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technical note

CATHODIC PROTECTION APPLIED TO THE AFK-12, LONG BEACH

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SUMMARY

Cathodic protection was applied to the underwater hull of the AFDL-12, a floating dry dock, on 3 November 1950. Its state has been continuously monitored with semiweekly surveys. A six months' study shows that protection can be achieved with a single properly placed anode and as little as eight amperes or thirty-five watts of electrical power. The total cost of materials used for the installation design resulting from this study is below $400. The single anode installation is shown to be satisfactory, yet less complex and less costly than previously recommended systems which involve structures to support strings of anodes from the mooring pier or booms holding anodes over the side. Test coupons, made of ships' hull steel, showed negligible loss of steel at the protected surfaces; whereas, unprotected surfaces may be losing metal from bare areas at the rate of 100 gms/sqft/yr. This study will continue for a year or more and/or until such time as the ship has her present mooring changed. A final report or addenda to this report will be made at that time, modifying, if required, the conclusions of this report.

Expansion of the cathodic protection system used on the AFDL-12 to a multiple ship installation would require very little additional equipment but would demand continual or periodic monitoring.

INTRODUCTION

Cathodic protection is a system of electrolytic corrosion mitigation in which a counter electromotive force is used to oppose the naturally occuring currents due to an ionic exchange between an electrolyte and a metallic surface in contact. The basic principles of cathodic protection are not new, being realized by Sir Humphrey Davies as far back as 1825 when he recommended the use of zinc to protect the copper hull of some of His Majesties ships. A discussion of the physical principles involved in cathodic protection is given in Appendix I.

THE DRY DOCK INSTALLATION AT LONG BEACH

The National Carbon Division of the Union Carbide and Chemical Corporation, Cleveland, Ohio, supplied a number of sodium-treated graphite anodes, four inches in diameter by forty inches long, to be used in an installation for applying cathodic protection to the underwater hull of the AFDL-12. The AFDL-12 is a 1000-ton floating dry dock and has about 12,000 square feet of underwater surface.

The installation, designed, installed and tested by members of the Laboratory technical staff, with the helpful suggestions of Mr. J. P. Oliver of the National Carbon Division, in addition to protecting the underwater hull of the AFDL-12, has and will continue to give helpful research and engineering data to be used in general underwater corrosion mitigation. The Public Works Department of the Long Beach Naval Station furnished a glass-enclosed, sentry-type building to house the instrumentation associated with the study. The building (Figure 1) was placed on the pier alongside the AFDL-12, and 110 volt ac power was supplied to four outlets in the interior.

An RA-91A Signal Corps Rectifier (Figure 2), on a special mounting frame, was placed in the building. The positive lead (#4 AWG Single Conductor, submarine cable) of the rectifier was connected through a waterproof splice to a single graphite anode (Figure 3). The graphite anode was placed on the bottom of the harbor in 28 feet of water directly under the bow of the AFDL-12. The negative lead from the rectifier was connected amidships, port to the upper deck through two threaded welded studs and a double run of the submarine cable.

The panel meter of the rectifier was considered not precise enough for the experiment, so a Weston (0-25 amp), bench-type, precision meter (Figure 4) was inserted in the positive line to measure the anode current.

The initial installation, consisting of the single anode under the bow, the rectifier, and the meter was completed on 3 November 1950. The initial installation was modified on 7 November 1950 by the addition of a second anode which was connected to the positive lead and placed on the bottom in 32 feet of water at the stern. On 6 February 1951, the bow and stern anodes were replaced with a single anode under the center (keel, Fr 13) of the ship. On 6 March 1951, the single anode under the ship's center and on the bottom was replaced by a single 'remote' anode placed about 400 feet off the starboard bow in shallow water about four feet below the low tide mark. On 17 April 1951, the remote anode was removed and the single anode under the center of the ship was again placed in service and is part of the present long-term installation.

Four coupons were added to the installation on 10 November 1950. Each coupon is a one foot square piece of ships' hull steel, 3/16 inch thick. Each was cleaned in an acid bath, photographed, weighed, and connected to a ten-foot length of #4 AWG submarine cable through a strong waterproof terminal connection. Two coupons were hung from the port bow into two and one-half feet of water about ten feet apart (Figure 11). The remaining two were hung similarly from the starboard stern. One bow and one stern coupon, called the in-circuit coupons, were bonded to the ship through threaded studs welded to the ship's lower deck. The remaining bow and stern out-of-circuit coupons were insulated from the ship.

A photographic record was made of the installation. Both 16 mm colored movies and four-inch by five-inch black and white still shots were taken of the electrical components as they were being installed and of the equipment used in the experimental study.

The location of the installation is the mooring on the west side of pier X-ray, in the inner harbor at the Long Beach Naval Station. The water is very well protected, running currents are mild, the waters are free from silt and pollution. The tide averages four feet in height.

EXPERIMENTAL PROCEDURE

A survey of the condition of the AFDL-12 was taken on 3 November 1950, just prior to the application of the first cathodic protection current. The survey consisted of measuring the emf, or polarization, between the ship and a saturated copper-sulfate reference half-cell suspended over the side and dipping into the harbor water. A Model B, Miller Multicombination Meter, a portable instrument widely used for cathodic protection testing, was used in the survey. Five equally spaced stations were established at the maindeck edge, both bow and stern. Ten more were established along the upper deck edge at even frame numbers both port and starboard, making a total of 30 stations around the ship. In addition, a remote reading was taken with the cell dipped into the harbor water about 150 feet off the starboard bow. An initial cathodic protection current of 15.4 amperes was applied on 3 November 1950 to the single bow anode and a second survey was taken as before. The current was set to run continuously at 15.6 amperes until 6 November 1950 when a third and a fourth survey were taken, the third with the anode current on and the fourth with the anode current off. Depending on the findings of semiweekly surveys, changes were made in the anode current and anode placement with the purpose of determining the optimum current for a satisfactory polarization and the optimum number and placement of anodes that would give the most uniform distribution of polarization over the underwater surface.

Later, equipment was added to increase the volume and quality of the survey data; a Brown Strip Chart Electronik Recorder was modified into a linear recording potentiometer for the range of 600 to 1200 millivolts, (see schematic Figure 12). In addition to reducing the human error in the taking of data, the recorder served in making time studies of the growth and decay of polarization during unattended periods. A calibrated Esterline-Angus Recording Milliammeter was connected across a shunt in the anode circuit and thereafter kept a continuous strip-chart record of the total cathodic protection current. Figure 17 is a block diagram of the essential parts of the cathodic protection installation.

After three months in which cathodic protection was applied to the ship, the two bow coupons were removed and returned to the laboratory where they were carefully checked for loss of metal. The weighings are tabulated in Table 2. One coat of #14 anti-corrosive (anti-fouling) paint was applied to

the bare metal plates in accordance with reference 5, and the two coupons were again installed at the bow. These plates are being watched closely for evidence of paint stripping.

The initial around-the-ship type of survey was established as being the most practical to give representative and fairly complete data on polarization and current distribution. It was quickly realized that this data was not complete in that the condition of large areas of the underwater hull could not be known by direct measurement. To remedy this situation, a rig was designed and fabricated at the laboratory (Figure 5), which rig served to carry a reference half-cell to all parts of the underwater hull by a keel-haul technique. From bottom surveys so made, equipotential contours were drawn (Figure 15), showing clearly the location, extent, and potential of the anodic and cathodic areas. The rig was fashioned from maple wood, boiled in paraffine, and lucite. Brass and copper hardware was used. Two, single conductor stranded wire cables, #18 flamenol, fastened to eyelets on opposite edges of the box-like rig, were used to tow the structure into the measuring positions. One of the two lines connected the half-cell mounted in the center of the rig to a measuring bus bonding all stations. Weights were attached to the rig and adjusted until the whole had a slightly negative bouyancy.

LABORATORY PHASE

The problems connected with the close surveillance of the underwater hull, namely the distance to Long Beach and underwater inspection, led to a decision to undertake some parallel experiments at the laboratory to better study the paint-stripping effects of the cathodic protection current. These tests, conducted with mild steel plates in a sea-water bath, include a study of the stripping effect on the types of paint used on the AFDL-12 of (a) a constant preset current and (b) a constant preset polarization regardless of current required to maintain polarization. In the course of these tests, a one-tube current stabilizer was designed and built (Appendix II), which device serves to keep essentially a constant current flowing into a load such as an electrolytic cell whose resistance tends to vary. This circuit differs from the usual pentode current stabilizer (Figure 19) in that the current may be adjusted by a change in the dc supply voltage.

An Industrial Instrument, Model RC-1b, conductivity bridge was used to check the salinity and conductivity of sea-

water samples taken from pier X-ray.

RESULTS AND DISCUSSION

Analysis of the harbor water showed a salinity of 34 ppt and a resistivity of 31 ohm-cm at 18 degrees Centigrade. These values agree closely with those from open sea water; and, since there are no fresh water or pollution sources in the harbor, the results gained here are considered typical for sea water.

Figure 13 is a double plot against time of the total cathodic protection current and the polarization as measured at the remote station. The remote station was chosen as reading an average polarization for the whole submerged surface and, therefore, the best single point to monitor. The rule, generally followed in these measurements, is that the reference half-cell measures an average of the polarization over a circular area whose radius is of the order of magnitude as the distance to the surface.

Figure 14 shows the variation of the polarization in successive surveys as measured at the 30 stations around the ship. The number to the left of each plot is the number of days that protection had been applied when the around-the-ship survey was made. The base line in each case is the remote polarization whose magnitude is recorded on the graph of Figure 13 described above.

Figure 15 shows four bottom contours which give a more nearly complete picture of the underwater hull conditions. The zero contour corresponds to the remote polarization given in Figure 13.

It will be noted that the remote polarization (Figure 13) as measured before the application of cathodic protection is 667 millivolts (mv). At the end of three days with 15.6 amps through a single bow anode, the polarization rose to 926 mv. For the next two months, using a bow and stern anode, the current was set at different levels and successive readings were taken to determine the steady state value of polarization that would occur with a given steady anode current. From the values obtained, the curve in Figure 16 is plotted. Britton and Ewing[10] state that such a curve should have a break or knee, and the value of polarization determined by the intersection of line segments above and below the knee and its

corresponding current are optimum for cathodic protection. The current required to maintain this polarization might change if the effective area of the metal in contact with the electrolyte should change.

Since the effective area of bare metal in contact with sea water is likely to change with time, due to deterioration of the protective coatings, this criteria is not to be fully trusted. However, it does offer an interesting correlation in that the optimum current by the potential break method is 7.2 amperes, and current actually used to maintain a remote polarization of 0.85 is 7.5 amperes.

Table II shows in tabular form the loss of metal from two bare, one foot square plates of ships' hull steel used as coupons. The one connected into the cathodic protection circuit for three months lost one-half gram of weight which is of the order of magnitude of error arising from repeated weighing of the samples. The coupon not connected into the cathodic protection system lost 48.5 grams in the same interval. Since each plate effectively has two square feet of area, this represents a corrosion loss of about 100 grams per square foot per year. If the surface corroded evenly, this loss would represent about 0.005 inches per year, an undesirable rate. When pitting and channeling occur, the depth penetrated can be much greater and more serious.

The benefits of cathodic protection must be reckoned in terms of economies gained in the hull maintenance of the dry docks. Used in conjunction with protective coatings, cathodic protection should more than double the normal time between dry dockings. A saving is effected in the cost of dry docking and repainting as well as keeping the ship in ready condition during the time that otherwise would be used for repair. The Hinchman Corporation[11] estimates the cost of one dry docking for hull reconditioning at about $5000. The cost of the materials for the single anode cathodic protection system installed in the AFDL-12 is listed.

1.	1 Rectifier, Signal Corps type No. RA-91A output: (0-20) amps dc, (0-96) volts in 144 steps input: 110, 220volts, ac, 60 cycles	$265
2.	1 Anode, sodium treated graphite, 4" diam x 40" long, waterproof connection	20
3.	50' Cable, #4 AWG, Submarine Buna-S or Neoprene covered	25
	TOTAL COST	$310

Monitoring equipment, such as the Multicombination Meter, Miller type, Model B3, sells for about $425, including copper sulfate reference cells. One such meter could be used to monitor several cathodic protection installations.

To the above basic material and instrumentation costs must be added the labor and miscellany involved in making the installation plus the cost of the engineering and monitoring services. The cost of power is negligible as evidenced by the thirty-five watts drawn from the rectifier in protecting the AFDL-12. However, supplying powered receptacles and housing for the rectifier on the mooring pier involves another unknown first cost, nevertheless small.

CONCLUSIONS AND RECOMMENDATIONS

In view of the fact that the work described herein, namely the study of a cathodic protection system on a floating dry dock, is not complete, the conclusions are based on short-term results (six months) and are subject to possible revision based on long-term findings (one year or more). It is recommended that the project be continued as long as the AFDL-12 can be made available.

It is thought that electrode placement for underwater hull protection has been explored sufficiently to warrant no further study on the AFDL-12. No further simplification of the anode configuration appears desirable since the results here reported indicate a single anode placed amidships and on bottom is sufficient. However, the problems should be studied for anodes supported from the ship and for multiple ship installations.

The short-term program has established the range of anode current required to insure a polarization greater than the solution potential of the ships' hull material. It remains for a larger scale statistical study to determine the critical polarization for complete protection.

No signs of paint stripping or damage to the protective coatings on the underwater hull, due to the currents used in the short term program, are evident.

The power and equipment requirements are shown by this study to be exceedingly small. Protection is maintained with less than eight amperes of direct current at four volts through

a single graphite anode lieing on the bottom and connected with submarine type (neoprene or Buna-S jacketed) cable.

The cost of the materials used in the installation is estimated to be under $400, excluding the testing equipment. Sufficient testing equipment, such as the Model B3, Miller Multicombination Meter, to install and monitor several dry dock cathodic protection systems can be procured for $500.

Monitoring surveys have been reduced in frequency to twice a month. It is believed that conditions are stable to the extent that bimonthly surveys will suffice.

The station power source has been sufficiently constant to carry on this study without additional current regulation. It is desirable for advancing the art that equipment be developed to automatically monitor the state of the ship and adjust the current to the optimum value. Such equipment would be especially desirable in areas where wide variations in the anode current are experienced and a close monitoring schedule is difficult to maintain.

Another study of interest would be the correlation between current required to maintain a steady state polarization and the effective uncoated area. Intuitively, one would assume them linearly proportional; however, the size of the vessel, movement of the waters, etc. may be factors. If the proportionality were established, one could apply cathodic protection to a ship in a known harbor, record the current required for protection and compare with the known area of the hull. From this data, and without a diver's survey, the effective bare area may be determined.

APPENDIX I

Basic Principles of Cathodic Protection

When a metal, labeled A, is partially submerged in an electrolyte (Figure 6), there is a tendency for the atoms of the metal to dissociate into an electron, ⊖, and a metallic ion, or cation, M^{+}. The cations go into the solution while the electrons remain in the metal, giving rise to an emf across the interface. This emf is called the solution pressure, and its magnitude depends on (a) the type of metal, (b) the type of electrolyte, and (c) the temperature. When a piece of metal, labeled B, having a lower solution pressure is connected to the piece of metal A (Figure 7), electrons migrate along the conductor from A to B. The precept of convention says that current flows in the conductor from B to A and a primary cell exists, of which A is the anode and B is the cathode. The current will continue to flow until the anode metal is completely consumed, while at the cathode any tendency for the metallic ions, M^{+}, to go into solution will be reversed and other cations of the electrolyte will be deposited there as neutral atoms. The process will continue until interrupted by one of the following eventualities: (a) a layer of the anodic material will deposit on the cathode, in which case a couple or primary cell no longer exists, (b) the circuit is broken so no current can flow, or (c) a reverse emf of a magnitude equal to that of the couple is inserted in the current path and the net driving voltage of the circuit vanishes.

The rate at which the corrosion occurs, or rather the anode is consumed, depends on (a) the magnitude of the resultant emf of the dissimilar metals in contact with the electrolyte, (b) the ohmic resistance in the current circuit, and (c) the amount of back emf inserted in the current circuit. All conductors or metals may be arranged in a table called the electromotive series (Table 1); the corresponding emf listed in the table is that of a primary cell which has the metal concerned in equilibrium with its ions as one electrode and hydrogen in equilibrium with hydrogen ions as the second electrode. The algebraic difference between any two elements listed here is the emf of a primary cell formed from the two in a solute containing, under standard conditions, the ions of each. In ideal cases, the electrolyte in contact with one electrode contains cations of only that metal and in known concentrations; a liquid junction is thus required to complete the circuit. The Daniell or gravity cell is a good example of

separating the electrolytes; in this case the liquid junction is maintained by a difference in the specific gravity of the two electrolytes.

The conductivity of the electrolyte is perhaps the determining ohmic element in the current circuit, thus it follows that sea water and soils with high salt content will be more corrosive than soils and water with small amounts and resulting low conductivity.

Back emfs arise from one of two causes: (a) The products formed by the passage of current may tend to collect or concentrate at one electrode. These products have their own solution pressures and consequent emf, and in keeping with the well-known principle of reaction, this emf opposes the primary cell and tends to reduce the driving voltage in the circuit. This effect is called polarization. (b) Current from an external source may flow in a resistance common to the primary cell circuit and in a direction such that the ohmic drop opposes the voltage of the primary cell. Mitigation of the current discharge from an anodic area by introducing a counter emf across a common resistance through the application of an external current or voltage is the basis of cathodic protection. Electrically, the former corroding or anodic area is made to receive a net current rather than to discharge current and in that sense becomes a cathode, hence the name 'cathodic protection'.

A single piece of metal in contact with an electrolyte can corrode electrolytically because of the existence of cathodic and anodic areas. Such areas are caused by local inhomogenieties in the material or electrolyte. Impurities, strains in the metal, differences in concentration and composition of the electrolyte can give rise to local primary cells on a seemingly homogeneous surface. The current flow in such a cell is shown in Figure 8 along with an equivalent circuit. Figure 9 shows the currents and voltages involved when cathodic protection is applied. V_a, V_b, and V_c, respectively, represent the open circuit potentials of the anodic area, the cathodic protection power source, and the cathodic area. R_a, R_b, and R_c are the effective resistances associated with the above voltages. i_a is the net current flow from the anodic area, i_b is the current from the cathodic protection source, and i_c is the net flow into the cathodic area. Complete protection is obtained when i_a becomes null which further requires $i_c R_c = V_a$.

Monitoring the net current flow into all parts of an extended anodic area is next to impossible, so one looks for a more practical way of determining when sufficient protection current has been applied.

Reference Half-Cells and Polarization

As stated earlier, the full electrochemical voltage as listed in the table of electromotive series (Table 1) exists when no current flows from the primary cell. When current does flow neutralized anions become atoms and are deposited at the anode; neutralized cations become atoms or molecules at the cathode. Each has its own solution potential and thus modifies the resultant emf in the circuit. The net driving voltage in the circuit is thus reduced to some value below the open-circuit electrochemical potential. In some cases, where the back voltage or polarization due to the products of electrolysis approaches the electrochemical open-circuit potential, the net current from the anodic area is reduced from an initial high value to a negligible one and further corrosion is arrested.

When a cathodic protection current is applied to a piece of metal, the electrolyte is first cleared of cations of the metal, then cations next above the metal in the electromotive series will become neutral atoms on the metal surface and the resulting polarization can be higher than the electrochemical potential of the metal. Polarization as used in this paper refers to the solution potential of the elements of electrolysis and does not include any voltage arising from the ohmic drops in the system; it is an open-circuit potential. From the foregoing discussion, one can see the merit in the criteria for protection which states that protection is complete when the polarization in the anodic area is equal to or greater than the anodic solution potential.

Reference half-cells are commonly used to determine the polarization of metals in an electrolyte. The following requirements are listed for a satisfactory reference half-cell:

1. It should have no polarization remaining from the passage of current other than its electrode solution potential. Consequently, a pure metal and an electrolyte containing cations of only the electrode metal is used. When the electrolyte solvent is water, as it nearly always is, the metal used lies below hydrogen in the electromotive series.

2. The potential of the reference half-cell should be

known, constant, and reproducible. Since the emf depends on the concentration of the cetions in the electrolyte, it is common to use a saturated solution. Saturation is maintained by leaving a surplus of undissolved salt in contact with the electrolyte at all times.

3. A porous membrane is required to separate the half-cell electrolyte from that of the protected specimen. The membrane permits ionic conduction but prevents circulation and contamination of the reference cell electrolyte.

4. The materials chosen should be readily obtainable and should possess small temperature coefficients.

The copper sulfate:copper reference half-cell shown in Figure 10 meets the above requirements adequately for most field work where large variations in temperature are not experienced. The theoretical potential E of bright steel against a saturated $Cu:CuSO_4$ half-cell is

$$E = 0.785 + 0.029 \log \frac{C_{Cu^{++}}}{C_{Fe^{++}}}$$

where $C_{Fe^{++}}$ is the effective concentration of ferrous ions in equilibrium with iron[8].

Criteria for Protection

Reduction of the anodic area current to zero is the ultimate criteria for determining the minimum applied current for complete protection. However, it remains an impractical one for an extended surface containing random anodic and cathodic areas. Practical criteria that one can use in the field fall into three main groups:

1. If one knows approximately the true solution potential between the metal to be protected and its environment, polarization produced by the cathodic protection current can be monitored at representative areas of the specimen and the current adjusted to give a polarization slightly greater than the solution potential.

2. By non-destructive testing methods, one can record the rate at which the specimen is deteriorating and then adjust the protection current until the rate is minimized.

3. A third criteria which may be used in addition to or in lieu of 1 and 2 is the use of coupons or test plates. Plates are made from material as near as practicable to the specimen and are placed in typical sections of the corrosive electrolyte. One group of coupons is allowed to corrode freely in the environment while a second group is connected into the cathodic protection system. Comparative weighing and inspection of the coupons before and after a specified period of time will indicate how successful is the protection system.

A range of polarization of 0.80 to 0.90 volts for ships' hulls in sea water has been recommended in a report to the Admiralty Corrosion Committee[4] as a safe range for monitoring. Complete protection should be obtained within this range with no tendency for paint stripping due to the evolution of hydrogen. The more narrow range of 0.80 to 0.85 volts is widely used as the safe protected zone for the polarization of iron using a saturated copper sulfate reference half-cell.

Precautions

Current in excess of the minimum required for complete protection will, by the process of electrolysis, deposit elements whose cations exist in the electrolyte. Two main dangers exist from the deposited elements:

1. If a gas is formed as in the case for hydrogen, blisters may form to loosen the paint or protective coating on the specimen.

2. A metallic element may be deposited which may in turn hydrolyze into a strong alkali tending to dissolve the specimen.

In general, no harm is done by a slight current in excess of that required for protection; the protection is no less complete and the excess products diffuse into the electrolyte or bubble harmlessly into the air.

APPENDIX II

Calculated loss rate without cathodic protection

Density of iron	7.86	grams/cubic centimeter
Bare area of coupon	2.0	sq.ft = 288 sq. in.
Weight lost by unprotected coupon	48.5	grams in 3 months

V, volume lost per yr $\quad \frac{48.5 \times 4}{7.86}$ cc $= \frac{48.5 \times 4 \times 0.061}{7.86}$ in.^{3}

Thickness lost per year $\quad \frac{V \text{ in}^3}{\text{Area in}^2} = \frac{48.5 \times 4 \times 0.061}{7.86 \times 2 \times 144} = 0.0052$ in.

APPENDIX III

A Dual-Triode Current Stabilizer

Figure 18a is the schematic diagram of a circuit used to stabilize the current in an electrolytic cell. The cell is used in the laboratory phase of the cathodic protection studies. The current is essentially independent of variations in the cell (herein called the load) resistance. It does not stabilize against supply voltage variations as does the better known pentode circuit which uses a stabilized screen grid voltage.

Figure 19 is the schematic of a typical pentode stabilizer.

When used with a regulated, adjustable voltage type of 'B' supply, the dual-triode stabilizer will maintain essentially constant the current in a variable load. The value of the current is determined by the 'B' supply voltage within the limits of the triode plate current. A brief analysis of the dual-triode current stabilizer follows.

Using the equivalent circuit theorem for triodes which permits the grid voltages to be increased by the amplification factor, u, and injected into the plate circuit along with the plate resistance, r_p, the equivalent circuit of Figure 18c is drawn from the idealized schematic of Figure 18b. If a change $\triangle R$ occurs in the load R without stabilization, a corresponding change of $\triangle i_1$ would occur in the load current i_1. However, with stabilization $\triangle i_1$ is made to approach zero so that in the load circuit

$$u R_L \triangle i_2 \approx i_1 \triangle R \qquad (1).$$

While in the plate circuit of the second triode

$$(r_p + R_L) \triangle i_2 = u R_g \triangle i_1 \qquad (2).$$

Eliminating $\triangle i_2$ from (1) and (2)

$$\frac{\triangle i_1}{i_1} = \frac{\triangle R}{u^2 R_g} \left[\frac{r_p + R_L}{R_L} \right] \qquad (3).$$

R_L can generally be chosen larger than r_p, so a good approximation to (3) is given by

$$\frac{\triangle i_1}{i_1} = \frac{\triangle R}{u^2 R_g}, \qquad (4).$$

or

$$\phi = \frac{1}{\triangle R} \cdot \frac{\triangle i_1}{i_1} = \frac{1}{u^2 R_g} \qquad (5).$$

The degree of stabilization ϕ, expressed as the fractional change in the load current per unit change in load resistance is inversely proportional to the product of the amplification factor squared and the grid resistance in series with the load.

In the circuit of Figure 18a where R = 100,000 ohms and u = 30,

$$\phi = \frac{1}{u^2 R_g} = \frac{1}{(900)\ (100{,}000)} = \frac{1}{9 \times 10^7} = 1.1 \times 10^{-8}$$

This amount of stabilization was not realized in practice because self-bias was used on the second triode, thereby reducing the effective u.

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Table 1

Series of Some Common Metals.*

ELEMENT		Eo (Volts)
Magnesium,	MG^{++}	+ 1.866
Zinc,	ZN^{+}	+ 1.248
Zinc,	ZN^{++}	+ 0.7618
Iron	Fe^{++}	+ 0.441
Tin,	Sn^{++}	+ 0.136
Hydrogen,	H^{+}	± 0.000
Copper,	Cu^{++}	- 0.3441
Iron,	Fe^{+++}	- 0.7477
Silver,	Ag^{+}	- 0.7978

* From Lange, Handbook of Chemistry (1935), pp 685.

Table 2

Comparison of Weight Lost by Protected and Unprotected Coupons.

		Coupon #1 (In circuit)	Coupon #2 (Out of circuit)
Weight:	Installed 11/10/51	3591.0 gm	3567.5 gm
Weight:	Removed 2/6/51	3590.5	3519.0
Weight Lost:	3 months submerged	0.5 gm	48.5 gm

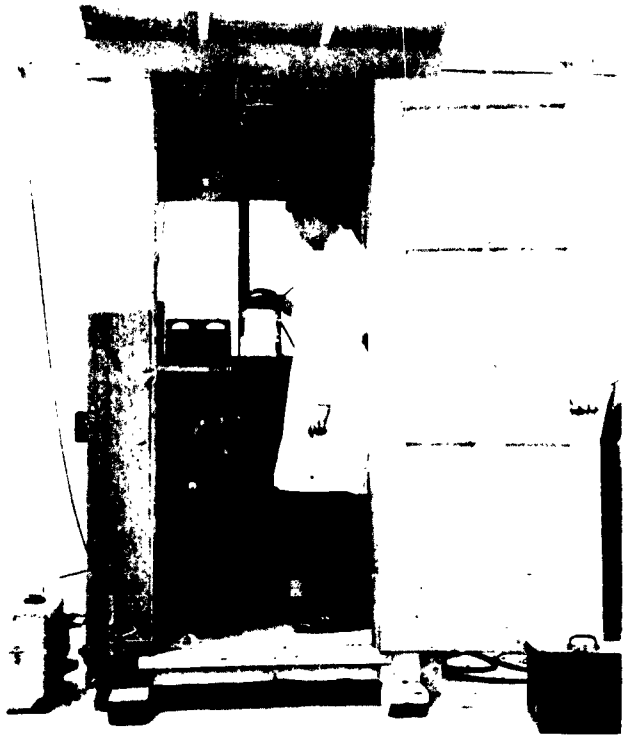


FIGURE 1. INSTRUMENT BUILDING.

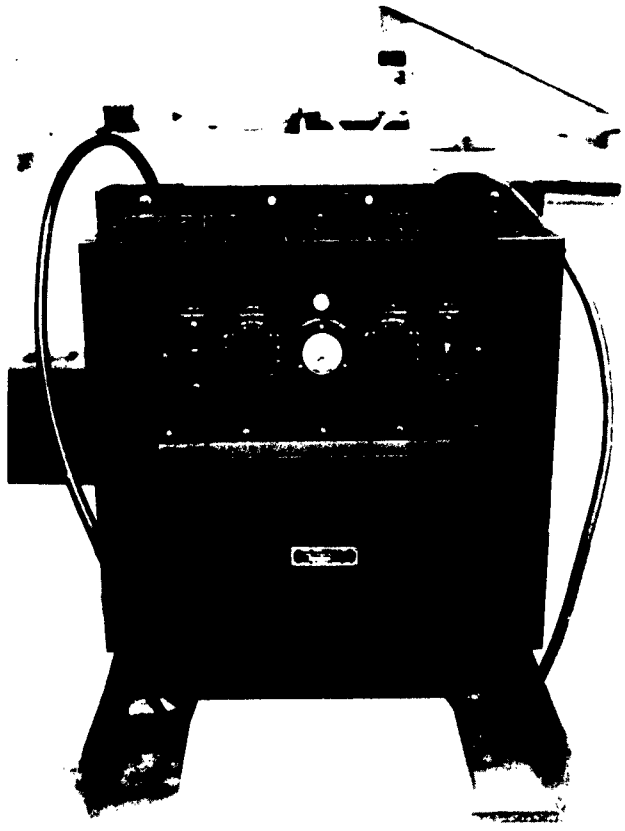


FIGURE 2. RA-91A RECTIFIER.

FIGURE 3. GRAPHITE ANODE.

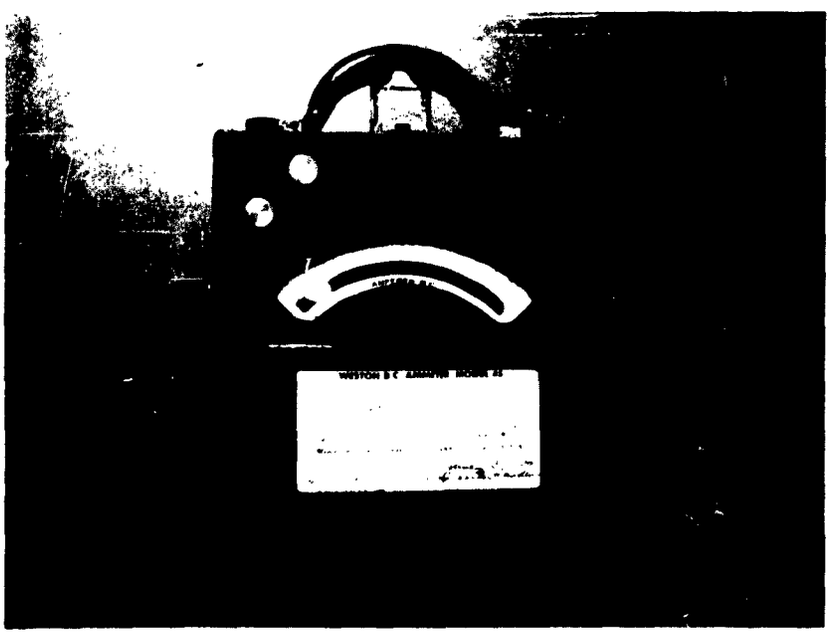


FIGURE 4. PRECISION BENCH TYPE AMMETER.

FIGURE 5a. BOTTOM OF KEEL HAUL RIG (AFDL 12).

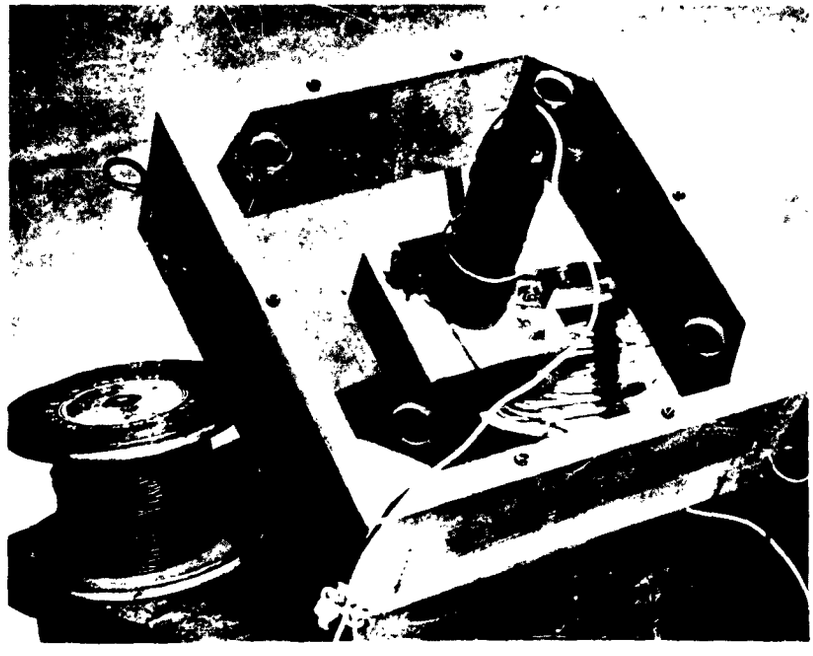
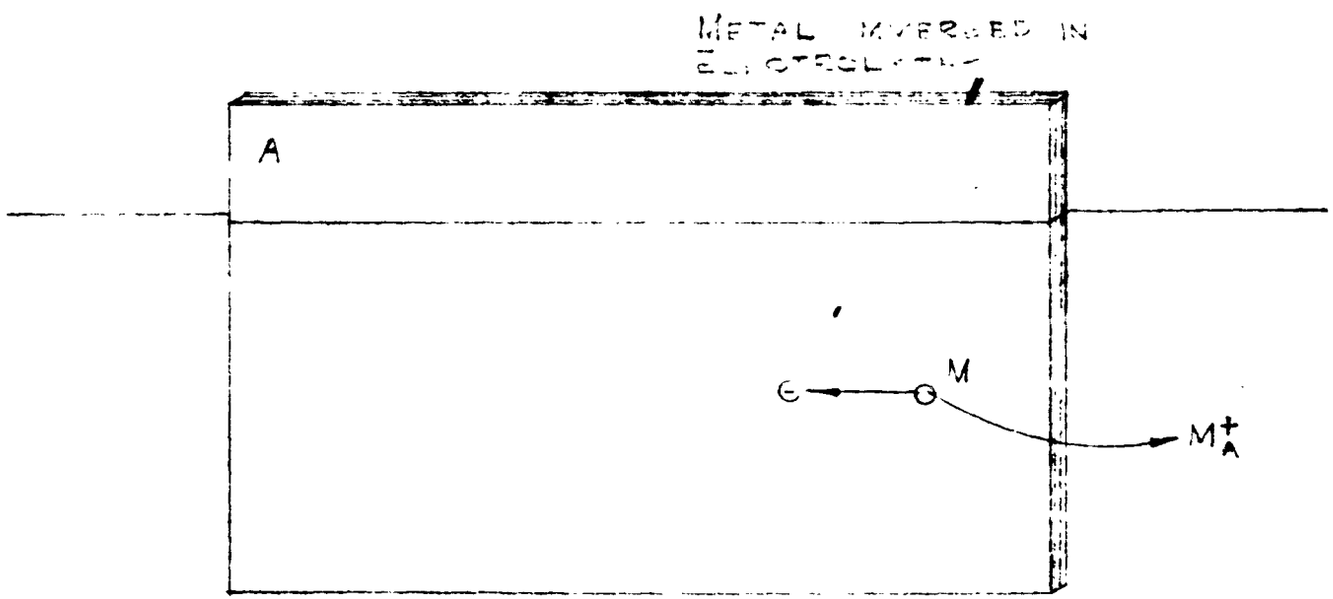


FIGURE 5b. TOP VIEW OF KEEL HAUL RIG (AFDL 12).

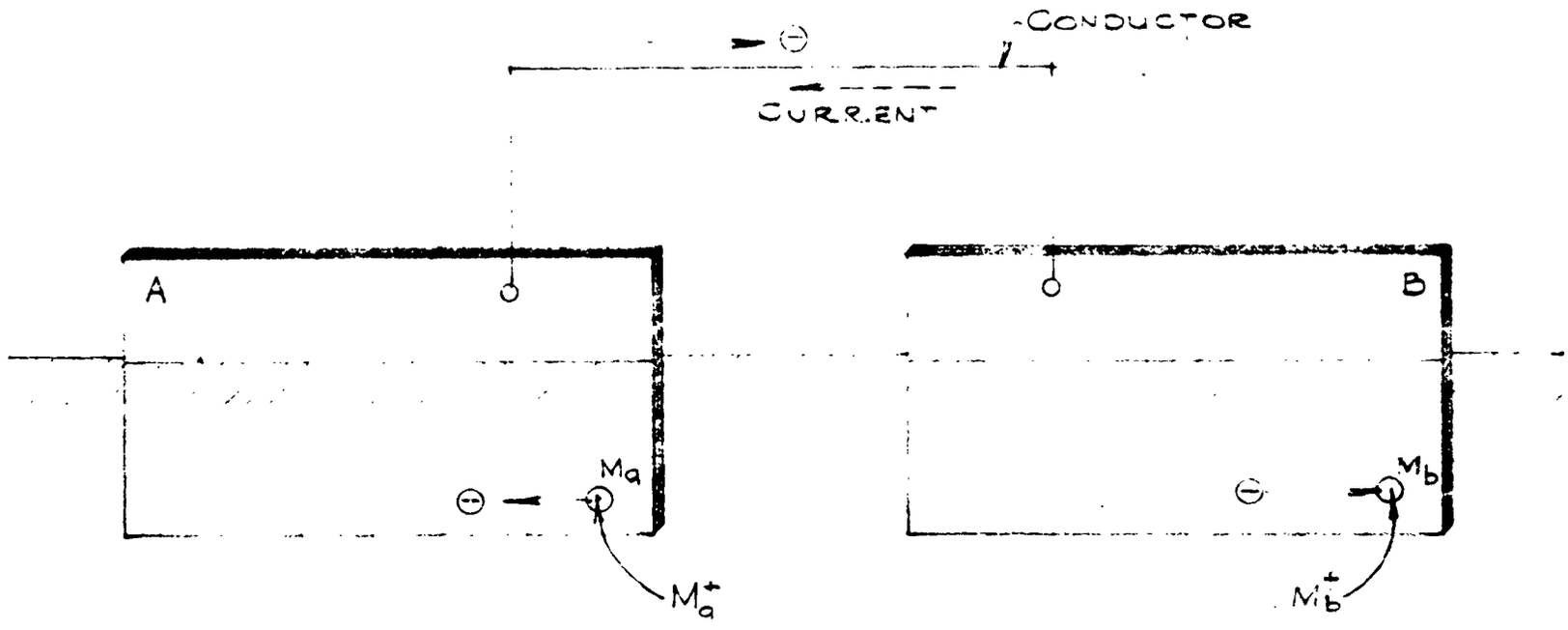


$\ominus$ = FREED ELECTRON IN METAL

M_A^+ = CATION IN ELECTROLYTE

IONIZATION DUE TO SOLUTION PRESSURE

FIGURE 6

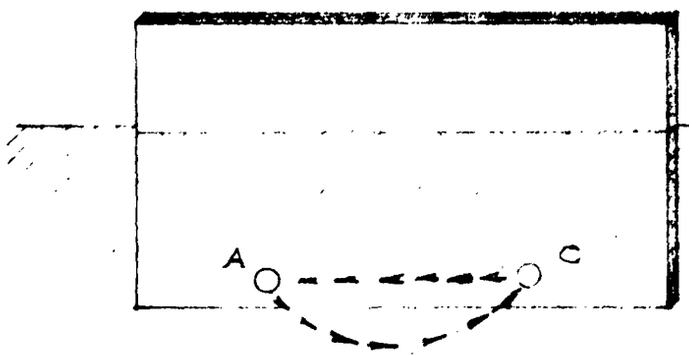


B HAS LOWER SOLUTION PRESSURE.
ELECTRONS TRAVEL FROM A TO B THROUGH CONDUCTOR.

SIMPLE BATTERY CELL

FIGURE 7

CURRENT FLOW IN LOCAL CELL ACTION



A TO C IN ELECTROLYTE
C TO A IN METAL

EQUIVALENT CIRCUIT

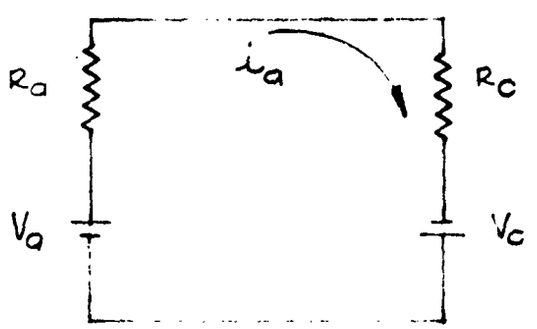
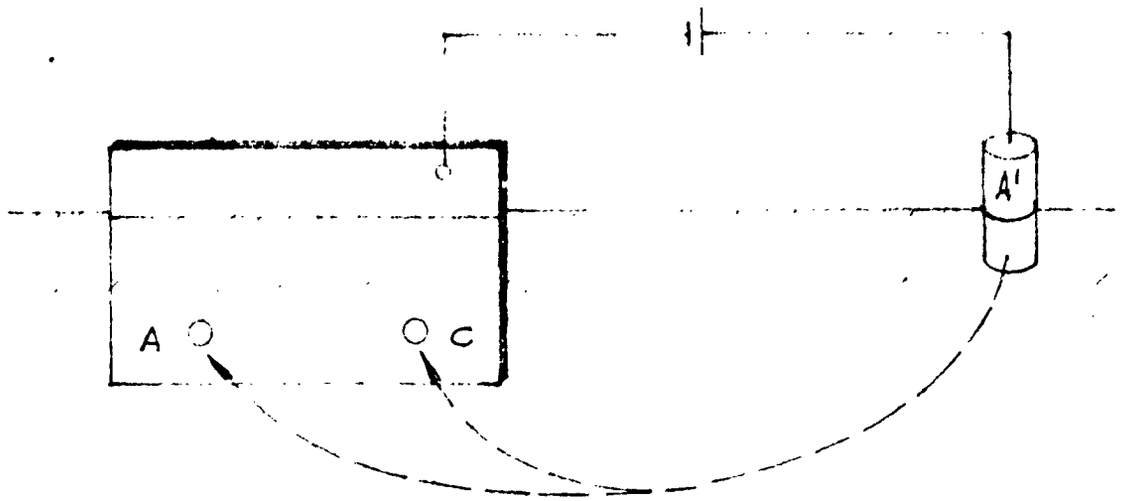
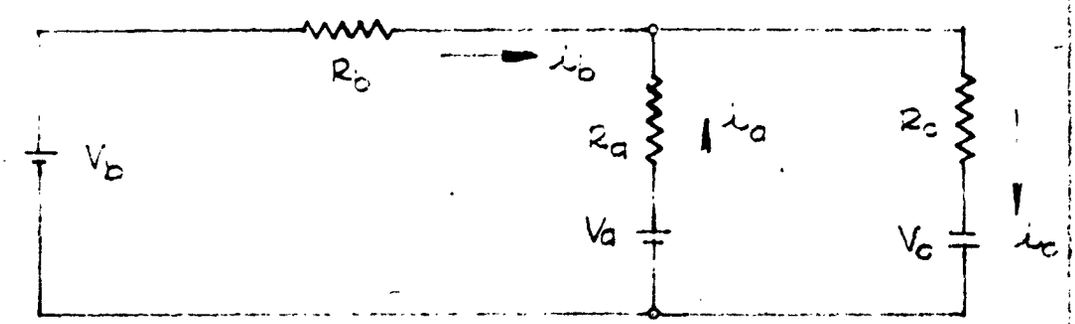


FIGURE 8



CATHODIC PROTECTION APPLIED



EQUIVALENT CIRCUIT

FIGURE 3

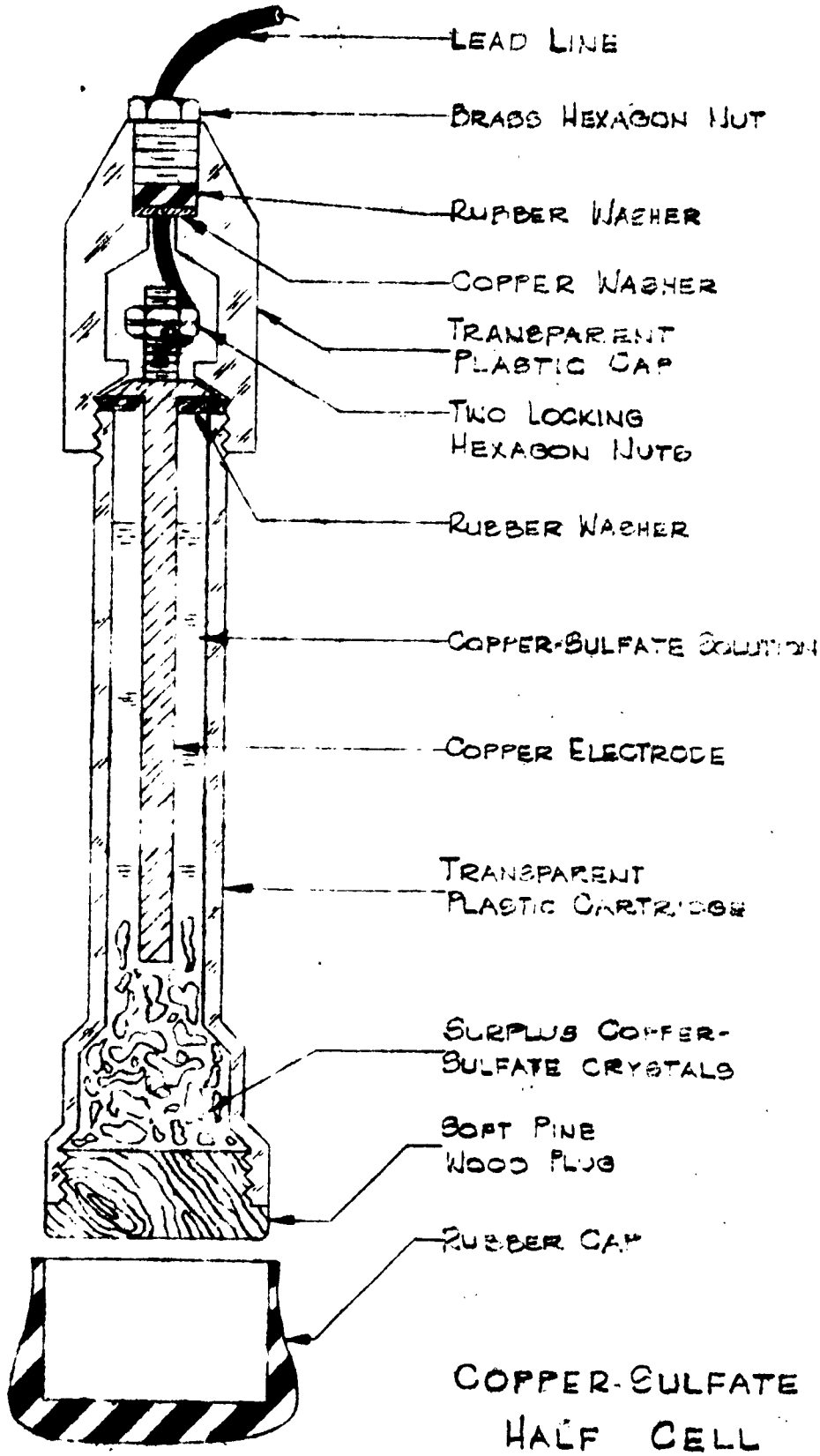
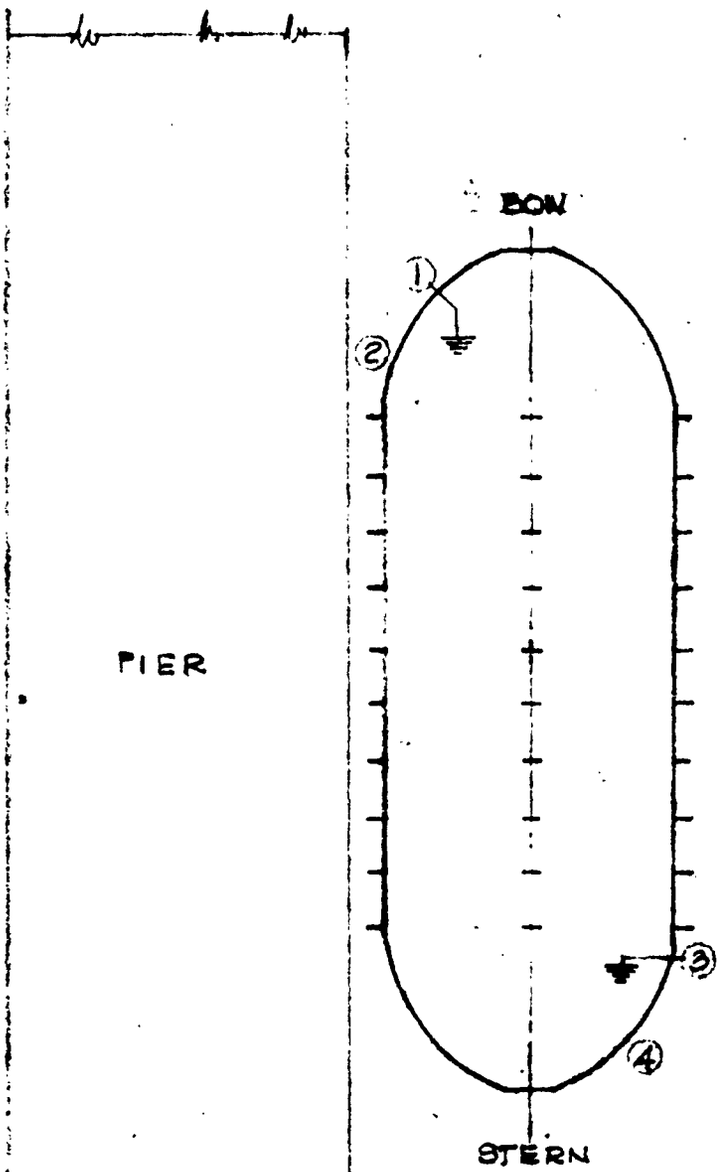

LEAD LINE
BRASS HEXAGON NUT
RUBBER WASHER
COPPER WASHER
TRANSPARENT PLASTIC CAP
TWO LOCKING HEXAGON NUTS
RUBBER WASHER
COPPER-SULFATE SOLUTION
COPPER ELECTRODE
TRANSPARENT PLASTIC CARTRIDGE
SURPLUS COPPER-SULFATE CRYSTALS
SOFT PINE WOOD PLUG
RUBBER CAP
COPPER-SULFATE HALF CELL

FIGURE 10

LOCATION OF TEST COUPONS ON AFDL-12



	BOW	STERN
IN CIRCUIT	1	3
OUT OF CIRCUIT	2	4

FIGURE 11

MODIFIED BROWN 'ELECTRONIC' RECORDER
USED AS A 600-1200 MILLIVOLT RECORDING POTENTIOMETER

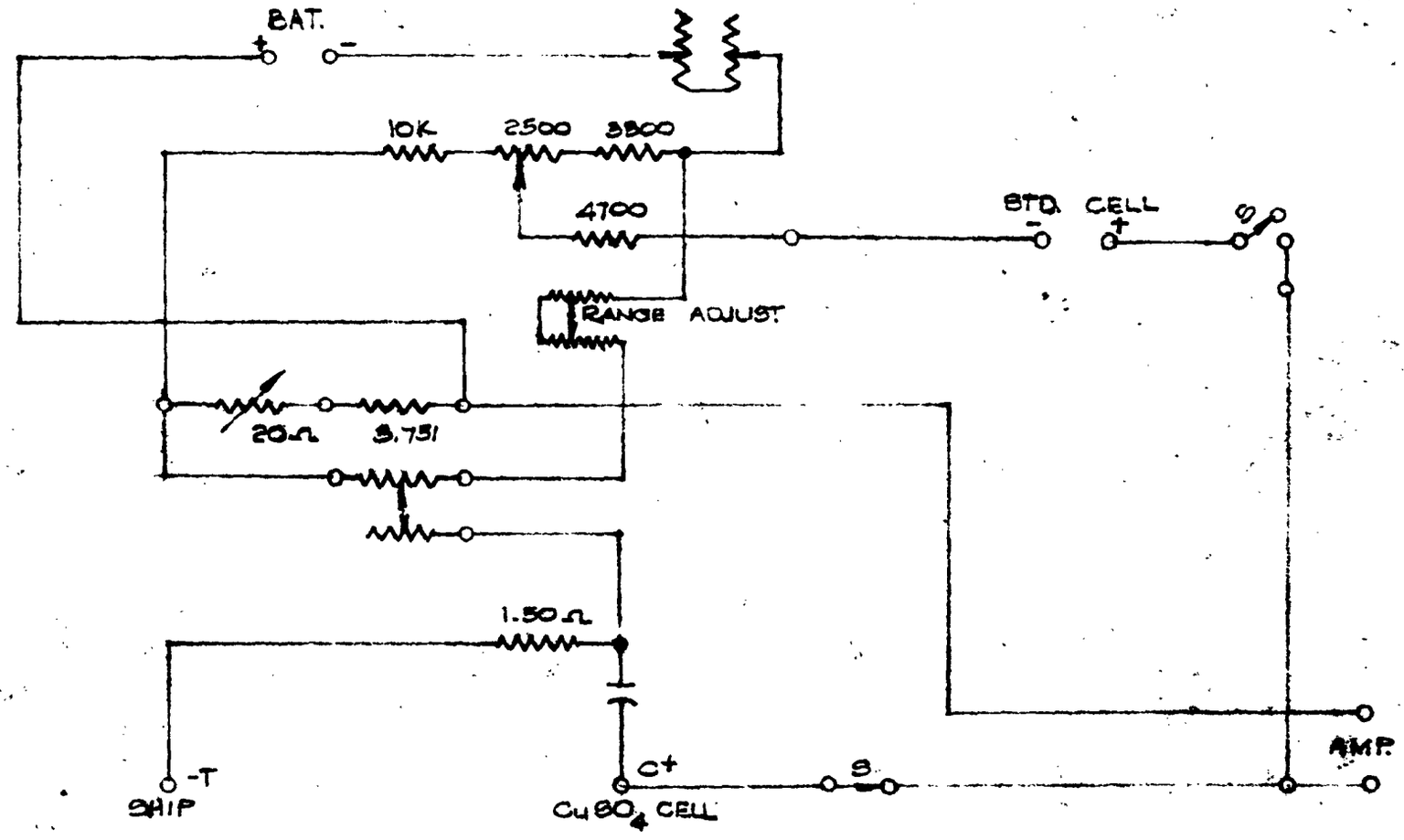


FIGURE 12

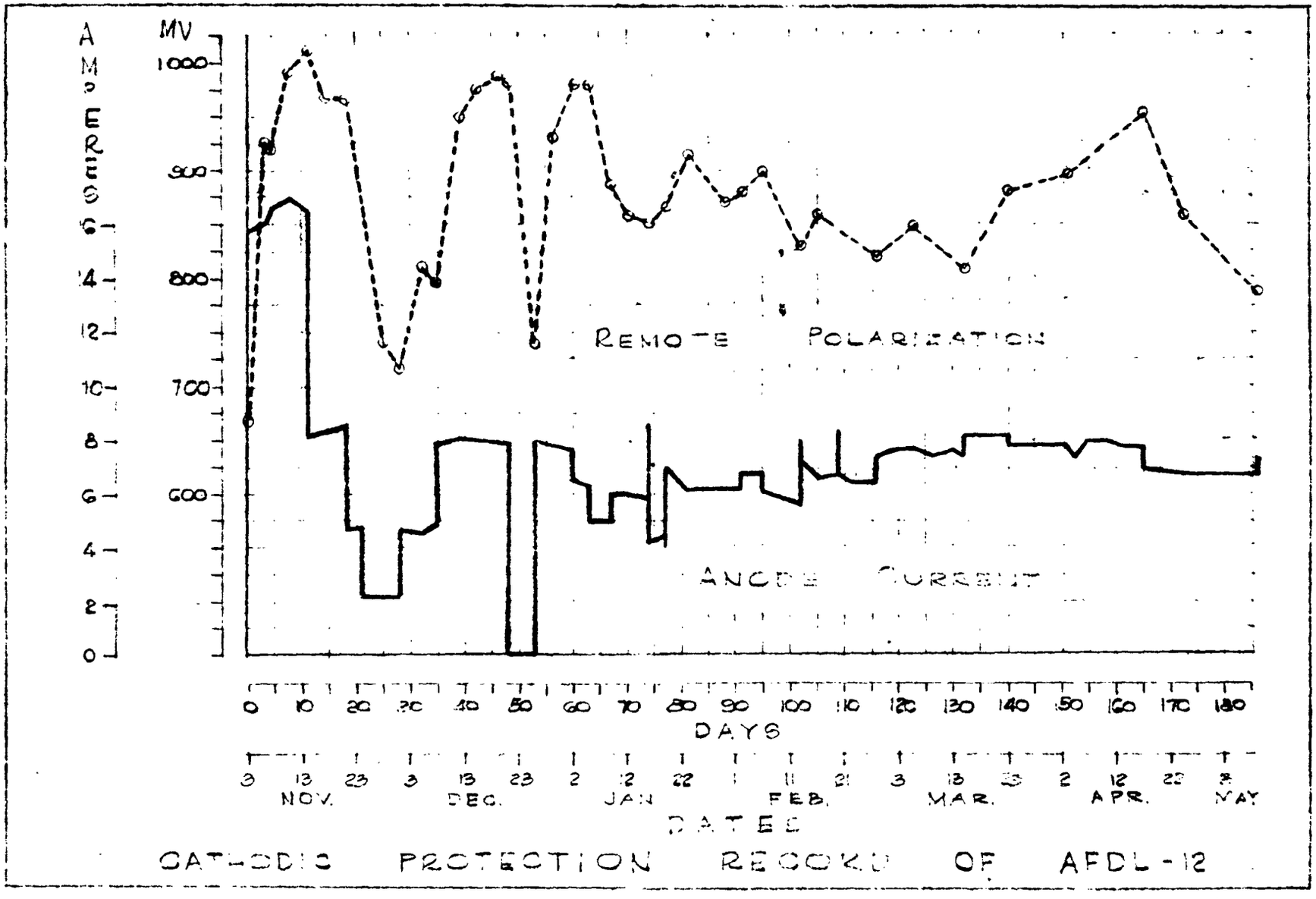
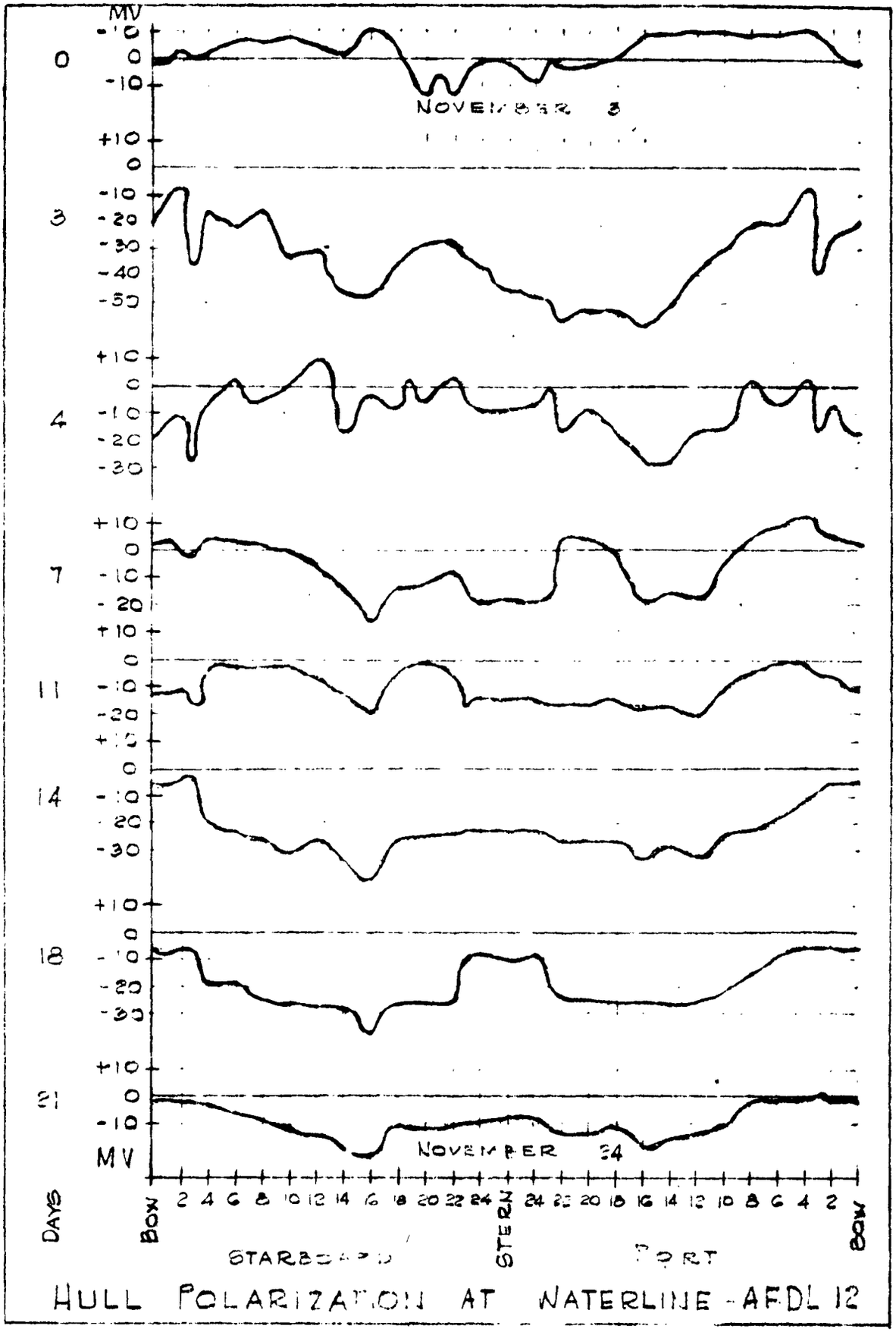
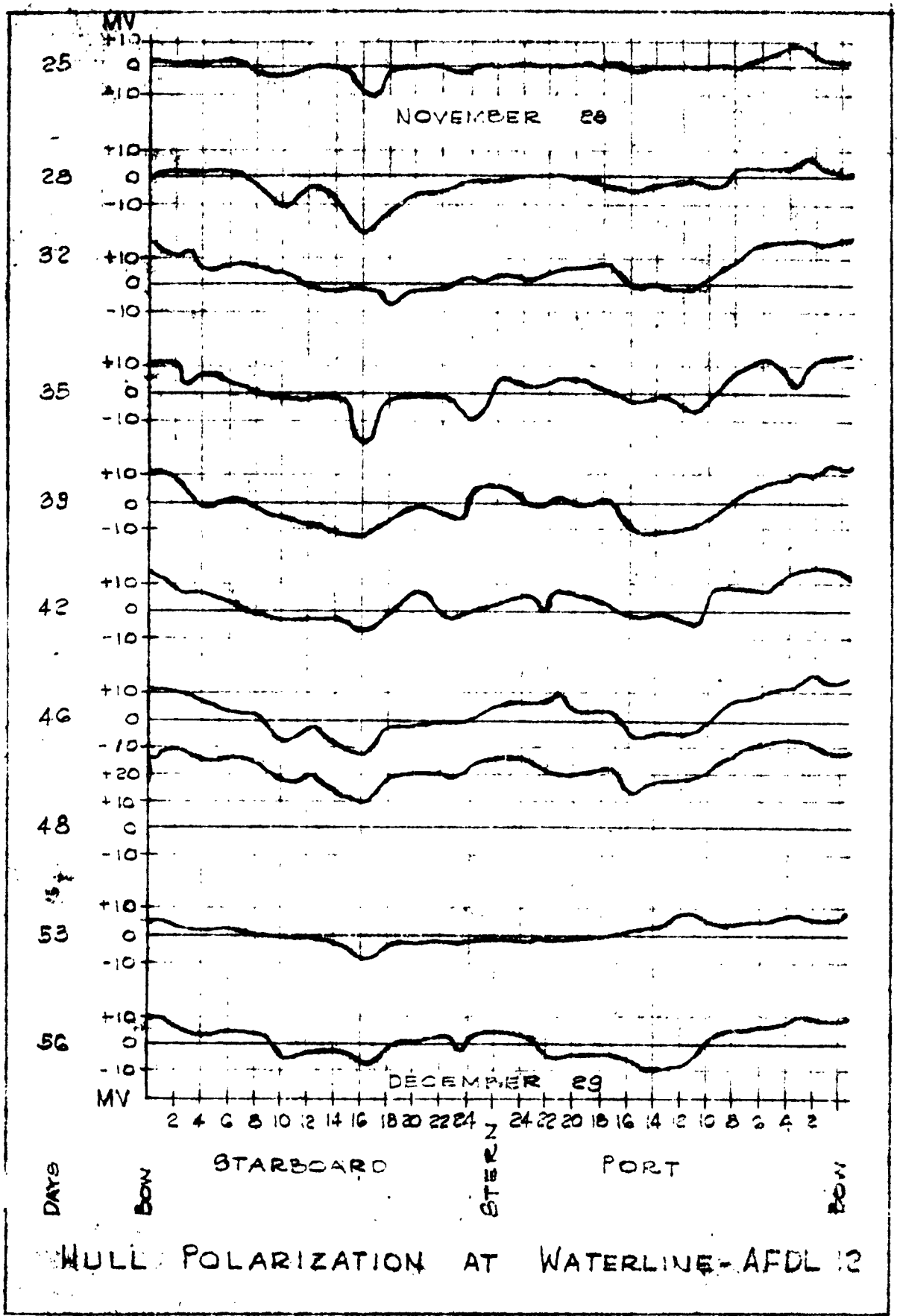

AMPERES
MV
1000
900
800
700
600
0
2
4
6
8
10
12
REMOTE POLARIZATION
ANODE CURRENT
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180
DAYS
3 13 23 3 13 23 2 12 22 1 11 21 3 13 23 2 12 22 3
NOV. DEC. JAN FEB. MAR. APR. MAY
DATES
CATHODIC PROTECTION RECORD OF AFDL-12

FIGURE 13



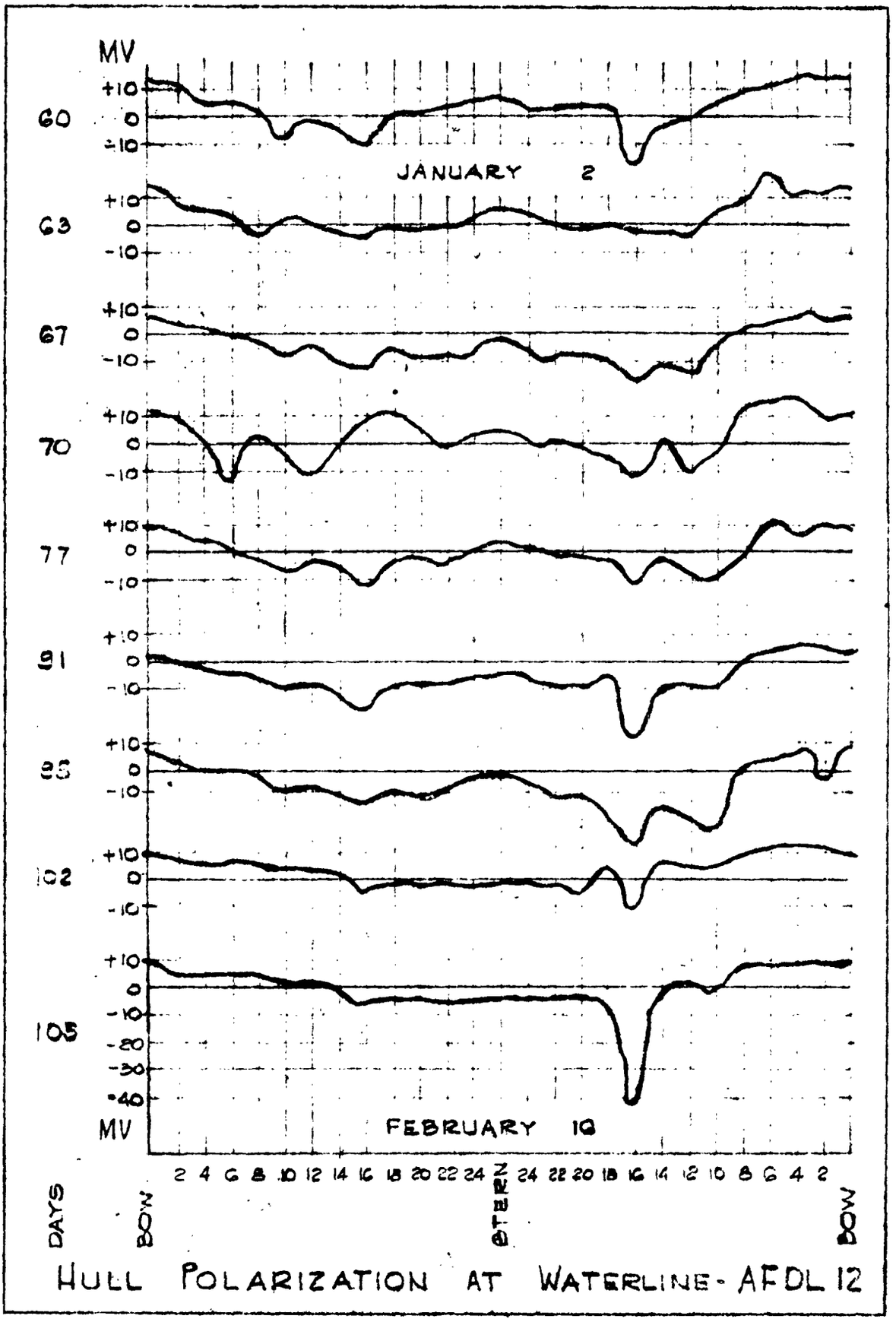
HULL POLARIZATION AT WATERLINE - AFDL 12

FIGURE 14a



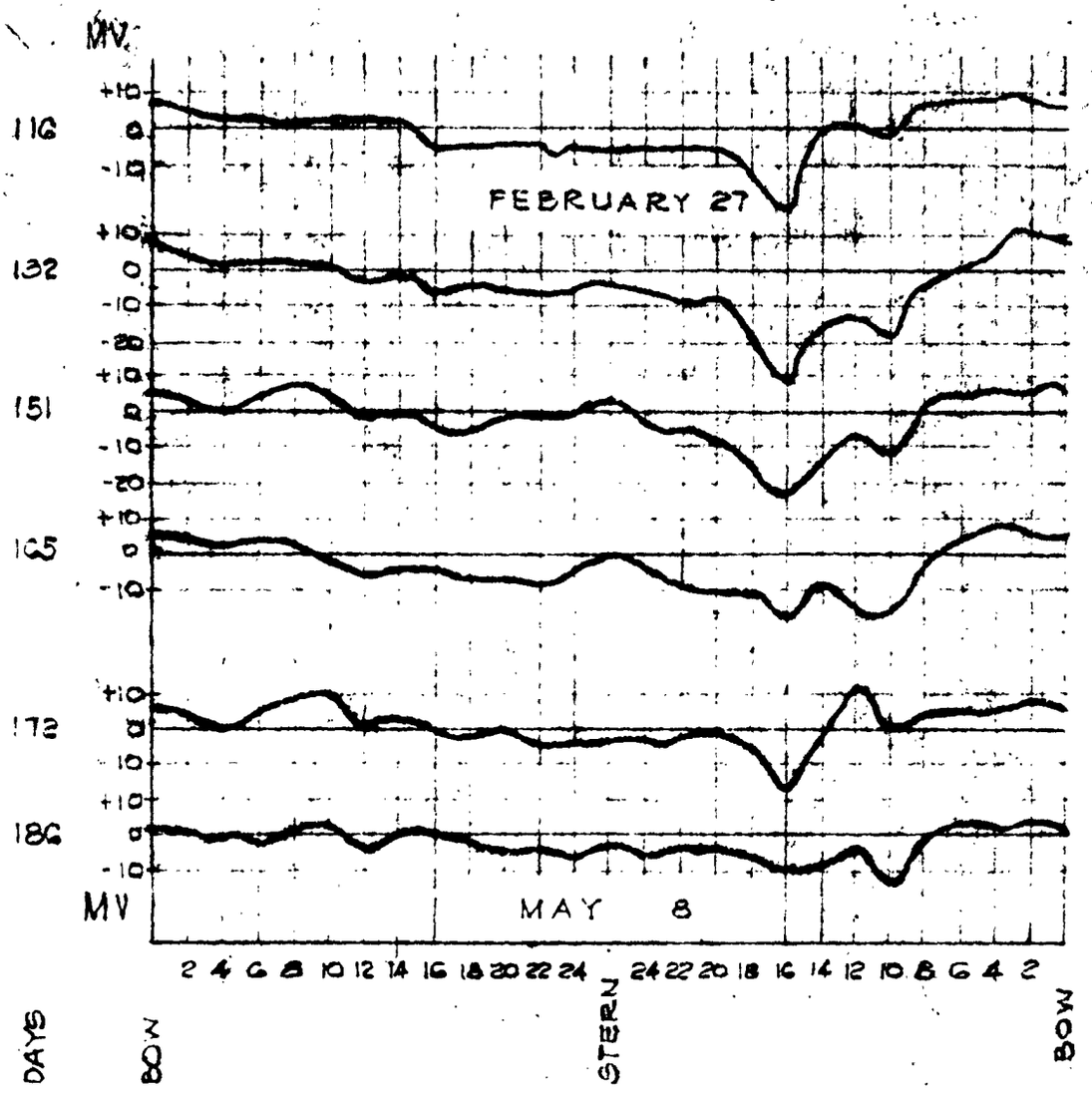
HULL POLARIZATION AT WATERLINE - AFDL 12

FIGURE 146



HULL POLARIZATION AT WATERLINE - AFDL 12

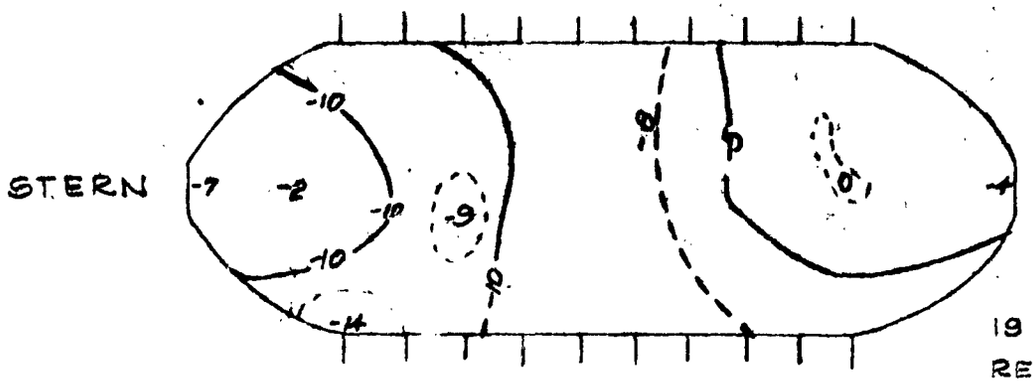
FIGURE 142



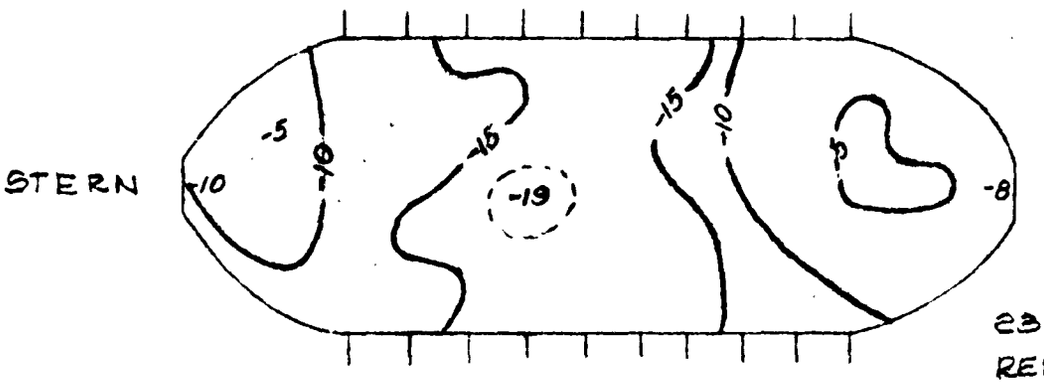
HULL POLARIZATION AT WATERLINE - AFDL 12

FIGURE 14d

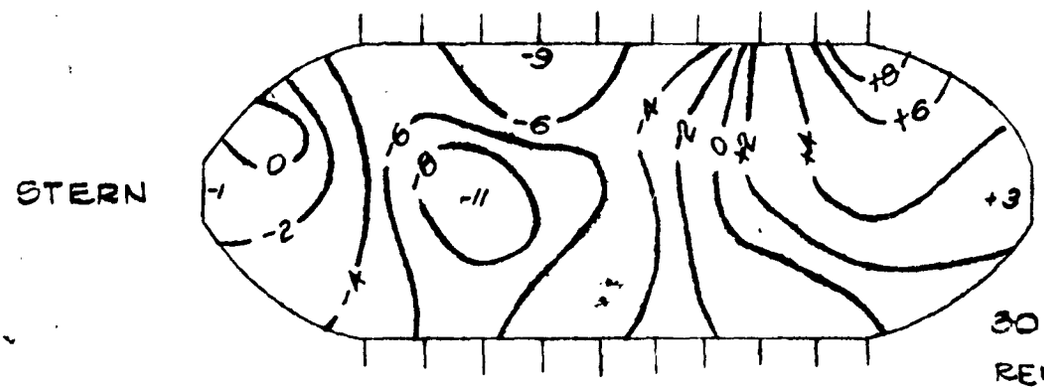
POLARIZATION - MILLIVOLTS
AFDL-12 HULL



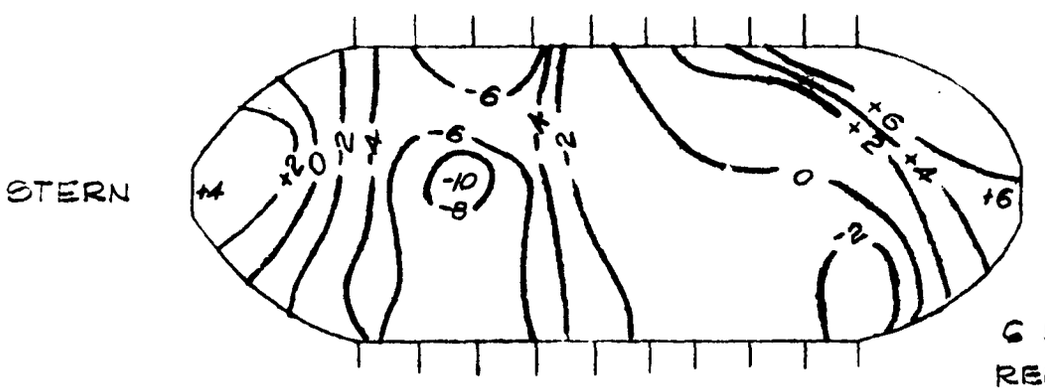
19 JANUARY 1951
REMOTE: 869 MV



23 JANUARY 1951
REMOTE: 920 MV



30 JANUARY 1951
REMOTE: 870 MV



6 MARCH 1951
REMOTE: 850 MV

EQUIPOTENTIAL CONTOURS
M.V. Above Remote

FIGURE 15

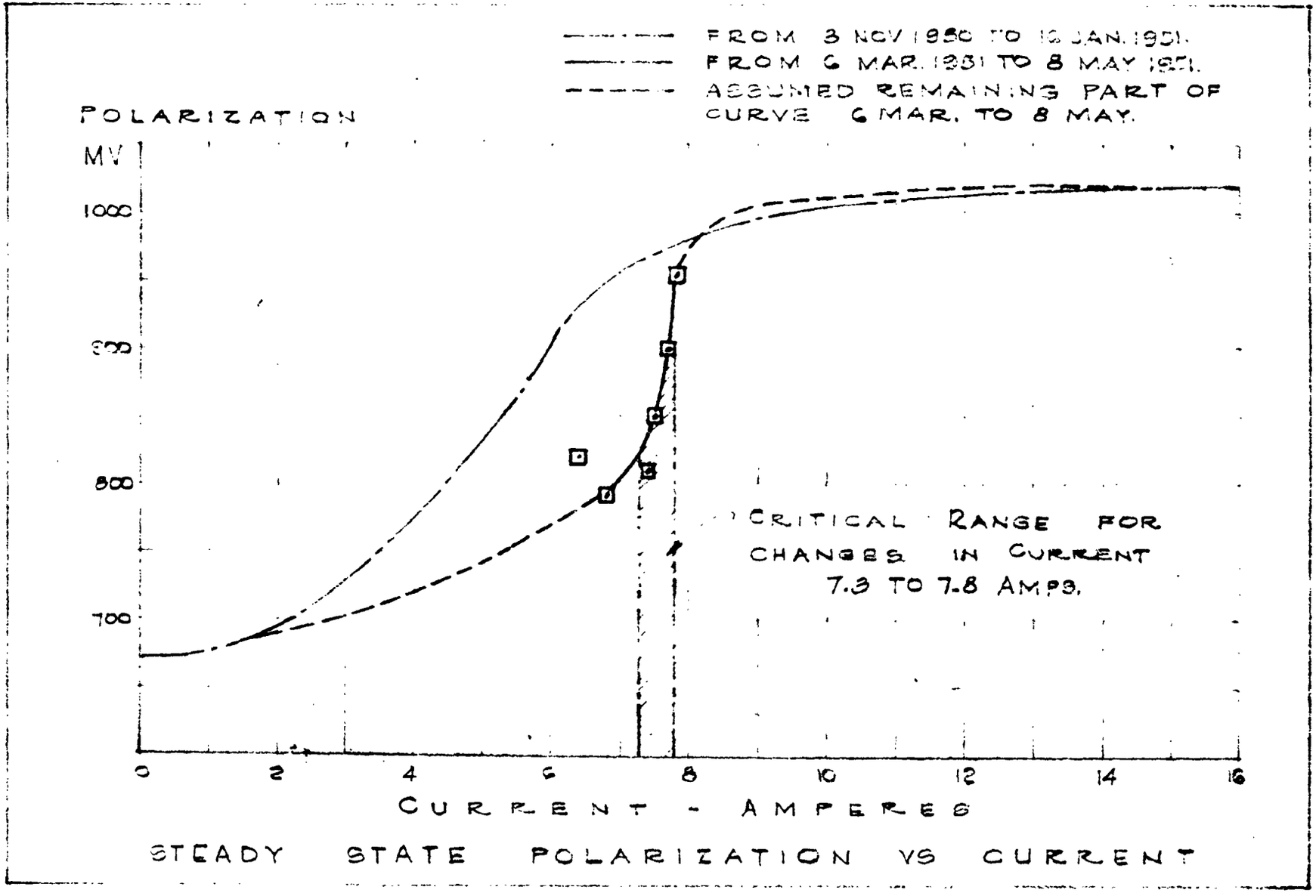

FROM 3 NOV 1950 TO 16 JAN. 1951.
FROM 6 MAR. 1951 TO 8 MAY 1951.
ASSUMED REMAINING PART OF CURVE 6 MAR. TO 8 MAY.
POLARIZATION
MV
1000
900
800
700
CRITICAL RANGE FOR CHANGES IN CURRENT 7.3 TO 7.8 AMPS.
0
2
4
6
8
10
12
14
16
CURRENT - AMPERES
STEADY STATE POLARIZATION VS CURRENT

FIGURE 16

BLOCK DIAGRAM OF CATHODIC PROTECTION SYSTEM OF AFDL-2

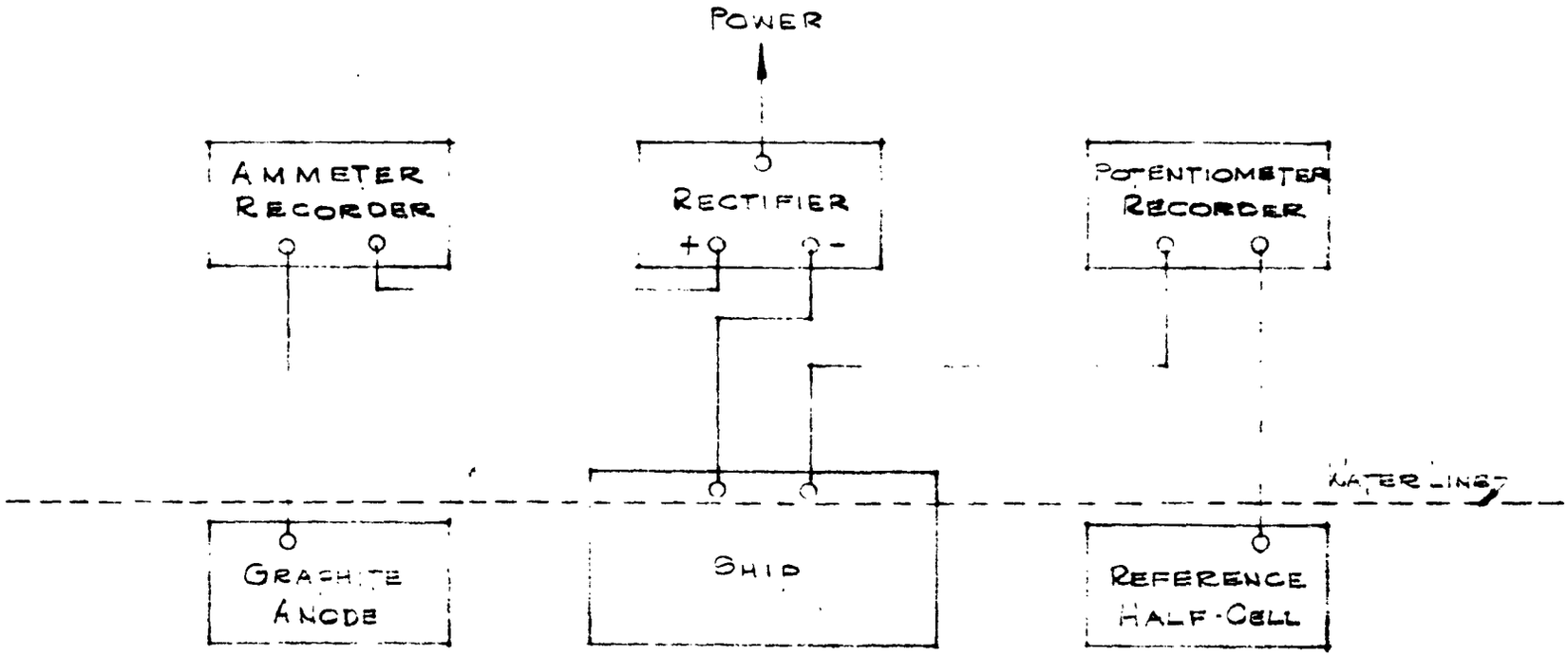
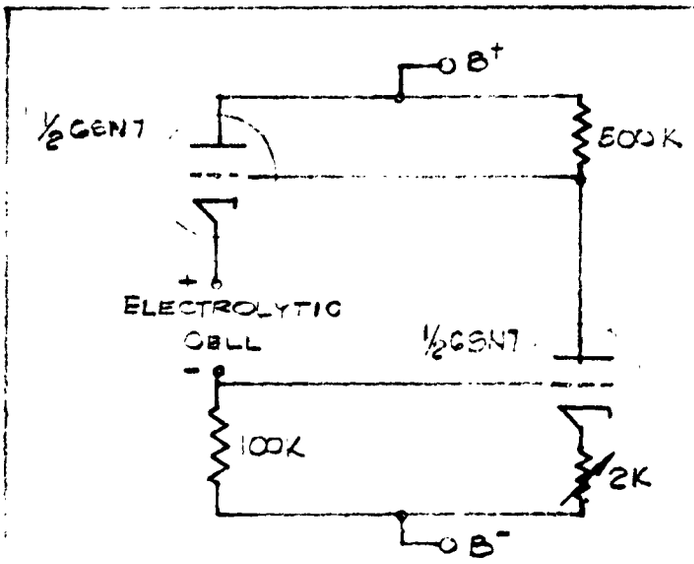
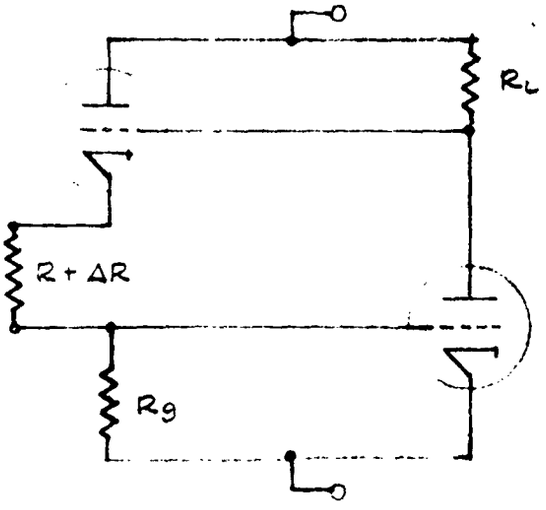


FIGURE 17



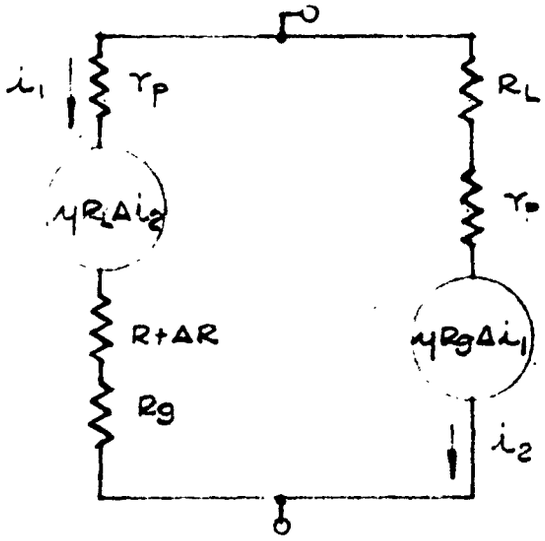
18 a

SCHEMATIC DIAGRAM OF DUAL-TRIODE CURRENT STABILIZER



18 b

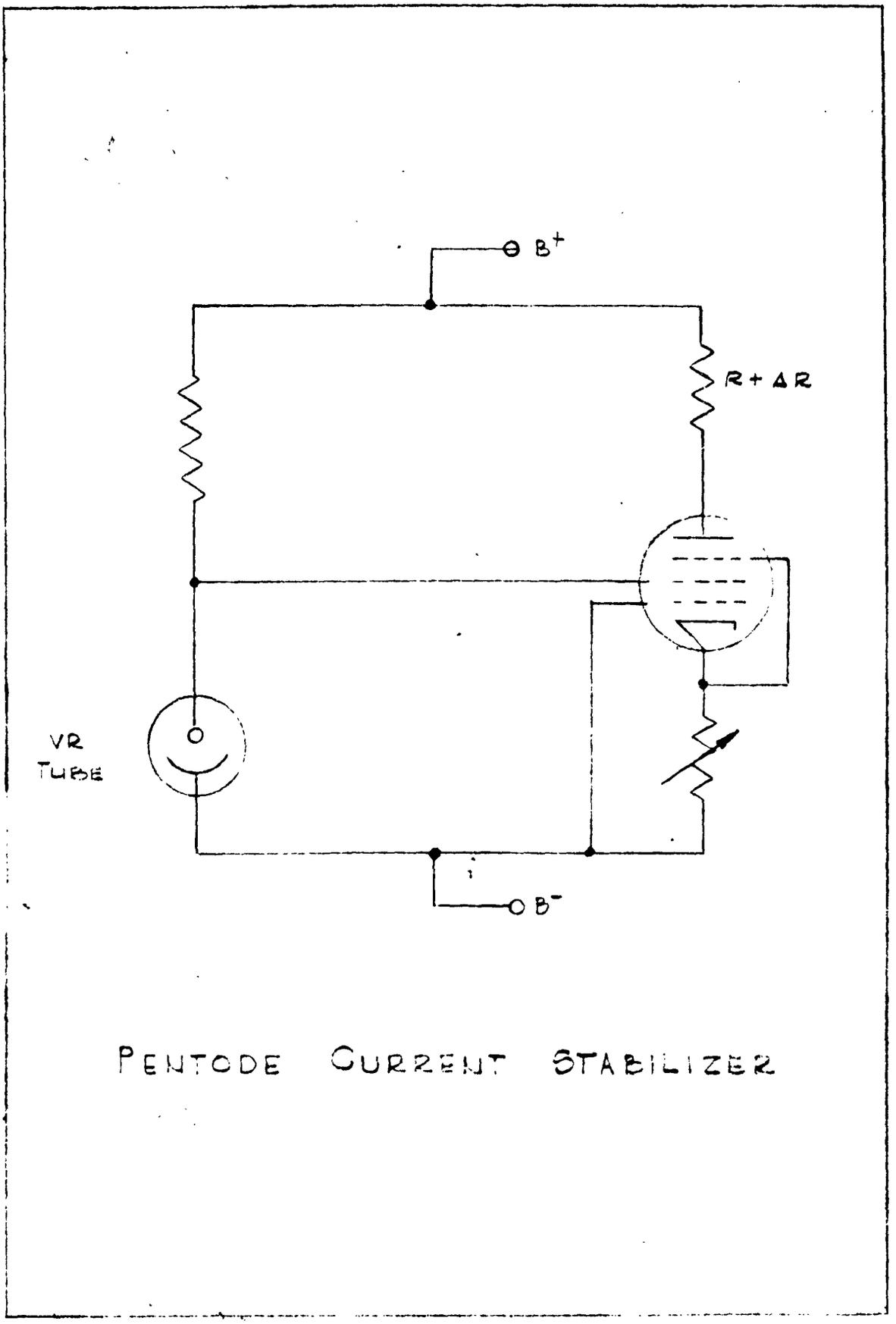
IDEALIZED CIRCUIT OF 18-a



18 c

EQUIVALENT CIRCUIT OF 18-b

FIGURE 18



PENTODE CURRENT STABILIZER

FIGURE 19

4/4 STI-ATI-209 595 **UNCLASSIFIED**

17/2 Naval Civil Engineering Research and Evaluation Lab., Port

31/5 Hueneme, Calif.

* CATHODIC PROTECTION APPLIED TO THE AFDL-12 LONG BEACH, by W.A. Bowen, Jr. 15 Nov 51, 20p. illus. tables. (Technical note no. N-060)

		SUBJECT HEADINGS
DIV:	Chemistry (4)	Hulls, Ship
SECT:	Physical Chemistry (4)	Corrosion
DIV:	Metallurgy (17)	Electrolysis
SECT:	Structural Metallurgy (2)	
DIV:	Ships & Marine Equipment (31)	
SECT:	Naval Architecture - Surface Ships (5)	

ASTIA 1/5 Oct 56 med

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