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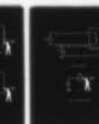
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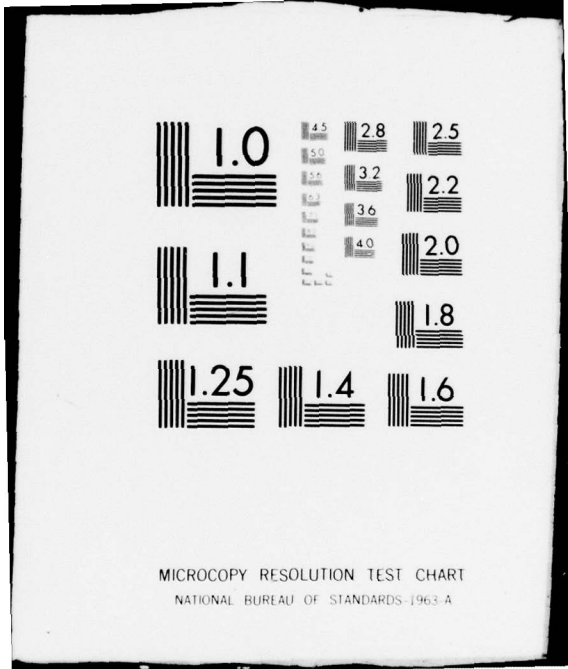
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Technical Report 356

## SAFETY CONSIDERATIONS FOR THE RUWS POWER SYSTEM

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## BACKGROUND

### RUWS DESCRIPTION

The Remote Unmanned Work System (RUWS) is a remotely controlled submersible system which can perform a variety of work tasks at ocean depths to 20,000 ft (6100 m). This depth capability gives the RUWS Vehicle access to more than 98 percent of the ocean floor. The system is designed for air transport and deployment from specified ships of opportunity. A high-accuracy deep ocean navigation system and local area bottom search sonar are used by the operator to guide the Vehicle to the work site. Once it is at the sea-floor site, an extremely versatile work capability enables the operator to accomplish a wide variety of tasks. Typical tools used by the Vehicle include a hydraulic drill and a cable cutter. The Vehicle design facilitates its use as a remote operator for auxiliary equipment.

RUWS equipment on the support ship consists of a Control Center, a Motion Compensation Deck Handling System (MCDHS), diesel power generators and a maintenance van. A single-coaxial-core, high-strength, synthetic cable connects the Control Center with the Primary Cable Termination (PCT). The PCT serves as a line weight to aid in station-keeping and to limit dynamic forces which otherwise might be transmitted to the work Vehicle. It is the power and signal distribution center between the Primary Cable and the flexible, multi-conductor Vehicle Tether. The PCT, with its own propulsion system, provides the capability for ship-coordinated transitting across the ocean floor to establish a new holding position. This obviates continuous recovery and redeployment during search operations.

The heart of the system is the work Vehicle, which moves freely at the end of a flexible tether. All signals and power necessary to control and operate the submersibles are multiplexed on the single coaxial core of the Primary Cable. Spare power and control channels are provided to facilitate interfacing with other systems.

The deep ocean navigation system provides coordinated navigational inputs to the Vehicle operators and the support ship's bridge. The system employs computerized sonar navigation coupled with real-time CRT displays to track the position of the surface ship, the PCT at the bottom of the primary cable, and the Vehicle as it is maneuvering over the ocean floor. A system display on the bridge indicates the ship's safe maneuvering area.

At the work site, a four-degrees-of-freedom grabber holds onto the workpiece, while a highly dexterous, seven-degrees-of freedom manipulator positions individually powered tools or performs other work functions.

After the Vehicle and PCT are deployed and at operating depth, three people are required for operation: a Vehicle Operator, a PCT Operator and an Operations Coordinator, all located in the CON/NAV Center. For deployment and recovery, an MCDHS Operator and several deck hands are required.

### POWER SYSTEM DESCRIPTION

The NOSC Drawing, RG8006, included as Appendix A to this document, illustrates the power system. The system consists of a main generator, a winch, generator, a high voltage

transformer, a van transformer, a signal separator for the MCDHS, and a signal separator on the PCT.

Power is supplied to the power system by the main diesel generator. The generator provides 440 volts, 3 phase, 60 Hz at up to a maximum of 100 kW. One phase of the 440-volt AC power is stepped up to 3000 volts AC in the High Voltage Console in the Control Van. The 3000-volt power is then transmitted to the MCDHS, which houses the Signal Separator. The Signal Separator combines the 3000-volt power with the command/instrumentation signals by means of filtering and transmits both to the PCT on the single coaxial Primary Cable.

At the PCT, the power is separated from the command/instrumentation signals in the Signal Separator Bottle. The 3000-volt power is distributed to (1) the 15-hp AC motor which drives the PCT hydraulic motor pump, (2) a power transformer with many low-voltage secondary windings for power supplies and various electronic subsystems, and (3) to the Vehicle.

Signals and power are transmitted to the Vehicle from the PCT via the vehicle tether, which consists of three conductors. Two high voltage power conductors transmit the 3000-volt power and a coaxial conductor transmits the signals.

The power distribution on the Vehicle is similar to that on the PCT. The 3000-volt power is distributed to the Vehicle motor pump and the power transformer.

## PRELIMINARY DATA

### GUIDELINES

In establishing the safety criteria for the RUWS Power System, four basic guidelines were considered to be of paramount importance. First, the most dangerous situation exists when personnel are working on the Vehicle and PCT while they are on the laboratory floor or the ship's deck. Second, it is believed that safety should be the first priority criterion for selection of either a grounded or isolated power system; thus, RF transmission will be a secondary consideration. Third, to limit analysis to a reasonable level, a maximum of two faults should be considered practical. Finally, component failure is not the most likely failure mode to occur. The electronic components used in the high voltage power system are of high quality and have low probabilities of failure when compared with other failure modes. Cable damage and a breakdown of insulation resistance in either the motor pump or transformer bottles have a much higher probability of failure.

Study of the literature then yielded the following information regarding the current levels considered to be hazardous to humans (References 1 and 2).

Current perceptible to women	0.7 mA
Current perceptible to men	1.1 mA
Trip level of Ground Fault Interrupters (National Electric Code dwelling requirements)	5.0 mA
"Let-go" current for women	10.5 mA
"Let-go" current for men	16.0 mA
Electrocution level (Adults, 0.1 sec)	380.0 mA



Also, it was determined that body resistance can be as low as 300 ohms. By combining this with the above data, the levels at which injury from electrical shock will occur can be calculated, as follows:

0.7 mA	—	.21 VAC
1.1 mA	—	.33 VAC
5.0 mA	—	1.50 VAC
10.5 mA	—	31.50 VAC
16.0 mA	—	48.00 VAC
380.0 mA	—	144.00 VAC

### **RUWS POWER SYSTEM CHARACTERISTICS**

The following RUWS Power System data have been either measured or calculated. These data are required if an accurate failure and effect analysis is to be performed.

- Operating voltage is 3000 VAC at 60 Hz.
- Full load current is 15 A.
- The center conductor of the primary cable has a resistance of 4.9 ohms and the shield has a resistance of 7.2 ohms. At full load this produces a voltage drop of 75 volts and 110 volts from the van to the PCT.
- The high voltage conductors in the secondary cable have resistance of 11 ohms. At full load, this produces a voltage drop of approximately 80 volts from the PCT to the Vehicle.
- There is stray capacitance from the shield of the Primary Cable to the storage reel. Early measurements of this capacitance was 0.03  $\mu$ f. At 60 Hz, this is an impedance of 88 K ohms. For 3000 VAC across 88 K ohms the current is 35 mA. Usage of the primary cable and the degree of wetness of the cable have varied this capacitance. Capacitance has been measured up to 2  $\mu$ f. 2  $\mu$ f is an impedance of 1300 ohms. At 3000 volts, the current through 1300 ohms is 2.3 A.
- During maintenance, grounding straps are attached to the frames of the PCT and Vehicle to prevent a buildup of electric potential to earth or ship's ground.

### **RUWS POWER SYSTEM CONFIGURATIONS**

#### **GROUNDED SYSTEM**

A grounded system is illustrated in Figure 1. Note that the shield of the Primary Cable is grounded at the van end only, preventing large ground currents from flowing during operation.

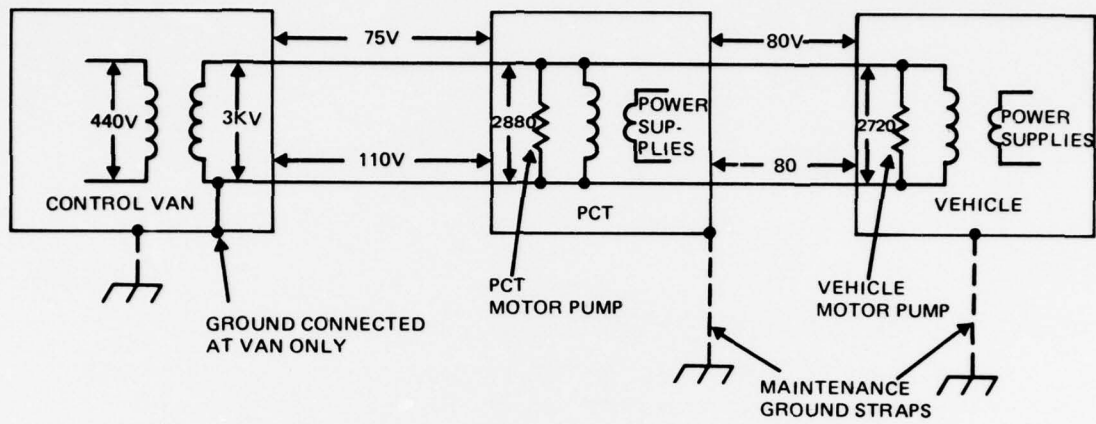


Figure 1. Grounded system.

### ISOLATED SYSTEM

An isolated system is illustrated in Figure 2. In this system there is no intentional connection to ground. Impedance from the shield to ground is from stray capacitance only.

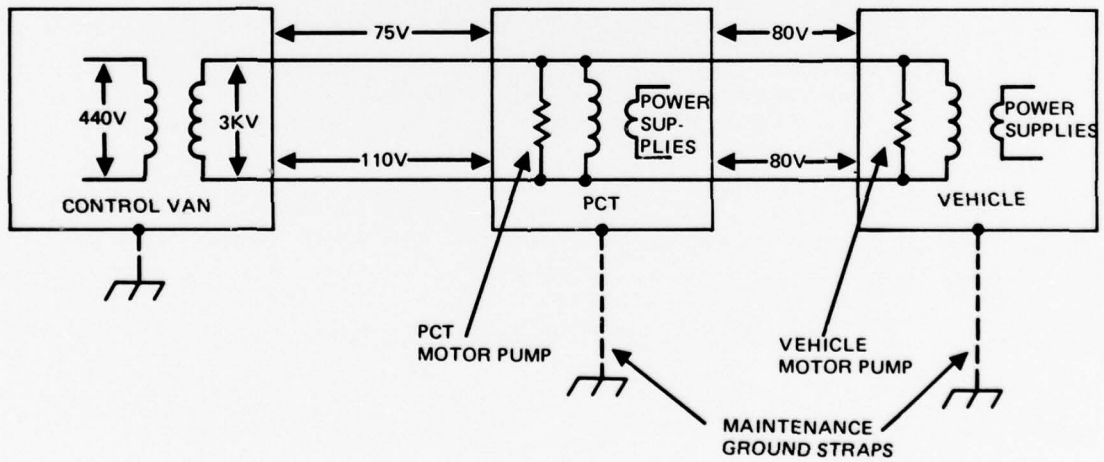


Figure 2. Isolated system.

## RESISTOR GROUNDED SYSTEM

A resistor grounded system is illustrated in Figure 3. In this case, the shield of the Primary Cable is grounded through a resistor. Impedance from the shield of the Primary Cable to ground is the grounding resistor in parallel with the stray capacitance.

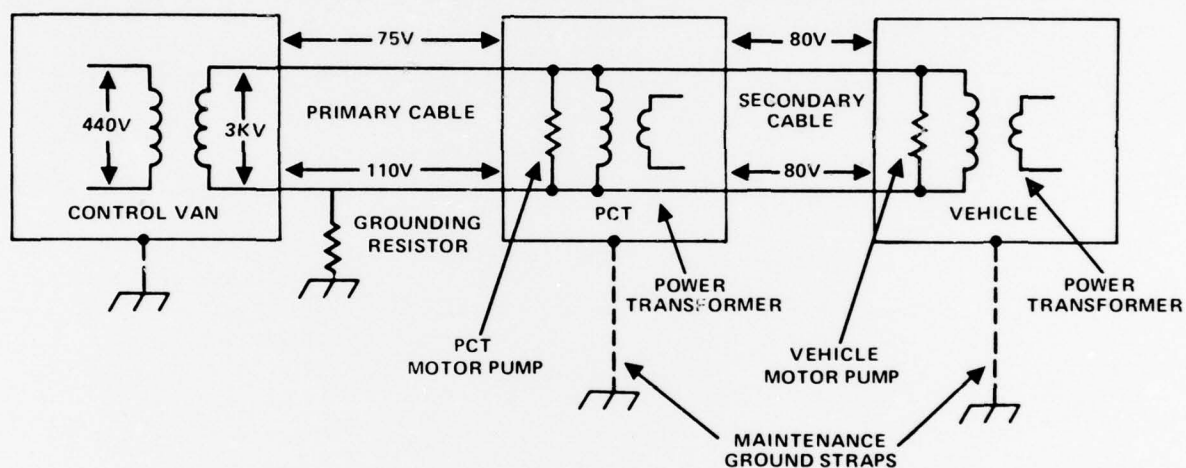


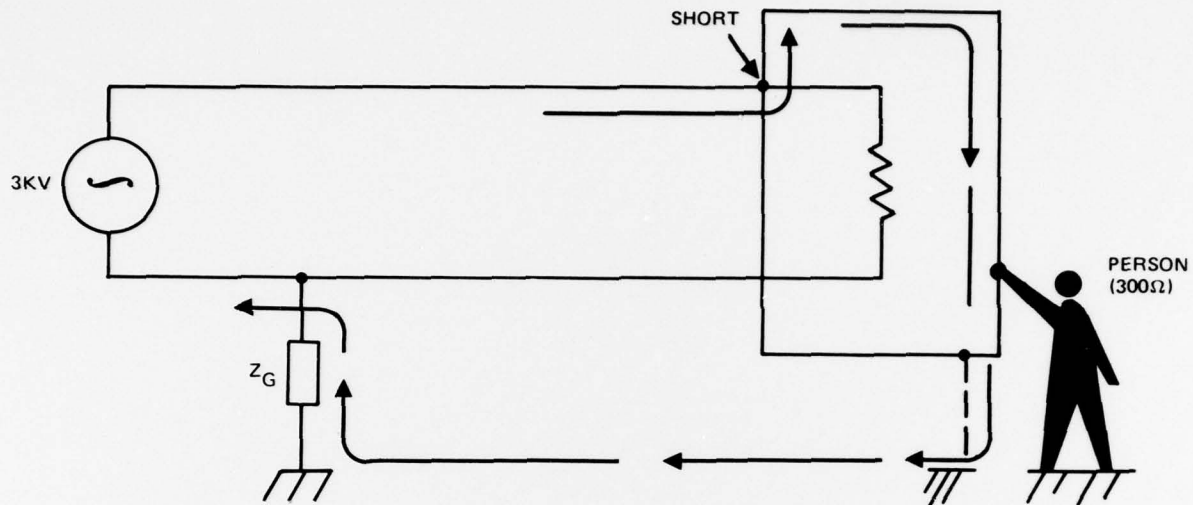
Figure 3. Resistor grounded system.

## FAILURE MODES AND EFFECTS ANALYSIS

The failure modes of all three candidate systems can be described simultaneously, since the only difference between the three systems is the impedance from the shield of the Primary Cable to ground. This impedance will be called  $Z_G$ . For the grounded system,  $Z_G$  is a direct short. For the resistor grounded system, the value of  $Z_G$  is the parallel combination of the grounding resistor  $R_G$  and the stray capacitance. The isolated system has the highest impedance of all, which is just the stray capacitance.

Four failure modes which have the highest probability of occurrence are considered. Basically, they are shorts from either the center conductor or the shield of the Primary Cable to the frame of the Vehicle or PCT. The Failure Modes (FM) are described as follows:

FM 1: A short has occurred from the center conductor of the Primary Cable to the frame of the Vehicle. The maintenance grounding strap is attached. The FM 1 fault circuit is illustrated in Figure 4.



NOTE: ARROWS INDICATE FAULT CURRENT PATH

Figure 4. Failure Mode 1.

FM 2: A short has occurred from the center conductor of the Primary Cable to the frame of the Vehicle. The maintenance grounding strap is not attached. The FM 2 fault circuit is illustrated in Figure 5. The 190 volts is the sum of the Voltage drops across one power conductor of the Vehicle Tether (80 volts) and the Voltage drop across the Primary Cable shield (110 volts).

FM 3: A short has occurred from the shield of the Primary Cable to the frame of the Vehicle. The maintenance grounding strap is attached. The FM 3 fault circuit is illustrated in Figure 6.

FM 4: A short has occurred from the shield of the Primary Cable to the frame of the Vehicle. The maintenance grounding straps are not attached. Figure 7 illustrates this fault circuit, while Figure 8 is a simplified diagram of the same failure.

In the following paragraphs, each of the systems is discussed in terms of its general characteristics, as well as an analysis of the effect of each of the failure modes.

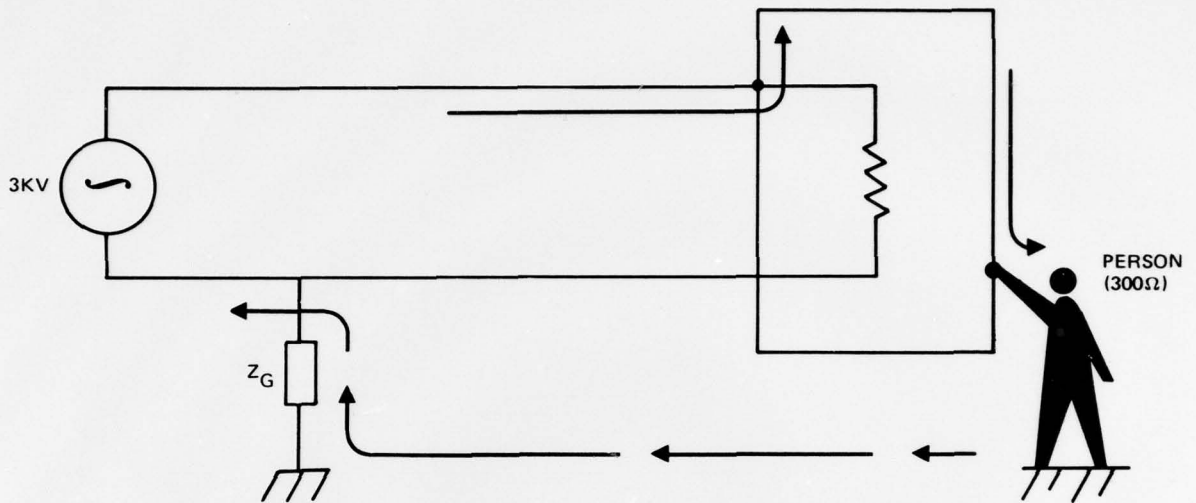


Figure 5. Failure Mode 2.

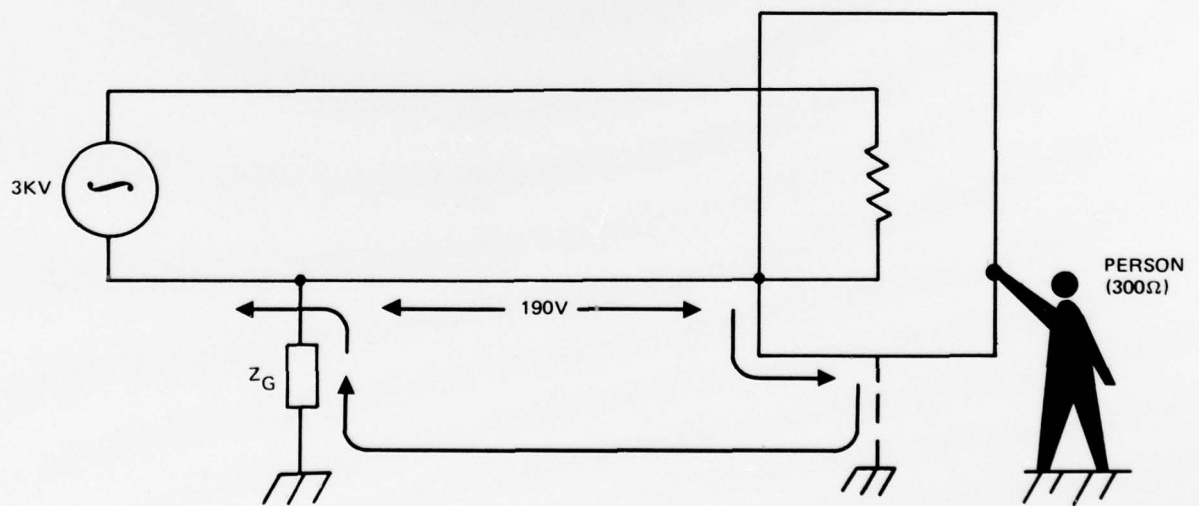


Figure 6. Failure Mode 3.

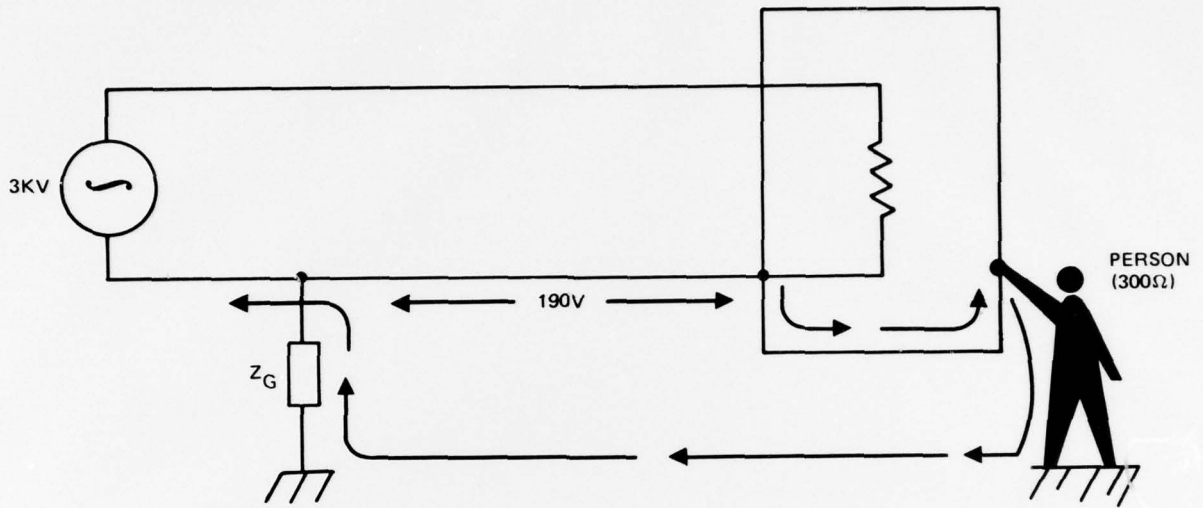


Figure 7. Failure Mode 4.

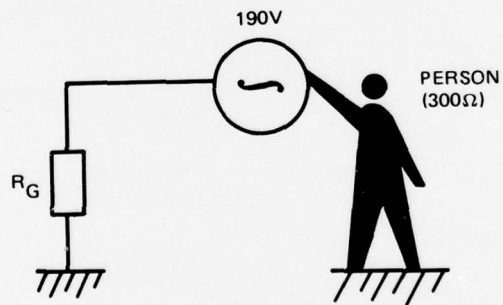


Figure 8. Failure Mode 4 simplified.

## GROUNDING SYSTEM

### General Characteristics

In this system, the shield of the Primary Cable is connected to earth or ship's ground. Ground faults are easily detected. The system is characterized by large fault currents. The fault detection system consists of monitoring the current through the ground connection. This could be used to trip breakers, as in a ground fault interrupter.

### Failure Mode and Effect Analysis

<u>Failure Mode</u>	<u>Results</u>
1	No danger exists, since the frame of the Vehicle is at ground potential. The large current drawn will trip the high voltage breaker. The fault current flows through the maintenance grounding strap.
2	Danger exists, since the frame of the Vehicle is at 3000 volts with respect to ground. Current through the victim is 10 A.
3	No danger exists, since the frame of the Vehicle is at ground potential. The ground current is large enough to be detected. The fault current flows through the maintenance grounding strap.
4	Danger exists, since the frame of the Vehicle is at 190 volts with respect to ground. Current through the victim is 633 mA.

## ISOLATED SYSTEM

### General Characteristics

Since no ground connection is incorporated into this system, ground faults are difficult to detect, and are possible only at the PCT/Vehicle end of the cable. Thus, any fault must be telemetered back to the surface. This would require an unacceptable time lag of  $> 0.1$  sec. In all failure modes, the ground current is dependent on the stray capacitance. Stray capacitance can vary by as much as 100 or 1000, depending on whether or not the cable reel is wet.

### Failure Mode and Effect Analysis

<u>Failure Mode</u>	<u>Result</u>
1	No danger exists, since the frame of the Vehicle is at ground potential. The fault current is 34 mA to 2.3 A and flows through the maintenance grounding strap.
2	Danger exists, since the frame of the Vehicle is at 3000 volts with respect to ground. The fault current through the victim is 34 mA to 1.9 A.
3	No danger exists, since the frame of the Vehicle is at ground. Ground current is 2.1 mA to 150 mA and flows through the maintenance grounding strap.
4	Danger exists, since the frame of the Vehicle is at 190 volts with respect to ground. The fault current through the victim is 2.1 mA to 120 mA.

### RESISTOR GROUNDED SYSTEM

#### General Characteristics

This system is grounded through a resistor at the van end, which limits fault currents and permits easy fault detection. The fault detection system is the same as that in the grounded system.

The value of the grounding resistor should be chosen low enough to be comparable to the 88K ohms, but high enough to limit the ground fault current to a safe level. For purposes of discussion, a resistance of 100K ohms was selected.

#### Failure Mode and Effect Analysis

<u>Failure Mode</u>	<u>Result</u>
1	No danger exists, since the frame of the Vehicle is at ground potential. The ground current is 45 mA to 2.3 A and there is no current through the victim.
2	Danger exists, since the frame of the Vehicle is at 3000 volts with respect to ground. The current through the victim is 45 mA to 1.9 A.
3	No danger exists, since the frame of the Vehicle is at ground potential. The ground current is 2.9 mA to 146 mA.



Failure Mode

Result

4 Danger exists, since the frame of the Vehicle is at 190 volts. The source impedance of the circuit is low, but the current is limited by the resistor. The current through the victim is 2.9 mA to 119 mA.

**COMPARISON**

The potential hazard current levels determined through the failure mode and effect analyses is illustrated in Table 1. Basically, it must be emphasized that no system can be considered "fool proof." Table 2 lists the most significant advantages and disadvantages of each.

Table 1. Potential Hazard Current Levels.

	FAILURE MODE 1	FAILURE MODE 2	FAILURE MODE 3	FAILURE MODE 4
GROUNDING SYSTEM	0	10 A	0	630 mA
ISOLATED SYSTEM	0	35 mA - 1.9 A	0	2.5 mA - 120 mA
RESISTOR GROUNDING SYSTEM	0	45 mA - 1.9 A	0	2.9 mA to 119 mA

Table 2. Power System Comparisons

	ADVANTAGES	DISADVANTAGES
GROUNDING SYSTEM	<ol style="list-style-type: none"> <li>1. Simple ground fault detection; build and install topside.</li> <li>2. Ground fault interrupters can be installed.</li> </ol>	<ol style="list-style-type: none"> <li>1. High fault current levels.</li> </ol>
ISOLATED SYSTEM	<ol style="list-style-type: none"> <li>1. Lower fault current levels.</li> </ol>	<ol style="list-style-type: none"> <li>1. Hard to implement ground fault detectors.</li> <li>2. Ground fault interrupters not practical; too much time in telemetry.</li> </ol>
RESISTOR GROUNDING SYSTEM	<ol style="list-style-type: none"> <li>1. Lower fault current levels than grounded system.</li> <li>2. Ground fault detection easily implemented.</li> <li>3. Ground fault interrupters can be used.</li> </ol>	<ol style="list-style-type: none"> <li>1. Higher current than in isolated case.</li> </ol>

## CONCLUSIONS

As was stated earlier in this document, no "fool proof" system exists which could be used for RUWS power. It has been determined, however, that the resistor grounded system is the most logical choice of the three candidate system types because of its low current levels and easy fault detection. Finally, if the highest level of safety is to be achieved, a complete and realistic operations procedure must be developed, and it is imperative that it be followed closely by all personnel involved in the operation of the RUWS. Appendix B illustrates such an operations procedure.

Appendix B applies only to the isolated system. For the grounded system and the resistor grounded system the intentional ground connection at the van end of the primary cable must be disconnected to achieve the insulation resistance from the Primary Cable to earth ground.

During the RUWS ocean operations of October-November 1977, burns were found on the Primary Cable Kevlar armor. At two of these points, definite breakdowns in the outer polyethylene insulation jacket were found. It appeared that arcing occurred between the primary cable shield and the external Kevlar armor. This probably happened during the fault when a high voltage connector pin, whose potential was the same as the primary cable center conductor, was shorted to the seawater. This produced a 3000 VAC potential across the primary cable shield and the Kevlar armor.

The resistance from the primary cable shield to the cable reel now measures as low as 200K ohms. The capacitance between the primary cable shield and the cable reel frame measured 2.4 microfarads. Because of this breakdown of the insulation jacket, the high stray capacitance between the primary cable shield and ground, and the low resistance from shield to ground, the shield of the primary cable was shorted to earth ground at the transformer in the High Voltage Console. So RUWS is now being operated as a grounded system.

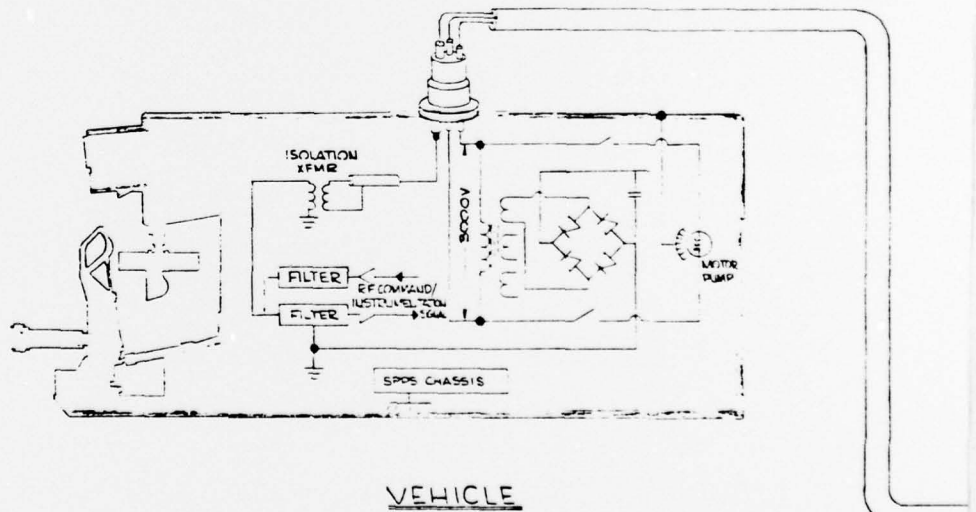
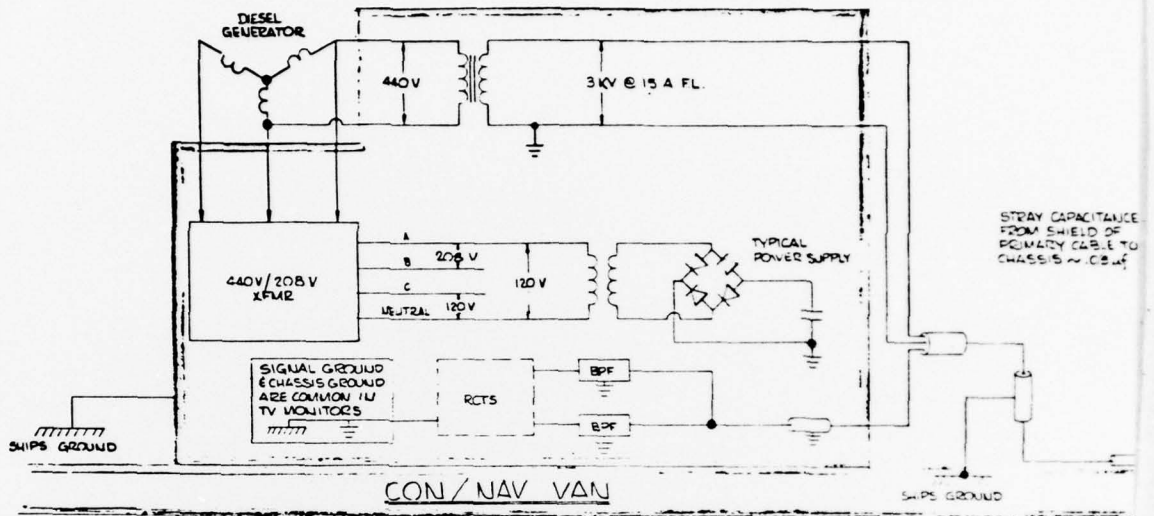
## REFERENCES

1. Dalziel, C. F., *Article X72-125*, IEEE.
2. *Electric Shock: Its Causes and Its Prevention*, Bureau of Ships, Navy Department, NAVSHIPS 250-660-42.

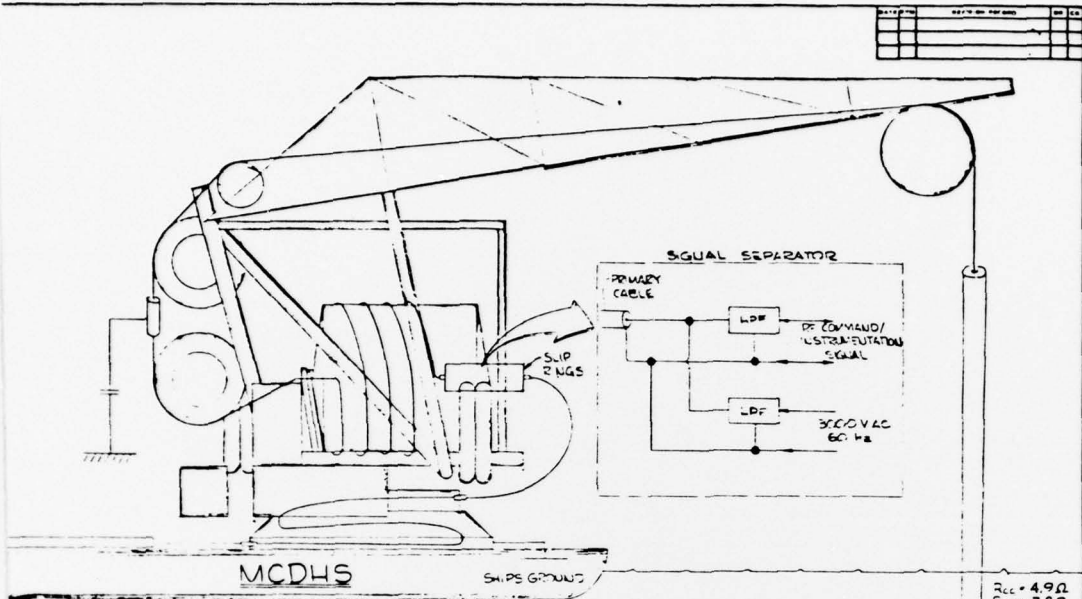
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APPENDIX A

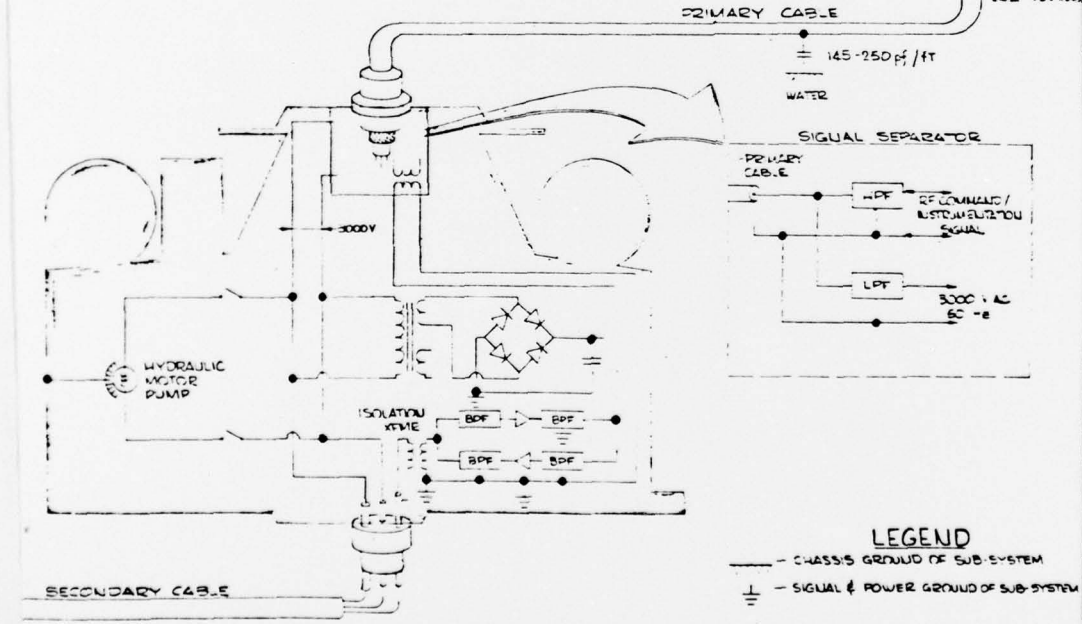
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$R_{cc} = 4.9 \Omega$   
 $R_{sh} = 7.2 \Omega$   
 $I_{c} = 95 \text{ V RMS}$



LEGEND

- CHASSIS GROUND OF SUB-SYSTEM
- $\pm$  — SIGNAL & POWER GROUND OF SUB-SYSTEM

PCT

DESIGNED BY	NAVAL UNDERSEA CENTER
DATE	12-1-78
BY	RJWS
APPROVED BY	CELESTIAL REGISTRATION OF
DATE	28-5-008

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## APPENDIX B SAFETY PROCEDURES

The effectiveness of a safely designed system is measured, in large part, by the way in which it is used. Even the best system, if operated in a careless manner, could prove hazardous. For this reason, the safety procedures listed below are recommended for all operation of the RUWS power system.

### SYSTEM CHECKOUT

The following procedures will be followed to check out the system before operation. The same procedures apply for land or shipboard checkout. Therefore, all references to earth ground apply to ship's ground.

1. Ground the generators and vans to earth or ship's ground.
2. Measure the resistance from the Vehicle frame to earth ground and from the generators and vans to earth ground. Resistance should be  $< 0.2 \Omega$ .
3. Measure the resistance from the MCDHS frame to earth ground. Resistance should be  $< 0.2 \Omega$ .
4. Prior to starting the generators, check the vans and the MCDHS cab to ensure that all breakers are OFF. Check the power cables from the generators to the vans and the MCDHS for physical damage.
5. Prior to switching power to the PCT and the Vehicle:
  - a. Ground the PCT and Vehicle frames by attaching maintenance line straps from both frames to earth ground.
  - b. Disconnect the high voltage plug at the Control Van. Measure the resistances from both high voltage power leads to earth ground. Resistance should be  $> 100 M\Omega$ . If the primary coaxial plug is disconnected at the PCT, measure the resistance across the two power leads. Resistance should be  $> 1000 M\Omega$ . Also measure the resistance from the coaxial signal cable center conductor and shield to both power leads. Resistances should be  $> 1000 M\Omega$ . (This test should be done on the plug of the cable leading to the MCDHS and on the van connector.)
  - c. At the PCT, measure resistances from signal ground to both power leads. Resistance should be  $> 100 M\Omega$ . Measure both power leads to the PCT frame. Resistance should be  $> 100 M\Omega$ .
  - d. Repeat step c. for the Vehicle.
  - e. If the SPPS liners are out of the bottles, attach grounding straps to the frame of the liners.
6. Switching power to the PCT and the Vehicle from the Control Van:

- a. With the 3000-VAC breaker on the Power Console OFF, switch on the 440-VAC breaker in the rear of the van.
  - b. Notify personnel in the area that power is being applied to the vehicles. Set the current trip indicator to 25 Amps on the current meter. Switch the 3000-VAC breaker ON.
7. Prior to switching on the motor pumps set the current trip indicator to maximum on the power console. Switch the bypass valve on the Control Console to open. Notify personnel that the motor pump is being switched on and ensure that no one is near the PCT and the Vehicle thrusters. Switch motor pump to ON. After switching on the motor pump, close the bypass valve and reduce the current trip indicator to a value 10 Amps higher than the current reading.
  8. Whenever the manipulator, grabber, and TV gimbal are activated, notify personnel and ensure that no one is near these devices.

#### **DEPLOYMENT AND RECOVERY**

The following procedures will be followed during all deployments and recoveries of the RUWS.

1. Personnel involved will wear hard hats, safety shoes and gloves.
2. Cable handlers will wear insulated shoes and insulated gloves. They will visually check the cable for damage as it is paid out or reeled in.
3. Swimmers and divers will remain clear of all RUWS elements whenever power is applied to the vehicles. They will not touch the frame of the Vehicle while power is on unless it is absolutely necessary. If such contact is required, they will avoid touching two points on the vehicles simultaneously. Swimmers and divers will avoid placing themselves between the vehicles and the ship.
4. Swimmers and divers will not place themselves under the vehicles during the launch or recovery of the vehicles.

#### **OTHER STANDING PROCEDURES**

The following procedures will be followed throughout all operations with the RUWS.

1. Whenever power tools are being handled, only tools with grounded frames will be used. They will be plugged into the ground fault interrupter boxes which are provided.
2. Oil spills will be wiped and cleaned immediately to prevent slipping or injury to personnel.
3. Standing safety precautions for the handling of explosive bolts will be followed at all times.

4. During ship deployment, all equipment will be latched down and secured.
5. Long coaxial cables (Primary Cable) can accumulate static charges of a sufficiently large magnitude to be a hazard to both personnel and test equipment such as TDR, spectrum analyzers, etc. Personnel should short the shield to earth ground; then short the center conductor to the shield to ensure no static charge exists before touching or making connections to the exposed leads.