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Tahsin Tezdogan
Yigit Kemal Demirel

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AN OVERVIEW OF MARINE CORROSION PROTECTION WITH A FOCUS ON CATHODIC PROTECTION AND COATINGS

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Summary

Corrosion is the gradual deterioration of a material or its properties through a chemical reaction with its environment. There are several methods of preventing a material from corroding. Cathodic protection (CP) and coatings are very popular methods for corrosion protection. Each individual method has its own benefits and drawbacks, whereas experience has shown that the most effective method of corrosion prevention is a combination of both CP and coatings. This combination can provide very good protection over a long period of time.

This paper focuses on the combined use of both CP and coatings for ships. Calculation of a CP design is explained briefly and the factors affecting the choice of the type of CP system are demonstrated. Then, a sample anode plan of a ship is shown. Finally, the calculation of a cathodic protection system of a ship is presented using data provided by coating manufacturers and shipyards.

Key words: *Corrosion; cathodic protection; coatings;*

1. Introduction

Cathodic protection (CP) is an electrical method used to protect steel structures buried in soil, or immersed in water, from corrosion. It has been applied to many structures such as underground storage tanks, lock gates and dams, water treatment facilities, well casings, rubbish racks, bridge decks, steel pilings, and, of course, ship-wetted hulls [1].

Cathodic protection systems found their earliest use in ships. Sir Humphry Davy pioneered cathodic protection systems on naval ships in 1824. Sir Davy described a method to prevent corrosion of the copper-clad wooden hulls of British naval vessels in a series of papers [2]. He protected copper immersed in sea water by attaching a small amount of iron or zinc, which acted as a sacrificial metal [3]. Today, Davy's procedure is still being used to minimise corrosion damage to steel vessels by installing zinc anodes on ships across the world [1].

Another remarkable development of the cathodic protection system was seen in the USA in 1945. In order to keep up with the fast-growing oil and gas industry, thin-walled pipes started to be used for transmission purposes. As a result of this, CP systems were installed to the underground pipelines to protect them from the corrosion damage and to provide a longer life [2, 3].

Low pressure thicker-walled cast iron pipelines were frequently used in the United Kingdom. However, the pipes were rarely protected by a CP system until the beginning of the 1950s. In 1952, a CP system was installed to protect a 1000-mile fuel-line network. This proved to be successful at preventing corrosion. Following this success, the use of CP systems dramatically increased [3].

The cathodic protection system is the most widely used method of protecting a material from corrosion, aside from coatings, in a marine environment. Today, many ships and offshore platforms are protected from corrosion by the aid of a CP system.

Cathodic protection may be used as a single protection method, or it may be used in conjunction with other protective systems. The specific combination of CP and coatings can be regarded as the most effective way of corrosion prevention from both practical and economical aspects [4].

This paper aims to emphasise the significance of cathodic protection methods. Firstly, corrosion is defined in Section 2. In Section 3, different methods of cathodic protection are briefly explained, along with their advantageous and disadvantageous. Then, a comparison between these methods is made in Section 4. Additionally, the costs of various protection methods for ships are illustrated graphically. In Section 5, the basic principles of paints and coatings are presented, and their effect on corrosion is explored. Section 6 concerns the concept behind the combined use of both CP and a coating as a corrosion protection technique. In Section 7, CP design principles are examined, by looking at the procedure of CP calculations. Following this, CP design calculations for two different tankers are given in detail as a real-life case study. Finally, in Section 8, a conclusion and general discussion is made according to the overall results in the paper.

2. What is corrosion?

Roberge states that, “corrosion is the destructive attack of a material by reaction with its environment” [5]. Rust is the most well-known corrosion product, which is yielded when steel and iron involve in the corrosion process. As this paper largely focuses on the economical aspects of corrosion, the chemistry of the corrosion process will not be explained in detail. However, Figure 1 gives a basic schematic of a corrosion cell.

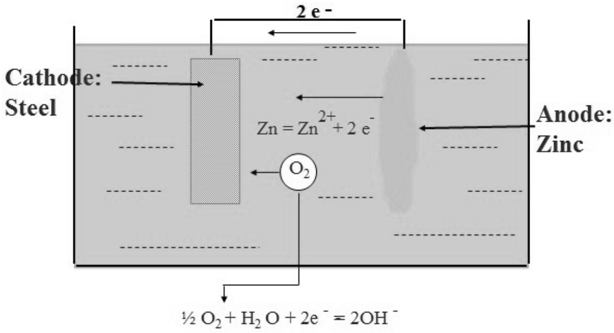

Fig. 1 A corrosion cell [4]

As corrosion damage costs a lot of money to repair, methods which are able to prevent corrosion are given great importance. It is stated that between 3 and 5 percent of the gross national product (GNP) of industrialised countries is associated with corrosion damage. Corrosion of metals causes the U.S. economy to loose approximately $300 billion each year.

Incredibly, 33 % of this cost could be prevented by the selection and use of an appropriate corrosion protection system.

3. Methods of cathodic protection

There are two main ways of achieving cathodic protection. These are the impressed current cathodic protection (ICCP) system and the sacrificial anodes cathodic protection (SACP) system.

3.1 The impressed current cathodic protection system

The impressed current system generates electrons from an external DC power source. As illustrated in Figure 2, an ICCP system consists of a rectifier, anodes, reference electrodes and a controlling unit. The required positive current is provided by the rectifier, and is delivered by the anodes to the structure to be protected. During this process, the reference electrodes track the protection level and the controlling unit regulates the produced current accordingly. Eventually, the metal structure becomes negatively charged, which ultimately leads to decrease of potential below a certain threshold value [4]. This threshold value is traditionally accepted that the steel is cathodically protected when it has a potential of -800 mV, or more negative. As it is written in NORSOK standards, regarding cathodic protection (M-503), "The CP system shall be capable of polarizing all submerged steel of the installations to a potential between -800 mV and -1100 mV vs. the Ag/AgCl/seawater reference electrode, and to maintain the potential in this interval throughout the design life of the installations" [6].

The ICCP system has been commonly used because it provides remarkable protection against corrosion in all types of ships and offshore platforms, pipelines, ports, and steel piles, etc. In spite of all the benefits of an ICCP system, it does have the following drawbacks [7]:

- Skilled workers are required.
- A continuous power supply must be sustained.
- The current must always be connected in the right direction.
- If permanent anodes are used, then current shields are required.

3.2 The sacrificial anodes cathodic protection system

There are a considerable number of older ships, with only short in-service lifetimes left, for which the installation of an ICCP system would not be desirable. Installing an SACP system is preferred for these ships as this would avoid the high initial costs of installing an ICCP system. SACP is mainly used for short term operation due to its low cost.

The basis of the SACP system is that the potential difference between the steel to be protected and a second metal in the same environment causes the driving voltage. If no anodes were attached to a ship's hull, then over time the steel would begin to interact with electrolytes and oxygen dissolved in seawater. Eventually the steel would undergo corrosion to revert back to a naturally-occurring ore, such as iron oxide. Sacrificial anodes can be used to prevent a hull from corroding in this manner. During installation, the anodes are either clamped or welded to the steel surface of the hull, to ensure permanent contact between the two types of metal. The two metals will have different electrochemical potentials, meaning a galvanic cell is generated between the two metals due to their difference in voltage. In this cell, the steel of the hull acts as a cathode, as a partner to the sacrificial anode. A redox reaction can then occur between the two metals, with electron transfer occurring from the anode to the cathode, dictated by their difference in electrochemical potentials. The cathode undergoes reduction, becoming more negatively-charged due to electron donation from the anode, and the anode undergoes oxidation, with positively-charged metal ions (cations) forming at its surface. These cations will undergo reactions with dissolved oxygen in seawater, leading to the formation of metal oxides (corrosion) at the surface of the anode. The favourable difference in electrochemical potential between the sacrificial anode and the ship's hull avoids corrosion occurring on the hull surface itself - instead, only the attached anode undergoes corrosion, and thus it is given the term "sacrificial anode" [2, 4].

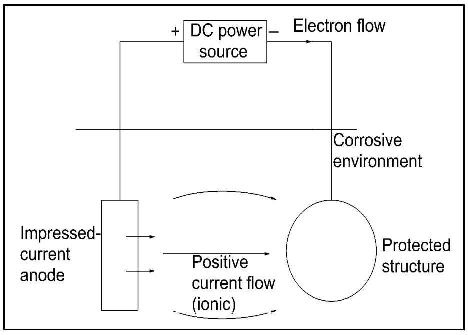

Fig. 2 A simple ICCP system [2]

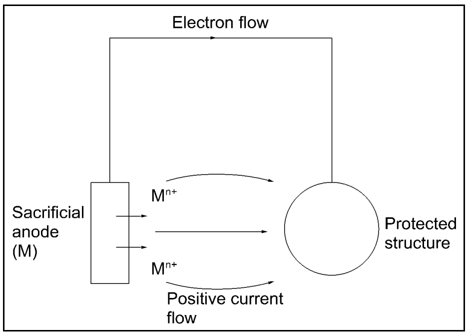

Fig. 3 A simple SACP system [2]

These anodes are generally made of aluminium, zinc or magnesium alloys, which are anodic with respect to steel materials [1]. A schematic illustration of a typical SACP system is given in Figure 3.

Determining the anode type is an important consideration. Anode selection depends on both economic factors and engineering calculations. Guidance to aid the selection of the optimum anode alloy is given in Section 4.

It is recommended that 15% - 20% of the sacrificial anodes should be installed to the stern and rudder area of the ship [7]. A typical installation of sacrificial anodes around the stern of a ship is shown in Figure 4. Calculating a cathodic protection system will be explained in Section 7.1.

Fig. 4 A typical installation of anodes around the stern of a ship [8]

The SACP system has some benefits: in addition to requiring no power supply to be installed, the sacrificial anode technique is also very simple to maintain and use. However, it is more expensive than an ICCP system for long term operation, although it has low initial costs.

4. Comparison of CP system features

It is very important to decide which CP system ensures the most efficient solution for the vessel. The decision depends on several factors. The most significant factors are the type of structure, and safety with regards to the environment and the cargo. The impressed current systems are generally employed to external areas of simple geometric structures because a complicated ICCP system is more expensive than a simple SACP system even over a long period. However, this does not pose a problem for a ship hull as it has a large plane surface.

The bullet points below list some of the biggest advantages of both systems [4]:

The ICCP system is used to protect hulls for these reasons:

- Smooth surface, no extra drag
- Flexibility
- Light for large displacement vessels
- Long life time
- No welding requirements
- Fully automatic

The SACP system is used to protect hulls for these reasons:

- Simple installation
- Maintenance-free between dry dockings
- Worldwide availability
- Low cost for short term operation

The SACP system is particularly very appropriate for internal use and complex structures since the protection of the entire structure is provided by distributing small anodes. For that reason, tanks in vessels are often protected using sacrificial anodes.

If it is concluded that the SACP system is the best option, then a decision should be made regarding which metal alloy to use. Several metals may be preferred, but zinc (Zn) or aluminium (Al) anodes are commonly used in the sector. Magnesium is not used in sea water since it releases a large volume of hydrogen gas due to a self-corrosion process.

Al is more expensive than Zn in terms of kilo price, while the consumption rate is 1/3 of the weight of an equivalent zinc anode. Consequently, distributing solely aluminium anodes over a ship's hull costs roughly half that of zinc anodes. Hence, Al anodes are advantageous over Zn anodes based on overall costs [7]. On the other hand, it should be borne in mind that "there are also restrictions in the use of aluminium anodes inside and adjacent to cargo tanks carrying cargoes with a low flash point. The reason being the danger of generating sparks if the anodes loosen and fall down" [4].

A life cycle cost for a Panamax with wetted area circa 9000 m^2 is illustrated in Figure 5. The costs (in USD) of using different CP systems or materials are shown in the figure with respect to service years.

As evidenced in Figure 5, the initial cost is slightly higher for ICCP, whereas the cost after 15 years is of the order of 7 to 8 times higher for SACP. Furthermore, if a comparison between sacrificial anode alloys is undertaken, the figure clearly demonstrates that an Al alloy is more cost effective than a Zn alloy.

Figure 6 is a demonstration of cost comparison between the submerged steel without any CP technique, with SACP, and with ICCP. As expected, applying no CP system results in the highest cost to the vessel in question (nearly 46,000 USD after 20 years). On the other hand, CP and corrosion repairs cost 10,000 USD to a ship with ICCP after 20 years in service. This amount reaches 25,000 USD for a vessel with SACP after the same length of time in service. It should be concluded that the cost after 20 years with sacrificial anodes is circa 2.5 times higher than the vessel with ICCP.

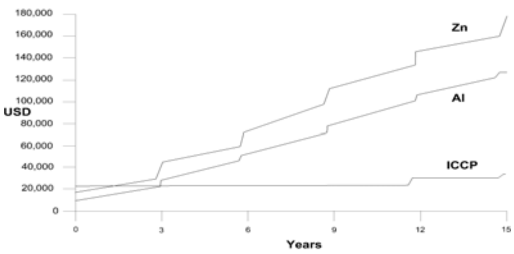

Fig. 5 Life cycle cost for a Panamax with wetted area circa 9000 m^2 [7]

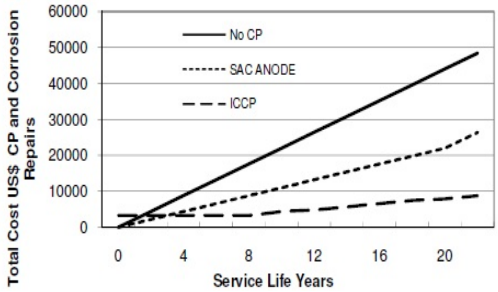

Fig. 6 Cost comparison of cathodic protection (per 100 m² of underwater steel) [9]

5. Paints and coatings

Paint is any liquid, liquefiable, or mastic product which contains pigments and which is converted to an opaque film after application to a substrate in a thin layer. The film provides protective and/or decorative features to the substrate.

The main components of paint are a binder, colour pigment, extender (filler), solvent and additives (auxiliary substances).

Paints are mainly discussed from a corrosion protection point of view in the following subsection.

5.1 Corrosion prevention by paints

Paint provides protection from corrosion in three ways; providing a barrier effect, providing an inhibitor effect, and providing a galvanic effect.

As the name suggests, the barrier effect generates a barrier between the material and the environment. There are no rust –inhibiting pigments inside the paints providing only a barrier effect. Most paints, many primers, all intermediate coats, and top coats appear in this group. In most applications, aluminium and glass flakes are used in primers to enhance the barrier effect.

Paints with the inhibitor effect contain inhibiting pigments such as zinc phosphate. Such pigments are only used in primers. It should be mentioned that these paints are not suited to under-water use.

Paints which use a galvanic effect contain pure zinc pigments and are used only as primers. The basic idea behind the galvanic effect is that the zinc forms a metallic contact with the steel; hence it can behave as an anode. Even if the paint coating cracks or flakes, the steel will still be protected by the zinc pigments acting in the manner of a cathode [4].

An impervious coating serves as an inert barrier to protect a material’s surface from corrosion. A simple illustration of an impervious coating system is shown in Figure 7.

In order to achieve the satisfactory application of a protective coating to a ship, the following fundamental requirements must be met [7]:

- Surface preparation
- Surface pre-treatment
- Anticorrosive or barrier coating application
- Antifouling coating application

Surface preparation to grade Sa 2½ according to the ISO 8501-1 standard prior to coating application is suggested to ensure a good adhesion. High pressure water jetting can also be performed since it provides a desired substrate with a surface more tolerant to paints [4].

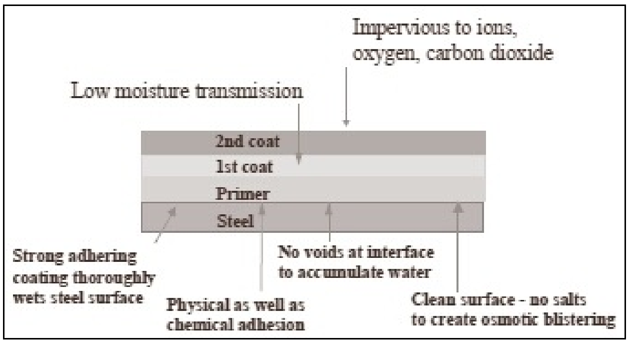

Fig. 7 An impervious coating system [4]

6. Combined use of both CP and coatings for ships

A painted coating is likely to break down over time. After a certain period of time in service, the properties of the system often fall below the limiting criterion, unless it is mended. This eventually leads to a high cost of renovation. Cathodic protection, however, can provide an improvement to the protection of the system.

Anodes can be installed at two main time points within the life of a vessel. One option involves installing the anodes during the construction of the vessel itself. The second option is to install the anodes after a certain service period.

From experience, installing the anodes at the ship building stage gives the best result for corrosion protection. “The calcareous deposit formed will precipitate on uncorroded steel at once, should a defect occur. If the anodes are installed after corrosion has propagated for a while the resulting layer at the steel surface will consist of a mixture of the already existing rust and the calcareous deposit. A layer like this will protect the base material, but will have a somewhat reduced protective property compared with the above case” [4].

It should also be emphasised that an excellent coating application to a hull involves almost no consumption of the anodes. In this situation, the anodes will only provide a guarantee for the construction and begin to work immediately after the coating deteriorates.

An illustration of the influence of using cathodic protection as a support for the coating is shown in Figure 8. The installation of a CP system after coating breakdown is a temporary and expensive solution. On the other hand, as it is evidently seen from the figure, the combination of CP and coating from the construction stage is the most effective and economical corrosion protection technique.

The compatibility of the paint system with the cathodic protection must also be taken into consideration in the CP design; otherwise protection cannot be properly ensured. The compatibility of the coatings is normally appraised by standard laboratory tests such as ASTM G8.

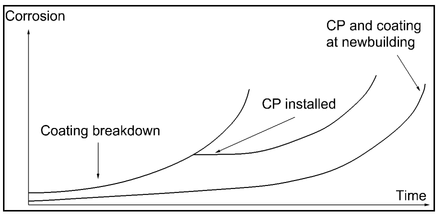

Fig. 8 Corrosion vs. time curves in different corrosion protection methods [4]

7. CP design principles

Corrosion leads to metal loss, surface roughness, and thus an increase in frictional resistance, which in turn affects fuel consumption. Hence, a cathodic protection system should be designed to maximise protection of the vessel from corrosion. Two basic groups of data are required for the design: background and dimensioning data [4].

The background data can be listed as follows:

- A general plan of the structure
- A statement of the current condition (paint break-down, corrosion damage …)
- The materials to be protected
- Information about the surrounding environment (cargo, external environment, etc)
- The cargo or ballast level in the tank
- The expected damage

Designing a CP system depends on the numbers and locations of sacrificial anodes. These calculations are performed with respect to following parameters:

- The area (m^2) to be protected
- Percent breakdown of the coating
- Mean current density (mA/m^2)
- The lifetime of the protection in years (y)
- Individual current output of the anode material (A/kg)
- The rate of consumption of the anode (kg/A.y)

Each vessel/structure requires a different current density. It varies depending on the type of vessel and condition of the hull. Table 1 gives a general idea about the current density requirements of different vessels in two different conditions. The first column lists the current density requirements of newly built vessels, and the second lists those for vessels in service [10].

The current density of a construction is widely affected by the quality of the coating system. The current density requirement for an unpainted material surface may increase up to 180 mA/m^2 [4]. Thus a CP method with paint system is strongly recommended since coating lowers the current density requirement of the structure to be protected.

Table 1 Current density requirements for a range of vessels [10]

Vessel Type	**New building mA/m^2**	**In service mA/m^2**
Ocean-going ships (coated)	10	15
Other ocean going ships	12	15
Coasters	14	20
Ro-Ro ferries	14	20
Trawlers	22	24
Kort nozzle tugs	22	24
Dredgers	24	27
Ice breakers	25	30
Tugs	18	22

7.1 CP design calculations

Cathodic protection design of a ship is carried out in accordance with very simple calculations. Firstly the total net anode weight requirement of the system is determined (Eq. 1), and then the number of anodes is found (Eq. 2). The formulae for these calculations are given below [10]:

$$W = \frac{A_x i_x C_x T}{1000} \quad (1)$$

where

W= Total net anode weight (kg)

A= Area to be protected (m^2)

i= Current density of the structure ($m.A/m^2$)

C= Anode consumption rate (kg/A/y)

T= Design life (y).

And the number of anodes is easily computed by

$$N = \frac{W}{w} \quad (2)$$

in which

N= Number of anodes, and

w= Individual net weight of anodes (kg).

7.2 Real case studies

The calculations given in Section 7.1 have been applied to an oil product tanker which has a 1835 m^2 wetted surface in the underwater hull, 15 m^2 in the sea chests, and 24 m^2 in the rudder blade. It is desired to achieve a 3-year protection by an SACP system. Aluminium anodes are chosen to be used. After the calculations, it is concluded that the vessel needs a total of 293 kg of anodes to provide external protection for 3 years.

Figure 9 shows the anode distribution around the stern of the ship where the anodes are installed in 3.750 metres separations based on the calculations performed.

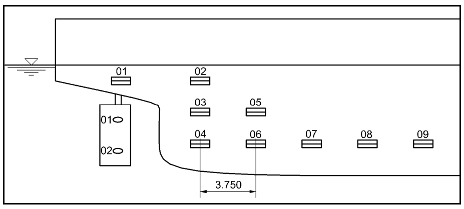

Fig. 9 Anode distribution of the vessel around the stern

A different and more detailed example is an 8400 DWT chemical tanker. Data of protected wetted areas of the ship is given below:

- Hull: 3310 m^2
- Rudder: 40 m^2
- Thruster Tunnels 18 m^2
- Sea Chests 15 m^2

The ship has an epoxy paint system, so it does not need as much current density in the hull.

The current density requirements of various areas of the vessel are listed as follows:

- Hull: 10 mA/m^2
- Rudder: 100 mA/m^2
- Thruster Tunnels 150 mA/m^2
- Sea Chests 40 mA/m^2

The aluminium anode alloy consumption rate is 3.39 kg/A in each year (given by the CP supplier).

The external CP system calculations have been performed in accordance with equations (1) and (2). The following values are the results, giving the total net anode weight requirement of the vessel in order to ensure a 5-year protection.

- Hull: 561.0 kg
- Rudder: 67.8 kg
- Thruster Tunnels 45.8 kg
- Sea Chests 10.2 kg

It is decided that 30% of the anodes in the hull should be mounted in the stern hull, and the rest should be mounted in the remain hull.

The number of anodes, and the net and gross weights of each anode are shown in Table 2. Different anode types are distributed in various areas on the ship's external surface in this example.

Table 2 Anode distributions in the external ship

ANODE DATA / AREA	ANODE TYPE	ANODE WEIGHT(KG)		Total net weight	Number of anodes	Total gross weight (kg)
		NET	GROSS			
STERN HULL	A-141	12.5	14.1	168.3	14	197.4
REMAIN HULL	A-141	12.5	14.1	392.7	32	451.2
RUDDER	A-98	8.6	9.8	67.8	8	78.4
THRUSTER TUNNELS	A-55	4.6	5.5	45.8	10	55.0
SEACHESTS	A-32	2.5	3.2	10.2	10	32.0

The calculations and results given in this section for both examples provide a general idea to engineers about an external CP system design. The calculations can easily be adapted to any ship as long as the current density requirements are known.

Current density requirement tests are carried out by applying a current using a temporary test setup, and adjusting the current from the power source until convenient protective potentials are attained [11].

8. Conclusions

A general review of cathodic protection methods has been presented. The two main methods are: ICCP and SACP, which have been described in the earlier sections.

The comparison of both methods suggests that in spite of the fact that the ICCP system has a slightly higher initial cost, it is more economical than SACP in the long term. Nonetheless, the SACP system is easy to be installed and apparently very convenient for internal use such as in ballast and cargo tanks.

The use of coatings for corrosion prevention was also examined. It is clearly shown in the paper that coatings provide the most effective protection when they are used in combination with a proper CP system.

The CP calculation procedure has also been explained and as an example, two real cases are considered. It was shown that cathodic protection calculations greatly depend on the area to be protected and the current density requirement of the structure.

It is of note that there has been a great effort to develop a novel, environmentally friendly and cost effective marine antifouling and anticorrosive coating, as reported in [12]. It is believed that these efforts will lead to the long term effective prevention of fouling and corrosion for all types of marine structures, while minimising the need for maintenance and repair.

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Tahsin Tezdogan
Yigit Kemal Demirel
University of Strathclyde Department of Naval Architecture, Ocean and Marine Engineering
Henry Dyer Building, 100 Montrose Street
Glasgow G4 0LZ, United Kingdom