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INVESTIGATION OF INTERMITTENT FAULTS IN 30.0-VOLT D-C AIRCRAFT ELECTRICAL SYSTEMS

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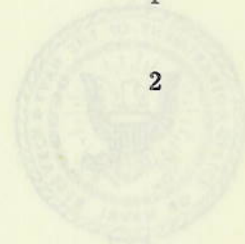
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AUTHORIZATION

NERL Problem Number E03-248
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ABSTRACT

Arcing faults have been demonstrated to cause severe damage to the plane structure under laboratory conditions. Information is needed on the characteristics of these phenomena in order that adequate protection can be devised. Faults totaling 2342 were established between conductors in a 30.0-volt d-c aircraft electrical system and a vibrating grounded plate simulating the aircraft structure. In this study approximately 77 percent of the faults established resulted in intermittent type faults. Further, it is shown that the contact resistance at the point of the fault as determined by the area of the contact and the arc resistance, if any, primarily determine the fault current magnitude in a particular system. No correlation was observed between structure vibration and the duration of the first fault pulse.

PROBLEM STATUS

This is a final report on this phase of the problem; work is continuing on other phases of the problem.

AUTHORIZATION

NRL Problem Number E03-24R
NR 423-240

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INVESTIGATION OF INTERMITTENT FAULTS IN 30.0-VOLT D-C AIRCRAFT ELECTRICAL SYSTEMS

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INTRODUCTION

In most electrical systems in military aircraft, a grounded installation is used, i.e., wire conductors form the positive leads while the conducting parts of the plane structure form the electrical return path to the generator. The conducting leads may be bundled and secured to the plane structure for support with the cable insulation preventing metal-to-metal contact. In an installation of this kind, contact between a positive lead and the plane structure with current flowing through this junction constitutes an electrical fault.

Electrical faults may be considered as being either of two types depending upon the nature of the contact at the point of the fault. The first type of fault is characterized by continuous metal-to-metal contact between the electrical conductor and the plane structure. This contact resistance may be high or low in magnitude depending upon the number of conductor strands in contact, the contact pressure, and the contamination of the contact surfaces. In vibrating systems, this resistance may be variable due to contact pressure variations. This type of fault usually results in damage to the electrical system and has received attention to the extent that circuits have been devised which are capable of minimizing damage in a limited section of the electrical system.

A second type of fault in an aircraft electrical system is characterized by separation of a faulted lead and the aircraft structure after contact has been made. Such separation may be intermittent or fixed and may result in a damaging arc being drawn out. This required separation for arcing may be caused by structure vibration or other mechanical force. Arcs are also drawn out when a few strands of a conductor make contact with the plane structure such that the fault current exceeds the current capacity of these contact strands. The strands become hot and form a bridge of molten metal which parts and causes an arc to be drawn out.

Due to the intermittent nature of the second type of faults, large areas of the plane structure may be melted or vaporized by the arc while the faulted conductor a short distance from the arc is not excessively hot. The existence and sustenance of an intermittent fault depends primarily upon (1) the generating system characteristics; (2) the structure vibration; and (3) the faulted circuit characteristics including the contact resistance. Prior to the development of a method to minimize damage from electrical faults it is essential to determine the magnitude and duration of such faults.

THE TEST CIRCUIT

Circuits of an aircraft generating system can be assembled on a vibrating platform to simulate the circuits in an aircraft. This arrangement, however, does not provide sufficient information for the study of fault currents for this current magnitude varies with the number of wire strands in contact with the plane structure, the contact pressure of each strand, the contact area, and the variation of arc length with time. In order to have this information it is necessary to know the exact manner in which the fault is

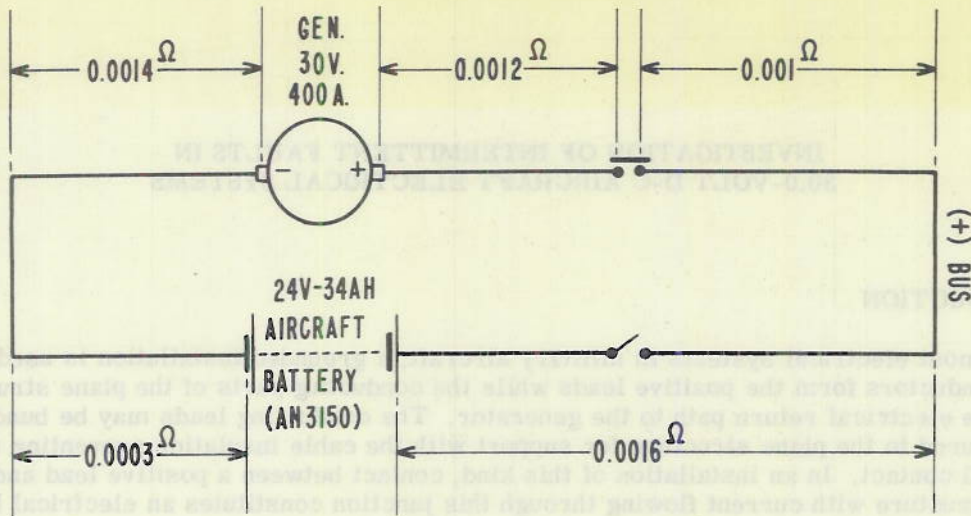


Figure 1 - Schematic diagram, showing main circuit resistances of the single generator system used in the study of electrical faults in a 30.0-volt d-c system

established. Such information, however, is not available and it is assumed that electrical faults in aircraft may be caused by parting a conductor in any number of ways.

Although exact prediction of fault current magnitude is not possible, it is possible to determine the probable fault currents in an aircraft by arbitrarily establishing faults on selected conductors in a generating system whose characteristics are known. A single generator system, composed of a General Electric aircraft generator type 2CM74B1 whose rated current capacity is 400 amperes (regulated by an Eclipse 1042-8-A regulator) in parallel with a 24.0-volt, 34-ampere-hour (AN 3150) aircraft battery was assembled for this study. This circuit is shown schematically in Figure 1. The transient and steady-state characteristics of the system used in this study are shown in Figure 2. This study was conducted at standard sea-level conditions and with the generator speed 5500 rpm. Voltage measurements were made at the point of application of the shock load.

Electrical faults were established in this circuit giving consideration to the parameters shown in Table 1. Data were collected for all possible meaningful combinations of the items listed on this table. The conductor sizes selected for this study are AN #2, #8, and #16. Size #2 is in the range of the largest diameter conductors used in an aircraft installation; size #8 is in the center of the range of conductor diameters used; and size #16 is in the range of smallest diameter conductors used in aircraft. The footage of each size wire and the longest and shortest length of each size wire in a two-generator aircraft electrical system are shown in Table 2.

An oscillographic record was made of each fault established and the characteristics of the first current pulse of each fault tabulated. Each fault was established on a clean (unburned) grounded plate. The first pulse was selected for study since it is desirable to detect a fault of any magnitude and duration if this fault or if successive applications of this fault will cause penetration of the aircraft structure. Complete penetration of an aluminum alloy structure can be an accumulative process whereby small electrical discharges melt a small volume of the plate. This globule of molten metal is forced by the conductor or by structure vibration from the crater, thereby exposing solid aluminum to the succeeding arc. Such continuous small arc discharges are made possible by the nature of the insulation of

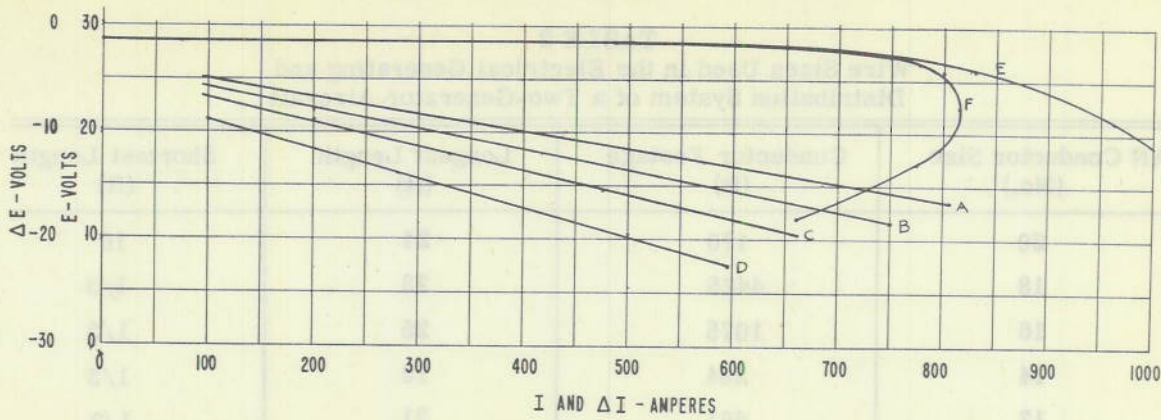


Figure 2 - Steady-state and transient characteristics of the electrical system used in the study of electrical faults

Transient characteristics

- Curve A - System composed of 1 generator and 1 battery, 200-ampere load
- Curve B - System composed of 1 generator and 1 battery, no load
- Curve C - System composed of 1 generator, 200-ampere load
- Curve D - System composed of 1 generator, no load

Steady-state characteristics

- Curve E - System composed of 1 generator and 1 battery
- Curve F - System composed of 1 generator

TABLE 1
Parameters Considered in the Study of Intermittent Faults in a 30.0-Volt D-C Aircraft Electrical System

Vibration			Faulted Conductor Characteristics			Fault Location	Structure Thickness (in.)	Battery †
Frequency (cps)	Total Displ. (in.)	Direction	Sizes	Distance From Clamp to Fault (in.)	Length (ft)			
0, 15, 30, 50	0.0125, 0.05	H _I *, H _{II} †, V	Stranded Copper #2, #8, #16	2, 8, 12	5, 25	Generator positive term., Bus	0.05, 0.091	Connected, Disconnected

*H_I indicates horizontal vibration perpendicular to the cable run.

†H_{II} indicates horizontal vibration parallel to the cable run.

‡See figures 1 and 2 for additional generating system data.

the AN conductors used. When ignited by the arc, the insulation burns and leaves a brittle residue. This residue is separated from the conductor by vibration and, thus, more bare wire is exposed to continue the arc.

Figure 3 shows typical damage to conductor insulation caused by arcing type faults. Conductors numbered (3), (7), (8), and (9) show AN JC 48a wire size #6, #16, and #18 with bare copper protruding from the insulation. Conductors (2), (4), (5), and (6) show conductors with plastic insulation whose sealing qualities are only slightly better than those with braided insulation. The insulation on conductors (1) and (10), although charred, retained its integrity well enough to seal the end of the wire.

PROPORTION OF ARCS AND WELDS

All established faults did not result in arcs. Of the 2342 faults established, 545 or 23.2 percent resulted in welded faults and the remaining 1797 resulted in intermittent faults.

TABLE 2
Wire Sizes Used in the Electrical Generating and
Distribution System of a Two-Generator Aircraft

AN Conductor Size (No.)	Conductor Footage (ft)	Longest Length (ft)	Shortest Length (ft)
20	170	24	10
18	4425	23	1/3
16	1075	25	1/3
14	294	18	1/3
12	691	21	1/2
10	145	25	1/3
8	16	8	8
6	71	28	4
4	115	12	6
2	16	5	3
0	153	16	2
00	1	1	1
	7172 (total)		

TABLE 3
Number of Intermittent Faults and Welds Which Resulted from
Establishing 2342 Faults in a 30.0-Volt D-C Aircraft Electrical System

Plate Thickness (in.)	Battery On		Battery Off		AN Conductor Size #16		AN Conductor Size #8		AN Conductor Size #2		Total Arcs	Total Welds	Total Faults
	Number of Arcs	Number of Welds	Number of Arcs	Number of Welds	Number of Arcs	Number of Welds	Number of Arcs	Number of Welds	Number of Arcs	Number of Welds			
0.05	581	146	556	172	303	179	412	73	422	66	1137	318	1455
0.091	505	166	155	61	185	112	241	51	234	64	660	227	887
TOTALS	1086	312	711	233	488	291	653	124	656	130	1797	545	2342

These data are presented in Table 3. It is possible to apply sufficient contact pressure to weld the conductor to the plate each time a fault is established; however, the electrical faults in this study were established by arbitrarily dropping the faulted conductor on a grounded plate. No marked difference is noted in the proportion of arcs to total faults with the battery connected to the bus or disconnected from the bus, nor is there a marked difference in this proportion for the two thicknesses of plane structure (0.050" and 0.091") used. Fewer welds resulted from establishing faults on a nonvibrating platform than from establishing faults on a vibrating platform. Further, more welds occurred from faults established on a vertically vibrating platform than from faults established on a horizontally vibrating platform. It was also noted that 53.5 percent of the total number of welds occurred in size #16 conductors while the number of welds on sizes #2 and #8 conductors were approximately equal at 23 percent of the total number of welds.

There are two conditions under which welds occur. First, if there is sufficient contact pressure to prevent separation of the conductors of opposite polarity and further; if there is sufficient circuit resistance to limit the current to a value lower than that

- (1) ALUMINUM CONDUCTOR RUBBER INSULATION COTTON BRAID SIZE #4
ALL OTHERS COPPER CONDUCTOR.
- (2) (4) (5) (6) PLASTIC INSULATION AN SIZES # 4 #8 #12 #14
- (3) (7) (8) (9) AN JC 48a WIRE SIZES #6 #16 #18
- (10) GLASS INSULATION
SIZE #18

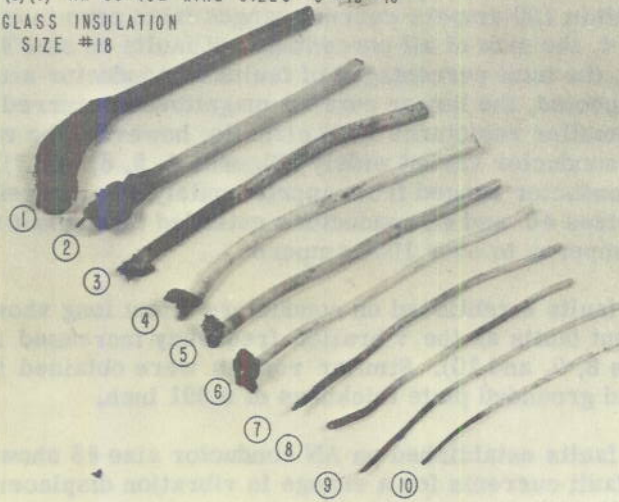


Figure 3 - Typical damage to cables by arcing faults at 30-volts

necessary to melt the contact strands, the electrical fault will be of the welded type. Second, the conductor strands are heated during the drawing out of the first arc and the conductor and plate again make contact. Prior to the second separation, the contact areas cool and weld together, provided further that the circuit resistance is large enough to limit the current to a value lower than that necessary to melt the conductor strands in contact with the grounded plate. Considering the flexibility and resistance of the AN size #16 conductor in comparison with that of size #8 and #2 conductors, more welded faults would be expected on the size #16 conductor in accordance with the conditions given for the welded fault to occur.

FAULT CURRENT MAGNITUDE

An arc produces two kinds of melting and vaporization of metal. Firstly, the energy necessary to cause melting is produced by charged particles forming the current falling through the potential drop at the electrode surface. Secondly, the high temperature produced in the arc causes normal evaporation by heat.^{1,2} For arc currents of the magnitude measured in this study, melting seems to be of the first kind, i.e., by an EI type heating. If damage from an electrical fault is measured in the volume of the plane structure melted or vaporized then fault current magnitude would be an important consideration in the operating requirements of a fault detector.

The fault current magnitude of the first pulse of intermittent-type faults established in the circuit shown in Figure 1 is shown in Figures 4 through 14.³ The magnitude shown

¹ Holm, Ragnar, "Electric Contacts," paragraph 57, Stockholm: H. Gebers, 1946

² Jones, T. B., Kowenhoven, W. B., and Skolnik, M. "Heat Effects in Anode Spots of High Current Arcs," *Welding Journal*, 28: pp. 461s - 465s, October 1949

³ Figures 4 through 25 appear at the end of report.

there is the average current for the time between the pulse start and the time that the current again reaches zero magnitude. The measured magnitudes are considered accurate to ± 5.0 amperes. The fault data are plotted in percent of total faults, established for a given condition, falling within 100 ampere current ranges from zero to over 1000 amperes. For example, in Figure 4, the sum of all percentages of faults on size #16 conductors equal 100 percent. Similarly, the total percentages of faults on conductor sizes #8 and #2 also equal 100 percent. As expected, the larger current magnitudes occurred with the larger diameter conductors or the smaller resistance fault circuits; however, the current magnitudes of the faults on each size conductor varied widely (Figures 4, 5, 6, and 7). For example, fault currents on size #16 conductor ranged from approximately 40 amperes to over 700 amperes. Fault currents on sizes #8 and #2 conductors extended throughout the range presented from approximately 50 amperes to over 1000 amperes.

Data from 622 faults established on conductors 5 feet long show a slightly greater number of higher current faults as the vibration frequency increased from 15 cps to 30 cps and 50 cps (Figures 8, 9, and 10). Similar results were obtained for faulted conductor length of 25 feet and grounded plate thickness of 0.091 inch.

Data from 208 faults established on AN conductor size #8 show a small change in the distribution of the fault currents for a change in vibration displacement from 0.0125 inch to 0.05 inch (Figure 11).

Data from 619 faults established on conductors 5 feet long show that the direction of vibration has relatively little effect upon the current magnitude of the first fault pulse (Figures 12, 13, and 14).

The grounded aluminum alloy plate on which faults are established may be anodized and, if intact, this surface covering acts as an effective insulator at 30.0 volts d.c. It was found, however, that when such coatings have been scratched, arcing faults can be readily struck on the plate, at the location of the scratch.

Based on 1797 intermittent faults established, recorded and observed, it is concluded that the resistance of the fault circuit and the physical configuration of the contact point primarily determine the character of the fault in a particular system. The initial contact area could be smaller than the area of one strand, but once the arc is established, the contact area may approximate the cross-sectional area of the conductor. The resistance of the contact, as determined by the area of the contact, and the arc resistance, if any, will primarily determine the fault current magnitude for a particular system.

THE EFFECT OF THE GENERATING SYSTEM CHARACTERISTICS ON FAULT CURRENT MAGNITUDE

The average current of the first fault pulse depends not only on the fault resistance but also system characteristics and operating conditions such as the number of generators and batteries in the system, system load, battery temperature, generator speed and circuit resistances. The effect on the fault current magnitude of connecting a battery to the bus and causing the system to furnish a 200-ampere load prior to faulting can readily be seen by referring to Figure 2. The data for this figure were taken with a generator speed of 5500 rpm, sea level conditions, and an ambient temperature of 25°C. In this figure, curves A, B, C, and D represent the transient characteristics of the system (ΔE vs. ΔI). The voltage was measured at the point of application of shock load.

If a load line were drawn on Figure 2 from the origin (0 volts - 0 amperes) to the intersection of the steady-state characteristic and the 500-ampere line, then the transient

currents for this resistance (load line) can be graphically determined. The intersection of the load line with curve B is at the 340-ampere line, while the intersection of this load line and curve D is at the 280-ampere line. Therefore, for the same fault resistance, the transient currents in an electrical system with a battery connected to the bus will be greater than with the battery disconnected. The change in transient characteristics with steady-state load prior to shock loading is expected since the regulator normally inserts less resistance in the shunt field when the generator is furnishing current.

FAULT CURRENT DURATION (FIRST PULSE)

In order to devise detection equipment to minimize the damage from intermittent faults it is necessary to know the duration as well as the magnitude of these faults. In this study the fault duration is defined as the time between the start of the first pulse of current and the return of this current to zero. Time data were taken from an oscillographic record and the pulse duration is estimated to be accurate to ± 0.002 second. Figures 15 through 18 show the duration of the first current pulse of faults established between different sizes of AN conductors and a grounded aluminum alloy plate.

Data from 612 faults, established on conductors five feet long, show that changes in the structure vibration frequency have relatively little effect upon the duration of the first pulse of fault current (Figures 19, 20, and 21).

Figure 22 shows that for 209 faults on size #8 conductor 5 feet long a change in total displacement of structure vibration has no marked effect on the duration of the first pulse of fault current.

Data from 614 faults, established on conductors five feet long, show no marked change in the duration of the first pulse of fault current for a change in the direction of vibration of the vibrating platform on which the fault is struck (Figures 23, 24, and 25). Similar results were noted for faults established on conductors 25 feet long and for faults established on grounded plates 0.091-inch thick.

From data presented in Figures 15 through 25, it has not been possible to correlate first fault pulse duration with structure vibration frequency, displacement, and direction. It appears that, in most instances, intermittent-type faults are started by the fault current being in excess of the very short time current ratings of the strands making contact with the grounded plate, causing the contact strands to become molten and to part.

CONCLUSIONS

Based upon the analysis of approximately 2300 faults established in a laboratory installation of a simulated single-generator aircraft electrical system, the following conclusions are drawn.

(a) A large proportion of faults established in an aircraft electrical installation whether on a vibrating platform or not are of the intermittent type. In this study 76.8 percent of the faults established were of the intermittent type.

(b) The variation of vibration frequency, displacement and direction used in study showed little effect on fault current magnitude of the first pulse. However, the resistance of the contact as determined by the area of the contact, and the arc resistance, if any, primarily determines the fault current magnitude in a particular system.

(c) Most intermittent faults start by fault current flow in excess of the current carrying capacity of the contact strands. The contact strands become molten and part causing an arc to be drawn out.

(d) It was noted that faults established on a vibrating platform burn completely clear less rapidly than faults struck on a nonvibrating platform. The platform vibration, although not usually starting the arc, does assist in re-establishing the fault by loosening insulation residue or by otherwise causing the plate and conductor to remake contact.

(e) A variation in fault current in different systems for the same value of fault resistance will occur because the fault current depends upon the stiffness of the system, the regulator recovery time on shock loading, the state of charge of the battery and circuit resistances.

(f) No correlation was observed between the structure vibration frequency, displacement and direction and the duration of the first fault pulse.

(g) A study of available reports of unsatisfactory or defective material involving aircraft electrical faults shows that approximately 10 percent of the electrical faults reported are on the main generator leads.

(h) Presently proposed protective systems may minimize damage from electrical faults on less than 10 percent of the conductor footage in an aircraft.

(i) Elements such as fuses and circuit breakers presently used in aircraft will not clear damaging faults established in a simulated aircraft electrical system set-up in a laboratory.

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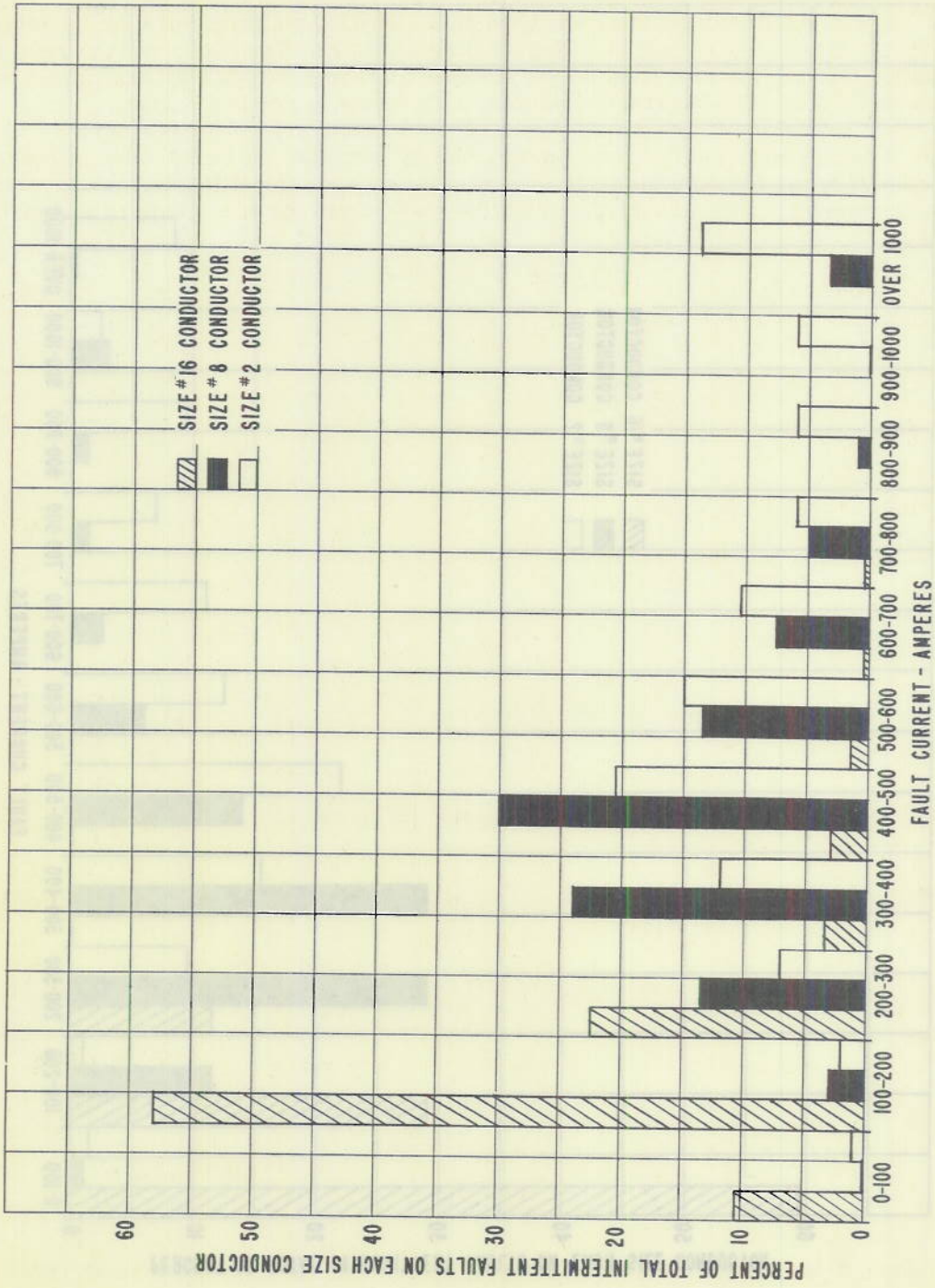


Figure 4 - Current magnitude of the first fault pulse of 621 faults established between AN conductors 5-feet long and an aluminum alloy plate 0.05-inch thick

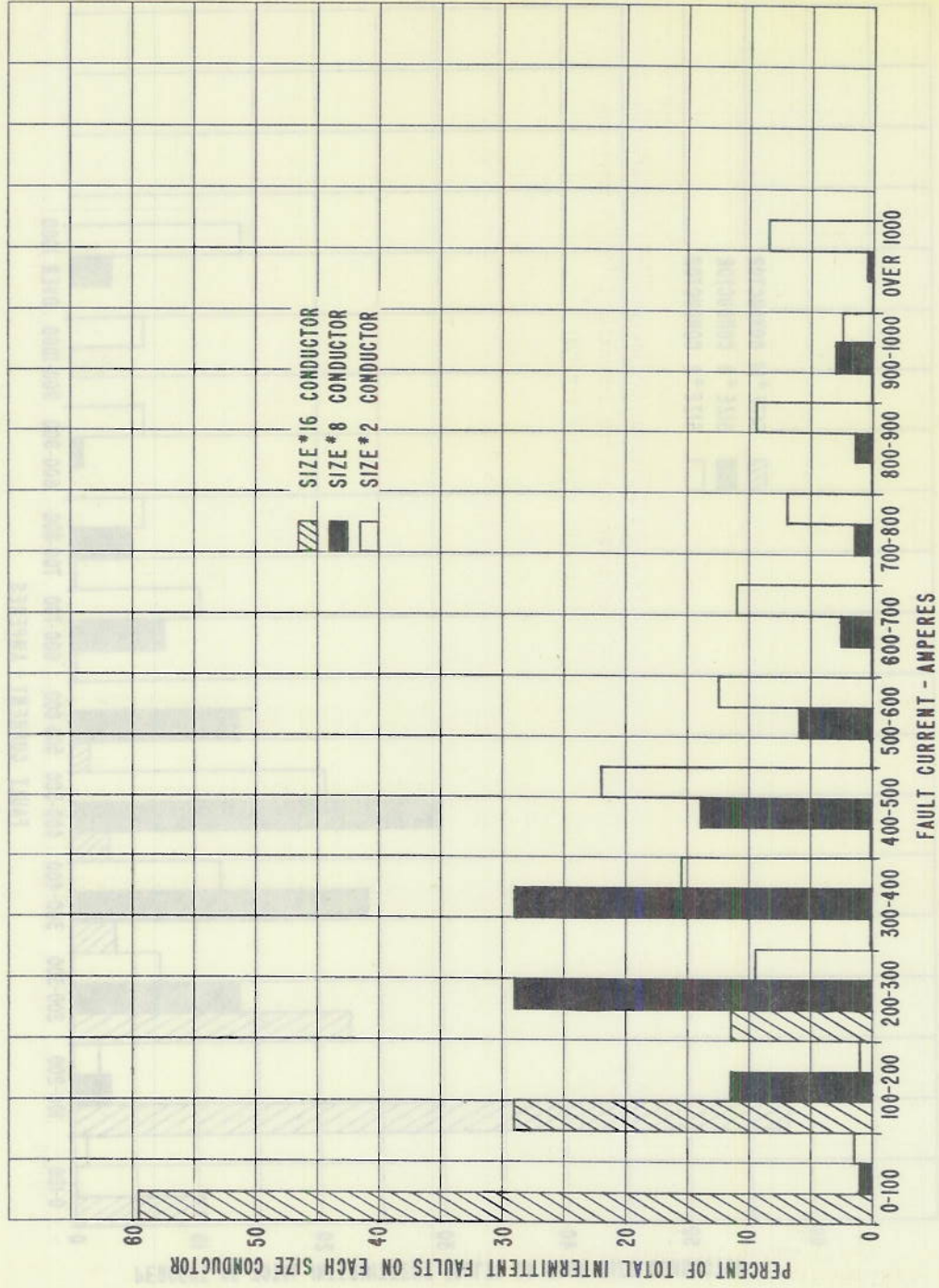


Figure 5 - Current magnitude of the first fault pulse of 506 faults established between AN conductors 25-foot long and an aluminum alloy plate 0.05-inch thick

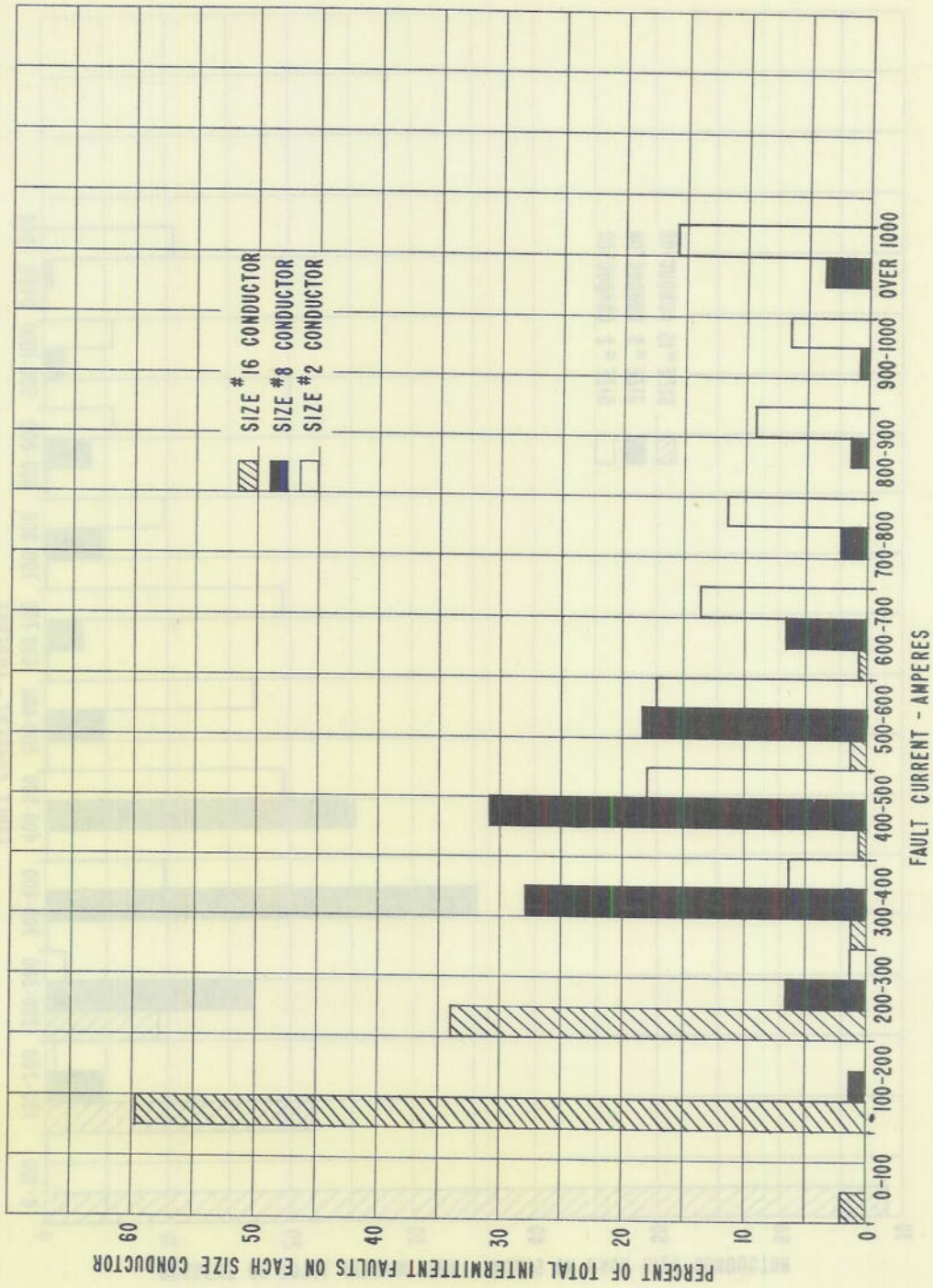


Figure 6 - Current magnitude of the first fault pulse of 419 faults established between AN conductors 5-foot long and an aluminum alloy plate 0.091-inch thick

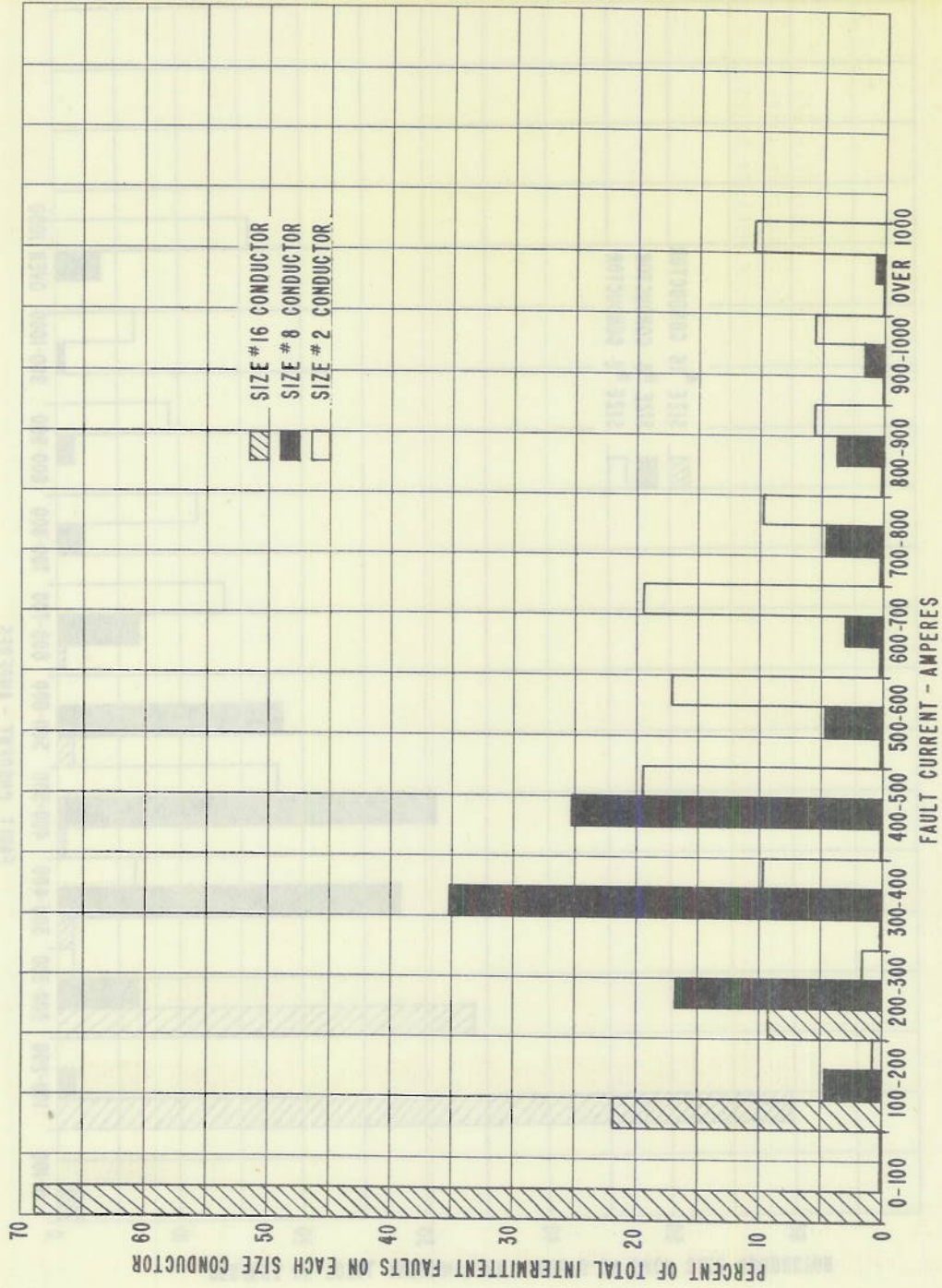


Figure 7 - Current magnitude of the first fault pulse of 318 faults established between AN conductors 25-foot long and an aluminum alloy plate 0.091-inch thick

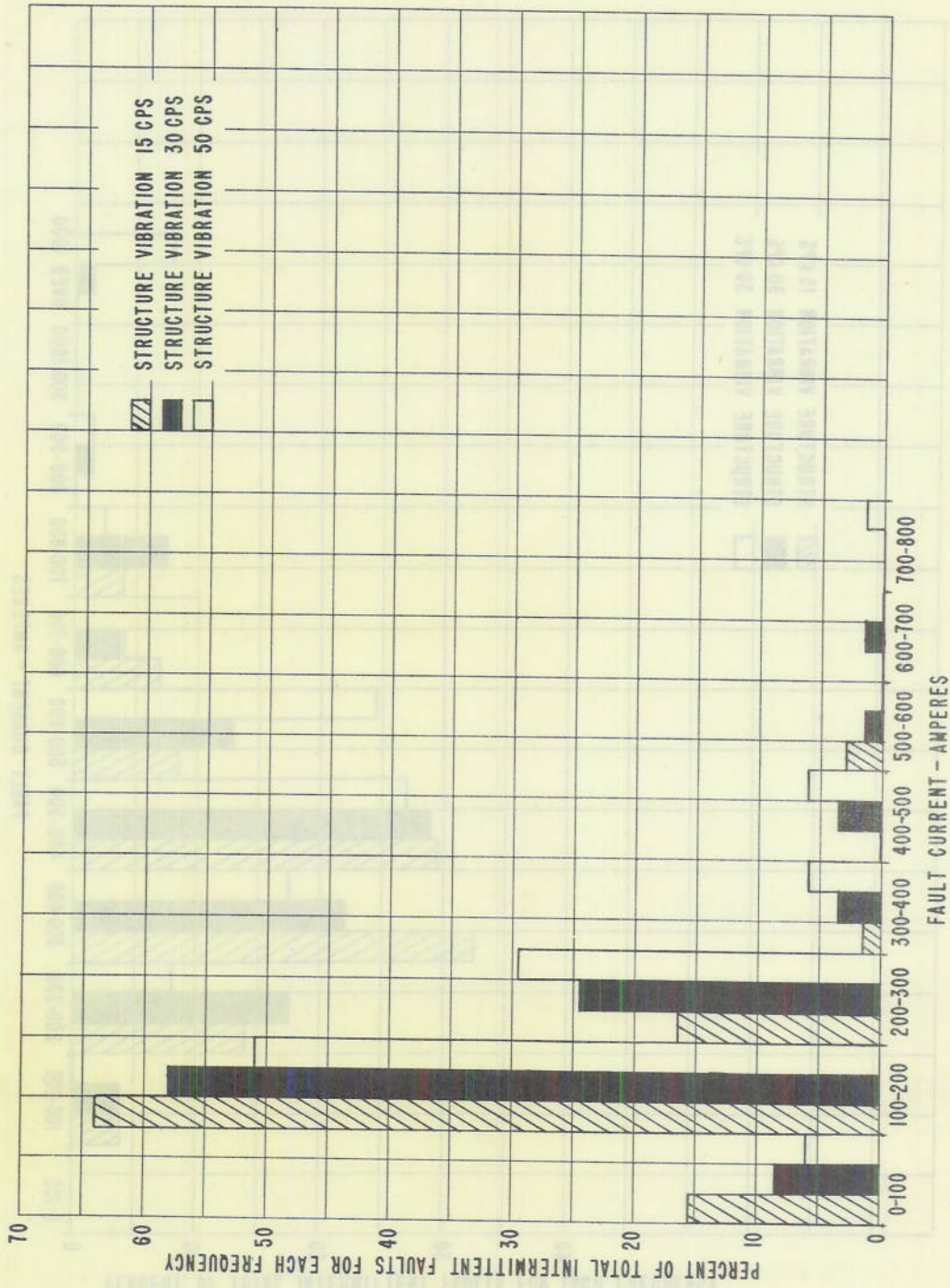


Figure 8 - Current magnitude of 206 faults established between AN conductor size #16 (5-foot long) and an aluminum alloy plate 0.05-inch thick

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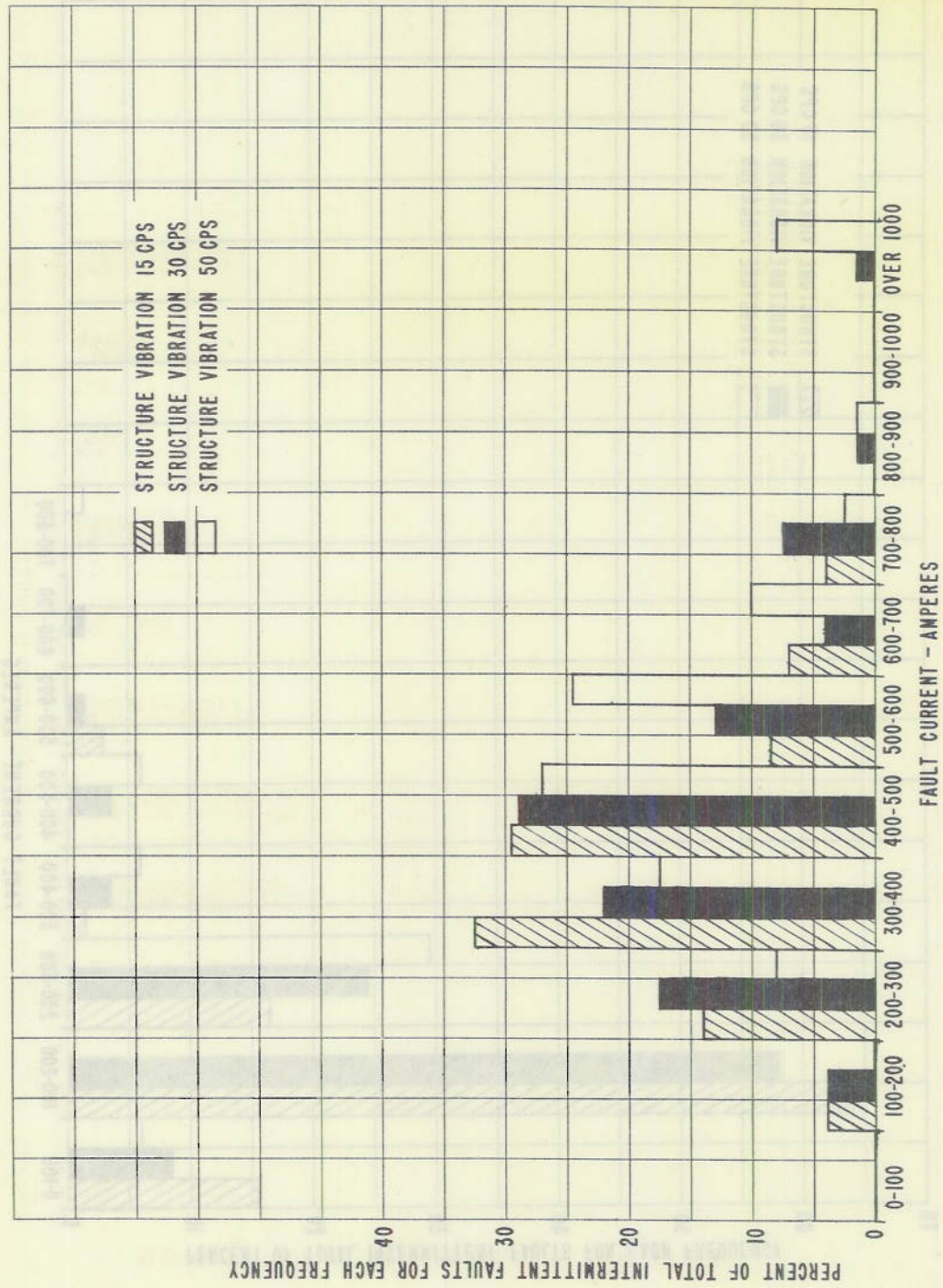


Figure 9 - Current magnitude of 214 faults established between AN conductor size #8 (5-foot long) and an aluminum alloy plate 0.05-inch thick

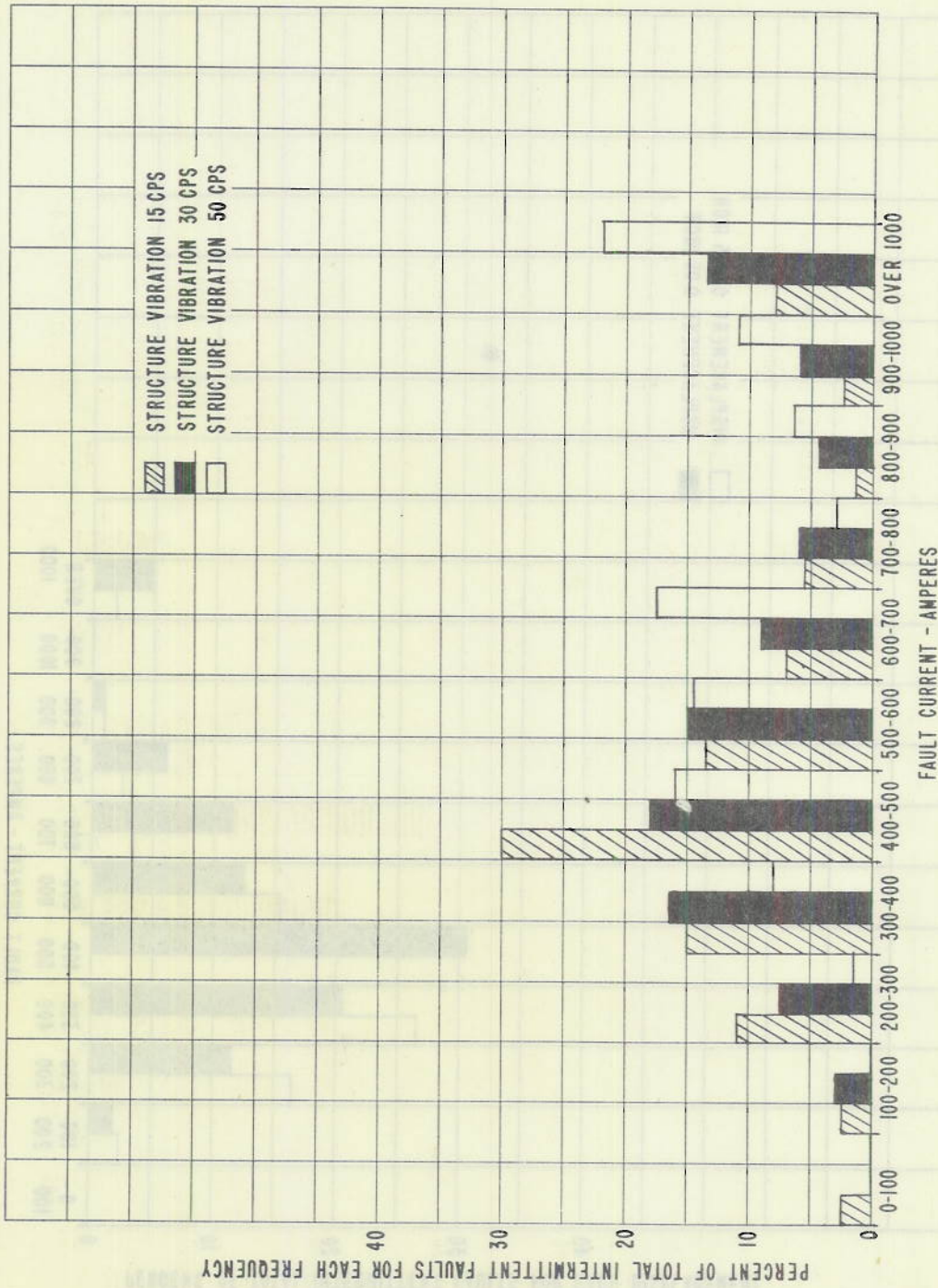


Figure 10 - Current magnitude of 202 faults established between AN conductor size #2 (5-foot long) and an aluminum alloy plate 0.05-inch thick

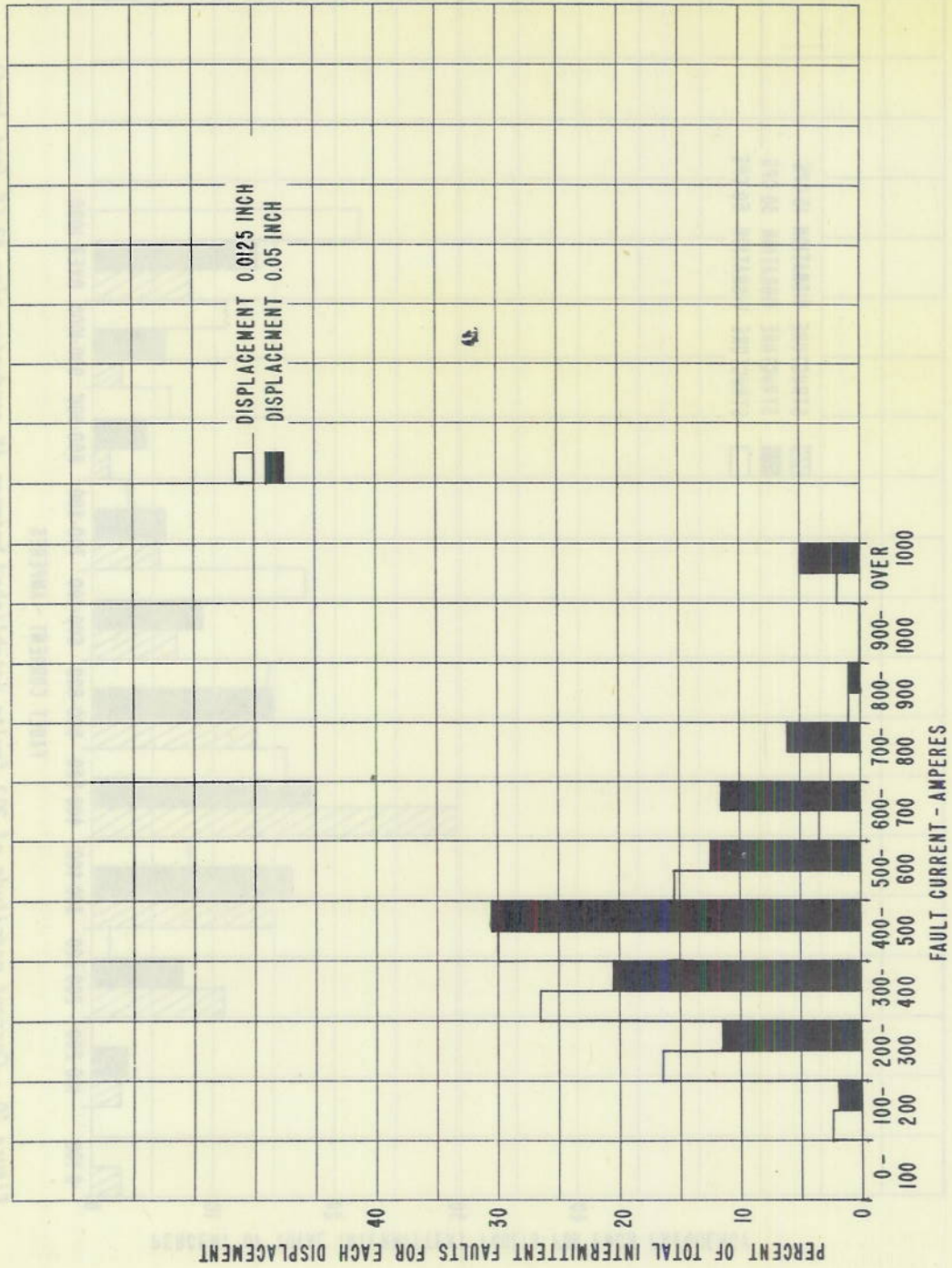


Figure 11 - Current magnitude of the first fault pulse of 208 faults established between AN conductor size #8 and an aluminum alloy plate 0.05-inch thick

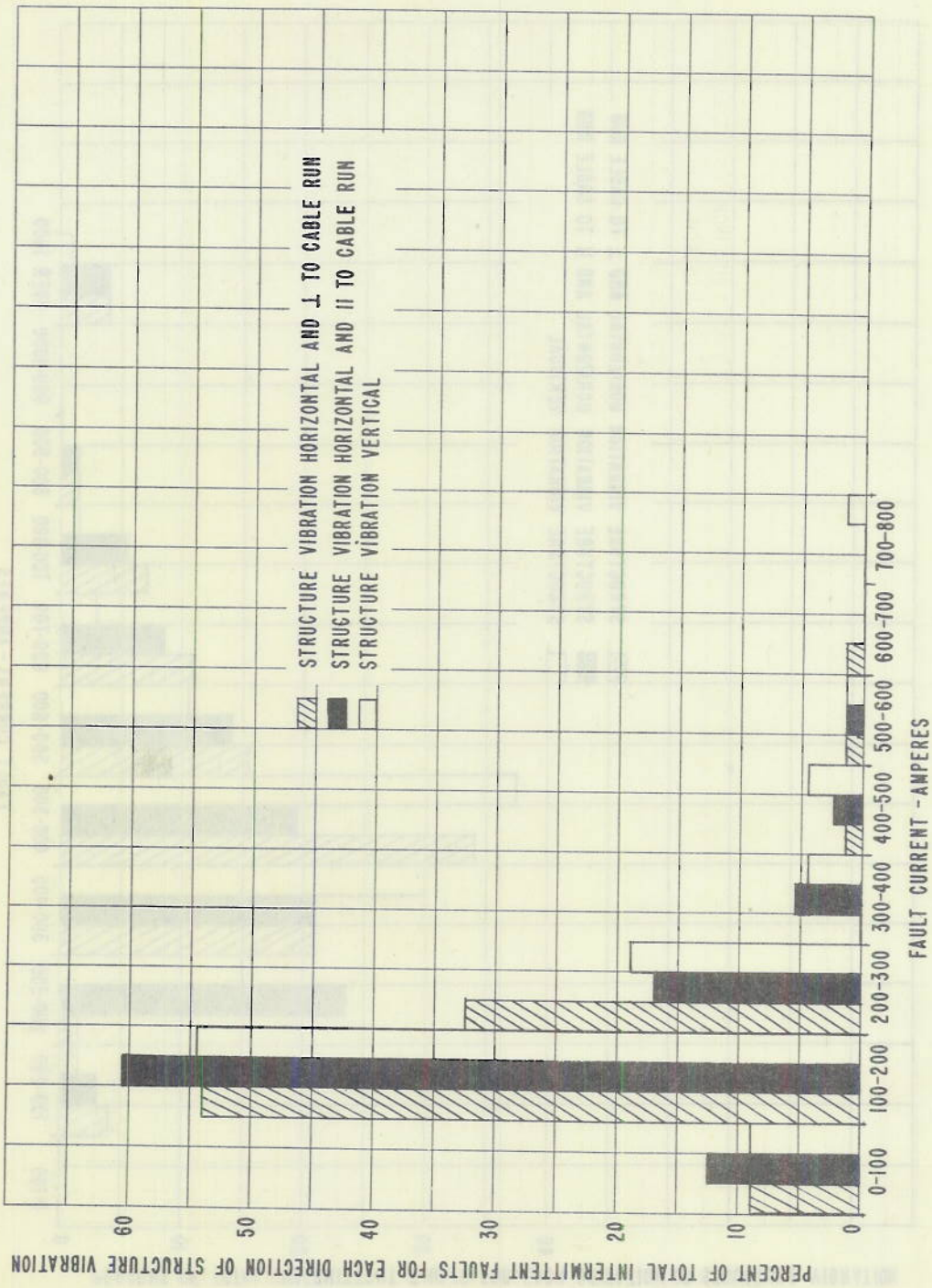


Figure 12 - Current magnitude of the first fault pulse of 203 faults established between AN conductor size #16 (5-foot long) and an aluminum alloy plate 0.05-inch thick

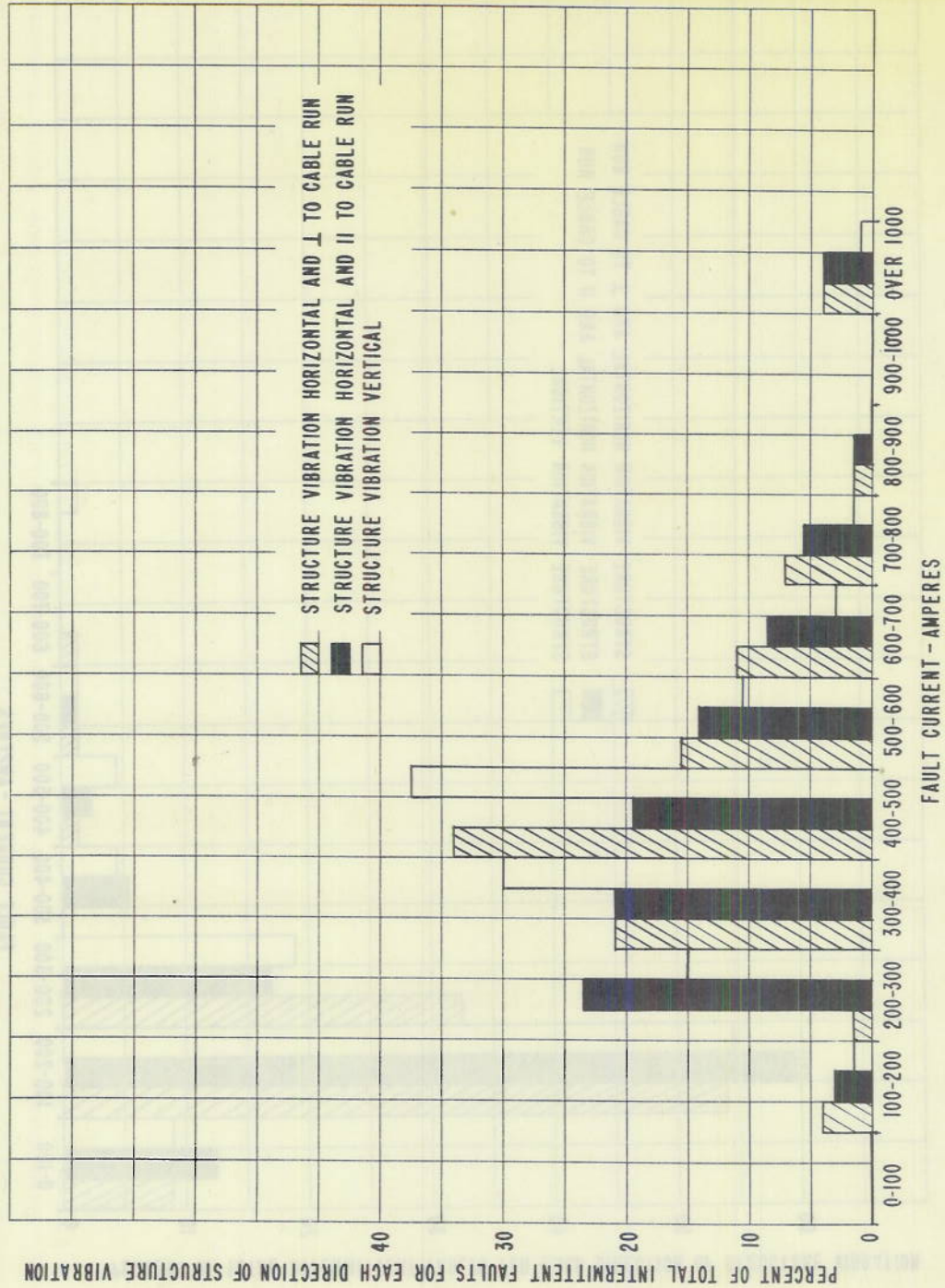


Figure 13 - Current magnitude of the first fault pulse of 210 faults established between AN conductor for size #8 (5-foot long) and an aluminum alloy plate 0.05-inch thick

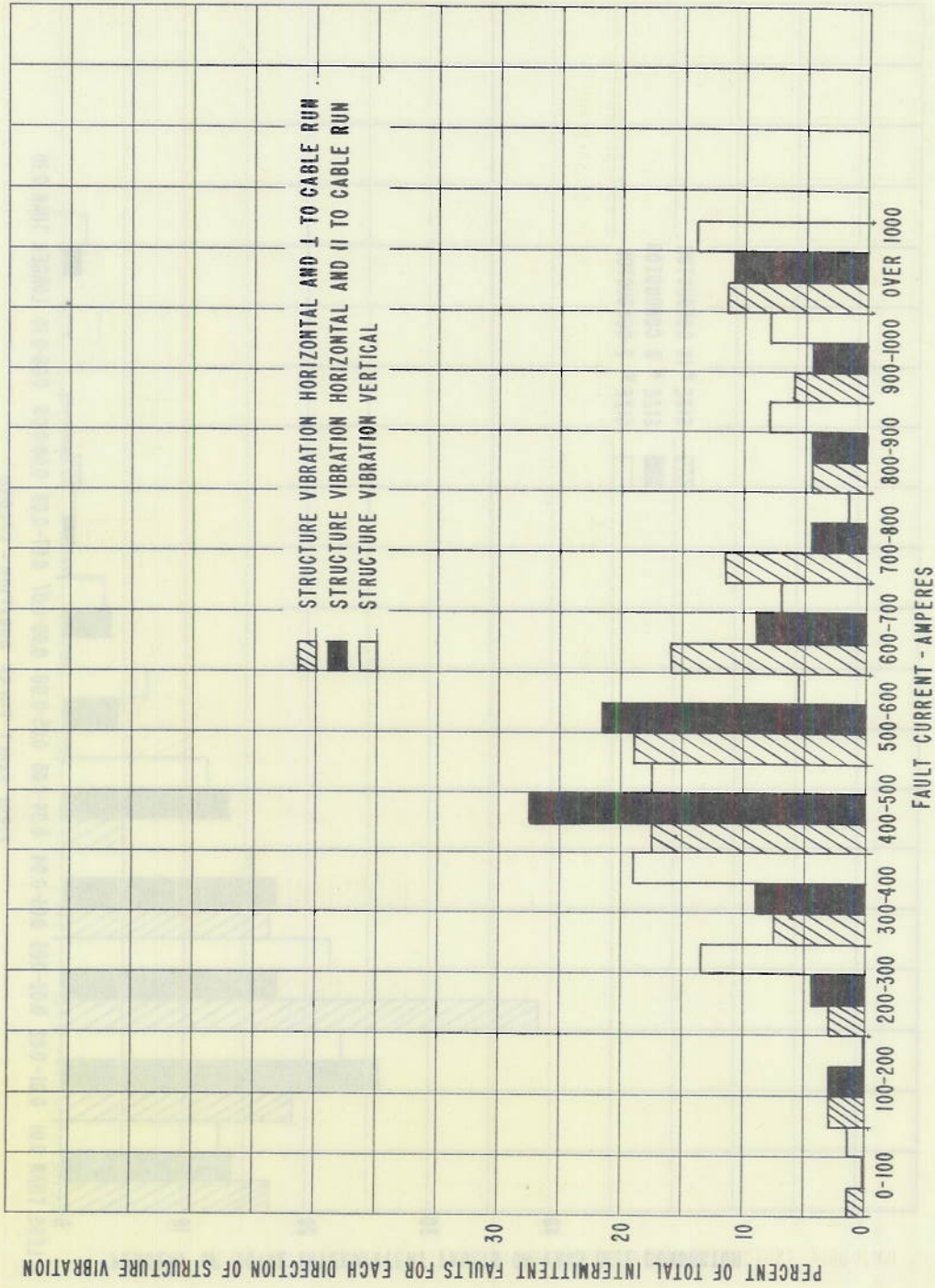


Figure 14 - Current magnitude of the first fault pulse of 206 faults established between conductor size #2 (5-foot long) and an aluminum alloy plate 0.05-inch thick

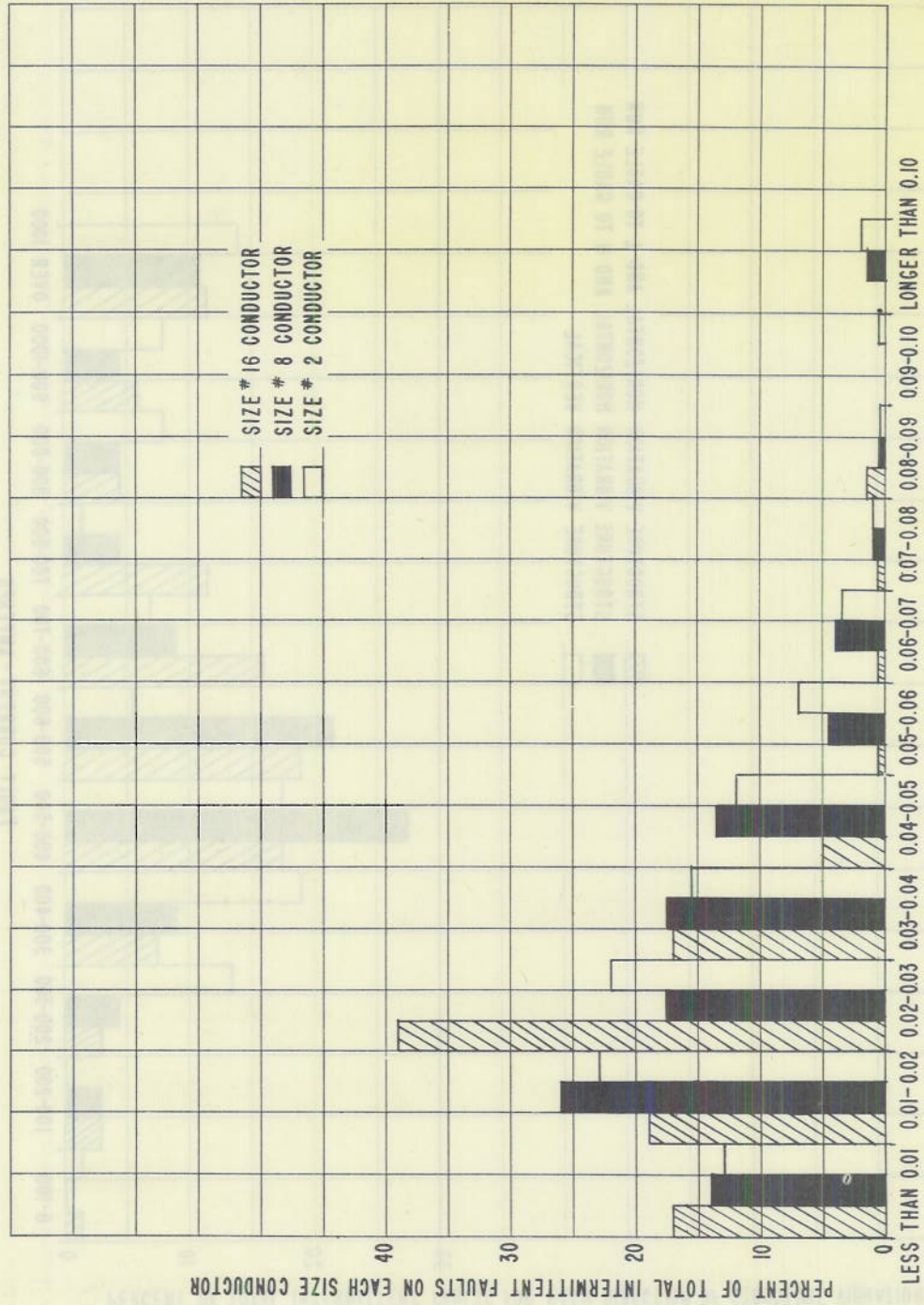


Figure 15 - Duration of the first fault pulse of 614 faults established between conductors 5-foot long and an aluminum alloy plate 0.05-inch thick

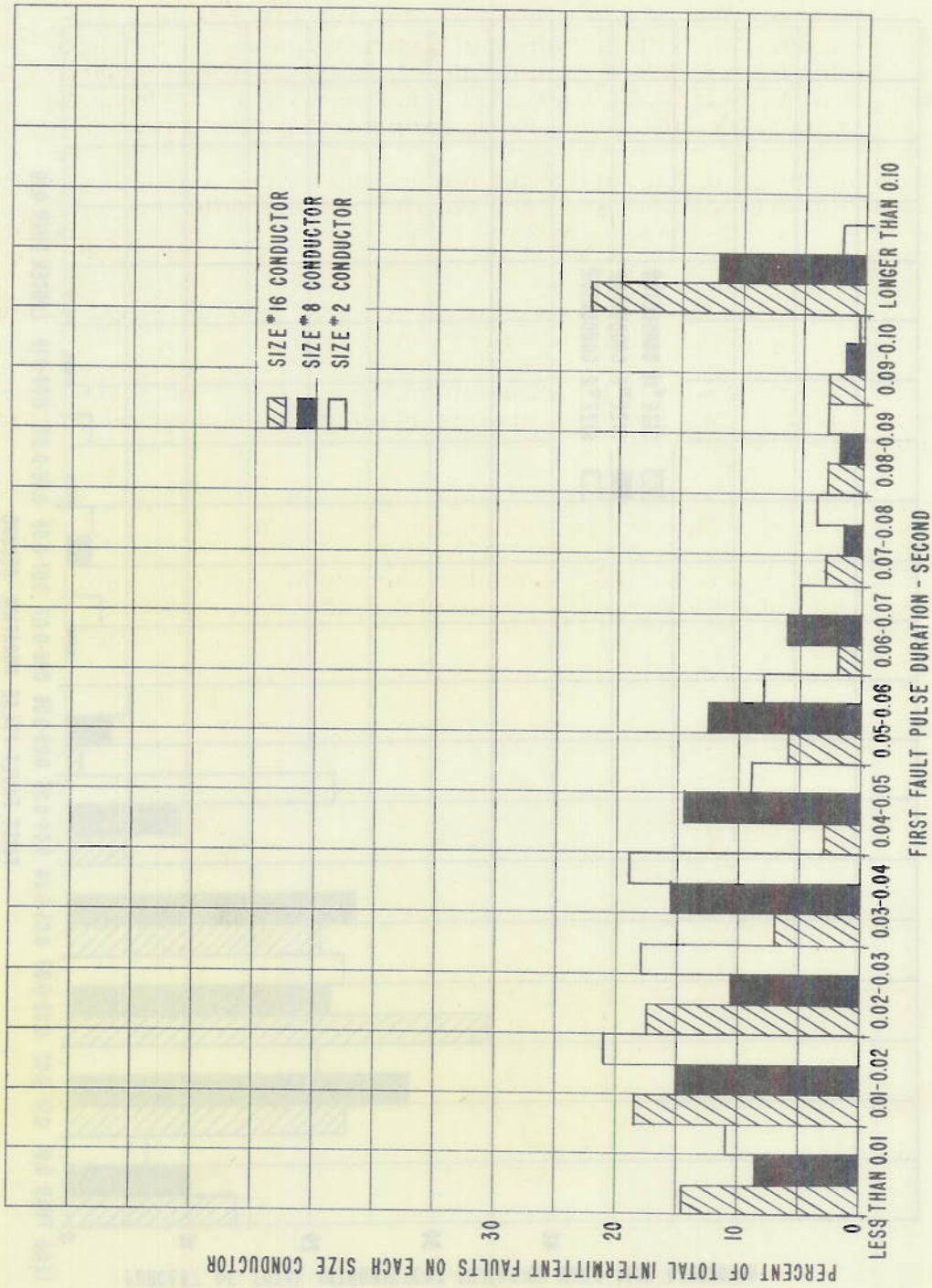


Figure 16 - Duration of the first fault pulse of 477 faults established between conductors 25-foot long and an aluminum alloy plate 0.05-inch thick

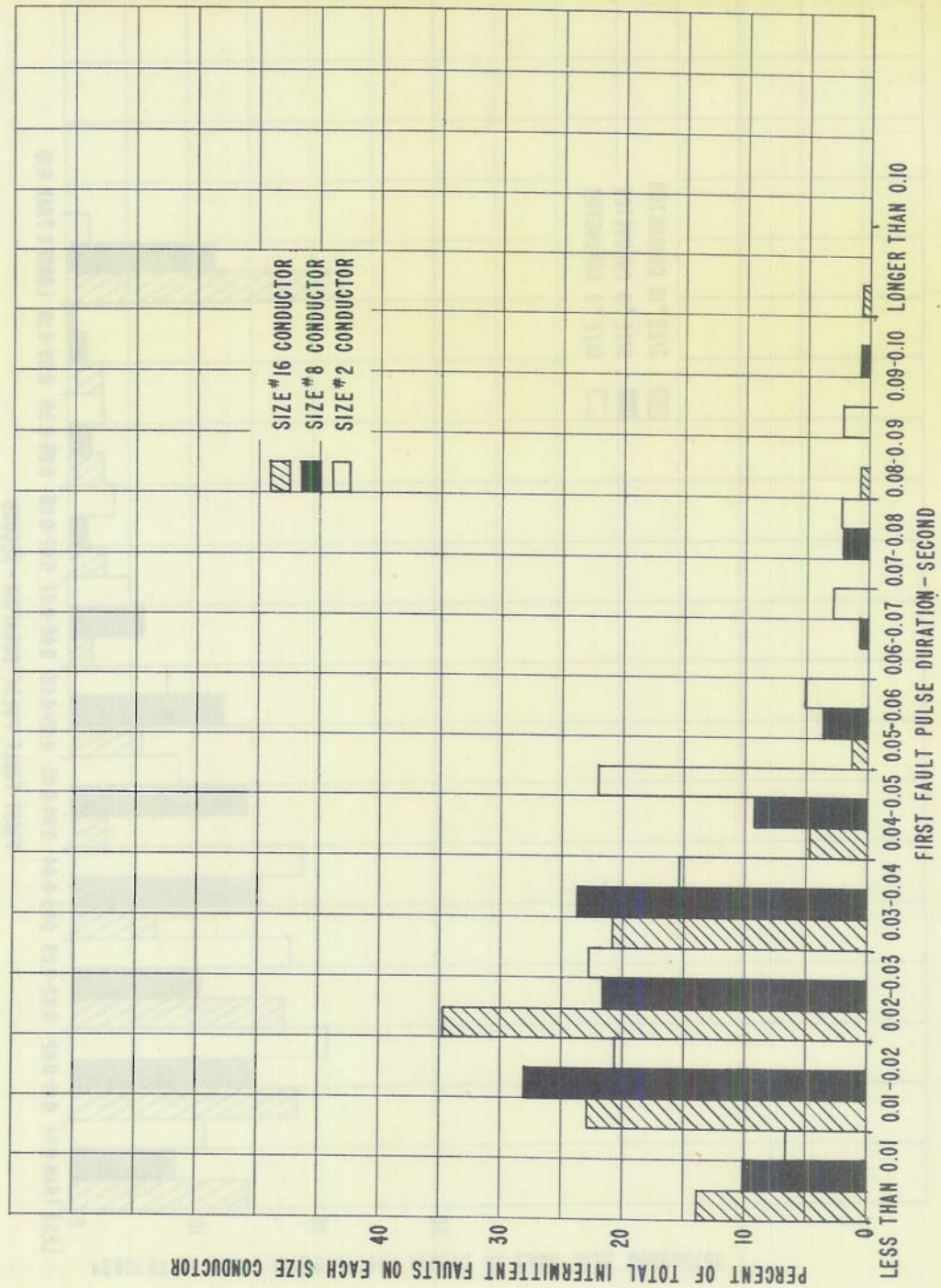


Figure 17 - Duration of the first fault pulse of 419 faults established between conductors 5-foot long and an aluminum alloy plate 0.091-inch thick

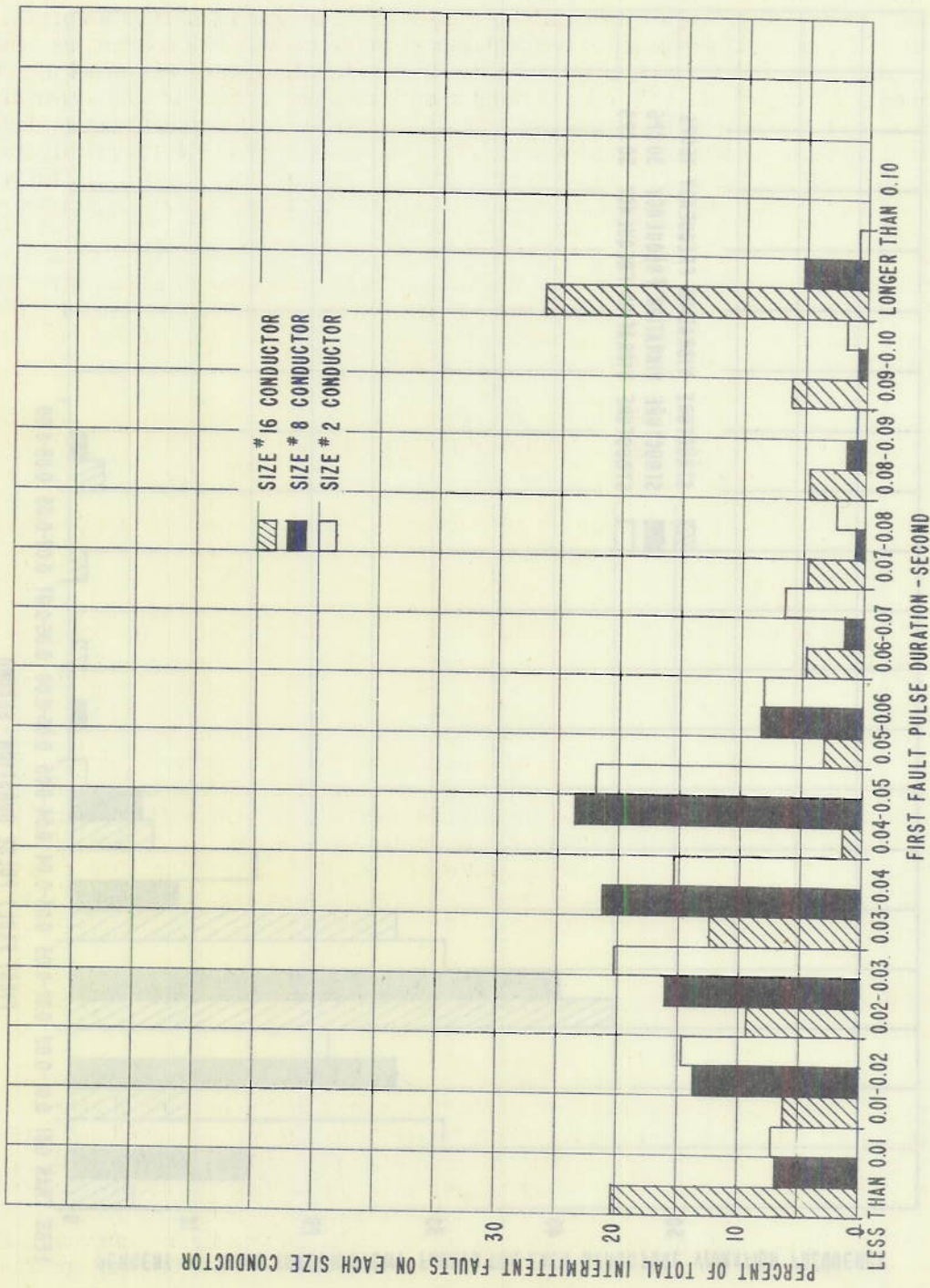


Figure 18 - Duration of the first fault pulse of 318 faults established between conductors 25-foot long and an aluminum alloy plate 0.091-inch thick

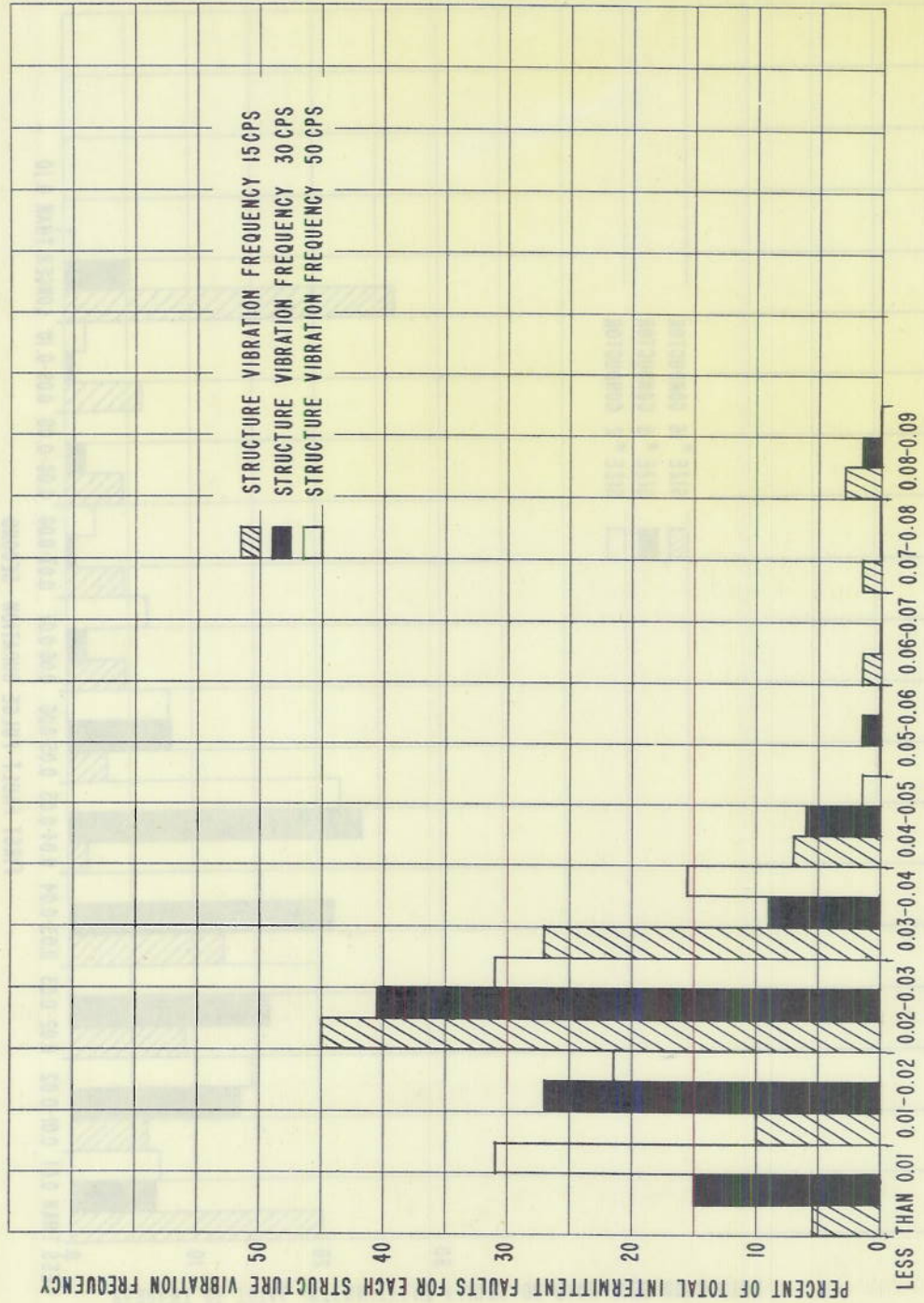


Figure 19 - Duration of the first fault pulse of 203 faults established between AN conductor size #16 (5-foot long) and an aluminum alloy plate 0.05-inch thick

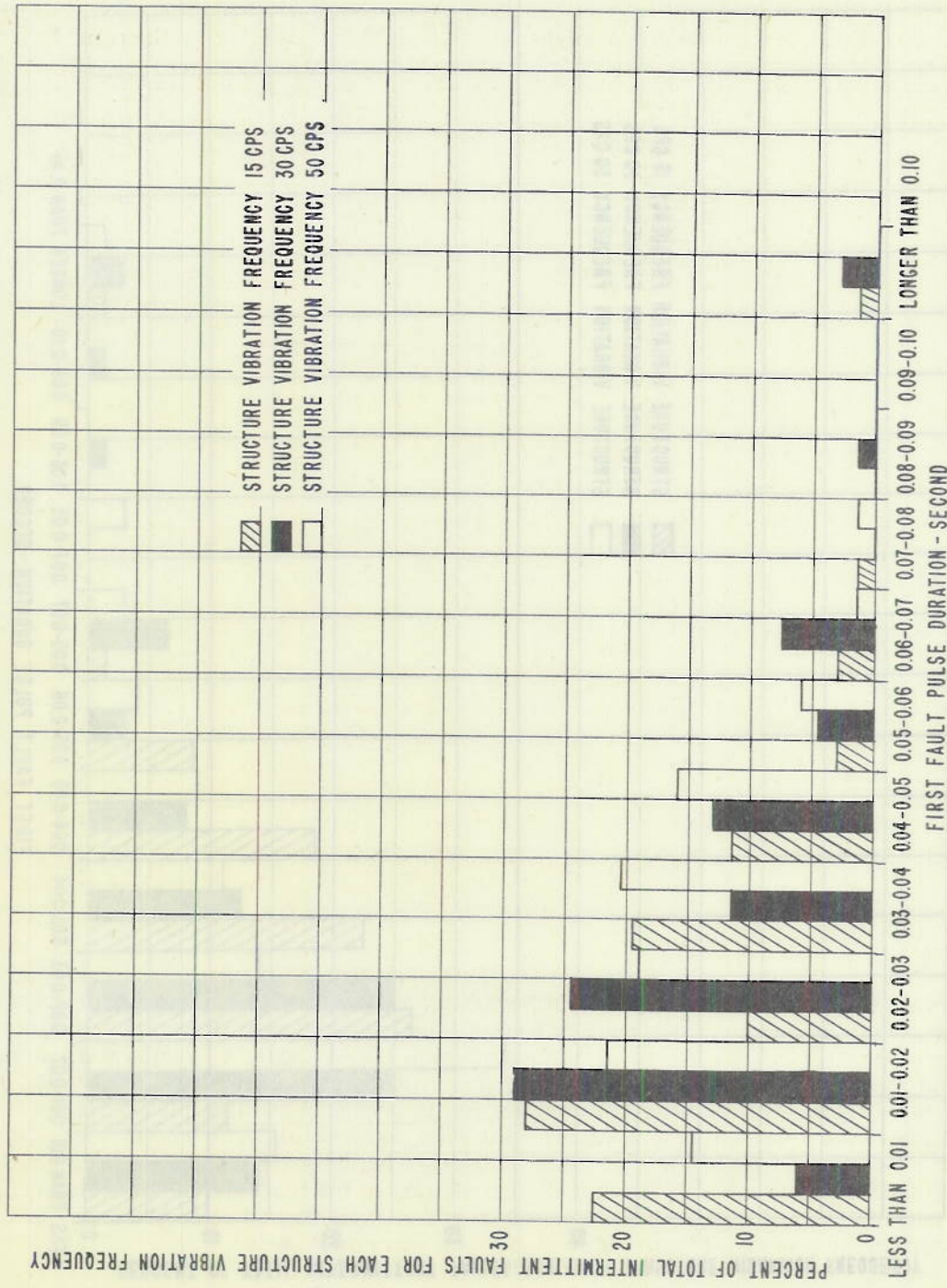


Figure 20 - Duration of the first fault pulse of 209 faults established between AN conductor size #8 (5-foot long) and an aluminum alloy plate 0.05-inch thick

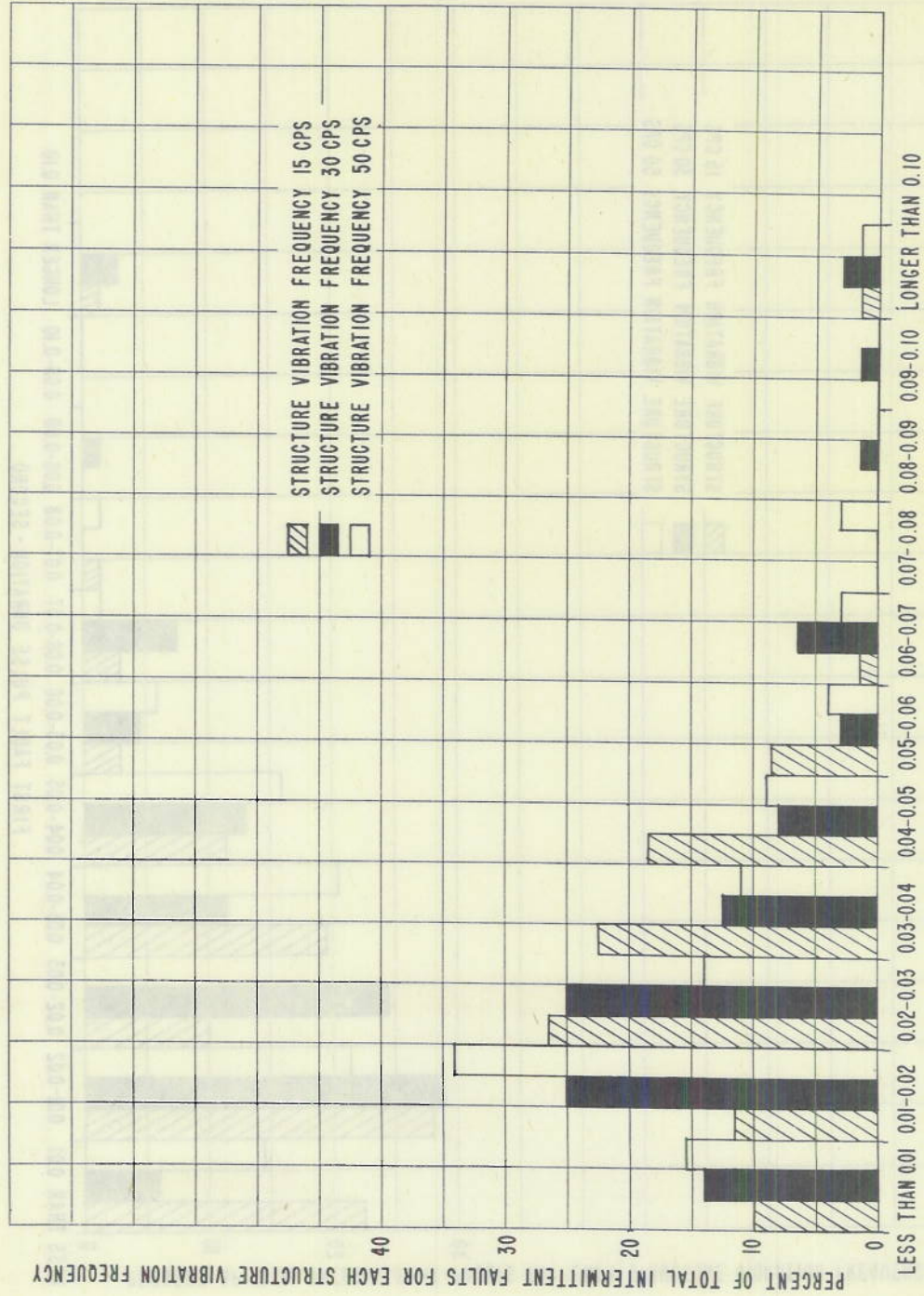


Figure 21 - Duration of the first fault pulse of 200 faults established between AN conductor size #2 (5-foot long) and an aluminum alloy plate 0.05-inch thick

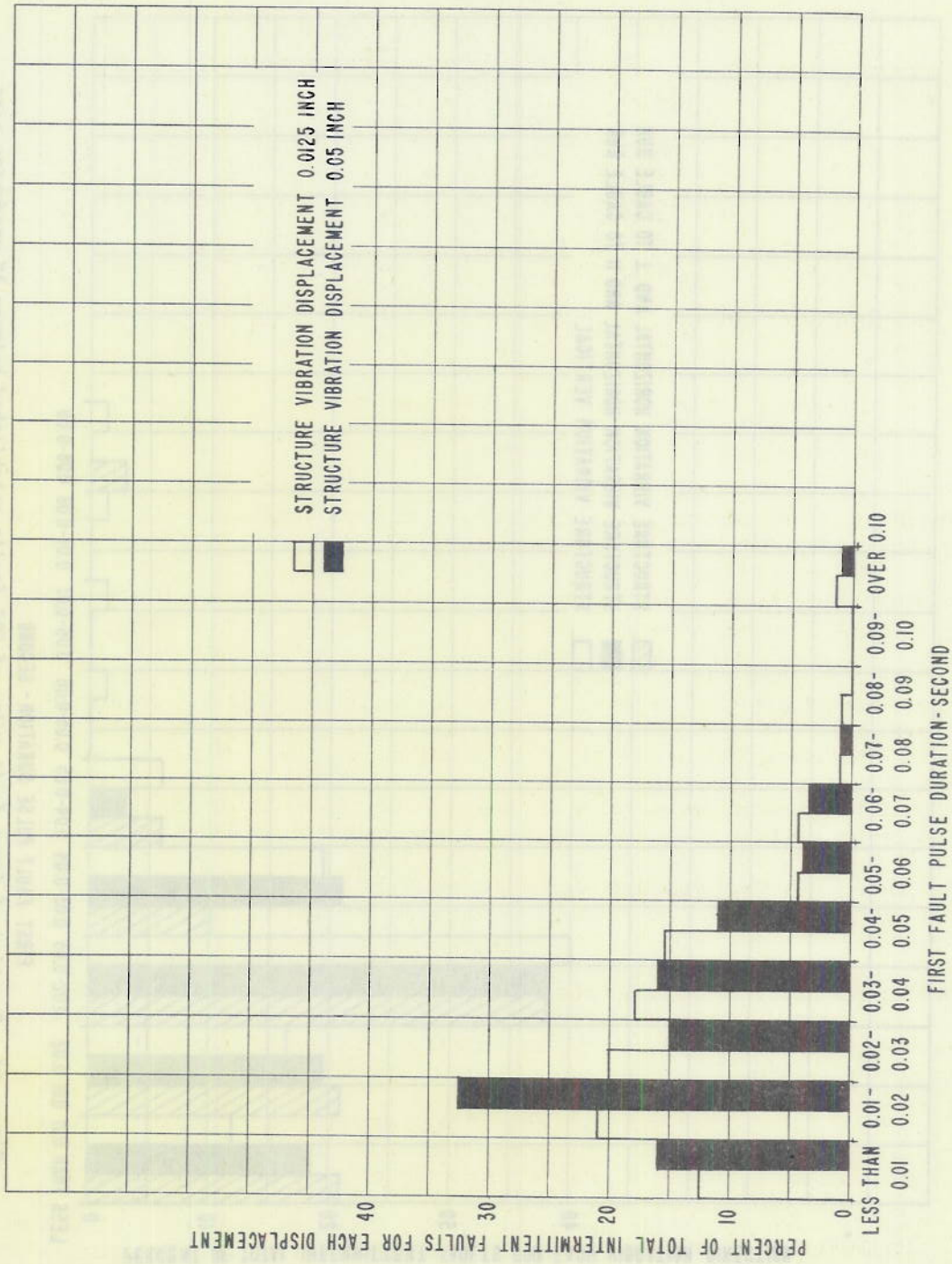


Figure 22 - Duration of the first fault pulse of 209 faults established between AN conductor size #8 (5-foot long) and an aluminum alloy plate 0.05-inch thick

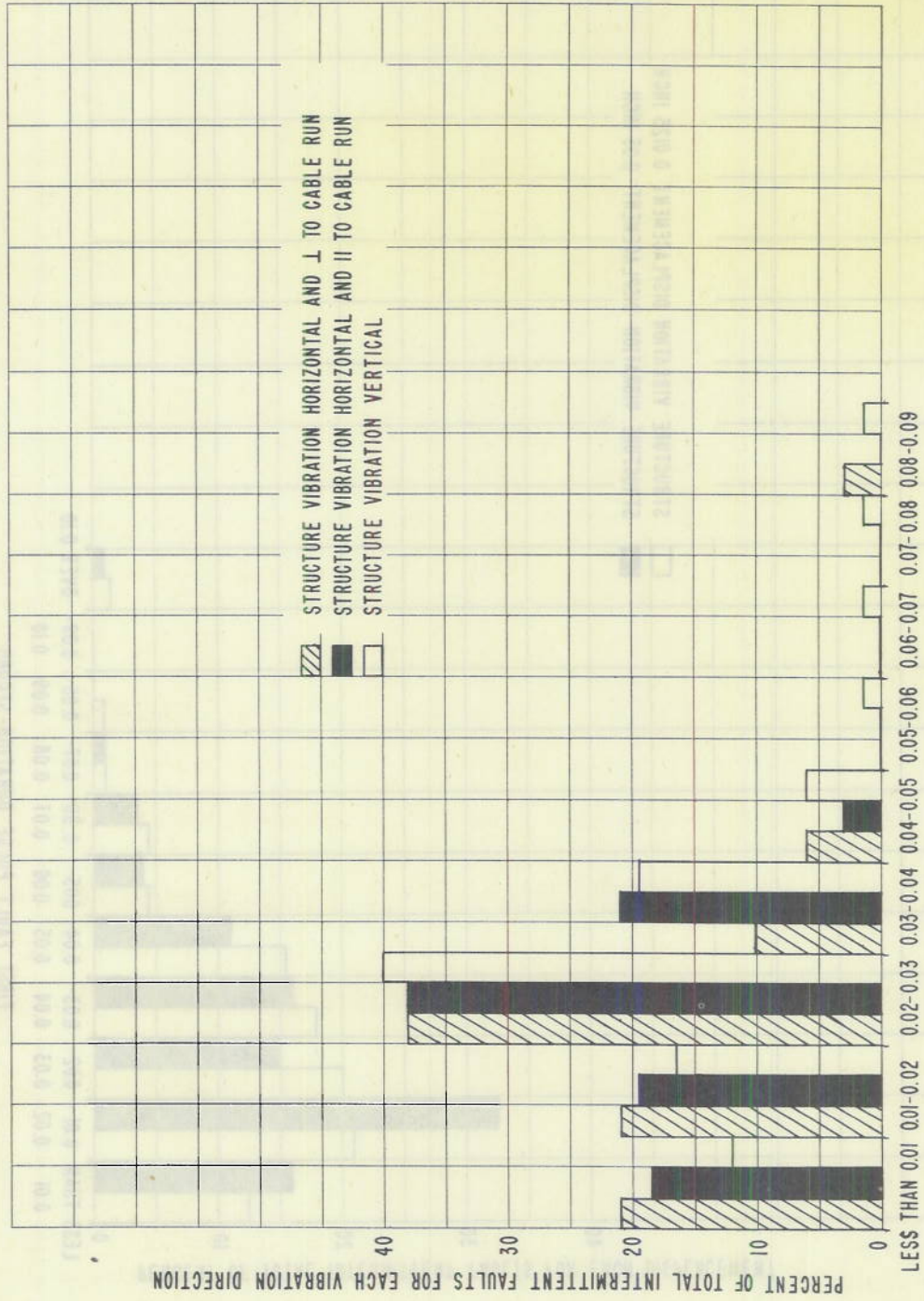


Figure 23 - Duration of first fault pulse of 204 faults established between AN conductor size #16 (5-foot long) and an aluminum alloy plate 0.05-inch thick

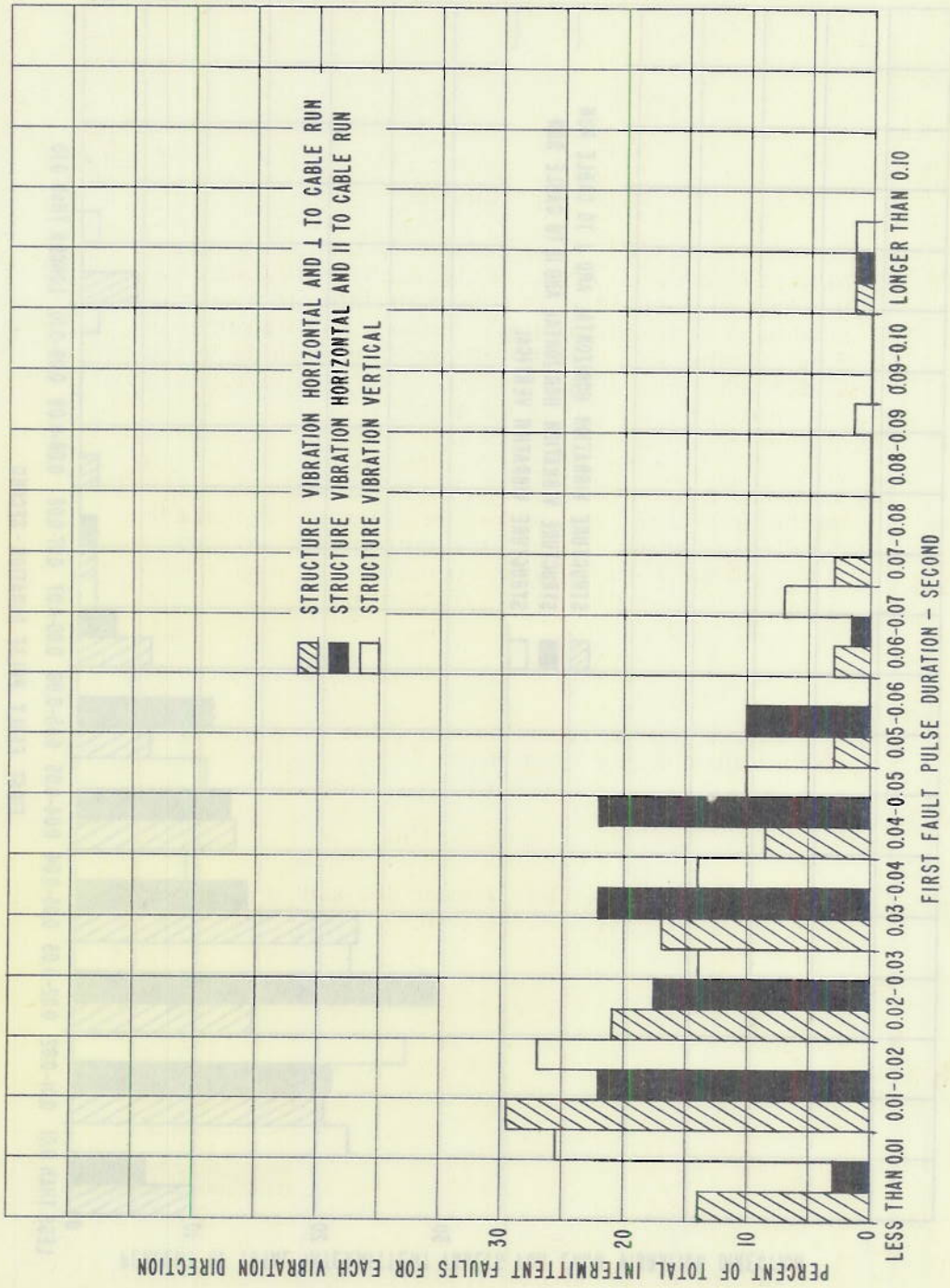


Figure 24 - Duration of the first fault pulse of 210 faults established between AN conductor size #8 (5-foot long) and an aluminum alloy plate 0.05-inch thick

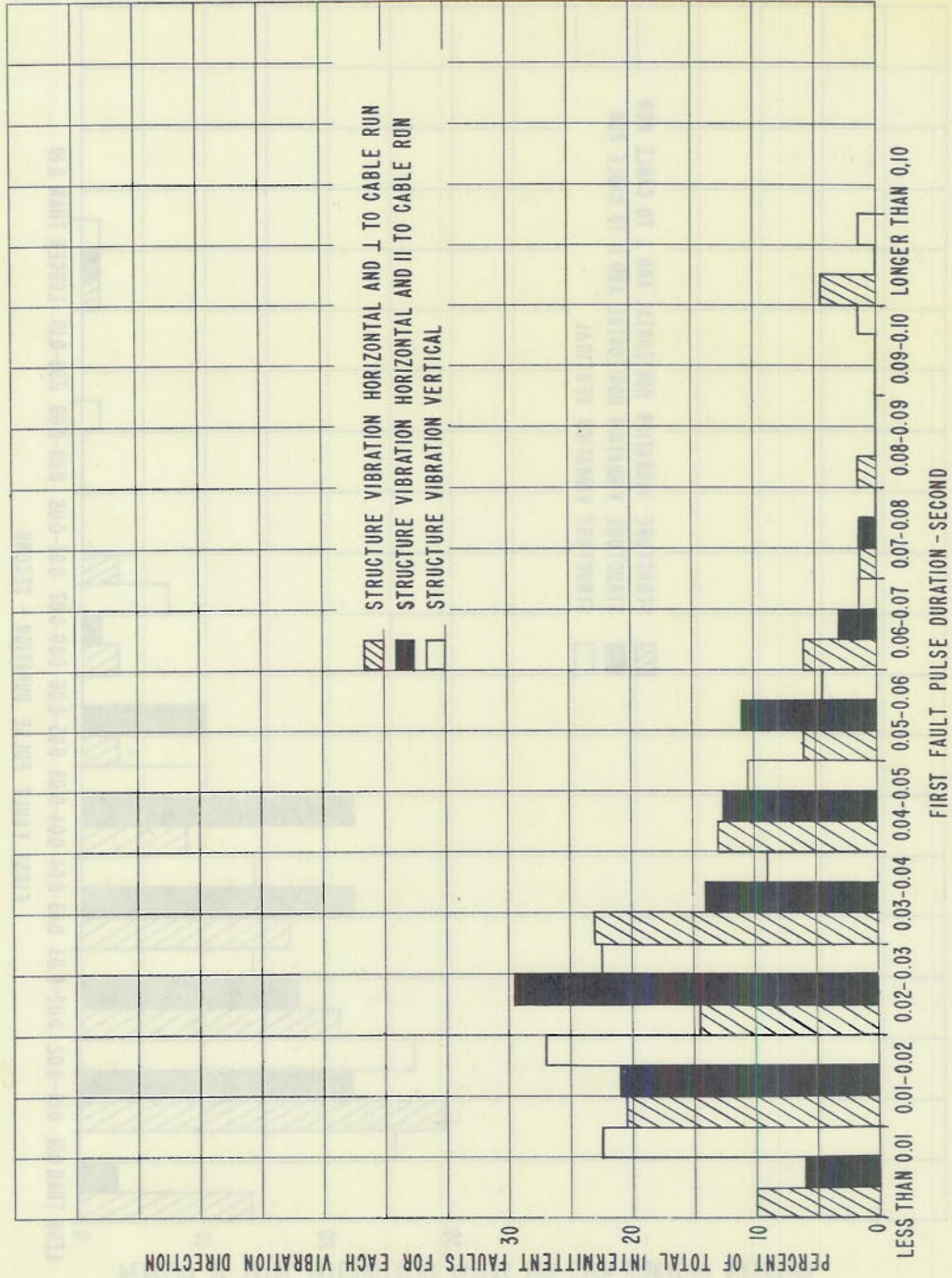


Figure 25 - Duration of the first fault pulse of 200 faults established between AN conductor size #2 (5-foot long) and an aluminum alloy plate 0.05-inch thick