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Cathodic Protection of Pipelines and Storage Tanks

BY

V. A. PRITULA

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DEPARTMENT OF SCIENTIFIC AND INDUSTRIAL RESEARCH

CATHODIC PROTECTION
OF PIPELINES AND STORAGE TANKS

by

V. A. Pritula

LONDON: HER MAJESTY'S STATIONERY OFFICE
1953

EDITOR'S NOTE

A new method of protection against corrosion of underground equipment namely, cathodic protection, is described. The purpose of the book is to make the reader familiar with investigation, design and operating conditions of cathodic protection. Particular attention has been paid to the calculation of the required rating of the installations and this is dealt with in such detail as is considered necessary for particular application.

It is recommended as a practical manual and also as a textbook.

This book has been translated from the Russian and was originally published in 1950 by the Chief Petroleum Marketing Organization of the Russian Ministry of the Petroleum Industry. It appeared in a series of Petroleum and Mined-Fuel Literature.

In some places in the text the Russian symbol for the decimal point is used, which is similar to a comma. The Russian symbol for voltage, namely "β", will sometimes be found on diagrams.

October, 1953.

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INTRODUCTION

A method of fighting corrosion of underground piping and storage tanks, which is one of the most expensive types of corrosion, is dealt with in this book. In addition to waste of metal, this corrosion involves losses of valuable petroleum products and gases. Leakage through spots damaged by corrosion may also involve danger of fire or explosion, since these products are inflammable.

At present, the network of piping for petroleum products and gas mains (in Russia) exceeds 500,000 km. Assuming as a rough estimate that the average diameter of these pipelines is 10", about 20,000,000 tons of metal are buried underground. The quantity of metal water piping laid underground will not be smaller. If other metallic equipment in the ground (tanks, structures, etc.) is also taken into consideration, the total quantity of metal subjected to such corrosion (in Russia) will greatly exceed 40 million tons. Assuming that corrosion involves a yearly loss of 3% of the equipment laid underground, this represents more than 1 million tons of metal per annum.

The most dangerous type of underground corrosion is the formation of pits penetrating the entire wall thickness. Often such corrosion occurs within three years of laying the pipes. However, cases are known of perforations in pipe lines of 8 mm wall thickness appearing for the first time within one year of laying the pipes. The number of perforations increases progressively if preventive measures are not taken. According to results of statistical investigations the number of perforations can be tentatively expressed by the relation:

$$R = e\,T^{f}, \quad \ldots \quad \ldots \quad \ldots \quad (1)$$

where: R - total number of perforations due to corrosion,
T - number of years of operation of the pipe line from the time of appearance of the first perforation,
e - the number of perforations during the first year from the time of their first appearance,
f - coefficient (of curvature) the value of which is usually between 1.5 and 3 (see Fig. 1).

A few examples will be given:

In one oil pipe line with tubes of 10" dia. and a wall thickness of 9.2 mm the first corrosion hole was observed only three years after laying; after a further three years the number of such holes increased to 200. The state of the pipe line, which was painted with a coating of red-lead during laying, was such that urgent measures of additional protection against corrosion of individual sections had to be taken. These consisted of applying a layer of bitumen insulation. Later perforation was found to exist also on the unrepaired sections and after a certain time they reappeared also on the sections which were coated with bitumen.

Bitumen coated water mains piping had after eight years of operation over 400 bursts due to corrosion. This disrupted normal operation to such a degree that a new pipe line had to be laid.

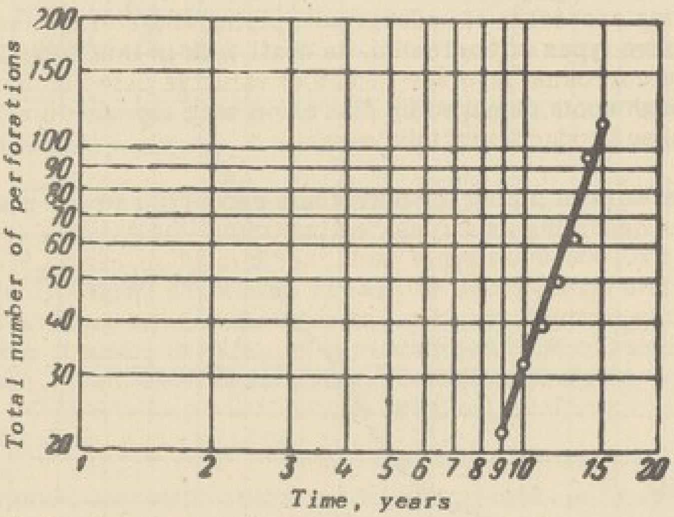


Fig. 1. Real number of perforations corresponding to the equation: $R = 0{,}0297\ T^{3{,}02}$.

Other water mains with tubes of 20" dia. showed about 80 perforations per year during 15 years operation, in spite of the fact that their wall-thickness was 16 mm. It was necessary to take urgent measures to prevent further disruption of this pipeline.

The water mains of a large town showed in eight years of operation corrosion cavities up to 8 mm deep in a wall-thickness of 12 mm.

Until relatively recently, the only method of protection against corrosion was to apply an insulated coating on the surface areas of equipment laid in the ground. At present, cathodic protection is widely used both for protection of newly laid piping and also for protection of old pipelines. In some cases it is used in addition to an insulation layer on the metal surface, but sometimes it is used exclusively. The first reference to the possibility of practical utilisation of cathodic protection dates back to 1824. It was used for underground piping for the first time between the years 1923-1928. In 1939 there were (in Russia) 542 cathodic protection stations; their number increased to 750 in 1940 and there are over 1000 at present.

The rapidly expanding application of cathodic protection is due to its high performance, simplicity and low cost. If correctly applied, cathodic protection not only prevents the initiation of corrosion but also arrests the process of disruption of already affected pipelines.

An example of the effect of cathodic protection on an extensive urban network is shown in Fig. 2.

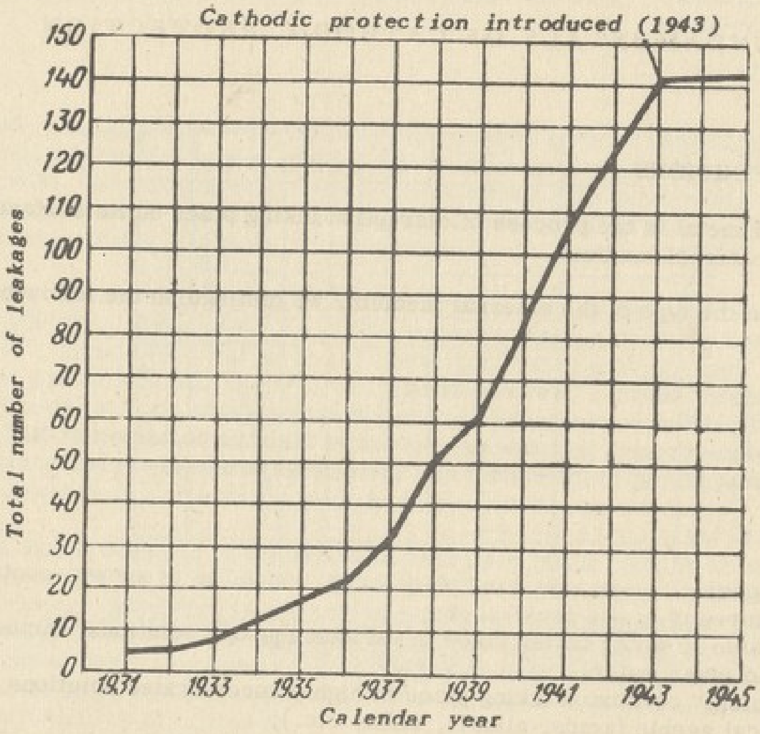


Fig. 2. Number of perforations on urban gas mains before and after introducing cathodic protection.

It is emphasized that not a single case is known where correctly applied cathodic protection failed to arrest disruption and protect the pipelines. Because of the low cost, simplicity and convenience, this method provides in many instances the only effective tool for fighting underground corrosion.

Chapter I

FUNDAMENTALS OF CATHODIC PROTECTION

CORROSION DEFINITIONS

Corrosion of metal is the process of disruption taking place on its surface through the action of an external medium.

Depending on the type of the external medium, we distinguish the following types of corrosion:

1. Corrosion in Non-electrolytes
   - (a) Corrosion of metal in gases or vapours at high temperatures ("gas" corrosion);
   - (b) Corrosion in non-electrolytic fluid (petroleum products, spirits, etc.)
2. Corrosion in electrolytes
   - (a) Atmospheric corrosion taking place in air which, as is known, contains admixtures of gases and vapours;
   - (b) Corrosion in water taking place in various aqueous solutions, including sea and river water;
   - (c) "Chemical" corrosion taking place in highly concentrated solutions of chemical agents (acids, alkalis, salts, etc.);
   - (d) Ground corrosion, taking place in soils of various types and compositions.
3. Corrosion due to stray currents

Soil corrosion and corrosion due to stray currents are denoted as "underground corrosion".

In this book, the problems of electrical protection of metallic pipelines and storage tanks against underground corrosion are investigated.

TYPES OF CORROSION

The corrosion of the metal can be (see Fig. 3):

Uniform, whereby the entire or almost the entire surface of the metal is affected, but in most cases only to a small depth (Fig. 3a);

Local, whereby the corrosion is distributed in patches and the attack is also not deep (Fig. 3b);

Point corrosion, or corrosion pits, whereby the attack is concentrated on a small area usually of the order of a few square cms. Although the area of attack is small, the rate of penetration is greatest. This type of corrosion is the most frequent in structures laid underground and represents a danger to the metallic pipelines and tanks which are intended for transportation or storage of petroleum (oil), petrol (gasoline), water, gases, and so on;

Selective (extractive) corrosion, whereby one component of the alloy is predominantly affected by the disruptive process (Fig. 3B); "c"

Inter-crystalline corrosion, whereby the metal is disrupted along the grain boundaries of the individual crystals (Fig. 3c); "d"

CORROSION MEASUREMENT

Uniform and localised corrosion is expressed in loss of weight of the metal part per unit of surface area corroded per hour, day or year (g/cm^2). Localised corrosion is thereby calculated only for the affected area.

If pits are caused by the corrosion, the corrosion intensity is determined by the depth of these pits and measured in mm/year. A favourable factor in the formation of corrosion pits is the fact that the process slows down with time. Fig. 4, shows curves of the speed of formation of pits in various soils. It can be seen that the curves are parabola-shaped and tend to become parallel to the abscissa; i. e., the speed of deepening of the pits slows down with the progress of time.

Nature of soil corrosion.

Soil corrosion is due to the interaction of the soil electrolyte and the metal.

According to theory, every metal placed in an electrolyte has the tendency to emit in the solution surrounding it positively charged ions from its crystal lattice. This tendency is denoted as solution pressure P. The osmotic pressure of the solution, p, acts in a direction opposite to that of the solution pressure of the metal. Three cases of interaction of these factors are possible:

If $P > p$, positively charged ions pass from the metal into the solution, but remain near to its surface, due to electrostatic attraction, by the negatively charged electrons which remain on the metal. Thus, the metal surface is negatively charged due to the remaining negatively charged electrons, and the solution in the neighbourhood of the metal is positively charged due to the ions which moved there from the metal (Fig. 5a);

If $P < p$, the metal surface becomes positively charged due to the separating out on its surface of positively charged ions from the surrounding solution. The necessary electrical equilibrium is thereby maintained by collection of negatively charged ions of

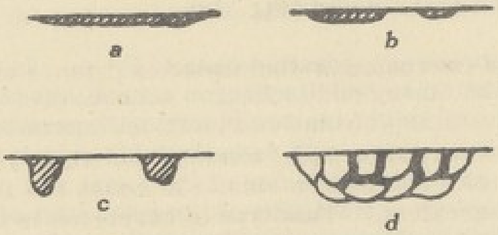


Fig. 3. Various types of corrosion damage.

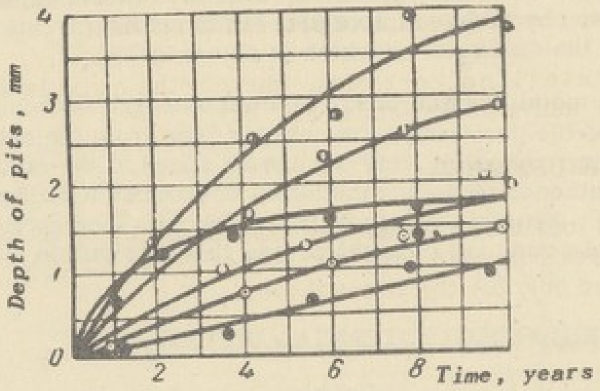


Fig. 4. Speed of formation of pits in various soils.

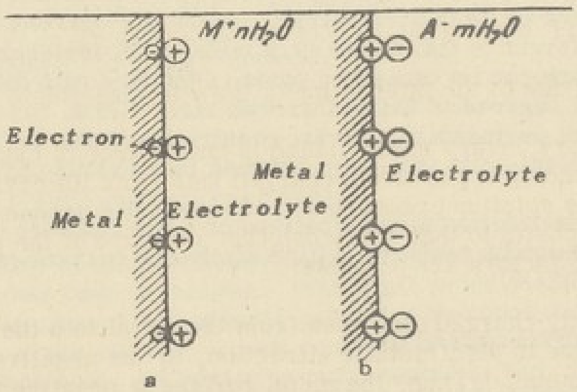


Fig. 5. Formation of a double electric layer at the metal surface

a - if the metal ion passes from the metal into the solution;

b - if the ions pass from the solution into the metal.

the solution near the surface of the metal (Fig. 5b).

Finally, there is the theoretically possible case of P = p. In this case, ions will not pass from one medium into the other and discharges cannot take place. Owing to the strong connection (mutual attraction) of the two electrical layers with charges, of opposite polarity, the electrical system will remain stable only if it is not disrupted by an external cause; then no noticeable corrosion of the metal will occur. If this double layer is disrupted, for instance by combination of liberated ions of the solution, the corrosion of the metal will continue as soon as the electrons liberated at the metal surface begin to flow from the inside of the (metal) part to its surface where there is an excess of positive charges. Thus, electricity will flow in a circuit comprising the surface of the metal and the adjacent electrolyte, forming a galvanic cell. Such a cell is schematically represented in Fig. 6. If there is a double layer of electric charges on the metal surface, the change of potential in the closed circuit is not continuous (represents a jump) the character of which is shown in Fig. 7.

The part of the metal surface where electric charges flow into the electrolyte is denoted as anode and the part where the charges flow from the electrolyte into the metal is denoted as cathode. Usually, only the anodic zones of the metal are endangered by corrosion; in the cathodic zones accumulation of corrosion products takes place without affecting the metal. A metal surface immersed in an electrolyte is covered by a large number of such local cells, the dimensions and the distribution of which do not remain constant.

CAUSES OF OCCURRENCE OF POTENTIAL DIFFERENCES

Potential differences between individual parts of the same metal are due to various factors. It may, for instance, occur between parts which are mechanically stressed and those which are stress free.

Potential differences may also be caused by differences in the composition of the electrolyte and differences in its concentration. Scale and corrosion products (rust) also have a potential different to that of the pure metal. Considerable potential differences on the metal surface can be caused by parts of the soil with different degrees of aeration, i. e., different degrees of saturation with air. Thus, for instance, lime and sandy soils have different permeability for air penetration to the surface of the buried pipeline, and therefore local cells will form between the various parts of the pipeline.

An example of the distribution along pipelines of large cathodic sections, into which current flows, and large anodic sections, which discharge current causing corrosion of the metal, is shown in Fig. 8.

POLARISATION AND DEPOLARISATION

Investigations have shown that the initial potential difference of a local cell almost always decreases rapidly. This is due to polarisation resulting from the current flow in the circuit of the local cell. This phenomenon occurs both near the surface of the anode and the surface of the cathode. In the first case, the polarisation is called anodic polarisation, whilst in the second case it is called cathodic polarisation.

Anodic polarisation is due to increase of the concentration of the dissolved metal near the anode, whereby the potential of the latter is increased towards the positive.

Cathodic polarisation increases the negative potential of the cathode and is due to the accumulation of electrons moving from the anodic parts and the formation of hydrogen.

Depolarisation, i. e., neutralisation of polarisation, is indispensable for maintaining the process of corrosion. Depolarisation can occur in two ways: the formed hydrogen combines with available oxygen or separates out from the surface in gaseous form. Change of the anode and cathode potentials of a local cell as a function of polarisation is shown in Fig. 9, and it can be seen that the cathodic polarisation is the more important one, influencing most markedly the change of potential difference of the local cell.

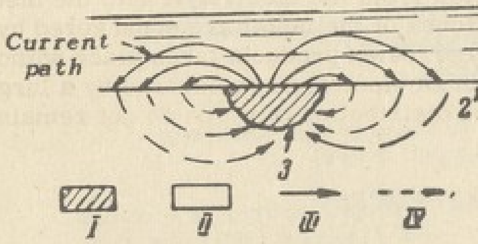


Fig. 6. Diagram of a local couple.

1 - electrolyte; 2 - metal surface; 3 - inclusion in the metal.

I - anode; II - cathode; III - direction of current flow in the electrolyte; IV - direction of current flow in the metal.

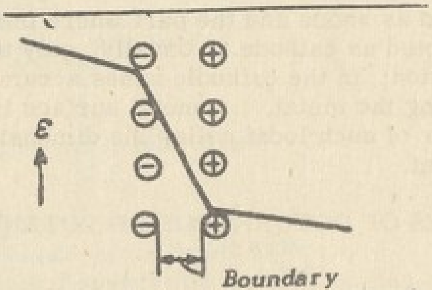


Fig. 7. Jump in the potential at the metal surface.

FUNDAMENTALS OF CATHODIC PROTECTION

On the basis of study of the previously described corrosion phenomena, a method of cathodic protection has been developed. The basic principle of this is to make the entire surface of the equipment cathodically protected by connecting it to a d. c. source. In this case the anode of the electric circuit consists of a specially earthed electrode. The basic principle of cathodic protection is represented in Fig. 10. The current from the positive pole of the d. c. source 1 flows through conductor 2 into the earthed anode 3 and thence into the soil. From the soil the current flows to spots of the piping to be protected where the insulation is defective 4 and flows on along the piping to the drainage junction point 6, the conductor 7 and back to the negative terminal of the current source. Thus, the entire surface of the underground equipment becomes cathodic and is protected from corrosion. The earthed anode, however, becomes corroded. Usually it is made of scrap metal, e. g., old tubes, rails, etc.

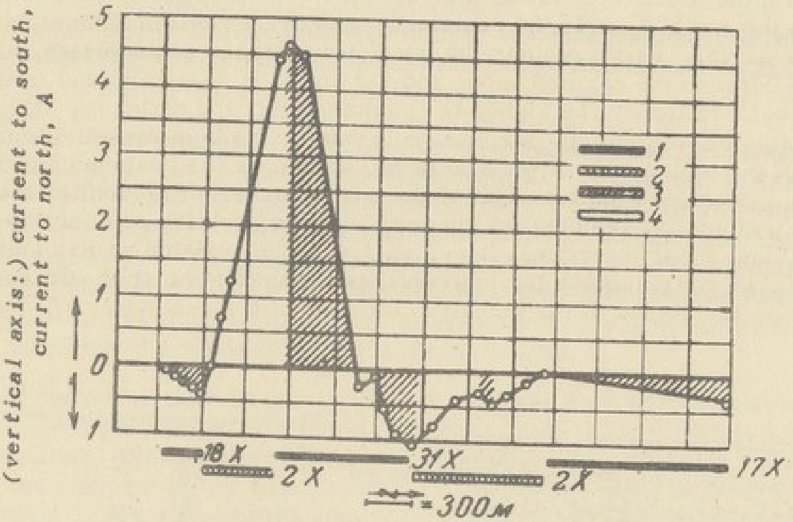


Fig.8. Relation between the discharge current and the damaged zones.

1 - zones with a large number of damaged spots; 2 - zones with hardly any damaged spots; the figures indicate the number of damaged spots; 3 - current discharge from the piping; 4 - current discharge into the piping.

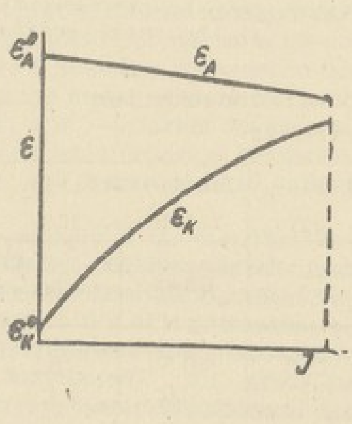


Fig.9. Change of the potentials of the anode and cathode as a result of polarisation.

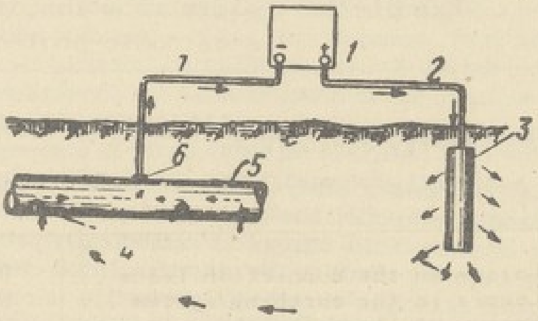


Fig.10. Basic outline of a cathodic protection system.

The basic electrical circuit of cathodic protection is shown in Fig. 11. The source 1 supplies at the terminals a d. c. voltage, E, required for protecting a given section of the piping. From the positive terminal the current flows through the lead of the resistance R_1 to the earthed anode the resistance of which is R_2 (including the contact resistance anode-earth); R_3 represents the contact resistance earth-piping. The earth resistance between the earthed anode and the piping is negligible and is therefore not taken into consideration. The higher is resistance R_3, the better the state of the anticorrosive insulation of the pipe line, which is usually made of dielectric material. The resistance of the piping to be protected is R_4, and R_5 is the resistance of the circuit from the point of drainage to the terminal of the d. c. source. Frequently, the total resistance from the positive terminal of the source to the earthing point and from the drainage point to the negative terminal (i. e., R_1 and R_5) is denoted by R_1, and R_3 includes the resistance R_4. Since the individual sections of the circuit are connected in series, the total resistance of the circuit is the sum of the resistances of its individual parts.

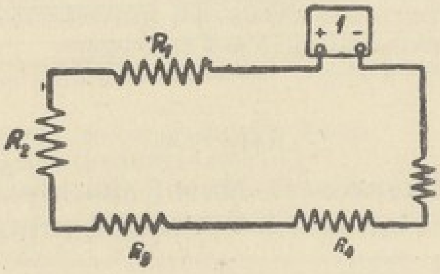


Fig. 11. Circuit diagram of a cathodic protection system.

Table 1.

Example of the distribution of the power consumption in a cathodic protection circuit

Energy consumption	1st installation 0.8 Ohms, 32V		2nd installation 2.7 Ohms, 108V	
	Ohms	%	Ohms	%
Losses in the connection leads ..	0,1	12,5	0,5	18,5
Losses in the earthing system ...	0.5	62,5	2,0	74,0
Energy utilised for the protection of the pipeline	0,2	25,0	0,2	7,5
Total . . .	0.8	100,0	2,7	100,0

Table 1 gives an idea of the numerical values of the resistances of individual sections of a protection circuit; the values are those of two typical cathodic protection installations. It can be seen from this table that the earthing resistance is the most important one, representing 60 to 80% of the total resistance of the circuit. The resistance of the connecting leads amounts to 10 to 20% of the total resistance and only a small part, amounting in most cases to only 5 to 10%, represents the resistance of the proper "protection" part of the circuit.

The energy losses in the circuit are directly proportional to the resistances and the major part of the losses is in the earthing section.

The energy consumption for cathodic protection is basically determined by the state of the protective coating, i. e., by its conductivity, which is the reciprocal value of the resistance:

$$g = \frac{1}{\varrho} \, . \qquad (2)$$

The basic unit of conductivity is the Siemens (S); smaller units are the millisiemens and the microsiemens. Earlier the Siemens unit was referred to as mho and correspondingly the smaller units used were millimho and micromho.

Table 2.

Influence of the conductivity of the pipe coating on the energy required for cathodic protection

Conductivity of the coating Microsiemens m^2	Current A	Voltage V	Power W
10	0,5	0,8	0,4
100	1,8	2,15	3,9
1 000	8,70	9,20	80,0
10 000	102,8	105,0	10 800,0

The conductivity of the protective coating has a direct influence on the length of the protected section. If the protective coating is in good condition a length of 15 km of pipeline can be protected by a total of 0. 05 kW, whilst if the protective coating is extensively broken down a ten times larger amount of electrical energy (0. 5 kW) will protect only a 1. 7 section of the pipe line.

Pipe lines which have no insulated coating whatever can also be cathodically protected, but in this case each protected section of the piping can only have a length of 300 to 400 m if the tubing has a diameter of 8 to 10".

The influence of the conductivity of the coating of the piping to be protected on the required power for cathodic protection is given in Table 2; it can be seen from this table how rapidly the required power increases with increasing conductivity of the coating.

In addition to pipe lines, any metallic equipment placed in the ground can be protected cathodically, e.g., tanks, metallic supporting structures, masts, cables, etc. However, attention is drawn to the fact that only for structures made of steel is the cathodic method of protection sufficiently tried and reliable. For other metals application of cathodic protection is more complicated. Thus, for instance, cathodic protection of underground equipment made of lead is considerably complicated by the fact that lead does corrode, not only on the anodic surfaces, but also on the cathodic ones. This is obviously due to the formation by the corrosion process of an alkaline film on the cathode, this film having a disruptive effect on the lead.

Application of cathodic protection for cables laid underground causes interference in telephone and telegraph lines in many cases. At present, cathodic protection is most widely used for long distance and urban piping systems and cables, and to a somewhat lesser extent for protection of the bottoms of tanks. Cathodic protection of other equipment made of steel and laid underground is applied relatively rarely.

Cathodic protection can also be applied when the equipment to be protected is situated in sea water, river water, mud, etc.

The practical use of cathodic protection requires solution of the following problems:

(1) carrying out investigations prior to design;
(2) design of cathodic protection system;
(3) construction of cathodic protection installation;
(4) regulation of the installation and electrical metering along the pipe line;
(5) organisation of the operation of the protection installation.

Although good results may be obtained in individual cases without carrying out detailed investigation and design, such a procedure not only reduces the reliability and economy of the protection, but may even bring about an increase of the corrosion in some points of the equipment. It is therefore, essential to carry out all the enumerated steps when cathodic protection is to be applied.

Chapter II

PRELIMINARY INVESTIGATION

DETECTION OF THE SECTIONS REQUIRING CATHODIC PROTECTION

To detect the sections which require additional protection, it is best to determine the corrosive effect of the soil by inspection of equipment which has been in the soil for a long time. This yields the most reliable results but special methods may sometimes be necessary.

At present the corrosive effect of the soil is classified in 5 categories, which are characterized in Table 3. The figures given in Table 3 represent examples of the time until the first perforation occures in a pipe of 12" dia. and a wall thickness of 8 - 10 mm, which is not coated with any protective insulation.

Table 3.

Soil categories classified according to corrosivity

Degree of corrosivity	Service time after which the appearance of corrosion perforations anticipated
Low	Over 25 years
Normal	10—25 »
Over normal	5—10 »
High	3—5 »
Very high	1—3 »

INSPECTION OF THE PIPING

To determine the state of a piping, inspection has to be carried out under certain well-defined conditions so as to obtain sufficiently reliable results. These are:

1. To inspect as large an area of the piping as possible. It would be best to inspect the entire length of the pipeline, but this requires too much excavation work. Therefore, in most cases it is considered satisfactory to inspect the piping at selected places, which are distributed at spacings of 50 to 1000 m from each other. With larger pipe diameters the spacing can be increased up to 2000 m.

2. Equal spacings between the points of excavation.

3. In addition to the excavated points spaced at equal distances from each other along the most characteristic parts of the route, it may be advisable to excavate also at other places namely: waterlogged areas and places where water-level varies on slopes, sections which are near to electrified railway lines, etc. It is however desirable that the total number of the additional excavated spots does not exceed 10% of the number of the "main" spots.

4. In each of these excavated places it is necessary to inspect an equal surface of the pipe; 1 square metre is usually considered sufficient. The tube must be inspected throughout its entire circumference.

5. The results of investigation and evaluation of the state of the tubes are expressed according to a special code which includes a marking system of evaluation of the damage to the metal and the protective coating [13].

If inspection of the pipeline which is in operation is not practicable, or in the case of designing a new pipeline, the corrosive effect of the soil must be determined by applying special methods. There are over 20 such methods; of these, the following are most commonly used: 1) determination of the specific resistance by means of a four-pole testing device, 2) by a two-pole testing device, 3) by the "tube and container" method.

According to the first method the so-called apparent soil resistance is measured by the four-pole test equipment, points AMNB, Fig. 12, [7]. All four electrodes are driven a few centimeters deep into the soil, and they should be distributed along a straight line. The d. c. source 2 feeds current through the outer electrodes A and B into the soil the current intensity being measured by a recording device 1. The potential difference between two points is measured by means of a potentiometer and the inner electrodes M and N; these two points must be within the zone of the generated electric field. The apparent resistance of the soil is then determined by using a special formula.

Determination of the specific resistance by means of a two-pole device [12] permits direct determination of the soil resistance along the trajectory of the pipeline at the depth at which it is laid. The measurements are carried out as shown in Fig. 13.

Two poles made of oakwood and fitted with steel tips are interconnected through a 3V

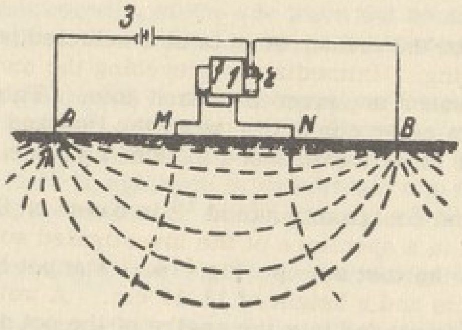
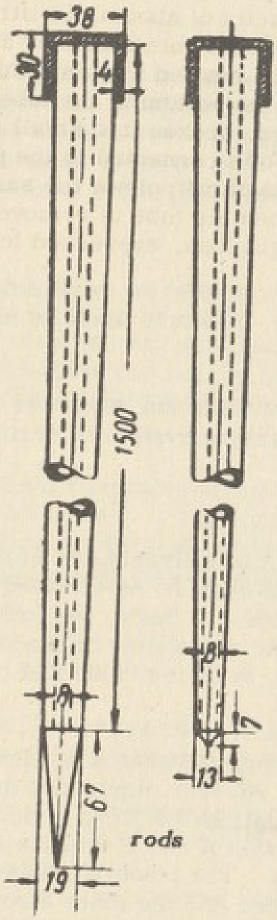


Fig. 12. Schematic representation of the determination of the apparent soil resistance by the 4-pole method.

1 - milliammeter; 2 - potentiometer; 3 - battery.



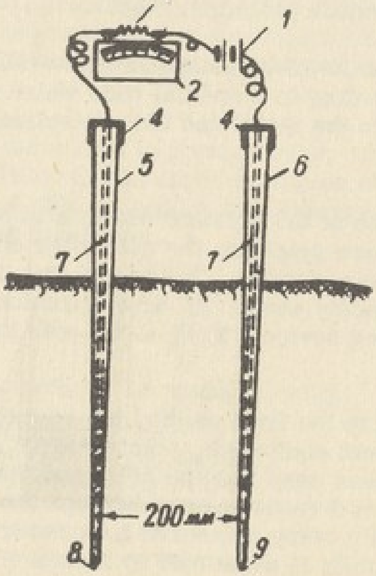


Fig. 13. Determination of the soil corrosivity by the two-electrode method.

1 - dry battery of 3V; 2 - milliammeter; 3 - shunt resistance; 4 - steel caps on the rod tops; 5 - cathode rod; 6 - anode rod; 7 - steel cores; 8 - cathode; 9 - anode.

d.c. current source (dry batteries) 1 and a milliammeter 2. The dimensions are shown in Fig. 13. The tip of the cathode pole has a considerably larger surface than the other pole to reduce the influence of polarisation.

To carry out the measurements at a selected point two holes are dug manually to the depth of the piping. Immediately preceding the measurements 50 cubic cms of distilled or well boiled water is poured into each hole. Then, the rods are driven into the holes so as to obtain a close contact between the tips and the soil. The resistance values in this method are mostly expressed in Ohm/cm, i.e., a unit 100 times smaller than Ohm/m.

The tube and container method[14] is based on the determination of the weight loss of the tube placed in a specimen of the investigated soil whereby a direct current is made to flow through the test set up, Fig. 14. The pot has a capacity of about 0.55 litre, a diameter of 8 cm and a height of 11-12 cm. A weighed tube of 19 mm diameter and 100 mm height is placed into the centre of the pot and made to rest on a 10 mm thick piece of rubber so as to obtain electrical insulation between the bottom of the tube and the pot. The pot is then filled with soil which has been dried, broken into small pieces and saturated with aerated distilled water. Then, the tube is connected to the positive pole of a 6 volt d.c. source and the pot is connected to the negative pole of the same source. The current flow is maintained for 24 hours and then the tube is removed, cleaned of corrosion products and weighed again. The weight loss, expressed in grammes, is indicative of the corrosive effect of the soil.

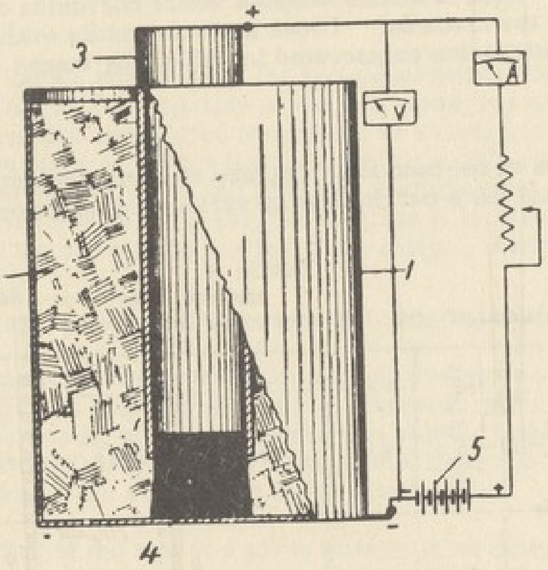


Fig. 14. Determination of the corrosive effect of soil by the tube and container method.

1 - 0.5 litre tin container; 2 - investigated soil; 3 - $\frac{3}{4}$" tube; 4 - rubber piece; 5 - 6 V battery.

These three methods have the following properties which determine their range of application.

The four point (pole) method does not require any digging work, since the tests are carried out directly at the soil surface, but necessitates special and expensive metering instruments of high accuracy and highly qualified personnel. Therefore this method can only be recommended in the case of long pipe lines, and where the necessary test apparatus is available.

The two point (pole) method necessitates drilling or digging holes in the ground, but the design of the required test apparatus is simple, and the test can be carried out by primitive means.

The method of "tube and pot" requires soil specimens to be taken from the depth at which the tubes are laid, which introduces a complication. However, the test arrangement is composed of very simple parts which are easily available anywhere and therefore this method is very convenient if it is necessary to carry out tests quickly on the corrosive effect of soils. This method can also be used as a check of results obtained by other methods of investigation.

It is worth noting that the foregoing methods of determination of the corrosive effect of the soil yield results of an accuracy of 80-90%, i. e., 80 to 90 of 100 test points will yield correct results. Such detection of spots where corrosion danger exist fully justifies application of the methods. These methods enable evaluation of the corrosivity of soils according to categories enumerated in Table 3 by means of the figures given in Table 4.

The limiting values of the individual degrees of corrosive action given in Table 4 are derived from special tests carried out by various investigators.

Table 4.

Evaluation of the corrosive effect of soil

Method of determination	Dimensions	Degree of corrosivity				
		Low	Normal	Over normal	High	Very high
Four-pole test equipment	Ohm m	Over 100	20—100	10—20	5—10	0—5
Two-pole test equipment	Ohm cm	Over 10 000	2 000—10 000	1 000—2 000	500—1 000	0—500
Tube and container method	g	Below 1	1—2	2—3	3—6	Over 6

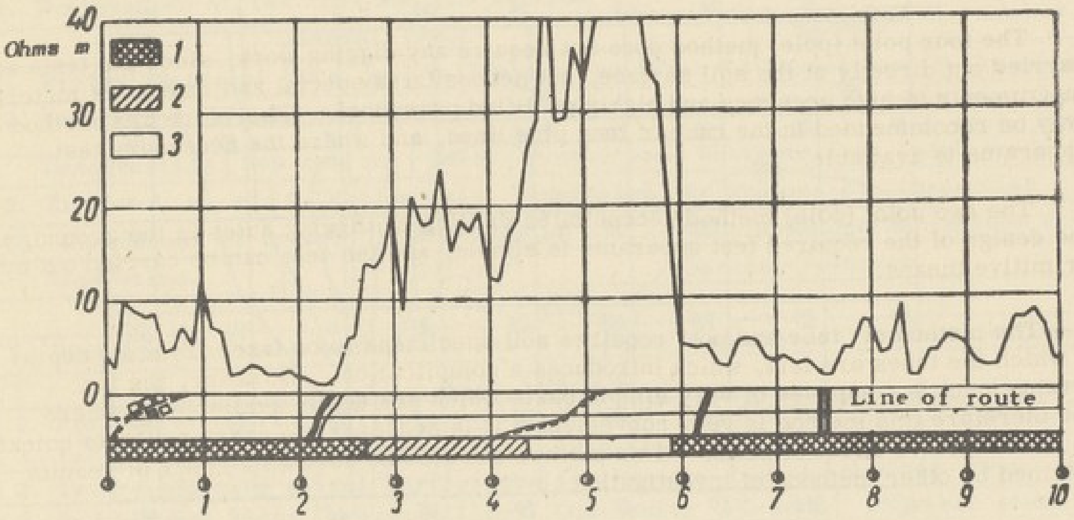


Fig. 15. Soil resistance along the pipeline route.

1 - very high corrosivity; 2 - increased corrosivity;
3 - normal corrosivity.

On the basis of the values obtained for the individual points the corrosive effect of each section is determined and appropriate protection measures are taken. For this purpose the measured results are plotted on a graph as shown in Fig. 15. The abscissa shows the location of the spots along the line; the ordinate axis represents the measured soil resistance values as derived from the first two methods, and the measured weight loss according to the third method. Below the abscissa it is convenient to show the (geographic) location of the spots along the pipe trajectory. Recommended scale:

abscissa: 1 cm per 2 km;
ordinate: 1 cm per 2 Ohm/m = 200 Ohm/cm = $\frac{1}{2}$ G

The test results on the corrosive effect of the soil are more accurate the smaller the distance between adjacent measuring points. However, since the amount of test work increases with decreasing distance between test points, tests are usually made at intervals of 100 metres in mains outside towns and at intervals of 50 metres in towns, where the characteristics of the soil change more quickly.

If the corrosive effect of the soil of a given area is to be determined, measurements are carried out on squares at the sides in accordance with the above indicated values. In this case the plan of the surface is drawn in preference to a graph and horizontal lines corresponding to various corrosion effects are entered. Such a plan is shown in Fig. 16.

Cathodic protection is usually applied in the first instance to sections of the soil with high or very high corrosive effects, since in these spots the most rapid disruption due to corrosion will occur.

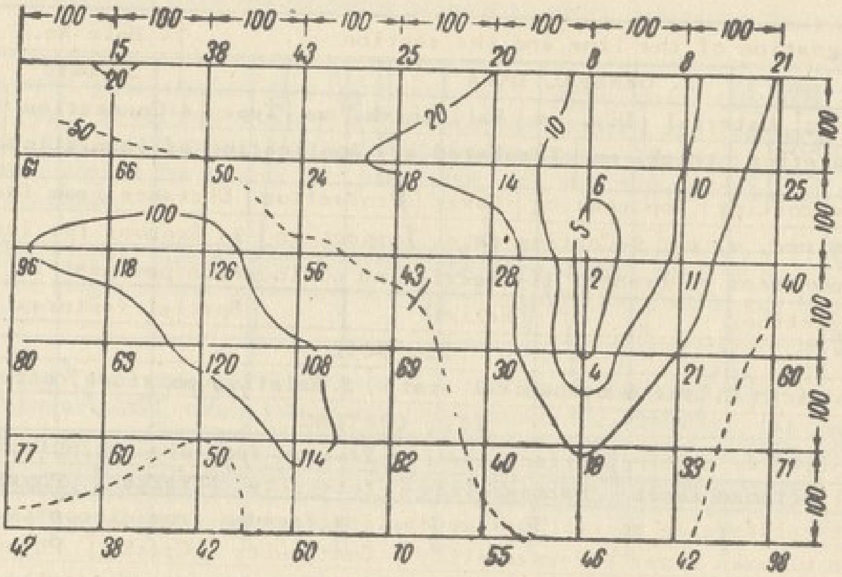


Fig. 16. Equi-resistance lines of a rectangular zone of the soil. The figures indicate the resistance values at the corners of the plotted grid, Ohm m; Equi-resistance Lines (5, 10, 20, 50, 100 Ohms m). Grid dimensions in metres.

If points on the pipe line have already failed by perforation their existence should be carefully recorded amongst the sections which require cathodic protection. These records should be made in accordance with the above mentioned code on a card index; a specimen card is shown in Fig. 17. In addition to recording in a card index, the spots affected by corrosion must also be plotted on a graph. An example is shown in Fig. 18. The sections requiring special protective measures are clearly apparent on such a graph.

After determination of the sections where cathodic protection should be applied it is necessary to obtain information required as a basis for the design of the protection system.

BASIC INFORMATION REQUIRED IN DESIGNING A CATHODIC PROTECTION SYSTEM

The following information must be obtained before designing a cathodic protection system:

(1) plan of the pipe line indicating its total length, tube diameter, wall thickness, material of which the tubes are made, method of joining the tubes, accessories;

(2) plan of the location of the section to be protected, the outline of the pipe-line route, the location of the power supply and earthing points;

(3) data on the soil resistance along the section to be protected and at the earthing

1. Designation of the line and the section					Hole No.	Card number
I. GENERAL DATA					3. Date	
2. Piping	Material	Dia. cm	Wall thick. mm	Type	4-Connection	5-Cleaning
6. Insulation	thick. mm	Insulated at	Application of insulation	7-Uncleaned spot, km+m		
Base coating	Top coating	Cover	Protection	Distance from local anode (m)		
8. Examined, m, m^2	9-Coating date	Inspection	9- Reasons for inspection			
10. Dimensions of trench	11-Description of location:pavement	To railway line,m				
Vegetation,	Relief	Special features				
II. SOIL						
1. District	2.Type & mechanical state	3.Relative moisture content	4.Density			
III. COATING						
1. Protective coating	Surface quality	Freedom from discontinuity	Physical state			
2. 1st bitumen layer	Permeability	Integrity	Cracks	Physical state		
3. 1st reinforcing spiral	Surface quality	Freedom from discontin.	Phys. state			
4. 2nd bitumen layer	Permeability	Continuity	Cracks	Physical state		
5. 2nd reinforcing spiral	Surface quality	Freedom from discontin.	Phys. state			
6. 3rd bitumen layer	Permeability	Continuity	Cracks	Physical state		
7. Adhesion	8.Traces of the coating on the soil	Special features				
IV. PIPELINE						
1. Corrosion: surface %	Colour	Depth of pits, mm - number	Graphitisation			

Fig. 17. Specimen of an index card on an uncovered pipeline.

point. This is most frequently situated near the current source, for instance, in the centre of the section to be protected. The soil resistance along the route is measured at intervals of 100 metres;

(4) data on the conductivity or resistance of the protective insulation on the section to be protected;

(5) information on the presence of current sources near the section to be protected, with data on the parameters and power, if these are applicable for the purpose of cathodic protection;

(6) information on the availability of spaces near the pipe line which are suitable for housing the current supply sources and the controls for cathodic protection;

(7) information on places suitable for erection of wind driven-equipment;

(8) data of availability of wind of various speeds at the points considered suitable for erecting wind-driven generating equipment;

(9) if the cathodic protection is designed for a pipe line which is already in use, data on the state of the pipe line (i.e., operation time of the pipe line, depth of the

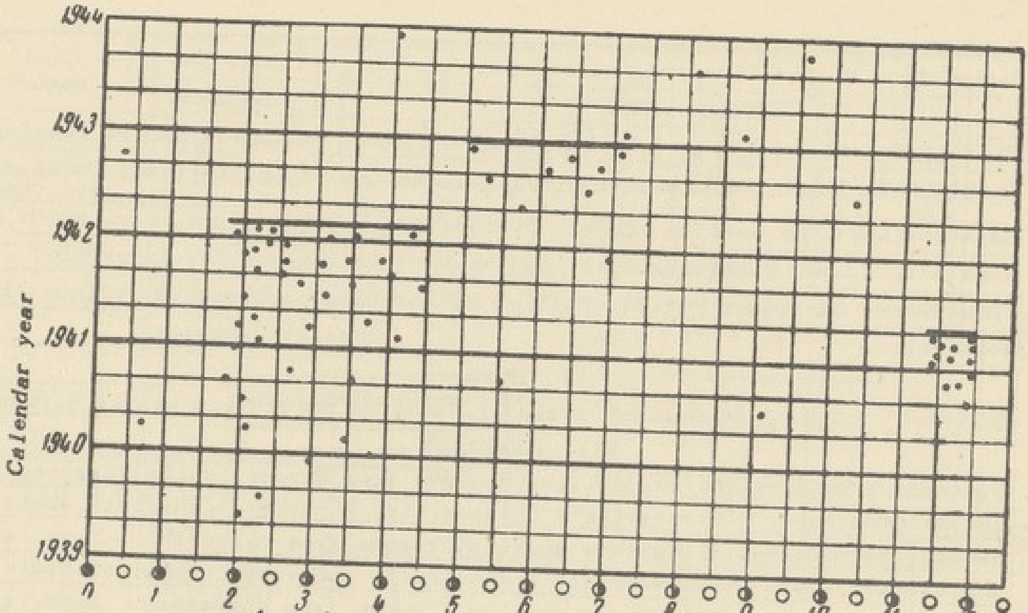


Fig. 18. Graph of the points of penetration of a pipeline.
1 - location of the corroded spots with the date when they were detected; 2 - repaired sections.

deepest corrosion pits, number and distribution of perforations, etc.).

PLAN OF THE LINE

The plan of the line to be protected (Fig. 19) should indicate every branch connection, the location of accessories, their joints (methods of joining), the location of special and threaded sleeve joints and also all points of incidental contact of the line to be protected, and adjacent metallic structures. For pipe lines outside towns preparation of such a plan is considerably simplified. In urban networks and pipe lines near oil storage installations preparation of the required plans is a complicated matter since it is very difficult to determine the necessary data without digging up the pipe lines. In such cases it is advisable to determine the location of the pipe network underground without digging by means of special equipment - tube detectors ^{4}.

The diameter and the wall thickness of the tubes are determined on the basis of technical documents.

The layout plan of the section to be protected is required for the purpose of correct choice of the location of the current source, the anodic earthing and the line equipment.

Data on soil resistance are required for calculation of the design of the anodic

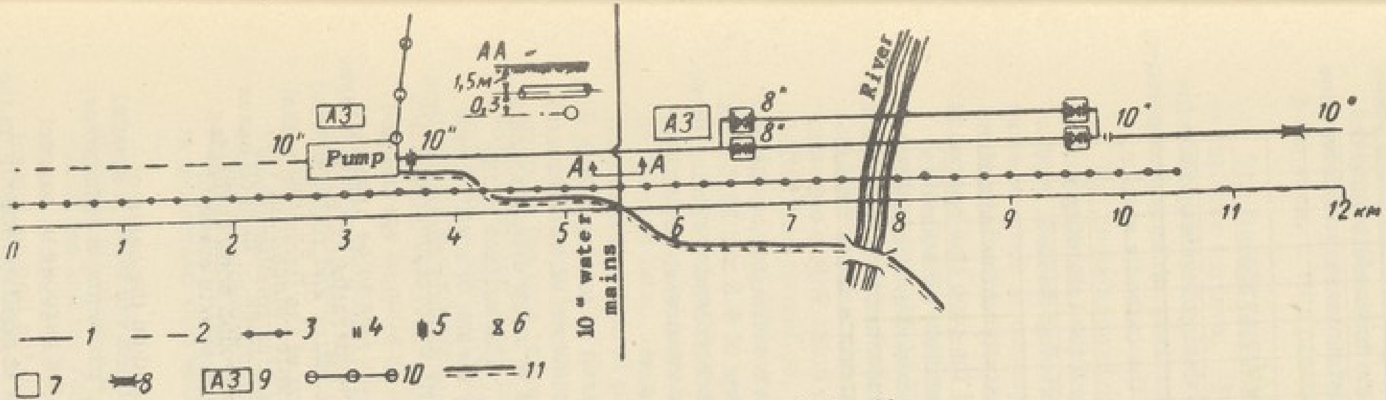


Fig. 19. Layout of a protected pipeline.

1 - pipeline with welded joints; 2 - pipeline with threaded joints; 3 - telephone lines on poles; 4 - flange connections; 5 ; insulating flange; 6 - slide valve; 7 - sump; 8 - insulating sleeve coupling; 9 - anode earthing area; 10 - high voltage line; 11 - country road.

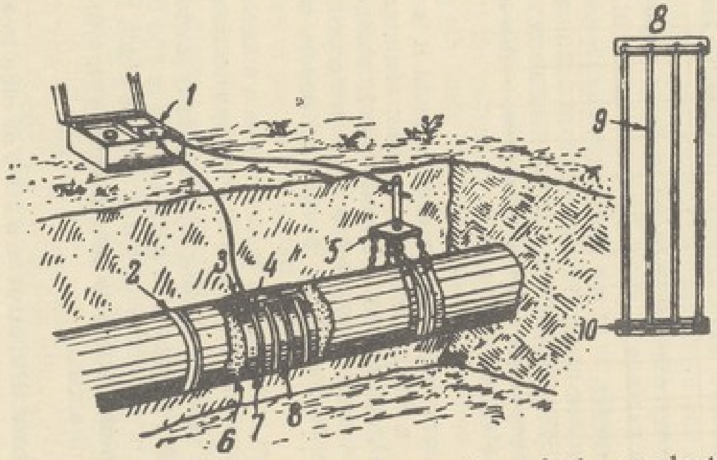


Fig. 20. Schematic representation of metering of the conductivity of the insulation by the "towel" method.

1 - milli and microammeter with baterries, resistances and switches; 2 - cut out strip of the insulation about 5 cm wide; 3 - connection to the pipe; 4 - clamp contacts to the pipe; 5 - connection to the pipe; 6 - clay paste; 7 - flannel soaked in a slat solution covered with grease-proof paper (pergament); 8 - contact saddle; 9 - flexible brass strips; 10 - terminals.

earthing and also for calculation of the required rating of the power source if the piping to be protected is not provided with insulation. If the pipe line is insulated and the sections where there is danger of corrosion are known it is not necessary to determine the soil resistance along the entire route of the pipe line.

DETERMINATION OF THE CONDUCTIVITY OF THE PIPE INSULATION

One of the most important and most laborious operations during investigations for designing cathodic protection is the determination of the conductivity of the pipe insulation. This has to be known for calculation of the required rating of the cathodic station.

The conductivity can be determined by various methods and the following will be described here: towel method, temporary station method, detector method.

The towel method is based on determination of the conductivity of the insulation layer on a surface of about 1 square metre at various spots of the pipe line spaced at equal intervals. At the test points the pipe line must be accessible all round its circumference along a stretch of 2 to 2. 5 metres, which is attained by appropriate digging. The conductivity of the insulation layer is thereby measured by means of a special electrode - a towel electrode. The metering arrangement and the "towel" design are shown in Fig. 20.

For carrying out the measurements it is essential to have a voltmeter, a microammeter, a milliammeter with shunt resistances, dry batteries of 4. 5 and 22. 5 V, a special contact saddle, a flannel towel, contact clamps, connection leads, kaolin, three enameled buckets, 30% solution of acetic acid, 10% solution of ammonia, crystalline potassium ferrocyanide, pergament paper, brushes and sponges.

Before starting the measurements a kaolin paste is prepared by mixing kaolin with water at the weight ratio 1:1. 5 (the paste should have the consistency of thick cream). The water used for mixing with kaolin is made acidic by means of a few drops of acetic acid. The resistance of such a paste is 700 to 1000 Ohm cm. The surface of the insulation is washed with water and the paste is then applied by means of a stiff brush so that it penetrates into places even where the insulation is only slightly damaged, thus displacing the air.

The paste is applied to a strip 30-40 cm wide. On the first layer a second thin layer of paste is deposited. The flannel towel is moistened in acidic water and rolled around the kaolin layer 2 or 3 times. A special saddle is placed on top of the flannel to assist in pressing it tightly on to the tube. This "saddle" consists of four flexible brass strips of a width of 10-12 mm each and a length sufficient to fully envelop the tube, Fig. 20. These strips are electrically interconnected on rigid supports made of bakelite or wood.

To establish the electric circuit between the second contact and the tube, a special screw with a sharp point is used which cuts into the tube metal, providing a satisfactory contact.

If the insulation coating on the tube is new, the kaolin paste is applied directly on the tube surface without any preliminary preparation. If the insulation coating of the investigated tube section is old, the surface has to be cleaned of soil and dirt by brushing and sponging. Then, the surface is carefully wiped and dried. At a distance of at least 15 cm from the edge of the surface prepared for the tests the protective insulation is removed from two circular strips one on either side of the prepared surface of a width of 5 cm each. This prevents leakage through the damp surface of the protective layer.

The flannel pad is moistened with water containing 1% of acetic acid before placing it on the tube surface. For carrying out the measurements a 4. 5 volt battery is used, the positive pole being connected to the threaded screw, the negative to the saddle and flannel contact arrangement.

The resistance of the investigated section of the surface is then determined, from the current intensity (measured by a milliammeter or a microammeter) and the known voltage, according to Ohm's law. Dividing the resistance value by the area of the surface which is covered by the kaolin paste, we obtain the resistance per unit of area of the insulation and the reciprocal value is the conductivity per unit of area.

The "towel" method enables the conductivity of the coating to be obtained at the individual test points. With satisfactory approximation these values can be applied to the entire length of the tested section. However, if this method is applied, particularly defective spots of the pipe line may be overlooked although these will have a considerable influence on the value and distribution of the potential after putting the cathodic protection station into operation. Also, carrying out tests according to this method is fairly laborious and difficult.

A considerably simpler method of determination of the conductivity of the insulation coating is by means of a temporary cathodic station[13] placed at the investigated section of the pipe line. As a d. c. source it is advisable to use a mobile welding set. The temporary station is placed in the centre of the investigated section.

The negative pole of the d. c. generator is connected to the pipe line. For this purpose the pipe is made accessible by digging and the insulation is removed from the metal surface of the tube. It is cleaned by filing to ensure good contact and this is made by a specially designed electrode with a belt which can be tightly fastened on the tube circumference. Contact with the tube can also be made without digging by applying a special electrode, the design of which is shown in Fig. 21. Such an electrode is fitted with a tip made of hardened steel which can cut into the tube metal. During intervals between individual measurements the tip is protected against damage and corrosion by a special rubber cap.

The positive pole of the generator is connected to the temporary earthing electrode, consisting of copper or iron tubing of small diameter and a length of 3-4 metres. The earthing electrode is driven into the ground to a depth of 1-3 m and the surrounding soil is moistened with salt water.

After switching on the current the potential differences "pipe-soil" are measured at equal spacings along the section to be investigated. The spacings depend on the local conditions and the required measuring accuracy; usually, these vary between 50 and 500 m. These measurement are carried out as shown in Fig. 22.

For earthing it is necessary to use non-polarising electrodes, e. g. , copper sulphate, cadmium sulphate or calomel electrodes. The design of the most frequently applied copper sulphate electrode is shown in Fig. 23. A red copper tube is fitted tightly onto

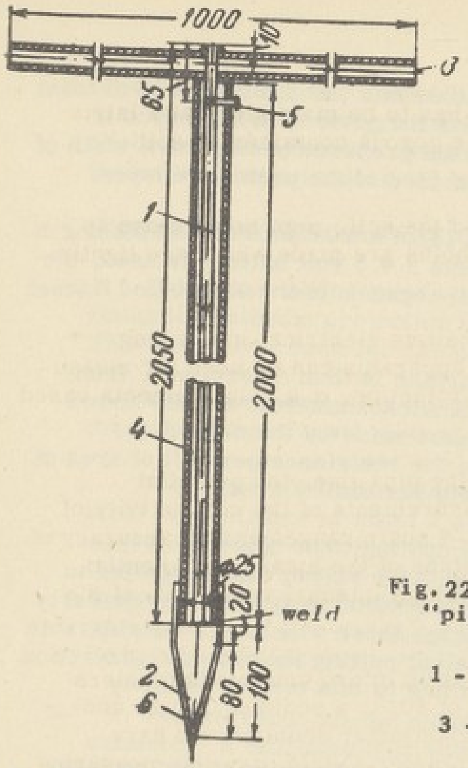


Fig. 21. Electrode for ensuring good contact with the piping.

1 - steel rod of 10 mm dia., 2050 mm length; 2 - steel tip; 3 - handle made of tubing; 4 - bakelite insulating tube 11 to 13 mm inside dia. 2000 mm length; 5 - terminal screw; 6 - rubber protection cap.

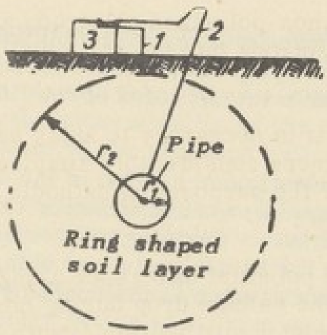


Fig. 22. Measurement of the potential "pipe-earth" using a temporary protection station.

1 - non-polarizing electrode;
2 - steel electrode;
3 - measuring instrument.

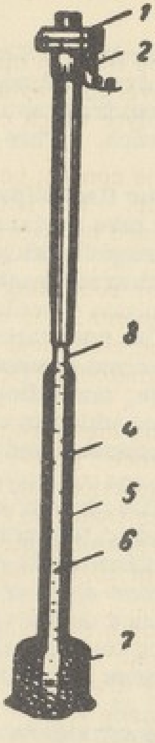


Fig. 23. Non polarising copper-sulphate electrode.

1 - screw; 2 - terminal; 3 - support made of a brass tube; 4 - copper tube; 5 - rubber hose; 6 - copper sulphate; 7 - porous container.

a clay container and is joined to it by any type of chemically inert substance, as for instance, shellac. The copper tube is fitted onto a brass tube which serves as a mounting. The top part of this tube is fitted with a terminal for connection to a conductor and a screw by means of which the electrode can be connected to the measuring instrument.

A saturated solution of chemically pure copper sulphate is poured into the tube and a few crystals of the salt are put into it to maintain the state of saturation. The solution is made up in a glass or porcelain container but not in a metal one. A rubber tube is drawn over the copper tube to insulate the current conducting parts. Thus, the electrode metal does not accidentally touch any soil electrolyte, but is in contact with a salt of the same metal. Therefore, measurements are not affected by external processes. However, a non-polarised electrode itself has a potential difference which must be deducted from the measured potential difference. This potential difference amounts to - 0.55 to 0.6 volts for a copper-sulphate electrode. The exact value of this potential has to be measured for each electrode before starting and after completing the field measurements. Thus, if a potential difference of, for instance, - 1.07 volts has been measured, the real potential difference will be: - 1.07 - (- 0.55) = - 0.52 V, where - 0.55 is the potential difference of the electrode itself.

The fluid in the tube of the non-polarised electrode has to be maintained at a fairly high level to prevent contamination of the fluid inside the porous container by soil electrolyte which could penetrate from the outside.

The contact between the non-polarized electrode and the soil must be as close as possible. For fitting the electrode into the soil small holes are made which are lightly moistened by water.

For recording the EMF it is necessary to apply sensitive electrical measuring instruments. In many instances considerably simpler apparatus can be used for measuring the electrical values for the purposes of cathodic protection, e. g. , instruments based on magnetoelectric principles .

For measurement of the potential difference along the pipe line, the potential difference "pipe-soil", and the voltage drop during measurements of the conductivity of the insulation coating, a precision millivoltmeter with 3-4 scale ranges and an accuracy of not less than 1 mV can be used. Owing to the small values of the measured potential differences the measuring instruments used must have a high internal resistance of the order of 10,000 ohms per volt.

For measuring the conductivity of the insulation coating micro and milliammeters are used. The microammeter must have a sensitivity of 10^{-6}, a scale of 0 to 20 and a scale division representing 4 microamps. The microammeter shunt should have resistance values from 1 to 10,000 ohms. The milliammeter should have the measuring ranges 0 - 5 and 0 - 50 mA and a low internal resistance.

Connection leads used in the metering circuit must have high grade insulation. The characteristics of these conductors are given in Table 5.

From the point of view of measuring accuracy, good contacts at all junction points are very important. The terminals and contacts of the instruments must be very clean and the connection leads must be fitted with special terminals or clips.

Table 5.

Characteristics of (Russian produced) conductors used in cathodic protection systems.

Characteristic of conductor	Type of conductor			
	PUM	PSM	PRGN	sapper
Conductor diameter, mm	6—7	6—7	4—5	6—7
Approximate weight per km, kg	50	60	30	50
Breaking strength, kg/mm^2 (appr.).	70	135	30	50
Resistance, Ohm/km	8	10	20	10
Insulation resistance, Ohm/km	600	600	200	800

The specific resistance of the insulation of a given section can be determined from the measured values by means of formulae given later on.

The conductivity value obtained represents a mean value for the given section. Thus, individual spots where the insulation is heavily damaged may reduce considerably the observed resistance value of a given section although the area of the damaged spots may only be small. It is, therefore, advisable to reduce the lengths of the individual metering sections. The recommended form of the records for entering the measured results is shown in Table 6, and the necessary composition of the investigation team is given in Table 7.

Determination of the conductivity of the insulation by means of a detector is the simplest method available, but it is also highly inaccurate. This method should be applied only if the working conditions are such that the previously described methods cannot be used and also for arriving at preliminary conclusions.

The main purpose of the detector[14] is the detection of damage of the insulation. A schematic representation of such apparatus is shown in Fig. 24. The direct current 6 V source 1 supplies a voltage to the l. v. winding of the coil 2. A voltage of 15,000 to 40,000 V is generated in the winding 3 due to the action of the circuit breaker 6. The negligible h. v. current permits apparatus to be used without danger to the personnel, although the current shocks are quite strong. One pole of the h. v. circuit is connected to the piping by a special contact. This contact can also be established through earth by earthing the pipeline and one pole of the circuit. The second pole of the h. v. circuit is connected to a special brush or electrode, usually ring-shaped. The edge of this electrode is situated 0. 5 - 1 cm from the surface of the piping. If the insulation of the pipeline is undamaged, it will interrupt the h. v. circuit owing to its high resistance and the spark closing the circuit will pass through contacts which are provided on the coil. If the ring passes a spot where the insulation is damaged, however small this damage may be, the high voltage circuit will close through the air gap between the electrode ring and the tube metal, causing a very bright spark accompanied by a loud noise. The direction of the spark indicates accurately the location of the defect. Some detector designs include a bell and a light signal which operates when a defect is detected.

The detector does not directly determine the value of the insulation resistance but permits evaluation of the order of magnitude of this value. For such evaluation which may vary within very wide limits, the information given in Table 8 will be useful.

Information on the presence of current sources near the pipeline route for the purpose of selection of suitable locations of cathodic protection stations. It is most economical to locate the control apparatus and the earthing points as near as possible to the current source so that the required length of the connection lines, fitted on poles or by laying cables, should be as short as possible. It is necessary to state for the available current sources the type of current, the voltage, the total power rating and the available power. The location of the junctions feeding the cathode protection station should be so selected that the control and measuring apparatus and, if necessary, the rectifiers can also be installed there. If there is no suitable room available for fitting this equipment, it is necessary to take into consideration that equipment of a cathodic protection station in which the current is supplied by rectifiers is very compact, and can be quite satisfactorily housed in a small kiosk.

Table 6.

Form of log book for recording the measured values of the conductivity of the coating.

No.	Location of the measuring point km + m	No. of measuring point	Distance from connection point to current sce. km + m	Date of measuring	Potentiometer reading V	Potential of the non-polar. electrode V
1	2	3	4	5	6	7

Voltage "pipe-soil" V	Pipe wall thickness mm	Spacing between individual measuring points, km	Voltage ratio $E_1 : E_2$	$\lg \frac{E_1}{E_2}$	$\left[\lg \frac{E_1}{E_2}\right]^2$	$39200 \frac{T}{L^2}$	$g_1 = 39200 \frac{T}{L^2}\left(\lg \frac{E_1}{E_2}\right)^2$
8	9	10	11	12	13	14	15

Table 7.

Composition of teams for measuring the conductivity of the insulation coating.

Name	Quality
Team leader (engineer)	1
Technicians for metering	2
Mechanic attending the generator .	1
Labourers	4

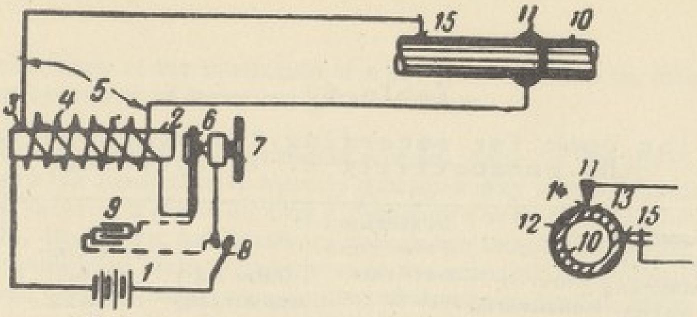


Fig. 24. Electrical circuit of the detector.

1 - 6 V d.c. source; 2 - magnetic core; 3 - l.v. winding; 4 - h.v. winding; 5 - connection leads; 6 - arm of contact breaker; 7 - regulating screw; 8 - closing key; 9 - condenser; 10 - insulated tube; 11 - metallic contact ring; 12 - bitumen insulation; 13 - break in the insulation, i.e., damaged spot; 14 - spark occuring between the tube and the metal ring; 15 - connection of the second pole to the tube.

Table 8.

Characteristics of the state of the insulation coating and its conductivity.

General appearance	Observed damage	Example of the limit values of the conductivity, Microsiemens m^2
Excellent	None	0 – 100
Good	Very slight in single spots	100—400
Satisfactory	Slight, small number	400 – 2 000
Bad	Appreciable, on a large area	2 000—20 000
Very bad	Coating severely damaged	20 000—200 000
Exceedingly damaged	Traces of the coating on the tube	Over 200 000

If wind-driven generators are used for supplying the necessary current, it is essential to collect data on the wind frequency at various wind speeds and suitable locations for erecting wind-driven generators. Wind data can be obtained from meteorological stations and it is important particularly to obtain data on winds with speeds exceeding 4 metres/sec. The location of the wind power station should be chosen so that the wheel of the wind turbine is not shielded by other local structures.

It is essential that earthing should be carried out at a spot where the soil resistance is as low as possible and usually spots with high moisture are satisfactory. Earthing in sandy soil should be avoided. Area dimensions are usually: a rectangle 100 x 20 m. It is desirable to make one or two holes in the selected area for the purpose of determining the geological composition of the soil and the presence of underground water. The desired depth of the holes is 4 to 6 metres.

Collection of the above information should be entrusted to an electrical survey team.

Chapter III

BASIC DATA FOR THE DESIGN OF A CATHODIC PROTECTION INSTALLATION

For calculating a cathodic protection system of a pipe line, knowledge of the following is required:

(1) **route of the pipe line to be protected;**
(2) **its diameter;**
(3) **the wall thickness of the tubes;**
(4) **the conductivity of the insulation;**
(5) **soil resistance;**
(6) **minimum protection voltage and sometimes, instead of this, the minimum current density;**
(7) **maximum protection potential.**

PIPE LINE ROUTE

Usually, the lengths and distribution of the sections subject to the most corrosive conditions and therefore requiring cathodic protection are known. In preliminary calculations, the length of the section to be protected by a single cathodic protection station located in the centre of the section can be assumed as being up to 25 km for a pipe diameter of 10 - 12", if the piping is coated by a high quality composition and 0. 3 km if the pipe line is uncoated. With increasing diameter the protection length decreases and vice versa. However, for several reasons, the length of a section protected by a single station is usually not larger than 25 km, even for small tube diameters.

PIPE DIAMETERS

The most frequently used pipe diameters (in Russia) are: 10-12" for oil and other pipe lines; for long-distance and urban distribution gas mains 12-24"; for water mains, tubes with diameters up to 48" are used.

Wall thickness of the pipes is standardized. Russian produced tubes of 10-12" dia.

have mostly a wall thickness of 8-9 mm. Tubes of 24-48" diameter usually have wall thicknesses of 14-16 mm. Data for the tubes used in the Soviet Union are given in Appendix 2.

The conductivity of the pipe coating represents a very important value for the calculation of the cathodic protection and can vary within very wide limits, namely between 10 and 1,000,000 microsiemens/square meter. If no accurate practical data are available on the value of the conductivity of the pipe coating the values given in Table 8 can be used as reference values. It is, however, necessary to take into consideration the time for which the pipe line has already been in operation and the type of coating. If well applied, any type of bitumen coating has only a low conductivity, not exceeding 400 microsiemens per square metre. However, if application of the coating is not carried out with sufficient care and has not been checked by a detector, the conductivity will be larger. The conductivity of a usual type of coating will in such a case amount to 2000 to 4000 microsiemens/square metre. Badly worn coating which is almost completely disrupted has a conductivity of several hundred thousand microsiemens square metre.

If the coating is severely damaged (or if the piping is not coated) the conductivity is usually so high that instead of this value the conductivity of the soil surrounding the piping is applied in the calculations; this soil conductivity is determined by a special formula given later on.

The soil resistance is determined during the investigations by measurements according to the methods already described.

Minimum protective voltage is the main parameter which ensures reliable protection. It is desirable that the minimum protective potential is determined experimentally in laboratory tests for each type of soil by means of a test arrangement according to Fig. 25 or 26. The steel specimens for these tests should be prepared as follows:

The surface of the steel specimen is ground with emery paper No. 0 or No. 00 and then carefully cleaned; polished specimens may also be used. Degreasing of the surface of the specimens after grinding and polishing is carried out by washing in benzol, acetone or water-free alcohol, or by treating with ether or pure trichlor-ethylene in a Soxhlet apparatus. If the specimens are pickled the pickling residues must be carefully removed from the surface of the specimens. The pickled and washed steel specimens must have clean surfaces completely free from deposit, film, dirt, etc. The cleaned specimens must not be touched by hand.

During voltage measurements a bridge consisting of a glass tube containing a 25% solution of gelatine in a 3% solution of common salt is used as a soil contact of the metallic electrode. Reversible, non-polarising electrodes are used, most frequently calomel ones. . A potentiometer is used as a metering instrument.

The most uniform current distribution over the surface of the specimen, and thus also the most uniform corrosion conditions, are obtained in test arrangements as shown in Fig. 26. Frequently, however, it is not possible to carry out the above tests for determination of the minimum prbtective potential and it is necessary to rely on values published in the literature.

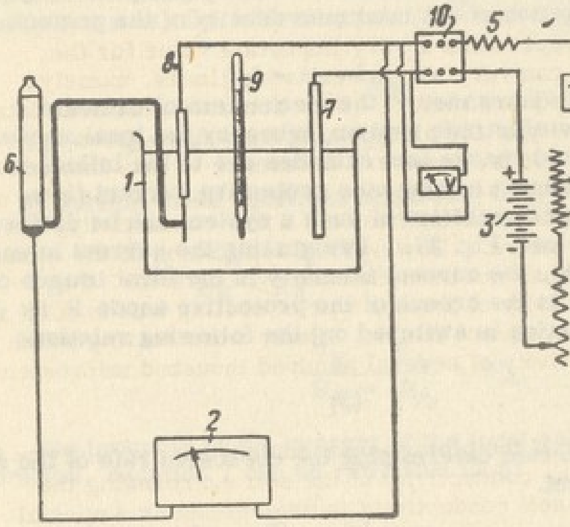


Fig. 25. Arrangement of an experimental set up for the determination of the minimum protection potential.

1 - the active medium in a glass container; 2 - potentiometer; 3 - battery of about 28 V; 4 - regulatihg resistance; 5 - constant resistance; 6 - calomel electrode; 7 - anode column; 8 - cathode wire; 9 - thermometer; 10 - switch; A - milliammeter; V - millivoltmeter.

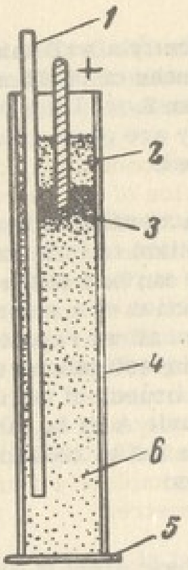


Fig. 26. Arrangement for measuring the minimum protection potential.

1 - glass tube filled with salt gelatine for establishing contact with the soil near the specimen; 2 - loose soil; 3 - carbon anode; 4 - glass tube 2.5 cm dia., 15 cm long; 5 - 2 mm thick steel specimen; 6 - investigated soil.

Although cathodic protection is a relatively recent application, the problem of the minimum protective potential has its history. Although all values in the literature on the subject are within relatively narrow limits (between - 0.1 and - 1.0 V), variation within these limits may involve a change of the current consumption, and thus also of the power rating of the cathodic protection station by 7-8 times.

The opinion that a minimum protective potential of - 0.1 V can be applied was expressed once only, in 1933. Later on there were numerous indications that this potential is insufficient for ensuring protection. In individual cases insufficient potential may have no effect at all on the progress of corrosion.

There were frequent indications of a minimum protective potential of - 0.2 V, but numerous investigations have shown that this value is also insufficient for effective and full protection. In specialized literature on the subject in 1938 the necessity for applying minimum potentials of - 0.24 V and also - 0.3 V, etc. were mentioned. However, all these were purely empirical values.

Dr. N. D. Tomashev 22 worked out in 1940 the theoretical foundations of cathodic protection on the basis of the theory of the multielectrode cell, submitted by correspondent member of the Soviet Academy of Science G. V. Akimov. The principles of this theory are given later on in the investigation of the minimum density of the protection current.

According to the hypothesis of N. D. Tomashev 22 the mechanism of cathodic protection is to be considered as a three electrode system, whereby the local anodes on the surface of the metal to be protected change into cathodes due to the influence of connection of a more negative electrode or by setting up a protective current flow. The mathematical relations of the conditions of operation of such a system can be derived from investigations of a three electrode cell Fig. 27. Designating the current intensity in the branch of the local cathode K by I_K, the current intensity in the local branch of the anode A by I_A, the current intensity in the branch of the protective anode P by I_P, for the initial conditions (until the protection is switched on) the following relation applies:

$$I^o_A = I_A = I_K, \quad \dots \quad \dots \quad \dots \quad (3)$$

where I^o_A is the intensity of the local current determining the corrosion rate of the metal owing to the influence of the local element.

After putting the protection anode into operation the current intensity of the local cathode will be equal to the sum of the currents in the local and the protection anodes, i. e. :

$$I_K = I_P + I_A \quad \dots \quad \dots \quad \dots \quad (4)$$

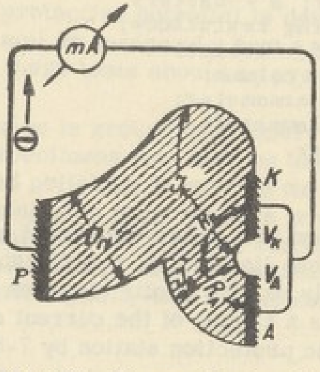


Fig. 27. Three-electrode galvanic cell.

P - protection anode;
A - anodic sections;
K - cathodic sections of the protected surface.

The value I_A is smaller than that of I^o_A which brings about a reduced rate of corrosion. If the value of I_A is reduced to zero, corrosion should stop because the operation of the local cell also stops.

Denoting by R_K the resistance of the cathodic section of the three-electrode element up to the branching off point, R_A the section of the total resistance of the local couple from the branching off point onwards V_A and V_K the effective potentials of the anode and cathode sections, the following relations will apply:

$$I_K = I_P + I_A; \quad \dots \quad \dots \quad \dots \quad (5)$$

$$V_K - V_A = I_K \cdot R_K + I_A \, . R_A; \quad \dots \quad \dots \quad \dots \quad (6)$$

By solving these equations according to I_A we obtain

$$I_A = \frac{(V_K - V_A) - I_P R_K}{R_K + R_A}; \quad \dots \quad \dots \quad \dots \quad (7)$$

Since:
$$\frac{V_K - V_A}{R_K + R_A} = I^o_A,$$

i. e., the intensity of the current of the local cell until the protective current is in operation, equation 7 can be rewritten thus:

$$I_A = I^o_A - b\,I_P; \quad \dots \quad \dots \quad \dots \quad (8)$$

where $b = \dfrac{R_K}{R_K + R_A}$.

It can be seen from equation 8 that the intensity of the protective current is directly dependent on the intensity of the initial current in the local cell. Since the coefficient b characterizes the ratio of the cathode surfaces to the anode ones, it can easily be seen that a reduction of the cathodic surfaces of the local cell relative to its anodic ones brings about an increase of the value R_K and of the coefficient b and results in a reduction of the required applied current.

By inserting $V_T : R_P$ instead of I_P in equation 7, where V_T is the voltage of the protection current and R_P is the resistance between the protective anode and the metallic structure, we obtain:

$$I_A = \frac{(V_K - V_A) - (V_T R_K) : R_P}{R_K + R_A} \quad \dots \quad \dots \quad \dots \quad (9)$$

By analysing equation 9 it is possible to clarify the conditions which bring about a reduction of the value of I_A, i. e., improved protection; it is thereby necessary to take into consideration that since the phenomena can always be investigated for unit dimensions the terms "current intensity" and "current density" will be equivalent in the given case. The following factors will be favourable for the protective action:

1. Reduction of the value $(V_K - V_A)$, i. e., reduction of the potential differences between the cathode and the anode parts of the surface to be protected. This decrease will manifest itself by:

(a) decrease of the potential of the anodic sections;
(b) increase of the negative potential of the cathodic sections, e. g., by reduced access of air oxygen to them.

2. Increase of V_T, i. e., of the voltage of the protection current.

3. Reduction of R_P, i. e., of the resistance between the protective anode and the surfaces to be protected; this reduction can be obtained by increasing the surface of the protective anode, reducing the soil resistance by addition of salt, etc.

4. Increase of R_K, i. e., of the resistance of the local cathode circuits. Practically, this means a reduction of the areas of the local cathodes relative to those of the local anodes.

5. Increase of $(R_K + R_A)$, i. e., increase of the resistance of the local cells on the surface to be protected. This factor is of great importance, since this resistance increases sharply if the surface of the metal to be protected is provided with a coating of a dielectric. This resistance also increases with the formation of protective films on the surface of the metal to be protected, as a result of corrosion processes.

Considering the protection systems as a three-electrode system represents a considerable simplification of the phenomena since it is to be assumed that in a protection system a large number of electrodes are present; however, this does not change the conclusions arrived at by N. D. Tomashev.

The minimum value of the protective potential is at present considered as being $E = -0.288$ V or, in the case of measurements by means of a copper sulphate electrode $E = -0.288 - 0.55 = -0.838$ V. The larger absolute values given by I. N. Frantsevich[25] appear to be too high and due to errors in the applied method and arithmetical errors.

The foregoing theoretically obtained values of the minimum protective potential have been checked experimentally under laboratory conditions and in a large number of practical installations for cathodic protection of underground steel pipe lines. The given minimum value of the potential proved in every case satisfactory to ensure effective protection, although lower voltage values did not always prove sufficient.

Accordingly, the minimum protective potential should be between the limits of -0.28 to -0.30 V -0.288V being the most suitable value.

The protective potential must be kept constant on the structure to be protected. In the first period of application of this method of protection, the assumption was expressed that long interruptions in the operation of this protection are permissible, since polarisation phenomena maintain the potential for a period after the current supply is switched off. However, further investigation of this problem has revealed that the current supply must not be interrupted, since the protective effect of polarisation ceases rapidly. After switching on the current, polarisation increases the value of the potential. The potential does not revert to the initial potential instantaneously after interrupting the current supply, but owing to depolarisation the potential drops slowly and approaches gradually the initial value. The speed of the voltage drop as a function of time from the instant of interruption of the current is given in Fig. 28. According to this graph, the potential drops to a value

Table 9.

Change of the density of the protective current as a function of the moisture content.

Number of the soil	Moisture content %	Density of the protec. current mA/m^2	Potential relative to earth, V
1	10	11,1	0,57
1	15	32.3	0,61
1	20	97	0,66
3	17,7	21,6	0,61
3	31	43,1	0,8
4	17,7	32,3	1,4

below that required for protection within 1.5 to 2 hours after switching off the current supply. It is, therefore, essential that the current supply is continuous and that interruptions do not last longer than 1.5 to 2 hours.

MINIMUM DENSITY OF THE PROTECTIVE CURRENT

Investigations in various types of soil have shown that the values of current density may differ considerably for individual types of soil. Thus, for instance, a current density of 4.65 mA/m^2 was required for a coated pipe line of 22" diameter which has been in operation for ten years. Another pipeline of 14" diameter, with a reinforced bitumen coating and the same duration of service, required about the same current density namely, 4.62 mA/m^2. A line of 8" diameter and a length of 64 km laid in soil of high resistance required only a current density of 0.895 mA/m^2. Another pipe line which had a severely damaged coating required a current density of 48.7 mA/m^2. There was even a case when the required current density amounted to 75.5 - 270 mA/m^2, having a mean value of 160 mA/m^2. Investigations on four different soils showed that the density of the protective current varied, not only with the individual soils but also with the moisture content; this can be seen from Table 9. Utilising the results obtained, Kalman[9] was able to plot a curve giving the density of the protective current as a function of the resistance value of the soil, Fig. 29.

The protective current density values obtained in laboratory and practical tests are given in Tables 10, 11 and 12. During laboratory investigations similar current density values were obtained for electrolytes and soil. In practical investigations, the required density values for the same pipeline fluctuated between 35.5 and 88.2 mA/m^2.

As a result of special investigations carried out on strongly corrosive lime soils a curve has been obtained which expresses the relation between the effectiveness of the cathodic protection and the value of the density of the protection current, Fig. 30.

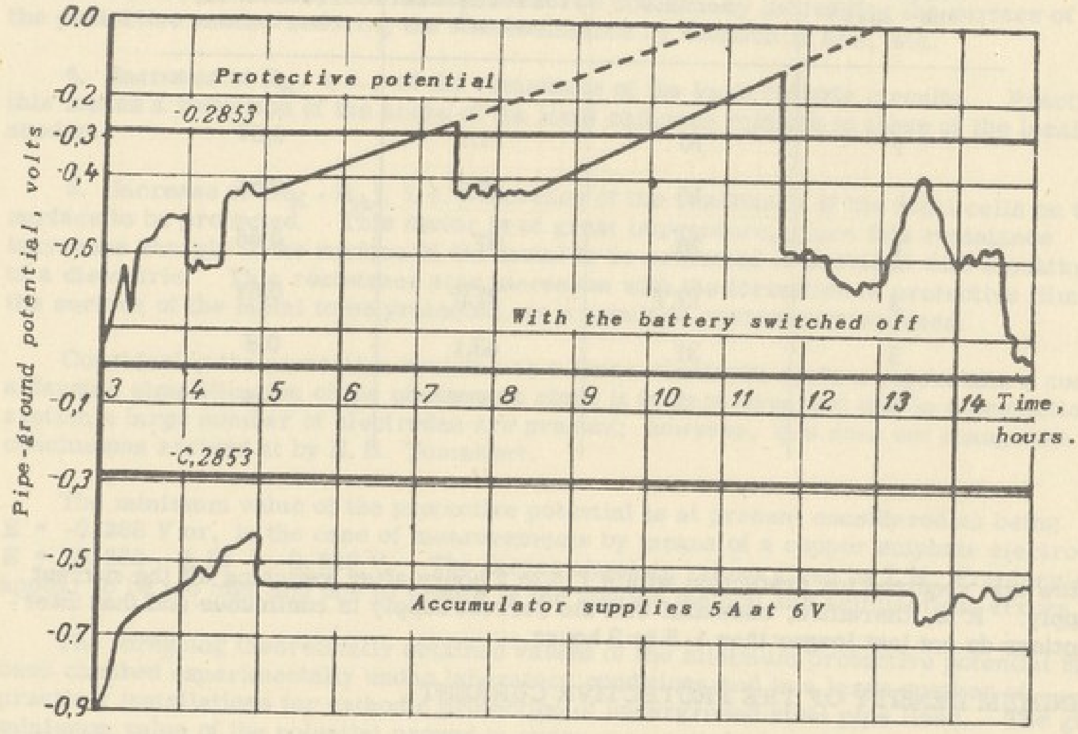


Fig. 28. Change of the pipeline potential as a function of the time after the instant of switching off.

It can be seen from this curve that maximum protection can be obtained by a relatively small change of the current density. Maximum protection was obtained with a current density of 31.0 mA/m^2; a density of 12.4 mA/m^2 provided only 50% protection, although under different conditions this current density is fully satisfactory for full protection. Practical data on the required current densities for pipes with differing state of the insulation are given in Table 13.

There are also other methods for determination of the current density required for protection. Specially plotted graphs showing the interrelation between the intensity of the protective current and the potential of the iron to be protected, obtained by measurements with a copper sulphate electrode are shown in Fig. 31. It can be seen from the graph that if the current decreases from a value which is very ample for protection, initially the absolute value of the potential will decrease. However, this decrease

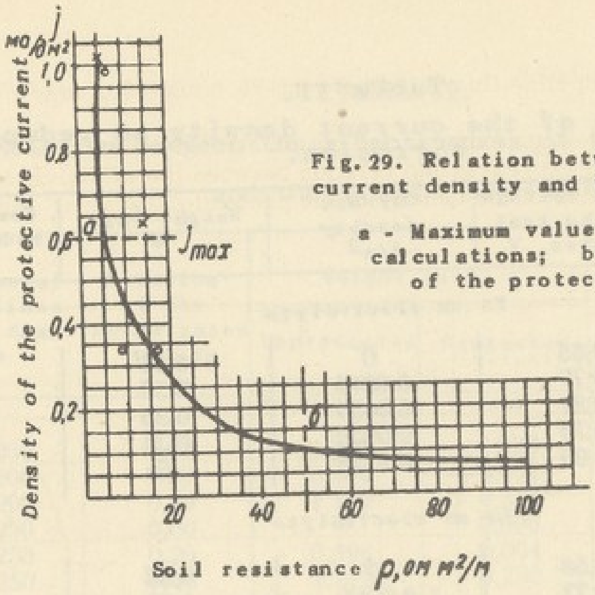


Fig. 29. Relation between the protective current density and the soil resistance

a - Maximum value to be assumed in calculations; b - minimum value of the protective current.

Table 10.

Current density of the cathodic protection current.

Soil moisture %	Density of the prot. current mA/cm^2	Acting time Hours	Weight loss of a specimen with a surface area of 25 cm^2	
			Individual specimen	Mean value
15	nil	500	0,0818 0,0908 0,0722	0,0816
15	0,005	500	0,0080 0,0384 0,0345	not representative 0,0343
15	0,010	500	0,0106 0,0372 0,0048	0,0175
15	0,030	500	'0,0050 0,0020 0,0026	0,0032
15	0,050	500	0,0014 0,0024 0,0026	0,0021
15	0,060	500	0,0006 0,0024 0,0018	0,0016

Table 11.

Influence of the current density on reducing corrosion.

Initial voltage of the test plates, V	Final voltage on the test plates, V	Current density A/m^2	Weight loss g	Corrosion reduced by %
In an electrolyte				
0,65	0,65	0	0,96	0
0,62	0,77	0,0215	0,56	45,8
0,64	0,81	0,0430	0,35	63,5
0,68	0,76	0,0860	0,35	63,5
0,72	1,00	0,1720	0	100
In an electrolyte				
0,58	0,58	0	0,98	0
0,70	0,73	0,0215	0,50	49,0
0,71	0,73	0,0430	0,28	71,5
0,63	0,71	0,0860	0,19	80,5
0,61	0,69	0,1720	0,01	99,0
In the investigated soil				
0,61	1+	0	1,59	0
0,60	1+	0,0215	0,73	54,1
0,61	1+	0,0430	0,47	70,3
0,68	1+	0,0860	0,28	82,4
0,61	1+	0,1720	0,10	93,7

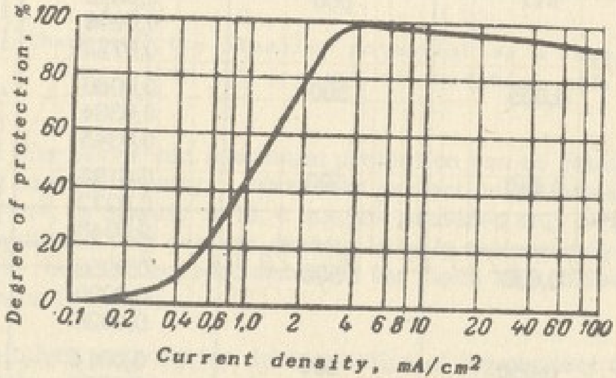


Fig. 30. Relation between corrosion rate and current density (laboratory data).

Table 12.

Relation between the effectiveness of the protection and the current density used

Number of pipelines and dia. mm	Location of the investigated spot, km	Weight loss, g		Protection %	Current density mA/m²
		Unprotected	Protected		
3 – 200	0,00	1,775	0,028	98,4	39,2
3 – 200	0,20	0,382	+0,052	100.0	53,3
3—200	0,40	1.330	0,316	76,2	68,8
1 – 250	0,00	—	0,000	100,0	39,3
1—250	0,20	0,496	0.004	99,0	35,5
1 – 250	0,40	1.289	0,230	82.1	88.2

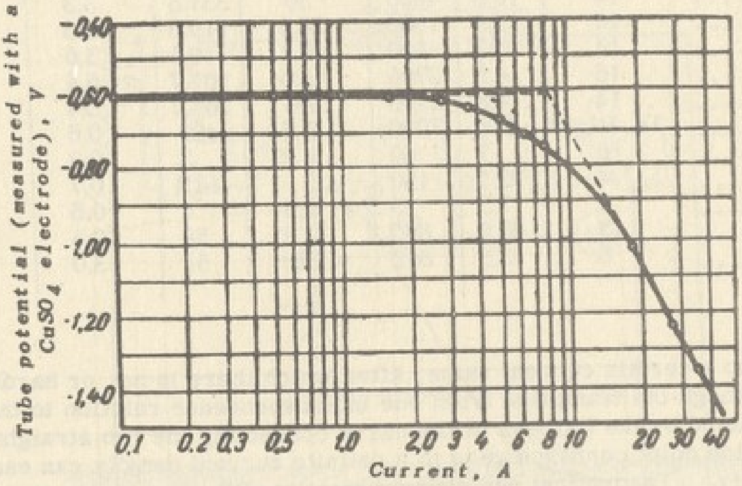


Fig. 31. Current-voltage curve for an arrangement with a 6" pipe.

Table 13.

Practical values of the density of the protection current.

Characteristics of the pipeline			Parameters of the cathodic protection				
			Consumed a. c.		d. c. in the protected system		
State of insulation coating	Outside diameter, inches	Length of the line km	Total V	For 1 km of a 3'' equivalent V	Total A	For 1 km of a 3'' equivalent A	Average value for pipe surface area mA/m^2
Not insulated	$8^5/_8$	7	2815	137	119	9,4	24,4
“	$8^5/_8$	1,9	900	163	60	17,6	45,7
“	$8^5/_8$	33,6	8400	87	724,8	12,1	26,0
“	16	7,7	2880	70	299,1	11,7	30,4
“	18	5	2600	87	197,1	10,6	27,4
“	$8^5/_8$	14,0	3200	80	154,6	6.2	16,2
“	12	3,4	—	—	92,8	15,5	40,1
Bad	14	1,6	230	30,6	29,6	6,3	16,6
Excellent	16	16,0	4800	30	331.5	3,3	8,6
Bad	14	16,0	4800	30	331,5	3,3	8,6
Excellent	16	5,3	1500	28,3	119,5	3.6	9,3
Bad	14	5.3	1500	28.3	119,5	3,6	9,3
Excellent	16	4.8	2700	5.6	161.7	5,4	14,0
Bad	14	4.8	2700	56	161.7	5,4	14,0
Excellent	14, 16, 18	218	7000	5.6	490	0,6	1,5
Good	6	7	60	4.25	3	0,3	0,7
Good	4	22,5	150	5	14,4	0,7	1,8
Excellent	4	7.5	25	2,5	4	0.6	1,5
Good	12	46.0	895	2,2	59	0,5	1,3
Good	6	13.5	812	30	51	3,0	7,8

proceeds only up to a certain current value, after which there is no, or hardly any, change in potential. Although the transition from one interdependence relation to the other is gradual and expressed by the flatness of the curve connecting the two straight lines of the graph, the transition point corresponding to a definite current density can easily be obtained graphically. Theoretical and experimental results have shown that this current density is necessary and sufficient for prevention of corrosion. Curves with a well defined transition point are obtained for soils of low resistance. For high resistance media the shape of the curves obtained is that shown in Fig. 32.

The value of the protective current density for any structure is obtained by a series of measurements providing the data necessary for plotting the curves.

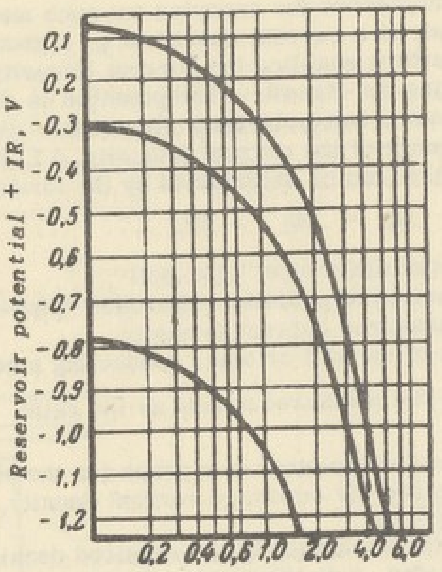


Fig. 32. Curves expressing the relation between the current intensity and the potential of the protected iron in a medium of high resistance.

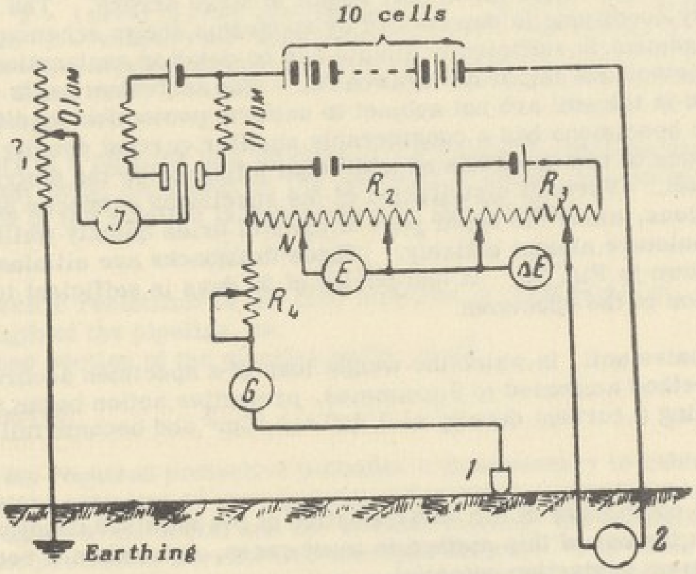


Fig. 33. Arrangement of the measuring circuit in which the voltage drop IR is eliminated from the "current-voltage" readings.
1 - copper sulphate electrode; 2 - pipe.

One of the circuits recommended for carrying out such measurements is shown in Fig. 33. The circuit consists of a current source (e. g. a group of batteries), a rheostat, an ammeter, a changeover switch enabling the current intensity to be varied by for instance, 10% without breaking the circuit. The potential is measured by means of a potentiometer arrangement and a non-polarising electrode. By measuring the voltage change ΔV caused by the change of the current intensity, ΔI, the real potential of the pipeline or another combination can be determined by the formula

$$E_0 = E_1 - IR, \quad \ldots \quad \ldots \quad \ldots \quad (10)$$

where E_0 is the real potential difference "pipe-soil";
E_1 is the initially measured potential difference "pipe-soil";
I is the initially measured current intensity;
R is the resistance of the soil or other conducting medium which is determined from the measured values as the ratio $\frac{\Delta V}{\Delta I}$

The values, of I, E and ΔE are plotted on a graph for the purpose of finding the transition point which determines the minimum current density.

Although this method of determination of the required density of the protective current is somewhat complicated, it is the most accurate one, since the soil resistance is taken into consideration.

Determination of the required current density under laboratory conditions on soil specimens is less accurate, but is in most cases still considerably more accurate than simply applying a mean value which may result in large errors. The current density under laboratory conditions is determined by apparatus shown schematically in Fig. 34. This test arrangement is sufficiently simple and no detailed explanation is necessary. However, the method has important drawbacks. The individual parts of the metal specimen placed in the soil are not subject to uniform protection conditions, for example the inside of the specimens has a considerably smaller current density than the outside. Also, the presence of end faces has an additional influence on the distribution of the protective current. Vertical distribution of the specimens produces non-uniform moisture conditions, since the upper part of the soil dries quickly whilst the lower part conserves its moisture almost entirely. These drawbacks are eliminated in the test arrangement shown in Fig. 35. A test period of 20 days is sufficient to obtain a pronounced corrosion of the specimen.

For a corrosive soil, in which the weight loss of a specimen according to the pipe and container method amounted to 9 grammes, protective action began to be noticeable only after reaching a current density of 0.020 mA/Cm^2 and became fully effective at 0.040 mA/Cm^2.

The relative complexity of the determination of the required density of the protective current prohibits the use of this method in most cases, and makes it necessary to apply instead the minimum protection potential.

In the case of storage tanks and other structures of non-linear shape, it is frequently advisable to carry out the calculations of the cathodic protection on the basis of the protective current density and not the protective potential.

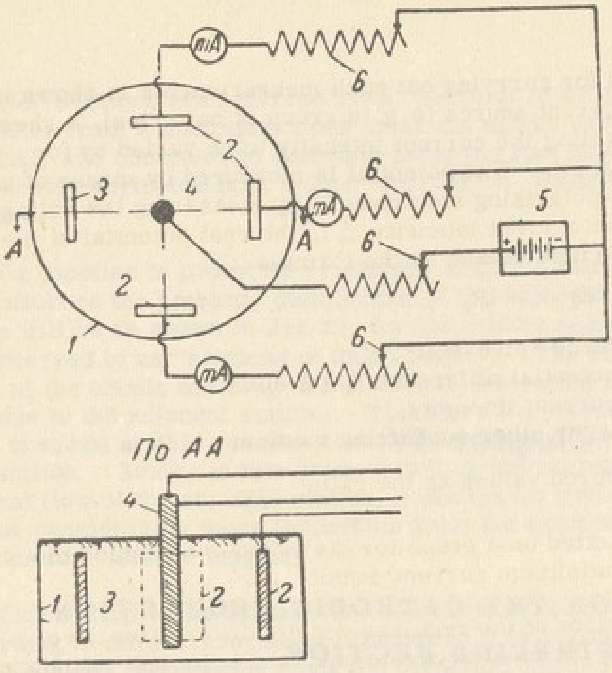


Fig. 34. Installation diagram of the equipment for investigation of the influence of current density on corrosion.

1 - glass container containing the investigated soil; 2 - investigated specimens 125 x 250 mm; 3 - comparison specimen 125 x 250 mm; 4 - anode column; 5 - d.c. source; 6 - regul. resistance; mA - milliammeters.

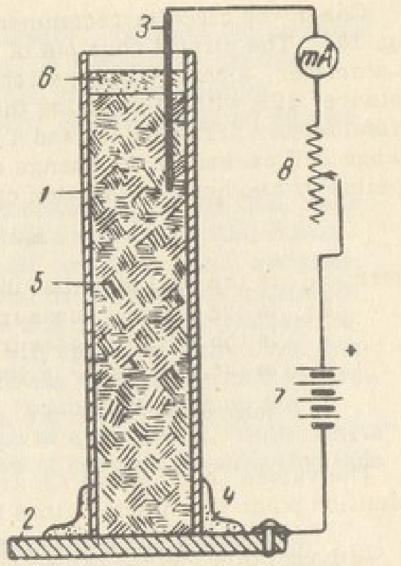


Fig. 35. Test arrangement for determination of the protective current density.

1 - glass tube; 2 - steel plate; 3 - steel rod; 4 - paraffin; 5 - investigated soil; 6 - layer of loose soil; 7 - d.c. source; 8 - regul. resistance.

The conductivity of a pipeline is a function of its linear dimensions and its specific resistance, the latter being dependent on the material of which the pipeline is made. The total resistance of the pipeline is determined by the formula

$$R_T = \frac{\rho \cdot L}{S}, \qquad (11)$$

where ρ is the specific resistance of the tube material in OHM mm^2/m;

L is the length of the pipeline, m;

S is the cross section of the pipeline walls, mm^2.

MAXIMUM POTENTIAL

In addition to the required protective potential it is necessary to calculate also the maximum permissible potential on the pipeline. Too high a potential may bring about a loss of adhesion between the metal and the bitumen coating, the insulation coating will peel off and thus the protective current will increase steeply. The value of the maximum permissible potential has been little investigated up to now. The only data available are those obtained in laboratory tests. Tubes provided with petroleum bitumen and coal pitch coatings showed considerable loss of coating adhesion on the metal of the tubes at the open end after being exposed to the action of a voltage of 1 to 4.3 V during 22-82 days.

Chapter IV

CALCULATION FOR THE CATHODIC PROTECTION OF A PIPELINE SECTION

INTRODUCTORY NOTES ON THE DERIVATION OF THE FORMULAE

Depending on the layout of the object to be protected and the location of the anodic earthing the laws governing the distribution of the protective current along the protected object may differ.

If cathodic protection is provided for a pipeline by one protection station and the section to be protected is not insulated electrically from the remaining part of the pipeline, the potential distribution along the line will be as indicated in Fig. 36. Such

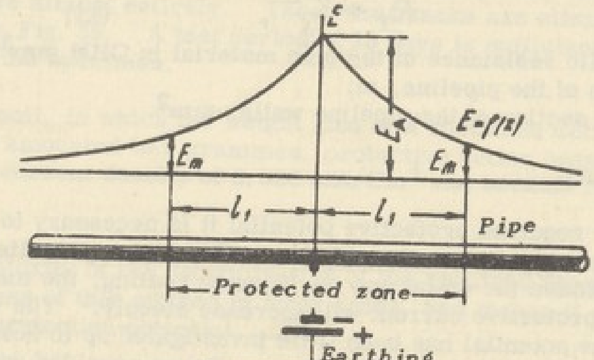


Fig. 36. Distribution of the protective potential along a section of "infinite length"

protected sections are referred to as "sections of infinite length", because the potential decreases from a maximum value (near the anodic earthing) to a minimum protective potential, and continues to decrease along the line outside the protected section approaching asymptotically a zero value which, theoretically, is reached at an infinite distance.

If a pipeline is protected by several stations which are spaced along the line, each will influence the potential distribution of the adjacent section and the potential distribution will be as shown in Fig. 37, for the middle sections BC and CD. Such sections are referred to as "sections of finite length". The potential drops from its maximum value at the anodic earthing to a minimum protection value and there it encounters the flow due to the adjacent station. Therefore the potential will again increase from this point onwards until it reaches a maximum value at the earthing point of the next protection station. Since, in this case, a part of the current is "squeezed" back by the current flow of the adjacent station, a station for protection of a section of "finite length" will be considerably more favourable from the point of view of current consumption than stations for "infinite lengths".

Calculation of the system for the two types of protection has to be carried out according to different formulae, therefore it is necessary to determine the character of the current distribution along the protected section before carrying out the actual calculations of protection systems.

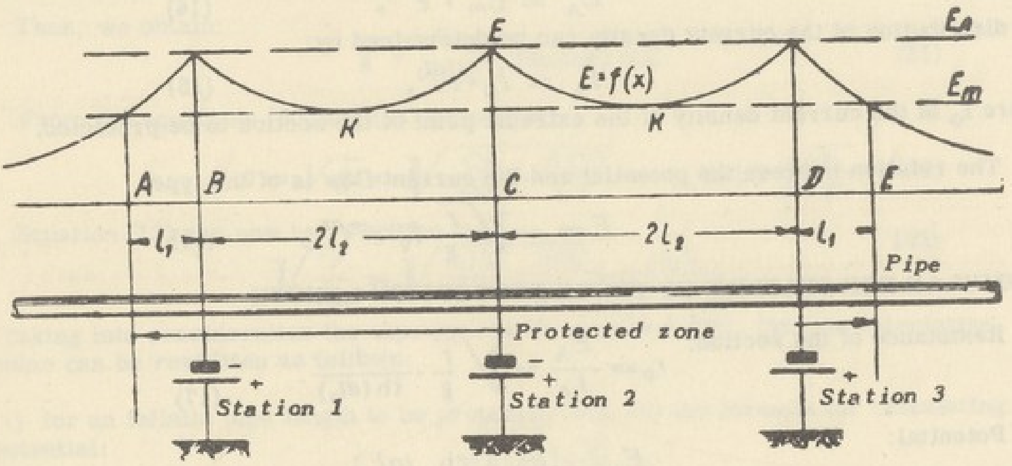


Fig. 37. Distribution of the protective potential along a section of "finite lengths".

In the following, cathodic protection stations for protection of sections of the above mentioned two types will be referred to briefly as "stations of infinite length" and "stations of finite length".

The theoretically derived formulae for calculation of cathodic protection systems are based on the assumption that the pipelines are provided with a coating of high dielectric strength. This corresponds, for instance, to a coating of a bitumen type in undamaged condition.

Taking into consideration that soil which has a corrosive effect also has a low resistance, the soil resistance can be neglected in the derivation of the formula. The derived formula will be less accurate for calculations relating to pipelines which are not coated, or for which the coating is in a bad state. In dealing with such pipelines, additional assumptions must be made which will be discussed later on.

FORMULAE FOR STATIONS OF INFINITE LENGTH

The potential at the point x is defined by:

$$E = E_{A} \cdot e^{-ax}. \qquad (12)$$

The resistance of the section is defined by:

$$\frac{E_A}{I_A} = r_0 = \frac{r}{\sqrt{rg}} = \sqrt{\frac{r}{g}}\ . \qquad (13)$$

For practical application equation (12) is rewritten. Assuming that the total length of the section to be protected $L = 2l_1$; where l_1 is the length from the earthing point to the end of one side of the section to be protected. Denoting the minimum protective potential at the most distant point by E_m , we obtain:

$$E_A = E_m \cdot e^{al_1}. \qquad (14)$$

the distribution of the current density can be determined by:

$$I_A = I_0 \cdot e^{al_1}, \qquad (15)$$

where I_0 is the current density at the extreme point of the section to be protected.

The relation between the potential and the current flow is of the type:

$$E = -\sqrt{\frac{r}{g}}\ I_0 \cdot e^{-ax}. \qquad (16)$$

FORMULAE FOR STATIONS OF FINITE PROTECTION LENGTH

Resistance of the section:

$$r_0 = \frac{E_A}{I_A} = \sqrt{\frac{r}{g}} \cdot \frac{1}{\operatorname{th}(al_2)}. \qquad (17)$$

Potential:

$$E_A = E_m \cdot \operatorname{ch}\ (al_2). \qquad (18)$$

These formulae can be transformed to be more convenient for practical use, since the values g and r can be expressed by practically measured parameters.

The resistance of the pipeline can be determined by:

$$r = \frac{\varrho l}{S} = \frac{\varrho \cdot l}{\pi \cdot D \cdot T}, \qquad (19)$$

where r is the resistance of the pipeline, Ohm/km;
ϱ is the specific resistance of the tube material, Ohm mm^2/m;
l is the length of the (considered) section, m;

D is the average tube diameter ($d_{\text{inner}} + T$), mm;
T is the wall thickness of the tube, mm;
S is the conductor (tube wall) cross section, mm^2.

On the average, the specific resistance of steel tubes can be assumed as being 0.135 Ohm mm^2/m.

Denoting by C the circumference of the tube in metres, we obtain:

$$\pi \cdot D = 1000\ C,$$

$$r = \varrho \frac{1000}{1000\,CT} = \frac{\varrho}{CT} = \frac{0{,}135}{CT}\,. \tag{20}$$

The conductivity of the insulation (Siemens per km) is determined by the formula:

$$g = lC\,\frac{g_1}{1000000}\,,$$

where g is the conductivity of the insulation, Siemens per km;
l is the length of the tube section per km in metres (i. e., 1000 metres);
C is the length of the tube circumference, m;
g_1 is the conductivity of the coating, microsiemens m^2.

$\frac{g_1}{1000000}$ - conductivity of the coating, Siemens m^2.

Thus, we obtain:

$$g = \frac{Cg_1}{1000}\ \text{Siemens km.} \tag{21}$$

From the equations (20) and (21) we obtain:

$$a = \sqrt{gr} = \sqrt{\frac{Cg_1}{1000} \cdot \frac{0{,}135}{CT}} = 0{,}0116\sqrt{\frac{g_1}{T}}\,. \tag{22}$$

Equation (13) can now be rewritten thus:

$$\sqrt{\frac{r}{g}} = \sqrt{\frac{0{,}135}{CT} \cdot \frac{1000}{Cg_1}} = \frac{11{,}6}{C\sqrt{Tg_1}}\,. \tag{23}$$

Taking into consideration the expressions of equations (22), (23) the calculation formulae can be rewritten as follows:

1) for an infinite tube length to be protected (Fig. 36) the formula for calculating the potential:

$$E_A = E_m \cdot e^{0{,}0116\sqrt{\frac{g_1}{T}} \cdot l_1}\,; \tag{24}$$

Resistance of one side of the section:

$$r_0 = \frac{11{,}6}{C\sqrt{Tg_1}}\,; \tag{25}$$

2) for a pipe line of finite length to be protected (Fig. 38) the formula for calculation of the potential will be:

$$E_A = E_m \cdot \text{ch}\left[0{,}0116 \cdot \sqrt{\frac{g_1}{T}} \cdot l_2\right]; \tag{26}$$

Resistance of one side of the section to be protected:

$$r_0 = \frac{11{,}6}{C\sqrt{Tg_1}} \cdot \frac{1}{\mathrm{th}\left[0\,0116\sqrt{\frac{g_1}{T}l_2}\right]} \cdot \qquad (27)$$

The sequence of application of these formulae will be described later on.

METHOD OF CALCULATION OF CATHODIC PROTECTION REQUIREMENTS

As has been said earlier, the electrical circuit of a cathodic protection system usually consists of a number of series connected resistances. Starting from the positive pole of the current source, the sequence of the resistances is usually as follows: 1) resistance of the conductors from the current source terminal to the earthing anodes; 2) contact resistance of the anode earthing (anode-soil); 3) soil resistance; 4) contact resistance "soil-piping"; 5) pipeline resistance; 6) resistance of the conductors connecting the pipeline with the negative terminal of the current source.

In practical calculations these resistances are combined into three resistances which are calculated, namely: the contact (transfer) resistance of the anode earthing; the sum of the pipeline and "soil-tube (contact)" resistances; the total resistance of all the connection leads (conductors). The earth resistance is usually neglected since it is small compared to the other resistances, but it has to be taken into consideration if the contact resistance "soil-tube" is very small, e. g. , in the case of blank tube surfaces or tube surfaces with a severely damaged coating.

Thus, the total resistance of a cathodic protection circuit can be determined by the formula:

$$R_0 = R_1 + R_2 + R_3 \quad \ldots \quad \ldots \quad \ldots \qquad (28)$$

where R_1 - contact resistance of the anodic earthing;
R_2 - contact resistance "soil-piping" and the resistance of the piping itself;
R_3 - the total resistance of all connection leads.

Since the current intensity is the same for the entire circuit, required total voltage of the protection station is determined by the formula:

$$E_0 = E_1 + E_2 + E_3 \quad \ldots \quad \ldots \quad \ldots \qquad (29)$$

where E_1 - voltage drop of the anodic earthing;
E_2 - voltage drop in the protected pipe line;
E_3 - voltage drop in the connection leads.

The intensity of the current flowing in the system can be determined by the formula:

$$I = \frac{E_0}{R_0} = \frac{E_2}{R_2} = \frac{E_1}{R_1}. \qquad (30)$$

In the case of a more complex protection system of several parallel pipelines (see Fig. 38), the electric circuit will consist of parallel-series connected resistances as is shown in Fig. 39.

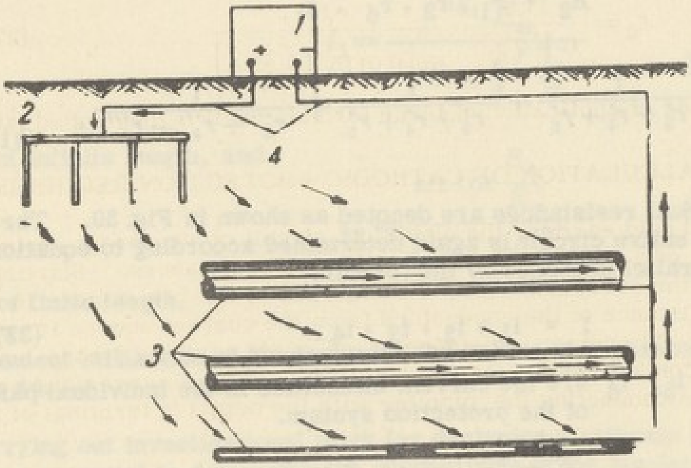


Fig. 38. Set-up for cathodic protection of a group of underground structures.

1 - current source; 2 - earthing; 3 - protected lines; 4 - connection leads. Arrows indicate the direction of the current flow.

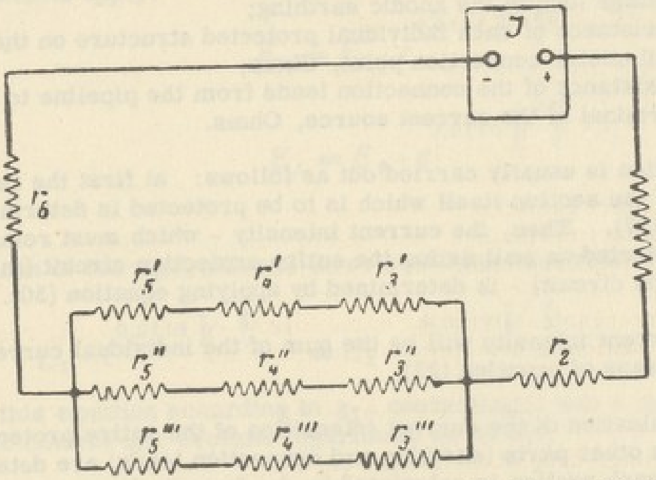


Fig. 39. Equivalent circuit of a cathodic protection installation for a group of underground structures.

J - d.c. source; Resistances: 1_1 - lead to earthing structure; r_2 - resistance of the earthing system; r_3', r_3'', r_3''' - contact resistance "earth-tube"; r_4', r_4'', r_4''' - individual pipeline resistances; r_5', r_5'', r_5''' - resistance of the connection leads of the individual pipelines; r_6 - resistance of the common connection lead to the current source.

Equation (28) will also be valid in this case but R_2 will be:

$$R_2 = r_1 + r_2 + r_6 + g,$$

where $$\frac{1}{g} = \frac{1}{r'_3 + r'_4 + r'_5} + \frac{1}{r''_3 + r''_4 + r''_5} + \frac{1}{r'''_3 + r'''_4 + r'''_5}, \qquad (31)$$

where the individual resistances are denoted as shown in Fig. 39. The current intensity for the entire circuit is again determined according to equation (30) and for the individual parallel branches by the formula:

$$I = i_1 + i_2 + i_3 + i_4, \qquad (32)$$

where i_1, i_2, i_3, i_4 are the current intensities in the individual parallel sections of the protection system.

Also: $$i_1 = \frac{E_0 - E_1}{r'_1 + r''_1}, \quad i_2 = \frac{E_0 - E_1}{r'_2 + r''_2}, \qquad (33)$$

where E_0 - total voltage of the protection circuit;
E_1 - voltage loss in the anodic earthing;
r'_1, r''_1 - resistance of each individual protected structure on the section soil-metal-connection point, Ohms;
r'_2, r''_2 - resistance of the connection leads from the pipeline to the negative terminal of the current source, Ohms.

The calculation is usually carried out as follows: at first the required voltage and the resistance of the section itself which is to be protected is determined by the equations (24) - (27). Then, the current intensity - which must remain constant for the section to be protected as well as for the entire protection circuit (in the case of a parallel protection circuit) - is determined by applying equation (30).

The total current intensity will be the sum of the individual current intensities determined by means of equation (33).

After determination of the current intensities of the entire protection system, the resistances of its other parts (earthing and connection leads) are determined. The voltage drop for each section is calculated by the formula

$$E = IR \qquad (34)$$

The required voltage of the current source will be the sum of the voltage drop along the individual sections of the circuit.

In some cases it is necessary to solve the reverse problem, namely, to determine for a given current source the limit of its protective effect. In this case, the formulae (24) to (27) can be rewritten thus:

$$l_1 = \frac{\lg_e \frac{E_A}{E_m}}{0.0116 \sqrt{\frac{g_1}{T}}} \qquad (35)$$

for a section of infinite length, and

$$l_2 = \frac{\arccos \frac{E_A}{E_m}}{0.0116 \sqrt{\frac{g_1}{T}}} \qquad (36)$$

for a section of finite length.

For convenient utilisation of the formulae the values of hyperbolic functions are given in Table 14.

When carrying out investigational work for designing a cathodic protection system it is sometimes essential to determine the conductivity of the insulation on individual pipeline sections. This is done by measuring the potentials at two points, applying a temporary protection station which is set up specially for test purposes. By carrying out the measurements according to the scheme, Fig. 22, the potentials E_1 and E_2 at the distances x_1 and x_2 from the connection point are obtained. Then, the following relations apply:

$$E_A = E_1 \cdot e^{0{,}0116 \sqrt{\frac{g_1}{T}} \cdot x_1}$$

$$E_A = E_2 \cdot e^{0{,}0116 \sqrt{\frac{g_1}{T}} \cdot x_2}$$

By comparison of the right sides of these equations we obtain:

$$E_1 \cdot e^{0{,}0116 \sqrt{\frac{g_1}{T}}\, x_1} = E_2 \cdot e^{0{,}0116 \sqrt{\frac{g_1}{T}}\, x_2}.$$

By solving this equation according to g_1, converting it into a logarithmic form and transforming the natural into decimal logarithms we obtain:

$$g_1 = 39200 \frac{T}{L_2} (\lg \frac{E_1}{E_2})^2 \text{ microsiemens m}^2 \qquad (37)$$

where $L = x_2 - x_1$, and the other symbols have the same meaning as in equation (24).

If the distance between the measuring points is 1 km, the formula will be simplified, namely:

$$g_1 = 39200\, T (\lg \frac{E_1}{E_2})^2 \text{ microsiemens m}^2 \qquad (38)$$

Due attention must be paid to the conductivity of the coating. It has already been shown earlier that this value can vary within very wide limits and that the results of the calculations are largely dependent on it.

The relation between the initial potential of the cathodic protection station, the distance from the connection point and the conductivity of the coating is shown in Fig. 40. It can be seen from this graph that the conditions for protection become much more exacting if the conductivity of the pipe coating exceeds 1000 microsiemens m^2.

It is necessary to point out that the deterioration of the coating is very non-uniform. The first incipient holes which occur in the coating during the initial period of its operation will increase the conductivity only insignificantly, whilst further use will bring about a considerable increase of the conductivity of the coating.

The resistance of the conductors connecting the individual parts of the protection circuit are determined according to equation (19); the calculation of the earthing resistance is described later on.

If the coating of the pipeline is severely damaged or if the pipe line has no coating calculation cannot be carried out according to the above formulae owing to the absence of values for the conductivity of the coating. In this case the reciprocal value of the resistance of the soil surrounding the pipeline is applied, which can be calculated by the equation:

$$R = \frac{0.366\varrho}{L} \lg\left(\frac{r_2}{r_1}\right) \quad \dots \quad \dots \quad \dots \qquad (39)$$

where R - soil resistance per square meter of the piping surface, Ohm m^2;
ϱ - specific soil resistance, Ohm m;
L - length of the pipeline having 1 m^2 surface area;
r_1 - inner diameter of the piping, m;
r_2 - distance from the centre of the pipe to the soil surface, m.

In the formulae for calculation of the potential and the resistance, the reciprocal value must be applied, i. e., $g = 1/R$. The further calculations are carried out in the same way (as in the earlier cases).

CHECK CALCULATION OF A CATHODIC PROTECTION SYSTEM ON THE BASIS OF THE CURRENT DENSITY

A check calculation on whether sufficient cathodic protection is provided can be carried out, in addition to the method described earlier on the basis of the minimum intensity of the current flow on the pipeline surface. As was shown, the voltage change along the pipeline is non-uniform; the current intensity at a given point of the line can be determined by means of the relation:

$$E = \int_0^L IRdx = R\int_0^L Idx, \qquad (40)$$

where E - is the voltage drop between the most distant point of the protected line and the drainage point, V;
x - distance from the point A, m;
R - resistance of the line per unit of length, Ohm m;

R dx - resistance of an elementary (infinitely small) length of the line, Ohms;
I - intensity of the current flowing through the pipeline at a distance x from the drainage point, A;
L - total length of the section to be protected, m.

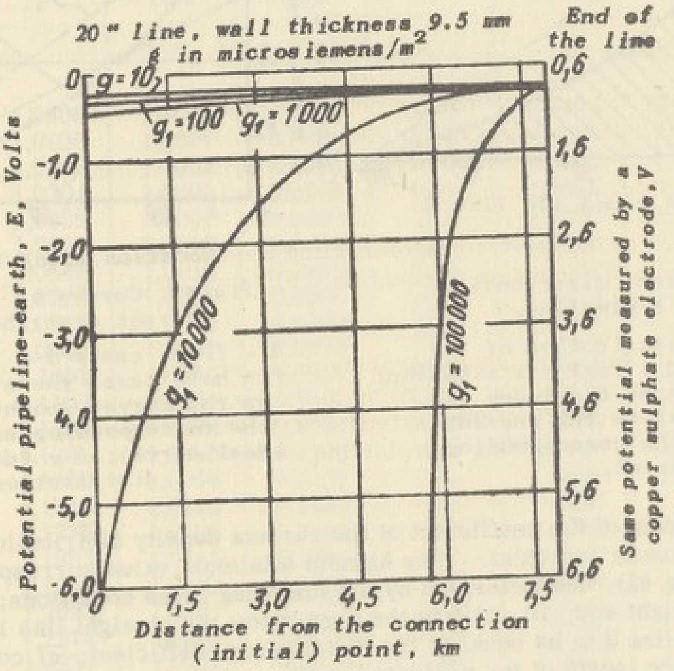


Fig. 40. Curves showing the relation between the initial potential of a cathodic station and the distance to the drainage point for various values of the conductivity of the insulation coating.

The value of the integral, equation (40), can be represented as an area which is limited by the curve of the function to be integrated, Fig. 41. The angle of a tangent at any point of the curve (the angle with the abscissa) is proportional to the density of the protective current flowing through the surface of the piping. It can thus be seen that the current will have a maximum density near the connection point and a minimum density at the distant end of the line. The broken, straight line in Fig. 41 shows the ideal current distribution along the pipeline when the current density is constant throughout the entire length of the line. The area limited by this straight line is larger than the area representing the real current density distribution. For the value of the coefficient equal to unity the density of the protective current must be the same for the entire length of the line to be protected. If the coefficient has a value of less than unity, the current density on one end of the pipeline will be less than the ideal value. The minimum current density at the most distant point is determined from the inclination angle of the curve, see Fig. 41.

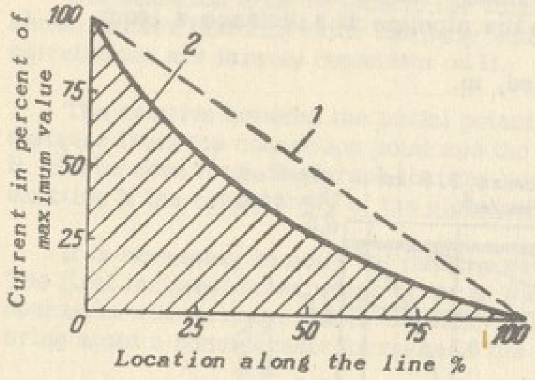


Fig. 41. Current distribution along a pipeline.

1 - ideal distribution of the current flow; 2 - real distribution; inclination of the curve is proportional to the current density at the corresponding point,

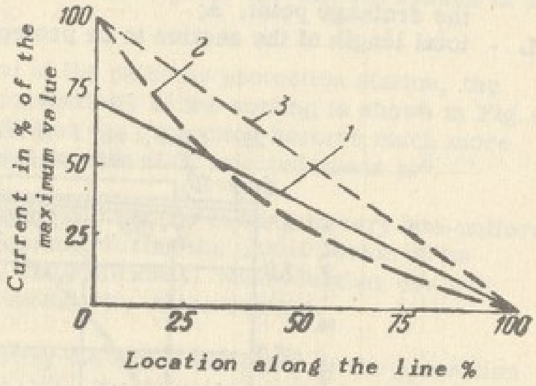


Fig. 42. Curves of the limit current distributions.

1 - first case; 2 - second case (in both cases the area limited by the curves amounts to 0.7x the corresponding area for the ideal curve); 3 - ideal, uniform distribution.

For a given value of the coefficient of the current density distribution two extreme values of this minimum can exist. The highest minimum value corresponds to the straight line 1 (Fig. 42), characterised by the following three conditions: a) maximum inclination at the right end; b) ratio of the area below the straight line 1 to the area below the straight line 3 to be equal to the distribution coefficient; c) constant inclination throughout the entire length of the protected section. The real density of the current flow at the end of the line, as a function of the distribution coefficient and the average density of the current flow along the entire line, can be determined by means of curve 1, Fig. 43.

The smallest minimum value is that corresponding to curve 2, Fig. 43, for the construction of which the following conditions apply: a) minimum inclination at the distant right end; b) ratio of the area below the curve to that below the straight line 3 to equal the value of the distribution coefficient; c) variable inclination along the entire length. In this case the real current density at the distant end of the section is determined from the values of the distribution coefficient and the average current density by means of the lower curve 2, Fig. 43.

The curve 3 (Fig. 43) represents intermediate values between those of curves 1 and 2. Applying the curves of Fig. 43, the practical problem on whether a given section of the pipeline is sufficiently protected can be determined by measuring the voltage drop near the connection point.

For a cathodic protection station as shown schematically in Fig. 44, the following data must be obtained in order to calculate the current density at the distant point of the section: the total length of the line L, m; the pipe diameter d, m; the cross section of the tube walls S, mm^2; the voltage drop along a section of l metres near the

Table 14.

Values of exponential and hyperbolic functions.

(e^x, cosh x, tgh x for x = 0.01 to 6.00)

x	e^x	ch x	th x	x	e^x	ch x	th x
0,00	1,0000	1,0000	0,0000	0,48	1,6161	1,1174	0,4462
0,01	1,0100	1,0001	0,0100	0,49	1,6323	1,1225	0,4542
0,02	1,0202	1,0002	0,0200	0,50	1,6487	1,1276	0,4621
0,03	1,0304	1,0005	0,0300	0,51	1,6653	1,1329	0,4700
0,04	1,0408	1,0008	0,0400	0,52	1,6820	1,1383	0,4777
0,05	1,0513	1,0012	0,0500	0,53	1,6989	1,1438	0,4854
0,06	1,0618	1,0018	0,0599	0,54	1,7160	1,1494	0,4930
0,07	1,0725	1,0025	0,0699	0,55	1,7333	1,1551	0,5005
0,08	1,0833	1,0032	0,0798	0,56	1,7507	1,1609	0,5080
0,09	1,0942	1,0041	0,0898	0,57	1,7683	1,1669	0,5154
0,10	1,1052	1,0050	0,0997	0,58	1,7860	1,1730	0,5227
0,11	1,1163	1,0061	0,1096	0,59	1,8040	1,1792	0,5299
0.12	1,1275	1,0072	0,1194	0,60	1,8221	1,1855	0,5371
0,13	1,1388	1,0085	0,1293	0,61	1,8404	1,1919	0,5441
0,14	1,1503	1,0098	0,1391	0,62	1,8589	1,1984	0,5511
0,15	1,1618	1,0113	0,1489	0,63	1,8776	1,2051	0,5581
0,16	1,1735	1,0128	0.1587	0,64	1,8964	1,2119	0.5649
0,17	1,1853	1,0145	0,1684	0,65	1,9155	1,2188	0,5717
0,18	1,1972	1,0162	0.1781	0,66	1,9348	1,2258	0,5784
0,19	1,2093	1,0181	0,1878	0,67	1,9542	1,2330	0,5850
0,20	1,2214	1,0201	0,1974	0,68	1,9739	1,2403	0,5915
0,21	1,2337	1,0221	0.2070	0,69	1,9937	1,2477	0,5980
0,22	1,2461	1,0243	0,2165	0,70	2,0138	1,2552	0,6044
0.23	1,2586	1,0266	0,2260	0,71	2,0340	1,2628	0,6107
0,24	1,2713	1,0289	0,2355	0,72	2,0544	1,2706	0.6169
0,25	1,2840	1,0315	0,2449	0,73	2,0751	1,2785	0,6231
0,26	1,2969	1,0340	0,2543	0,74	2,0959	1,2865	0,6292
0,27	1,3100	1,0367	0,2636	0,75	2,1170	1,2947	0,6352
0,28.	1,3231	1,0395	0,2729	0,76	2,1383	1,3030	0,6411
0,29	1,3364	1,0424	0,2821	0,77	2,1598	1,3114	0,6469
0,30	1,3499	1,0453	0,2913	0.78	2,1815	1,3199	0,6527
0,31	1,3634	1,0484	0,3004	0,79	2,2034	1,3286	0,6584
0,32	1,3771	1,0516	0,3095	0,80	2,2255	1,3374	0,6640
0,33	1,3910	1,0550	0,3185	0,81	2,2479	1,3464	0,6696
0,34	1,4050	1,0584	0,3275	0,82	2,2705	1,3555	0,6751
0,35	1,4191	1,0619	0,3364	0,83	2,2933	1,3647	0,6805
0,36	1,4333	1,0655	0,3452	0,84	2,3164	1,3740	0,6859
0,37	1,4477	1,0692	0,3540	0,85	2,3997	1.3835	0.6911
0,38	1,4623	1,0731	0,3627	0,86	2,3632	1,3932	0,6963
0,39	1,4770	1,0770	0,3714	0,87	2,3869	1,4029	0,7014
0,40	1,4918	1.0811	0,3800	0,88	2,4109	1,4128	0,7064
0,41	1,5069	1,0852	0,3885	0.89	2,4351	1,4229	0,7114
0,42	1,5220	1,0895	0,3969	0,90	2,4596	1,4331	0,7163
0,43	1,5373	1,0939	0,4053	0,91	2,4843	1,4434	0,7211
0,44	1,5527	1,0984	0,4136	0,92	2,5093	1,4539	0,7259
0,45	1,5683	1,1030	0,4219	0,93	2,5345	1,4645	0,7306
0.46	1,5841	1,1077	0,4301	0,94	2,5600	1,4753	0,7352
0,47	1,6000	1,1125	0,4382	0,95	2.5857	1,4862	0,7398

Continuation of Table 14.

x	e^x	ch x	th x	x	e^x	ch x	th x
0,96	2,6117	1,4973	0,7443	1,49	4,4371	2,3312	0,9033
0,97	2,6379	1,5085	0,7487	1,50	4,4817	2,3524	0,9052
0,98	2,6645	1,5199	0,7531	1,51	4,5267	2,3738	0,9069
0,99	2,6912	1,5314	0,7574	1,52	4,5722	2,3955	0,9087
1,00	2,7183	1,5431	0,7616	1,53	4,6182	2,4174	0,9104
1,01	2,7456	1,5549	0,7658	1,54	4,6646	2,4395	0,9121
1,02	2,7732	1,5669	0,7699	1.55	4,7115	2,4619	0,9138
1,03	2.8011	1,5790	0,7739	1,56	4,7588	2,4845	0,9154
1,04	2,8292	1,5913	1,7779	1,57	4,8067	2,5074	0,9170
1,05	2.8577	1,6038	0,7818	1,60	4,9530	2,5775	0,9217
1,06	2,8864	1,6164	0,7857	1,70	5,4740	2,8283	0,9354
1,07	2,9154	1,6292	0,7895	1,80	6,0497	3,1075	0,9468
1,08	2,9447	1,6421	0,7932	1,90	6,6859	3,4177	0,9562
1,09	2,9743	1,6552	0,7969	2,00	7,3891	3,7622	0,9640
1,10	3,0042	1,6685	0,8005	2,10	8,1662	4,1443	0,9705
1,11	3,0344	1,6820	0,8041	2,20	9,0250	4,5679	0,9757
1,12	3,0649	1,6956	0,8076	2,30	9,9742	5,0372	0,9801
1,13	3,0957	1,7093	0,8110	2,40	11,0232	5,5570	0,9837
1,14	3,1268	1,7233	0,8144	2,50	12,1825	6,1323	0,9866
1,15	3,1582	1,7374	0,8178	2,60	13,4637	6,7690	0,9890
1,16	3,1899	1,7517	0.8210	2,70	14,8797	7,4735	0,9910
1,17	3,2220	1,7662	0,8243	2,80	16,4447	8,2527	0,9926
1,18	3,2544	1,7808	0,8275	2,90	18,1742	9,1146	0,9940
1,19	3,2871	1,7957	0,8306	3,00	20,0855	10,0677	0,9951
1,20	3,3201	1,8107	0,8337	3,10	22,1980	11,1215	0,9960
1,21	3,3535	1,8258	0,8367	3,20	24,5325	12,2867	0,9967
1,22	3,3872	1.8412	0,8397	3,30	27,1126	13,5748	0,9973
1,23	3,4212	1,8568	0,8426	3,40	29,9641	14,9987	0,9978
1,24	3,4556	1,8725	0,8455	3,50	33,1155	16,5728	0,9982
1,25	3,4903	1,8884	0,8483	3,60	36,5983	18,3128	0,9985
1,26	3,5254	1,9045	0,8511	3,70	40,4473	20,2360	0,9988
1,27	3,5609	1,9208	0,8538	3,80	44,7012	22,3618	0,9990
1,28	3,5966	1,9373	0,8565	3,90	49,4025	24,7114	0,9992
1,29	3,6328	1,9540	0,8591	4,00	54,5982	27,3082	0,9993
1,30	3,6693	1,9709	0,8617	4,10	60,3403	30,1784	0,9995
1,31	3,7062	1,9880	0,8643	4 20	66,6863	33,3507	0,9996
1,32	3,7434	2,0053	0,8668	4,30	73,6998	36,8567	0,9996
1,33	3,7810	2.0228	0,8693	4,40	81,4509	40,7316	0,9997
1,34	3,8190	2,0404	0,8717	4.50	90,0171	45,0141	0,9998
1,35	3,8574	2.0583	0,8741	4,60	99,4843	49,7472	0,9998
1,36	3,8962	2,0764	0,8764	4,70	109,9472	54,9781	0,9998
1,37	3,9354	2,0947	0,8787	4.80	121,5104	60,7593	0,9999
1,38	3,9749	2,1132	0,8810	4,90	134,2898	67,1486	0,9999
1,39	4,0149	2.1320	0,8832	5,00	148,4132	74,2099	0,9999
1,40	4,0552	2,1509	0.8854	5,10	164,0219	82,0140	0,9999
1,41	4,0960	2,1701	0,8875	5,20	181,2722	90,6389	0,9999
1,42	4,1371	2,1894	0,8896	5,30	200,3368	100,1709	0,9999
1,43	4,1787	2,2090	0,8917	5,40	221,4064	110,7055	1,0000
1,44	4,2207	2,2288	0,8937	5,50	244,6920	122,3480	1,0000
1,45	4 2631	2,2488	0,8957	5,60	270.4264	135,2150	1.0000
1,46	4,3060	2,6991	0,8977	5.70	298,8674	149,4354	1,0000
1,47	4,3492	2,2896	0,8996	6,00	403,4288	201,7156	1,0000
1,48	4,3930	2,3103	0,9015				

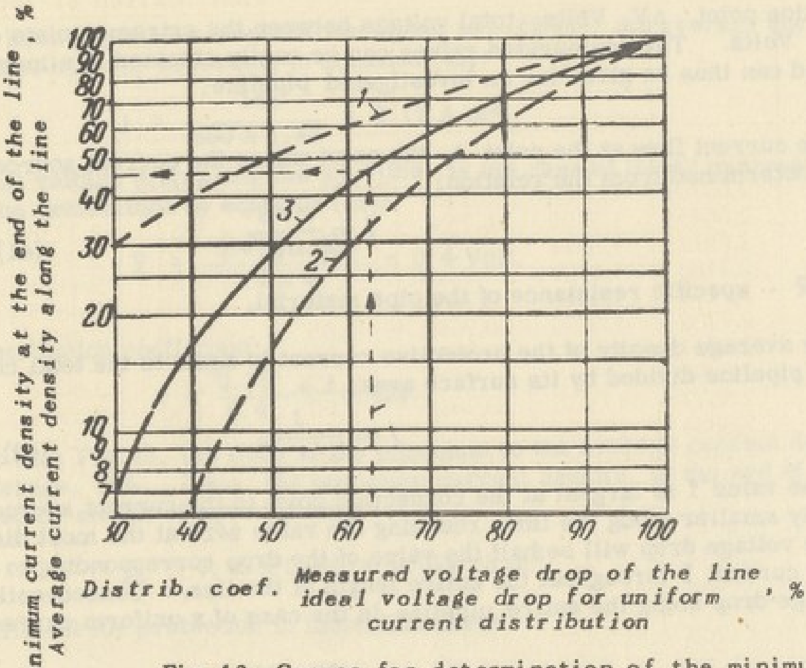


Fig.43. Curves for determination of the minimum (required) current density.

1 - limit case for the anode being near; 2 - limit case for the anode being more distant; 3 - intermediary case.

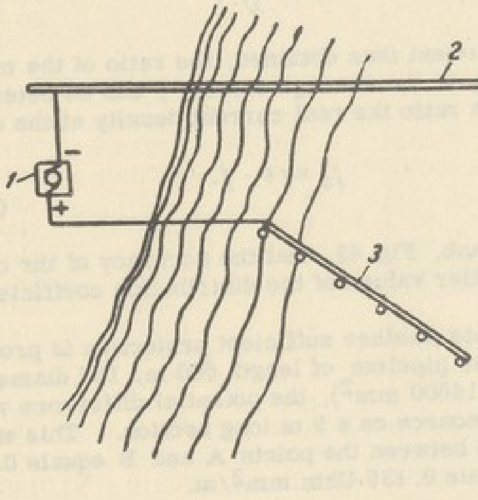


Fig.44. Arrangement for determining whether the protection is adequate.

1 - d.c. source; 2 underwater pipeline B; 3 - anode.

connection point, ΔV, Volts; total voltage between the extreme points of the protected line V, Volts. The enumerated values can be easily obtained in almost every practical case and can thus be given for an investigated pipeline.

The current flow at the point A, the point where the current source is connected, can be determined from the relation:

$$I = \frac{\Delta V S}{l \varrho}, \qquad (41)$$

where ϱ - specific resistance of the pipe material.

The average density of the protective current is equal to the total current flowing into the pipeline divided by its surface area, i. e.

$$j = \frac{I}{L \cdot \pi \cdot D}. \qquad (42)$$

If the value I is largest at the connection point to the current source and becomes uniformly smaller along the line, reaching the value zero at the most distant end of the line, the voltage drop will be half the value of the drop corresponding to a flow of a constant current I throughout the entire length of the line. Consequently, the theoretical voltage drop along the entire pipeline in the case of a uniform current consumption will be:

$$V = \frac{L \cdot \Delta V}{l \cdot 2}. \qquad (43)$$

Since the voltage drop along the line V_0 is known, the distribution coefficient can be determined according to the equation

$$\varepsilon = \frac{V_0}{V}. \qquad (44)$$

With the distribution coefficient thus obtained, the ratio of the minimum current density at the end of the line j_0 to the average density j can be determined by means of the graph, Fig. 43. From this ratio the real current density at the end of the line can be determined by the formula:

$$j_0 = \varepsilon \cdot j. \qquad (45)$$

It can be seen from the graph, Fig. 43, that the accuracy of the calculation will decrease appreciably with smaller values of the distribution coefficient.

Example: To investigate whether sufficient protection is provided in a system as shown in Fig. 44, of a submarine pipeline of length 600 m, 16" diameter, 12 mm wall thickness (wall cross section: 14600 mm^2), the potential difference was measured at the connection point to the current source on a 9 m long section. This was found to be 12 mV. The total voltage drop between the points A and B equals 0.25 V. The specific resistance of steel equals 0.135 Ohm mm^2/m.

According to equation (41) the current intensity in the line:

$$I = \frac{12 \times 14600}{9 \times 0.135 \times 1000} = 144 \text{ A}$$

If the surface area per metre length of the piping is 1.42 m^2, the average current density along the line will be, according to equation (42):

$$j = \frac{144}{600 \times 1.42} = 0.17 \text{ A } m^2.$$

The theoretical voltage drop along the pipeline, in the case of linear current distribution, can be determined by equation (43):

$$V = \frac{0.012 \times 600}{2 \times 9} = 0.4 \text{ Volt.}$$

Thus, the distribution coefficient:

$$\varepsilon = \frac{0.25}{0.4} = 0.625.$$

In agreement with Fig. 43, the ratio of the minimum to the average current density equals, on the average, 46%. Thus, the minimum current density, at the end of the line, is determined by means of equation (45):

$$j_0 = 0.46 \times 0.17 = 0.078 \text{ A } m^2,$$

which may be sufficient for protection in individual cases.

Chapter V

ANODIC EARTHING

The main power losses of the whole cathodic protection system occur in the anodic earthing. Therefore, the design of this earthing is of considerable importance for the entire protection installation, and it is essential that the earthing resistance should be as low as possible. However, in most cases this necessitates very large structures and it is therefore necessary to select a design which ensures a low resistance without excessively large dimensions.

The earthing can be carried out by any metal of various shapes and also by carbon, coke and graphite. Most frequently steel or iron parts are used for this purpose, e.g., scrap cast iron pulleys, scrap sheet steel, sections, etc. In most cases old tubes of various diameters are used for earthing. The advantages of using tubes for earthing are: absence of sharp edges, which are most affected by corrosion; long shape permitting optimum utilisation of their surface as a contact with the soil; maximum economy of the consumption of metal; convenient installation and general availability of scrap pipes.

Since tubes are mainly used for earthing, it is necessary to describe the calculation appropriate for such earthing methods. Generally, the resistance of any type of earthing will decrease with increasing surface area, but the decrease will not be proportional to the increase of the surface.

TYPE OF EARTHING

Tubular and other linear earthing structures can be of three types: horizontal, vertical and combined.

Horizontal earthing consists of a tube or a strip laid into the ground at some depth in horizontal position. Its advantages compared to vertical earthing systems are:

(a) easy access for inspection of all parts of the earthing;
(b) ability to provide convenient joints to the earthing conductor to various parts

of the earthing structure, thus ensuring the earthing will continue to function even in case of local failures;

(c) possibility of using large parts for earthing;
(d) all parts of the earthing system have relatively uniform conditions of operation;
(e) simplicity of the excavation work during laying of the earthing.

Vertical earthing consists of one or several vertically placed tubes. The advantages of vertical earthing are:

(a) it is easier to ensure that the earthing structure is in constantly moist ground all the year round;
(b) if an earthing tube breaks down, a tube or another type of electrode of smaller diameter can be fitted;
(c) for equal dimensions, the earthing resistance is lower for vertical earthing than it is for horizontal earthing.

Since each of the above mentioned types of earthing has its advantages and disadvantages, earthing is in most cases carried out by a combined system consisting of horizontal and vertical elements, thus obtaining the advantages of both. The distribution of the vertical earthing parts in a combined system can vary considerably. It is necessary therefore, to take into consideration that if the individual earthing elements are too close to each other a screening effect will occur, i. e., the effect of some elements will be partly cancelled out by other elements. Most frequently a combined earthing system is distributed as shown in Fig. 45. In some cases however, it is carried out as shown in Fig. 46, but such a distribution creates favourable conditions for screening, reducing the performance of the earthing system.

On designing an earthing system it is necessary to take into consideration the influence of the dimensions of the earthing parts and their location on the earthing resistance. Other conditions being equal, it is essential to aim at obtaining the lowest practicable resistance of the anodic earthing with a minimum of metal.

DIAMETER OR WIDTH OF THE EARTHING PARTS

Although tubes of any diameter can be used for earthing, usually, tubes of 2 to 8" diameter are used for this purpose. With tubes of smaller diameters there are difficulties in driving them into the ground. For diameters over 8", installation work becomes complicated. From the point of view of the electrical resistance, increase of the tube diameter does not have a marked effect, as can be seen from the graph, Fig. 47.

It is also necessary to take into consideration the following: during operation the earthing system is subject to electrolytic corrosion, each ampere flowing through the system removing approximately 7.8 kg of iron per year. It is, therefore, inadvisable to use tubes of too small diameters because the wall thickness of such tubes is small; tubes of 4-6" diameter are most suitable and their service life is calculated to be not less than 2½ to 4 years.

LENGTH OF THE EARTHED PARTS

A horizontally earthed part operates at equal soil conditions throughout its entire

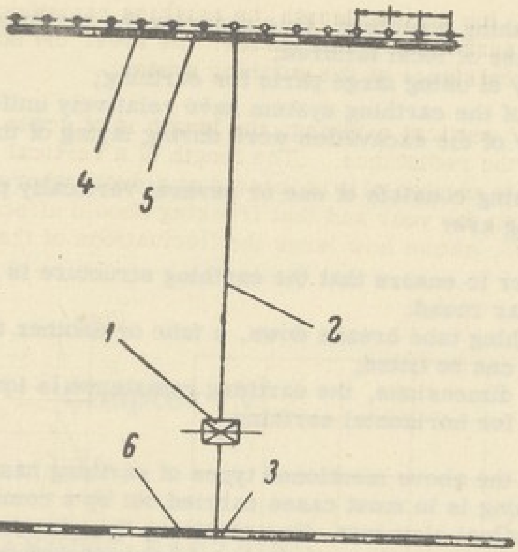
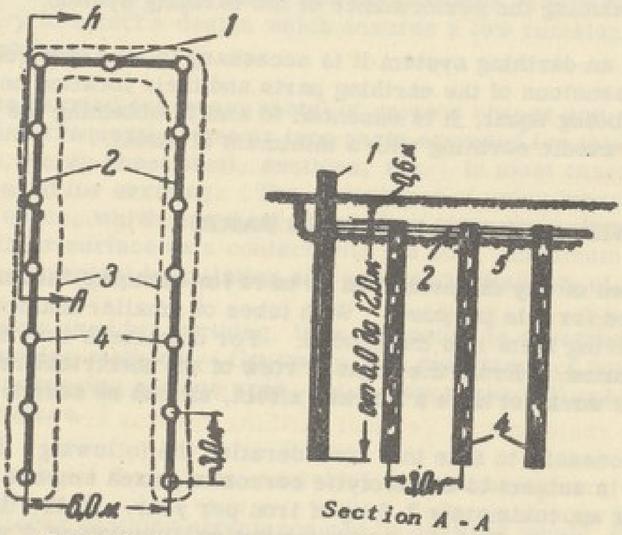


Fig. 45. Combined earthing (vertical and horizontal).
1 - current source; 2 - cable; 3 - cable terminal; 4 - vertical earthing tube; 5 - horizontal earthing tube; 6 - protected pipeline.



Plan view

Section A-A
Side view

Fig. 46. Combined type of earthing.
1 - pipe rigging out to the surface; 2 - 4" or 6" tubes; 3 - trenches; 4 - 6" or 12" tubes; 5 - bottom of trench.

length, therefore, for a given length the earthing resistance will vary only if the resistance of the surrounding soil varies: the lower the soil resistance, the smaller will be the total resistance of the earthing system.

In the case of vertical earthing, the length is of great importance from the point of view of reducing the resistance. The length of a vertical earthing part must be such, that a considerable section of it is located at a depth where the soil moisture is sufficiently constant throughout the year and that freezing should affect only the upper part of the earthing. Fig. 48, shows how large the fluctuations of the resistance of a short earthing part (0.5 m long) are during a year. Fig. 49, shows that the resistance of a longer earthing part fluctuates considerably less. Permanent moisture of the soil is of great importance for normal operation of the earthing, since moisture considerably reduces the soil resistance. The influence of the depth of a vertical earthing system on its resistance during the various parts of the year is also shown in Fig. 50.

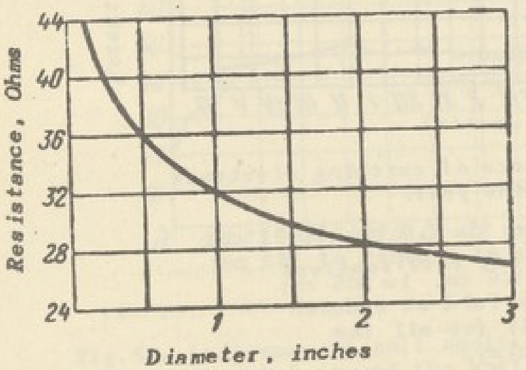


Fig. 47. Resistance of a vertical (earthing) tube as a function of of its diameter. Depth 3 m.

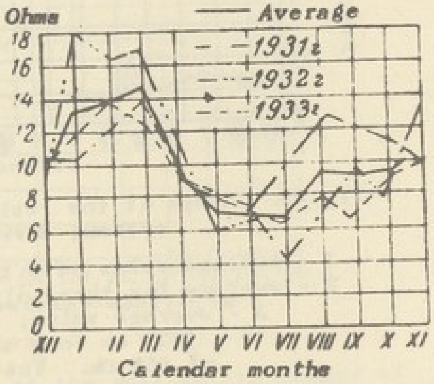


Fig. 48. Change of the resistance of long (extensive) earthings during the year, 1 = 0.5 m (VYeN).

The relation between the length and the resistance of a tube earthing, other conditions being equal, is shown in Fig. 51.

The resistance of vertical earthing drops most appreciably if the length is increased to 3-4 m, a further increase of the length will bring about only a relatively small decrease of the resistance. Vertical earthing systems are usually of the indicated lengths.

As already mentioned the soil resistance is of great importance and determines the resistance of an earthing system. The aim is to find a stretch of soil which has a minimum resistance. This depends, in addition to moisture content, also on the content of dissolved salts in the soil moisture. It is desirable to install the earthing system in a stretch where the soil resistance does not exceed 10 Ohms m. Since it is not always possible to find a stretch of soil which complies with this condition, it is sometimes necessary to mix artificial salts with the soil. Such added salts will reduce the soil resistance up to a relatively small distance from the electrodes. Thus, it can be seen from Fig. 52, that addition of salts considerably reduces the soil resistance only up to a

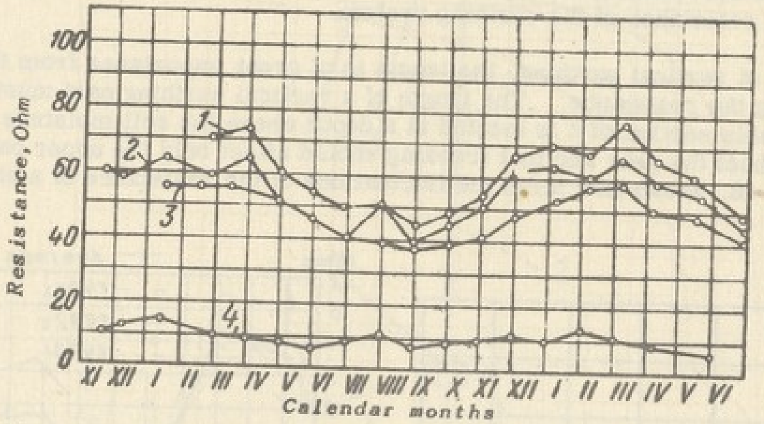
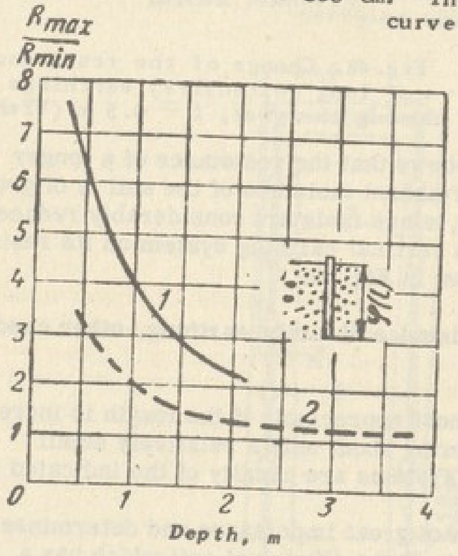


Fig.49. Change of the resistance of earthing electrode systems during the year.

1 - average value of 8 tubes, d= 1.9 cm, 1= 91 cm;
2 - average for three plates at a depth of 152 cm;
3 - average value, d= 1.9 cm, 1= 305 cm;
4 - 1829 cm long strip laid at a depth of 368 cm. The soil for all the curves - clay.



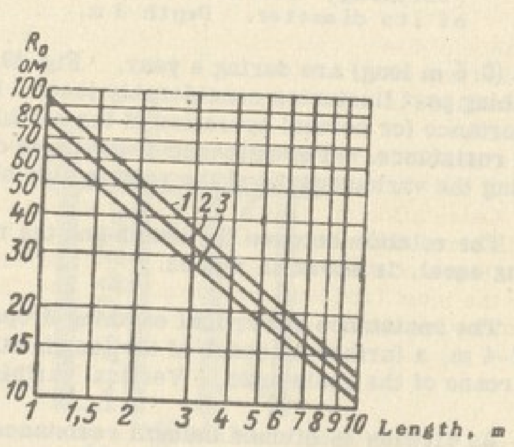


Fig.50. Influence of the laying depth of a vertical earthing element (tube) on its resistance during the year.

1 - data of physical laboratory;
2 - experimental data.

Fig.51. Earthing resistance of a tube electrode as a function of the tube length.

1 - d_1 = 1 cm; 2 - d = 2.5 cm; 3 - d = 5 cm. Soil resistance $\rho = 10^4$ Ohm cm.

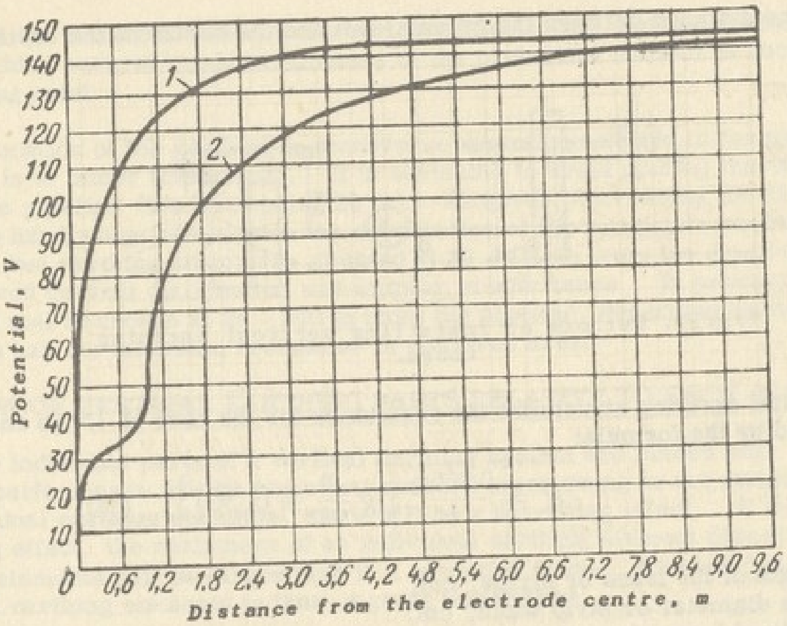


Fig. 52. Influence of salt additions to the soil on the change of potential around the vertical earthing structure.

1 - without salt additions; 2 - with salt addition.

distance of 3-4 m from the electrode. However, addition of salts gives positive results and is frequently applied. Practical values of the "salt addition" coefficient applied in calculations of anodic earthing are given later on.

CALCULATION OF THE EARTHING SYSTEM.

Calculation of the earthing system of a cathodic station$^{(2)}$ consists of determination of its size, depending on its resistance. This resistance depends predominantly on the resistance of the soil surrounding the earthing parts and the distribution of these parts. For the most frequently used earthing consisting of vertical tubes, the resistance of one element for the case that $l \geqslant d$ can be determined by:

$$R = \frac{0{,}366\,\varrho}{l}\left[\lg\frac{l}{d} + 0{,}602\right], \qquad (46)$$

where l - length of the tube below ground as shown in Fig. 53, cm;
d - tube diameter, cm;
ϱ - specific resistance of the soil, Ohm/cm^3.

If the entire earthing tube is situated below ground its resistance R, in the case that $l \geqslant d$ and $\frac{4t}{l} > 2$, can be determined by the formula

$$R = \frac{0{,}366\,\varrho}{l}\left|\lg\frac{2l}{d} + \frac{1}{2}\lg\frac{4t+l}{4t-l}\right|, \qquad (47)$$

where t - is the distance between the ground level and the centre of the earthing tube, in cm.

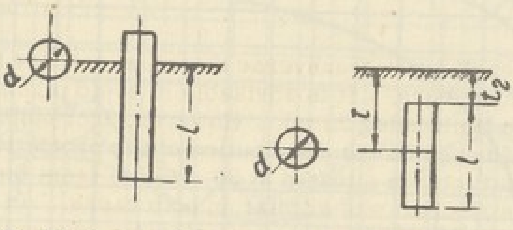


Fig. 53. Methods of installing vertical earthing tubes.

For horizontal earthing structures the resistance for the case of $l > \frac{1}{2}b$ and $\frac{l}{2t} > 2.5$ can be calculated by the formula:

$$R = \frac{0{,}366\,\varrho}{l}\left[\lg\frac{l^2}{bt} + 0{,}301\right], \quad (48)$$

where l - length of the tubes or strips, cm;
b - tube diameter or strip width, cm;
t - depth of laying from the surface of the soil to the centre of the tube or strip, cm;
ϱ - soil resistance, Ohm/cm.^{3}

For earthing consisting of a buried ring-shaped part, the resistance is determined by the formula:

$$R = \frac{0{,}366\,\varrho}{l}\left[\lg\frac{l^2}{bt} + 0{,}406\right]. \quad (49)$$

For a circular disc of a diameter of d centimeters, laid into the ground at the depth t cm, the resistance can be determined by the formula:

$$R = \frac{\varrho}{d}\left[0{,}25 + 0{,}159 \arcsin\frac{d}{\sqrt{(4t)^2 + d^2}}\right] \quad (50)$$

provided $t > \frac{1}{2}d$.

DISTANCE BETWEEN THE EARTHING STRUCTURE AND THE PIPELINE

The question of position must be considered from two aspects, position of the earthing in longitudinal direction of the pipeline and its position transverse to the pipeline. Central positioning of the earthing relative to the pipeline to be protected, i. e., location in the middle of the section to be protected, is usually the most advantageous. Generally, the earthing can be situated at any point along the pipeline to be protected, but in that case the distribution of the protective current is not uniform at both sides of the earthing structure and it will be necessary to apply a current source of higher capacity. Placing of the earthing structure elsewhere than in the middle of the section to be protected is justified only if the pipe diameter is not uniform for the entire pipeline, if the state of the insulation along the pipeline is not uniform, or if the soil resistance at the individual sides of the earthing is not equal, and a non-central location of the earthing ensures equal parameters of the protective current in each direction from the earthing point.

The location of the earthing in transverse direction relative to the pipeline to be protected is of minor importance. It is advisable to avoid placing the earthing too near to the pipeline (the limit being 25 m). However, increasing the distance to 150 - 200 m has hardly any influence on the distribution of the protective potential. Special tests with two earthing structures situated at 30 - 150 m from the pipeline showed that the observed current distribution was similar in both cases. In practical work, a stretch of soil is chosen at 25 - 200 m from the pipeline, depending on the location of soil which has the minimum resistance in the given area.

LOCATION OF VERTICAL EARTHING PARTS RELATIVE TO EACH OTHER

If the individual parts of a vertical earthing system are placed near to each other the total performance will be somewhat reduced since owing to the mutual influence of the individual earthing elements, there will be a screening effect. If there is a screening effect, the resistance of an individual earthing element placed near other earthing elements will be larger than if it is placed alone. The spacing between the individual earthing elements is thus of great importance.

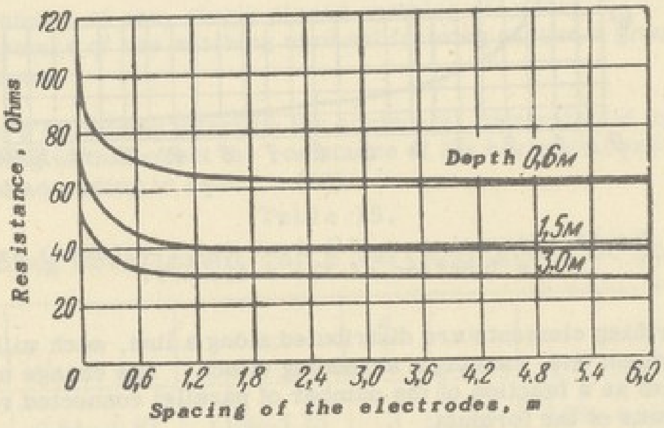


Fig. 54. Relation between the resistance of a vertical earthing element and its distance from the neighbouring one.

Fig. 54, shows the relation between the resistance of an earthing element as a function of the spacing between the individual electrode elements at various laying depths. It can be seen from this graph that the resistance of an element is affected most by the adjacent element of the earthing system. In addition to the absolute value of the distance between the individual earthing elements, the resistance is also influenced by the ratio of this distance to the length of these elements, i. e., a/l. Increase of the resistance due to the placing of the earthing elements into a single line can be determined by the formula:

$$R = R_0 + \Delta R = R_0 + \frac{1}{2\pi k a} \qquad (51)$$

where R - the resistance of tube earthing when there is a screening effect, Ohms;
R_0 - tube resistance in absence of a screening effect, Ohms;
ΔR - resistance increase due to the effect of the adjacent earthing element, Ohms;
a - distance between the individual earthing elements, m;
k - soil conductivity, Siemens m.

The value ΔR can be determined by the formula:

$$\Delta R = \frac{1}{kl}\xi, \qquad (52)$$

where the new value ξ is obtained from the graph Fig. 55, and l is the length of the earthing element in cm.

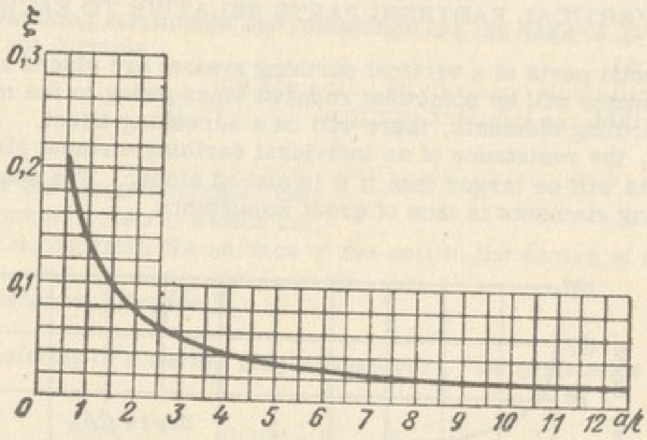


Fig. 55. Screening coefficient (of two tubes) as a function of the ratio a/l.

If several earthing elements are distributed along a line, each will have some influence on the adjacent one, causing a screening effect. The change of the resistance of an earthing element as a function of the number of parallel connected vertical tubes is determined by means of the formula:

$$R'_B = \frac{R_0}{n\eta}, \qquad (53)$$

where R'_B - total resistance of all the earthing tubes, Ohms;
R_0 - resistance of a single earthing element, Ohms;
n - number of earthing elements;
η - screening coefficient, the values of which are given in table 15.

Distribution of the vertical earthing tubes along a curve, and not along a straight line, is applied relatively seldom in pipeline protection systems and may be justified only by shortage of space. Distribution along a curve brings about an increased screening effect and is therefore avoided. Calculation in the case of rectangular distribution can be carried out according to the formula:

$$R = \frac{R_0}{n} + \frac{1}{2\pi k \, 2\varrho_m} \cdot j(n) - \theta, \qquad (53a)$$

where R - resistance of all earthing elements, Ohms;
R_0 - resistance of a single earthing element, Ohms;
n - number of earthing elements of the group;
ϱ_m - radius, equivalent to the perimeter of the circuit, cm;
$j(n)$ - coefficient depending on the number of tubes, the values of which are given in Fig. 56;
θ - coefficient, determined by the formula

$$\theta = \frac{1}{knl} \left(\xi' - \xi \right), \qquad (54)$$

whereby the difference $(\xi' - \xi)$ is determined by means of the diagram, Fig. 57.
k - specific soil conductivity, Siemens cm;
l - length of the earthing part, cm.

The total screening coefficient of the closed circuit:

$$\eta = \frac{R_0}{R'_0}, \quad \dots \quad \dots \quad \dots \qquad (55)$$

where R_0 - resistance of one, singly placed earthing element;
R'_0 - resistance of one earthing element forming part of a group of earthing elements.

There is also a screening effect on the horizontal connection of the vertical earthing elements, and owing to this effect the resistance of the horizontal part is larger than the value obtained according to equation (48).

Table 15.

Screening coefficient for a vertical group of pipes.

$\frac{a}{l}$	n	η	$n \cdot \eta$	$\frac{a}{l}$	n	η	$n \cdot \eta$
1	2	0,84—0.87	1,69—1,75	3	10	0,79—0,83	7,9—8,3
2	2	0.90—0,92	1,81—1,85	1	15	0,51—0,56	7,7—8,5
3	2	0,93—0,95	1,86—1,89	2	15	0,66—0,73	10,0—11,0
1	3	0.76—0,80	2,3 —2,4	3	15	0,76—0,80	11,5—12,1
2	3	0,85—0,88	2,55—2,65	1	20	0.47—0,50	9,5—10,5
3	3	0,90—0.92	2,7 —2,75	2	20	0.65—0,70	12,9—14,0
1	5	0,67—0,72	3,35—3,59	3	20	0,74—0,79	14,8—15,8
2	5	0,79—0,83	3,95—4,15	1	50	0,38—0,43	19,0—21,5
3	5	0,85—0,88	4 25—4,42	2	50	0,56 - 0,63	28.0—31,5
1	10	0,56—0,62	5,6 —6,2	3	50	0,68—0,74	34 —37
2	10	0,72—0,77	7,2 —7,7				

a - tube spacing

The smallest value of η corresponds to $\frac{l}{d} = 20$;

the largest value of η corresponds to $\frac{l}{d} = 68$.

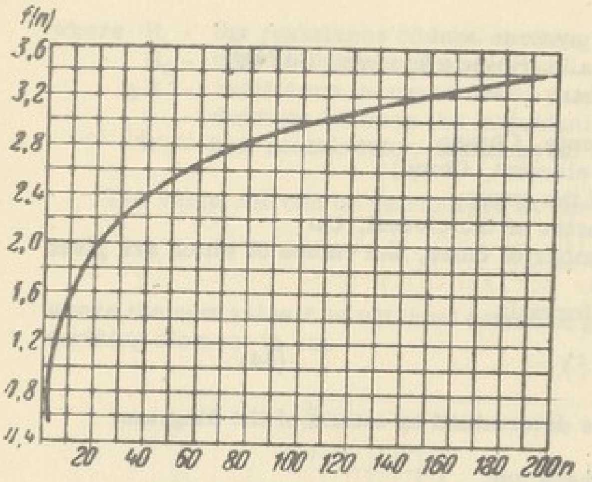


Fig. 56.

Auxiliary curve for n > 50.

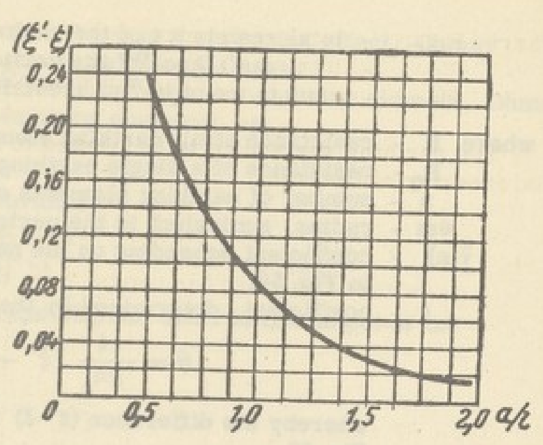


Fig. 57. Correction curve for calculation of the utilisation coefficient.

$$R = \frac{R_0}{n} + \frac{1}{2\pi k 2\varrho_m f(n) - \theta},$$

where ϱm — radius of curvature of an equivalent perimeter

$$\theta = \frac{1}{nkl}(\xi' - \xi);$$

θ — takes into consideration error in the auxiliary curve.

The resistance increase in this case is determined according to the formula:

$$R'_h = \frac{R_h}{\eta_1}, \quad \dots \quad \dots \quad \dots \qquad (56)$$

where R'_h - resistance of the horizontal section taking into consideration the screening effect of the vertical tubes, Ohms;

R_h - resistance of the horizontal section without taking into consideration the screening effect, Ohms;

η_1 - screening coefficient, which can be determined from Table 16.

The depth of laying of the horizontal section should be as great as possible, to reduce the influence of soil freezing. The importance of this measure can be seen from Table 17, which shows that in a particular case the earthing resistance increased to almost 9 times as a result of a drop in temperature from +18 C to -11 C. It is therefore advisable to lay the horizontal header at a depth of 0.5 to 0.8 m and not less than 0.3 m.

The vertical earthing elements are connected by a horizontal header and owing to its considerable length the resistance of the entire system will be noticeably reduced, which has to be taken into consideration in the calculation and design of such earthing systems. The total resistance of the vertical earthing elements which are connected by a horizontal strip can be determined by the formula:

$$R\ \text{total} = \frac{1}{\frac{1}{R'_в} + \frac{1}{R'_г}}, \qquad (57)$$

where R_{total} - total resistance of the entire system Ohms;
R'_{B} - total resistance of the vertical earthing elements, Ohms;
R'_{r} - resistance of the horizontal strip, Ohms.

The earthing resistance is influenced to a large extent by two factors: salt addition and freezing of the soil.

Table 16.

Screening coefficients for the horizontal header tube.

Type of earthing structure	Distribution of the earthing structure in the soil	Ratio tube spacing to tube length	Number of tubes in the row, n								
			3	4	5	8	10	20	30	50	65
A number of tube elements joined in the soil by a horizontal header	In a row	1	0,81	0,77	0.74	0,67	0.62	0,42	0,31	0,21	0,20
		2	0,91	0,89	0.86	0,79	0,75	0,56	0,46	0,36	0,34
		3	0,94	0,92	0,90	0,85	0,82	0,68	0,58	0,49	0,47

Table 17.

Influence of freezing on the earthing resistance of a steel strip placed horizontally in the soil.

Date of test	Air Temperature °C	Resistance of the horizontal strip Ohms
November 1930	—5,5	14
January 1931	—4	57
February 1931	—11	72
March 1931	—5	52
April 1931	+ 12	21
May 1931	+ 18	8,1

NOTE: The figures given in the table are mean values of measured results on three strips each 25 m long, laid in clay soil at a depth of 0.3 m.

As has been said earlier, salt addition is used to reduce the soil resistance and consequently also the earthing resistance. For this soil treatment various salts can be applied namely, calcium chloride, copper sulphate, soda and so on. Most frequently, sodium chloride is used, i. e., common salt, which is easily available and cheap. The decrease of the earthing resistance resulting from addition of salt can be determined by the formula:

$$R_{oc} = \frac{R_o}{\beta_e}, \qquad (58)$$

where R_{oc} - resistance after adding salt, Ohms;
R_o - resistance before adding salt;
β_e - salting (salt adding) coefficient, which can be determined from Table 18

Table 18.

Coefficient for calçulation of the earthing resistance in the case of salt addition to the soil.

ϱ_0, $OM \cdot CM \cdot 10^4$	$\frac{\varrho_0}{\varrho_{oc}}$	R_0	$\beta = \frac{R_0}{R_{oc}}$	βcalc.	Soil
—	—	20	2,3	—	Clay
0,5	1,5	40	2,7	1,5	"
1	2	60	3,2	1,5	Loam
2	2,5	100	4	2	"
3	3,4	150	5	2	Sandy loam
4	4	200	6	2	"
5	4,4	250	6,5	2,5	"
6	5	300	7,5	2,5	Sand
10	8	—	—	2,5	"

NOTES: Tube length 1.5 to 3 m.
Solution of common salt, at least 30-40 kg per pipe with 1-1.5 litres water per kg salt.
ϱ_0 — specific resistance before adding salt;
ϱ_{oc} — specific resistance after adding salt;
R_0 — Resistance of pipe earthing before adding salt;
R_{oc} — resistance of pipe earthing after adding salt;
βcalc. — given taking into consideration the season of the year (rough appr.)

Freezing is the main factor bringing about an increase of the earthing resistance. The influence of freezing on the resistance increase was shown earlier. In practical calculations the effect of freezing is taken into consideration as follows: if the vertical earthing elements are 2. 5 to 3 m long, laid at a depth of 0. 5 to 0. 7 m (measured to the upper end), the freezing coefficient can be assumed as being between the limits 1. 5 - 3. If the vertical earthing elements are 4 m or longer, the freezing coefficient is not taken into consideration, i.e., it is assumed as being equal. For horizontal strips laid at a depth of 0.5 to 0.7 m, the freezing coefficient equals 2 - 4. The increased resistance of the earthing due to soil freezing is determined by the equation:

$$R_3 = R_{0_\varphi} \quad \dots \quad \dots \quad \dots \qquad (59)$$

where R_3 - the resistance of the earthing system taking into consideration the freezing coefficient, Ohm;
R_0 - same resistance without taking into consideration the freezing coefficient, Ohms;
φ - freezing coefficient.

SOIL TREATMENT IN THE EARTHING ZONE

Artificial reduction of the soil resistance can be obtained by one of the following methods:

1) Moistening the soil;
2) salt addition, i.e. saturation of the soil by the solutions of sodium chloride, calcium chloride, soda, copper sulphate;
3) materials which conserve the moisture: coke, slag, soot, crushed charcoal.

The first method is effective only for a few days in the most favourable cases and is useless after that time. Also, it is difficult to carry out during the winter.

The third method considerably reduces the soil resistance but also necessitates frequent moistening.

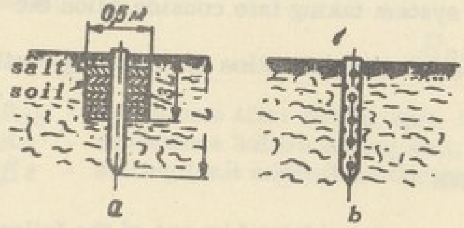
The best results are obtained by addition of salts to the soil. In addition to reducing the soil resistance it also reduces the freezing point, thus conserving the moisture. Salt addition can be done by one of the following methods:

First method. For driving the earthing element into the soil, a hole of 0.5 m diameter and a depth of one third of the length of the earthing element is dug in the soil (Fig. 58a.) The earthing element is then driven into the soil at the bottom of the hole to a depth of the remaining two-thirds of its length and then alternate layers of salt and soil are placed round its upper part. The thickness of each layer is, for instance, 1 cm, and each layer is moistened with water, for example, 1 - 2 litres per 1 kg of salt. The total quantity of salt for each tubular earthing element is usually 30 - 40 kg.

Second method. (Fig. 58b). The earthing tube is provided with holes of 1 cm diameter which are distributed over the entire surface chessboard fashion. There should be six holes for each 20 cm length of the earthing tube. The tube is then driven into the earth to the required depth and a boiled solution of common salt (1-2 litres of water per kg of salt) is poured into the tube; a total of 20-40 kg of salt is required per tube. The solution penetrates through the holes into the surrounding soil, reducing its resistance. This method is somewhat more difficult than the first method because holes have to be drilled into the earthing tubes.

The horizontal section is welded on to the upper ends of the vertical earthing elements; the welding is not done from the top but from the sides as shown in Fig. 59.

Fig. 58. Various methods of soil treatment



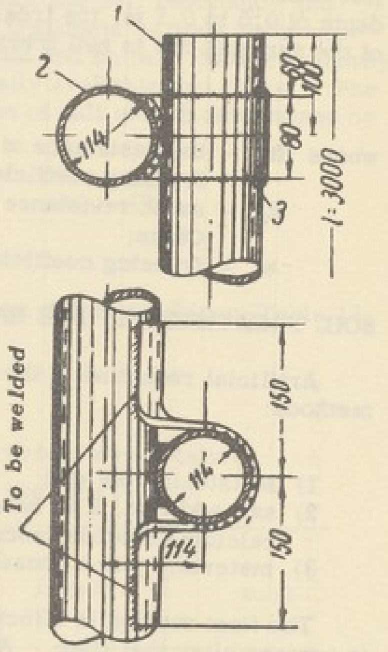


Fig. 59. Joining the horizontal header tube to the vertical earthing tubes.

1 - vertical earthing tubes;
2 - horizontal header tube;
3 - connection strip.

The earthing elements are covered by wooden caps to protect them from becoming clogged with earth. If the vertical earthing element is disrupted after it has been in service for some time due to the action of current, a new earthing element of smaller diameter can be fitted inside it.

CARBON AND GRAPHITE ELECTRODES

Carbon electrodes are also used for earthing in cathodic stations. The fundamental material of such an electrode is carbon or graphite pressed into the shape of a circular bar and impregnated by a special composition or by linseed oil to make it impenetrable to moisture. The length of such bars is 1-2 m. A steel core is provided to increase their strength; the total diameter of such an electrode being 5, 10 or 15 cm.

The advantage of carbon electrodes is their higher durability in soil conditions as compared to metal electrodes; their disadvantage is that their resistance is higher and that connection to the other parts of the circuit is more difficult. Connection of standard electrodes is carried out as shown at the right of Fig. 60. If a prefabricated joint is not available, the connection can be made as shown in Fig. 61.

As can be seen from Fig. 60, a hole of 150 - 200 mm diameter must be dug in the ground for each carbon electrode. Finely ground carbon is poured into the hole and then the electrode is placed into it.

In some cases, earthing of the following design has been successfully used: the vertical tube earthing element is tightly filled with carbon residue from the carbon black plant. Thus, there will be a carbon electrode inside the tube which will continue

Table 19

Resistance of the anode earthing structure.

Designation of the values	Calculation values in the case of special resistance 200 Ohm cm					
	For earthing resistance of approximately					
	0.02 Ohm		0.1 Ohm		1 Ohm	
Length of the vertical tube, cm	300	300	300	300	300	300
Outside diameter of the tube, cm	11.4	11.4	11.4	11.4	11.4	11.4
Depth of laying centre of gravity of tube, cm	230	230	230	230	230	230
Resistance of one vertical tube, Ohms	0.456	0.456	0.456	0.456	0.456	0.456
Coefficient of salt addition	-	-	-	-	-	-
Distance between individual tubes, cm	300	600	300	600	300	600
Resistance of one tube taking into consideration salt addition coefficient, Ohms	0.456	0.456	0.456	0.456	0.456	0.456
Total number of vertical tubes in earthing structure	100	60	10	6	1	-
Length of header tube, cm	29700	35400	2700	3000	-	-
Outside diameter of horizontal header tube, cm	11.4	11.4	11.4	11.4	-	-
Resistance of the header tube, Ohms	0.0144	0.0123	0.103	0.0975	-	-
Screening coefficient of vertical tubes	0.32	0.53	0.57	0.78	1	-
Freezing coefficient	1.8	1.8	1.8	1.8	1.8	-
Total resistance of vertical tubes taking into consideration screening and salt addition coefficients	0.0257	0.0258	0.142	0.173	0.82	-
Screening coefficient of the horizontal tube	0.18	0.35	0.62	0.83	-	-
Freezing coefficient of the horizontal header tube	2.2	2.2	2.2	2.2	2.2	-
Resistance of horizontal header tube taking into consideration screening effect	0.173	0.077	0.368	0.258	-	-
Total resistance of earthing structure, Ohms	0.0224	0.0214	0.103	0.103	0.82	-

Table 19 (contd.)

Designation of the values	Calculation values in the case of special resistance 1500 Ohm cm					
	For earthing resistance of approximately					
	0.02 Ohm		0.1 Ohm		1 Ohm	
Length of the vertical tube, cm	300	300	300	300	300	300
Outside diameter of the tube, cm	11.4	11.4	11.4	11.4	11.4	11.4
Depth of laying centre of gravity of tube, cm	230	230	230	230	230	230
Resistance of one vertical tube, Ohms	3.42	3.42	3.42	3.42	3.42	3.42
Coefficient of salt addition	-	-	-	-	-	-
Distance between individual tubes, cm	300	600	300	600	300	600
Resistance of one tube taking into consideration salt addition coefficient, Ohms	3.42	3.42	3.42	3.42	3.42	3.42
Total number of vertical tubes in earthing structure	900	550	180	100	8	5
Length of header tube, cm	269700	229400	53700	59400	2100	2400
Outside diameter of horizontal header tube, cm	11.4	11.4	11.4	11.4	11.4	11.4
Resistance of the header tube, Ohms	0.0163	0.0186	0.066	0.061	0.962	0.89
Screening coefficient of vertical tubes	0.3	0.5	0.3	0.52	0.61	0.80
Freezing coefficient	1.8	1.8	1.8	1.8	1.8	1.8
Total resistance of vertical tubes taking into consideration screening and salt addition coefficients	0.0228	0.0224	0.114	0.119	1.26	1.54
Screening coefficient of the horizontal tube	0.16	0.16	0.18	0.33	0.67	0.86
Freezing coefficient of the horizontal header tube	2.2	2.2	2.2	2.2	2.2	2.2
Resistance of horizontal header tube taking into consideration screening effect	0.224	0.255	0.806	0.406	3.16	2.27
Total resistance of earthing structure, Ohms	0.0207	0.0206	0.10	0.092	0.91	0.92

F

Table 19 (contd.)

Designation of the values	Calculation values in the case of special resistance 5000 Ohm cm					
	For earthing resistance of approximately					
	0.02 Ohm		0.1 Ohm		1 Ohm	
Length of the vertical tube, cm	300	300	300	300	300	300
Outside diameter of the tube, cm	11.4	11.4	11.4	11.4	11.4	11.4
Depth of laying centre of gravity of tube, cm	230	230	230	230	230	230
Resistance of one vertical tube, Ohms .	11.4	11.4	11.4	11.4	11.4	11.4
Coefficient of salt addition	1.5	1.5	1.5	1.5	1.5	1.5
Distance between individual tubes, cm .	300	600	300	600	300	600
Resistance of one tube taking into consideration salt addition coefficient, Ohms	7.6	7.6	7.6	7.6	7.6	7.6
Total number of vertical tubes in earthing structure	2000	1200	380	220	25	15
Length of header tube, cm	599700	719400	113700	131400	7200	8400
Outside diameter of horizontal header tube, cm	11.4	11.4	11.4	11.4	11.4	11.4
Resistance of the header tube, Ohms ...	0.026	0.022	0.114	0.102	1.22	1.07
Screening coefficient of vertical tubes	0.3	0.5	0.3	0.95	0.5	0.67
Freezing coefficient	1.8	1.8	1.8	1.8	1.8	1.8
Total resistance of vertical tubes taking into consideration screening and salt addition coefficients	0.0205	0.0228	0.120	0.124	1.10	1.36
Screening coefficient of the horizontal tube	0.16	0.16	0.18	0.32	0.37	0.60
Freezing coefficient of the horizontal header tube	2.2	2.2	2.2	2.2	2.2	2.2
Resistance of horizontal header tube taking into consideration screening effect	0.358	0.302	1.4	0.705	7.25	2.79
Total resistance of earthing structure, Ohms	0.019	0.021	0.11	0.105	0.96	0.91

to operate as an earthing electrode after the tube is destroyed by corrosion.

Examples of calculation of earthing systems are given in Chapter VII. Table 19 shows the process of calculation and results obtained for typical earthing systems.

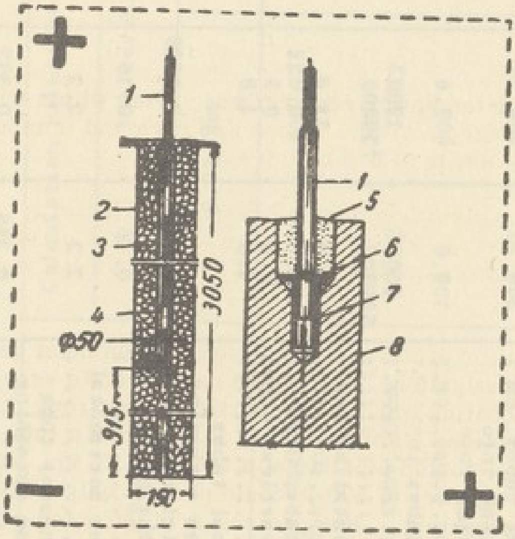


Fig. 60. Carbon electrode for anodic earthing.

1 - insulated conductor; 2 - contour of of the hole in the ground; 3 - filler, broken up carbon; 4 - graphite or carbon rod; 5 - pitch seal; 6 - copper ring; 7 - copper terminal; 8 - moisture tight carbon or graphite.

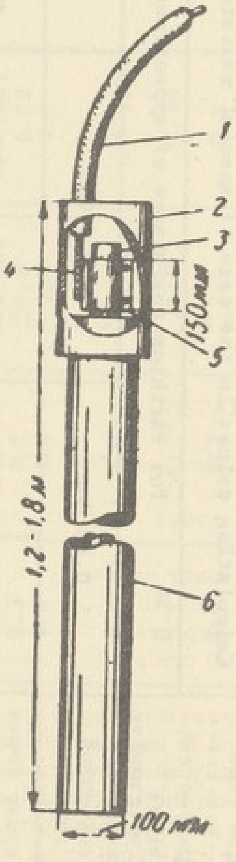


Fig. 61. Connection of the carbon electrode to the insulated wire.

1 - insulated wire; 2 - tube filled with bitumen enamel; 3 - steel core of the electrode; 4 - blank wire soldered to the clip; 5- copper clip; 6 - graphite or carbon electrode.

Chapter VI

CURRENT SOURCES FOR CATHODIC PROTECTION SYSTEMS

POWER RATING

In existing cathodic protection stations the power requirement varies within wide limits, from 10 W up to 15-20 kW. However, extreme values are rare and in most cases the power requirement is within the limits of 0.4 to 7.5 kW.

The power required for a protection system depends on a number of factors, mainly, 1) length of the section to be protected, 2) type and state of the coating of the pipeline, 3) pipeline diameter, 4) wall thickness of the piping, 5) corrosivity of the soil, and 6) design of the anode earthing.

The power rating of a current source for protection of a given section must be determined in each individual case by investigation. The value can fluctuate very considerably with the conductivity of the coating which has a particularly strong influence on the length of the protected section. For instance, in one case a total of 50 W was sufficient for protection of a well coated pipeline of a length of 15 km, whilst in another case equipment operating with a power of 500 W could protect only a 1730 m section of a pipeline with a badly damaged coating. For protection of uncoated pipelines with a very badly damaged coating 1.5 kW was hardly sufficient for protecting a section of only 300 - 400 m.

If a given section cannot be protected by a single station, several stations must be provided along the pipeline. It is then necessary to take into consideration that by increasing the number of stations to an optimum limit the total electricity consumption for the protection can be reduced since energy losses at the stations increase progressively with the power of the station. For instance, for the protection of a pipeline of 6.4 km length, 410 W (41 A x 10 V) were required, the unproductive energy consumption amounting to about 50% of the useful energy consumption. By doubling the number of stations it was possible to reduce the total power required for protection to 45 W (15 A x 1.5 V x 2) and to reduce the unproductive energy consumption to 25 - 30%.

However, increase of the number of cathodic stations is economical only up to a certain limit since the capital costs and the amortisation costs are also increased thereby. A correct solution can only be obtained on the basis of technical and economical calculations.

POSSIBLE CURRENT SOURCES.

Any type of d.c. source can be applied for cathodic protection, particularly the following:

1) d. c. generators driven by : a) electric motors, b) oil engines, c) gas engines, d) wind turbines;
2) converters - rectifiers, particularly: a) mercury arc rectifiers, b) copper oxide rectifiers, c) selenium rectifiers, d) valve rectifiers;
3) batteries (accumulators) namely: a) acid batteries, b) alkaline batteries;
4) dry batteries;
5) galvanic cells.

The choice of a d. c. current source depends in many cases mainly on the required power. Although it is difficult to apply rigid rules, the following data are given for guidance:

1) for larger power requirements, 1. 5 to 7. 5 kW and more, it is usually most convenient to use generators driven by electric motors, oil engines, or gas engines;
2) for medium power requirements, 0. 5 to 1. 5 kW it is most convenient to use dynamos driven by petrol engines, wind turbines, or rectifiers;
3) for small ratings, 50 - 500 W, it is usually most convenient to use rectifiers if a current supply is available, and in absence of a power supply a wind turbine driven generator or an accumulator;
4) for very small power requirements, 10 to 100 W, it is best to use a rectifier and in absence of a power supply an accumulator or a galvanic cell.

When selecting a current source, it is necessary to take into consideration that it is often possible to reduce the power rating of an individual station by increasing the number of stations, as has been mentioned earlier.

The advantages of rectifiers are so considerable that their utilisation is justified in all cases where an a. c. supply of sufficient power is available.

RECTIFIERS.

The main advantages of rectifiers as compared to other d. c. sources are: 1) absence of moving parts, thereby eliminating the necessity of constant supervision; 2) small size, which enables frequent installation of the rectifiers without erecting a special building; 3) simplicity of maintenance; 4) stability of operation; 5) high efficiency; 6) low first costs.

However, if the a. c. supply is distant from the location of the cathodic station, the use of a rectifier is not economical, particularly for distances exceeding 2 km. The final solution in such cases should be determined by technical and economical calculations.

SELENIUM RECTIFIERS.

Of all types of rectifiers, selenium rectifiers are at present the most widely used. Their efficiency equals 75-85%.

Selenium rectifiers, compared to other types of rectifiers, have the following advantages: longer life, considerably smaller volume, low sensitivity to air humidity, resistance to operating temperatures of up to 75 - 85 C without ageing. They withstand a reverse voltage of twice the value of a cuprous-oxide rectifier.

The limiting rating of selenium rectifiers produced at present (in the Soviet Union) does not exceed 5 kW. Table 20 gives the data of selenium rectifiers produced in the USSR. The outside view and a circuit diagram of one of these (VSA-1) is shown in Fig. 62.

Table 20.

Data of selenium rectifiers.

Designation	Current supply: Single phase	Rectified current		Rectifier dimensions, mm; width x length x height	Weight kg	Regulation method
		V	A			
VSG-3	220 V	6	180 ± 20	640 × 427 × 1502	150	—[1]
VSG-3V	220 V	6	180 ± 20	640 × 427 × 1502	150	—[1]
VSA-1	120/220 V	6	12	317 × 158 × 320	20	none
VSA-3M	120/220 V	80	8	460 × 328 × 860	70	—[2]
VSI-2	220 V	4	0.5	95 × 70 × 90	1	none
VSA-6	120/220 V	to 24	to 12	560 × 318 × 550	65	»
VSA-7	120/220 V	to 24	to 24	560 × 318 × 550	65	»

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[1] Charging tappings of the transformer to obtain rectified voltages of 3.5, 4.5 and 6V.

[2] Regulator and magnetic shunt.

CUPROUS OXIDE RECTIFIERS.

These consist of copper discs with cuprous oxide formed thereon and a lead disc placed on the oxidized side. These rectifiers are now being displaced by selenium rectifiers on an increasing scale. The data of cuprous oxide rectifiers produced by the Kozitsk Works are given in Table 21.

The individual elements of the cuprous-oxide rectifiers (and also of the selenium rectifiers) can be connected in parallel or in series, as required.

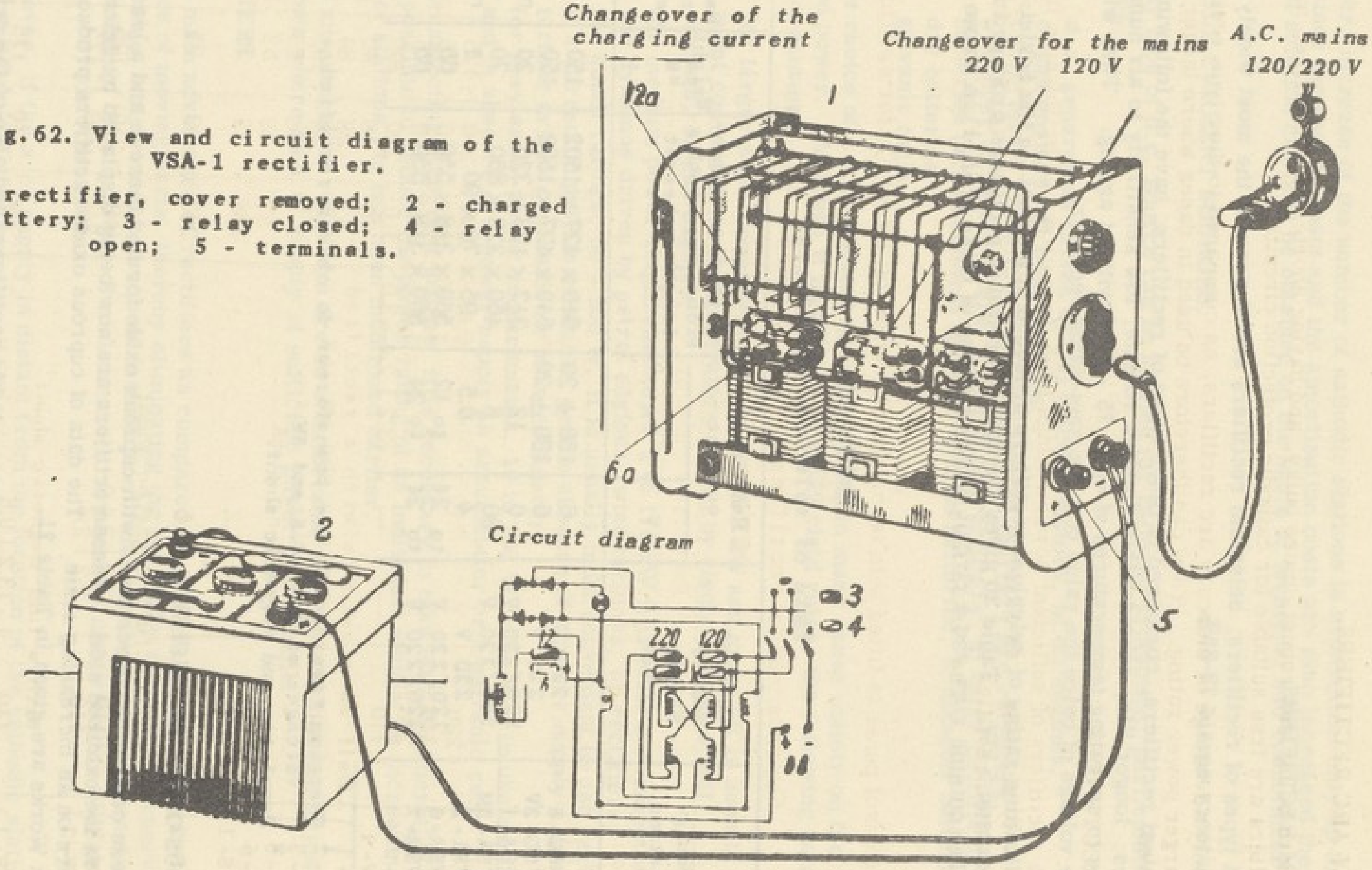


Fig.62. View and circuit diagram of the VSA-1 rectifier.

1 - rectifier, cover removed; 2 - charged battery; 3 - relay closed; 4 - relay open; 5 - terminals.

MERCURY ARC RECTIFIERS.

Owing to being less robust, more bulky, and having shorter service lives, mercury arc rectifiers are less suitable for cathodic protection circuits.

The only advantage of mercury arc rectifiers, as compared to disc type rectifiers, is their larger power rating. They can therefore be used in cases where larger currents are required.

VALVE RECTIFIERS.

Valve rectifiers of sufficient power ratings have been produced by Russian industry only relatively recently. One type of such rectifiers is the VG-1-B of 144 W operating with a gas-filled rectifier tube VG-176. The weight of this rectifier is 15 kg, its size 330 x 265 x 400 mm. The circuit diagram and a view of this rectifier are shown in Fig. 63.

The control panel is fitted with terminals (1), an on-off switch (2) for switching the

Table 21.

Cuprous oxide rectifiers (from the Radio Manual, GINKIN. 1948).

Designation and type of rectifier	Voltage supplied to the rectifier	Rectified current				Dimensions, mm			Weight, kg
		With shunt on		With shunt off		Length	Width	Height	
		V	A	V	A				
TV-1	220	4	0,45	6,0	0,6	236	210	175	6,5
KP-1	110	2	1	4	1,5	236	210	175	6,5
KP-2	220	2	1	4	1,5	236	210	175	6,5
KTV-1	110	—	—	13,2	2.4—3.0	310	220	200	13
KV-1	Half wave columns with a rectified current of 250 - 300 mA and a reverse current not exceeding 8 mA					70	48	46	from 0,25 to 0,75
KV-2						62	48	80	
KV-3						62	48	105	
KV-5							48	55	
KV-6						57	48	63	
NKS-1	50	24	1,2 or			188	10	75	1,65
NKS-2		32	0,6			263	10	75	3,0
	With a full magnetic shunt								
PTV-1	110	2,2	2,4			240	210	175	6,5
PTV-2	110	2,2	2,4			240	210	175	6,5
	With a full magnetic shunt								
STV-1	110	13,2	0,6			240	210	175	6,55
STV-2	110	13,2	0,6			240	210	175	6,50

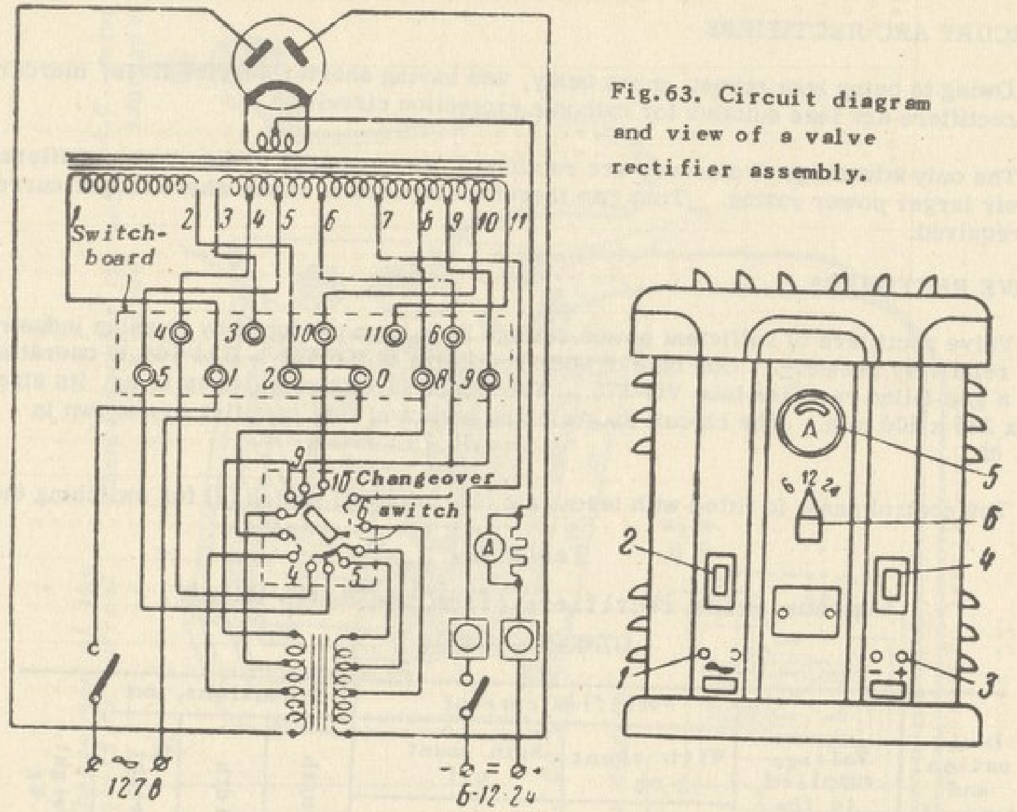


Fig. 63. Circuit diagram and view of a valve rectifier assembly.

rectifier on and off to the a. c. supply of 110, 127 or 220 V, terminals (3), switch 4 for switching on batteries for charging, and ammeter (5) for measuring the charging current, a change-over switch (6) for changing over the rectifier circuit to d. c. voltages of 6, 12 or 24 V. The rectifier is designed to operate on 110, 127 and 220 V, 50 c. p. s. current. The rectified d. c. voltage depends on the position of the change-over switch and can be 6, 12 and 24 V with a current of 6 amps. in each case. A weakness of valve rectifiers is the rectifier tube which is very sensitive to shock and vibration and which must be kept in a vertical position during storage and transport.

DYNAMOS.

If there is no local current supply available, the current must be produced by a dynamo driven by some type of engine. Since an electric motor requires a current source, and the use of an IC engine requires continuous day and night operation involving consumption of fuel, lubricant, and provision for housing the equipment, it is preferable to use wind turbines.

WIND TURBINE EQUIPMENT.

Cathodic protection stations are frequently located directly along an oil pipeline in the open field where continuous maintenance of the wind turbine and the generator is

Table 22.

Average monthly and average yearly wind speeds (in the USSR).

Geographical location	Months												Yearly average without correc- tion co- efficient	Yearly average with correc- tion co- efficient
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII		
Ay Petri	7,3	6,9	6,2	6,1	4,7	5,0	5,2	5,3	5,6	5,3	6,3	7,0	5,9	6,2
Alexandrovsk	6,1	5,9	5,9	5,0	4,8	4,6	4,1	4,0	4,6	5,6	5,6	5,8	5,2	5,9
Alexandrovsk (Sakhalin)	5,1	4,1	5,4	4,8	4,2	3,5	3,4	4,1	3,1	6,8	6,9	6,1	4,2	4.5
Arkhangelsk	4,1	4,1	4,0	3,6	4,0	3,9	3,2	3,5	4,2	4,5	4,5	4,2	4,0	4.65
Akhtuba	4,7	4,9	5,2	5,0	4,4	4,0	3,5	3,8	3,8	4,2	4,4	4,5	4,4	5.1
Blagoveshchensk	2,0	2,3	3,1	4,2	3,7	3,4	2,6	2,7	2,8	3,2	2,6	2,2	2,9	3.5
Vaygach	9,8	8,8	8,5	8,2	6,9	6,0	6,9	5,9	7,2	7,5	8,7	8,9	7,8	9.8
Veliki Ustyug	3,4	3,2	3,7	3,4	3,8	3,3	3,0	2,9	3,7	3,8	3,9	3,6	3,5	4.03
Vladimir	5,3	5,6	5,1	4,5	4,1	3,3	3,4	3,4	4,1	4,7	5,0	4,6	4,4	5.3
Vologda	6,6	5,9	6,6	6,4	5,8	5,0	4,5	4,4	5,7	6,6	6,5	6,3	5,9	5.7
Voronezh	6,1	5,6	5,1	5,1	4,9	4,1	3,8	3,7	4,2	5,2	5,3	5,4	4,9	5.7
Voroshilovgrad	7,0	7,1	8,1	7,3	5,4	5,0	4,6	4,7	4,7	6,4	6,5	7,2	6,1	6.7
Voroshilovsk	4,0	5,9	6,0	5,1	3,9	2,7	3,2	2,9	2,4	4,6	3,6	4,5	4,1	4.9
Vyazma	4,5	4,8	3,9	3,6	3,9	3,1	2,8	3,1	3,6	4,1	4,6	3,8	3,6	4.0
Gdov	5,0	4,7	4,9	4,3	4,6	5,0	4,3	4,4	5,3	6,0	5,7	4,7	4,9	6.1
Gorki	4,8	4,6	4,6	4,3	4,0	3,7	3,4	3,4	4,2	4,9	5,0	4,7	4,3	4.8
Dnepropetrovsk	3,9	4,0	3,7	3,6	3,1	2,8	2,6	2,6	2,8	3,1	3,3	3,6	3,3	4.2
Eniseysk	2,3	2,2	2,5	2,6	3,0	2,4	1,8	1,9	2,3	3,0	3,3	2,3	2,4	3.0
Irbit	3,4	3,4	3,6	4,0	4,1	3,1	3,0	3,2	3,5	3,8	3,9	3,5	3,5	3.8
Irkutsk	2,2	2,3	2,8	3,4	3,4	2,8	2,2	2,2	2,6	2,8	2,3	1,7	2,5	2.9
Karabi Yayla	7,3	7,2	7,8	8,1	6,6	6,2	5,4	6,1	6,6	7,0	7,0	7,7	6,9	7.6
Kern Port	5,1	5,2	5,0	5,1	4,7	4,4	4,2	4,7	4,6	5,1	4,7	5,1	4,9	5.9
Kirov	5,2	5,3	5,4	5,0	5,0	4,2	3,7	4,2	4,9	5,5	5,6	4,8	4,9	5.4
Kostorma	4,4	4,4	4,1	3,6	3,6	3,5	3,1	3,2	3,5	3,7	4,1	4,3	3,8	4.2
Kuzneck	4,3	3,9	4,2	3,5	3,9	3,1	2,6	2,5	3,3	4,2	4,2	4,0	3,7	4.5
Kursk	5,0	5,1	5,1	4,8	4,4	3,9	3,8	3,8	4,3	4,5	4,9	4,7	4,5	5.2
Maloyaroslavec	4,1	4,0	4,5	3,8	3,6	3,6	3,0	2,8	3,4	3,9	4,5	3,8	3,8	4.6
Mariupol	4,7	5,0	4,7	4,6	4,3	3,9	3,4	3,9	4,0	4,4	4,2	5,1	4,3	4.9
Markhotski Pereval	10,9	10,4	10,0	9,2	8,0	7,1	6,9	7,6	8,3	9,2	10,5	10,5	9,0	9,0
Matochkin Shar	7,1	7,6	8,6	7,2	6,6	7,2	6,6	5,0	6,2	7,0	7,9	6,8	6,9	7,6
Minsk	4,2	4,6	5,2	4,8	4,2	3,6	3,6	3,4	3,5	3,9	4,3	4,6	4,2	4,8
Mogilev	4,5	4,3	4,8	4,0	3,6	3,8	3,7	3,4	3,5	4,4	4,5	4,1	4,1	4,9
Moskva	4,6	4,6	4,7	4,3	4,1	3,5	3,2	3,3	3,9	4,3	4,6	4,4	4,1	4.26

Table 22 (contd.)

Geographical location	Months												Yearly average without correction coefficient	Yearly average with correction coefficient
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII		
Narim	2,5	2,5	2,6	2,6	3,2	3,3	2,6	2,8	3,0	3,3	3,2	2,8	3,0	3,8
Novorossiysk	5,2	5,4	6,0	5,1	4,7	4,1	4,2	3,9	4,1	5,0	5,0	5,0	4,8	5,4
Novosibirsk	3,6	3,2	3,6	3,2	3,3	2,8	2,3	2,5	2,8	3,7	3,8	3,5	3,2	3,6
Novocherkask	5,0	5,8	4,5	4,4	4,2	3,5	3,1	3,4	4,5	4,6	4,0	4,5	4,5	4,5
Obdorsk	3,9	3,7	4,4	5,1	5,7	6,2	5,3	5,5	5,0	5,7	4,5	4,2	4,9	6,0
Odessa	5,7	5,7	5,5	5,6	4,6	4,1	4,0	4,0	4,5	4,8	5,2	5,4	4,9	5,4
Olonets	4,1	3,6	3,9	3,9	3,8	3,6	3,7	3,6	3,3	4,6	4,2	4,2	3,9	4,8
Orel	4,4	4,5	4,3	4,2	3,8	3,2	2,8	3,0	2,6	3,7	4,0	4,1	3,8	4,7
Okhotsk	4,3	3,9	3,6	3,8	3,6	4,0	3,7	3,4	4,0	4,7	5,1	4,7	4,1	5,5
Pensa	3,5	3,4	3,2	2,6	2,7	2,6	2,1	2,2	2,8	3,1	3,2	3,0	2,9	2,9
Molotov	4,0	4,1	4,4	4,8	4,0	3,8	3,0	3,3	3,6	4,4	4,5	4,0	3,9	4,3
Petrozavodsk	5,2	4,8	5,0	4,4	4,4	4,2	4,0	4,3	5,4	5,0	5,3	4,9	4,8	5,8
Petropavlovsk	4,9	5,2	5,2	4,8	4,6	4,3	3,7	3,7	4,1	4,8	5,3	4,8	4,6	5,7
Pinega	3,9	3,8	4,4	3,6	4,1	3,7	3,1	3,1	3,7	3,5	4,1	3,7	3,8	4,8
Poltava	4,0	3,8	4,9	4,1	4,1	2,8	2,8	3,0	3,7	4,6	4,3	3,8	3,8	5,2
Pskov	4,3	4,3	4,4	3,7	3,8	3,6	2,9	2,8	3,6	4,4	4,3	4,3	3,9	4,8
Rzhev	4,5	4,3	4,3	3,6	3,7	3,4	3,1	3,3	3,7	3,6	4,3	4,1	3,8	4,7
Rostov on Don	5,2	5,1	4,8	4,8	4,3	3,8	3,6	3,8	4,0	4,2	4,6	4,7	4,4	4,7
Sarapul	3,7	3,9	3,6	3,4	3,5	3,4	2,9	3,2	3,4	3,4	3,5	2,7	3,4	3,6
Saratov	5,6	4,6	4,9	4,4	4,0	3,7	3,6	3,2	4,2	5,2	4,7	4,8	4,4	4,6
Sverdlovsk	4,6	4,5	4,8	4,8	4,6	4,0	3,8	3,9	4,4	5,1	5,1	4,4	4,5	4,6
Sevastopol	5,2	5,3	5,2	5,1	3,9	4,4	4,1	4,3	4,4	4,7	4,8	4,7	4,7	4,5
Smolensk	4,1	3,7	3,7	3,5	3,0	2,6	2,5	3,1	3,6	4,1	4,0	3,5	3,45	4,0
Stalingrad	6,3	6,3	6,9	6,0	5,5	5,3	4,8	4,7	4,7	5,5	5,3	5,8	5,7	6,1
Sum'i	5,5	5,1	5,4	5,0	4,3	3,6	3,4	3,7	4,1	4,7	5,7	5,3	4,6	5,0
Tobolsk	4,1	4,3	4,3	4,5	4,8	4,2	3,6	3,4	3,8	3,9	3,9	3,9	4,1	4,5
Turgay	5,7	6,2	6,3	5,8	5,4	4,7	4,4	4,4	5,0	5,1	5,0	5,1	5,2	5,7
Uralsk	4,0	4,4	4,3	4,3	4,2	3,8	3,5	3,6	3,9	3,9	4,1	4,1	4,1	4,5
Ust Kamchastk	6,0	5,9	5,2	4,8	3,2	4,6	3,4	3,4	2,9	3,1	4,3	6,2	4,4	5,6
Ufa	5,5	5,4	6,4	5,5	5,0	4,6	4,0	2,9	4,8	5,9	6,5	5,4	5,2	5,2
Kharabovsk	2,7	2,0	3,1	3,2	2,6	2,6	2,4	2,4	2,6	3,6	3,2	3,2	3,1	3,9
Kharkov	3,7	3,9	3,7	3,6	3,4	3,0	2,8	2,9	3,3	3,2	3,6	3,5	3,4	3,7
Kherson	4,6	4,7	4,4	4,3	3,5	3,2	3,1	3,3	3,3	3,7	4,1	4,3	3,9	4,4
Chelyabinsk	3,1	3,0	4,2	3,8	4,0	3,5	3,4	3,3	3,2	3,6	3,8	2,7	3,5	3,5
Cherdin	3,1	3,8	3,5	3,4	3,4	3,8	3,3	2,9	3,5	3,7	3,4	3,1	3,4	3,7
Chkalov (Orenburg)	4,8	4,6	4,9	4,5	4,4	3,9	3,7	3,5	4,1	4,4	4,5	4,6	4,3	4,2

not possible. It is therefore essential to use wind-driven equipment of such types as do not require attention more than once or twice a week. Most types of wind engines produced in Russia require continuous attention and the possibility of using them on a large scale for current generation in cathodic protection stations is therefore limited to some extent. However, individual types of wind turbines (of small power ratings) are already available which comply with the above mentioned requirements and can be applied successfully for cathodic protection at points which are far away from inhabited areas.

The possibility of using wind engines also depends on the average speed and duration of wind where the turbine is to be erected. Most types of wind turbines start to operate only if the wind speed exceeds 4 m/sec. and some require wind speeds of at least 5 m/sec. Only some wind turbines of small power ratings are able to operate at wind speeds from 3 m/sec. onwards. Therefore, the first requirement which has to be fulfilled before wind power can be used is that the meteorological conditions are suitable for the purpose. The wind speed is highly variable and therefore for characterising the wind in a given area average yearly and monthly indices are applied. The average monthly speed values for various places in the Soviet Union are given in Table 22. From the average yearly and monthly wind speeds the effective duration of the wind of a given speed can be determined with a satisfactory degree of accuracy. Fig. 64, gives curves 24) of the wind speed distribution in per cent of their effective duration as a function of the average speed. The number of hours per year of the availability of wind (of various given speeds) according to M. M. Pomorts are given in Table 23, and according to Gullen are given in Table 24.

On the basis of the average yearly wind speeds given in these tables the operation of a selected wind generator can be determined. The "repetition" curves according to Gullen are more accurate for zones with higher average yearly wind speeds, whilst the curves according to Pomorts are more accurate for zones with low average yearly wind speeds. The operation time of the wind generator determines the operation time of the cathodic protection system.

The question of continuous operation of the cathodic protection being necessary has been a subject of investigation ever since cathodic protection was first used. At the beginning the opinion was held that an interruption lasting 25% of the total time is not

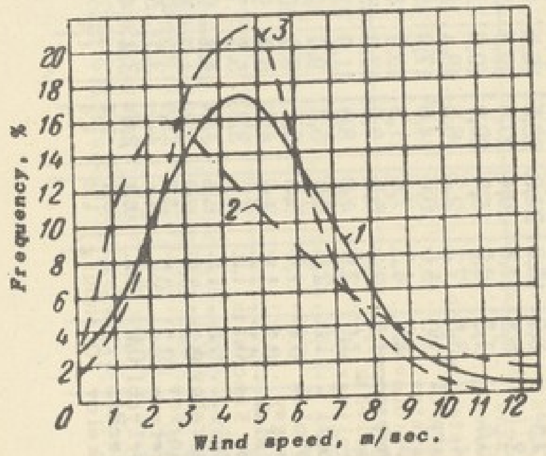


Fig. 64. Wind frequency curves.

1 - according to Pomorts; 2 - according to Gullen; 3 - amenograph recordings at the TsVYen tower between 1927 and 1943.

Table 23.

Frequency of wind speeds in percent according to Pomorcev.

Average yearly wind speed m/sec	Frequency of various wind speeds in percent for a given average speed in m/sec.																				
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	25,5	41,0	25,0	7,5	1,0	0,9	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1,5	11,8	32,0	28,0	16,0	5,0	1,0	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
2	10,0	23,0	29,8	23,0	10,0	3,8	0,6	—	—	—	—	—	—	—	—	—	—	—	—	—	—
2,5	9,0	16,0	24,0	23,5	16,0	8,0	3,0	0,5	—	—	—	—	—	—	—	—	—	—	—	—	—
3	5,8	11,8	19,4	27,7	19,5	12,0	6,0	2,2	0,7	—	—	—	—	—	—	—	—	—	—	—	—
3,5	1,5	9,0	15,0	20,0	19,0	15,0	9,5	5,0	2,0	0,5	—	—	—	—	—	—	—	—	—	—	—
4	3,5	7,2	12,2	16,5	18,4	16,5	12,2	7,3	3,6	1,7	0,6	0,3	—	—	—	—	—	—	—	—	—
4,5	3,0	5,0	10,0	14,0	17,0	16,5	14,0	10,0	5,5	3,0	0,65	0,5	—	—	—	—	—	—	—	—	—
5	2,0	4,3	7,8	11,3	15,0	16,5	15,0	12,0	8,0	4,3	0,8	0,6	0,3	—	—	—	—	—	—	—	—
5,5	1,5	3,3	6,0	9,5	13,0	15,0	15,5	13,2	10,0	6,5	3,2	1,8	0,8	0,5	0,2	—	—	—	—	—	—
6	1,0	2,6	4,8	8,0	11,0	13,8	15,0	14,0	10,0	8,0	6,0	3,5	1,5	0,6	0,3	—	—	—	—	—	—
6,5	1,0	2,0	4,0	6,4	9,0	12,0	14,0	14,0	11,0	9,5	6,0	4,2	2,5	1,5	0,5	0,1	—	—	—	—	—
7	0,6	1,7	3,0	5,4	8,0	10,6	12,6	13,5	12,3	11,0	8,2	5,7	3,5	2,0	0,8	0,4	0,2	—	—	—	—
7,5	0,5	1,4	2,4	4,3	6,8	9,0	11,4	12,8	12,5	11,4	9,5	7,0	5,0	3,0	1,8	0,9	0,3	—	—	—	—
8	0,5	1,0	2,1	3,8	5,6	7,8	10,0	11,8	12,5	11,8	10,2	8,2	5,9	4,0	2,3	1,3	0,7	0,3	0,2	—	—
8,5	0,5	1,5	1,8	3,0	4,8	6,8	9,0	10,5	11,0	11,5	10,5	9,0	7,0	6,0	3,5	2,0	1,0	0,5	0,4	—	—
9	0,2	0,7	1,6	2,6	4,9	5,7	8,0	9,6	11,0	11,3	11,0	9,7	8,0	6,0	4,2	2,8	1,8	1,0	0,6	0,2	—
9,5	0,2	0,5	1,2	2,2	3,5	5,0	7,0	8,5	10,0	11,0	11,0	10,0	8,5	7,0	5,3	3,5	2,5	1,5	1,0	0,4	0,2
10	0,0	0,2	0,8	2,0	3,2	4,5	6,0	7,8	9,0	10,0	10,2	10,0	9,1	7,8	6,0	4,8	3,3	2,2	1,5	0,9	0,7

Table 24.

Frequency of wind speeds in hours per year according to Gullen.

(v_0 - average yearly wind speed)

v, m/sec.	$v_0 = 4$, m/sec.	$v_0 = 5$, m/sec.	$v_0 = 6$, m/sec.	$v_0 = 7$, m/sec.	$v_0 = 8$, m/sec.	$v_0 = 9$, m/sec.	$v_0 = 10$, m/sec.
to 0,5	368	245	172	130	103	83	65
0.5—1,5	1104	788	585	453	369	300	245
1,5—2,5	1505	1167	919	739	615	508	432
2,5—3,5	1449	1230	1025	863	735	625	543
3,5—4,5	1223	1139	1011	887	775	682	601
4,5—5,5	953	979	933	854	771	694	625
5,5—6,5	698	803	819	787	735	676	622
6,5—7,5	490	634	696	701	678	643	605
7,5—8.5	336	485	576	611	612	599	575
8,5—9.5	233	362	464	522	545	546	534
9,5—10,5	153	269	367	436	476	490	490
10,5—11,5	94	201	286	359	408	435	445
11,5—12,5	59	146	224	292	346	383	400
12,5—13,5	40	102	177	237	290	333	358
13,5—14,5	28	68	137	191	242	285	316
14,5—15,5	19	46	102	155	199	244	277
15.5—16,5	8	33	75	126	165	206	240
16,5—17,5	—	25	54	99	137	174	208
17,5—18,5	—	19	39	77	115	147	180
18,5—19,5	—	14	30	59	96	126	154
19,5—20,5	—	5	23	44	74	107	132
20,5—21,5	—	—	18	33	58	90	115
21,5—22,5	—	—	14	27	46	74	100
22,5—23,5	—	—	10	22	36	61	86
23,5—24,5	—	—	4	18	28	49	73
24,5—25,5	—	—	—	14	23	39	60
25,5—26,5	—	—	—	12	20	31	50
26,5—27,5	—	—	—	8	17	25	41
27,5—28,5	—	—	—	4	14	20	34
28,5—29,5	—	—	—	—	12	18	27
29,5—30,5	—	—	—	—	9	16	22
30,5—31,5	—	—	—	—	8	14	19
31,5—32,5	—	—	—	—	3	11	17
32,5—33,5	—	—	—	—	—	9	14
33,5—34,5	—	—	—	—	—	8	12
34,5—35,5	—	—	—	—	—	6	11
35,5—36,5	—	—	—	—	—	3	9
36,5—37,5	—	—	—	—	—	—	9
37,5—38,5	—	—	—	—	—	—	7
38,5—39,5	—	—	—	—	—	—	5
39,5—40,5	—	—	—	—	—	—	2

harmful to the protected structure. It was assumed that owing to polarisation the protective effect continues during interruptions, provided these do not last longer than 1 - 2 days. However, later investigations showed that 2 to 2.5 hours after switching off the protective current, the potential of the "pipeline-soil" is reduced to a value which is lower than that required for full protection. Fig. 28, shows, for instance, that even if the initial potential is double that required for full protection, the metal is no longer sufficiently protected 2 hours after switching off the protective current. It is therefore considered essential to provide continuous protective current so that there are no interruptions in the current supply lasting longer than 1 - 1.5 hours. If the interruption of operation of the wind motors lasts longer owing to meteorological conditions, it is necessary to apply an alternative current source (usually accumulators) during such interruptions, or to accept the fact that during these interruptions the protection of the pipeline concerned is inoperative.

The wind driven wheel is fitted on a mast or a supporting structure. The generator can be fitted either at the bottom, coupling it to the wind wheel shaft by means of a vertical shaft, or at the top coupling it directly to the shaft of the wind motor.

A very important part of the wind motor is the speed regulator, the function of which consists of maintaining constant speed (r.p.m.) of the generator shaft. This is attained either by deflecting the entire wind wheel from the direction of maximum wind intensity or by deflecting the individual blades of the wheel.

The height of the supporting structure and its siting must thus be chosen so that the windpower is utilised as fully as possible. Frequently, the wind speed is reduced near the earth surface due to the variations of the ground and it increases rapidly with height. It is also important that the wind wheel is not screened from the wind by other structures in the neighbourhood.

From the technical point of view it is advisable that a wind turbine is sited in an open space, at the top of a gentle slope where there is no turbulence due to a rapid change of the relief, and as far as possible from forests, high structures and so on. However, local conditions sometimes make it possible to disregard some of the aforementioned requirements. For instance, local winds may permit the erection of the wind turbine in a valley. In one case, a wind turbine was sited between two mountains which formed a narrow corridor through which winds were constantly blowing. If wind charts indicate that winds in a direction transverse to the "corridor" are rare, it is advisable to place the wind wheel near the point where power is required between the mountains and not on top of the mountains as would at first seem advisable.

Over forty types of wind turbines have been developed in the Soviet Union and after investigation only five were recommended for production on an industrial scale. One of these is the wind-electric plant VD-3.5, which is of the high speed type with a wheel diameter of 3.5 m. Its shaft is coupled to the generator of a constant output of 1000 W by means of a reduction gear. The normal speed of the wind wheel is 400 r.p.m. The equipment also contains a storage battery of 144 AH capacity, 24 V, which supplies current when the wind turbine is not operating. The total weight of the assembly is approximately 180 kg and it is suitable for use in places where the average yearly wind speed does not exceed 4 m/sec.

A second type of wind turbine suitable for cathodic protection and recommended for

Table 25.

Characteristics of the wind motor D-12.

Designation	Type TsVYeL	Type VIMYe
Wind wheel diameter, m	12	12
Number of blades	3	3
Height of wind motor axis above ground, m	12	16
Wheel r.p.m.	55–70	55–70
Non-uniformity of the rotation speed of the wind motor	±1,6–2,6	±1,6–2,6
Coefficient of utilisation of the wind	0,35	0,35
Range of operating speeds of the wind, m/sec	4–50	4–40
Rated ouput at wind speeds of 8 m/sec, HP	15,5	1 5,5
R.P.M. of the wheel of the reductor gear	640	420
Continuous rating of dynamo type MP-510 (n = 1400 r.p.m., 115/160 to 220 V) kW	13,5–15	8,5–10,5
Span of the feet of the structure at the foundation, m	3,2	3,8
Dimensions of the angles of the feet of the structure in foundation, mm	90 × 100 × 10	75 × 75 × 10
Total weight, kg	5897	4946
Comprising:		
windwheel	1129	955
tower and vertical shaft	2553	2501
lower reduction gear	400	269

Table 26.

Output of the wind motor TsVYeN D-12 at the generator terminals at various wind speeds for 60 r.p.m.

Wind speed m/sec.	4	5	6	7	8	9	10	11	12 and over
Output at generator terminals kW	0,7	2,4	3,8	5,5	7,2	8,7	10,4	12,2	13,5

series production is the type D-12, which is a high-speed wind turbine with a three-blade wind wheel. The main characteristics of two models of this wind motor (which show only slight differences in design) are given in Table 25. The power available at the generator terminals depends on the wind speed and is given in Table 26.

The wind turbine VISKHOM UD-1.9 designed by V. V. Utkina-Egorova [20] should also be mentioned. Its main characteristic is that it can operate reliably without interruptions and without any attendance for a long time, of the order of two years. Investigation of such a wind turbine, which was in operation for 20 months in arctic conditions, showed that its operation is fully satisfactory. A three-phase generator with permanent magnets is fitted directly on the shaft of the wind wheel which has a diameter of 1.9 m. The generator is covered by a hood which has a tail for turning the wind wheel; the data of this wind motor are given in Table 27.

Table 27.

Characteristics of the a.c. generator of the VISKHOM UD-1.9

Minimum r.p.m.	300
Maximum r.p.m.	900
Rated r.p.m.	840
Output at n = 900 r.p.m.	190 V at 45 V
Output at n = 840 r.p.m.	150 V at 30 V
Number of phases	3
Phase voltage, V	20
Pole number of rotor	32

The generated a.c. is rectified by cuprous-oxide rectifier which is fitted into a box at the bottom of the supporting mast. The output of the generator as a function of the wind speed is given in Table 28. The output at the cuprous-oxide rectifier terminals is 90 to 125 W. The output of this wind turbine is low, also its cost is high and therefore its use for cathodic protection is inadvisable, in spite of the advantages of this machine. However, if this wind turbine is further improved and its cost reduced, it will be a very desirable machine for the purpose under consideration.

Table 28.

Output of the wind-electric set VISKhOM UD-1.9 at various wind speeds.

Eff. wind speed, m/sec	4	5	6	7	8	9	10	11	12
Output at gen. terminals, V ...	14.5	30.5	46.2	63.0	87.5	114,5	136	160	160

Other types of wind turbines, e.g., VIMYe D-3, VISKhOM D-3, PD-3, VIMYe D-5, VISKhOM RD-1.5, VIMYe D-18 and others can also be applied for cathodic protection stations, although these are less suitable.

MOTOR GENERATORS.

If an a. c. supply is available, motor-generator sets can be used for supplying the current necessary for cathodic protection in cases where the power requirement is too large for using rectifiers. Any type of motor-generator furnishing current of the required voltage can be used, particularly welding type motor-generators, e. g., type SMG-2, which is driven by a three phase motor MT-61/4 of 10 kW and is designed to supply a continuous load of 250 A at 40 V. The recently manufactured sets of this type are marked SMG-2b.

The portable welding motor-generator SUG-2 consists of a three-phase motor and a welding generator fitted on a single shaft. The data of two types of this set are given in Table 29[25]

Table 29.

Characteristics of the motor-generator set SUG-2.

Type	Generator		Motor			Weight of set, kg	Dimensions, mm		
	Rated Voltage V	Rated current, continuous A	kW	V	r.p.m.		Length	Width	Height
SUG-2 . .	40	250	11,6	127	1450	550	1270	626	1150
SUG-2a . .	25	250	11,6	220 380 500	1450	550	—	—	—

Table 30.

Characteristics of the motor-generator sets SUP

Type	Generator		Motor	Weight of the set kg
	Voltage V	Current rating, continuous A	Output kW	
SUP-0	25	80	4,2	—
SUP-1	30	150	10	350
SUP-2	30	250	11,5	500

Table 31.

Data of motor-generators for cathodic protection installations

Designation	D. C. generator					Type of motor	Set		
	Type	Output kW	Voltage V	Maximum current A	r.p.m.		Efficiency %	cos φ	Weight kg
Charging set AZD-4/30	ZD-4	4	24 + 36	166 + 111	1420	NKB-14/4	61,2	0,863	328
Charging set AZD-7½/30	ZD-7½	7½	24 + 36	312 + 208	1450	MKMB-15/4	67,6	0,87	—
Charging set AZD-7½/60	ZD-7½	7½	48 + 72	156 + 104	1460	MKMB-15/4	68,2	0,87	—
Charging set AZD-12/60	ZD-12	12	48 + 72	250 + 166	1460	MKB-18/4	69,2	0,872	600
Low voltage high current set type AND	ND-(500) 250	3	6/12	500/250	1450	MKB-13/4	50	0,84	—
" " " "	ND-(1000) 500	6	6/12	1000/500	970	MKMB-15/6	67,5	0,815	—
" " " "	ND-(1500) 3750	9	6/12	1500/750	950	MKB-19/6	69	0,825	—

The welding set, type SMP-3 consists of a 36 kW 3-phase motor and a d. c. generator of 40 V, 400 A, mounted on a single foundation plate.

The data of larger stationary motor-generators are given in Table 31; those of motor-generators of smaller output in Table 32.

Table 32.

Data of d.c. generators for cathodic protection

Designation and type of the generator	Output kW	Voltage V	Maximum current, A	r.p.m.	Efficiency %
Two-commutator d.c. generator type ZIN-1000 AN for battery charging	0.432/0.48	36/120	12/4	1800	65
Same, type ZIN-1500 N	0.75/0.75	60/60	12½/12½	2850	70
Same, type ZIN-3000 A	1½/1½	60/60	25/25	220	75

I. C. ENGINES.

In absence of power supply lines, I. C. engines can also be used for driving generators. The choice of the type of engine to be used depends primarily on the local fuel supply; thus, petrol engines can be conveniently used along petrol pipe lines and gas engines along gas pipe lines.

In some cases it may be convenient to use portable generating sets. Data of such sets are given in Table 33.

Table 33.

Main data of the portable set ZhYeS-3.5 used for cathodic protection installations

Rating, kW	3.5
D. C. voltage, V	115/230
Engine: type	L-6/2
output, HP	6
r.p.m.	2200
fuel	petrol (gasoline)
Generator	d.c., type GP-3.5
Dimensions (length, width, height), mm	1128x593x842
Weight, kg	285

Low power paraffin engines can also be used for driving the generators and the characteristics of such engines are given in Table 34.

In some cases it may be advisable to use for cathodic protection installations, I. C. powered welding sets, e. g., the types SAK-2-1, SAK-2-II, SAG-2, SAT-2.

The set SAK-1 consists of a GAZ-K engine [24] of 28 brake HP, 1430 r. p. m., petrol consumption 270 to 300 g/HP, total weight of engine in operating condition, including water and lubricant, 375 kg, and a generator type SMG-2b, which has already been mentioned earlier.

The set SAK-2-II is fitted with a kerosene engine, type U-2, of an output capacity at the output shaft of 20 HP at 120 r. p. m. and a generator type SMG-2d-U, having a rated voltage of 25 V, 1250 r. p. m., 250 A for continuous load. The total weight of the set SAK-2-I is 1050 kg, its maximum dimensions 2250 x 1100 x 1730 mm. The set is mounted on a frame and can be transported on a truck or on bogies.

Table 34.

Data of I.C. engines used in cathodic installations.

Designation and type of engine	Output H.P.	Number of cilinders	Normal r.p.m.	Piston stroke mm	Cylinder dia. mm	Average piston speed m/sec.	Number of strokes
L-3-2 4-stroke stationary petrol engine	3	1	2200	90	60	6,6	4
L-6-2 4-stroke etc. ...	6	2	2200	90	65	6,6	4
N-15 type engine	12	1	650	200	160	4.3	2

Designation and type of engine	Consumption g/HP hour			Temp. of cooling water °C	Dimensions mm			Weight, kg
	Fuel	Oil	Water		Length	Width	Height	
L-3-2 4-stroke stationary petrol engine ..	350	10	0,8	8,5	590	450	735	80
L-6-2 4-stroke etc.	340	8	0,8	8,5	737	463	770	102
N-15 type engine ..	220+10%	15+10%	25	10	945	800	1180	630

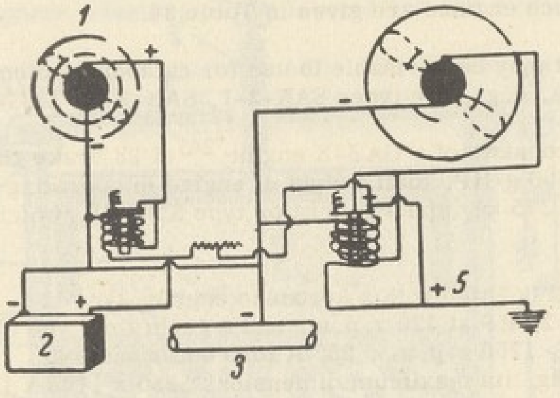


Fig. 65. Wiring of 2 wind-electric sets with a storage battery.

1 - 6 V wind-electric set; 2 - 6 V battery;
3 - pipeline; 4 - wind-electric set 32 V;
5 - earthing of + pole.

STORAGE BATTERIES.

If the power requirement for cathodic protection is small, which may be the case if a small structure is to be protected, e. g. , a single storage tank, a small pipeline, or if the protective coating is of very high quality, batteries can be used as a current source. The battery capacity must be large enough to supply the required protective current during a period necessary for charging a second battery at the nearest charging station and replacing the one in use. Data on the batteries produced in the Soviet Union are contained in the publication "Manual on the electric equipment of industrial undertakings".

Batteries are frequently used for supplementing wind-electric sets, supplying protective current when the wind turbine is not in operation due to too low wind speed (usually 4 m/sec). Fig. 28, shows the graph of the protective current of a wind-electric set combined with batteries. The batteries can be charged by a second wind-electric set working in parallel with the first. When the wind turbine stops the battery is connected into the protection circuit automatically by means of a relay, see Fig. 65.

GALVANIC CELLS.

For very small power requirements galvanic cells can be used as a power source. They are suitable in places where other current sources are difficult to apply and services for battery charging are not available. Such cells are usually produced industrially. The Spiridinov cell is made in two types; one has a capacity of 3000 AH and a maximum discharge current of 1. 0 - 1. 5 A; the second type has a capacity of 3000 AH and a maximum discharge current of 3-4 A. Their voltage fluctuates between the limits 0. 9 - 1. 2 V.

Galvanic cells can also be made directly on the spot. A lead-zinc cell is shown schematically in Fig. 66. It consists of a wooden box lined on the inside with sheet

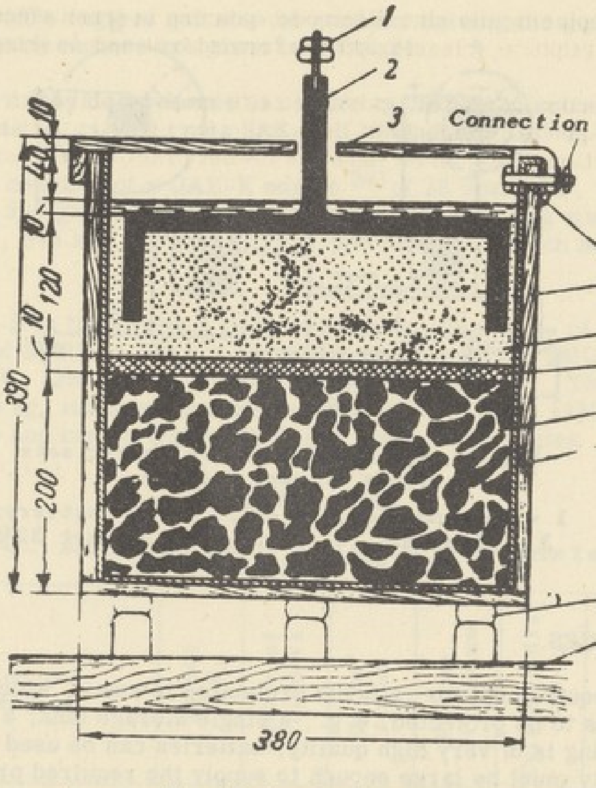


Fig.66. Lead-zinc cell.

1 - terminal clamp; 2 - terminal post; 3 - wooden cover; 4 - bolt; 5 - wooden battery box type Zh-330; 6 - washed sand or boiled wood shavings; 7 - felt; 8 - $CuSO_4$ crystals; 9 - lead lining; 10 - rollers; 11 - shelf.

lead. 20 kg of copper sulphate crystals are poured into the box, these are covered by a felt separator on top of which a layer of washed sand or boiled wood shavings is placed. Then a zinc electrode is placed on top of the sand either in the shape of a cap or disc-shaped. The space between the vertical part of the zinc electrode and the lead lining of the box is also filled in with sand or wood shavings and a cover is then placed on the top. A copper terminal is fixed on to one of the edges of the box and, to improve its contact with the lead lining of the box, lead is soldered on to it inside and outside. The soldered surface and the adjacent lead-lined surface are then coated with an asphalt lacquer for insulation. The cell is then filled with an electrolyte consisting of a 10% solution of magnesium sulphate in distilled, rain, snow or boiled water.

To prevent contamination of the cell and the supporting shelves with zinc sulphate which is generated as a result of the chemical reactions, 30-50 g kerosene is poured on top of the electrolyte and the cover is greased on its inside with vaseline.

Such a cell can remain in operation 12-15 and even up to 20 months. Refitting used cells is done by replacing the zinc electrode, pouring in fresh electrolyte and a fresh supply of copper sulphate, cleaning off the formed salt and washing the sand.

To prevent their becoming frozen, galvanic cells must be placed in a heated space. Owing to their low voltage, all elements of the protection circuit, particularly the earthing and the connection leads, must have the lowest practicable resistance.

Chapter VII

DESIGN OF A CATHODIC PROTECTION INSTALLATION

BASIC STAGES OF WORKING OUT A PROJECT.

A cathodic protection project should include the following:

1) general explanatory notes;
2) determination and choice of the basic data for the design calculations;
3) calculation of the current parameters;
4) selection of the type of current source and earthing to be used;
5) design of the line equipment;
6) installation details;
7) specification on materials and equipment;
8) estimates.

The general explanatory notes are compiled after the entire project is ready. These should contain a description of the distribution of the objects to be protected and the reasons why these objects must be protected. They should contain a description of the protection systems to be adopted, e.g., the number of protection stations, the type and circuit of the power supply, the earthing equipment, etc. In the other parts of the project these questions are investigated from all relevant aspects, the purpose of the explanatory notes being to provide a general description.

The basic data necessary for carrying out the design calculations have been enumerated in the chapter on preliminary investigations. In addition to the data obtained by field investigations it is also necessary to collect information on availability of equipment, which may have an appreciable influence on the choice of a current source or the solution of other design problems.

The problem of the required voltage of the protective potential or alternatively the required current density demands particular attention. In every case local conditions and the special features of the objects to be protected must be taken into consideration.

The parameters of the current source are determined by calculations which have been described in Chapter IV. Following that, a current source and the design of the anode earthing are chosen. The cathodic protection system may consist of a single or several stations. If several anodes distributed at certain distances from each other (0.2 to 1 km) are fed from the same current source, the system is referred to as a protection system with distributed anodes. The arrangement of such a protection scheme is shown in Fig. 67. Such a system is characterised by considerably reduced dimensions of the individual earthing structures. However, owing to their larger number and distance it is necessary to transport the current at a voltage as high as possible to reduce losses and to apply transformers and rectifiers which are fitted in boxes on the poles supporting the supply line.

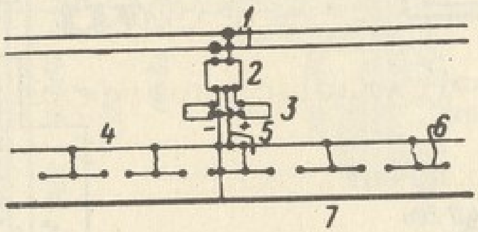


Fig. 67. Cathodic protection installation with distributed anodes.

1 - 2300 V transmission line;
2 - transformer; 3 - rectifier;
4 - distribution line 5 V d.c.;
5 - regular resistance;
6 - anode group; 7 - pipeline.

After the type of system has been determined, the design of the cathodic station can be started. For this purpose it is first necessary to draw the circuit diagram. The simplest is a circuit with a single rectifier, as for instance, the one shown in Fig. 68. If the power requirements are such that a number of series and parallel connected rectifiers have to be used, the circuit diagram will change somewhat and will become similar to that of Fig. 69; 3-phase current of 380 V is supplied through a transformer. The current is rectified by cuprous oxide rectifier columns type T-134, each of which supplies a d. c. of 20 A, 20 Volts. The individual columns are connected into the 3-phase system, so that each circuit consists of two parallel branches of two series connected rectifier columns each. Thus, with a total of 24 columns a rectified current of 40 V, 40 A is obtained. Protective devices are provided in each phase of the 3-phase system and also in both leads of the rectified current.

Fig. 70, shows the circuit diagram of a cathodic protection system with distributed anodes. The power supply is from a 3-phase overhead transmission line of 6000 V. This line feeds two transformers, one at the connection point to the transmission line,

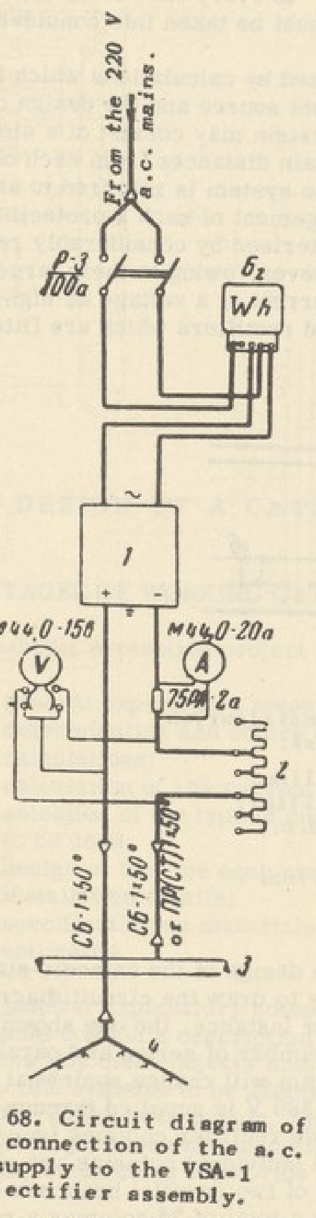


Fig. 68. Circuit diagram of the connection of the a.c. supply to the VSA-1 rectifier assembly.

1 - rectifier type VSA-1; 2 - resistance box YaS-101 with cast iron resistances NS-101/105; 3 - pipeline to be protected; 4 - anode earthing.

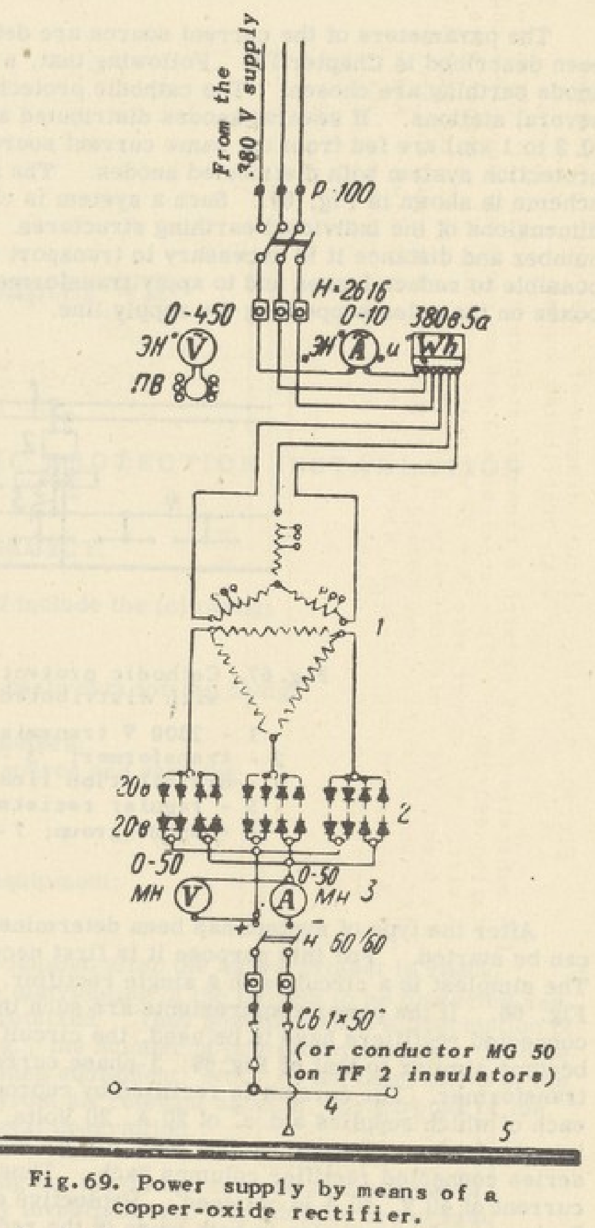
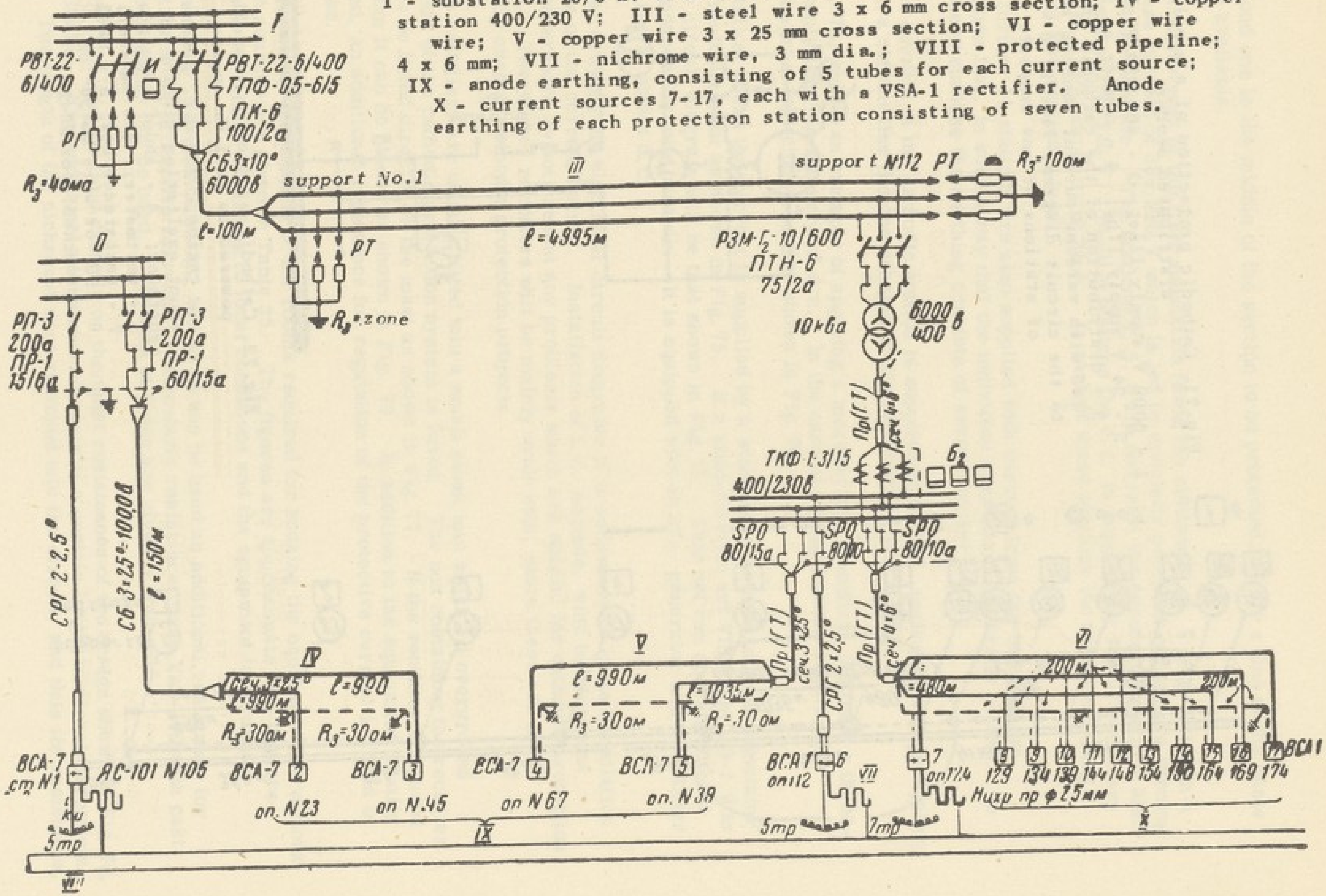


Fig. 69. Power supply by means of a copper-oxide rectifier.

1 - transformer of rectifier assembly; 2 - 24 cuprous oxide rectifiers T-124, 20 V, 20 A; 3 - 40 V side; 4 - anode earthing; 5 - pipeline.

Fig. 70. Schematic circuit diagram of a cathodic protection with distributed anodes.

I - substation 20/6 kV with a transfer station of 6 kV; II - transformer station 400/230 V; III - steel wire 3 x 6 mm cross section; IV - copper wire; V - copper wire 3 x 25 mm cross section; VI - copper wire 4 x 6 mm; VII - nichrome wire, 3 mm dia.; VIII - protected pipeline; IX - anode earthing, consisting of 5 tubes for each current source; X - current sources 7-17, each with a VSA-1 rectifier. Anode earthing of each protection station consisting of seven tubes.



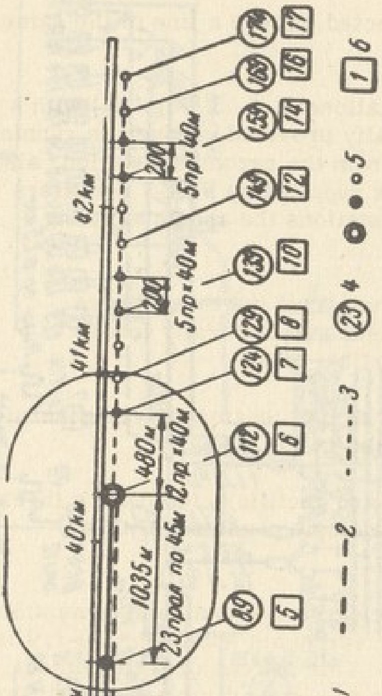


Fig. 71. Cathodic protection of a pipeline with distributed anodes.
1 - 6000 V supply line; 2 - 400/230 V supply line; 3 - 24 V supply line; 4 - number of support; 5 - distribution of the cathodic stations fed with various current sources according to the circuit diagram, Fig. 70; 6 - group of stations at one support.

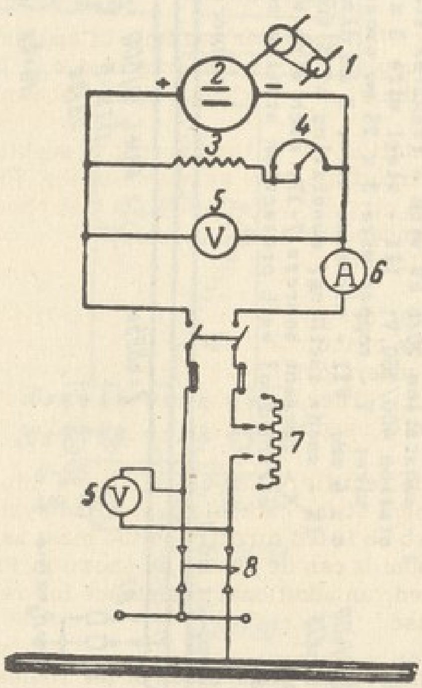


Fig. 72. Cathodic protection installation powered by an I.C. engine.
1 - I.C. engine; 2 - d.c. generator; 3 - shunt excitation winding of the generator; 4 - shunt regulator; 5 - voltmeter; 6 - ammeter; 7 - resistance box; 8 - SB-1 50° or wire MG-50° on insulator TF-2.

and a second one in the middle of the section to be protected, where a line of the same voltage is available.

The transformer of the first substation feeds the stations 1, 2, 3 (Fig. 71) with a three-phase current of 380/220 V which is led by specially provided conductors running parallel to the pipeline. The stations 4, 5, 6 are fed from the second substation, also by a current of 380/220 V. In all 6 stations the d. c. is supplied by VSA-7 rectifiers at 24 V with a total capacity of 24 A. In each of these stations the anodic earthing consists of five vertical pipes.

The further 11 stations are also supplied with current from the three-phase transmission line, in such a way that the individual phases are uniformly loaded. In each of these stations the earthing consists of seven vertical tubes.

If the current of the cathodic station is supplied by an I. C. engine-driven generator, we obtain a circuit like the one schematically represented in Fig. 72.

Fig. 73, shows an example of applying a mercury-arc rectifier, fed from a three-phase supply line, as a source of d. c. In the case of a single phase supply, the circuit diagram will change to that shown in Fig. 74.

A station where the current is supplied by a wind-electric set and an accumulator has a circuit diagram as shown in Fig. 75. If a wind-electric set VISKhOM UD-1.9 is used the circuit diagram will be that shown in Fig. 75. This set can operate without any attendance for long periods. It is equipped with an a. c. generator and a rectifier is required to obtain d. c.

After drawing the electrical circuit diagrams it is necessary to make installation drawings of the current source. Installation of I. C. engines, wind turbines and motor generators do not present any problems which are special for cathodic protection stations. Therefore, rectifiers will be mainly dealt with, since these are most frequently used in cathodic protection projects.

The rectifiers are usually fitted into a small kiosk into which all overground equipment of the cathodic protection system is fitted. The box containing the rectifier can also be fitted directly on the mast as shown in Fig. 77. If the rectifier is housed in a room it can be placed as shown in Fig. 78. In addition to the equipment usually installed, an additional resistance for regulation of the protective current is fitted in this case.

The overall dimensions of the rooms required for housing the equipment for various current sources are given in Table 35. The figures are approximate only and are subject to variations according to local conditions and the equipment to be used.

Rheostats, resistance boxes, and so on can be used as additional resistance for regulation of the protective current. Particularly resistance boxes YaS-100 with cast iron resistances can be used. The data of these are given in Table 36.

For fitting in the field directly on the mast resistances of the design shown in Fig. 79, are suitable. The additional resistance consists of a certain length of nickel-chromium wire. The length of the nichrome wire switched into the circuit, and thus its resistance,

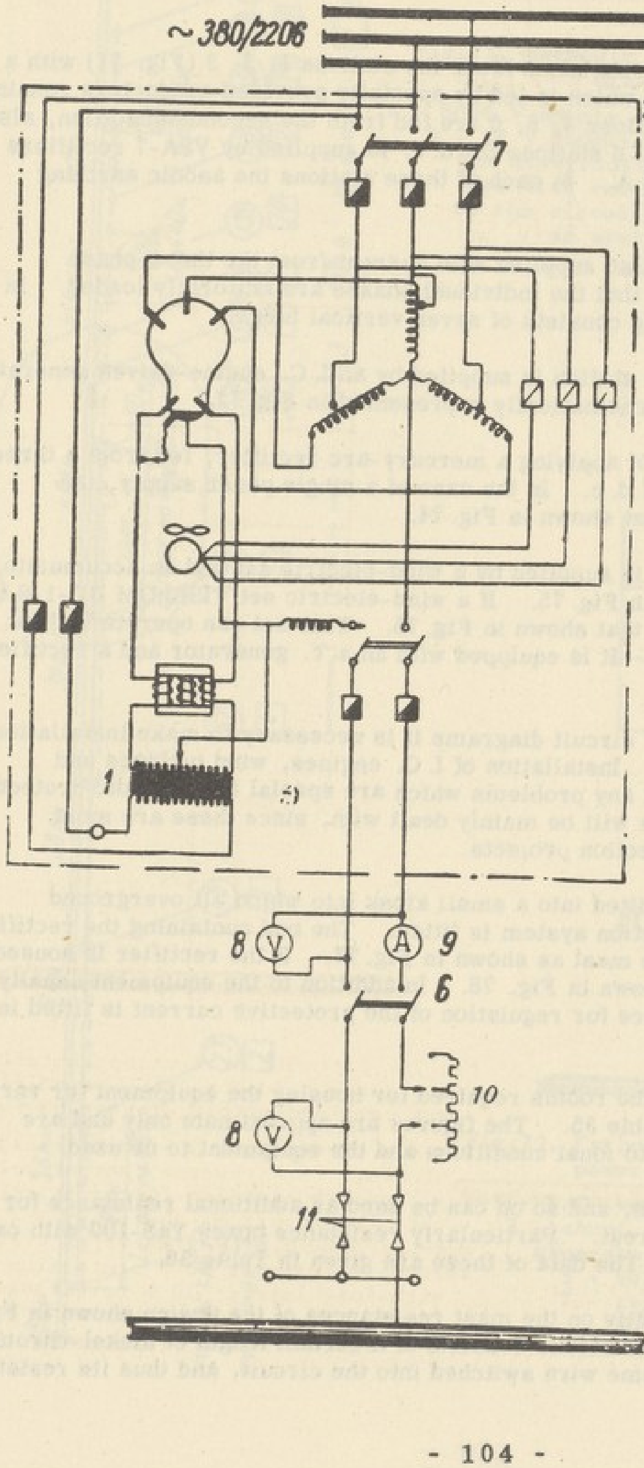


Fig. 73. Circuit diagram of a cathodic protection installation with a mercury arc rectifier fed from a three phase line.

1 - mercury arc rectifier; 2 - a.c. ammeter; 3 - d.c. ammeter; 4 - a.c. meter; 5 - current transformer; 6 - two pole switch; 7 - 3-pole switch; 8 - d.c. voltmeter; 9 - d.c. ammeter; 10 - resistance box; 11 - SB x 500 or wire NG-500 on insulator TF-2.

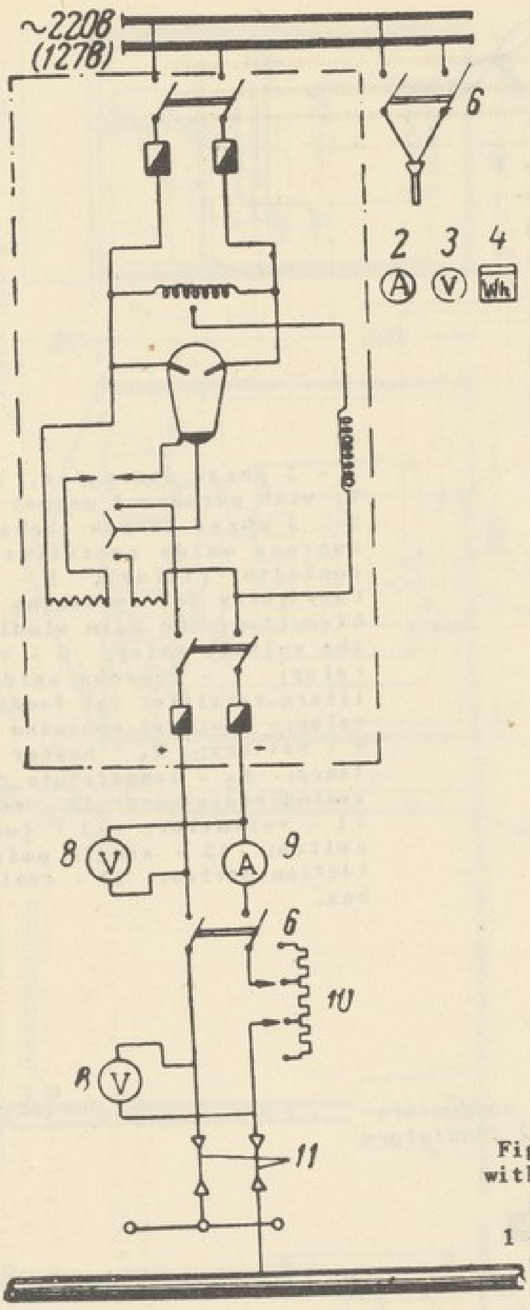


Fig.74. Cathodic protection installation employing a mercury arc rectifier by single phase current.

Designation of symbols as in Fig. 73.

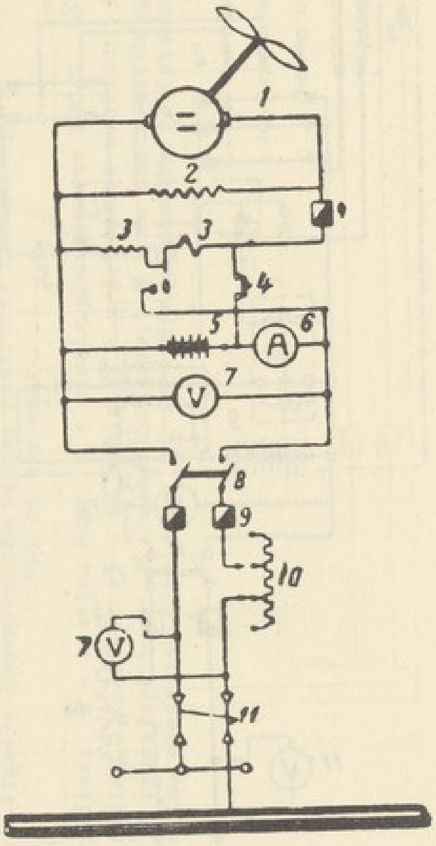
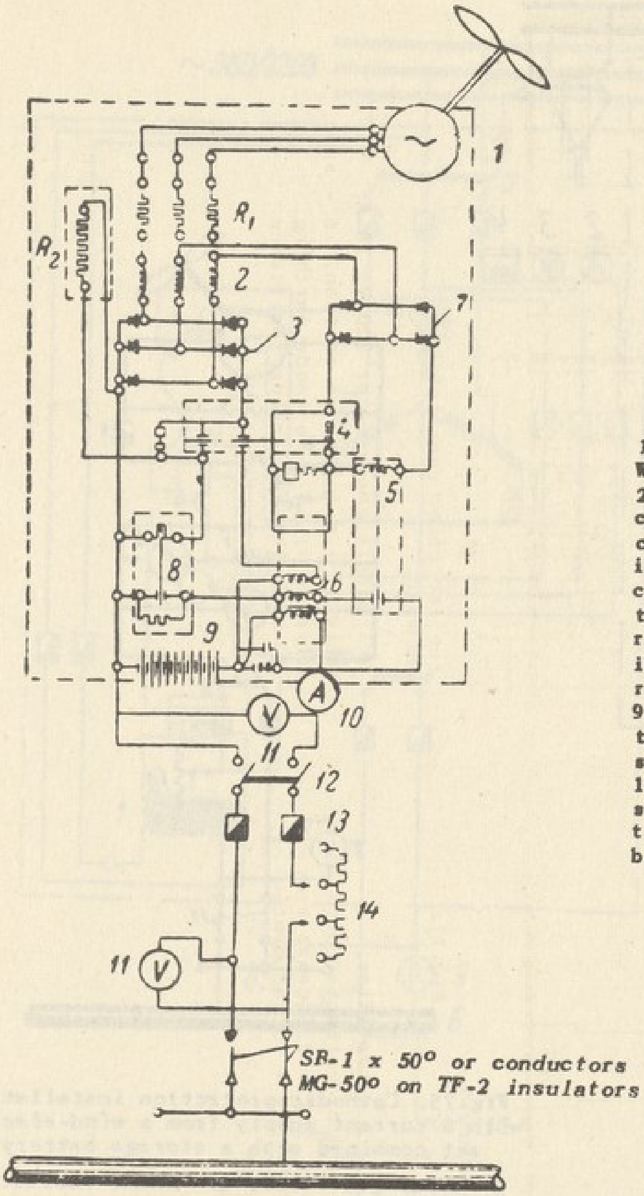


Fig.75. Cathodic protection installation with a current supply from a wind-electric set combined with a storage battery.

1 - d.c. generator; 2 - shunt excitation winding; 3 - reverse current relay; 4 - push button for forced starting of the wind motor; 5 - battery; 6 - d.c. ammeter; 7 - d.c. voltmeter; 8 - two-pole switch; 9 - single pole protection device with fuse insert; 10 - resistance box; 11 - SB-1 x 50° or by conductor MG-50° on TF-2 insulators.



SR-1 x 50° or conductors MG-50° on TF-2 insulators

1 - 3 phase generator, 160-190 W, with permanent magnet poles; 2 - 3 phase series choke; 3 - cuprous oxide rectifier; 4 - contactor (relay); 5 - auxiliary relay for switching on the circuit of the main windings of the voltage relay; 6 - voltage relay; 7 - cuprous oxide auxiliary rectifier for feeding the relay; 8 - heat operated relay; 9 - battery; R_1 - heater resistance; R_2 - temperature compensating resistance; 10 - ammeter; 11 - voltmeter; 12 - two pole switch; 13 - single pole protection device; 14 - resistance box.

Fig.76. Cathodic protection installation with a power supply from a wind motor VISKhOM-1.9.

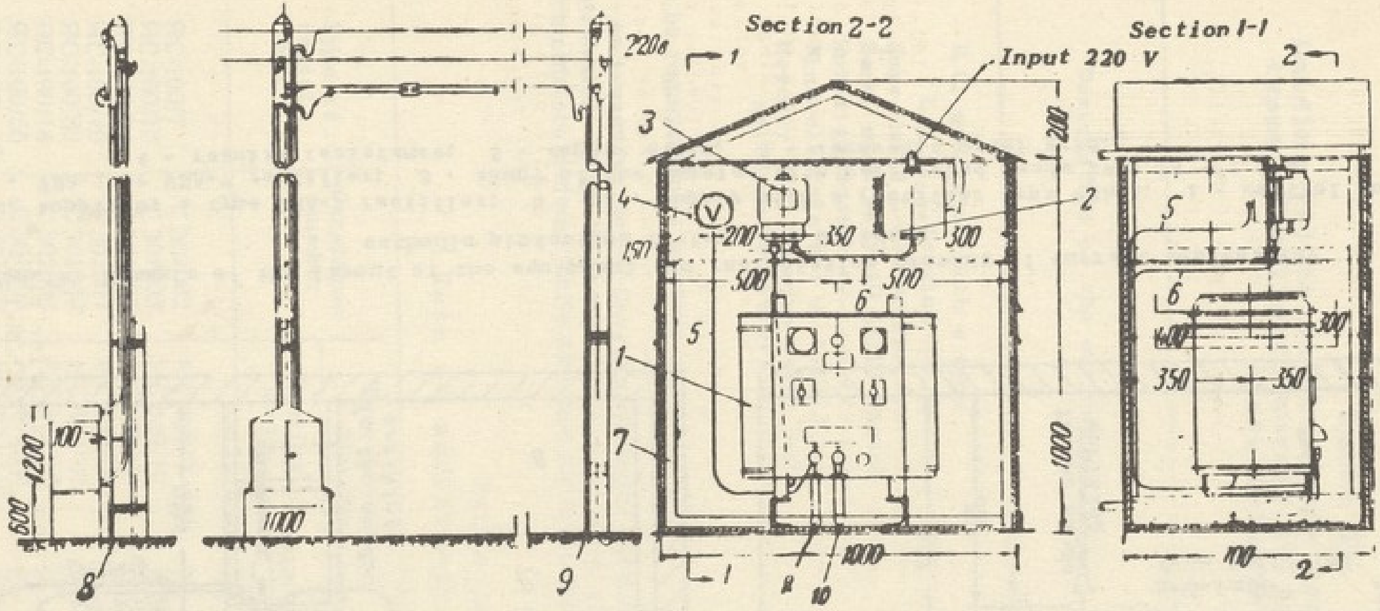


Fig.77. Installation of the rectifier containing box on the mast.

1 - rectifier; 2 - starter box; 3 - single phase meter 220 V, 10 A;
4 - d.c. voltmeter 0 to 30 V; 5 - SG cable of 1 x 1.5 cross section; 6 - same, 2 x 2.5 cross section; 7 - metallic case; 8 - to anode earthing;
9 - to the protected pipeline; 10 - to the regulating resistance.

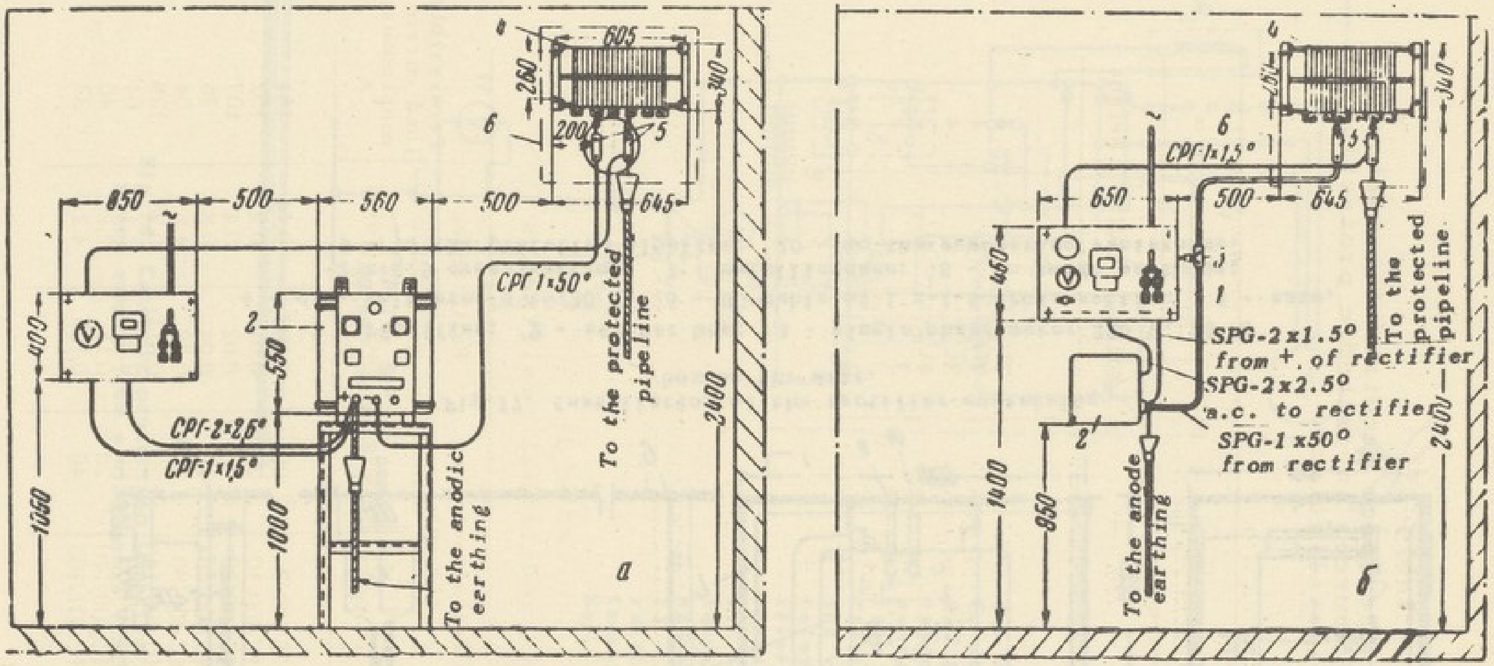


Fig.78. Example of the layout of the equipment and installation drawing of current sources for cathodic protection fitted in a building.

a - d.c. supply by a type VSA-7 rectifier; b - d.c. supply with a rectifier type VSA-1; 1 - control board; 2 - VSA-1 or VSA-7 rectifier; 3 - shunt of the ammeter with calibrated leads $l = 0.75 + 1.5$ m; 4 - regular resistance; 5 - copper strip; 6 - removable metal grid.

Table 35.

Guiding values on the space required for various types of current sources in cathodic protection installations.

Designation of the current source	Dimensions, in m		
	Length	Width	Height
D.C. generator with a type L-3 I.C. engine	$7^{1}/_{2}$	4	4
Same, with L-6/2 engine	$7^{1}/_{2}$	4	4
Same, with N-15 1D 16/20 engine	8	4	4
Motor generator	$4^{1}/_{2}$	$4^{1}/_{2}$	$3^{1}/_{2}$
Wind-electric set	3	3	$3^{1}/_{2}$
Mercury arc, cuprous oxide and selenium rectifiers	3	3	$3^{1}/_{2}$

can be regulated by a movable clamp contact.

An important part of the current supply equipment is the instrument panel and the switchboard. Fig. 80 shows such a panel which contains a. c. and d. c. voltmeters and ammeters and also knife switches for controlling two lines.

Table 36.

Data of additional resistances

Type of resist. box	Catalogue number	Resistances in the box		Resistance, Ohms		Permissible load current continuous, A
		Marking (type)	Number	Each	Total	
ЯС-100/7	C 301002	HC 400/7	20	0,007	0,14	181
ЯС-100/10	C 301003	HC 400/10	20	0,01	0,2	152
ЯС-100/20	C 301005	HC 400/20	20	0,02	0,4	107
ЯС-100/40	C 301007	HC 400/40	20	0,04	0,8	76
ЯС-100/80	C 301009	HC 400/80	20	0,08	1,6	54
ЯС-100/14	C 301004	HC 400/14	20	0,014	0,28	128
ЯС-100/55	C 301005	HC 400/55	20	0,055	1,1	64
ЯС-100/110	C 301010	HC 400/110	20	0,11	2,2	46
ЯС-100/105	C 301114	HC 401/105	40	0,105	4,2	33

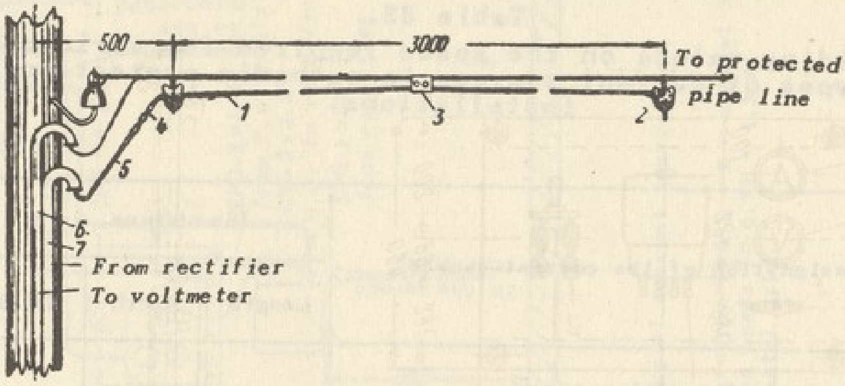


Fig. 79. Line equipment for additional regulation of the resistance of the protected pipeline.

1 - nichrome resistance wire; 2 - porcelain insulator; 3 - movable contact clamp; 4 - tubular oval joining piece; 5 - copper conductor; 6, 7 - ½" dia. tubes.

The complete circuit diagram of the earthing is given in the chapter on anodic earthing. The installation work must be preceded by design work of the individual junction points of the earthing system, the connection of the overhead line to the earthing and to the pipeline to be protected. Fig. 81, shows the junction of a connection conductor. The main requirement for these junction points is that they should be in service for a long time, and it is therefore necessary to take precautions against their being damaged by corrosion or mechanical action. The junction points between the horizontal and the vertical parts of the earthing system must also have joints which are sufficiently reliable, as for instance those shown in Fig. 82.

The design work of the project should also include the high voltage and low voltage supply lines, the by-pass shunt conductors, the insulation compounds, leads for check tests from the protected underground structure and test plates. The transmission lines can be either overhead lines or underground cables. Overhead lines are cheaper and therefore more frequently used.

For overhead lines up to 1000 V conductors of the MG type are suitable; in the case of power transmission by cable, cables SB are suitable. Table 37 gives the values of the permissible continuous load of the blank conductors in transmission lines from the point of view of permissible temperature increase. The resistance values of these conductors and cables can be determined from Table 38. Conductors of a cross-section of 50 square mm are used most frequently for such lines.

The standard specifications governing suspension of high voltage lines in inhabited and non-inhabited areas differ. For cathodic protection installations the second case is the most frequent. The supporting structures differ in design, depending on whether they are intermediary, anchored, or end ones. If it is necessary to place a transformer also on a supporting structure, its design will be more complicated.

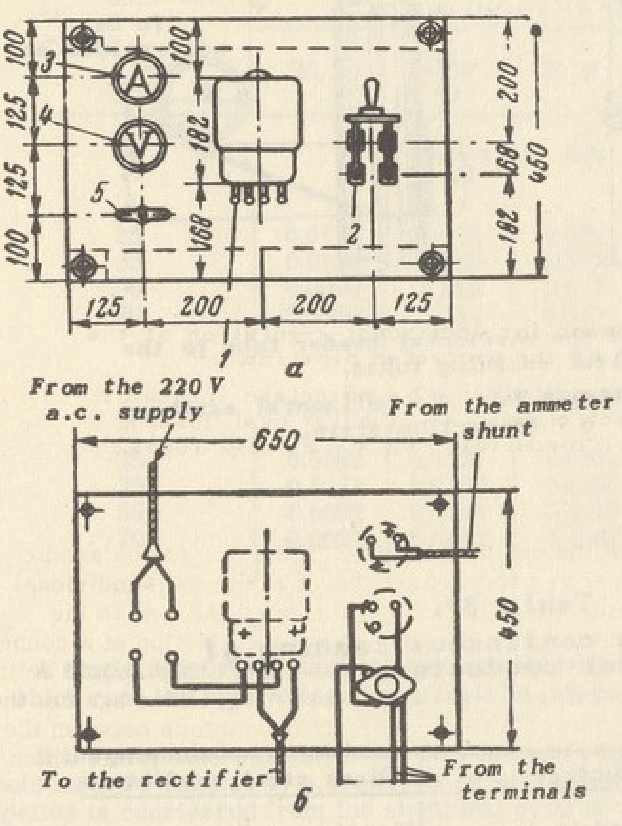


Fig. 80. Panel at the current source of an installation with a VSA-1 rectifier.

a - panel front (top); b - wiring diagram (bottom). 1 - single phase meter; 2 - switch; 3 - d.c. ammeter 0-20 A; 4 - voltmeter 0-15 V; 5 - voltmeter changeover switch.

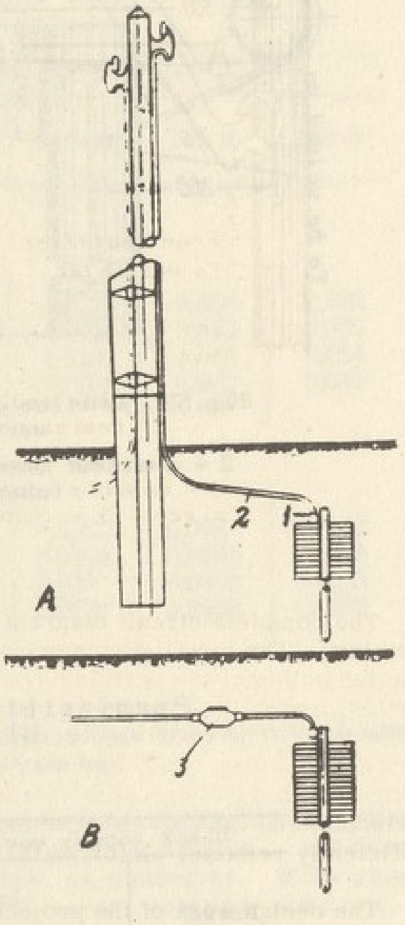


Fig.81. Lead to the earthing and its connection to the earthing system.

A - (top drawing) conductor from an overhead line. B - (bottom drawing) conductor from a cable joint. 1 - terminal; 2 - conductor in an insulated pipe; 3 - junction box.

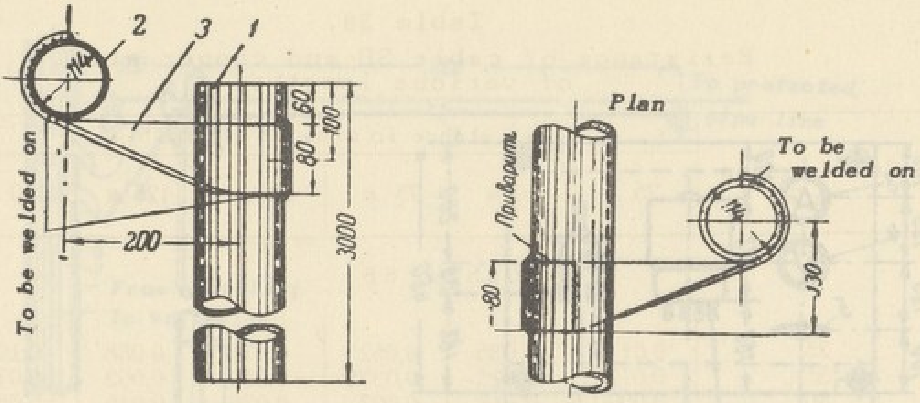


Fig.82. Junction of the horizontal header tube to the vertical earthing tubes.

1 - vertical earthing tube; 2 - horizontal earthing tube; 3 - connection strip.

Table 37.
Permissible continuous loading of blank conductors

Blank copper conductors			Blank steel conductors	
Rated cross section mm^2	Load in A		Diameter and cross section of steel conductors type Zh	Load current A
	In enclosed spaces	In open air		
4	57	58	4 мм	35
6	73	75	5 »	40
10	103	108	6 »	60
16	130	150	—	—
25	165	205	—	—
35	210	270	35 мм²	80
50	265	335	50 »	90
70	340	425	70 »	125
90	410	510	95 »	140
120	490	595	120 »	175

Table 38.

Resistance of cable SB and copper wire of various lengths.

Cross section mm^2	Resistance in Ohms of a length of					
	25 м	50 м	75 м	100 м	125 м	150 м
Cable SB						
25	0,0175	0,035	0,052	0,071	0 088	0.106
35	0,0125	0,025	0,0375	0,050	0,062	0,075
50	0,0090	0,018	0,027	0,036	0,045	0,054
70	0,0066	0,013	0,019	0,026	0,032	0,039
Copper conductor						
25	0,0188	0,0376	0,0564	0,0752	0,094	0,0128
35	0,0133	0,0266	0,0399	0,0582	0,0665	0.0798
50	0,0092	0,0185	0,0277	0,037	0,0462	0,0555
70	0,0067	0,0135	0,0202	0,0271	0,0338	0,0406

A single supporting mast can be used for both high-voltage and low-voltage lines, in which case the high voltage lines must be placed at the top.

If the protected pipeline has a discontinuous electric conductivity, the discontinuity spots must be shunted by a conductor of sufficiently large cross section. A welded pipeline is considered from the electrical point of view, as continuous. If the pipeline has flange connections, or special joining sleeves with rubber washers, and so on, such joints must be shunted. The question whether shunting is required in the case of threaded joints is decided separately in each case and depends on the electric conductivity of the joint, which must be measured. Shunting is carried out by metal wire or strip.

The insulation joints used for the object to be protected must be such that wasteful current losses are avoided and optimum protection conditions ensured. Such joints insulate from the protected system those sections which do not require application of a protective current, and in some cases they are also provided at the limits of the protected section. Incidental contacts of the protected pipeline with other underground structures are particularly undesirable, since they cause large leakages of the protection current. Fig. 83, shows the influence of such an incidental contact on the protection potential of a pipeline. It can be seen that the left section of the pipeline has a normal distribution of protection potential along its length. The right hand side of the pipeline which was affected by an incidental contact showed an increased current consumption, and the part of the line beyond the point of contact proved insufficiently protected. It is, therefore, essential to detect possible points of contact during the preliminary investigations, so that they can be eliminated. It is desirable that the distance between two adjacent lines, one of which is unprotected and the other protected, should be at least 0.5 m.

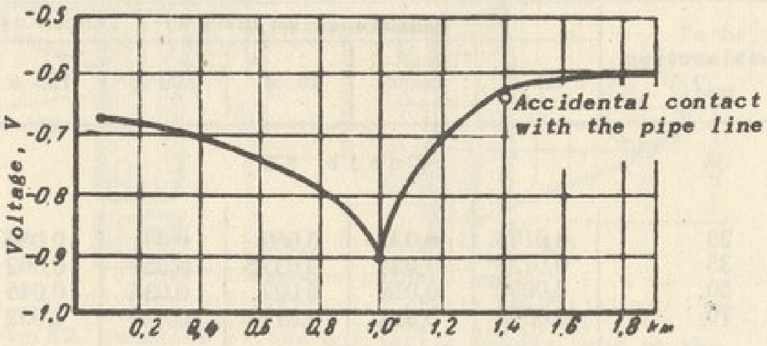


Fig.83. Voltage distribution along the protected line in case of accidental contact with another metallic structure.

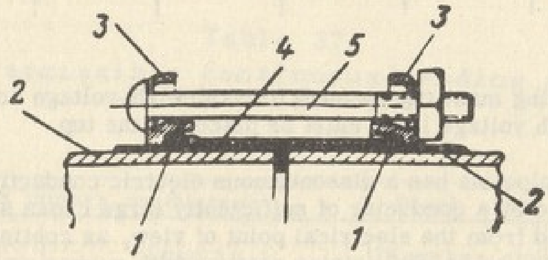


Fig. 84. Insulating connection sleeve.
1 - insulating rubber ring; 2 - pipes; 3 - supporting collars; 4 - centering ring; 5 - bolt.

Provision of insulated joints at the limit points of the protected sections reduce considerably the current consumption of the protection system. Therefore, provision of such joints is important in all cases where this can be done without excessive difficulty. A design of insulated sleeves is shown schematically in Fig. 84. Special flange designs as, for instance, the one shown in Fig. 85, can also be used. The insulating washers can be made of any type of suitable dielectric, e. g., rubber, thiokol, polyvinyl chloride, etc.

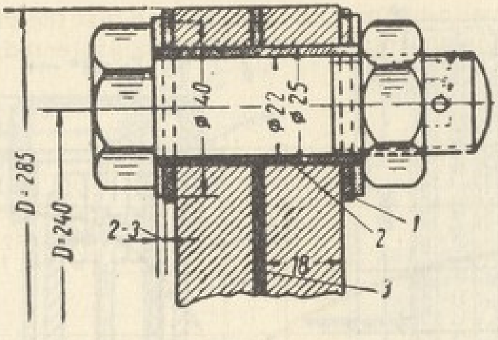


Fig.85. Insulating flange joint.

1, 2, 3 - ring, bushing and washer made of an insulation material, e.g., ticolin, polyvinyl chloride, rubber; 4 - lockpin.

LEADS FOR CHECK MEASUREMENTS

It is very important to provide leads at intervals along the pipeline to enable quick and convenient measurement of the potential differences between the pipeline and the surrounding soil. Such measurements should be carried out periodically so as to check the performance of the protection system. The design of such a control terminal is shown in Fig. 86. It is desirable that the intervals between individual check-points should be as small as possible. Owing to economic considerations, however, they are usually provided at intervals of 250 - 500 m.

For checking the performance of the cathodic protection along the pipeline, test plates are fitted into the ground and the efficiency of the cathodic protection is determined on the basis of the weight loss of these test plates. Two such plates are always placed together, one of which is electrically connected to the protected pipeline and is thus also protected. The second plate, of equal dimensions, is placed at the same point on the pipeline but at a certain distance from the first plate and is not cathodically protected. Before putting the plates into position they are weighed, with an accuracy of up to 0.01 g. The recommended dimensions of these test plates and the way they should be joined to the pipeline are shown in Fig. 87. The location of the two test plates relative to the pipeline is shown in Fig. 88. The plates must be so placed that they can be easily removed for checking. To enable easy location of the test plates, suitable markings should be provided above ground bearing appropriate inscriptions, as is shown in Fig. 89. The project must be accompanied by a specification of the equipment and materials compiled in the usual way. An example of such a specification is given in Appendix 1.

EXAMPLES OF CALCULATIONS FOR CATHODIC PROTECTION SYSTEMS

Example 1. The required rating of the d. c. source for a cathodic protection station of a 10 km long pipeline, with a pipe diameter of 12" a wall thickness of the tubes of 9 mm, a conductivity of the protective coating of 1000 microsiemens m^2, a solid

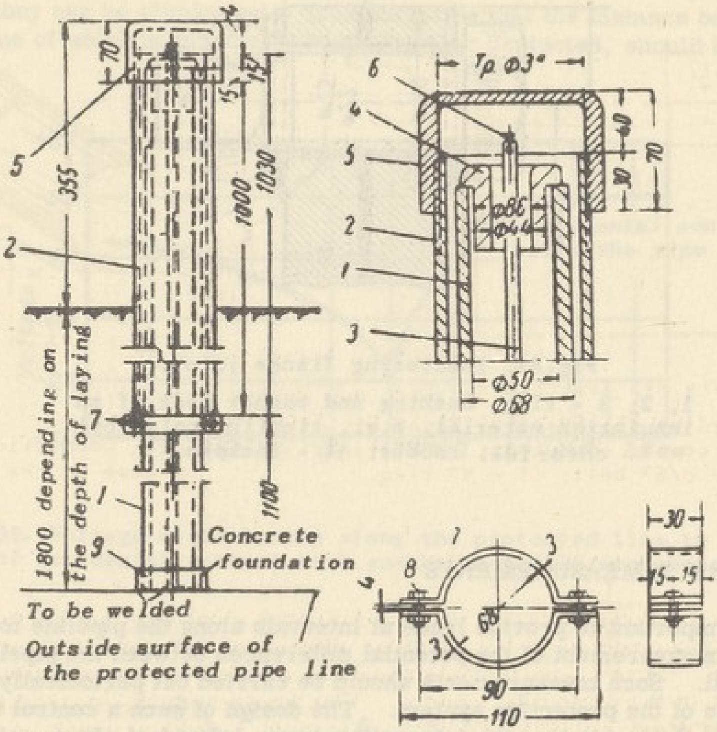


Fig. 86. Design of the connection to a test point.

1 - asbestos cement tube; 2 - clearing tube; 3 - rod; 4 - insulation bushing; 5 - cover of the tube; 6 - screw; 7 - clamp; 8 - bolt and nut with washer; 9 - steel tube.

resistance of 400 Ohm cm. The protection station is situated in the middle of the line to be protected at a distance of 25 m from the pipeline and 25 m from the earthing. The earthing consists of three vertical tubes of a length of 4 m each, which are joined by a horizontal header 30 m long.

The necessary potential of the pipeline to be protected and the required current intensity at the station must be determined in the first instance.

Since in this case the station has to protect a section of "infinite" length, the potential of the pipeline at the station can be determined by equation (24):

$$E_A = E_m \cdot e^{0{,}0116 \sqrt{\frac{g_1}{T}} \cdot l_1}$$

According to information given in the earlier chapters, the minimum protection

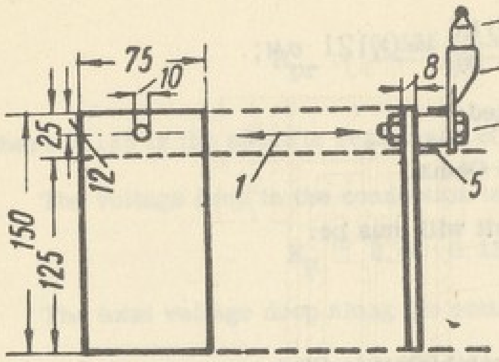


Fig. 87. Test plate.

1 - covered by a protective layer of mastic; 2 - copper conductor; 3 - steel lug; 4 - 3/8" bolt; 5 - ¾" ring.

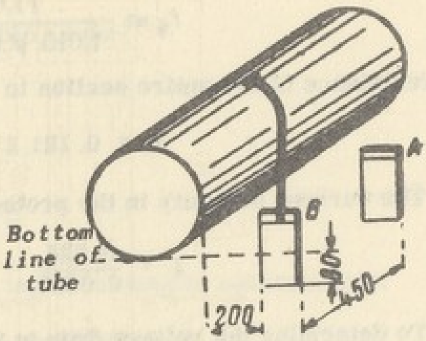


Fig. 88. Connection of test plates to the tube.

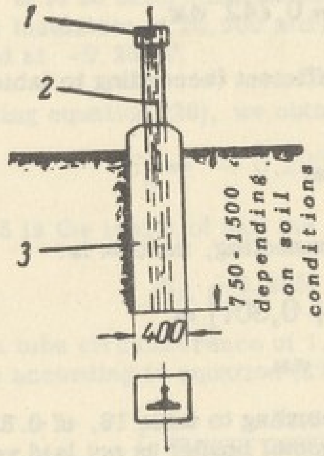


Fig. 89. Overground marking on top of test plates.

1 - shield for markings; 2 - rail, up to 2300 mm long; 3 - foundation.

potential can be assumed at $E_m = -0.285$ V. If the station is situated at the centre of the pipeline to be protected, the length of each section will equal 5 km (i. e., 10:2), and we obtain:

$$E_A = -0,285 \cdot e^{0,0116\sqrt{\frac{1000}{9}}\,5} = -0,285\, e^{0,611} = \\ = -0,285 \cdot 1,84 = -0,525\,\text{в}.$$

Since the minus sign only indicates that the applied potential is negative, it will be omitted in further calculations.

The resistance of one side of the pipeline, which has an outside circumference of 0.323.3.14 = 1.015 m, is according to equation (25):

$$r_0 = \frac{11{,}6}{1{,}015\sqrt{9\cdot 1000}} = \frac{11{,}6}{96} = 0{,}121 \text{ ом};$$

the resistance of the entire section to be protected:

$$R = 0.121:2 = 0.0605 \text{ Ohms.}$$

The current intensity in the protection circuit will thus be:

$$I = \frac{0.525}{0.0605} = 8.68 \text{ A.}$$

To determine the voltage drop in the anode earthing it is first necessary to determine the resistance.

With $t = 50 + \frac{1}{2}400 = 250$ **cm, we obtain according to equation (47):**

$$R_т = 0{,}366 \frac{400}{400}\left[\lg\frac{2\cdot 400}{11{,}2} + \frac{1}{2}\lg\frac{4\cdot 250 + 400}{4\cdot 250 - 400}\right] =$$
$$= 0{,}366\cdot(1{,}854 + 0{,}184) = 0{,}742 \text{ ом}.$$

With three earthing sections and a screening coefficient (according to table 15) of 0. 78, we obtain by using equation (53):

$$R'_T = \frac{0.742}{3\cdot 0.78} = 0.318 \text{ Ohms.}$$

According to equation (48) the horizontal, interconnecting, section is:

$$R_м = \frac{0{,}366\cdot 400}{1200}\left[\lg\frac{1200^2}{11\cdot 2\cdot 50} + 0{,}301\right] =$$
$$= 0{,}122\cdot 3{,}711 = 0{,}451 \text{ ом}.$$

Taking into consideration a screening coefficient, according to table 16, of 0. 83 and a freezing coefficient of 2, due to the fact that the horizontal header is not laid very deep, we obtain according to equation (56):

$$R'_M = 0.451\cdot 2 : 0.83 = 1.085 \text{ Ohms.}$$

The total resistance of the anodic earthing will thus be:

$$R_0 = \frac{1}{\frac{1}{0{,}318} + \frac{1}{1{,}085}} = \frac{1}{4{,}06} = 0{,}246 \text{ ом}.$$

The corresponding voltage drop in the anodic earthing:

$$E_A = 8.68\cdot 0.246 = 2.13 \text{V.}$$

The resistance of the iron conductors to the line which have a cross section 50 mm^2 is, according to equation (19):

$$R_{pr} = \frac{0.135\,(25 + 25)}{50} = 0.135 \text{ Ohms},$$

where 0.135 is the specific resistance of iron.

The voltage drop in the connection leads is:

$$E_p = 8.68 \cdot 0.135 = 1.17\text{ V}.$$

The total voltage drop along the entire system is, according to equation (29):

$$E = 0.525 + 2.13 + 1.17 = 3.825\text{ V}.$$

Rounding off the obtained values and taking into consideration that a certain power reserve is necessary the required rating of the power source can be assumed at 6 V, 10 A.

Example 2. The voltage and current intensity at the connecting junction point which is necessary for cathodic protection of a pipeline 5 km long, 12" diameter, 9 mm wall thickness, is to be determined assuming a "finite" protection length. The conductivity of the pipe insulation is 10,000 micro-Siemens/m^2 and the minimum protection potential is assumed at -0.285 V.

Applying equation (26), we obtain:

$$E_A = -0{,}285 \cdot \mathrm{ch}\left[0{,}0116\sqrt{\frac{10000}{9}} \cdot 2{,}5\right],$$

where 2.5 is the length of half the protected section, km.

$$E_A = -0.285 \cdot \cosh 0.967 = -0.285 \cdot 1.124 = -0.321\text{ V}.$$

For a tube circumference of 1.02 m the resistance of one side of the protected section is according to equation (27):

$$r_0 = \frac{11{,}6}{1{,}02\sqrt{10000 \cdot 9}} \cdot \frac{1}{\mathrm{th}\,0{,}967} = 0{,}0253 \text{ ом}.$$

Correspondingly the current intensity of one side of the protected section is:

$$I_1 = \frac{0.321}{0.0253} = 12.7\text{ A}.$$

and the current intensity of the entire section:

$$I = 12.7 \times 2 = 25.4\text{ A}.$$

Example 3. The rating of a cathodic protection station of an uncoated pipeline is to be determined, the main data of which are the following:

1) specified tube diameter 20";
2) real outside diameter 508 mm;

3) wall thickness of piping 16 mm;
4) length of section to be protected 232 m;
5) connection point is located in the centre of the section to be protected;
6) soil resistance along the protected section 5 Ohm, m;
7) minimum protection potential to be applied -0. 285 V;
8) earthing consists of 15 vertical tubes each being 4 m long and 4" diameter, spaced at 6 m from each other and connected at their top ends to a horizontal tube of 4" diameter laid at a depth of 80 cm below ground; soil resistance in the earthing zone 5 Ohm m;
9) freezing coefficient for the horizontal tube equals 2;
10) the protection system corresponds to a protected section of "infinite" length;
11) the total length of the copper conductors equals 116 + 116 = 232, its cross section is 100 mm^2.

Before determining the required potential at the connection point, it is necessary to determine the resistance of the soil layer surrounding the pipeline. This must be determined instead of the resistance of a protective coating which is absent in the present case. The resistance of the soil layer surrounding the pipe line is determined according to equation (39):

$$R_n = \varrho \cdot r_1 \cdot \lg_e \frac{r_2}{r_1} = 500 \cdot 25{,}4 \lg_e \frac{203}{25{,}4} =$$
$$= 500 \cdot 25{,}4 \cdot 2{,}3 \cdot 0{,}902 = 26300 \text{ ом см}^2 = 2{,}63 \text{ ом м}^2.$$

thus, the conductivity:

$$g_1 = \frac{1}{2.63} = 0.381 \text{ Siemens m}^2 = 381000 \text{ microsiemens m}^2.$$

The protection potential at the connection point is determined by means of equation (24):

$$E_A = -0{,}285 \cdot e^{0{,}0116 \sqrt{\frac{381000}{16}} \, 0{,}116} =$$
$$= -0{,}285 \cdot e^{0{,}0116 \cdot 154{,}5 \cdot 0{,}116} = -0{,}285 \cdot e^{0{,}207} =$$
$$= -0{,}285 \cdot 1{,}23 = -0{,}350 \text{ в.}$$

The resistance of the protected section according to equation (25) is:

$$r_0 = \frac{11{,}6}{1{,}6 \sqrt{381000 \cdot 16}} = \frac{11{,}6}{1{,}6 \cdot 618 \cdot 4} = 0{,}00294 \text{ ом.}$$

Thus, the current intensity for one side:

$$I_1 = \frac{0.350}{0.00294} = 119 \text{ A},$$

and the current intensity for the entire protected section:

$$I = 119 \cdot 2 = 238 \text{ A}.$$

The resistance of the anode earthing is determined as follows: the resistance of one vertical earthing element (tube)

$$R_{\text{тр}} = \frac{0{,}366\,\varrho}{l}\left[\lg\frac{2l}{d} + \frac{1}{2}\lg\frac{4t+l}{4t-l}\right] =$$
$$= \frac{0{,}366\cdot 500}{400}\left[\lg\frac{800}{11{,}6} + \frac{1}{2}\lg\frac{1000+400}{1000-400}\right] = 0{,}457\left[\lg 69 + \frac{1}{2}\lg 2{,}33\right] =$$
$$= 0{,}457\left[1{,}838 + \frac{1}{2}\cdot 0{,}367\right] = 0{,}457\cdot 2{,}021 = 0{,}925.$$

Taking into consideration the screening effect, the resistance of the 15 parallel (vertical) earthing tubes is, according to equation 53:

$$R_{Tp} = \frac{0.925}{15\cdot 0.62} = 0.1 \text{ Ohm}.$$

The resistance of the 90 m long horizontal section connecting the vertical earthing tubes is, according to equation (48):

$$R_{\text{м}} = \frac{0{,}366\cdot 500}{9000}\left[\lg\frac{9000^2}{80\cdot 11{,}6} + 0{,}301\right] =$$
$$= 0{,}0203\,[\lg 87500 + 0{,}301] = 0{,}0203\,[4{,}942 + 0{,}301] =$$
$$= 0{,}0203\cdot 5{,}243 = 0{,}106 \text{ ом}.$$

For a screening coefficient (taken from the tables) of 0.59 and a freezing coefficient 2, the resistance of the horizontal earthing section will be:

$$R'_{\text{м}} = \frac{0{,}106\cdot 2}{0{,}59} = 0{,}36 \text{ ом}.$$

The total resistance of the earthing structure:

$$R_{\text{об}} = \frac{1}{\frac{1}{0{,}1} + \frac{1}{0{,}36}} = \frac{1}{10 + 2{,}78} = \frac{1}{12{,}78} = 0{,}078 \text{ ом}.$$

The resistance of the connection leads, made of copper (i.e., specific resistance 0.0175 Ohm mm^2/m), amounts to:

$$R_{\text{пр}} = 0{,}0175\,\frac{116\cdot 2}{100} = 0{,}0406 \text{ ом}.$$

The voltage loss in the anode earthing system and in the connection leads will be:

$$E_2 = 238\,(0.078 + 0.0406) = 238\cdot 0.1186 = 28.2 \text{ V}.$$

Thus, the total voltage required for the entire protection system:

$$E_0 = 28.2 + 0.350 = 30 \text{ V},$$

and the power output:

$$W = 30\cdot 238 = 7140 \text{ вт} \cong 7{,}2 \text{ квт}.$$

Example 4. The rating of a cathodic protection station for the following operating conditions is to be determined:

1) pipe diameter 12";
2) length of section to be protected 10 km;
3) the station is placed in the centre of the section to be protected;

4) the limits of the protected section are not insulated from the remaining part of the pipeline, i. e., the system corresponds to a section of "infinite length",
5) minimum protection potential to be -0.285 V;
6) wall thickness of the piping 8 mm;
7) the anodic earthing is located at a distance of 25 m from the current source, which is itself at a distance of 30 m from the protected pipeline;
8) the soil resistance in the earthing zone 1500 Ohms/cm^3;
9) earthing to consist of 5 vertical tubes 6" diameter, 4 m long interconnected by means of a horizontal tube 6" diameter, and 4 m long; the vertical tubes are spaced at 5 m from each other; the horizontal tube is laid at a depth of 0.8 m;
10) the soil freezing coefficient equals 1 for the vertical tubes and 2 for the horizontal one;
11) the copper wires used for interconnection have a cross section of 20 square mm;
12) the conductivity of the tube insulation is 1500 microsiemens m^2.

First, the required potential at the connection point of the cathodic protection, which would ensure the necessary voltage of -0.285 V at the ends of the protected section, must be determined.

Since the condition given in 4) is applicable, this voltage is calculated according to equation (24):

$$dl_1 = 0{,}0116 \sqrt{\frac{1500}{8}}\, 5 = 0{,}794$$

and

$$E_A = 0{,}285 \cdot e^{0{,}794} = 0{,}285 \cdot 2{,}21 = 0{,}63\ в.$$

The length of the section l_1 equals 5 km, i. e., half the total length of the section to be protected, provided the station is situated in the centre of the section to be protected. The minus symbol is dropped since it only indicates the direction of the voltage drop.

The resistance of half the protected section is determined by means of equation (25). If the outside circumference of the pipe is:

$$C = 323 \cdot \pi = 1015\ мм = 1{,}015\ м,$$

and thus:

$$r_0 = \frac{11{,}6}{1{,}015\sqrt{1500 \cdot 8}} = \frac{11{,}6}{111} = 0{,}1045\ ом.$$

The current intensity for half the protected section is:

$$I_1 = \frac{0.63}{0.1045} = 6\ A$$

The current intensity for the entire protected section will be twice as large, i. e.:

$$I = 2I_1 = 2 \cdot 6 = 12\ A.$$

and this current will flow through all parts of the protection circuit.

Let us now determine the resistance of the other parts of the circuit, namely the earthing and the connection leads. According to equation (47) the resistance of one vertical earthing tube will be:

$$R_{\text{тр}} = \frac{0{,}366 \cdot 1500}{400}\left[\lg\frac{2 \cdot 400}{15 \cdot 2} + \frac{1}{2}\lg\frac{4 \cdot 280 + 400}{4 \cdot 280 - 400}\right] =$$

$$= 1{,}375\left[\lg 52{,}6 + \frac{1}{2}\ \lg 2{,}11\right] = 1{,}375 \cdot 1{,}88 = 2{,}58\ \textit{ом},$$

whereby, according to condition 9):

$$t = 80 + \frac{400}{2} = 280\ \textit{см}.$$

If the calculation were carried out by the less accurate formula (46), which is applicable in this case, we would obtain:

$$R_{\text{тр}} = \frac{0{,}366 \cdot 1500}{400}\left[\lg\frac{400}{15{,}2} + 0{,}602\right] = 1{,}375 \cdot 2{,}022 = 2{,}78\ \textit{ом}.$$

For the five parallel connected vertical earthing tubes, taking into consideration that the freezing coefficient according to 10) equals 1 and the screening coefficient according to Table 15 equals 0.7, we would obtain by applying equation (53):

$$R'_{\text{тр}} = \frac{2{,}58 \cdot 1}{5 \cdot 0{,}7} = 0{,}738\ \textit{ом}.$$

The resistance of the interconnecting horizontal section is determined by equation (48):

$$R_{\text{м}} = \frac{0{,}366 \cdot 1500}{2000}\left[\lg\frac{2000^2}{15{,}2 \cdot 80} + 0{,}301\right] =$$

$$= 0{,}275\ [\lg 3290 + 0{,}301] = 1{,}05\ \textit{ом}$$

For a freezing coefficient 2 and a screening coefficient, according to Table 16, of 0.74 we obtain by equation (56):

$$R = \frac{1.05 \cdot 2}{0.74} = 2.84 \text{ Ohms}.$$

The total resistance of the earthing system, according to equation (57), will be:

$$R_{\text{c}} = \frac{1}{\frac{1}{0{,}738} + \frac{1}{2{,}84}} = \frac{1}{1{,}355 + 0{,}346} = 0{,}588\ \textit{ом}.$$

The voltage drop in the earthing system will thus be:

$$E_2 = I \cdot R_c = 12 \cdot 0.588 = 7.05 \text{ V}.$$

The connection leads have a total length of 25 + 30 =55 m, 20 square mm cross-section, 0.0175 Ohm mm^2/m spec. res. (copper). Thus, their resistance:

$$R_1 = 0.0175\ \frac{55}{20} = 0.048 \text{ Ohms},$$

and the voltage drop in these connection leads:

$$E_1 = IR_1 = 12 \cdot 0.048 = 0.575 \text{ V}.$$

The total required voltage will thus be, according to equation (29):

$$E = 7.05 + 0.63 + 0.575 = 8.255\ V.$$

Taking into consideration that a certain excess voltage is required, the current source should be able to supply 10 V. Thus, the output of the d. c. source should be:

$$W = 12 \cdot 10 = 120\ W.$$

Example 5. The required rating of the current source is to be determined for a protection installation with the same operating conditions as in the case of Example 4, except that the cathodic protection is to be provided by sections of "finite length".

The required potential at the connection point is in this case determined by means of equation (26):

$$E = 0{,}285 \cdot \mathrm{ch}\left[0{,}0116 \sqrt{\frac{1500}{8}} \cdot 5\right] = 0{,}285 \cdot \mathrm{ch}\ 0{,}794 = $$
$$= 0{,}285 \cdot 1{,}333 = 0{,}38\ в.$$

The value of the required voltage will in this case be about half that required for a section of "infinite length".

According to equation (27), the resistance of the protected section will be:

$$r_0 = \frac{11{,}6}{1{,}015\sqrt{1500 \cdot 8}} \cdot \frac{1}{\mathrm{th}\left[0{,}0116\sqrt{\frac{1500}{8}} \cdot 5\right]} = 0{,}1045 \frac{1}{\mathrm{th}\ 0{,}794} =$$
$$= 0{,}1045 \cdot 1{,}52 = 0{,}159\ ом.$$

The current intensity for one side of the protected section will equal:

$$I = \frac{0.38}{0.159} = 2.39\ A.$$

and for the entire protected section:

$$I_A = 2.39 \cdot 2 = 4.78,\ \text{i. e., appr. } 5\ A,$$

as compared to 12 A for protection by the system of a section of "infinite" length.

The earthing resistance was already determined in Example 4, and amounts to 0.588 Ohm. Thus, the voltage drop in the earthing system will be:

$$E_2 = I \cdot R_c = 5 \cdot 0.588 = 2.94\ V.$$

The resistance of the connection leads is 0.048 Ohms and thus the voltage drop in these leads is:

$$E_1 = I \cdot R_1 = 5.0 \cdot 0.048 = 0.24\ V.$$

The required total voltage for the cathodic protection:

$$E = 0.38 + 0.24 + 2.94 = 3.56\ V.$$

and the required power output:

$$W = 5 \cdot 3.56 = 17.8\ W,$$

as compared to 120 W (i. e., six times the value) for protection by the system of "infinite" length.

Example 6. The pipeline length which is sufficiently protected is to be determined for the following conditions:

1) outside diameter of the 12" pipeline: 323 mm;
2) pipe wall thickness: 9 mm;
3) the ends of the sections are insulated from the remaining parts of the pipeline (sections of "finite" length);
4) the conductivity of the protective coating: 1000 microsiemens m^2;
5) minimum potential necessary to ensure protection: -0. 285 V;
6) potential available at the connection point: -0. 60 V.

According to equations (24) and (35):

$$l_2 = \frac{\text{arc ch}\left(\frac{E_A}{E_m}\right)}{0{,}0116\sqrt{\frac{g_1}{T}}} = \frac{\text{arc ch}\left(\frac{0{,}6}{0{,}285}\right)}{0{,}0116\sqrt{\frac{1000}{9}}} = \frac{\text{arc ch } 2{,}1}{0{,}0116\sqrt{111}} =$$

$$= \frac{1{,}37}{0{,}122} = 11{,}25 \text{ км}.$$

The length of the protected section on both sides of the connection point will be:

$$L = 11.25 \cdot 2 = 22.5 \text{ km}.$$

If the conductivity of the pipe coating should increase to $g_1 = 10000$ microsiemens m^2, the protected section would be reduced to:

$$l_2 = \frac{1{,}37}{0{,}0116\sqrt{\frac{10000}{9}}} = \frac{1{,}37}{0{,}387} = 3{,}54 \text{ км},$$

i. e., the total protected length on both sides of the connection point would amount to:

$$3.54 \cdot 2 = 7.08 \text{ km}.$$

Example 7. The conductivity of the coating is to be determined for the following conditions:

1) wall thickness of the pipeline tubes: 9 mm;
2) distance between the measuring points: $(x_2 - x_1) = L = 1$ km;
3) potential at the first measuring point: $E_1 = -0.320$ V;
4) potential at the second measuring point: $E_2 = -0.300$ V.

The average conductivity along the 1 km stretch between the two measuring points is determined according to equation (38), thus:

$$g_1 = 39200 \cdot 9\left[\lg\frac{0{,}32}{0{,}30}\right] = 39200 \cdot 9 \cdot 0{,}000785 = 276\ \mu c\ м^2.$$

Chapter VIII

PROTECTION BY GALVANIC ANODES

The usual system of cathodic protection requires permanent maintenance and continuous electricity supply, but these are not required for cathodic protection systems operating with galvanic anodes. The characteristic of this system is that the required current is supplied by an artificial galvanic couple in which the part to be protected, usually steel, forms the cathode. Every metal has a certain definite potential if placed in an electrolyte. If two metals are connected by a conductor, the metal having the higher galvanic potential will be the anode and that with the lower potential will form the cathode of the circuit. Table 39 provides data required to determine which of the metals of such a couple will be the cathode. This table gives the values of the potential of various metals relative to a hydrogen electrode. These values should be used only for guidance since the potential of the metal can change quite appreciably with the type and concentration of the electrolyte into which it is placed.

Table 39.

Equilibrium potentials of electrodes of various metals.

Metal	Symbol	Standard potential	Metal	Symbol	Standard potential
Silver	Ag	+0,80	Cobalt	Co	—0,29
Copper	Cu	+0.34	Cadmium	Cd	—0.40
Bismuth	Bi	+0,28	Iron	Fe	—0,44
Antimony	Sb	+0,25	Chromium	Cr	—0.557
Hydrogen	H	0	Zinc	Zn	—0,76
Tin	Sn	− 0.1	Manganese	Mn	—1,04
Lead	Pb	—0,12	Aluminium	Al	—1,34
Nickel	Ni	−0,23	Magnesium	Mg	—2,34

PRODUCTION OF GALVANIC ANODES

Metals used for galvanic anodes must be more negative than iron. At present zinc, aluminium and magnesium are used for this purpose and each must contain only up to certain percentages of admixtures of other metals if they are to be suitable for use as galvanic anodes. If these metals are not sufficiently pure they will not provide sufficient protection. Cases are known where zinc did not provide sufficient protection because it was not sufficiently pure. Investigations have shown that for effective protection it is absolutely necessary to use refined zinc containing a minimum of impurities, lead, iron, cadium, copper, antimony, nickel and arsenic. Of the zinc produced in the Soviet Union, the TsO zinc is the most suitable, whilst the zinc TsI is less suitable. The compositions of these two makes of zinc, according to the specification GOST 4740 and also the optimum composition are given in Table 40.

Pure magnesium is too unstable in the soil, and optimum results are obtained with a magnesium alloy containing admixtures of aluminium, zinc, manganese in quantities given in Table 41. The use of magnesium for galvanic anodes is relatively recent and so is the use of aluminium having additions of zinc from 5 to 15%.

Comparison of the performance of individual anode materials can be on the basis of the degree of protection and on economic considerations. The fullest information is available on zinc electrodes, whilst the least information is available on aluminium ones.

An indication on the economics of such anodes is primarily their current output. For zinc the current output is 740-820 AH per kg, for magnesium 1322 AH per kg, for aluminium 1490 AH per kg. Thus, aluminium anodes yield most current, and it can be seen from Table 42 that these are also cheapest.

Galvanic anodes can be made in a variety of shapes, e. g., as plates, bars of various cross-sections, etc. The most widely used anodes are: a) zinc plates of 13 x 76 x 9.15 mm, weighing 6.3 kg; b) square shaped zinc plates of 13 x 305 mm x 305, weighing 5.4 kg; c) zinc bars 25 x 25 x 120 mm; d) zinc bars 3.5 cm diameter and 60 or 120 cm long containing an iron core; the total weight of these is 4 and 8 kg respectively with zinc weights of 1.3 and 2.6 kg respectively; e) magnesium anodes of 10 cm diameter and a length of 50 cm weighing 7.2 kg including the steel core; f) D-shaped magnesium anodes the plane side of which is 10 cm wide, the curvature radius of the semi-circle 10 cm and the length 150 cm weighing for instance 25 kg; g) magnesium rods of, for instance, 20 cm diameter and a weight (including a steel core) of 24 kg; h) aluminium rods of 6 to 10 cm diameter, a length of 50 cm and weighing about 12 kg.

INSTALLATION OF GALVANIC ANODES

Investigations have shown that the performance and service life of independent anodes depend to a considerable extent on the soil surrounding them. Therefore, use of special materials for filling-in may, in many cases, result in a considerable increase of the current yield of the anodes.

Investigations carried out with various filling materials showed results which are given in Table 43. As can be seen, the best results are obtained by using a mixture of clay and gypsum powder for which the highest yield of current and the lowest

Table 40.

Composition of zinc for galvanic anodes

Element	Contents in % not to exceed		
	Zinc TsO	Zinc Ts1	Optimum
Lead	0,015	0,024	—
Iron	0,020	0,020	0,008
Cadmium	0,010	0,014	0,004
Copper	0,001	0,002	—
Tin	0,001	0,001	0,080
Antimony	0,002	0,005	—
Nickel	0,001	0,001	—
Arsenic	0,002	0,005	—
Total percentage of impurities	0,040	0,060	0,100

Table 41.

Composition of the magnesium alloy for galvanic anodes.

Element	%
Aluminium	5,3–6,7
Manganese (minimum)	0,18
Zinc	2,5–3,5
Silicon (mazimum)	0,3
Copper (mazimum)	0,05
Nickel (maximum)	0,003
Iron (maximum)	0,003
Other admixtures (maximum)	0,3
Magnesium	The rest

Table 42.

Comparative data on the economics of galvanic anodes of various metals.

Metal	Current yield AH/kg	Metal consumption kg/A year	Cost index
Aluminium	1490	5,9	1,00
Magnesium	1322	6,7	1,62
Zinc	740	11,9	1,81

resistance of the anode earthing is obtained. If unsuitable filling materials are used, the current yield becomes smaller and the resistance larger. For instance, for clay without gypsum powder the current yield was only half the value obtained for clay with gypsum powder, and the resistance was twice as high. For lime filling material the current yield was only one-tenth of the optimum value.

The gypsum mixture should consist of two parts of gypsum powder and eight parts of clay. The component must be thoroughly mixed and a quantity of water added to make the mass sufficiently fluid so that it can be poured into the hole where the anodes are to be buried. Such mixtures should have a resistance of 200 to 400 Ohm cm.

For magnesium anodes a special filling material of the following composition is used:

1) for soils of low resistance: three parts of bentonite and one part of hydrated gypsum powder;
2) for high resistance soils: two parts of bentonite, one part of hydrated gypsum powder, one part of anhydrous sodium sulphate. Use of chlorides is undesirable.

Table 43.

Influence of various filling materials on the operation of zinc anodes (test results obtained with plates laid 1.27 m deep).

No. of months in operation	Filling material: clay + component	Current yield per plate, mA		Average potential to earth V[1])	Average earthing resistance Ohms
		Average during entire period	At the end of operation period		
23	Gypsum powder	55	61	1.09	5,1
16	Gypsum powder, sand and magnesium sulphate.....	45	38	1,09	5,7
16	Gypsum powder and zinc sulphate..........	45	46	1,09	6,2
16	Gypsum powder and sand	37	34	1,08	6 2
23	Clay	30	20	1,06	8.4
23	Ammonium chloride (NH_4Cl)	18	2	0,95	8.7
15	Lime	6	—	0,82	8.0
Mean values per plate of 10 sets fitted for gas mains (with 4 or 5 plates in each group)					
20 - 23	Gypsum powder	29	—	1,09	1.54[2]
20—23	Clay	18	—	1,06	1,84

[1] Measured by a copper sulphate electrode

[2] Resistance of the group of plates

Table 44.

Current and voltage values for galvanic anodes made of aluminium plus 5% zinc in a moist filling compound consisting of lime, salt and calomel (in alluvial soil with a specific resistance of 1000 Ohm cm)

Time of test	Potential, V		Current intensity, mA
	"Pipe-soil"	"Anode-soil"	
Anode No. 1			
Measured at the beginning of the tests	0,74	1,19	115
Measured after 60 days ..	0,73	1,10	117
Anode No. 3.			
At beginning of tests ...	0,70	1,21	120
After 60 days	0,725	1,11	130

The anodes were cast, 113 mm diameter, 533 mm long and weighed 13.5 kg.

For aluminium anodes the recommended filling material is a mixture of common salt with lime. The electrical parameters of such a system are given in Table 44.

The current flow from galvanic anode systems cannot be increased once they are installed, except by complicated and difficult methods. It is therefore of utmost importance to insulate the protected section of the pipeline very carefully from the other sections to prevent current leakages.

A plan of an installation of a galvanic anode is given in Fig. 90. The vertically placed anode is situated at some distance from the pipeline to be protected and is connected to it by a conductor, usually of copper. It is advisable to place the leads from the anode and the pipeline connection into a special box. If a section of considerable length is to be protected, anode earthing, consisting of a group of anodes, is made. An example of a group consisting of 5 anodes is shown in Fig. 91. Each anode feeds its current through a condutor into a separate junction box, which also contains the conductor from the pipeline, thus making it easy to check the operation and the current flow of each anode. It can be seen from Table 45 that in the case of a group of 5 zinc plates placed into soil of resistance of 5 to 10 Ohms m, the lowest plate yields the largest current. The top plate is influenced considerably by the weather, therefore such anodes should

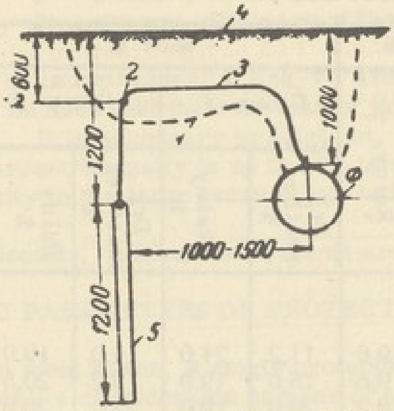


Fig.90. Layout of a zinc anode.

1 - ditch made for laying the connection lead; 2 - location of the connection point of the conductors from the anode and from the tube; 3 - rubber insulated conductor of 10 mm2 cross section; 4 - soil surface; 5 - zinc anode weighing 8 kg.

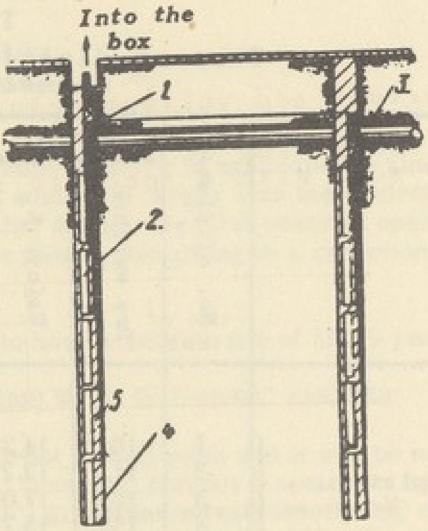


Fig.91. Group assembly consisting of 5 zinc anodes.

1 - conductor; 2 - zinc plates 900x75x12.5 mm; 3 - protected pipeline; 4 - hole (in the ground) of 10 cm diameter; 5 - filling material.

be placed at a depth of at least 1.5 m. The outside influence is then negligible.

The distance between a galvanic anode and the tubing to be protected is of great importance; this distance usually depending to some extent on the length of the pipeline to be protected. When this length is increased the distance between the pipeline and the anode should also be made larger, but not directly in proportion to the increase of the pipeline length. The minimum anode-pipeline distance should be that given in Fig. 92, the maximum for a group of plates being 4.5 m.

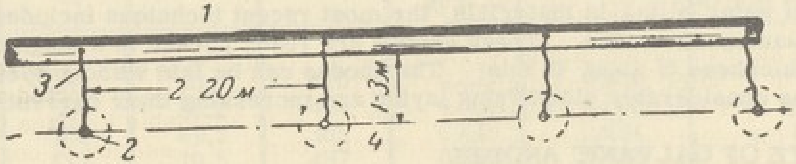


Fig.92. Schematic representation of a protection arrangement with galvanic protector anodes.

1 - protected pipeline; 2 - galvanic protector anode; 3 - connection leads; 4 - ditch for laying the anodes and re-filling it.

Table 45.

Current distribution of five plates connected in series.

	No. of plate	Spot A		Spot B		Spot C			
						Group 1		Group 2	
		Dry weather %	Rainy, %	Dry weather %	Rainy, %	Dry weather %	Rainy %	Dry weather %	Rainy %
Top plates ...	1	16,0	14,3	9,0	19,6	11,2	21,0	14,0	19.0
	2	11,2	12,2	11,0	19,6	18,0	19.0	19,2	20.5
	3	16,0	17,0	22,0	18,2	20,0	19,0	22,0	20.0
	4	18,0	15,7	19,5	18,6	21,0	21,7	22,5	21.0
Bottom plate ...	5	38,5	41,0	28,5	24.7	27,0	21,7	21,0	21,0
Resistance of entire group, Ohms	—	1,72	1,70	1,22	1,20	1,26	1,29	1,37	1,36
Digging depth, m	—	5,5		5,8		5,8		5,8	

Galvanic anodes are placed in ditches with dimensions as shown in Fig. 90, a hole being dug to receive the anode. The hole can be dug manually or by mechanical means. After placing the anode in position, the ditch is filled with suitable mixtures given earlier in this Chapter. The conductor must be soldered to the piping to be protected and it must be sufficiently insulated, either by rubber or other suitable insulation.

Instead of using filling-in materials, the most recent technique includes the use of "packaged" aluminium anodes. These anodes are ready packed in a magnesium chloride cement of a thickness of about 40 mm. The anodes can be laid without special filling material, thus considerably simplifying laying and increasing their current yield.

SERVICE LIFE OF GALVANIC ANODES

An important characteristic of independent anodes is their service life which can be calculated by the formula:

$$L = \frac{K \cdot I \cdot 1000 \cdot \varrho}{U \cdot 365 \cdot 24}, \qquad (60)$$

where L -service life, years;
K -weight of the anode metal, kg;
I -current yield of the used metal, AH/kg;
U -intensity of the anode current, mA;
ℓ -current efficiency of the anode.

The latter values, U and ℓ, are given in Table 46 which is applicable to zinc anodes. It can be seen that the real loss of the anodes is somewhat larger than the theoretical value. It is necessary to point out, however, that during the first years of operation the current intensity is up to 25% larger than the mean value owing to a reduction of the intensity in the later years of operation.

Usually, such anode systems are designed to have a service life of 10-15 years.

BASIC PARAMETERS OF PROTECTION SYSTEMS WITH GALVANIC ANODES

In most cases, a single protector anode will not be sufficient and it will be necessary to install a considerable number of such anodes, obtaining thereby a system of stations with "finite length" sections as shown in Fig. 92. To obtain normal functioning of such a system, the spacing between the individual anodes along the pipeline must be uniform. There is no special method of calculation at present for determining these spacings but it can be assumed that the methods of calculation applied for the standard type of cathodic protection are also applicable in this case. However, since there are no data so far on the correctness of the results obtained by such calculations it is preferable to work with empirical data. Table 47 gives values of the current and of the number of anodes required for a protection system. It is worth noting that the required current densities are very small and in some cases they are as low as 0.08 mA m^2.

The change of current yield with time is illustrated by the values given in Table 48. From this it can be seen that 15 months after putting the anodes into operation the current

Table 46.

Service life and efficiency of zinc anodes according to data obtained on test samples.

Number of plate	Working time, days	Average current output, mA	Current yield AH	Theoretical weight loss kg	Real Weight loss, kg	Efficiency: Theoretical
						Actual values, %
S-1	284	40,5	276	0,337	0,367	92
B-7	304	55.2	404	0.490	0,608	81
B-8	304	49.5	362	0.440	0,494	89
S-1	512	39,5	487	0,598	0,635	93
C-1	653	29.5	464	0,566	0,680	83
C-4	653	35,0	550	0,670	0,680	98
					Mean value	89

Table 47.

Practical data on the cathodic protection of pipelines by zinc anodes

Line	Number of zinc anodes	Total number of zinc plates	Current yield of the zinc		Potential[1] "pipe-soil" V	Length of the protected pipeline, m	Tube (surface) area, m2	Average current consump. mA/m2	Current consump-tion A/km
			Total	Per plate					
A	3	25	595	24	0,866	455	219	2,72	1310
B	5	52	1242	24	0,983	887	411	3,02	1400
C	5	50	1303	26	0,904	1370	457	2,85	950
D	5	55	1322	24	0,912	1980	738	1,80	670
E	5	52	814	16	0,908	1200	373	2,17	680
F	1	8	110	14	0,980	238	114	0,96	462
G	2	20	382	19	0,885	301	153	2,51	1270
H	1	12	230	19	0.93	3110	1115	0,20	75
I	8	156	1990	19	0,85	2990	1205	2.49	1000
J	1	7	90	13	1,01	2130	1115	0,08	42

[1] The potential " tube-soil " measured using the copper-sulphate electrode.

[2] Pipes of 2 - 8" diameter.

yield drops to a third of its initial value.

Table 49 gives practical data on spacings between zinc anodes. It can easily be seen that the spacing between anodes decreases with increasing tube diameters, i. e., with increasing area of the surface to be protected.

Table 50 gives the required spacings between zinc electrodes so as to obtain the necessary protective current of 5 mA m^2 for coated pipelines and 10 mA m^2 for uncoated. One 120 cm long anode is sufficient for protection of the surface requiring 20 mA. Such an anode contains 2. 6 kg of pure zinc on a steel core.

ECONOMICS OF GALVANIC ANODES

Since this method of protection has not been applied for very long, relatively little data is available on costs. The distribution of costs in the case of two pipelines protected by means of zinc anodes is given in Table 51.

It is particularly interesting to compare the economics of such a protection with that of an ordinary type of cathodic protection operating with an external current source.

Table 48.

Change of the parameters of a protection system as a function of time for zinc anodes of 35 mm dia., 120 cm long, weighing 8 kg.

No. of test	Operation in days	E_s, mV	E_{CuSO_4}	I_z, mA	i_o, mA	I_t, A	Average service life, years
1	Initially	+196	—	368	1,56	26,5	21
2	52	— 56	—	338	1,43	24,3	23
3	73	—117	—	310	1,31	22,3	25
4	296	—433	—	145	0,61	10,4	53
5	449	—217	924	110	0,47	7,9	70
6	830	—198	990	—	—	—	—

E_S — "Pipe-soil" potential, measured by means of a steel electrode.

E_{CuSO_4} — "Pipe-soil" potential, measured with a non-polarizing electrode.

I_Z — current output of an installation comprising 10 zinc anodes.

i_o — specific current flow per 0.1 m^2 of pipe surface.

I_t — total current output of 72 zinc anode sets, each consisting of 10 anodes.

Table 49.

Practical data on the spacing of galvanic anodes.

Diameter of pipe to be protected mm	Coating of the pipe-line	Total length km	Number of sections	Length of sections, m		No. of zinc anodes	Average spacing of the anodes, m
				Max.	Min.		
63	None	0,092	1	—	—	12	7,6
114	None	2,6	1	—	—	610	4,2
168	Existing ..						
168	None	9,0	6	4300	230	2016	4,45
220	None	7,9	19	1525	30	2438	3,2
455	None	0,55	2	366	184	450	1,2
	Total	20.14	—	—	—	5526	—

Zinc anodes were used as follows: 1100, square cross section, 122 cm long weighing about 5 kg, the others - 3.5 cm dia. 122 cm long, weighing about 8 kg.

Table 50.

Distance between (adjacent) zinc anodes.

Rated dia. of pipeline inches	Distance between the zinc anodes, m			
	Insulated pipes		Blank pipes	
	120 cm anode	60 cm anode	120 cm anode	60 cm anode
6	—	4,1	—	2,1
8	—	2,9	2,9	—
10	—	2,4	2,4	—
12	—	2,0	2,0	—
14	—	1,7	1,7	—
16	2,9	—	1,5	—
18	2,6	—	1,3	—
20	2,3	—	1,2	—
22	2,1	—	1,0	—
24	1,9	—	0,9	—

The cost of operation of the latter during ten years is higher than the cost of protection by galvanic anodes for twenty years. This is fully understandable since galvanic anodes involve hardly any operation costs whilst external current supplies usually involve appreciable overheads.

The costs of protection by galvanic anodes would be appreciably higher in the case of pipeline networks in towns since it would be necessary to suppress incidental contacts and to improve the electrical insulation.

Table 51.

Cost of cathodic pipeline protection with zinc anodes.

Cost items	Percent of average cost per meter	
	For a 6" pipeline 8.4 km long	For a 8" pipeline 13.2 km long
Materials:		
Zinc anodes	57,57	60,40
Copper conductor	6,34	5,62
Filling compound	0,66	0,82
Total	64,57	66,84

Table 51. (Contd.)

Cost of cathodic pipeline protection with zinc anodes.

Cost items	Percent of average cost per meter	
	For a 6" pipeline 8.4 km long	For a 8" pipeline 13.2 km long
Transport and other road costs	10,45	6,22
Work:		
Preparation of conductors	1,21	0,68
Junction of the conductors	0,77	1,56
Carrying out of the measurements	0.35	0.21
Fitting the zinc anodes	9,36	10.72
Digging of ditches	3,20	4,80
Filling up	1,26	1,57
Welding and junction	0,32	0,14
Tests	—	0,08
Observations	4,33	3,28
Total	20,80	23,04
Technical inspection	4,18	3,90
Final total	100,00	100.00

Chapter IX

CATHODIC PROTECTION OF OIL STORAGE INSTALLATIONS

OBJECTS TO BE PROTECTED

It is necessary first to see which objects are endangered by soil corrosion. The storage tanks can from this point of view be subdivided into the following types.

1) Tanks above ground, endangered by soil corrosion only at the outside bottom surface. Underneath such tanks there is usually a sand layer a few centimetres thick. If thoroughly washed river sand is used for this purpose it can be assumed that the possibility of soil corrosion of the reservoir bottom is eliminated. However, penetration of salt-containing soil moisture, due to capillary action, provides danger of rapid corrosion, in spite of the presence of the sand layer, if the soil underneath has a high corrosivity. For sand of average grain size, the penetration of soil moisture reaches to a height of about 0.5 m. Therefore the tank bottom will be subject to the corrosive effect of the soil in spite of the layer of sand.

2) Underground or semi-underground tanks without encasement. In underground tanks the entire outside surface is subject to soil corrosion and in semi-underground tanks the entire surface in contact with the ground is subject to soil corrosion. The materials used for filling-in around the tank have little influence on the corrosion since their properties change rapidly. Owing to penetration by capillary action of salt solutions contained in the subsoil their properties will become equal to those of the surrounding soil.

3) Underground or semi-underground encased tanks. In underground tanks the outside of the bottom surface and, to a lesser extent, the surface of the cover are affected by soil corrosion. In semi-underground tanks, only the bottom is subject to soil corrosion.

CONDITIONS OF PROTECTION

An important factor in the protection of tanks is the fact that the wall thickness is considerably less than the wall thickness of pipelines, The wall thickness of new tanks is usually 3 - 8 mm. Assuming that the rate of pitting is characterized by a parabola, it is evident that a reduction of the wall thickness to, for instance, half a certain value, will bring about a reduction of the service life to less than half. Therefore, the reliability of protection required for such structures is higher.

A characteristic of oil storage installations is usually that the arrangement of the objects to be protected is a complex one, consisting of one or several groups of tanks with an interconnecting network of pipelines and other metal parts underground. In individual cases, protection is provided for large oil storage installations containing several tanks and many kilometres of internal pipelines.

To ensure safety against fire, cathodic protection in oil storage installations must be carried out with such currents as will not constitute a fire hazard. Numerous investigations of cathodic protection in various oil storage installations, including very large ones where various types of petroleum products are stored, have shown that application of cathodic protection in oil storage installations is entirely safe, provided certain precautions are observed.

According to regulations of the Russian Fire Inspection Services, cathodic protection in oil storage installations must comply with the following specifications:

1) The potential difference of containers with inflammable materials must not exceed 1 Volt;
2) the effective power must not be larger than 0. 5 W;
3) maximum voltage at the output terminals of the current source, 10 Volts.

To comply with these regulations, cathodic protection of oil storage installations must be carried out by a number of individual cathodic stations, each with a separate earthing system since only in this way is it possible to provide protection for installations distributed over such a large area without exceeding the permissible voltage. It is pointed out that about three-quarters of the total voltage drop is usually in the earthing system, and therefore the specified safety conditions can easily be complied with even in the case of individual protection stations which have an output of 0. 3 kW. From the literature on the subject it is known that cathodic protection is in use for oil storage installations with voltages at the current source terminals of 30 to 35 V, and currents of 200 to 250 A are known to exist. However, the potential difference of the individual tanks does in no case exceed 1 V by more than 0. 10 to 0. 15 V.

The fundamental circuit for cathodic protection of a group of tanks is the same as that applied to pipelines, the only difference being that the negative terminal of the current source is connected to the tank. It can also be connected to a pipeline which is electrically efficiently connected with the tank to be protected.

CIRCUIT DIAGRAM OF THE PROTECTION SYSTEM

The circuit for cathodic protection of an oil storage installation differs somewhat from that applicable to pipelines since in this case the protection is usually carried out by means of several parallel connected electrical circuits. Fig. 93, shows an example of such a protection circuit for a small petrol store consisting of 9 tanks of 1130 m^3 each, the electrical circuit is shown in Fig. 94.

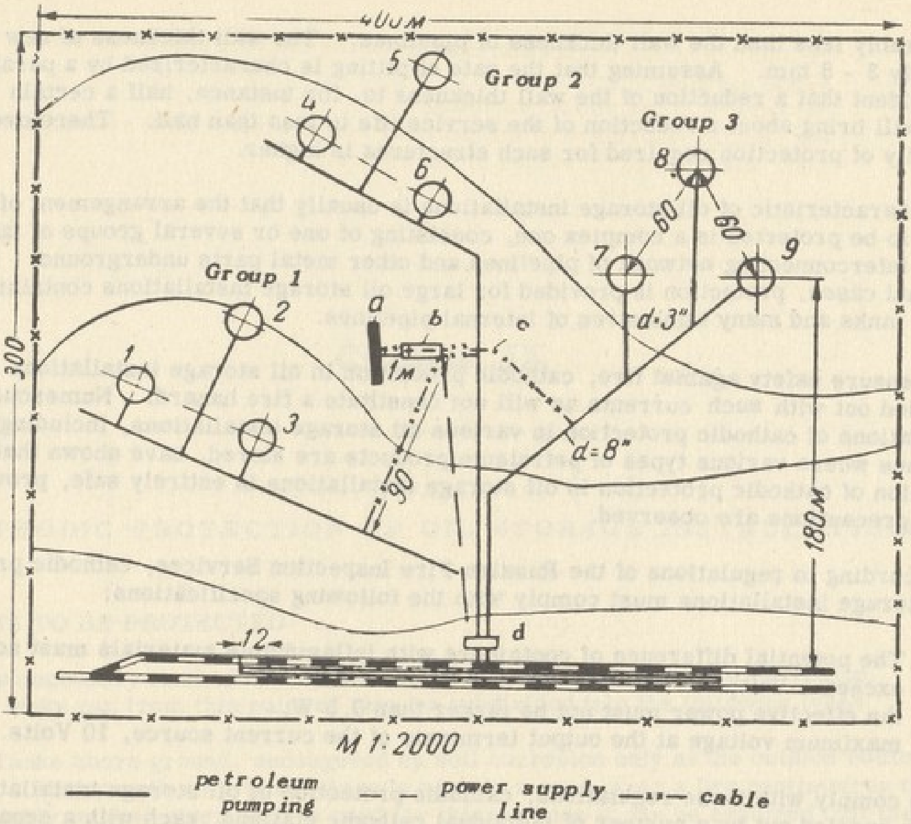


Fig. 93. Cathodic protection installation of a small petrol (gasoline) store.

1 to 9 - number of reservoir, each of 1130 m^3;
a - anode earthing; b - rectifier equipment;
c - underground cable; d - pumping station.

The contact resistances of the individual tanks and also the resistances of the connection tubes to these tanks are connected in parallel in the general circuit, but relative to each other these resistances are connected in series for each of the tanks. The resistances of the connection cable, the earthing and the second connection cable, are also connected in series. According to the circuit diagram, the total current in the circuit equals the sum of the individual currents in the parallel sections of the circuit, i. e.

$$I = i_1 + i_2 + i_3 + i_4, \quad \dots \quad \dots \quad \dots \qquad (61)$$

where I - the total current in the circuit A;
i_1, i_2, i_3, i_4 currents in the 1st, 2nd, 3rd, 4th, etc., parallel circuit, Amps.

The total resistance of the entire protection circuit:

$$r_0 = r_1 + r_2 + r_E + r_3, \text{ Ohms} \quad \dots \quad \dots \qquad (62)$$

where r_0 - total resistance of the circuit;

r_1 - resistance of the connection lead from the current source to the anode earthing;

r_2 - resistance of the anodic earthing;

r_Σ - the contact resistance of the protected object (structure) and the return lead, determined by means of the equation:

$$\frac{1}{r_\Sigma} = \frac{1}{r'_1 + r''_1} + \frac{1}{r'_2 + r''_2} + \frac{1}{r'_3 + r''_3} + \ldots + \frac{1}{r'_9 + r''_9}, \qquad (63)$$

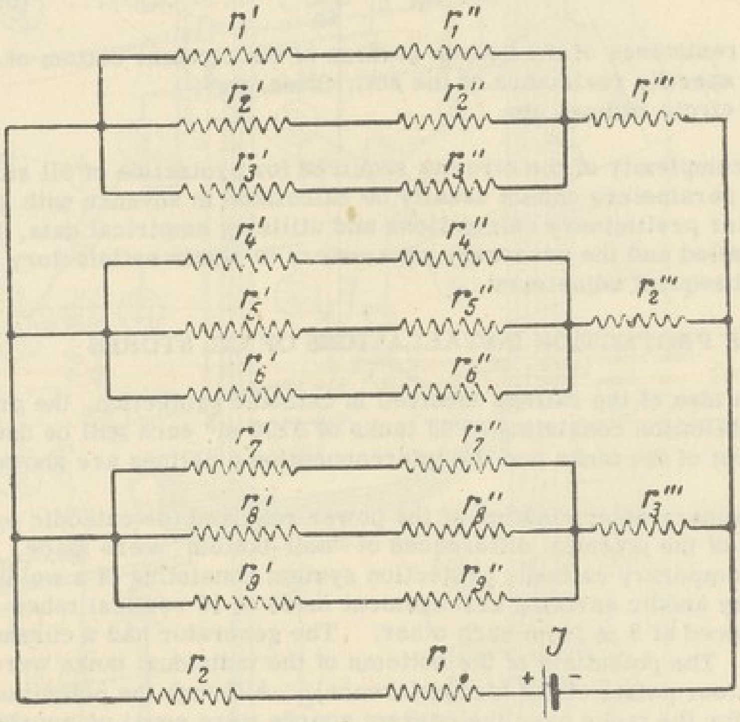


Fig. 94. Electrical equivalent circuit of the protection system of a petrol (gasoline) store.
r_1 - resistance of the cable connecting the positive pole of the current source with the earthing system; r_2 - resistance of the anode earthing system; $r'_{1\text{-}9}$ - resistances of the individual protected reservoirs; $r''_{1\text{-}9}$ - resistance of the cable connecting the protected system to the negative pole of the current source; $r'''_{1\text{-}3}$ - resistance of the binding tubes; I - current source.

K•

where r'_1, r'_2 - contact resistance of the protection of the individual tanks;
r''_1, r''_2 - resistance of the reservoir body;

$$\frac{1}{r_3} = \frac{1}{r_1'''} + \frac{1}{r_2'''} + \frac{1}{r_3'''} . \qquad (64)$$

The resistance of the earthing and the connection leads is determined by means of the formulae given in Chapter VI, the contact resistance between the bottom of the tank (which is of circular shape) and the soil is determined by the formula

$$R_d = \frac{\varrho}{4b} , \quad \ldots \ldots \ldots \qquad (65)$$

where R_d - resistance of the bottom surface of the circular bottom of the tank, Ohms;
ϱ - specific resistance of the soil, Ohms/cm^3;
b - circle radius, cm.

Owing to complexity of the circuits required for protection of oil storage installations, the necessary parameters cannot usually be calculated in advance with sufficient accuracy. Therefore, after preliminary calculations and utilising empirical data, the protection system is installed and the necessary parameters to obtain satisfactory operation are obtained by subsequent adjustment.

EXAMPLES OF PROTECTION INSTALLATIONS OF OIL STORES

To give an idea of the ratings involved in cathodic protection, the protection of a large oil storage installation consisting of 45 tanks of 8700 m^3 each will be described. The schematic layout of the tanks and the interconnection pipelines are shown in Fig. 95.

For preliminary determination of the power required for cathodic protection, test measurements of the potential differences of "soil-bottom" were made. This was done by applying a temporary cathodic protection system consisting of a welding generator and a temporary anodic earthing arrangement made of 10 vertical tubes 6" diameter, 3 m length, spaced at 3 m from each other. The generator had a current output of 75.5 A, 31 V. The potentials of the bottoms of the individual tanks were measured (sometimes at four points of the circumference). Although the potential differences of "bottom-soil" for the tanks near the current source were equal or appreciably larger than the required minimum value, i.e. -0.85 V (measured by means of a non-polarising copper-sulphate electrode), the necessary potential differences were not attained for the tanks at a greater distance from the current source.

On the basis of the test results obtained, the protection of the storage installation was carried out by means of four cathodic stations, the characteristics of which were:

Station No. 1, with a rating of 85 A, 15V and an anode earthing consisting of a horizontal pipe header of 8" diameter, 60 m long, laid at a depth of 0.75 m, and 10 vertical tubes 6" diameter and 3 m long each, placed at 3 m from each other. The resistance of this earthing was 0.175 Ohms.

Station No. 2, 90 A, 11 V with an anode earthing consisting of a horizontal header tube 82.5 m long, 8" diameter laid at a depth of 0.9 m, and 10 vertical earthing tubes, each 3 m long and 6" diameter, spaced at intervals of 3 m. The resistance of

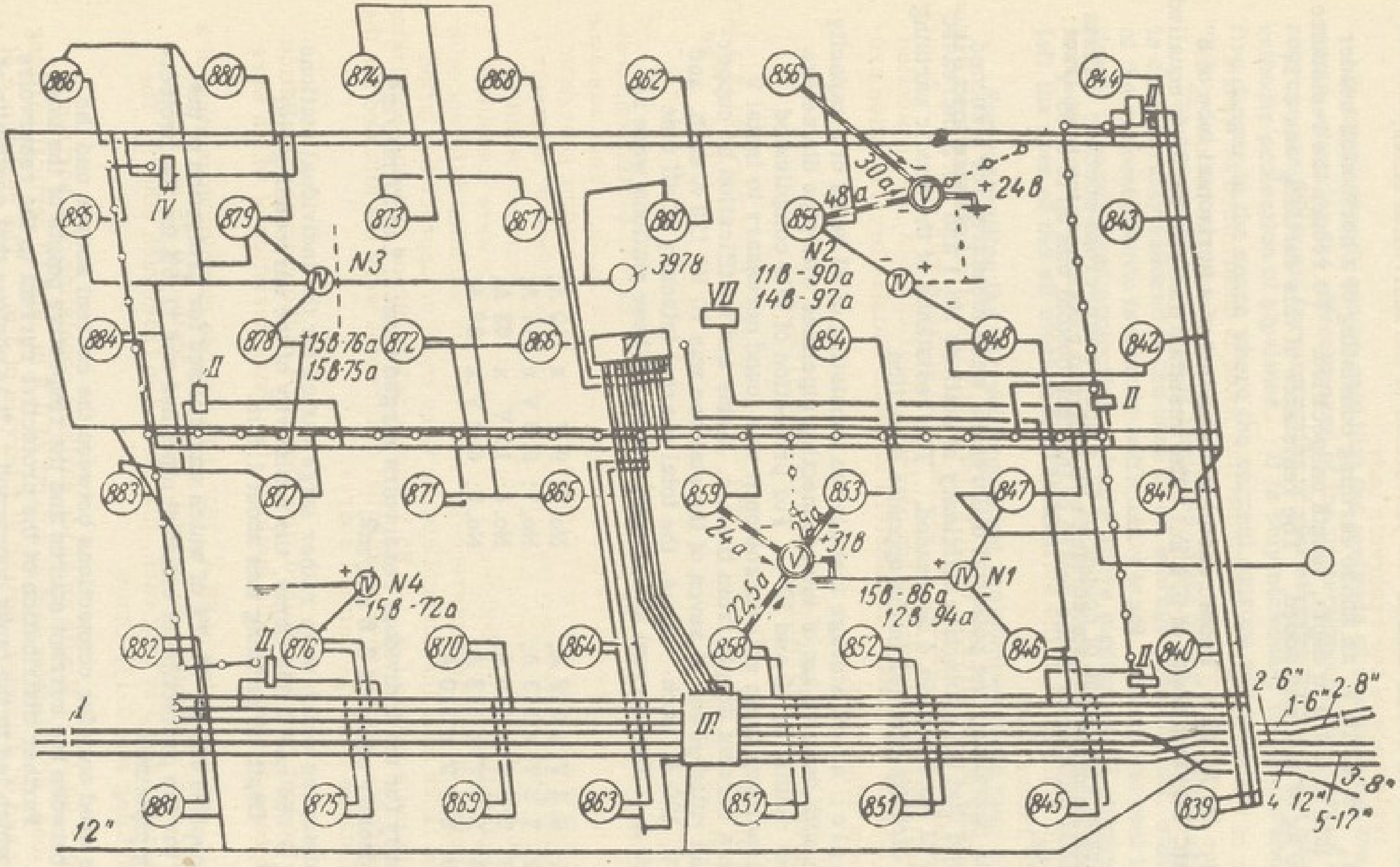


Fig. 95. Cathodic protection installation of a large oil storage installation.

I - insulating flanges; II - auxiliary pumping station; III - field manifold; IV - stationary equipment; V - installation for carrying out initial measurements; VI - manifold of the pumping station; VII - stores.

such an earthing structure is 0. 122 Ohms.

Station No. 3, 76 A, 15 V, an anode earthing consisting of a horizontal header tube of 8" diameter, laid at a 0. 9 m depth, length unspecified. To reduce the resistance of the sandy soil, 900 kg of salt was added. The resistance of this earthing was 0. 197 Ohms.

Station No. 4, 72 A, 15 V, anodic earthing consisting of a horizontal tube of 8" diameter, 90 m length, laid at a depth of 0. 9 m. The resistance of this earthing equalled 0. 208 Ohms.

The connection leads were made of copper of 67. 4 square mm cross-section. Tests showed that the potential difference in the centre of the tank bottom was up to 0. 05 V lower than at the edges.

After nine months operation, the potential differences were measured for a second time, and these showed that the protective efficiency of stations No. 1 and No. 2 increased slightly, whilst those of No. 3 and No. 4 decreased. The resistance of the anodic earthing in the corresponding circuits changed in the opposite direction.

Second example: an oil storage installation consisting of 63 tanks of a capacity of over 8000 m^3 each with over 45 km of interconnecting pipelines with pipe diameters between 2 and 16", but mainly 8, 10 and 12". For protection of this complicated system of metallic structures from soil corrosion it was found necessary to instal 9 cathodic stations with a current supply from the a. c. mains and rectification by copper-oxide rectifiers. The rated power of seven of the stations was 10 V, 120 A each, and of two stations 10. 5 V, 130 A, each. Thus, the total current intensity of all nine stations equalled 1100 A. The current and voltage values of these stations were as follows:

No. 1: 8. 2 V x 118 A;
No. 2: 7. 8 V x 113 A;
No. 3: 9. 5 V x 115 A;
No. 4: 5. 8 V x 112 A;
No. 5: 6. 1 V x 110 A;
No. 6: 9 V x 110 A;
No. 7: 9. 8 V x 111 A;
No. 8: 10 V x 63 A;
No. 9: 6. 4 V x 86 A;

The current density for the individual reservoirs ranged from 1. 7 to 27 mA/m^2; the average current density equalled 8. 8 mA/m^2.

The earthing resistances which were rather large varied for the individual stations between the limits of 0. 054 and 0. 095 Ohms, the resistivity of the surrounding soil being 500 $Ohms/cm^3$. Depth of earthing was about 1. 5 m.

The rectifiers supplied 958 A, 57. 7% of which was utilised for protection of the tank bottoms, 10. 7% for the protection of external pipelines and 31. 6% for the protection of interconnecting pipelines.

Conductors were used only for connections between the current source and the anode earthings and between the current source and the respective points of the interconnecting pipelines. Further distribution of the protective current to the reservoirs was by the pipelines which led to the tanks concerned. It is obvious that continuity of the electric conductivity was established on these pipelines.

In conclusion it can be said that the methods of carrying out the necessary measurements, checking the effectiveness of the protection and the types of applicable current sources are the same for protection of soil storage installations as they are for the cathodic protection of pipelines. It is only necessary to ensure absolute safety against fire danger in the space where the current sources are located.

The necessity of providing insulated joints at the ends of the sections to be protected is considerably reduced in the case of oil storage installations, since the power reserve of the current source is usually sufficiently large. Small current leakages will not result in insufficient protection. In the above mentioned oil storage installations insulated joints were only provided at single points, for example where the pipeline mains left the area of the oil storage installation.

For controlling the current regulating resistances fitted near the current source are recommended.

Chapter X

CONSTRUCTION OF CATHODIC PROTECTION STATIONS

Generally, construction of cathodic protection stations consists of erecting of a kiosk for housing the equipment, installation of a current source, supply and distribution lines, equipment for check measurements, construction of earthing structures and work along the pipeline to make provision for carrying out operational tests.

The volume of work involved in the installation of a current source depends on the type used. If an engine-driven dynamo is employed suitable foundations must be provided. Installation of the instrument and control panel is important and skilled workers must be employed in this work.

The earthing circuit may be of substantial size involving considerable soil work. Usually combined vertical and horizontal earthing structures are employed. If salt addition is not required, this work is usually carried out as follows. A ditch of the necessary depth is dug for the horizontal tube; the vertical earthing tubes are sharpened at their bottom ends by acetylene cutting and welding equipment and driven into the soil at the bottom of the ditch into which the horizontal tube is to be laid. If salt addition to the soil is necessary, it is advisable to drill holes for laying the vertical tubes with a drill driven by an automobile engine. Such drilling equipment is also used for drilling the necessary holes for erection of masts for electrical transmission lines. The ditch for laying the horizontal earthing tube can be dug with an excavator if one is available in the area.

On the protected pipeline insulated joints, shunting connections, control wires, and so on, are fitted. When uncovering the pipeline care must be taken that the coating of the pipe is not damaged and the last 10 cm of the soil covering the pipeline should be removed with wooden spades. For removing the last 2-3 cm the spades must be covered with soft rags to prevent damage to the coating.

When installing a cathodic protection system it is necessary to make a number of connections, e. g. , between conductors and pipes, between the various conductors, between individual parts of the earthing system, connections of shunt leads, and so on.

To do this it is essential to have available a welding set and also equipment and materials for replacing the damaged coating of the pipeline.

After installing the current source and constructing the earthing structure, electrical measurements must be carried out along the pipeline to determine the necessary value of the protective current. Primarily, the potential difference of "pipe-soil" is measured at the most distant point of the pipeline to be protected. If the measured potential difference is not large enough, the current fed into the pipeline must be increased. If the discrepancy between the calculated values of the system and the measured values is too large, the electrical continuity of the pipeline and the state of the coating along the section to be protected must be examined.

The spots of electric discontinuity along the pipeline are characterized by jumps in the protection potential along the line. The measurements are carried out utilising the test leads which are welded on to the pipeline, or by means of differential test equipment.

Chapter XI

OPERATION AND MAINTENANCE OF CATHODIC PROTECTION INSTALLATIONS

After putting the cathodic stations into operation, their normal and continuous operation must be ensured. The extent and type of maintenance work depends to a large extent on the type of equipment which is used in the installation. I. C. engines require constant attendance and it is thus necessary to have qualified personnel available on a three-shift basis. Daily supervision is also required in the case of wind-electric sets, motor-generators and other current sources which have moving parts.

Considerably less attendance is necessary in the case of rectifiers, storage batteries and dry batteries; only periodic checks differing in each individual case. It is, however, necessary to compile graphs containing the results of inspection and showing the repairs which have been done.

In the case of galvanic anodes, i. e. the anodic parts of galvanic couples, maintenance is simpler still.

In addition to maintenance, periodic checks of the working of the protection system are necessary. These consist of electrical measurements along the pipeline and observation of test specimens, and should be carried out preferably every six months but at least once a year.

The electrical measurements during periodical tests consist of measuring the potential difference between the pipeline and the soil along the pipeline, utilizing the leads along the line which are specially provided for this purpose. If the potential difference values are not large enough, it is necessary to increase them to the required values. The measures to be taken are eliminating discontinuities of electric conductivity along the line, and increasing the protective current.

Increase of the conductivity of the pipe coating due to damage may also be the reason for inadequancy of the cathodic protection and changes in the parameters. These may be so serious that it is sometimes necessary to repair the coating on the pipeline surfaces. Particular attention must be paid to local damage of the coating. Thus, as a result of accidental damage during small repairs, a "window" may occur causing considerable current leakage in a pipeline, which is otherwise perfectly protected. Such a current leak can be detected by measuring the potential along the pipeline, but it is much simpler to detect such leakages by the tube detectors mentioned earlier.

In the case of localised damage to the coating it is preferable to uncover the pipeline and repair the insulation rather than to increase the protection current.

Removal and treatment of the test plates should also be a part of the periodical tests. It is uneconomical to remove these plates more frequently than six months since it would be difficult to obtain a clear picture of the effectiveness of the protection. However, too long intervals are also unsatisfactory since sufficiently early warning of the necessity of increasing the protection may not be obtained. It is therefore advisable not to increase the time interval between the periodic tests to more than one year. The test plates along the line must not all be removed at the same time. It is necessary to remove them in stages, i. e., the first pair after six months, the second pair after a year, the third pair after two years, and so on. Each pair removed must be immediately replaced by a new pair. Before placing the plates into position, they must be weighed. The test plates must not be numbered or marked by a stamping tool because such spots are liable to increased corrosion. Placing, removal and results of inspection and weighing the test plates must be recorded in a special log book.

If weighing and inspection of test plates show inadequate protection, it is necessary to check carefully whether the connection between the test plate and the pipeline was interrupted, whether there is interruption in the electrical conductivity of the pipeline, whether the protective current is out of operation for longer periods, and so on. If none of these conditions is operative the protective current must be increased. It is, however, necessary to take into consideration that if the protective current is increased to an excessive degree it will have an unfavourable effect on the bitumen coating.

It is also necessary to periodically check the state of the anode earthing by measuring its resistance. Increased earthing resistance indicates the necessity of additional soil treatment or repair of the earthing structure. This is damaged in time, due to the action of the electric current. Repairs can be effected by driving new tubes of smaller diameter into the vertical earthing tubes.

The earthing resistance is measured by measuring the current intensity in the circuit and the potential difference between the soil and the earthing structure, as shown schematically in Fig. 96.

If galvanic anodes are used, the state of the anodes and the adequancy of the protection current must be checked periodically.

In each cathodic station records should be kept in which the voltage and current of the current source are recorded daily. The apparent reason for a change in these values and the measures taken to re-establish them should also be recorded. As has already been mentioned, the dates of placing and removal of test plates and their weight when new and after removal must also be recorded. The same applies to the results of check

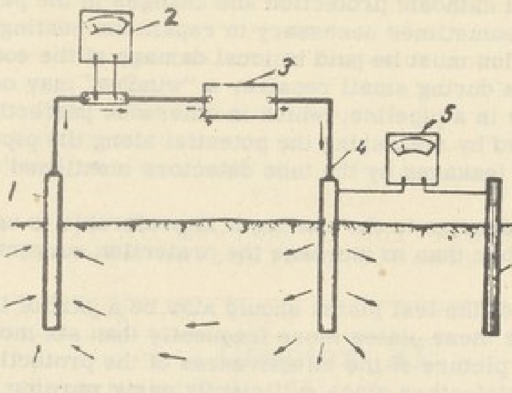


Fig. 96. Schematic representation of a test arrangement for measuring the earthing resistance.

1 - earthed electrode No. 2; 2 - ammeter; 3 - d.c. source; 4 - earthing electrode No. 1; 5 - voltmeter; 6 - earthing electrode No. 3.

measurements of the potential differences, details of repairs and detected damage on the protected pipeline. Detected damage must also be entered on a special card index in which details on the observations made in each case should be recorded. Such an index card is shown in Fig. 17.

The number of personnel required for normal operation of cathodic protection stations of various types is indicated in Table 52, and the composition of teams for

Table 52.

Example of the composition of the operating personnel of a cathodic installation as a function of the type of current supply.

Personnel	Number per installation		
	With the rectifiers	With the I.C. engine, etc.	With the storage battery
Installation manager ...	—	1	—
Mechanic	—	2	—
Electrician	1	1	1
Total	1	4	1

various check tests is indicated in Table 53.

Specially worked out technical rules and instructions apply to the operation and maintenance of the equipment.

Table 53.

Example of the composition of a team of line inspection of a cathodic protection system.

Personnel	Number per team during:		
	Voltage measurement	Gravimetric measurements	Pipeline inspection
Team leader	1	1	1
Technician	1	—	—
Lab. assistant	—	1	1
Labourers for digging ...	—	10	6
Other labourers	2	1	2
Total	4	13	10

Chapter XII

ECONOMICS OF CATHODIC PROTECTION

There is no doubt from the technical point of view, of the value of cathodic protection. Arguments against the use of such protection can only be based on costs and therefore serious attention must be paid to the economics of such systems.

The economic justification of cathodic protection depends to a large extent on the operation costs which consist of the following:

1) cost of wages of the personnel required for operation and maintenance;
2) cost of the consumed electrical energy;
3) cost of technical inspection;
4) cost of repairs of the cathodic stations;
5) amortisation;
6) cost of materials required in normal operation.

Until there is a decision on the equipment to be used in a station it is not always possible to make a detailed estimate of the costs. Therefore, these costs have to be estimated on a calculated basis. The cost is composed of the cost of the d. c. source, the cost of the electric wiring, the cost of earthing and the cost of the equipment to be fitted along the line.

If galvanic anodes are used the costs consist only of the costs of the anodes, laying and connection to the pipeline to be protected.

For guidance on amortisation values, the following figures are given for the individual items:

1) d. c. source:
    (a) selenium and copper-oxide rectifiers 10%;
    (b) mercury arc rectifiers 15%;
    (c) galvanic cells 33%;

(d) other current sources 20%;

2) anodic earthing:
   (a) steel electrodes 20%;
   (b) carbon or graphite electrodes 5%;
   (c) independent anodes made of magnesium, aluminium, zinc between 20-50%;
3) electric wiring 5%;
4) equipment along the pipeline 5%.

To determine the maximum permissible cost of a cathodic protection system, the following formula can be applied:

$$K = \frac{A(B - C)}{C}, \quad \ldots \quad \ldots \tag{66}$$

where K - the maximum yearly operation costs of the cathodic protection;
A - total cost of the structure to be protected;
B - percentage of yearly depreciation without cathodic protection;
C - percentage of yearly depreciation with cathodic protection.

To determine the values of B and C it is necessary to clarify the assumptions of the service life of the object to be protected with and without protection. For such evaluation the corrosive properties of the soil surrounding the structure and the protective coating on the structure have to be taken into consideration. For rough calculations to determine the service life of pipelines with various types of protective coatings laid in different soils

Table 54.

Increase of the service life of pipelines for various insulation coatings. (Without cathodic protection).

Soil corrosivity	Increase of service life if a coating is applied			Anticipated service life of the unprotected pipeline
	Normal coating	Strengthened coating	Very much strengthened	
Low	—	—	—	Over 25 years
Normal	10—20	—	—	10-25 »
Increased	1—3	4-7	6—10	7—12 »
High	0-2	2-5	4—8	5-10 »
Very high	0-1	1-3	3-5	3—7 »

Note: The given service life values apply to standard type steel tubes with a wall thickness of 8 mm and an internal pressure not lower than 5 atm.

the basic data on the corrosion rate of Russian pipelines are given in Table 54.

If cathodic protection is applied in time it can be assumed that the service of the pipeline or tank is increased by at least twenty years.

The economics of cathodic protection are strongly affected by the selection of the system. A section can be protected by a single or by several stations. Both solutions are technically equivalent, and a decision whether one or the other is to be used is based purely on economic considerations. It is therefore necessary to calculate by means of general indices the cost of each alternative and to determine the cost of yearly operation. Although the electricity consumption will decrease with increasing number of stations, the capital costs, and thus also the yearly depreciation, will increase. However, a reduction of the required power rating may permit the use of rectifiers in the individual stations, which reduces the costs of maintenance and operation. All these factors can be taken sufficiently into consideration only by detailed economic calculations carried out separately in each individual case.

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APPENDIX 1

SPECIFICATION OF THE MAIN EQUIPMENT AND MATERIALS OF A CATHODIC INSTALLATION FOR TEST PURPOSES

No.		Unit	Number	Manufactured by
1.	Complete rectifier assembly consisting of 24 cuprous oxide rectifier columns type T-134, series-parallel connected into a 3-phase system, fed by a 380 V 3-phase transformer with leads for regulating the voltage within the limits +10, +5; 0 - 5; 10%, and supplying a direct current of 40 A at 40 V	Complete unit	1	Kozicky Works
2.	Three-pole knife switch 500 V, 100 A, with casing on the (foundation) plate and a set of bolts for fastening from the rear	units	1	-
3.	Same, two-pole unit ·	"	1	-
4.	Fuse (cut-out), type N, 60 A, 500 V, with 60 A insert and 60 A thread	"	2	Yelektrosbit
5.	Same, for 25 A with a 6 A insert and a thread for 6 A	"	3	"
6.	Electromagnetic (moving iron) ammeter type YeN with a 10 A scale for direct connection into the circuit	"	1	-
7.	Moving-iron voltmeter type YeN for direct connection into the circuit, 450 V scale	"	1	-
8.	Moving-coil ammeter type MN, 50 A scale	"	1	-
9.	Moving-coil voltmeter type MN, 50 V scale	"	1	-
10.	Two-pole voltmeter changeover switch with three positions	"	1	-
11.	Three-phase meter type I, 220 V, 5 A	"	1	-

		Unit	Number	Manufactured by
11a.	Steel plates 150 x 75 x 8 (mm)	"	30	-
12.	Cable, 50 mm^2 cross section, type SB, for voltages up to 1000 V	m	200	Moskabel
13.	Copper conductor, MG-50	m	200	"
14.	Gas pipes, 4" diameter, 3 m long		3	-
15.	Same	m	12	-
16.	Coated welding electrodes		20	-
17.	Instrument panel for the cuprous oxide rectifier, about 800 x 2000 mm on a double frame with a steel panel including all the necessary equipment for adjustment, etc.		1	locally manufactd.
18.	Conductor, PR-380, 2.5 mm^2 cross section	m	30	Moskabel
19.	Same, 10 mm^2 cross section	m	20	-
20.	Same, 50 mm^2 cross section	m	10	-
21.	Insulator type TF-2		4	-
22.	Hook, type KN-2		4	-
23.	Solder	kg	0.3	-
24.	Insulating tape	kg	0.3	-
25.	Bakelite lacquer	kg	0.1	-
26.	Thread	kg	0.2	-
27.	Paraffin oil (kerosene)	kg	5	-
28.	Petrol (gasoline)	kg	3	-
29.	Cement	kg	10	-
30.	Tow (rope)	kg	5	-
31.	Pine pole, 16 cm dia., 6.5 m long		4	-
32.	Common salt	kg	500	-

APPENDIX 2

Data of seamless steel pipes for oil, water and gas pipelines. (Specifications GOST 301-44, GOST 301-46)

Out-side dia. MM	Wall thickness, mm															
	4,5	5,0	5,5	6,0	7,0	8,0	9,0	10	11	12	13	14	15	16	18	20
	Theoretical weight per metre (spec. gravity 7.85), kg															
146	15,70	17,39	19,06	20,72	24.00	27,23	30,41	33,54	36.62	39.66	42,64	—	—	—	—	—
168	18.14	20,10	22,04	23,97	27.79	31,56	35.29	38,97	42,59	46.17	49,69	—	—	—	—	—
194	21,03	23,31	25,57	27,82	32,28	36,70	41,06	45.38	49,64	53,86	59,03	—	—	—	—	—
219	—	—	—	31,52	36,60	41,63	46.61	51,54	56,43	61,26	66,04	70.78	—	—	—	—
245	—	—	—	—	41,09	46.76	52,38	57,95	63,48	68,95	74,38	79,76	—	—	—	—
273	—	—	—	—	45,92	52,28	58,60	64,86	71.07	77,24	83,36	89,42	95.44	101,41	—	—
299	—	—	—	—	—	57,41	64.37	71,27	78,13	84,93	91,69	93,40	105,06	111,67	—	—
325	—	—	—	—	—	62,54	70,14	77,68	85,18	92,63	100,03	107,38	114,68	121,93	136,28	-
351	—	—	—	—	—	67,67	75,91	84,10	92,23	100,32	108,36	116,35	124,29	132,19	147.82	—
377	—	—	—	—	—	72,80	81,68	90,51	99,29	108,02	116.70	125,33	133.91	142,44	159,36	176,08
426	—	—	—	—	—	—	92,55	102,59	112,58	122,52	132,41	142,25	152,04	161,78	181,11	200,25

APPENDIX 2

Dimensions and weights of longitudinally welded pipes of larger diameters for water and gas pipelines

(Specification GOST 4015-48)

Conditional passage min. internal diameter	Outside dia. mm	Wall thickness, mm					
		9	10	11	12	13	14
		Theoretical weight per metre at a spec. gravity of 7.85, kg.					
400	426	92.56	102.6	112.5	122.5	132.4	142.3
450	478	104.1	115.4	126.7	135.0	149.1	160.2
500	529	115.4	128.0	140.5	153.0	165.4	177.8
600	630	137.8	152.9	167.9	182.9	197.8	212.7
700	720	157.8	175.1	192.3	209.5	226.7	243.8
800	820	180.0	199.8	219.5	239.1	258.7	278.3
900	920	202.2	224.4	246.6	268.7	290.8	312.8
1000	1020	224.4	249.1	273.7	298.3	322.8	347.3
1200	1220	-	298.4	328.9	357.5	387.0	416.4
1400	1420	-	-	382.2	416.7	451.1	485.4

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