

# Cathodic Protection – Electrochemical Principles and Design Considerations

*This document was prepared by Corrosion Probe Inc. to educate our clients and staff about the technology behind, and typical system design requirements for, cathodically protecting steel components in natural water and soil environments.*

## Introduction

Cathodic protection is an electrical method of preventing corrosion of metallic structures in electrolytes such as soil or water. It has widespread application on underground pipelines, and is increasingly used as cost-effective corrosion control for many buried and immersed structures such as water storage tanks, lock gates and dams, steel pilings, underground storage tanks, well casings, ship hulls and holds, water treatment equipment, trash racks and screens.

This guide describes the basic principles of cathodic protection, the areas of use, and the general factors to be considered in the choice and design of a system. It gives a basic introduction and simple technical data on cathodic protection. Further information and assistance is available from publications by national corrosion associations. Corrosion Probe, Inc. personnel have the expertise and experience to design cathodic protection systems and specify equipment, as well as to review and troubleshoot existing systems in all industries and service environments.

## History

Potential differences between different metals in an electrolyte - the technical basis for batteries and galvanized steel, was investigated by Galvani and Volta in the late 18<sup>th</sup> century, leading Volta to name the phenomenon “galvanism” after his colleague. Volta's galvanic cells were described in a paper to the Royal Society in 1799. The history of galvanizing starts in 1742 when a French chemist, P.J. Malouin, described a method of coating iron by dipping it in molten zinc to the French Royal Academy. In 1836, Stanilaus Sorel, another French chemist, obtained a patent for a means of coating iron with zinc. By 1850 the galvanizing industry was using 10,000 tons of zinc a year.

The first practical use of cathodic protection is credited to Sir Humphrey Davy in the 1820s. Davy studied Volta's cells containing copper, zinc and iron to advise the Royal Navy's investigation into premature loss of copper sheathing used to clad the hulls of naval vessels. Davy showed that corrosion of the steel nails fixing the copper sheathing to wooden ships was mitigated by attaching small quantities of iron, zinc or tin.

Extensive use of low-pressure, thicker-walled cast iron pipe meant little cathodic protection was applied before the 1950s. Wide use of cathodic protection expanded through N. America in the second half of the 20<sup>th</sup> century due to the expanding oil and gas industry using steel pipes for underground product transmission and steel drilling platforms and pipes in the ocean. Cathodic protection now is well established and provides corrosion control on a wide variety of immersed and buried facilities and infrastructure, including reinforced concrete structures.

Corrosion Probe Inc. (CPI) offers materials & corrosion engineering and project supervision services, through a staff of highly skilled multi-disciplinary professionals, to pulp and paper mills, wastewater treatment plants and other industries. Those services include designing, commissioning and auditing cathodic protection systems.

## Advantages and Uses of Cathodic Protection

A substantial advantage of cathodic protection (CP) over other forms of corrosion mitigation is that it is achieved simply by maintaining a DC electrical circuit, the effectiveness of which can be continuously monitored. CP commonly is applied to a coated structure to control corrosion at surfaces where the coating fails or is damaged. Specifying CP in new construction avoids the need to provide a “corrosion allowance” to thin sections of structures. CP is used to provide extra corrosion mitigation where even small leaks are unacceptable for reasons of safety or the environment. CP can be retrofitted to existing corroding structures to prolong their life.

CP can, in principle, be applied to any metal structure in contact with a bulk electrolyte, including concrete. CP's main use is in protecting steel structures buried in soil or immersed in natural waters. CP does not prevent atmospheric corrosion on metals but can be used to protect steel in both buried and atmospherically exposed reinforced concrete as long as the concrete contains sufficient moisture to act as the electrolyte. (Dry concrete is not corrosive.)

Structures commonly protected by CP include *exterior* surfaces of:

- Buried pipelines
- Storage tank surfaces in contact with the earth
- Jetties and harbor structures
- Steel sheet, tubular and foundation pilings
- Ship hulls, offshore platforms, floating and sub-sea structures

CP also is used to protect *interior* surfaces of:

- Large diameter pipelines
- Ship's holds and tanks (product and ballast)
- Storage tanks (oil and water)
- Water-circulating and cooling systems.

Less routinely, CP is applied to copper alloys in water systems, to lead-sheathed cables and to aluminum alloys, where cathodic potentials must be carefully controlled to avoid corrosion from excessive cathodic alkalinity.

## Electrochemical fundamentals

Metal is refined from primary ore (metal oxides or other free radicals) by applying energy and many metals naturally try to revert to the lower energy, combined state when in contact with oxygen, water and other corrosives. A common example of this corrosion phenomenon is rusting of steel exposed in the atmosphere and in fresh and natural waters.

Corrosion is an electro-chemical process in which metal in an oxidizing electrolyte dissolves to produce ions by an "anodic" (oxidation) reaction:

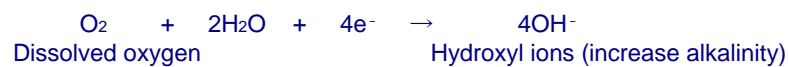


An example, iron oxidizes to ferrous ions,  $\text{Fe} \rightarrow \text{Fe}^{++} + 2\text{e}^-$  or to ferric ions  $\text{Fe} \rightarrow \text{Fe}^{+++} + 3\text{e}^-$  in more oxidizing solutions. Electrons generated by oxidation reactions at anodic sites "pass through the metal" and are consumed by reduction reactions at the cathodic sites.

In acid solutions the cathodic reaction is reduction of hydrogen ions (protons) to produce hydrogen gas:

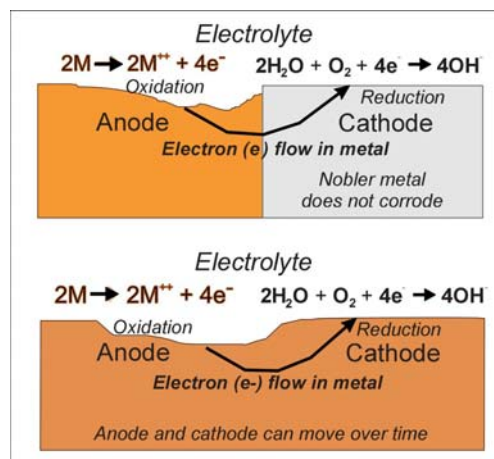


In neutral solutions the cathodic reaction involves reduction of dissolved oxygen (or other reducible species):



Oxidation and reduction reactions *must* generate and consume equal numbers of electrons – one reaction cannot occur without the other. Anodic and cathodic micro-sites are not fixed but corrosion often is concentrated where surface conditions accelerate oxidation. Corrosion reactions therefore convert metal to ions at anodic sites and convert solution acidity to alkalinity at cathodic sites.

As shown in **Figure 1**, the anode and cathode in a corrosion process may be on two different metals connected to form a bimetallic couple, or, as with rusting of steel, they may be two areas on the same metal surface. The electrolyte must conduct ions - water and soil are the most common electrolytes when it comes to cathodic protection.



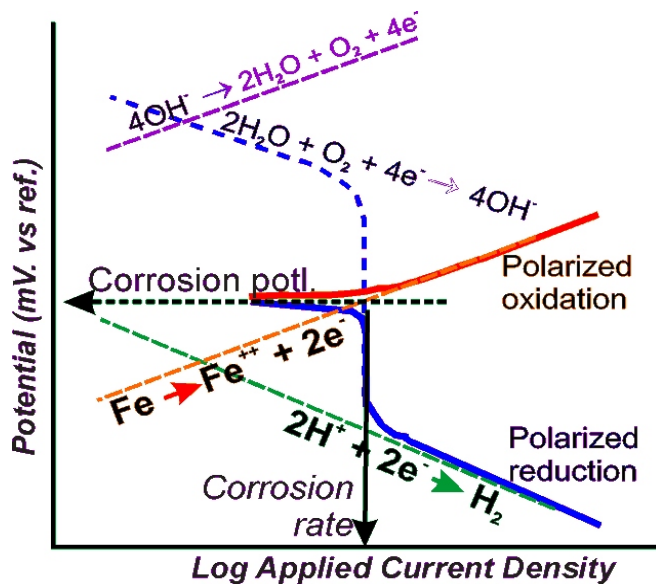
**Figure 1.** 'Corrosion cell' reactions on bimetallic couple (top) and one metal (bottom).

The electrochemical corrosion reactions involved are driven energetically (thermodynamically) by:

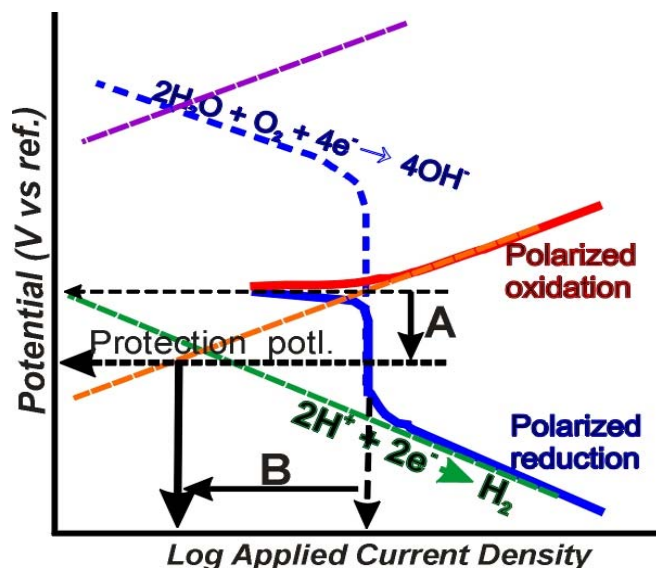
- Differences in the corrosion potential in galvanic (bimetallic) couples.
- The concentration of reducible species, e.g., dissolved oxygen, is not uniform over the surface of a metal. Oxygen-rich areas favor reduction reactions, becoming cathodic; oxygen depleted areas favor oxidation reactions, becoming anodic. Anodic and cathodic areas can move around over time.
- Metallurgical differences in the metal surface, e.g., welds, may make one area more or less anodically active.

CP basically involves connecting the target metal to an auxiliary anode and applying enough DC current (electrons) to satisfy the reduction reactions, making the protected surface cathodic. The oxidation reactions occur at the auxiliary anode, which is “sacrificial” and provides the current galvanically, or is an inert electrode that is immersed in the electrolyte to complete the circuit that impresses the DC current on the system with an external power source - usually an AC rectifier but nowadays possibly a solar or wind power source.

The applied current negatively shifts the potential of the metal in the contacting electrolyte solution so the corroding (anodic) reactions cease and only cathodic reactions occur at the metal surface. **Figure 2** illustrates the “freely corroding” scenario and **Figure 3** illustrates the effect on the corrosion rate of depressing the potential with impressed or galvanic cathodic current. In the following discussion it is assumed that the protected metal is carbon steel due to its ubiquity in construction. (CP of reinforcing carbon steel in reinforced concrete structures is applied in a like manner.)



**Figure 2.** Electrochemical kinetics with no cathodic protection. Intersection of steel oxidation reaction line (red) and (dissolved) oxygen reduction reaction line (blue) defines the corrosion potential, at which oxidation and reduction rates are equal. This intersection also defines the steel corrosion rate (current density) at that potential.



**Figure 3.** Electrochemical kinetics with cathodic protection. Shifting the steel potential (“polarizing it”) cathodically (negative) by A - by connecting the steel to the negative DC pole or to a more active metal - reduces corrosion rate by B. (B is the applied cathodic current.)

As already stated, CP is achieved in two ways:

- (i). By the use of galvanic (sacrificial) anodes.

Galvanic anode systems employ 'active' metal anodes directly connected to the steel to be protected. The difference in potential between the anode and the steel, as indicated by their relative positions in the galvanic series for the environment in question, causes a positive current to flow in the electrolyte from the anode to the steel, negatively polarizing the surface of the steel to make it the cathode. Metals used for sacrificial anodes include aluminum, zinc and magnesium, often with minor alloy additions to improve their performance.

- (ii). By use of "impressed" current.

Impressed-current systems use 'inert' anodes and an external source of DC power (rectified AC, solar panels) to impress current from the external anode onto the cathode surface. The connections are similar for the application of cathodic protection to metallic storage tanks, jetties, offshore structures and reinforced concrete structures. Protection potential for steel in soil is -0.85V w.r.t. Cu/CuSO<sub>4</sub> reference.

## Design considerations

Essential requirements of two types of systems for cathodically protecting metals immersed in an electrolyte are:

Galvanic systems require:

- i) Sacrificial anodes
- ii) Direct welding to the structure or a conductor connecting the anode to the structure
- iii) Secure and low resistance connections between conductor and structure, and between conductor and anode.

Impressed-current systems require:

- i) Inert anodes (clusters of which, connected together often in a backfill, are called the "ground-bed").
- ii) DC power source.
- iii) Electrically well insulated, minimum resistance and secure conductors between anodes and power source.
- iv) Secure and minimum resistance connections between power source and structure.

For both types of system the designer selects the type of anode based on the current demand, the immersion/burial environment and other factors; the size and number of the power sources or sacrificial anodes, and their distribution in, along or around the target structure. Other considerations to achieve protection economically and reliably are:

- a) Electrical continuity of the protected components.  
Resistance of the conductor and structure control the IR voltage drop of return currents through the structure and should be as low as practical. Cast iron pipe is "bonded" across joints to ensure continuity.
- b) Conductivity (resistivity) of the electrolyte greatly influences the "throwing power" of the system
- c) Coatings.  
A good coating decreases CP current demand and increases the effective 'throw' of the current: combining a coating and CP provides the most economic overall protection. Acceptable coatings have high electrical resistance and good adhesion to the metal surface. The coating also should be chemically resistant stability in the environment, abrasion resistance, and compatibility with the alkalinity created or enhanced by CP.
- d) Structure isolation.  
The inverse of continuity, isolation limits the effective zone of a CP system. For piping and pipelines this involves inserting electrically isolated joints in the structure - insulating flange kits are commercially available. Polarization cells that restrict low voltage DC currents but allow passage of high voltage AC currents are used to isolate low-resistance 'earthing' systems from protected structures with a high quality coating.
- e) System test facilities.  
It is important to consider where to locate test connections and stations, corrosion monitoring coupons, permanent half cells (reference electrodes), and how the data is routinely collected and reviewed.

### 1. Initial design analysis

Modifications to the structure to incorporate the requirements discussed above should be made at the design and pre-construction phases of the project. On underground structures and pipelines it may be necessary to visit the site or route to obtain additional information on low-resistivity areas, availability of electric power, possible existence of 'stray' DC currents or other possible interactions, etc. If the structure already exists, measuring existing structure-to-

soil potentials gives valuable information as to which areas or lengths of pipe are anodic and cathodic. Applying a temporary CP current to the structure with a convenient DC source and a temporary anode system (ground-bed), gives a more reliable assessment of current demand and the likely attenuation of currents onto and around the structure.

Electrical design of a CP system for a new structure requires determining or calculating:

- Current demand
- Resistance to earth of the anodes
- Quantity and location of anodes or anode systems
- Electrical supply requirements
- Where to locate testing/monitoring connections

Project specifications and national guideline documents should be consulted.

Negotiation with landowners, public authorities, etc. for easements for ground-beds, cable routes, transformer-rectifier sites, and electricity supplies should also be undertaken at the design stage.

## 2. Specified potential and protection distance/range

The structure potential is measured with respect to a standard reference half-cell. A common protection criterion used for steel in a neutral, aerobic electrolyte, e.g., soil, is *minus 850 mV* with respect to a copper/copper sulfate half-cell. When sulfate-reducing bacteria influence the steel corrosion the recommended potential is *minus 950 mV*. Potentials measured at a particular location on a cathodically protected structure depend on the anodic and cathodic reactions, structural geometry, and internal electrical resistance. More reliable and accurate potential readings are obtained when the reference half-cell is closer to the target metal surface.

A protective coating has a major effect on the current required to reach the target potential. The induced potential typically is most negative closest to the anode or ground-bed, and attenuates towards the natural corrosion potential as distance from the anode or ground-bed increases. Voltage attenuation is demonstrated by the fact that one impressed current CP system can protect up to 100 miles of properly coated buried pipeline in the right soil, but a bare (uncoated) pipeline of the same size may need a CP system for every two miles. Soil or water conductivity (resistivity) significantly affects the reach (throw) of the CP system: lower conductivity attenuates the current and consumes more power.

Sacrificial anodes are independent sources of external electric power, especially suitable for local corrosion protection. They are less susceptible to and less likely to cause interference on nearby structures. The current output capacity of commercial galvanic anodes is limited and the number of anodes required depends greatly on the electrical conductivity (resistivity) of the electrolyte (local environment if buried / submerged / concrete).

Galvanic anodes of aluminum and zinc have similar driving voltage to steel of approx. 0.5V, are limited to use in electrolytes of  $\rho < 5 \text{ ohm.m}$  resistivity. Sacrificial anodes are self-regulating because their current output is usually less than their maximum output capability and is controlled by the difference in potential between the two metals. Sacrificial anodes provide immediate protection. Since current from anodes is limited but not controllable, changes in the current demand, e.g., due to coating loss, may necessitate installing additional sacrificial anodes to provide acceptable protection. Sacrificial anodes tend to be used for small, well-coated structures or for localized protection - examples are the Mg rod in a domestic hot-water heater and Al anodes on steel off-shore platforms.

Impressed-current installations have the advantages of being able to –

- a) Supply a relatively large current
- b) Provide high DC driving voltages (up to 50V) to enable use in most electrolytes
- c) Provide a scalable output to accommodate changes in and extension of the protected structures.

Care must be exercised in a design to minimize interaction with nearby structures. If no AC power is available, an alternative power source (solar, diesel, etc.) is required. Impressed current systems are utilized for large, complex structures, which may be bare, poorly coated or well coated. In some circumstances impressed current and sacrificial CP systems are used together in an appropriately designed system.

## 3. Problems to avoid

Potential problems with CP in neutral environments involve increased alkalinity generated at protected surfaces: this can attack coatings or cause them to disbond. Alkalinity also can corrode lead and aluminum. Problems in acidic environments arise from hydrogen gas produced at cathodic sites: hydrogen gas causes coatings to disbond and hydrogen absorbed into high strength steel lowers its impact toughness.

Steel under a disbonded coating can be shielded from full cathodic protection. Another problem is the possibility of hazardous consequences from sparks (arcing) created by introducing electric currents into a structure. Sacrificial anode systems generally do not have these problems and typically are viewed as 'set and forget' systems in which anodes are sized to provide protection for the specified period.

Secondary structures sharing the same electrolyte, e.g., soil or water, may receive and discharge protection currents by acting as an alternative low-resistance path (interaction). Corrosion on the secondary structure is accelerated where current leaves the metal, in a phenomenon called "*stray current corrosion*". Stray currents can occur, for example, on a ship moored alongside a cathodically protected jetty, or on a pipeline or metal-sheathed cable that crosses near a cathodically protected pipeline.

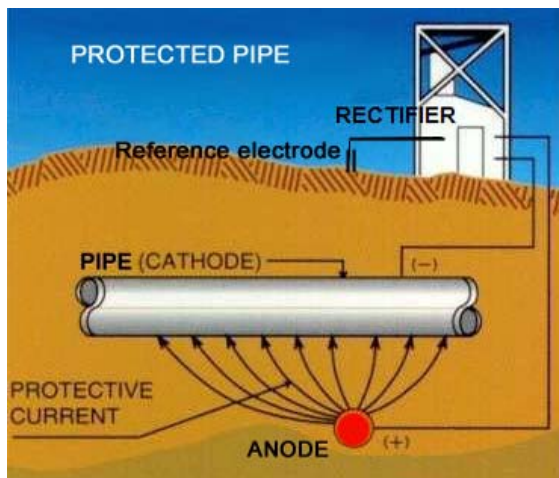
Interaction may be minimized by careful CP system design, in particular by minimizing the required current density and by maintaining good separation between the protected structure and the secondary structure, as well as between the anodes (ground-beds) and the secondary structure. Because sacrificial systems do not create severe interaction problems, they are popular for protecting targets in congested locations. Testing for stray currents should be witnessed by the interested parties so the methods and procedures for mitigating interaction to acceptable limits may be agreed.

#### 4. Types of equipment

Various galvanic anode alloys of magnesium, aluminum or zinc are available in a variety of block, rod or wire forms. These alloys are cast around steel inserts to enable fixing of the anode and to maintain electrical continuity and mechanical strength towards the end of the anode life. The insert may be directly welded or bolted to the structure to be protected, or anodes may be connected to the structure by means of an insulated lead, usually of copper, as for onshore and offshore pipelines.

Impressed-current ground-beds in soils have traditionally consisted of high-silicon cast iron. Mixed metal oxide (MMO) anodes are increasingly selected for all environments because of their robustness, good electrical characteristics and compact size. For seawater applications and other areas with chlorides present, MMO anodes and anodes of high-silicon cast iron alloyed with chromium work well. Other anodes include lead alloy and a thin layer of platinum on a titanium or niobium base. **Figure 4** shows the basic components for protecting a buried pipe with impressed current.

There are many sources of DC power, including selenium plate or silicon-diode rectifiers with a transformer unit connected to either an existing AC supply or a diesel- or gas powered generator. In remote areas, power sources include thermo- electric generators, closed-cycle vapor turbines, and solar or wind generators. The latter two are used in conjunction with storage batteries. The final design depends on power requirements, maintenance capabilities and environmental conditions. There also are automatic control units available that will adjust current output in accordance with potential changes at a half-cell.



**Figure 4.** Four basic components of impressed current system for buried pipe: rectifier (power supply), reference electrode, "inert" anode and target structure with continuous conductivity.

#### Monitoring and Maintenance

CP systems are monitored by measuring structure-to-electrolyte potentials, using a high input impedance voltmeter and reference half-cell. Standard half-cells are copper/copper sulfate, silver/silver chloride/seawater, silver/silver chloride/ potassium chloride and zinc. The CP current output is controlled to maintain the protecting potential at the specified value. The standard protection potential in soils and water is -850 mV (wrt. Cu/CuSO<sub>4</sub>), or -800 mV (wrt. Ag/AgCl).

Transformer rectifier outputs may be monitored by telemetry at central control stations. Many CP systems are controlled and monitored by remote computers and internet links. Some communication systems enable pipe-to-soil potentials to be monitored from a helicopter or airplane. Galvanic anode outputs can be monitored, as can currents in electrical bonds between structures.

Systems traditionally are tested annually - to meet jurisdictional requirements. Maintenance includes mechanical maintenance of power supply equipment and maintaining painted surfaces on equipment. It always is good practice to inform owners of CP systems and infrastructure susceptible to a new CP system or the effects of significant changes to an existing system, in order to assess the effects of the changes.

## Supplementary Information

### Books and manuals:

*Cathodic Protection*, (2<sup>nd</sup>. Ed., 1987) J.H. Morgan, National Association of Corrosion Engineers (NACE), Houston, TX

*Peabody's Control of Pipeline Corrosion*, (2<sup>nd</sup>. Ed., 2000) Edited by R. Bianchetti, NACE, Houston, TX

*Handbook of Cathodic Corrosion Protection*, (3<sup>rd</sup> Ed., 1997) von Baeckmann, Schwenk and Prinz, Gulf Publishing, ISBN-10 0-88415-056-9

*Pipeline Corrosion and Cathodic Protection*, (3<sup>rd</sup> Ed., 1995) Parker and Peattie, Butterworth-Heinemann, ISBN-10 0-87201-149-6

*Cathodic Protection Criteria - A Literature Survey*, 1989. NACE, Houston, TX

*Corrosion Engineering*, (3<sup>rd</sup>. Ed., 1985) M.G Fontana and N.D. Greene, McGraw-Hill, ISBN-10 0-07021-463-8

### Standards

#### North American

NACE SP0169:2007 - Control of External Corrosion on Underground or Submerged Metallic Piping Systems

NACE TM 0497 - Measurement Techniques Related to Criteria for Cathodic Protection on Underground or Submerged Metallic Piping Systems

#### European

EN 12068:1999 - Cathodic protection. External organic coatings for the corrosion protection of buried or immersed steel pipelines used in conjunction with cathodic protection. Tapes and shrinkable materials

EN 12473:2000 - General principles of cathodic protection in sea water

EN 12474:2001 - Cathodic protection for submarine pipelines

EN 12499:2003 - Internal cathodic protection of metallic structures

EN 12696:2000 - Cathodic protection of steel in concrete Part 1: Atmospherically exposed concrete

EN 12954:2001 - Cathodic protection of buried or immersed metallic structures. General principles for pipelines

EN 13174:2001 - Cathodic protection for harbor installations

EN 13509:2003 - Cathodic protection measurement techniques

EN 13636:2004 - Cathodic protection of buried metallic tanks and related piping

EN 14505:2005 - Cathodic protection of complex structures

EN 50162:2004 - Protection against corrosion by stray current from direct current systems

BS 7361-1:1991 - Cathodic Protection Part 1 - Code of Practice for Land and Marine Applications