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Workboat DC Electrical Systems: Design, Installation, and Repair

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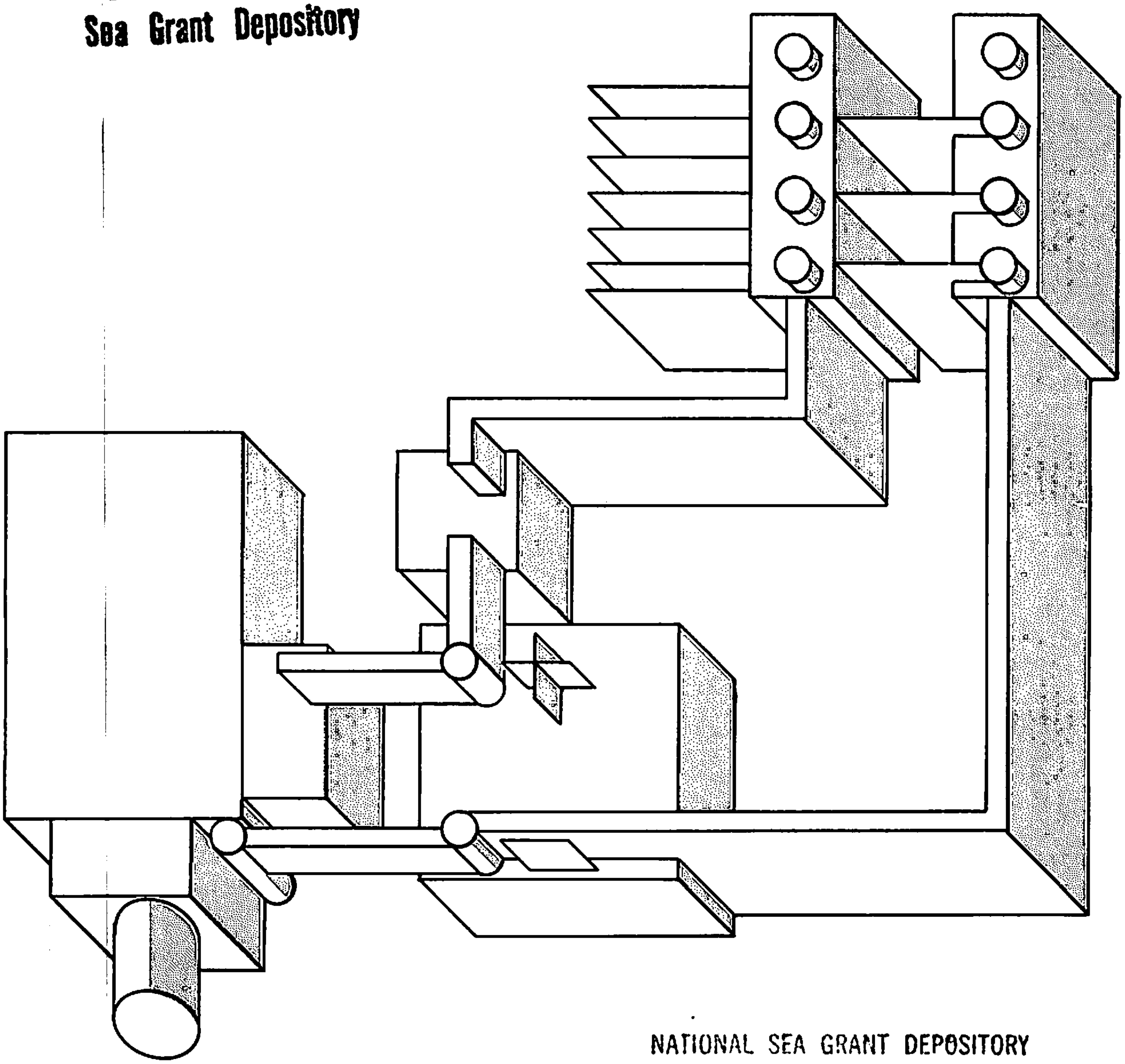

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WORKBOAT DC ELECTRICAL SYSTEMS: DESIGN, INSTALLATION, AND REPAIR

F. W. Wheaton and G. L. Smith

Boat electrical systems are more economical, reliable and safe if they are well designed, installed and maintained. Good electrical systems reduce emergency repairs which may endanger the life or safety of the captain and crew. Boat downtime is also reduced, increasing the economic return from the workboat.

Both alternating current (AC) and direct current (DC) systems are used on boats; however, AC current finds only limited application on board workboats that are less than 15 meters (50 feet) in length. Since this publication is primarily concerned with these smaller craft, DC systems will be emphasized here.

Direct current is used aboard workboats for two general systems: the engine ignition system and the electrical accessories system (e.g. bilge pump, lights, depth finder). Although some parts of the engine ignition will be discussed (e.g. battery), major emphasis in this publication will be on the accessories electrical system. Workboats under 15 meters (50 feet) in length nearly always use either 6- 12- or 24-volt systems, the 12-volt system being most popular. Larger boats often use voltages in the 30- to 70-volt range.

DEFINITIONS

The terms defined here are elementary in the discussion of any electrical system, and understanding them is essential for developing sound electrical systems.

Ampere - Amount of electricity flowing through a conductor or wire. Amperage is analogous to flow rate in a water pipe.

Conductor - Any material capable of conducting electricity without excessive resistance. Copper, aluminum and other metals are examples of conductors.

Floating ground - Arbitrary voltage selected to represent zero volts.

Ground - Voltage equal to that of the surface of the Earth.

Insulator - Any material having a very high resistance to the flow of electricity. Rubber and several types of plastic are examples of insulators.

Kilowatt - 1,000 watts.

Ohm - Resistance to flow of electricity. Ohms are analogous to pressure drop or resistance to flow through a water pipe.

Volt - Potential causing electricity to flow through a conductor. It is analogous to pressure in a water pipe.

Watt - A unit of electrical power. One horsepower is equal to 746 watts.

The basic electrical units of volts, amperes, ohms and watts are related by simple mathematical relationships in DC circuits. Ohm's Law defines the relationship between pressure (volts), flow (amperes) and resistance (ohms).

$V = IR$ Ohm's Law

Where, V = volts, I = amperes and R = ohms. Ohm's Law states that 1 volt will cause 1 ampere to flow through a conductor having a resistance of 1 ohm.

Electrical power can be calculated by the relationship:

$W = VI$ Electrical Power

Where, W = watts, V = volts and I = amperes. Thus, 1 ampere flowing through a device under a potential of 1 volt produces 1 watt of power. Ohm's Law and the electrical power equation are helpful in determining wire size, battery size and other parameters.

Example 1

A bilge pump has a resistance of 24 ohms and has a maximum current rating of 0.5 amperes. Can this pump be operated on a 12-volt battery?

$$V = IR$$
$$V = (0.5)\ (24)$$
$$V = 12 \text{ volts}$$

Thus, the pump can be operated on 12 volts without exceeding its amperage rating.

Example 2

A DC motor on the bilge pump is rated at 1/4 horsepower. If operated on a 12-volt system, how many amperes will it draw? Since 1 horsepower equals 746 watts, 1/4 horsepower will be $\frac{746}{4}$ = 186.5 watts.

$$W = VI$$

$$186.5 \text{ watts} = (12 \text{ volts})\ (I)$$

$$\frac{186.5}{12} = I$$

$$15.5 \text{ amperes} = I$$

Note that this is the running amperage. Most motors require about 50 percent greater amperage when starting. Thus, this must be considered in circuit designs.

TYPES OF CIRCUITS

Two types of circuits are found in nearly all wiring systems -- series circuits and parallel circuits. These two types may also be combined in a single wiring system.

Series Circuits

Series circuits (Figure 1) have the same current flow through all elements. In a series system, current flows out of the battery, through all loads and back to the battery. The loads may be motors, lights or other components. The current is the same through all loads, but the voltage drop across each load will be proportional to the resistance of that load. If a 12-volt battery is connected in a series circuit with a 12-ohm and a 6-ohm load, the current through the system can be calculated by Ohm's Law. Since it is a series circuit, the resistances will add to give a total resistance for the circuit of:

$$R = R_1 + R_2 = 6 + 12$$

$$R = 18 \text{ ohms}$$

Thus, using Ohm's Law you can compute the current that will flow through the system.

$$V = IR$$

$$12 \text{ volts} = (I)\ (18 \text{ ohms})$$

$$0.67 \text{ amperes} = I$$

Since the current through each load is the same, Ohm's Law can be used to determine the voltage drop across each load. Across the 12-ohm load the voltage drop is:

$$V = IR$$

$$V = (0.67 \text{ amperes})\ (12 \text{ ohms})$$

$$V = 8 \text{ volts}$$

The voltage drop across the 6-ohm load is:

$$V = IR$$

$$V = (0.67 \text{ amperes})\ (6 \text{ ohms})$$

$$V = 4 \text{ volts}$$

Voltage drops and current flows in this circuit can be determined easier by using Table 1. The total series resistance was determined to be 18 ohms. Since it is a 12-volt system, enter Table 1 at 12 volts. Follow the line horizontally from 12 volts until it intersects the vertical column below 18 ohms. The value read, 0.67 amperes, is the circuit current. To find the voltage drop across load 1, enter Table 1 at 12 ohms, the resistance of load 1, and project downward until the circuit current flow is located, 0.67 amperes. Project horizontally from the 0.67 amperes and read 8 volts on the voltage scale. This is the voltage drop across load 1, a 12-ohm load with a current of 0.67 amps flowing through it.

Parallel Circuits

Parallel circuits (Figure 2) have the same voltage drop across each load, but different current through each load. Thus, there are 12 volts across both load 1 and load 2 in the parallel circuit. The current through each load can be determined using Ohm's Law or Table 1.

Ohm's Law

$$V = IR$$

$$I = \frac{V}{R}$$

$$I_1 = \frac{12 \text{ volts}}{12 \text{ ohms}}$$

$$I_1 = 1 \text{ ampere}$$

$$I_2 = \frac{12 \text{ volts}}{6 \text{ ohms}}$$

$$I_2 = 2 \text{ amperes}$$

Table 1: Since a 12-volt potential is applied across a 12-ohm resister (load 1), enter Table 1 at 12 volts and move horizontally until the vertical column below 12 ohms is reached. Read the current flow through load 1 at the intersection, 1 ampere. Similarly for load 2, a 6-ohm load, the current is read from Table 1 as 2.0 amperes.

The total current drawn from the battery is the sum of the current through the two loads:

$$I_1 + I_2 = 3 \text{ amperes.}$$

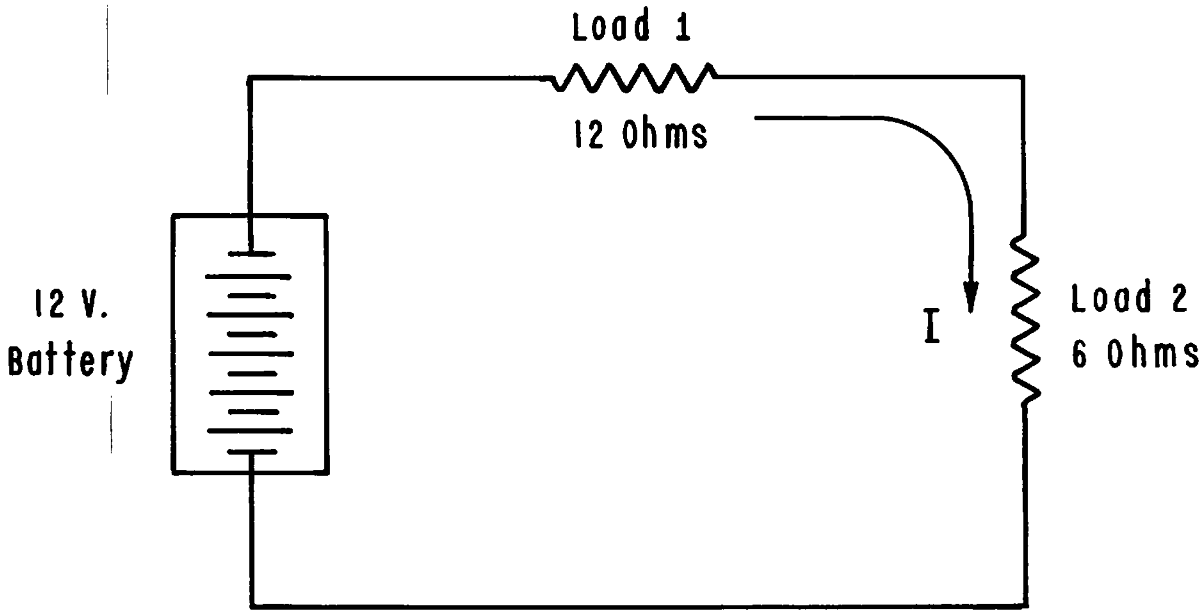

FIGURE 1. SERIES CIRCUIT

Table 1. Current (amperes) flowing through loads of various resistances when operating at various voltages.

VOLTAGE (volts)	RESISTANCE (ohms) 1	2	3	4	5	6	7	8	9	10	12	14	16	18	20	25	30	35	40	45	50
1	1	.05	.33	.25	.20	.17	.14	.13	.11	.10	.08	.07	.06	.06	.05	.04	.03	.03	.03	.02	.02
2	2	1.0	.67	.50	.40	.33	.29	.25	.22	.20	.17	.14	.13	.11	.10	.08	.07	.06	.05	.04	.04
3	3	1.5	1.0	.75	.60	.50	.43	.38	.33	.30	.25	.21	.19	.17	.15	.12	.10	.09	.08	.07	.06
4	4	2.0	1.3	1.0	.80	.67	.57	.50	.44	.40	.33	.29	.25	.22	.20	.16	.13	.11	.10	.09	.08
5	5	2.5	1.7	1.3	1.0	.83	.71	.63	.56	.50	.42	.36	.31	.28	.25	.20	.17	.14	.13	.11	.10
6	6	3.0	2.0	1.5	1.2	1.0	.86	.75	.67	.60	.50	.43	.38	.33	.30	.24	.20	.17	.15	.13	.12
7	7	3.5	2.3	1.8	1.4	1.2	1.0	.88	.78	.70	.58	.50	.44	.39	.35	.28	.23	.20	.18	.16	.14
8	8	4.0	2.7	2.0	1.6	1.3	1.1	1.0	.89	.80	.67	.57	.50	.44	.40	.32	.27	.23	.20	.18	.16
9	9	4.5	3.0	2.3	1.8	1.5	1.3	1.1	1.0	.90	.75	.64	.56	.50	.45	.36	.30	.26	.23	.20	.18
10	10	5.0	3.3	2.5	2.0	1.7	1.4	1.3	1.1	1.0	.83	.71	.63	.56	.50	.40	.33	.29	.25	.22	.20
11	11	5.5	3.7	2.8	2.2	1.8	1.6	1.4	1.2	1.1	.92	.79	.69	.61	.55	.44	.37	.31	.28	.24	.22
12	12	6.0	4.0	3.0	2.4	2.0	1.7	1.5	1.3	1.2	1.0	.86	.75	.67	.60	.48	.40	.35	.30	.27	.24
13	13	6.5	4.3	3.3	2.6	2.2	1.9	1.6	1.4	1.3	1.1	.93	.81	.72	.65	.52	.43	.37	.33	.29	.26
14	14	7.0	4.7	3.5	2.8	2.3	2.0	1.8	1.6	1.4	1.2	1.0	.88	.78	.70	.56	.47	.40	.35	.31	.28
15	15	7.5	5.0	3.8	3.0	2.5	2.1	1.9	1.7	1.5	1.3	1.1	.94	.83	.75	.60	.50	.43	.38	.33	.30
16	16	8.0	5.3	4.0	3.2	2.7	2.3	2.0	1.8	1.6	1.3	1.1	1.0	.89	.80	.64	.53	.46	.40	.36	.32
17	17	8.5	5.7	4.3	3.4	2.8	2.4	2.1	1.9	1.7	1.4	1.2	1.1	.94	.85	.68	.57	.49	.43	.38	.34
18	18	9.0	6.0	4.5	3.6	3.0	2.6	2.3	2.0	1.8	1.5	1.3	1.1	1.0	.90	.72	.60	.51	.45	.40	.36
19	19	9.5	6.3	4.8	3.8	3.2	2.7	2.4	2.1	1.9	1.7	1.4	1.2	1.1	.95	.76	.63	.54	.48	.42	.38
20	20	10.0	6.7	5.0	4.0	3.3	2.9	2.5	2.2	2.0	1.7	1.4	1.3	1.1	1.0	.80	.67	.57	.50	.44	.40
21	21	10.5	7.0	5.3	4.2	3.5	3.0	2.6	2.3	2.1	1.8	1.5	1.3	1.2	1.1	.84	.70	.60	.53	.47	.42
22	22	11.0	7.3	5.5	4.4	3.7	3.1	2.8	2.4	2.2	1.8	1.6	1.4	1.2	1.1	.88	.73	.63	.55	.49	.44
23	23	11.5	7.7	5.8	4.6	3.8	3.3	2.9	2.6	2.3	1.9	1.6	1.4	1.3	1.1	.92	.77	.66	.58	.51	.46
24	24	12.0	8.0	6.0	4.8	4.0	3.4	3.0	2.7	2.4	2.0	1.7	1.5	1.3	1.2	.96	.80	.69	.60	.53	.48

Series-Parallel Combination Circuits

Many practical circuits are combinations of series and parallel circuits. However, similar principles apply to these circuits. All the current must pass through load 1 (see Series-Parallel Combination Circuit, Figure 3) and the voltage across loads 2 and 3 must be equal. Thus, loads 2 and 3 are in parallel with each other and in series with load 1. We know the voltage drop across loads 2 and 3 are equal, but we do not know what it is since there is an unknown voltage drop across load 1. Thus, to find the current through the circuit, loads 2 and 3 must be replaced by a single load which will provide the equivalent resistance to that generated by the parallel system of loads 2 and 3. This can be done using the following relationship:

$$\frac{1}{R_E} = \frac{1}{R_2} + \frac{1}{R_3}$$

Where R_E is the equivalent load (resistance) generated by the parallel combination of loads 2 and 3.

$$\frac{1}{R_E} = \frac{1}{12 \text{ ohms}} + \frac{1}{6 \text{ ohms}}$$

$$\frac{1}{R_E} = \frac{1}{12} + \frac{2}{12} = \frac{3}{12} = \frac{1}{4}$$

$$\frac{1}{R_E} = \frac{1}{4}$$

Multiplying both sides by 4 R_E to clear the fraction gives:

$$4 \text{ ohms} = R_E$$

Thus, R_E, the equivalent resistance, is in series with load 1 (see Equivalent-Series Circuit, Figure 4). The current through load 1 can be determined by using Ohm's Law and the fact that resistance is additive in a series circuit.

$$V = IR$$

$$I = \frac{V}{R}$$

$$I = \frac{12}{6 + 4}$$

$$I = 1.2 \text{ amperes}$$

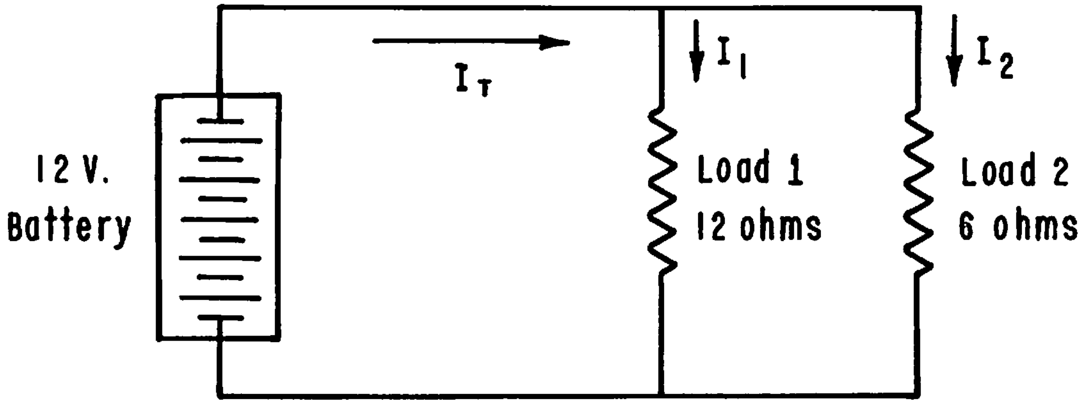

FIGURE 2. PARALLEL CIRCUIT

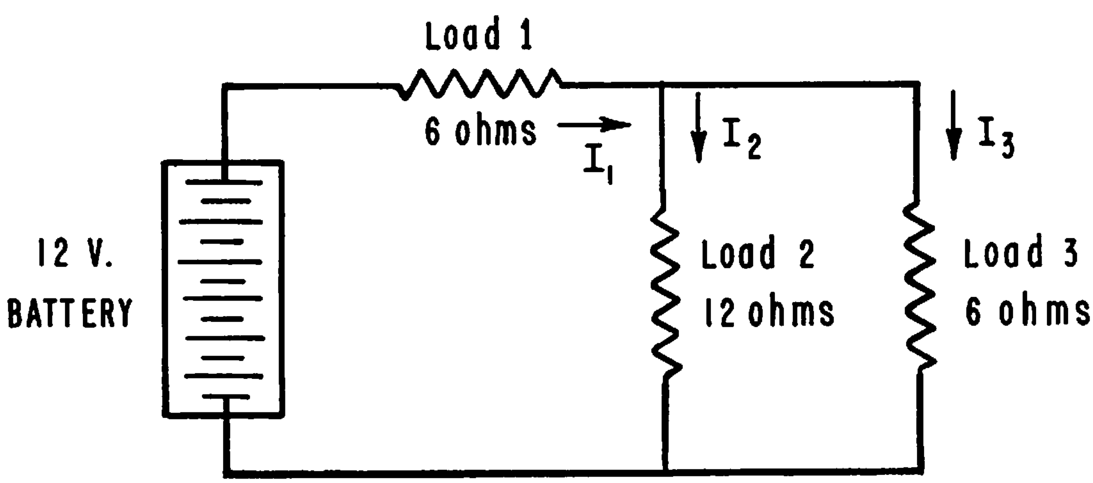

FIGURE 3. SERIES-PARALLEL COMBINATION CIRCUIT

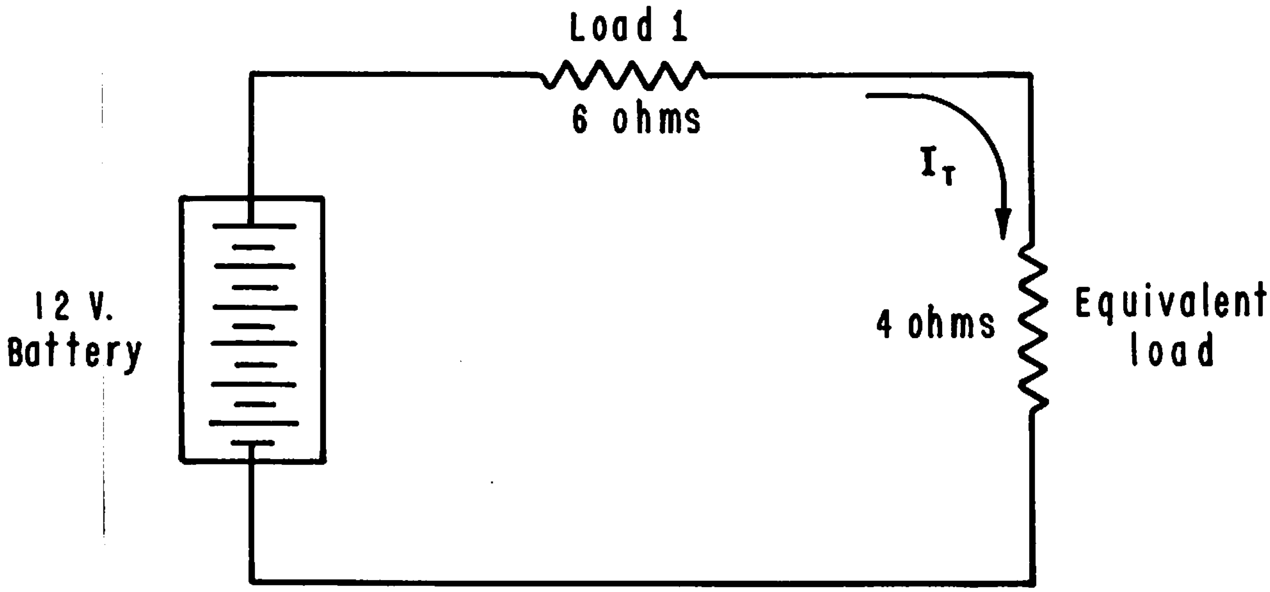

FIGURE 4. EQUIVALENT SERIES CIRCUIT REPLACING A SERIES-PARALLEL COMBINATION

The current through load 1 can also be determined using 12 volts, Table 1, and the equivalent circuit resistance of 10 ohms (i.e., 6 + 4 ohms).

The voltage drop across load 1 can be determined using the current flow, resistance of load 1 and either Ohm's Law or Table 1.

$$V = IR$$

$$V = (1.2)\ (6)$$

$$V = 7.2 \text{ volts}$$

Note that the answer given in Table 1 is 7 volts. The difference between 7.0 and 7.2 volts is due to the rounding off of the numbers used while constructing Table 1.

Thus, there are 4.8 volts (12 - 7.2) across the parallel resistors in the series-parallel combination circuit. I_2 and I_3 can be directly calculated from Ohm's Law or Table 1.

$$V = I_2R$$

$$I_2 = \frac{V}{R}$$

$$I_2 = \frac{4.8}{12}$$

$$I_2 = 0.4 \text{ amperes}$$

Table 1 does not show a value of 0.4 amperes; however, the voltage is 4.8, a value between 4 and 5 volts. Four volts across a 12-ohm resistor gives 0.33 amps while 5 volts gives 0.42 amperes. A voltage of 4.8 is 0.8 of the way between 4 and 5 volts. Thus, you must interpolate between the 4- and 5-volt value in Table 1. Do this by subtracting the amperage at 4 volts from that at 5 volts (0.42 - 0.33 = 0.09). Next multiply the difference by 0.8, the part 4.8 is above 4 volts, giving (0.8 x 0.09 = .07). Then add the resulting number to the 4-volt amperage (0.33 + 0.07 = 0.4 amp) to give the correct value.

$$I_3 = \frac{4.8}{6}$$

$$I_3 = 0.8 \text{ amperes}$$

Any circuit can be analyzed using the relationships discussed above. The more complicated the circuit, the more steps involved. However, the method of computing is no more complicated.

BATTERIES

Batteries, in combination with the generator or alternator, provide electrical power to operate all DC electrical devices on board a boat. Correct selection and maintenance of the battery are necessary to provide a reliable electrical system.

Battery Selection

Almost all boat batteries are the lead-acid type. These batteries use lead plates and sulfuric acid as the electrolyte. A chemical reaction between these two materials generates and stores electricity.

Battery voltage must be chosen to be compatible with existing equipment. Nearly all small workboats utilize 12-volt batteries; however, some of the older boats may still require 6-volt batteries. Occasionally a boat will require 24 volts, which is usually achieved by connecting two 12-volt batteries in series.

Wet charge, dry charge and sealed batteries are available commercially. Dry charge batteries require the addition of electrolyte for operation. They also require that the electrolyte level be maintained above the battery plates throughout their life.

Sealed batteries, also referred to as "maintenance free" batteries, are sealed and do not require addition of liquid before, or periodically, during use. Wet charge batteries are shipped from the factory with electrolyte already in the battery. Wet charge batteries are not as widely used today as they once were, primarily because dry charge batteries have a much longer storage life. Batteries that have been stored an extended period of time should not be purchased because they are more subject to early failure. The best guarantee of obtaining a fresh battery is to buy one from a reputable dealer, preferably one with a reasonable sales rate. Dealers selling a reasonable volume of batteries generally will have only fresh batteries in stock.

Battery Ratings

Battery energy storage capabilities are typically expressed in ampere hours or amp hour (e.g. 200 AH). Amp hour ratings are simply the product of the discharge rate in amperes multiplied by the hours which the battery will sustain the discharge rate while maintaining a certain cell voltage. Typically, minimum cell voltage is specified at 1.5 or 1.75 volts per cell, or 9 or 10.5 volts, respectively, for a 12-volt battery. A single value such as 200 amp hour rating has little meaning unless discharge rate, battery temperature during discharge, specific gravity of the electrolyte, and final voltage at discharge are specified.

Battery output is decreased when high discharge rates are required. For example, Table 2 shows the amp hour value obtainable from one battery under various discharge rates. As the discharge rate (current flow) rises, the total amp hours extractable from the battery decreases. The battery used to develop the data in Table 2 will produce 290 amperes for 1 minute (4.8 amp hours). Since engine cranking ratings are sometimes based on a 1-minute discharge period (a representation of what is demanded of a battery starting a cold engine), this battery also could be classified as a 4.8-amp hour battery. Furthermore, if in rating the battery the cell voltage is allowed to drop to a minimum of 1.5 volts instead of the 1.75 volts used in Table 2, the battery will produce 535 amps for 1 minute or 8.9 amp hours. Often the 1-minute ratings are given in terms of amperage available for a 1-minute discharge rather than as amp hours.

Table 2. Ampere-hour output from the same battery when it is discharged at various rates. Battery end-point is taken when voltage drops below 1.75 volts/cell.

Discharge Current (amp)	Discharge Time (hours)	Ampere-hours Produced
25	8	200
35	5	175
50	3	150
100	1	100

Temperature also influences battery performance. Catalog ampere-hour ratings are usually specified at a battery temperature of 25° or 27°C (77° or 80°F). Increasing the temperature above 25° or 27°C increases the ampere-hour output, while decreasing the temperature lessens battery output. For example, lead-acid batteries will produce only about 45 percent of the watts at -29°C (-20°F) that the same battery will at 27°C (80°F). Many battery manufacturers specify a <u>cold power rating</u> (e.g. 470 amps). This is the amperes of current the battery is capable of producing for a 30-second period when held at -17°C (0°F) and voltage is maintained at or above 1.5 volts per cell. Cold power ratings are indicative of a battery's engine-starting capability during cold weather.

Increasing electrolyte specific gravity increases battery ampere-hour output. However, increasing specific gravity decreases useful life and reduces the time an idle battery will hold its charge.

Since several items influence battery output, there are several "standard" rating methods used for batteries. The ampere-hour rating achieved by discharging a battery held at 27°C (80°F) over a 20-hour period, the 20-hour rating, is a common value used. Ampere-hour ratings sometimes used are for different time periods, such as 8-hour or 100-hour rating. Since discharge rate is slower when longer time periods are used, the ampere-hour rating for a battery will increase as the time period for rating it increases.

The cold-power rating has been previously mentioned. A related value is the cold rating. This is obtained by discharging a fully charged battery held at -17°C (0°F) at a constant rate of 150 or 300 amperes, depending upon voltage and ampere-hour rating of the battery. Two values are obtained: the first is the battery voltage after a 5- or 10-second discharge, and the second is the time in minutes required to discharge the battery to the designated minimum cell voltage. Thus, a 12-volt battery having a 10-second voltage rating of 6 volts at 300 amperes will maintain a voltage of at least 6 volts for 10 seconds when discharging at 300 amperes.

Reserve capacity is another rating that is often used. Reserve capacity is the time in minutes required for a fully charged battery held at 27°C (80°F) to discharge at a constant rate of 25 amperes to an end point voltage of 1.75 volts per cell. Reserve capacity is an estimate of the running time available from a battery when running with lights on and no generator output.

Battery Maintenance

Acid fumes released from the battery may cause corrosion of the battery terminals. Corrosion and an accumulation of dirt mixed with very small amounts of acid can create an electrical conducting path from battery terminals to ground, causing the battery to slowly discharge. Periodic cleaning of the battery and clamps will prevent this problem.

How to Clean the Battery:

1. Disconnect cables (ground strap first to prevent short circuits and arcing) from battery terminals using a box-end wrench and screwdriver. Use the screwdriver to open the terminal connections after loosening the bolt. If you remove the battery tag the terminals to assure correct polarity when replacing the battery. Incorrect polarity can damage the voltage regulator and/or alternator.

2. Clean cable clamps of corrosion and oxide using a wire brush, rat tail file or sandpaper. Clean battery posts with a wire brush, file or sandpaper.

3. Remove dirt and corrosion particles from the battery with water and bristle brush.

4. Brush a soda-water mixture of 15 mL (2 tablespoons) baking soda and about 1/2 liter (1 pint) of water on top of battery, posts and clamps. This mixture will react with any remaining acid creating considerable foam. Continue applying until foaming stops. Hot water, 51° to 66°C (125° to 150°F), may be used in making up the solution to speed up the reaction. WARNING - keep soda-water mixture out of breather holes in battery caps. It will weaken the acid electrolyte if it enters the battery.

5. Wash away residue with clean water, being sure that any material left on the battery, battery frame or boat is removed.

6. Dry battery using a clean cloth.

7. Reconnect battery cables replacing power cable before ground cable. Spread the clamp so it is not necessary to hammer the clamp. Hammering clamps onto the battery posts may crack the battery case. Tighten bolts in clamps until clamps are tight on battery posts.

8. Apply a coating of Vaseline or grease to post and cable-clamp connections to reduce future corrosion problems.

Check Electrolyte Level

The electrolyte level in the battery must be checked as part of your routine maintenance, unless you own a sealed battery. The electrolyte level in all cells should be checked at least once a week. If the electrolyte is below the plates in any cell, add clean water, preferably distilled water.

Specific gravity of the battery electrolyte should be checked periodically, at least once a month. Electrolyte specific gravity of a fully charged battery after correction for temperature should be close to 1.270. Significant deviations from this value indicate the battery needs more acid or is nearing the end of its useful life.

WIRING

There are two primary considerations in selecting wire for the electrical system on a boat: 1) the wire must have sufficient cross sectional area to carry the necessary current; and 2) the insulation on the wire must withstand the environment in which it will be placed.

Wire Size

Wire has some resistance, although in good copper wire it is low. Thus, as current passes through the wire, heat is generated according to the relationship.

$$\text{Watts} = (\text{amperes})^2 (\text{resistance})$$

or

$$W = I^2 R$$

Heating increases as the square of current, and directly as the resistance. The smaller the wire, the greater the resistance per unit length. Hence, the greater the heating for the same current. Heat generated in the wire tends to break down the insulation with time, or if sufficient heat is generated, will melt the insulation. Both of these situations create a safety and fire hazard.

Resistance in the wire causes a voltage drop in the wire according to Ohm's Law ($V = IR$). Voltage drop increases with increased wire length, increased current flow and decreased wire diameter. Many electronic instruments will not operate properly if the voltage is too low. Thus, if an instrument requires a minimum of 11 volts to operate properly, and there is a 2-volt drop in the wire between the battery and instrument, trouble will be experienced with the instrument. Proper wiring will eliminate the trouble.

Typically there are two standards of allowable voltage drop. For lights and other noncritical systems, the voltage drop allowed is often 10 percent. Thus, the minimum voltage at the point of use is 10.8 volts on a 12-volt system and 5.4 volts on a 6-volt system. Critical equipment is usually wired for a maximum of a 3 percent voltage drop in the wiring. This means there must be a minimum of 11.64 volts at the point of use in a 12-volt system and 5.72 volts at the point of use in a 6-volt system. Table 3 shows the wire size required in circuits for a 10 percent voltage drop, and Table 4 shows the wire size for a 3 percent voltage drop.

Example 3

The wire length from a 12-volt battery to a light is 25 feet and the light requires 5 amperes (i.e., 60 watts). A voltage drop of 10 percent will not impair operation of the light.

To determine the correct wire size to use, enter Table 3 (10 percent voltage drop table) and locate the values for 12-volt systems. The wire length is 25 feet from the fuse box to light and 25 feet back from light to fuse box for a total of 50 feet. Locate the 50-foot wire length in Table 3 and read downward until it intersects the horizontal line from the 5-amp row in the 12-volt system table. The value here is 14 indicating a no. 14 AWG (American Wire Gauge) wire is sufficient for this application. Note that if 10 amperes were required, a no. 12 wire would be necessary to maintain less than a 10 percent voltage drop. Also note that this wire (carrying 5 amperes) must be a no. 10 wire if a 3 percent or less voltage drop is all that can be tolerated (Table 4).

The National Fire Code recommends that no electrical conductor be smaller than a no. 16 AWG wire. Wire should be of the stranded type (as opposed to solid) to better withstand vibration found on boats. The wire should be copper (do not use aluminum), preferably tinned or lead alloy coated.

Table 3. AWG** wire sizes based on a 10 percent voltage drop.

Total Current on Circuit in Amps	Length of Conductor (feet)*** 20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170
	6 Volts															
5	14#	14	14	12	12	12										
10	14	12	10	10	8	8										
15	12	10	8	8	8	6										
20	10	8	8	8	6	6										
25	10	8	6	6	4	4										
	12 Volts															
5	14#	14#	14#	14#	14	14	14	14	12	12	12					
10	14#	14	14	12	12	12	10	10	10	10	8					
15	14	14	12	10	10	10	8	8	8	8	8					
20	12	12	10	10	8	8	8	6	6	6	6					
25	10	10	10	8	8	8	6	6	6	6	4					
	32 Volts															
5	14*	14*	14*	14*	14*	14*	14*	14*	14#	14#	14#	14#	14#	14#	14	14
10	14*	14*	14*	14#	14#	14#	14	14	14	14	14	12	12	12	12	12
15	14*	14*	14#	14#	14	14	14	12	12	12	12	10	10	10	10	10
20	14*	14#	14	14	14	12	12	12	10	10	10	10	10	10	8	8
25	14#	14	14	12	12	12	10	10	10	10	10	8	8	8	8	8
30	14#	14	14	12	12	10	10	10	10	8	8	8	8	8	8	6

* "Safety Standards for Small Craft, 1975-1976", American Boat and Yacht Council, recommends no. 18 wire for these voltage-amperage-length combinations.

\# "Safety Standards for Small Craft, 1975-1976", American Boat and Yacht Council, recommends no. 16 wire for these voltage-amperage-length combinations.

** AWG is American wire gauge. Wire size is often indicated only as wire number (e.g. no. 14 wire). This number really indicates the wire gauge in AWG sizes.

*** Length of the conductor is from source of power to most distant use point and back.

Source: National Fire Codes, Vol. 10, Section 302, 1978.
"Safety Standards for Small Craft, 1975-1976", American Boat and Yacht Council, 1975.

Table 4. AWG** wire sizes based on a 3 percent voltage drop.

Total Current on Circuit in Amps.	Length of Conductor (feet)***															
	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170
	6 Volts															
5	12	10	8	8	6	6										
10	8	6	6	4	4	2										
15	6	4	4	2	2	2										
20	6	4	2	2	1	1										
25	4	2	2	1	0	0										
	12 Volts															
5	14	12	12	10	10	8	8	8	8	8	6					
10	12	10	8	8	6	6	6	4	4	4	4					
15	10	8	6	6	4	4	4	4	2	2	2					
20	8	6	6	4	4	2	2	2	2	2	1					
25	8	6	4	4	2	2	2	1	1	1	0					
	32 Volts															
5	16*	16	16	14	14	14	12	12	12	12	10	10	10	10	10	10
10	16	14	12	12	10	10	10	10	8	8	8	8	8	6	6	6
15	14	12	10	10	10	8	8	8	6	6	6	6	6	6	4	4
20	12	10	10	8	8	8	6	6	6	6	4	4	4	4	4	4
25	12	10	8	8	6	6	6	6	4	4	4	4	4	2	2	2

* "Safety Standards for Small Craft, 1975-1976", American Boat and Yacht Council, recommends no. 18 wire for these voltage-amperage-length combinations.

** AWG is American wire gauge. Wire size is often indicated only as wire number (e.g. no. 14 wire). This number really indicates the wire gauge in AWG sizes.

*** Length of the conductor is from source of power to most distant use point and back.

Source: National Fire Codes, Vol. 10, Section 302, 1978.
"Safety Standards for Small Craft, 1975-1976", American Boat and Yacht Council, 1975.

Conductor Insulation

Table 5 lists conductor insulation types (from the National Electrical Code) recommended for use on boats and their general application. Those classified for general use can be used anywhere on the boat. Others such as type TW can be used anywhere on the boat except in machinery spaces. Thus, when purchasing wire for boat wiring, an insulation type needs to be specified in addition to a wire size.

Table 6 gives the same information as Table 5 except it is based on recommendations by the Society of Automotive Engineers. Classification given in Table 6 may appear if wire is purchased in automotive supply stores and related outlets.

The wire coding system used by the Institute of Electrical and Electronic Engineers (IEEE) for boat wiring is shown in Table 7. Table 8 gives the designations for flexible cord insulation which can be used on boats. It should be noted that standard wiring cables (two or more wires banded together in a single plastic or rubber casing) such as used for home wiring are not recommended for boat wiring, primarily because those having usable insulation are solid wire. Stranded wire is recommended for all boat wiring to reduce vibration-induced breaks in the wire.

Color Coding

Color coding is the use of wire of different colors for different circuits or uses. For example, purple wires may be used for ignition circuits while dark blue wire is used for cabin and instrument lights. Color coding eases repairs and troubleshooting and reduces safety problems. Required and recommended wiring color codes are listed in Tables 9 and 10 for DC circuits under 50 volts.

SWITCHES

Only high quality marine switches should be used if placed in the fuel tank or engine compartments. Switches intended for household or automotive use corrode quickly and cause trouble. Switches should be approved by Underwriters Laboratories (UL) and should be labeled as to the maximum amount of current they can handle. Always use a marine switch with a current rating greater than or equal to the current flowing in the switched circuit.

Switches should be mounted in well-ventilated, easily accessible areas and protected from direct water splash. The switch mounting should be labeled with the appropriate labels, such as "on" and "off", with easily-read, durable labels. Switching the wrong switch accidentally can be a safety hazard at best, and fatal at worst.

Table 5. Conductor insulation types recommended for use on board and their general use classification (National Electrical Code Conductors).

Type	Insulation	Maximum Operating Temperature *	Use
RW***	Moisture resistant rubber with oil resistant neoprene jacket	60°C (140°F)	General use except machinery spaces
RH-RW***	Moisture and heat resistant rubber with oil resistant neoprene jacket	60°C (140°F) 75°C (167°F)	General use except machinery spaces General use
RHW***	Moisture and heat resistant rubber with oil resistant neoprene jacket	75°C (167°F)	General use
TW	Moisture resistant thermoplastic flame retardant	60°C (140°F)	General use except machinery spaces
THW	Moisture and heat resistant thermoplastic flame retardant	75°C (167°F)	General use
THWN**	Moisture and heat resistant thermoplastic	75°C (167°F)	General use
XHHW**	Moisture and heat resistant cross-linked synthetic polymer	75°C (167°F)	General use
MTW**	Moisture, heat and oil resistant thermoplastic	60°C (140°F)	General use except machinery spaces

Source: The National Fire Codes, Section 302, Vol. 10, 1978.
"Safety Standards for Small Craft, 1975-1976", American Boat and Yacht Council, Inc.

*NOTE: Maximum operating temperatures refer to the insulation operating temperatures of the wire.

**Wire types are recommended by the American Boat and Yacht Council, but do not appear in the National Fire Codes, Vol. 10, Section 302, 1978. They do appear in the National Electrical Code, 1975.

***Acceptable in the National Fire Codes, Vol. 10, Section 302, but are not recommended by the "Safety Standards for Small Craft, 1975-1976", American Boat and Yacht Council because "...they have proven unsatisfactory", according to Mr. G.J. Lippmann, Executive Director, American Boat and Yacht Council.

Table 6. Conductor insulation types recommended for use on boats and their general use classification (Society of Automotive Engineers Classification).

Type	Description	Application
GPT	Thermoplastic, insulated braidless	General use in multiple conductor cables
HDT	Thermoplastic, insulated braidless	General use
SGT	Thermoplastic, insulated braidless	General use Starter and ground
STS	Thermosetting synthetic rubber insulation-braidless	General use in multiple conductor cables
HTS	Thermosetting synthetic rubber insulation-braidless	General use
SXL	Thermosetting cross-linked polyethylene insulation braidless	General use

Source: "Safety Standards for Small Craft, 1975-1976", American Boat and Yacht Council, Inc., 1975.

Table 7. Conductor insulation types recommended for use on boats and their general use classification (IEEE designation for conductors).

Type	Description	Maximum Operating Temperature	Application
R	Thermosetting heat resistant rubber	75°C (167°F)	General use
B	Thermosetting high temperature	85°C (184°F)	General use
T	Thermoplastic polyvinyl chloride	75°C (167°F)	General use
V	Varnished cloth	85°C (184°F)	General use
AV	Asbestos varnished cloth	95°C (204°F)	General use
TA	Asbestos thermoplastic	------	General use
M	Mineral	85°C (184°F)	General use
S	Silicone rubber	95°C (204°F)	General use

Source: "Safety Standards for Small Craft, 1975-1976", American Boat and Yacht Council, 1975.

Table 8. Flexible cord designations acceptable for use on board boats.

Type	Description	Maximum Operating Temperature	Application
SO	Hard service cord - oil resistant compound	60°C (140°F)	General use
ST	Hard service cord - thermoplastic	60°C (140°F)	General use
STO	Hard service cord - oil resistant thermoplastic	60°C (140°F)	General use

Source: "Safety Standards for Small Craft, 1975-1976", American Boat and Yacht Council, 1975.

Table 9. Required marine wiring color code for DC systems under 50 volts.

Color	Use
Green	Bonding
White or black	Return, negative main
Red	Positive mains, particularly unfused

Notes: 1) The above colors shall be reserved for the uses as indicated only.

2) When the color (white or black) is selected for the negative side of the system, it shall be used throughout the system to the exclusion of the other color (black or white).

Source: "Safety Standards for Small Craft, 1975-1976", Section E, American Boat and Yacht Council, New York.

Table 10. Recommended marine wiring color code direct current systems under 50 volts.

Color	Item	Use
Yellow w/red stripe (YR)	Starting circuit	Starting switch to solenoid
Yellow (Y)	Generator or alternator field	Generator or alternator field to regulator field terminal
	Bilge blowers	Fuse or switch to blowers
Dark gray (Gy)	Navigation lights	Fuse or switch to lights
	Tachometer	Tachometer sender to gauge
Brown (Br)	Generator armature	Generator armature to regulator
	Alternator charge light	Generator terminal/alternator auxiliary terminal to light to regulator
	Pumps	Fuse or switch to pumps
Orange (O)	Accessory feed	Ammeter to alternator or generator output and accessory fuses or switches
	Accessory common feed	Distribution panel to accessory switch
Purple (Pu)	Ignition	Ignition switch to coil and electrical instruments
	Instrument feed	Distribution panel to electrical instruments
Dark blue	Cabin and instrument lights	Fuse or switch to lights
Light blue (Lt Bl)	Oil pressure	Oil pressure sender to gauge
Tan	Water temperature	Water temperature sender to gauge
Pink (Pk)	Fuel gauge	Fuel gauge sender to gauge

Source: "Safety Standards for Small Craft 1975-1976", Section E, American Boat and Yacht Council, New York.

CIRCUIT PROTECTION

Circuit protection can be provided either by fuses or trip-free, manual-reset circuit breakers. Circuit breakers are recommended since they can be reset without a new part. Fuses must be replaced if overloaded, a potential problem on the water if you are out of spare fuses. Trip-free, manual-reset circuit breakers are the type that cannot be held in manually against an overload, and they must be manually reset. Automatically resetting and nontrip-free circuit breakers should not be used on boats.

Fuses or circuit breakers are used to protect the wiring as well as items on the circuit. Thus, circuit breakers or fuses must be sized at or below the maximum current carrying capacity of the smallest wire in each circuit. If a circuit has both no. 10 and no. 12 wire in it, the protective device size must not exceed the current carrying capacity of the no. 12 wire.

Maximum amperage allowable through any conductor can be read from Tables 11 and 12. Table 13 gives maximum allowable amperage for flexible cords. Values in Tables 11 through 13 should not be confused with wire size selection tables for a given voltage drop, Tables 3 and 4. Current flow for a given wire size in Tables 11 through 13 cannot be exceeded without serious safety hazards from wire heating and/or insulation failure. Tables 3 and 4 assure that a minimum voltage will be available at the point of use. Thus, current flow limits in Tables 11 through 13 should never be exceeded even if voltage drop is not an important consideration. Usually if voltage drop limitations exist, allowable current ratings will not be exceeded. However, allowable current flow tables should always be checked, even if using a 3 percent voltage drop table.

Fuse and circuit breaker panels should be of the dead front type and made of metal or other noncombustible material. They must also be protected from spray and direct deck wash. Distribution panels and switchboards have similar requirements.

CONNECTIONS AND TERMINALS

Terminals must provide a low-resistance continuous electrical path despite vibration and a corrosive atmosphere. Crimped-type solderless, tinned copper or brass terminal lugs with ring ends are recommended. A ring end will stay in place even if the lug nut loosens where spade or forked terminals will drop out. Eyelet connectors, captive spade connectors, mechanical locking connectors and spring locking connectors also may be used. Soldering and wire or screw nuts are not recommended.

Most solderless connectors require crimping. For reliable connections, this must be done with the proper crimping tool and not with a pair of pliers.

Connections should be made inside a box unless unusual circumstances prevent this. No more than four wires can be attached to one terminal lug, and all terminals must have means of relieving strain on the terminal. Strengthening of the wire at the terminal connection can be done by proper wrapping of the joint with electrical tape, covering the joint with a tight fitting plastic or rubber tube or other similar device. Mechanical clamps ahead of terminal points relieve mechanical strain at the terminal.

Table 11. Maximum allowable amperage for conductors used everywhere except in engine spaces.

Conductor size (AWG)	Temperature Rating of Conductor Insulation						
	60°C (140°F)	75°C (167°F)	80°C (176°F)	90°C (194°F)	105°C (221°F)	125°C (257°F)	200°C (392°F)
18	10	10	15	20	20	25	25
16	15	15	20	25	25	30	35
14	20	20	25	30	35	40	45
12	25	25	35	40	45	50	55
10	40	40	50	55	60	70	70
8	55	65	70	70	80	90	100
6	80	95	100	100	120	125	135
4	105	125	130	135	160	170	180
3	120	145	150	155	180	195	210
2	140	170	175	180	210	225	240

Source: "Safety Standards for Electrical and Gasoline Fuel Sytems", Subpart 1, Electrical Systems. Regulations published by the Coast Guard in the Federal Register, Vol. 42, No. 20, Jan. 31, 1977.

Table 12. Maximum allowable amperage for conductors used in machinery spaces.

Conductor size (AWG)	Temperature Rating of Conductor Insulation						
	60°C (140°F)	75°C (167°F)	80°C (176°F)	90°C (194°F)	105°C (221°F)	125°C (257°F)	200°C (392°F)
18	5	7	11	16	16	22	25
16	8	11	15	20	20	26	35
14	11	15	19	24	29	35	45
12	14	18	27	32	37	44	55
10	23	30	39	45	49	62	70
8	31	48	54	57	66	80	100
6	46	71	78	82	99	111	135
4	60	93	101	110	132	151	180
3	69	108	117	127	149	173	210
2	81	127	136	147	174	200	240

Source: "Safety Standards for Electrical and Gasoline Fuel Systems", Subpart 1, Electrical Systems. Regulations published by the Coast Guard in the Federal Register, Vol. 42, No. 20, Jan. 31, 1977.

Table 13. Maximum allowable amperage for flexible cords of types SO, ST and STO.

Wire Size (AWG)	No. of Current-Carrying Conductors in One Cord	
	2	3
18	10	7
16	13	10
14	18	15
12	25	20
10	30	25
8	40	35
6	55	45
4	70	60
2	95	80

Source: National Electrical Code, Article 400-5, 1978.

Table 14. Minimum stud sizes for terminal studs*

Nominal Stud Size	Minimum Stud Diameter (inches)	Conductor Size** (AWG)
No. 6	0.138	Not recommended***
No. 8	0.164	16
No. 10	0.190	14 or 12
1/4 inch	0.250	8 or 10
5/16 inch	0.3125	6
3/8 inch	0.375	4

*Source: National Fire Codes, Vol. 10, NFPA No. 302, 1978.

**Based on the use of 4 conductors to each terminal stud.

***"Safety Standards for Small Craft, 1975-1976", American Boat and Yacht Council, recommends no. 6 stud for no. 18 AWG wire.

Terminal Studs

Terminal studs should fit snugly into the terminal eye. Table 14 gives minimum stud sizes for various sizes of wire.

SECURING THE WIRE

Conductors must be supported as high as possible above the bilge to prevent short circuiting by water. Wires passing through bulkheads or other areas with risk of mechanical damage should be protected by a grommet, loom, conduct or other means to prevent mechanical damage.

Conductors must be supported every 14 inches along their length unless they are enclosed by conduct. Metal or nonmetallic clamps must be used to support the conductors. Wiring staples should not be used. Use clamps free of sharp edges and of adequate width to prevent conductor insulation damage. In the engine compartments and other locations where failure due to fire could cause an additional hazard, use metal clamps. A coil of wire between the hull and engine reduces the possibility of wire failure from vibration.

BONDING SYSTEM

The bonding system on a boat has three primary functions: 1) it prevents stray current corrosion by confining stray current leakage inside the hull; 2) it provides a low resistance path for currents far in excess of design load, such as lightening or a faulty piece of equipment; and 3) it minimizes radio interference. The bonding system provides a means to ground all equipment, engines and other items on the boat.

The bonding system usually consists of a main cable running the length of the boat with jumpers running from the main cable to each piece of equipment. All conductors in the system should have a copper or bronze cross sectional area at least equal to that of a no. 6 AWG wire (0.02 square inches). If wire is used, a tin or lead alloy coated wire is recommended. The main cable may also be made of copper tubing or a solid copper or bronze strip. The large cross sectional area of copper or bronze is required since the bonding system must carry high current loads when a short occurs or lightening strikes.

The bonding jumpers connect the case of all cabinets, electronic equipment cases, the engine, or other large metal objects in the boat and all electrical equipment such as bilge pumps and generators with the main bonding conductor. The main bonding conductor is connected with the ground side of the electrical system (on boats using a fixed ground) at only one point.

SYSTEM DEVELOPMENT

Figure 5 shows the basic design of a grounded electrical system for a boat. The positive battery terminal connects directly to the starter and the distribution box through a main trip-free circuit breaker or fuse. The main circuit breaker must be within 182 centimeters (72 inches) (measured along the conductor) of the battery, unless there is a disconnect switch between the main circuit breaker and the battery

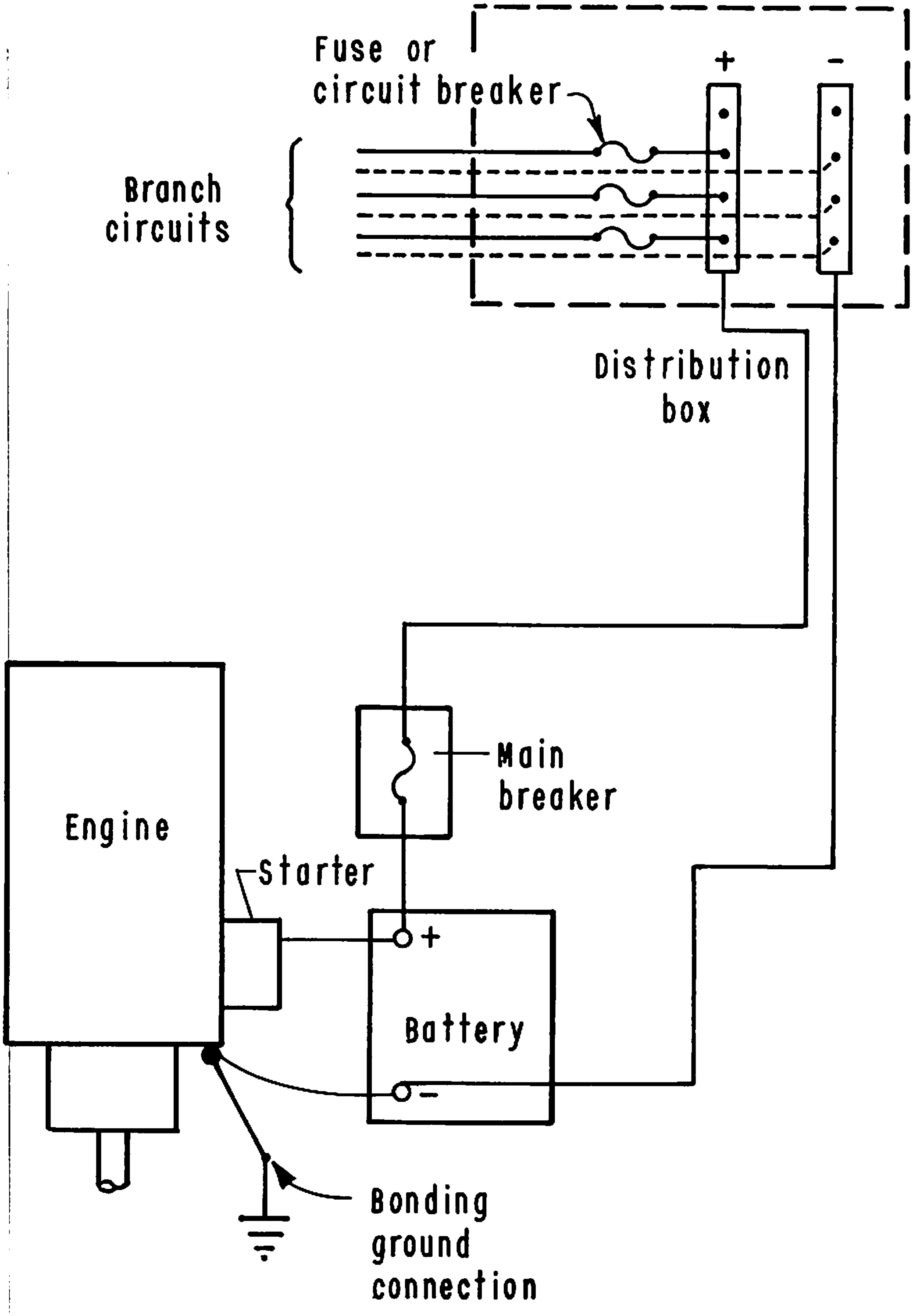

FIGURE 5. BASIC WIRING DIAGRAM OF A GROUNDED WORKBOAT ELECTRICAL SYSTEM

and that switch is within 182 centimeters of the battery. Typically, a dead front distribution box is installed within 182 centimeters of the battery. The main circuit breaker and the branch circuit breakers are located in this box. The main circuit breaker protects the wire from the battery to the distribution box and provides a means to cut off all electrical systems, except engine related ones, with one switch in an emergency or when doing repair work.

Branch circuits then distribute power to the various locations on the boat. Each circuit has its own circuit breaker or fuse sized for the circuit wire size and/or load. It is recommended that all running lights be placed on a single circuit and at least one circuit be provided for each general use. For example, the bilge pump may be the only item on one circuit, cabin lights on another and so on. Reduced electrical noise will usually result if electronic gear is on a separate circuit.

Branch circuit design should begin by developing a circuit diagram for the boat. Branch circuits are determined by the various uses. The load (amperage) on each branch circuit can be determined from requirements of components and number of components per circuit. Once the amperage is determined, the wire size can be selected using Tables 3 or 4 and Tables 11, 12 or 13. Wire insulation can be selected using Tables 5, 6 or 7 and knowing what wire is stocked by the local suppliers. Circuit breakers or fuses are then sized based on circuit load or wire size, whichever is less.

Begin installation once all components and necessary tools are selected, purchased and/or assembled. Be sure to purchase distribution boxes, circuit breakers, wire supporting brackets, wire end terminals, switches, electrical tape and other necessary items. Follow good installation practices outlined in the previous material to produce a reliable boat electrical system.

SYSTEM USE

Once you have drawn the circuit diagram, make several copies. Keep the original at home for reference and carry at least one copy on the boat at all times. The diagram on the boat should be protected from water, weather and abuse. One good method is to laminate it in plastic sheets. If lamination is not possible, keep the copy in a waterproof container and store it in a convenient on-board location. A Zip-Loc plastic bag provides waterproof storage but not mechanical protection.

Even a good electrical system may experience occasional problems, so carry a few repair parts and tools on the boat. You should always have at least these spare items on board:

1. 3 to 6 meters (10 to 20 feet) of extra wire
2. New conductor terminal ends
3. Fuses of all sizes used (at least two of each size)
4. A roll of plastic electrical tape
5. Screwdrivers, two sizes each of straight bit and phillips types

6. A set of nut driver wrenches

7. A set of small end wrenches

8. Wire cutters

9. Crimping tool

10. Needle nose pliers

11. Wire strippers

12. Assorted small screws

13. Volt-ohm meter or test light

This equipment can be sealed in Zip-Loc plastic bags and stored for long periods without deterioration, even in salty air.

TEST EQUIPMENT

Troubleshooting electrical systems is often difficult without some type of test equipment because you cannot see an electrical leak or a flow of current. A test light is the minimum equipment required. This consists of a bulb of the same voltage rating as used in the boat circuits, a socket for the bulb and some extended lead wires to the socket. Connecting this bulb between a hot wire and ground determines if voltage is present. If the bulb lights up, the wire has voltage supplied to it; if not, the problem is between the test point and battery. A test bulb is cheap, convenient, commercially available and provides sufficient information in many cases.

A meter capable of reading volts, ohms and amperage is a much better troubleshooting tool because it gives more information than a test bulb. It can be used to check some components for which a test bulb is inadequate. However, a volt-ohm-ampere (VOM) meter is more expensive. The cost of VOM meters varies with their complexity, ranging from $20 to $300. Usually the cheaper ones are sufficient. These meters can be used to check voltages between any two points, resistance between any two points and flow of current through most locations.

TROUBLESHOOTING

Every electrical system occasionally breaks down. When this occurs, it is desirable to repair the malfunction as swiftly and as economically as possible. In this section, troubleshooting common malfunctions is discussed. The discussion assumes the system was installed at some point in the past and was working properly before the malfunction occured.

Problem: Dim lights

Probable Causes:

1. Battery charge low (check voltage).
2. Poor connection in system between battery and light.
3. Insulation on wires leaking to ground causing excess current flow.

Problem: Lights out

Probable Causes:

1. Fuse blown or circuit breaker tripped.
2. Bulb burned (usual cause if other lights remain lighted).
3. Broken connection in wiring.
4. Wire insulation damaged causing short circuit.
5. Battery discharged.

Problem: Bilge pump will not run

Probable Causes:

1. Fuse blown or circuit breaker tripped.
2. Battery discharged.
3. Pump rotor clogged.
4. Broken connection in wiring.
5. Wire insulation damaged causing short circuit.
6. Pump motor burned out.
7. If pump runs but slower than normal, check voltage across pump. Low voltage reduces speed and draws excessive current which will overheat the motor.

Problem: Wipers will not run

Probable Causes:

1. Fuse blown or circuit breaker tripped.

2. Battery discharged.

3. If engine is running, voltage regulator in charging circuit for battery may be bad.

4. Mechanical binding of wiper arms or bearing seized.

5. Wire connection broken.

6. Wire insulation damaged causing a short circuit.

7. Wiper motor burned out.

Problem: Radio will not receive and/or send signals

Probable Causes:

1. Fuse blown or circuit breaker tripped.

2. No power to set because:

   a) the battery is discharged;
   b) there is a broken connection in the wiring;
   c) the wire insulation is damaged and is causing a short circuit;
   d) it is unplugged.

3. Low voltage to receiver.

4. Antenna disconnected.

5. Improperly tuned or operated.

6. Receiver has internal electrical problem and needs repair.

Problem: Radio has excessive static

Probable Causes:

1. Radio not properly bonded (grounded).

2. Bonding connection loose or improperly made.

3. Poorly tuned engine causing arcing in ignition system (e.g. points, leaking wires, etc.).

4. Leak in electrical wiring system insulation.

5. Poor or damaged connection in electrical connections somewhere on boat.

6. Electric motors (particularly DC motors with brushes) operating in close proximity to radio because the:

   a) brushes are arcing too much (install new brushes or clean armature);
   b) motor setting up a field interfering with radio system.

7. Antenna connection not secure.