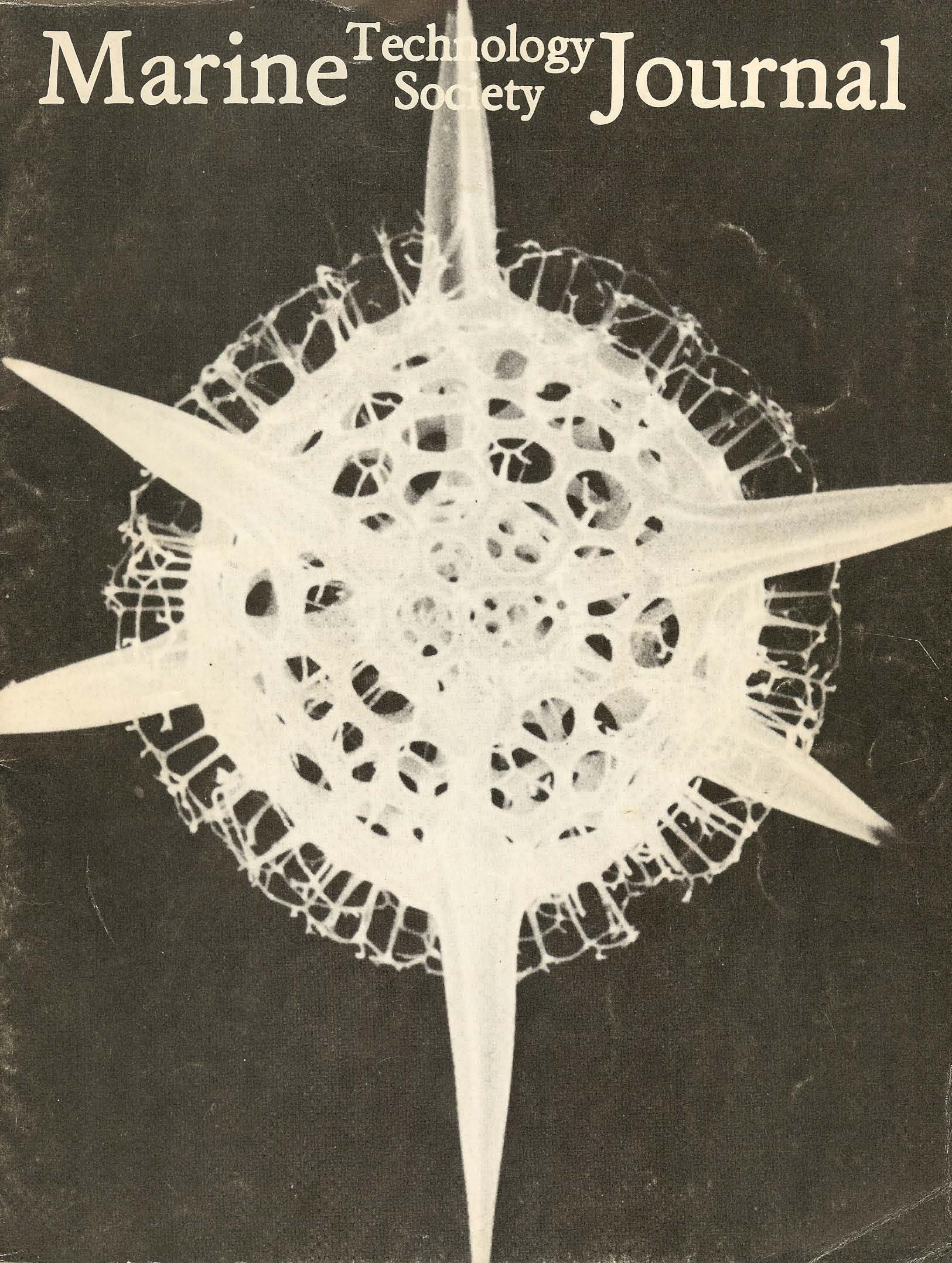
# Marine Technology Society Journal



# Grounded vs. Ungrounded Electrical Systems for Use in Manned Submersibles

**Kenneth W. Privitt**
*MARFAB*
*Santa Ana, California*

In recent months a controversy has developed over the use of a grounded electrical system in manned submersibles. The purpose of this paper is to examine the basic engineering principles governing the use of any electrical system in manned submersibles, and to make the designer cognizant of the important factors to be considered in utilizing a proposed system. I will explore the reliability, corrosion, shock, and penetrator design aspects for both a grounded and ungrounded electrical system, and, contrast the two systems showing the applicability of each in undersea vehicles.

## INTRODUCTION

A grounded electrical system uses either a single wire and the hull or frame to carry current to the load or two wires with one leg connected to the hull (as in automobiles and airplanes). An ungrounded system uses two wires to carry the current, leaving the hull or frame isolated. In recent months a controversy has developed over the use of grounded electrical systems in manned submersibles. The regulatory agencies overseeing the classification of manned submerisibles have taken the stand that all electrical systems shall be of the ungrounded type, even though many years of operating experience have demonstrated the soundness and safety of the grounded system. Several prominent builders and operators of small submersibles take exception to the blanket exclusion of the grounded system because of the inherent simplicity, reliability, and reduction of through hull penetrators with the grounded system.

In the following analysis I will make a comparison of the grounded and ungrounded systems in terms of reliability, galvanic corrosion, shock hazard, and penetrator design. In each case I will cover the basic engineering principles governing both systems and point out the primary areas of concern, so that an intelligent decision can be made on the applicability of a proposed system.

## RELIABILITY

In an electrical system the two major modes of failure are short and open circuiting. Typical modes of short circuit failure are abrasion of the wiring, deterioration of the insulation due to age or environmental conditions, human error, etc. Typical modes of open circuit failure are: shearing, excessive current, fatigue, human error, etc. The probability of a system failure is proportional to the complexity of the system, and to the length of time it is in service. Let $P_S$ and $P_O$ equal the probability of a unit piece of wire to have a short and open circuit failure respectively, over the life of the system. Let the amount of wire used in a grounded system equal $\ell$. For a similar ungrounded system, the amount of wire necessary is equal to $2\ell$.

The probability of a short circuit failure for a gounded system is $P_{S1} = 1 - (1 - P_S)^{\ell}$. The probability of a short circuit failure in an ungrounded system is $P_{S2} = 1 - (1 - P_S)^{2\ell}$. Expanding each in a McLauren series and retaining only the first two terms yields:

$$P_{S1} \approx -\ell \; \ell n\,(1 - P_S) \qquad \left| P_S \right| \leqslant 1$$

$$P_{S2} \approx -2\ell \; \ell n\,(1 - P_S)$$

$$\ell n\,(1+x) = x - \frac{x^2}{2!} + 2!\frac{x^3}{3!} - \cdots + (-1)^{n-1}(n-1)!\frac{x^n}{n!} + \cdots$$

$$-1 < x \leqslant 1$$

Substituting and retaining only the first term yields:

$$P_{S1} \approx P_S\ell$$

$$P_{S2} \approx 2P_S\ell$$

In the ungrounded system there are two degrees of short circuit failure. The first (Type 1) is when a single wire becomes shorted. Ungrounded systems should utilize a ground detector to monitor such a failure. When such a failure occurs, immediate attention must be given to the situation, because if the positive leg was the one to become shorted, a subsequent failure could cause serious hull corrosion. The second type of failure is when two shorts occur (Type 2), distributed one on each leg. Two shorts on a single leg is still a type 1 failure. Therefore, the probability of a type 2 failure is reduced, and is

$$P_{s2}' = \frac{P_{s2}}{4} \approx \frac{P_s \ell}{2}.$$

The probability of an open circuit failure for a grounded system is equal to $P_{o1} = 1-(1-P_o)^{\ell}$. The probability of an open circuit failure for an ungrounded system is equal to $P_{o2} = 1-(1-P_o)^{2\ell}$. A similar expansion as for the short circuit case yields:

$$P_{o1} \approx P_o \ell$$

$$P_{o2} \approx P_o \ell$$

The total probability of failure for the two systems are:

$$P_{F1} = P_{s1} + P_{o1} - P_{s1}P_{o1}$$

$$\approx \ell (P_s + P_o - P_s P_o \ell)$$

$$P_{F2} = P_{s2} + P_{o2} - P_{s2}P_{o2} \quad \text{Type 1}$$

$$\approx 2\ell (P_s + P_o - 2P_s P_o \ell)$$

$$P_{F2}' = P_{s2}' + P_{o2} - P_{s2}' P_{o2} \quad \text{Type 2}$$

$$\approx 2\ell \left(\frac{P_s}{4} + P_o - \frac{P_s P_o \ell}{2}\right)$$

Plotting the relative magnitude of the total probability ($P_{F1}/P_{F2}$) as a function of the relative probability of short and open circuit failures ($P_s/P_o$) yields:

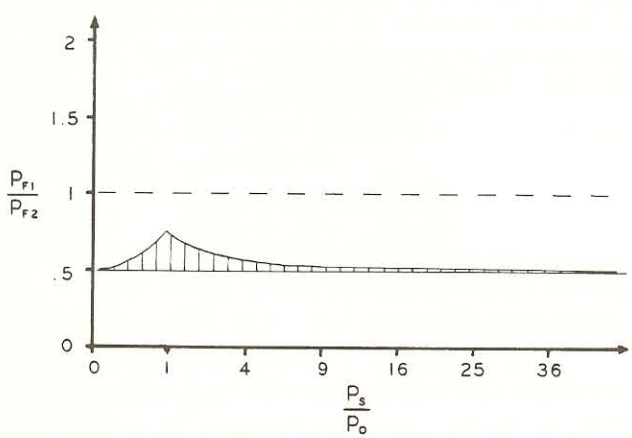



**Figure 1. Reliability Profile for a Typle 1 Failure.**

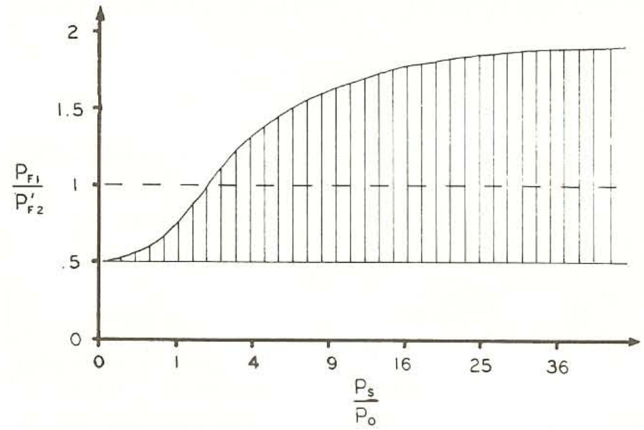



**Figure 2. Reliability Profile for a Type 2 Failure.**

In terms of a type 1 failure, the grounded system is always more reliable than the ungrounded system. In terms of a type 2 failure, either system may be more reliable depending on the relative probability of short and open circuit failures. An additional feature of the grounded system is that there is a 50 percent reduction in through hull penetrators, due to the fact that the hull is the return.

## CORROSION

"The requirements for the electrochemical nature of the corrosion process are: (1) anodes and cathodes must be present to form a cell, (2) the anode and cathode must be in electrical contact, and (3) the liquid environment must serve as an electrolyte. At the anodic site an oxidation process occurs and metal goes into solution via a reaciton of the type

$$Fe \text{ (metal)} \rightarrow 2e^- + Fe^{++} \text{ (ion in solution)}.$$

At the cathode a reduction process occurs that generally results in the reduction of dissolved oxygen or the liberation of hydrogen gas. These two reactions can be written as:

$$O_2 \text{ (in solution)} + 4e^- + 2H_2O \rightarrow 4OH^- \text{ (ion in solution)}$$

$$2H^+ \text{ (in solution)} + 2e^- \rightarrow H_2 \text{ (gas)}.$$

The actual corrosion process occurs at the anode, where metal ions leave the metal surface and enter solution. At the cathodic region there is no corrosion, and this is the area where electrons flow from the metal to the solution."[1]

In the grounded system, the negative terminal of the battery is connected to the hull, forcing the hull to be cathodic in any galvanic action driven by the battery. Under normal operating conditions all electrical conductors are insulated. Thus, condition (2) is not met and corrosion will not take place. In the event of a fault satisfying condition (2) the hull will be protected by the

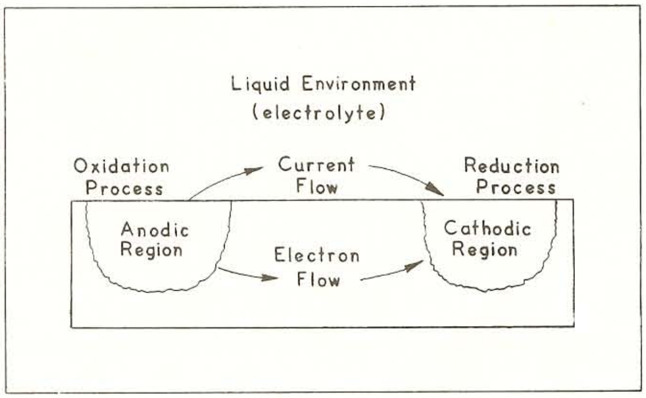



**Figure 3. Schematic Illustration of Metallic Corrosion[1].**

cathodic reaction—(i.e., Ions in solution will be plated onto the hull).

If a fault occurs in an ungrounded system the positive terminal of the battery could become grounded, forcing the hull to become anodic in any galvanic action driven by the battery. Serious hull corrosion would result upon the satisfaction of condition (2), a type 2 short. Therefore, it is necessary to carry a gound fault detector in an ungrounded system to ensure against such potentially hazardous situations.

It should be noted that high currents are not recommended for use in a single wire grounded system due to the fact that the hull has a finite resistance. It is possible that high currents could cause a potential difference large enough to make a portion of the hull anodic and subject to corrosion. The vehicle should be coated with a zinc based paint to combat this problem, along with general corrosion associated with any steel vessel in a salt water environment. Note that this form of grounded system has been in use for more than 20 years and 3,000 dives on the Nekton vehicles, with no evidence of corrosion due to galvanic action.

## ELECTRICAL SHOCK

In a grounded system human contact with one leg of the potential is readily available throughout the vessel (the hull), while in an ungrounded system the hull is isolated, and human contact with the potential is greatly reduced. A shock is essentially a short circuit through the human body. From the reliability analysis, the probability of a shock (short) in a grounded system is $P_{S\ell}$ and for an ungrounded system is $\frac{P_{S\ell}}{2}$. Therefore, an ungrounded system is twice as safe as a grounded system for high system voltages. The U.S. Government MIL-STD-454E[2] requires no special protection for systems utilizing voltages of less than 30 V. DC or RMS. From 30-70V. no specific requirements exist, however, the design should be reviewed for possible hazards in accordance with Table 1.

**TABLE 1**
**Probable Effects of Shock[2]**

| Current value (milliamperes) | | |
|---|---|---|
| AC 60 Hz | DC | Effects |
| 0-1 | 0-4 | Perception |
| 1-4 | 4-15 | Surprise |
| 4-21 | 15-80 | Reflex action |
| 21-40 | 80-160 | Muscular inhibition |
| 40-100 | 160-300 | Respiratory block |
| Over 100 | Over 300 | Usually fatal |

"A shock current readily overpowers the millivolt operating levels of the nerve electrical system. It drives the muscles much harder than normal command impulses, either throwing the victim vigorously away from the contact or freezing him onto the contact so that he cannot be released until it is de-energized."[3] The current level required to freeze a person's motor system is approximately 10mA. @ 60 Hz. and 60 mA. @ DC.[2,3,4] "By Ohms law, current is voltage divided by resistance. The resistance in this case is the resistance of the human body and any other elements in the path of the current, such as the floor, shoes, or gloves."[3]

The worst case shock situation which could arise in a grounded electrical system is to have your foot in the bilge while grabbing a hot wire with your wet hand. The resistance of a wet hand-wire interface with an area of one square inch is 8,000 ohms.[3,5] The resistance of an immersed foot with an area of approximately 60 square inches is 100 ohms. The internal resistance of the human body is 500 ohms. This worst case total resistance is 8,600 ohms. The DC voltage required to freeze a person's motor system is 60mA × 8600 ohms = 516 VDC, allowing for a safety factor of 10 yields 51.6 V≈50VDC. Therefore, there is no shock hazard in a system using a voltage of 50 VDC or less. Systems requiring large amounts of power must use higher voltages because of the excessively large currents required at lower voltages. Higher voltage systems should not use a grounded system because of the increased likelihood of serious injury due to current flow. Although, the lowest possible voltage is the safest.

## PENETRATOR DESIGN

Consider the electrical penetrator configurations for a grounded and ungrounded system shown below.

LaPlace's equation states that $\nabla^2 V = 0$.[5] In cylindrical coordinates this becomes $\nabla^2 V = \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial V}{\partial r}\right) + \frac{1}{r^2}\frac{\partial^2 V}{\partial \phi^2} + \frac{\partial^2 V}{\partial z^2} = 0$. For the coaxial arrangement of conductor and insulation, let a equal the radius of the conductor and b equal the radius of the insulation. Let the potential difference between the inner conductor and the hull equal $V_O$. By symmetry considerations the electric field is only a function of the radius so, $O=\frac{1}{r}\frac{\partial}{\partial r}(r\frac{\partial V}{\partial r})$ or $O=\frac{1}{r}\frac{d}{dr}(r\frac{dV}{dr})$. If we multiply both sides by r and integrate we get $r\frac{dV}{dr}=A$ or $\frac{dV}{dr}=\frac{A}{r}$. Integrating again yields $V=A\,\ell n\,r+B$. Choosing $V=V_O$ @ $r=a$ and $V=O$ @ $r=b$ (a grounded hull) and solving for the two constants of integration yields $V=V_O\frac{\ell n(b/r)}{\ell n(b/a)}$, from which $\hat{E}=\frac{V_O}{r}\frac{1}{\ell n(b/a)}\hat{a}_r$. For a given potential, the peak electric field is approximately proportional to $1/\ell$ where $\ell$ is the insulation thickness $(b-a)$.

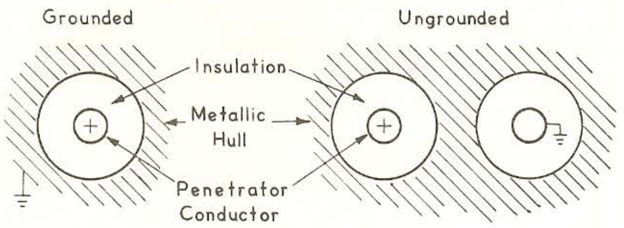



**Figure 4. Penetrator Configurations.**

Consider now the ungrounded system. By definition the potential difference between any two points is equal to

$$V_{ab}=-\int_b^a \hat{E}\cdot d\ell .$$

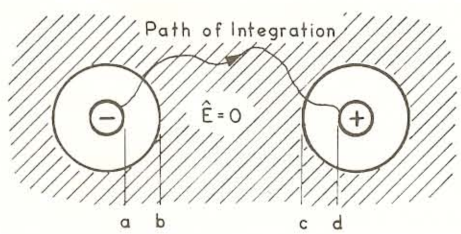



**Figure 5. Ungrounded Configuration.**

Let $V_{ad}=V_O$ (the system voltage). The electric field in the metallic hull between the two penetrators is equal to zero. If it were not, there would be current flow. Obviously there is none. So,

$$V_{ad}=-\int_a^b \hat{E}\cdot d\ell -\int_c^d \hat{E}\cdot d\ell .$$

From before, $V=A\,\ell n\,r+B$ in a coaxial arrangement. Letting $V=O$ at $r=a$ and $V=V'$ at $r=b$, $V'=\frac{1}{\alpha}$, $\alpha$ = non-negative real number; we get

$$V=V'\frac{\ell n(r/a)}{\ell n(b/a)}$$

Letting $V=V'$ at $r=c$ and $V=V_O$ at $r=d$ we get

$$V=\frac{V_O-V'}{\ell n(c/c)}\ell n\,r-\frac{V_O\,\ell nc-V'\,\ell nd}{\ell n(d/c)}.$$

From which;

$$\hat{E}\,(a<r<b)=-\frac{V'}{r}\frac{1}{\ell n(b/a)}\hat{a}_r$$

$$\hat{E}\,(d<r<c)=\frac{V_O-V'}{r}\frac{1}{\ell n(d/c)}\hat{a}_r$$

solving for $V'$ yields; $$V'=\frac{\frac{V_O}{c\,\ell n(d/c)}}{\frac{1}{c\,\ell n(d/c)}+\frac{1}{b\,\ell n(a/b)}}$$

For a given potential the peak electric field is approximately proportional to $1/\ell'$, where $\ell'$ is the sum of the two insulation thicknesses $(b-a)+(c-d)$.

The critical factor in insulation breakdown is the electric field intensity. As the electric field strength increases, the force on the bound electrons in the insulator increases until a point is reached where the field is large enough to strip the electrons away from their parent atoms. At this point current flow dramatically increases. The electric field strength where this occurs is called the dielectric strength of the material.

The parameters determining penetrator failure are the voltage applied and the amount and quality of the insulation provided. For grounded and ungrounded systems operating under the same potential and using the same insulating material, the probability of penetrator failure is inversely proportional to the amount of insulation provided. For the same amount of insulation there is no difference in penetrator failure rates. The fact that a submersible's hull is grounded has no bearing on penetrator failure. The question is not grounded vs. ungrounded but penetrator design vs. voltage applied.

## CONCLUSIONS

The main consideration in determining whether a grounded or ungrounded system be used is the system voltage, which is a function of the power requirements. Systems utilizing a voltage of 50VDC or more should use an ungrounded system because of the increased shock hazard to personnel at higher voltages. Systems utilizing a voltage of 50V DC or less, can be of the grounded or ungrounded type. However, because of the reduction of through hull penetrators and increased reliability, the grounded system is preferred. It is my opinion that the regulatory agencies are in error, and hampering the interests of safety, by their blanket requirement of an ungrounded system. I feel they should recognize the fact that low voltage grounded systems have merit, and should revise their rules to reflect this fact.

## REFERENCES

1. C.R. Barrett, W.D. Nix, A.G. Tetelman, "The Principles of Engineering Materials," Inglewood Cliffs, N.J., Prentice Hall, 1973, p.182-183.

2. U.S. Department of Defense, "Standard General Requirements for Electronic Equipment," MIL-STD-454F, 15 March 1978, Requirement 1.

3. R.H. Lee, "Human Electrical Safety," Electrical Safety Practices, ISA Monograph #110, p.27-33, 1965.

4. D.J. Hackman, D.C. Doerschuk, "Underwater Electric Shock Hazard," Battelle Columbus Laboratories, April 1974.

5. AFSC DH 1-6, Ch. 4, 20 July 1974.

6. W.H. Hayt, Jr., "Engineering Electromagnetics," New York, N.Y., McGraw-Hill, 1974.



**Kenneth W. Privitt** received his B.S. degree in Engineering from the University of California, Los Angels, in 1977 and his M.S. in Electrical Engineering in 1981 from that institute. He is now Project Engineer at MARFAB, engaged in the construction of an improved version of the "NEKTON" type submersibles with his father Douglas N. Privitt, designer of the NEKTONS.