIATIONS.

(D) The relative STIFFNESS of the four systems is shown in TABLE V, and the values plotted on PLATE III.

TABLE V

STIFFNESS, $\frac{\Delta E}{\Delta I}$, IN PER CENT
(Steady-State Conditions)

	1/4 LOAD	1/2 LOAD	3/4 LOAD	FULL LOAD
Standard Navy	0.205	0.191	0.274	0.417
Compensating Coil	0.034	0.052	0.158	0.293
Army I	0.158	0.222	0.251	0.384
Army II	0.210	0.225	0.282	0.411

A sample calculation of STIFFNESS for the Army I System at full load follows:

$$\begin{array}{r} \frac{25.0 - 23.8}{1091 - 883} \times 100 = 0.577\% \text{ (4000 r.p.m.)} \\ \phantom{\frac{25.0 - 23.8}{1091 - 883} \times 100} = 0.393\% \text{ (4500 r.p.m.)} \\ \phantom{\frac{25.0 - 23.8}{1091 - 883} \times 100} = 0.346\% \text{ (6000 r.p.m.)} \\ \phantom{\frac{25.0 - 23.8}{1091 - 883} \times 100} = 0.220\% \text{ (8000 r.p.m.)} \\ \phantom{\frac{25.0 - 23.8}{1091 - 883} \times 100} = 1.536 \end{array}$$

$$\text{Stiffness} = \frac{1.536}{4} = 0.384\%$$

It can be seen, particularly by means of the plotted curves, that the Compensating Coil System gives the desired lowest percentages of STIFFNESS. This is to be expected because, as previously stated, the STIFFNESS as herein calculated represents the slope of the VOLTAGE REGULATION curves, and we have seen that these are flattest for the Compensating Coil System.

13. Transient or Shock Loading.

(A) Some 90 oscillograms were taken during the shock loading tests. These covered, as previously recorded, three conditions of pre-shock, steady-state loading; and two speeds and three battery conditions for each of the four systems under consideration, as well as for the Standard Navy System with stabilizing transformer attached.

(B) Measurements made on the oscillograms, and calculations involving these measurements and other data, lead to the values tabulated in TABLE VI. It seems logical to assume that a system should be able to handle a shock load without drawing too heavily upon the batteries attached, and without adversely affecting the steady-state load already connected. The optimum results to be sought are, therefore, the minimum battery current and load loss while supplying a maximum current to the shock load. The data were consistent enough to warrant taking averages over the various speed and loading ranges; however, it is felt that the

results of the tests can only be interpreted qualitatively, inasmuch as there were many possible errors which, if additive, would reach the order of difference in the values between systems. The RANGE and STIFFNESS have been calculated as in TABLES I and V respectively. The Voltage Drops, Battery Currents, Recovery Times and Inverter Currents are straight-forward averages.

TABLE VI
OBSERVED VALUES OF SHOCK LOADING FACTORS

	Standard deviation in amps. per generator	Average range in amperes	Voltage drop at bus in volts	Voltage drop at Gens. in volts	Stiffness in Per Cent	Bat. current at load max. in amperes*	Bat. current at bat. max. in amperes*	Recovery time at bus in seconds	Recovery time at generators in seconds	Steady load lost in % of steady load	Average current supplied to Inverters
Standard Navy	9.64	23.6	6.6	4.7	0.368	329	430	0.09	0.06	36.1	1912
Compensating Coil	12.5	34.8	6.7	5.3	0.354	310	447	0.08	0.05	40.5	1998
Army I	14.8	38.6	7.0	5.4	0.397	340	459	0.11	0.07	40.3	1904
Army II	12.2	29.5	7.0	5.2	0.397	443	456	0.11	0.06	43.6	1864

* Two batteries only.

A sample calculation of STANDARD DEVIATION for Army II System under shock loading follows:

$$\sqrt{\frac{18^2 + 9^2 + 9^2 + 19^2}{4}} = \begin{matrix} 14.5 \text{ amperes} & \text{(No-load 4500 r.p.m.)} \\ 8.2 \text{ amperes} & \text{(1/4 load 4500 r.p.m.)} \\ 9.0 \text{ amperes} & \text{(3/4 load 4500 r.p.m.)} \\ 12.5 \text{ amperes} & \text{(No-load 6000 r.p.m.)} \\ 15.2 \text{ amperes} & \text{(1/4 load 6000 r.p.m.)} \\ 11.4 \text{ amperes} & \text{(3/4 load 6000 r.p.m.)} \end{matrix}$$

$$\begin{aligned} \text{Standard Deviation} &= \sqrt{\frac{14.5^2 + 8.2^2 + 9.0^2 + 12.5^2 + 15.2^2 + 11.4^2}{6}} \\ &= 12.2 \text{ amperes generator} \end{aligned}$$

A sample calculation of STEADY LOAD LOST for Compensating Coil System under shock loading is as follows:

$$\frac{28.7 \times 288 - 21.8 \times 210}{28.7 \times 288} \times 100 = \begin{array}{l} 44.5\% \text{ (1/4 load 4500 r.p.m.)} \\ 37.4\% \text{ (3/4 load 4500 r.p.m.)} \\ 44.0\% \text{ (1/4 load 6000 r.p.m.)} \\ 36.2\% \text{ (3/4 load 6000 r.p.m.)} \\ \hline 162.1 \end{array}$$

$$\text{Steady load lost} = \frac{162.1}{4} = 40.5\%$$

Examination of the above values allows us to draw the conclusion that there is a consistent indication of superiority on the part of the Standard Navy and Compensating Coil Systems as far as the factors listed are concerned.

14. General.

(A) The investigation of the factors which affect any system of regulation and paralleling resulted in the following findings, TABLE VII presents the calculated values of the VOLTAGE REGULATION in per cent for the various combinations of lead lengths and regulation points listed in CIRCUITS, (paragraph 7 (A)). The previously recorded results from the unchanged Standard Navy System are repeated here, and in the other tables in this section, for comparative purposes.

TABLE VII
VOLTAGE REGULATION AT BUS IN PER CENT

GENERATOR R.P.M.	4000	4500	6000	8000
Standard Navy RP at Gens. Lt #12	16.01	13.04	9.92	9.33
RP at Junct. Lt #12	17.0	12.24	6.79	5.51
RP at Bus Lt #12	12.55	7.09	2.45	1.73
RP at Gens. Lt #14	17.1	12.4	9.2	7.46
RP at Gens. Lt #10	16.6	12.66	9.02	8.15
RP at Junct. Lt #14	---	10.98	7.4	6.18
RP at Junct. Lt #10	---	9.8	6.78	5.15

These values are plotted in various combinations on PLATES IV, V, VI and VII. It can be seen that for the same wire size (#12 in PLATE IV, #14

and #10 in PLATE VII), the nearer the regulation point is moved to the bus, the better the VOLTAGE REGULATION. The problem was how to accomplish this without extra wiring, relays, etc. If the REGULATION AT BUS curve is compared with the Compensating Coil VOLTAGE REGULATION curve, a one to one correspondence is evident.

(B) Changing the size of wire used for the L+ lead from #12 to #10 or #14 causes practically no variation in the VOLTAGE REGULATION for either regulation at the generator terminals, (PLATE V), or regulation at the junction, (PLATE VI). This is to be expected, since the current in this lead is small, and much smaller sizes of wire could be used, probably being limited only by mechanical strength requirements.

(C) The RANGE, as shown by TABLE VIII and PLATES IV, V, VI and VIII, is adversely affected by these changes in regulation point and wire size, i.e., it increases to values between those of the regular Standard Navy System and the Army systems. This is to be expected, since no corresponding changes were made in the equalizing circuits, and the regulators, in an effort to balance the equalizing currents, have unbalanced the generators.

TABLE VIII
RANGE IN PER CENT OF LOAD

SYSTEM	1/4 LOAD	1/2 LOAD	3/4 LOAD	FULL LOAD
Standard Navy RP at Gens. L+ #12	3.5	1.91	1.2	1.06
RP at Junct. L+ #12	6.42	3.68	2.17	1.65
RP at Bus L+ #12	8.17	5.00	2.61	1.71
RP at Gens. L+ #14	10.7	4.83	2.42	1.69
RP at Gens. L+ #10	8.08	3.38	1.69	1.23
RP at Junct. L+ #14	7.0	2.83	1.48	1.14
RP at Junct. L+ #10	7.0	2.66	1.59	1.14

(D) The AVERAGE DEVIATION with respect to LOAD DIVISION is presented in TABLES IX and X, and PLATES IX and X. The same remarks can be made concerning these values, as were just made about the RANGE.

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TABLE IX

AVERAGE DEVIATION IN PER CENT OF LOAD

SYSTEM	1/4 LOAD	1/2 LOAD	3/4 LOAD	FULL LOAD
Standard Navy RP at Gens. Lt #12	1.15	0.62	0.36	0.34
RP at Junct. Lt #12	2.25	1.28	0.73	0.52
RP at Bus Lt #12	2.9	1.56	0.85	0.56
RP at Gens. Lt #14	3.35	1.4	0.72	0.52
RP at Gens. Lt #10	2.8	1.08	0.52	0.41
RP at Junct. Lt #14	2.55	1.05	0.55	0.4
RP at Junct. Lt #10	2.4	0.94	0.51	0.46

TABLE X

AVERAGE DEVIATION IN AMPERES PER GENERATOR

SYSTEM	4000	4500	6000	8000
Standard Navy RP at Gens. Lt #12	6.75	4.13	1.13	2.63
RP at Junct. Lt #12	11.1	6.7	5.9	9.4
RP at Bus Lt #12	11.0	8.6	7.7	5.3
RP at Gens. Lt #14	10.7	8.8	6.4	5.4
RP at Gens. Lt #10	8.5	6.9	5.2	3.9
RP at Junct. Lt #14	---	8.5	5.4	3.9
RP at Junct. Lt #10	---	7.5	5.9	3.9

(E) The computed values for the STIFFNESS of these various combinations, which are tabulated in TABLE XI and plotted on PLATE XI, indicate better performance for regulation at the junction and the bus than with

the Standard Navy System at the generator terminals. This was due to the fact that the STIFFNESS reflects the VOLTAGE REGULATION and we have already seen that regulating at the bus resulted in less voltage drop with load.

TABLE XI
AVERAGE STIFFNESS, $\frac{\Delta E}{\Delta I}$, IN PER CENT
(Steady-State Conditions)

SYSTEM	1/4 LOAD	1/2 LOAD	3/4 LOAD	FULL LOAD
Standard Navy RP at Gens. L+ #12	0.205	0.191	0.276	0.417
RP at Junct. L+ #12	0.16	0.185	0.23	0.349
RP at Bus L+ #12	0.055	0.085	0.104	0.233
RP at Gens. L+ #14	0.177	0.233	0.251	0.389
RP at Gens. L+ #10	0.203	0.201	0.244	0.407
RP at Junct. L+ #14	0.105	0.13	0.187	0.164
RP at Junct. L+ #10	0.08	0.131	0.177	0.25

(F) The results of the shock-loading tests, as applied to the Standard Navy System with stabilizing transformer and with no batteries and with four batteries, are presented in TABLE XII.

TABLE XII
OBSERVED VALUES OF SHOCK LOADING FACTORS

	Standard deviation in amps. per generator	Average range in amperes	Voltage drop at bus in volts	Voltage drop at Gens. in volts	Stiffness in Per Cent	Bat. current at load max. in amperes	Bat. current at bat. max. in amperes	Recovery time at bus in seconds	Recovery time at generators in seconds	Steady load lost in % of steady load	Average current supplied to alternators
Standard Navy	9.64	23.6	6.6	4.7	0.368	329	430	0.09	0.06	20.1	1912
Stabilizing Transformer	12.58	31.3	6.9	5.4	0.386	354	459	0.11	0.06	22.5	1914
Stand. Navy No battery	16.6	30.8	8.7	7.0	0.536	---	---	0.11	0.07	23.2	1762
Stand. Navy 4 batteries	8.6	22.0	5.7	4.5	0.309	458	612	0.08	0.05	24.9	1944

CONCLUSIONS

15.

(A) A comparison of the factors discussed in EXPERIMENTAL OBSERVATIONS (paragraph 12), enables us to judge the overall efficiency of paralleling the four systems studied. The Compensating Coil System gives the best performance, especially with regard to maintaining rated voltage at the bus. The Standard Navy System has very nearly the same overall performance as the Compensating Coil System, but due to voltage regulation at the generator terminals and consequent generator lead drop to the bus, does not maintain bus voltage as well. The two Army systems (particularly the Army II with shunt in the positive generator lead) compare favorably with the Navy system as far as voltage regulation is concerned, but the method of equalizing load (which does not compensate for individual generator installations) is not as effective as the Compensating Coil or Standard Navy Systems. This evaluation is borne out further by the shock-loading tests, to the extent that there is a previously mentioned consistent indication of superior performance by the Compensating Coil and Standard Navy Systems.

(B) As has already been stated, the runs involving variation of regulator lead lengths or wire size were inconclusive. The variation of the regulation point resulted in better maintenance of rated voltage at the bus as the point was moved nearer the bus. This routine conclusion emphasizes the necessity for actually or effectively regulating the voltage at the bus in a large system.

(C) The question of the number of batteries to be used with an aircraft electrical system can be partially answered in favor of the practice of using two. This is shown in the evaluation of the data and oscillographs taken when the systems were tested without batteries and with four batteries. The average voltage drop under shock load for the systems without batteries was 8.7 volts. This drop was reduced to 6.9 volts by two batteries, which supplied an average of 354 amperes of the 2000-ampere shock load. The addition of two more batteries resulted in a further reduction of the drop by 1.2 volts and supplied only 100 amperes more. Since operation of the systems is satisfactory with two batteries, it would seem unnecessary to double the battery capacity and weight to accomplish the relatively small increases in overall performance to be gained.

(D) Comparison of the values in TABLE XII leads to the conclusion that the stabilizing transformer has a very slight effect on the system.

RECOMMENDATIONS

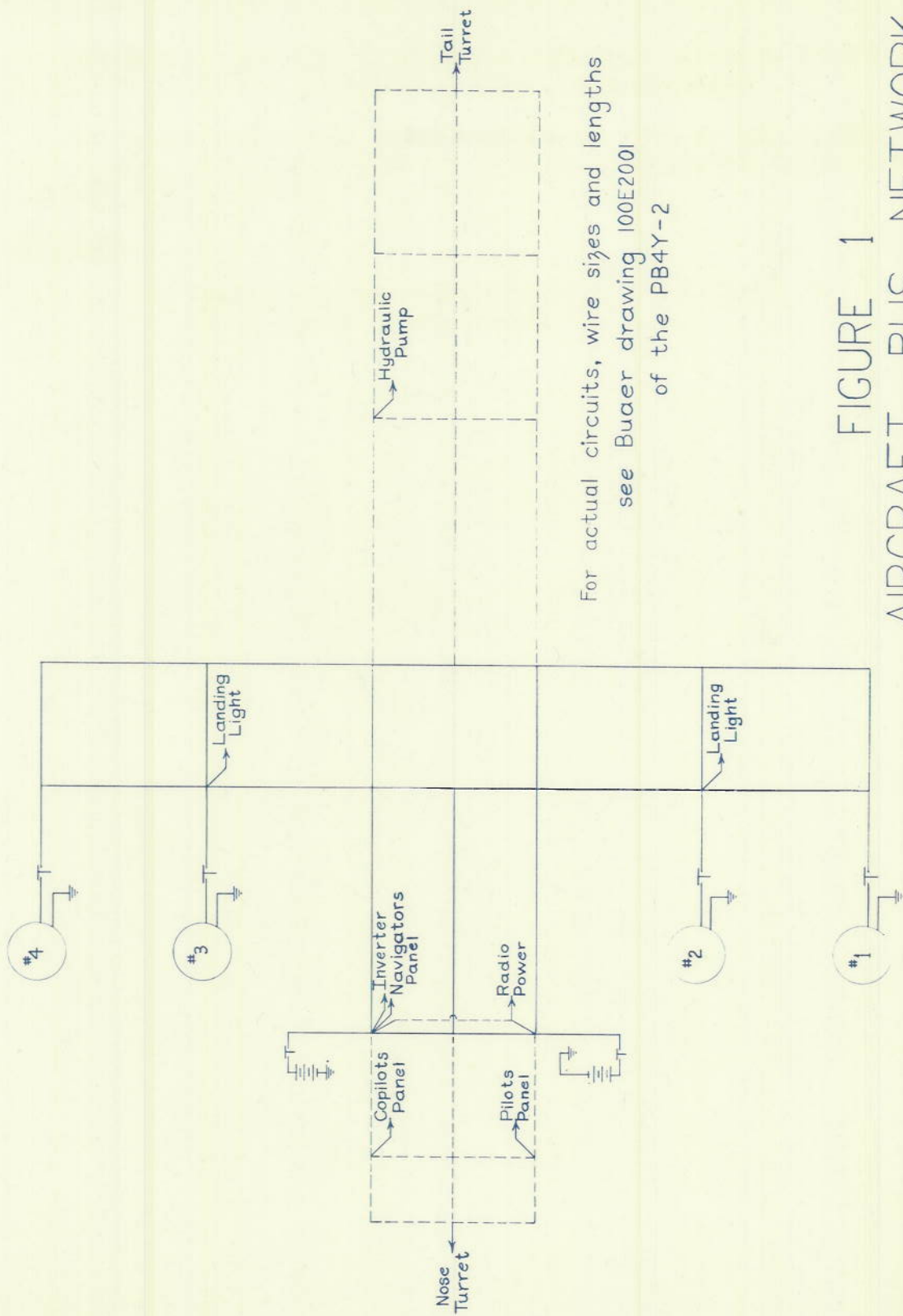
16. The following recommendations are based on the above conclusions and are applicable to aircraft electrical systems comparable to the system used for the PB4Y-2 aircraft:

(A) Despite increased installation adjustment problems, the installation of the Compensating Coil System is recommended.

(B) Unless operational factors beyond the scope of this project are involved, it is recommended that battery installations be restricted to two AN 3150 batteries.

REFERENCE

17. (a) BuAer ltr to NRL, Aer-E-3124-GJA, F36-1, Serial No. 127668, dated 1 August 1945.

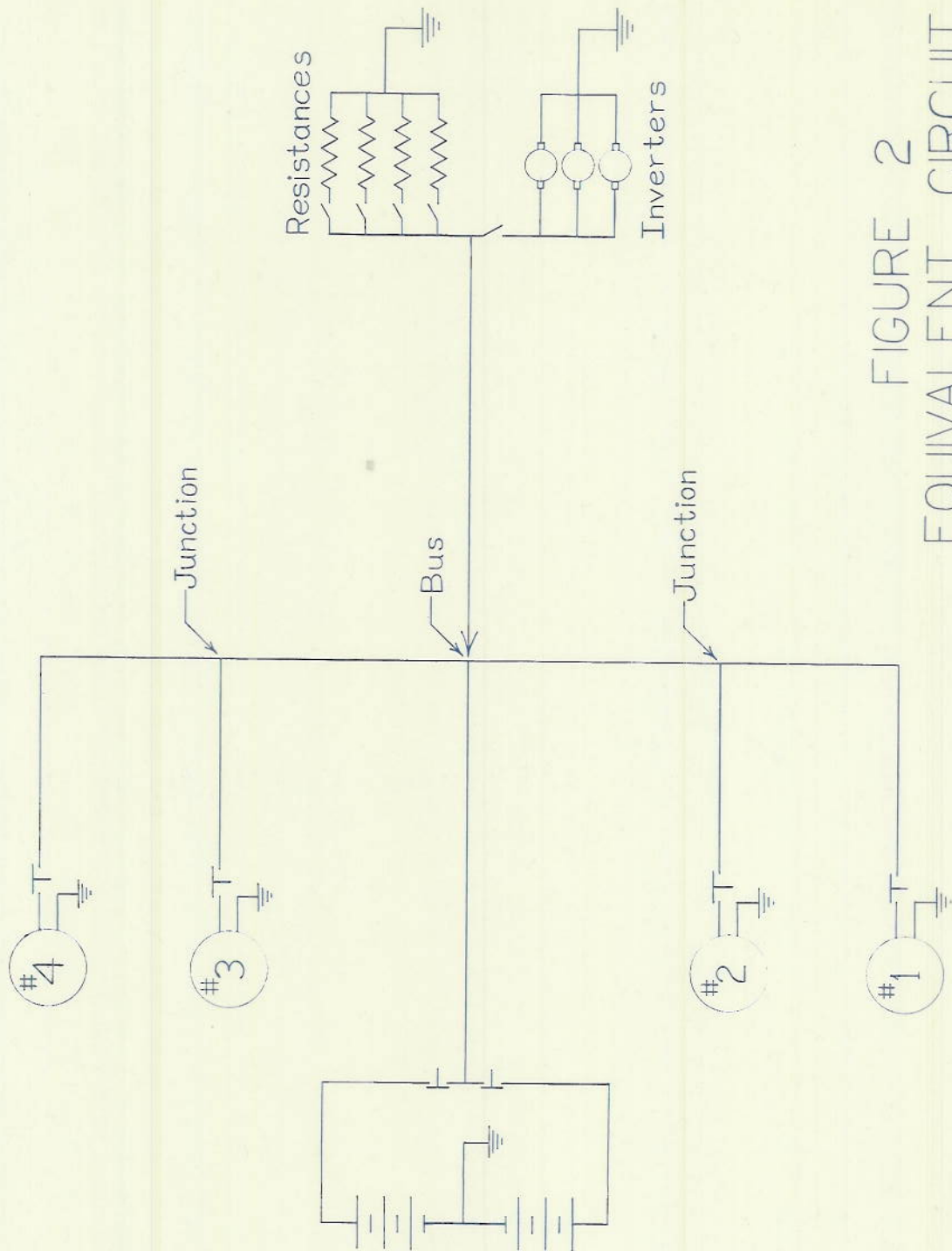


For actual circuits, wire sizes and lengths
 see Buaer drawing 100E2001
 of the PB4Y-2

FIGURE 1

FIGURE 1
 AIRCRAFT BUS NETWORK

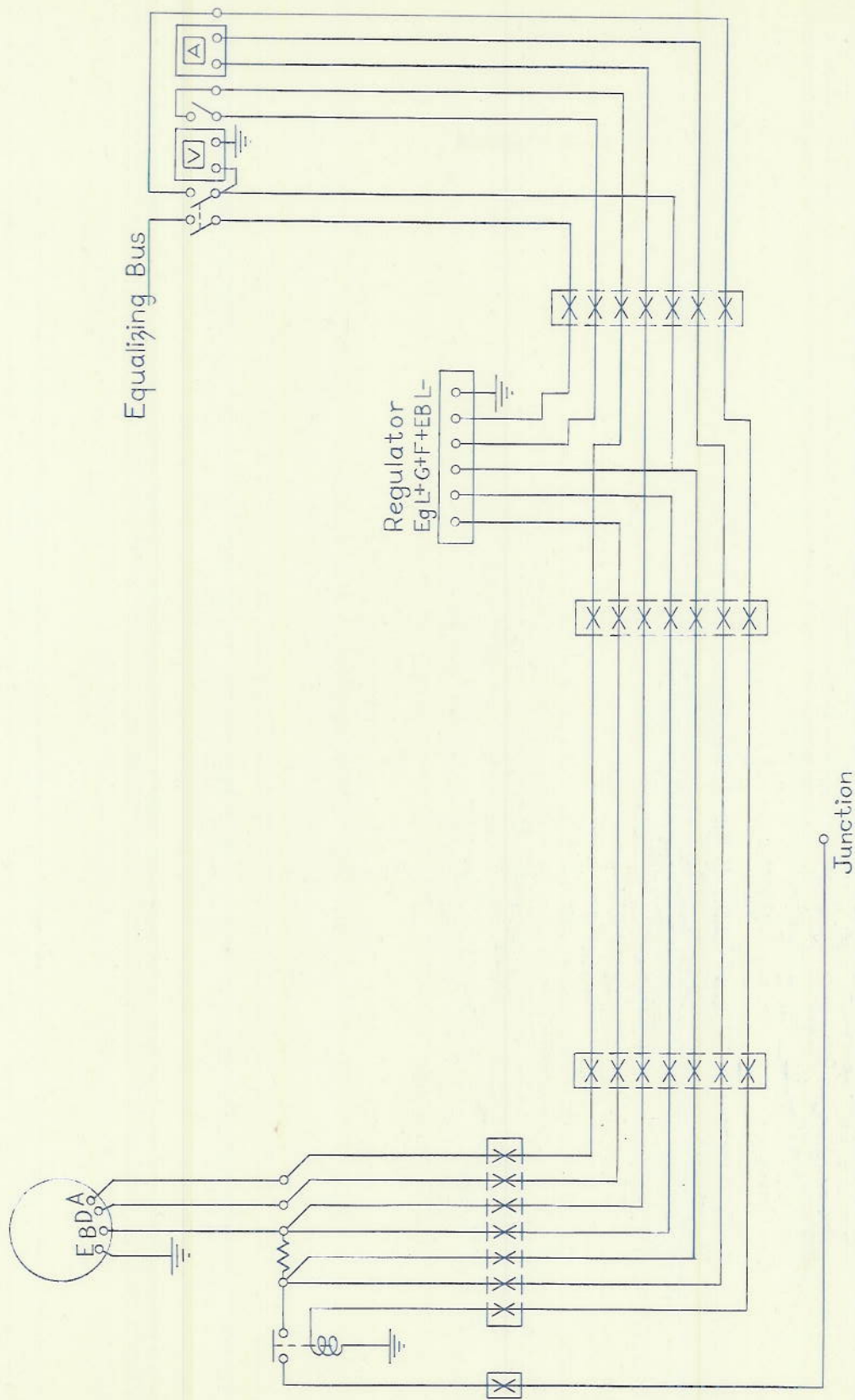
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FIGURE 2

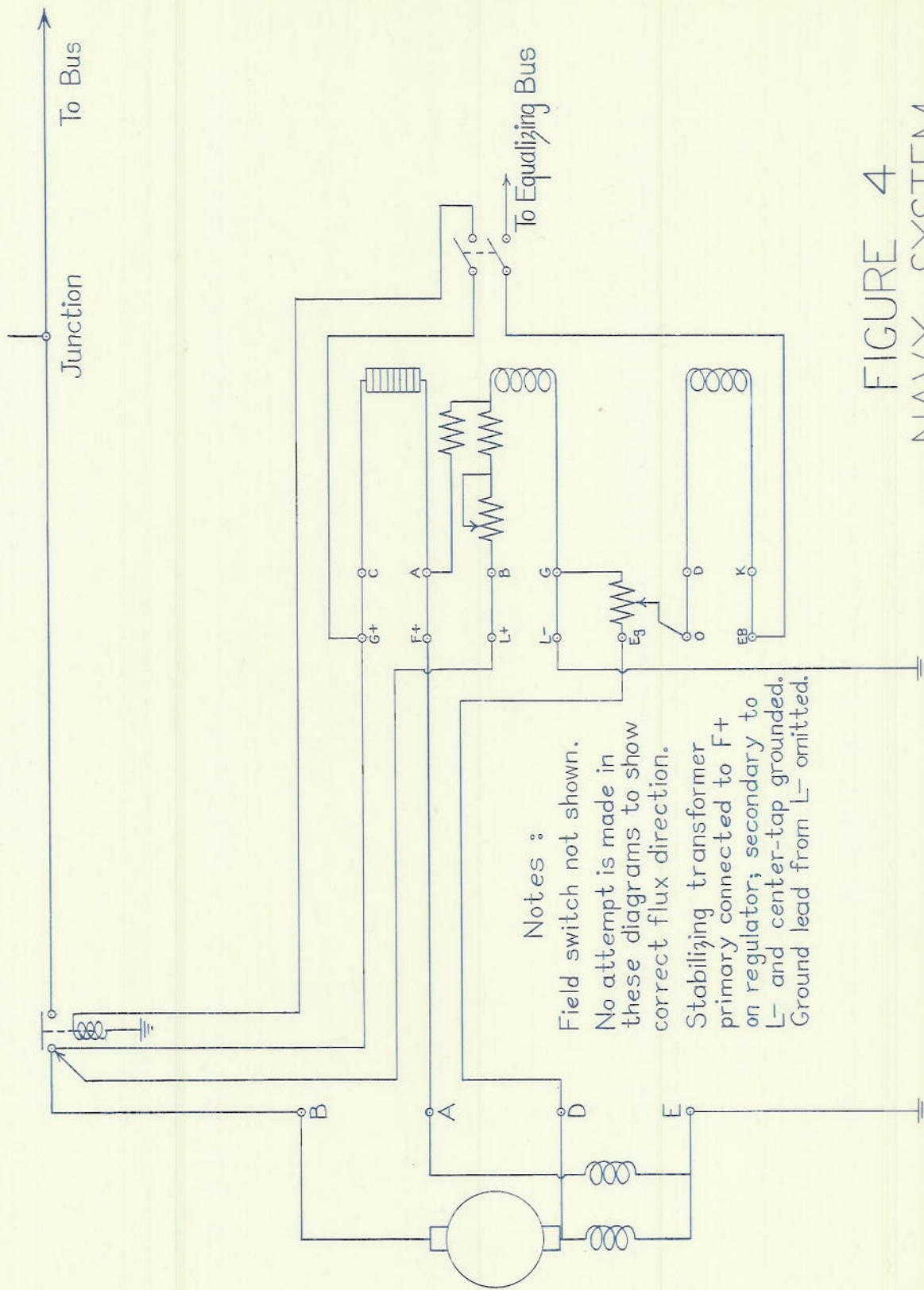
FIGURE 2
EQUIVALENT CIRCUIT



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FIGURE 3

FIGURE 3
VOLTAGE REGULATOR CIRCUIT



Notes :

- Field switch not shown.
- No attempt is made in these diagrams to show correct flux direction.
- Stabilizing transformer primary connected to F+ on regulator; secondary to L- and center-tap grounded.
- Ground lead from L- omitted.

FIGURE 4
NAVY SYSTEM

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FIGURE 4

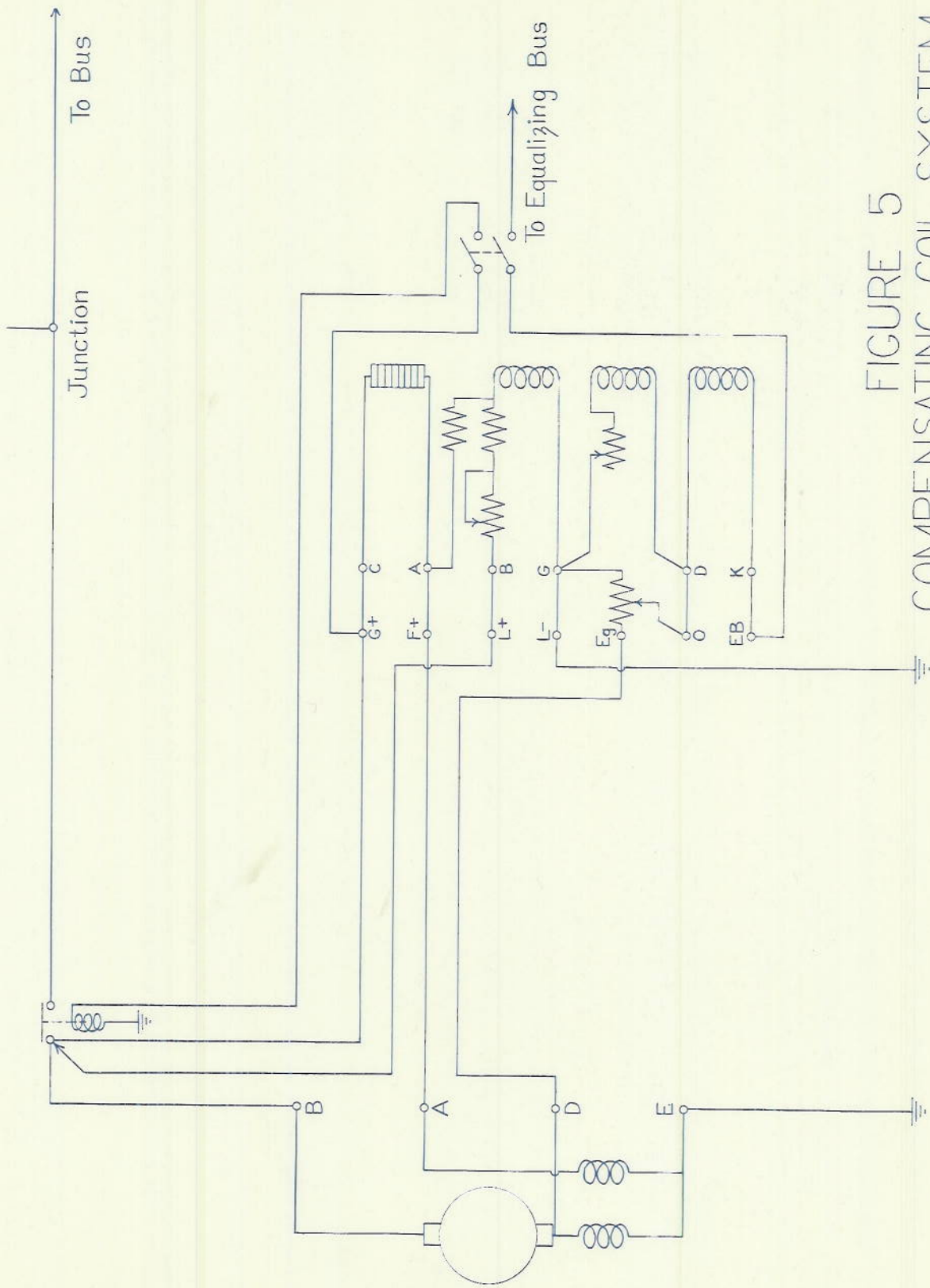


FIGURE 5
COMPENSATING COIL SYSTEM

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FIGURE 5

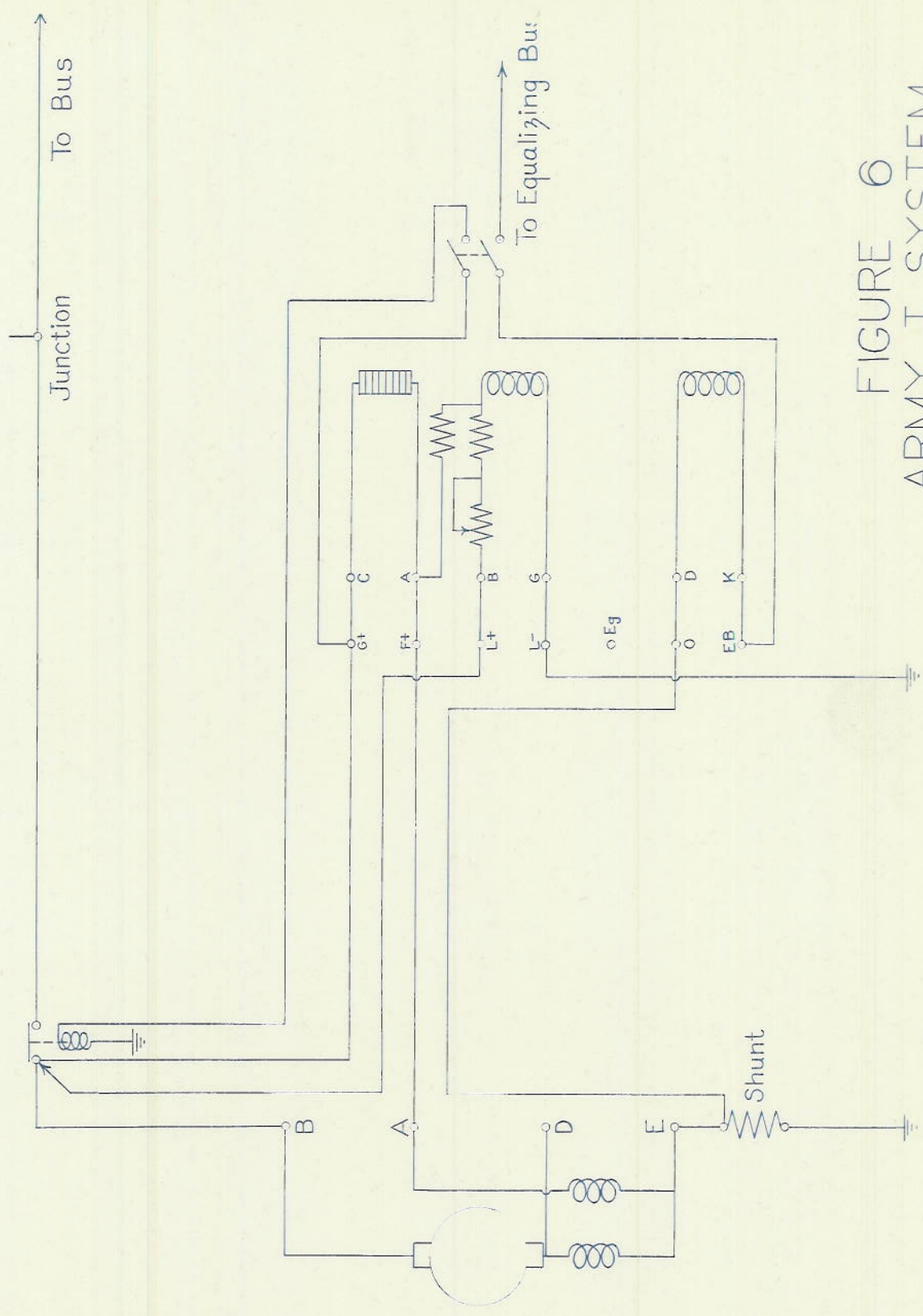


FIGURE 6
ARMY I SYSTEM

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FIGURE 6

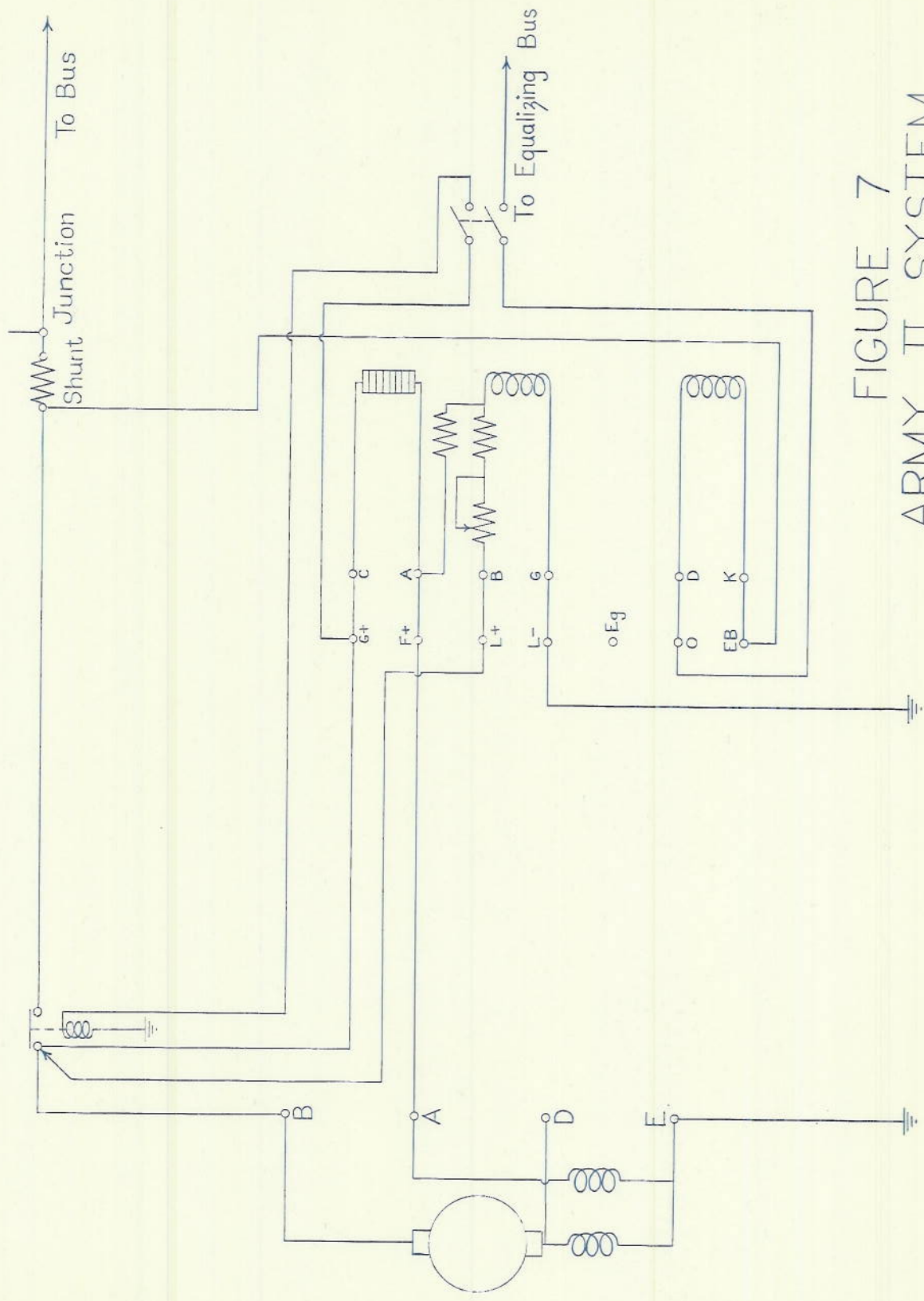
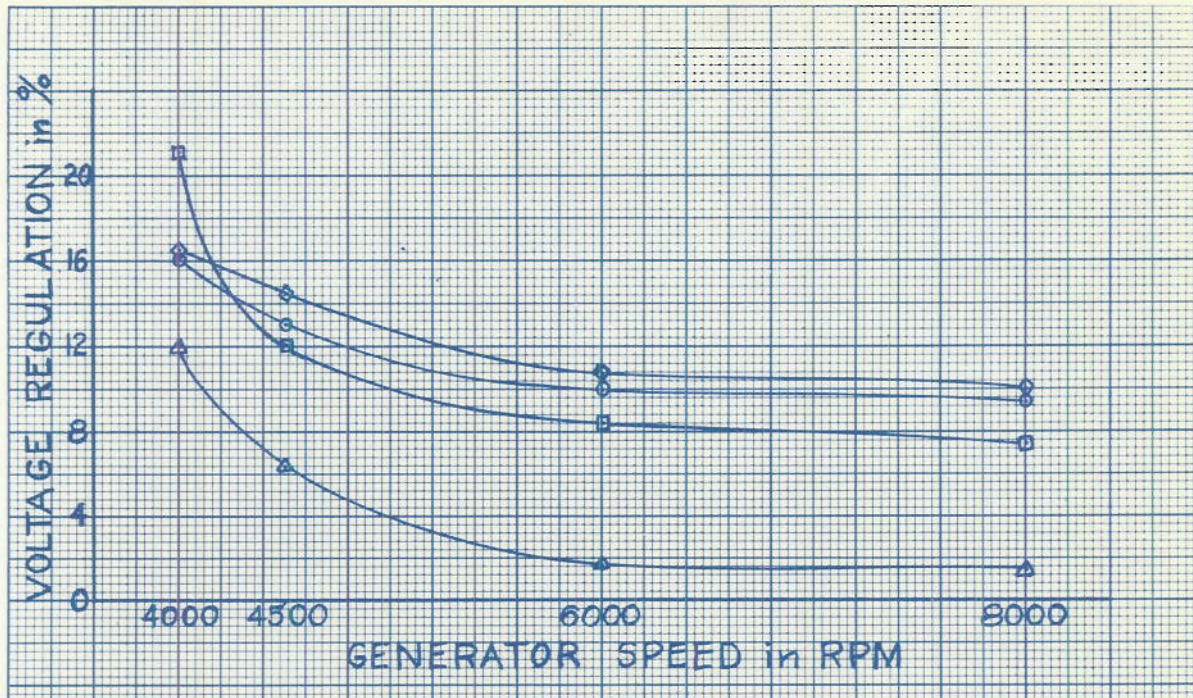


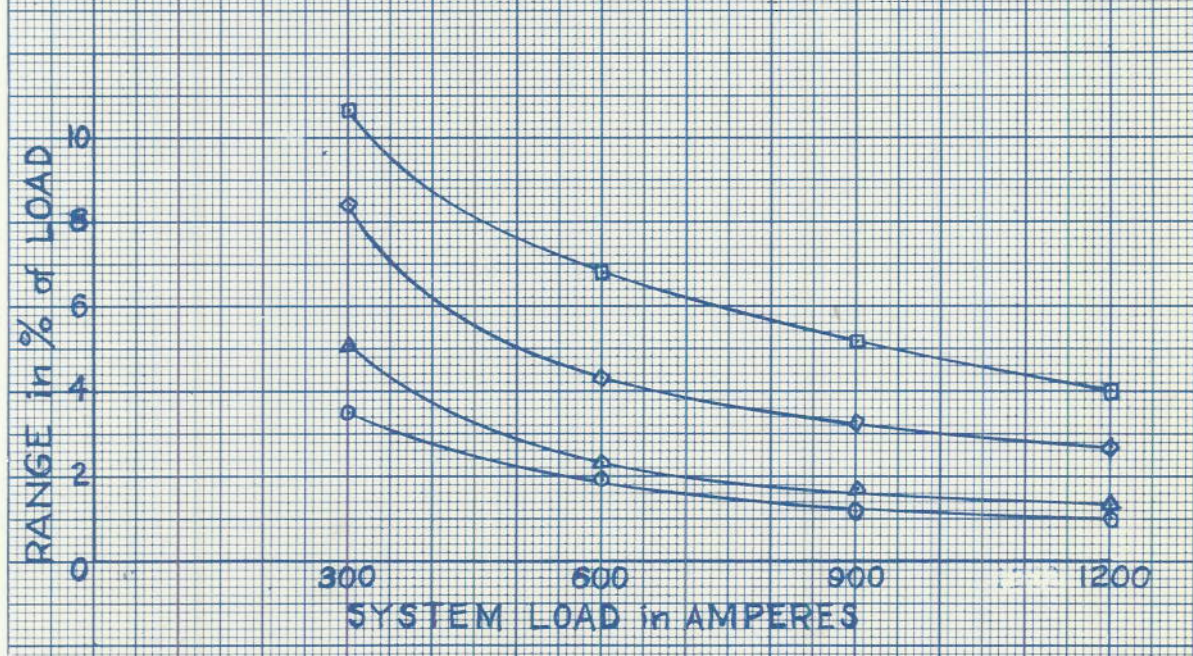
FIGURE 7
ARMY II SYSTEM

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FIGURE 7



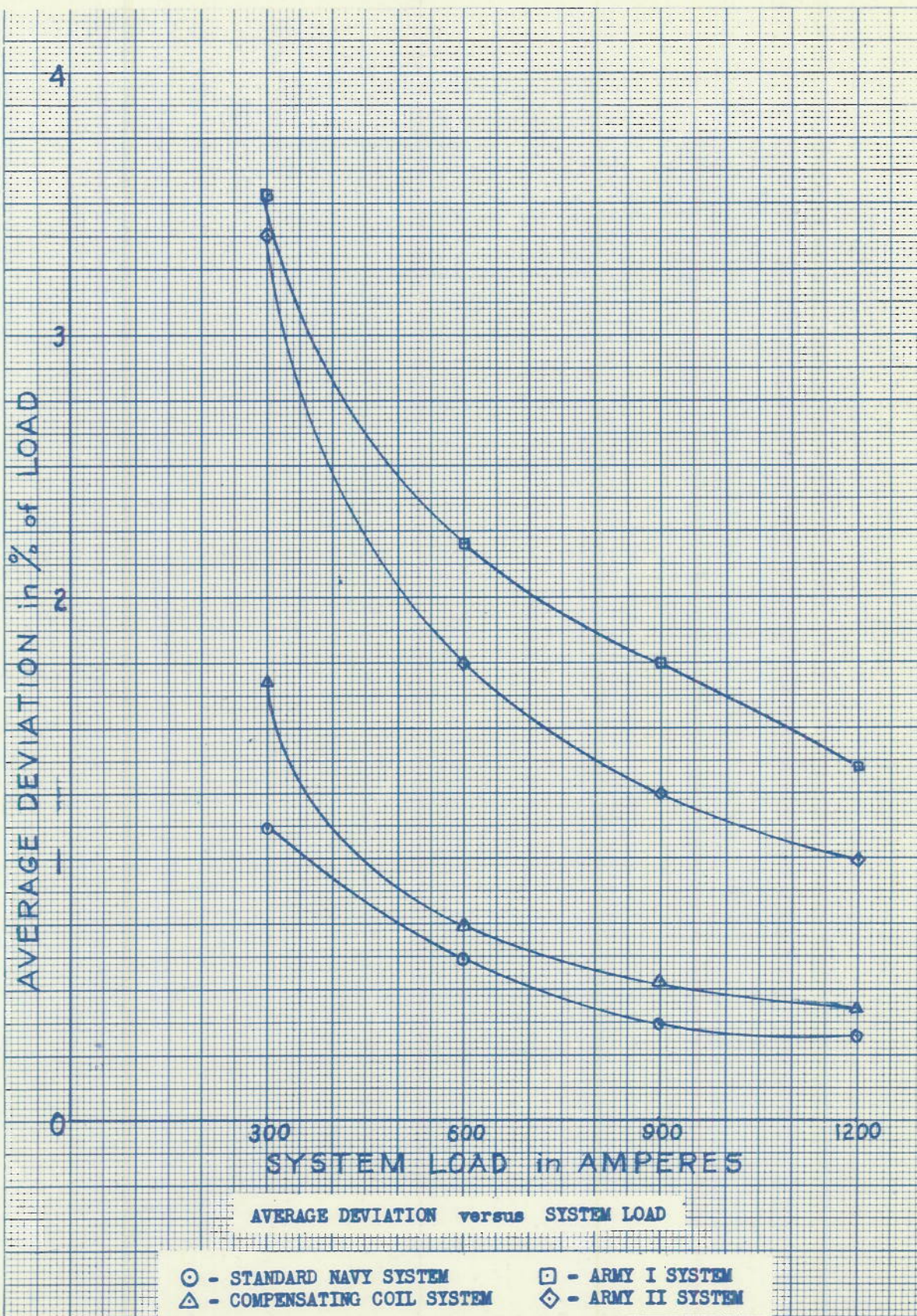
VOLTAGE REGULATION versus GENERATOR SPEED



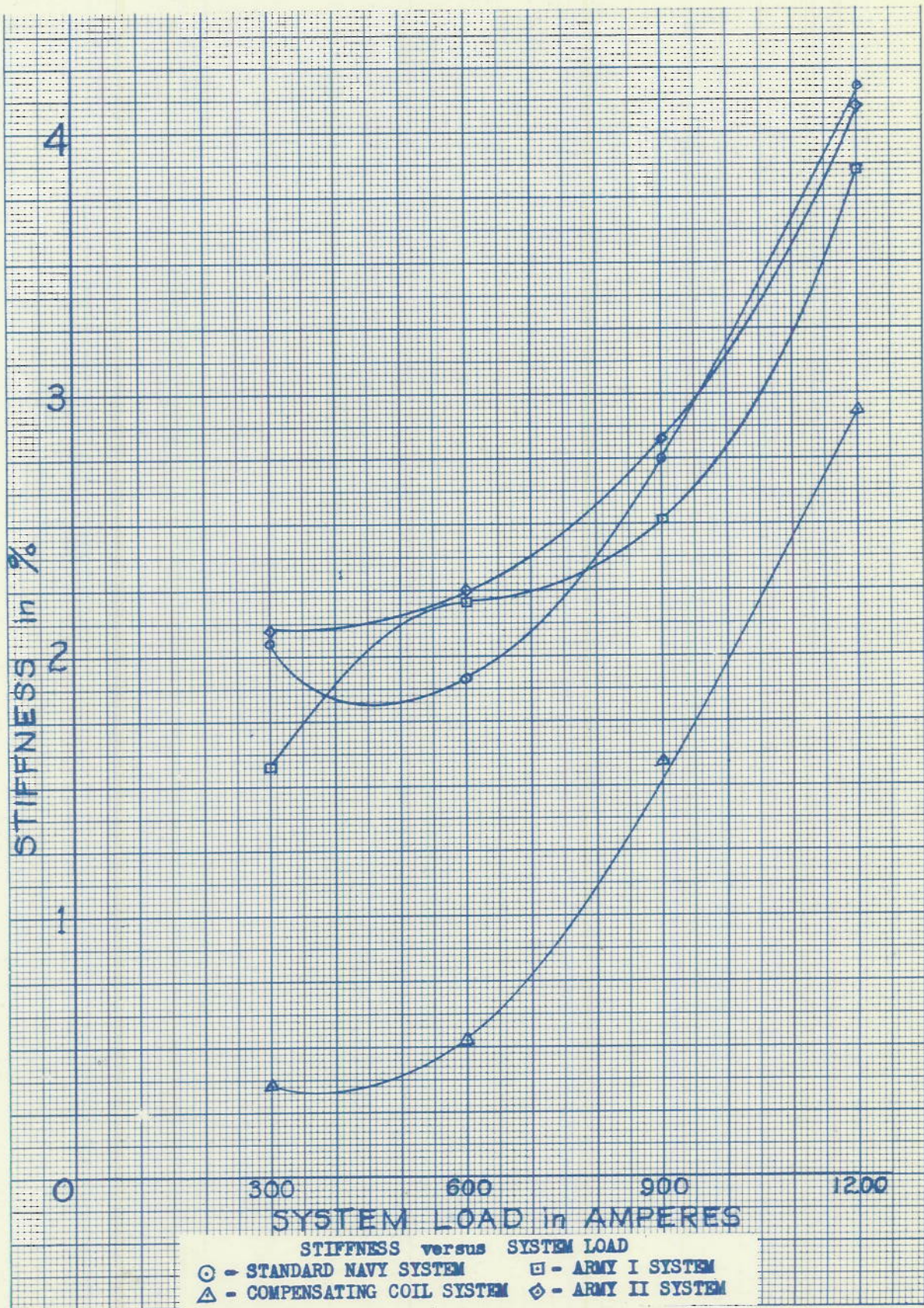
RANGE versus SYSTEM LOAD

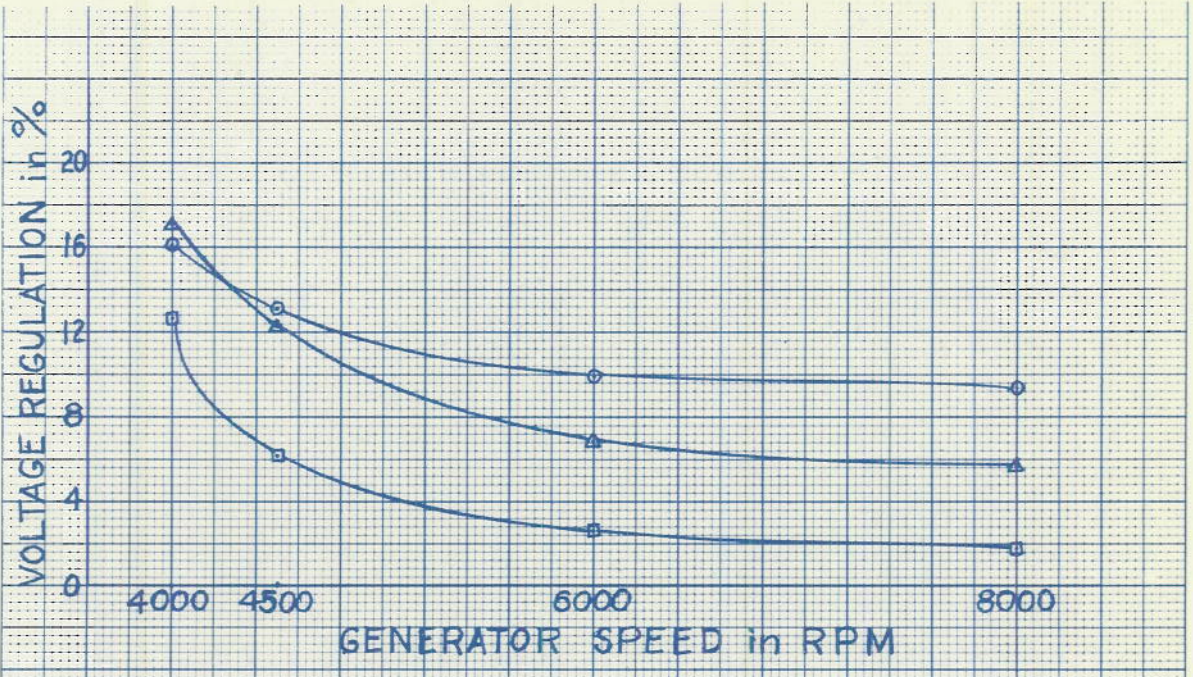
- - STANDARD NAVY SYSTEM
- - ARMY I SYSTEM
- △ - COMPENSATING COIL SYSTEM
- ◇ - ARMY II SYSTEM

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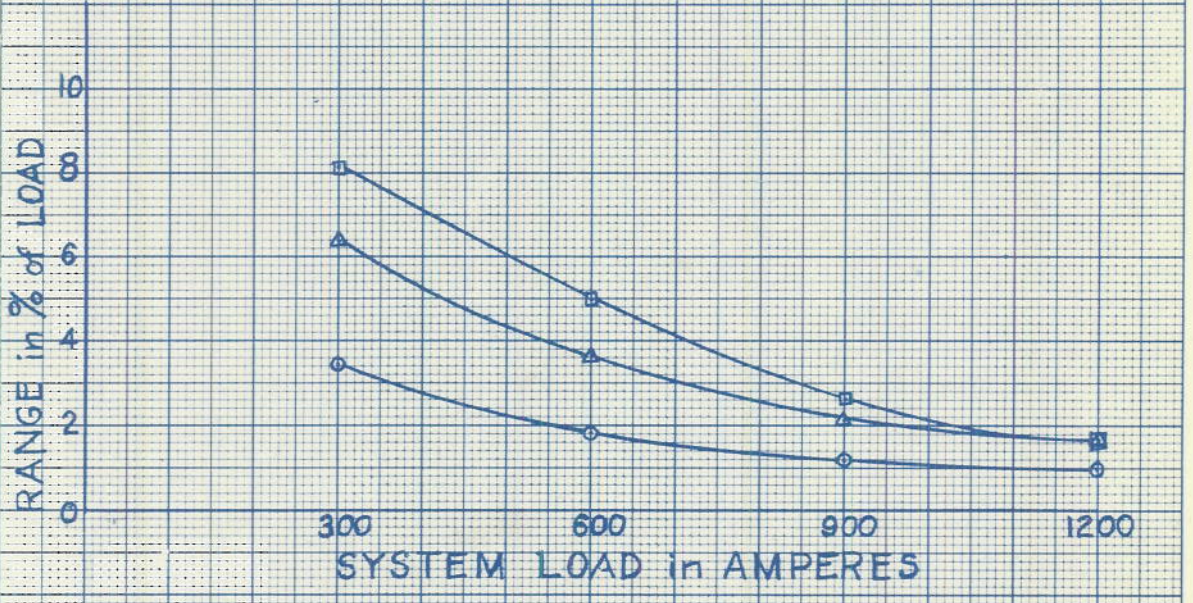


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 .07 10 to the 1/4 inch, 5th lines accepted.
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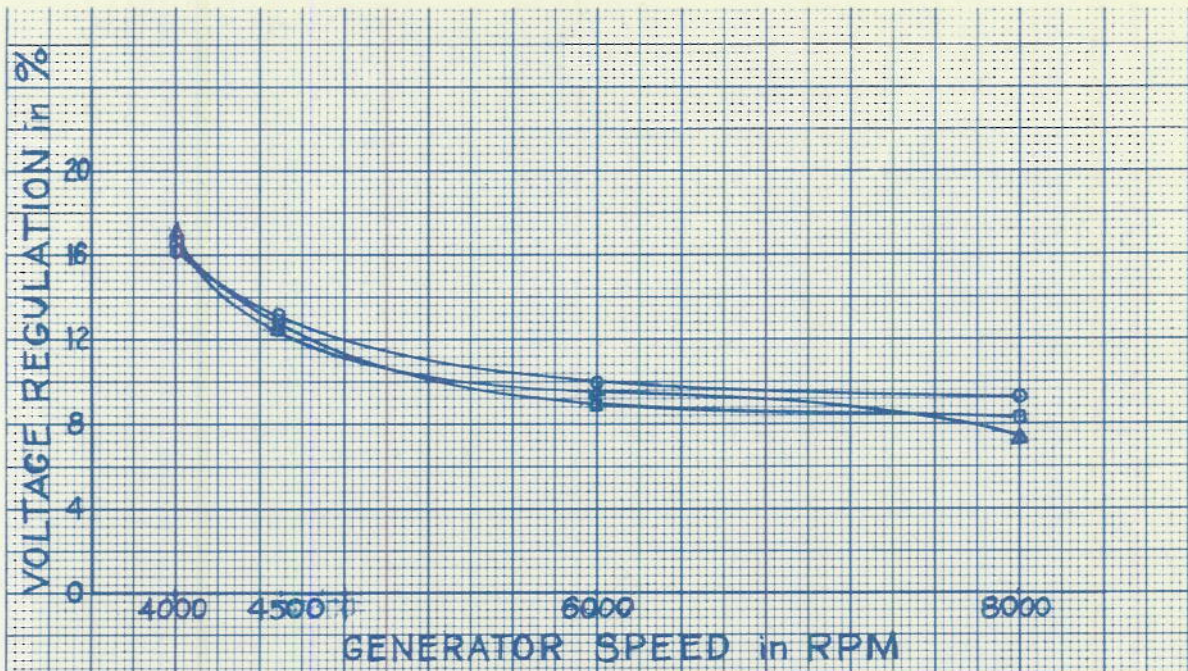
VOLTAGE REGULATION versus GENERATOR SPEED



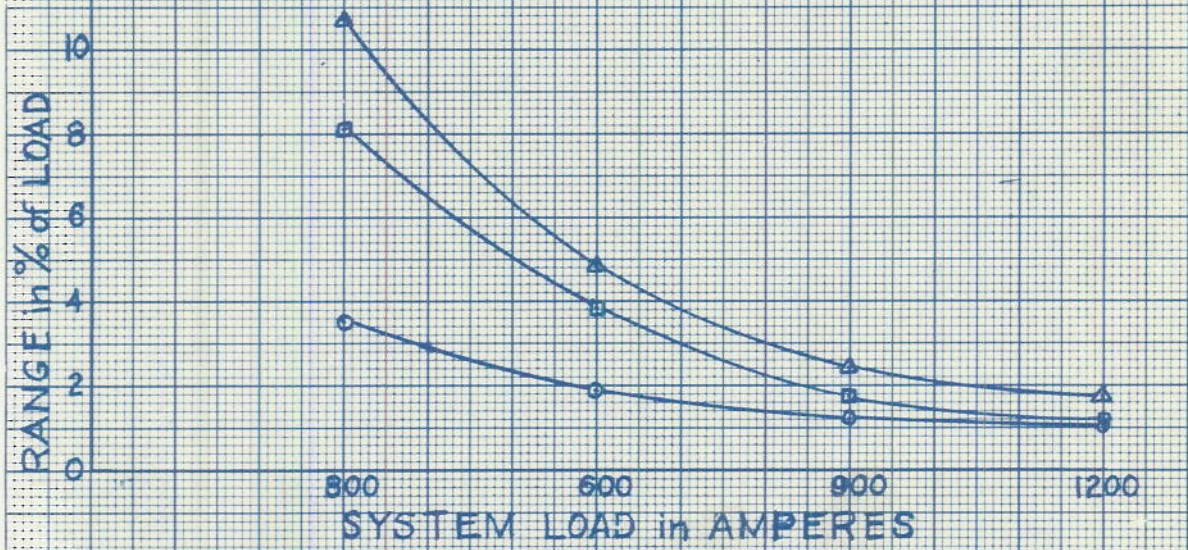
RANGE versus SYSTEM LOAD

STANDARD NAVY SYSTEM L+ #12
 ○ - REGULATION POINT at GENERATORS
 △ - REGULATION POINT at JUNCTION
 □ - REGULATION POINT at BUS

0.10 to the 1/4 inch, 6th lines corrected
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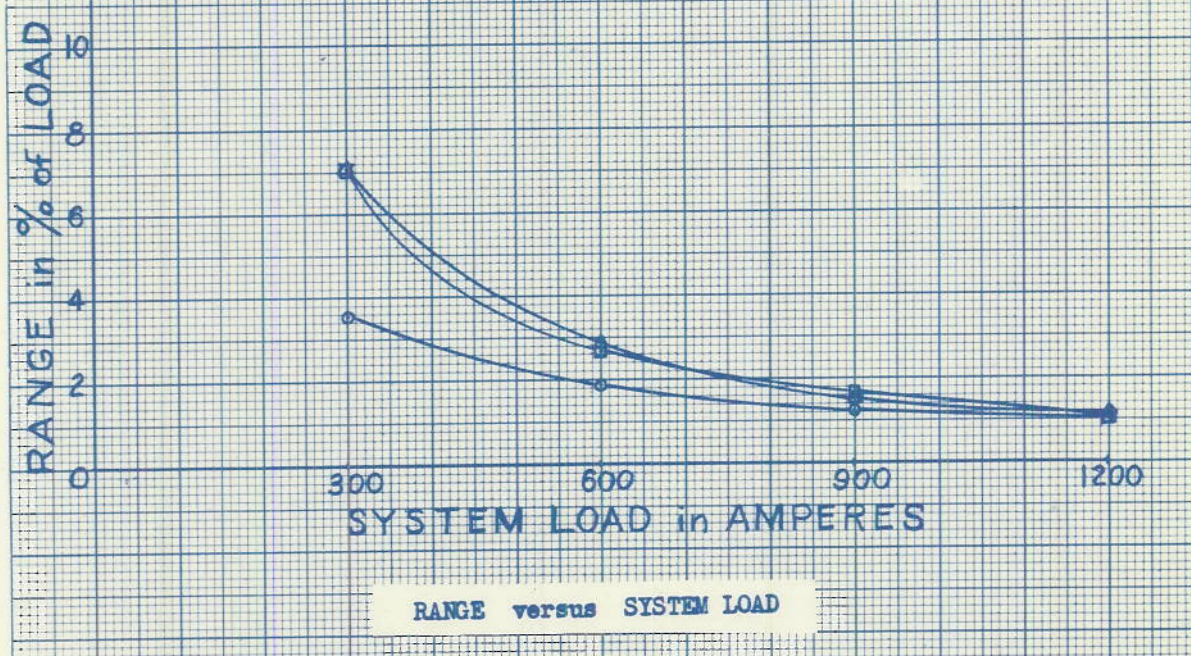
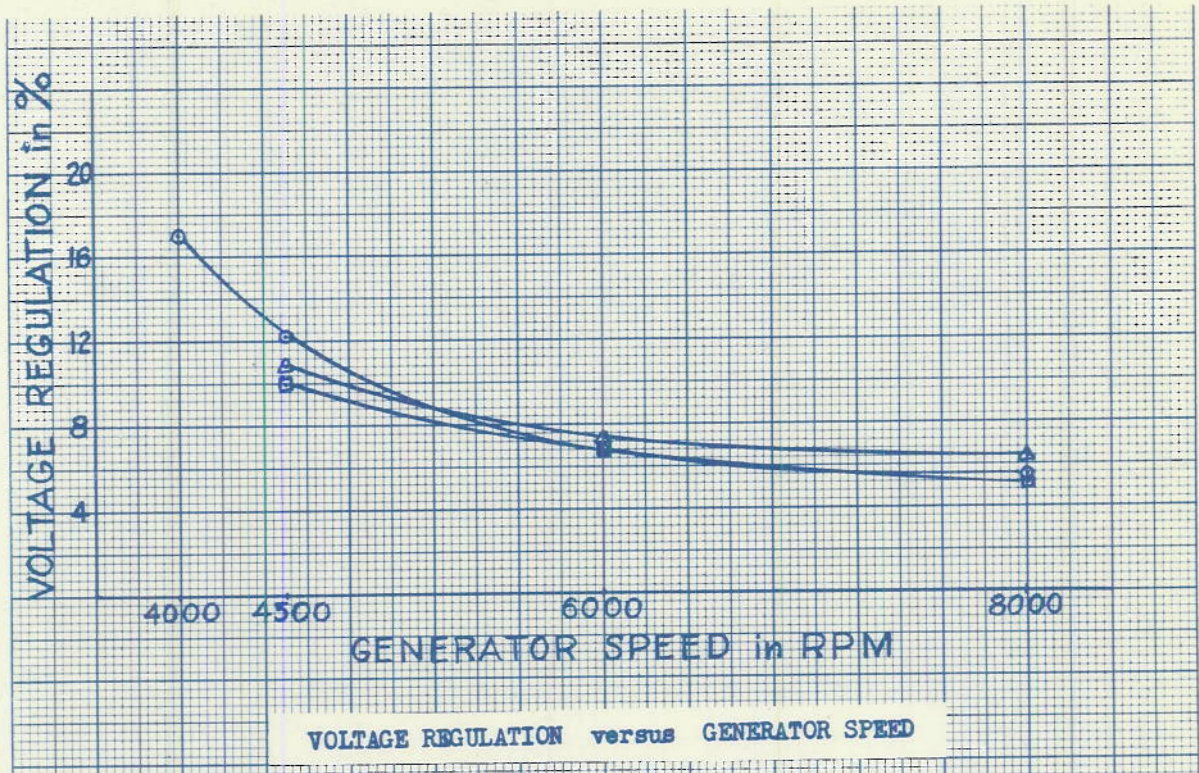
VOLTAGE REGULATION versus GENERATOR SPEED



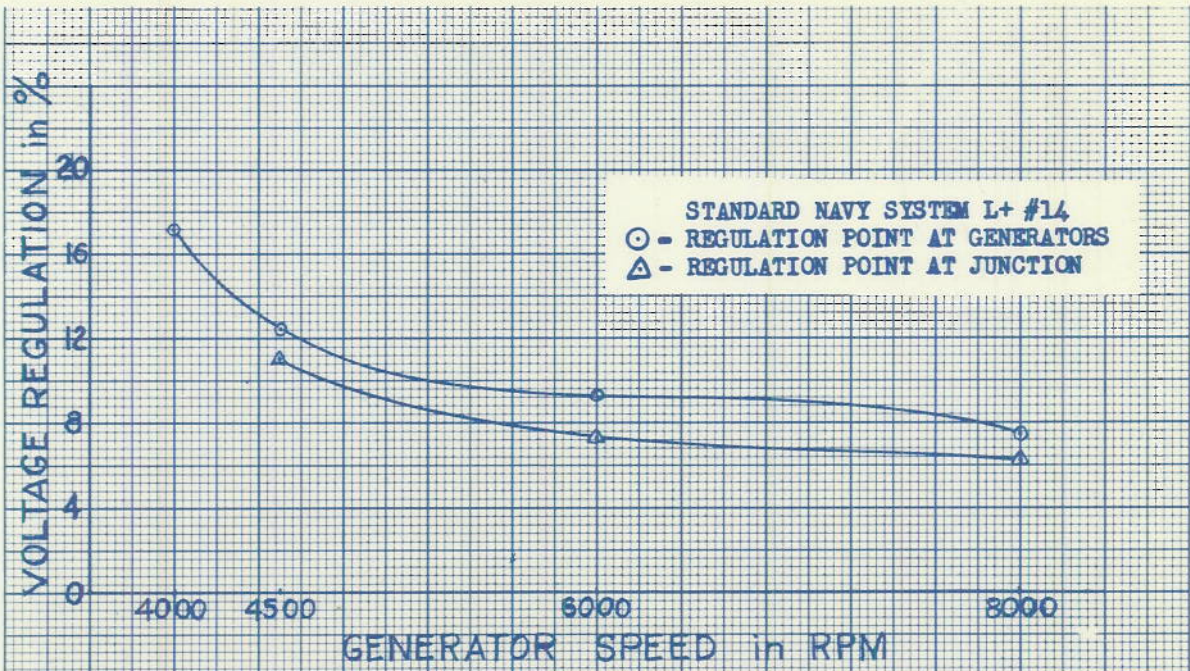
RANGE versus SYSTEM LOAD

STANDARD NAVY SYSTEM REGULATION POINT AT GENERATORS

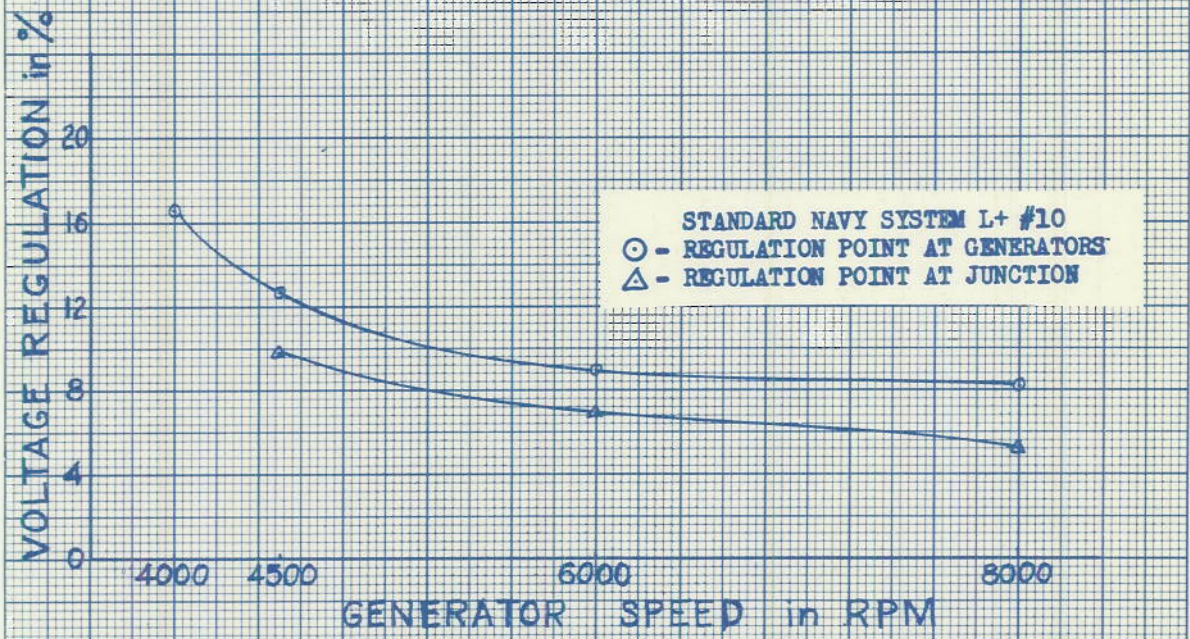
- - L+ REGULATOR LEAD #12 WIRE
- △ - L+ REGULATOR LEAD #14 WIRE
- - L+ REGULATOR LEAD #10 WIRE



STANDARD NAVY SYSTEM with REGULATION POINT at JUNCTION
 ○ - L+ REGULATOR LEAD #12 WIRE
 △ - L+ REGULATOR LEAD #14 WIRE
 □ - L+ REGULATOR LEAD #10 WIRE

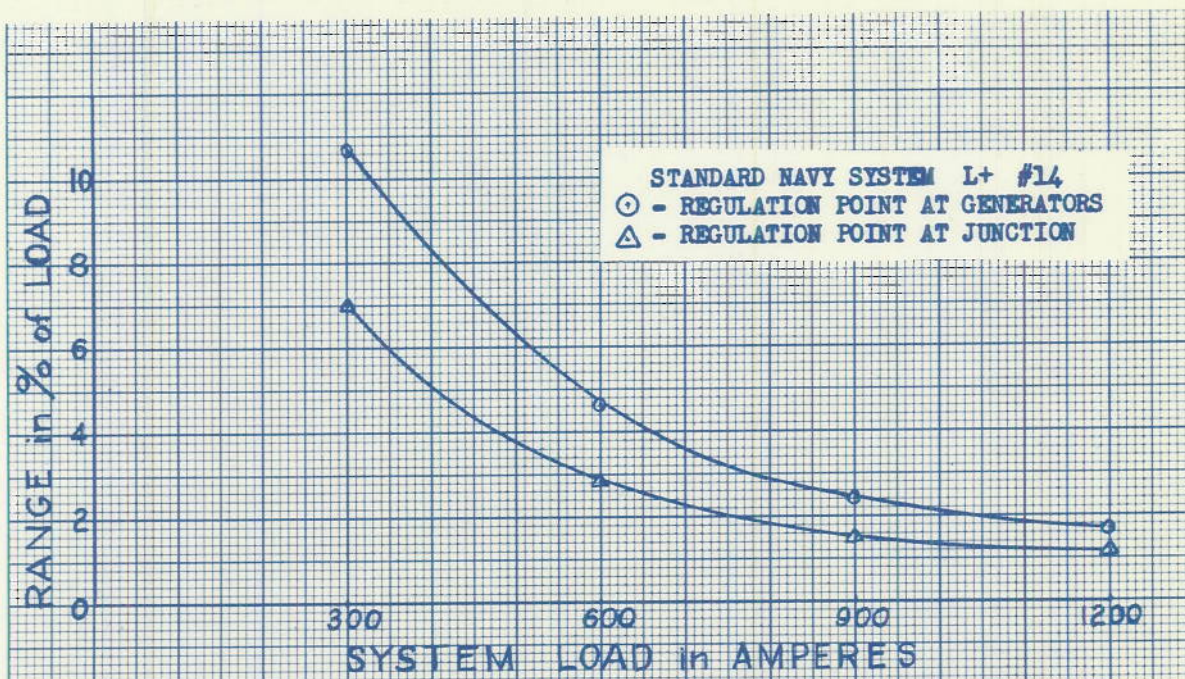


VOLTAGE REGULATION versus GENERATOR SPEED

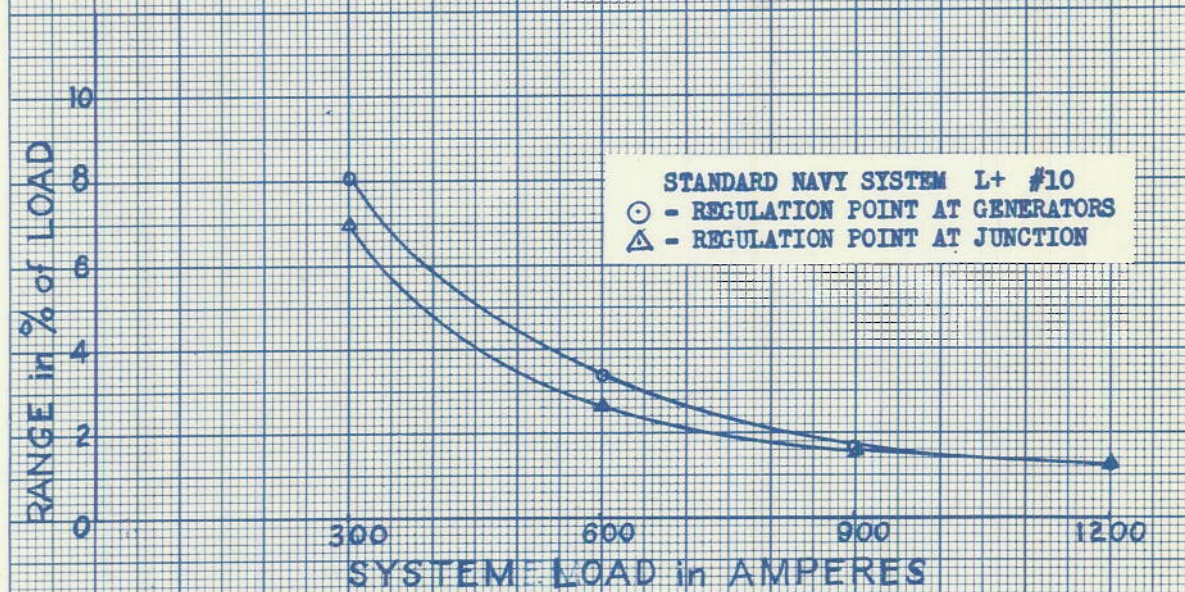


VOLTAGE REGULATION versus GENERATOR SPEED

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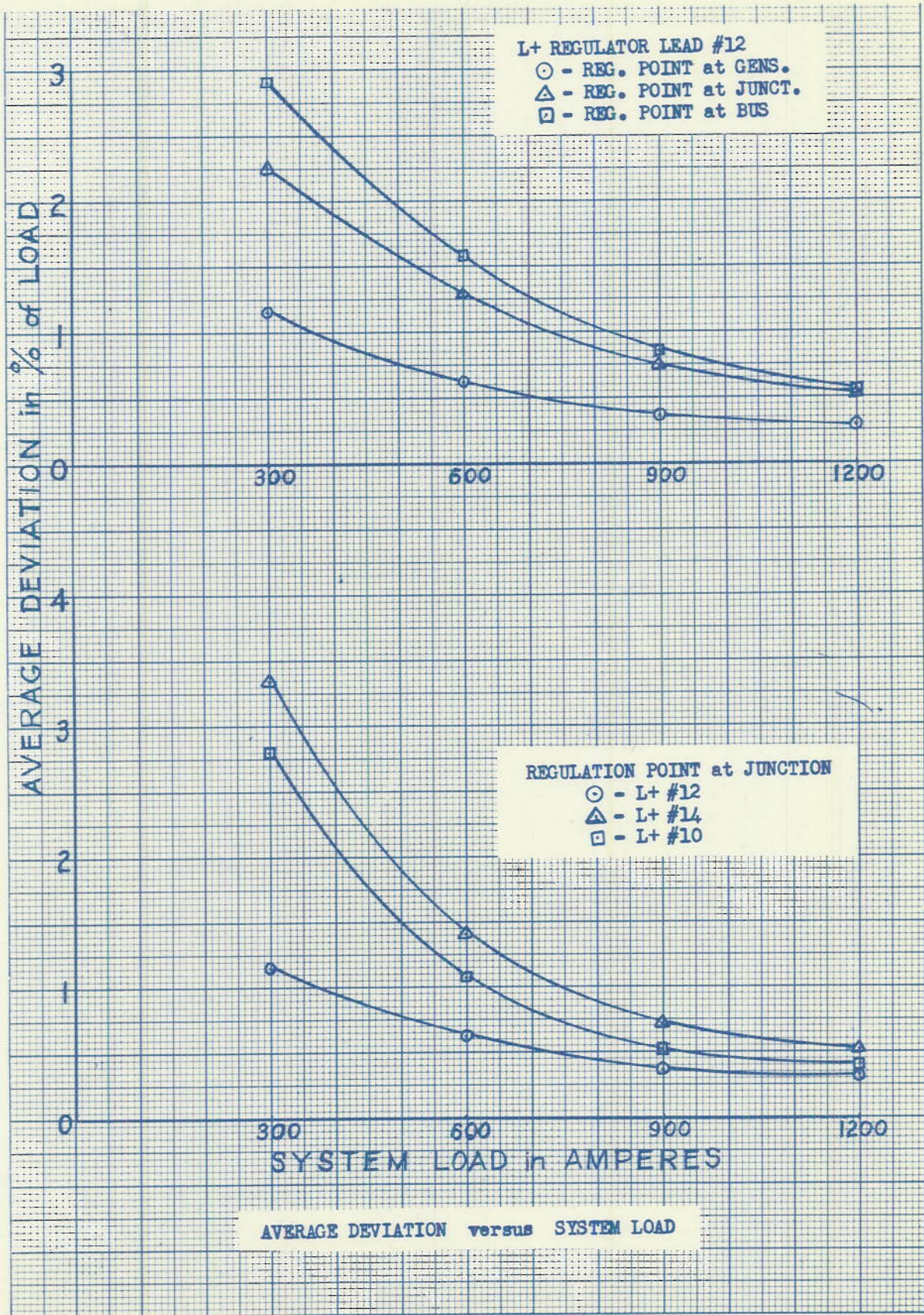


RANGE versus SYSTEM LOAD

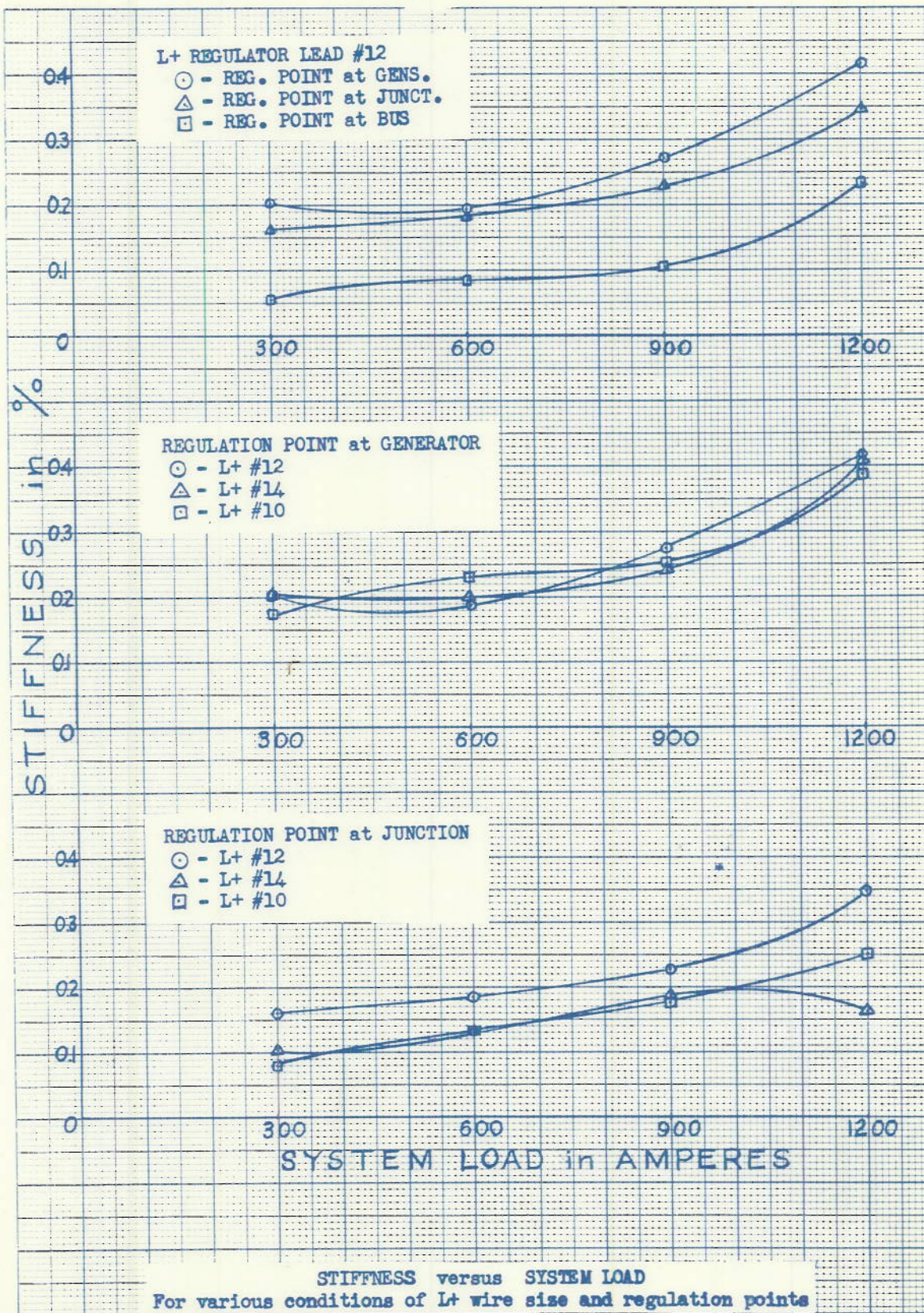


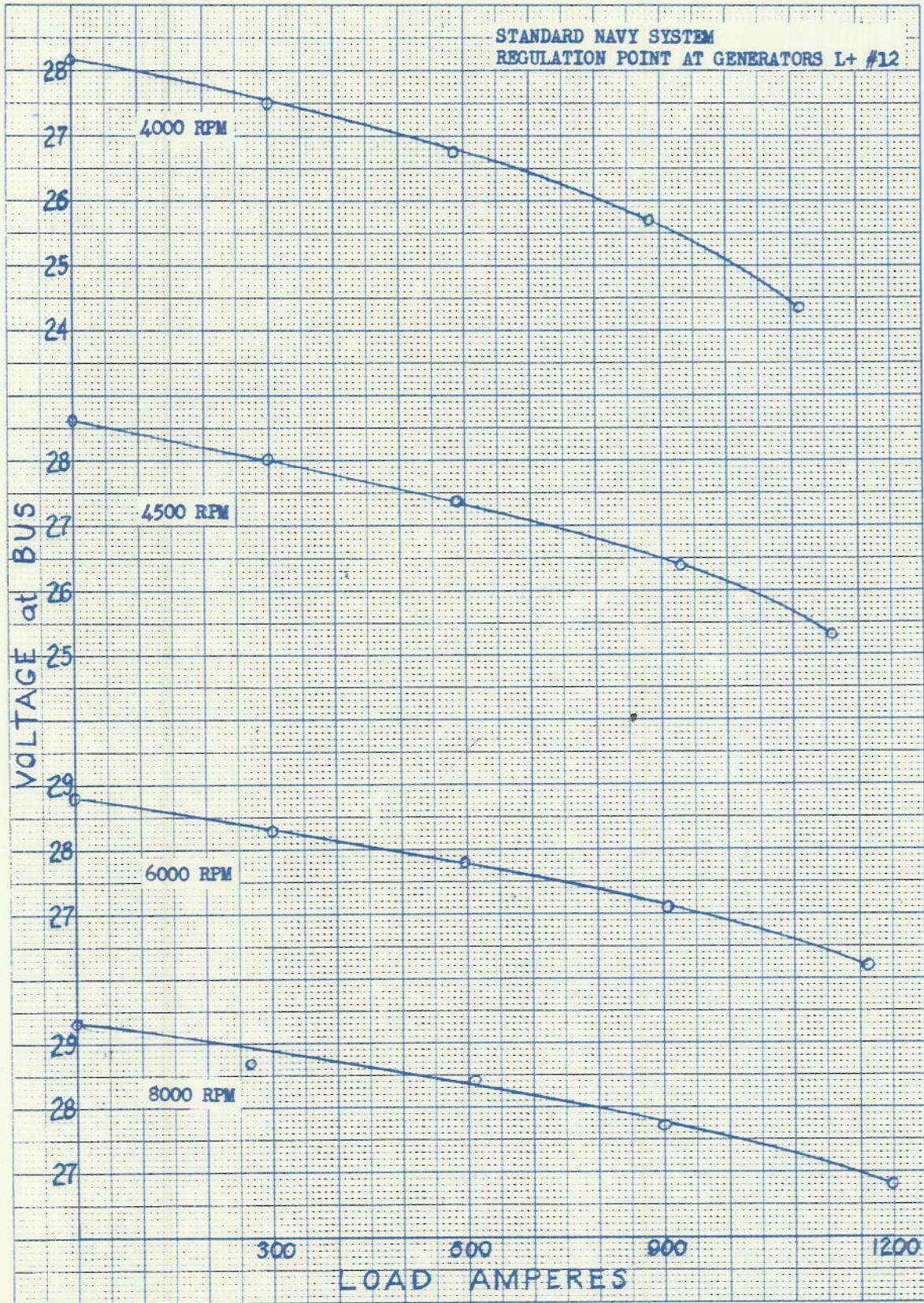
RANGE versus SYSTEM LOAD

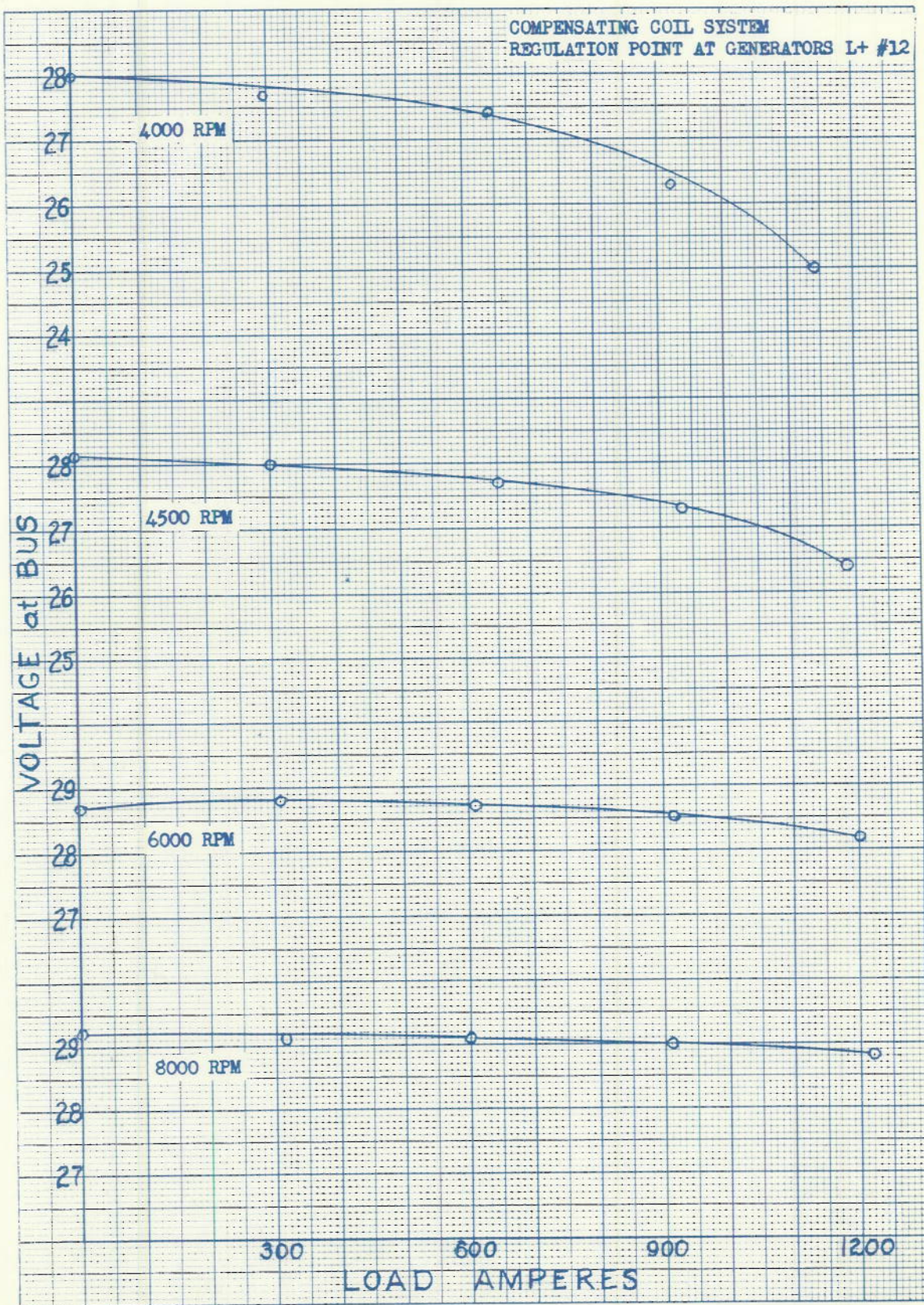
10 x 10 to the 1/4 inch, 5th lines accented.
 MADE IN U. S. A.

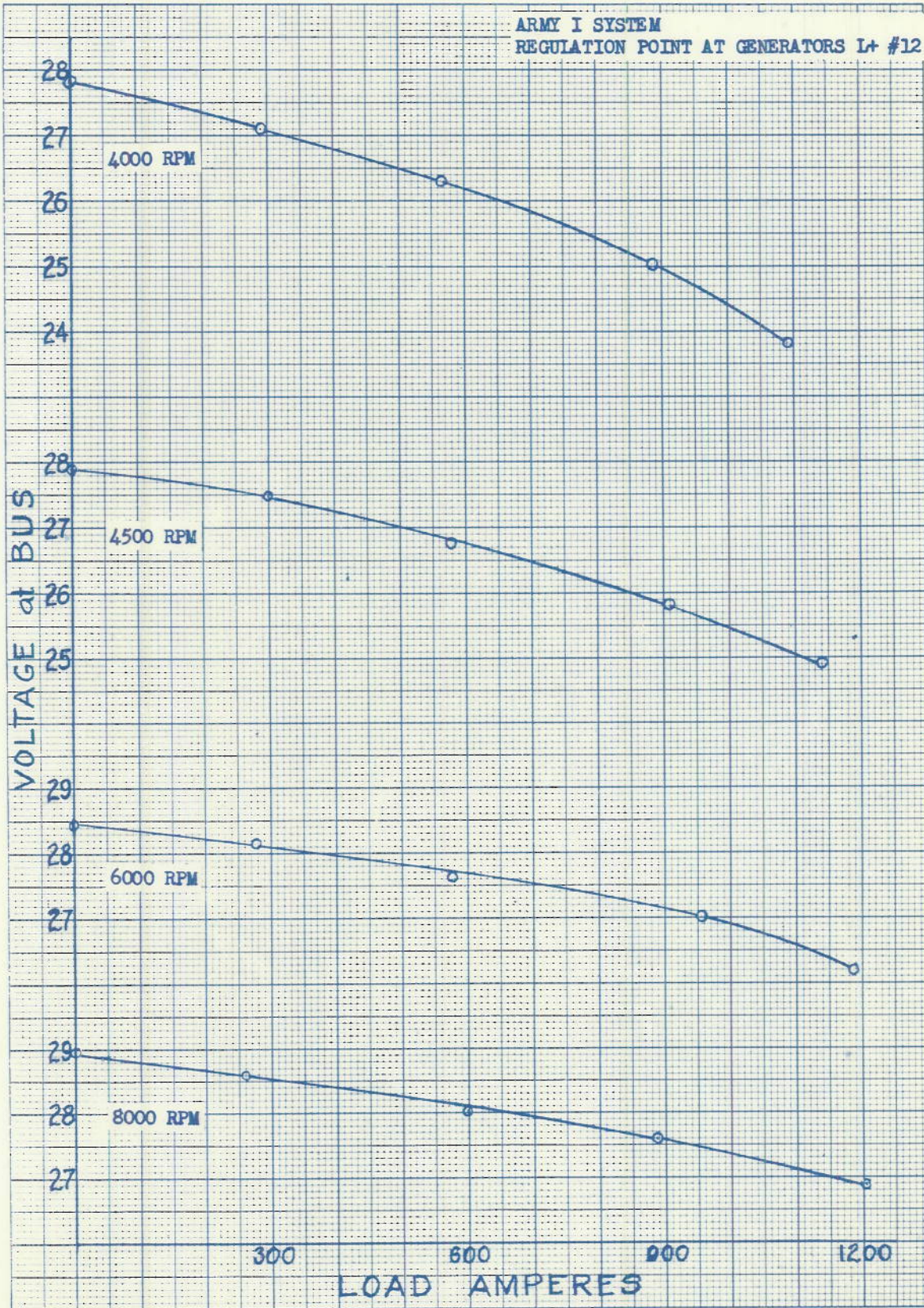


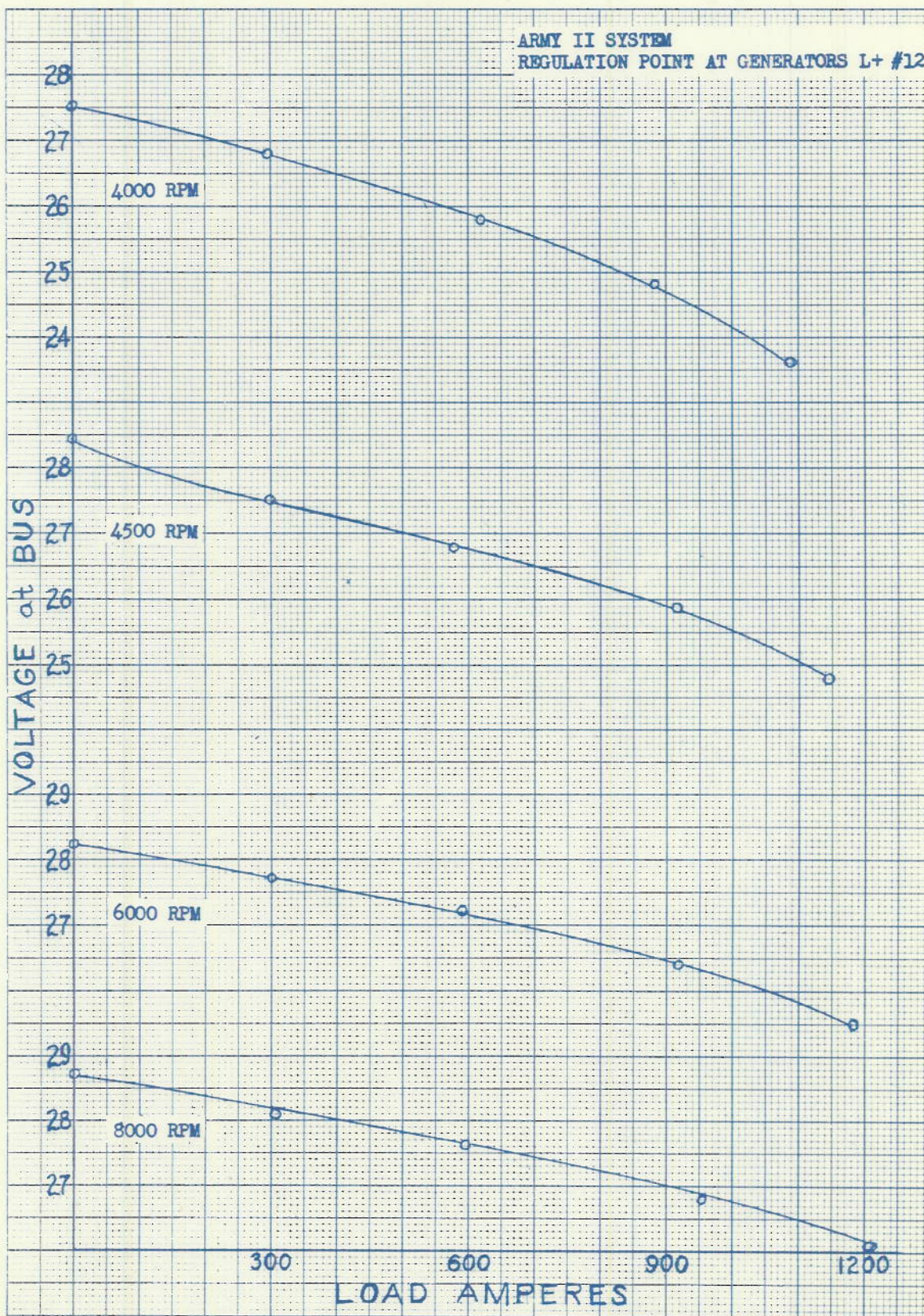
10 / 19 to the 1/2 inch, 6th then accepted.











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