EVALUATION OF BRIDGE DECK MEMBRANE SYSTEMS

AND MEMBRANE EVALUATION PROCEDURES

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16. Abstract This study was undertaken to evaluate the field performance of 24 membrane systems and to identify the limitations of the nondestructive tests currently being used to evaluate membrane waterproofing systems.

Chemical analysis of concrete samples taken from 131 locations on 37 bridges revealed chloride contamination at 44 percent of the locations tested. The chloride concentrations averaged 50 ppm or 0.20 pounds of chloride per cubic yard of concrete above base levels in the top inch of the contaminated samples. Satisfactory performance was obtained with several of the systems including the standard preformed sheet membranes which were free of chloride contamination at 84 percent of the test locations.

The validity of the nondestructive tests was determined by comparing results with the presence or absence of chloride contamination at the nondestructive test locations. Based upon the results obtained, the resistivity test has a reliability factor in the range of 60 percent. Variations in pavement porosity and moisture conditions are believed to be the major cause of incorrect resistivity readings. Electrical half-cell potential surveys were in agreement with core results which indicated chloride levels were insufficient to cause corrosion of the reinforcing steel. The performance of moisture detection strips as an indicator of membrane performance was generally unsatisfactory. The performance of the membrane systems in general did not indicate a protective course is required to extend their service life.

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EVALUATION OF BRIDGE DECK MEMBRANE SYSTEMS AND MEMBRANE EVALUATION PROCEDURES

INTRODUCTION

The premature deterioration of reinforced concrete bridge decks is considered to be the most serious problem currently facing Highway and Transportation Agencies throughout a large portion of the United States. Major factors contributing to the premature deterioration include poor concrete quality, improper construction practices, corrosion of the reinforcing steel, and freeze-thaw action.

Spalling or delamination of the concrete caused by corrosion of the reinforcing steel is considered to be the most serious form of deterioration. This problem has been directly related to large increases in the use of deicing chemicals by Highway Agencies[1-2].

Improvements in mix design and construction practices have been implemented to retard the rate of chloride intrusion and thus extend the time to corrosion of the steel. These include a reduction in the water-cement ratio and an increase in the concrete cover over the top mat of reinforcing steel. However, such procedures are not believed to be sufficient to protect structures located in areas given heavy applications of deicing chemicals since at least one study[3] has shown that chlorides are capable of migrating through one inch of typical bridge deck concrete in as few as seven days.

Other methods currently being tried in an attempt to prevent deck deterioration include the use of membrane waterproofing[4-6] mastic asphaltic concrete overlays (Gussasphalt)[7-8], low slump Portland Cement and latex modified concrete overlays[9], epoxy coated or galvanized reinforcing steel[10], cathodic protection[11], polymer, polymer modified, and polymer impregnated concrete[12], and internally sealed concrete[13]. Research is also in progress on both neutralization of chlorides and the removal of chlorides from contaminated concrete by electrochemical means[14].

SCOPE AND OBJECTIVE

Membrane waterproofing is currently the most widely used method of attempting to protect bridge decks from deterioration. Although limited use of membranes has been in effect for an excess of 20 years, the recent emphasis on bridge deck protection has resulted in a large increase in the number of products available with approximately 200 systems currently in place or available for use.

Many agencies are currently evaluating the performance of the various membrane systems using the electrical resistivity and steel potential tests established by the California Division of Highways[15-16]. The greatest single advantage of both tests is that they are nondestructive and can be carried out over extensive areas using any test pattern desired. Experience has shown that the electrical resistivity test is capable of indicating the presence or absence of holidays in a membrane when such tests are taken directly on the surface of the material. However, when resistivity reading are taken on a membrane which has been overlaid with a bituminous pavement, the results may be questionable depending on a variety of conditions. These include pavement porosity, wetting time, and moisture conditions in the overlay and/or at the membrane-overlay interface. The latter condition may create a circuit of low resistance which would bypass the assumed circuit through the membrane with false readings resulting. The possibility that such conditions may have been the cause of progressively lower readings on systems being evaluated on an annual basis has resulted in some agencies discontinuing the use of the resistivity test. In other cases, agencies have rejected further use of membranes based upon low resistance readings which may or may not be valid[17].

The objective of this study is to evaluate the field performance of membrane systems and to identify the limitations of the nondestructive tests currently being used to evaluate them. It will attempt to determine the validity of resistivity and half-cell corrosion readings by comparing such test results with chloride levels detected in concrete samples taken at nondestructive test locations. An additional objective is to evaluate the need for protective layers on membranes for long term performance.

EVALUATION PROCEDURE

Field tests for this investigation were conducted in 1975 and 1976 on bridges which were constructed between 1971 and 1974 and were waterproofed prior to being opened to traffic. The membrane systems used on the subject bridges were considered experimental, and therefore the applications were closely monitored and reported under the National Experimental and Evaluation Program #12, Bridge Deck Protective Systems[18-22]. The information included background data on deck construction, concrete test results, condition of the decks, membrane product data, laboratory test results, observations made during the membrane applications, cost information, preliminary field test results and discussions on the applications. Summaries of each membrane system were concluded with recommendations on further use.

The first year of the investigation included testing 22 bridges which had been waterproofed with 14 different membrane systems. The structures had been subjected to deicing salt applications for two to four winters. Evaluations the second year included retesting the original 22 decks plus the testing of 15 additional structures with ten different membrane systems which had been subjected to two winters of chemical applications. The physical test area on the decks consisted of a five foot grid pattern established at 1, 5, 10, and 15 foot offsets from the curb line and covered 40 to 50 feet in length. The one foot offset was selected because of the potential for leakage at the critical curb line area while testing at the 15 foot offset established membrane performance in the wheel path area which is subject to aggregate puncture under continuous traffic. The five and ten foot offsets were located in the breakdown lane. In most cases the test areas were located on the low end of the decks where chloride concentrations would be heaviest. Where superelevations resulted in drainage away from the breakdown lane, concrete samples for chemical analysis were obtained from the opposite curb line. The test areas also included portions of paved but otherwise unprotected approach slabs on 18 of the structures for comparitive purposes.

Resistivity readings were obtained using a Simpson Model 372 ohmmeter. The instrument has a six range selection with capabilities of measuring resistance values from 0.2 ohms to 50 megohms with an accuracy of ± 3% of arc. Prior to beginning the field tests, several checks were made to insure that moisture levels in the pavement were not sufficient to cause irregularities in resistance readings. This procedure was accomplished by attaching the ohmmeter leads to two test probes placed several feet apart rather than between a single probe and the reinforcing steel. Immediate low readings indicated excessive pavement moisture and further testing was postponed. When moisture levels were not considered to be a problem the test grid was marked on the pavement and pre-wet 9 inch by 7 inch by 1-3/4 inch polyurethane sponges were placed at each test location. The water contained two ounces of wetting agent (10 percent aerosol O-T) per five gallons of water. Care was taken to insure there was no run off of water from the sponges. The ground wire connection to the top mat of reinforcing steel was made via guard rail anchor bolts. To insure that a satisfactory ground was obtained, checks were made by connecting to drain scuppers or structural steel members.

Approximately 30 minutes after the sponges were placed, the initial set of resistance readings were obtained by moving from point to point with the sensor plate and convenience handle. Additional resistivity readings were obtained at 30 minute intervals until the readings stabilized. Testing was normally carried out over a 1-1/2 to 2 hour period although it was found that most of the readings became stable within one hour. Experience with the test procedure revealed that it was necessary to re-wet the surface of each sponge just prior to taking a series of readings. Failure to do so would often result in higher resistance readings than those obtained earlier due to evaporation of moisture from the surface of the sponges.

Electrical half-cell potential readings were generally taken during the interval between the first and second resistivity test series. The readings were obtained with a copper-copper sulfate half-cell and a Hewlett Packard DC Null Voltmeter, Model 419A. Resistance readings were also taken on moisture detection strips where applicable.

Concrete samples were obtained from resistivity and half-cell potential test locations at 1, 5, and 15 foot offsets from the curb line. The selection of specific core locations was made upon completion of nondestructive testing. On systems where the resistivity readings varied, the sample locations were selected to include one or more areas where low readings were obtained. The concrete samples were procured from 1 inch and 2 inch depths with the aid of a rotary hammer and 3/4 inch carbide tipped twist drill. Removal of the overlying bituminous pavement was accomplished by coring and cleaning with a blow out bulb. A depth gauge attached to the drill was used to obtain the proper depth. A metal template was used to catch the pulverized sample brought up by the bit. Material remaining in the core hole was removed with a scoopula and blow out bulb. Core holes were patched with a quick-set cement.

A wet chemical analysis was used to determine the total chloride content in the recovered concrete samples. The basic procedure consisted of freeing chloride ions with nitric acid, adding silver nitrate solution, filtering, and titrating with a solution of ammonium thiocyanate (see test procedure in Appendix D).

DISCUSSION

Membrane Performance

A major objective of the study was to determine the waterproofing effectiveness of the membrane systems. With the exception of a membrane evaluation summary on Table 3, page 13, no attempt will be made to discuss factors such as cost, difficulty of application or other characteristics of the individual systems, since such information was covered in initial reports covering the installation of the membrane systems. Since the validity of resistivity readings was one of the subjects under question, the performance of the membranes will only be discussed in relation to the presence or absence of chloride above base levels as determined by chemical analysis of core samples.

The 24 different membrane systems under evaluation were exposed to an average of 2.3 winters of deicing salt applications when field tests were conducted in 1975 and 3.3 winters in 1976. Chloride applications during the winters of 1971-1972 through 1975-1976 averaged 32.2 tons per two lane mile. Although field testing included a significant number of bridges, only 8 of 24 membrane systems were evaluated on more than a single structure. For this reason, the performance of the membrane systems will be discussed in relation to the class of material rather than by individual products. The systems were broken down into seven classes as follows:

1. Standard Preformed Membranes - Three preformed sheet membranes no longer considered experimental under FHWA NEEP #12.
2. Miscellaneous Preformed Membranes - One experimental preformed sheed membrane system.
3. Project 12-11 Preformed Membranes - Five vulcanized, cured or cross-linked elastomer systems selected as the most promising membrane materials under phase one of the NCHRP Project 12-11.
4. Polyurethanes - Three asphalt modified, tar modified, or 100 percent solids polyurethane systems.

5. Thermoplastic or Thermosetting - Three hot applied rubberized-asphalt, mopped asphalt and glass fabric or PVC polymer systems.

6. Epoxys - Seven solvent cut, coal tar modified or 100 percent solids epoxy systems.

7. Emulsions - Two systems consisting of two coats of tar emulsion or five coats of tar emulsion and two layers of glass fabric.

The standard preformed sheet membranes provided the best performance with 84 percent of the concrete samples free of chloride contamination. Four of the five samples with contamination were located one foot from the curb line. The results point out the difficulty of obtaining a complete seal along the deck-curb joint and lower portion of the curb section which consists of a rough granite face on most Vermont bridges. Curb line leakage on later installations will hopefully be prevented with the use of compatible liquid polyurethane sealants applied along the membrane perimeter and vertical curb face on two of the three systems. The occasional formation of blisters which occured prior to, during, or after the pavement installations has not resulted in leakage to date, based upon the field test results obtained.

The single miscellaneous preformed membrane was not recommended for further use based upon observations made during the installation. Chloride contamination found at all sample locations after two winters further supports the initial recommendations.

The National Cooperative Highway Research Program Project 12-11 preformed sheet membranes have prevented chloride intrusion on 67 percent of the cores recovered after two winters of deicing salt applications. Leakage detected on three of the five systems may have been due in part to blisters which occured during and after the installation of the first one inch course of pavement.

Three polyurethane membrane systems have prevented chloride contamination on 57 percent of the samples obtained from four decks exposed for an average of three winters. Chloride levels in the top inch of contaminated cores were limited to 32 parts per million (ppm) over base chloride levels or 0.13 pounds per cubic yard of concrete. The low chloride levels and random occurance may have been due to the pinholing and bubbling which occured during the application of the liquid applied materials.

Hot applied materials and epoxy systems had 50 and 43 percent of the samples respectively free of chloride contamination. Once again, chloride levels ranging from 0.16 to 0.22 pounds per cubic yard of concrete suggest that the leakage relates to pinholing or blistering which occured with most of the systems.

Contamination was found on 61 percent of the samples obtained from six bridges treated with two emulsion systems. Leakage along curb line areas where surface drainage is normally poor accounted for 46 percent of the contaminated samples.

The performance of individual membrane installations can be seen in Appendix A. A summary of membrane performance by class is also shown on Table 1, page 11. The table reveals that chloride contamination was present at 44 percent of all locations tested. It should be noted that the concrete samples were obtained from areas where low resistivity readings were obtained whenever possible, rather than by random sampling. The amount of chloride above the base level averaged 50 ppm or 0.20 pounds of chloride per cubic yard of concrete in the top inch of the contaminated samples. Seven of the 131 test locations exhibited chloride levels over one-half pound in the top inch of concrete with the highest reading recorded at 1.03 pounds. Contamination in the second inch of concrete was found on 32 percent of the cores with chloride levels averaging 36 ppm above base levels or 0.14 pounds per cubic yard of concrete. Chloride levels slightly over one-half pound were recorded on two samples. The difficulty of obtaining a satisfactory seal along the curb lines was evidenced by the detection of contamination in 66 percent of the cores taken at the one foot offset. Such cores made up 48 percent of all the contaminated samples while 30 percent were located at the 5 foot offset and the remaining 22 percent were at the 15 foot offset.

The field testing included 19 bridges which had paved but otherwise unprotected approach slabs (Table 2, page 12). 89 percent of the concrete samples taken from the approach slabs disclosed contamination in the top inch of concrete. The levels ranged from an average of 0.31 pounds to 0.78 pounds of chloride per cubic yard of concrete above base levels. The average of all the contaminated samples was 0.50 pounds of chloride. The relatively low level of chloride contamination over an average of 3.5 winters can be attributed to the waterproofing characteristics of the bituminous pavements. The overlays consisted of two one-inch courses and included 1-1/2 percent asbestoes fibers by weight in the bottom course on eight of the 18 areas tested. Concrete samples taken at the same five foot offset from the curb line on the membrane systems disclosed contamination on 61 percent of the specimens. The levels ranged from an absence of contamination to 0.31 pounds with an average of 0.20 pounds of chloride above base levels. The most noteable contrast between protected and unprotected areas occured on the three structures treated with the standard preformed membranes. Concrete samples taken from the bridge decks were free of chloride contamination while an average of 0.78 pounds of chloride was detected in the top inch of the cores taken from the approach slabs.

In general, the test results indicate that few of the membrane systems under evaluation were able to seal off all areas of the bridge deck surfaces. Such results were not surprising considering that 17 of the 24 systems were not recommended for further use based upon initial observations and test results. The remaining seven systems recommended for use with or without limitations have generally performed well with chloride contamination limited to 18 percent of the areas tested. Where leakage did occur, chloride levels averaged 0.14 pounds in the top inch of concrete. Such chloride concentrations are not significant when compared with the one to two pound concentrations required at the rebar level in order to create active corrosion of the steel. The results indicate the most effective membrane systems have prevented or reduced the level of chloride penetration to the extent that they may be considered an acceptable bridge deck protective system until other more effective methods or systems become available.

TABLE 1

SUMMARY OF MEMBRANE PERFORMANCE BY CLASS
BASED UPON CHEMICAL ANALYSIS OF CORES

Membrane Type	Average Winters Cl^- Applied	Average Base Cl^- in ppm	% Cores OK	% Cores Contaminated	*Ave. Cl^- above base level in contaminated cores ppm	#/cy
Standard Preformed	2.5	42	84	16	37	0.15
Miscellaneous Preformed	2	55	0	100	39	0.22
Project 12-11 Preformed	2	66	67	33	58	0.23
Polyurethane	3	48	57	43	32	0.13
Thermoplastic or Thermosetting	3.3	37	50	50	40	0.16
Epoxy	2.7	36	43	57	55	0.22
Emulsion	3.8	30	39	61	75	0.30
Weighted Average of All Systems	2.8	42	56	44	50	0.20

* Results based on samples taken from the top inch of concrete.

TABLE 2

MEMBRANE PERFORMANCE CONTRASTED
WITH UNPROTECTED APPROACH SLABS

1976 Test Results on Top Inch of Concrete

Membrane Type	No. of Structures	Average Winter's Cl^- Applied	% Cores Contam-inated at 5' offset	Ave. Cl^- above base level in contaminated cores at 5' offset #/cy	% Cores Contam-inated on app. slabs offset	Ave. Cl^- above base level in contaminated cores on app. slabs #/cy offset
Standard Preformed	3	3.3	0	0	100	0.78
Polyurethane	3	3.7	66	0.18	100	0.59
Thermoplastic or Thermosetting	2	3	100	0.19	100	0.44
Epoxy	6	3.3	67	0.25	83	0.45
Emulsion	4	4	75	0.31	75	0.31
Weighted Average		3.5	61	0.20	89	0.50

TABLE 3
MEMBRANE EVALUATION SUMMARY

Membrane Type	Ease of Application	Flexibility	Bond & Seal at Curb	Blisters or Pinholes	Bond between Concrete Membrane & Pavement	Problems with Pavement Application	Cost per sy	Overall Performance	Recommendation
Standard Preformed	easy	good	fair	yes/ no	fair/ good	occ.	$ 4.50	good	Continue Use
Miscellaneous Preformed	easy	good	poor	yes/ no	poor/ fair	yes	$ 5.00	poor	Not recommended for use
Project 12-11 Preformed	hard	exc.	fair	yes/ no	good/ good with prot. boards	yes	$10.65	fair to good	Not recommended unless other systems prove to be unsat.
Polyurethane	easy	good	exc.	no/ yes	good/ poor	occ.	$ 5.19	fair	Restrict Use
Thermoplastic or Thermosetting	hard	poor to good	fair	no/ yes	fair/ fair	occ.	$ 4.00	fair	Restrict Use
Epoxy	easy	poor	fair	no/ yes	good/ poor	no	$ 9.42	poor	Not recommended for use
Emulsion	very easy	poor	poor	no/ no	good/ good	no	$1.32/ $3.50	poor	Restrict Use

Validity and Limitations of Electrical Resistivity Test Results

The method used to establish the validity of electrical resistivity readings was to compare the readings with the presence or absence of chloride in concrete samples taken from selected resistivity test locations.

The pulverized concrete core samples were recovered from 35 locations on 16 bridges in 1975 and from 96 locations on 35 bridges in 1976. Of the total, 74 of the resistance readings were in agreement with the chloride levels when 500,000 ohms was used as the minimum acceptable reading which would indicate an impervious pavement membrane system. Based upon such results the resistivity test would have a reliability factor of 57 percent.

35 of the 57 resistance tests which did not correlate indicated acceptable or infinite resistance at locations where chlorides were found to be above base levels. With the possible exception of lateral chloride migration occuring beneath membranes not completely adhered to the deck surface, such resistivity readings would be considered incorrect.

The remaining 22 readings which did not correlate were low indicating leakage but the chloride results were unchanged from base levels. Due to several factors, it is possible that the results of both tests are accurate even though the results do not agree. The most likely reason for the lack of correlation may relate to the difference in the physical areas involved with each test procedure. The resistivity test covers an area at least the size of the sponges used and in all likelihood an even larger area due to the migration of the wetting agent in the pavement and/or at the pavement-membrane interface. Accordingly a low resistivity reading could be due to holidays in the membrane throughout the test area or simply due to a porous condition at a single small location. If the latter occured and the concrete sample was not recovered from the immediate area of leakage, chloride contamination would not be found and the resistivity and core results would not support one another. Low resistivity readings could also occur without evidence of contamination in cases where membrane failures result just prior to resistivity testing, but when chlorides have not had sufficient time to penetrate through the membrane at the failure points. A low resistivity-no chloride condition would also exist if the low reading was due to a false electrical circuit caused by moisture in the pavement or at the pavement-membrane interface. Every attempt was made to avoid the latter condition since moisture was recognized as a potential problem prior to initiating the study.

If the 22 low resistivity-no chloride test results were not included in the 131 field tests, the reliability factor of the remaining 109 resistance tests would improve from 57 percent to 68 percent. The reliability of the resistivity test varied between 1975 and 1976 with factors of 69 percent and 52 percent obtained in consecutive years. Varying the acceptable resistance level above or below 500,000 ohms did not improve the reliability factor. The use of one million ohms as the minimum acceptable level resulted in 66 percent correlation with the core results while a 100,000 ohm level resulted in a factor of 55 percent.

In general, the number of satisfactory resistivity readings has decreased with time as evidenced by 81 percent satisfactory readings in 1975 as compared to 71 percent satisfactory readings in 1976.

Validity and Limitations of Steel Potential Test Results

Steel potential readings were obtained at the same grid points as the resistivity tests. In nearly all cases the electrical half-cell readings were below the -0.35 volt level considered to be the corrosion threshold. Such readings were in agreement with the core results which indicated chloride levels were insufficient to cause corrosion of the reinforcing steel.

The potential measurements are shown in contour form in Appendix E. Since the readings were obtained with a DC Null Voltmeter which featured an essentially infinite input impedance, it was not necessary to alter the voltage readings with a correction factor. High potential readings obtained on a number of the approach slabs were believed due to an improper electrical circuit caused by unsatisfactory ground connections.

Although potential readings could be expected to indicate membrane performance over an extended period of time, the results of this study show that the test is not effective in providing an early indication of unsatisfactory membrane performance or failure. The value of the test as an indicator of membrane performance would also be questionable on decks where corrosion was present prior to waterproofing since the potential readings would be expected to vary even if the chloride level remained unchanged.

Validity and Limitations of Moisture Detection Strips

Copper foil strips were placed at 40 locations on 23 bridges in an attempt to detect the permeation of deicing salt solutions through the membranes. The presence of such moisture beneath and between parallel pairs of strips is indicated by lowered electrical resistance values measured on connecting lead wires. Although the resistance values will fluctuate widely with changes in moisture and temperature at the concrete-membrane interface, the presence of a conductive chloride solution between the parallel strips will result in generally stable readings of less than 500 ohms.

The limitations of the moisture strips became apparent during their installation and with continuous monitoring. Liquid applied membranes often required heavier application rates over the plastic tape covered strips and lead wires in order to ensure complete coverage. Such a variation in coating thickness could result in a different membrane performance at strip locations as compared to the rest of the deck. The bond breaker effect of the strips resulted in failures during paving on several systems including epoxys which depend on adhesion to the substrate for strength. The moisture strips appear to be best suited for use with the preformed sheet membrane systems. 13 of the original 40 installations were found to be inoperable after two to five years of field service. The failure of most of these systems related to snowplow or other damage to lead wires which had been extended to the curb lines. The best method found for protecting lead wires was to install the moisture strips at locations adjacent to drain scuppers and place the leads down the scuppers.

The main advantage of the moisture strips is that they can be easily checked by a single individual, with an ohmmeter the only necessary equipment. Their disadvantage is that even if they perform as designed, they are only capable of indicating membrane performance within their general area of installation which may or may not be representative of the overall membrane condition.

Based upon results obtained after two to five years of field service, the moisture strips do not appear to be an effective means of evaluating membrane performance. Of 14 bridges which had one or more sets of strips, only one set of strips produced low resistance readings indicating definite chloride penetration although 36 of 71 cores from the same decks disclosed some degree of chloride contamination. Such results suggest the strips require a high rate of moisture penetration in order to reach the saturated condition required to promote low resistance readings.

Requirements for Protection Courses On Membranes

Protection courses consisting of roofing paper or various types of protection boards are often specified for use with membrane systems. Requirements for the use of such materials may be established by the membrane manufacturer or user agencies. The purpose of a protection course varies with individual membrane systems but includes one or more of the following reasons ; a means of providing protection from construction activities, paving equipment, high bituminous overlay termperatures, and aggregate penetration during paving or under continuous traffic. Protection courses may also be used to provide increased membrane stability during paving and under traffic, promote adhesion between the membrane and overlay and protect against incompatibility between the membrane and bituminous pavement.

A protection course should only be specified and used when necessary since there are disadvantages in the use of such materials. These include the additional cost for materials and labor, problems in obtaining adhesion to the membrane, and the potential for incomplete curing of the membrane due to entrapment of solvents or moisture. Protection courses were required and used on all or a portion of six membrane systems field tested for this study. Because of the different products used and varying years of service, it is not possible to compare performance between systems used with or without protection.

A protection course comparison may be drawn on an asphalt modified polyurethane placed on bridges #15 and #17. Both structures contained areas with and without a roofing sheet protection course. After four winters, tests conducted on bridge #15 on the area with roll roofing produced 67% passing resistivity readings and chloride contamination was detected only at the curb line core location. By comparison, the test area of bridge #17 without a protection course has disclosed chloride contamination at all core locations and unsatisfactory resistance readings in the wheel path area after three winters. Satisfactory resistivity readings were obtained at nearly all other test areas both with and without protection. Such readings would tend to indicate the product requires a protection course as recommended by the manufacturer.

Portions of bridges #34 and #48 included areas with a 45 mil cohesively bonded protection sheet which was produced to complement the preformed sheet membrane. Test results after two winters of service do not confirm the need for the protection course since unprotected areas have remained waterproof except for slight leakage detected at a single curb line location. The value of a protection course, if it were required, probably would become more apparent over a longer service period. Four other membrane materials installed with a protection course have remained waterproof in the wheel path area although 50 percent of the cores at the one and five foot offsets show leakage.

The performance of the membranes in general does not indicate a protective course is required to prevent damage due to cold flow or aggregate penetration under continuous traffic. Cores taken from wheel path locations indicate some degree of leakage on 29 percent of the areas tested. By comparison, cores taken at the five foot offset in the breakdown lane disclosed chloride contamination on 40 percent of the samples. Average daily traffic on the subject bridges has ranged from 1400 to 4100 vehicles. If the traffic volume had been substantially higher, it is possible a protection course would have been required to prevent damage to some of the membrane systems.

SUMMARY AND CONCLUSIONS

The method used to evaluate the performance of the membrane systems was to determine the presence or absence of chloride above base levels in the bridge decks after exposure to deicing salt applications for an average of 2.8 winters. Specific sample locations were selected to include areas where low resistivity readings were obtained, whenever possible, rather than by random sampling.

The test results indicated that chloride contamination was present at 44 percent of the locations tested. The chloride concentrations averaged 50 ppm or 0.20 pounds per cubic yard of concrete above base levels in the top inch of contaminated samples. Chloride concentrations over 0.50 pounds in the top inch of concrete were recorded at five percent of the test locations. Difficulties in obtaining a satisfactory seal along curb line areas was evidenced by the detection of chloride contamination in 66 percent of the samples taken at the one foot offset. Such cores made up 48 percent of all contaminated samples.

Satsifactory performance was obtained with several of the systems including the standard preformed membranes which were free of chloride contamination on 84 percent of the samples tested. The performance of the majority of the 24 systems under evaluation was less than satisfactory. Such results were not surprising considering that 17 of the systems were not recommended for further use following their initial installation. The results indicate the most effective membrane systems have prevented or reduced the level of chloride penetration to the extent that they may be considered an acceptable bridge deck protective system until other more effective methods or systems become available. This appears especially true of some of the newer preformed and cast in place systems.

The electrical resistivity test has generally been accepted as a valid indicator of waterproofing effectiveness. This nondestructive test is capable of indicating the presence or absence of holidays in a membrane when such tests are taken directly on the surface of the material. However, when resistivity readings are taken on a membrane which has been overlaid with a bituminous pavement, the results may be questionable depending on a variety of conditions. These include; pavement porosity, wetting time, and moisture conditions in the overlay and/or at the membrane-overlay interface.

The method used to establish the validity of electrical resistivity readings was to compare the results with the presence or absence of chloride in concrete samples taken from selected resistivity test locations. Based upon the test results obtained at 131 test locations, the resistivity test has a reliability factor in the range of 60 percent. 35 of the 57 tests which did not correlate indicated acceptable or infinite resistance at locations where chlorides were found to be above base levels. The remaining 22 readings which did not correlate were low indicating leakage but the chloride results were unchanged from base levels. Such a low resistivity-no chloride condition could occur when there are holidays within the resistivity test area but the concrete samples are not recovered from the immediate area of leakage. The lack of correlation could also result when a membrane failure occurs prior to testing, but chlorides have not had sufficient time to penetrate into the concrete or when the low reading is due to a false electrical circuit caused by moisture in the pavement or at the pavement-membrane interface. The elimination of the 22 low resistivity-no chloride test results would improve the reliability factor of the resistivity test to approximately 70 percent.

Electrical half-cell potential readings taken at resistivity test locations were in agreement with the core results which indicated chloride contamination was insufficient to cause corrosion of the reinforcing steel. The potential readings would not provide an early indication of unsatisfactory membrane performance but the test would indicate poor membrane performance when the penetration of chloride is sufficient to initiate corrosion of the reinforcing steel.

Moisture strip readings taken on 14 bridges indicated a single membrane system was not performing satsifactorily. By comparison, chemical analysis of concrete samples taken from the same structures disclosed limited chloride contamination at 36 of 71 sample locations. Such results indicate the strips are not able to provide an early indication of unsatisfactory membrane performance when the rate of chloride penetration is low. A major disadvantage of the moisture detection strips is that they are only capable of indicating membrane performance within their general area of installation which may or may not be representative of the overall membrane condition. Other disadvantages or limitations which became apparent with the use of the moisture strips include the need for heavier than normal application rates of liquid applied membrane materials in order to insure complete coverage of the strips, localized membrane failures caused by the strips, and a high rate of loss due to lead wire damage.

Protection courses were placed on all or a portion of six membrane systems field tested for this study. Definite conclusions could not be drawn on the necessity of using such materials on the subject membrane systems due in part to insufficient service time. The performance of the membrane systems in general did not indicate a protective course is required to extend the service life of the systems.

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APPENDIX A
SUMMARY OF MEMBRANE PERFORMANCE
BASED UPON CHEMICAL ANALYSIS OF CORES

BRIDGE NO.	MEMBRANE SYSTEM	WINTERS CL^- APPLIED	BASE CL^- LEVEL (PPM)	1 FOOT OFF CURB Chloride Content (PPM)		5 FEET OFF CURB Chloride Content (PPM)		15 FEET OFF CURB Chloride Content (PPM)	
				AREAS WITH CL^- INTRUSION UNDERLINED					
				0-1"	1-2"	0-1"	1-2"	0-1"	1-2"
	STANDARD PREFORMED SHEET SYSTEMS								
11	65 Mil Preformed Sheet	3 4	34	35 <u>84</u>	32 <u>53</u>	 36	 32	32 35	42 43
24	75 Mil Preformed Sheet	2 3	28	37 48	39 40	35 43	34 32	40 53	52 37
25	70 Mil Preformed Sheet	2 3	28	32 <u>112</u>	46 <u>56</u>	44 43	21 42	37 <u>58</u>	40 50
28	75 Mil Preformed Sheet	2	61	70	50	73	67	60	56
34	70 Mil Preformed Sheet	2	52	50	55	56	50	55	54
36	65 Mil Preformed Sheet	2	61	<u>117</u>	<u>80</u>	70	65	70	70
43	70 Mil Preformed Sheet	2	37	25	43	42	44	28	37
48	70 Mil Preformed Sheet	2	33	<u>70</u>	50	48	25	35	25

APPENDIX A

SUMMARY OF MEMBRANE PERFORMANCE BASED UPON CHEMICAL ANALYSIS OF CORES (continued)

BRIDGE NO.	MEMBRANE SYSTEM	WINTERS CL⁻ APPLIED	BASE CL⁻ LEVEL (PPM)	1 FOOT OFF CURB Chloride Content (PPM) 0-1"	1 FOOT OFF CURB 1-2"	5 FEET OFF CURB Chloride Content (PPM) 0-1"	5 FEET OFF CURB 1-2"	15 FEET OFF CURB Chloride Content (PPM) 0-1"	15 FEET OFF CURB 1-2"
	MISCELLANEOUS PREFORMED SHEET SYSTEMS								
47	Uncured Hydrocarbon Rubber	2	55	90	85	105	65	95	50
	PROJECT 12-11 PREFORMED SHEET SYSTEMS								
32	125 Mil PVC Polymer	2	48	68	57	85	50	45	35
33	65 Mil Neoprene Rubber	2	128	140	110	105	75	90	110
38	65 Mil EPDM Rubber	2	56	84	64	84	69	60	56
39	65 Mil Butyl Rubber	2	56	60	46	70	30	60	60
40	Butyl Rubber & Felt	2	44	105	70	245	195	50	60

AREAS WITH CL⁻ INTRUSION UNDERLINED

SUMMARY OF MEMBRANE PERFORMANCE BASED UPON CHEMICAL ANALYSIS OF CORES (continued)

BRIDGE NO.	MEMBRANE SYSTEM	WINTERS CL^- APPLIED	BASE CL^- LEVEL (PPM)	1 FOOT OFF CURB Chloride Content (PPM)		5 FEET OFF CURB Chloride Content (PPM)		15 FEET OFF CURB Chloride Content (PPM)	
				AREAS WITH CL^- INTRUSION UNDERLINED					
				0-1"	1-2"	0-1"	1-2"	0-1"	1-2"
POLYURETHANE SYSTEMS									
7	Tar Modified Polyurethane	3 4	38	63 124	52 99	46 94	45 76	45 120	52 79
15	Asphalt Modified Polyurethane	3 4	37	53 109	40 60	32 30	37 20	31 53	38 35
17	Asphalt Modified Polyurethane	2 3	35	29 75	26 50	36 70	32 50	30 60	24 50
30	100 % Solids Polyurethane	2	81	40	40	61	75	114	99
THERMOPLASTIC OR THERMOSETTING SYSTEMS									
2	Hot Rubberized Asphalt	4	41	52	56	82 50	50 38	63 48	51 38
4	Hot Rubberized Asphalt	4 5	39	60 61	51 57	35 50	33 40	46 150	37 85
18	Hot Asphalt & Glass Fabric	2 3	21	57 175	43 55	24 78	32 75	42 65	29 45
20	Hot Asphalt & Glass Fabric	2 3	26	26 68	31 50	21 66	27 61	32 94	32 64

APPENDIX A
SUMMARY OF MEMBRANE PERFORMANCE
BASED UPON CHEMICAL ANALYSIS OF CORES
(continued)

BRIDGE NO.	MEMBRANE SYSTEM	WINTERS CL^- APPLIED	BASE CL^- LEVEL (PPM)	1 FOOT OFF CURB Chloride Content (PPM) 0-1"	1 FOOT OFF CURB Chloride Content (PPM) 1-2"	5 FEET OFF CURB Chloride Content (PPM) 0-1"	5 FEET OFF CURB Chloride Content (PPM) 1-2"	15 FEET OFF CURB Chloride Content (PPM) 0-1"	15 FEET OFF CURB Chloride Content (PPM) 1-2"
				AREAS WITH CL^- INTRUSION UNDERLINED					
	EPOXY SYSTEMS								
27	100 % Solids Epoxy	2	50	96	66	75	50	64	30
	EMULSION SYSTEMS								
1	Tar Emulsion	4 5	32	138 149	67 66	37 60	35 60	43 25	44 25
3	Tar Emulsion	4 5	31	164 186	136 125	36 85	33 80	35 150	34 85
6	Tar Emulsion & Glass Fabric	3 4	33	86 75	67 50	42 85	35 75	46 100	35 60
8	Tar Emulsion & Glass Fabric	3 4	30	48 50	35 23	118 58	66 17	61 65	45 35
12	Tar Emulsion & Glass Fabric	3 4	29	56 215	48 148	52 185	45 168	46 152	29 123
14	Tar Emulsion & Glass Fabric	3 4	25	183 106	85 45	38 33	40 24	45 33	45 50

APPENDIX A
SUMMARY OF MEMBRANE PERFORMANCE
BASED UPON CHEMICAL ANALYSIS OF CORES
(continued)

BRIDGE NO.	MEMBRANE SYSTEM	WINTERS CL^- APPLIED	BASE CL^- LEVEL (PPM)	1 FOOT OFF CURB Chloride Content (PPM) 0-1"	1 FOOT OFF CURB 1-2"	5 FEET OFF CURB Chloride Content (PPM) 0-1"	5 FEET OFF CURB 1-2"	15 FEET OFF CURB Chloride Content (PPM) 0-1"	15 FEET OFF CURB 1-2"
	THERMOPLASTIC OR THERMOSETTING SYSTEMS								
35	Hot PVC Polymer	2	60	70	66	93	66	61	61
	EPOXY SYSTEMS								
9	Solvent Cut Epoxy	3 4	39	296 109	89 75	126	106	50	29
10	Coal Tar Modified Epoxy	3 4	32	117 135	64 80	82 114	84 90	109 50	81 50
16	100 % Solids Epoxy	2 3	35	50 68	31 46	55 55	36 41	22 62	41 63
19	100 % Solids Epoxy	2 3	25	78 117	58 42	45 65	39 47	43 56	29 46
22	Solvent Cut Epoxy	2 3	27	127 103	69 36	38 46	34 38	55 55	39 43
23	Coal Tar Modified Epoxy	2 3	26	30 50	29 55	40 70	35 63	39 75	32 48
26	Solvent Cut Epoxy	2	50	115	80	90	75	64	70

AREAS WITH CL^- INTRUSION UNDERLINED

APPENDIX B

Correlation of Resistivity Test Results And Chloride Levels

			1 Foot off Curb				5 Feet off Curb				15 Feet off Curb			
Bridge No.	Winters CL^- Applied	Base CL^- Level (PPM)	CL^- Content 0-1"/1-2"	Leakage Indicated	Ohms Resistance (In Millions)	Correlation Between Tests	CL^- Content 0-1"/1-2"	Leakage Indicated	Ohms Resistance (In Millions)	Correlation Between Tests	CL^- Content 0-1"/1-2"	Leakage Indicated	Ohms Resistance (In Millions)	Correlation Between Tests
1	4	32	138/67	Yes	∞	No	37/35	No	∞	Yes	43/44	No	∞	Yes
	5		149/66	Yes	∞	No	60/60	Yes	∞	No	25/25	No	0.2	No
2	4	41	52/56	No	--	--	82/50	Yes	7	No	63/51	Yes	.019	Yes
	5		--	--	--	--	50/38	No	.35	No	48/38	No	.015	No
3	4	31	164/136	Yes	--	--	36/33	No	5	Yes	35/34	No	4	Yes
	5		186/125	Yes	--	--	85/80	Yes	∞	No	150/85	Yes	2.6	No
4	4	39	60/51	Yes	--	--	35/32	No	3	Yes	46/37	No	.02	No
	5		61/57	Yes	.23	Yes	50/40	No	.26	No	55/60	Yes	.09	Yes
6	3	33	86/67	Yes	.5	Yes	42/35	No	--	--	46/35	No	.18	No
	4		75/50	Yes	--	--	85/75	Yes	1M	No	100/60	Yes	.2	Yes
7	3	38	63/52	Yes	.25	Yes	46/45	No	.28	No	45/52	No	3	Yes
	4		124/99	Yes	.03	Yes	94/76	Yes	.03	Yes	120/79	Yes	.3	Yes
8	3	30	48/35	No	9	Yes	118/66	Yes	∞	No	61/45	Yes	.24	Yes
	4		50/23	No	--	--	58/17	Yes	∞	No	65/35	Yes	.16	Yes
9	3	39	296/89	Yes	.22	Yes	--	--	--	--	--	--	--	--
	4		109/75	Yes	.007	Yes	126/106	Yes	20	No	50/29	No	.4	No
10	3	32	117/64	Yes	--	--	82/82	Yes	--	--	109/81	Yes	--	--
	4		135/80	Yes	.05	Yes	114/90	Yes	.02	Yes	50/50	No	5	Yes
11	3	34	35/32	No	--	--	--	--	--	--	32/42	No	--	--
	4		84/53	Yes	--	--	36/32	No	.1	No	35/43	No	.5	Yes

APPENDIX B

Correlation of Resistivity Test Results And Chloride Levels

			1 Foot off Curb				5 Feet off Curb				15 Feet off Curb			
Bridge No.	Winters CL^- Applied	Base CL^- Level (PPM)	CL^- Content 0-1"/1-2"	Leakage Indicated	Ohms Resistance (In Millions)	Correlation Between Tests	CL^- Content 0-1"/1-2"	Leakage Indicated	Ohms Resistance (In Millions)	Correlation Between Tests	CL^- Content 0-1"/1-2"	Leakage Indicated	Ohms Resistance (In Millions)	Correlation Between Tests
12	3 4	29	56/48 215/148	Yes Yes	-- --	-- --	52/45 185/168	Yes Yes	∞ --	No --	46/29 152/123	No Yes	∞ --	Yes --
14	3 4	25	183/85 106/45	Yes Yes	∞ ∞	No No	38/40 33/24	No No	∞ ∞	Yes Yes	45/45 33/50	No No	∞ ∞	Yes Yes
15	3 4	37	53/40 109/60	No Yes	.12 .025	No Yes	32/37 30/20	No No	.3 .13	No No	31/38 53/35	No No	50 5	Yes Yes
16	2 3	37	50/31 68/46	No Yes	∞ ∞	Yes No	55/36 55/41	No No	3 ∞	Yes Yes	22/41 62/63	No Yes	∞ ∞	Yes No
17	2 3	33	29/26 75/50	No Yes	-- .17	-- Yes	36/32 70/50	No Yes	∞ ∞	Yes No	30/24 60/50	No Yes	-- .17	-- Yes
18	2 3	21	57/43 175/55	Yes Yes	.75 --	No --	24/32 78/75	No Yes	∞ ∞	Yes No	42/29 65/45	No Yes	∞ ∞	Yes No
19	2 3	25	78/58 117/42	Yes Yes	-- .8	-- No	45/39 65/47	No No	∞ ∞	Yes Yes	43/29 56/46	No Yes	1.6 20	Yes No
20	2 3	26	26/31 68/50	No Yes	-- ∞	-- No	21/27 66/61	No Yes	-- ∞	-- No	32/32 94/64	No Yes	-- ∞	-- No
22	2 3	27	127/69 103/36	Yes Yes	-- .3	-- Yes	38/34 46/38	No No	-- ∞	-- Yes	55/39 55/43	No No	-- 5	-- Yes
23	2 3	26	30/29 50/55	No Yes	-- --	-- --	40/35 70/63	No Yes	-- 20M	-- No	39/32 75/48	No Yes	-- .24	-- Yes

APPENDIX B

Correlation of Resistivity Test Results And Chloride Levels

Bridge No.	Winters CL^- Applied	Base CL^- Level (PPM)	1 Foot off Curb: CL^- Content 0-1"/1-2"	1 Foot off Curb: Leakage Indicated	1 Foot off Curb: Ohms Resistance (In Millions)	1 Foot off Curb: Correlation Between Tests	5 Feet off Curb: CL^- Content 0-1"/1-2"	5 Feet off Curb: Leakage Indicated	5 Feet off Curb: Ohms Resistance (In Millions)	5 Feet off Curb: Correlation Between Tests	15 Feet off Curb: CL^- Content 0-1"/1-2"	15 Feet off Curb: Leakage Indicated	15 Feet off Curb: Ohms Resistance (In Millions)	15 Feet off Curb: Correlation Between Tests
24	2 3	28	37/39 48/40	No No	-- .12	-- No	35/34 43/32	No No	-- ∞	-- Yes	40/52 53/37	No No	-- 30	-- Yes
25	2 3	28	32/46 112/56	No Yes	-- .026	-- Yes	44/21 43/42	No No	-- .36	-- No	37/40 58/50	No Yes	-- ∞	-- No
26	2	50	115/80	Yes	1	No	90/75	Yes	∞	No	64/70	No	10	Yes
27	2	50	96/66	Yes	.14	Yes	75/50	Yes	20M	No	64/30	No	.14	No
28	2	61	70/50	No	--	--	73/67	No	--	--	60/56	No	--	--
30	2	81	40/40	No	∞	Yes	61/75	No	10M	Yes	114/99	Yes	.015	Yes
32	2	48	68/57	No	9	Yes	85/50	Yes	.06	Yes	45/35	No	.01	No
33	2	128	140/110	No	--	--	105/75	No	∞	Yes	90/110	No	∞	Yes
34	2	52	50/55	No	--	--	56/50	No	7M	Yes	55/54	No	.4	No
35	2	60	70/66	No	∞	Yes	93/66	Yes	∞	No	61/61	No	.079	No

APPENDIX B

Correlation of Resistivity Test Results And Chloride Levels

			1 Foot off Curb				5 Feet off Curb				15 Feet off Curb			
Bridge No.	Winters CL^- Applied	Base CL^- Level (PPM)	CL^- Content 0-1"/1-2"	Leakage Indicated	Ohms Resistance (In Millions)	Correlation Between Tests	CL^- Content 0-1"/1-2"	Leakage Indicated	Ohms Resistance (In Millions)	Correlation Between Tests	CL^- Content 0-1"/1-2"	Leakage Indicated	Ohms Resistance (In Millions)	Correlation Between Tests
36	2	61	117/80	Yes	.05	Yes	70/65	No	3	Yes	70/70	No	.06	No
38	2	56	84/64	Yes	.1	Yes	84/69	Yes	4	No	60/56	No	10	Yes
39	2	56	60/46	No	.12	No	70/30	No	10	Yes	60/60	No	.04	No
40	2	44	105/70	Yes	.02	Yes	245/195	Yes	∞	No	50/60	No	∞	Yes
43	2	37	25/43	No	.3	No	42/44	No	∞	Yes	28/37	No	10	Yes
47	2	55	90/85	Yes	2	No	105/65	Yes	∞	No	95/50	Yes	20	No
48	2	33	70/50	Yes	.03	Yes	48/25	No	∞	Yes	35/25	No	2.4	Yes

APPENDIX C

Comparison Between Moisture Strip Readings, Resistivity Readings and Core Results

Bridge Number	Membrane System	Winters CL^- Applied	Strip Reading In Ohms	% Passing Resistivity Readings	% Cores Uncontaminated
# 6	Tar Emulsion & Glass Fabric	3 4	240,000 70,000	89 72	67 0
# 7	Tar Modified Polyurethane	3 4	*700 *250	66 29	67 0
# 8	Tar Emulsion & Glass Fabric	3 4	180,000 180,000	66 61	33 33
# 10	Coal Tar Modified Epoxy	3 4	6,000 —	81 68	0 33
# 11	Preformed Sheet System	3 4	**300,000 - 2M 50,000 - 300,000	19 0	100 67
# 17	Asphalt Modified Polyurethane	2 3	4,000 - 14,000 1,600 - 5,000	86 86	100 0
# 18	Hot Asphalt & Glass Fabric	2 3	300,000 11,000	100 100	67 0
# 20	Hot Asphalt & Glass Fabric	2 3	20,000 - 300,000 18,000 - 550,000	100 100	100 0
# 24	Preformed Sheet System	2 3	20,000 10,000	91 90	100 100
# 25	Preformed Sheet System	2 3	700,000 - 2M 120,000 - 700,000	83 48	100 33
# 32	PVC Polymer Sheet System	2	10,000 - 40,000	3	67

* Reading indicates definite CL^- intrusion.
** Dual readings indicate two sets of strips.

APPENDIX C

Comparison Between Moisture Strip Readings, Resistivity Readings and Core Results (continued)

Bridge Number	Membrane System	Winters CL^- Applied	Strip Reading In Ohms	% Passing Resistivity Readings	% Cores Uncontaminated
# 38	EPDM Rubber Sheet System	2	70,000 - 200,000	Conductive Membrane	33
# 39	Butyl Rubber Sheet System	2	12,000 - 14,000	Conductive	100
# 40	Butyl Rubber & Felt Sheet System	2	1,400 - 7,000	78	33

* Reading indicates definite CL^- intrusion.

** Dual readings indicate two sets of strips.

APPENDIX D
PROCEDURE FOR DETERMINATION OF CHLORIDE IN CONCRETE

Procedure:

Weigh into a 400 ml. beaker, 10 grams of pulverized concrete, to the nearest 0.01 grams.

Add 100 ml. hot distilled water, stir.

Add 10 ml. Nitric Acid slowly, with stirring.

Cover with a ribbed watch glass and boil for 2 minutes.

Cool

Add an excess of 0.0140 N $AgNO_3$ (1) slowly from buret, with stirring. Record amount added.

Allow slurry to settle at least 15 minutes.

Decant the solution into a 500 ml. Erlenmeyer flask thru a double thickness of filter paper, using a 12.5 cm. diameter Whatman No. 41, coarse porosity, inside a No. 40, medium porosity.

Wash residue and paper at least four times with Nitric Acid (1:99), being sure to wash entire paper each time.

The filtrate should be clear and have a volume of about 150 ml. (2).

Titrate the filtrate with 0.0140 N NH_4SCN to the first permanent pink end point (3).

Calculations - % Chloride = $(V_1N_1 - V_2N_2)\ 0.03545 \times 100 \div S$
PPM Chloride = $\%Cl^- \times 10^4$

V_1 = ml. Silver Nitrate Solution used.
N_1 = normality of Silver Nitrate Solution used.
V_2 = ml. Ammonium Thiocyanate Solution used.
N_2 = normality of Ammonium Thiocyanate Solution used.
S = Grams of Concrete sample used.
0.03545 = conversion factor.

(1) A slight excess of 1-3 mls. must be added. Five mls. of 0.0140 N $AgNO_3$ is sufficient for a 10 g sample containing less than 0.0200 $\%Cl^-$

(2) If filtrate is turbid, add 3 ml. Benzyl Alcohol and shake vigorously.

(3) Titration should be performed in subdued light. If the first drop of NH_4SCN added gives a permanent color change, insufficient $AgNO_3$ was originally added. More $AgNO_3$ solution may be added to obtain an approximate chloride content, but benzyl alcohol should be added with vigorous shaking to prevent end point from fading.

Ferric indicator may be added but concrete and cement samples usually contain sufficient Ferric Iron for a good color change.

APPENDIX E
BRIDGE LOCATION KEY

BRIDGE NO.	TOWN	ROUTE	MILEAGE MARKER	STATE BR. NO.
1	Castleton	WB US 4	05.45	10-W
2	Castleton	EB US 4	05.45	10-E
3	Fair Haven	WB US 4	01.95	5-W
4	Fair Haven	EB US 4	01.95	5-E
6	Barton	NB I 91	156.81	T-89-N
7	Barton	SB I 91	156.81	T-89-S
8	Barton	NB I 91	157.53	T-90-N
9	Barton	SB I 91	157.53	T-90-S
10	Barton	NB I 91	160.22	T-91-N
11	Barton	SB I 91	160.22	T-91-S
12	Barton	NB I 91	161.96	T-92-N
14	Irasburg	NB I 91	163.50	T-93-N
15	Irasburg	SB I 91	163.50	T-93-S
16	Barton	NB I 91	156.38	T-88-N
17	Barton	SB I 91	156.38	T-88-S
18	Lyndon	NB I 91	139.18	T-81-N
19	Lyndon	SB I 91	139.18	T-81-S
20	Lyndon	NB I 91	140.30	T-82-N
22	Lyndon	NB I 91	141.94	T-83-N
23	Lyndon	SB I 91	141.94	T-83-S
24	Sheffield	NB I 91	146.13	T-85-N
25	Sheffield	SB I 91	146.13	T-85-S
26	Bradford	SB I 91	97.62	58-S
27	Bradford	NB I 91	97.62	58-N
28	Bradford	NB I 91	97.88	59-N
30	Bradford	NB I 91	97.98	60-N
32	Bradford	NB I 91	98.43	61-N
33	Bradford	SB I 91	98.43	61-S
34	Newbury	NB I 91	103.52	63-N
35	Newbury	SB I 91	103.52	63-S
36	Newbury	NB I 91	105.95	64-N
38	Newbury	NB I 91	110.62	67-N
39	Newbury	NB I 91	110.62	67-N
43	Bennington	WB67-ACONN	0.42	1-W
45	Bennington	WB67-ACONN	0.75	3-W
47	Bennington	WB67-ACONN	0.70	2-W
48	Berlin			

KEY
None - Not Completed
N/A - Not Required
- Not Contoured

LIST OF CONTOUR SHEETS

BRIDGE	1975 POTENTIAL	1976 POTENTIAL	1975 RESISTIVITY	1976 RESISTIVITY
1	∞	∞	∞	∞
2	Figure 1	Figure 2	Figure 3	Figure 4
3	Figure 5	Figure 6	Figure 7	Figure 8
4	Figure 9	Figure 10	Figure 11	Figure 12
6	Figure 13	None	None	None
7	Figure 14	Figure 15	Figure 16	Figure 17
8	Figure 18	Figure 19	Figure 20	Figure 21
9	Figure 22	Figure 23	Figure 24	Figure 25
10	Figure 26	None	Figure 27	Figure 28
11	Figure 29	None	Figure 30	Figure 31
12	∞	None	∞	None
14	None	∞	None	∞
15	Figure 32	Figure 33	Figure 34	Figure 35
16	∞	∞	∞	∞
17	∞	∞	∞	∞
18	∞	∞	∞	∞
19	Figure 36	None	None	Figure 37
20	Figure 38	∞	Figure 39	∞
22	Figure 40	None	Figure 41	Figure 42
23	Figure 43	None	Figure 44	None
24	Figure 45	Figure 46	Figure 47	Figure 48
25	None	Figure 49	Figure 50	Figure 51
26	N/A	∞	N/A	∞
27	N/A	None	N/A	Yes
28	N/A	None	N/A	None
30	N/A	None	N/A	None
32	Figure 52	None	Figure 53	Figure 54
33	N/A	None	N/A	None
34	N/A	None	N/A	None
35	N/A	∞	N/A	∞
36	N/A	None	Figure 55	Figure 56
38	N/A	None	*Conductive	Conductive
39	N/A	None	Conductive	Conductive
43	N/A	None	N/A	None
45	N/A	∞	N/A	∞
47	N/A	∞	N/A	∞
48	N/A	∞	N/A	∞

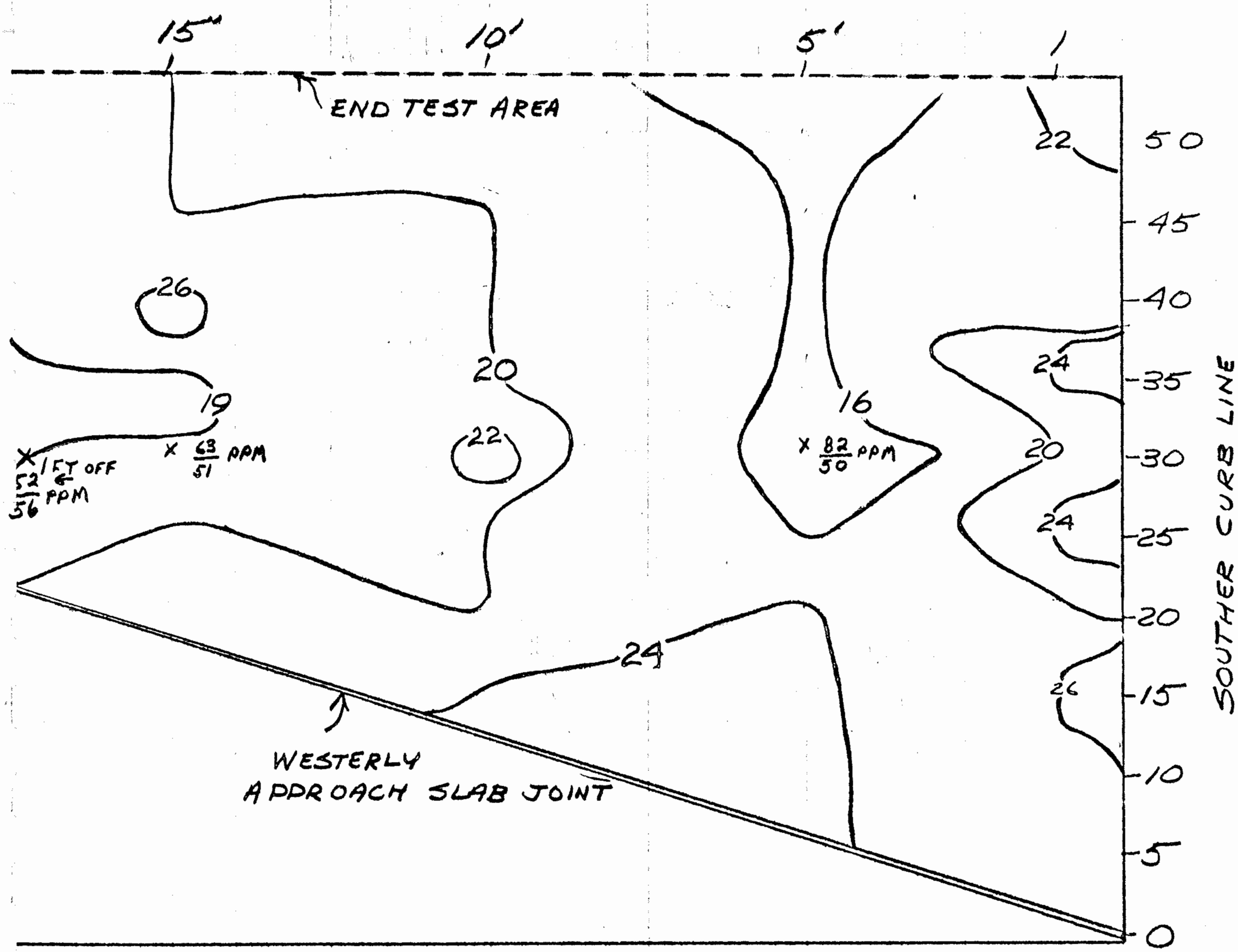
* Conductive - Membrane is Conductor

FIGURE 1

BRIDGE #2 - HOT RUBBERIZED ASPHALT
HALF CELL POTENTIAL CONTOURS
CASTLETON, VT. EB US 4 / VT RT 30

MM 5.45   BR # 10-E

TESTED 75
PLOTTED 12/75
PLOTTED BY J.S.



READINGS
OHMS × 10^{-6}

TESTED 76
PLOTTED 12/76
PLOTTED BY J.S.

FIGURE 2
BRIDGE #2 - HOT RUBBERIZED ASPHALT HALF-CELL POTENTIAL CONTOURS
CASTLETON, VT EB US 4 / VT. RTE 30
MM 5.45 BR #10-E

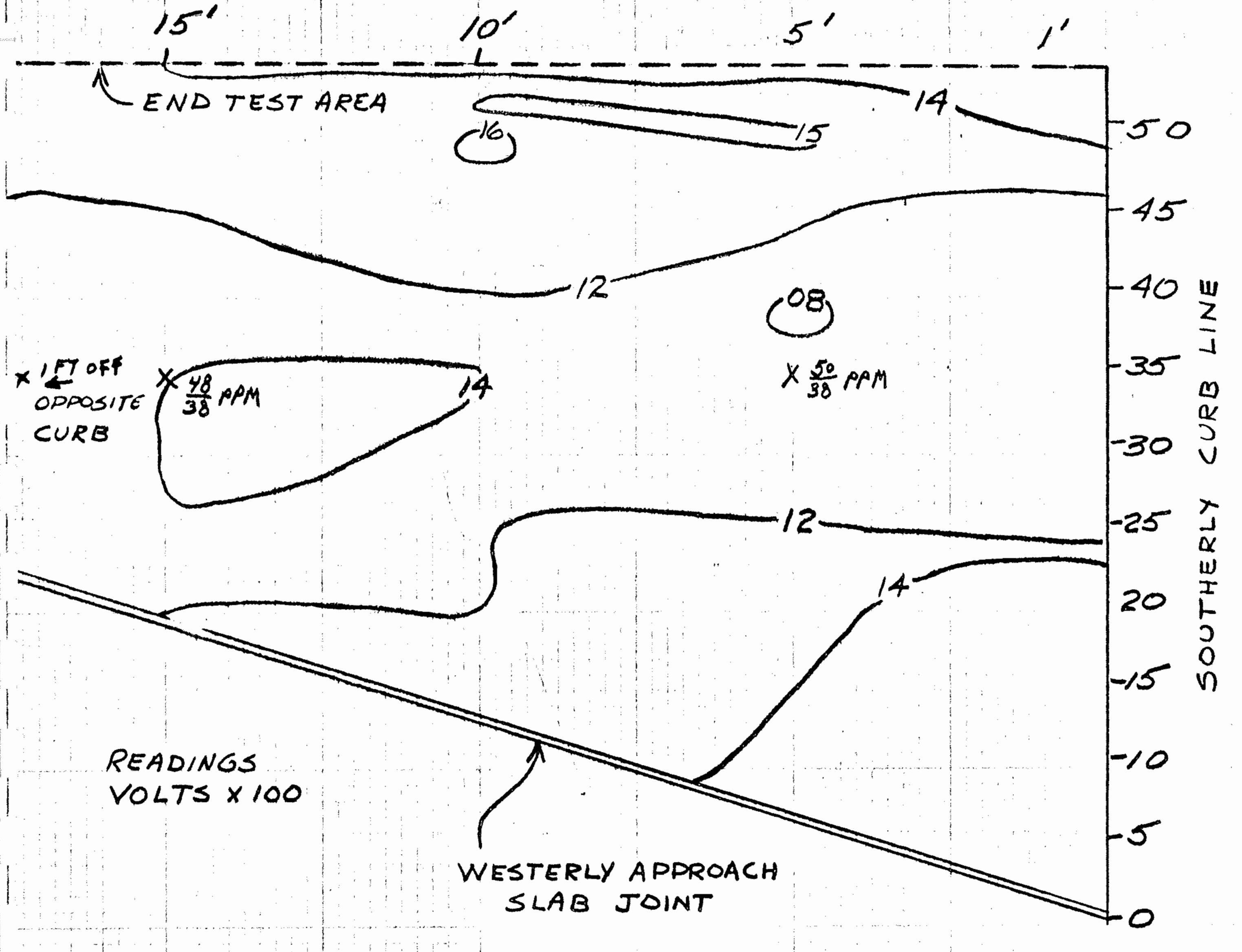


FIGURE 3
BRIDGE #2 - HOT RUBBERIZED ASPHALT
ELECTRICAL RESISTIVITY CONTOURS
CASTLETON, VT EB US 4 / VT. RT. 30
MM 5.45 BR# 10-E

TESTED 75
PLOTTED 12/75
PLOTTED BY J.S.

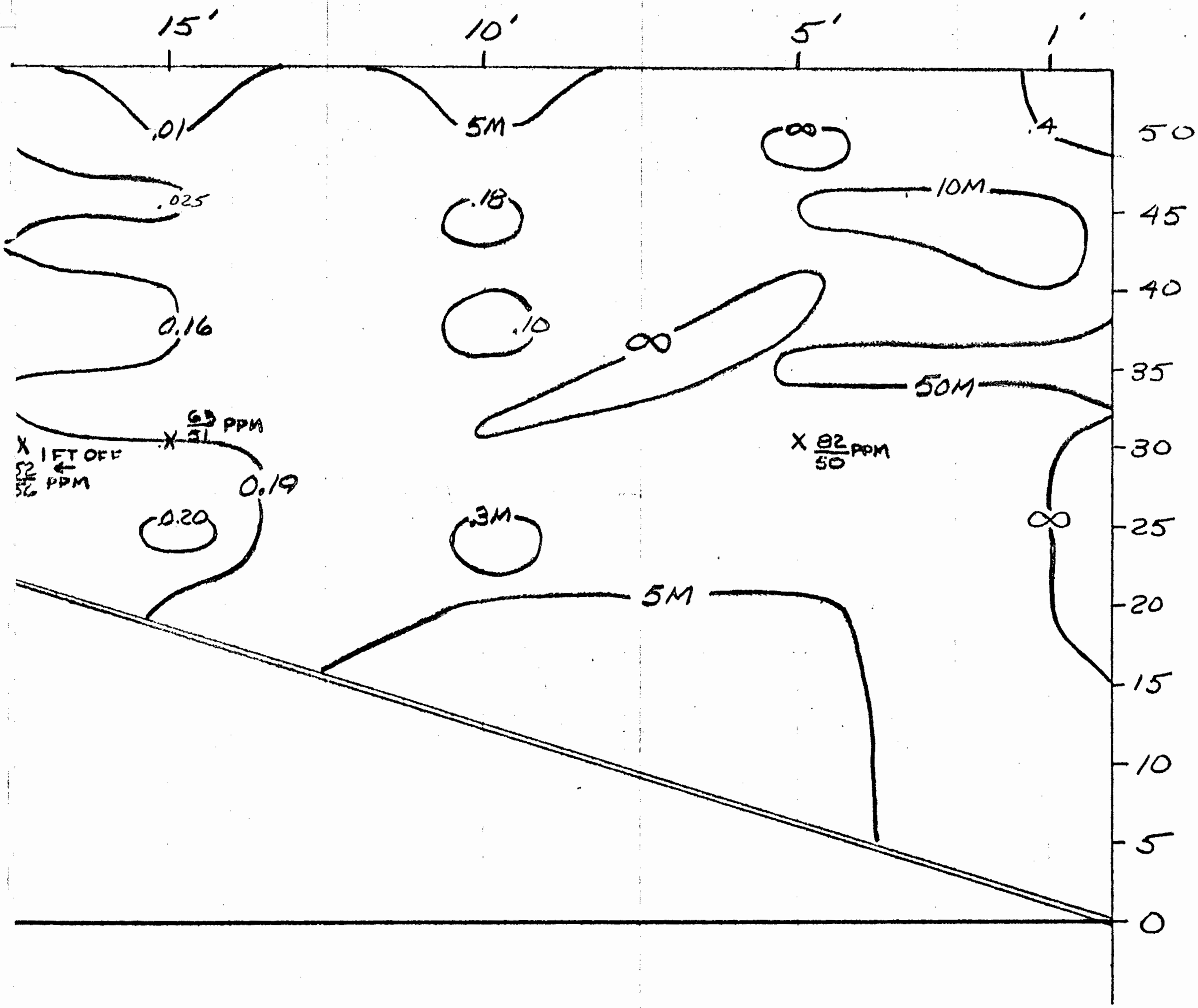


FIGURE 4

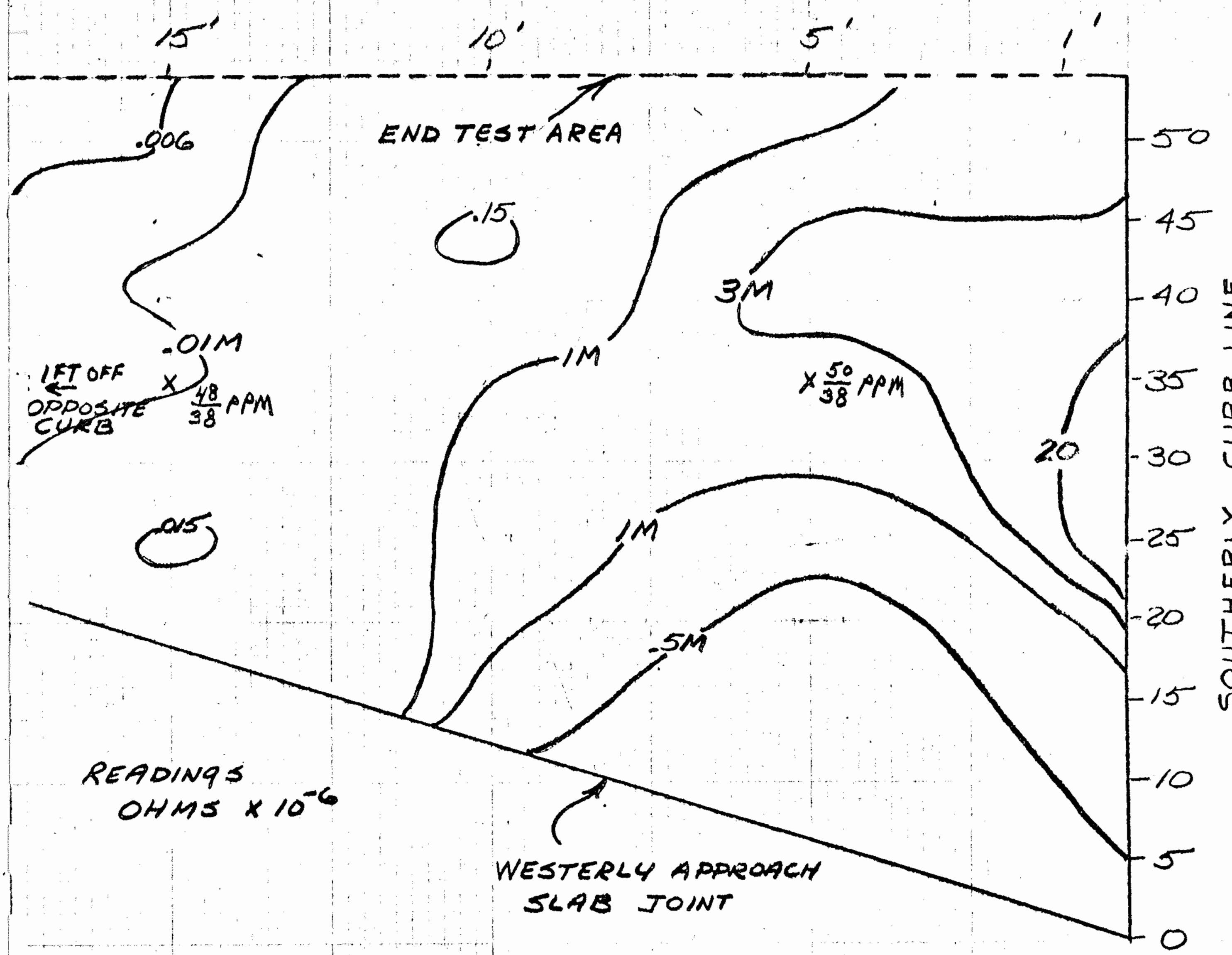
BRIDGE #2 - HOT RUBBERIZED ASPHALT

ELECTRICAL RESISTIVITY CONTOURS

CASTLETON, VT. EB US4 / VT. RT. 30

MM 5.45 BR# 10-E

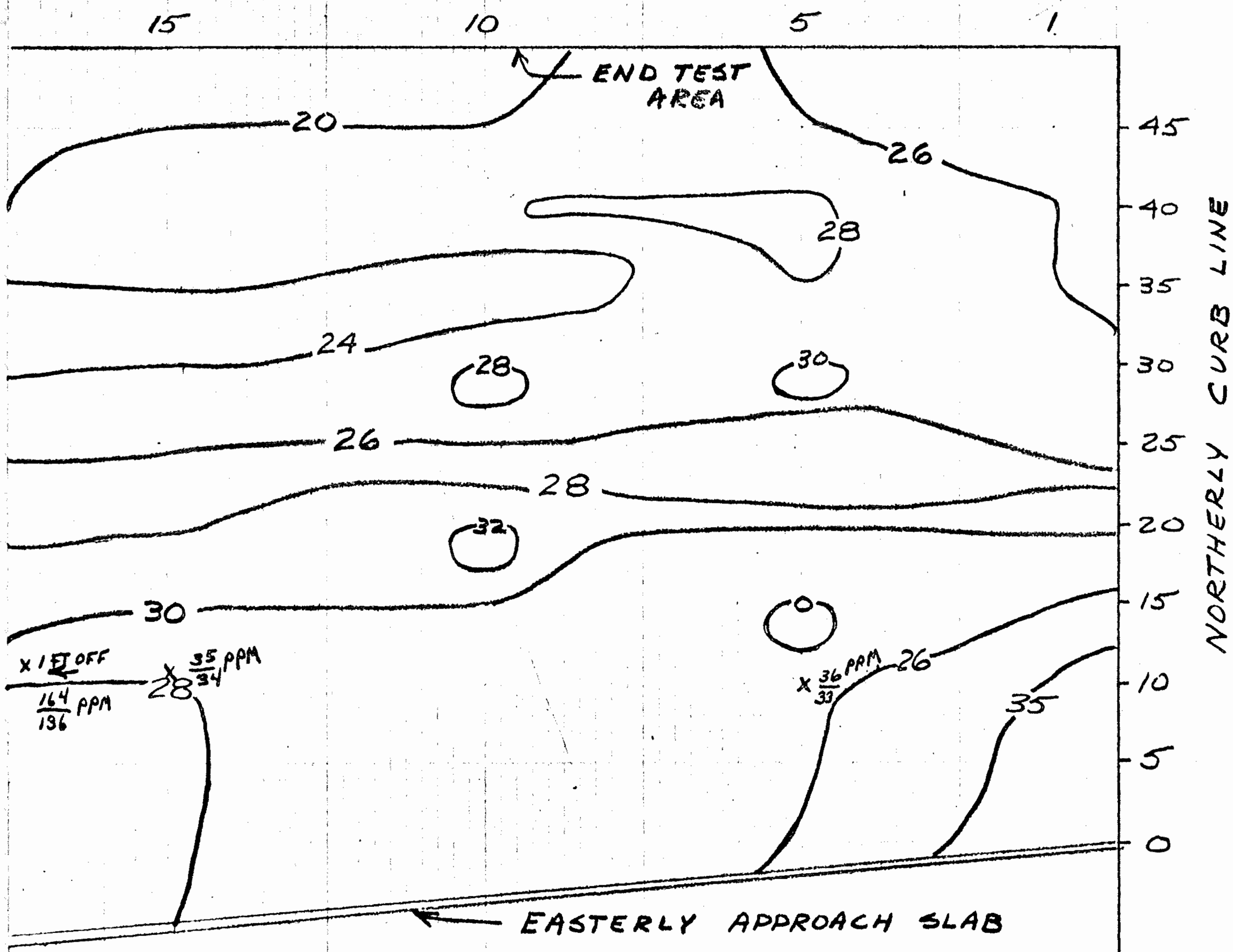
TESTED 1/76
PLOTTED 12/76
PLOTTED BY J.S



TESTED 75
PLOTTED 12/7[illegible]
By J.S.

FIGURE 5

BRIDGE #3 - TAR EMULSION
HALF CELL POTENTIAL CONTOURS
FAIR HAVEN, VT WB US4 / VT22-A
MM 1.95 BR # 5-W

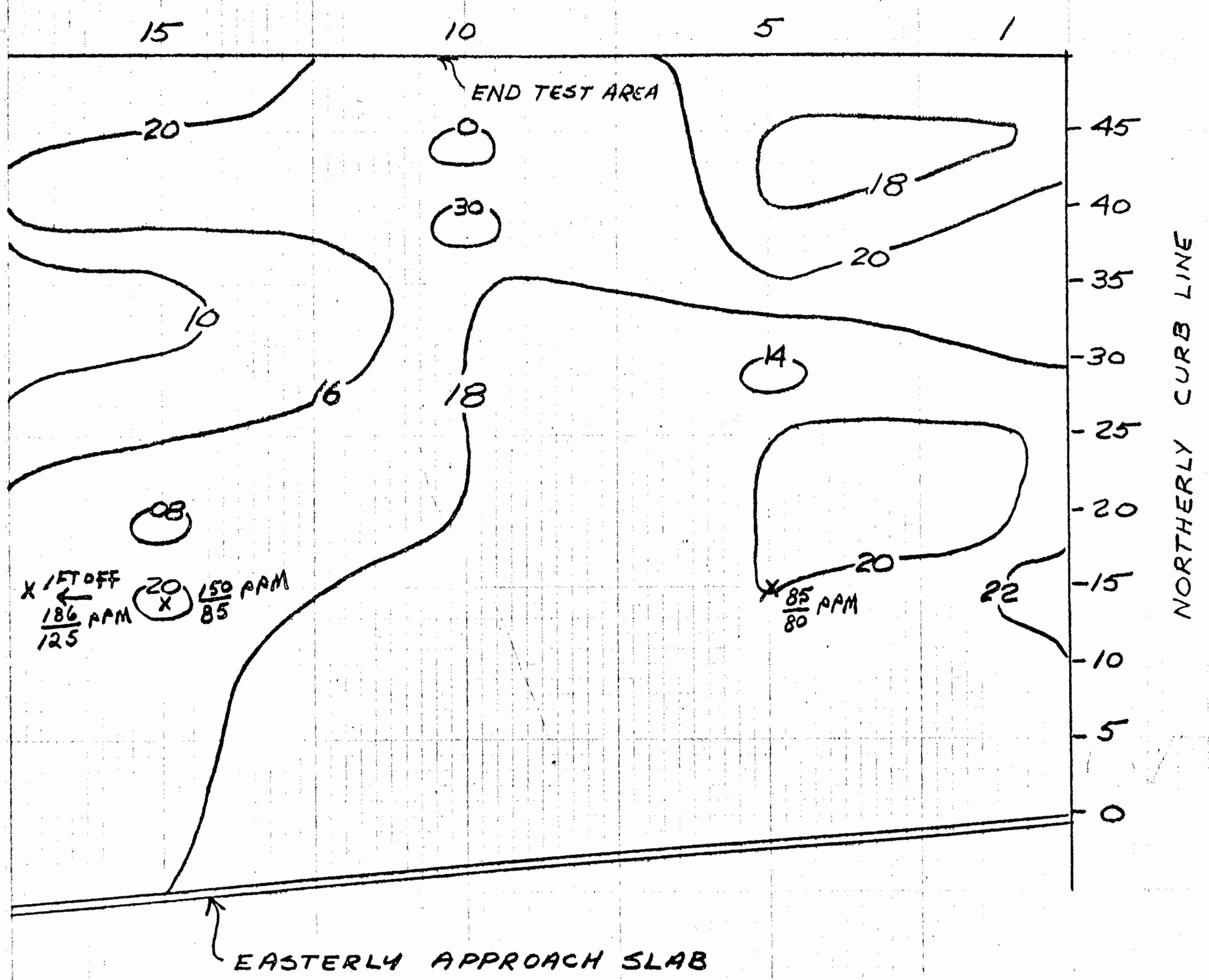


READINGS
VOLTS X 100

FIGURE 6

TESTED -76
PLOTTED 12/76
By JS

BRIDGE #3 - TAR EMULSION
HALFCELL POTENTIAL CONTOURS
FAIR HAVEN, VT WBUS4 / VT 22-A
MM 1.95 BR #5-W



READINGS
VOLTS x 100

TESTED 75
PLOTTED 12/76
By J.S.

FIGURE 7
BRIDGE #3 - TAR EMULSION
ELECTRICAL RESISTIVITY CONTOURS
FAIR HAVEN, VT WB US4 / VT 22-4
MM 1.95 BR # 5 - W

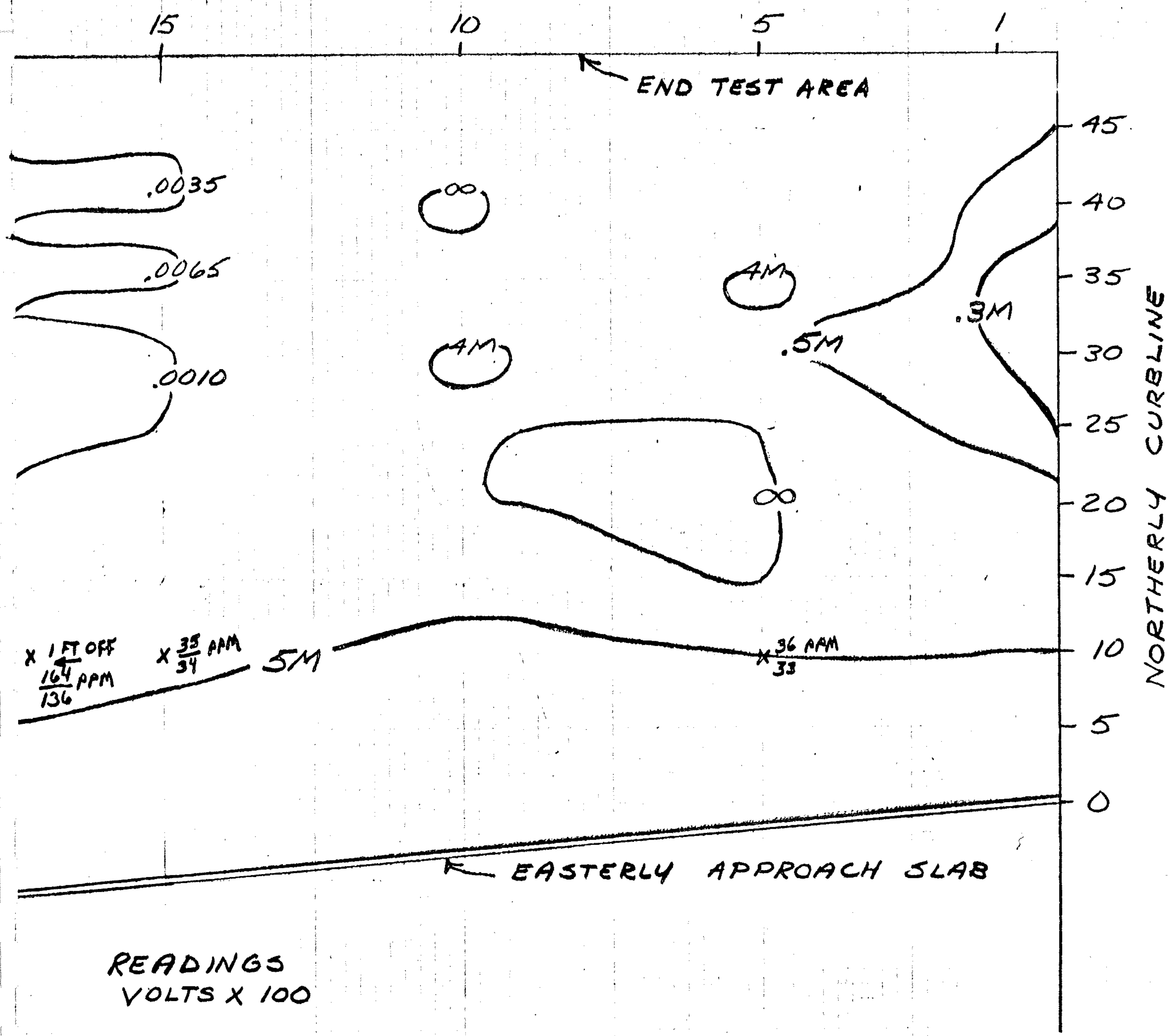
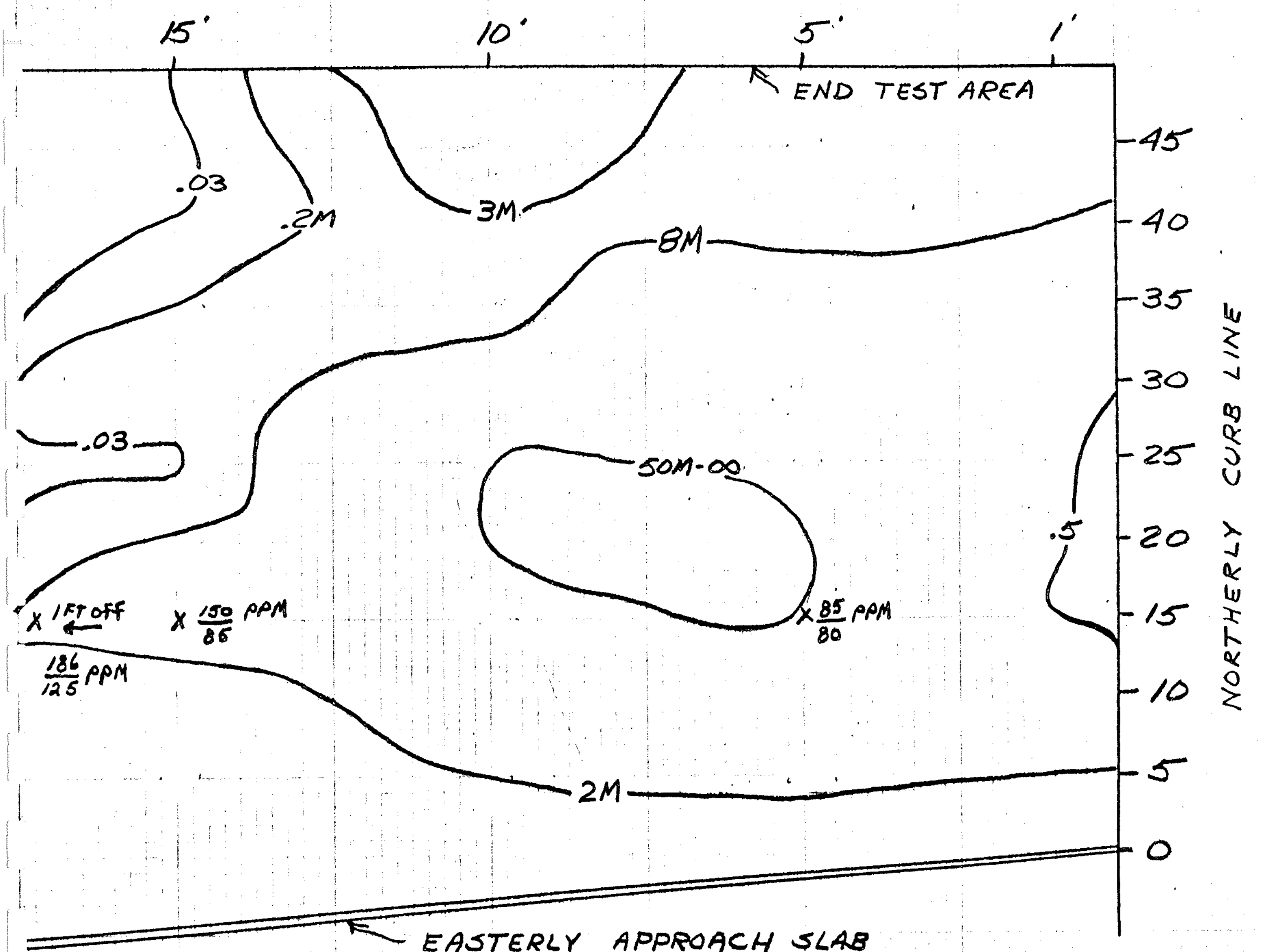


FIGURE 8

TESTED 76
PLOTTED 12/76
By J.S

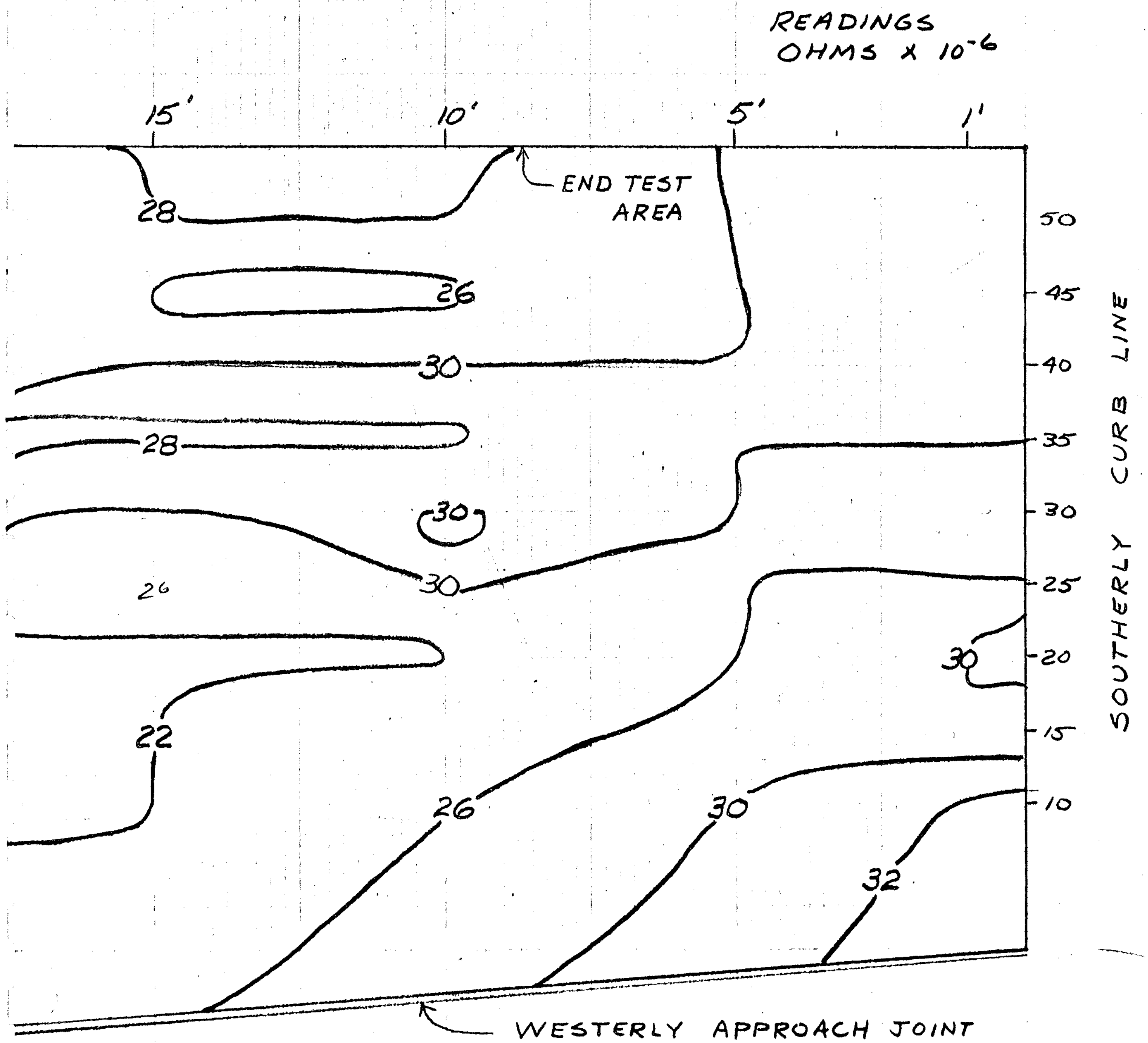
BRIDGE #3 - TAR EMULSION
ELECTRICAL RESISTIVITY CONTOURS
FAIR HAVEN, VT WBUS4 / VT 22-A
MM 1.95 BR # 5-W



READINGS
VOLTS X 100

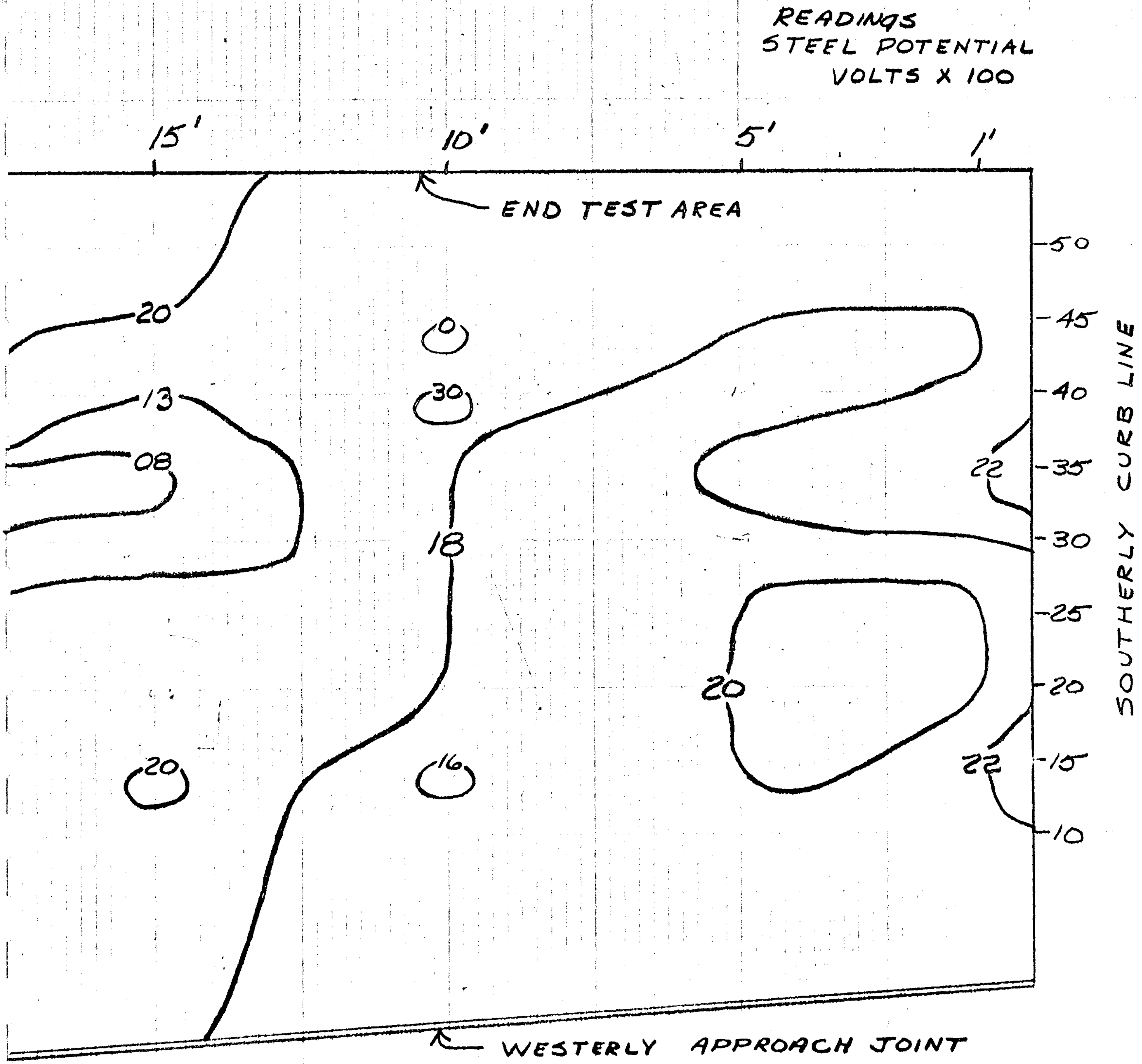
TESTED 75
PLOTTED 12/75
BY J.S

FIGURE 9
BRIDGE #4 - HOT RUBBERIZED ASPHALT
HALF CELL POTENTIAL CONTOURS
FAIR HAVEN, VT EB US4 / VT RTE. 22-A
MM 1.95 BR #5-E



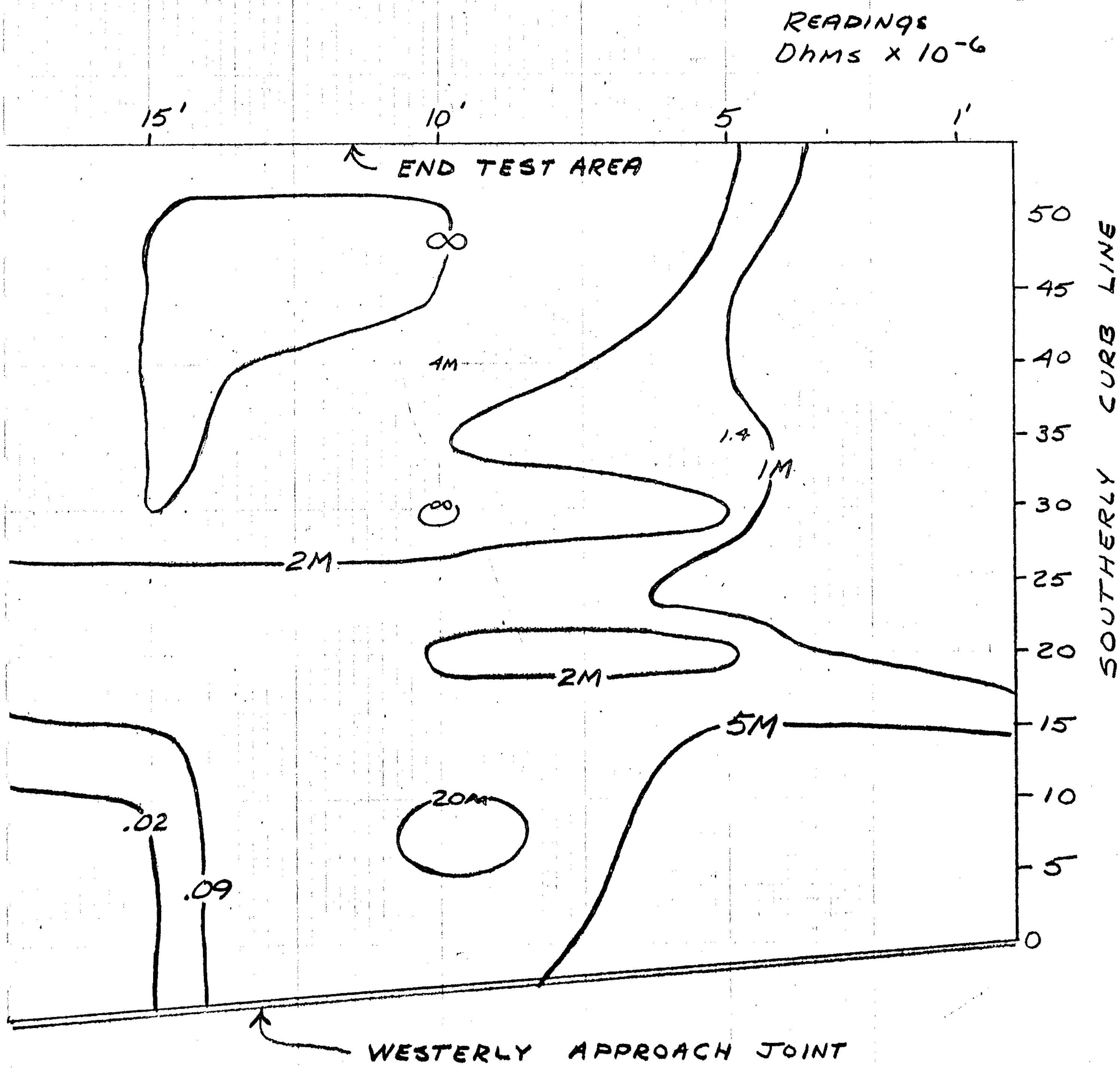
TESTED 76
PLOTTED 12/76
BY J.S.

FIGURE 10
BRIDGE #4 - HOT RUBBERIZED ASPHALT
HALF CELL POTENTIAL CONTOURS
FAIR HAVEN, VT EB US4 / VT RT. 22A
MM 1.95 BR # 5-E



TESTED 75
PLOTTED 12/75
BY J.S.

FIGURE 11
BRIDGE #4 - HOT RUBBERIZED ASPHALT
ELECTRICAL RESISTIVITY CONTOURS
FAIR HAVEN, VT EB US4 / VT. RTE. 22-A
MM 1.95 BR #5-E



TESTED 76
PLOTTED 12/76
By J.S

FIGURE 12

BRIDGE #4 · HOT RUBBERIZED ASPHALT
ELECTRICAL RESISTIVITY CONTOURS
FAIR HAVEN, VT EB US4 / VT RTE. 22A
MM 1.95 BR # 5-E

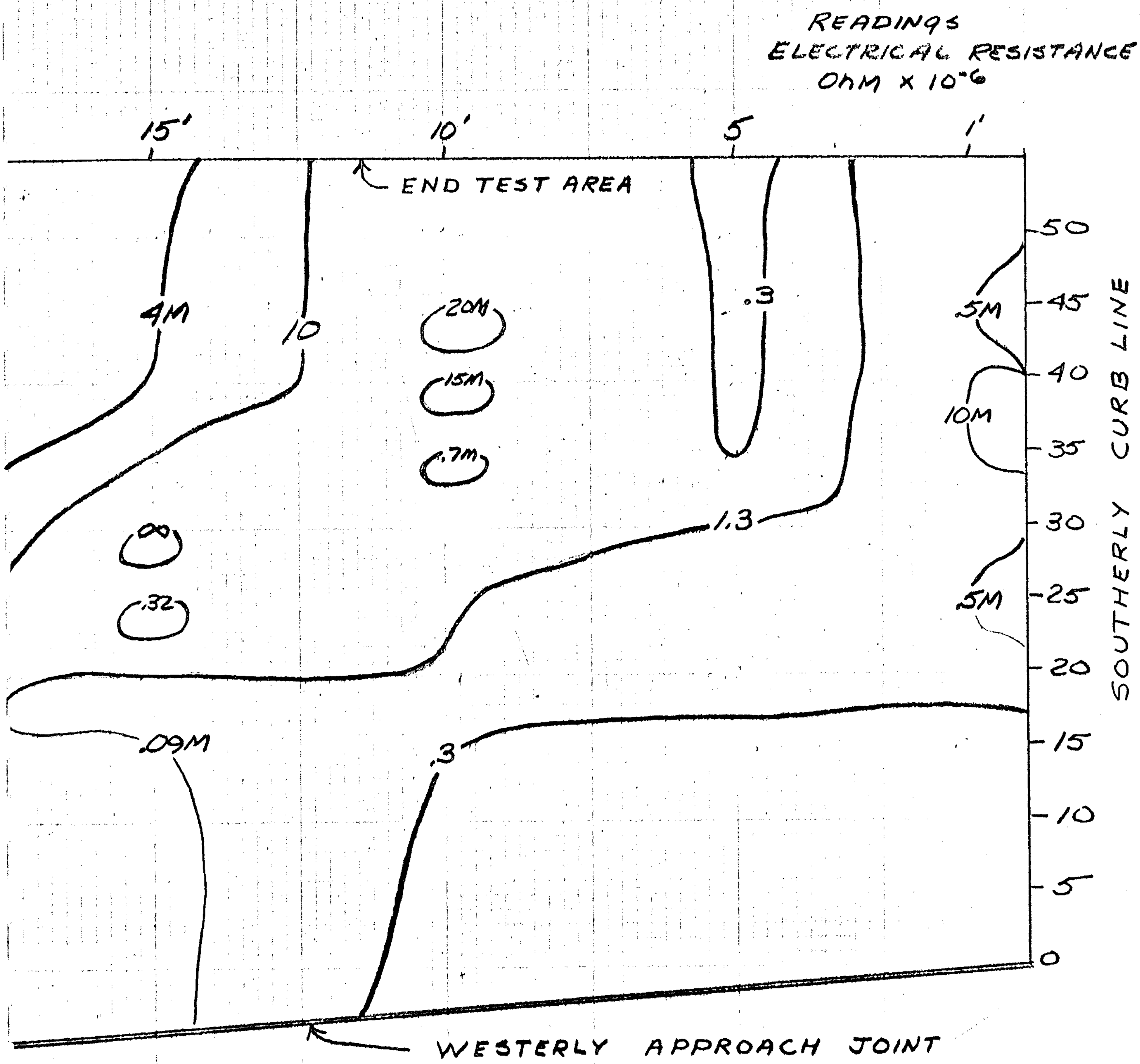


FIGURE 13

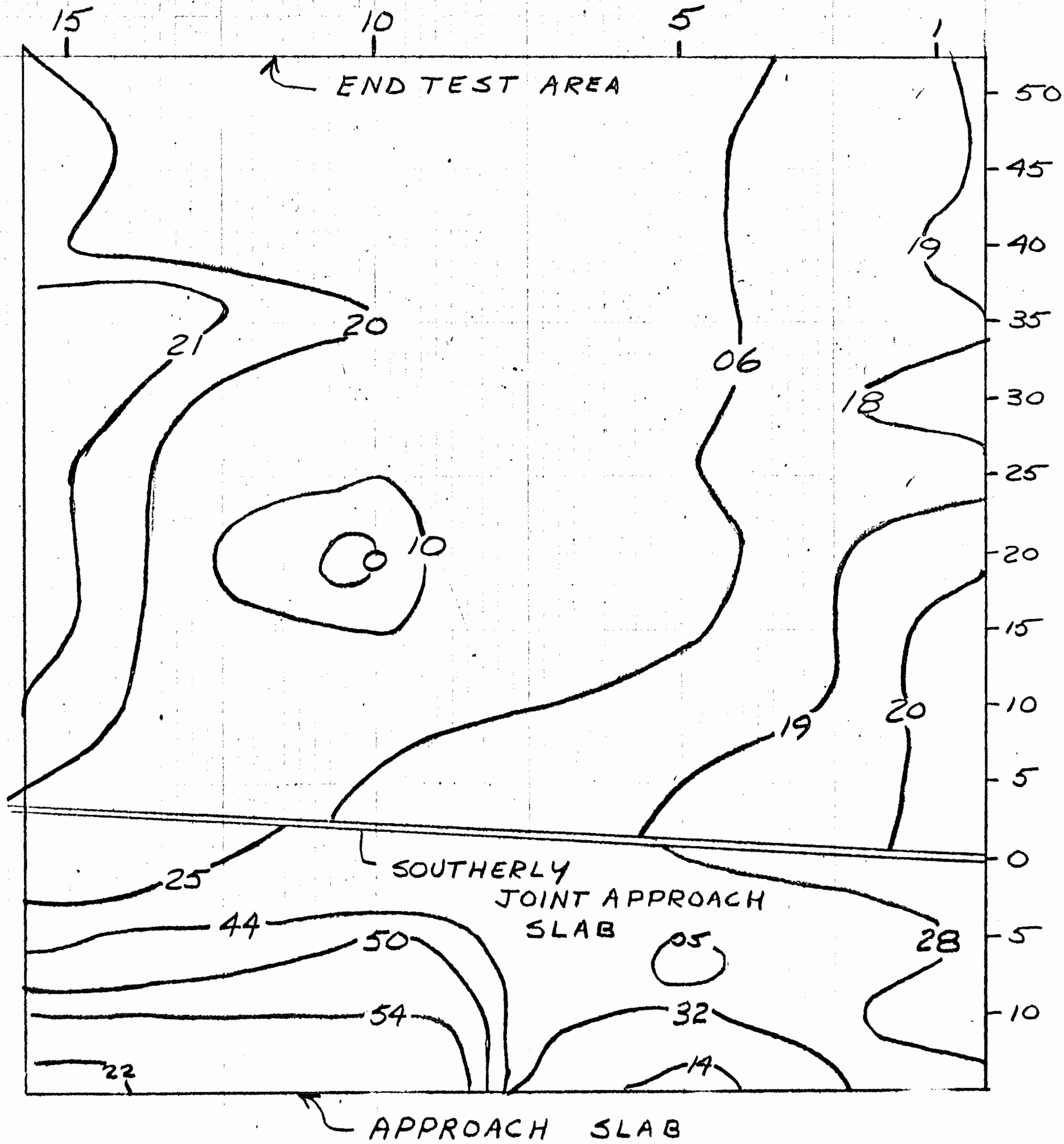
BRIDGE #6 TAREMULSION & GLASS FABRIC

HALF CELL POTENTIAL CONTOURS

BARTON, VT I 91 NB / SA #2

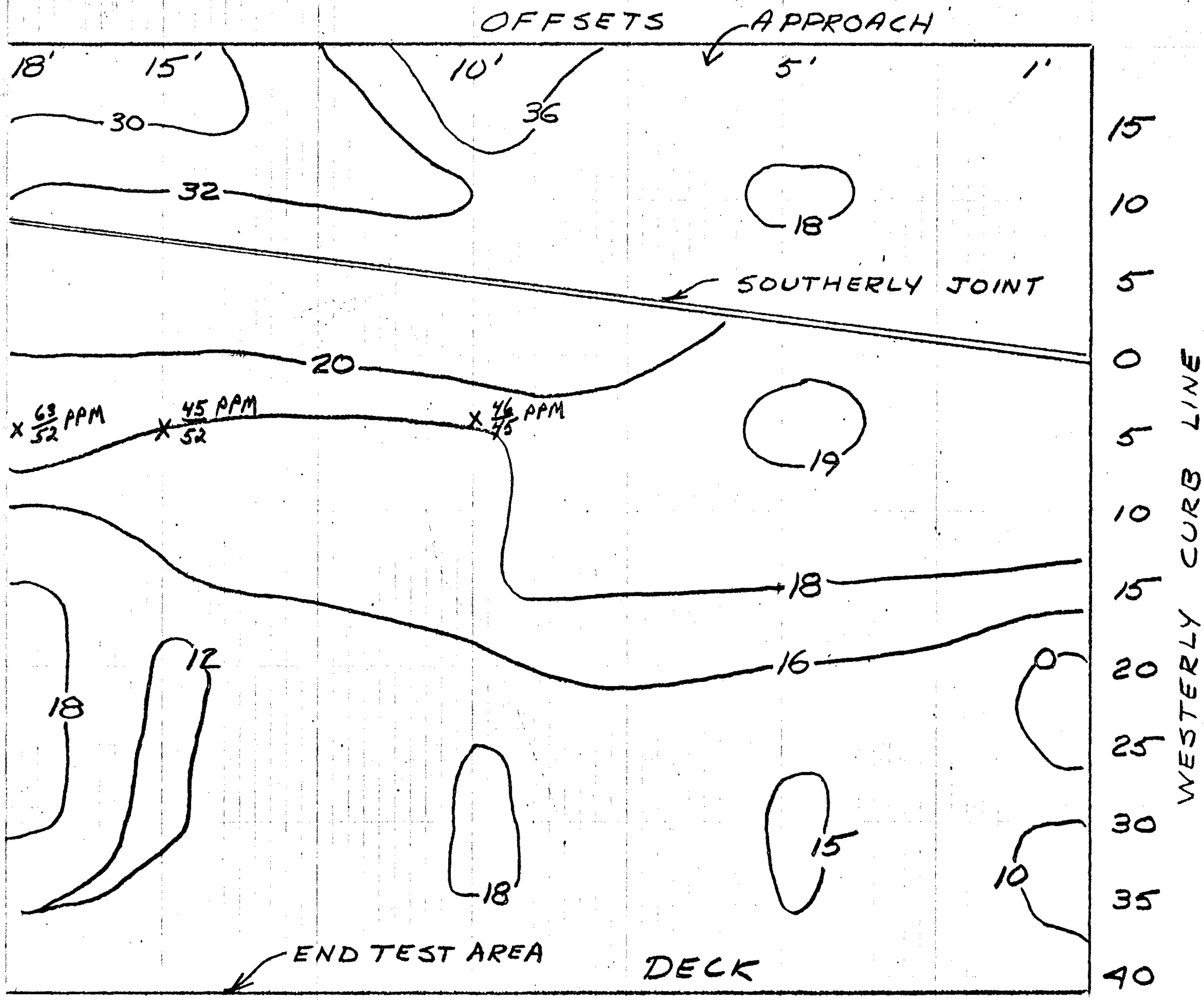
MM 156.81 BR # T 89-N

TESTED 75
PLOTTED 12/75
By J.S.



TESTED 75
PLOTTED

FIGURE 14
BRIDGE #7 - TAR MODIFIED POLYURETHANE
HALF CELL POTENTIAL CONTOURS
BARTON, VT I91 SB / SA#2
MM 156.81 BR #T89-5



READINGS
VOLTS x 100

FIGURE 15

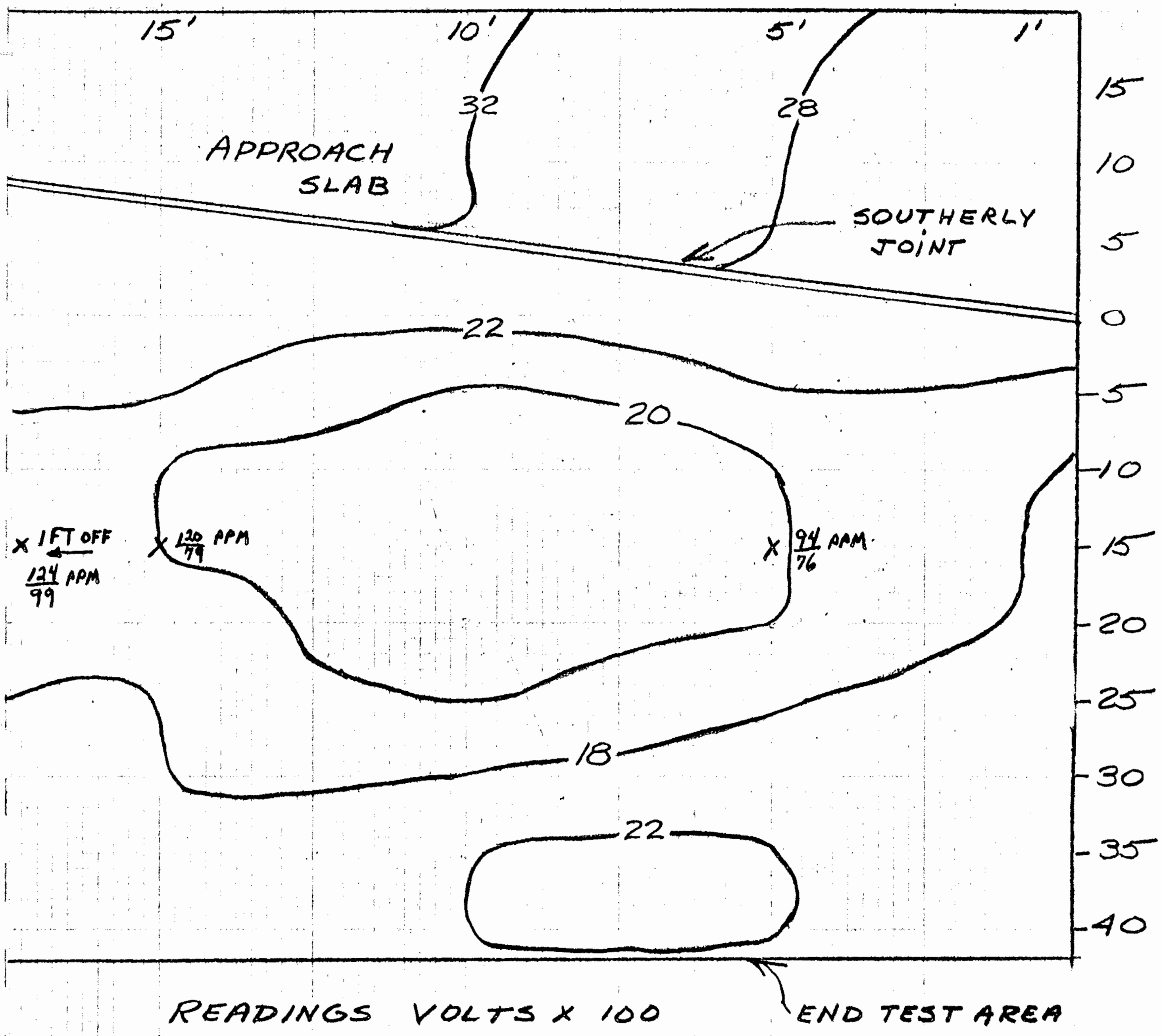
TESTED 76
PLOTTED

BRIDGE #7 - TAR MODIFIED POLYURETHANE

HALF CELL POTENTIAL CONTOURS

BARTON, VT I91 SB / SA #2

MM 156.81 BR T 89-S

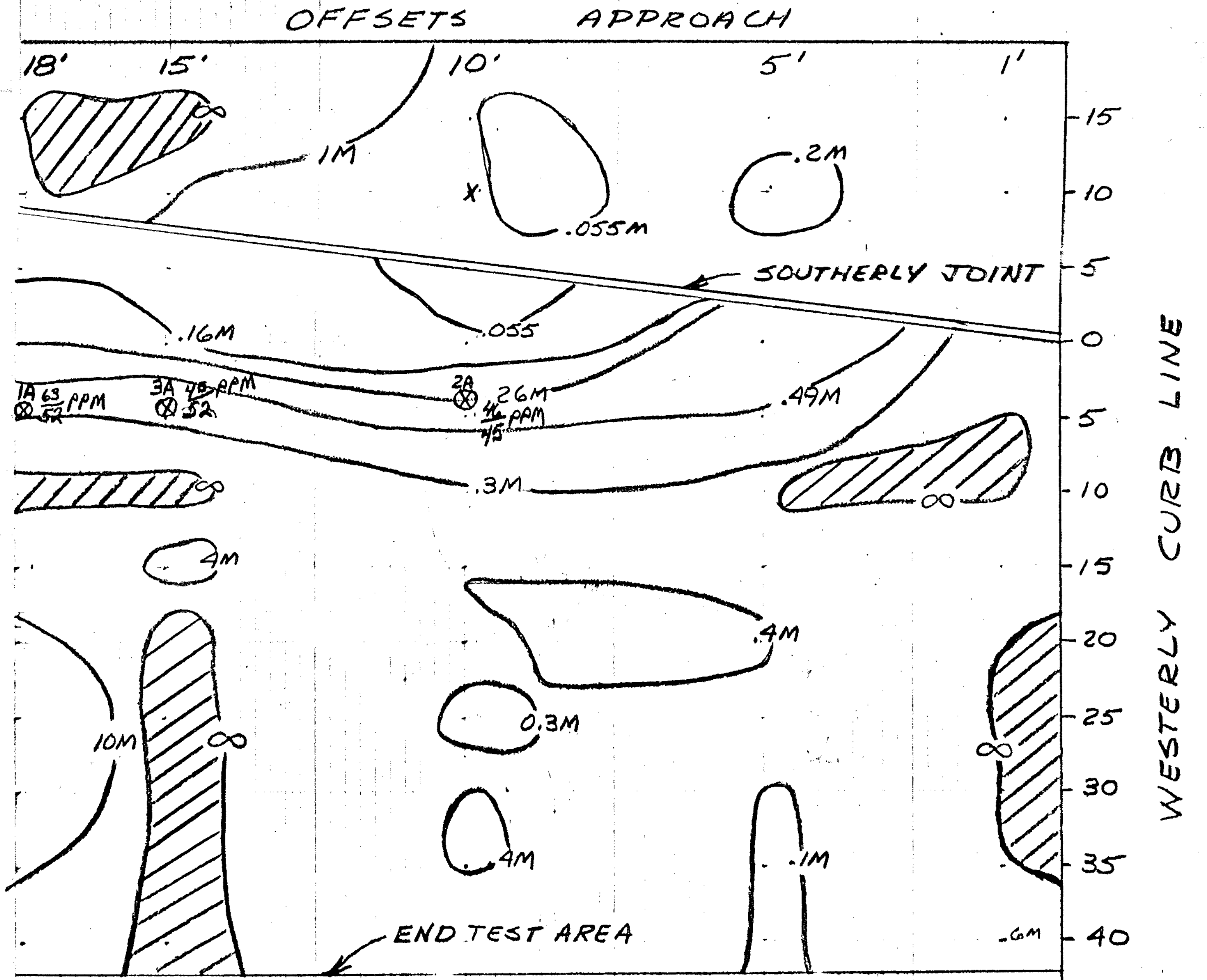


READINGS VOLTS x 100

TESTED 75
PLOTTED

FIGURE 16

BRIDGE #7 - TAR MODIFIED Polyurethane
ELECTRICAL RESISTIVITY CONTOURS
BARTON, VT I91 SB / SA #2
MM 156.81 BR # T89-S



⊕ 1975 CORES

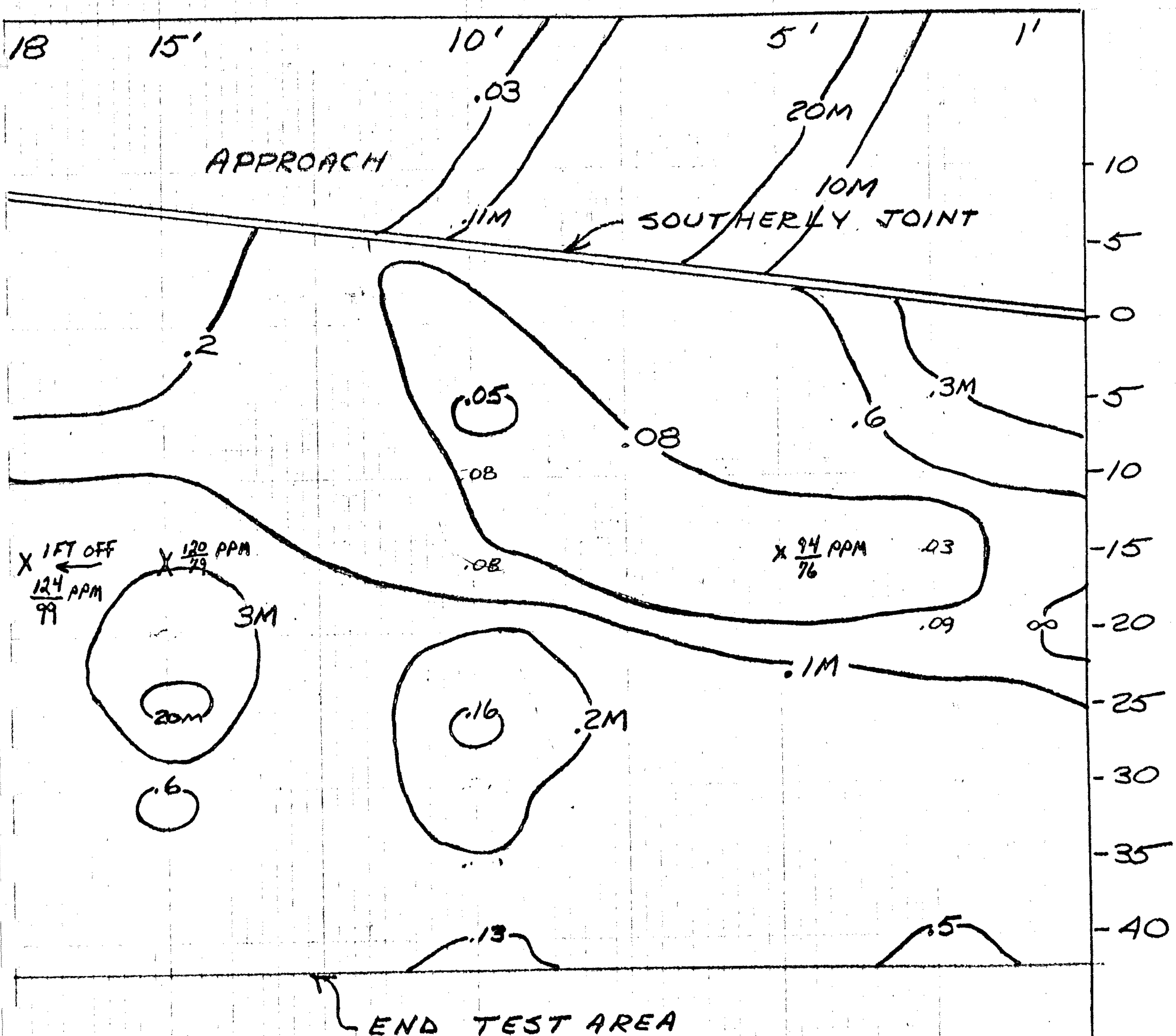
READINGS ∞

1A -
2A -
3A -

TESTED 76
PLOTTED 12/76
By J.S.

FIGURE 17

BRIDGE #7 - TAR MODIFIED POLYURETHANE
ELECTRICAL RESISTIVITY CONTOURS
BARTON, VT I91 SB/SA #2
MM 156.81 BR# T89-5



TESTED 75
PLOTTED 12/75
By J.S

FIGURE 18
BRIDGE #8 - TAR EMULSION & GLASS FABRIC
HALF CELL POTENTIAL CONTOURS
BARTON, VT I91 NB / TH#40
MM 157.53 BR# T90-N

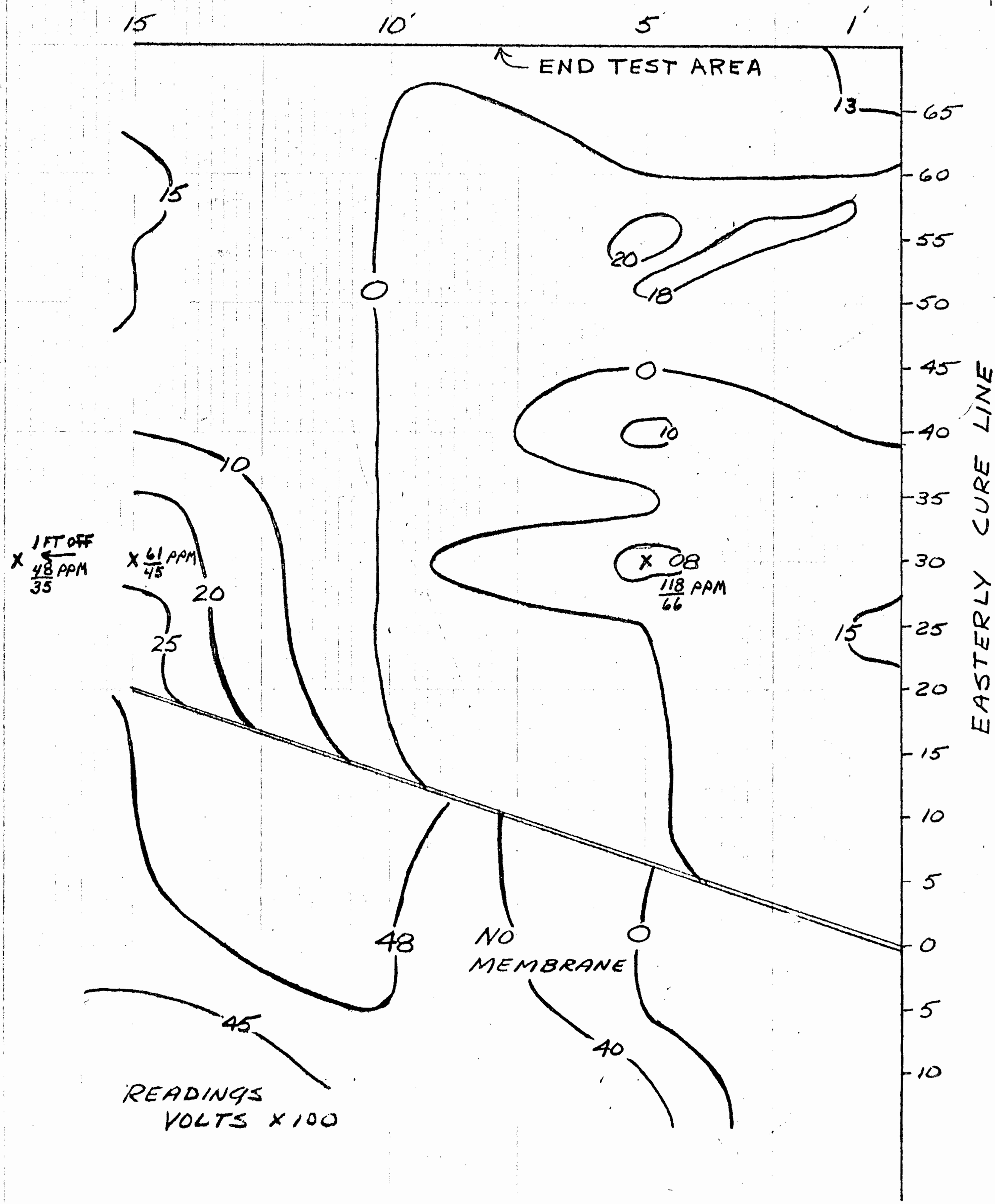
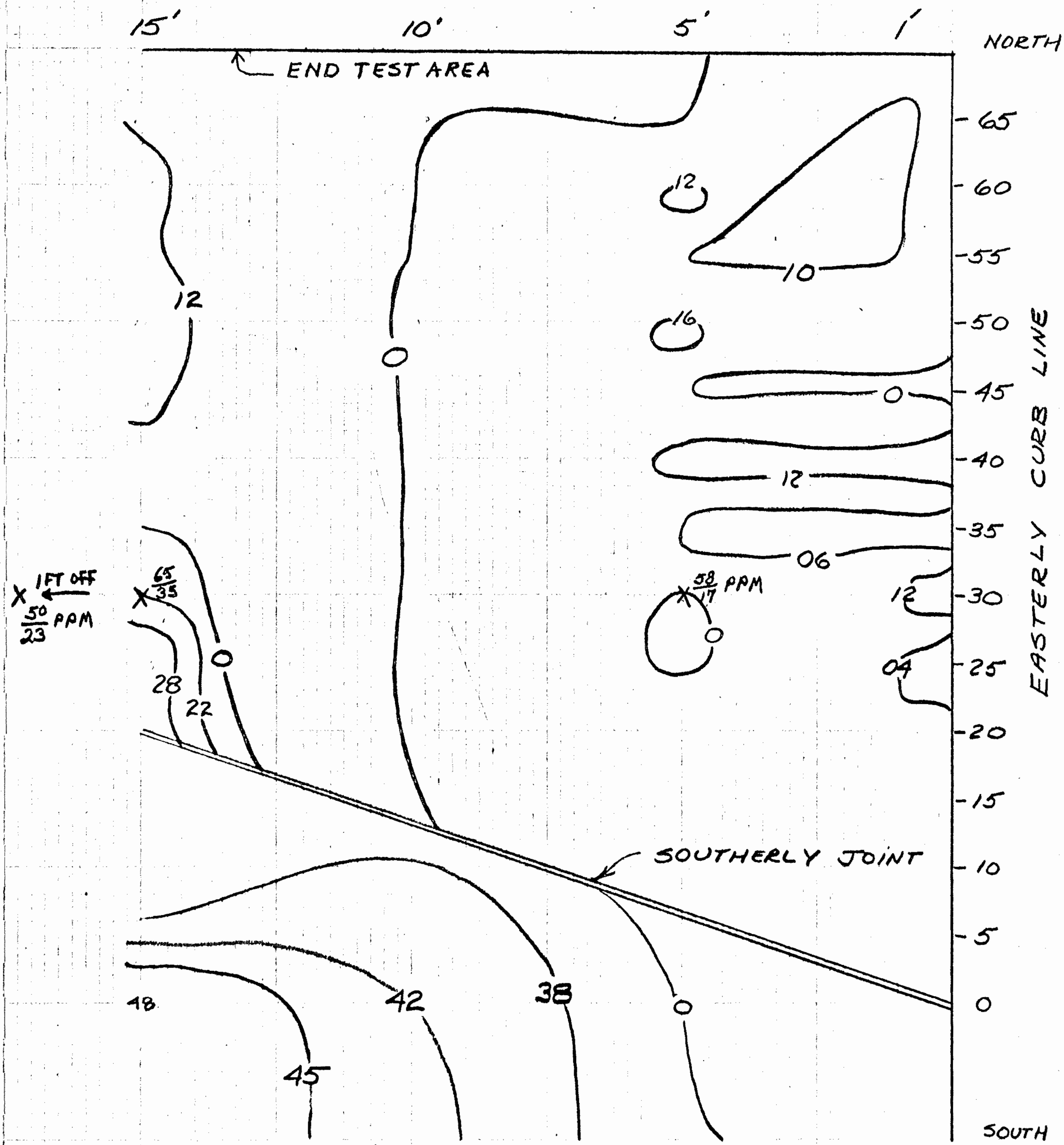


FIGURE 19
BRIDGE #8 - TAR EMULSION & GLASS FABRIC
HALF CELL POTENTIAL CONTOURS
BARTON VT. I 91 NB. / TH #40
MM 157.53 BR # T90-N

TESTED 76
PLOTTED 12/76
By J.S.



READINGS
VOLTS X 100

FIGURE 20

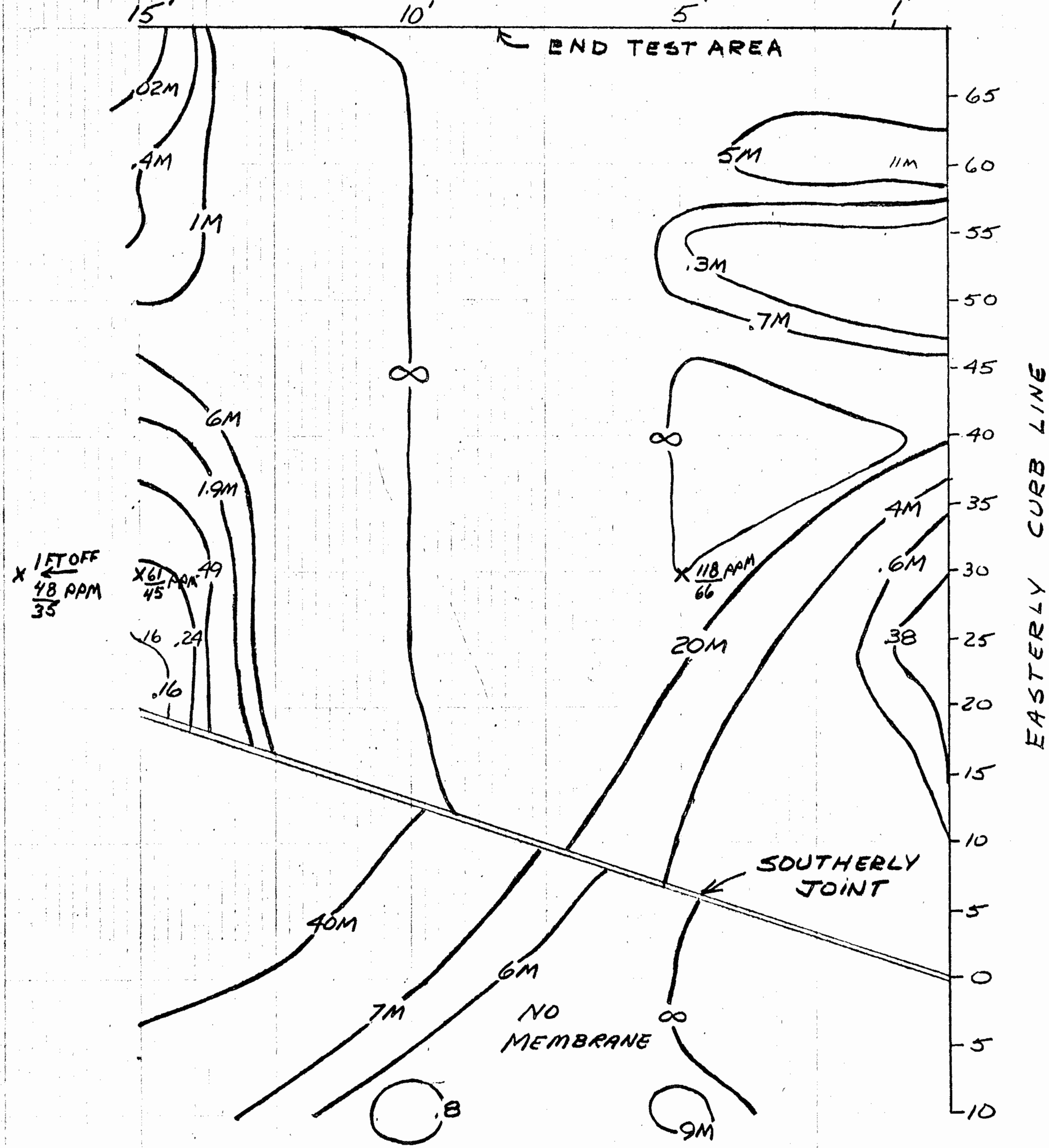
BRIDGE #8 - TAR EMULSION & GLASS FABRIC

ELECTRICAL RESISTIVITY CONTOURS

BARTON, VT I 91 NB / TH#40

MM 157.53 BR# T90-N

TESTED 75
PLOTTED 12/75
By J.S.

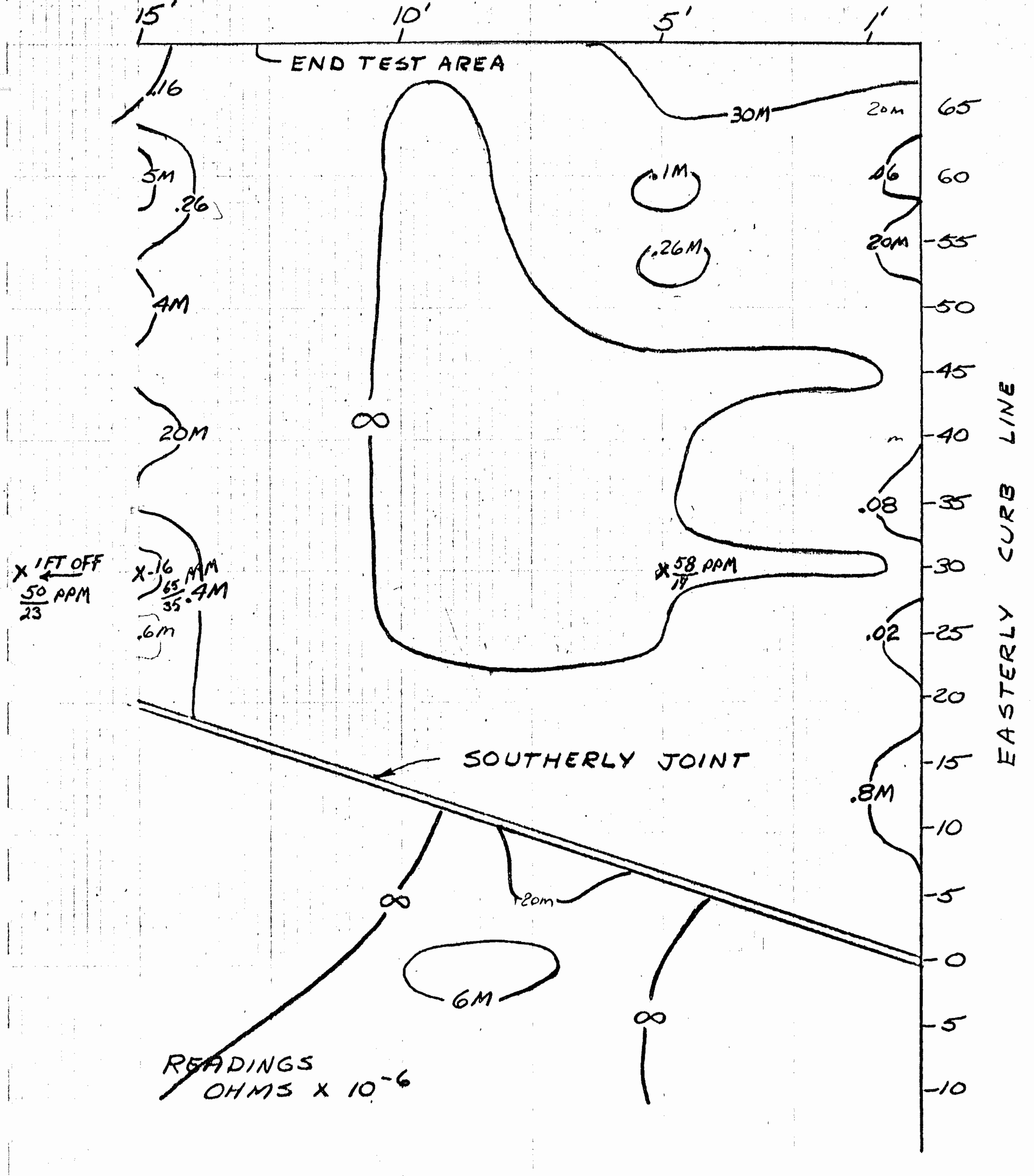


READINGS
OHMS x 10^{-6}

FIGURE 21

TESTED 76
PLOTTED 12/76
BY J.S.

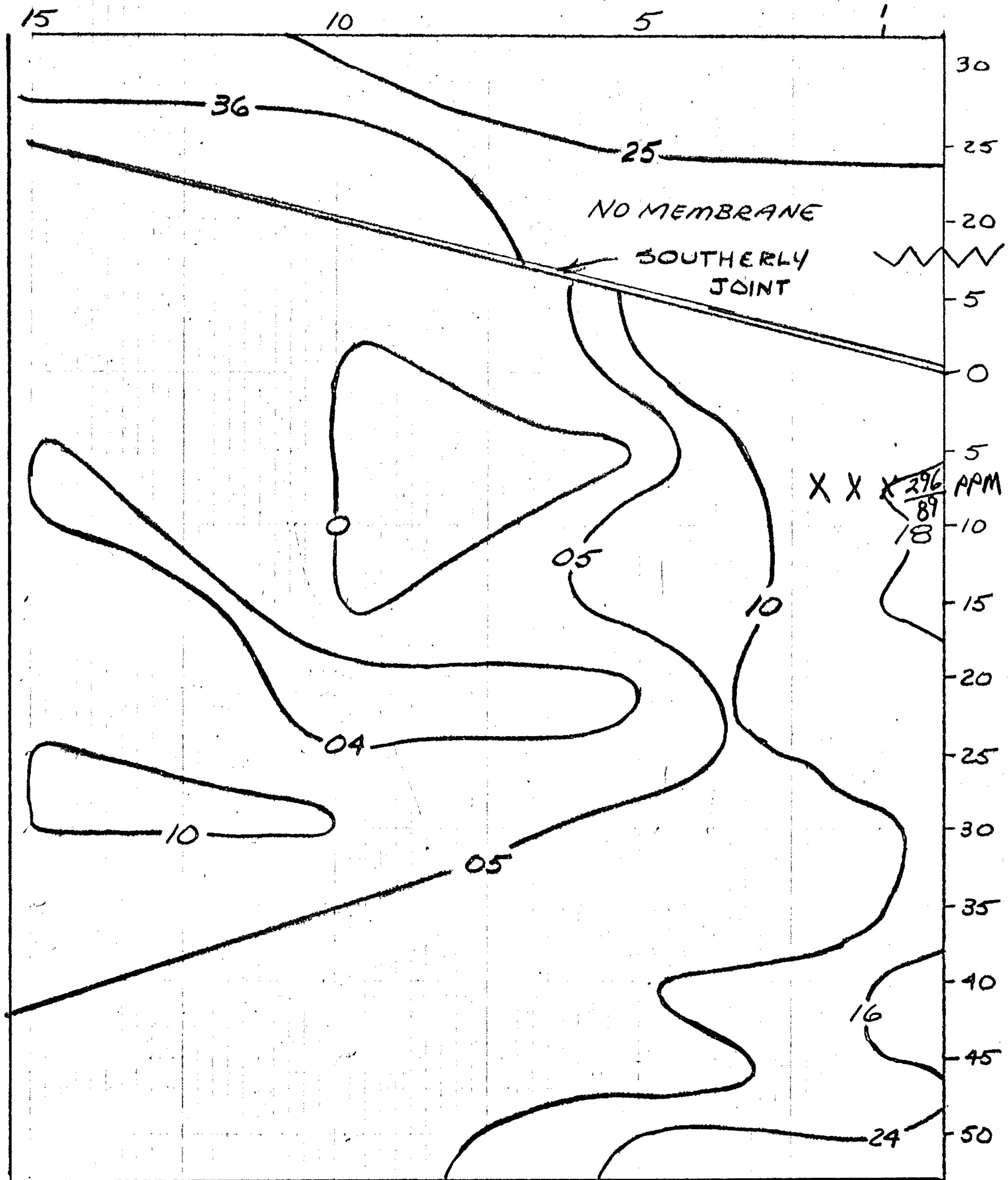
BRIDGE #8 - TAR EMULSION & GLASS FABRIC
ELECTRICAL RESISTIVITY CONTOURS
BARTON, VT I 91 NB / TH#40
MM 157.53 BR# T90-N



PLOTTED 75
TESTED 12/75
By J.S.

FIGURE 22

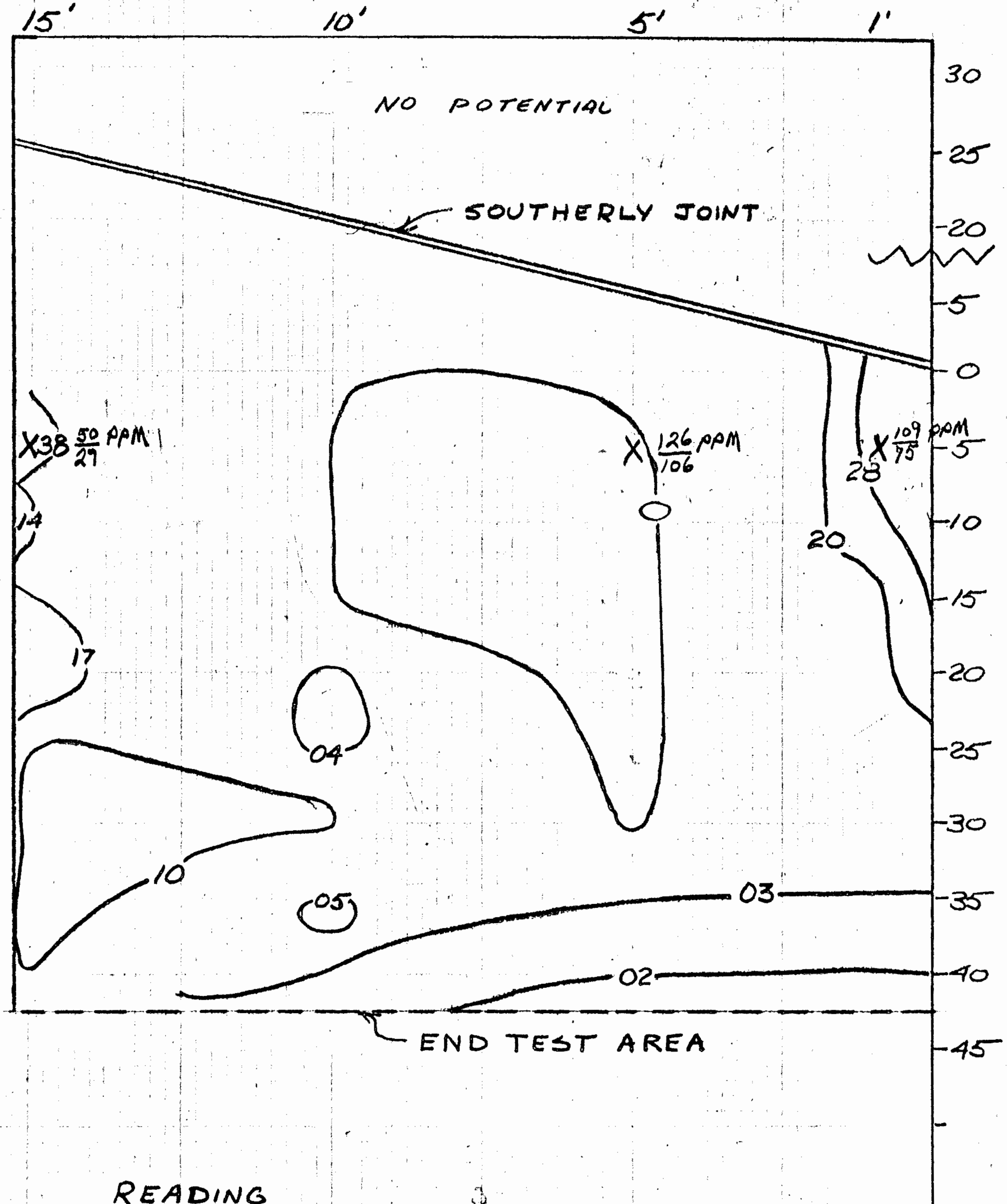
BRIDGE #9 - SOLVENT CUT EPOXY
HALF CELL POTENTIL CONTOURS
BARTON I91 SB / TH #40
MM 157.53 BR# T90-S



END TEST AREA

Tested 76
Plotted ______

Figure 23
Bridge 9 - Solvent Cut Epoxy
Half Cell Potential Contours
Barton I 91 SB / TH#40
MM 157.53 BR# 90-5



READING
VOLTS X 100

FIGURE 24

BRIDGE #9 - SOLVENT CUT EPOXY

ELECTRICAL RESISTIVITY CONTOURS

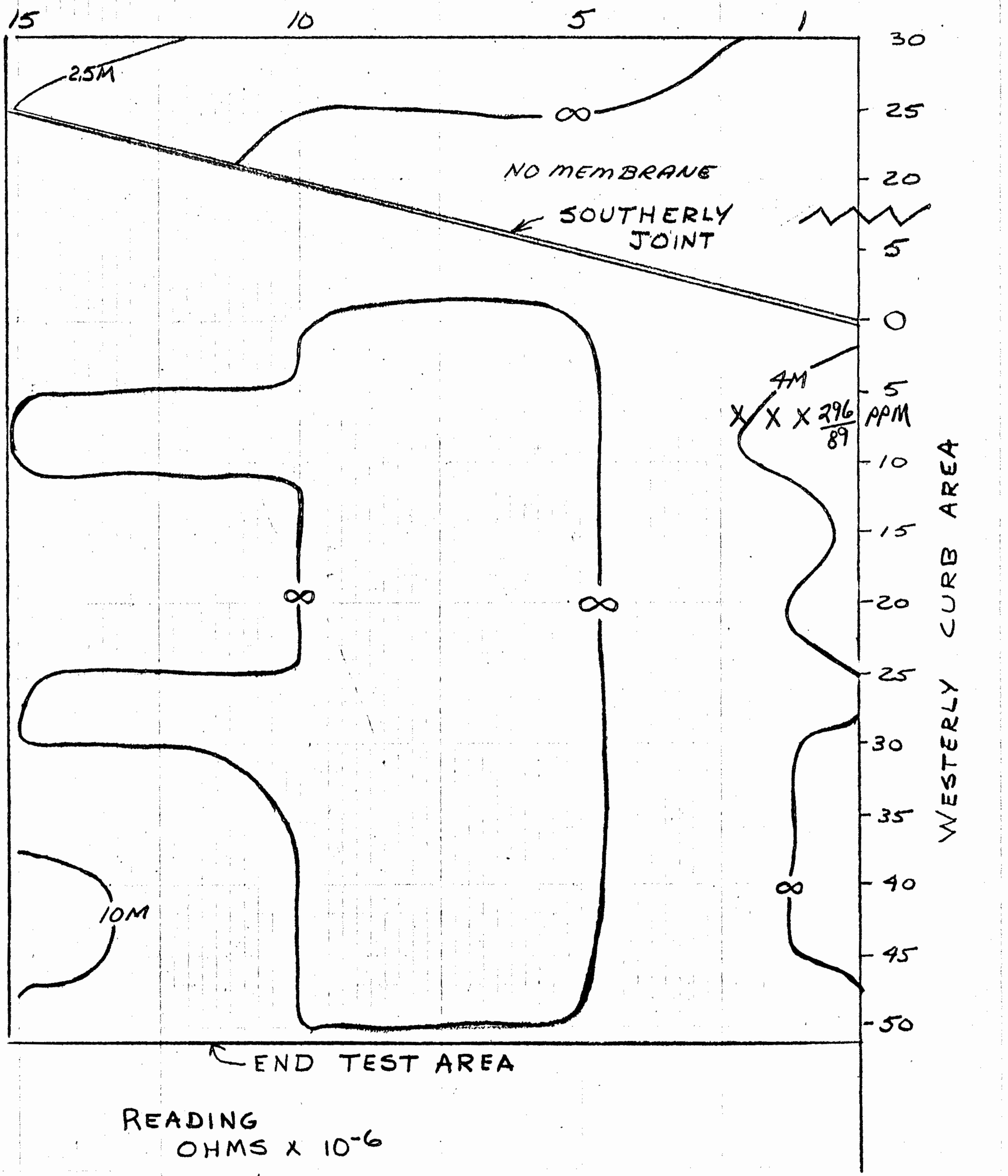
BARTON I 91 SB / TH #40

MM 157.53 BR# T90-S

TESTED 75

PLOTTED 12/75

By J.S

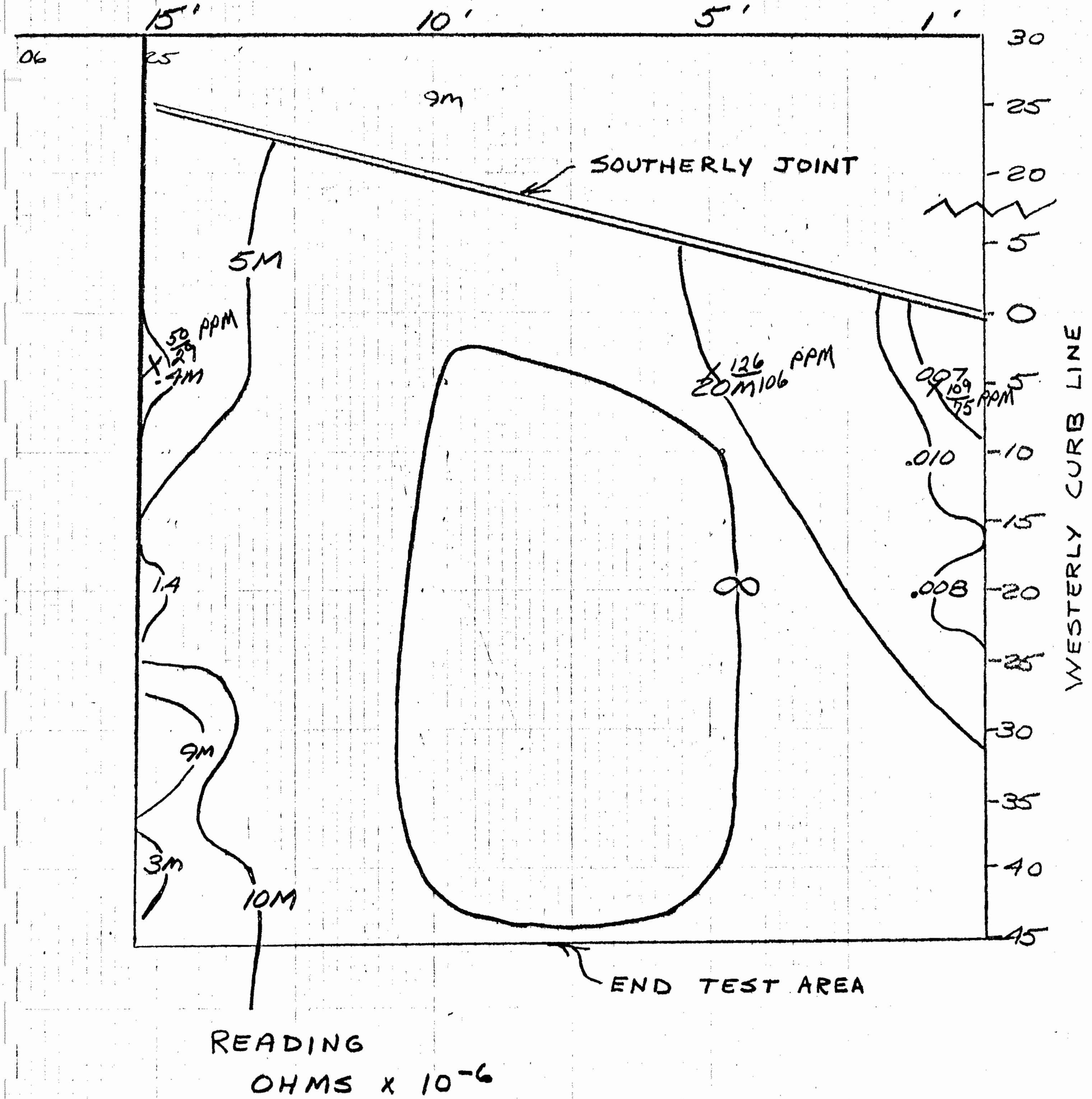


READING
OHMS x 10^{-6}

TESTED 76
PLOTTED 12/76
By J.S.

FIGURE 25

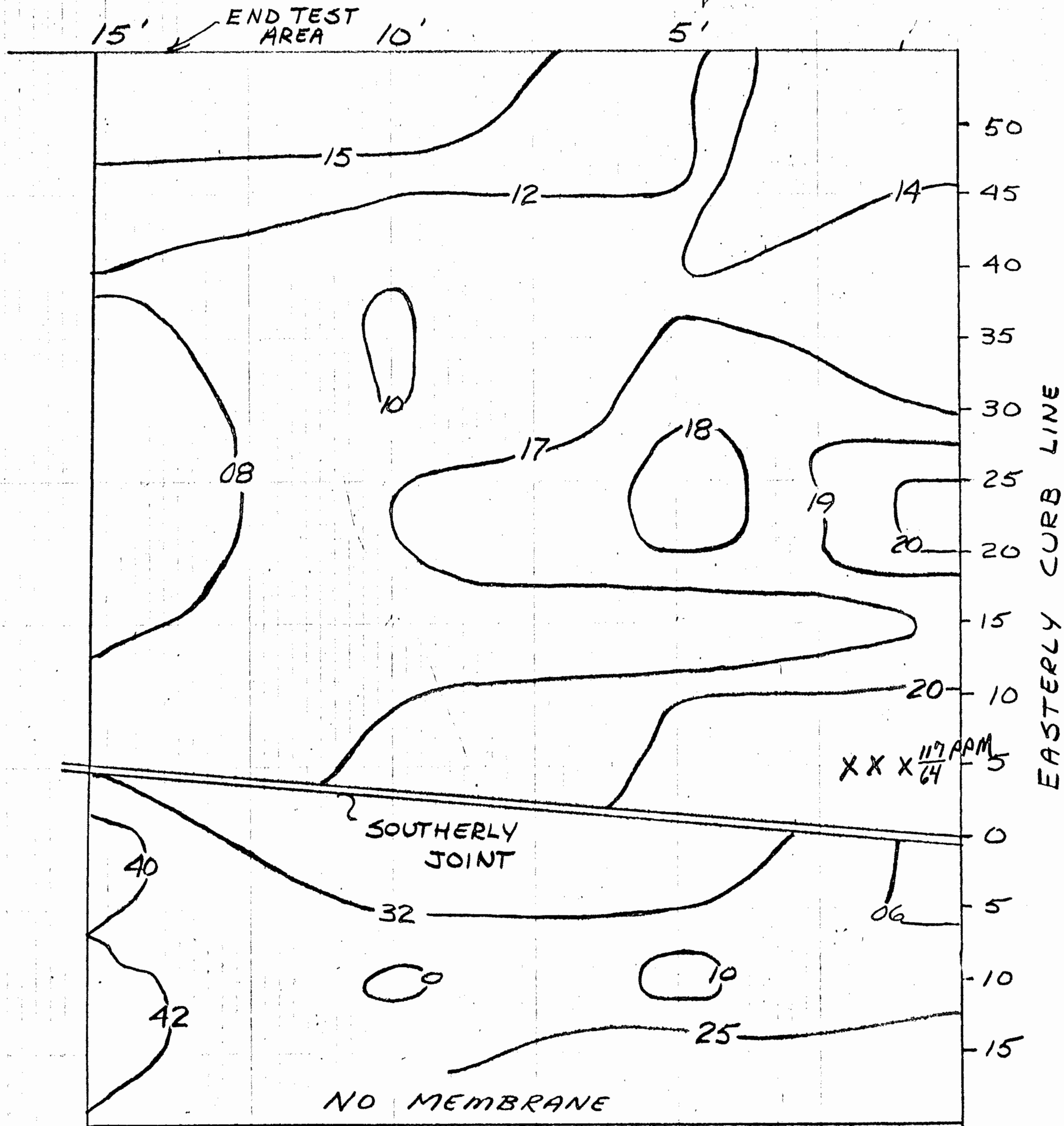
BRIDGE #9 - SOLVENT CUT EPOXY
ELECTRICAL RESISTIVITY CONTOURS
BARTON I 91 SB / TH #40
MM 157.53   BR# T 90-S



TESTED 75
PLOTTED 12/75
By J.S.

FIGURE 26

BRIDGE #10 - COAL TAR MODIFIED EPOXY
HALF CELL POTENTIAL CONTOUR
BARTON I91 NB / TH #29
MM 160.22 BR# T91-N



1976 - NOT ENOUGH STEEL

FIGURE 27
BRIDGE #10 - COALTAR MODIFIED EPOXY
ELECTRICAL RESISTIVITY CONTOURS
BARTON I 91 NB / TH #29
MM 160.22 BR # T91-N

TESTED 75
PLOTTED 12/75
By JS

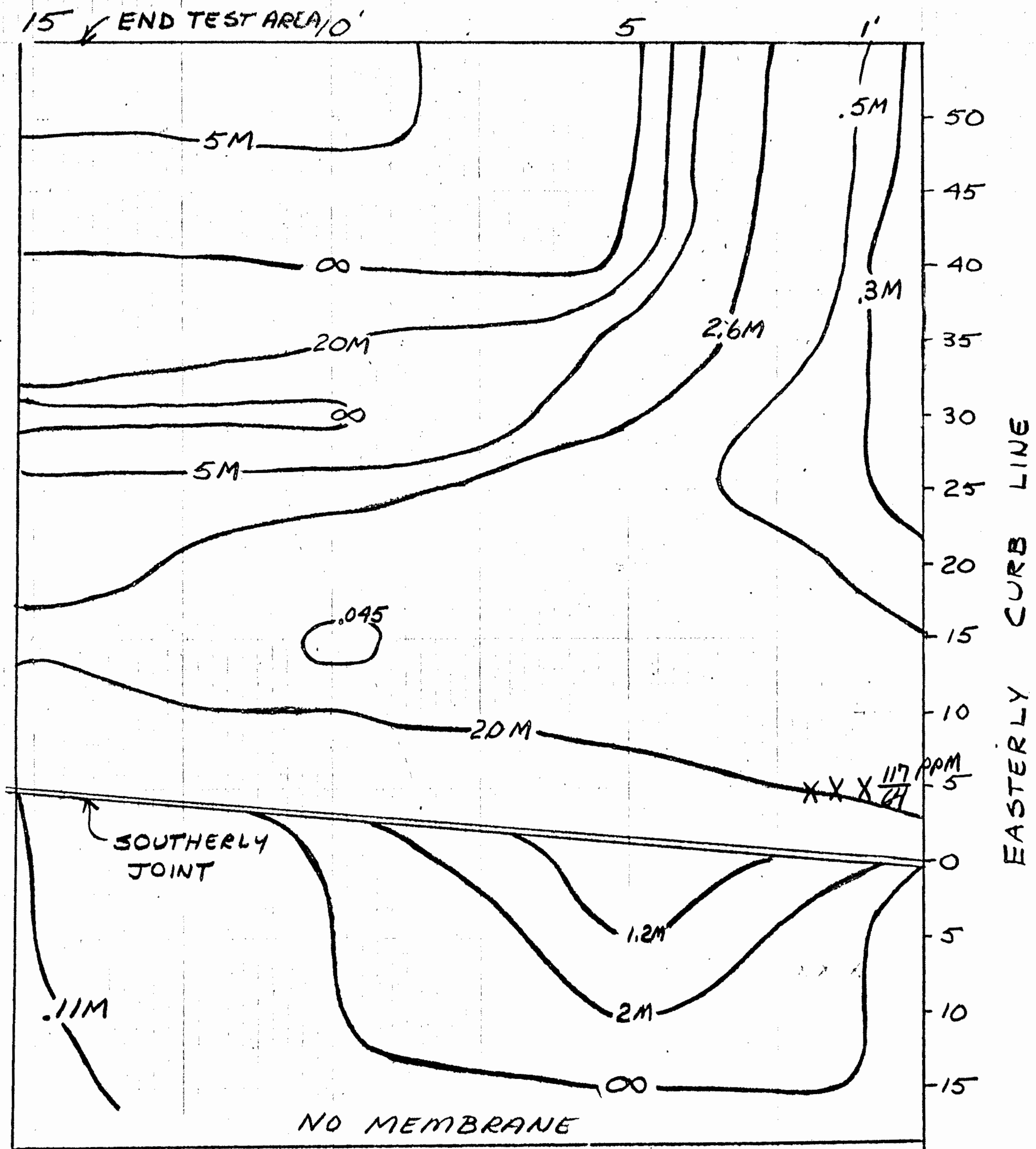
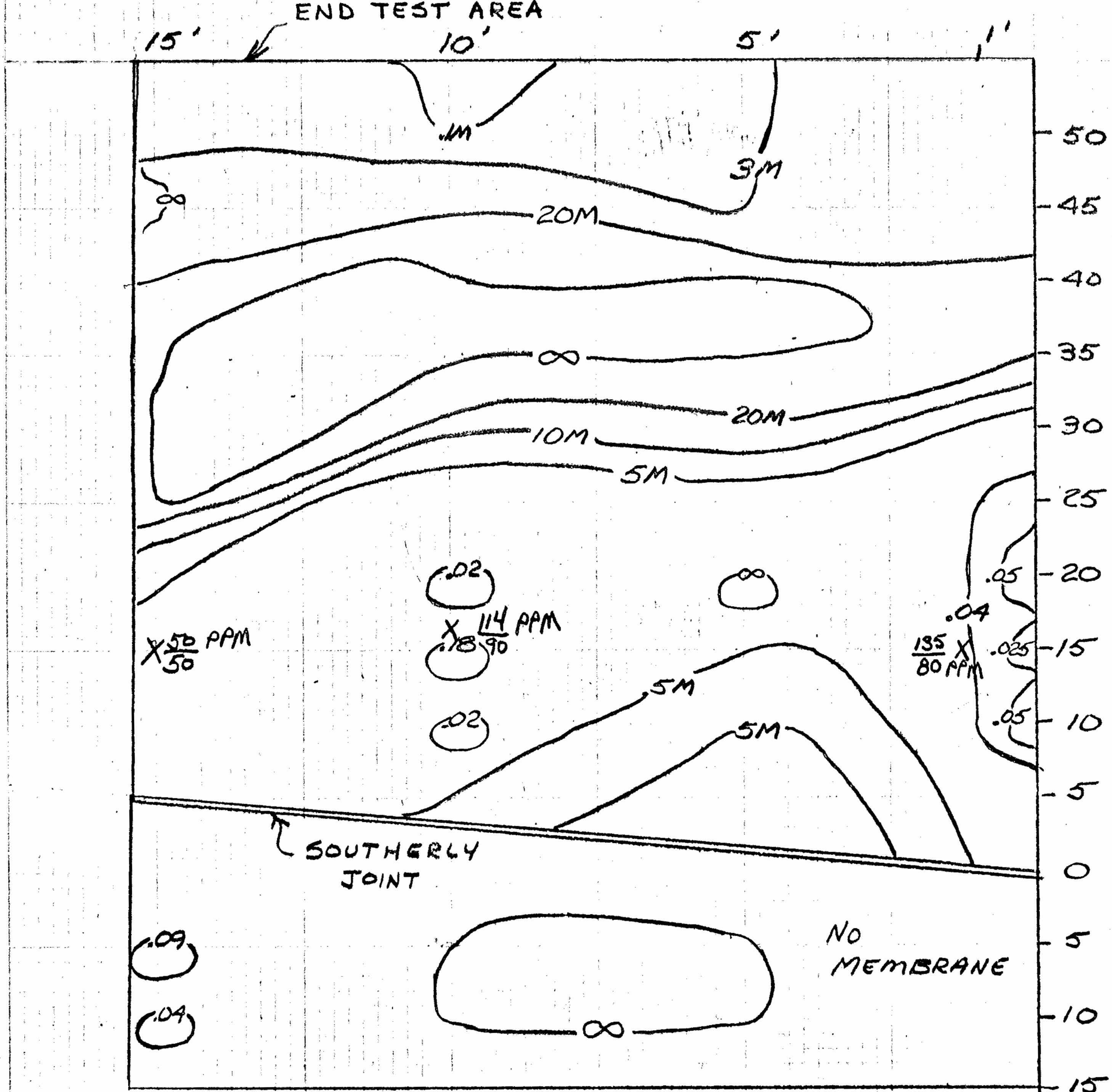


FIGURE 28

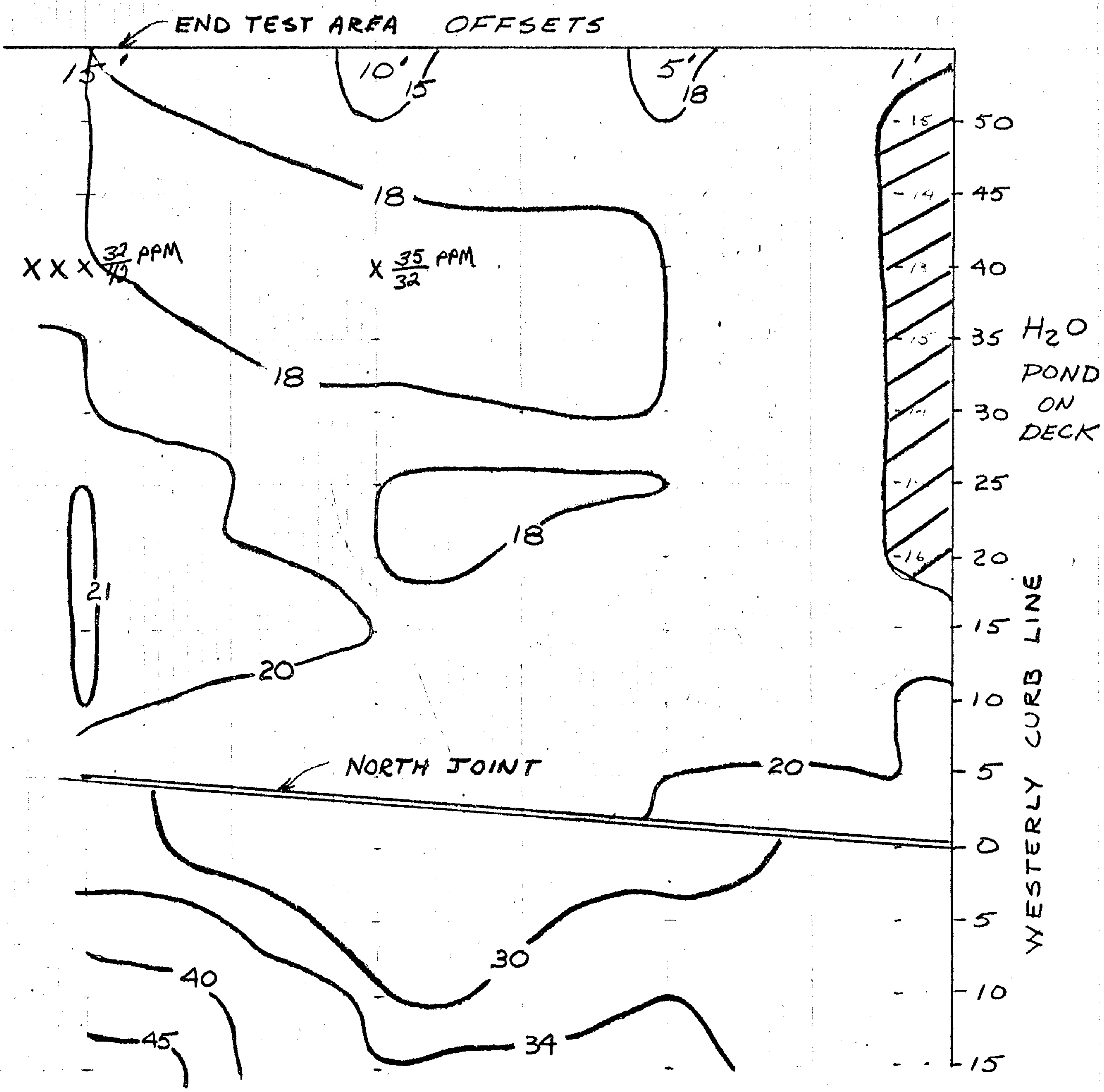
BRIDGE #10 - COAL TAR MODIFIED EPOXY
ELECTRICAL RESISTIVITY CONTOURS
BARTON I91NB / TH #29
MM 160.22 BR# T91-N



TESTED 75
PLOTTED 12/75
BY J.S

FIGURE 29

BRIDGE #11 - 65 MIL PREFORMED SHEET
HALF CELL POTENTIAL CONTOURS
BARTON I 91 SB / TH#29
MM 160.22 BR# T91-S



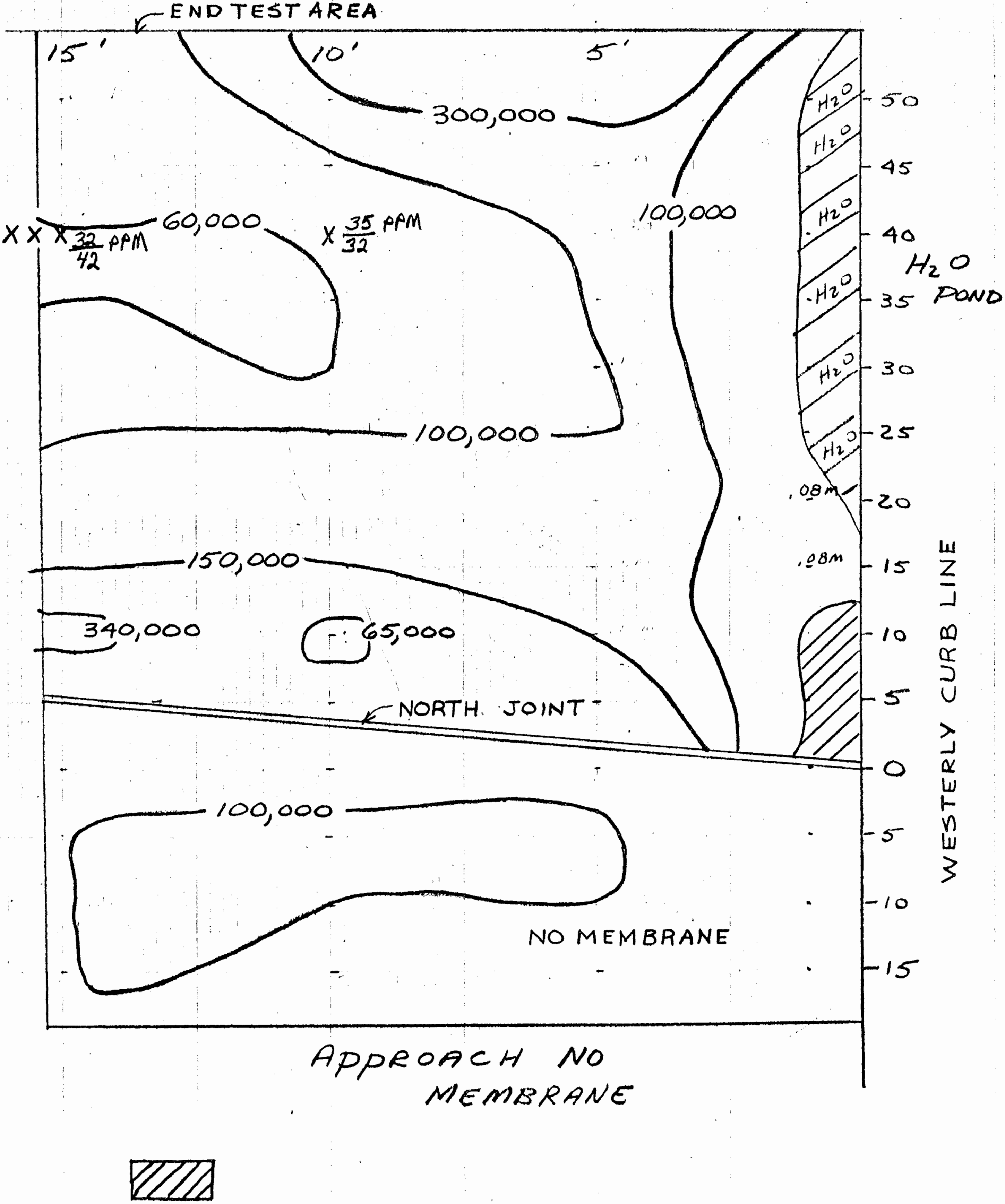
READINGS
VOLTS

APPROACH NO MEMBRANE

76 - NO STEEL

FIGURE 30
BRIDGE #11 - 65 MIL PREFORMED SHEET
ELECTRICAL RESISTIVITY CONTOURS
BARTON I 91 SB / TH #29
MM 160.22 BR # T91-5

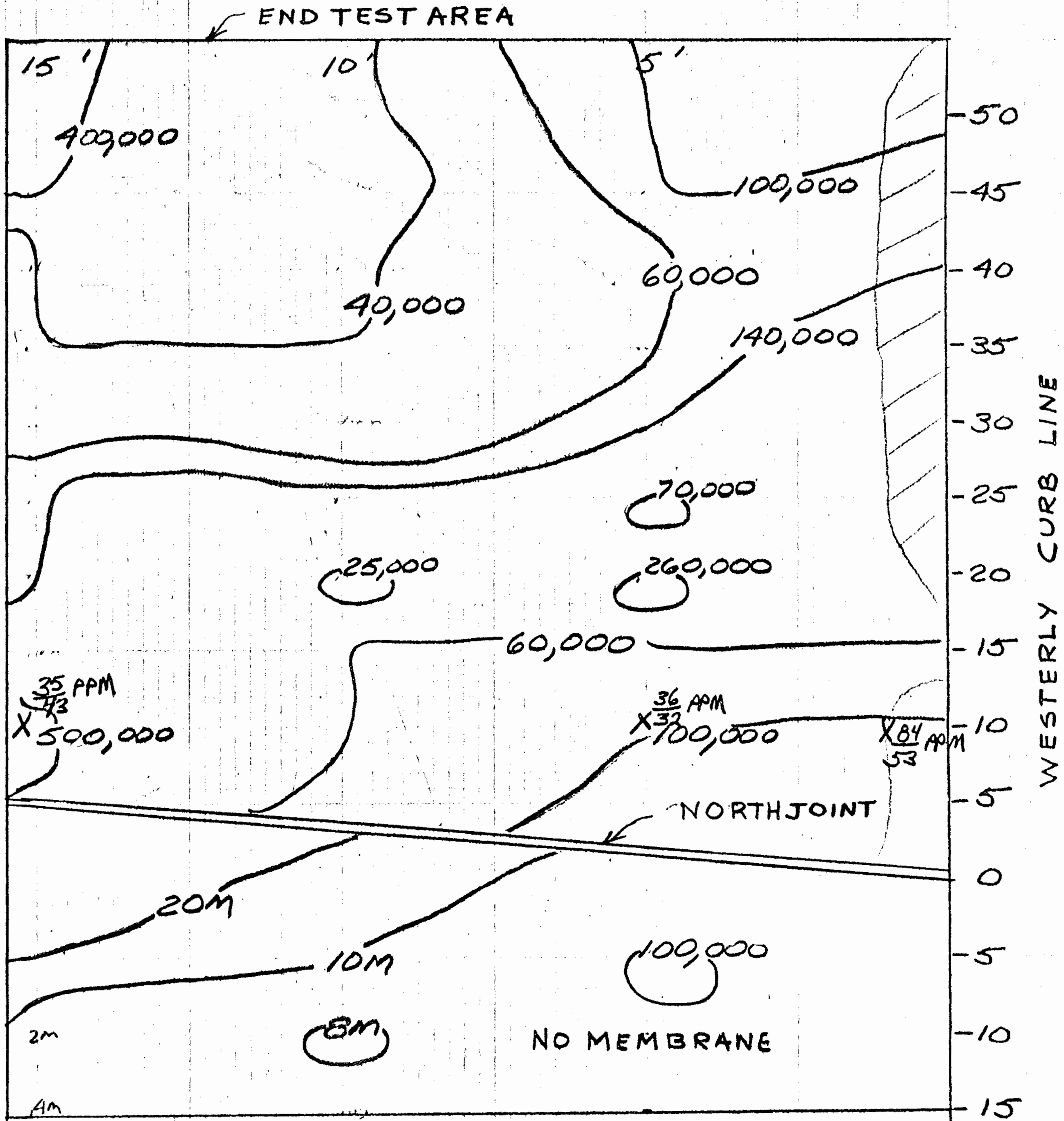
TESTED 75
PLOTTED 12/75
BY J.S.



APPROACH NO MEMBRANE

TESTED 75
PLOTTED 12/76
By J.S

FIGURE 31
BRIDGE #11 - 65 MIL PREFORMED SHEET
ELECTRICAL RESISTIVITY CONTOURS
BARTON I 91 SB / TH#29
MM 160.22 BR # T91-S

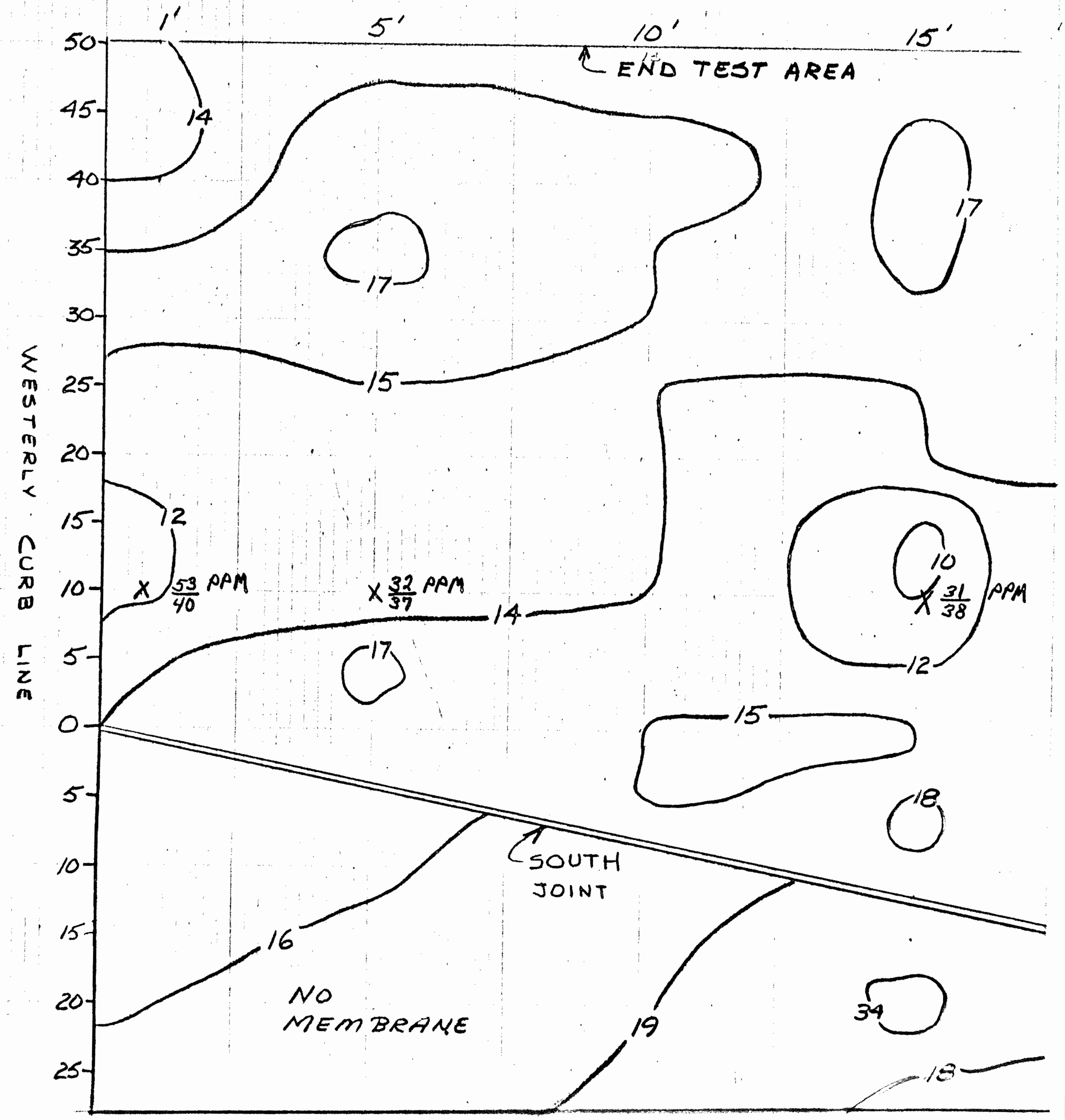


READINGS
OHMS X 10^{-6}

TESTED 75
PLOTTED 12/75
By J.S.

FIGURE 32

BRIDGE #15 - ASPHALT MODIFIED POLYURETHANE
HALF CELL POTENTIAL CONTOURS
IRASBURG I91 SB / SA#3, ORLEANS RIVER



READINGS
VOLTS X 100

FIGURE 33

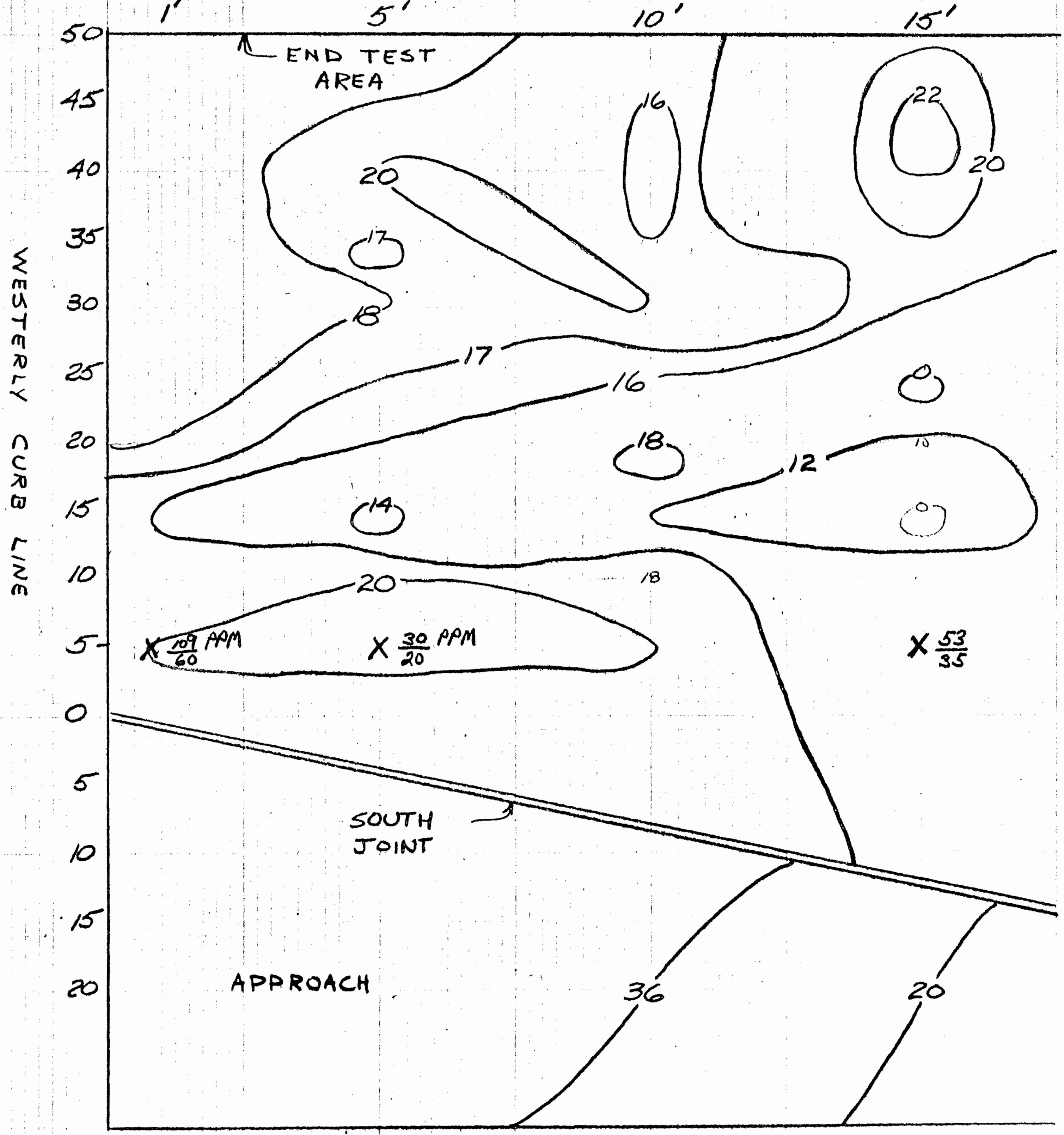
BRIDGE #15 - ASPHALT MODIFIED Polyurethane

HALFCELL POTENTIAL CONTOURS

IRASBURG I 91 SB / SA#3, ORLEANS RIVER

MM 163.50 BR# T 93-S

TESTED 76
PLOTTED 12/76
By J.S

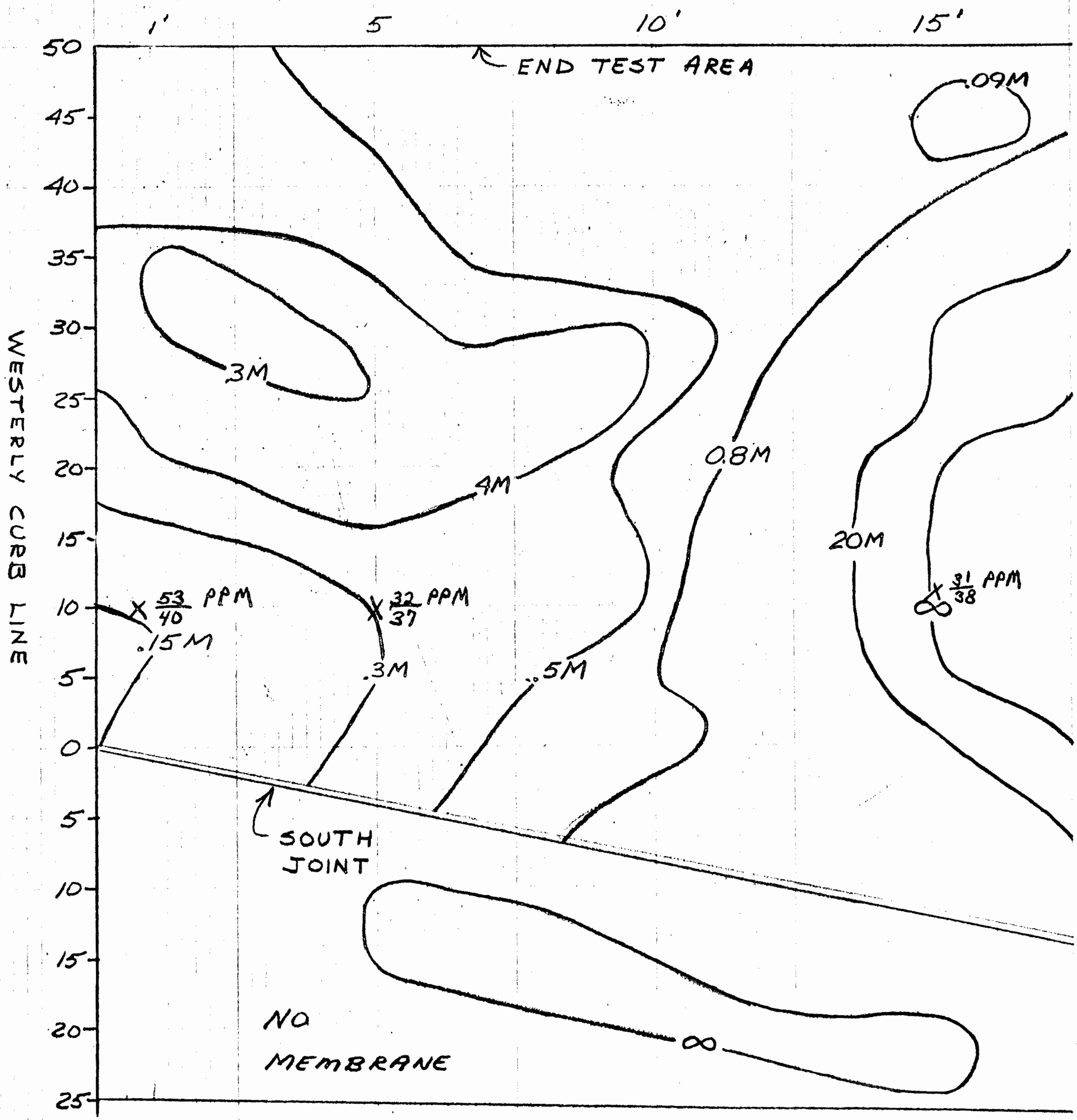


READINGS
OHM x 10^{-6}

FIGURE 34

TESTED 75
PLOTTED 12/75
BY J.S.

BRIDGE #15 - ASPHALT MODIFIED Polyurethane
ELECTRICAL RESISTIVITY CONTOURS
IRASBURG I91 SB / SA#3 ORLEANS RIVER
MM 163.50 BR T93-S

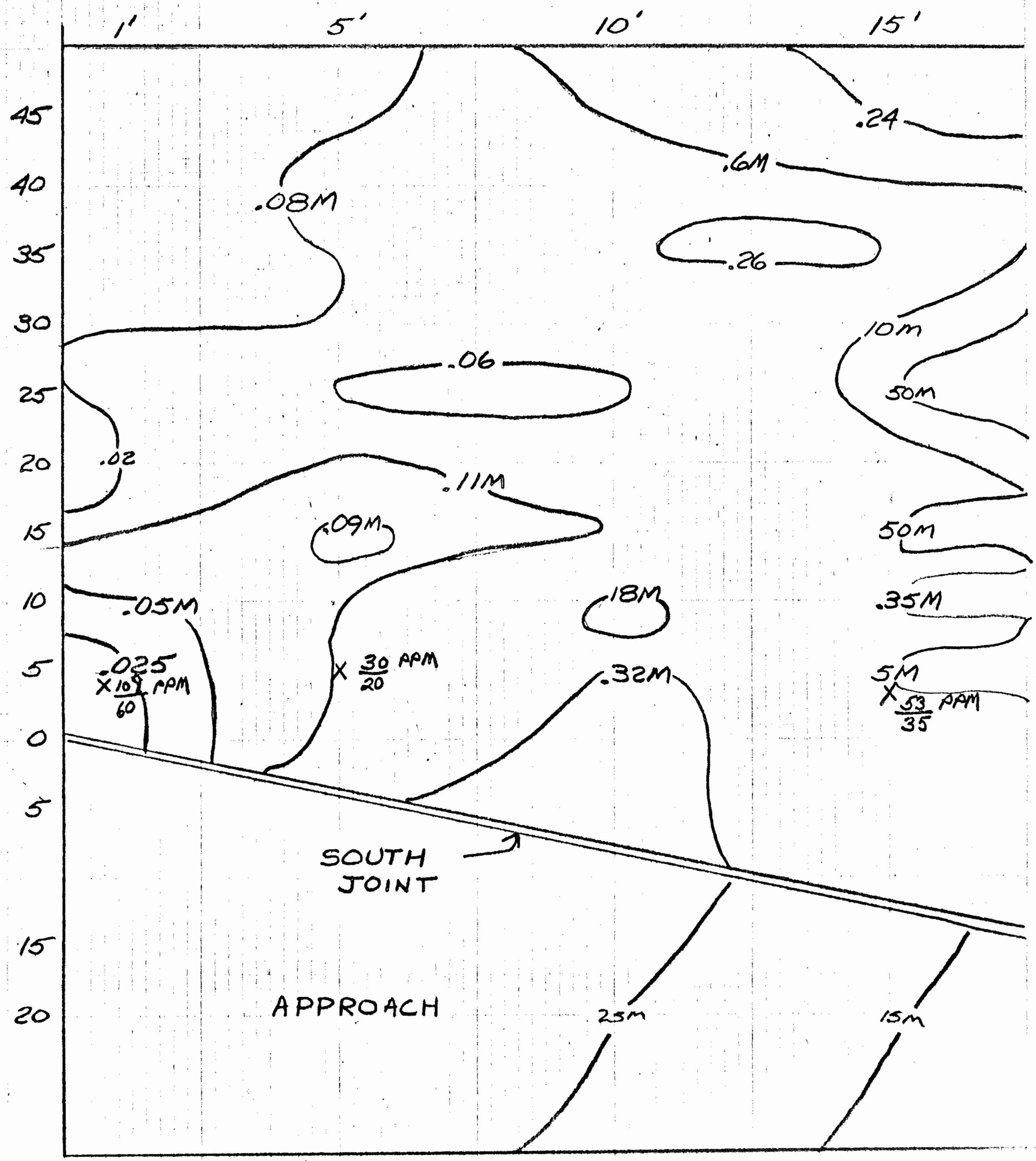


READING
OHMS X 10^{-6}

Tested 76
Plotted 12/76
By J.S

FIGURE 35

BRIDGE #15 - Asphalt Modified Polyurethane
ELECTRICAL RESISTIVITY CONTOURS
IRASBURG I91SB / SA#3, ORLEANS RIVER
MM 163.50 BR# T93-S

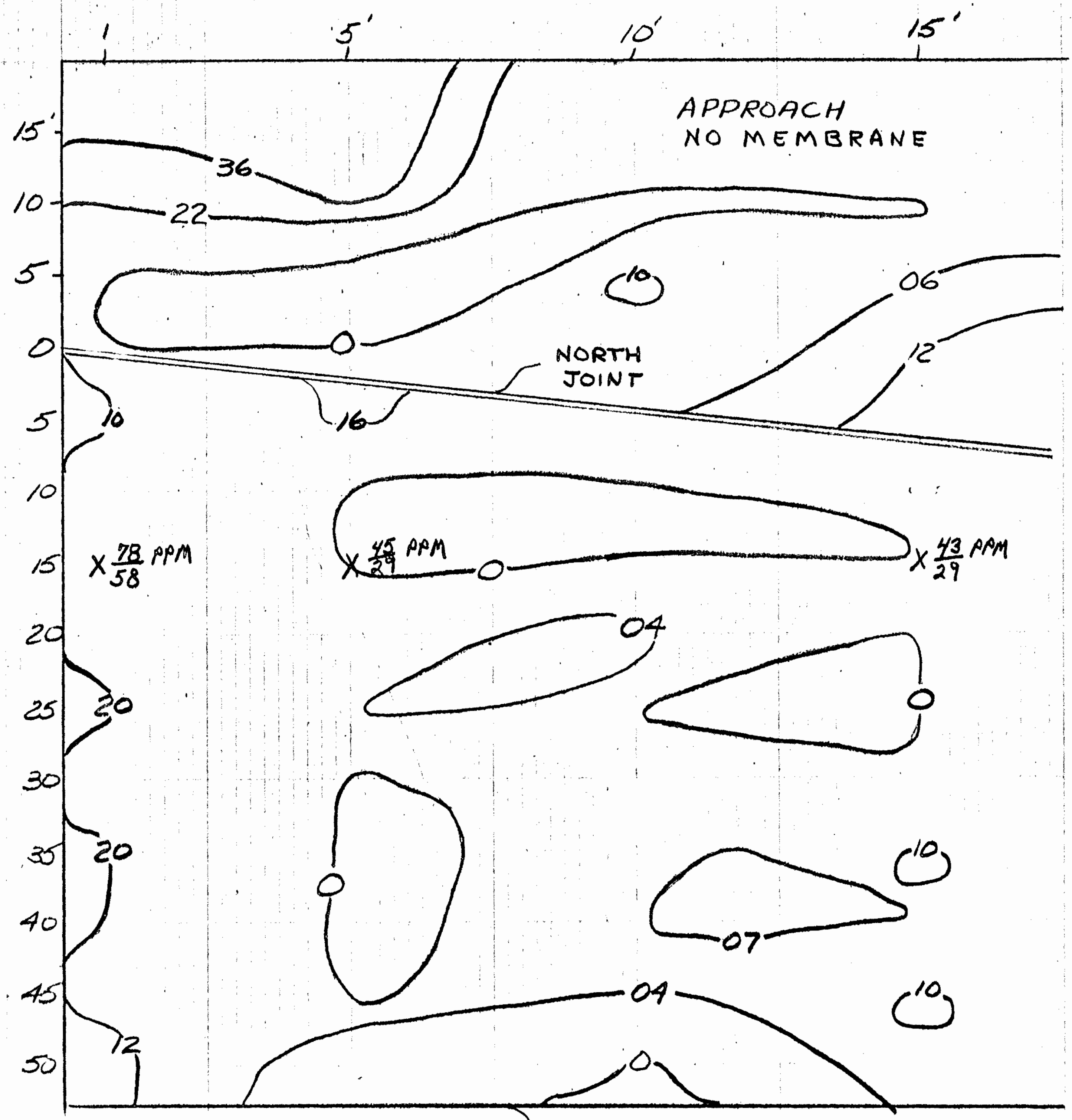


READINGS
OHMS x 10^{-6}

TESTED 75
PLOTTED 12/7
BY J.S

FIGURE 36

BRIDGE #19 - 100% SOLIDS EPOXY
HALF-CELL POTENTIAL CONTOURS
LYNDON I91 SB / SA#9
MM 139.18 BR# T-81-S



READINGS
VOLTS X 100

TESTED 76
PLOTTED 12/76
BY J.S.

FIGURE 37
BRIDGE #19 - 100% SOLIDS EPOXY
ELECTRICAL RESISTIVITY CONTOURS
LYNDON I91 SB / SA #9
MM 139.18 BR # T 81-S

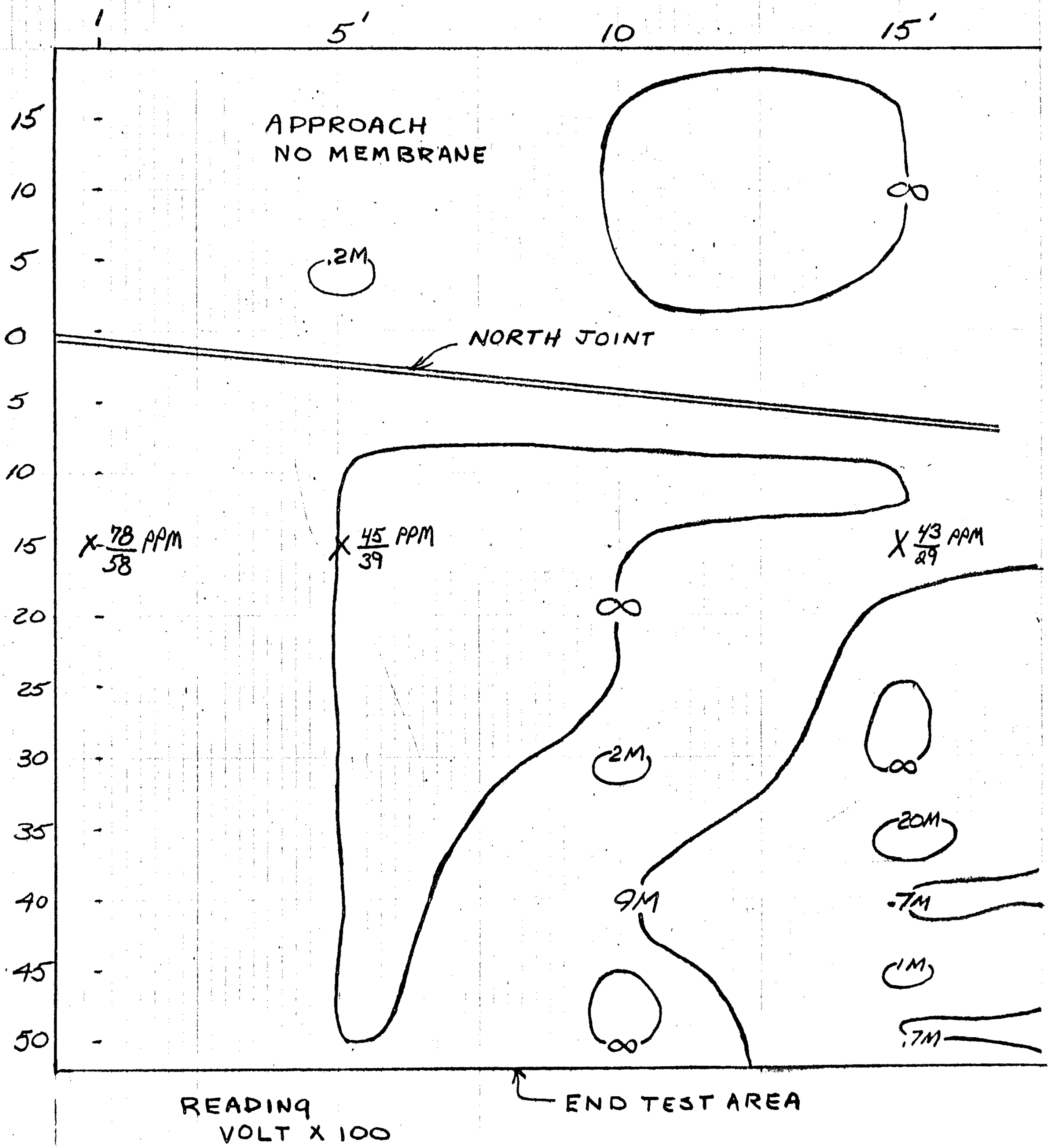


FIGURE 38

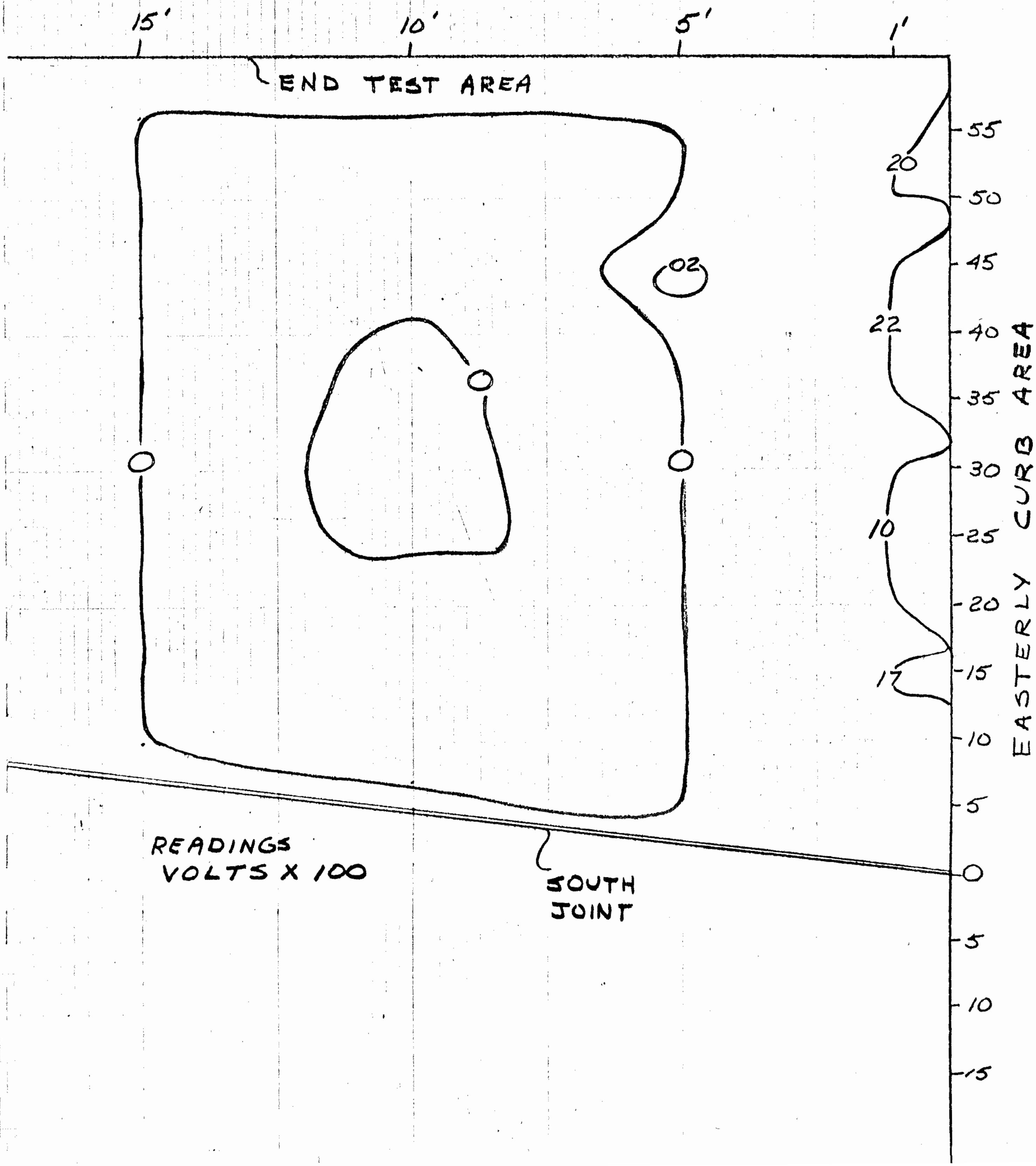
BRIDGE #20 - HOT ASPHALT & GLASS FABRIC

HALF CELL POTENTIAL CONTOURS

LYNDON I 91 NB /RTE. 122

MM 140.30 BR # T 82-N

TESTED 75
PLOTTED 12/75
BY J.S



TESTER 75
PLOTTED 12/75
BY J.S

FIGURE 39

BRIDGE #20 - HOT ASPHALT & GLASS FABRIC
ELECTRICAL RESISTIVITY CONTOURS
LYNDON I91 NB / RTE 122
MM 140.30 BR# T82-N

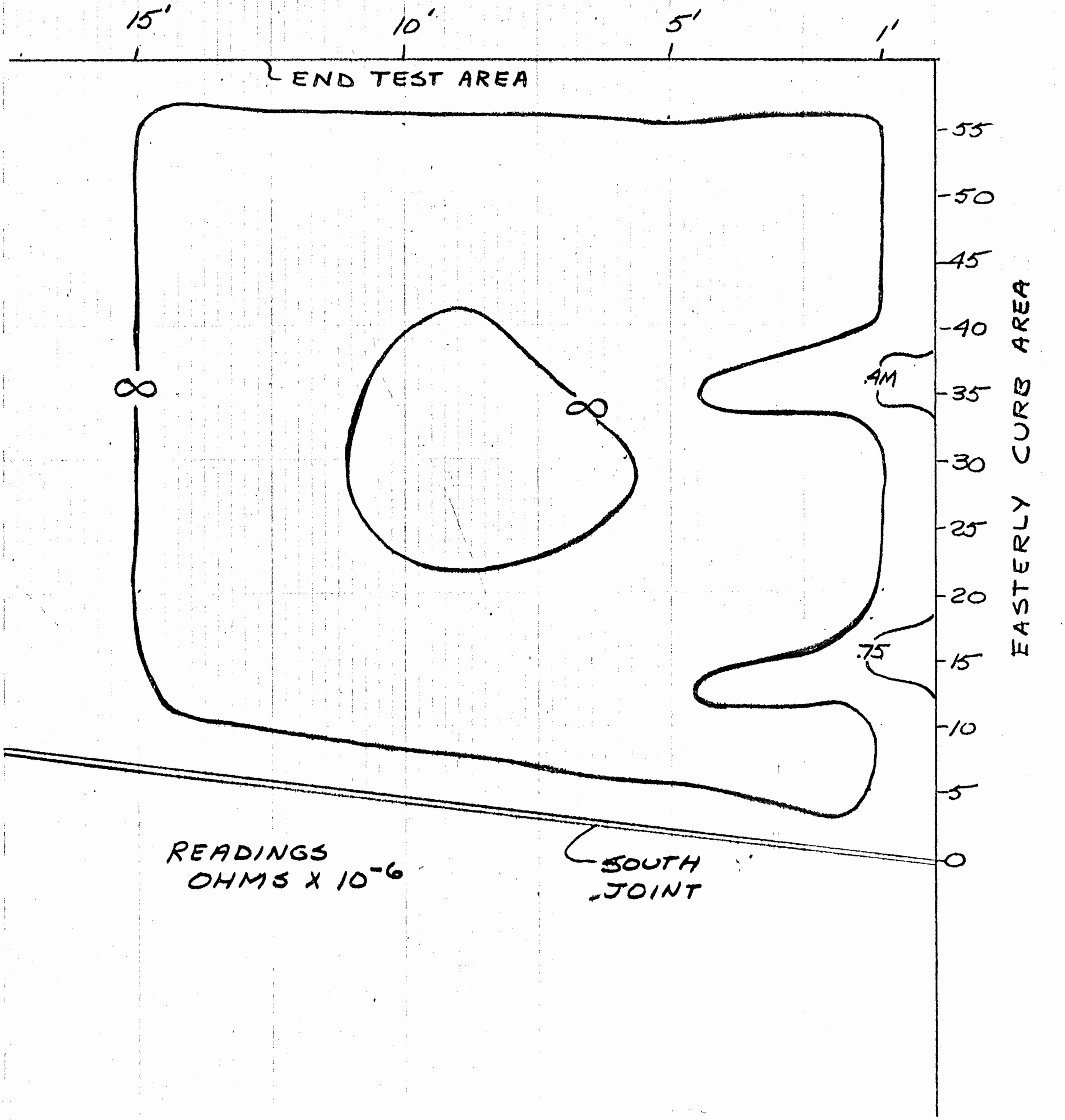


FIGURE 40

BRIDGE #22 - SOLVENT CUT EPOXY
HALF CELL POTENTIAL CONTOURS
LYNDON I91NB / TH#29
MM 141.94 BR# T83-N

TESTED 75
PLOTTED 12/75
BY J.S

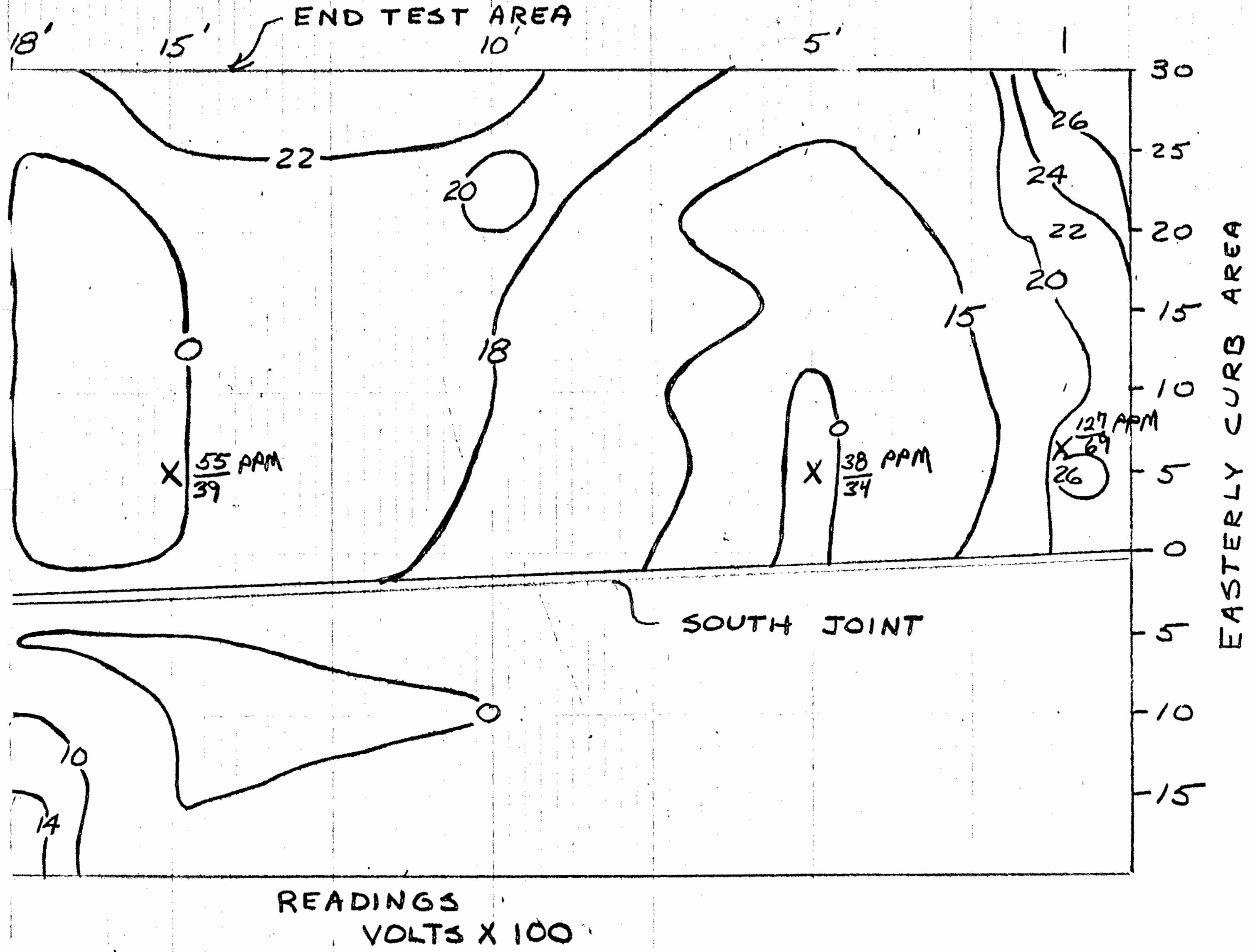
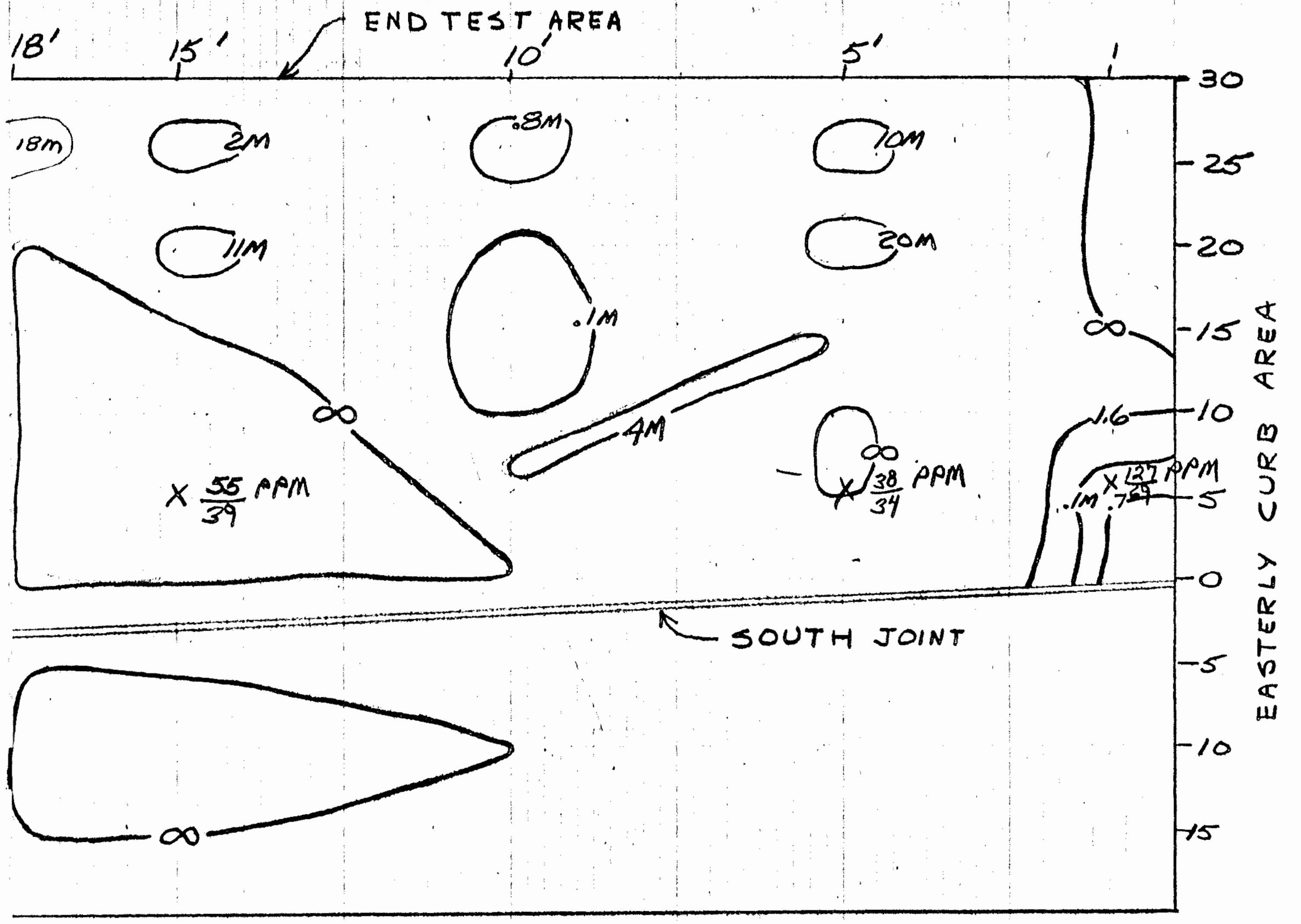


FIGURE 41
BRIDGE #22 - SOLVENT CUT EPOXY
ELECTRICAL RESISTIVITY CONTOURS
LYNDON I91 NB / TH #29
MM 141.94 BR # T-83-N

TESTED 75
PLOTTED 12/75
BY J.S

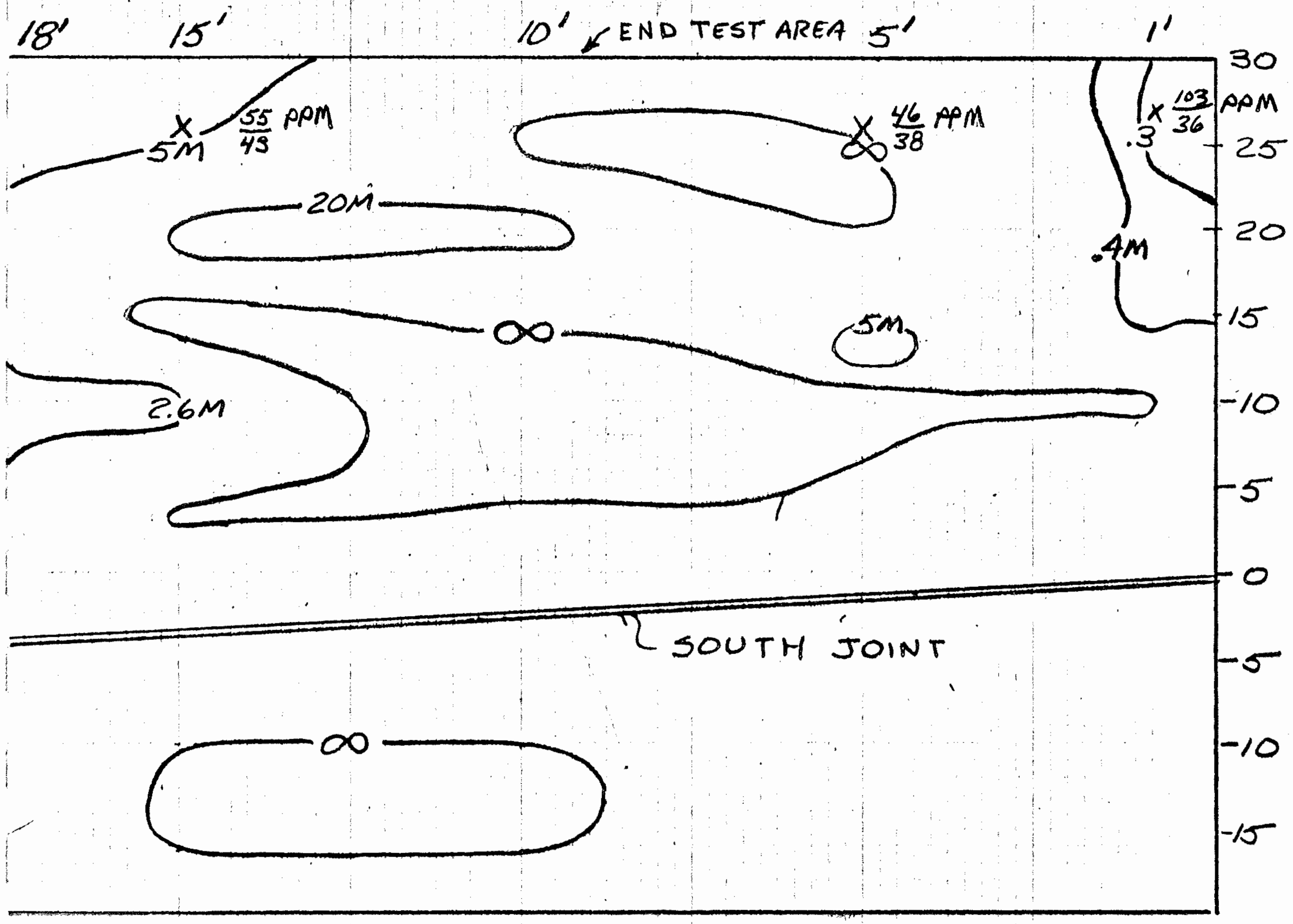


READINGS
OHMS X 10^{-6}

TESTED 76
PLOTTED 12/76
BY J.S

FIGURE 42

BRIDGE 22 - SOLVENT CUT EPOXY
ELECTRICAL RESISTIVITY CONTOURS
LYNDON I 91 NB / TH #29
MM 141.94 BR# T-83-N

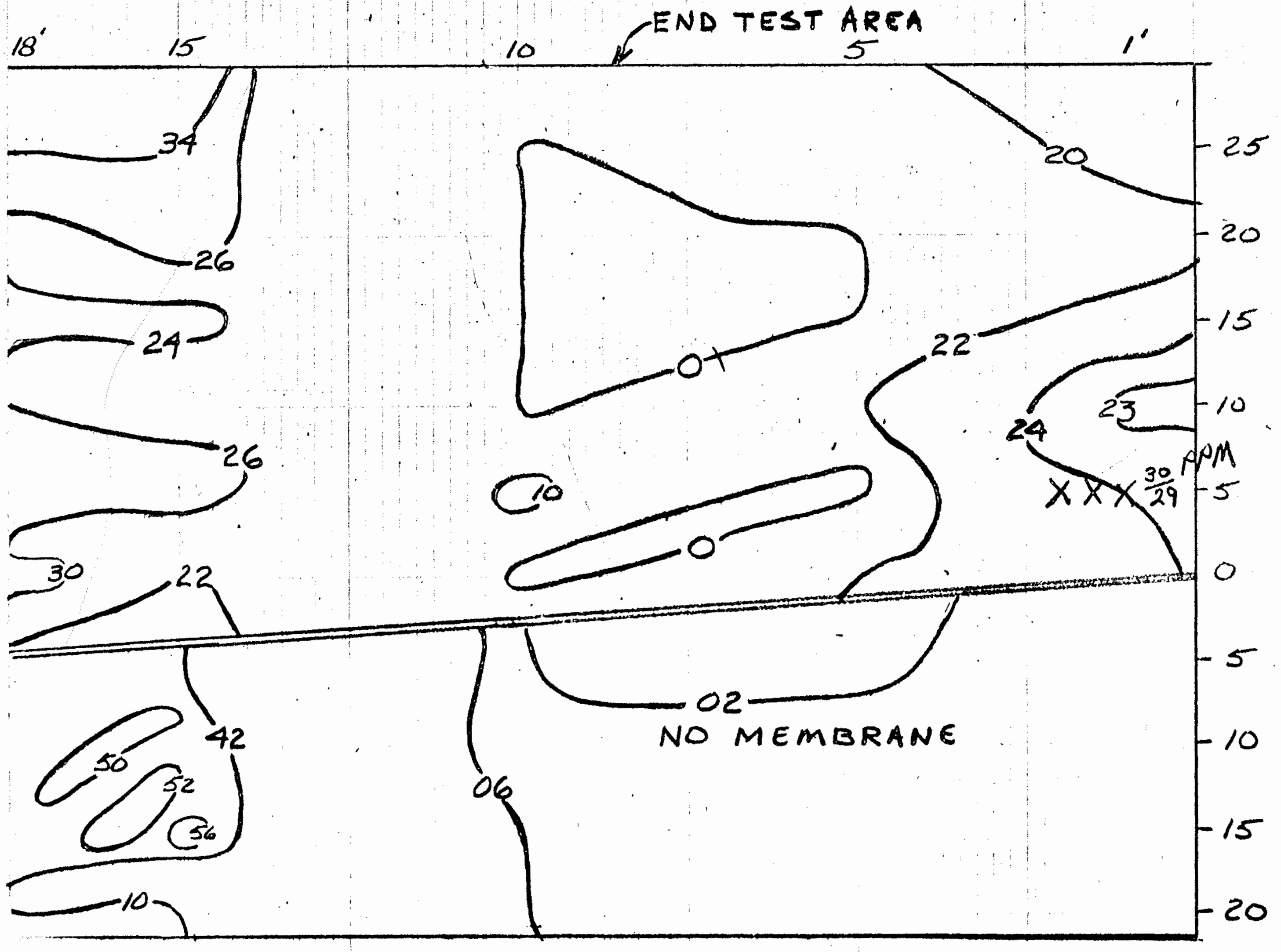


READINGS
OHMS X 10^{-6}

FIGURE 43

BRIDGE #23 - COAL TAR MOD. EPOXY
HALF CELL POTENTIAL CONTOURS
LYNDON I 91 SB / TH#9
MM 141.94 BR# T 83-S

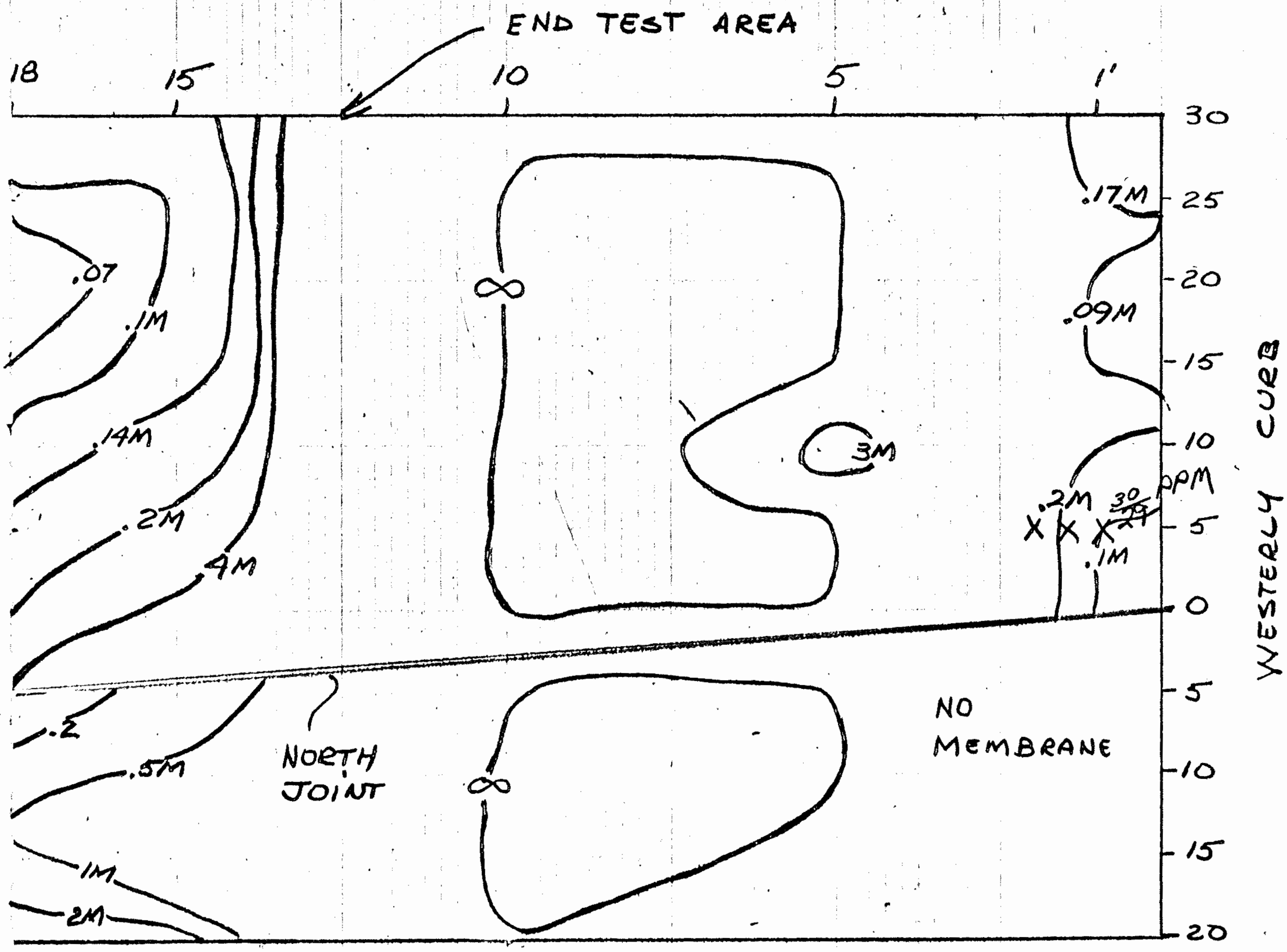
TESTED 1 75
PLOTTED 12/75
BY J.S



READING
VOLT X 100

Tested 75
Plotted 12/75
By J.S

FIGURE 44
BRIDGE #23 - COAL TAR MOD. EPOXY
ELECTRICAL RESISTIVITY CONTOURS
LYNDON I 91 SB / TH #9
MM 141.94 BR# T 83-S



READING
OHMS x 10^-6

FIGURE 45

BRIDGE #24 - 75 MIL PREFORMED SHEET

HALF CELL POTENTIAL CONTOURS

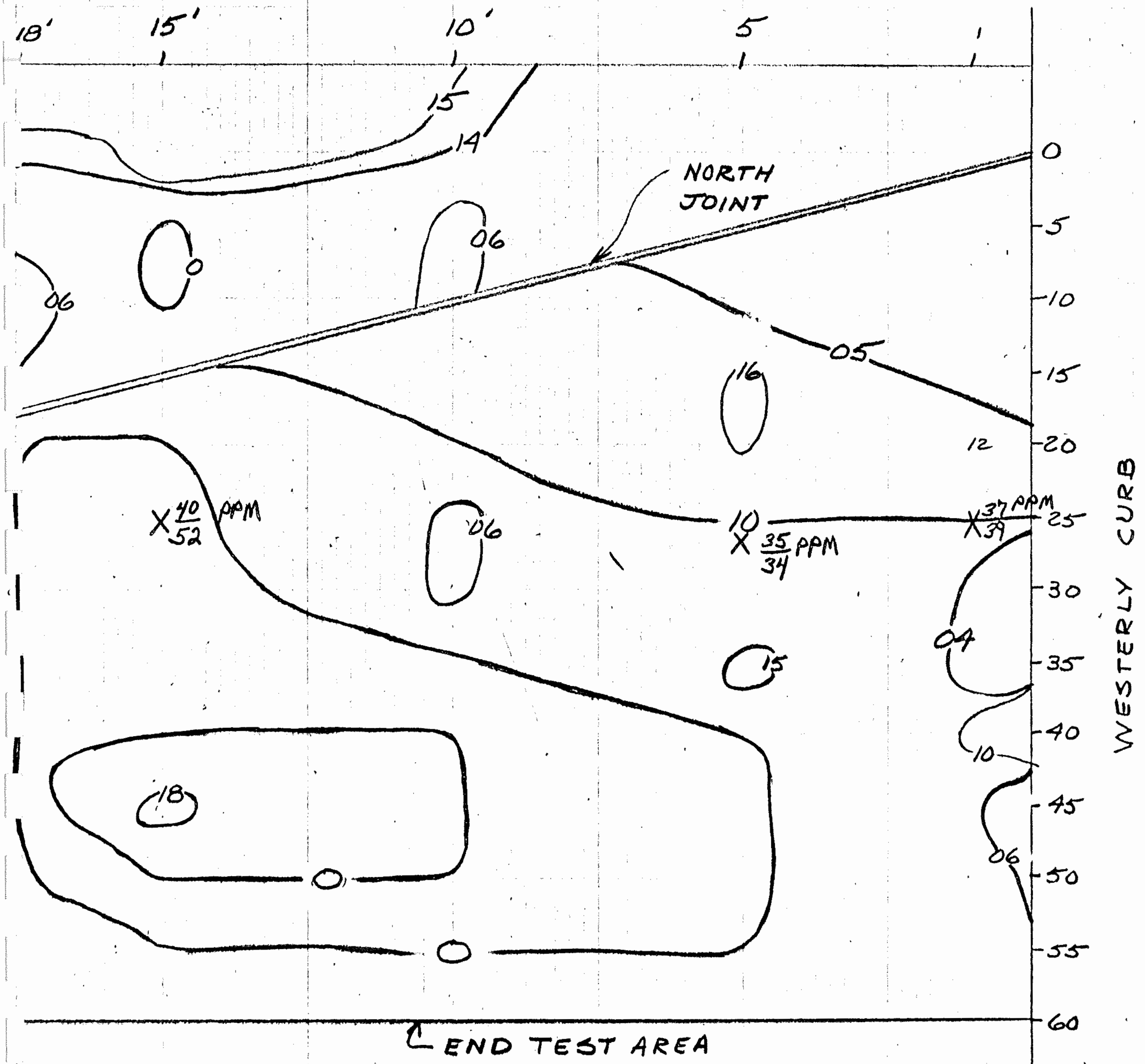
SHEFFIELD I 91 NB / SA#1

MM 146.13 BR# T 85-N

TESTED 75

PLOTTED 12/75

BY J.S

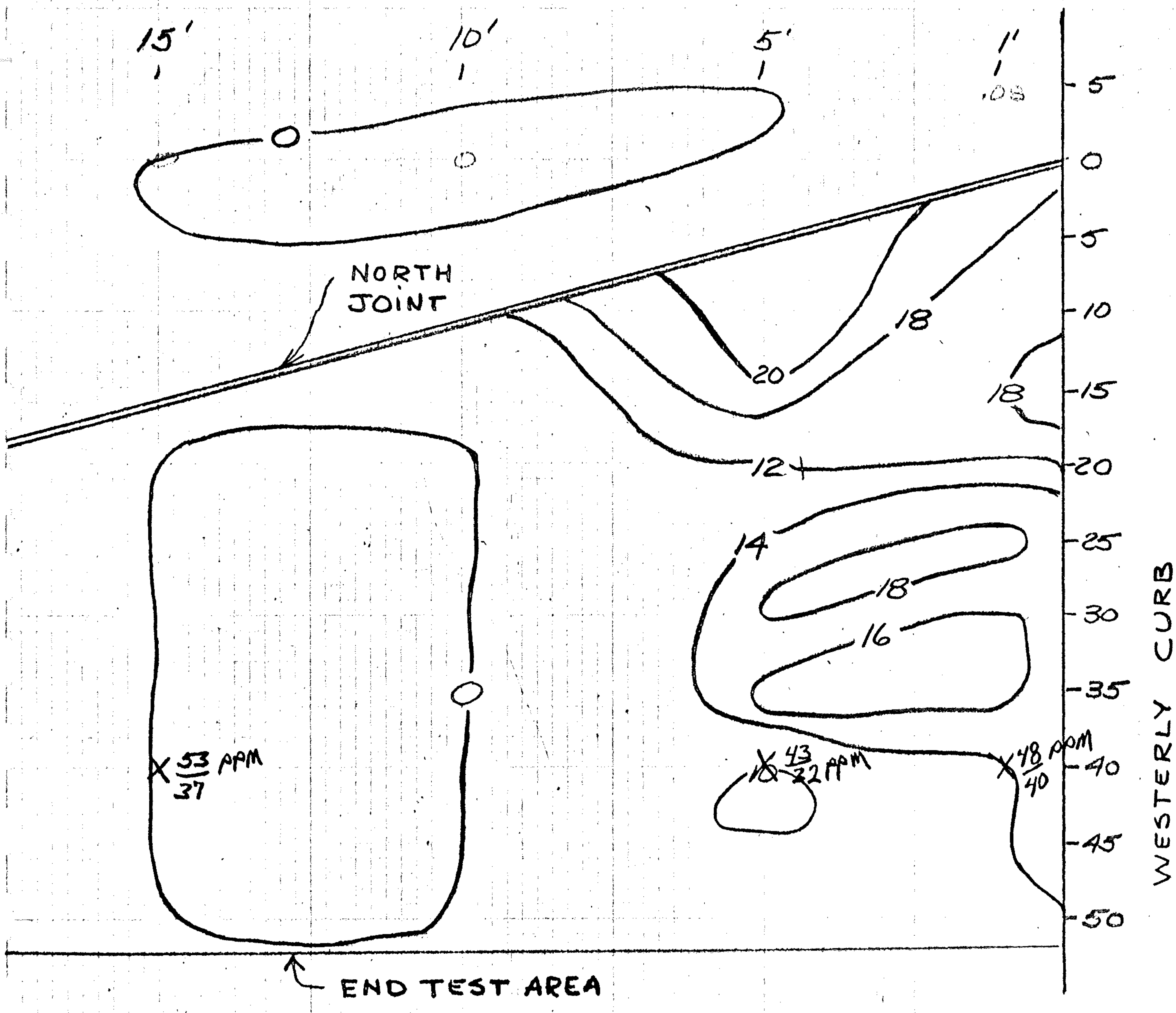


READINGS
VOLTS X 100

TESTED 76
PLOTTED 12/76
BY J.S.

FIGURE 46

BRIDGE #24 - 75 MIL PREFORMED SHEET
HALF CELL POTENTIAL CONTOURS
SHEFFIELD I 91 NB / SA #1
MM 146.13 BR# T85-N

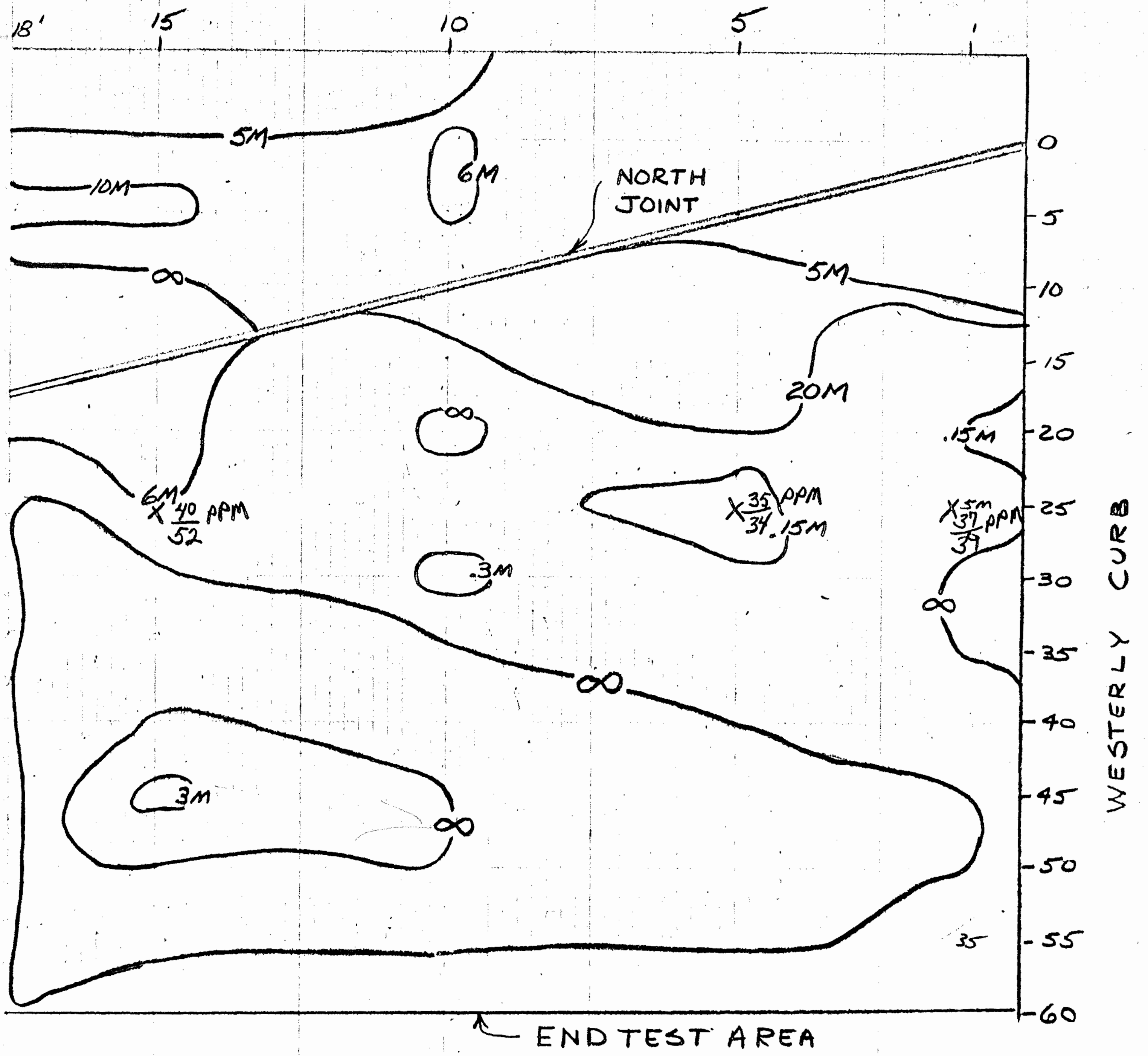


READING

VOLTS X 100

TESTED 75
PLOTTED 12/75
BY J.S

FIGURE 47
BRIDGE #24 - 75 MIL PREFORMED SHEET
ELECTRICAL RESISTIVITY CONTOURS
SHEFFIELD, I91 NB / SA #1
MM 146.13 BR #T85-N



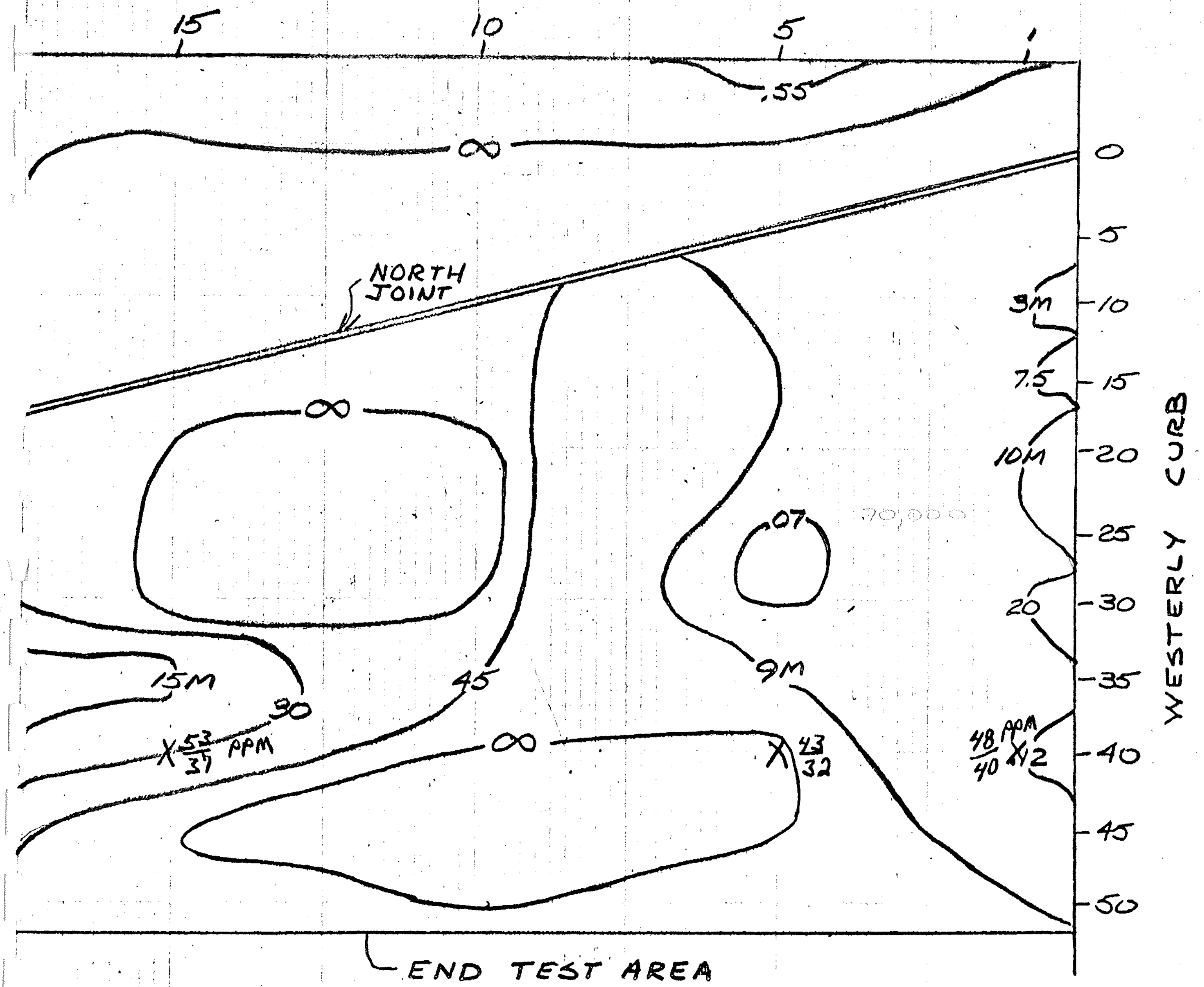
READING

Ohms x 10^{-6}

TESTED 76
PLOTTED 12/76
BY J.S

FIGURE 48

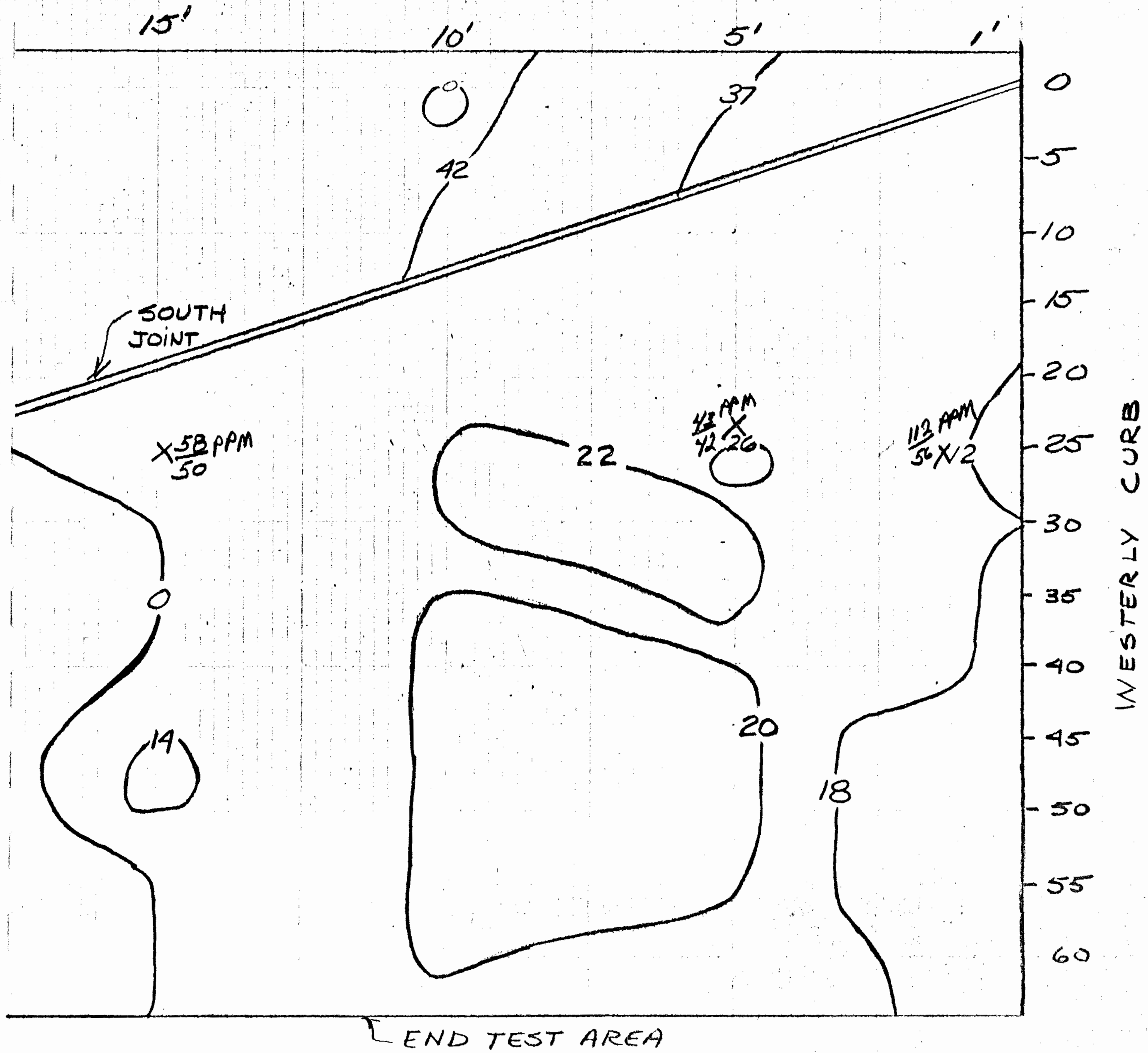
BRIDGE #24 - 75 MIL PREFORMED SHEET
ELECTRICAL RESISTIVITY CONTOURS
SHEFFIELD I91 NB / SA #1
MM 146.13 BR # T85-N



TESTED 76
PLOTTED 12/76
BY J.S

FIGURE 49

BRIDGE #25 - 70 MIL PREFORMED SHEET
HALF CELL POTENTIAL CONTOURS
SHEFFIELD I91 SB / SA #1
MM 146.13 BR# T85-S

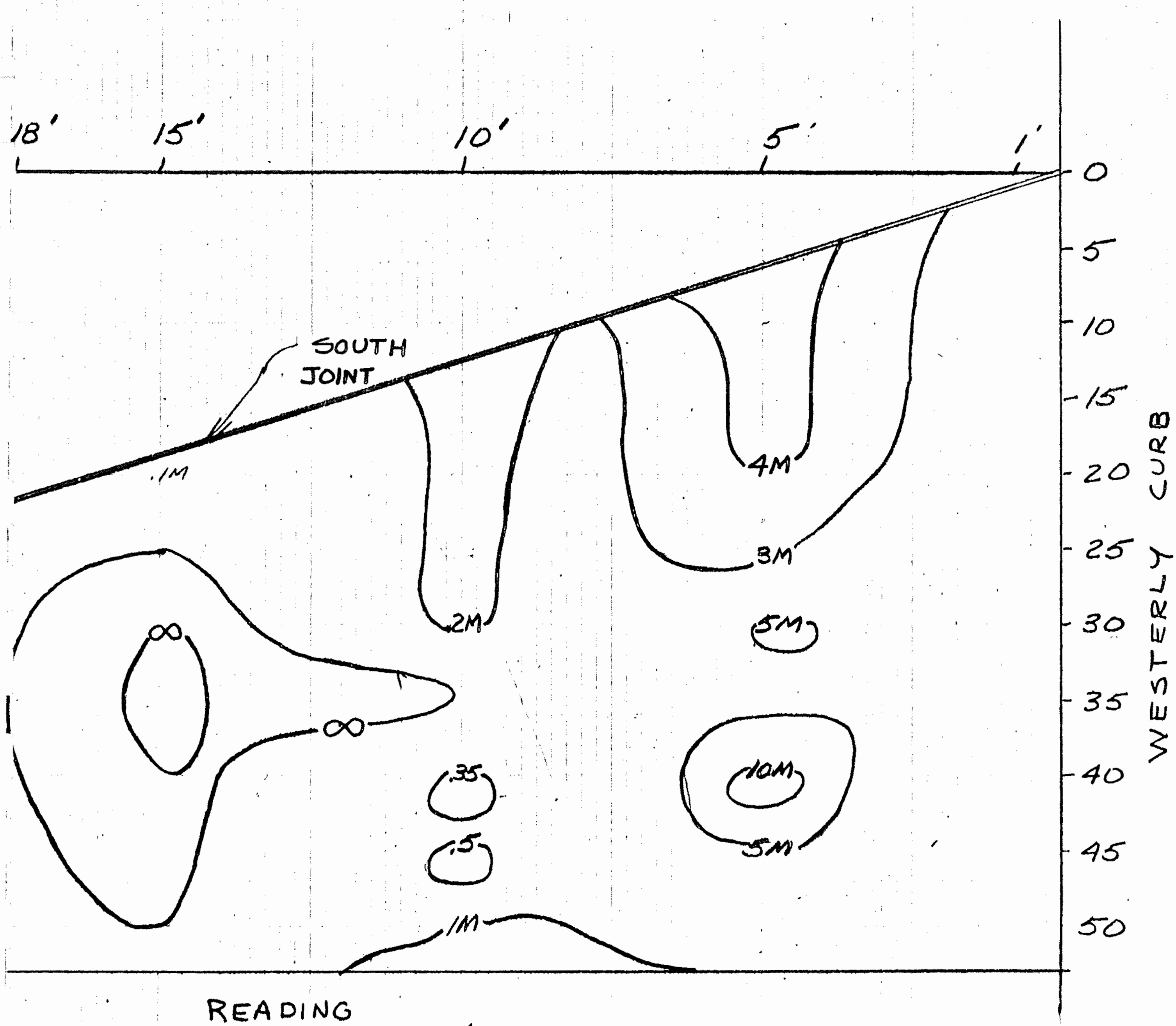


READING
VOLTS X 100

FIGURE 50

TESTED 75
PLOTTED 12/75
BY J.S

BRIDGE #25 - 70 MIL PREFORMED SHEET
ELECTRICAL RESISTIVITY CONTOURS
SHEFFIELD I 91 SB / SA#1
MM 146.13 BR# T 85-S

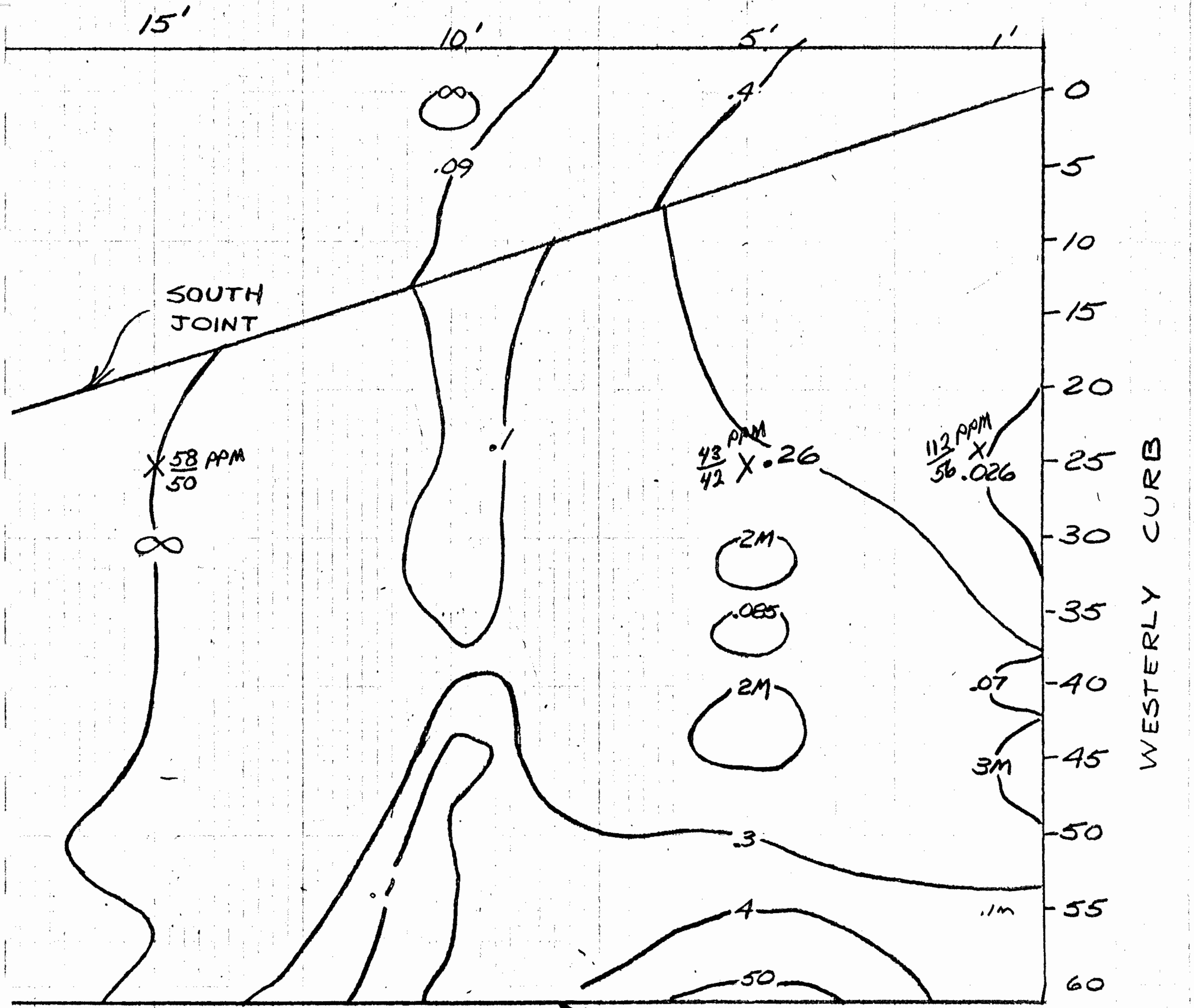


READING
OHMS x 10^{-6}

FIGURE 51

BRIDGE #25 - 70 MIL PREFORMED SHEET
ELECTRICAL RESISTIVITY CONTOURS
SHEFFIELD I91SB /SA#1
MM 146.13 BR#T 85-S

TESTED 76
PLOTTED 12/76
BY J.S



READING
OHMS X 10^{-6}

TESTED 75
PLOTTED 12/7
BY JJS

FIGURE 52

BRIDGE #32 - 125 MIL PVC POLYMER
HALF CELL POTENTIAL CONTOURS
BRADFORD I91 NB / TH #6
MM 98.43 BR# 61-N

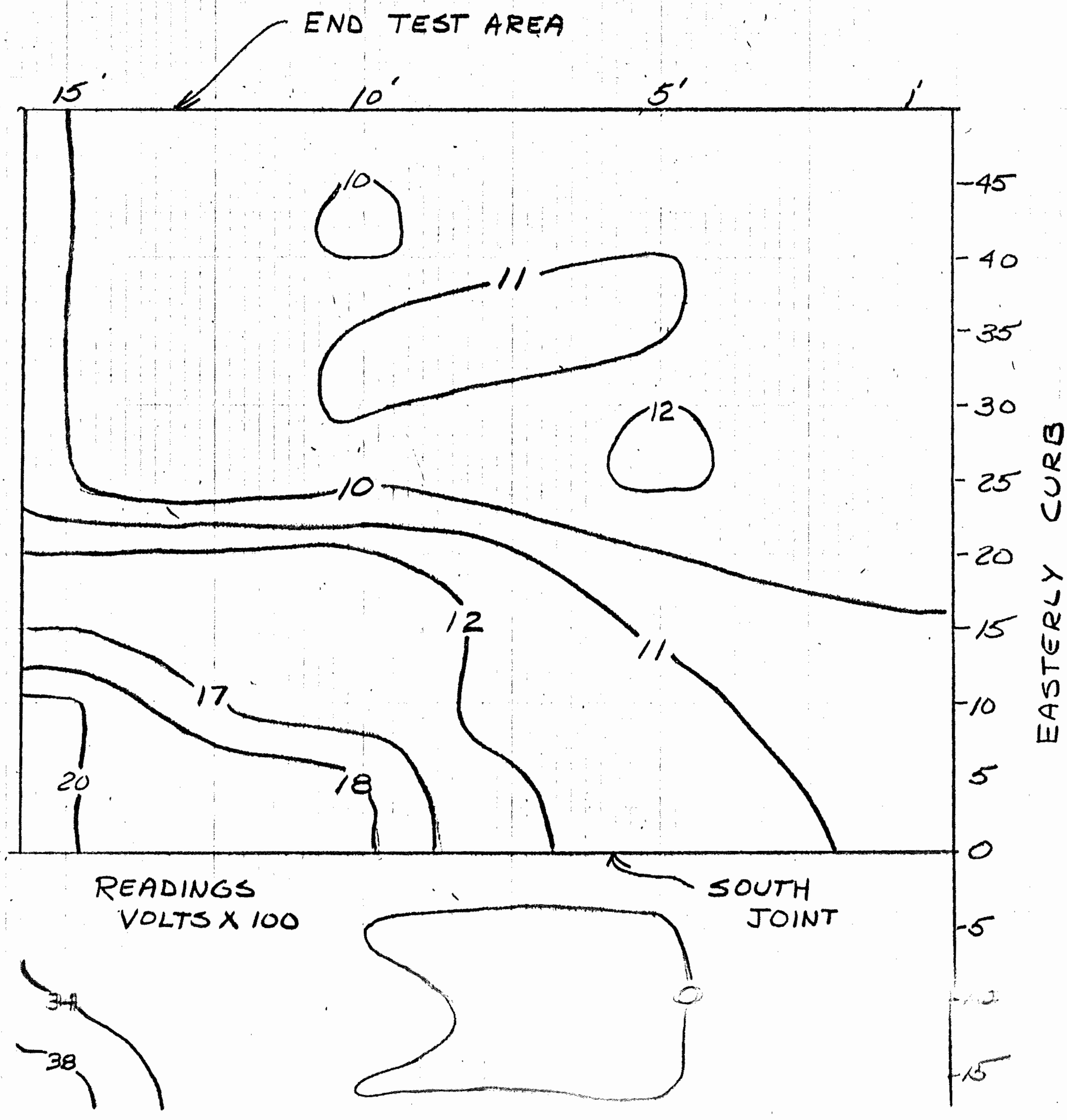


FIGURE 53

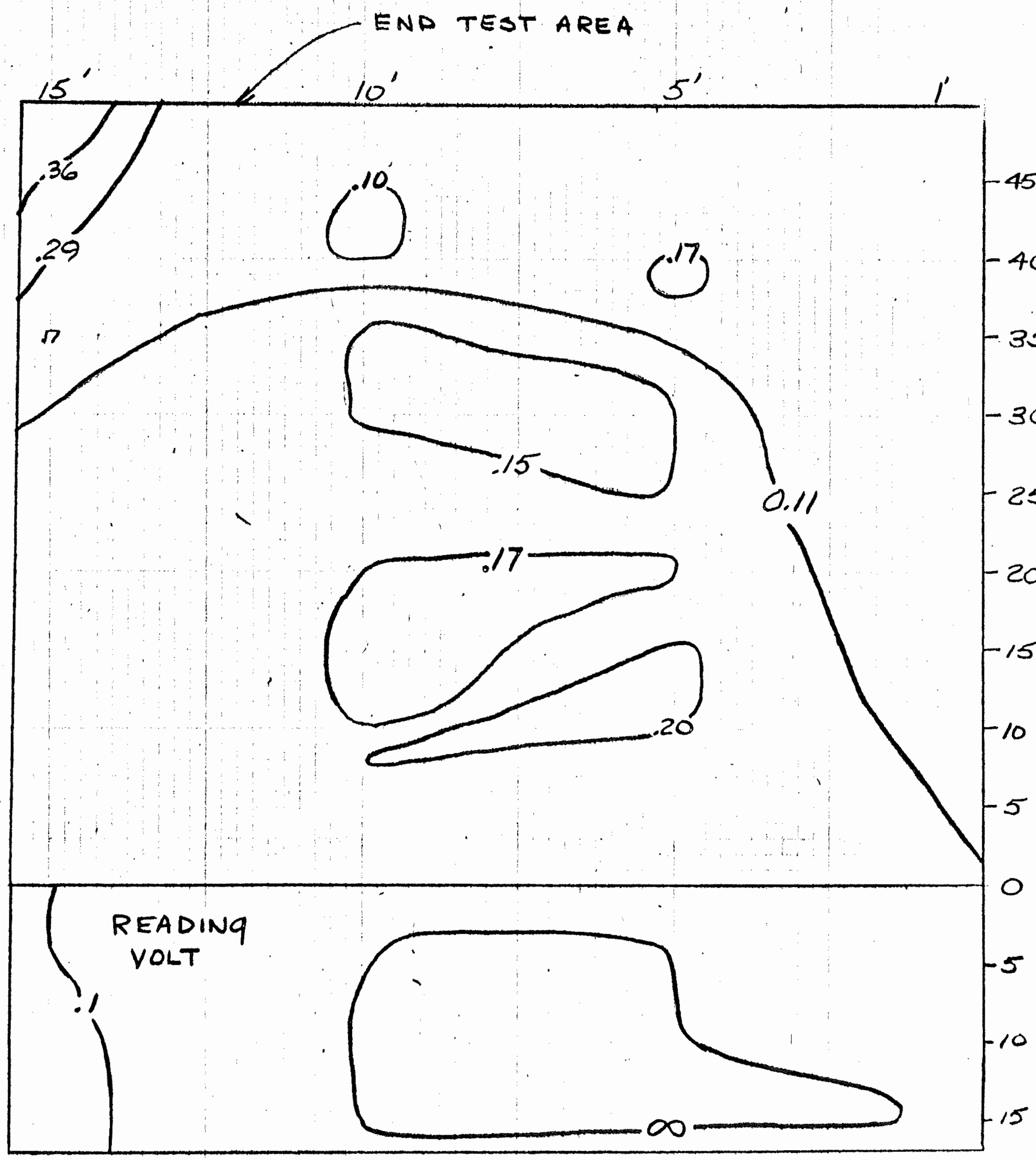
BRIDGE # 32 - 125 MIL PVC POLYMER

ELECTRICAL RESISTIVITY CONTOURS

BRADFORD I 91 NB / TH # 6

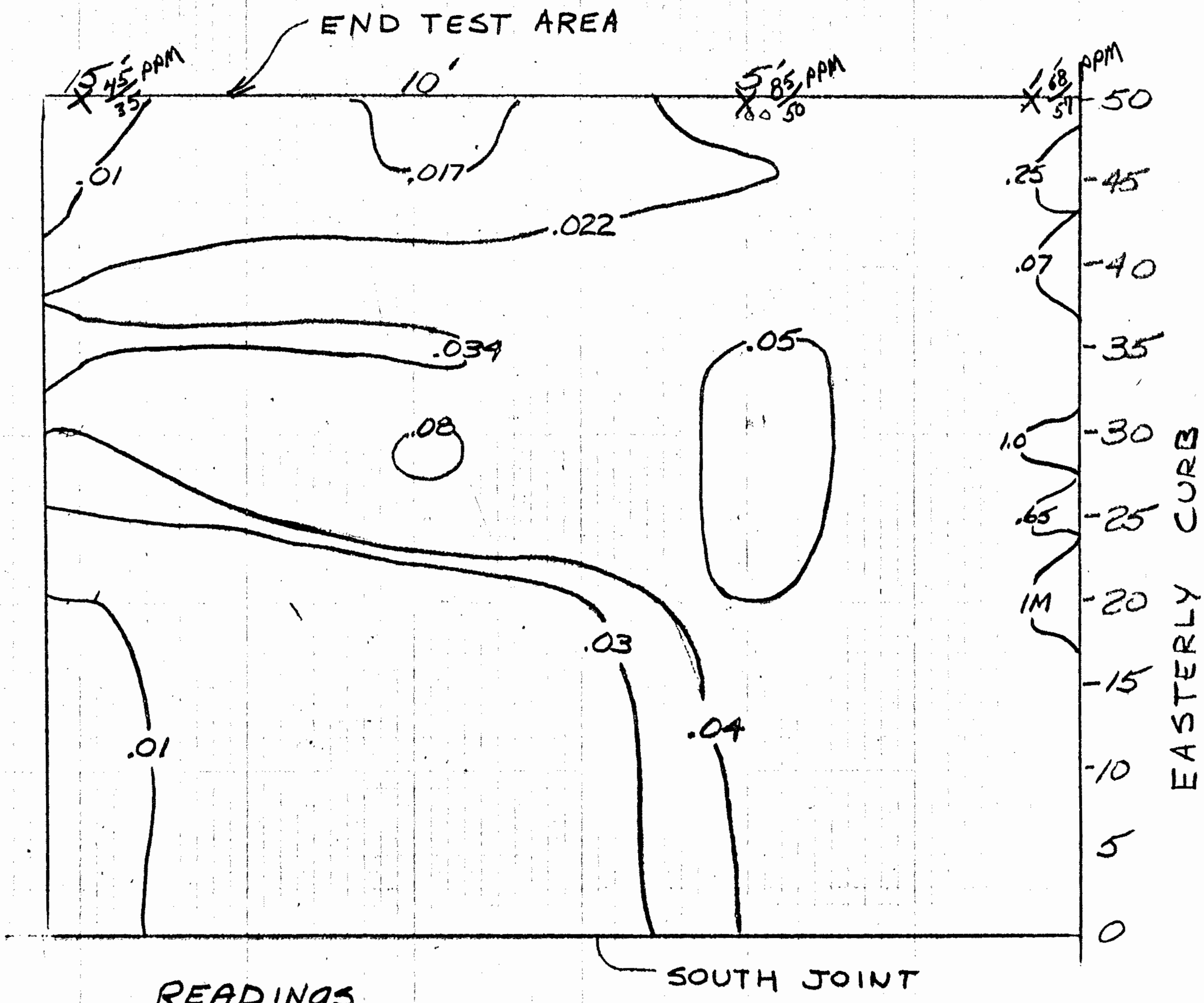
MM 98.43 BR # 61-N

TESTED 75
PLOTTED 12/75
BY J.S



TESTED 76
PLOTTED 12/76
BY J.S

FIGURE 54
BRIDGE #32 - 125 MIL PVC POLYMER
ELECTRICAL RESISTIVITY CONTOURS
BRADFORD I 91 NB / TH#6
MM 98.43 BR#61-N



READINGS
OHMS X 10^{-6}

TESTED 75
PLOTTED 12/75
BY J.S

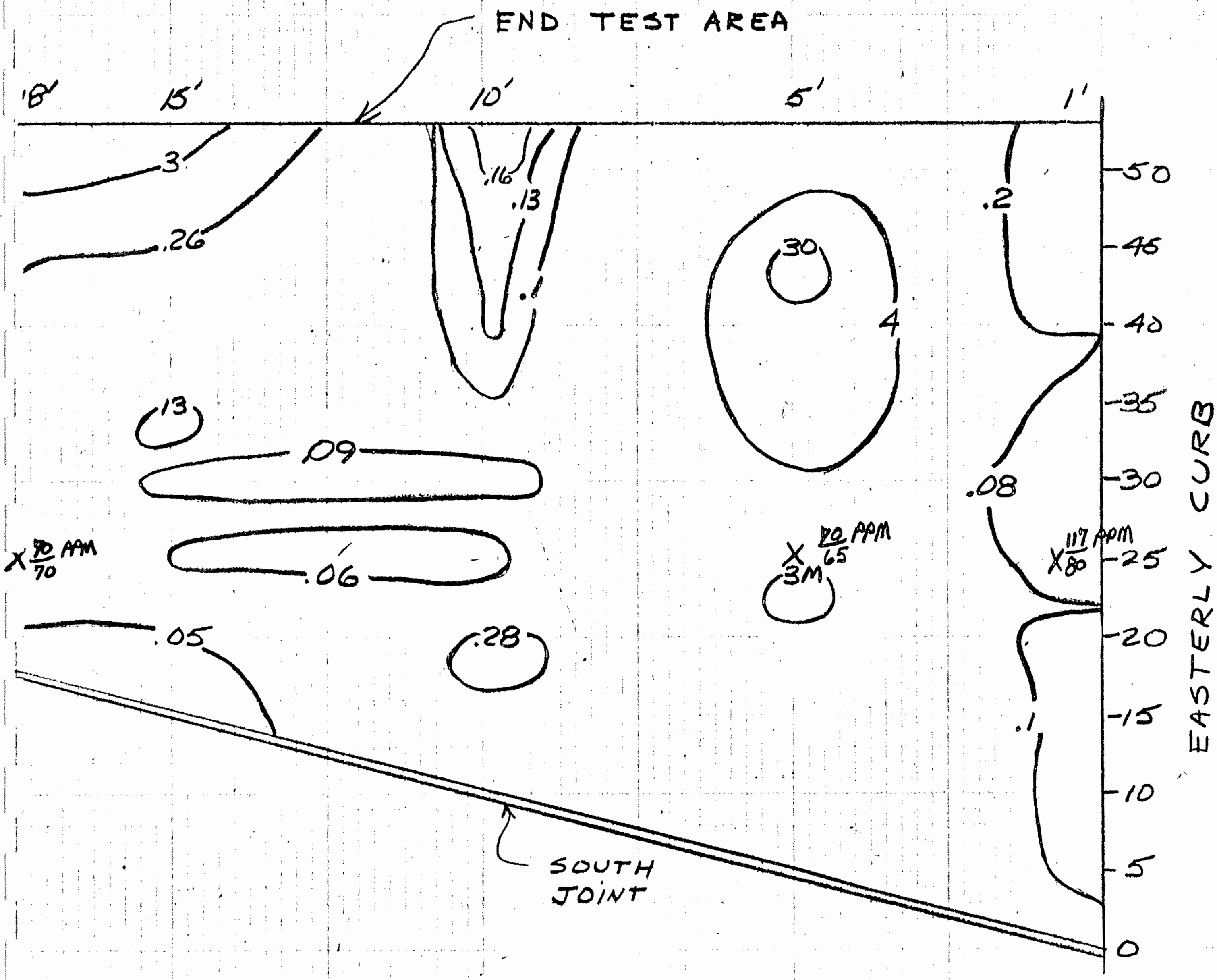
FIGURE 55

BRIDGE #36 - 65 MIL PREFORMED SHEET

ELECTRICAL RESISTIVITY CONTOURS

NEWBURY I 91 NB / SA#5

MM 105.95 BR # 64-N



TESTED 76
PLOTTED 12/76
BY J.S

FIGURE 56

BRIDGE #36 - 65 MIL PREFORMED SHEET

ELECTRICAL RESISTIVITY CONTOUR

NEWBURY I 91 NB / SA#5

MM 105.95 BR#64-N