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ELECTRICITY, ELECTROLYSIS, AND GALVANIC CORROSION

These notes were developed to accompany a presentation which was given to the Royal Victoria Yacht Club on February 10th, 2015.

INTRODUCTION

Many boaters do not have a technical background, and the subjects of electricity and underwater corrosion are mystifying to them. Even so-called "experts" can't seem to agree on some of the issues! This document will attempt to provide pertinent information on these subjects in an easily-accessible manner.

Most boaters have heard of the term "electrolysis", and understand that this is some type of problem that can cause extensive damage to the underwater metallic components of a vessel. There are actually several different mechanisms involved, and we will address them one at a time. The common thread in all of this is "electricity", so we will start out with a quick review of some of the basics of electrical systems before moving on to the corrosive material.

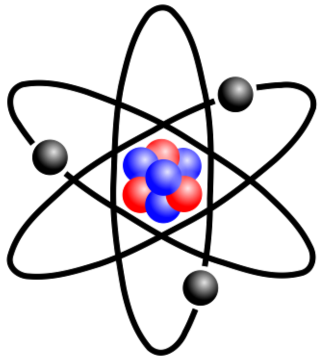
Throughout this document, an attempt has been made to use bold face on any technical term the first time it is used.

PART 1: ELECTRICITY

The Basics

Electricity is a subject area that is sometimes difficult to explain. The actual definition is: "*The set of physical phenomena associated with the presence and/or flow of electric* ***charge***." This seems like a circular definition, because now we need to know what constitutes an electric charge, which is defined as: "*Electric charge is created by the presence or absence of* ***electrons***."

Hopefully everyone will recall from high school that the basic building block for anything in the universe is the **atom**. No one has actually ever seen an atom, but it is generally accepted that one might look like this:



The centre of the atom is called the nucleus, and it consists of positively-charged protons, and neutrally-charged neutrons. A group of electrons are in orbit around the nucleus. When in a stable situation, the number of electrons is equal to the number of protons, so their charges cancel out, and the atom has no net electrical charge.

If an electron is pulled away from an atom, what remains will have a net positive charge, and is referred to (at least by electronic engineers) as a "**hole**". Nature is always looking to restore equilibrium, so the electron that we removed will experience an attractive force urging it to rejoin the atom.

A cloud of electrons creates a negative charge. A cloud of holes creates a positive charge.

The flow of electrons in a conductor creates an **electrical current**. Electrons (being negatively-charged) always want to move from negative to positive. Unfortunately, modern usage has stated that "conventional current flow" is from positive to negative, so this is actually describing the direction that holes flow! As an electronic engineer, I understand when I am designing circuitry that the electrons are going from negative to positive, but for this set of notes, I will conform to modern usage, and pretend that electrical currents flow from positive to negative!

Electrical current <u>appears</u> to flow through a conductor at a speed of just less than the speed of light, but actual electron movement within the conductor itself can be considerably slower. For the purposes of this document, we will declare that current flow is "instantaneous".

Different materials have different atomic structures, and therefore different abilities to allow for the flow of an electrical current. Materials that allow for the easy passage of electrical currents (such as most metals) are referred to as good "**conductors**". Materials that do not allow for easy passage of electrical currents (such as most plastics) are referred to as "**insulators**". An "**electrolyte**" is a liquid through which an electrical current is passed.

Electricity and **magnetism** are very closely related. The flow of an electrical current creates a magnetic field, and a varying magnetic field can cause a current flow in a conductor.

Electrical Measurement Units

A **VOLT** is a measure of the potential difference in charge. It describes the potential for an electrical current to flow (if given a chance). It is analogous to **pressure** (in psi) in a hydraulic system.

A Coulomb is a measure of electrical charge, and represents a charge of 6.24×10^{18} electrons. There is no need to use this unit in practise, but it is used to define the unit of electrical current flow given below.

An **AMPERE** is a flow rate of 1 Coulomb per second. This is analogous to flow rate (in gpm) in fluids. It is often abbreviated as an "Amp".

An **OHM** is a measure of the **resistance** to electrical flow. This is analogous to the size of a constriction in a pipe conveying fluid flow.

A **SIEMENS** is a measure of the conductance. Conductance describes how easy it is for electricity to flow, and it is the reciprocal of resistance. This is seldom used in practise, but will sometimes be specified when dealing with electrical flow in fluids (such as water).

Correct Usage Of Units

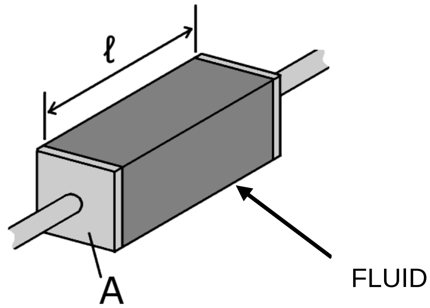
Popular literature often uses incorrect terminology when discussing electrical components or systems! Sometimes new electrical units are just "made up", causing confusion for most readers, and extreme frustration for those in the industry. Here are two of the most common examples of technical sloppiness:

Amps per Hour — An Amp is a measure of current flow rate. As such, it defines the flow of a quantity of electrical charge per unit time. The nonsensical term "Amps per Hour" denotes "quantity per unit time per unit time", and therefore is actually a measure of current flow acceleration, which is seldom what the authors intended!

Amp-Hours per Hour — An Amp-Hour is the product of Amps multiplied by time. It is commonly used to indicate the capacity of a battery, or the "dosage" of a leakage current. It is a flow rate multiplied by time, and therefore denotes a "quantity" of electrical charge. The nonsensical term "Amp-Hours per Hour" denotes "quantity per unit time multiplied by time divided by time", and therefore is actually a measure of Amps!

Electrical Resistance Of Water

It is easy to specify the resistance of a length of copper electrical wire, if you know its length and diameter (gauge), because the electrical current is constrained to flow only in the wire, and not through the air surrounding it. It is more difficult to measure or predict the resistance between conductive electrodes immersed in fluids such as water, but a standard way of specifying a measuring setup is as follows:



In this diagram, there are two metal plates, each with an area of A. A column of fluid that is "***ℓ***" units long exists between the two plates. For any given fluid, the electrical resistance between the two plates can be decreased either by increasing the area of the plates, or by decreasing the distance "***ℓ***".

The same units must be used for A and ***ℓ***, but they can be anything convenient, such as inches, metres, miles, or microns.

If the area A is equal to the distance ***ℓ***, we can easily predict the electrical resistance using published data as follows:

Air	$2x10^{16}$ Ohms
De-Ionized Water	200,000 Ohms
Drinking Water	20 To 2000 Ohms
Sea Water	0.2 Ohms

As you can see, fresh water is a poor conductor, but sea water is an excellent one!

Note that if these same two plates were immersed in the actual sea, the measured resistance would be lower, because current flows off of both sides of the plates.

Electrical Relationships

The basic electrical measurement units are inter-related, and a simple relationship known as "**Ohm's Law**" allows you to determine one unit if you know two others:

V = I x R (Voltage drop is equal to the current in amps times the resistance in ohms)

I = V/R (Current in amps is equal to the voltage drop divided by the resistance)

R = V/I (Resistance in ohms is equal to the voltage drop divided by the current)

If a voltage is applied to a device, and a current flows, that device is absorbing energy. The rate at which energy is absorbed is termed "Power", and it is measured in **Watts**.

In electrical terms, **W = I x V** (power in Watts is equal to voltage times the current in amps). There is an equivalence between electrical power, mechanical, power, and heat. Using Imperial units, we have:

746 Watts = 1 horsepower

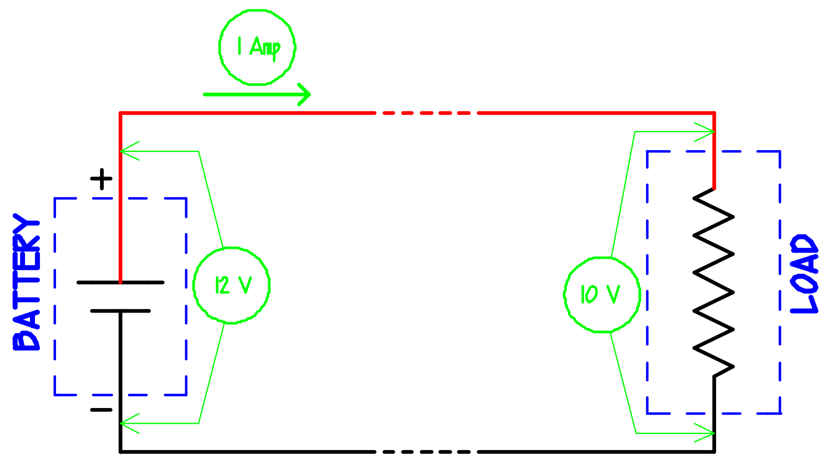
1 Watt = 3.4 BTU/hour

Consider the following example. An electrical motor is connected to 120 volts, and is drawing 6 amps. It is consuming 6 x 120 = 720 Watts of power. If the motor had no losses, we would expect it to be delivering 720/746 = 0.965 horsepower. If we actually measure the horsepower being developed and discover it is only 3/4 horsepower, the difference (0.965 - 0.75) represents the losses in the motor which are being converted into heat.

The principle of **Conservation Of Energy** states that in a given system, energy can neither be created nor destroyed - it can only be converted from one form to another. As an example, consider a stationary vehicle at the top of a hill. The car has "potential energy" because of the height of the hill. If the car starts to roll down the hill, it loses potential energy as its altitude decreases, but gains "kinetic energy" as the speed builds. If the brakes are now applied, the car slows down, but the brakes heat up as they absorb the car's kinetic energy and convert it into heat. At all times, the total energy of the system (potential energy + kinetic energy + thermal energy) is the same.

We will now put all of this together in a simple electrical example. Consider the following:

Here we have a battery supplying power to an electrical load (such as a light bulb) via some long electrical wires. We take some measurements, and observe the following:



There is a potential of 12 volts at the battery, and it is delivering a current of 1 amp. There is 10 volts across the load, so it must be absorbing 10 x 1 = 10 Watts of power. But the battery is supplying 12 x 1 =12 Watts of power, so we are missing 2 Watts! However, we know that the long electrical cables must have a total voltage drop of 2 Volts, so each of the two cables must be dropping 1 volt. The current is the same through the entire circuit (1 Amp), so we know that the resistance of each wire must be 1 Ohm, and we know that each of the two wires must be absorbing 1 Watt of power. Remembering that energy can neither be created nor destroyed, we realize that each of the two wires will be converting 1 Watt of electrical energy into heat, and indeed, the wires will become warm. If the load is an incandescent light bulb, the majority of the load's absorbed power will be converted into heat, and a smaller part will be converted into light (which is a form electromagnetic energy).

Whew! That wasn't too bad - you just break down the circuit into its component parts and analyze the data you have available. Remember that electricity can't just pour out onto the floor - it has to go somewhere!

Sources Of Electrical Energy

One of the first practical sources of electrical energy was the electro-chemical battery, as developed by Volta in 1800. This is a device that converts chemical energy into electrical energy, and is the principle of most batteries today. Many electronic devices today are powered by disposable batteries (such as alkaline AA cells) - these are not rechargeable, and are referred to as **Primary** Batteries.

Heavy consumers of electrical energy (such as boats, cars, and computers) are equipped with batteries that can be recharged - these are called **Secondary** Batteries. During the charging process, electrical energy is converted into stored chemical energy. As a battery supplies electrical current, the reverse occurs - chemical energy is converted into electrical energy. The "round trip" (charging and discharging) has losses of about 30%, and this "lost" energy is converted into heat. The most common storage battery formulations are based on lead-acid, Nickel-Cadmium, or polymers of Lithium.

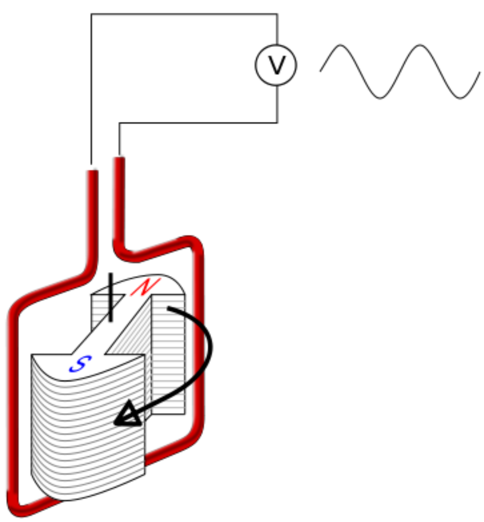
All batteries produce what is referred to as **DC** (Direct Current) - there is a positive terminal and a negative terminal on the battery.

Another source of DC that is likely to be used on a boat is the photovoltaic cell, sometimes referred to as a "solar cell". These directly convert incident sunlight into a direct current, with a conversion efficiency of 10 - 20% (depending on the type of cell). If the sun is directly overhead on a clear day, the sun is bombarding the earth's surface with approximately 1,000 Watts over every square metre of surface area. Of course, this irradiance decreases as the sun moves away from perpendicular (due to Lambert's Law), or when clouds intervene. Photovoltaic cells are always used in conjunction with some type of energy storage device (such as a secondary battery) in order to provide a continuous source of electrical energy as the output of the cells vary.

A source of DC that does not rely on the sun is the **Fuel Cell**. These devices combine hydrogen and oxygen to produce water and a supply of electrical energy. When comparing the electrical energy produced versus the chemical energy consumed, the overall efficiency is about 70%. This type of energy source first came into prominence during the "space race" in the 1960's. Today there are portable fuel cells available that convert methanol and air into electricity, water, and CO_2 - efficiencies are low, but portability and convenience is high.

All of the sources described so far produce DC, but the vast majority of the electrical power in the world today is generated by converting <u>**mechanical rotational energy**</u> into Alternating Current (**AC**).

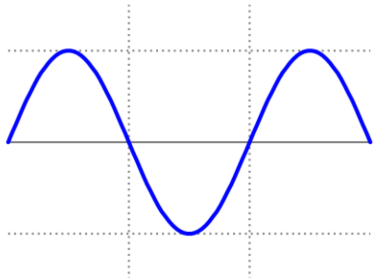
Here is a diagram showing a magnet being rotated within a coil of wire, thereby producing a time-varying electrical voltage:



This "**alternator**" could also have been constructed by using a fixed magnet, and having the coil of wire rotate within its magnetic field.

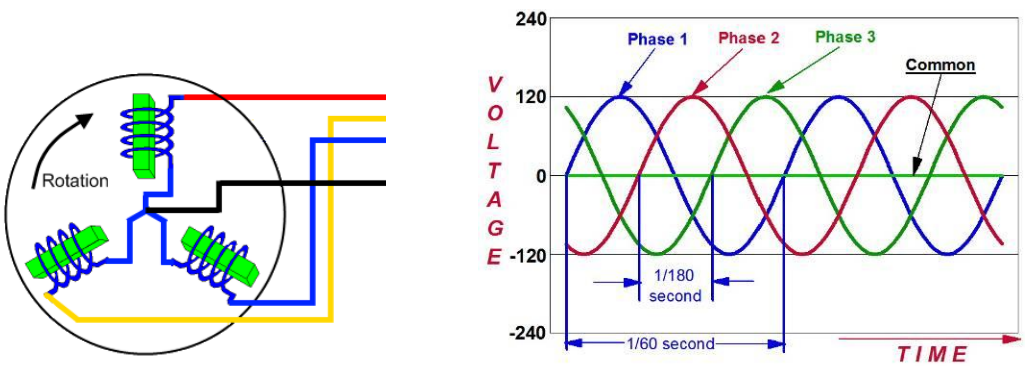
The instantaneous voltage produced is a function of the angular position of the coil as it rotates. For continuous rotation, this instantaneous voltage describes a sinusoidal relationship with time. The rate at which the cycles repeat is called the **frequency** (measured in **Hertz**).

The actual voltage produced as a function of time is typically called a "sine wave", and looks like this:



Those of you who remember trigonometry from high school, will recognize that the voltage varies as the sine of alternator's shaft position.

Alternators can be driven by a variety of mechanical sources of energy, and can be equipped with multiple windings to produce what is called "3-phase power". The diagram below shows a 3-phase alternator configuration, and the resulting voltage outputs of each of the coils:



3-Phase power is exceptionally well-suited for driving large electric motors because it is easy to create a rotating magnetic field. Most power distribution and industrial applications of electricity use 3-phase power.

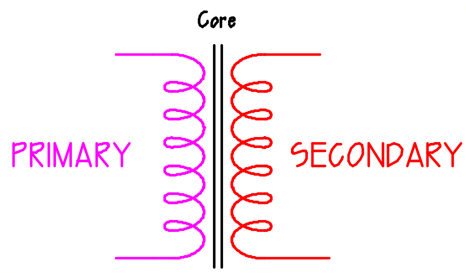
The alternators on most boat and car internal combustion engines generate multi-phase AC that is then **rectified** into DC by the use of diodes. A **diode** is a solid-state device that permits current to flow only in one direction (sort of like a plumber's "check valve").

Shore-based alternators can be driven by any rotational energy source. These are typically turbines powered by water, steam, gas, or wind. The steam to power steam turbines is produced from burning fossil fuels, nuclear fission, or geothermal. Marine and portable alternators are usually driven by an internal combustion engine (either diesel or gasoline), and the entire package (alternator + engine) is typically called a "**generator**".

The term "alternator" is often used interchangeably with the term "generator" to describe the component on a car or boat engine that produces electrical current to charge batteries. Note that even though it appears that these devices produce DC, at their core they are actually inherently AC devices, which then convert the AC to DC by rectifying it with diodes or commutating it with brushes.

Transformers

One of the advantages of AC is that it is compatible with the use of electrical transformers. A transformer consists of two or more coils of wire wound onto a core material (usually strips of steel). One of the windings is connected to a source of AC current, thereby producing a time-varying magnetic field in the core material. This varying magnetic field then induces an AC voltage in the other winding that also surrounds the core. The electrical symbol for a transformer actually shows this relationship quite clearly:



If there are the same number of turns on the primary and secondary windings, the output voltage will be nominally the same as the input voltage. If the number of turns is not the same, the voltage can be stepped up or stepped down, depending on the ratio of the turns.

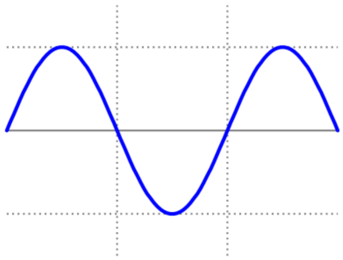
Transformers provide complete electrical isolation from the primary and secondary circuits, as there is no direct electrical connection between the two.

Transformers usually have very low losses, which result in only a slight temperature rise of the windings and the core.

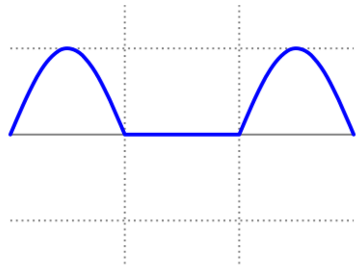
AC to DC Conversion

It is often necessary to convert an AC source of electrical energy into a DC supply (for charging secondary batteries or equivalent). This is easily done by using diodes, which are "electrical check-valves".

Here is the basic idea:

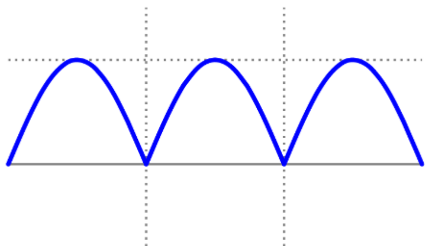


Input



After Passing Through A Single Diode Rectifier

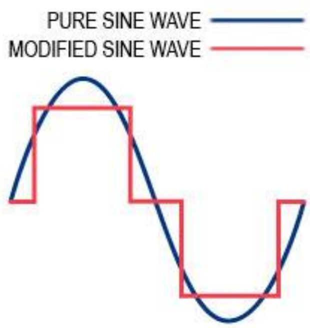
This is termed "half-wave rectification", because only half of the original AC waveform is used. If additional diodes are employed, it is possible to use both halves of the input signal to implement "full-wave" rectification, with an output waveform that looks like this:



DC to AC Conversion

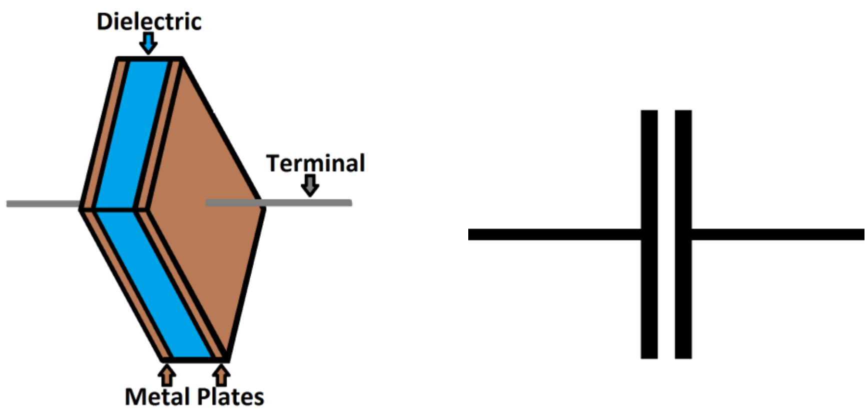
Boats often want to have a source of AC power when they are away from the dock to run various appliances and gadgets. If the boat does not have a generator, a battery can be used to create a regular 120 V AC, 60 Hz supply using a device known as an "**inverter**".

An inverter uses transistors to synthesize a sine wave with "slices" of DC. A step-up transformer is used to raise the voltage. Early inverters used a fairly simple circuit that produced what is called "modified sine wave", but modern units use more sophisticated approaches to generate "pure sine wave" outputs that closely match the type of power available from shore power systems:



Capacitors

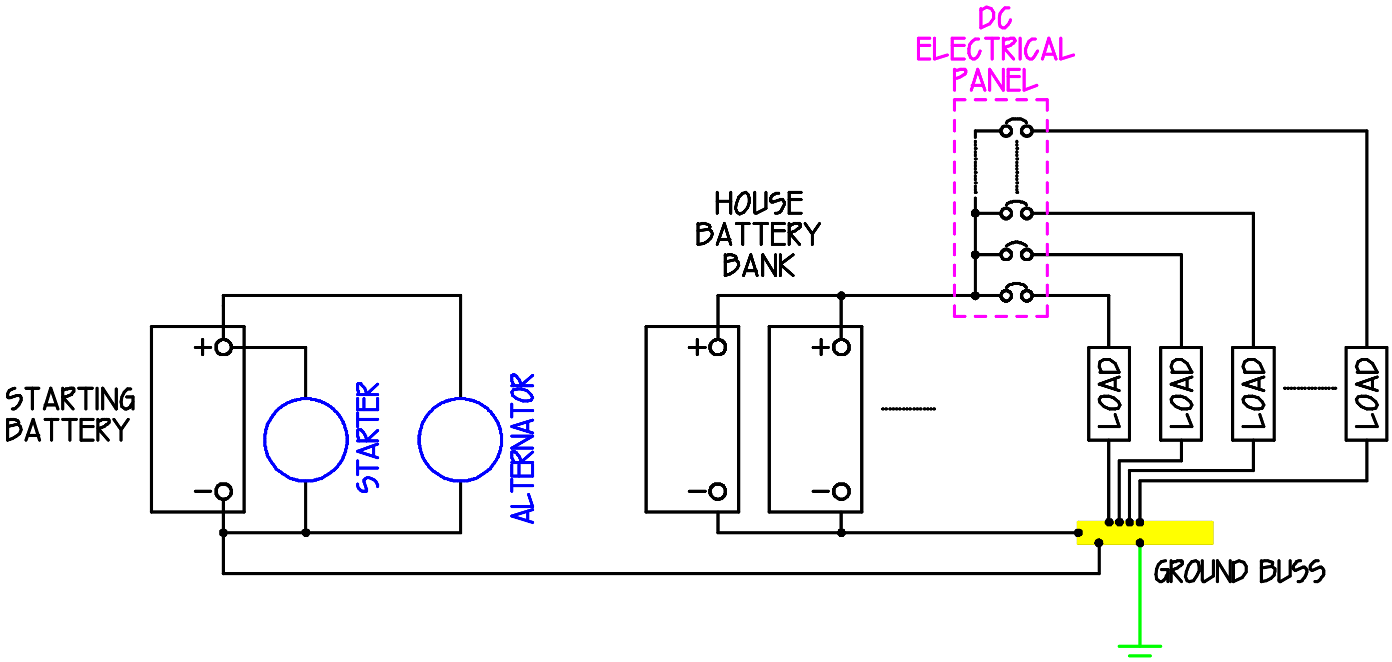
A capacitor is a two-terminal device that has no direct connection between the terminals. It consists of two conductive plates that are in close proximity and separated by material such as Teflon, plastic (or even air) that is referred to as a **dielectric**. The electrical symbol for a capacitor looks quite similar to the actual physical configuration:



A capacitor blocks the flow of a DC current, but allows AC to pass with low hindrance. This hindrance is referred to as the capacitor's "**reactance**", and is a function of the size of the capacitor and the frequency of the AC. Higher frequencies result in lower reactance.

PART 2. - BOATS AND ELECTRICITY

Now we have reviewed the basics of electricity, let's look at typical electrical systems that can be found on board boats. We will start out by looking at a basic setup that might be found on any smaller vessel (sail or power):

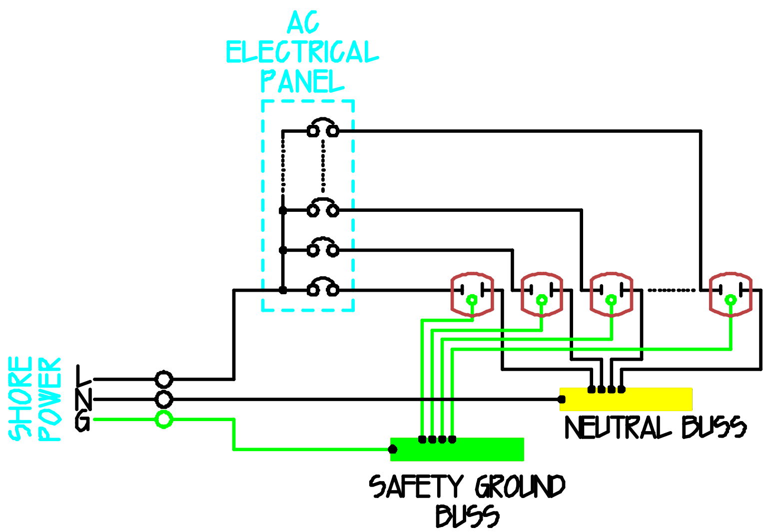


We will start our discussion in the middle of the diagram: the "**House Battery Bank**". The house batteries are intended to provide power to various on-board loads (lights, pumps, electronics, etc.) during the period when the engine is not running and no shore power is available. An electrical panel containing a series of circuit breakers is used to distribute the electrical energy from the house batteries to the various loads. The House Battery Bank is usually 12 volts, although larger boats commonly use 24 V systems. The House Batteries must have the ability to store sufficient electrical energy to power the loads in between the times that the batteries are charged up. Battery capacity is specified in **Amp-Hours** (abbreviated as A-H). This number <u>theoretically</u> represents the product of the number of hours times the current that a fully-charged battery can supply until it is totally exhausted. In practise, you never want to discharge a storage battery below 50% of its capacity. The A-H rating of a battery is normally specified when a current is being drawn that would theoretically discharge the battery in 20 hours time (this is called the "**20 hour rating**").

If the House battery has a capacity of 200 A-H, you would expect to be able to draw 10 A from it for a period of 20 hours, at which time the battery would be completely flat (and damaged). Knowing that you don't want to discharge a battery by more than 50%, this suggests that the battery bank can be used for only 10 hours if supplying 10 A of current. If you reduced the current consumed to 5 A, you would expect that the usable life would be doubled, but it is actually slightly <u>more</u> than doubled, because of the "**Peukert Effect**". House Battery Banks usually consist of multiple batteries connected in parallel to achieve the desired A-H rating. Note that all batteries must be the same type, voltage, and capacity. Note that all of the loads have their "common" or negative lead connected to a central point in the boat called the "**ground bus**", which is typically a strip of brass with tapped holes for lugs and screws. The ground bus is then connected to the engine block and possibly also to keel bolts and other underwater fittings (this will be discussed later).

This boat is equipped with an engine, and a separate starting battery has been provided so that you can be confident of getting the engine started even if the house batteries are discharged. An alternator is used for charging both the house and starting batteries. A "splitter" consisting of two diodes is used to allow the alternator to charge both batteries at the same time while keeping them separate with respect to discharge currents. Remember that current can only flow in one direction through a diode.

Boats are often equipped with shore power systems that allow you to plug into a convenient outlet on a dock and activate a series of standard AC outlets throughout the boat to power loads such as appliances, chargers, heaters, etc. A very basic shore power installation might look like this:

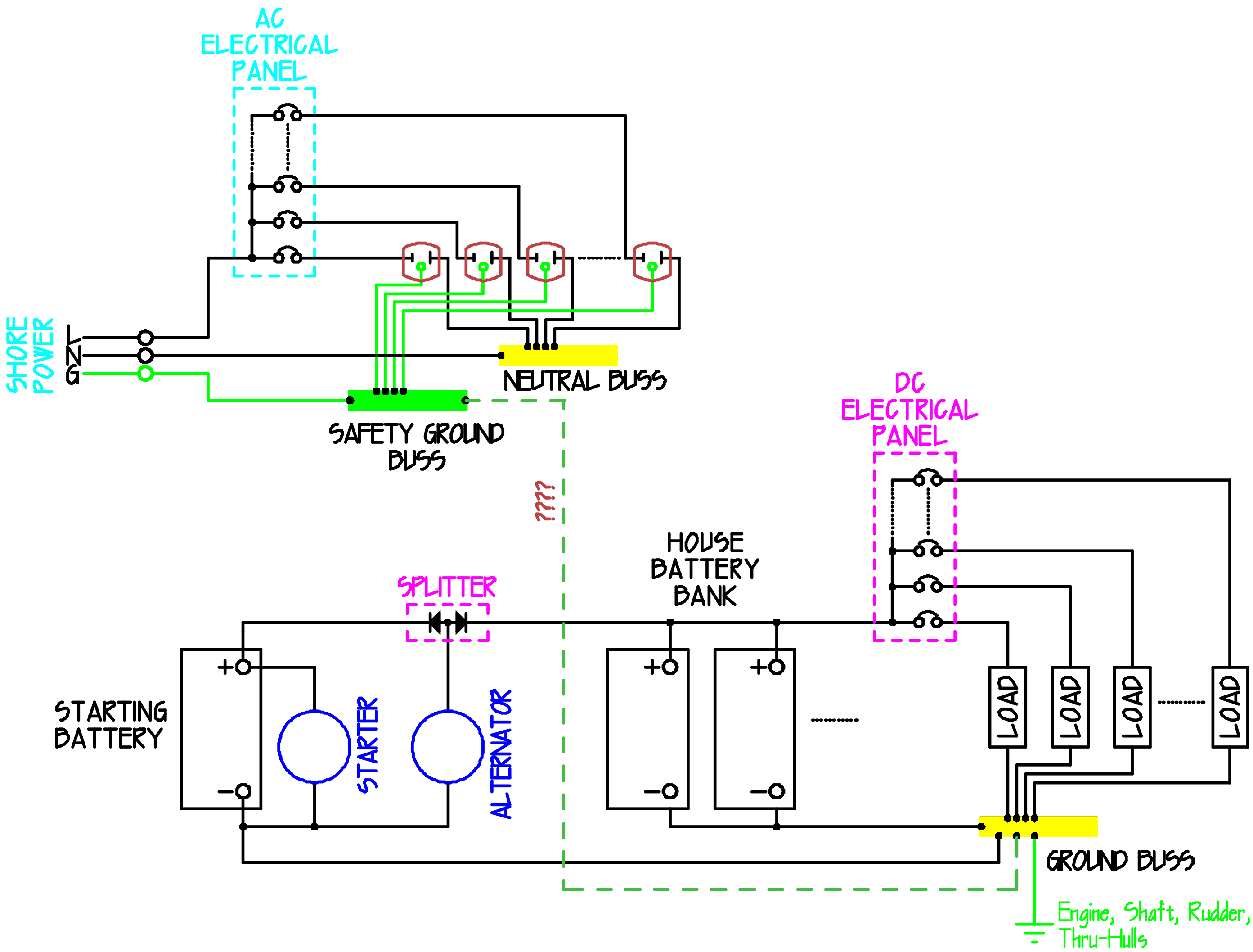


The shore power connector has three electrical connections. They are labelled as Line (this is the "hot" one), Neutral, and Ground. The colour code in a shore power cord reflects this: L is black, N is white, and G is green.

The ground connections on all the AC outlets are connected to a safety ground bus, which then connects to the G terminal on the shore power connector. All of the neutral connections on the AC outlets are connected to a common connection called the neutral bus, and this is connected to the N terminal on the shore power connector. Note that there **<u>must not</u>** be a connection between the safety ground bus and the neutral bus! On shore, there is a **<u>single</u>** connection between N and G, and it is at the secondary of the transformer which is feeding the dock.

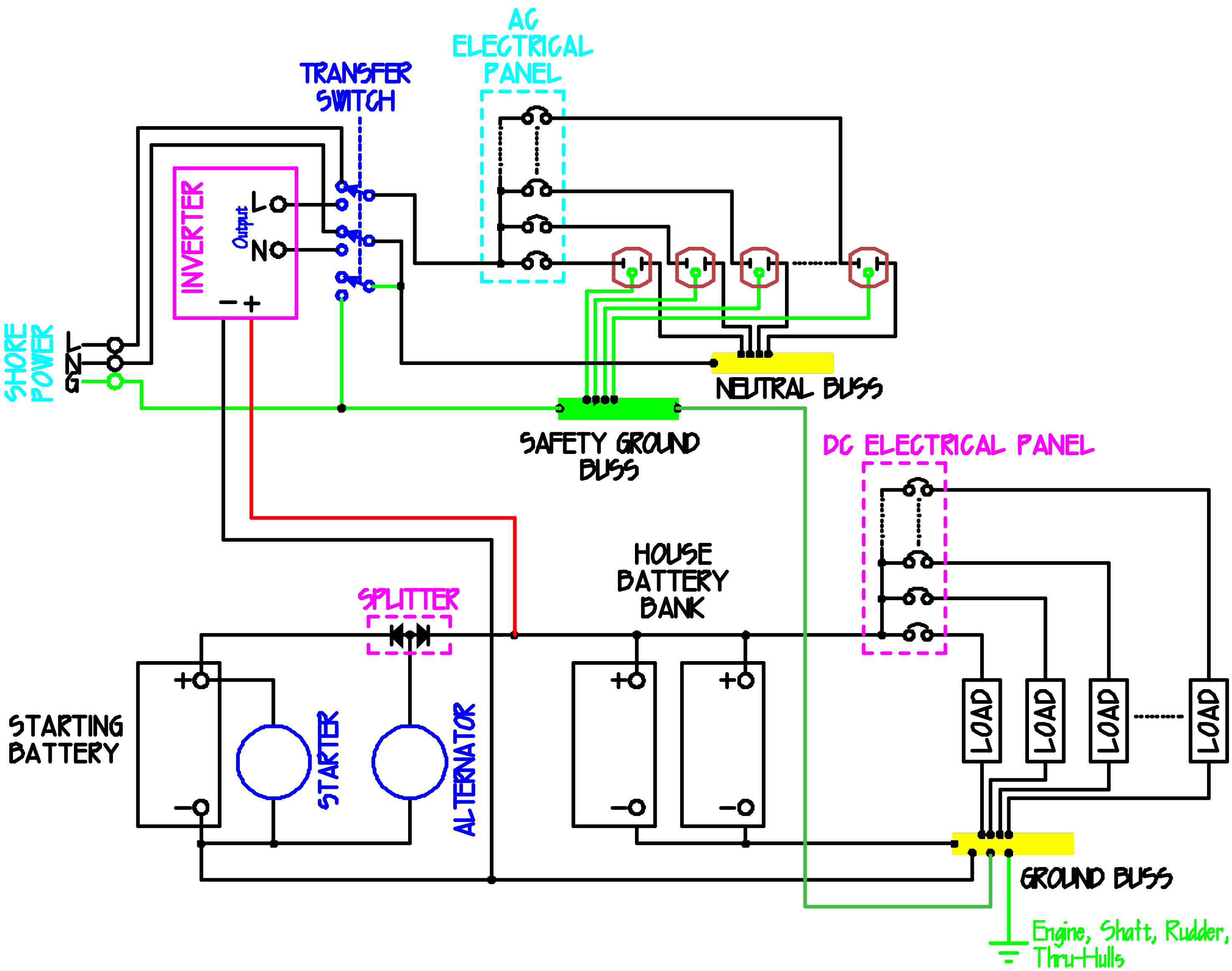
In the case of an insulation fault in an electrical appliance that would otherwise put 120 V on the exterior metal case of the appliance, the purpose of the safety ground is to ensure that no lethal voltages are allowed to exist where a person might touch them. The safety ground continues to conduct this "**fault current**" until the circuit breaker (on board or on shore) trips.

Now, let's show both the AC and the DC wiring on this boat:



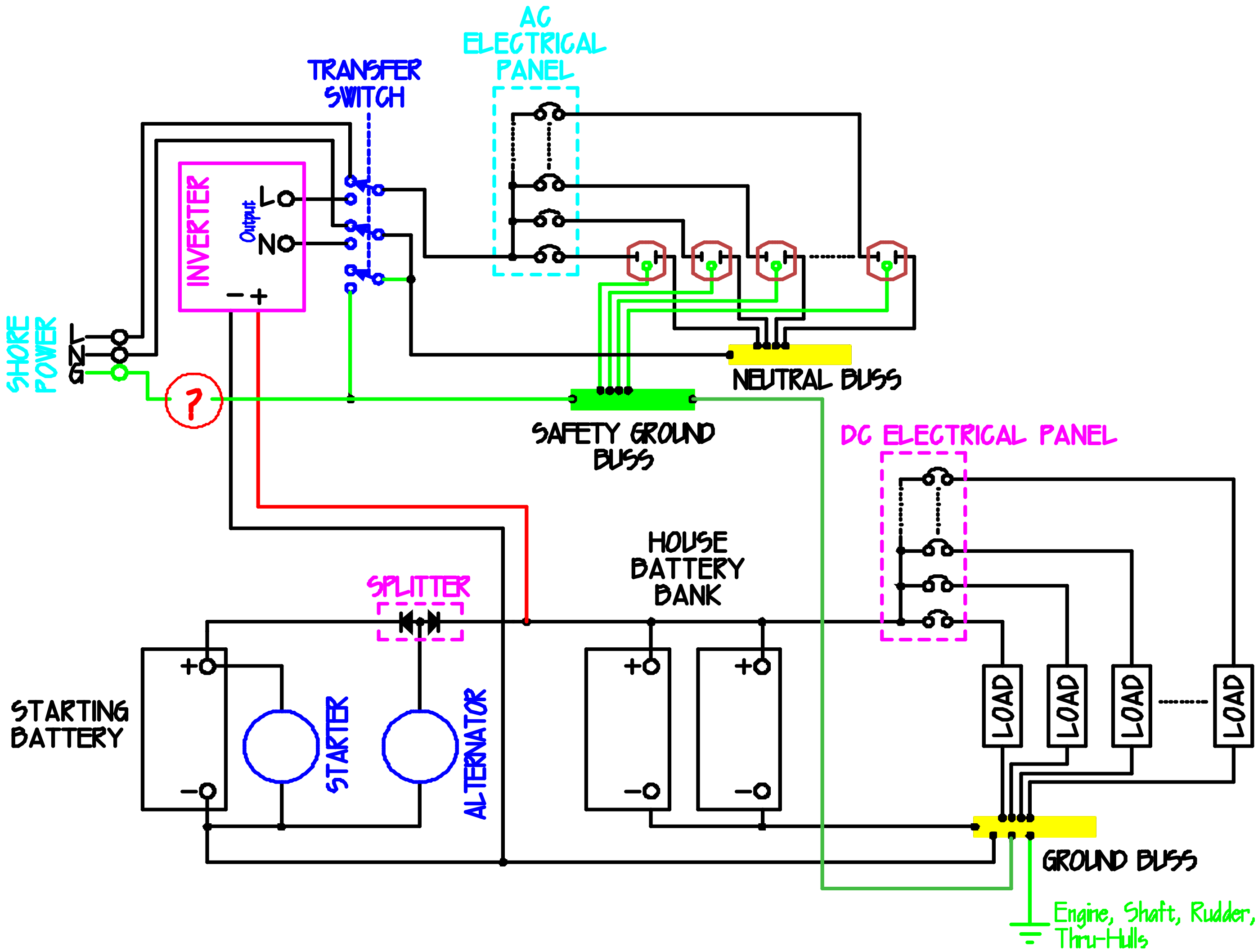
You will note that there is a green dotted line joining the safety ground bus and the boat's ground bus. It is recommended (but not required) that this connection be present, but many older boats do not have this. This connection **<u>is</u>** required if you have an inverter or generator on board (more on this later).

It is now time to complicate matters further by installing an **inverter**. This will allow you to use AC-powered devices when not plugged in to shore power. Most modern inverters include what is known as a "**transfer switch**", that automatically connects the boat's AC outlets to shore power (if present) or to the output of the inverter.



The inverter is connected to the boat's house battery bank, and draws current from these batteries when it is creating AC in the absence of any shore power. The transfer switch actually has three different sections: two switch the L and N connections between shore power and the inverter, and the third connects the neutral bus to the safety ground bus <u>when shore power is not present</u>. Note that the safety ground bus is connected <u>all of the time</u> to the boat's ground bus.

The green wire running from the shore power's G terminal and the boat's safety ground bus is a subject of much discussion.

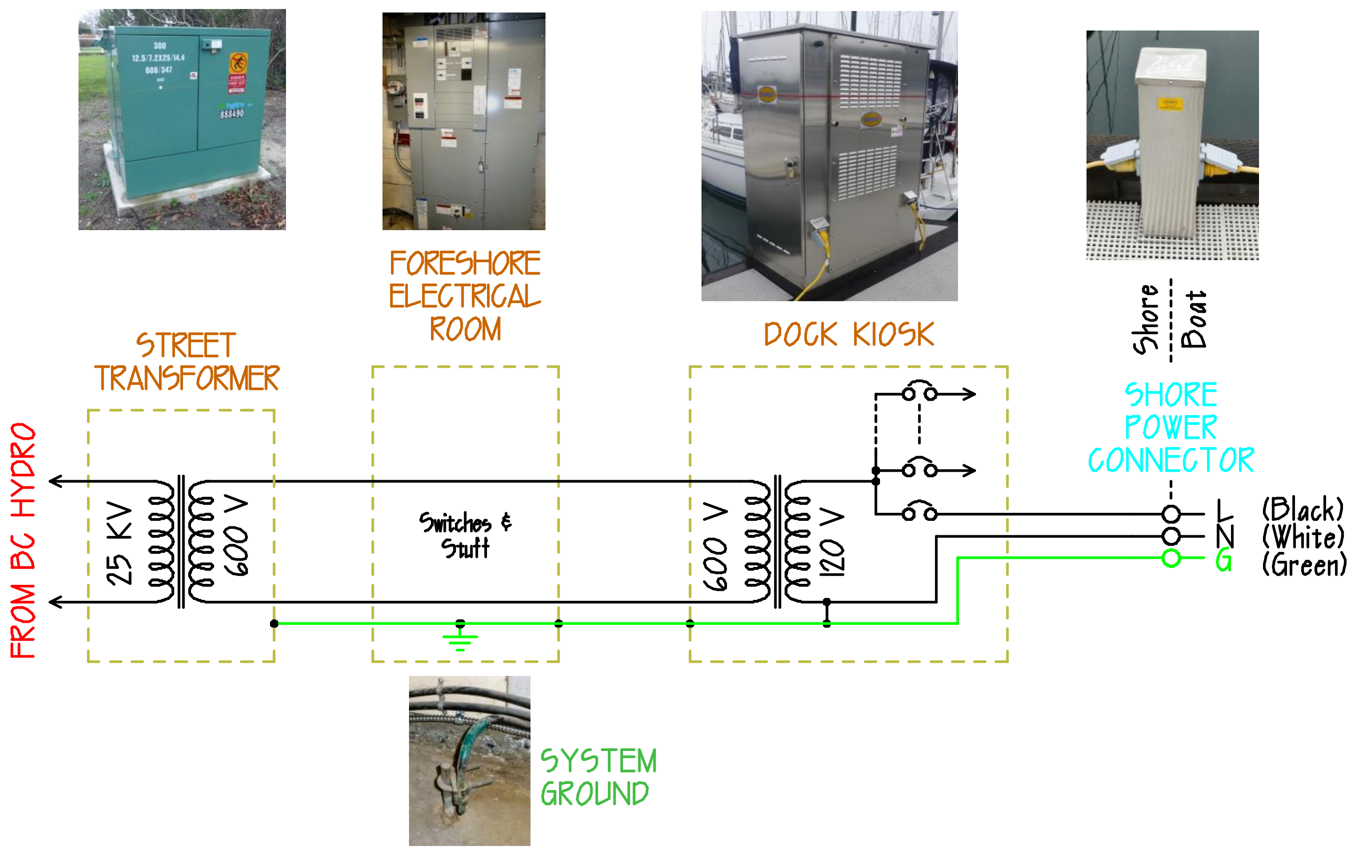


The red circle indicated on the diagram above is what we are referring to. When we get to our discussions of electrolysis and galvanic corrosion, it will be realized that it might be nice not to make this connection, but there are reasons of safety why it should be retained. A good compromise is a **galvanic isolator**, but we will discuss this later also. This connection has been the subject of many controversial discussions!

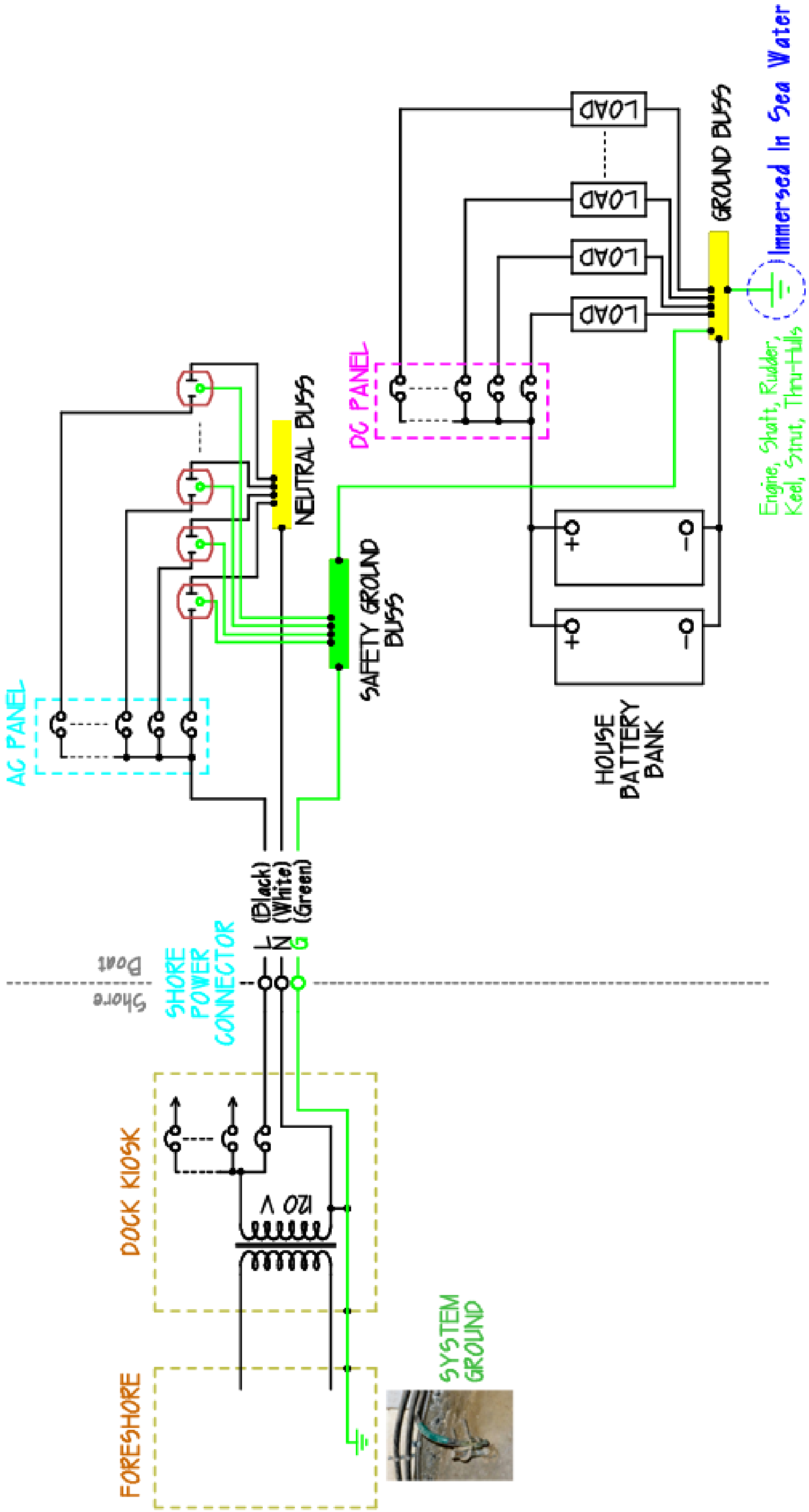
Consider what might happen if you were plugged in to shore power, the circled connection to the shore power's G terminal was not present, and an AC device such as a battery charger suffered an insulation failure that connected the unit's external metal case to the 120 V line. Because the metal case is connected to the AC safety buss, a fault current would flow into the boat's ground bus, and out into the water via the underwater fittings. If the fault current was less than the circuit breaker's rating, this current would continue to flow indefinitely. If the boat was in fresh water, the higher resistance of this medium would allow a large and potentially lethal (to swimmers and divers) electrical field to develop in the water around the boat! There have been documented case of electrocution in this manner in fresh water. If the boat was in salt water, the low resistance of this medium would prevent this field from developing for most expected fault currents (less than 30 A).

Shore Power at RVYC

The shore power system at RVYC's Cadboro Bay facility was completely replaced in 2014 as part of the ambitious Moorage Rebuild Program. All of the components are new, but the basic configuration matches that of most other modern marinas:



Note that there is a single ground point for the entire marina infrastructure. Each of the seven docks has a dock kiosk containing a transformer and a series of circuit breakers feeding each of the shore power outlets (over 30 per dock). The neutral connection of the secondary on each of the transformers is connected to the ground right in its kiosk (and nowhere else). The diagram below completes the picture by showing a moored boat connected to shore power:



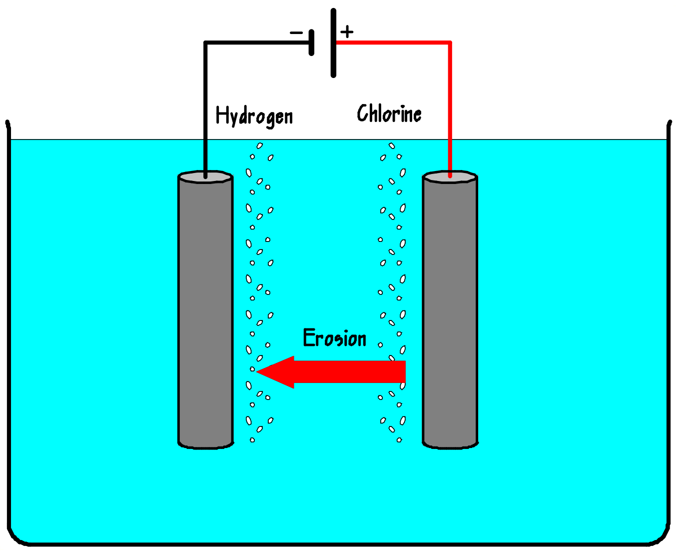
AC PANEL
NEUTRAL BUSS
SAFETY GROUND BUSS
DC PANEL
LOAD
LOAD
LOAD
LOAD
GROUND BUSS
Immersed In Sea Water
Engine, Shaft, Rudder, Keel, Strut, Thru-Hulls
HOUSE BATTERY BANK
L (Black)
N (White)
G (Green)
SHORE POWER CONNECTOR
Boat
Shore
DOCK KIOSK
120 V
FORESHORE
SYSTEM GROUND

PART3. - ELECTROLYSIS

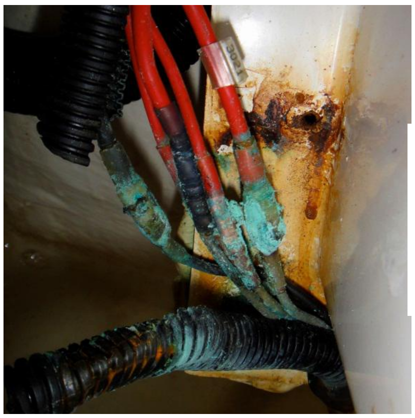
The term "electrolysis" is often used (incorrectly) to describe any form of under-water metallic corrosion. A more accurate definition for electrolysis is:

ELECTROLYSIS – the decomposition of an electrolyte into its component parts via the passage of an electrical current. An example of this is the creation of hydrogen and oxygen when passing direct current through fresh water. If salt water is used, the gases produced are hydrogen and chlorine. As part of this process, metal can be eroded from one of the electrodes.

If two electrodes (pieces of metal) are connected to a battery and immersed in a container of sea water, we will get the following situation:

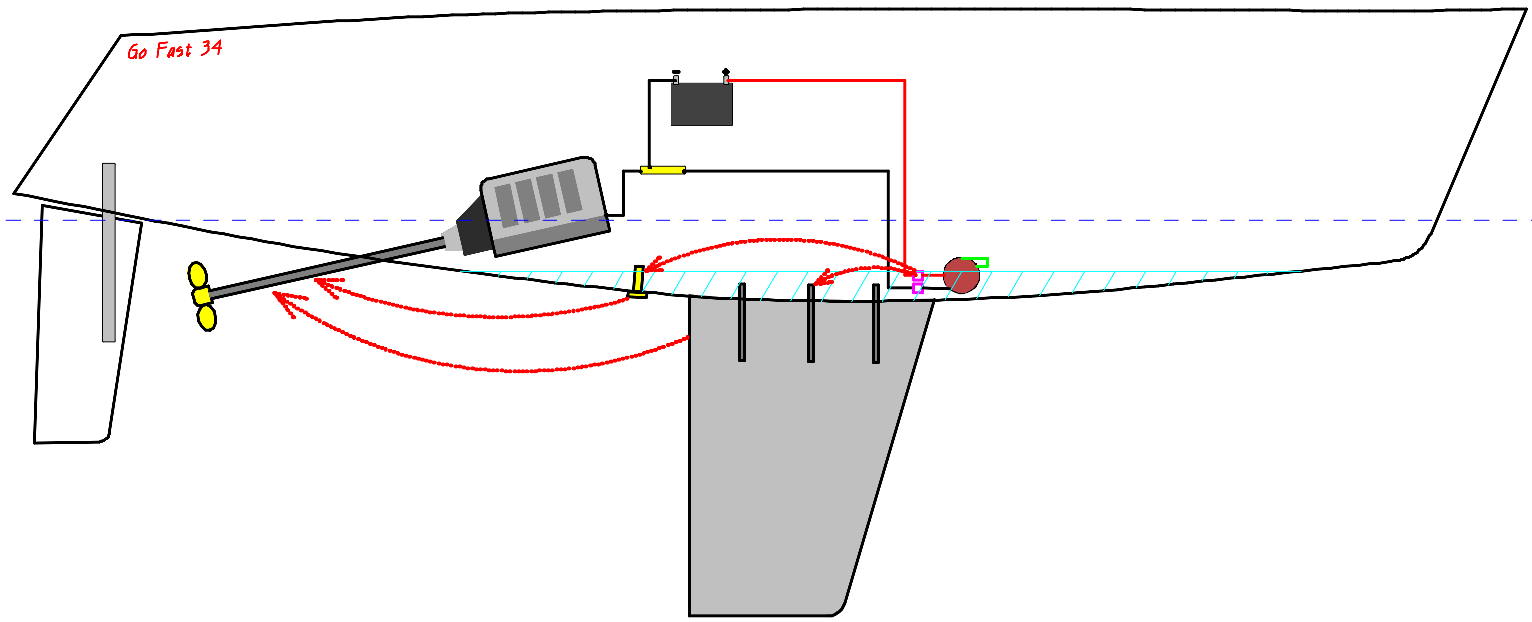


Metal is eroded from the surface of the electrode on the right, and deposited on to the electrode on the left. This process is commonly used for "electro-plating" thin layers of metal (such as copper, gold, or silver) onto the surface of other metallic objects. In a boat, electrolysis occurs because of stray electrical currents:



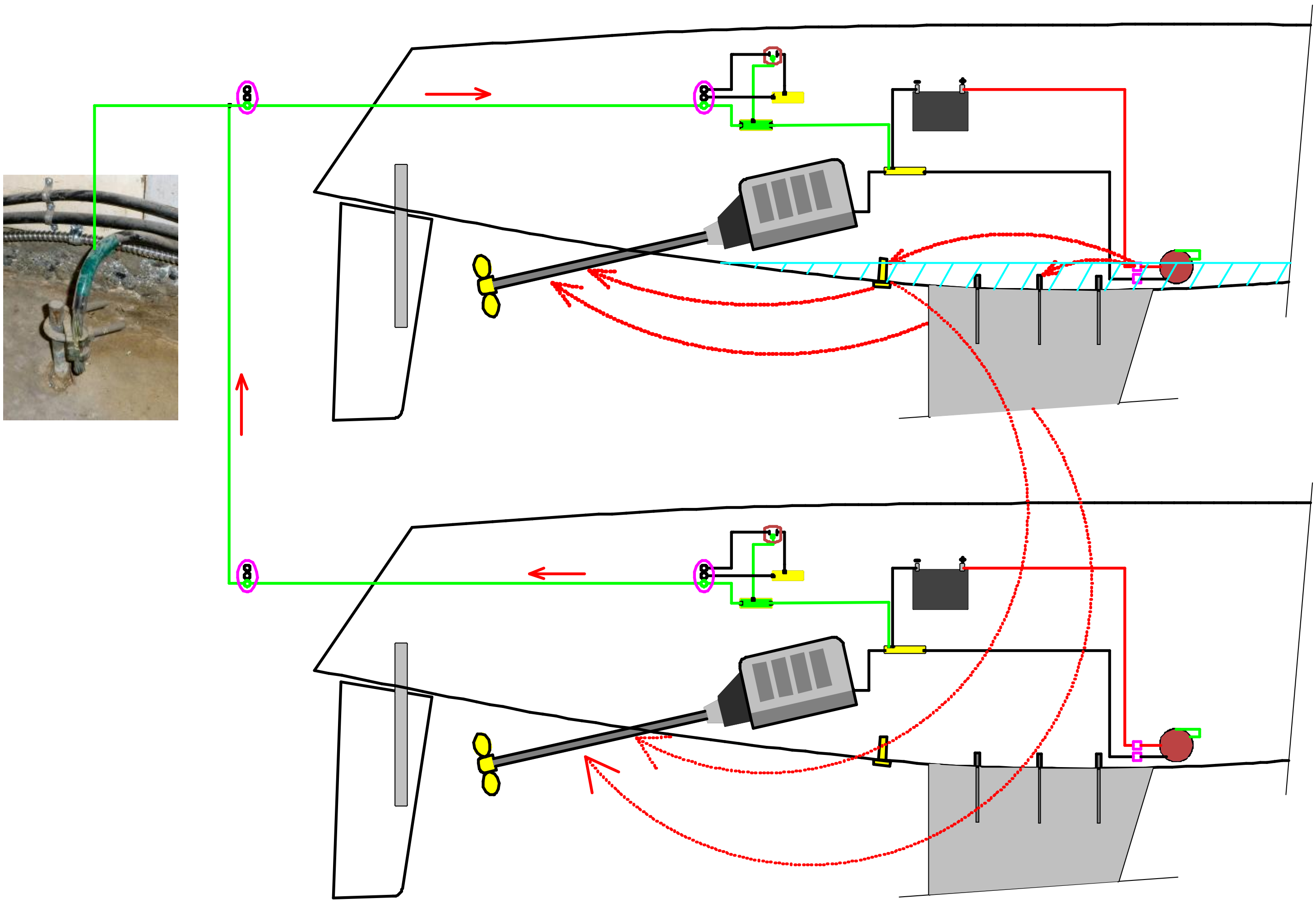
Electrical connections in a boat's bilge can suffer electrolysis when they are submerged in bilge water!

Bilge pumps are a common source of on-board electrolysis. If the positive wire of a bilge pump or switch is joined by a "crimp connector" or attached to a terminal strip in a boat's bilge, it might become submersed with bilge water. Electrical current will then flow into the bilge water until it encounters a piece of hardware (such as a keel bolt or through-hull fitting) that is in contact with the sea water outside the boat. The through-hull will now be at a positive potential with respect to any under water objects (such as the shaft and propeller) which are connected to the boat ground (and hence to the negative terminal of the house battery), and metallic erosion will occur. This is illustrated below:



In this example, we should be concerned about the through-hull fitting and the keel bolts!

A more insidious problem occurs when two boats are moored nearby, and both are connected to the shore power without the use of a galvanic isolator or similar device. The shore power's ground wiring means that the electrical grounds of boats are tied together - the following diagram shows what can happen:

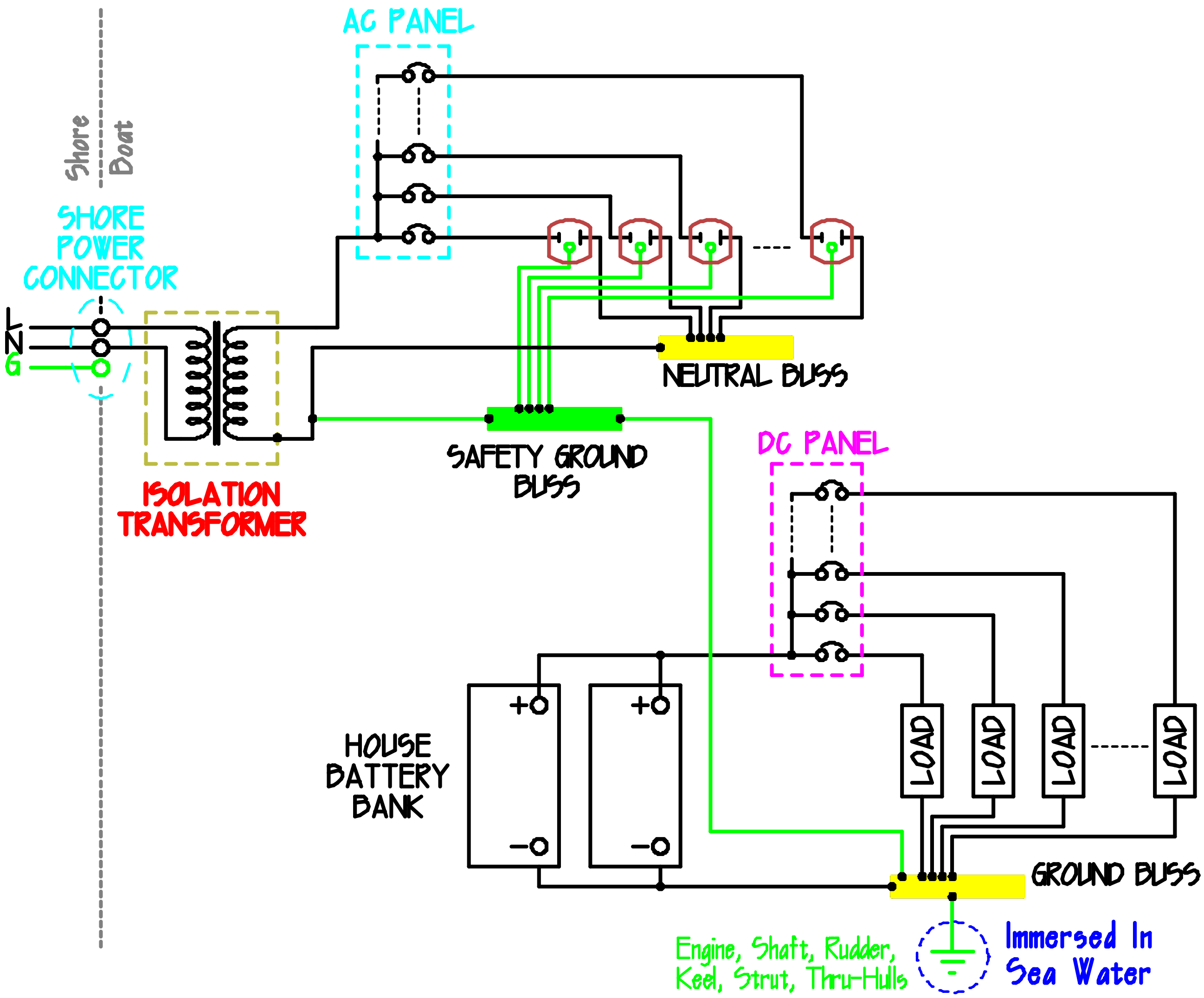


The single ground rod is located many hundreds of feet away, so a significant portion of the stray current from the top boat's defective bilge pump wiring is going to end up affecting the bottom boat as well!

DC Electrolysis is always caused by a DC leakage path on your boat, or your neighbour's (if they are interconnected by a shore power ground path). DC leakage on your boat can be checked with a DMM (Digital Multi Meter). Check that there is no current being drawn from the battery if everything is turned off. Then start turning on circuits one at a time to see if current starts to flow when the circuit is energized but the load is actually turned off.

Marinco makes a testing device (called the "GalvanAlert") that can quickly be installed in series with your shore power cord. It uses two LEDs to indicate if there is DC current flowing in the ground wire of your shore power cable.

One way to be absolutely certain that the shore power connection is not having any affect on your boat's electrolysis situation is to use an isolation transformer as shown below:



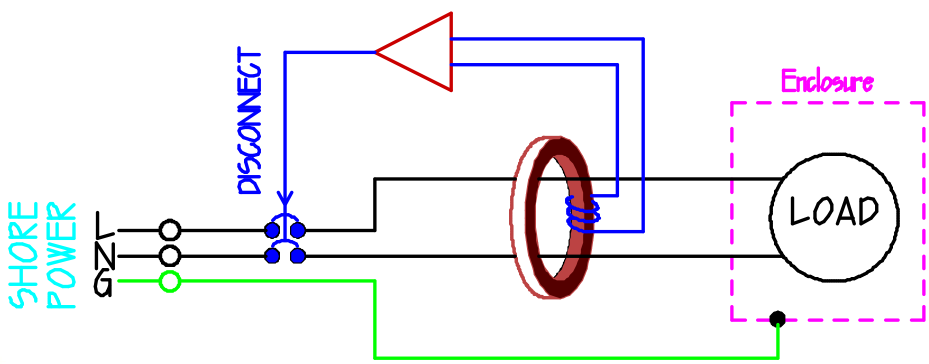
As we learned earlier, a transformer is ideal for providing isolation because there is no direct electrical connection between the primary and secondary - the power transfer occurs because of magnetic coupling. Note that the ground connection on the shore power outlet is not even connected! All of the AC electrical outlets have their safety ground connections tied to the boat's ground bus, and thence to underwater fittings. The neutral bus is tied to the safety ground bus at the transformer.

A galvanic isolator could also be used, and we will discuss these devices later in these notes.

So Why Do We Need An AC Safety Ground At All?

Our discussions so far have identified a number of problems that seem to be centred around the issue of "grounding", so why do we need to even have an AC safety ground? The issue is explained in the title itself: "safety"! Consider the following example: if there is an insulation failure in the heating element of the hot water tank, it is possible that the exterior metal housing of the tank could become connected to the live AC line connection. In the absence of a proper AC ground connection, it would be possible for someone to touch the water tank while they were also touching a grounded item (such as the engine block), and receive a shock. By having a connection between the metal housing of the tank and a proper ground (either on shore and/or on board), the housing will not reach a lethal voltage, and the fault current will be passed to ground until the circuit breaker finally trips.

Homes have many areas (kitchens and bathrooms) where electrical devices are used in proximity to water and/or grounded plumbing. Boats have galleys and heads, and bilges which are never perfectly dry, so the potential safety issues are even more severe. If a toaster, or curling iron or hair drier or electric drill fall into a sink/bilge/shower, electric currents will flow, and potentially unsafe conditions will appear! In these areas, the AC outlets should be a special type, referred to as GFI (Ground Fault Interrupter) or GFCI (Ground Fault Current Interrupter), or ELCI (Electrical Leakage Current Interrupter). These all work on the same principle, as shown below:



Under normal conditions, AC electrical current flows to the load via the L (line) connection, and returns via the N (neutral) connection. These currents would normally be exactly equal. In the case of an insulation fault, some of the return current will now be via the ground wire, and the line and neutral currents are no longer exactly matched. A GFCI uses a special transformer (shown as the brown "ring" in the above diagram), that detects the net difference between the L and N currents, and induces a small voltage on a secondary winding. This difference voltage is amplified, and used to "trip" a disconnect device. These devices trip at an imbalance of between 5 and 30 mA, depending on the class of unit.

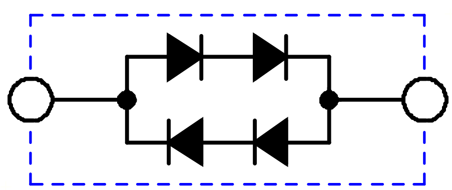
We already discussed the potential problem of an AC fault on board a boat causing an electrical field in the fresh water near a boat that could be lethal to swimmers and divers. The conditions are these:

> If there is a "ground fault" on a piece of on-board AC equipment,
>
> *AND*
>
> The equipment is not plugged in to a GFCI or equivalent,
>
> *AND*
>
> The boat's AC safety ground is not connected to the shore power ground connection either directly or via a galvanic isolator,
>
> *THEN*
>
> High AC currents can flow into the water through the immersed fittings of the boat. These currents will set up electrical fields in the water, which can be fatal to divers and swimmers **if** the water is fresh.

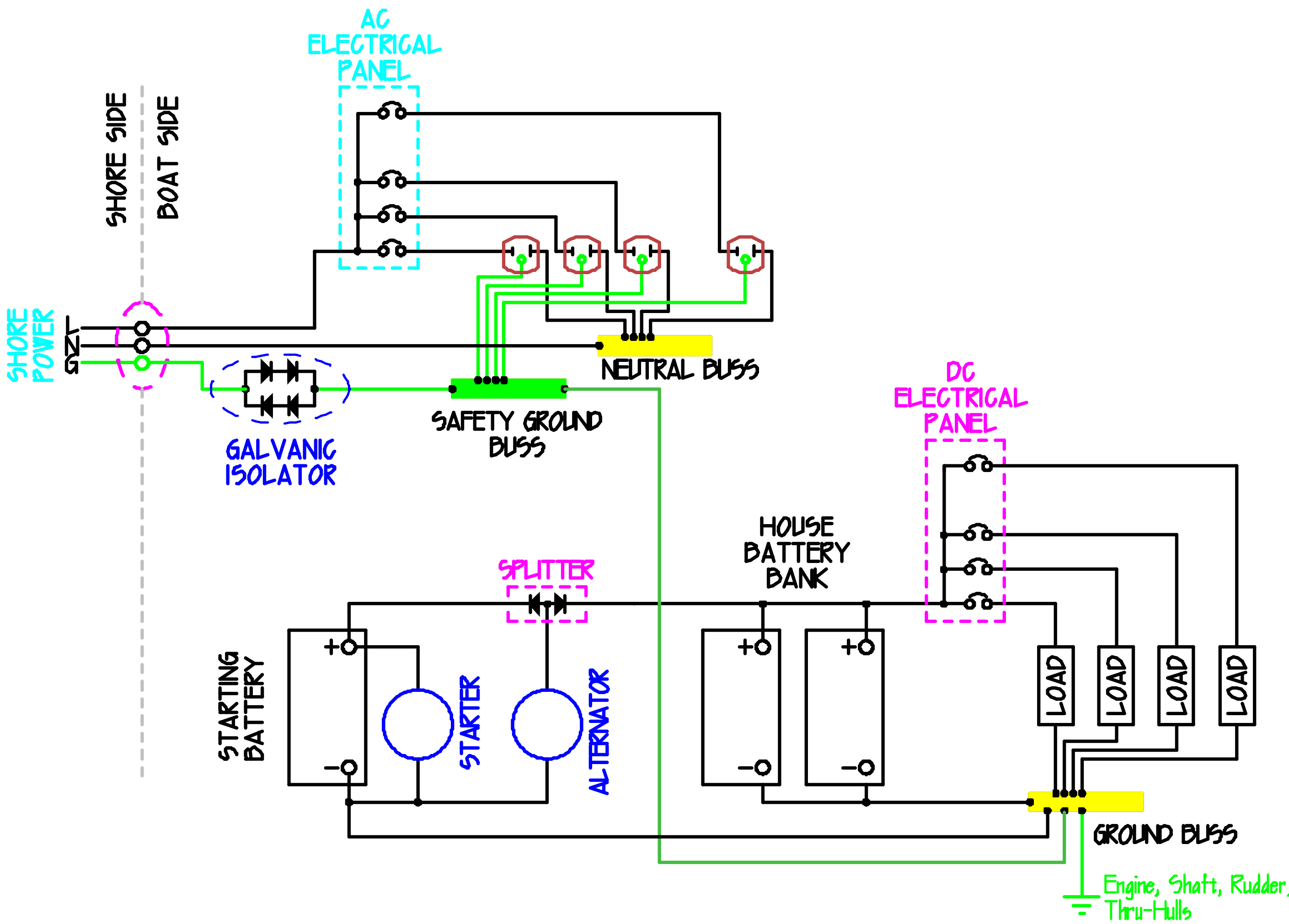
Galvanic Isolators

Galvanic isolators are devices that are placed in series with the shore power connection's ground lead. They act as an "open circuit" for voltages of less than about +/- 1 volt, but act as a "short circuit" for higher voltages, thereby continuing to provide protection under AC fault conditions.

Galvanic Isolators use diodes. You will recall that a diode allows electric current to flow in one direction only. While conducting current, a diode has a voltage drop of just over one half a volt, so a series-parallel configuration of four diodes as shown below will act as an open circuit for voltages of less than plus or minus one volt, but will act as a conductive path for higher voltages.



If a galvanic isolator is put in series with the shore power connection's ground lead, it will act as an open circuit for small voltages that might be caused by electrolysis (either on board your boat or a neighbour's), while providing a conductive path for any fault currents that might occur. The diagram below shows where the galvanic isolator is normally installed:



Some AC electrical devices on board boats have high speed digital switching circuitry or filters that create a small amount of AC current in their ground connections. Concern has been expressed that these small AC leakage currents may cause the diodes in a galvanic isolator to conduct some of the time, thereby eliminating the isolation properties of the device. Because of this, so-called "fail-safe" galvanic isolators include a **capacitor** in parallel with the diodes so that AC current bypasses the diodes. This is recommended by the ABYC (American Boat and Yacht Council), and many manufacturers have adopted this policy. Not everyone agrees that this is either necessary or a good idea - this is another one of those "***Controversial Topics***"!

A Galvanic isolator can be tested using a digital multimeter (DMM) in its "Diode Test" position. With the shore power cable unplugged, connect the DMM (in "Diode Test" position) across the two terminals of the isolator - it should indicate a voltage of approximately 0.9V, but this reading may not stabilize for a minute or two if there is a capacitor present. Now reverse the test leads (and wait for any capacitor to become charged) - the voltage indication should be approximately the same.

AC Electrolysis

The electrolysis discussion so far has been discussing stray DC currents originating on board your boat (or your neighbours). But what about stray AC currents (originating on-shore or on-board)? Very little has been published on this topic! An extensive literature search and numerous discussions with "experts" all over North America led me to conclude that AC electrolysis exists, but it is much less damaging than DC electrolysis. So the question is: "*How much less damaging*?". No one could answer this question definitively, so I decided to do a series of experiments to come up with my own estimate.

AC electrolysis will usually involve only boats that are plugged in to shore power, unless boats are left at the dock with their generators running continuously (unlikely at RVYC).

AC electrolysis implies that there is a stray AC current on board a boat (plugged in to shore power) that is finding its way into the water via an underwater metallic appendage. If this is the case, the current will be slightly different between the L and N wires in the shore power cord (because a small amount of the return current is going into the water rather than in to the N). This makes it extremely easy to measure non-invasively by using a "Clamp-On AC Leakage Tester", such as the Amprobe AC50A or the Fluke 360. Both of these devices are simply "clamped on" to the shore power cable (while it is still plugged in), and can show leakage currents down to well under 1 mA. If there is no leakage on board a boat, the shore power cord's L and N currents are equal, and there is no current on the G wire, so the clamp-on tester should register zero. Using one of these devices, it is possible to check every power cord in a 300 boat marina in a couple of hours.

RVYC Testing

One afternoon in November of 2014, we tested every boat's power cord that was plugged in to shore power at RVYC's Cadboro Bay marina. The results were as follows:

0 – 10 mA AC	Most Boats
10 – 30 mA AC	Around a Dozen Boats
30 – 100 mA AC	5 Boats
100+ mA AC	3 Power Boats (*the bigger the props, the bigger the current!)*

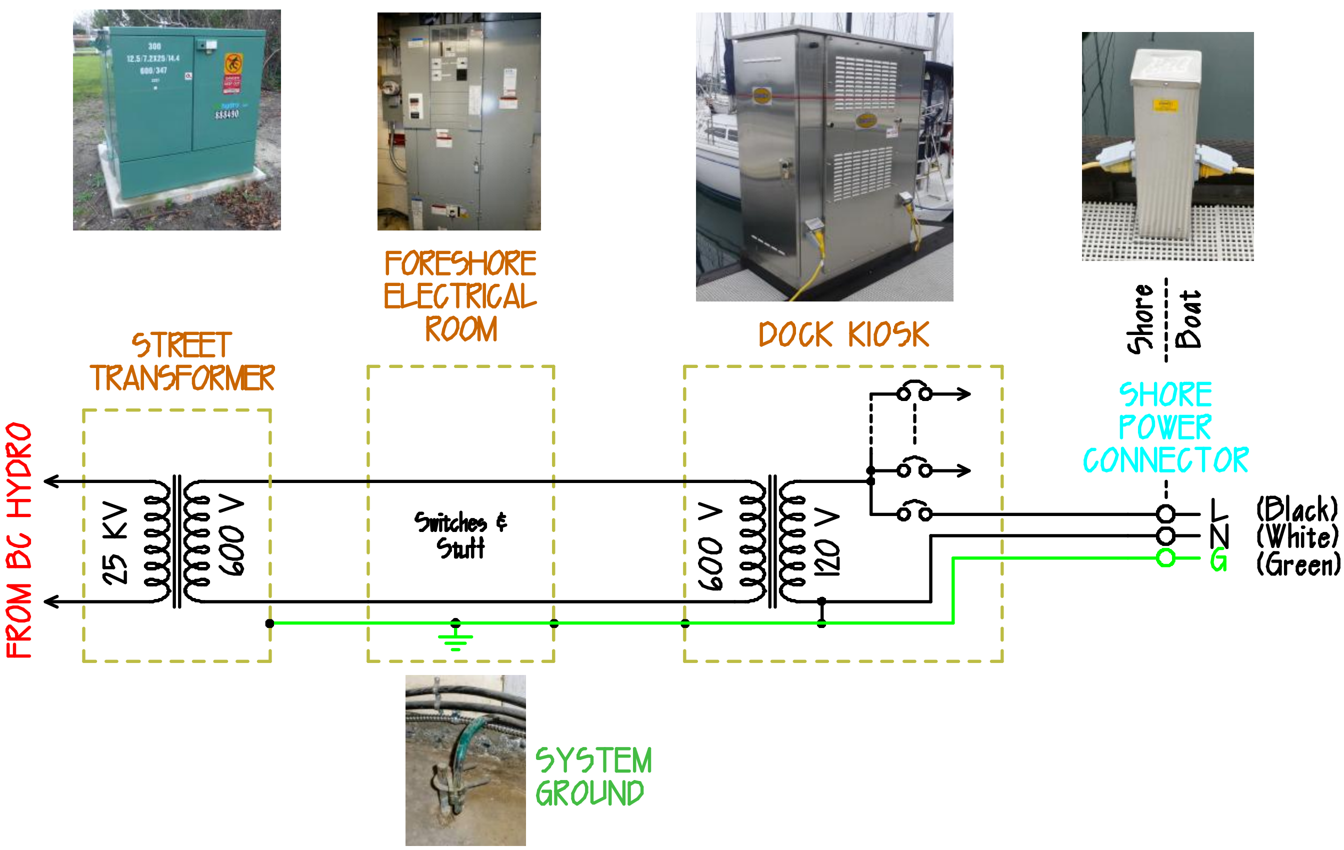
At the time of the test, we didn't know which boats were equipped with galvanic isolators, and whether or not they had capacitors. We therefore made up a simple 2-diode galvanic isolator for testing purposes, and installed it in a "pigtail" cable that could be put in series with a boat's power cord. Using this pigtail galvanic isolator, we re-tested all the boats that had previously exhibited leakage currents of over 30 mA, and observed that the leakage current was reduced to virtually zero in every case!

Discussions with the owners of some of the boats exhibiting high AC leakage currents indicated that they already had galvanic isolators installed. Subsequent investigation showed that these isolators were of the type that had a built-in capacitor, so from an AC standpoint, they were acting almost like short circuits!

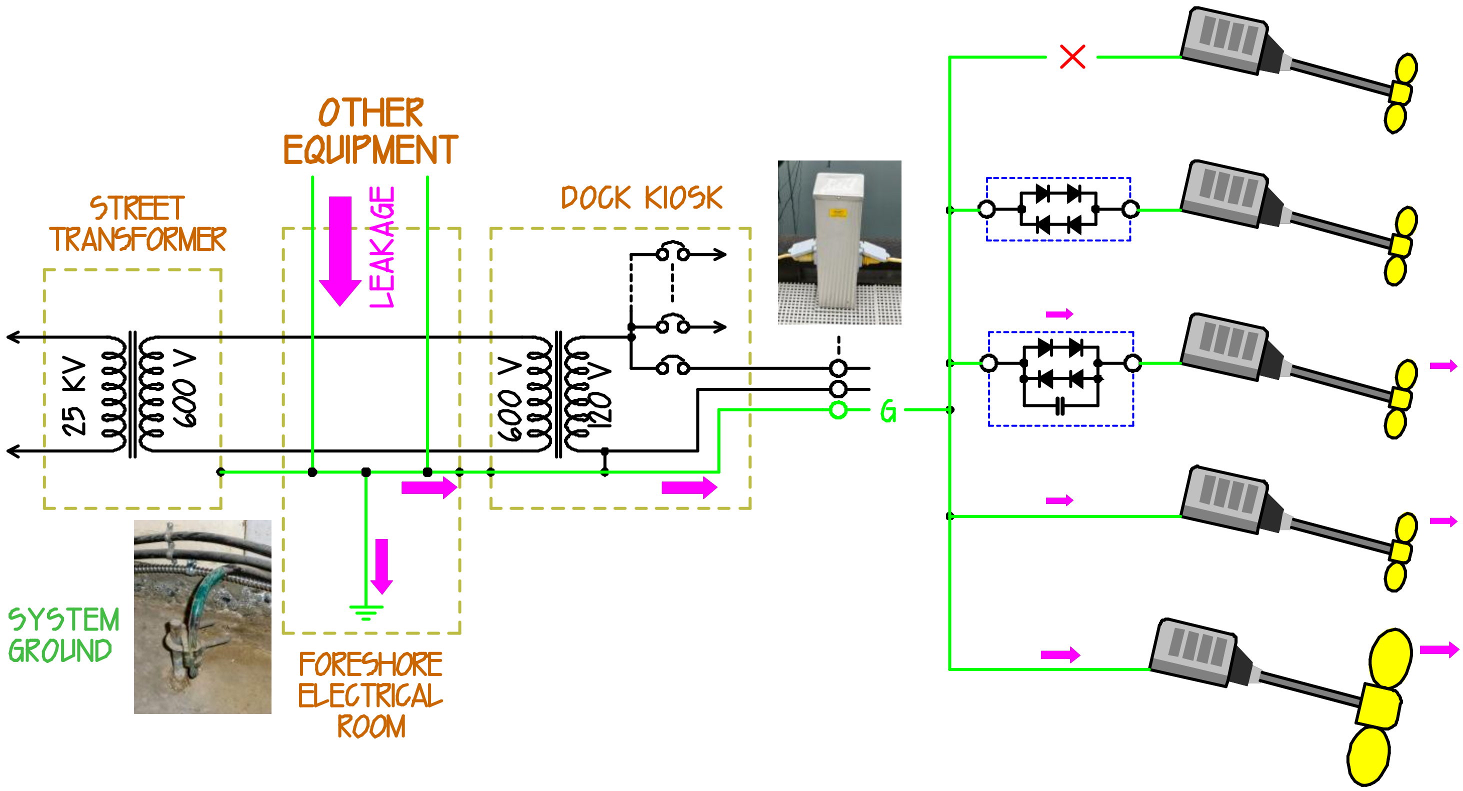
We then talked to the owners of a couple of the boats exhibiting no AC leakage. It turns out that these boats had fairly basic AC systems, and did not have inverters. They also met at least one (or more) of the following criteria:

- No connection between the AC safety ground and the boat ground.
- An older galvanic isolator without a capacitor.
- No connection to the shore power ground wire.

It was starting to sound as though the AC leakage current was actually originating on shore, and using the moored boat's underwater appendages as a ground to dissipate them! To test this theory, a piece of aluminum plate (about 10 inches square) was connected to a wire and hung in the water. The wire was then connected to the ground connection on a convenient shore power outlet, and the leakage current was checked: it was over 10 mA! This test was repeated at different locations throughout the marina, and similar results were observed. This indicated that there was a small AC potential between the salt water and the shore power's ground system. Measurements indicated that it was less than 100 mV. Let's review the shore power infrastructure:



We were doing our testing out on the docks, which are about 500 feet from the system ground (the rod driven into the ground) located in the foreshore electrical room. Further investigation disclosed that the system ground is also shared by all the foreshore infrastructure (offices, appliances, hoists, etc.) Using the clamp-on leakage tester, we were able to determine that some of this other older equipment and wiring had leakage problems that were putting several amps of AC leakage current into the ground rod! Now we can complete the picture:



The pink arrows show AC leakage currents. The size of the arrows indicate the approximate magnitude of the current. In the foreshore room, the leakage current from the "Other Equipment" splits: part goes into the ground rod, and part heads down to the docks, where it splits up again, and enters the sea water via the underwater appendages of **<u>some</u>** of the moored boats. No leakage current flows into the two top boats illustrated above. The bottom three boats <u>do</u> provide a path to the water, and boats with more submersed grounded area carry more current.

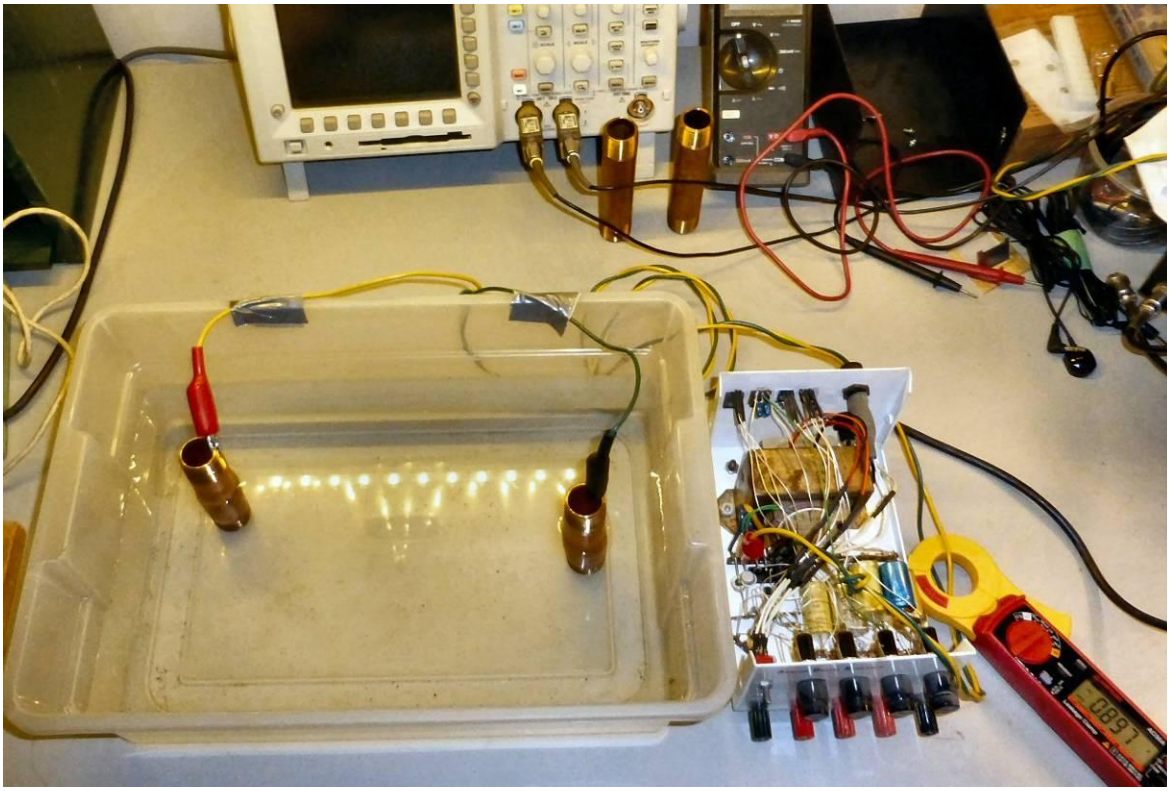
In order to eliminate these currents, repairs need to be made to the old equipment and wiring on shore to locate and repair the cause of this leakage. This is planned.

So .... mystery solved! We know where the current is coming from, and can explain the difference in observed results. But, we still don't know if this is even a problem or not! If every boat was equipped with an isolation transformer or an older galvanic isolator without a capacitor, the AC leakage currents would be zero, and we wouldn't have to worry about this issue, but we have to deal with the current situation.

We need to answer the question: "***How much AC leakage current is too much***?".

Bench Testing

Because of the lack of published information, it was decided to do some simple tests to compare the rates of DC and AC electrolysis to get a "feel" for the issues. A series of brass fittings were used for the tests, which were conducted in a plastic container filled with salt water taken from Oak Bay. The brass fittings each had a surface area of 6 square inches immersed in the water. The tests were started using AC, and the voltage was adjusted until 1 amp of current was passing through the system. Here is the test setup:



Things progressed surprisingly slowly: minimal bubbling or water discoloration, no initial erosion of the metal. After 24 hours, the surface of the brass had a definite discolouration, but it still felt <u>fairly</u> smooth when dragging a finger nail across it.

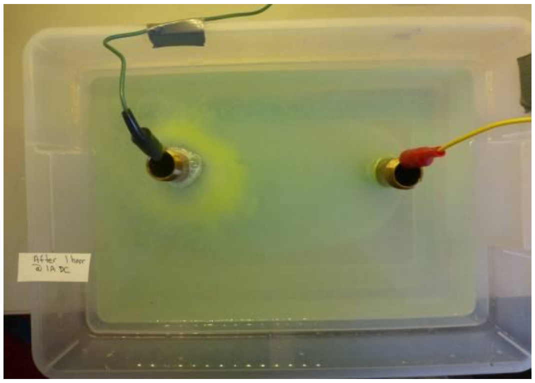
After 5 days of 1 Amp AC, the surface of the water around the electrodes had obvious discolouration, and the brass fittings exhibited some pitting and surface roughness.

This AC test was stopped after 5 days. New electrodes and salt water were then employed to do the same test using 1 Amp of **<u>DC</u>** current:

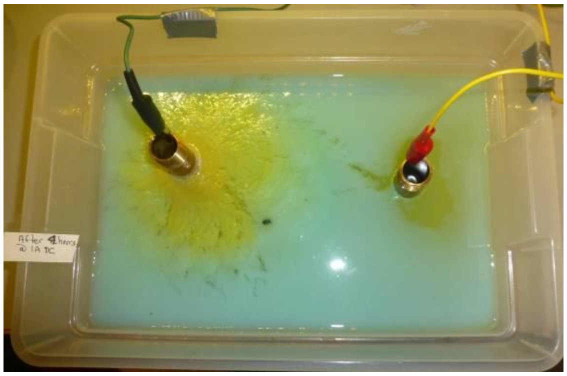
DC

Things happened much more rapidly with the DC test. As soon as DC power was applied, bubbling was seen (and heard), especially around the negative electrode (these were presumably Hydrogen gas bubbles).

After 1 hour, it was obvious that there was a lot of activity in the water:



After 1 hour



After 4 hours

The DC test was stopped after 4hours, and the electrodes were examined. The positive electrode exhibited a very rough surface:

Based on this test, it is estimated that 1 hour of DC electrolysis caused as much erosion as 5 days of AC electrolysis. This implies that AC electrolysis is approximately 1/100 as damaging as DC electrolysis.

Note that the above tests were just looking at the point where metal erosion became visible, and could start to be noticeable with a fingernail. Not overly precise! A more exacting test would have used a very sensitive laboratory balance to carefully weigh the electrodes on a regular basis and track the actual change in mass of them.

Subsequent discussions with the head technology manager at a major manufacturer of marine electrical equipment suggested that under some conditions the difference may be even ten times larger.

We will therefore go out on a limb and declare that:

"DC Electrolysis is between 100 and 1000 times as damaging as AC Electrolysis."

"Tolerable" Levels Of Leakage Current

So .... we know what the difference is between AC and DC electrolysis, but we still haven't determined what current levels are tolerable. We can use data from the previously-described experiments to estimate this as follows:

From our experiments, we estimated that the first visible signs of physical electrode erosion occurred after 10 to 15 minutes of 1 Amp DC current. The electrode area was 6 square inches, which means that the "**current density**" was 0.17 Amp/square inch. We can abbreviate this as 0.17 A/in.^{2}

We combine both of these pieces of data to estimate that the first signs of visible signs of electrode erosion occurred after an "**exposure**" or "**dosage**" of about 0.035 A-H/in.^{2}

Assume that a 33 foot sailboat has a bronze propeller that is 14 inches in diameter. The total area of the blades (both sides) and hub is about 100 square inches. Therefore, we would need a DC leakage exposure of about 3.5 A-H before the first signs of metal erosion become visible on the propeller. Note that this assumes that the only underwater object is the propeller - it ignores the shaft, strut, and any other connected underwater electrical components.

If there was a continuous DC leakage current of 5 mA, we would reach this exposure level after about 1 month.

Assume for the moment that AC electrolysis is 100 times less damaging than DC. This means that we would see the same levels of damage to the 14 inch propeller after 1 month's continuous exposure to 500 mA of AC, or 1 year's exposure to 40 mA.

There are a lot of approximations and assumptions in the above analysis, but it gives us a "feel" for the magnitudes of leakage current that can be problematic.

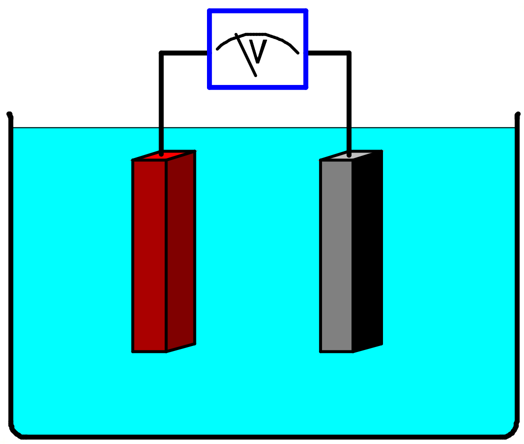
PART 4: GALVANIC CORROSION

Electrolysis (as described earlier) is caused by an external energy source, such as a battery or shore power. We are now going to discuss **Galvanic Corrosion**, which does not require an external source of electrical energy.

Galvanic corrosion occurs when two dissimilar metals are joined electrically and both are submersed in an electrolyte (such as water). Galvanic Corrosion is caused by a flow of DC current which originates in the metals themselves. Note that both Electrolysis and Galvanic Corrosion result in the erosion of metal!

Any metal submersed in an electrolyte (such as sea water), develops an electrical voltage known as the "**standard electrode potential**" (sometimes referred to as the "**self potential**" or "**freely existing potential**"). This is due to interaction of the electrons on the surface of the metal with the electrolyte's ions. This voltage potential is different for different metals and their alloys.

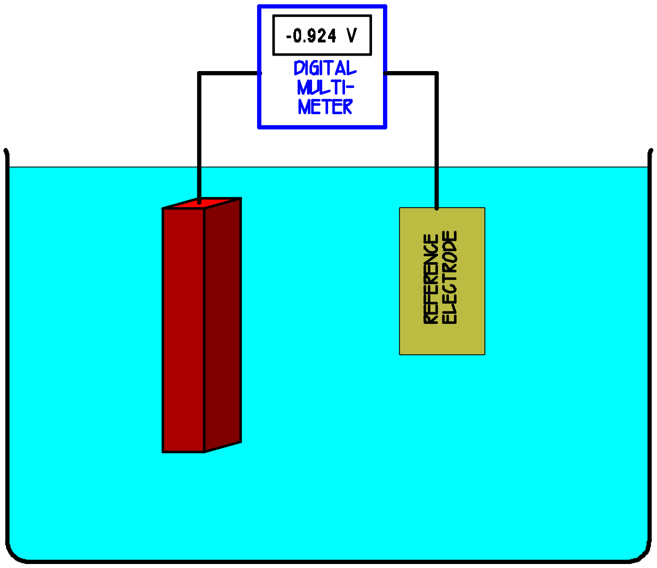
If two different metals are submersed in sea water, there will be a voltage difference between them. This is actually creating a basic form of a primary battery.



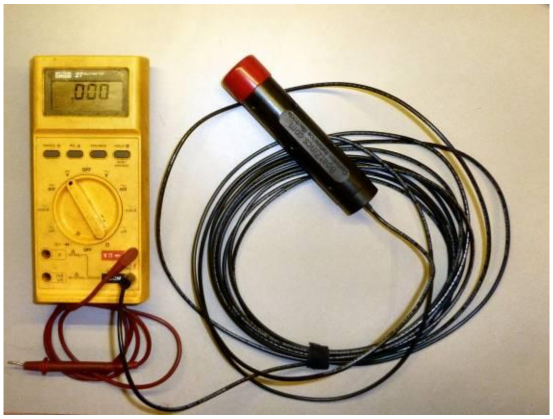
If these two electrodes are now connected together with a wire (or some other conductive path), current will flow, and one of the electrodes will suffer erosion. Note that if the two electrodes are touching each other, current will flow across the junction, and erosion will occur on the exposed surface of one of the electrodes. Determination of which electrode gets eroded has to do with the relative "**nobility**" or "**activity**" of the metals used in the two electrodes. The most "active" electrode (the one with the least "nobility") will be eroded - this is the one whose "self potential" is the most negative.

The relative nobility or activity of two metals can be determined by looking at their relative positions on the **Galvanic Table**:

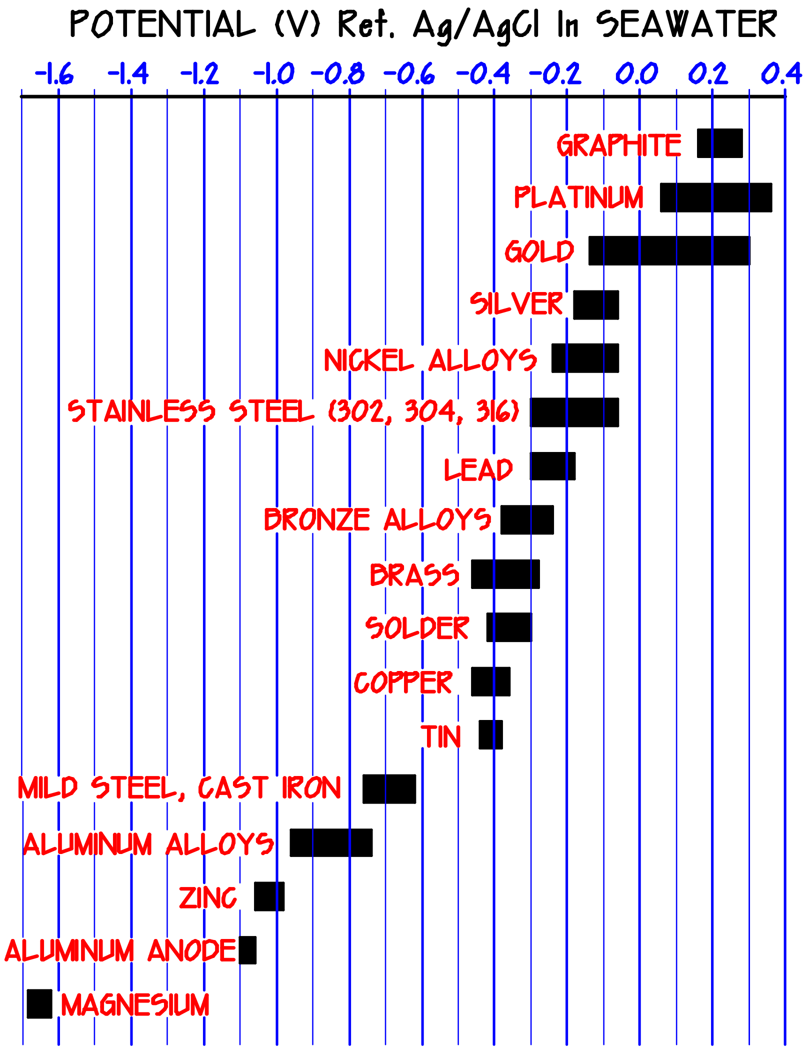
The order of the materials in the above chart is based on the "**freely existing potential**" of each metal. It is relatively easy to measure this potential by using a digital voltmeter and a "**reference electrode**":



There are several different reference electrodes that are used in the field of "electro-chemistry", but the most common one used for marine applications is referred to (because of its composition) as the **Silver/Silver Chloride Reference Electrode**. This is abbreviated as Ag/AgCl. Here is a typical Ag/AgCl electrode, together with a digital voltmeter:



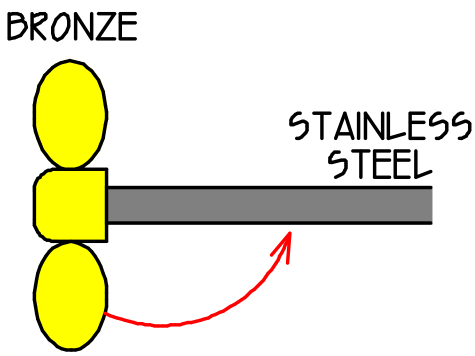
Using this equipment, you can determine the freely existing potential of any material; which should fall into the ranges shown on the chart below:



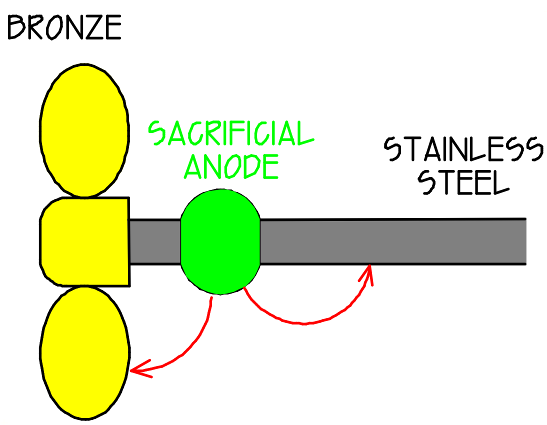
NOTE – Potentials are affected by specific alloy, water aeration, temp. & flow rate, and slime due to bacteria.

Sacrificial Anodes

Most galvanic corrosion problems occur (on boats with conventional inboard engines and shaft configurations) when a bronze propeller is fitted to a stainless steel shaft. Referring to the chart above, we can see that bronze has a potential of about -0.3 volts, and stainless steel has a potential of about -0.07 volts. Because the two materials are in electrical contact, the bronze propeller (being the most active) will be eroded, and some of its metal will actually be "plated" on to the shaft:



The photo on the right indicates an extreme condition, where a propeller has been almost completely eroded away! To protect expensive propellers, a **sacrificial anode** can be mounted on the shaft (so that it makes electrical contact) that is <u>less noble</u> than the bronze:



The sacrificial anode is eroded, thereby protecting the bronze propeller and the stainless steel shaft. Looking at the galvanic table, almost any metal located below bronze could be used as a sacrificial anode, but in practise the two most commonly used materials are **zinc** and aluminum.

Metal-hulled boats often have sacrificial anodes welded directly to the hull, while smaller boats use anodes that are clamped (via bolts) to the components that they are to protect. Here is a photo of a steel-hulled boat using large zincs welded on to the keel to protect the hull, plus a zinc mounted on the shaft nut to protect the propeller, and a smaller zinc bolted on to the steel rudder:

For protecting aluminum, especially in fresh water, magnesium anodes are sometimes used because of their very low potential (less than -1.6 volts)

Aluminum anodes are often made from a special aluminum alloy composed of Aluminum, Indium, and Zinc. These have a longer service life than pure zinc anodes, and are also sometimes used with aluminum outdrives and sail drives.

Some companies offer proprietary formulations (such as Galvalum or Navalloy) that are optimized for specific marine galvanic protection applications.

A sacrificial anode <u>must show signs of erosion</u> to confirm that is working properly. If an anode looks almost new after several months of use, it is not doing anything! This is probably due a poor electrical contact with the item to be protected. Anodes should not be painted!

Some boat owners do not like to have permanently fitted sacrificial anodes, but instead prefer a temporary arrangement whereby an anode is fixed (mechanically and electrically) to a wire hung over the side of the boat. The wire must be firmly attached to the boat's ground system, or perhaps directly to the shaft if it is easily accessible.

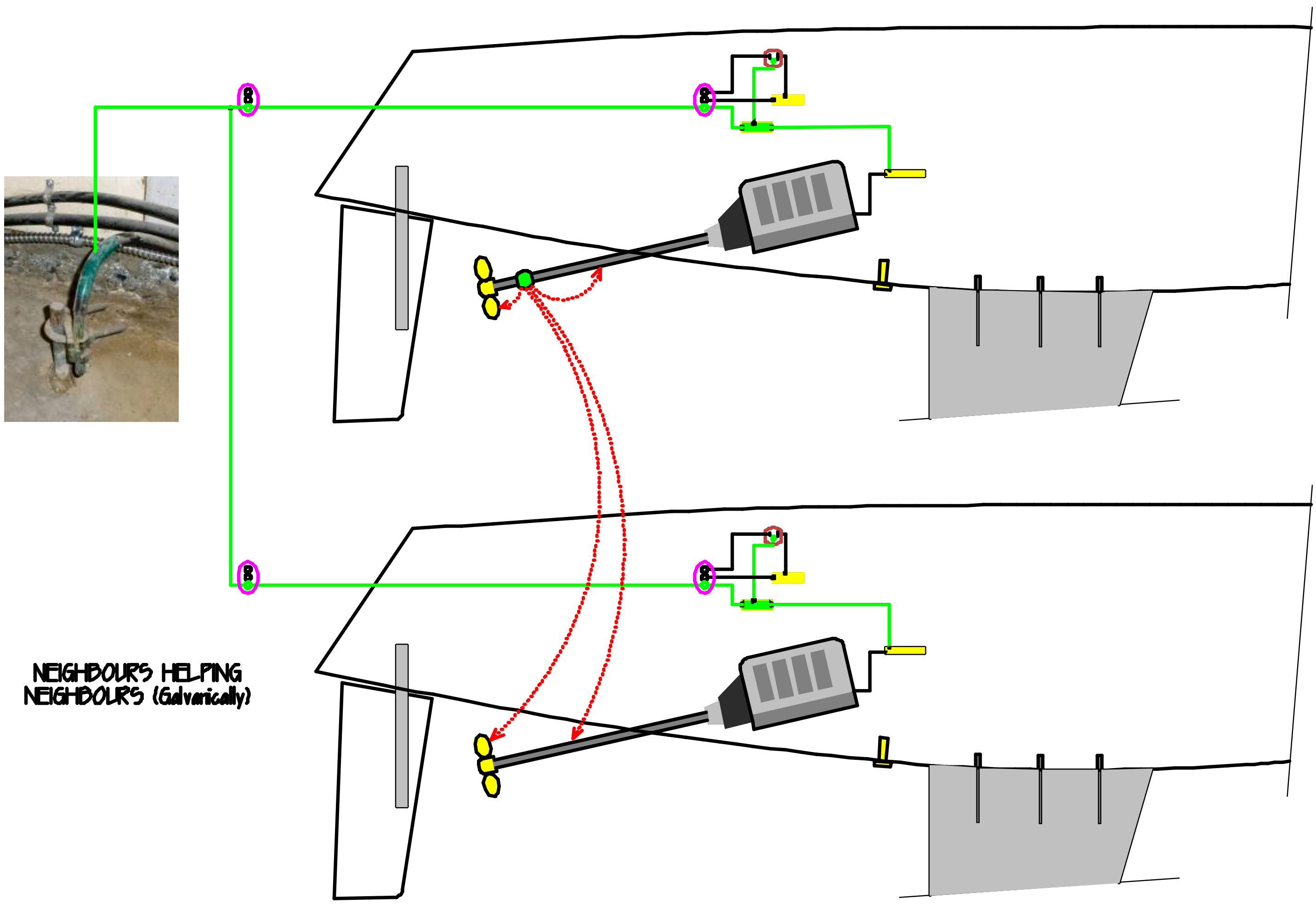
If too small an anode is used, its surface area may have a difficult time overcoming the potential of the least noble item to be protected. If too large an anode is used, it is possible that paint blistering might occur, and wooden boats will suffer wood damage around the through-hull fittings if they are connected electrically to the shaft.

In order to ensure that there is adequate protection, an Ag/AgCl reference electrode and digital voltmeter can be used. Connect the voltmeter between the reference anode (suspended over the side, within about 5 or 10 feet of the propeller) and a good connection to the boat's ground. Unplug the shore power, and turn off all DC loads. This test should be done after the boat has been sitting stationary for at least 8 hours. The voltage you read will be the <u>net effect</u> of the sacrificial anode and the various underwater metals to which it is attached. A larger surface area on the sacrificial anode will result in a more negative voltage on the digital voltmeter. As an absolute minimum there needs to be sufficient anode area such that the net voltage displayed is at least 0.25 volts more negative than the freely existing potential (as determined from the chart above) of the least noble material to be protected. This does not apply to the protection of aluminum components. The voltage that is measured using this technique is sometimes referred to as the "**hull potential**".

As a rough guide, the hull potential should fall into the following ranges:

Fiberglass hull with conventional shaft and bronze propeller:	-750 mV to -1000 mV
Fiberglass hull with outboard, saildrive or stern drive:	-900 mV to -1050 mV
Aluminum hull:	-800 mV to -1100 mV

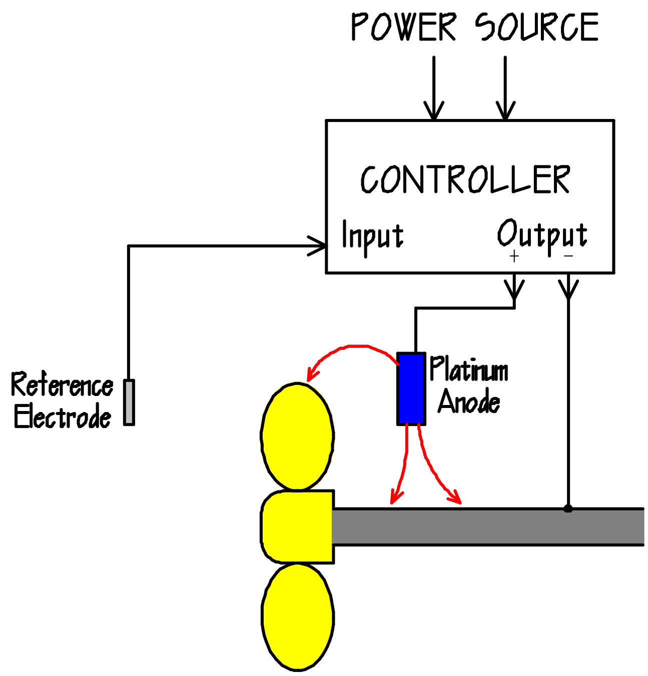
Unless an isolation transformer or galvanic isolator is installed, you should be concerned about boat-to-boat galvanic corrosion due the shore power connection! See below:



Your sacrificial anode could be providing protection to your neighbour's boat if you are both plugged in to shore power and neither boat has an isolation transformer or galvanic isolator. The life of your sacrificial anode will be adversely affected in this case!

Impressed Current Cathodic Protection Systems (ICCP)

Many large commercial ships, oil rigs, and pipelines do not rely on sacrificial anodes for galvanic corrosion protection, but instead use a system called an "Impressed Current Cathodic Protection System" (ICCP) that is based on applying an external voltage to overcome the galvanic voltages. See below:



The advantage of this system is that there is no need to replace a consumable sacrificial anode, and it is easy to adjust the protection parameters over a large area (perhaps over the length of a pipeline) from one location. The disadvantage is one of cost, and the fact that electrical power is being consumed (potentially draining a battery). If the control electronics of an ICCP system develop a fault, it is possible to cause a lot of damage to the boat quite quickly!

At least two manufacturers of stern drives and saildrives (Mercury and Volvo) offer small ICCP systems to protect their delicate aluminum structures. It is important to follow the manufacturer's recommendations exactly to ensure that these systems are providing the required protection.

Electrically Isolated Metallic Components

Galvanic corrosion occurs when dissimilar immersed metals make electrical contact. But what about the case where there is no contact (such as an isolated bronze through-hull fitting, strut, or rudder post) - do these need sacrificial anodes? **Maybe!**

Even though it may appear that you have a single piece of the same material, there will be local impurities, voids, pits, or welds that may not be obvious at first - these local areas will have a different galvanic potential, and the possibility exists of galvanic corrosion. Not only can the base metal have localized differences, but so can the sea water itself - galvanic potential is affected by water velocity, temperature, aeration, salinity, and pollution. It is for this reason that all the electrically isolated steel pilings at RVYC are protected by sacrificial anodes suspended on steel cables.

Metal rudder posts and shaft struts need to be considered in this regard. Seacocks definitely need some type of protection, because internally they contain different materials (usually bronze and stainless steel).

Propeller Blade Tips

The extreme tips of Manganese Bronze propellers (an alloy of Copper, Manganese and Zinc) often exhibit a "pink colour". This is because the higher water velocity at the tip creates a different galvanic potential in its bronze, and a galvanic reaction is set up that slowly depletes the zinc content, leaving an appearance that almost looks like it was caused by cavitation problems. Note that this is not a problem with propellers fabricated from Nibral (an alloy of Nickel, Bronze, and Aluminum).

Bonding

This is another controversial topic! The idea is to use internal wiring (often copper strap is used) to connect all the underwater fittings, and shaft to a large zinc that is often located in an area where its condition can be checked easily from the dock. Here are some photographs taken of a boat with a bonding system:

Note that the shaft and propeller are connected to the bonding system with a "shaft brush" so that we are not relying on good electrical connectivity through the engine's transmission. Each of the green wires shown in the photos are firmly connected to a brass strip that runs around the boat (well out of the bilge), and connects to two zincs on the stern via through-bolts. The condition of the two stern zincs can be checked from the dock without using a diver.

The <u>claimed disadvantage</u> is that if the boat is moored in fresh water and there is a large DC gradient through the water (possible, but not likely), the current can enter the boat through one through-hull fitting, travel through the bonding system, and exit through another fitting (or the prop or the zincs), thereby creating the possibility of electrolysis. However, this would not be a problem in salt water, because the much lower resistivity of salt water would make it extremely unlikely that a problematic DC gradient field could exist.

PART 5: SUMMARY AND RECOMMENDATIONS

We will now summarize what has been discussed so far, and make a few recommendations for various situations.

On-Board 120 V AC Systems

- Keep the wiring out of the bilge!
- If there is no inverter and/or AC generator, the AC safety ground does not need to be connected to the boat's ground buss, although it is recommended.
- If there is an inverter and/or AC generator, the AC safety ground **must** be connected to the boat's ground buss.
- There is a possible electrocution hazard for swimmers or divers in the case of a ground fault if the boat is in fresh water, not in salt water, and there is not a good connection with the shore power's ground connection (the "green wire").
- If the AC safety ground is connected to the boat's ground buss, the shore power's ground connection (the green wire) should be connected to the AC safety either via an isolation transformer or a galvanic isolator. A "direct connection" will work from a safety standpoint, but opens the door to possible "boat-to-boat" issues with both electrolysis and galvanic corrosion.

Terminology

- **Electrolysis** is caused by leakage currents, and can affect similar submersed metals.
- **Galvanic Corrosion** is caused by submersed dissimilar metals in electrical contact.
- **Electrolysis** requires an external source of current, **Galvanic Corrosion** does not.

On – Board DC Systems

- Keep the wiring out of the bilge
- The boat's ground buss should be connected to the engine block. (and possibly also to all of the components in contact with the water if a bonding system is installed).
- Check for leakage currents inside the boat.
- If a shore power system is also present, make sure that the ground connection (green wire) from shore is **not** directly connected to the boat's ground (by using an isolation transformer or galvanic isolator).

Galvanic Corrosion Considerations

- A shaft sacrificial anode and/or impressed current system should be installed.
- Alternatively, a suspended zinc that is firmly attached (electrically) to the boat's ground can be considered.
- Use a reference electrode and digital voltmeter to confirm the adequacy of the protection system.
- Worry about unprotected but homogenous submersed metallic components (such as rudder posts, shaft struts, and through-hulls).
- Consider the use of a bonding system.
- Consider the use of a shaft brush
- Check the rate of erosion of the sacrificial anodes!

About The Author

Roger Palmer received an Electrical Engineering degree from McMaster University (1969), and an MBA from the University of Washington (1986). He is a retired Professional Engineer in B.C., and is a Life Member of the Institute of Electrical and Electronic Engineers in New York. He co-founded several successful "High Tech" companies, and has been designing electronic equipment for almost 60 years. Roger was one of the pioneers in the development of bar code technology in the 70's and 80's. He is the author of two text books: one on bar code technology, and one on RF circuit design. He has been "messing about in boats" even longer than he has been chasing electrons.

More information from the author on a variety of topics is available on his web site:

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A video of this material is available on YouTube at:

https://youtu.be/t6Ge7_RTtJg