A SEARCH FOR AQUIFERS OF SAND AND GRAVEL BY ELECTRICAL RESISTIVITY METHODS IN NORTH - CENTRAL NEW CASTLE COUNTY, DELAWARE

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CONTENTS

ILLUSTRATIONS

ABSTRACT

A search for aquifers in an area immediately north of the Chesapeake and Delaware Canal in New Castle County, Del., has been made by an electrical resistivity study. This search located 32 sites that may be underlain by sand and gravel. The thicker deposits are significant with respect to the occurrence of ground water, and all of them are of interest as possible sources of sand and gravel for construction purposes, such as for highway construction. The thickness of these deposits ranges from 4.4 feet to 77 feet, and the computed resistivity for them ranges from a low of 97,800 ohm-cms to a high of 423,800 ohm-cms. The study located with certainty one buried channel filled with sand and gravel deposits and pointed out the possibility of others which may be aquifers. The interpretations show that a large deposit of sand and gravel is present in the eastern part of the area investigated and it is tentatively assumed that this deposit is continuous and may yield large quantities of ground water. Places where the deposit was found to be thickest and of high resistivity are described.

INTRODUCTION

PURPOSE AND SCOPE

The electrical-resistivity measurements in the Newark area, Delaware, were undertaken as a part of the ground-water investigations of the U. S. Geological Survey in cooperation with the Delaware Geological Survey and the Delaware Highway Department. The project was conceived with two objectives in mind. The one was to differentiate the Pleistocene deposits from the older geological materials, and in this way, locate buried channels which were known to exist in the older deposits, and at the same time, determine the character of materials which might be possible aquifers. A subsidiary objective was to locate deposits which might serve as sources of materials for highway construction.

Examination of the area to be studied prior to the field work placed it in the group which, insofar as expected electrical-resistivity results were concerned, may be termed poor. Several factors entered into this evaluation. There are many extensive earthed conductors criss-crossing the area such as pipe-lines, metal fences on steel posts, power-line grounds, and so forth, which distort near-by observations. Open fields of adequate size to obtain suitable electrode spreads are few in number. The near-surface soil is a well drained sandy silt in which suitable contact for the electrodes is difficult to obtain. A brief study of the geologic map showed that each formation to be encountered in the study is widely variable in its electrical characteristics, and that a large variation in the thicknesses of the formations, or electrical layers as they are termed, is prevalent.

PERSONNEL AND ACKNOWLEDGEMENT

The field observations and preliminary interpretations of the apparent resistivity curves were done by the junior authors, who are members of the Ground Water Branch, under the direct supervision of the senior author, who is a member of the Geophysics Branch and whose services were made available to the Ground Water Branch for this study. The program was under the broad supervision of W. C. Rasmussen, District Geologist of the Ground Water Branch in Delaware. Technical review was done by Irwin Roman, Geophysicist, Geophysics Branch. The text was not reviewed for conformance with editorial standards of the U. S. Geological Survey.

The cooperation extended by J. J. Groot, State Geologist, and his staff is gratefully acknowledged.

LOCATION AND TOPOGRAPHY

The area in which the present measurements were made lies mainly to the north of the Chesapeake and Delaware Canal in New Castle County, Delaware and about 9 miles south of Newark, figure 1. The area extends from a location in Maryland near the Maryland-Delaware state line eastward to the Delaware River.

The area has little relief, the highest altitude encountered being about 80 feet and the lowest just a few feet above mean sea level. Most of the slopes are very gentle and, in this respect, it was easy to select places for locating the line of electrodes.

GEOLOGICAL SUMMARY

The geology of the deposits of the Chesapeake and Delaware canal is discussed by Clark (1895), Miller (Bascom and Miller, 1920), Carter (1937), Spangler and Petersen (1950) and Groot, Organist and Richards (1954). The bedrocks of the area are older crystalline rocks, whose upper surface dips gently to the southeast; thus they are at a depth great enough that they do not affect the resistivity measurements. The sedimentary formations which overlie these crystalline rocks range in age from Early Cretaceous to Recent. They also dip gently to the southeast, but they are not everywhere continuous beds and unconformities are present between most of the formations. Outcrops of the older formations appear at the surface near the east border of the Piedmont province, and the younger ones are found as bands of outcrops successively farther to the southeast. In general, the dips grow progressively flatter to the southeast as the younger beds appear.

The formations present in the canal area are of the Upper Cretaceous series and the Pleistocene series. The Upper Cretaceous series, in stratigraphic succession, older to younger, and in appearance along the canal, west to east, are: the Raritan formation; the Magothy formation; the Matawan group, composed of the Merchantville clay overlain by the Wenonah sand; and the Monmouth group, composed of the Mount Laurel sand, the Navesink marl, and the Red Bank formation (Groot, Organist, and Richards, 1954, p. 23). The Upper Cretaceous series strikes northeastward to Delaware Bay, and into New Jersey.

The Pleistocene series mantles the Upper Cretaceous series unevenly as surficial terrace deposits, of approximately horizontal bedding. The series consists of silts, sands and gravels of the Talbot formation, from 0 to 40 feet above sea level, and the Wicomico formation, 40 to 85 feet above sea level (Bascom and Miller, 1920).

PREVIOUS GEOPHYSICAL STUDIES

No previous geophysical studies, known to the authors, have been made in the immediate area of this investigation. Groot and Rasmussen (1954) summarize the geophysical work done in an area about 3 miles south of Newark near the Fall Line and about 6 miles north of the present study. Their survey included measurements with the magnetometer, surface electrical resistivity measurements, and electrical logging.

INSTRUMENTS AND METHODS OF THE PRESENT STUDY

The observations of surface potential were made with the Earth Resistivity Apparatus, a commercially available Gish-Rooney type instrument which has the motor-driven commutator integral with the measuring unit. The wire reels, wire, batteries, and copper-clad steel electrodes used were also commercially available equipment.

For the resistivity depth profiles, the electrodes were set according to the Lee (1929) modification of the Wenner (1917) arrangement to obtain the potential measurements. This included both the vertical electrical drilling and the horizontal constant depth profiling observations. Most of the vertical electrical drilling measurements were stopped around the 100-foot interval, though a few were extended beyond this separation distance to obtain the information about the earth materials needed for the interpretation of the apparent resistivity curves.

All observations of surface potential were converted to apparent resistivity by the Wenner formula,

$$\rho_a = 2\pi a \frac{E}{I}.$$

The three values of ρ_a were plotted on logarithmic paper as the computations were completed, enabling the operators to recheck any observations that did not locate properly on the chart. This gives three curves of apparent resistivity which are termed the Full, P-1, and P-2 curves and are indicated by circles, triangles, and crosses respectively on the curves given in the Appendix.

The preliminary interpretations of the apparent resistivity curves were completed during the course of the operations and were accomplished by a combination of comparison with theoretical curves and experience gained in evaluating field measurements of resistivity. The final interpretations were made using a group of methods which have been published and are derived from electrical theory. These include the works of: Hummel (1931); Roman (1934); Watson (1934); Watson and Johnson (1938); and Wetzel and McMurry (1937). In one or two apparent resistivity curves, the above quantitative methods could not be applied, or only partially so, and the interpretations were made by a qualitative method based entirely on experience and judgment.

Interpretations of apparent resistivity curves made by an experienced operator may be expected to have an error of less than 10 percent. The error for shallow depth measurements has, in general, been found to be much less. It should be mentioned, though, that close correlation between resistivity interpretations and drilling information cannot be expected at every location, because electrical layers and geological formation boundaries seldom coincide exactly. Furthermore, the drill hole gives definitive information at a spot location; the electrical depth profile gives average information over the area traversed.

In order to obtain a background of the electrical character of the geological materials of the area to assist in evaluating the apparent resistivity curves "formation tests", (abbreviated FmT in figure 1.) were obtained on the geological materials. These are very short vertical electrical profiles obtained on an outcrop of the earth material from which the electrical resistivity may be computed. Formation tests were made on Pleistocene fill in the channel visible in the bank of the Chesapeake and Delaware Canal, on the Raritan formation, the Matawan group, the Patapsco formation, and the Wicomico formation.

RESULTS OF THE INVESTIGATION

GEOLOGICAL MATERIALS

The interpretations of the apparent resistivity curves are grouped as cross sections 1, 2, and 3 and are shown on figures 2, 3, and 4. Each resistivity depth profile is represented as a vertical column which is placed on the figure with respect to both altitude above mean sea level and separation distance of the depth profile centers. The geological materials at each depth profile are represented by appropriate symbols and the computed resistivity in kilohm-cms for each material adjoins the column. In general, the higher the resistivity the more gravel one may expect in a deposit of sand and gravel.

Cross section 1, Figure 2.

Two possibilities for coarse materials were noted on this profile. The better one is at resistivity depth profile A-32 with 4 feet of silt, clay, and gravel at the surface over a bed of sand, gravel, and silt having a resistivity of 117,100 ohm-cms and a thickness of 14 feet. The horizontal extent of the bed was not determined. The other possibility is at A-30 where 4.5 feet of sandy silt overlies a bed of sand, gravel, and silt that has a resistivity of 103,700 ohm-cms and a thickness of 17½ feet. The horizontal extent of the bed was not determined.

Cross section 2, Figure 3.

A number of possibilities are present along this profile for coarse materials and they are described in order from west to east.

A-2A. Gravel and sand are present from 3.6 feet to 25 feet and has a resistivity of 149,600 ohm-cms. The surface cover material is composed of silty soil, clay, some sand and gravel.

A-2. Gravel and sand that are probably free of silt or clay are indicated between 3.8 feet and 25 feet. They have a resistivity of 214,800 ohm-cms. The cover material is loam, sand, silt, and some gravel.

A-5. Gravel and sand are found here between 4.8 feet and 27 feet that have a resistivity of 159,500 ohm-cms and are considered to contain very little silt or clay. The surface materials above them are silt and clay.

A-6. The sand and gravel deposit here contains some silt which is indicated by the 119,000 ohm-cms resistivity, and it occurs between depths of 3.2 feet and 28 feet. The overlying material is silt and sand. There is a possibility that the bed of sand and gravel may be continuous eastward to A-7.

A-7. There are two beds of sand and gravel at this location, and one may be the continuation of the bed indicated in the previous profile. The upper bed is between 2.4 feet and 6 feet, and the lower between 16 feet and 45 feet. The surface material is sand, silt, and clay, and the material separating the two sand and gravel beds is silt with some sand and gravel content. The resistivities of the sand and gravel layers respectively downward are 118,600 and 135,600 ohm-cms.

A-9. A thin bed of sand and gravel is indicated between 4.5 feet and 9 feet which has a resistivity of 246,000 ohm-cms and is considered to be free of clay or silt.

A-10. Sand and gravel with some silt content are indicated here between 6.9 feet and 10.5 feet. The cover material is silt, sand and some gravel.

A-12. The sand and gravel bed is 3 feet thick, 6.5 to 9.5 feet, and has a resistivity of 105,600 ohm-cms indicating some silt content. The surface beds are composed of silt, sand, and some gravel.

A-14. A thicker bed of sand and gravel nearer the surface is noted here, 3.2 feet to 12.8 feet, and it has a resistivity of 132,000 ohm-cms. The silt content is considered low. The surface bed is composed of silt and gravel.

A-15. At this location the sand and gravel layer contains very little silt as indicated by the high resistivity, 193,900 ohm-cms. The bed extends from 3.8 feet to 11 feet. The surface cover is loam, sand, silt, clay, and some gravel.

A-18. A silt and sand surface layer extends to 3.5 feet in depth and a nearly silt-free bed of sand and gravel extends to 14.5 feet. It has a resistivity of 193,100 ohm-cms.

A-19. At this location, the sand and gravel bed is one of the group having the thickest deposit; it extends in depth from 3.6 feet to 46 feet. The resistivity of 177,600 ohm-cms indicates that it contains very little silt or clay. The covering layer is silt, sand, and clay.

A-20. Very little silt or clay is present in the sand and gravel bed at this location; the resistivity is 253,600 ohm-cms. The cover layer composed of clay, silt, and sand is 6.1 feet thick; the sand and gravel extend to 25 feet. The sand and gravel bed may be a continuation of the deposits noted in A-18 and A-19, and may also extend on eastward to A-21 or a short distance beyond.

A-21. The sand and gravel bed extends from 10.5 feet to 37 feet in depth. The resistivity is high, 237,300 ohm-cms, indicating a deposit nearly free of silt or clay. The covering bed is sand and clay.

A-22. Here the layer of sand and gravel extends from 3.6 feet to 57 feet and has a resistivity of 140,100 ohmecms which value indicates some silt or clay content. This is another in the group of thick deposits of sand and gravel.

A-23. The sand and gravel layer begins at 4.3 feet and continues to 34 feet. The material has a resistivity of 142,500 ohm-cms thus indicating a small content of silt or clay. Sand and silt constitutes the cover layer.

A-24. The sand and gravel deposit at this location has the highest resistivity of all the locations observed, 289,800 ohm-cms. This very high value indicates the deposit to be clean. The deposit occurs between 6.2 feet and 41 feet in depth. The overlying layer is composed of sand and silt.

A-25. The thickest sand and gravel deposit, 77 feet thick, was encountered at this location. The resistivity, 177,700 ohm-cms indicates a low silt content. The surface cover is composed of silt, sand, clay, and some gravel and is 7 feet thick.

A-26. This location has a bed of sand and gravel which extends in depth from 7 feet to 62 feet, and second thickest deposit found. It has a resistivity of 149,500 ohm-cms, indicating a small content of silt or clay. The surface material is sand, silt, and clay.

Resistivity depth profile A-26 marks the eastern-most extent of what appears to be a continuous bed of sand and gravel. It begins at A-18 and continues to, and perhaps a short distance beyond, A-26, a distance of about 2.2 miles. The thickness of the bed and its resistivity, which is directly related to the content of silt or clay, are variable; the thickness ranges from 11 feet to 77 feet, and the resistivity from 140,000 to 289,800 ohm-cms.

<u>Cross section 3, figure 4</u>.

The sand and gravel deposits on this cross section are described in order from west to east.

B-1. Sand and silt are present between the depths 5 and 17 feet and have a resistivity of 97,800 ohm-cms. The cover material is silt, clay and sand.

B-2. The cover material here is thin, 2.4 feet, and is composed of silt and sand. The sand and gravel which extend beneath this layer to a depth of 18 feet contain very little silt; the resistivity is 164,900 ohm-cms.

B-3. At this location the sand and gravel layer is between 4.2 feet and 34 feet in depth and contains very little silt; the resistivity is 169,300 ohm-cms. The cover material is silt and sand.

B-5. The surface material here is silt, clay, and sand 3.2 feet thick. The sand and gravel layer with a resistivity of 236,000 ohm-cms extends to a depth of 16 feet and is considered to be free of silt or clay.

B-4. Curve distorted, no quantitative interpretation.

B-6. The sand and gravel layer extends from 5.8 feet to 30 feet in depth and has a resistivity of 123,400 ohm-cms. The surface materials are silt, sand, and clay.

B-7. The thick bed of sand and gravel, overlain by 4.8 feet of sand, silt and clay, extends to a depth of 65 feet; the resistivity is 180,400 ohm-cms.

B-8. A qualitative interpretation is necessary from this curve but sand and gravel with some silt or clay are indicated between 9 and 41 feet in depth.

B-9. A thin bed of gravel and sand with a very high resistivity, 428,800 ohm-cms; appears between 4.6 and 9 feet in depth. The cover material is silt and sand.

B-10. The cover material here is thick extending to 9 feet in depth. The sand and gravel extend below this to a depth of 18 feet and have a resistivity of 171,300 ohm-cms.

B-11. The sand and gravel layer which begins at 3.3 feet and continues in depth to 57 feet, has a resistivity of 146,600 ohm-cms. The near-surface materials are silt, sand, and clay.

Between B-11 and B-12, the sand and gravel layer increases in silt and clay content as shown by the resistivity 46,800 ohm-cms at the latter site, which marks the eastern limit of the layer. The thickness of the bed and its resistivity, as in cross section 2, ranges in thickness from 4.4 feet to 60.2 feet, and in resistivity from 97,800 to 423,800 ohm-cms. The very high resistivities indicate the presence of clean sand or gravel.

GROUND-WATER RESERVOIRS

Observations along the banks of the Chesapeake and Delaware Canal indicate that stream channels had been cut in the Cretaceous sediments and later filled with Pleistocene deposits. One of the objectives of the geophysical study was to locate and map these filled channels and to obtain the thickness of character of the fill. Correlation of the resistivity interpretations with the geological materials of the area was provided by a formation test, and by means of shallow auger holes.

Formation test 1 was made on the south bank of the Chesapeake and Delaware Canal (see figure 1) to determine the resistivities of the Pleistocene materials in the old filled channel visible in the bank. Resistivity of the surface material was computed to be 57,000 ohm-cms and thickness 1.1 feet; the next lower layer, 19,000 ohm-cms, thickness 4 feet; and the material beneath this, at depths from 5.1 to 25 feet, 548,500 ohm-cms. Two auger hole logs, 12 and 13, were bored on the north side of the canal relatively near this formation test. Neither of these holes entered the channel-filling material.

With this information on the resistivities of the Pleistocene materials, correlation was made with the interpretations of the resistivity depth profiles. On cross section 1, figure 2, resistivity depth profiles A-29, A-30, and A-32 show that high resistivity material is present, and in A-32 extends to a depth of 9 feet above mean sea level or 58 feet below the land surface. Because of interference from artificial sources, including power lines and material dumped over the area from channel dredging operations, more depth profiles along this cross section could not be obtained to locate the deepest part of the channel. On cross section 2, high resistivity material is present at A-2A and A-2. The map, figure 1, shows these locations about 1 3/8 miles northerly from the filled channel which crops out in the bank of the canal. The interpretations indicate that the deepest part of the channel is near these depth profiles.

A horizontal depth profile was obtained near A-2 with three depths and in some places four depths. The results are plotted on figure 5 with apparent resistivity as the ordinate and station separation the abscissa. The figure shows that material with high resistivity is located about 500 feet east of A-2. It is considered that this may be the northward continuation of the channel found in the canal.

Another channel, or perhaps a branch of the one described above, may extend northward through or near A-32 and A-5; these depth profiles both have high resistivity material present to considerable depth. A-33, (figures 1 and 4), north of this area showing possible channels, did not show the presence of any high resistivity material. No other definite indications of a channel were found in the resistivity measurements, but the high resistivity material present to a depth of 25 feet below mean sea level at A-25 should be investigated further either by resistivity measurements or by drilling; the same is true at B-7 where the high resistivity material extends to 5 feet below mean sea level.

In the previous section describing the geological formations considered suitable for highway materials, it was tentatively pointed out that a continuous bed of sand and gravel extends a distance of about 2.2 miles between A-18 and A-26 on cross section 2, and for a distance of 3.1 miles between B-1 and B-11 on cross section 3. If this bed of sand and gravel is continuous between the two cross sections, this area may be a good aquifer. The most likely places for wells would be at A-25, B-7 and B-11.

CORRELATION OF INTERPRETATIONS AND DRILLING

Prior to the electrical resistivity survey in this area, considerable boring was done to relatively shallow depths with a power auger, and samples were collected and studied. Approximately coincident to the electrical resistivity survey, the Tide Water Associated Oil Co. was prospecting for a large ground-water supply on optioned land in the vicinity of Delaware City. One resistivity depth profile, A-19, was suitably located for comparison with auger hole 21, and with Tide Water deep test hole 8 (SW corner of the Leski farm). The sites are shown on the map, figure 1, along Stewart's Road (State 356), about 0.3 mile west of the junction with McCoy Road (State 407).

The comparison is illustrated in figure 6. The resistivity depth profile agrees fairly well with the deep test hole, and not so well with the shallow borehole. However, the variations are consistent with the range in lithology, both laterally and vertically, within short distances, which characterize the geologic formations involved.

The upper member, composed of sand and gravel, with small quantities of silt, is correlated as the Pleistocene series. This series occupies channels in the eroded surface of the Cretaceous system. Such a channel occurs in the vicinity of A-19, so the increase in thickness of 25 to 30 feet from auger hole 21 to test hole 8, and to the resistivity depth profile A-19, is a normal occurrence.

The lower member, logged as clay and silty fine sand in test hole 8, and as clay in A-19, is correlated as formations of the Cretaceous system, which are lenticular and grade within short distances from clays to silts to pebbly fine sands.

Formation tests were obtained on identified formations to assist in the evaluation of the interpretations. The one at the gravel pit north of Glasgow, FmT 2, gave a value 103,000 ohm-cms for the near surface material, 308,000 ohm-cms for the deeper gravel, and 9,930 ohm cms for the clay, sand, and gravel below it. The gravel had been identified by the State geologist as a member of the Raritan formation and the clay as possibly a lower member of the same formation. FmT 3 was on the Matawan group south of the canal near the Maryland-Delaware state line. The value obtained was 11,400 ohm-cms, with an unidentified clay below which had a resistivity of only 2,850 ohm-cms. FmT 4 was obtained near B-12 on continuous clay of the Patapsco formation which had a resistivity of 4,380 ohm-cms.

It has not been possible from the limited study of the area to identify with certainty any of these formations on the apparent resistivity curves. In fact, it may never be possible to do so because of the large variations in resistivity found in the geological materials of the area.

COMPARISON OF PRESENT RESULTS WITH PREVIOUS MEASUREMENTS

Resistivity measurements had been made previously in an area about 6 miles north of the area presently under study and were reported by Groot and Rasmussen (1954, p. 31-33). A formation test and resistivity depth profile was completed very close to the center of depth profile 53, given in their report. The resistivity of the Wicomico formation was found to be 45,200 ohm-cms at this location as part of the FmT 5 in the present measurements. As a further comparison and as a possible means for relating the two studies, the results for depth profile 53 were replotted, using the method employed in the present investigation, and compared with FmT 5. This comparison is shown in figure 7. It is evident from the figure that the earlier study cannot be directly related to the results presented in FmT 5 even though there is a parallel trend; the previous measurements are much lower in value and more erratic, being particularly so beyond the 70-foot depth interval.

SUGGESTIONS FOR FUTURE WORK

Plans for resistivity work should be made far in advance of field work. The general area should be selected by the cooperating agencies sponsoring the study.

SUMMARY

In relation to ground-water problems, the interpretations of the resistivity observations have shown that sands and gravels can be located and evaluated in terms of their possibilities as an aquifer. The interpretations have also shown that it is possible to intersect the buried channels of the area when they are filled with sand and gravel, but much additional work will be necessary if the channels are to be completely outlined and their values as aquifers determined.

The interpretations have shown that it is possible to locate materials suitable for use in highway construction and to evaluate them in terms of their sand and gravel content as well as to depth beneath the surface and thickness of the deposit. No effort was made to determine the areal extent of any deposit during the limited time available in the preliminary investigation, but this can be done with adequate means.

Although the electrical resistivity measurements can determine clean sand and gravel, and differentiate these deposits from silty and clayey members on the basis of very high resistivity, it should be emphasized that there is no conclusive indication of gravel content. That is to say, a clean medium to coarse-grained sand, with no gravel at all, will give a very high resistivity. The method does not reveal the gravel content in any proportion. This is borne out by the comparison, figure 6, which shows sand and gravel in the resistivity depth profile A-19, correlated with clean sand in Tide Water test hole 8.

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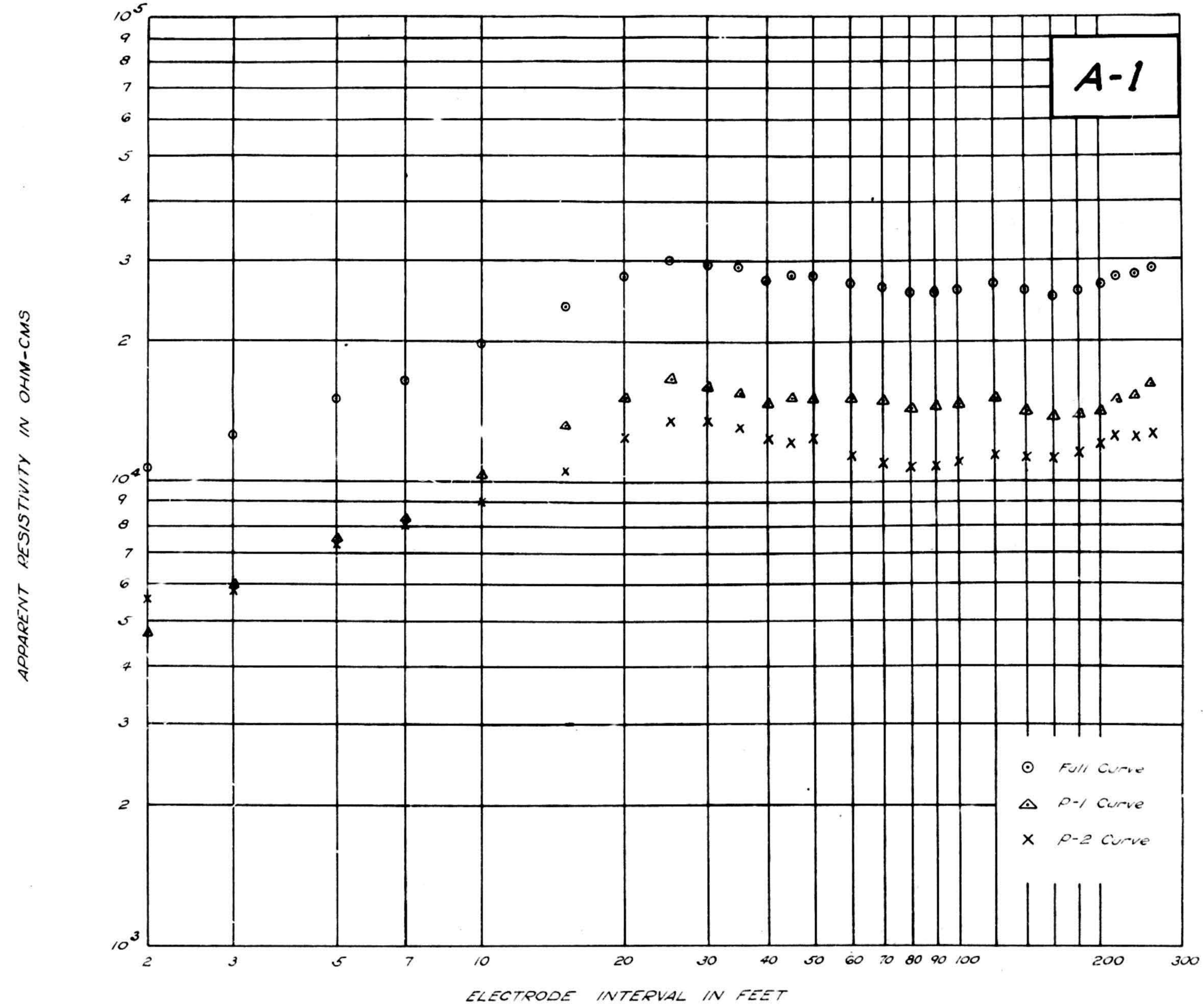
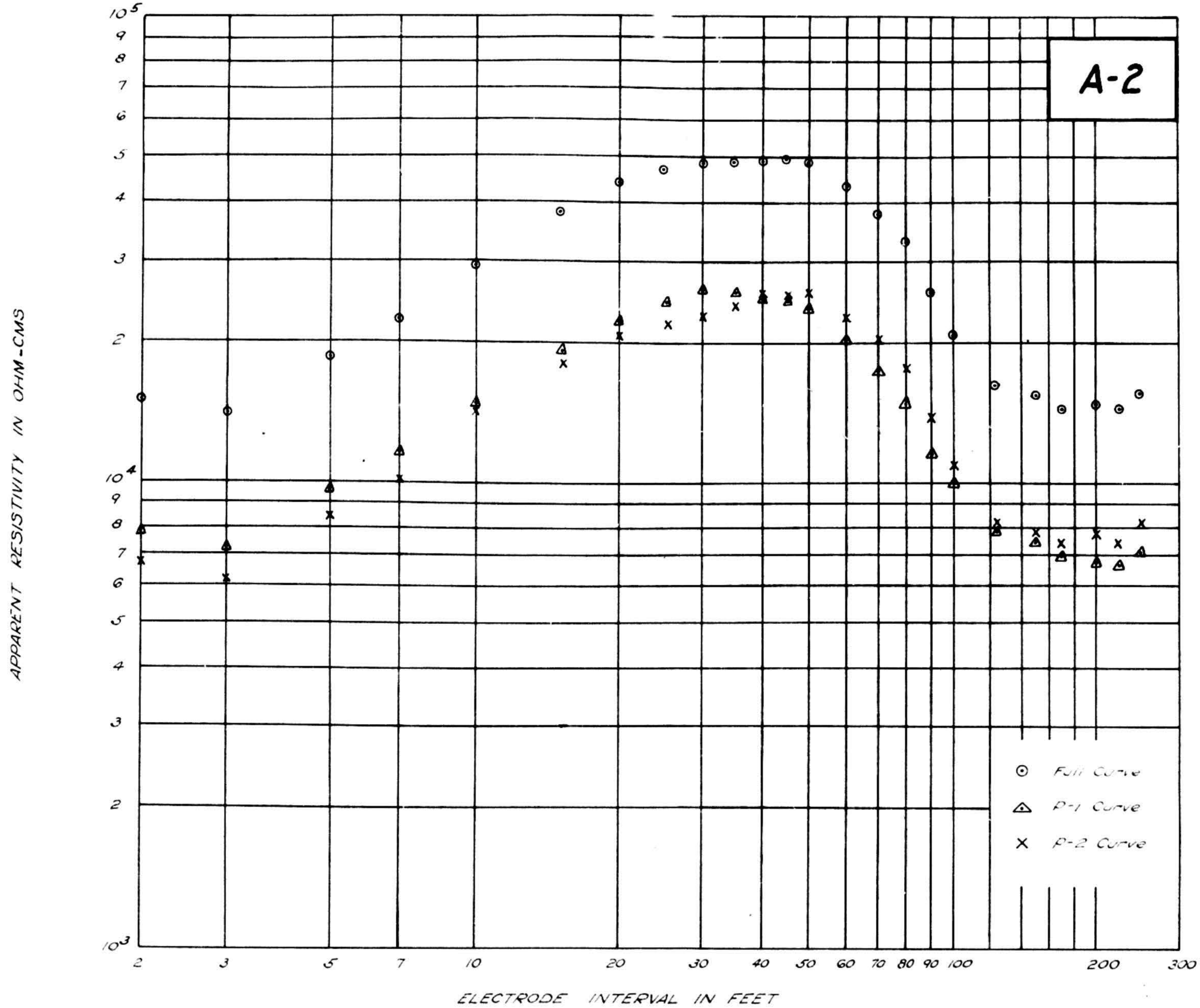
APPENDIX

APPENDIX-Continued



A-1
APPARENT RESISTIVITY IN OHM-CMS
ELECTRODE INTERVAL IN FEET
Full Curve
P-1 Curve
P-2 Curve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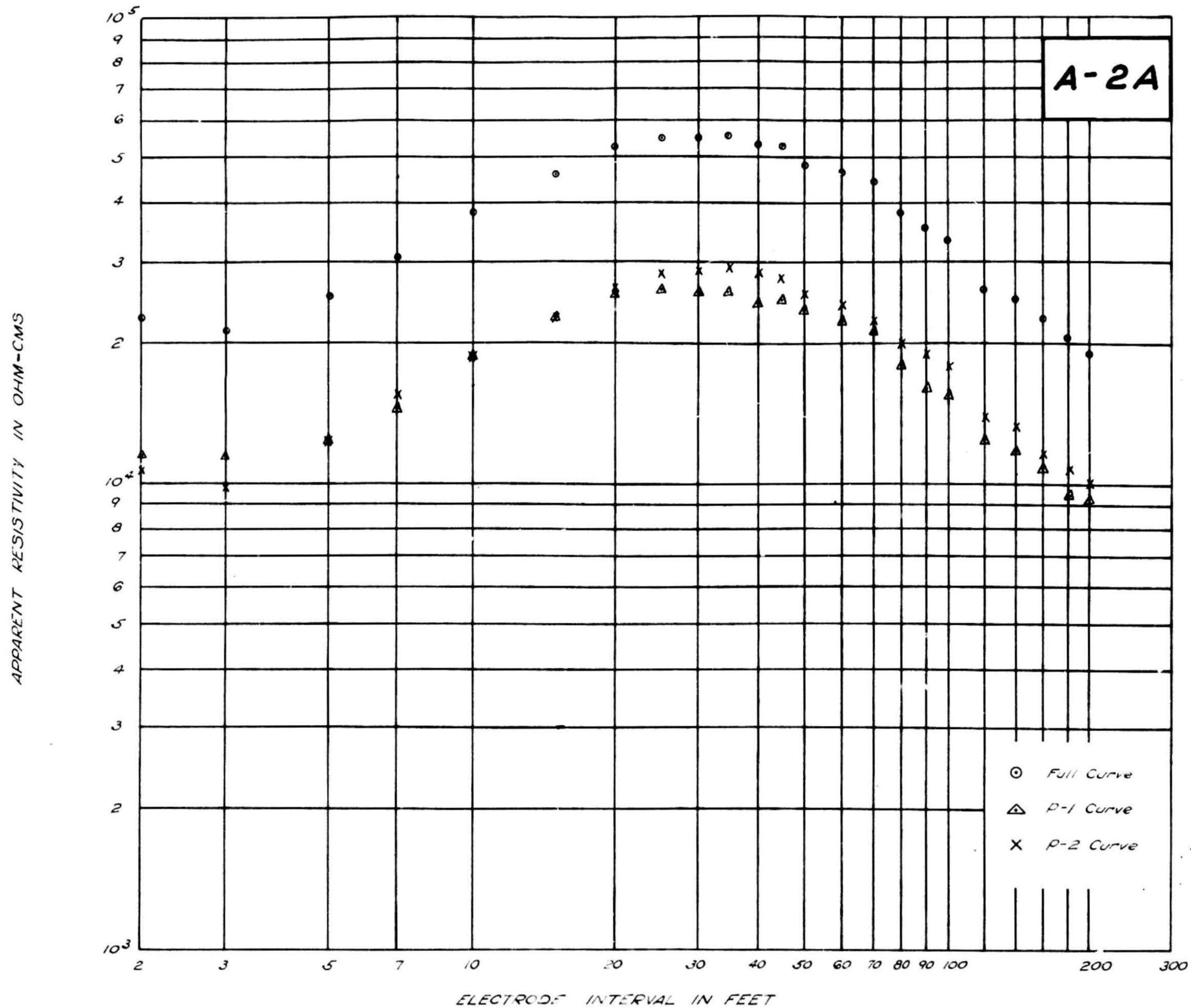
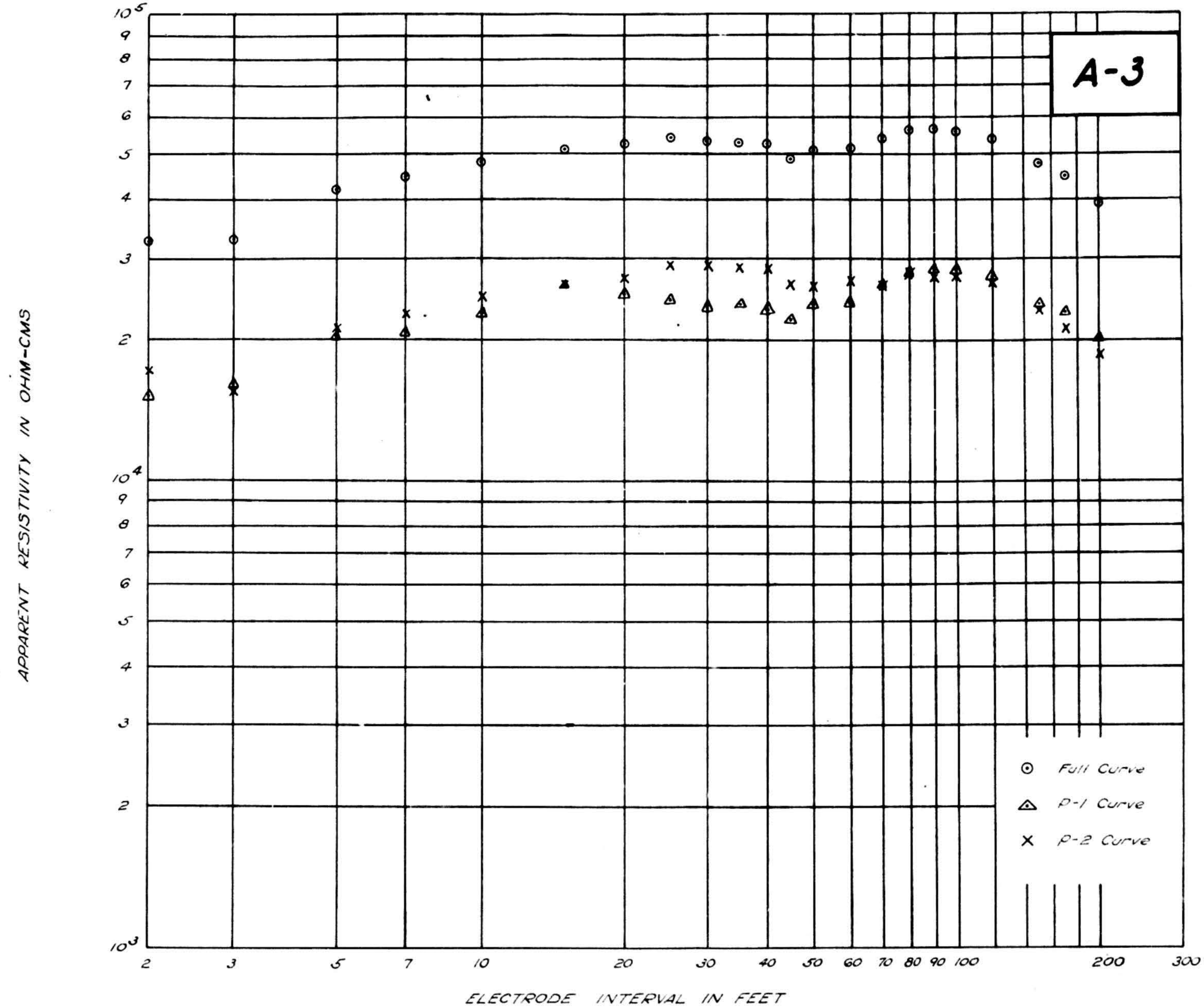
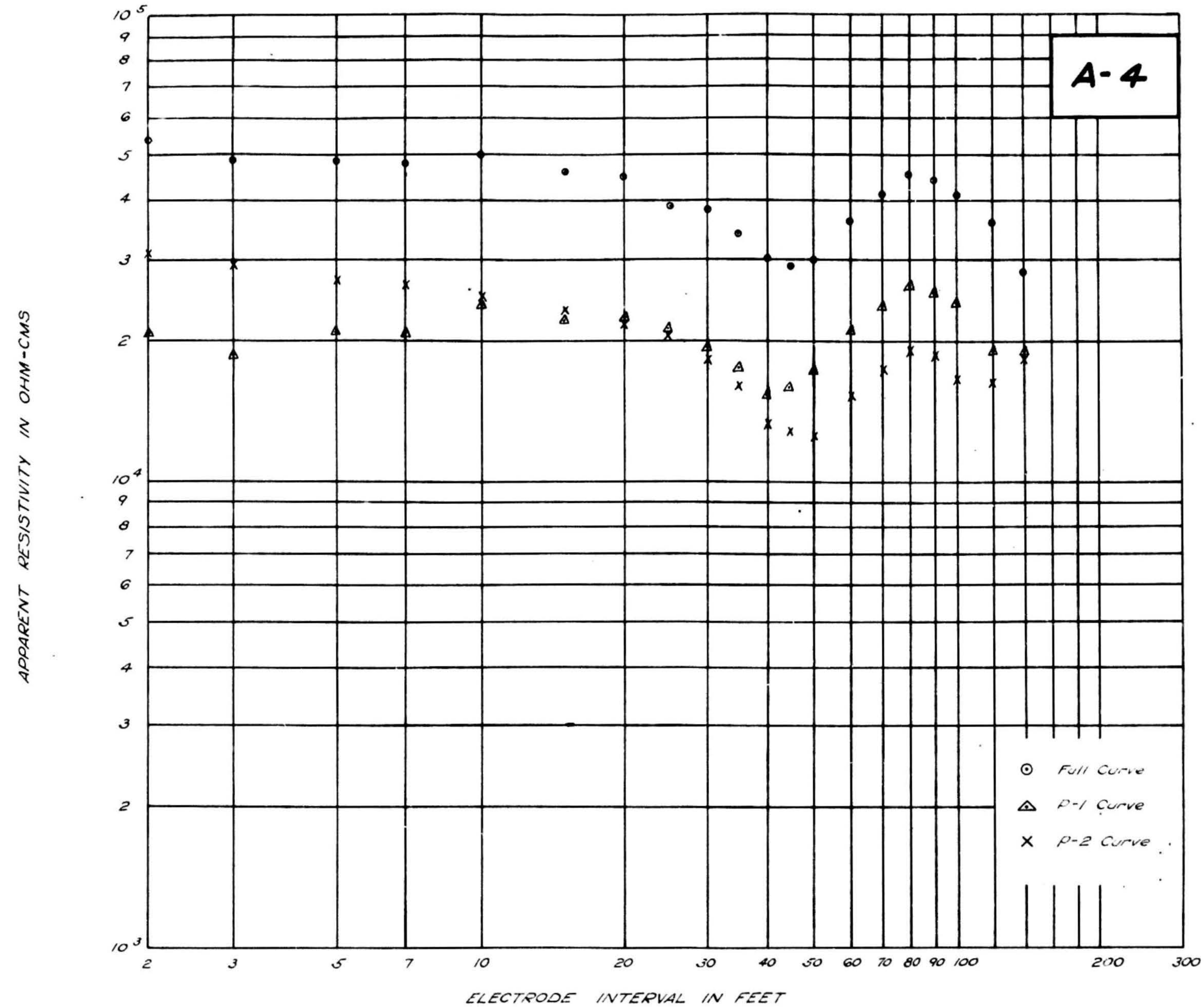
APPARENT RESISTIVITY IN OHM-CMS
ELECTRODE INTERVAL IN FEET
Full Curve
P-1 Curve
P-2 Curve

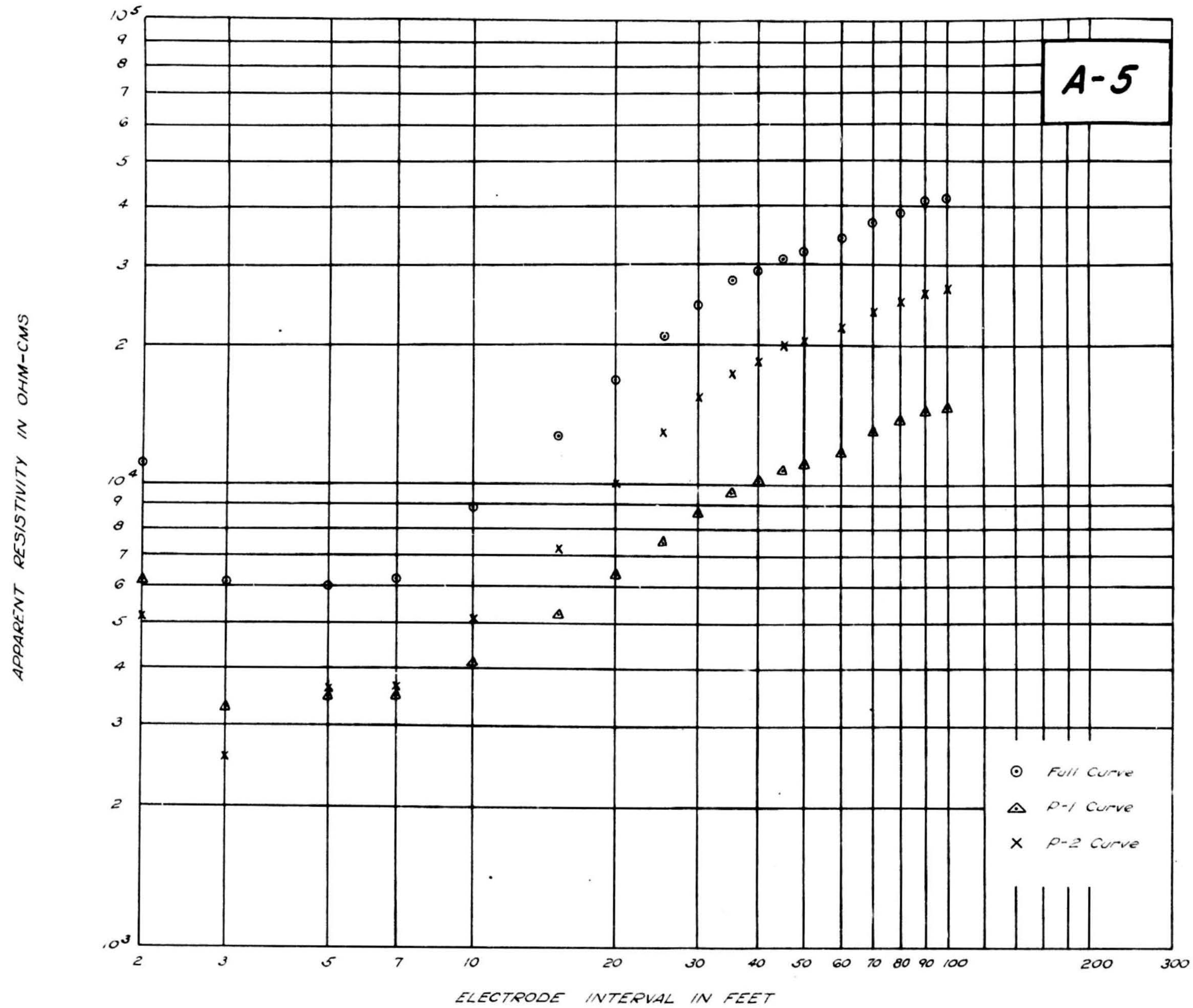


A-2A
APPARENT RESISTIVITY IN OHM-CMS
ELECTRODE INTERVAL IN FEET
Full Curve
P-1 Curve
P-2 Curve



A-3
APPARENT RESISTIVITY IN OHM-CMS
10^5
9
8
7
6
5
4
3
2
10^4
10^3
2
3
5
7
10
20
30
40
50
60
70
80
90
100
200
300
ELECTRODE INTERVAL IN FEET
Full Curve
P-1 Curve
P-2 Curve


A-4
APPARENT RESISTIVITY IN OHM-CMS
ELECTRODE INTERVAL IN FEET
Full Curve
P-1 Curve
P-2 Curve
2
3
5
7
10
20
30
40
50
60
70
80
90
100
200
300


A-5
APPARENT RESISTIVITY IN OHM-CMS
ELECTRODE INTERVAL IN FEET
Full Curve
P-1 Curve
P-2 Curve
10^3
2
3
4
5
6
7
8
9
10^4
2
3
4
5
6
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200
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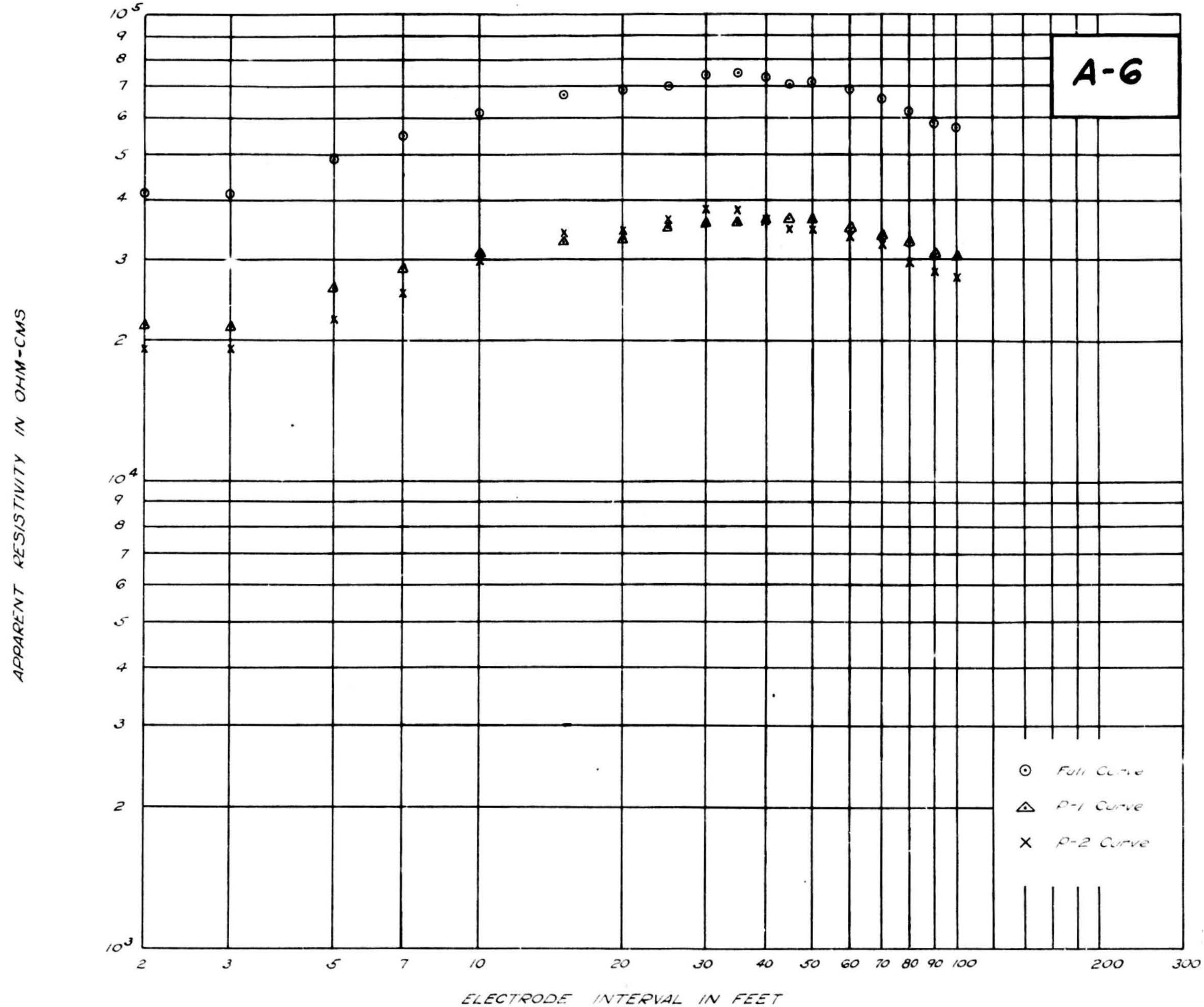
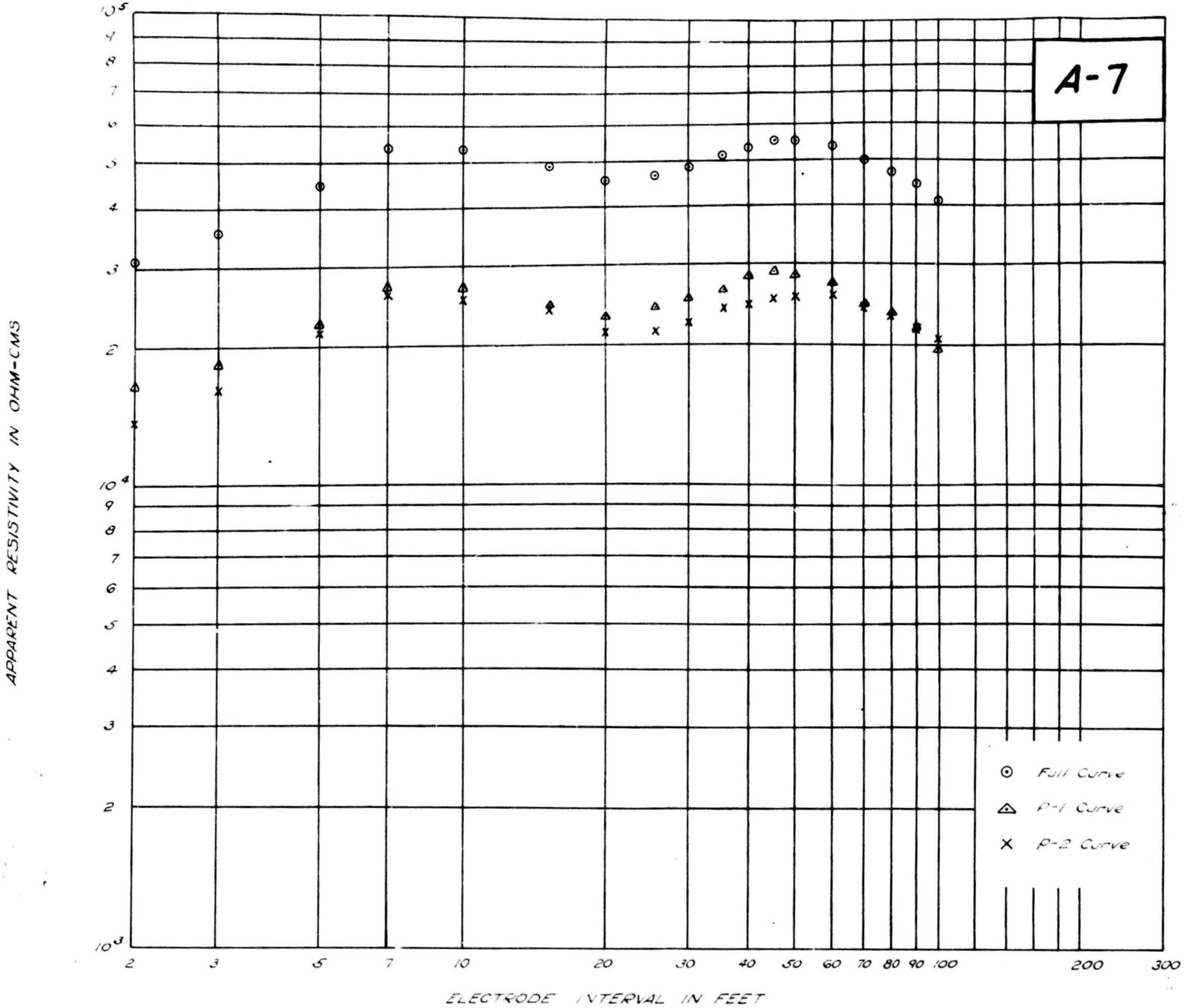
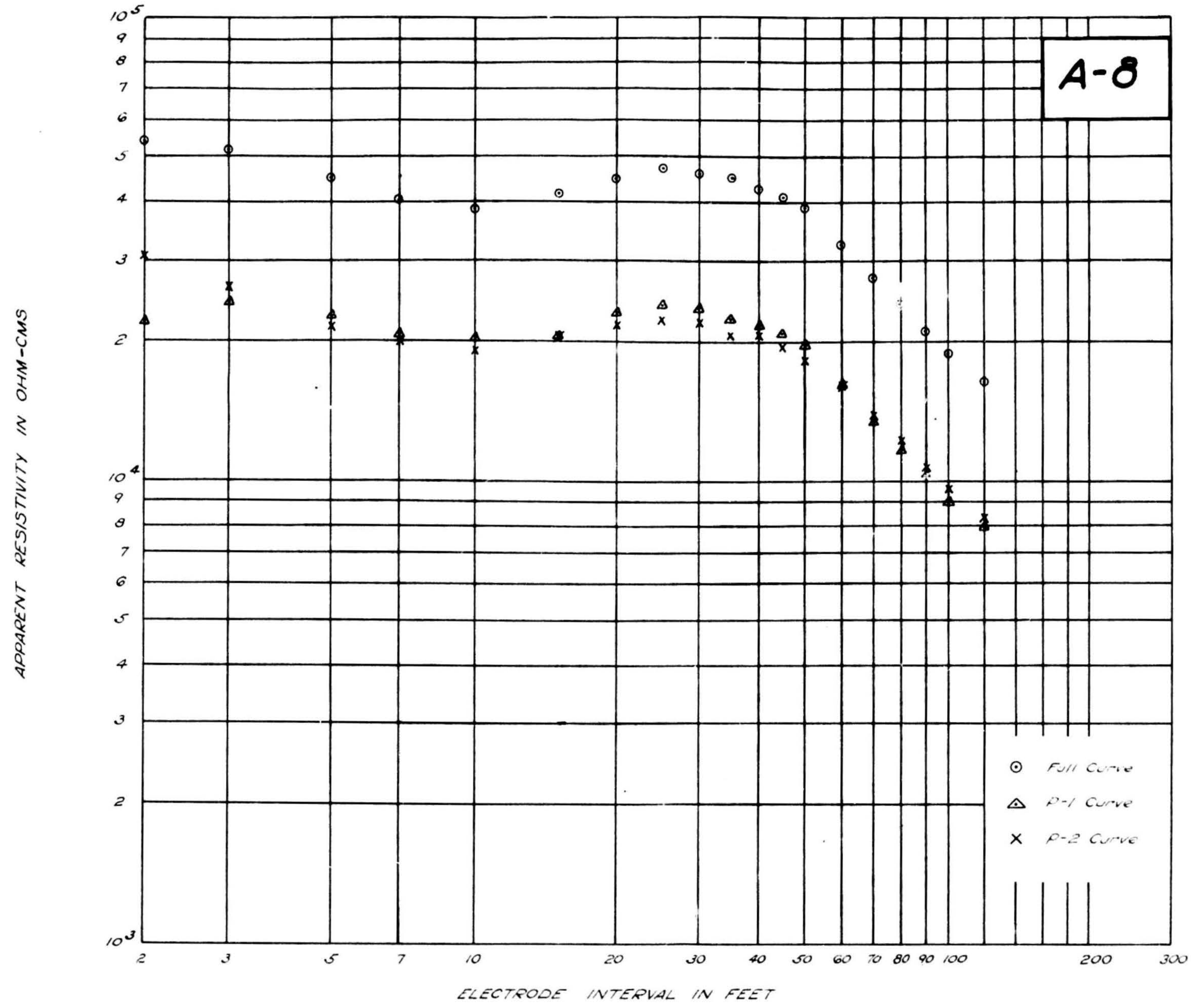
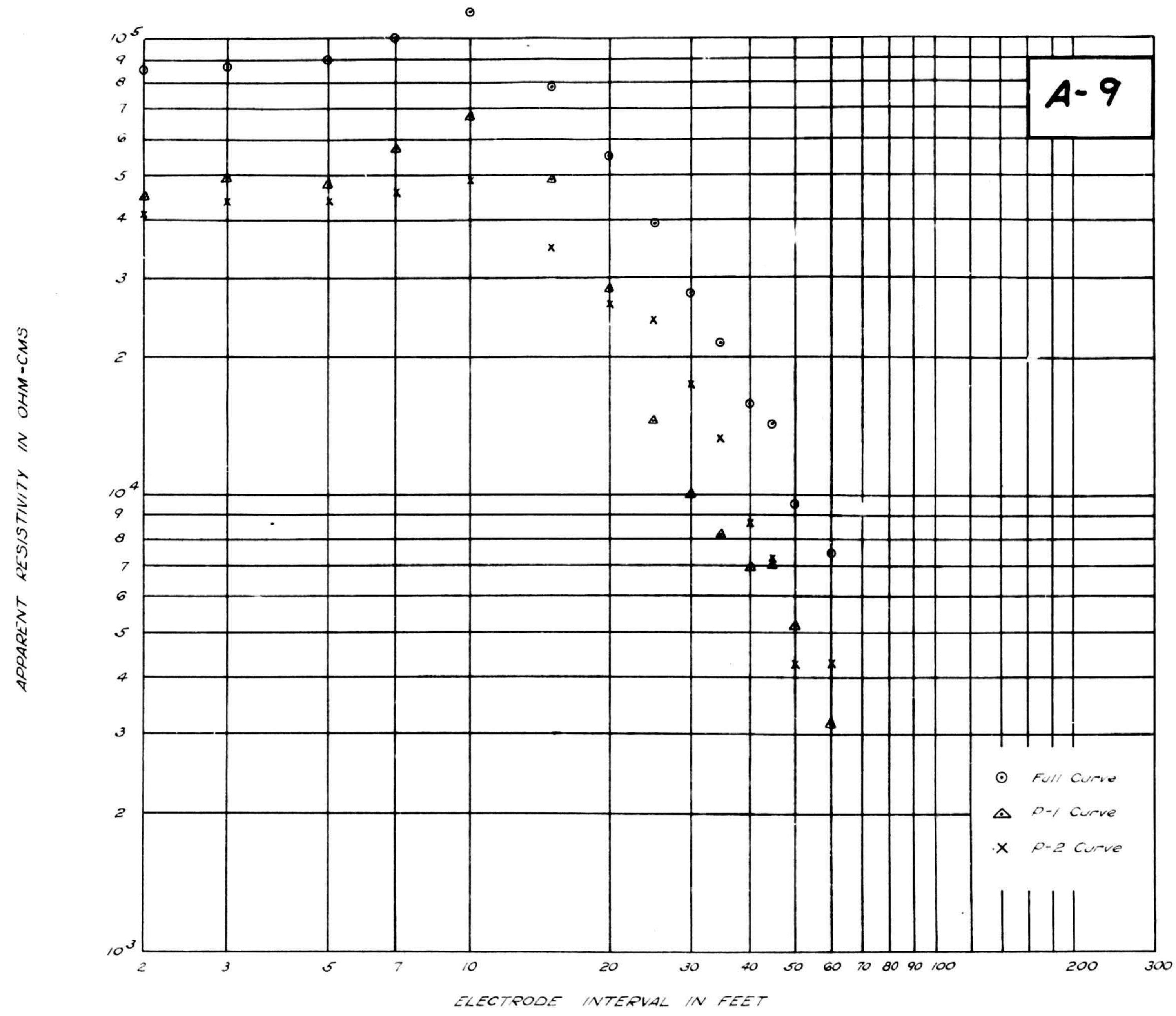
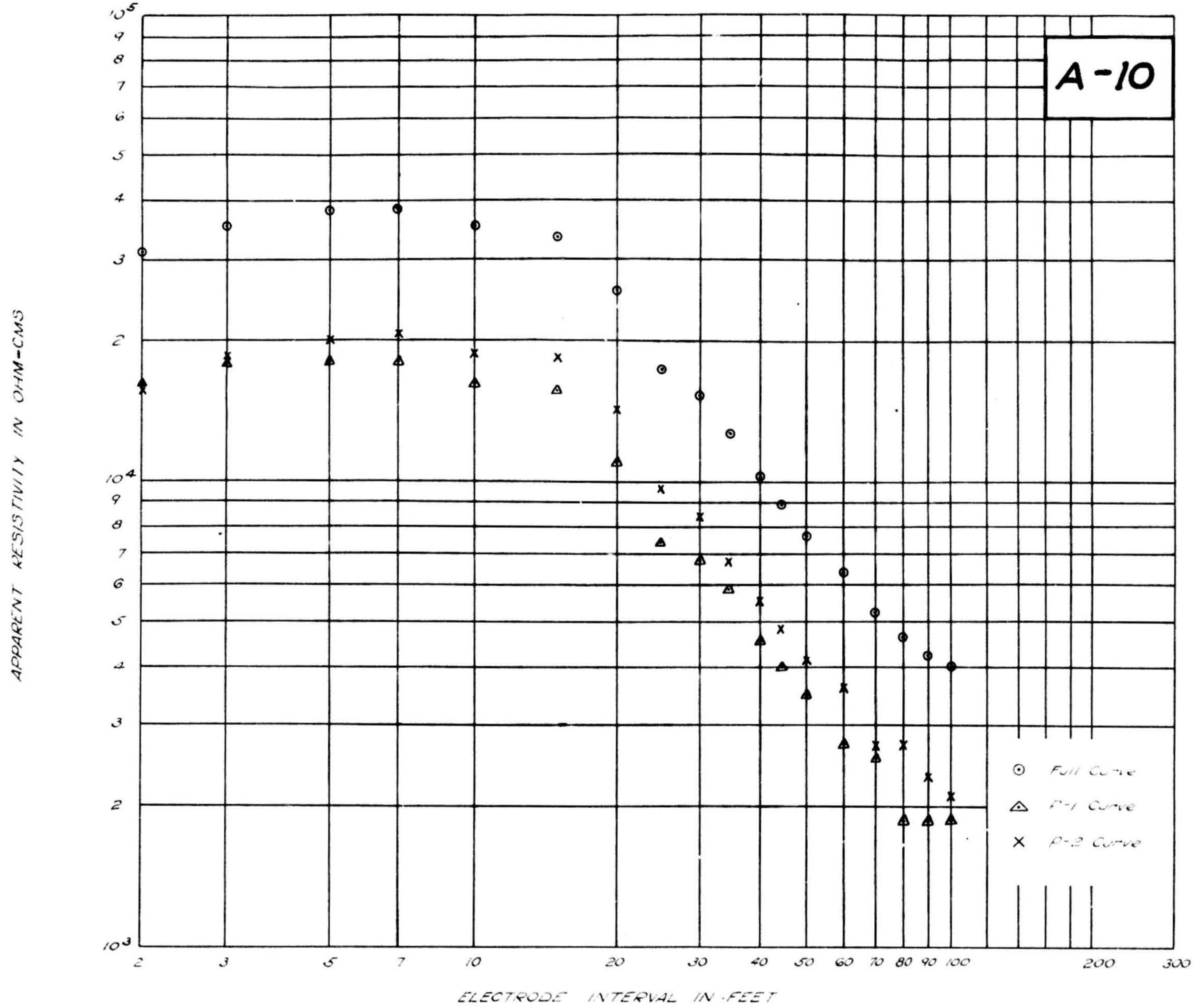

A-6
APPARENT RESISTIVITY IN OHM-CMS
ELECTRODE INTERVAL IN FEET
Full Curve
P-1 Curve
P-2 Curve

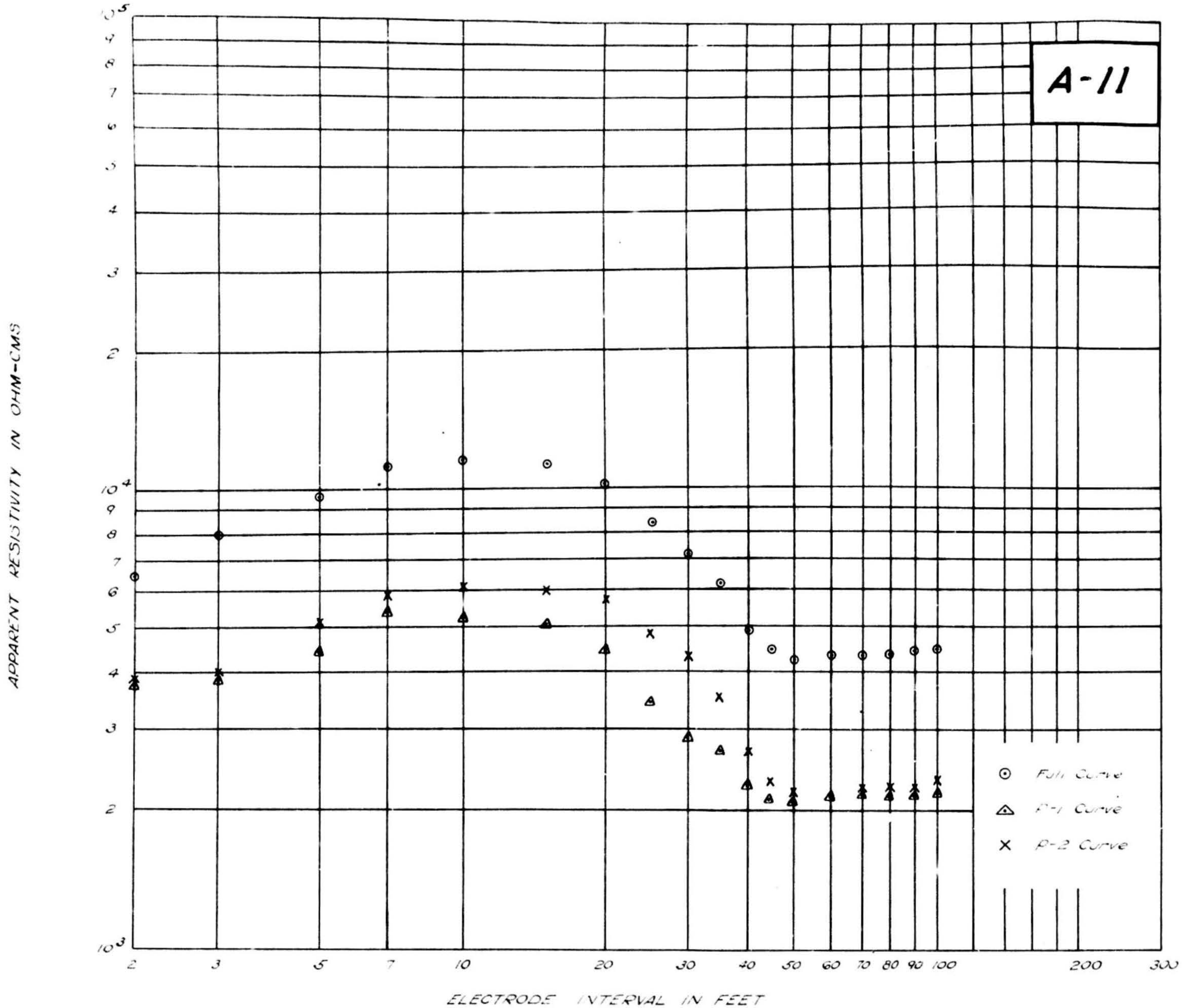

A-7
APPARENT RESISTIVITY IN OHM-CMS
ELECTRODE INTERVAL IN FEET
Full Curve
P-1 Curve
P-2 Curve
2
3
5
7
10
20
30
40
50
60
70
80
90
100
200
300

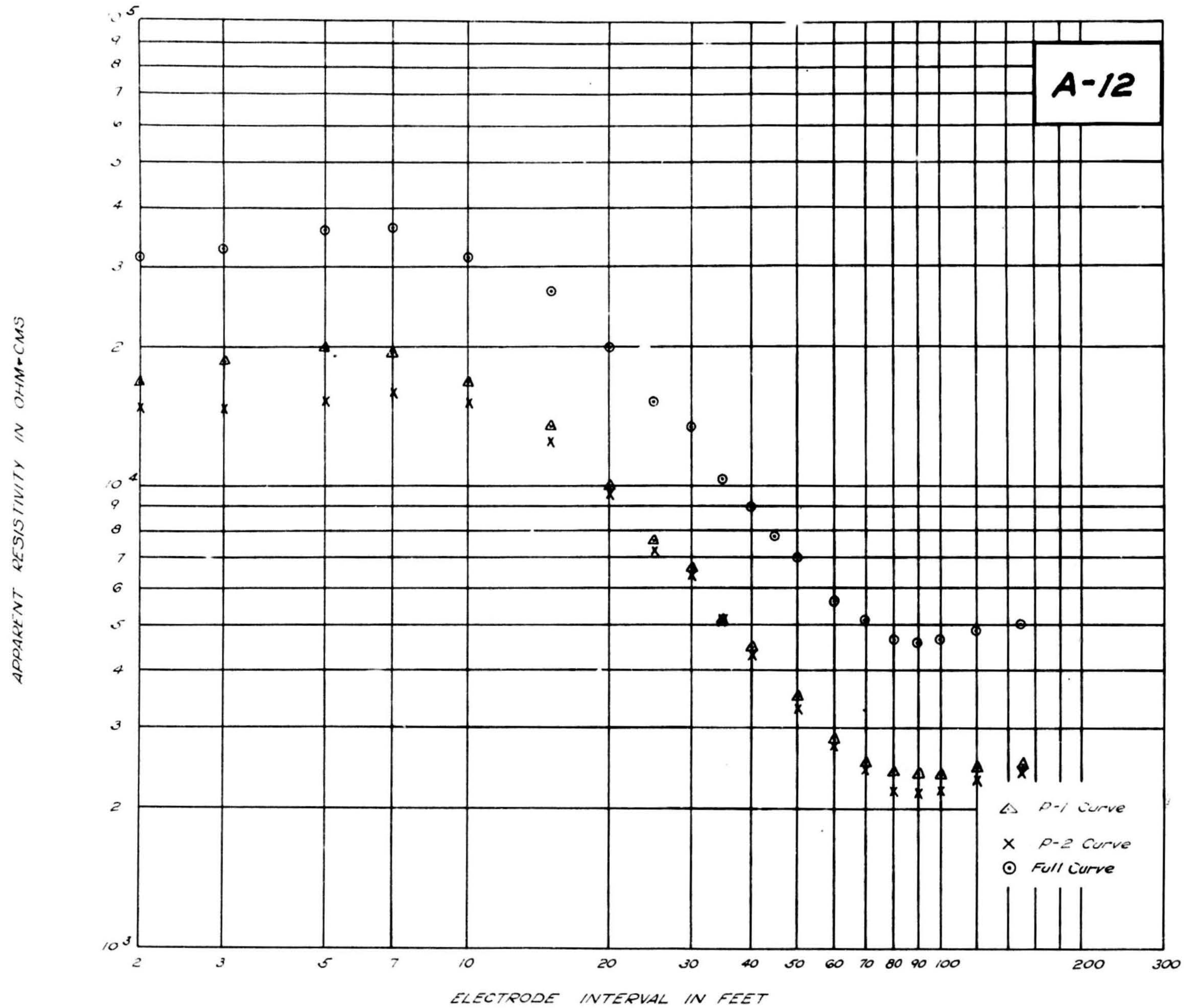

A-8
APPARENT RESISTIVITY IN OHM-CMS
10^5
9
8
7
6
5
4
3
2
10^4
9
8
7
6
5
4
3
2
10^3
2
3
5
7
10
20
30
40
50
60
70
80
90
100
200
300
ELECTRODE INTERVAL IN FEET
Full Curve
P-1 Curve
P-2 Curve


A-9
APPARENT RESISTIVITY IN OHM-CMS
ELECTRODE INTERVAL IN FEET
Full Curve
P-1 Curve
P-2 Curve
10^5
10^4
10^3
2
3
5
7
10
20
30
40
50
60
70
80
90
100
200
300

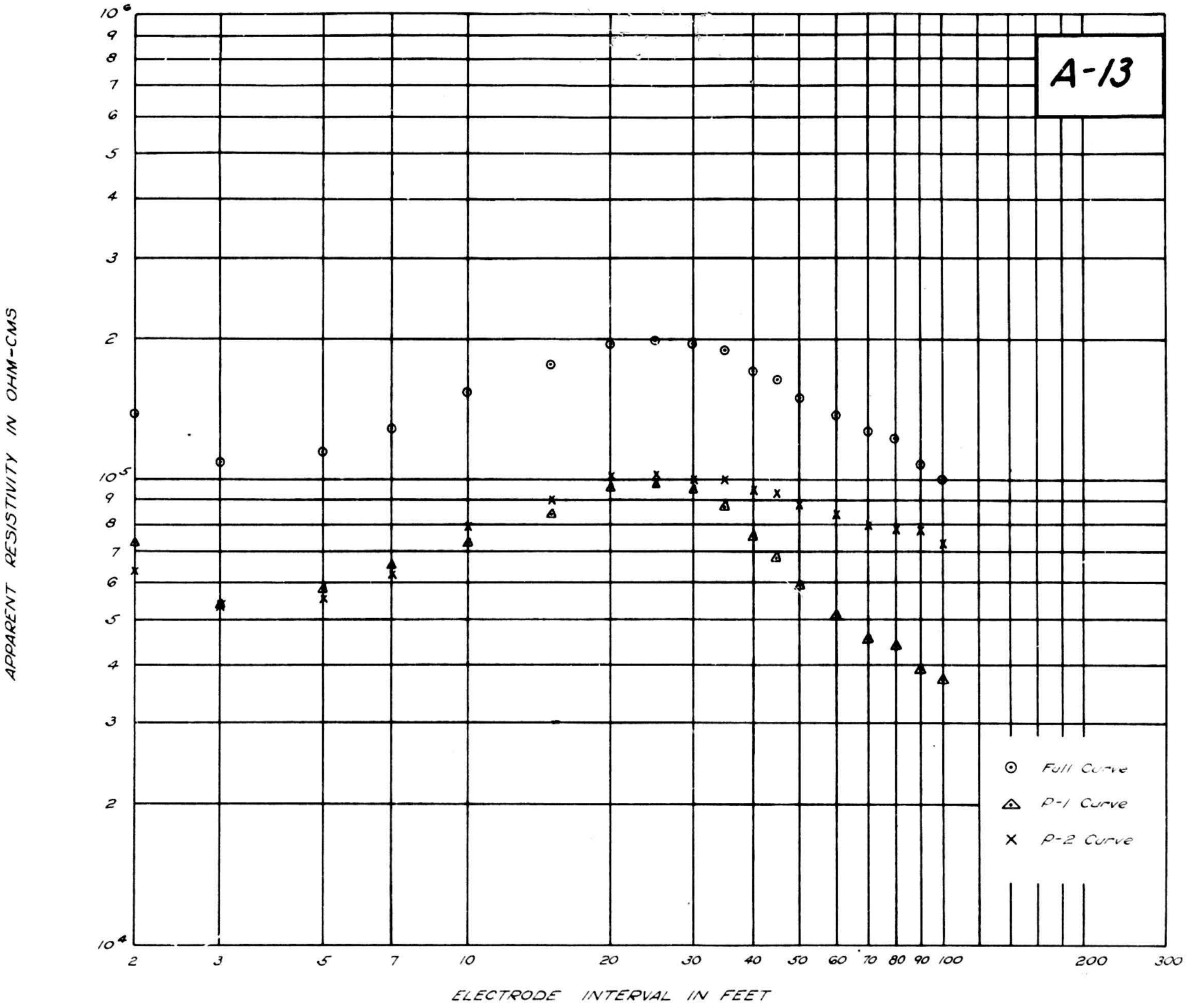


A-10
APPARENT RESISTIVITY IN OHM-CMS
ELECTRODE INTERVAL IN FEET
Full Curve
P-1 Curve
P-2 Curve

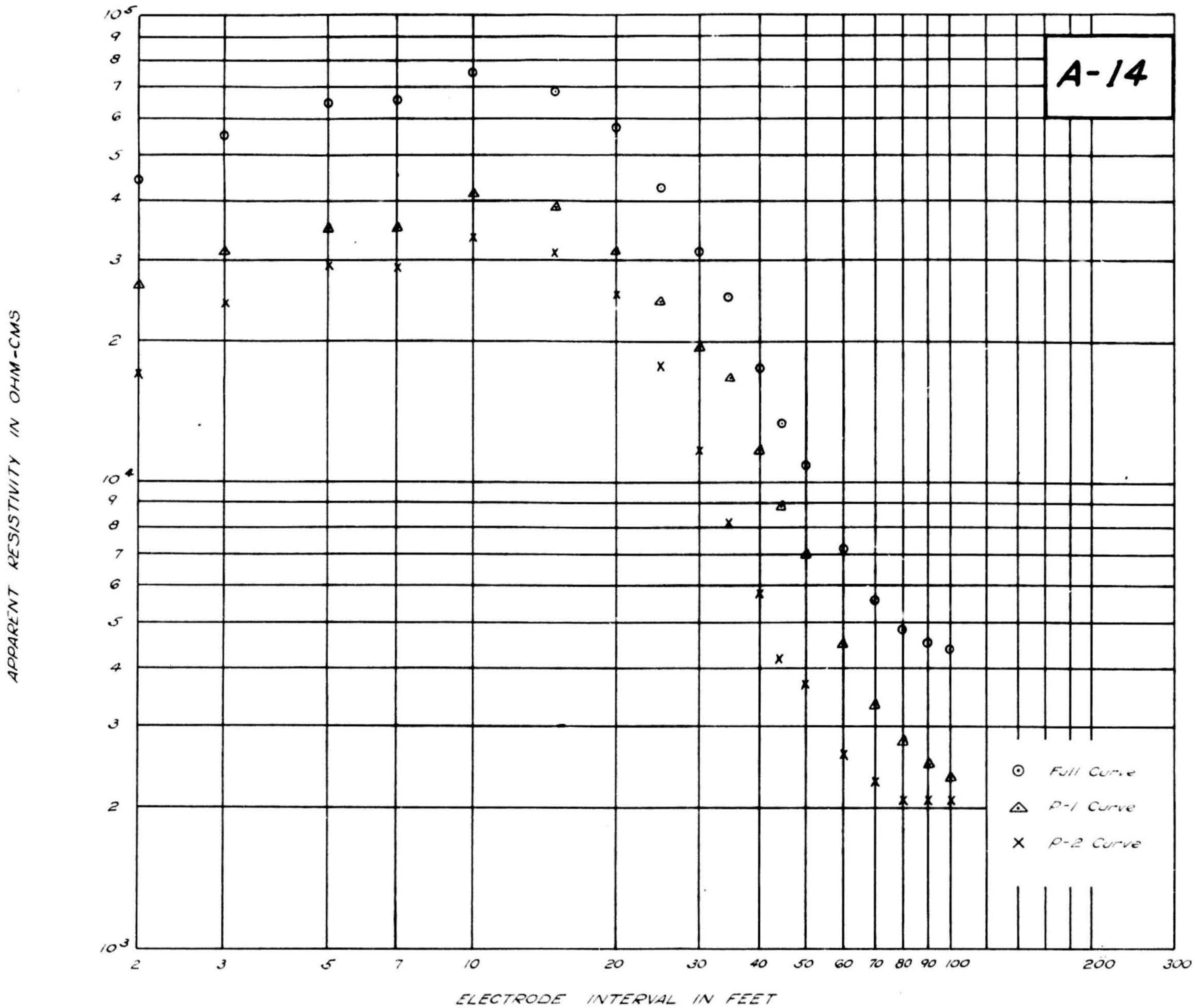

A-11
APPARENT RESISTIVITY IN OHM-CMS
ELECTRODE INTERVAL IN FEET
Full Curve
P-1 Curve
P-2 Curve

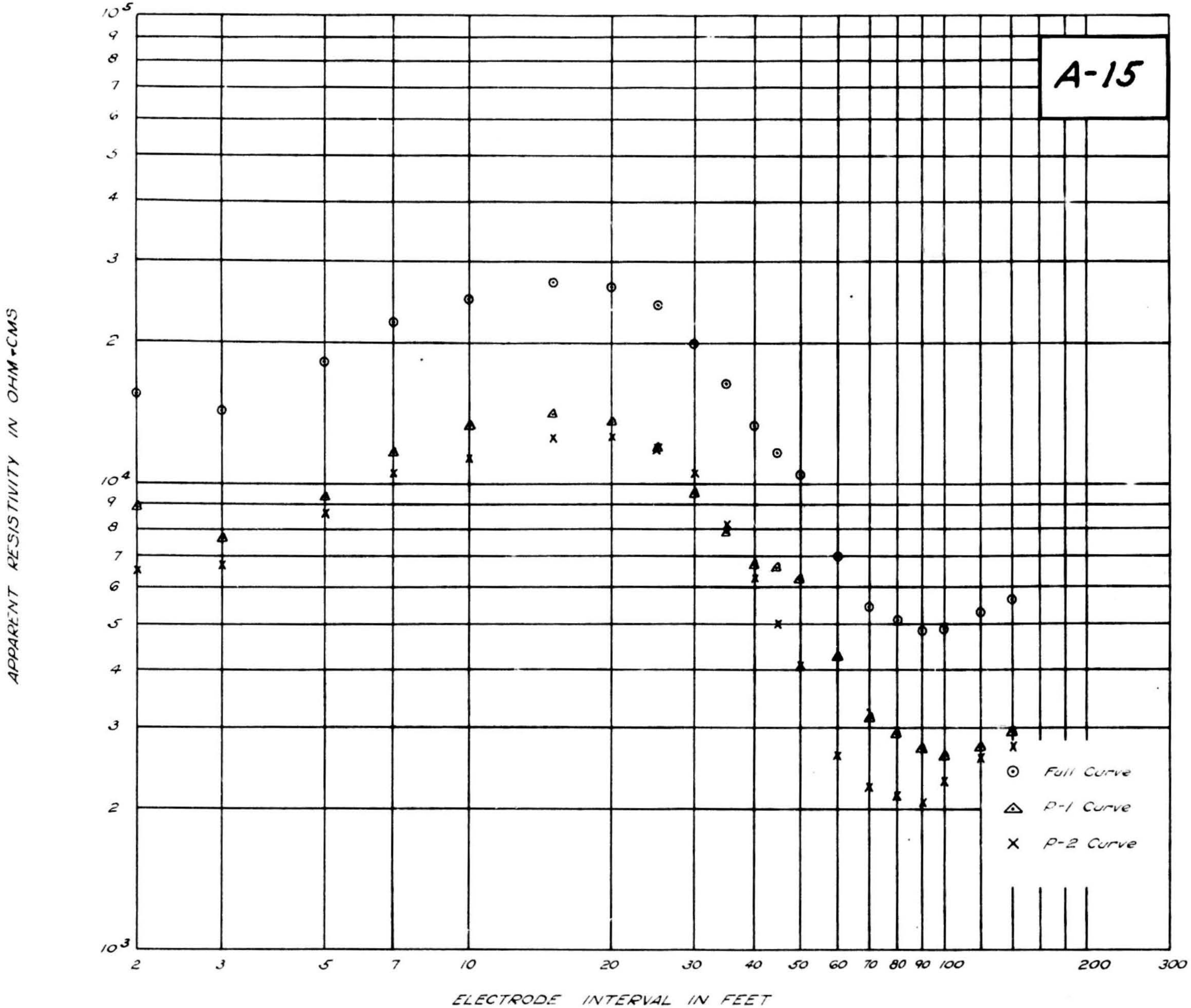


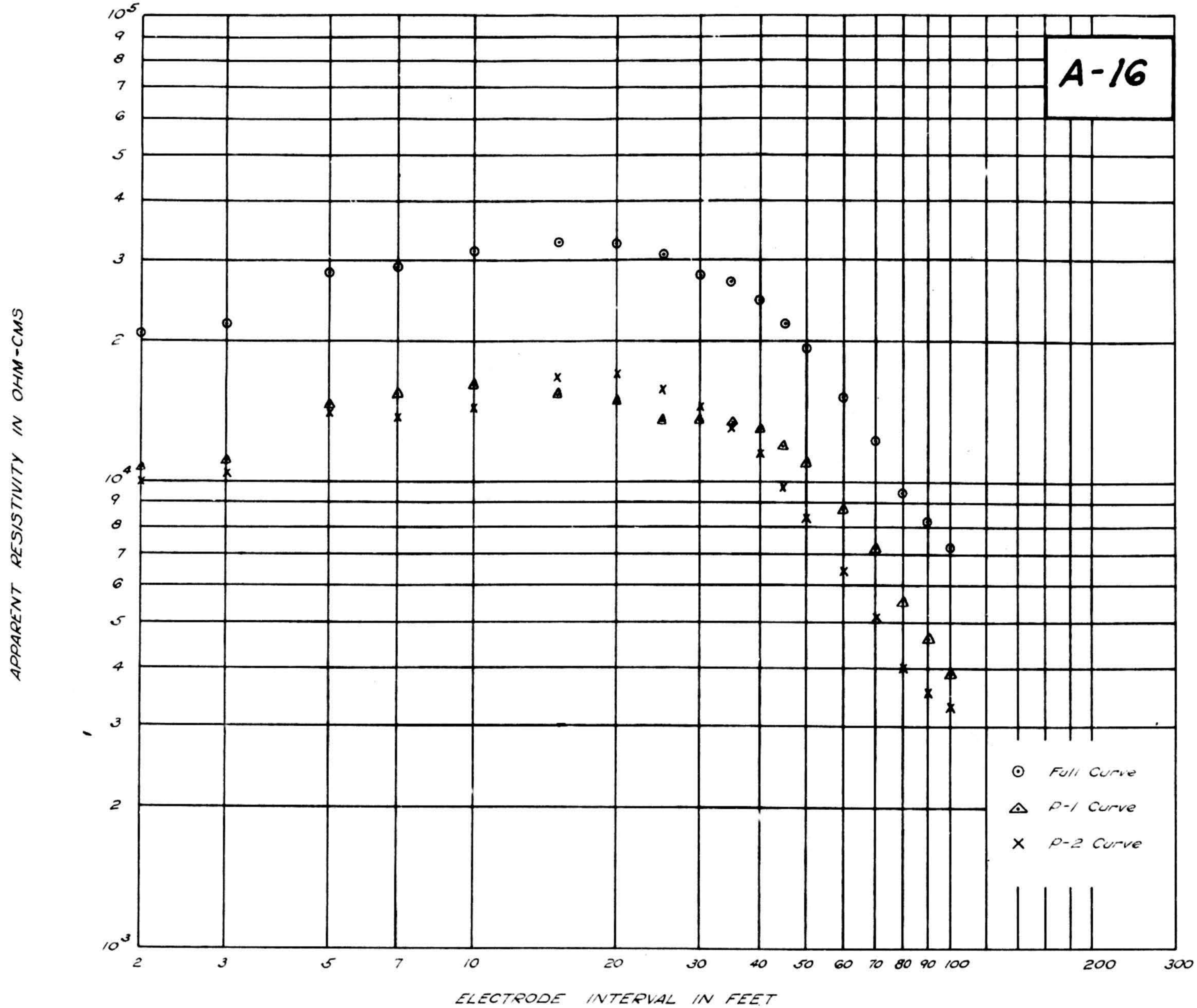
A-12
APPARENT RESISTIVITY IN OHM-CMS
ELECTRODE INTERVAL IN FEET
P-1 Curve
P-2 Curve
Full Curve

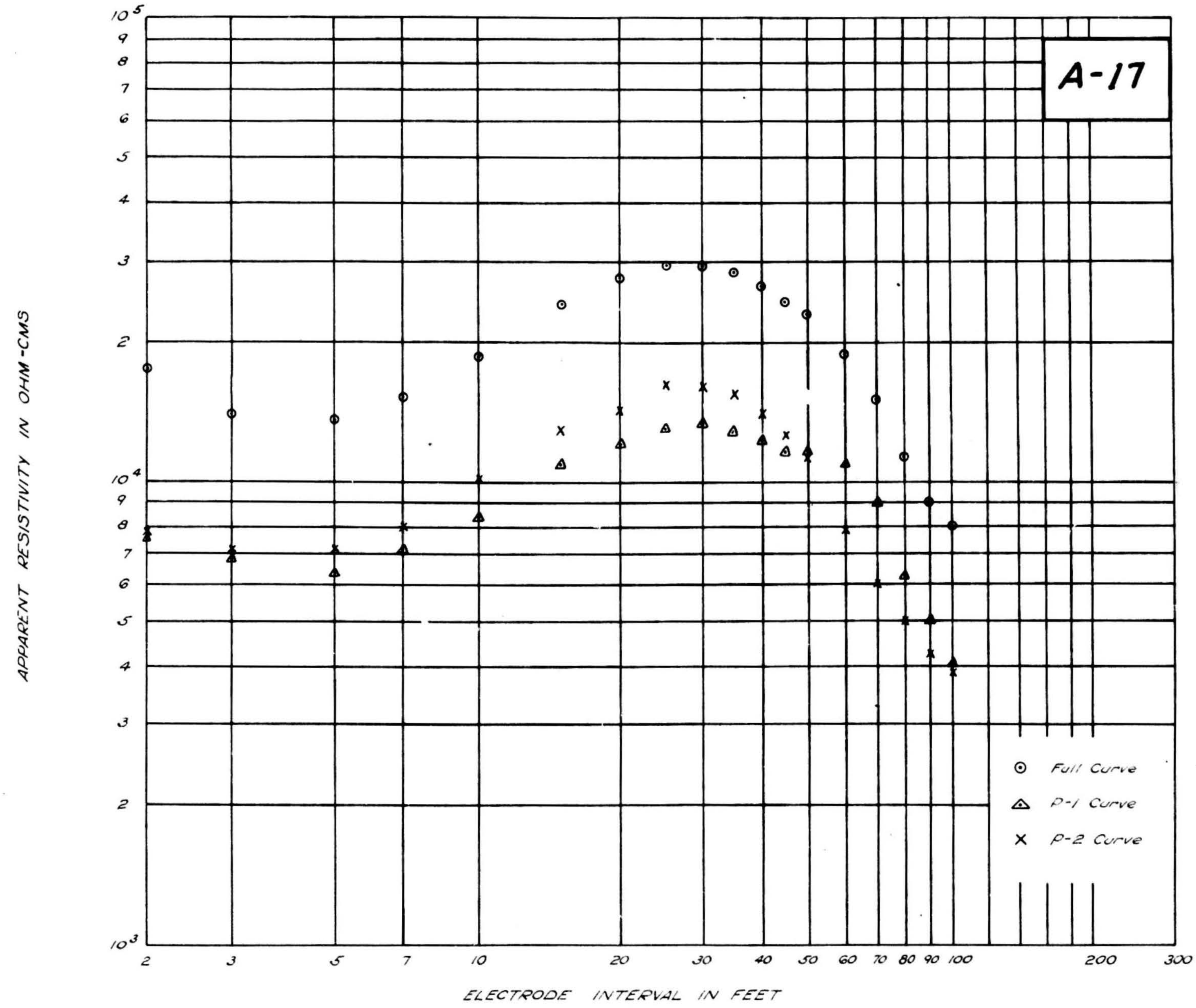


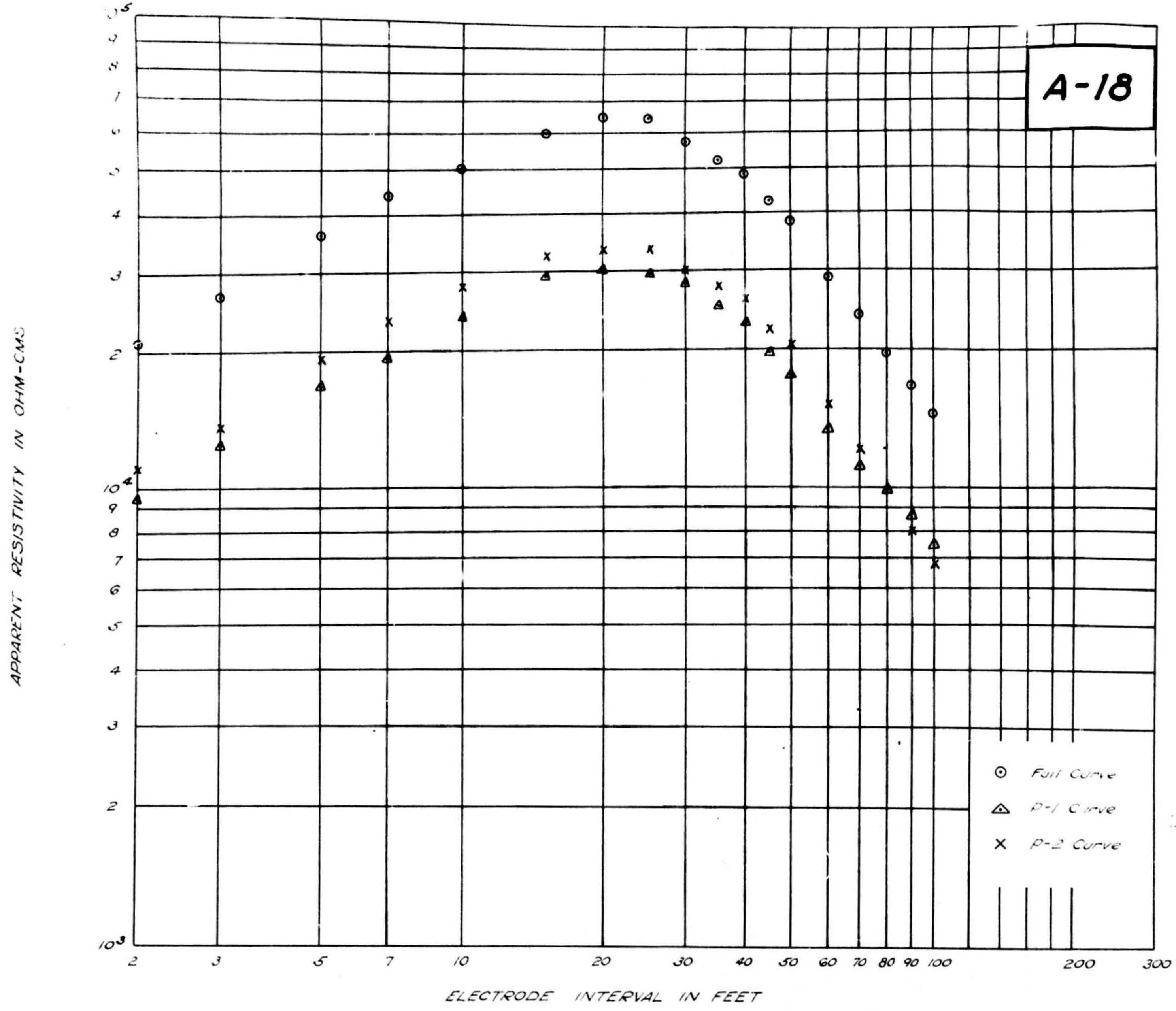
A-13
APPARENT RESISTIVITY IN OHM-CMS
ELECTRODE INTERVAL IN FEET
Full Curve
P-1 Curve
P-2 Curve

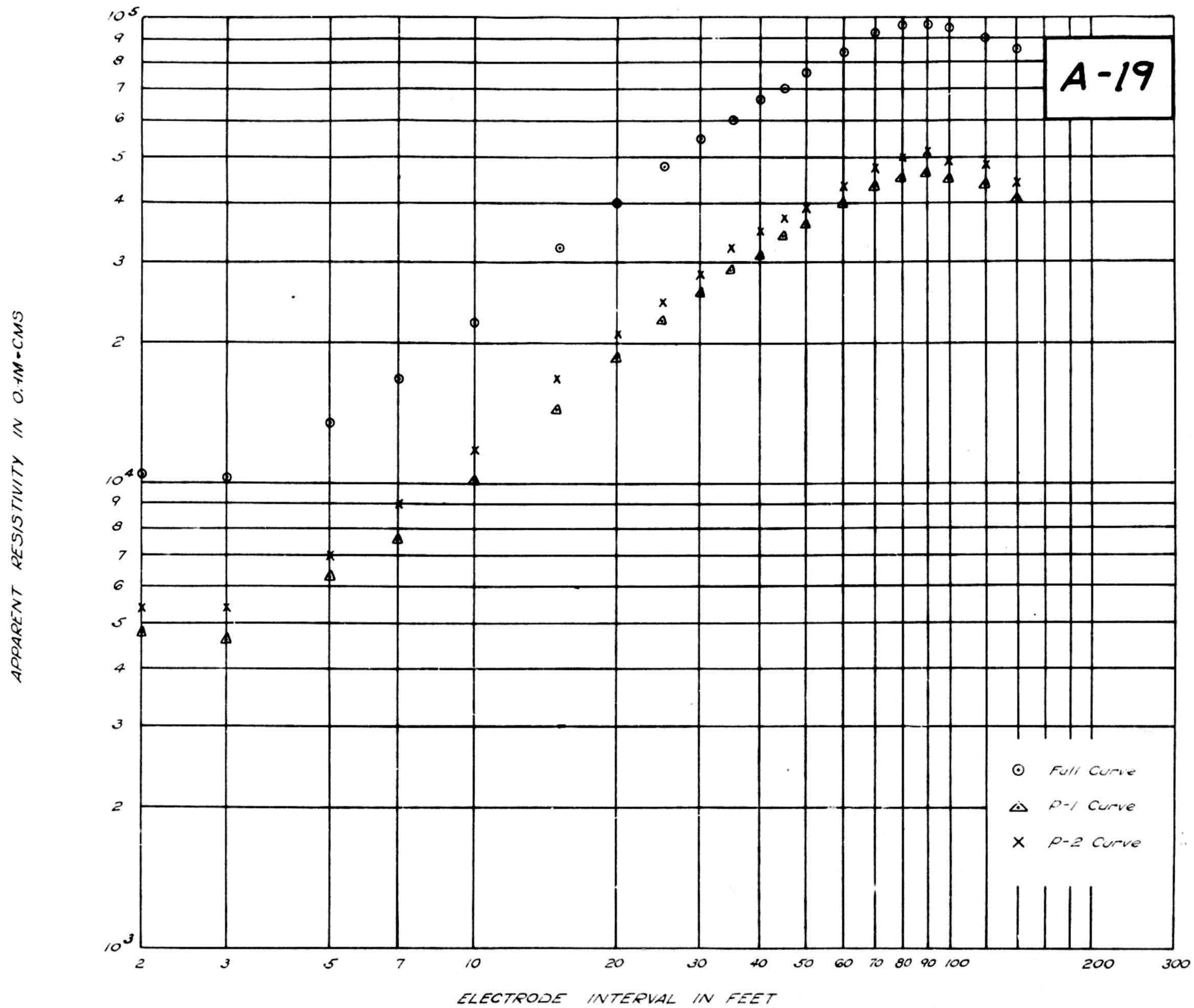

A-14
APPARENT RESISTIVITY IN OHM-CMS
ELECTRODE INTERVAL IN FEET
Full Curve
P-1 Curve
P-2 Curve


A-15
APPARENT RESISTIVITY IN OHM-CMS
ELECTRODE INTERVAL IN FEET
10^5
9
8
7
6
5
4
3
2
10^4
10^3
2
3
5
7
10
20
30
40
50
60
70
80
90
100
200
300
Full Curve
P-1 Curve
P-2 Curve

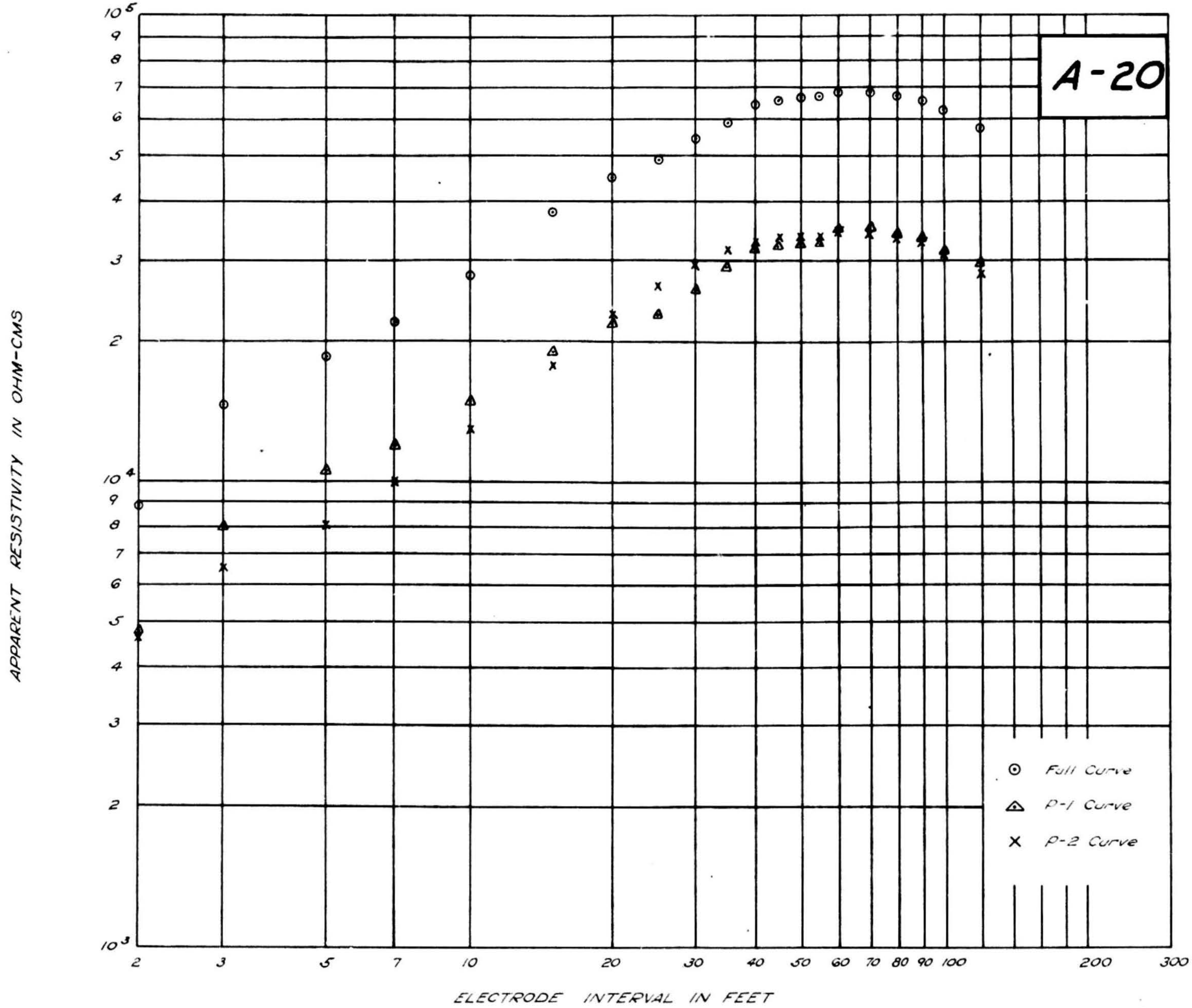

A-16
APPARENT RESISTIVITY IN OHM-CMS
ELECTRODE INTERVAL IN FEET
Full Curve
P-1 Curve
P-2 Curve
10^5
10^4
10^3
2
3
5
7
10
20
30
40
50
60
70
80
90
100
200
300


A-17
APPARENT RESISTIVITY IN OHM-CMS
ELECTRODE INTERVAL IN FEET
Full Curve
P-1 Curve
P-2 Curve
10^5
10^4
10^3
2
3
5
7
10
20
30
40
50
60
70
80
90
100
200
300


A-18
APPARENT RESISTIVITY IN OHM-CMS
ELECTRODE INTERVAL IN FEET
Full Curve
P-1 Curve
P-2 Curve



A-19
APPARENT RESISTIVITY IN OHM-CMS
ELECTRODE INTERVAL IN FEET
Full Curve
P-1 Curve
P-2 Curve


A-20
APPARENT RESISTIVITY IN OHM-CMS
ELECTRODE INTERVAL IN FEET
Full Curve
P-1 Curve
P-2 Curve
10⁵
10⁴
10³
2
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7
10
20
30
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200
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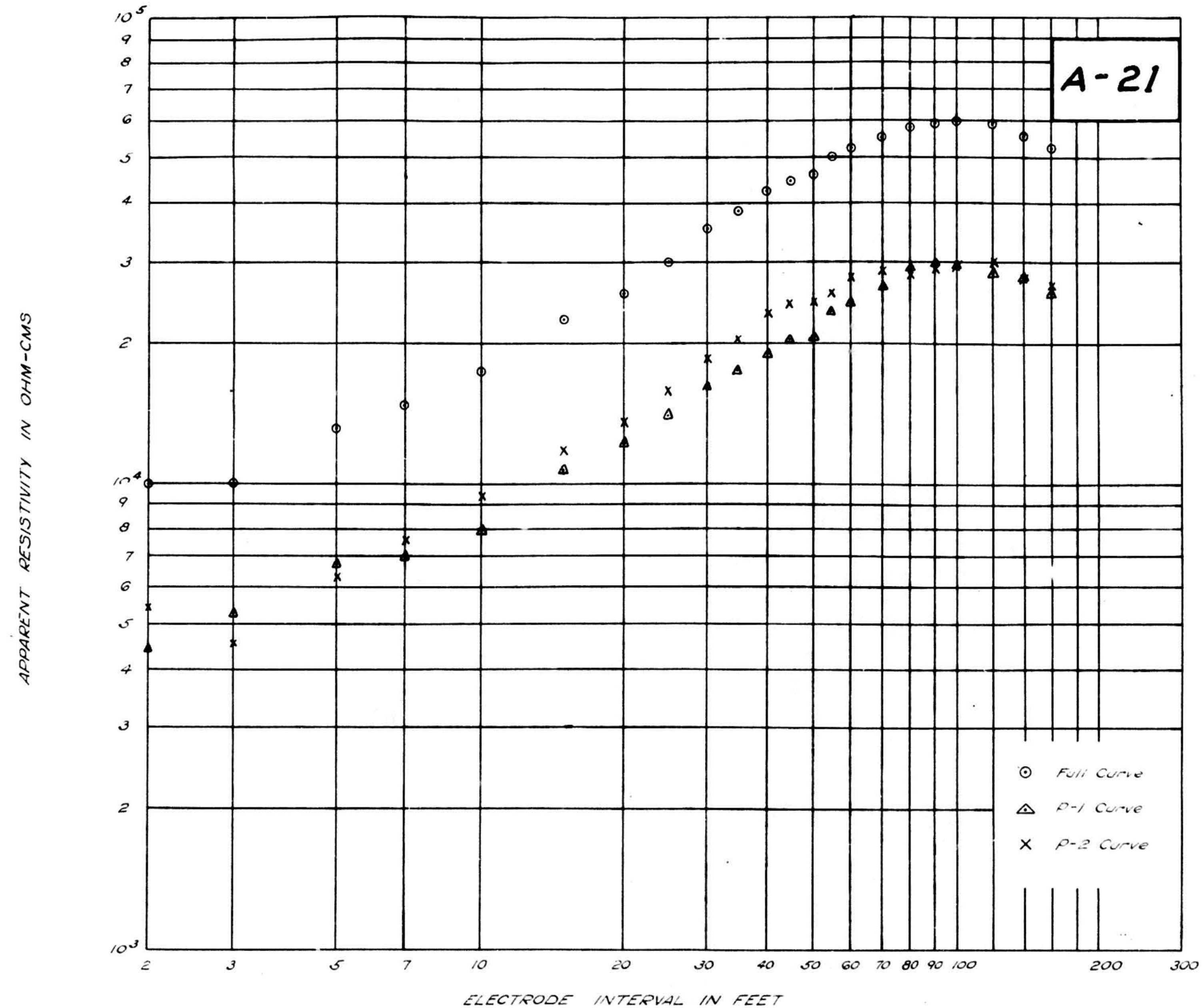
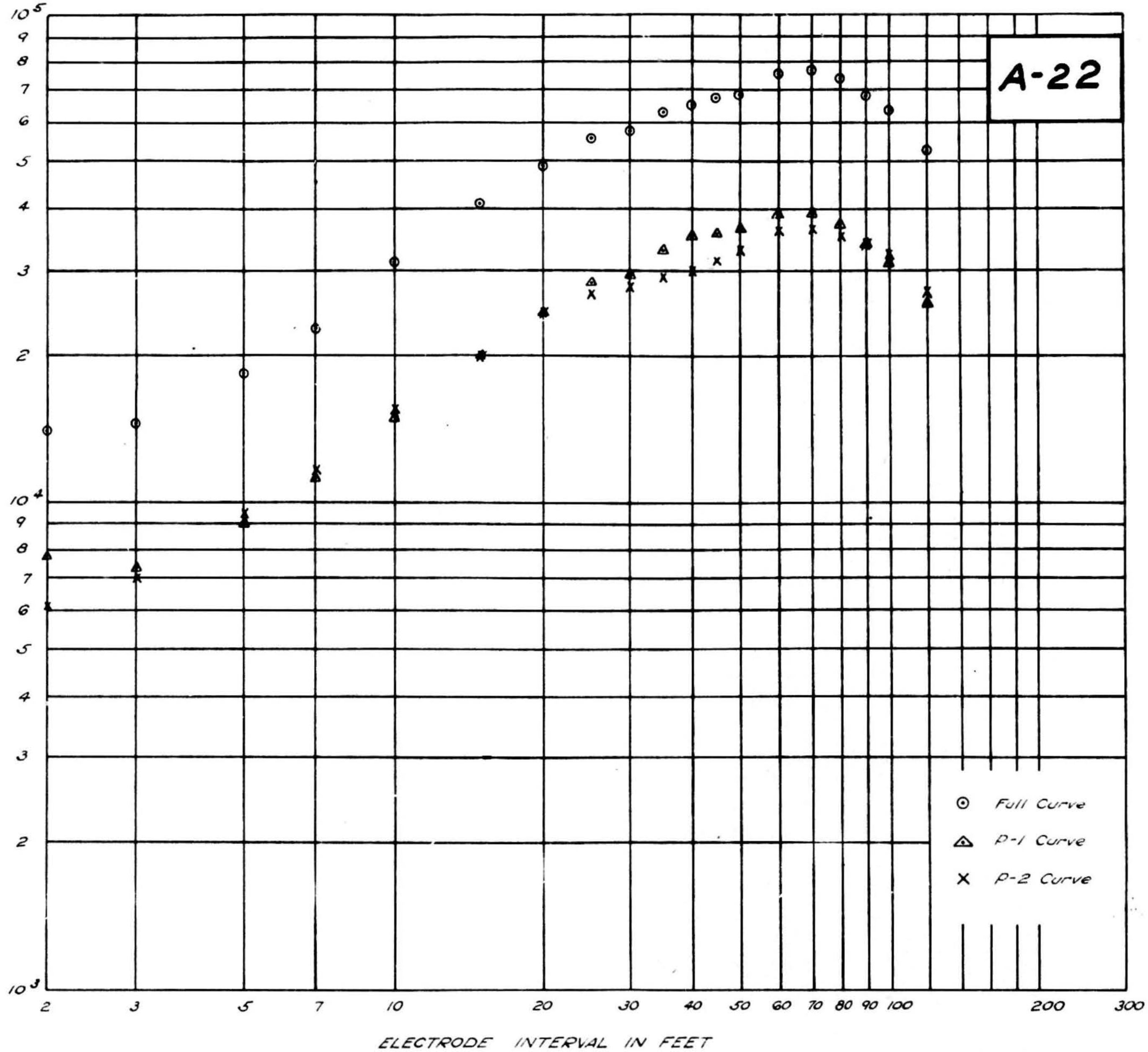


A-21
APPARENT RESISTIVITY IN OHM-CMS
ELECTRODE INTERVAL IN FEET
Full Curve
P-1 Curve
P-2 Curve


A-22
APPARENT RESISTIVITY IN OHM-CMS
ELECTRODE INTERVAL IN FEET
Full Curve
P-1 Curve
P-2 Curve
10^5
9
8
7
6
5
4
3
2
10^4
9
8
7
6
5
4
3
2
10^3
2
3
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7
10
20
30
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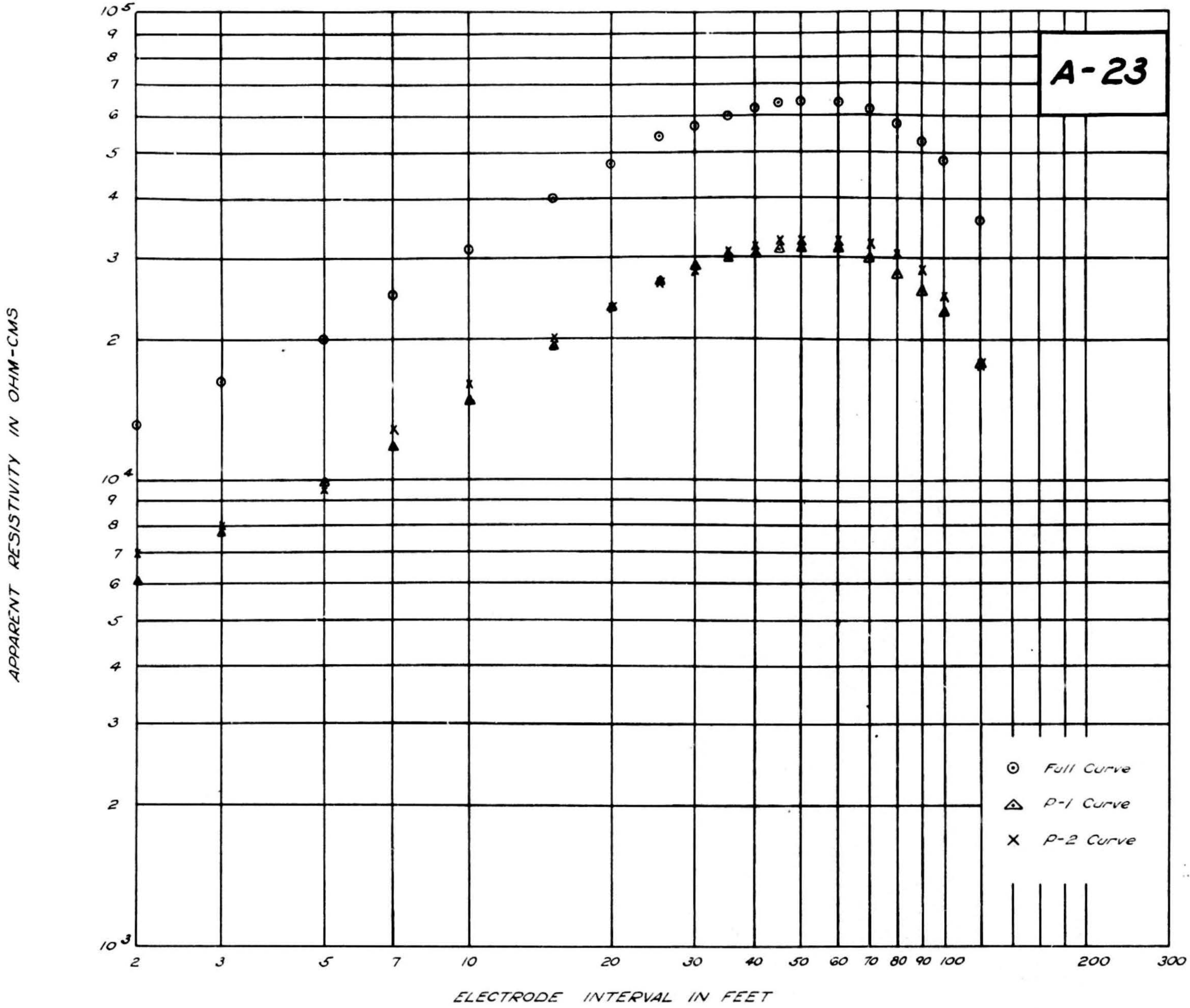
A-23
APPARENT RESISTIVITY IN OHM-CMS
10^5
9
8
7
6
5
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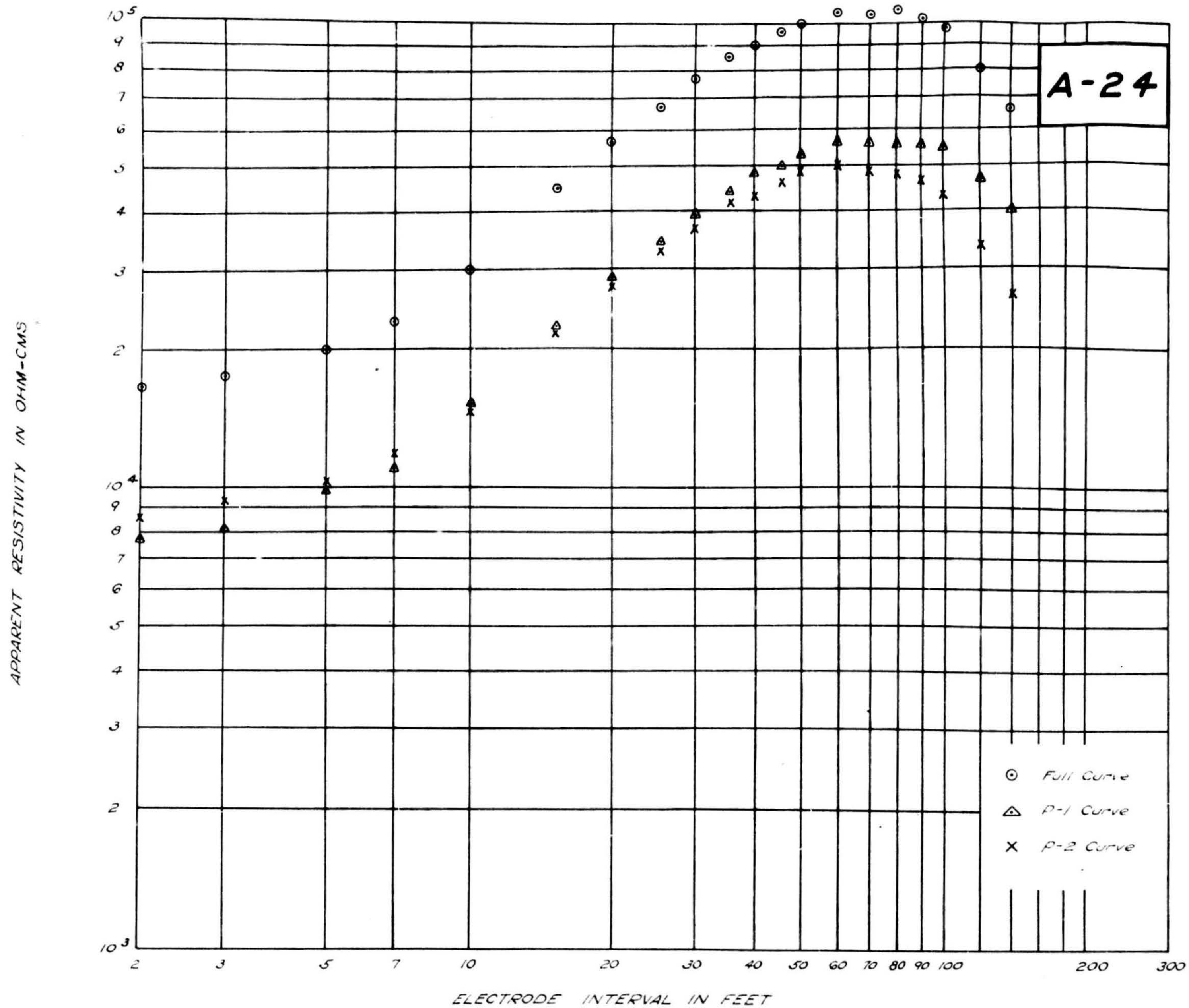
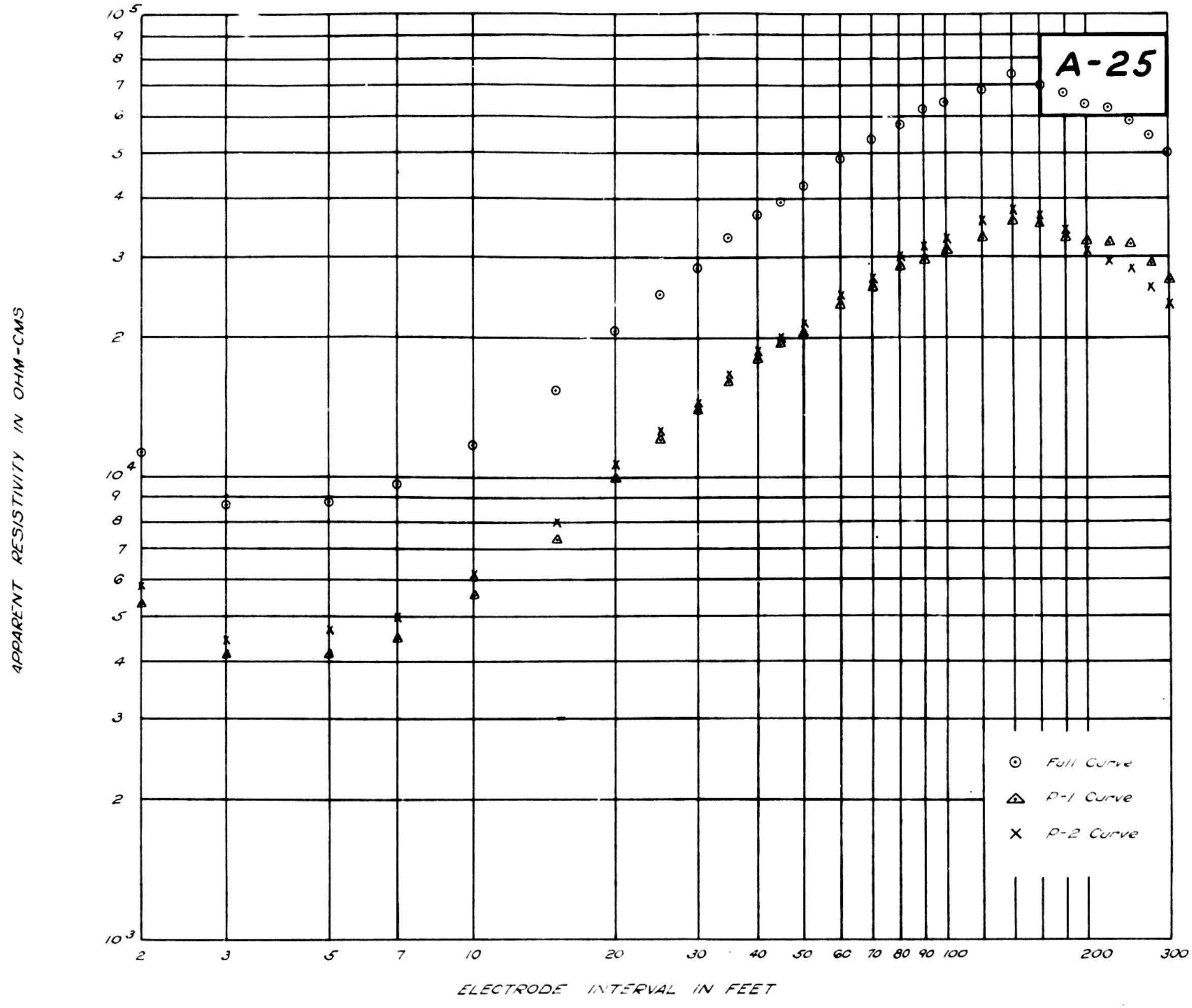
3
2
10^4
9
8
7
6
5
4
3
2
10^3
2
3
5
7
10
20
30
40
50
60
70
80
90
100
200
300
ELECTRODE INTERVAL IN FEET
Full Curve
P-1 Curve
P-2 Curve


A-24
APPARENT RESISTIVITY IN OHM-CMS
ELECTRODE INTERVAL IN FEET
Full Curve
P-1 Curve
P-2 Curve


A-25
APPARENT RESISTIVITY IN OHM-CMS
ELECTRODE INTERVAL IN FEET
Full Curve
P-1 Curve
P-2 Curve
10^5
10^4
10^3
2
3
5
7
10
20
30
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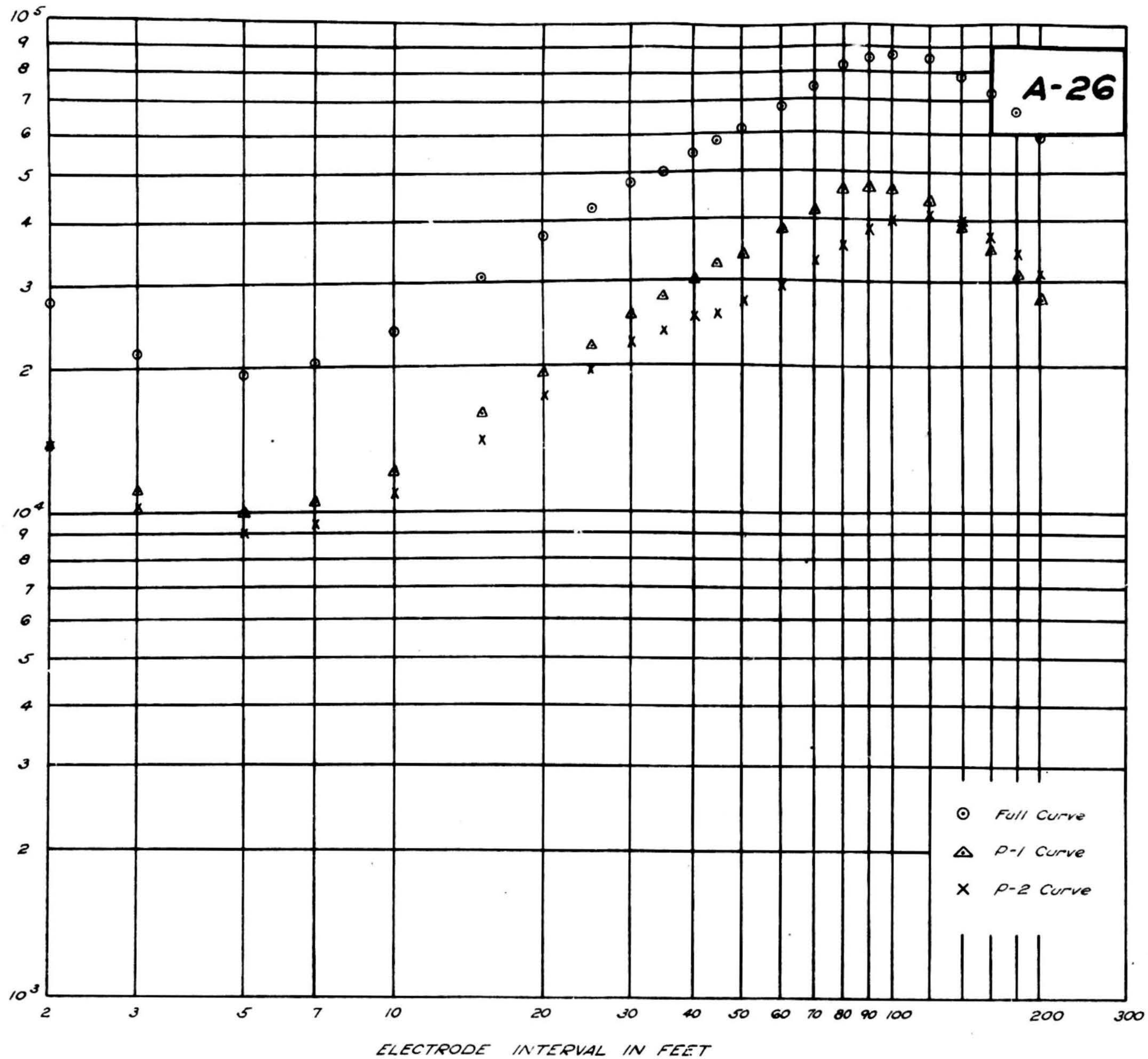
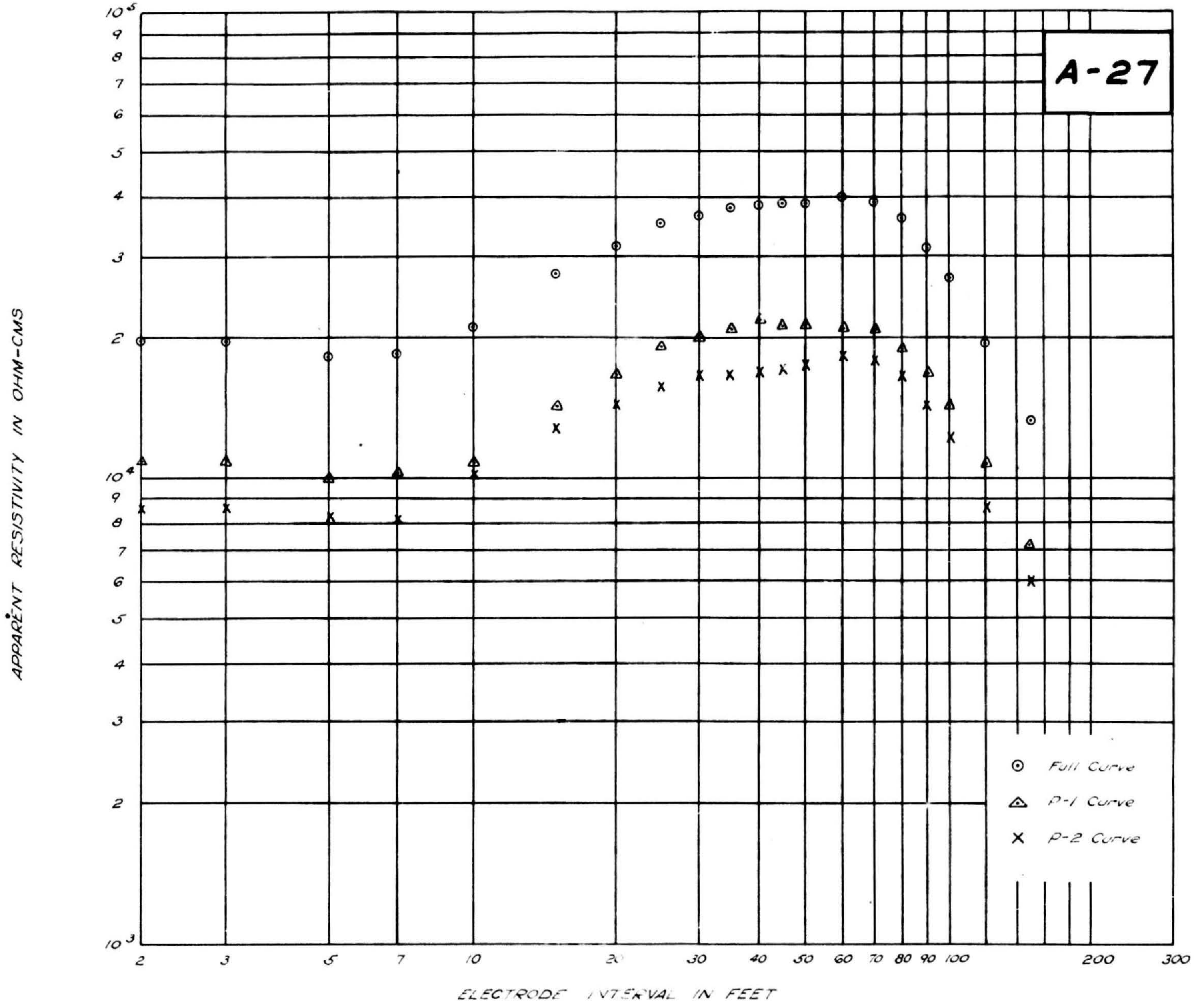
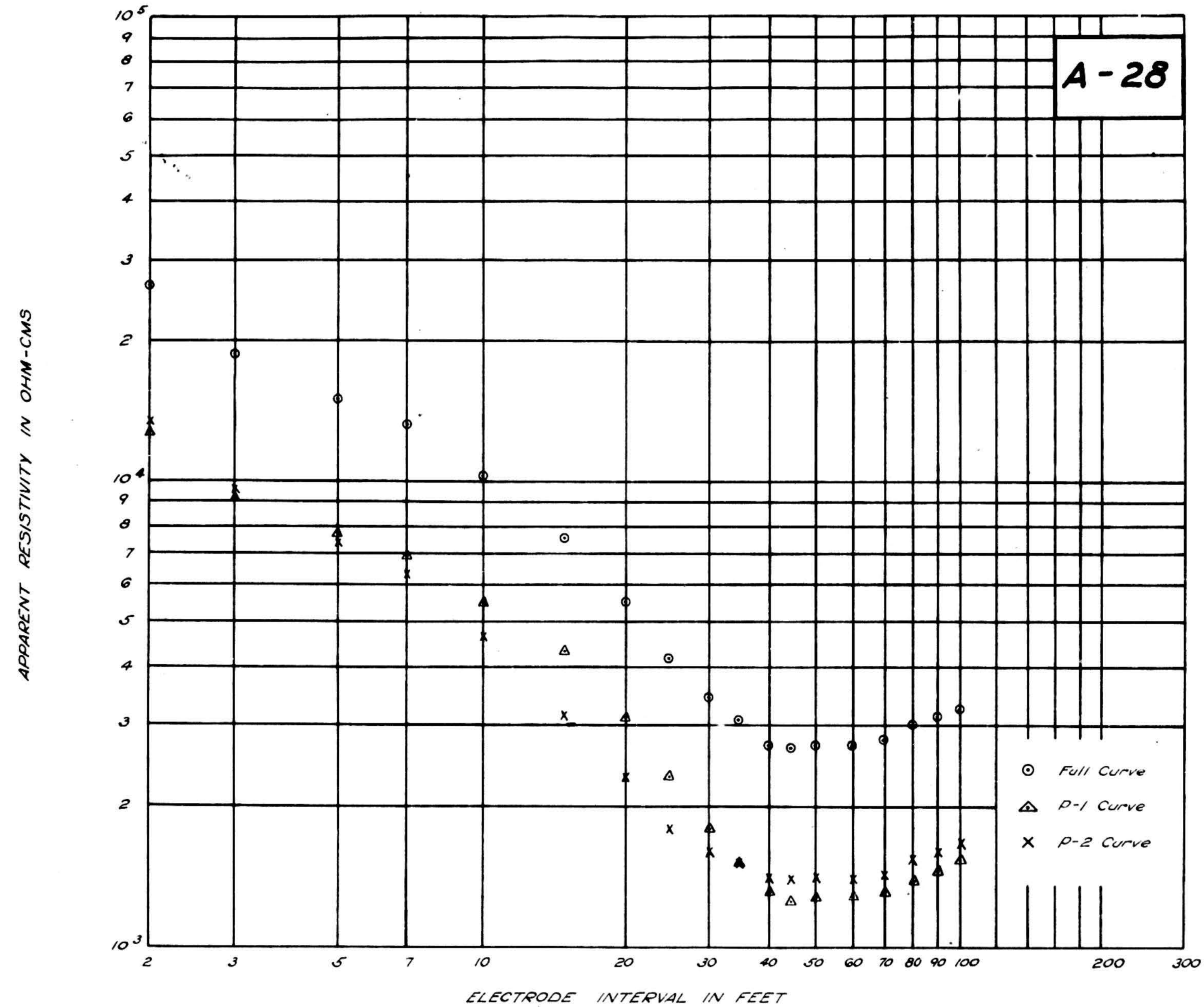
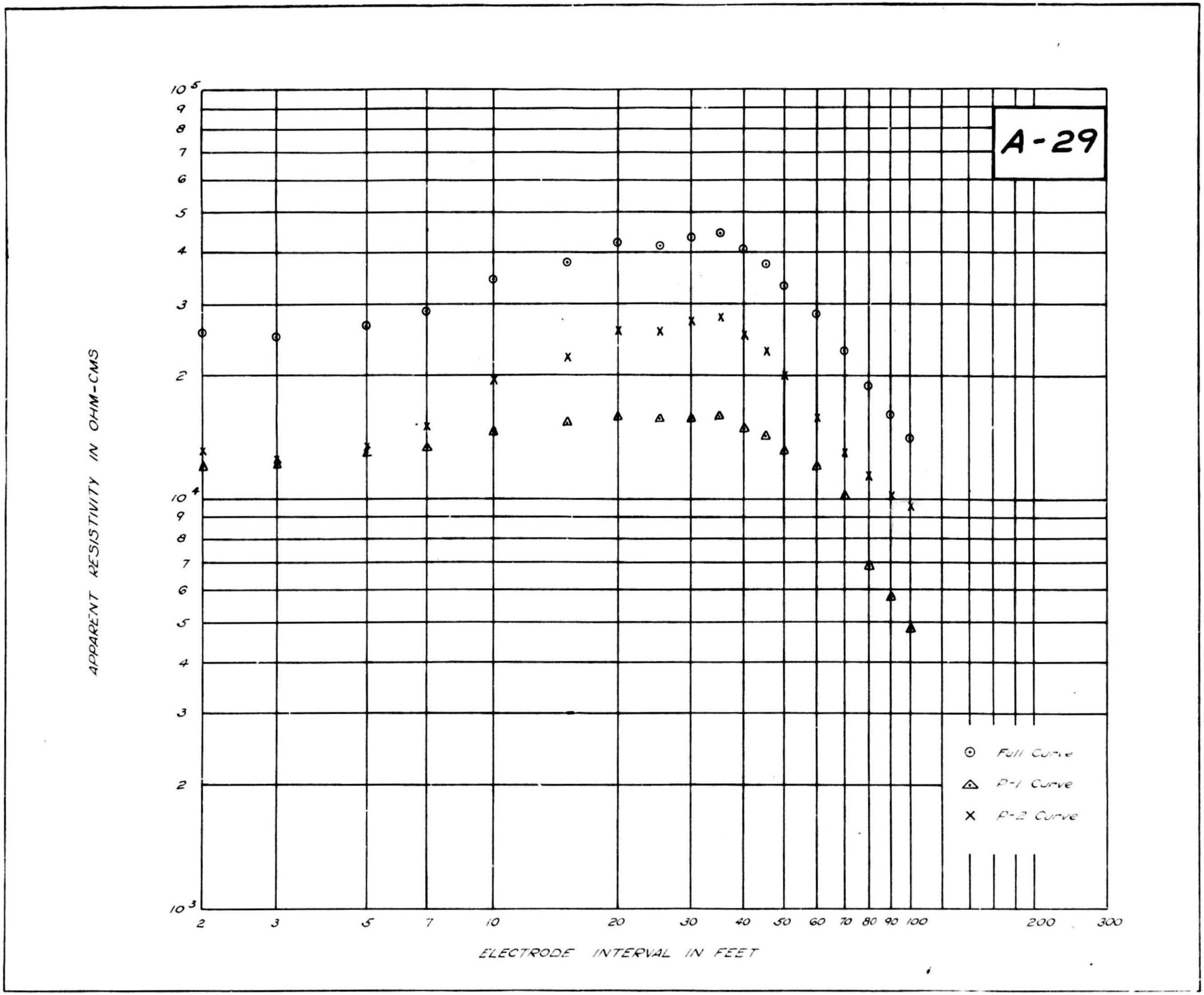
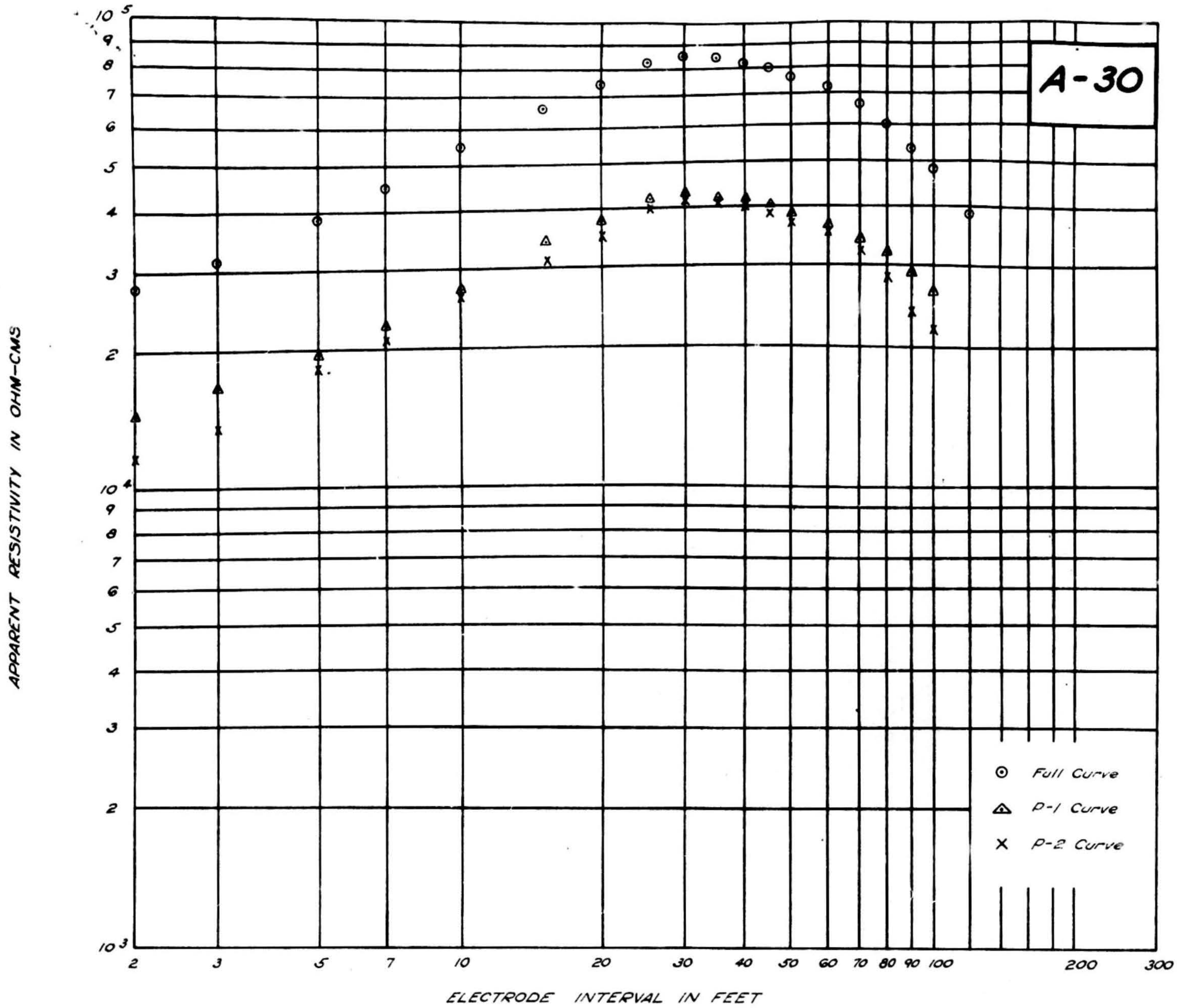
100
200
300

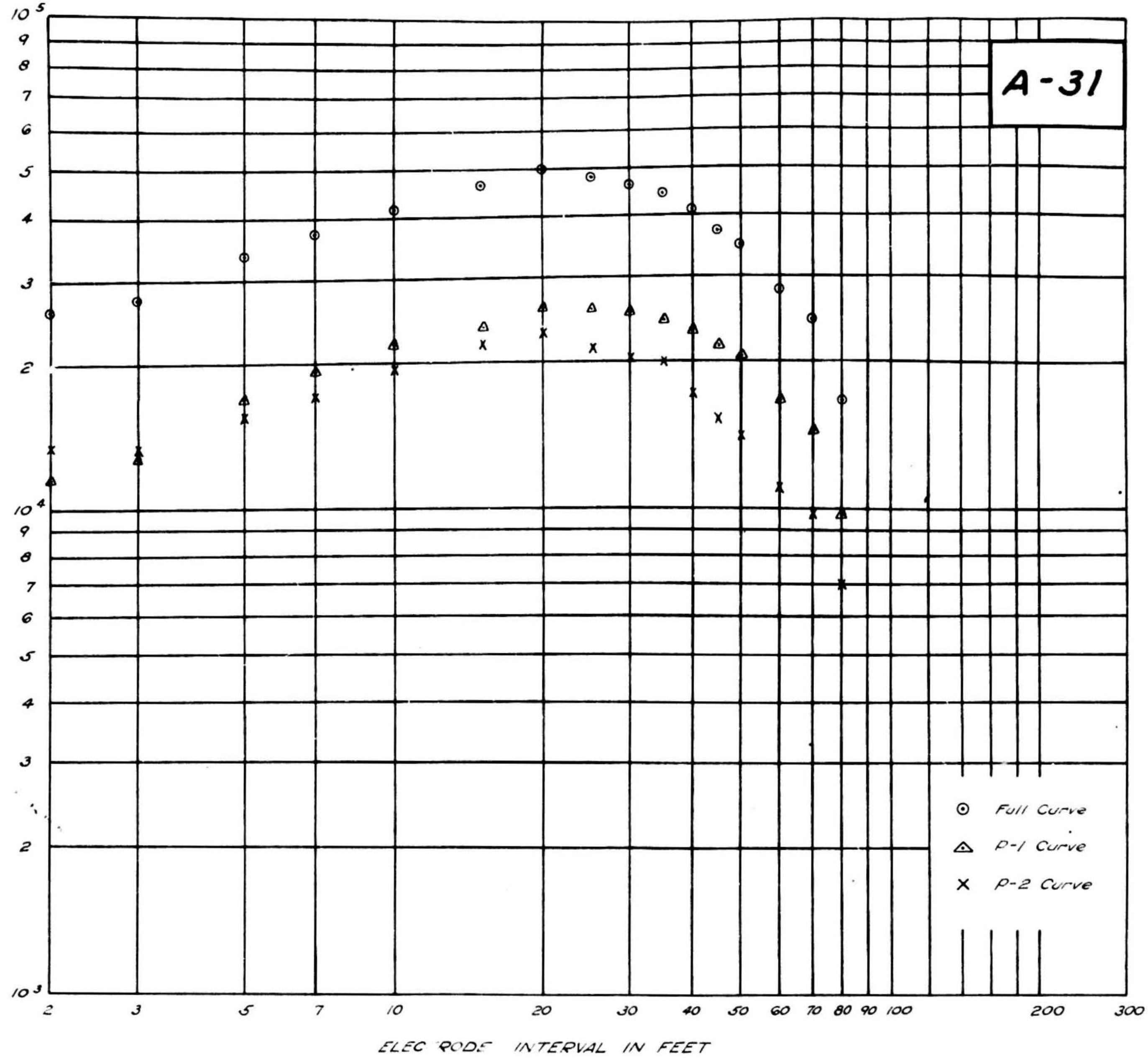

A-26
APPARENT RESISTIVITY IN OHM-CMS
10^5
9
8
7
6
5
4
3
2
10^4
9
8
7
6
5
4
3
2
10^3
2
3
5
7
10
20
30
40
50
60
70
80
90
100
200
300
ELECTRODE INTERVAL IN FEET
Full Curve
P-1 Curve
P-2 Curve

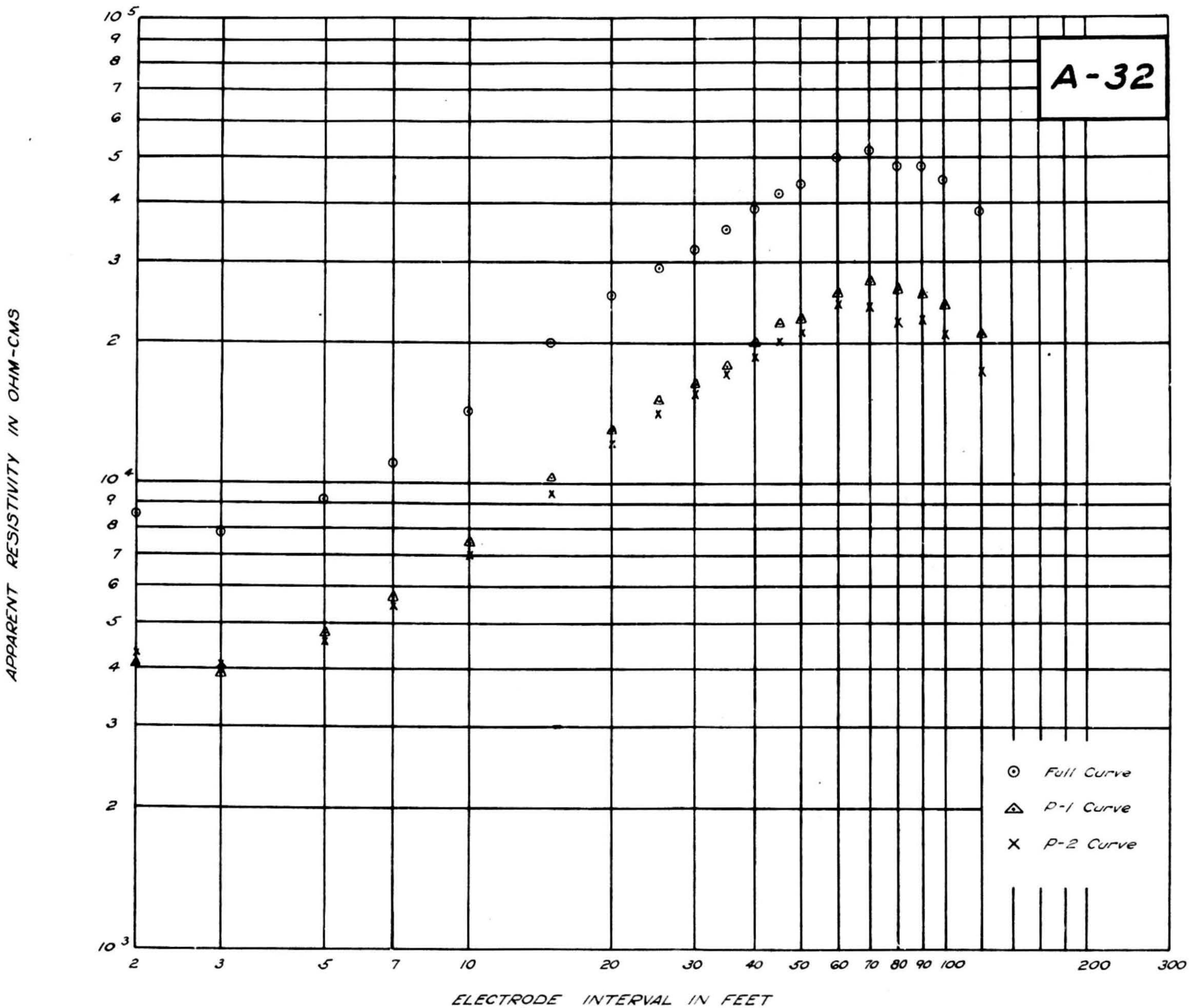

A-27
APPARENT RESISTIVITY IN OHM-CMS
ELECTRODE INTERVAL IN FEET
Full Curve
P-1 Curve
P-2 Curve


A-28
APPARENT RESISTIVITY IN OHM-CMS
ELECTRODE INTERVAL IN FEET
Full Curve
P-1 Curve
P-2 Curve

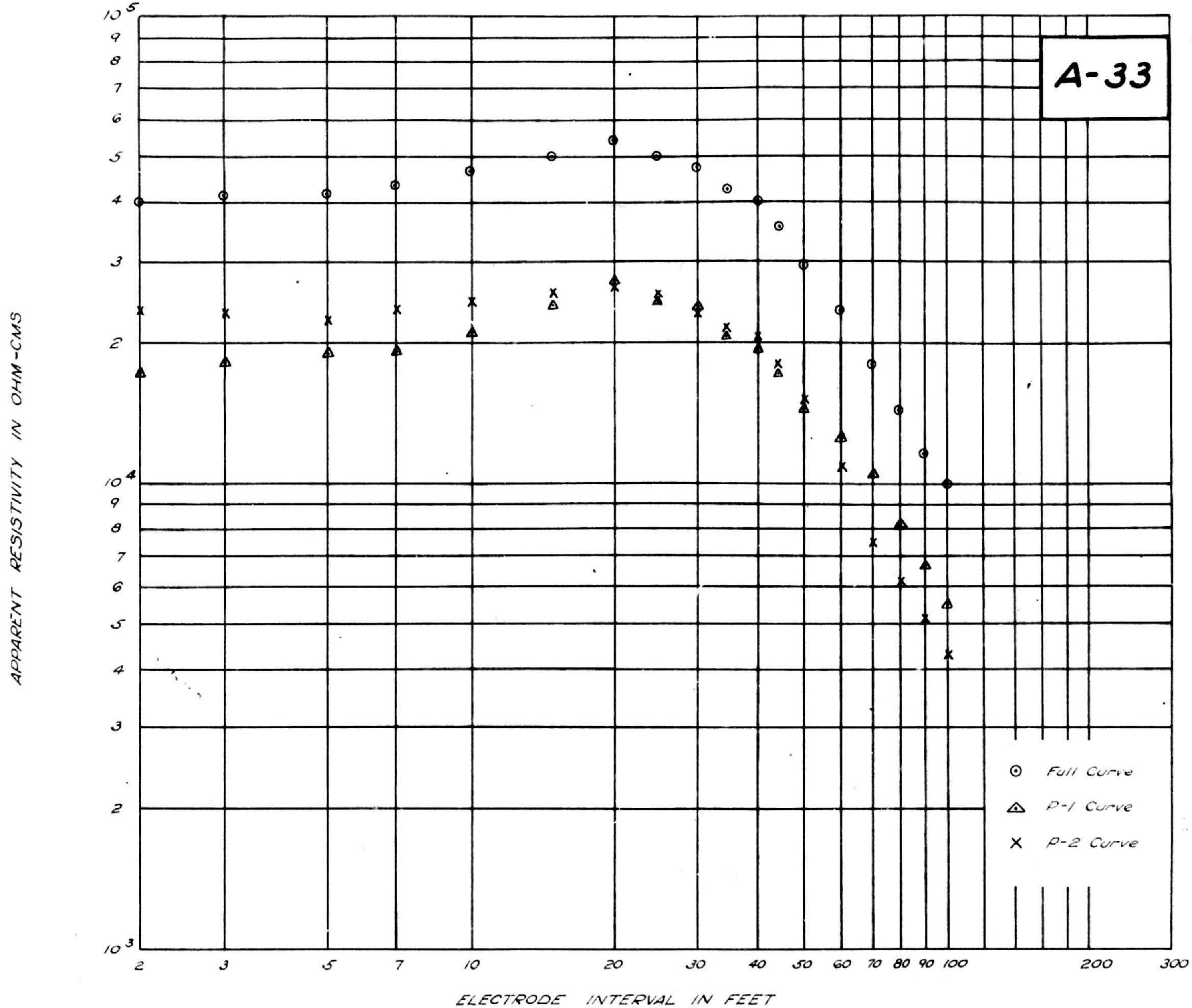

A-29
APPARENT RESISTIVITY IN OHM-CMS
ELECTRODE INTERVAL IN FEET
Full Curve
P-1 Curve
P-2 Curve

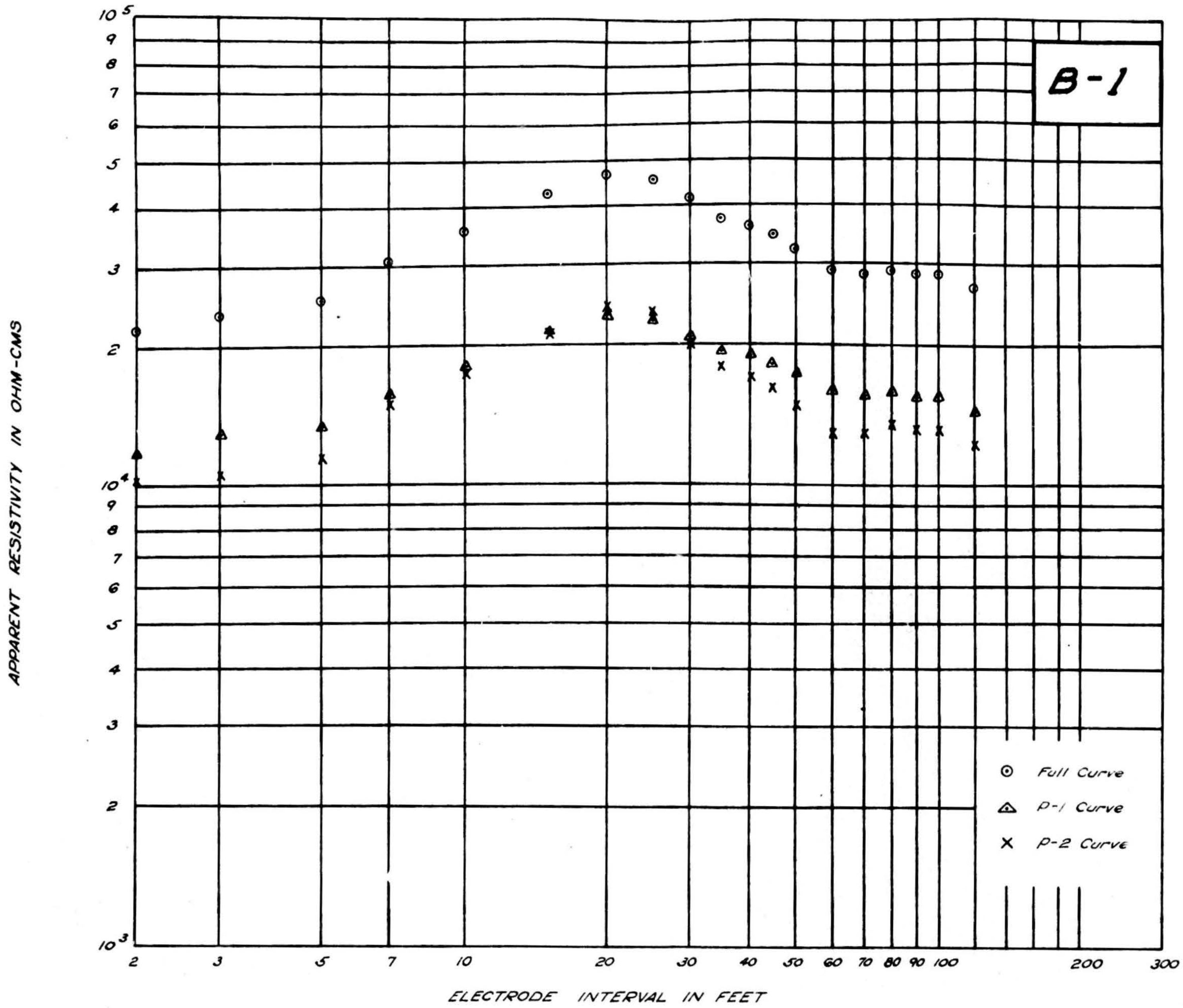

A-30
APPARENT RESISTIVITY IN OHM-CMS
ELECTRODE INTERVAL IN FEET
10^5
9
8
7
6
5
4
3
2
10^4
9
8
7
6
5
4
3
2
10^3
2
3
5
7
10
20
30
40
50
60
70
80
90
100
200
300
Full Curve
P-1 Curve
P-2 Curve

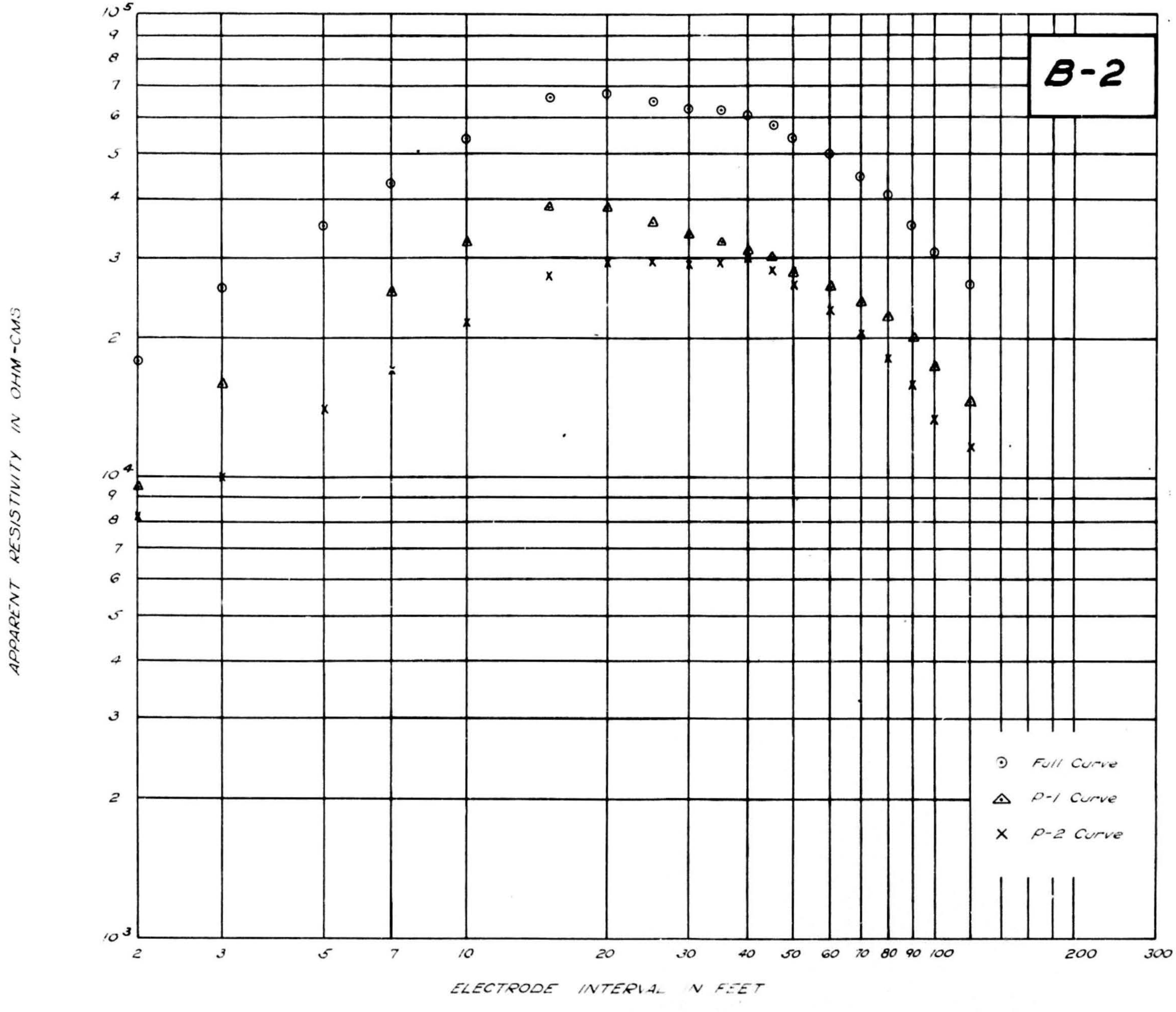

A-31
APPARENT RESISTIVITY IN OHM-CMS
ELECTRODE INTERVAL IN FEET
Full Curve
P-1 Curve
P-2 Curve
10^5
10^4
10^3
2
3
5
7
10
20
30
40
50
60
70
80
90
100
200
300



A-32
APPARENT RESISTIVITY IN OHM-CMS
ELECTRODE INTERVAL IN FEET
Full Curve
P-1 Curve
P-2 Curve


A-33
APPARENT RESISTIVITY IN OHM-CMS
ELECTRODE INTERVAL IN FEET
Full Curve
P-1 Curve
P-2 Curve


B-1
APPARENT RESISTIVITY IN OHM-CMS
ELECTRODE INTERVAL IN FEET
Full Curve
P-1 Curve
P-2 Curve


B-2
APPARENT RESISTIVITY IN OHM-CMS
ELECTRODE INTERVAL IN FEET
Full Curve
P-1 Curve
P-2 Curve
10^5
10^4
10^3
2
3
5
7
10
20
30
40
50
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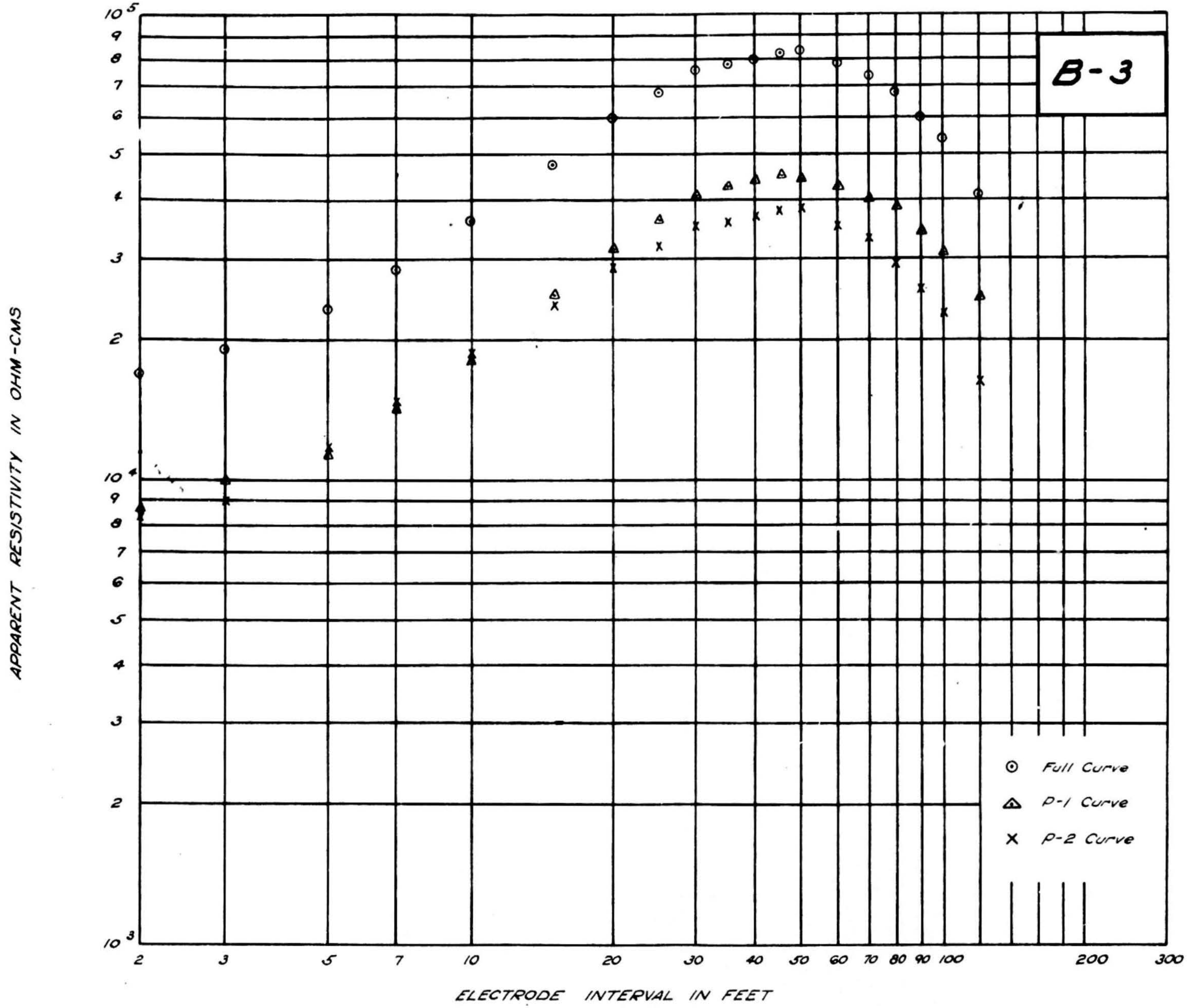
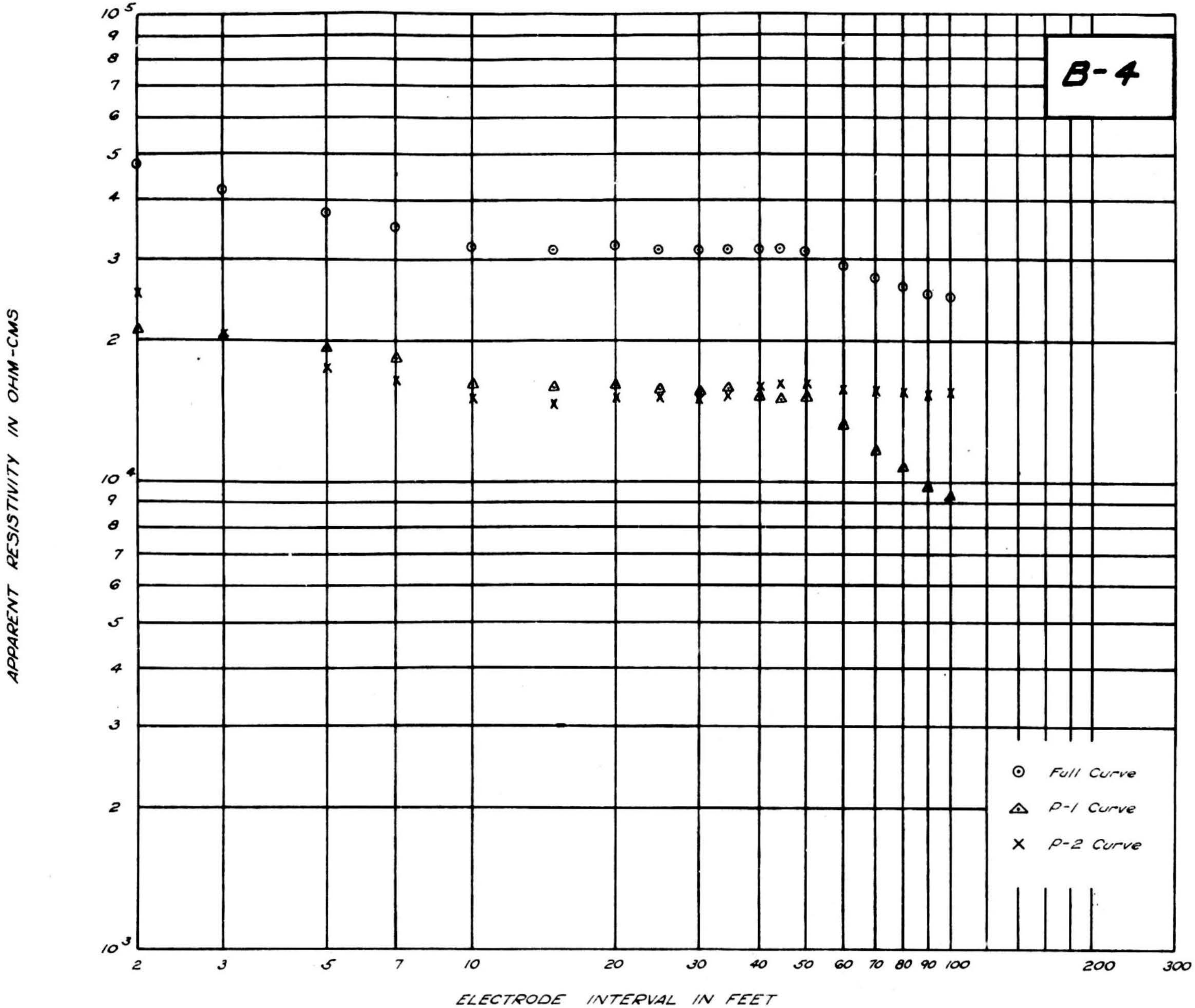
80
90
100
200
300


B-3
APPARENT RESISTIVITY IN OHM-CMS
ELECTRODE INTERVAL IN FEET
Full Curve
P-1 Curve
P-2 Curve
10^5
10^4
10^3
2
3
5
7
10
20
30
40
50
60
70
80
90
100
200
300


B-4
APPARENT RESISTIVITY IN OHM-CMS
ELECTRODE INTERVAL IN FEET
Full Curve
P-1 Curve
P-2 Curve
10^5
10^4
10^3
2
3
5
7
10
20
30
40
50
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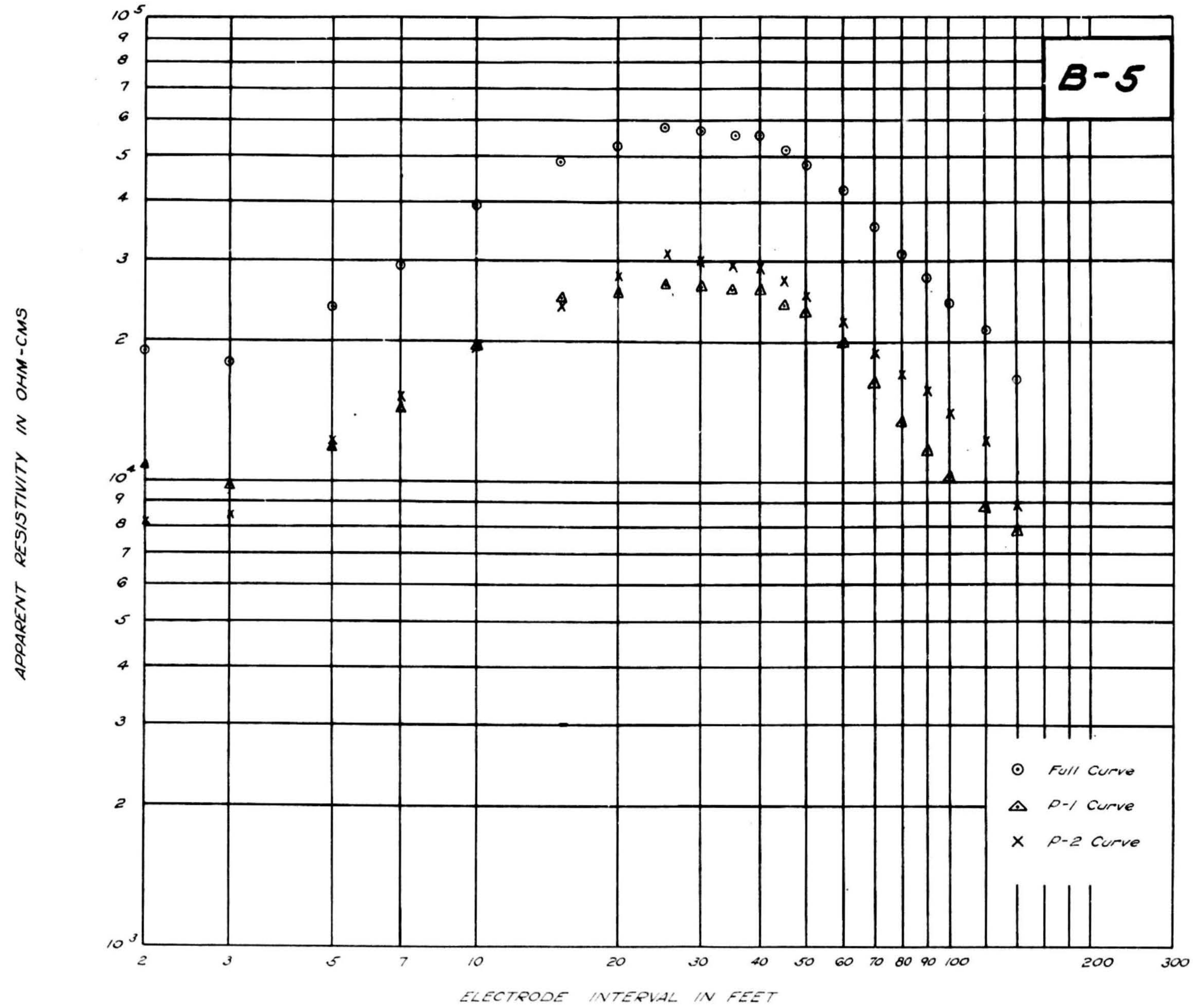
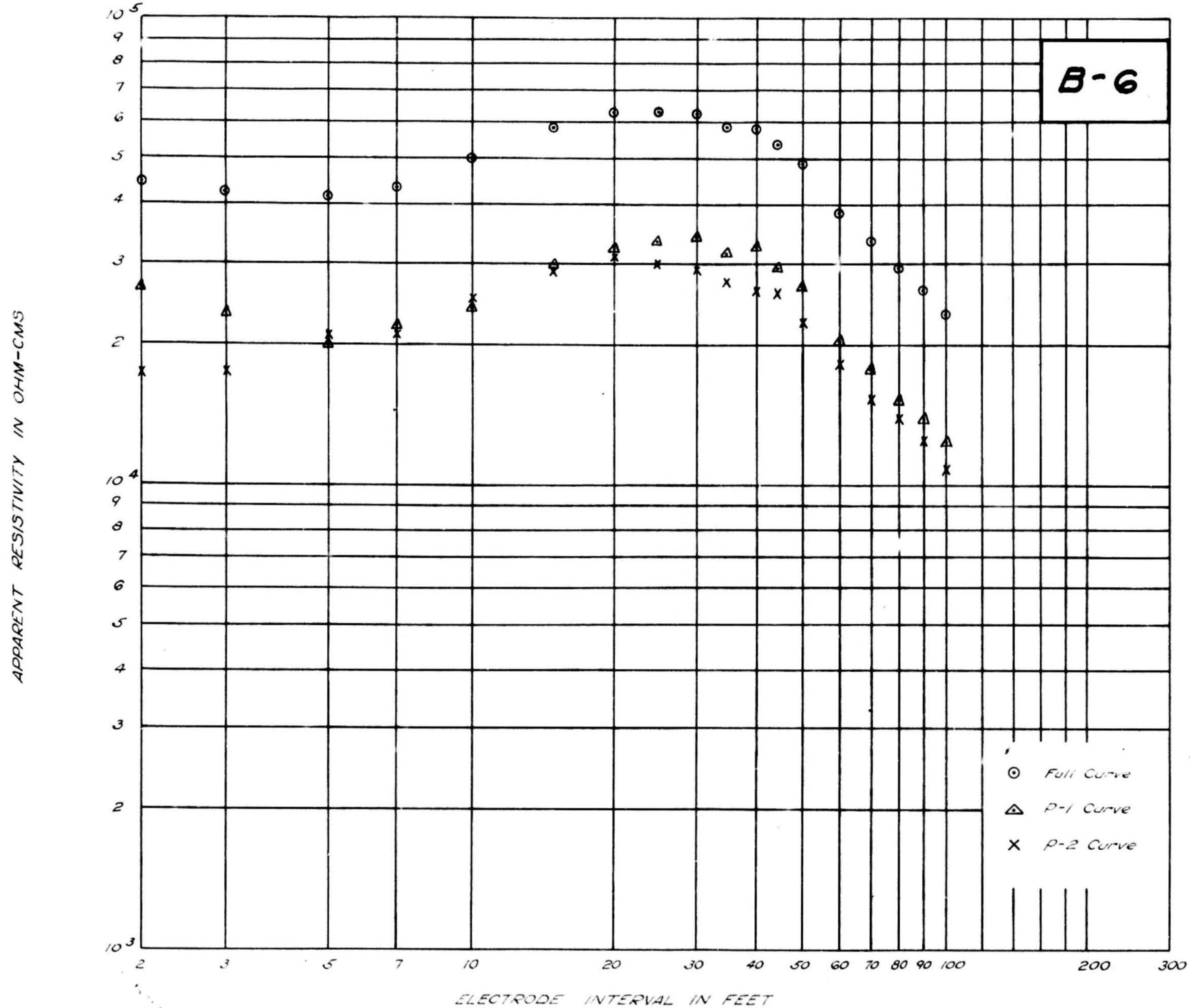
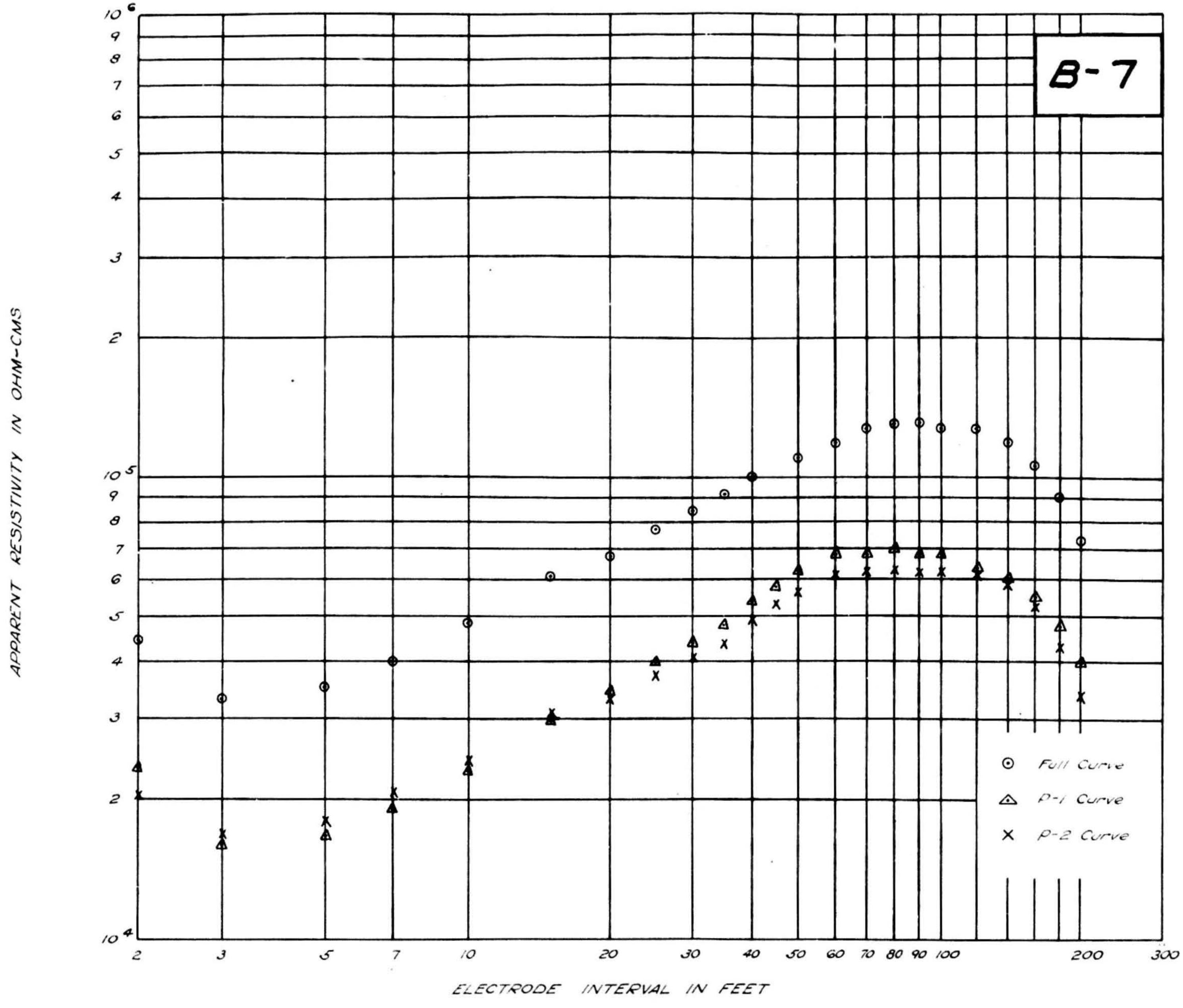
80
90
100
200
300



B-5
APPARENT RESISTIVITY IN OHM-CMS
ELECTRODE INTERVAL IN FEET
Full Curve
P-1 Curve
P-2 Curve


B-6
APPARENT RESISTIVITY IN OHM-CMS
ELECTRODE INTERVAL IN FEET
10^5
10^4
10^3
2
3
5
7
10
20
30
40
50
60
70
80
90
100
200
300
Full Curve
P-1 Curve
P-2 Curve


B-7
APPARENT RESISTIVITY IN OHM-CMS
ELECTRODE INTERVAL IN FEET
Full Curve
P-1 Curve
P-2 Curve
10^6
10^5
10^4
2
3
5
7
10
20
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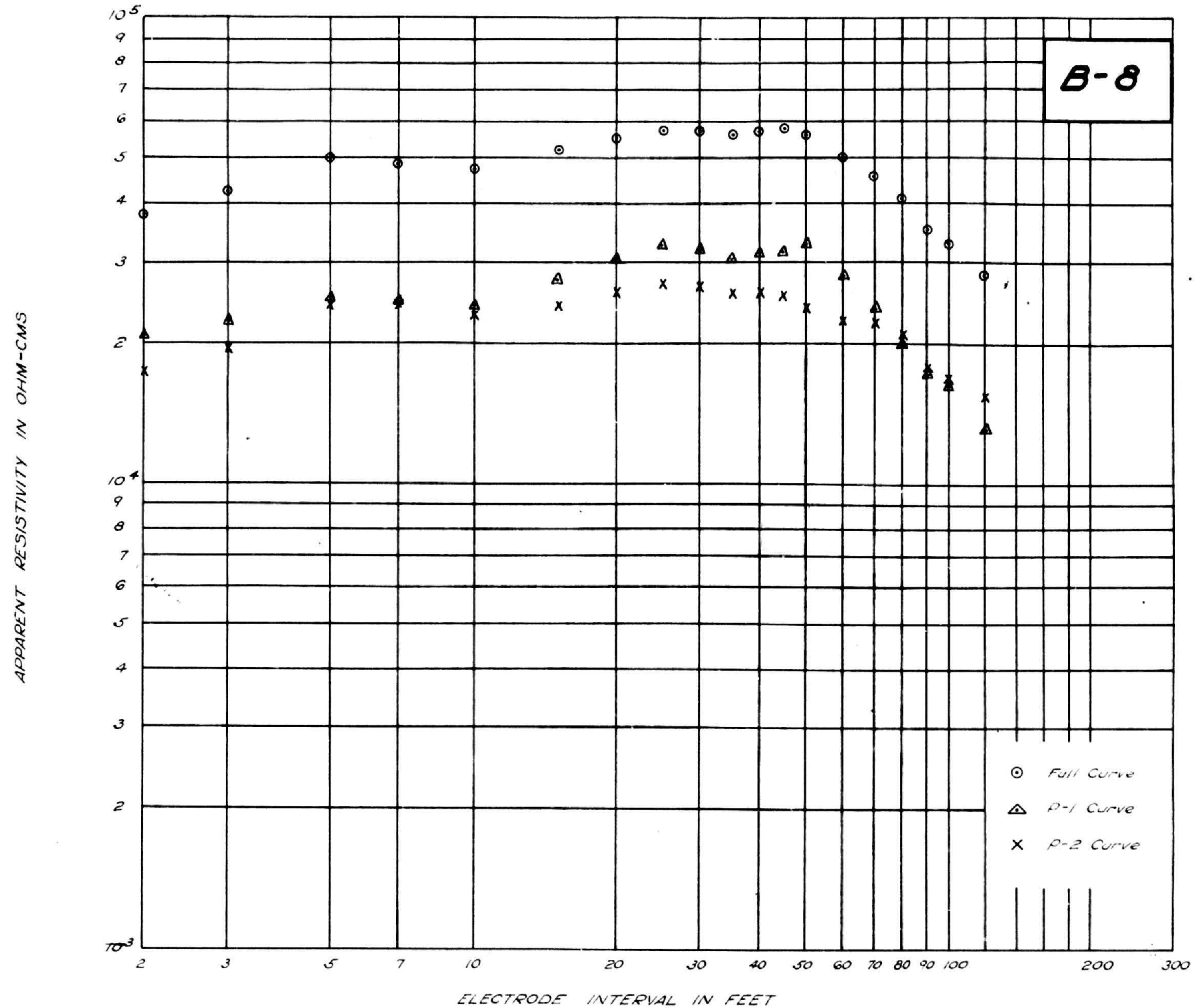
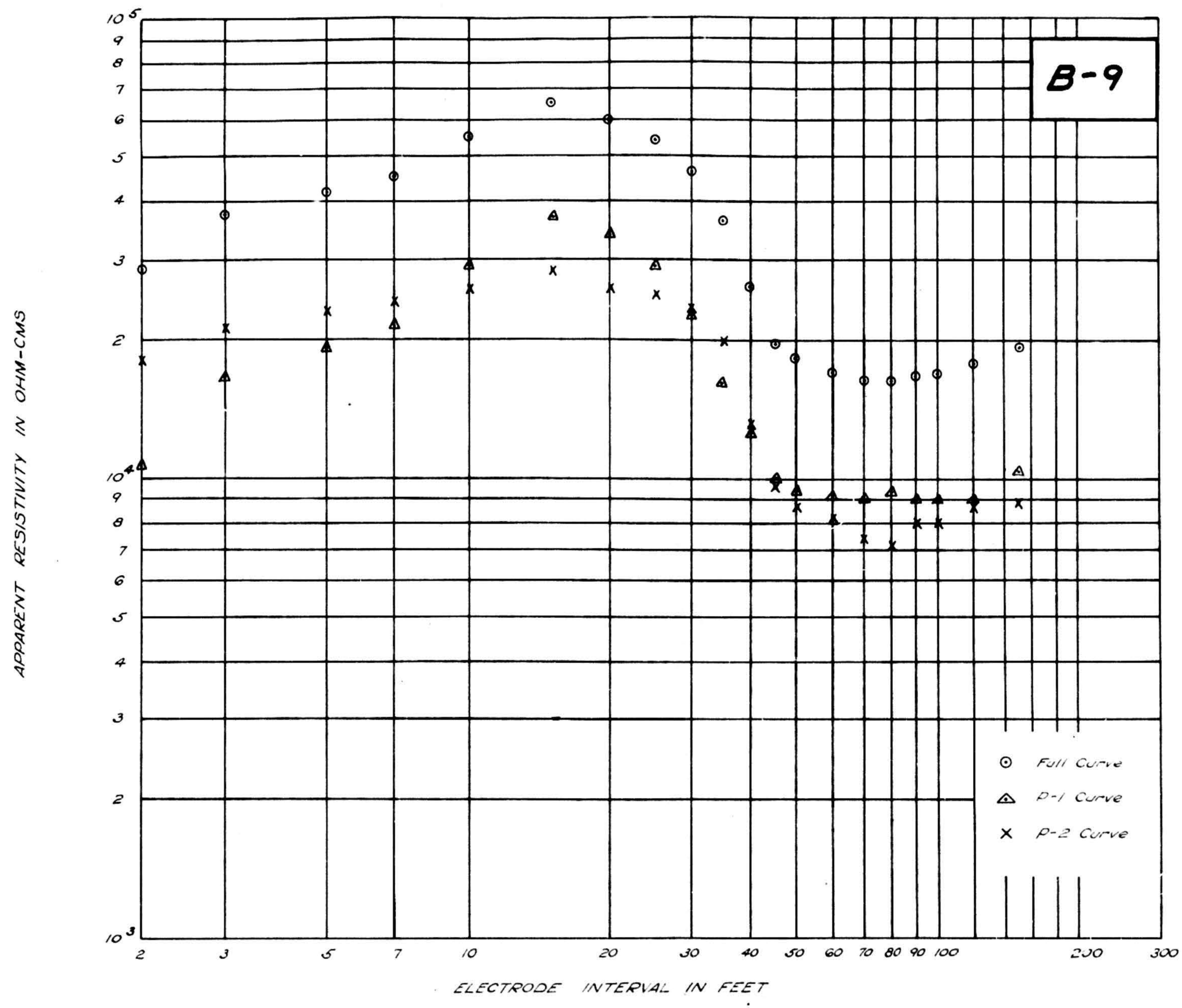
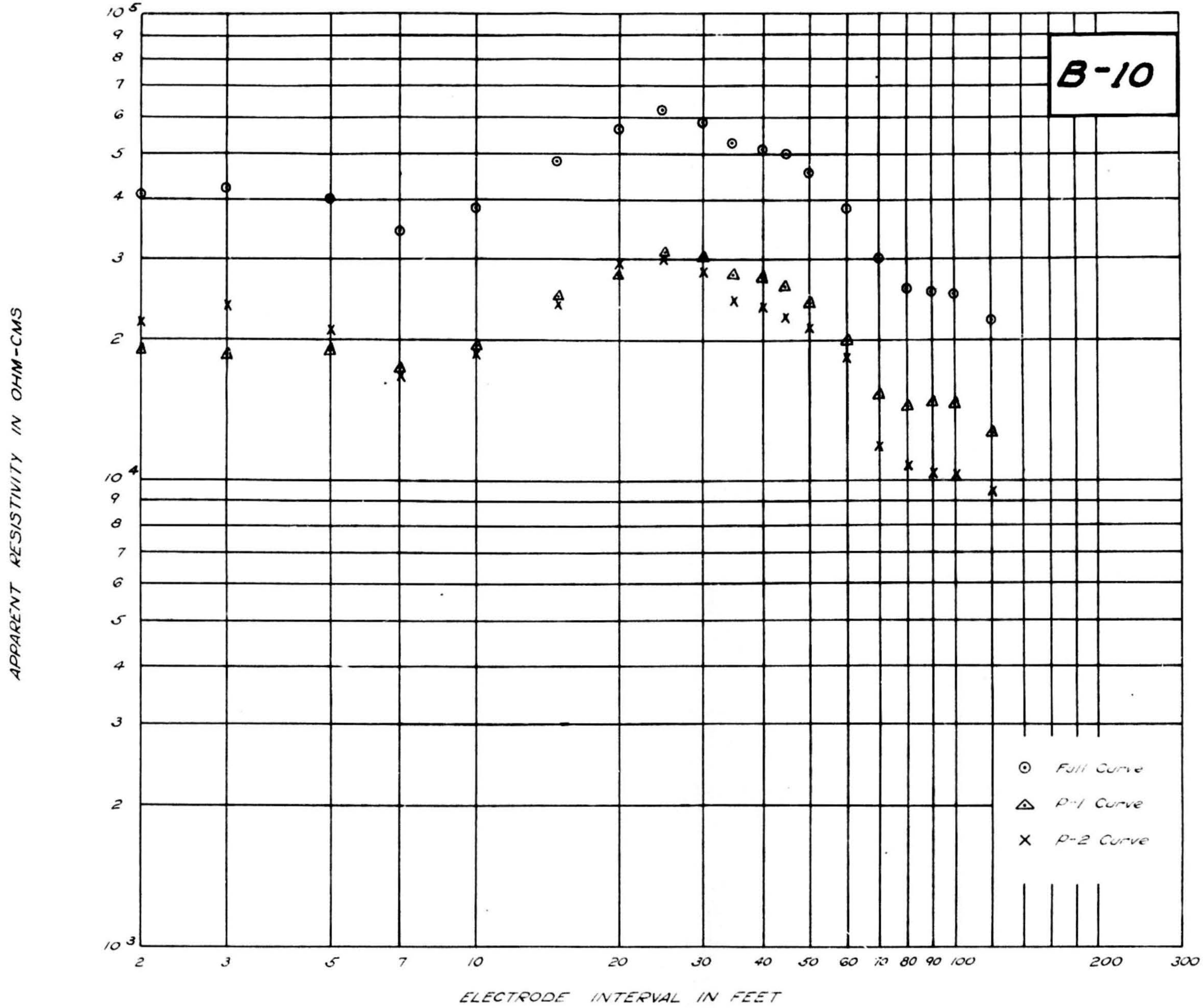
80
90
100
200
300

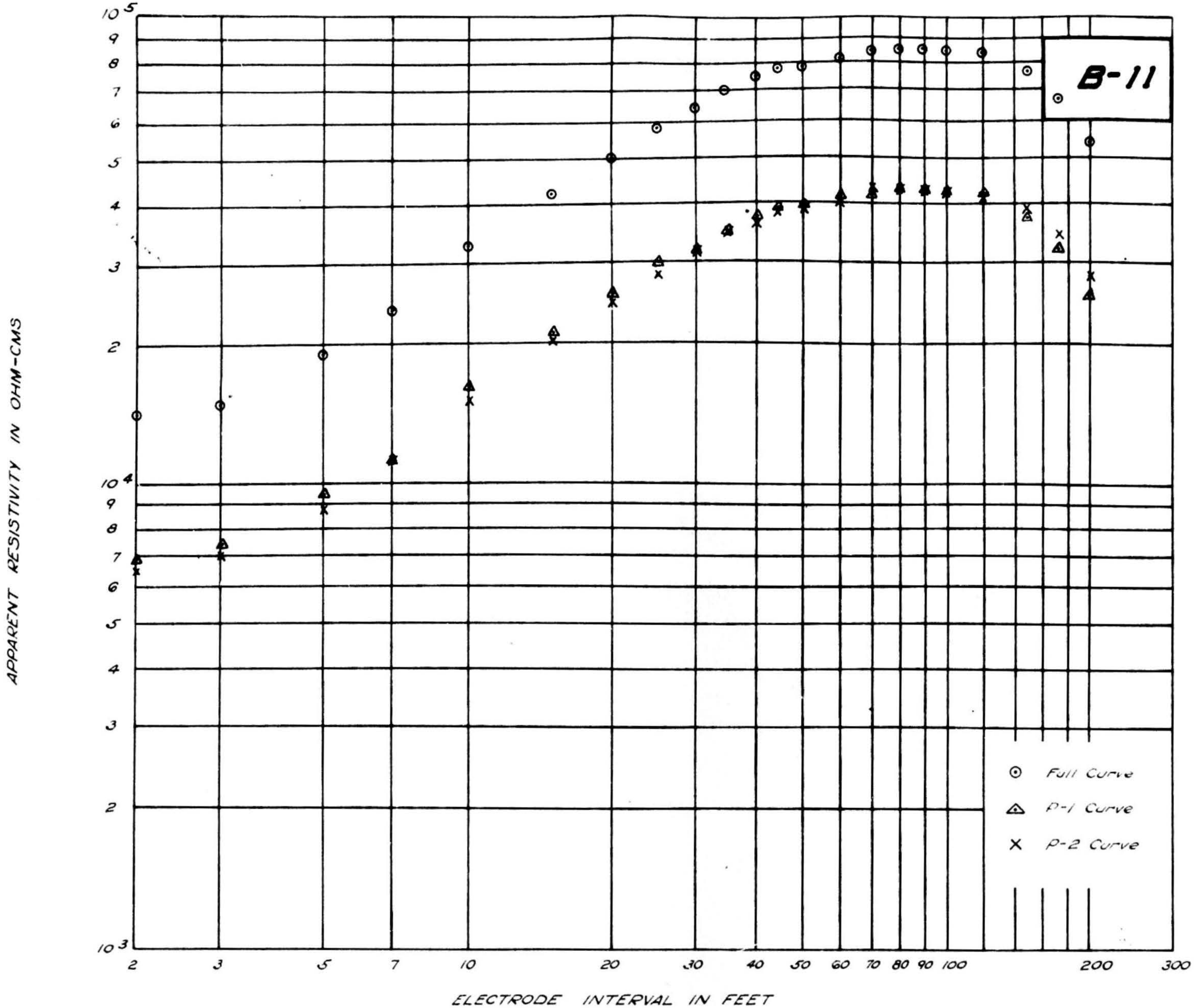

B-8
APPARENT RESISTIVITY IN OHM-CMS
10^5
9
8
7
6
5
4
3
2
10^4
9
8
7
6
5
4
3
2
10^3
2
3
5
7
10
20
30
40
50
60
70
80
90
100
200
300
ELECTRODE INTERVAL IN FEET
Full Curve
P-1 Curve
P-2 Curve



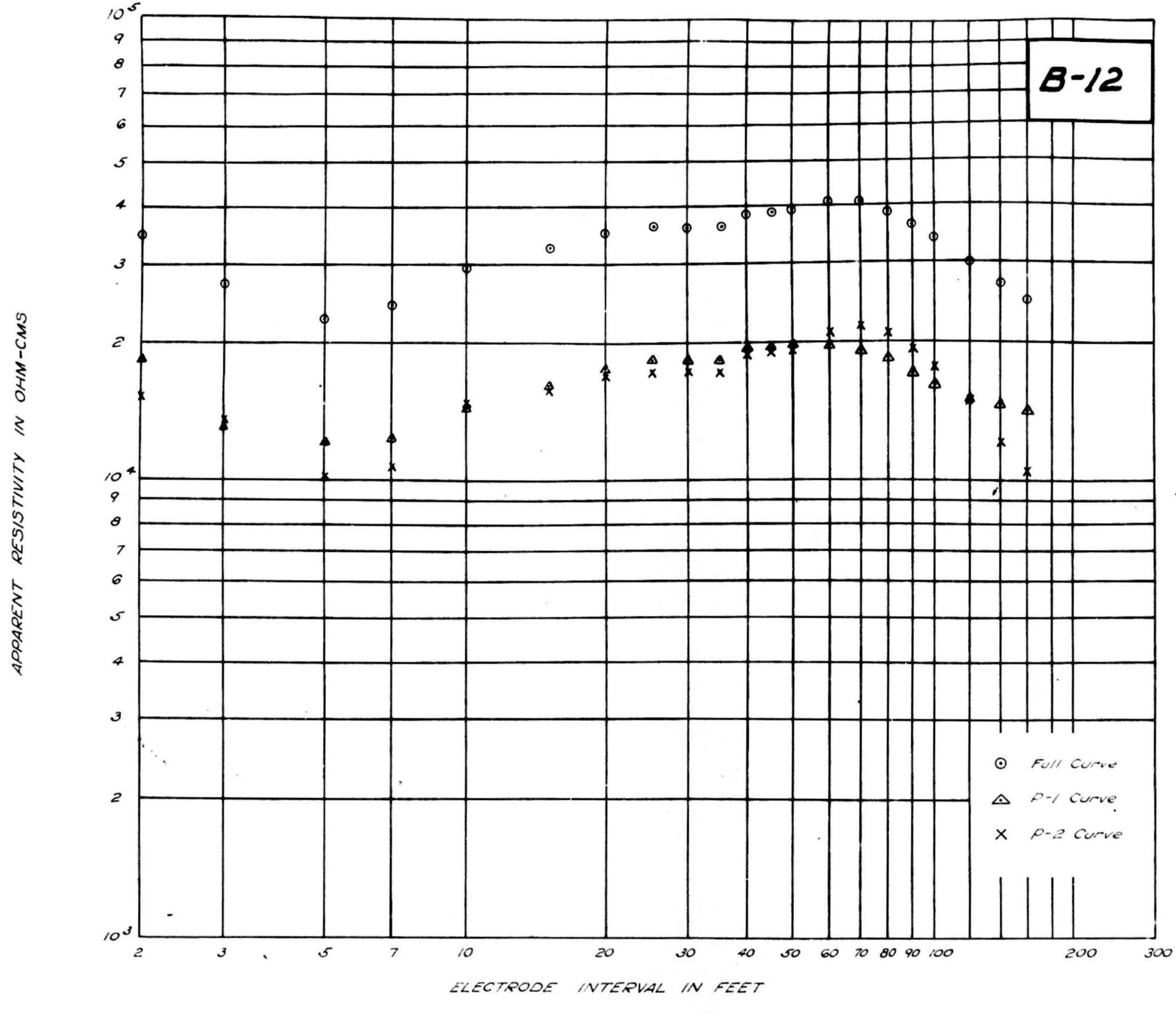
B-9
APPARENT RESISTIVITY IN OHM-CMS
ELECTRODE INTERVAL IN FEET
Full Curve
P-1 Curve
P-2 Curve



B-10
APPARENT RESISTIVITY IN OHM-CMS
ELECTRODE INTERVAL IN FEET
Full Curve
P-1 Curve
P-2 Curve



B-11
APPARENT RESISTIVITY IN OHM-CMS
ELECTRODE INTERVAL IN FEET
Full Curve
P-1 Curve
P-2 Curve


B-12
APPARENT RESISTIVITY IN OHM-CMS
ELECTRODE INTERVAL IN FEET
Full Curve
P-1 Curve
P-2 Curve
10^5
10^4
10^3
2
3
5
7
10
20
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200
300

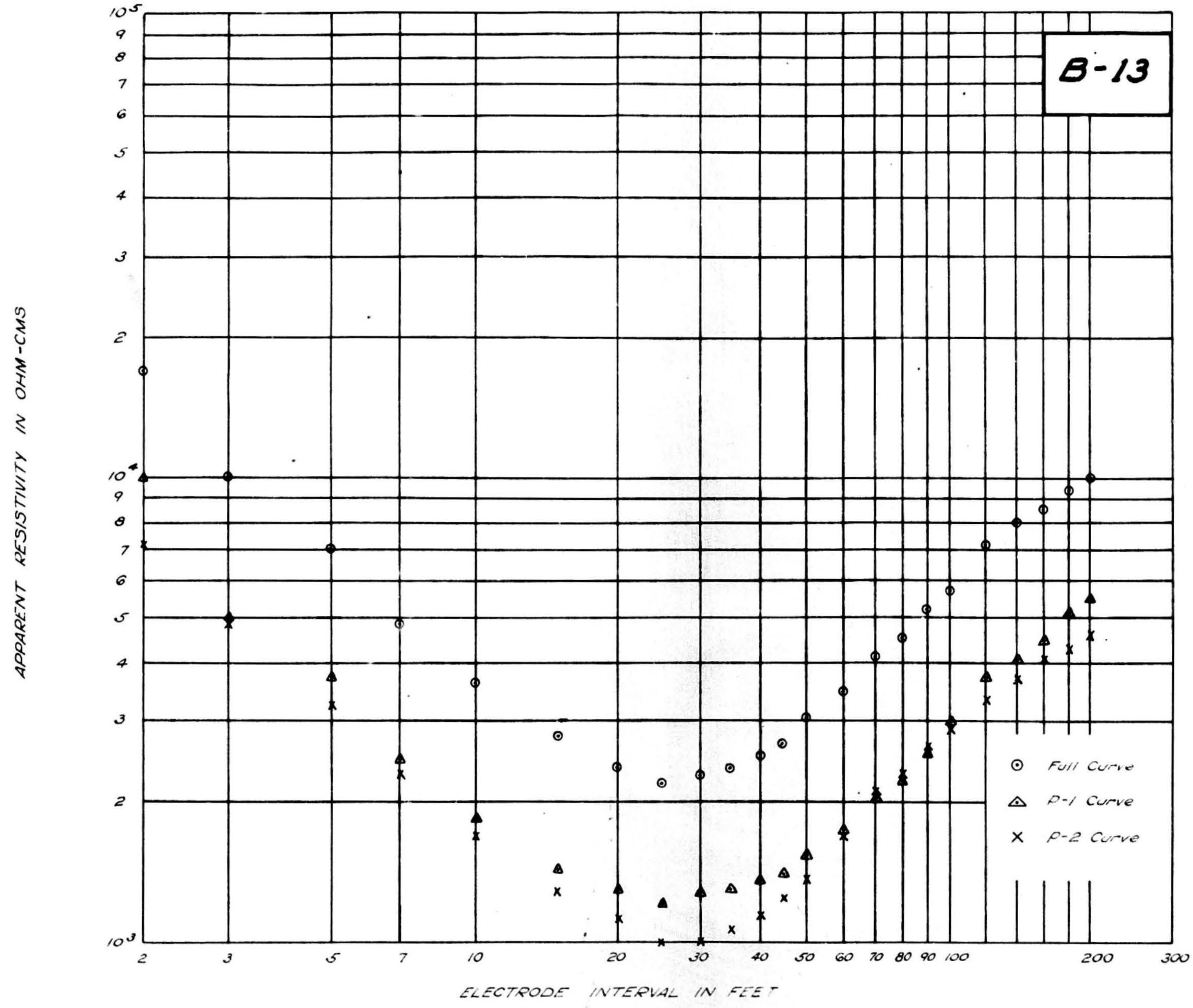
B-13
APPARENT RESISTIVITY IN OHM-CMS
ELECTRODE INTERVAL IN FEET
Full Curve
P-1 Curve
P-2 Curve
10^5
10^4
10^3
2
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FIGURE 1

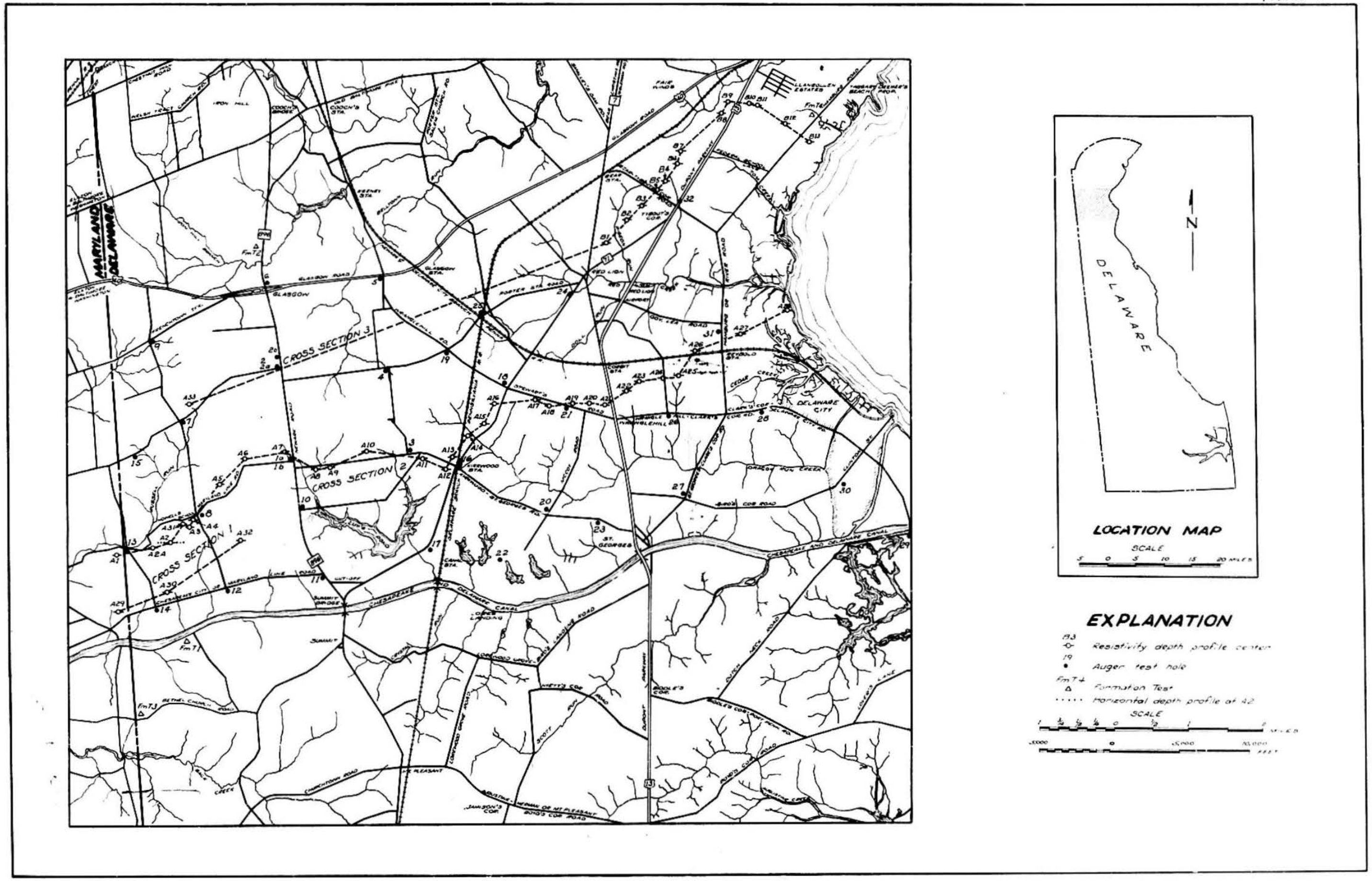

Figure 1. -Map showing location of the area in the state, area where resistivity measurements were made, resistivity depth profile line centers, formation tests, and auger hole locations.

FIGURE 2

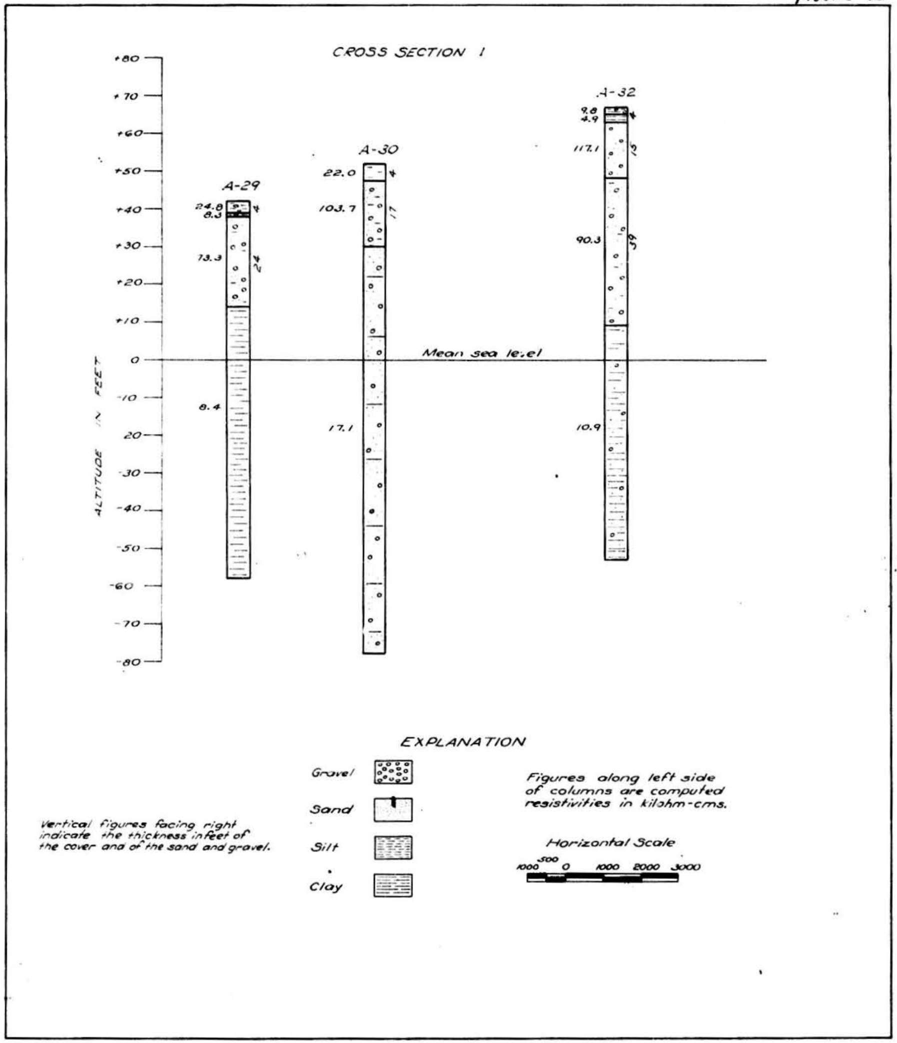

Figure 2.–Cross section 1 showing the interpretations of the apparent resistivity curves.

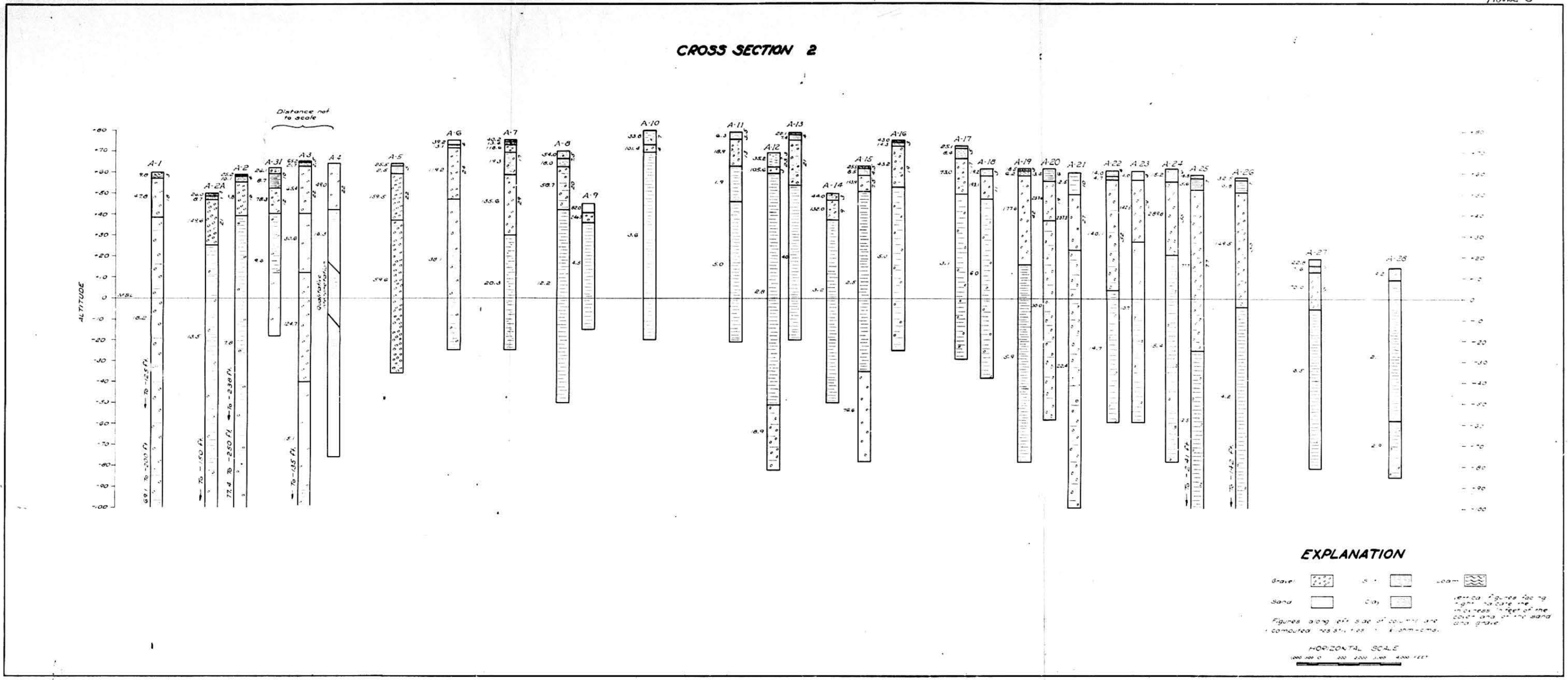

Figure 3.-Cross section 2 showing the interpretations of the apparent resistivity curves.

FIGURE 4

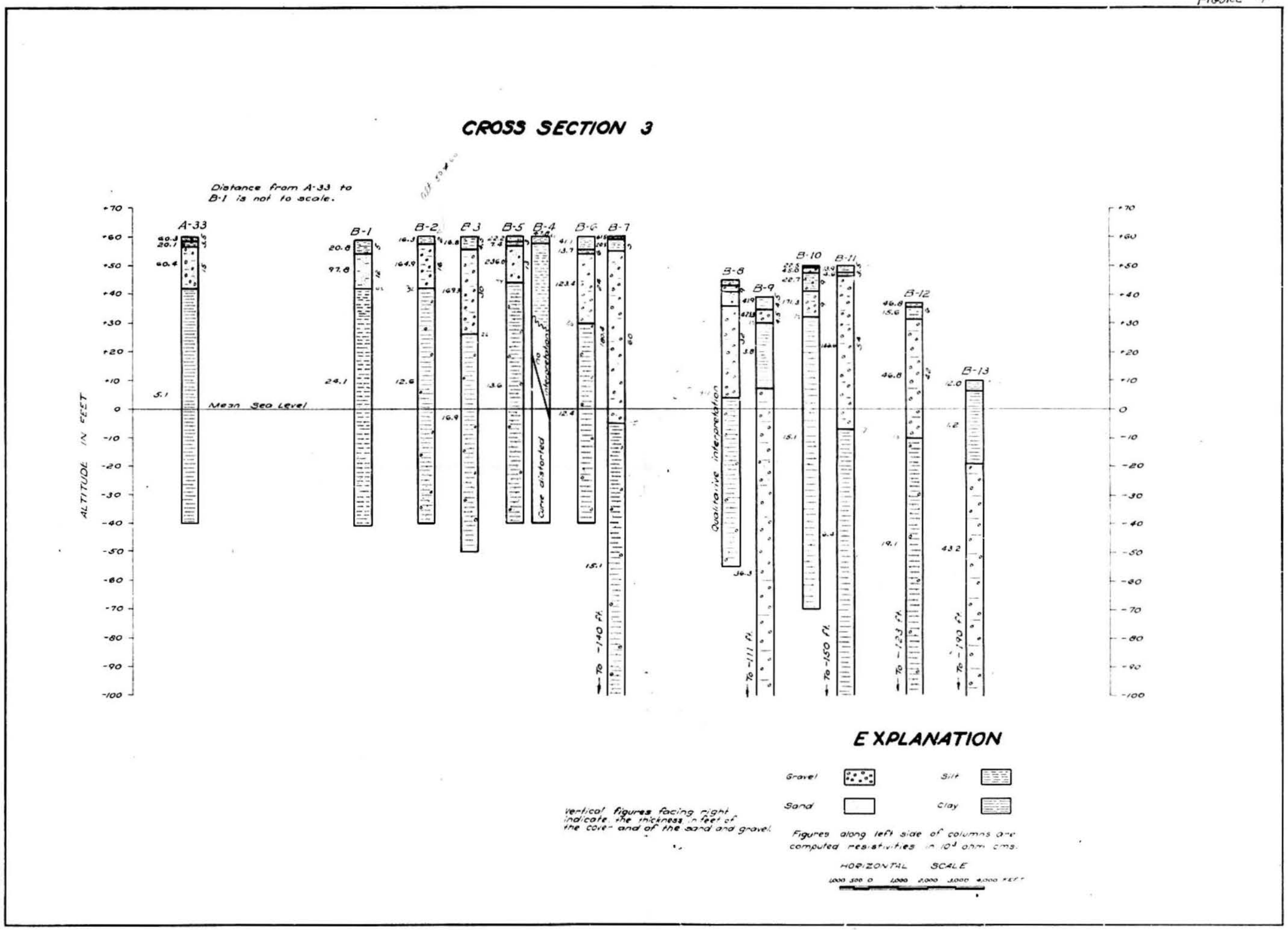

Figure 4.—Cross section 3 showing the interpretations of the apparent resistivity curves.

FIGURE 5

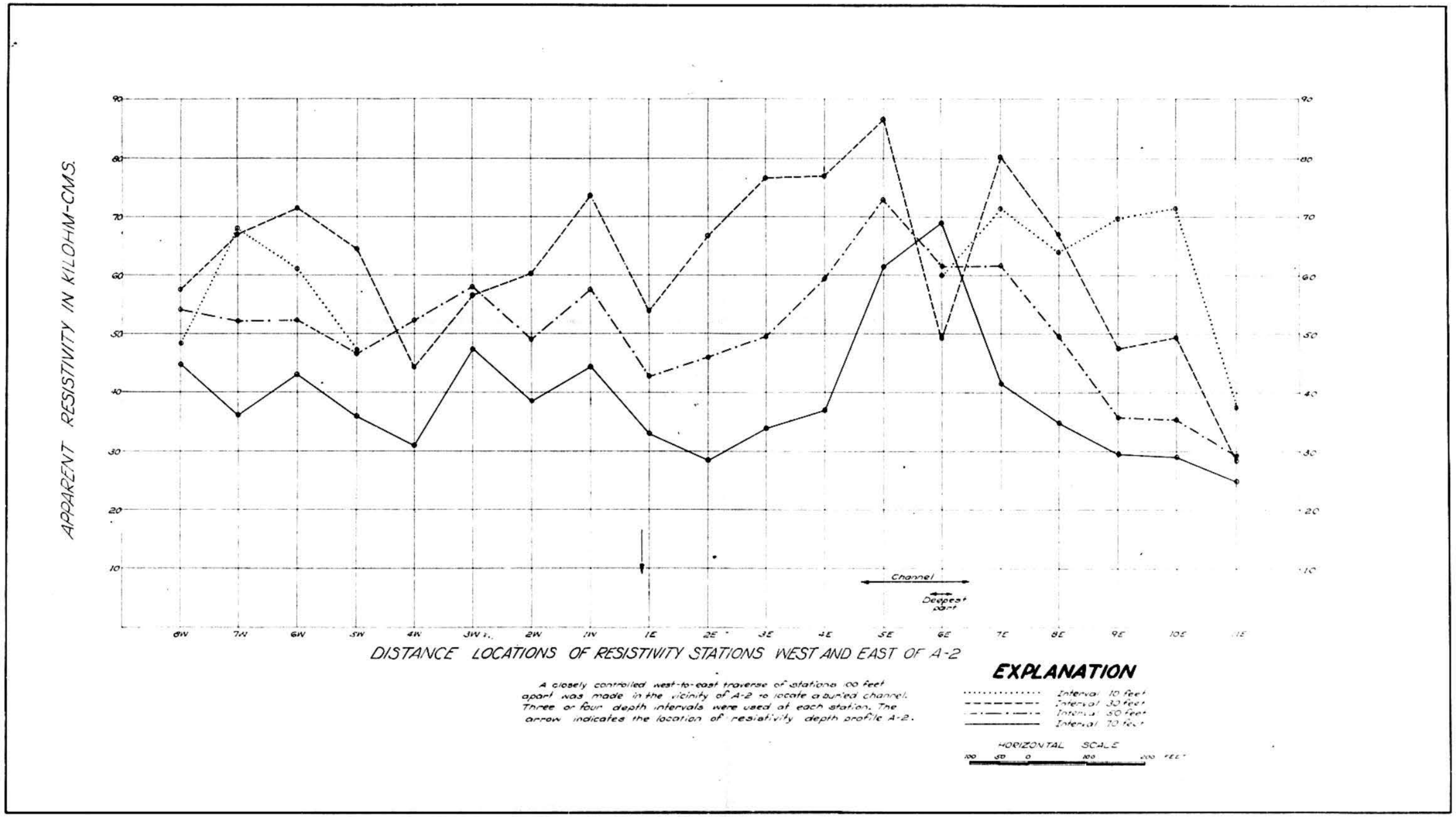

Figure 5.-Horizontal depth profile showing the variation of resistivity across a channel area.

FIGURE 6

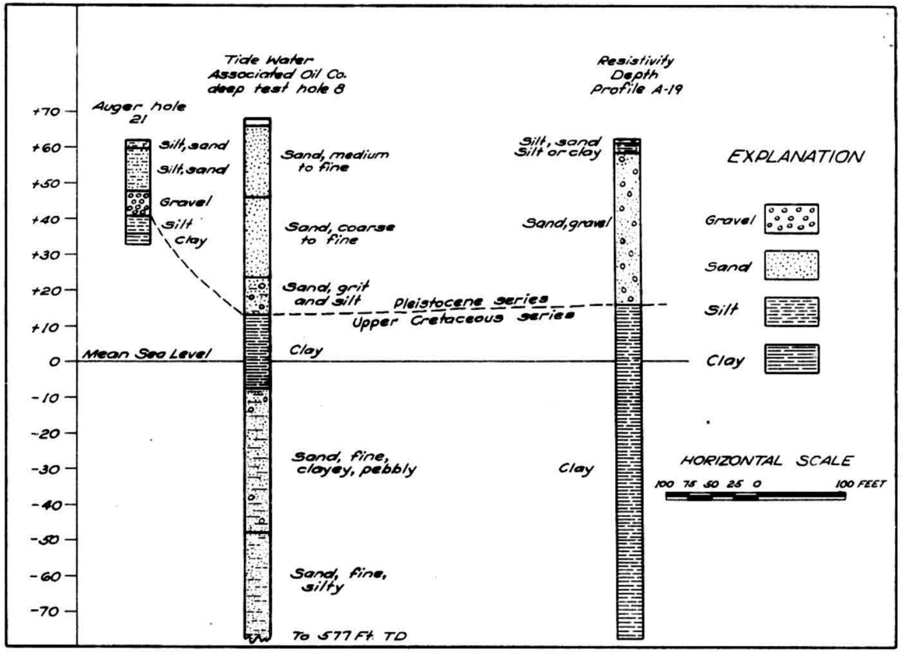

Figure 6.–Comparison of logs of test hole 21 and Tide Water Associated Oil Co. deep test hole 8 with interpretations of resistivity depth profile A-19.

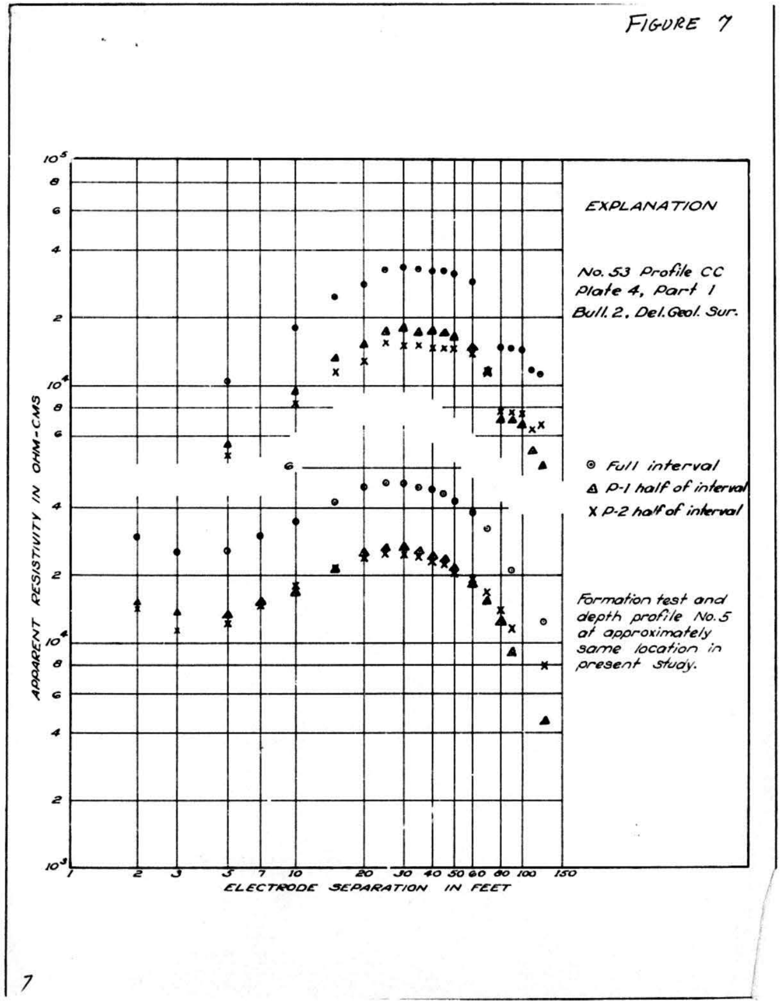

Figure 7.-Comparison of resistivity depth profile 53, Lines C and E from the Newark report with Formation Test 5 of present study.