TERCJA
SYSTEMY POMIAROWE I KOMPUTEROWE

MOP-X1 Corrosion Rate Meter

User Manual

Version 1.0 English, Grudzień 2012

In case of problems

Contact the device’s producer.

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Warranty

The MOP-X1 corrosion rate meter is covered by a 2 year limited warranty from the moment of purchase. The warranty does not cover defects resulting through fault of the user. Any signs of mechanical damage along with internal interference will invalidate the device’s warranty.

The TERCJA Company reserves the right to change the device’s configuration and the programming of its products without requiring the introduction of these changes to the already purchased products. Any changes can be made without further information.

Disclaimer

The information contained in this manual has been thoroughly checked and appeared to be correct at the time of the publication of this document. TERCJA Company assumes no responsibility for any errors that may be revealed in the future.

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1 INTRODUCTION

Thank you for your interest in our product. A corrosion rate meter is used to determine the rate at which material diminishes due to corrosion, which is inevitable. The results are given in very simple units of mm / year. This allows you to estimate the life expectancy of an existing installation. The measurement is instantaneous and reflects the corrosion rate at the moment of measurement. As a result, it is possible to test the performance of applied corrosion protection e.g. inhibitors.

The meter operates on the generally accepted method of linear polarization (**LPR** - Linear Polarization Resistance) and is used in conductive environments. It can be used in assessing the corrosion rate of all water pipes made of various metals such as structural steel, stainless steel, brass, copper etc.

Should you require the measurement of corrosion rate in non-conductive media such as liquid hydrocarbons or gases we invite you to examine our other products – electrical resistance meter to measure corrosion rate. It also operates on a generally accepted principle – electrical resistance method.

The meters can also be produced in a stationary version and, together with sensors, possess the appropriate certificates allowing operation in explosion hazard areas.

2 TECHNICAL SPECIFICATION

Power	4 ‘AA’ Batteries
Operating time on fully-charged batteries:	Up to 400 hours*
Standby time	Approximately 1 year
Power consumption in standby mode:	0.1 mA
Power consumption in active mode:	4 mA
Power consumption during test:	6 mA
Backlight power consumption	6 mA
Clock backup time	3 minutes
Dimensions (length X width X height)	185 x 80 x 45 mm
Weight (without batteries)	570 g
Degree of Protection	IP67
Display	Monochromatic Display 128x64
Signal	Sound

* when backlight is deactivated

3 METER FUNCTIONS

The **MOP-X1** corrosion rate meter contains the following functions:

- Corrosion rate measurement using the linear polarization method
- Display of measurement results in mm/year (mmpy) or mils/year (mpy)
- Temperature measurement if the sensor is equipped with this feature.
- Measurement of the quality assessment algorithm (scale 0-100) based on multiple parameters, such as the potential difference between the electrodes, voltage and current fluctuations, and the exceeding of ranges, etc.
- Automatic signaling for suspected pitting corrosion, and also for damage or measurement sensor wear.
- Automatic connection with the measurement sensor and collect from it, data with respect to the test material, geometrical properties and the properties of the corrosive environment.
- The ability to change the functions of the individual electrodes in the measurement sensor, and thus executing three independent measurements with one sensor.
- The ability to connect your own corrosion sensors and set up data with respect to the test material, geometrical properties, and the properties of the corrosive environment.

  (OPTIONAL – using an MOP-X1-US adapter)

- The ability of quick measurements with your own sensors, using the empirical relationship for structural steel and brass.
  (OPTIONAL – using an MOP-X1-US adapter)
- The ability to save up to 100 results in the device's memory along with a description and allowing their later reading.
- The ability to record the results to a computer, export them to a text file, and analyze them in *MOPCorr* dedicated software.
  (OPTIONAL – using an MOP-X1-USB adapter)

4 PACKAGE CONTENTS

The basic set consists of:

- **MOP-X1** corrosion rate sensor
- Calibration tip
- 4 X NiMH 2200mAh batteries
- Battery charger
- 4 mm Allen key
- Instruction Manual
- Carrying case for the device

Optional items in the set include:

- **MOP-X1-USB** Adapter
  Allows for connection of the meter to a computer
- **MOP-X1-US** Adapter
  Allows for the use of your own corrosion sensors.

5 MEASUREMENT SENSORS

Apart from just the meter, measurement sensors are also necessary in performing measurements; these are also known as corrosion sensors.

The most important element of the sensor is the electrodes. It is on them where the corrosion reaction occurs. At least one of the electrodes, that on which the corrosion reaction will be measured, should be comprised of a material for which the corrosion rate is being tested. Naturally, it is most often the metal from which the construction element is made and on which the sensor is mounted. This electrode is called the testing, or working electrode.

The remaining two electrodes are an auxiliary electrode and a reference electrode which is also known as the reference.

It is most common to find that sensors have three electrodes. Sometimes a dual electrode system is also used, in which the auxiliary and reference electrodes are shorted.

In addition to the electrode, the sensor is comprised of a housing on which is most commonly found a thread used to screw in a probe which extends from the structure. Of course, it is possible to apply other methods for installing the sensor on a structure required in a given situation.

From the sensor extends a cable which ends in a DIN tip. There should be free access to this tip for the purpose of connecting the **MOP-X1** meter and performing a measurement.

An option is equipping the device with a temperature sensor. Then there is the option of simultaneous measurement of the corrosion rate and the temperature, and the results are then correlated and can be read later, and processed.

A common practice is to use three electrodes of the same (test) material. This allows for performing up to three measurements on a single sensor, changing the functions of the individual electrodes. As a result, it is possible to average the results of these three measurements. This is of great importance for the sensors already mounted for some time on the installation, since the electrode in such a sensor are covered with various sediments from corrosion and also from the environment. In this case, the electrode continually operating as a test electrode could lose its properties. Changing the function of the electrode allows for a sequential measurement of all the electrodes as testing electrodes.

The process for setting up the order of the electrodes is described in chapter 10.2.5.

Of course, in the case of sensors where the electrodes are not made of the same material, enabling this feature distorts the results, and, in extreme cases, can lead to the destruction of the electrodes.

ATTENTION: Averaging the results of the three measurements is not just simply arithmetic averaging. You should consider the quality of each individual measurement. Therefore, if on any electrode configurations the result is of a low quality, then to a lesser degree this will influence the overall result. The concept of the quality of results and averaging algorithm is explained in Chapter 11.

The calculation of corrosion rate requires the input of much information with respect to the sensor itself along with the environment in which it operates. This information can be determined once and stored permanently in the sensor so that the meter will be able to use them during each measurement. It is also possible to just enter these parameters manually. It depends on the type of sensor used. Environmental parameters are described in Chapter 12. In the case of the **MOP-X1** device, there are two main types of sensors – dedicated sensors and your own sensors.

5.1 DEDICATED SENSOR

Dedicated sensors are the basic sensors intended to work with the device itself. Each sensor is constructed for the specific needs of the user. It has the required shape, size, and type of mounting for the structure. The most important thing is that it contains saved electrochemical environmental parameters and information on the type and size of the electrodes used. This information is read from the sensor whilst connected and is used to calculate the correct rate of corrosion. . Amazingly, it eases work, as it eliminates the need to enter the sensor parameters before each consecutive measurement on another sensor. In the case of using a sensor with a temperature sensor, it is detected automatically, and the result of the temperature measurement is included in the result of the corrosion rate measurement.

In Conclusion: With this meter, customers are supplied with the appropriate amount of sensors and the proper required framework. The sensors are configured to work in a specific location. To complete such a configuration, our company needs to be provided with data on the type of metal that makes up the structure at the measurement location, information on the size of the flow or lack of a medium, and preferably a sample of the medium for a laboratory to determine the electrochemical factors of the environment.

For customers who wish to use their own corrosion sensors (purchased from another supplier or produced by their own means) this has been provided for.

5.2 CUSTOM SENSOR

It is possible to use your own sensors that contain the information about the environment and the electrodes. These are classical sensors from other companies or those made by hand.

To be able to use such sensors you need to connect them via a special **MOP-X1-US** adapter (see Chapter 13).

In this case, all the information needed to properly determine the corrosion rate should be entered into the meter before measurements. One should know the surface of the test electrode, the environmental resistance, Tafel coefficients for the given metal in the given environment, coefficients associated with the corrosive metal, and the coefficient associated with the distribution of the electrical field between the electrodes.

These parameters are described in further detail in Chapter 12; and the basics of electrochemical methods for linear polarization in Appendix A

It is necessary to remember, that accurate determination of Tafel coefficients is possible with a professional potentiostat and, in general, they are most conveniently carried out in a laboratory on a sample of the metal and the environment; although in some cases it is possible to assume some approximate values of these coefficients.

For convenience, it is possible for the meter to make measurements without entering Tafel coefficients, of which the determination can be difficult. It is a measurement method reserved for measuring ordinary carbon steel, or MC70-type brass in a typical, moderately corrosive water. Incorporating this option is described in Section 10.2.3.

This became possible thanks to the empirical formulas given by the Industrial Chemistry Institute in Warsaw. These patterns are the result of the correlative results of more than a hundred different waters with different inhibitors. The use of these empirical models provides an accuracy of 30%, which very often is an acceptable value. For better accuracy, however, it is necessary to determine the Tafel characteristics, and count the corrosion rate with their help.

ATTENTION: Use of empirical formulas only allows the avoidance of entering Tafel coefficients and the alpha coefficients for metal. One should still enter the electrode surface, environmental resistance, and the coefficient of the electrical field distribution between the electrodes (see Chapter 11).

ATTENTION: The use of empirical formulas is reserved for measuring the normal corrosion rate of carbon steel or MC70-type brass in typical, moderately corrosive water.

In the case of using your own sensors you should keep in mind a proper connection to the meter (via adapter MOP-X1-US). It should be noted that the electrodes are hooked up to the appropriate pins on the plug. A description of connections in the case of using your own sensors is presented in Section 7.1.

6 FRONT PANEL

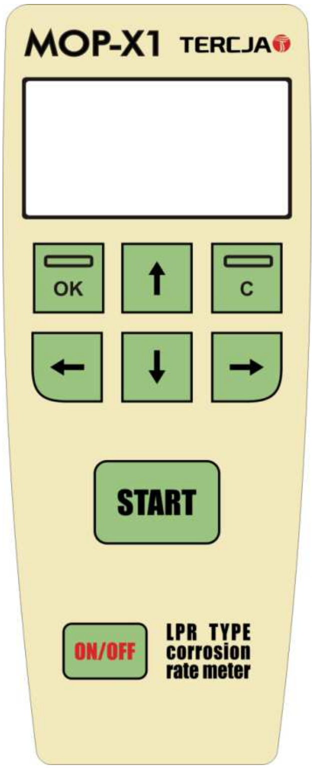
The diagram presents a front view of the device.

The **ON/OFF** button is used to activate and de-activate the meter.

In order to activate or de-activate the device, one should hold the button for approximately three seconds.

The buttons ↑↓←→ are used to move to the options menu and set the numerical and letter values.

The **OK** and **C** keys' effects are dependent on the options displayed in the lower, extreme positions on the screen. The most frequently used **OK** button is used to enter the menu and accept the changes, whilst the C button is used to cancel the changes and return to the previous menu.

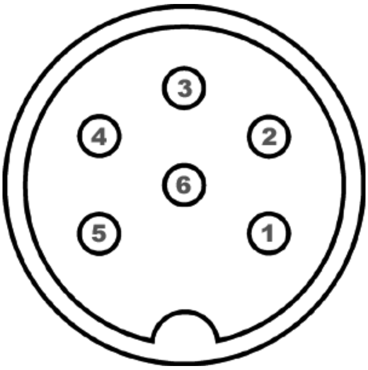


The **START** button, in effect, is used to start the measurement of corrosion rate, unless another application is indicated on the screen.

The meter has a monochrome backlit display with a resolution of 128x64 pixels.

7 CONNECTOR

Connectors used to connect to the measurement device, as well as to connect the meter to a computer with the help of a **MOP-X1-USB** adapter can be found on the bottom of the device. A 6-pin screw-type DIN 45 322 female connector is used, with an internal thread that assures an IP67 airtight classification.



Correct connection of the plug and tightening of the screw allows for protection against the entry of water and protection against IP67 solid bodies.

ATTENTION: During connection of any additional devices to the meter, the message **CONNECTION** should appear on the screen. Upon disconnection, the message **DISCONNECT** will appear. In the case of any other type of problem with the additional device the message **FAILURE** will appear on the screen.

7.1 CONNECTING YOUR OWN SENSORS

By using an **MOP-X1-US** adapter, it is possible to use your own corrosion sensors. The sensors should be tri-electrode. One electrode should be made of the same metal as the metal being measured and is referred to as the tested electrode. The remaining two are respectively referred to as the reference electrode (reference) and the auxiliary.

With the plug design, one should know that the sensor electrodes should be connected to connector pins 1, 2 and 3.

The meter offers the possibility of switching the electrode’s function as described in section 10.2.5. With respect to the above, each configuration of the electrode’s individual pins on the connector also changes their function.

Configuration **A**

Pin 1 – working electrode

Pin 2 – reference electrode

Pin 3 – auxiliary electrode

Configuration **B**

Pin 1 – reference electrode

Pin 2 – auxiliary electrode

Pin 3 – working electrode

Configuration **C**

Pin 1 – auxiliary electrode

Pin 2 – working electrode

Pin 3 – reference electrode

8 PREPARATION FOR USE

The device communicates with the user only in English. Even so, the interface was prepared in such a way, to make it simple and intuitive.

Before its first use, the meter should be calibrated; the correct date and time should be set.

When you activate the device, it will prompt you to perform these activities. You can also do it yourself. These options are respectively:

MENU → MOP SETTINGS → DATE/TIME

MENU → MEASURE SETTINGS → MOP CALIBRATION

The procedure for setting these options is described in Sections 10.1.1 and 10.2.6.

ATTENTION: You should be careful in the correct setting of the date and time to maintain a continuous series of measurements.

ATTENTION: An incorrect calibration may lead to erroneous measurement results.

8.1 BATTERY REPLACEMENT

The meter is powered by four AA batteries (big finger). Both conventional alkaline batteries with a voltage of 1.5 V and batteries with a voltage of 1.2 V can be used. A fully charged battery with a capacity of 2200 mAh allows up to 400 hours of use.

In the case of nearing the moment of battery depletion, the message **LOW BATTERY** will be displayed in the upper left corner of the display.

To replace the battery, remove the black round caps and unscrew the two screws indicated in the figure below. To loosen them, use a 4mm Allen key.

ATTENTION: To maintain an IP67 airtight classification, after replacing the batteries, you should tighten the casing.

ATTENTION: After removal of the batteries for a period longer than the standby, it may be possible that the correct date and time settings may disappear. In such a case, the device will inform of this upon start-up.

9 MEASUREMENT

After activating the meter with the **ON/OFF** button, one may immediately begin performing measurements. After connecting the meter to a properly installed corrosion sensor the meter will detect its presence:

The word **CONNECTION** will appear on the screen, and after a short time, if the sensor connections are correct – the message **SENSOR DETECTED**.

At this point it is possible to review the information stored in the sensor, scrolling through the screens by pressing **MORE**. The Information will include the sensor and its serial number, the material from which the sensor is made, the active surface of the electrodes, and the environmental resistance and electrochemical coefficients specifically designated for the sensor and its mounted location.

To begin the measurement, click the large **START** button on the keypad. At this point the device begins a measurement or a series of measurements (depending on the setting of the order of electrodes - see section 10.2.4). When the progress bar reaches the end, the value of the corrosion rate and the estimated quality of the measurement will be displayed on the screen.

At this moment it is also possible to see a report on the measurement sequence. The device can detect any irregularities associated with the measurement. To view the report, although it is not written on the screen, press the large **START** button. Therein will be contained messages informing of both correct operation and noted irregularities. To scroll through these information pages you should press **MORE**. More about these messages and measurement quality can be found in Chapter 11.

Once a measurement has been taken, you can save the measurement result in the device’s memory under any name. As a default, when entering the name of the measurement, the most recently entered name appears. For convenience, it is suggested that the name consist of a descriptive part and a sequential number such as "valve 1 - 1", "valve 1 - 2", "valve 1 - 3", etc.

To move between lettered fields, you should use the ←→ keys. Yet, to select a respective symbol, you should use the ↑↓ keys.

One can easily and automatically record to a PC. To connect the meter to a computer via USB one needs an **MOP-X1-USB** adapter. The included software allows you to collect and export the results to a text file. For each result, the sensor number is stored which thus allows one to independently follow the progress of corrosion for each individual sensor.

MOPCorr software is also included, allowing for data visualization.

ATTENTION: The meter contains memory for the last 100 measurements. Further results are recorded in the next available space. At the moment of exhaustion of all of the available space the oldest results are overwritten. Keep this in mind so as not to lose the oldest, and yet to be archived, measurement results.

10 USER MENU

The device has a menu where you can set options for the meter, measurement options, and read recorded measurement results.

10.1 METER OPTIONS

It is possible to set the following parameters associated with this meter.

10.1.1 DATE AND TIME

To set the date and time you should sequentially enter:

MENU → MOP SETTINGS → DATE/TIME

There, use the ←→↑↓ keys to set the correct date and time. The date should be re-set after each battery change. In the case of incorrect settings, the meter itself informs you of the necessity of settings during start-up.

ATTENTION: One should maintain the correct date and time settings to keep a continuous series of measurements.

10.1.2 AUTOMATIC SHUTOFF

It is possible to activate an automatic shut-off feature in the meter, which turns it off the after a set period of time. To do this, next enter:

MENU → MOP SETTINGS → AUTO OFF

Set the **ACTIVE** feature to ON. The **TIME** parameter corresponds to the time after which the meter should turn off. The time is measured in minutes. The possible values are: 1, 2, 3, 4, 5, 7, 10, 15, 20, 30, 45 and 60.

10.1.3 SETTING THE DISPALY AND SOUND

In this menu, you can set the display contrast, the backlight time, and enable or disable sounds.

MENU → MOP SETTINGS → DISPLAY & SOUND

The contrast is set by changing the **CONTRAST** setting to the range 0 - 60.

The Backlight time is set by changing the **BACKLIGHT** setting. It is possible to turn it on permanently (ON), turn it off completely (OFF), or set if for a certain period. The possible values are: 5, 10, 20, 30 seconds; and 1 or 5 minutes.

ATTENTION: Working with a fully backlit meter consumes twice as much power than when working with the backlight off entirely. As a result, the maximum operating time is reduced to approximately 200 hours.

It is possible for the meter to emit a short sound signal. The possible values for the **BEEP** option are:

OFF – no sound

MEASURE – sound signal after completing a measurement.

KEYS – sound signal when keys are depressed.

BOTH – sound signal when keys are depressed and upon measurement completion.

10.1.4 RESETTING TO DEFAULT VALUES

To reset the meter to default values, one should sequentially enter:

MENU → MOP SETTINGS → LOAD DEFAULTS

To the question "**ARE YOU SURE TO LOAD DEFAULTS?**" one should confirm by pressing **OK**. The meter will be returned to its default values.

10.2 MEASUREMENT OPTIONS

Using these options, it is possible to set measurement parameters such as environmental characteristics and the sensor used. During standard use, the only available options from the entire menu are the options for automatic measurement mode and electrode order. By using an adapter, you can activate the other options (see the information in the boxes).

10.2.1 MEASUREMENT UNITS

The meter can present the rate results in two units - mm / year or mils / year. To select the displayed units, one should enter:

MENU → MEASURE SETTINGS → MEASURE MODE

Set the respective **UNITS** option. The possible settings are:

mmpy – millimetres per year

mpy – one thousandth of an inch (mils per year)

ATTENTION: Setting this option only affects the display of the results. Results are always stored using the *mmpy* unit in the meter's memory. When setting the units to *mpy,* the results are converted to *mpy* for the purpose of displaying them on the screen only.

10.2.2 AUTOMATIC MEASURE MODE

It is possible to set the meter so that it performs a measurement by itself at a specified time interval. To do this, one should sequentially enter:

MENU → MEASURE SETTINGS → MEASURE MODE

Then, set the **MODE** option to AUTO and define how many hours the meter should automatically awaken and perform a measurement. This time is set via the **INTERVAL** option. The possible values are: 1, 2, 4, 6, 8, 12, 24, 48, 72 and 96 hours.

The final step is to set the hour of the first measurement– **START** option.

Measurements are performed in a daily cycle, which means that during the first 24 hours the first measurement will be performed at the hour set in the **START** option. In a case where the setting of time between measurements exceeds 24 hours, the measurements will be performed at the hour set in the **START** option, every 2, 3, or 4 days.

ATTENTION: All measurements are automatically stored in memory under the name **AUTOMEASURE**.

To disable the automatic measurement mode, one should set the **MODE** option to MANUAL.

10.2.3 SENSOR SETTINGS

In the case of using your own measurement sensors, one should define their parameters so that the corrosion rate will be properly calculated.

ATTENTION: These options are only available with an additional **MOP-X1-US** adapter, which allows you to connect any custom sensor and set all its parameters. In the case of an absence of this adapter, the meter automatically downloads the information from a compatible sensor and bases its measurement on it. The possibility to change the above options is then inactive, and some of them remain invisible.

To get to the sensor settings, one should next enter:

MENU → MEASURE SETTINGS → SENSOR SETTINGS

It is possible to configure:

AREA - allows you to set the surface of the test electrode. The maximum value is 600.00 cm^2.

MATERIAL – allows the setting of the method of determining the corrosion rate. The meter is able to use empirical formulas developed on the basis of years of observation. In the case of measuring the corrosion rate of **St3S**-type structural steel in standard tap water, one can choose the **STEEL** option. When performing measurements on the corrosion rate of brass in tap water, one can choose the **BRASS** option. Measuring the corrosion rate of practically any metal can be done by selecting the **COMMON** option. The meter then uses the theoretical correlation of the underlying theoretical linear polarization technique. In this case, however, one needs to know the appropriate electrochemical properties of the environment, which should be determined by another electrochemical method, such as using Tafel constants. These properties are:

- **Ba** – Tafel anodic coefficient. Range 0 – 6000 mV.
- **Bc** – Tafel cathodic coefficient. Range 0 – 6000 mV.
- **ALPHA** – coefficient associated with corrosive metal Range 0 – 60000.
- **GEOM** – electrical field distribution coefficient. Range 0 – 6000.

The importance of the above parameters, as well as empirical formulas, is described in Chapter 12 – **Method for calculating corrosion rate.**

ATTENTION: These parameters are only visible after connecting an **MOP-X1-US** adapter. Without it, one can only see the size of the electrode surface permanently stored in the dedicated sensor, and the electrochemical properties of the environment stored in the sensor can be seen when connecting the sensor to the meter (see Chapter 9).

With the use of an **MOP-X1-US** adapter, measurements are possible when using any corrosion rate sensor, including those produced by you. The possibility of using empirical formulas for setting the **MATERIAL** option to **STEEL** or **BRASS,** exempts one from having to know the above electrochemical coefficients**.**

Actually, one most frequently measures common St3S structural steel or similar non-alloy steel in environments with aggressiveness similar to that of tap water. In such a case, the possibility of using the **STEEL** setting greatly simplifies measurements on non-standard electrodes.

ATTENTION: Setting the **MATERIAL** option on **STEEL** or **BRASS** further requires the defining of the electrode surface as well as environmental resistivity (see section 10.2.4).

10.2.4 ENVIRONMENT RESISTANCE

In the case of using non-standard sensors one should know the resistance between the electrodes. Its value can be estimated or determined. To determine it, one should measure the resistivity of the environment, for example, with a conductometer, and then calculate the value of resistance on the section between the surfaces of the electrodes. Setting a value significantly lower than a real one may result in a large measurement error, or the inability to complete the measurement. To set an appropriate value, one should next enter:

MENU → MEASURE SETTINGS → ENVIRONMENT SETTINGS

Set **RESISTANCE**. The range of setting is 0 – 60 000 Ω.

ATTENTION: The changing of this parameter is only possible by using your own sensor. Standard sensors have the value permanently stored, and in such a case this menu you can only preview without the possibility of editing.

10.2.5 ELECTRODE ORDER

This is a setting of the previously mentioned sensor setup menu (see Section 10.2.3). It has been described separately as the menu can only be changed when an **MOP-X1-US** is not connected.

The measurement sensor is in most cases composed of three electrodes. One of them (the test electrode) is made of the material being tested, the other (the reference electrode and auxiliary electrode) are also usually of the same material. In such a case, it is possible to exchange the functions of the individual electrodes and conduct three measurements, where each electrode will make its own measurement. This approach allows the extraction of an average corrosion rate value from three measurements. This is often the best solution as over time, the electrodes wear and with some configurations, can produce results of poor quality.

To access these electrode settings, one should next enter:

MENU → MEASURE SETTINGS → SENSOR SETTINGS

Here, one should change the **CONFIG** option.

Possible settings are **A**, **B**, **C** and **ALL**. The **ALL** option performs a sequential measurement on all configurations and provides an averaged result. The remaining options are used to include just one particular configuration of electrodes called **A**, **B** or **C**.

ATTENTION: In the case of using the **ALL** option, the averaging of the results from the three measurements is not just simple arithmetic averaging. The quality of the individual measurements is also taken into account. Therefore, when with any of the electrode configurations the result is of a low quality, to a lesser degree it will have an influence on the overall result. The concept of result quality and averaging algorithm is explained in Chapter 11.

ATTENTION: The **ALL** option is turned on by default and is recommended, but only under the assumption that all of the sensor electrodes being used are made of the same material. When the electrodes that are used are made of different materials, which is possible in certain specific applications, one should perform the measurement on a single and appropriate setting. Using the **ALL** option can cause incorrect results during averaging.

10.2.6 CALIBRATION

After each battery replacement the device should be calibrated. Calibration means short-circuiting with each other, the tips of three measurement electrodes. To simplify this, a calibration tip is included in the set supplied with the meter.

To calibrate the meter, one should next enter:

MENU → MEASURE SETTINGS → MOP CALIBRATION

Next, put on the calibration tip and press the **CALIBRATE** button.

ATTENTION: Improper calibration can result in incorrect measurement results.

10.3 READING MEASUREMENTS RESULTS

In this menu, you can review the recorded corrosion rate measurements. The menu can be navigated by using the ↓ and ↑ keys. Saved data includes:

- Measurement name (entered by the user)
- Date and Time of Measurement
- Measurement Result
- Measurement Quality
- Temperature (when the sensor was used with a temperature sensor)

11 MEASUREMENT RESULTS

Corrosion rate can be ideally determined by measuring with new, clean electrodes in good laboratory conditions. The working environment of real sensors strongly deviates from laboratory conditions. The electrodes sometimes get covered with corrosion products and the results of the measurements can vary.

The ability to assess the accuracy of a measurement is essential. The **MOP-X1** meter has been implemented with an innovative method for evaluating the quality of a performed measurement. After each measurement, its quality is calculated as a number in the range from 0 to 100.

The quality of a measurement is determined based on a number of factors automatically measured before the actual performing of the measurement. These include the value of the potential between the electrodes, both potential and current fluctuations, any exceeding of measurement ranges, etc.

This data, apart from it use in calculating the quality of the result, are also used to inform the user about the correctness of the measurement. This information is available immediately after performing the measurement (see Chapter 9).

Possible information is:

Current values in range in all measured configurations.

This message states that the values of the current measurement are in the range of the measuring device.

Voltage values in range in all measured configurations.

This message states that the values of the potential measurement are in the range of the measuring device.

General corrosion observed in all measured configurations.

This is a correct message indicating that the corrosion being monitored has the form of general corrosion, and therefore that to which is adapted the linear polarization method. In the case of potential fluctuation where corrosion pitting overlap is suspected, the device will communicate the message **Pitting corrosion observed** and skips such a result.

Normal anode current in all measured configurations.

Information states, that the current direction is consistent with the direction of polarization (positive polarity, positive current). When poorly defined starting potential, such as those arising from large fluctuation, it may happen that the current will have a negative value, which will disqualify such a result.

Proper environment parameters in all measured configurations.

This message states that the environmental resistance is not set to a value which is too low.

The information above is displayed when there are no problems with the configuration of all the electrodes (A, B and C). Otherwise, the device will inform about specific problems with the configurations in which they occur. As a result, it is possible to quickly detect problems with the sensor or the measurement destabilizing factors (e.g. local corrosion).

Yet another message which may be displayed is **Electrodes disconnected**. This message states that the electrodes are not connected. This signals that there is a physical problem with the sensor connection (e.g. damaged cable) or the actual electrode tips in the sensor housing.

ATTENTION: The above information is displayed on the screen immediately after performing the measurement, albeit being stored in memory together with rate results. There is no possibility of seeing them in the result browser menu. Access to this data is possible after recording the results to a computer. It is then possible to observe the result history together with noticed problems, which allows quick assessment of the nature of problems encountered while monitoring corrosion.

As previously mentioned, for each result its quality is provided. This quality is in the range of 0 to 100, and is calculated based on several factors. As a result, it becomes possible to orientate how reliable the result is. Observing the trend of quality is equally essential. If it drops it usually implies the need for sensor replacement due to wear.

In the case of using three consecutive measurements on the same sensor with an exchange of the functions of the individual electrodes as described in Section 10.2.5, the results are averaged, yet this averaging is weighed, where the weight is the quality of each of the individual measurements involved. As a result, the final result will be influenced by these measurements, or measurement, which has the highest quality. Average score also has its average quality. This is done using the below general equations.

$$V = \frac{V_A \cdot f(Q_A) + V_B \cdot f(Q_B) + V_C \cdot f(Q_C)}{f(Q_A) + f(Q_B) + f(Q_C)} \tag{11.1}$$

$$Q = f(Q_A, Q_B, Q_C) \tag{11.2}$$

A single result which has quality equal to zero has no influence on the overall result. The higher the quality, the more each measurement will have an impact on the averaged result. For this reason, it is worth using the function of performing measurement on the following configurations. Averaging the three results gives a more reliable result.

12 METHOD FOR CALCULATING CORROSION RATE

Presented below is the correlation used to determine the corrosion rate in the classical way (using Tafel coefficients). Empirical formulas (see Section 5.2) have not been cited.

Corrosion rate is directly proportional to the so-called corrosion currentI_{corr}, the coefficient associated with a corroding metalα, and the inverse of the surface area.

$$V_{corr} = \frac{I_{corr}\alpha}{S} \tag{12.1}$$

Measurement of the corrosion rate relies on producing excitement between the electrodes U in the form of the voltage difference and measuring the value of the current I induced by the excitation. Knowing the value of the excitation and its response, it is possible to determine the polarization resistance R_p.

$$R_p = \frac{U}{I} \tag{12.2}$$

In fact, the polarization resistance value is influenced by the so-called ohmic drop IR, which occurs during the flow of current through the resistance. In the case of measuring LPR resistance there is electrolyte resistance R_e, that is, the liquid in which the measurement is performed.

$$R_p = \frac{U - IR_e}{I} \tag{12.3}$$

Knowledge of the electrolyte resistance between the electrodes is essential to perform a correct measurement. The dedicated sensors are ready for the environment and have these values stored within it. In the case of using one's own sensors it is necessary to input the resistance into the settings (see section 10.2.4).

The ohmic drop is also influenced by electrode placement relative to each other. One should therefore take into account the geometric coefficient β .

$$R_p = \frac{U - \beta IR_e}{I} \tag{12.4}$$

The most used sensors are those in which the electrodes are arranged at the vertices of an equilateral triangle. In this case, the geometrical coefficient β takes the value of 0.5. As in the previous case, the dedicated sensors have this parameter stored within, while for one's own sensors it should be entered in the settings (GEOM coefficient - see section 10.2.3).

The corrosion current I_{corr} is directly proportional to the corrosion rate (equation 12.1) and is determined from Ohm's law using the following correlations:

$$I_{corr} = \frac{B}{R_p} \tag{12.5}$$

The parameter B itself has the same voltage dimensions and is associated with the specific environment.

$$B = \frac{b_a b_c}{2{,}303(b_a + b_c)} \tag{12.6}$$

Found in the equation are b_a and b_c coefficients and Tafel coefficients, the anodic and cathodic, respectively. These coefficients are determined through the laboratory testing of the given metal in the environment in which it operates. As with the previously mentioned parameters, the dedicated sensors have the coefficients stored within, and as a result are ready to operate in a specific environment. In the case of using one's own sensors you should estimate the Tafel coefficients themselves. Before taking a measurement they should be entered into the device settings (parameters Ba and Bc - see Section 10.2.3)

ATTENTION: Because of the difficulty in determining Tafel coefficients, in certain circumstances, it is possible to perform a measurement without any knowledge of them, by using empirical formulas. More information can be found in Section 5.2.

Another essential parameter of equation 12.1 is the coefficient associated with the corroding metal α. It is dependent on the electrochemical equivalent of the metal E_w and the metal density d.

$$\alpha = \frac{3{,}27E_w}{d} \tag{12.7}$$

The model shows the constant value $3{,}27$ defining the corrosion rate unit. In this case, it is millimeters per year (*mmpy – millimeters per year*).

ATTENTION: One should always calculate the value of the corrosion rate in *mmpy* because the device stores the results in this particular unit and has the ability to convert them to other units.

The electrochemical equivalent of the metal E_w is dependent on the molecular weight of the corroding metal M_m and the quantity of electrons n that are exchanged during the oxidation reaction (galvanic corrosion).

$$E_w = \frac{M_m}{n} \tag{12.8}$$

Below is an example of calculating the coefficient α for iron and the corrosion rate *millimetre/year*:

$$\alpha = \frac{3{,}27 \cdot \frac{56}{2}}{7{,}86} = 11{,}65 \tag{12.9}$$

Similar calculations for brass produce the value $12{,}28$.

In dedicated sensors, the coefficient associated with the corroding metal α, is stored permanently. For one's own sensors one should calculate it according to the above calculation and input it into the setting (ALPHA parameter - see Section 10.2.3)

The corrosion rate calculated in the above-noted way should be adjusted by the amount of the surface corrosion, that is, the electrode surface area as the test electrode. This is the Sparameter in equation 12.1. It is given in cm^2. For one's own sensors this size should be input into the settings (AREA parameter - see section 10.2.3).

13 ADDITIONAL ADAPTERS

The meter can be connected to additional equipment in the form of an adapter (adapters). We currently offer two such devices.

13.1 MOP-X1-US

This adapter allows for the use of non-standard corrosion sensors. Standard sensors provided by our company automatically communicate with the meter. Contained within them is information concerning the sensor, such as the electrochemical values associated with the test metal or environmental electrochemical parameters of the sensor’s environment are used to calculate the corrosion rate, and releases the user from the necessity of their individual input on each occasion.

However, should the need arise to use a custom sensor, for example, made on your own, one can disable the automatic configuration mechanism by connecting one’s sensor to an **MOP-X1-US** adapter. In this case, one should input all the environmental parameters. To do this, activate the relevant option in the user menu. This has been described in Section 10.2.3.

After connecting the adapter to the meter this message should message should be displayed - **CONNECTION**, and after a short time - **ADAPTER DETECTED**.

13.2 MOP-X1-USB

This adapter allows one to connect the meter to a computer to record data. Connection is made by a USB interface. The included software allows you to archive measurement results and grouping them depending on the sensor number. In this way it is possible to observe corrosion rate values for each sensor separately for any length of time. Results can be saved in the form of a table in a text file making them easy to visualize with any software that creates charts or with the dedicated *MOPCorr* software.

After connecting the **MOP-X1-USB** adapter to the meter it will not indicate any action. It is not until it is entirely connected to a computer and initiating a connection with software that the message **CONNECTION** will appear on the meter's display, an after a short time the message **PC-LINK DETECTED**. At this point, you can save data with the *MOPCorr* software.

We cannot exclude the fact that in the future new adapters may appear that offer additional functionality. For further information we encourage you to contact our company.

14 REFERENCES

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15 APPENDIX A – METHOD BASICS

The linear polarization method for measurement of corrosion rate relies on electrochemical reactions. Therefore, before explaining the method itself, this chapter will discuss the electrochemistry basics that are required to understand the issue.

A.1 INTRODUCTION TO ELECTROCHEMICAL METHODS

Electrochemical methods are based on the study of redox processes in relation to the environment in which we are interested. Oxidation and reduction reactions accompany a clear flow of charge between reactive substances. In general, the process of corrosion depends on the oxidation of the metal according to the reaction below:

$$Me^0 \rightarrow Me^{n+} + ne^- \qquad \text{(A.1)}$$

The resultant process of the release of electrons is the formation of an electric current. What is easily noticed is that the amount of transferred electrons and thus the value of the current is directly proportional to the amount of metal that has oxidized. This current is called the *corrosion current* and is named I_{corr}. If its value is divided by the surface area of the corroding metal (electrode surface area) then we get a value of the *corrosion current density* named j_{corr}.

$$j_{corr} = \frac{I_{corr}}{A} \tag{A.2}$$

where:

A - electrode surface area

From its value, it is possible to calculate the mass of oxidized metal. Used for this purpose is the well-known and common Faraday's Law, which associates the amount of transferred charge and the amount of the substance that has oxidized or reduced.

$$Q = znF \tag{A.3}$$

where:

Q - charge associated with corrosion current, *C*

z - number of electrons exchanged during the process

n - mole count of the substance which created or reacted

F - Faraday Constant (load of one mole of electrons), $96485 C \cdot mol^{-1}$

Unfortunately, there is no possibility of directly measuring the corrosion current, since for this purpose one would have to place an ammeter between the oxidation molecule and the reduction, which is obviously unrealistic. Fortunately, it is possible to indirectly determine this value by measuring changes in the electrical parameters of the test system (potential, current flowing through the working electrode).

Thanks to the electrochemical method there exists a possibility to obtain an instantaneous corrosion rate value and not, as in the case of non-electrochemical methods, averaged values over time, which will be explained later in this work.

A.2 EQUILIBRIUM POTENTIAL E_R AND CORROSION POTENTIAL E_{CORR}

To further discuss methods for measuring corrosion rate we should begin by recalling the basic facts in the field of electrochemistry.

For instance, when an iron plate is immersed in a solution of iron ions, the plate will gain an electric potential. It is associated with the reactions that occur. The oxidation of iron takes place:

$$Fe^0 \rightarrow Fe^{2+} + 2e^- \qquad \text{(A.4)}$$

That is, metallic iron releases ions into the solution, and leaves electrons in its crystal lattice, which obviously gives the plate potential.

One should not forget that every chemical reaction is accompanied, to a greater or lesser degree, by a reverse reaction:

$$Fe^{2+} + 2e^{-} \rightarrow Fe^{0} \tag{A.5}$$

In the case of the discussed system the reverse reaction rate is so large that one can speak of thermodynamic equilibrium. That is to say, simultaneously with the oxidation of iron, its reduction also equally occurs. The reaction rate of both is described as a kinetic equation:

$$V_{ox} = k_{ox} \cdot C_{red} \tag{A.6}$$

$$V_{red} = k_{red} \cdot C_{ox} \tag{A.7}$$

where:

V_{ox}, V_{red} - oxidation and reduction rates

k_{ox}, k_{red} - coefficients of the oxidation and reduction reaction rates

C_{ox}, C_{red} - molar concentrations of the oxidized and reduced forms

After a while, the rates will equalise:

$$V_{ox} = V_{red} \tag{A.8}$$

Simultaneously therefore, the same amount of iron will be oxidized as will be reduced. The system obtains a state of thermodynamic equilibrium. Observing this at the macro level, it is possible to get the impression that the iron dissolution reaction stopped after a while because the plate no longer reduces its mass, and the concentration of Fe^{2+} ions does not change.

Under such conditions as previously mentioned, the potential does not change, so it is called the equilibrium potential E_r. Its value can be calculated using the Nernst equation:

$$E_r = E_0 + \frac{RT}{zF} ln \frac{a_{ox}}{a_{red}} \qquad \text{(A.9)}$$

where:

E_r - equilibrium potential, *V*

E_0 - standard potential, *V*, for Fe/Fe^{2+} is *-0.76V*

R - universal gas constant, $8{,}31\ J \cdot mol^{-1} \cdot K^{-1}$

T - temperature, *K*

a_{ox} - activity of the oxidized form, in this case Fe^{2+} ions

a_{red} - activity of the reduced form, in this case iron plate

Without any objection, at low concentrations of substances one can assume that the active ions are equal to the molar concentrations, and the activity of the solid metal is always equal to 1, thus equation (A.9) simplifies to the form:

$$E_r = E_0 + \frac{RT}{zF} lnc_{ox} \qquad \text{(A.10)}$$

Considering corrosion processes, which in most cases differ from the above-noted simple example, imagine therefore, that the opposite reaction to oxidation is not the reduction of Fe^{2+} to Fe, but the reduction of another substance, known as a depolarizer. Such depolarizers are all molecules capable of receiving electrons, and so very often, for example in water hydrogen cations, oxygen reduces itself according to the equations:

$$2H_2O + 2e^- \rightarrow H_2 + 2OH^- \tag{A.11}$$

$$2H^+ + 2e^- \rightarrow H_2 \tag{A.12}$$

$$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \tag{A.13}$$

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^- \tag{A.14}$$

In such a case, it is also possible to mention thermodynamic equilibrium, since the rates of the oxidation of iron and the rate of the depolarizer reduction are equal. Unfortunately, the electrons produced in the oxidation of iron (A.4) do not cause its re-reduction (A.5), and that is why it can be stated in very simple terms, that the iron plate gradually disappears, passing into the solution. However, in such a system with a depolarizer, it constantly retains certain potential, called the *corrosion potential* E_{corr}, which is a special case of equilibrium potential. It is also called *mixed potential*, because the oxidation process and the depolarization process equally have influence on its value.

To sum up, metal found in an electrolytic corrosive environment irreversibly changes into an oxidized state, that is to say, corrodes and obtains a certain potential called corrosion potential, and depends on many factors - the type of metal, the qualitative and quantitative composition of the corrosive environment, and temperatures.

A.3 EXCHANGE CURRENT I_O AND CORROSION CURRENT I_{CORR}

In section A.1 it was written, that a redox reaction accompanies the flow of charge, where the carrier is electrons, and we therefore have to deal with the flow of electric current.

During equilibrium potential, the oxidation rate is the same as the reduction rate, that is, the current associated with the oxidation reaction, called the *anode current* I_a is identical to the value of the current associated with the reduction reaction – the cathode current I_c. The current flowing at equilibrium is called the *exchange current* I_0.

Electrochemistry has adopted a way to distinguish the anode from the cathode current, by treating the anode current as positive, while the cathode current as negative. Therefore, the value of exchange current is equal to the absolute value of the anodic or cathodic current during equilibrium potential:

$$I_0 = |I_a| = |I_c| \tag{A.15}$$

Something can also be said about the value of the resultant current, which is the sum of the anodic and cathodic current values:

$$I = I_a = I_c \tag{A.16}$$

Of course, in the case of equilibrium potential, if the anodic and cathodic currents are equal in value, but opposite as to their character, then the resultant current is zero:

$$I = I_a = I_c = 0 \tag{A.17}$$

When metal is oxidized, but another substance is reduced and equilibrium is determined during a certain corrosion potential E_{corr}, we also have to deal with current exchange. In this case, however, this current is called the *corrosion current* I_{corr}. In each electrochemical study, there is the obvious aim of precisely determining this value because, as was previously mentioned, the corrosion current density is directly proportional to the corrosion rate, and just calculating the rate of loss comes down to the simple use of Faraday's Law.

A.4 OVERPOTENTIAL, POLARIZATION CURVES, BUTLER-VOLMER EQUATION

The state of equilibrium can be easily upset, for example, it is enough that an external current is connected to a system in equilibrium. Various effects will be obtained depending on the value of the applied voltage. If a potential higher than the equilibrium potential is applied to the system, it is said to be anodic polarization, in which case the anodic reaction rate becomes higher than the cathodic reaction, which manifests itself in a positive resultant current; as is apparent in equation A.16. In this case the anodic current is higher than cathodic current. Conversely, when the applied potential is lower than the equilibrium potential, it is said to be cathodic polarization, and the reduction reaction is faster than the oxidation reaction – the cathodic current is higher than the anodic, the resultant current is therefore negative. The deviation of potential from equilibrium is called the *overpotential* η.

$$\eta = E - E_r \tag{A.18}$$

where:

η - overpotential, *V*

E - applied potential, *V*

E_r - equilibrium potential, *V*

It is extremely essential that the correlation of the current values of the overpotential is exponential or, the faster the overpotential value changes, the faster the corrosion current changes. This is illustrated in Chart A.1.

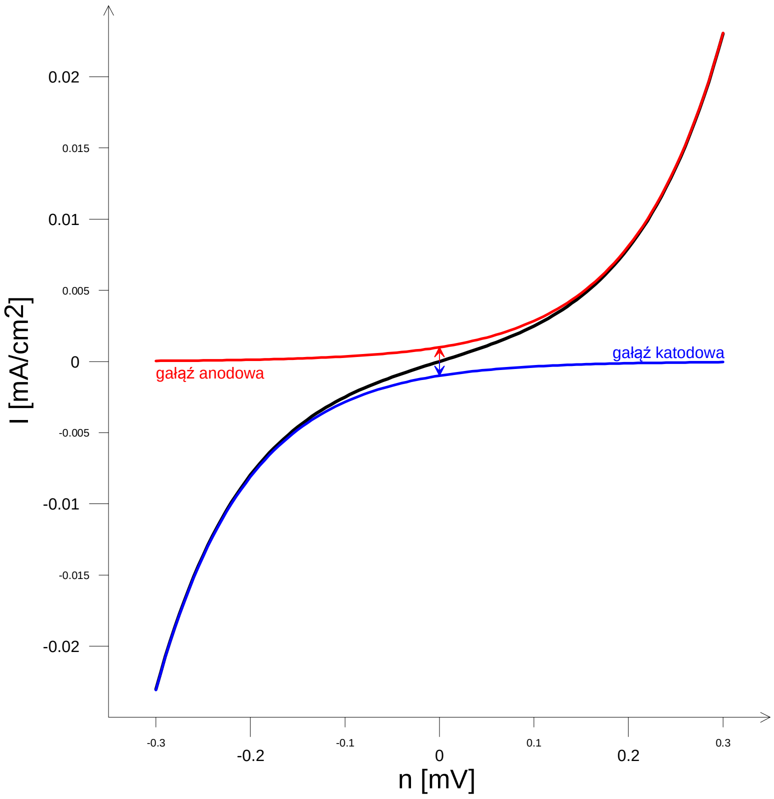

Fig. A.1. Sample graph of the Butler-Volmer Equation

The anodic branch has been highlighted in red. One will notice that for negative and low positive overpotential the current associated with the oxidation process is insignificant, almost zero, but begins to grow strongly with a positive overpotential. Similarly, an opposite situation takes a place in the reduction process, where the value of the cathodic current, highlighted in blue, is the highest in the case of negative overpotential.

The course of the black line is the graph of the sum of anodic and cathodic currents, or the resultant current in the overpotential field. This graph (A.1) is formed from solving a Butler-Volmer equation:

$$i = i_0 \left\{ exp\left[\frac{(1-\beta)F\eta}{RT}\right] - exp\left[\frac{-\beta F\eta}{RT}\right] \right\} \qquad \text{(A.19)}$$

where:

i - resultant current density, *A*

i_0 - exchange current density for the system, *A*

β - symmetry coefficient

The first part of the exponential equation describes the anodic curve, while the second exponential part is the cathodic curve. A graph analysis provides some interesting conclusions. When there is negative overpotential the cathodic current is many times larger than the anodic, which means that in such a polarization reaction the reduction is many times much faster than the oxidation reaction. It can be said, that there is practically only a reduction.

It is similar for positive overpotential, where it is possible to neglect the rate of the reduction reaction, however, oxidation occurs very quickly. One can see that with an equlibrium potential, and therefore with an overpotential of zero, the resultant current is zero and therefore only an exchange current is flowing. The value of the exchange current is represented by an arrow on the chart - red for the anodic exchange current, and blue for the cathodic exchange current. Of course, their absolute values are equal.

It should be noted, that the above-mentioned form of the Butler-Volmer equation (A.19) makes sense only when the half-reaction rate is activation controlled , and therefore when the slowest of its steps is the electron transfer step from/to the elecroactive substance. In a case where other factors, such as the rate of ions reaching the electrode surface (diffusion control) are slower than the charge-transfer reaction, then the current-voltage graph has a completely different appearance.

Figure (A.1) presents a model of a Butler-Volmer equation graph , with a symmetry coefficient $\beta=0.5$, assuming a reversible redox reaction. Of course a true graph is obtained in the laboratory, polarizing the sample negatively and positvely from the equilibrium potential and measuring the flowing current. It should also be noted, that in the case of a multi-stage reaction, the Butler-Volmer equation symmetry coefficient β is replaced by the *general charge transfer coefficient* α separate for the cathodic and anodic process (α_c i α_a). Its value may exceed the value of 1.

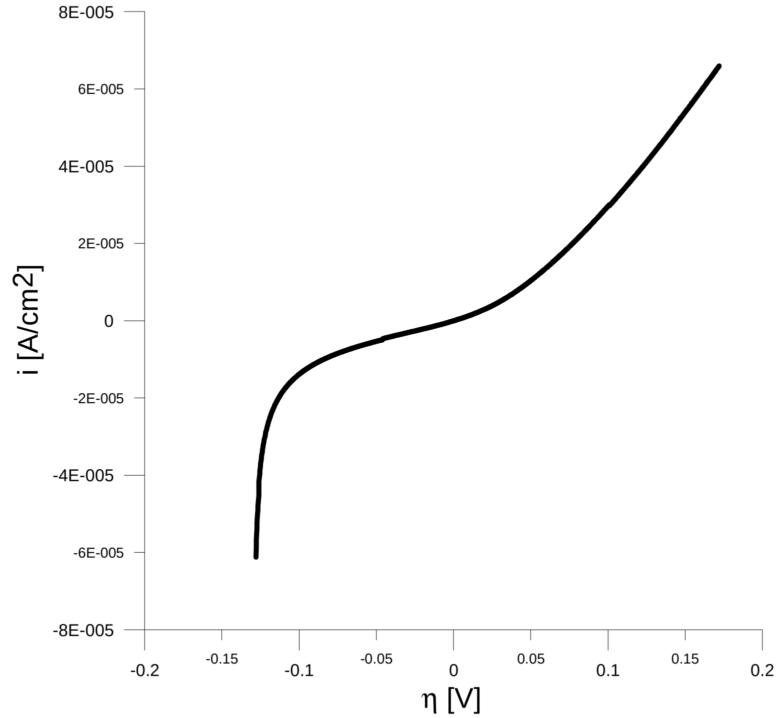

Fig. A.2. Polarization diagram for cast-iron exposed to tap water

Figure A.2 shows an actual polarization graph of iron exposed to tap water. The corrosion potential, from which the equilibrium deviated, was *-0.835 V*.

After quickly reminding oneself of the fundamentals of electrochemistry, one can begin to discuss specific methods to estimate the value of corrosion current, and therefore the rate of corrosion.

A.5 TAFEL CURVES (TP – TAFEL PLOT)

If you introduce the overpotenial graph - the current density in a decimal logarithm form with an absolute value of current density to overpotential, the so called Tafel plot is obtained. As shown in Figure A.3, the Tafel plot is the effect of transforming graph A.2.

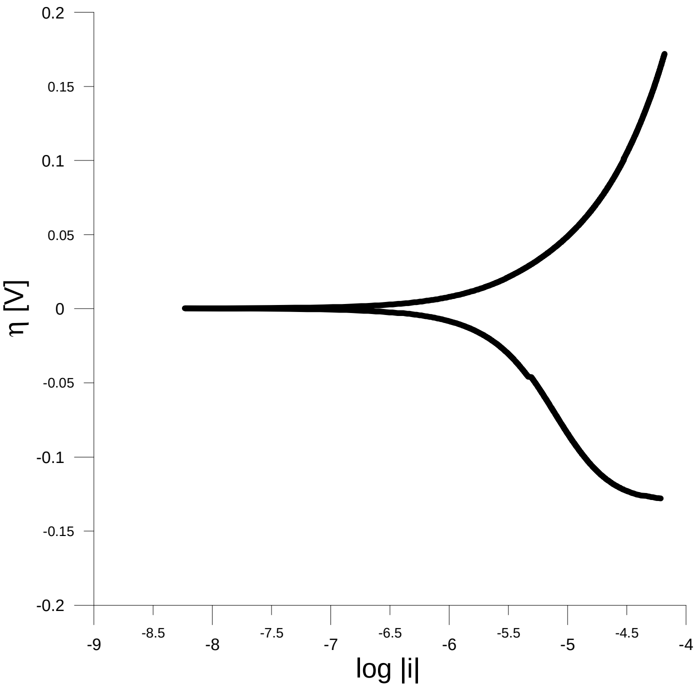

Fig. A.3. Tafel diagram for cast-iron exposed to tap water

The upper branch is the anode part, the bottom the cathode. If one extrapolates their straightline parts then two straight intersecting lines are obtained. The intersection point falls on the value of the logarithm with the corrosion current density on the abscissa and the corrosion potential on the ordinate.

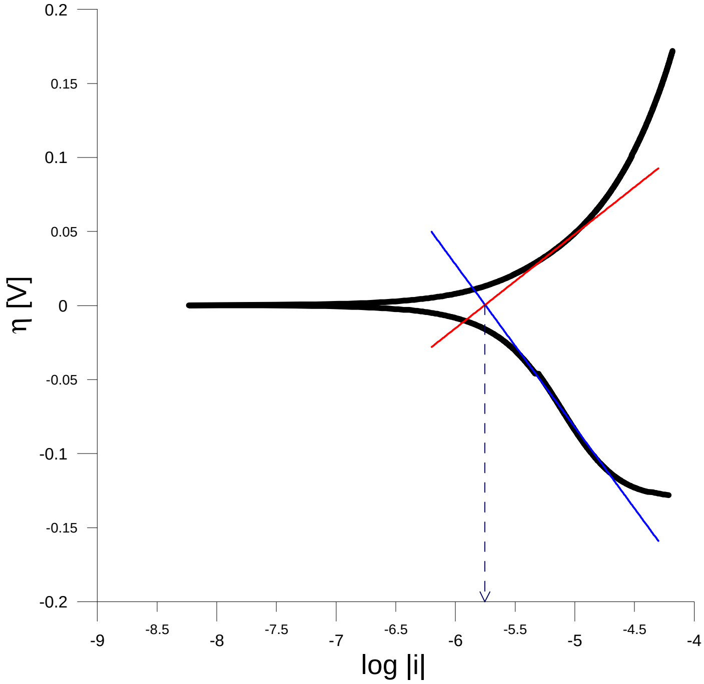

Fig. A.4. Extrapolation of Tafel curves for cast-iron exposed to tap water

These simple equations can be calculated using the Butler-Volmer Equation (A.19).

For large positive overpotential (anodic - $\eta > 100mV$) the cathodic portion can be neglected, since its size is more or less smaller than the anodic:

$$i = i_0 \left\{ exp \left[\frac{(1-\beta)F\eta}{RT} \right] \right\} \tag{A.20}$$

After taking the logarithm of both sides in the above equation and determining the overpotential one obtains:

$$\eta_a = -\frac{RT}{(1-\beta)F}\ln i_0 + \frac{RT}{(1-\beta)F}\ln i_a \qquad \text{(A.21)}$$

After further conversion, one obtains a linear equation, called the *Tafel equation for an anodic process*:

$$\eta_a = a_a + b_a \, log \, i_a \qquad \text{(A.22)}$$

where:

$$a_a = -2{,}303\frac{RT}{(1-\beta)F} log \, i_0 \qquad \text{(A.23)}$$

$$b_a = 2{,}303\frac{RT}{(1-\beta)F} \qquad \text{(A.24)}$$

a_a and b_a are called the *Tafel coefficients for an anodic process* and as one can see, they are parameters in the linear Tafel equation. With their help it is possible to calculate the symmetry coefficient values as well as the current exchange density , therefore in the case of corrosion, the corrosion current density.

A similar procedure can be repeated for large cathodic overpotential ($\eta < 100mV$), omitting in the Butler-Volmer equation (A.19) the small anodic part. The resulting *Tafel equation for a cathodic process* has the following form:

$$\eta_c = a_c + b_c \log(-\mathrm{i_c}) \qquad \text{(A.25)}$$

and the Tafel coefficients for the cathodic process:

$$a_{\mathrm{c}} = 2{,}303\frac{RT}{\beta F}\log \mathrm{i_0} \qquad \text{(A.26)}$$

$$b_c = 2{,}303\frac{RT}{\beta F} \tag{A.27}$$

Through anodic and cathodic polarization of the tested system, and the measurement results of the Tafel curves, one can determine the corrosion current density, and therefore its rate. However, this method has some drawbacks which limits it only to laboratory conditions. Tests cannot be performed directly on the structure, so it is necessary to take a sample for testing in a laboratory. A qualified individual is needed who can perform the appropriate extrapolation of the obtained curves, which is the basis for obtaining the correct result. In addition, to obtain curves requires application of a high potential, which may result in an disorder of the state of equilibrium, that the obtained corrosion rate results will not be correct.

Extrapolation of the Tafel curves after all, is often used for the purpose of determining the anodic and cathodic Tafel coefficients, specifically the coefficients straight slope (b) necessary to determine the corrosion rate through the next described method - the linear polarization method.

A.6 LINEAR POLARIZATION (LPR – LINEAR POLARIZATION RESISTANCE)

In a very small overpotential range ($-20mV < \eta < 20mV$), the Butler-Volmer equation (A.19) can be greatly simplied by doing away with exponential expressions. It then takes a linear form dependant on electrode current from the appplied overpotential:

$$i = i_0 \left(\frac{\eta F}{RT}\right) \tag{A.28}$$

When looking at graph A.1 it is possible to see that near the low overpotential it is linear, this is actually described in equation A.28.

Corrosion rate testing with the assistance of the LPR technique involves only a slight deviation of the state of equilibrium (maximum 20 mV) in both directions and the measurement of the flowing current. The resulting dependence should be linear in nature. A real linear polarization graph is presented in Figure A.5.

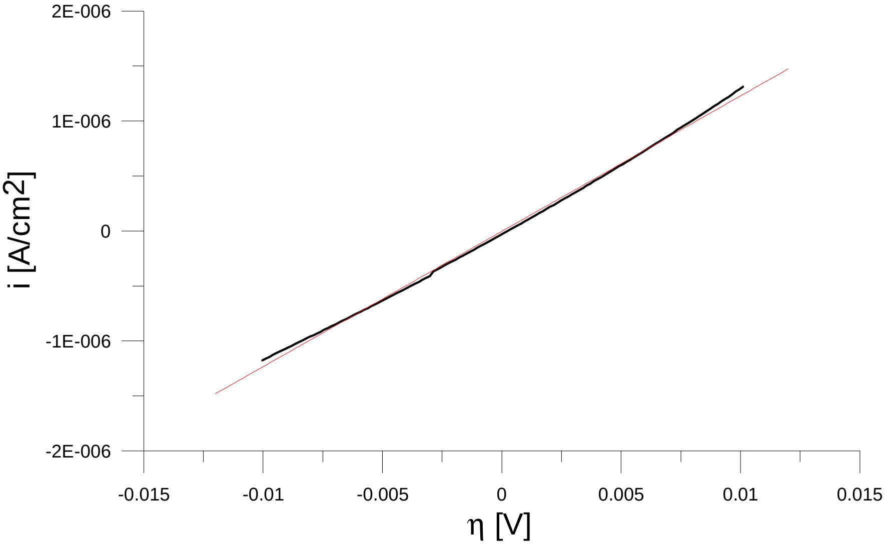

Fig. A.5. Linear Polarization Graph for cast-iron exposed to tap water

At this moment it is possible to define a new parameter called the polarization resistance R_p, which is directly associated with the charge exchange reaction. It's measurement is possible after simply determining polarization slope:

$$R_p = \left.\frac{\Delta E}{\Delta I}\right|_{\Delta E \to 0} \tag{A.29}$$

Polarization resistance can easily be imagined as a resistance during the forced electrode reaction with the help of polarization. The more overpotential given, the smaller the current produced will be, and hence slower electrode reaction, with a greater R_p value. In a very simple way, polarization resistance is related to corrosion current density:

$$i_{corr} = \frac{B}{R_p} \tag{A.30}$$

Parametr *B* związany jest z badanym układem korozyjnym, ma wymiar woltów. W praktyce używa się miliwoltów. Dla większości układów korozyjnych przyjmuje on wartości w przedziale *18mV* do *59mV*, lecz najczęściej mieści się w zakresie od *20mV* do *30mV*. Wyznacza się go stosując *równanie Sterna-Gearyego*, w którym to właśnie używa się, jak wspomniano w poprzednim rozdziale, anodowych i katodowych współczynników nachyleń prostych Tafela:

$$B = \frac{b_a b_c}{2{,}303(b_a + b_c)} \tag{A.31}$$

Expression for current corrosion, thus, it takes the final form:

$$B = \frac{b_a b_c}{2{,}303(b_a + b_c)} \cdot \frac{1}{R_p} \tag{A.32}$$

It is also possible to determine Parameter *B* using many other methods:

- using the gravimetric method
- using an appropriate alternating-current technique
- finding it in appropriate literature

Linear polarization is a technique often used for the rapid, continuous, and non-destructive monitoring of corrosion rate. Its usefuleness is shown by the fifty year career of this method in the fight against corrosion. It is used in such systems as:

- water cooling systems

- systems for the preparation and distribution of drinking water
- wastewater treatment systems
- processing of minerals
- paper production
- processing of hydrocarbons

This technique works best when it is used for continuous monitoring, and the analyzing of results in the field of time. Polarization may take place either in the direction of the cathode and anode, and also if necessary, only in the direction of the anode, or just in the direction of the cathode.

In field installations, there is the possibility of using a dual electrode system (the working electrode and the reference electrode) and the classical tri-electrode (the working electrode, the reference electrode, and the auxiliary electrode). In the case of a dual electrode system, the electrodes are made of the same metal. In the case of a tri-electrode system, the reference electrode can be a typical reference electrode as used in the laboratory (e.g. silver chloride). In both cases, the electrodes are made in the form of rods or thin discss and spaced symmetrically, relative to each other.

The method also has some disadvantages. It is limited to electrolytic environments. One should carefully arrange the electrodes, avoiding for example, incomplete immersion. LRP also works just for steady corrosion, or alternatively, with its help it is possible to estimate occurrence of localized corrosion. Systems with turbulent flow, showing strong potential-drift, oscillations, electrochemical noise make it very difficult to get accurate results using linear polarization. One must also use equimpent of an appropriate class, because such low voltage values can result in large errors (1 mV incorrectness at 10 mV polarization is a 10% error). The LPR method is also burdened with ohmic component error. Between the working electrode and the reference, there is a voltage drop on the resistance of the electrolyte:

$$R_p = R_p^0 + R_\Omega \tag{A.33}$$

This decrease should initially be estimated and from its value increasing the polarization voltage.

Despite its shortcomings, the method of linear polarization, when properly calibrated, superbly proves itself as suitable in its applied environments. Although, field results are not as ideal as those in the case of laboratory testing, it is still possible to easily corrosion damage.