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A METHOD OF ESTABLISHING THE BEST VOLTAGE LEVELS FOR FUTURE NAVAL AIRCRAFT

J. P. O'Connor

Energy Conversion Branch
Electronics Division

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CONTENTS

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INTRODUCTION

Electric power systems on aircraft have been undergoing a continuous evolution since the airplane was invented. The earliest airplanes were equipped with a 6-volt dc system similar to that of the automobile. Increasing power requirements led to the adoption of a 12-volt system and later to the presently used 28-volt dc system. A few airplanes have been operated with 120-volt dc systems and an increasing number of the larger airplanes are at present using the standard 208/115-volt, 3-phase, 400-cycle system. Present voltages for naval aircraft are established at 28 volts dc and 208/115 volts, 3-phase, 400 cycles. Neither of these systems is ideal for all planes. The system chosen for a particular plane depends on many factors such as altitude, range, mission, and magnitude of total electrical load demand. Although the best power system would be one tailored to each type of plane, it is found that the advantages of standardizing system parameters such as voltage and frequency far outweigh the disadvantages that may exist in certain types by the restriction to a standard voltage and frequency.

In considering the best electric system for any particular aircraft, there is general agreement that it should incorporate the following:

1. Maximum reliability under all conditions encountered in operation.
2. Minimum weight.
3. Minimum space requirements.
4. Simplicity.
5. Minimum aerodynamic penalty.
6. Adequate life of all components.
7. Minimum cost.
8. Use of existing designs.

Although all these factors are important and desirable, it is apparent that not all are equally important. For example, the minimizing of cost to the detriment of reliability or of weight would not lead to the best system. Hence, the factors must be weighed in terms of their relative importance. In addition, it should be considered that a minimum-weight electric system cannot be considered "the best" if the resulting poor efficiency incurs an added fuel penalty or if there is an increased aerodynamic drag which again results in an increased weight of fuel.

Most of the desirable characteristics of an electric power system can be evaluated only in a qualitative fashion. The best and final criterion of any system or component is successful use in the aircraft itself. For this reason, an existing design or system will be used in perference to a system or design which, although fully tested under simulated environmental and use conditions, has not been used under actual flight conditions. For example, it was apparent for a considerable time before the introduction of the presently used 208/115-volt, 3-phase, 400-cycle system that an increase in voltage would lead to a considerable reduction in weight. Because of the anticipated problems in paralleling of ac generators and in the development of lightweight reliable constant-speed drives, the older 28-volt dc was continued in use until the weight of wiring on the more heavily loaded (electrically) aircraft became intolerable.

Today, increasing the voltage level and/or the frequency level is often proposed as one of the most profitable methods of saving weight. As has been indicated, this has been the basic reason for increase in the voltage levels in the past. The present 400 cycles has not been definitely proved as the "optimum" frequency, However, for any appreciable increase in frequency, corresponding generator and motor speeds, with the practical limitation on the number of poles, present a problem, in addition to higher mechanical stresses. These difficulties would have to be balanced against the appreciable savings in transformer weight with increasing frequency. Cable reactance increases with frequency and for the larger size cables, at 400 cycles, the reactance already exceeds the resistance; at low power factor the reactance becomes the dominant factor in line-drop limitations. Although increase of frequency cannot be eliminated as a method of saving weight, the lack of reliable and accurate basic data makes the analysis difficult, if not impossible. In contrast to this, with increasing voltage levels the weight of generators, motors, and most other utilization equipment can, with reasonable accuracy, be assumed to remain constant. Hence, the principal saving in weight results from the decrease of weight in the main feeders and transmission system. However, since a minimum-size conductor is specified by mechanical considerations, it is apparent that the saving in weight to be attained by an increase in voltage level is limited to a reduction in size and weight of wire above minimum size. The scope of this study is limited to a consideration of the reduction in weight of present wiring for a maximum wire temperature of 100°C. All basic data have been taken or computed in accordance with specifications MIL-W-5086A and MIL-W-5088B(ASG).

THE NEED FOR HIGHER SYSTEM VOLTAGE

The need for higher system voltages on aircraft today stems from the same causes as brought about higher system voltages in the past, namely, increased overall load demand and increased individual load demand. However, even without load increases, other factors emphasize the need for higher system voltage to avoid an increase in system weight. In supersonic aircraft higher ambient temperatures are encountered, and the reduced air density at high altitudes impairs cooling so that the current in wires must be reduced. For example, it is indicated that a typical operating altitude of 70,000 feet will cause a reduction in wire current capacity of approximately 20%. Assuming a conductor temperature of 750°F, corresponding to the higher Mach numbers, the resistance is about 2.5 times that at room ambient temperature. Based on resistance alone, it would take 2.5 times as much copper to carry the same current as at room ambient. Hence, although there may be no increase in individual loads or overall load, the voltage level of a system must be increased when the ambient temperature increases if a weight penalty is to be avoided.

The need for higher system voltage as outlined above has been based solely on the criterion of weight, yet the system voltage cannot be increased without due regard to the problems that would arise as the voltage is increased. Some of these problems are: increased weight of insulation, the adapting of utilization equipment, increased danger of arc-over, detrimental effects of corona, and increased personnel hazard.

SCOPE OF STUDY

The scope of this study is limited to a weight analysis of the feeder and distribution wiring of one airplane (WF-2). The length of wiring in each gage size has been taken from the airframe manufacturer's production wire sheets, and weight calculated. If 400-cycle, 3-phase power transmission is compared with dc power transmission with ground return at any given voltage, it is evident that for the same configuration more kilowatts can be transmitted by the dc system. The distribution of ac power suffers from the disadvantages of power factor and reactance drop. In this study the effect of reactance has been omitted, since at 400 cycles in the smaller wires the effect is negligible and in the larger wires the transmission distance for the allowable 4-volt drop is so large that the reactance is usually not a limiting factor.

ASSUMPTIONS AND APPROXIMATIONS

1. It is assumed that wiring installed on the WF-2 aircraft for power transmission is in accordance with MIL-W-5088B(ASG) and MIL-W-5086A. It further is assumed in weight calculations that all wire is Type II.

2. It is assumed that the system configuration on the WF-2 aircraft is typical of present and future aircraft.

3. It is assumed that on present 208/115-volt ac systems the number of load circuits limited by voltage drop is negligible. This is the equivalent of assuming that all circuits are only limited by the current-carrying capacity of the wires.

4. It is assumed that the weight of generating equipment, the associated controls and regulating equipment, and all utilization equipment will not change appreciably within the voltage levels considered.

5. It is assumed that the presently used 600-volt wire is adequate at the higher voltage levels proposed.

CHARACTERISTICS OF AIRCRAFT WIRES

Figure 1 indicates the characteristics and limitations of aircraft wiring at the present 208/115-volt voltage level subject to the 4-volt (3-1/2%) maximum allowable voltage drop. It will

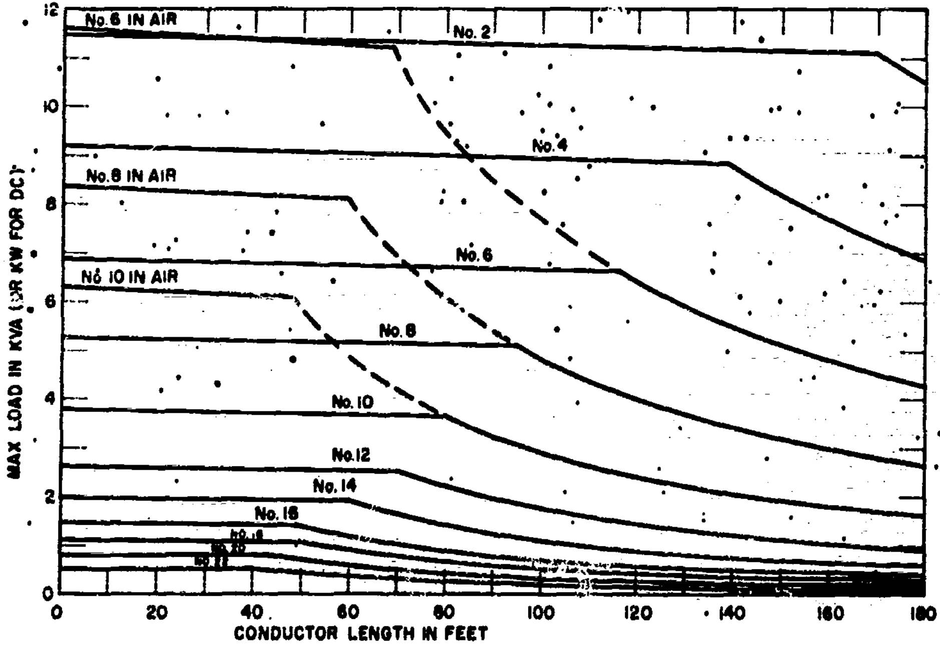

Fig. 1 - Characteristics and limitations of aircraft wiring at 115 volts in accordance with MIL-W-5088A(ASG). The curves labeled "in air" refer to single wires in free air as opposed to wires in bundles

be observed that the larger size wires can transmit power at rated capacity greater distances than the smaller wires. The curved portion of the plots for each size wire represent the effect of voltage drop limitation on the power (kva) carrying capacity. If the voltage of the system were doubled, then, under the same conditions, each wire could transmit twice the load to twice the distance, or to make the weight that would be saved more apparent, the load now carried by a No. 6 wire could be handled by a No. 10 wire.

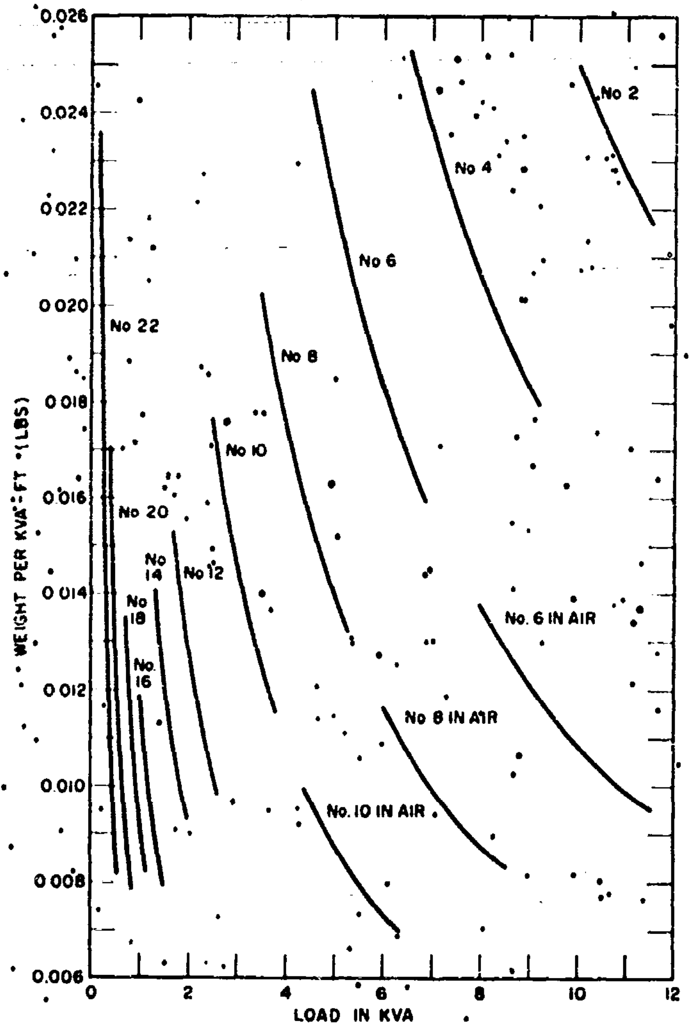

Fig. 2 - Relative weight penalties of transmitting power

Figure 2 shows the relative weight penalty of transmitting power over any particular wire. The plots were made assuming 115-volt ac single-phase loads. For any other system voltage, the relative weights would be the same. The weight advantage of using the smaller size wires is apparent, as is the use of single wire in free air. In practice it is not possible to take advantage of the "single wire in free air" rating except for a few of the larger size wires (usually the generator feeders). The number of loads accommodated by the smaller size wires is so great that they must be run in bundles and hence must conform to the "bundled rating." In some cases it is advantageous to substitute several smaller size conductors for a large size conductor. For example, a No. 8 conductor may be used to supply a 5-kva load at a weight cost of 0.014 lb per kva-ft. The same load can be supplied by two No. 12 conductors, and the cost is only 0.010 lb per kva-ft. However, in wire size No. 16 and below, this is not possible. These are minimum weight conductors and the weight cost per kva-ft is approximately the same. There are two factors to be considered in the weight of any conductor: the weight of the copper or conductor and the weight of the insulation. In aircraft cable the insulation accounts for about 20% of the weight in the larger size cables and about 50% in the smaller size wires. If the permissible current density was the same for all size wires, the minimum weight conductors would be the larger size wires. As a conductor increases in size, however, the ratio of the surface area to the enclosed volume decreases, and the ability to dissipate heat is a function of the surface area. Hence the permissible current density in the larger size wire is less than in the smaller size. The result is that the smaller size wires (No. 16 and smaller) can transmit more power for given weight of wire than the larger sizes (No. 14 and larger). It should be observed, however, that when advantage can be taken of the single-wire-in-free-air rating for some of the larger size wires, they are, on the basis of weight the equal of the smaller size wires.

The advantage of using certain size wires will always exist irrespective of the system voltage. Figure 3 is based upon the same data as Fig. 2, and perhaps indicates more clearly the relative weight advantage of certain size wires. It should be noted that the weight per kva-ft for No. 16 wire and No. 20 wire is smaller than for No. 22 wire. Wire No. 10, when operated as a single wire in free air is better than all the others. Hence, if the system voltage were increased so that all wires were decreased to size No. 22, it would still be advantageous to use any of the wires shown below No. 22. In practice, in accordance with specifications, size No. 18 is the minimum size for engine mounted accessories, and the use of No. 22 is limited, so that No. 20 is frequently a minimum size. Hence, conductors No. 16 and smaller will be considered minimum size conductors. Stated briefly, any conductor which, because of mechanical strength considerations, is specified as minimum, or where the weight cost per kva-ft is smaller than for gage No. 22, is considered a minimum weight conductor.

CHARACTERISTICS OF AIRCRAFT LOADS

The requirements of utilization equipment on aircraft, in general, demand both ac and dc power. Hence, if the main power supply is ac, a certain portion of this power must be converted to dc power, and conversely, when the main power supply is dc, a certain portion of this must be converted to ac. Furthermore, there are requirements for both ac and dc voltages at various levels, and with varying requirements in the allowable voltage variation. Whether the main power supply is ac or dc, conversion equipment is needed to meet the power requirements of the loads. It is therefore apparent that a change in voltage of the main power system can only affect the size of the wiring to the conversion equipment or the load equipment that can utilize the power directly. For this reason there is a considerable amount of wiring on aircraft that is unaffected by a change in voltage of the main power supply. In particular, the increased use of electronic equipment on modern aircraft has greatly increased the proportion of wiring that is not affected by a change in voltage of the main power supply.

The possibility of weight savings in the electronic load by transistorization and improved packaging, resulting in lower power demand and a decrease in cooling requirements, is so great that it may well overshadow the possible savings in weight by an increase in voltage in the main power supply. However, although methods of reducing weight by means other than a change in the voltage of the main power supply should be considered, they do not fall within the scope of the present study.

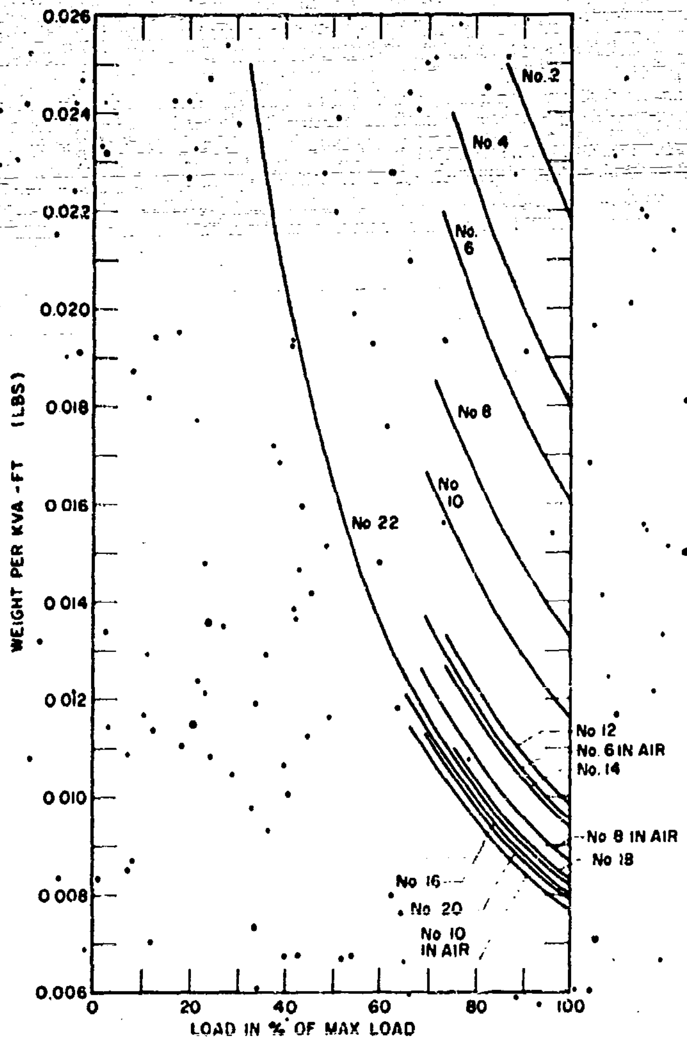

Fig. 3 - Data of Fig. 2 referred to maximum load in each case. (the lower ends of the curves in Fig. 2)

TRANSMISSION SYSTEM UTILIZATION

Since only a few of the electrical loads are required to operate continuously from the beginning to the end of flight mission; it is found that the total installed maximum load capacity of the wiring exceeds the actual load by a factor perhaps as great as two to one. Viewed on this basis, the utilization of the transmission system is very poor. The limited number of wire sizes also leads to poor utilization since any particular wire must accommodate all loads where rated maximum current lies between the maximum for that wire and the maximum for the next smaller size wire. Hence, the use of intermediate and smaller size wires would improve utilization and decrease weight. It is, however, improvement in utilization, with increase in system voltage, that is of primary interest here. Improvement in utilization, when system voltage is increased, occurs because of higher permissible current density as the size of wire required for a particular load decreases. However, for loads initially carried by No. 22 wire, the current density and utilization decrease with increase in voltage. Utilization as used here is directly proportional to current density. Since there is a wide range in the number and magnitude of loads on any aircraft, it is apparent that with the present type wiring, there will be considerable variation in current density in the wiring of the transmission system. Maximum current density exists in No. 22 conductor at rated maximum current. It is therefore desirable to change system voltage so that the greatest possible part of the load is transmitted at or near the maximum current rating of No. 22 wire. This means that for every transmission system there is a particular voltage that results in maximum average current density for the system. It will be shown that this voltage is significant in determining the "optimum" system voltage.

ANALYSIS OF WIRING ON THE WF-2 AIRCRAFT

The weight of wire in each gage size on the WF-2 aircraft as determined from the manufacturer's production wire sheets and weight data given in specification MIL-W-5086B is shown in Table 1. For convenience in analysis, the wire weights in each gage are grouped as "DC," "Electronics," and "AC." "DC" is wiring from the 28-volt transformer-rectifier-battery system. Wiring in this system would not be changed by a change in the voltage of the 208/115-volt, 3-phase, ac system. "Electronics" is interconnecting wiring installed by the aircraft manufacturer for the electronic equipment and operates at voltages other than 28 volts dc or 208/115 volts 400-cycle ac. Changing the power supply voltage (either ac or dc) will not affect the weight of this wiring. "AC" is all wiring in the 208/115-volt 3-phase 400-cycle primary power system. Only this wiring will be affected by a change in the ac voltage. In addition, only that part of the wiring that is not already of minimum size can be affected by a change in system voltage. Hence, out of a total of 418 lb of wiring on this aircraft, only 144 lb (or one-third the total wiring) can be affected by a change in the ac voltage. In the 28-volt dc system, the total weight of wiring is 168 lb, and is equal to the weight of wiring in the ac system. The possibility of saving weight in the dc system by increasing the dc system voltage is as favorable as in the ac system.

Table 1
System Wire Weight on the WF-2

Wire Size	Weight (lb)		
	AC	DC	Electronics
2	-	20.5	-
4	-	1.75	-
6	-	-	-
8	4.48	0.53	0.09
10	1.43	0.78	-
12	11.30	8.00	0.12
14	5.70	5.26	0.02
16	34.00	20.20	2.54
18	10.80	20.60	3.17
20	76.80	50.00	8.07
22	23.40	40.00	68.50
Total	167.91	167.62	82.51

If the primary purpose in increasing the voltage were to reduce the total weight of wiring to a minimum, ignoring the problems of corona, insulation, and personnel hazard, the procedure is simply to increase the voltage until the load carried by the present largest size conductor could be carried by the smallest size conductor (gage No. 22). At the present voltage (115 volts), a No. 2 conductor can supply a single-phase load of 11.1 kva up to a distance of 170 feet. The weight of the wire is 42.5 lb. If the voltage were increased to 2237 volts, the same load could be supplied by a No. 22 wire weighing only 0.8 lb and the voltage drop would be only 0.78% (17.4 volts) compared to 3-1/2% (4 volts) for the No. 2 conductor. Such a great reduction in weight appears very attractive, but it is apparent that this extreme voltage (even if it were feasible) would result in very poor utilization for loads smaller than 11.1 kva. The overall percentage reduction in weight of the system wiring would be much less than for the No. 2 conductor, since a large proportion of the wire is already at minimum size, and it is in this wire already at minimum size than an increase in voltage can result only in poor utilization.

For example, in a No. 22 wire carrying the maximum rated current of 5 amperes or less the effect of increasing system voltage on this wire is to lower the current density so that when the voltage is doubled the current density is halved; therefore, the copper utilization is also halved, while the weight remains the same.

An ideal system of wires would be one with an infinite number of wire sizes to accommodate every load. The weight of each wire for a given distance would be proportional to its current carrying capacity. In such a system each wire would be fully utilized. The weight of the system would vary inversely as the system voltage. Figure 3 indicates there is considerable deviation from the ideal in the system of wires which must be used. There is, however, a particular voltage for this system of wires at which the weight of the system will vary inversely with the voltage (as in the ideal system), which would correspond to maximum utilization, not for each wire, but for the overall system.

In an accurate and precise determination of the weight change in a system of wires, the current to each load and the length of run must be known. Then each load must be treated separately, and the weight of wiring required of any voltage may be determined. To do this for a modern military aircraft is a formidable task. It is relatively simple, however, to determine the total length of wire in each gage size, and then compute the weight of wire in each gage size. If it is then assumed that none of the wires are voltage-drop limited, then the current carried by the wires in each gage size is between the maximum specified for that gage size and the maximum specified for the next lower gage size. For example, the maximum specified current for No. 16 wire is 13 amperes and the maximum specified current for the next lower size, No. 18 wire, is 10 amperes. Hence the range of load currents for all loads supplied by No. 16 wire is between 10 and 13 amperes. It is apparent that the voltage must be increased by 30% to insure that all the load carried by No. 16 at the initial voltage will be carried by No. 18 wire at the increased voltage. The actual variation of weight between the original voltage 1 per unit (pu) and 1.3 pu is a function of the current distribution.

Figure 4 shows a plot of the weight data for the ac system given in Table 1 as a function of current. Because of the uncertainty of the weight distribution within the current range normally carried by each conductor a bar graph is used. It is considered sufficiently accurate and convenient to assume an equal and linear distribution of weight with current for each conductor size. This means that for No. 16 wire the weight of conductor carrying 12 amperes is the same as the weight of conductor carrying 11 amperes. The assumption of equal distribution of weight is the same as that of equal distribution of a number of conductors all of equal length so that their total weight is equal to the actual weight. With this assumption, the percentage decrease in weight of wire in any particular gage size as a function of system voltage can be determined. Stated in other terms, weight factors can be derived corresponding to incremental increases in voltage for each size of wiring in the system.

To illustrate the method of computing weight factors a plot of maximum and minimum currents (i_1,i_2) normally carried by No.16 wire is shown in Fig. 5 as a function of voltage. The band of currents from i_1 down to i_2 at 1 pu voltage is carried by No. 16 wire. As the voltage is increased, part of the current band remains in the range for No. 16 wire, and the remainder is carried by the next smaller size wire, No. 18 gage. The fractional part carried by No. 16 wire is

$$N_{16} = \frac{i_1 - 0.769}{i_1 - i_2} \qquad \text{(1a)}$$

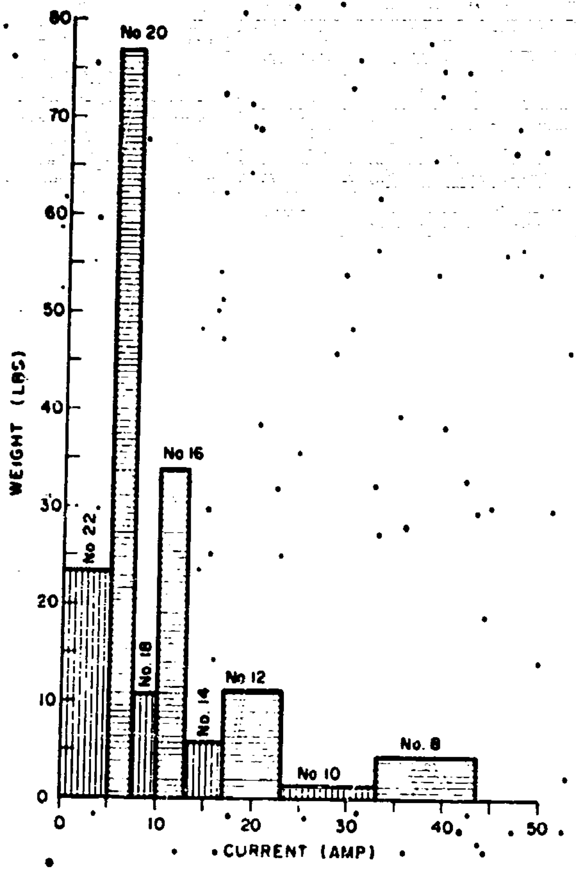

Fig. 4 - Weights given in Table 1 of the various wire sizes in the ac system on the WF-2 plotted as a function of the current distribution

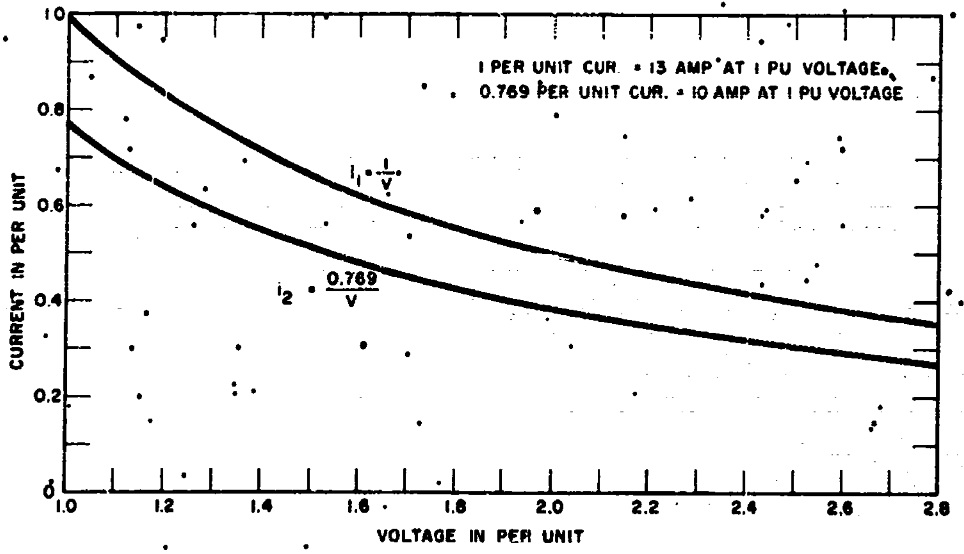

Fig. 5 - Variation of maximum and minimum currents normally carried by No. 16 wire with voltage

and that carried by the next smaller gage size, No. 18, is

$$N_{18} = \frac{0.769 - i_2}{i_1 - i_2} . \qquad (2a)$$

In general, the equation for the number of conductors in any gage size smaller than the initial gage size is

$$N_n = \frac{C_n - i_2}{i_1 - i_2} .$$

where C_n is the ratio of maximum current in the gage size considered to maximum current in the initial gage size. The variables i_1 and i_2 are respectively the maximum and minimum currents in the initial gage size divided by the voltage. All quantities are expressed in per unit values and the maximum current in the initial gage size is taken as 1 pu. Substituting $i_1 = \frac{1}{V}$ and $i_2 = \frac{0.769}{V}$, Eqs. (1a) and (2a) become

$$N_{16} = 4.33 - 3.33V \qquad 1(b)$$

$$N_{18} = 3.33V - 3.33 . \qquad 2(b)$$

In a similar manner the fractional part of the current band, or of the number of conductors, in each of the lower gage sizes may be determined as the voltage is increased. For the succeeding lower gage sizes the equations are,

$$N_{20} = 2.50V - 3.33 \qquad (3)$$

$$N_{22} = 1.67V - 3.33. \qquad (4)$$

The number of loads at the initial voltage carried by No. 16 wire is expressed as 1 pu. Since the number of loads does not change with voltage, this limits the applicable voltage range of the equations derived, for $\Sigma(N_{16} + N_{18} + N_{20} + N_{22})$ must equal 1 at any voltage. Further, since the length of wire to each load does not change with voltage, the total weight of wiring at any voltage is given by the equation

$$W_w = \Sigma(N_{16} + N_{18}W_{18} + N_{20}W_{20} + N_{22}W_{22}) \qquad (5)$$

where W_{18} is the ratio of weight for any length of No. 18 wire to the same length of No. 16 wire, and W_{20} is a similar ratio for No. 20 and No. 16 wire. The weight ratios for all wires smaller than No. 16, as computed from weight data in the specifications, is as follows:

W_{18}	W_{20}	W_{22}
0.798	0.572	0.395

A solution of the equations derived above for the variation of weight of wiring, initially No. 16, with increasing voltage is shown in Table 2. When the copper weight in each of the conductors is expressed as a fractional part of the total weight of the wire, copper weight ratios are obtained and for No. 16 wire and succeeding smaller sizes are:

W_{16C}	W_{18C}	W_{20C}	W_{22C}
0.625	0.613	0.536	0.485

Table 2
Variation in Weight of Wiring, Initially No. 16, with Increase in Voltage as Calculated Using Eqs. (1) -(5)

Voltage (pu)	Number of Wires (pu)				Weight Ratios				Wt (pu) ΣNW
	N_{16}	N_{18}	N_{20}	N_{22}	W_{16}	W_{18}	W_{20}	W_{22}	
1.0	1.00	-	-	-	1.000	-	-	-	1.00
1.1	0.69	0.33	-	-	1.000	0.798	-	-	0.934
1.2	0.334	0.666	-	-	1.000	0.798	-	-	0.866
1.3	0	1.000	-	-	-	0.798	-	-	0.798
1.4	-	0.830	0.17	-	-	0.798	0.572	-	0.759
1.5	-	0.580	0.42	-	-	0.798	0.572	-	0.703
1.6	-	0.330	0.67	-	-	0.798	0.572	-	0.590
1.7	-	0.08	0.92	-	-	0.798	0.572	-	0.590
1.8	-	-	1.00	-	-	-	0.572	-	0.572
1.9	-	-	1.00	-	-	-	0.572	-	0.572
2.0	-	-	0.99	0.01	-	-	0.572	0.395	0.569
2.2	-	-	0.665	0.345	-	-	0.572	0.395	0.510
2.4	-	-	0.320	0.680	-	-	0.572	0.395	0.451
2.6	-	-	-	1.000	-	-	-	0.395	0.395
2.8	-	-	-	1.000	-	-	-	0.395	0.395
3.0	-	-	-	1.000	-	-	-	0.395	0.395

The total weight of copper at any voltage greater than 1 pu is then given by the equation

$$W_C = \Sigma(N_{16}W_{16C} + N_{18}W_{18}W_{18C} + N_{20}W_{20}W_{20C} + N_{22}W_{22}W_{22C}) . \tag{6}$$

The wire weight factors and copper weight factors for No. 16 wire were determined by the equations derived above. In a similar manner, the wire weight factors and copper weight factors for all wire gage sizes between 22 and 2 were determined for voltages between 1 pu and 3 pu, and are given in Tables 3 and 4. By multiplying the appropriate factors corresponding to increased values of voltage by the initial weight of wire in each gage size, system wire weight and copper weight may be determined as a function of increasing voltage. If the variation of wire weight and copper weight with voltage are known, then the current density, utilization, and voltage drop may be determined.

Since the magnitude of the loads and the length of runs do not change in a given system with increase in voltage, the average resistance of all conductors is inversely proportional to the system copper weight and the current is inversely proportional to the voltage. Hence the average voltage drop can be expressed as

$$V_D = \frac{1}{VW_C} \tag{7}$$

where all quantities are in per unit. Current density is equal to current divided by cross-sectional area of copper, but since the length of runs are constant, the cross-sectional area of the copper is proportional to the weight, and current is inversely proportional to the voltage. Hence, current density (pu) is

$$J = \frac{1}{VW_C} . \tag{8}$$

Table 3
Wire Weight Factors

Voltage (pu)	Weight of the Various Wire Sizes (pu) – ΣNW										
	2	4	6	8	10	12	14	16	18	20	22
1.0	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1.1	0.864	0.900	0.871	0.906	0.906	0.916	0.886	0.934	0.914	0.938	"
1.2	0.723	0.800	0.762	0.812	0.812	0.832	0.775	0.866	0.828	0.877	"
1.3	0.660	0.700	0.643	0.718	0.718	0.749	0.659	0.798	0.744	0.815	"
1.4	0.616	0.613	0.630	0.629	0.609	0.654	0.617	0.759	0.716	0.753	"
1.5	0.550	0.557	0.576	0.600	0.547	0.603	0.585	0.703	0.716	0.692	"
1.6	0.484	0.502	0.520	0.555	0.518	0.547	0.553	0.647	0.671	"	"
1.7	0.440	0.446	0.465	0.506	0.487	0.493	0.519	0.590	0.625	"	"
1.8	0.417	0.424	0.409	0.464	0.452	0.441	0.502	0.572	0.583	"	"
1.9	0.381	0.403	0.400	0.418	0.403	0.426	0.473	0.572	0.539	"	"
2.0	0.344	0.377	0.400	0.360	0.372	0.410	0.446	0.569	0.495	"	"
2.2	0.280	0.325	1.346	0.333	0.335	0.379	0.391	0.510	"	"	"
2.4	0.280	0.273	0.292	0.306	0.292	0.346	0.372	0.451	"	"	"
2.6	0.250	0.267	0.238	0.271	0.254	0.322	0.372	0.395	"	"	"
2.8	0.215	0.243	0.228	0.238	0.243	0.295	0.337	"	"	"	"
3.0	0.181	0.218	0.211	0.219	0.232	0.269	0.314	"	"	"	"

Table 4
Copper Weight Factors

Voltage (pu)	Weight of the Various Wire Sizes (pu) – ΣNW										
	2	4	6	8	10	12	14	16	18	20	22
1.0	0.790	0.782	0.730	0.724	0.694	0.724	0.647	0.625	0.613	0.536	0.485
1.1	0.680	0.692	0.634	0.651	0.652	0.648	0.569	0.581	0.544	0.496	"
1.2	0.571	0.604	0.553	0.577	0.571	0.572	0.493	0.535	0.474	0.456	"
1.3	0.516	0.516	0.465	0.505	0.510	0.496	0.402	0.489	0.406	0.415	"
1.4	0.478	0.447	0.456	0.436	0.434	0.421	0.384	0.458	0.384	0.375	"
1.5	0.421	0.405	0.414	0.418	0.388	0.386	0.362	0.413	0.384	0.336	"
1.6	0.363	0.364	0.370	0.389	0.361	0.348	0.341	0.368	0.355	"	"
1.7	0.325	0.323	0.327	0.356	0.333	0.310	0.318	0.321	0.337	"	"
1.8	0.307	0.307	0.284	0.329	0.304	0.275	0.303	0.306	0.297	"	"
1.9	0.279	0.290	0.277	0.299	0.263	0.265	0.282	0.306	0.269	"	"
2.0	0.251	0.270	0.277	0.261	0.239	0.255	0.259	0.304	0.240	"	"
2.2	0.202	0.230	0.242	0.234	0.213	0.233	0.215	0.266	"	"	"
2.4	0.202	0.189	0.207	0.210	0.184	0.208	0.199	0.228	"	"	"
2.6	0.178	0.185	0.172	0.180	0.158	0.189	0.199	0.192	"	"	"
2.8	0.153	0.169	0.163	0.153	0.150	0.168	0.170	"	"	"	"
3.0	0.126	0.153	0.148	0.139	0.143	0.146	0.162	"	"	"	"

The utilization of copper is proportional to the current density. Hence, a plot of the expression, $1/VW_c$ as a function of voltage is of great importance in establishing the point of "optimum" system voltage.

In Fig. 6 wire weight, copper weight, utilization, and load current are plotted as a function of load voltage for all No. 16 wire. If "optimum" voltage is defined as a point of minimum weight and maximum utilization at minimum voltage, there are two points of optimum voltage: one at 1.7 pu and another at 2.6 pu. It will also be observed that points of maximum utilization correspond to points of minimum weight. Hence, a point of maximum utilization is a point of optimum voltage. It should be pointed out, however, that a practical optimum voltage is not independent of the relation of voltage drop to load voltage and the absolute magnitude of voltage. For example, the plots in Fig. 6 show that at 3.26-pu voltage, the voltage drop is the same as at 1-pu voltage and the wire weight is a minimum. Low voltage drop, which is the same as lower utilization, results in better regulation, and if the regulation of the power system is improved, weight in regulation equipment is saved. However, desirable as this may appear, it must be considered that if this is initially a 208/115-volt system, then 3.26-pu voltage represents a 660/380-volt system, and for the wire now in use this exceeds its voltage limitations. In this analysis, it is assumed that improvement in regulation, while desirable, is not the primary purpose, but that the primary purpose is reduction in wire weight at practical voltage levels and with maximum utilization of copper.

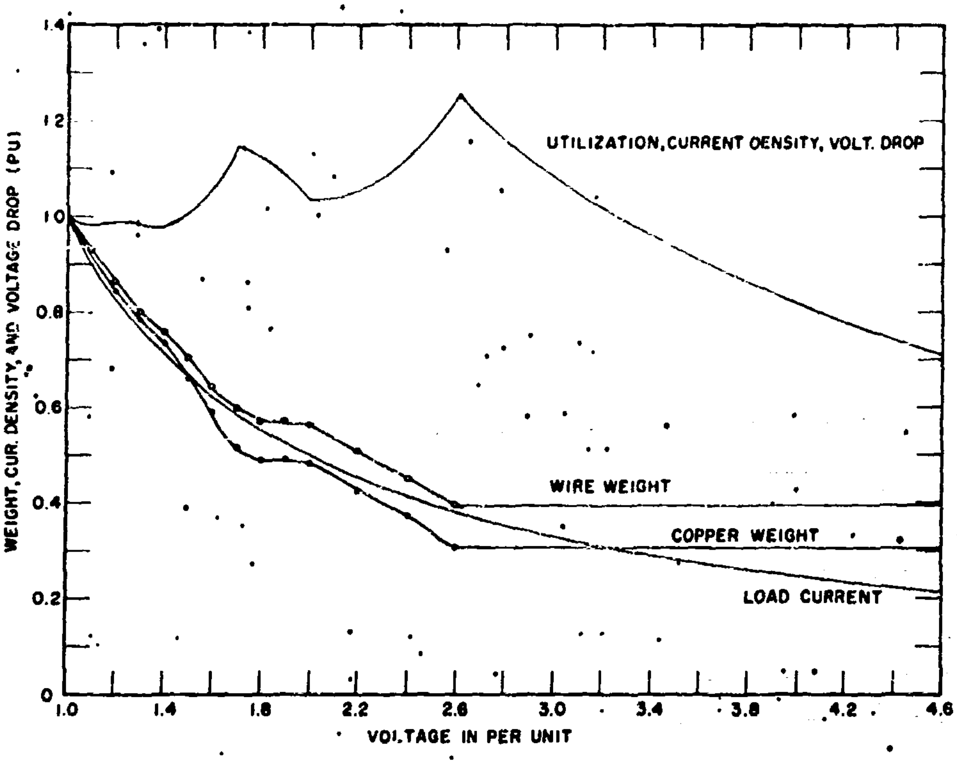

Fig. 6 - Variation of weight, utilization, and voltage drop for loads initially supplied by No. 16 wire at 1-pu voltage

The weight of wire and of copper for all gage sizes as a function of voltage has been determined for both the ac system and the dc system on the WF-2 aircraft (Tables 5-8). The actual weight of wire and of copper at present system voltages (1 pu) are assumed as 1 pu, as is the current, current density, and voltage drop. Plots of these quantities as a function of voltage are shown in Figs. 7 and 8 and correspond to the plot in Fig. 6 for

Table 5
Variation of AC System Wiring Weight with Voltage on the WF-2

Voltage (pu)	Weight of the Various Wire Sizes (lb)								Total Wt (lb)	Wt (pu)
	8	10	12	14	16	18	20	22		
1.0	4.48	1.43	11.30	5.70	34.00	10.80	76.80	23.40	167.9	1.00
1.1	4.06	1.29	10.35	5.05	31.80	9.87	72.00	"	157.8	0.94
1.2	3.63	1.16	9.40	4.41	29.40	8.94	67.30	"	147.6	0.877
1.3	3.22	1.03	8.46	3.76	27.10	8.04	62.60	"	137.6	0.82
1.4	2.82	0.87	7.39	3.52	25.80	7.74	57.80	"	129.3	0.77
1.5	2.68	0.783	6.81	3.33	23.90	7.74	53.10	"	121.7	0.726
1.6	2.48	0.730	6.19	3.15	22.00	7.25	"	"	118.3	0.705
1.7	2.26	0.696	5.57	2.96	20.05	6.75	"	"	114.8	0.684
1.8	2.08	0.646	4.98	2.86	19.45	6.29	"	"	112.8	0.672
1.9	1.87	0.576	4.81	2.69	19.45	5.83	"	"	111.7	0.665
2.0	1.61	0.531	4.64	2.54	19.35	5.35	"	"	110.5	0.658
2.2	1.49	0.479	4.28	2.23	17.35	"	"	"	107.7	0.642
2.4	1.37	0.418	3.91	2.12	15.32	"	"	"	105.0	0.625
2.6	1.21	0.363	3.64	2.12	13.42	"	"	"	102.6	0.610
2.8	1.065	0.348	3.34	1.92	"	"	"	"	101.9	0.607
3.0	0.977	0.332	3.04	1.70	"	"	"	"	101.4	0.604
9.2	0.29	0.153	2.04	1.46	"	"	"	"	99.2	0.591

Table 6
Variation of AC System Copper Weight with Voltage on the WF-2

Voltage (pu)	Weight of the Various Wire Sizes (lb)								Total Wt (lb)	Wt(pu)
	8	10	12	14	16	18	20	22		
1.0	3.250	0.993	8.20	3.69	21.25	6.62	41.2	11.35	96.6	1.000
1.1	2.910	0.932	7.32	3.24	19.75	5.88	38.0	"	89.4	0.926
1.2	2.585	0.816	6.46	2.81	18.20	5.13	35.0	"	82.4	0.854
1.3	2.261	0.729	5.61	2.29	16.65	4.39	31.85	"	75.1	0.777
1.4	1.950	0.621	4.76	2.19	15.58	4.15	28.80	"	69.4	0.718
1.5	1.870	0.555	4.36	2.06	14.05	4.15	25.80	"	64.2	0.664
1.6	1.740	0.516	3.93	1.945	12.52	3.84	"	"	61.6	0.638
1.7	1.595	0.476	3.50	1.813	10.91	3.64	"	"	59.1	0.612
1.8	1.475	0.435	3.11	1.725	10.04	3.21	"	"	57.1	0.591
1.9	1.340	0.376	2.99	1.620	10.04	2.91	"	"	56.4	0.584
2.0	1.170	0.342	2.88	1.480	10.33	2.59	"	"	55.9	0.599
2.2	1.050	0.304	2.635	1.225	9.05	"	"	"	54.0	0.560
2.4	0.941	0.263	2.350	1.135	7.75	"	"	"	52.2	0.540
2.6	0.806	0.226	2.138	1.135	6.54	"	"	"	50.6	1.524
2.8	0.685	0.214	1.900	0.970	"	"	"	"	50.0	0.518
3.0	0.622	0.204	1.650	0.924	"	"	"	"	49.7	0.515
9.2	0.141	0.073	0.990	0.708	"	"	"	"	48.2	0.488

Table 7
Variation of DC System Wiring Weight with Voltage on the WF-2

Voltage (pu)	Weight of the Various Wire Sizes (lb)										Total Wt (lb)	Wt (pu)
	2	4	8	10	12	14	16	18	20	22		
1.0	20.5	1.72	0.53	0.775	8.00	5.26	20.2	20.68	50.0	40.00	167.7	1.0
1.1	17.8	1.55	0.481	0.702	7.33	4.65	18.83	18.93	46.8	″	157.1	0.936
1.2	15.0	1.375	0.430	0.629	6.66	4.07	17.48	17.16	43.9	″	146.7	0.874
1.3	13.6	1.202	0.380	0.556	6.00	3.96	16.10	15.40	40.7	″	137.4	0.820
1.4	12.7	1.055	0.332	0.472	5.23	3.24	15.35	14.85	37.8	″	131.0	0.780
1.5	11.32	0.960	0.318	0.424	4.82	3.07	14.20	14.85	34.6	″	124.6	7.42
1.6	9.96	0.864	0.294	0.401	4.38	2.90	13.10	13.90	″	″	120.4	7.18
1.7	9.06	0.766	0.268	0.377	3.95	2.73	11.90	12.95	″	″	116.6	6.99
1.8	8.60	0.730	0.246	0.350	3.53	2.64	11.55	12.10	″	″	114.3	6.83
1.9	7.85	0.693	0.221	0.312	3.41	2.48	11.55	11.17	″	″	112.3	6.71
2.0	7.10	0.649	0.191	0.288	3.28	2.34	11.48	10.25	″	″	110.2	6.58
2.2	5.77	0.559	0.176	0.256	3.04	2.05	10.30	″	″	″	107.0	6.44
2.4	5.77	0.470	0.162	0.226	2.77	1.95	9.10	″	″	″	105.3	6.30
2.6	5.15	0.459	0.144	0.197	2.58	1.95	7.98	″	″	″	103.3	6.17
2.8	4.43	0.418	0.128	0.188	2.36	1.77	″	″	″	″	102.1	6.10
3.0	3.73	0.377	0.116	0.180	2.15	1.65	″	″	″	″	101.0	6.02
20.0	″	″	″	″	″	″	″	″	″	″	″	″

Table 8
Variation of DC System Copper Weight with Voltage on the WF-2

Voltage (pu)	Weight of the Various Wire Sizes (lb)										Total Wt (lb)	Wt (pu)
	2	4	8	10	12	14	16	18	20	22		
1.0	16.25	1.34	0.384	0.538	5.79	3.40	12.62	12.70	26.80	19.4	99.2	1.0
1.1	14.00	1.19	0.345	0.506	5.18	2.99	11.75	11.25	24.80	″	91.4	0.920
1.2	11.75	1.04	0.306	0.443	4.58	2.59	10.80	9.81	22.80	″	83.5	0.841
1.3	10.60	0.89	0.268	0.395	3.96	2.11	9.90	8.40	21.75	″	77.7	7.83
1.4	9.84	0.770	0.231	0.346	3.36	2.02	9.25	7.95	18.73	″	71.9	7.24
1.5	8.65	0.700	0.222	0.301	3.09	1.90	8.34	7.95	16.80	″	67.4	6.79
1.6	7.47	0.626	0.208	0.280	2.76	1.79	7.43	7.35	″	″	64.1	6.46
1.7	6.68	0.556	0.189	0.258	2.48	1.67	6.48	6.98	″	″	61.5	6.20
1.8	6.32	0.528	0.181	0.236	2.20	1.59	6.18	6.15	″	″	59.6	6.00
1.9	5.74	0.498	0.159	0.204	2.12	1.48	6.18	5.57	″	″	58.2	5.80
2.0	5.16	0.465	0.138	0.185	2.04	1.36	6.14	4.96	″	″	56.6	5.72
2.2	4.16	0.396	0.124	0.165	1.86	1.13	5.37	″	″	″	54.4	5.48
2.4	4.16	0.326	0.111	0.143	1.67	1.05	4.60	″	″	″	53.2	5.36
2.6	3.66	0.318	0.095	0.122	1.51	1.05	3.88	″	″	″	51.8	5.22
2.8	3.12	0.291	0.081	0.116	1.35	0.89	″	″	″	″	50.9	5.14
3.0	2.59	0.263	0.074	0.111	1.17	0.85	″	″	″	″	50.1	5.05

gage No. 16 wire. However, in Fig. 6 it will be observed that minimum weight occurs at maximum utilization; if plots were made for wire in each gage size it would be found that minimum weight occurs at maximum utilization. The exception is, of course, No. 22 wire. In this case any increase in voltage results in a decrease in utilization. Hence for all wire above the minimum size an increase in voltage will result in an increase in utilization and a decrease in weight. For wire already at minimum size an increase in voltage results in a decrease in utilization and no saving in weight. In both the ac and dc systems on the WF-2 aircraft a considerable portion of the wiring is already of minimum size, and little improvement in system utilization can be expected with increase in voltage. In the ac system, Fig. 7 indicates that the maximum system utilization occurs at 1.5-pu voltage. For higher voltages the utilization decreases rapidly and there is little decrease in system weight. In the dc system (Fig. 8) there is no increase in system utilization with increase in system voltage. It will be observed, however, that the utilization remains high up to a voltage of 1.5 or 1.6 pu, and at these voltages a considerable savings in system weight is realized. The load distribution on both the ac system and the dc system is such that in the vicinity of maximum utilization there is a fairly sharp descent in the utilization curve, and higher voltages beyond this point result in progressively lower and lower utilization with negligible savings in system weight. In general, from the viewpoint of reduction in system weight, it would appear impractical in increase system voltage beyond the point where the utilization continually descends with increasing voltage.

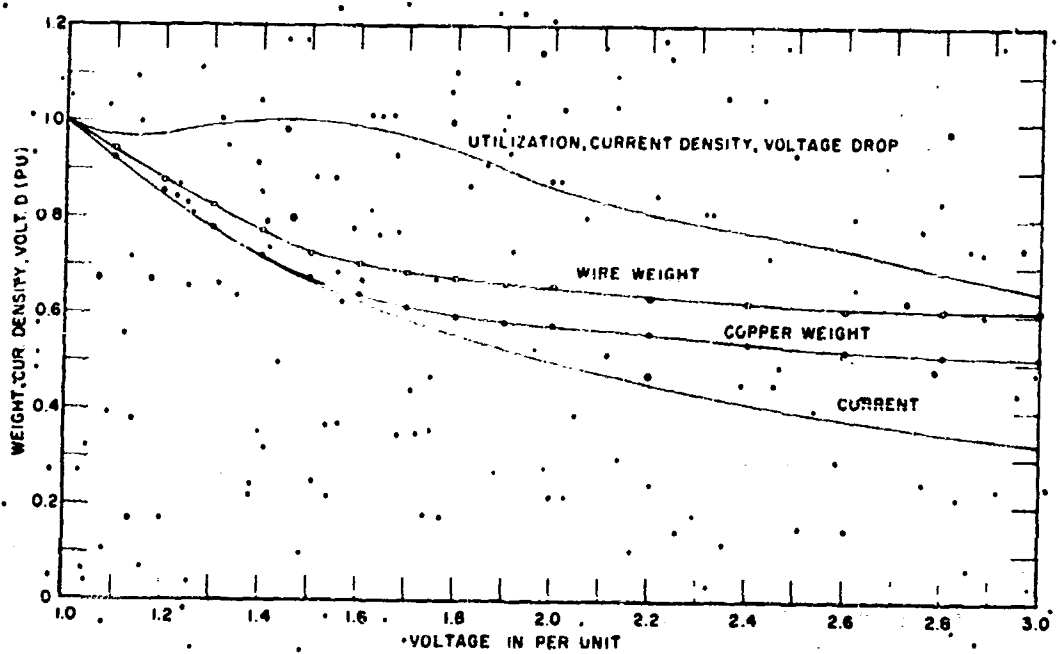

Fig. 7 - Average characteristics of the ac power transmission system on the WF-2 versus voltage

System voltage, allowable voltage drop, and voltage regulation are related. In this analysis it has been assumed that the ratio of maximum allowable line drop to system voltage (that is, regulation) is to remain constant. Hence, as the system voltage is increased, the allowable voltage drop is increased in the same ratio. Figure 7 shows no increase in the average voltage drop as the system voltage was increased from 1 pu to 1.5 pu. It might be concluded that the allowable voltage drop could be kept unchanged and this would represent an improvement in regulation. It must be emphasized, however, that the voltage drop shown in Fig. 7 and 8 is an average for the system. For loads still carried by wires above minimum size after an increase in system voltage, there is an increase in voltage drop proportional to the increase in current density. For loads initially carried by minimum size wires the voltage drop decreases as the system voltage increases and there is no saving in weight. The increase in current density that results with increase in system voltage as a given load is carried by smaller and smaller size wires is not so great as to prevent some improvement in regulation. Hence, with increasing system voltage there will be a marked improvement in the regulation of the small loads carried by minimum size wires and some improvement in the larger loads. Advantage of this uneven improvement in regulation can be taken by specifying narrower voltage regulation bands for some utilization equipment. For example, it is indicated in Naval Air Development Center Report NADC-EL-6029 (see item 13 in the Bibliography) in connection with the present ac voltage systems that designers of utilization equipment should be given the opportunity to provide lighter equipment with less heat problem by taking advantage of the 2-volt line drop wherever it could be anticipated. Because of the great variation in length of runs on a given aircraft and among planes of different size it is important that advantage be taken of the small line drop on short runs, and it is also important that the maximum permissible line drop be not so small that long runs are subject to weight penalty.

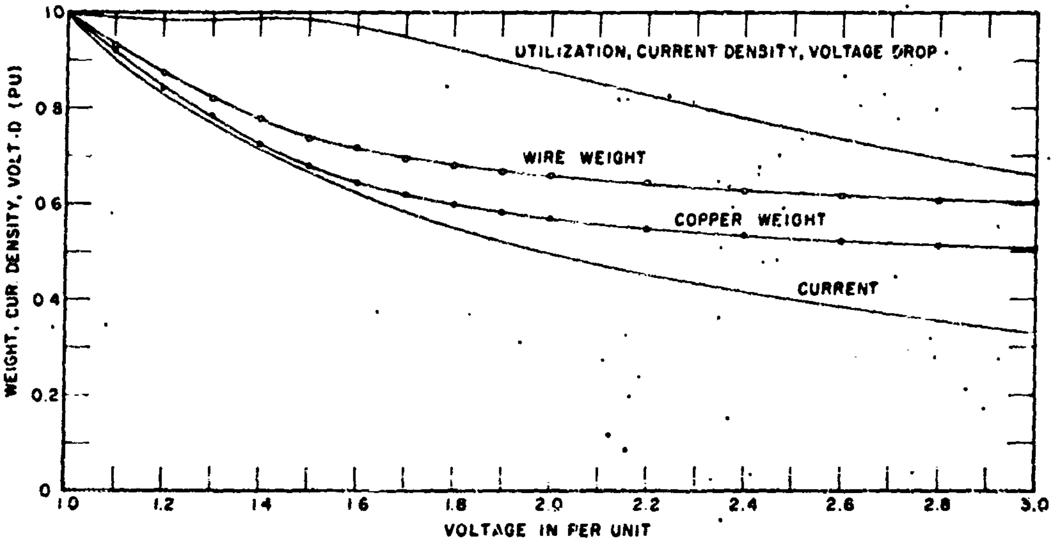

Fig. 8 - Average characteristics of the dc power transmission system on the WF-2 versus voltage

CONCLUSIONS

1. A simple method has been evolved for determining system characteristics with an increase in system voltage.

2. This method has been applied to the ac and dc wiring systems on the WF-2 aircraft and indicates worthwhile advantages for a modest increase (50%) in system voltage.

3. The analysis must be applied to a representative sample of all types of naval aircraft before a determination of optimum system voltage could be made.

4. Indications are that optimum system voltage for present and future naval aircraft is not so high that corona and insulation would present a serious problem.

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system is used to establish the optimum system voltage, the weight of wiring in the transmission system is reduced to within 5% to 10% of the theoretical minimum with only a moderate increase (50%) in present system voltages. A simple method has been evolved to determine the variation of system wiring weight and other system parameters with increase in system voltage. The method is applicable to any system, dc or ac, and to any aircraft. Application of the method to the dc and ac transmission systems on the WF-2 aircraft indicates that a weight reduction of 30% in system wiring will result with an increase of approximately 50% in systems voltage. On application of the analysis to several representative naval aircraft, best system voltage levels for future aircraft can be determined.

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