# UNITED STATES COAST GUARD
# OCEANOGRAPHIC SENSOR STUDY

Contract DOT-CG-9C505-A

Prepared for
UNITED STATES COAST GUARD
1300 E Street
Washington, D.C. 20591

TEXAS INSTRUMENTS
INCORPORATED
SERVICES GROUP
Dallas, Texas 75222



MAY 1970

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# UNITED STATES COAST GUARD OCEANOGRAPHIC SENSOR STUDY

## VOLUME III

## THE SURVIVAL ENVIRONMENT FOR OCEANOGRAPHIC AND METEOROLOGICAL SENSORS

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UNITED STATES COAST GUARD OCEANOGRAPHIC SENSOR STUDY reports consist of

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|---|---|
| VOL. I | STATE-OF-THE-ART OF OCEANOGRAPHIC AND METEOROLOGICAL SENSORS (Tutorial Discussion) |
| VOL. II | STATE-OF-THE-ART OF OCEANOGRAPHIC AND METEOROLOGICAL SENSORS (Catalog) |
| VOL. III | THE SURVIVAL ENVIRONMENT FOR OCEANOGRAPHIC AND METEOROLOGICAL SENSORS |
| VOL. IV | THE FORMATTING AND TRANSMISSION OF DATA FROM OCEANOGRAPHIC SENSORS |
| VOL. V | ANALYSIS OF APPLYING STANDARDIZATION TECHNIQUES TO OCEANOGRAPHIC SENSORS |
| VOL. VI | TEST REQUIREMENTS FOR OCEANOGRAPHIC AND METEOROLOGICAL SENSORS |

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# PREFACE

The United States Coast Guard — in its involvement in the National Data Buoy Project and other ongoing oceanographic programs such as the International Ice Patrol, the Buzzards Bay oceanographic data system (SWORD), and the large navigation-buoy oceanographic and meteorological systems (OMDAS) — is on the threshold of a significant effort in collecting marine environmental information for use by various government and civilian agencies. As these efforts will require large expenditures, this study was assigned the primary objectives of developing concepts leading to the maximum commonality in Coast Guard-procured oceanographic and meteorological hardware and software to be used with various data-gathering platforms having different operational requirements. The ultimate aim is to realize cost savings in procurement, maintenance of equipment, and management of data.

A second objective was to develop calibration and test standards to be applied to Coast Guard-procured oceanographic and meteorological hardware to determine compliance with performance, mechanical, and electrical specifications.

To achieve these goals, the study was divided into the following five tasks:

- Task 1 gathered information needed to assess the ability of current technical design approaches to meet Coast Guard operational requirements
- Task 2 developed the environment in which the instrument systems would be expected to survive to perform their purpose
- Task 3 analyzed the data-transmission problem from sensor to user and recommended approaches to use
- Task 4, based on the information gathered in the first three tasks, made specific recommendations as to the approaches the Coast Guard could take in achieving its desired goal of standardization
- Task 5 developed calibration and test requirements to be utilized by the Coast Guard in sensor procurement

Neither the Coast Guard nor Texas Instruments expected this study to solve the problem of standardization for the entire oceanographic community, but it is believed that the materials generated as a result of the study can be used as a starting point toward achieving that goal. All conclusions were reviewed prior to publication by the Ad Hoc Advisory Committee composed of representatives from the various engineering branches of the Coast Guard, the National Oceanographic Instrumentation Center, and the National Oceanographic Data Center. Throughout the study, a close liaison was maintained with industry; in addition, Dr. George Huebner of Texas A&M Oceanographic and Meteorological Department reviewed all parts of the study for their possible impact on the academic community.

Volume III, the result of the Task-2 effort, establishes the survival environment for oceanographic and meteorological sensors from time of vendor shipment to operation in the environment. The purpose of Task 2 is to describe the operational, transport, and storage environments for field instruments. In several instances, the environmental investigation has resulted in recommendations for environmental protection; in other instances, the task has revealed the need for further work leading toward adequate sensor protection.

Many people in industry, government, and educational institutions were consulted during the task's data-collection phase. Thus, the environmental description represents a consensus of many sources, all involved in some way with measurements and the protection of equipment at sea.

The Coast Guard technical monitor was LCDR J. W. Coste, and the project was managed at Texas Instruments by Donald W. Branham. Principal contributors for this volume were Robert M. Crosby, Frank H. MacDonald, Thomas R. Livermore, and William Gumma. Editorial and production management and other valuable assistance were provided by Mrs. M. R. Wilson and Miss Beverly Littlejohn. Many others contributed in many ways, and their efforts are also gratefully acknowledged.

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# LIST OF ABBREVIATIONS

| | |
|---|---|
| amp | ampere |
| atmos | atmosphere |
| C | Celsius |
| cm | centimeter |
| cu ft | cubic feet |
| db | decibel |
| F | Fahrenheit |
| ft | foot |
| g | gravity |
| hr | hour |
| Hz | Hertz |
| in. | inch |
| K | Kelvin |
| kg | kilogram |
| kHz | kilohertz |
| ksi | thousands of pounds per square inch |
| lb | pound |
| m | meter |
| max | maximum |
| mbar | millibar |
| MHz | megahertz |
| μin. | microinch |
| mi | mile |
| min. | minute |
| msec | millisecond |
| mv | millivolt |
| pcf | pounds per cubic feet |
| pf | picofarad ($1 \times 15^{-12}$) |
| pH | acidity and alkalinity |
| psi | pounds per square inch |
| sec | second |
| sq ft | square feet |
| vs | versus |
| w | watt |
| wk | week |

## SECTION I
## SUMMARY

The survival of oceanographic and meteorological measuring equipment has been considered in two broad environmental classifications: the operational and the transport and storage environments. The fact that neither environment has been adequately considered by many sensor manufacturers is demonstrated by the present marginal-to-poor retrieval rate of meaningful data at sea. A disproportional amount of effort has been placed on what goes inside sensor packages, and environmentally exposed components have frequently rated the design effort of an afterthought.

The most serious environmental factors affecting the measurement of oceanographic parameters are corrosion and marine fouling. The prevalence of corrosion may be attributed to the manufacturer's incomplete knowledge of the eight basic corrosion processes or to the designer's inability, for any reason, to use good design practice including correct application of corrosion-resistant metals and alloys and accepted coating systems. Marine fouling has been extensively studied, and the problem is now recognized as universal. Fouling will result on any unprotected marine surface — and, more important, the problem is largely preventable. A long-term development and evaluation program by the Navy's Mare Island Paint Laboratory has resulted in the development of coating systems which, if properly formulated and applied, prevent the attachment of gross fouling organisms to sensor packages for periods of more than 1 year. An unresolved problem is whether microorganisms are also discouraged from attachment by the toxic antifouling compounds. The potential effect of these organisms on measurements needs assessment.

Corrosion is not such a serious problem for measurements in the marine atmosphere because of the wide variety of suitable materials available, but fouling again emerges as a serious limitation for some measurements — particularly optical and radiometric. In the case of the marine atmosphere, the offending fouler is not an organism but salt incrustation (and, in some cases, bird guano).

The study has also addressed temperature extremes, high hydrostatic pressures, sensor-motion effects, structural-proximity effects, the quality of electrical power, conducted and radiated electromagnetic interference, thermal shock, wave and tide ranges, flotsam, wind extremes, and precipitation effects.

Water-temperature ranges and rates of change are considered. The actual range of temperatures encountered in the ocean is not considered problematical to sensors but should normally range from -2° to 35°C for all platforms. In exceptional cases, -3°C or +56°C may be encountered in making measurements from shipboard. Vertical and horizontal gradients, however, will affect the modes of data-taking. One must carefully consider the methods and time intervals used for each platform and vary them according to the goals of a particular experiment. Temperature ranges in the marine atmosphere are typically much greater than those underwater but much less than the extremes over a continental mass. Inasmuch as atmospheric-temperature records are continually being broken, it is difficult to assign extremes; rather than assign a lower temperature that will never be reached, it is more effective to estimate an extreme for each deployment locale.

The extremely high hydrostatic pressures encountered in deep-ocean work may cause failure of apparently properly designed package configurations because long-term immersion at high stress levels can introduce creep strain.

The most promising preventive measures include the avoidance of high tensile stress on critical components, the use of creep-resistant materials such as glass or 6Aℓ-2Cb-1V-1Mo titanium when high tensile stress is unavoidable, or the application of pressure equalization techniques. High pressures are naturally of small concern to fixed-platform and navigational-buoy systems.

The motion of sensors with respect to a fixed reference point on the earth's surface makes current-velocity measurement difficult on all except a fixed-platform system. Current measurements are subject to errors greater than the velocity to be measured, so results must be carefully interpreted to prevent a false sense of security about the meaningfulness of the data. For meteorological measurements — particularly those of wind velocity, temperature, pressure, precipitation, and radiation — the motions encountered on a platform can render the sensor outputs meaningless or severely limit achievable accuracy.

The proximity of measurement systems to the platforms will, in several cases, affect the measured parameters. The primary effect is the "reef" formed by hulls and cables, attracting various fouling organisms that can be expected to influence the measurement of chemical and optical parameters. In addition, the perturbation of flow around hulls and tower structures renders the interpretation of current-velocity and wind-speed data difficult if not impossible.

The stability of primary platform power and the generation or transmission of transient energy are considerations to be given to all measurement systems. Logical microcircuitry is particularly prone to damage or error introduction by transient spikes that may originate in switching heavy loads, particularly reactive loads, elsewhere on a platform. The use of common power sources on multiuse platforms emphasizes the need for adequate transient protection as a part of a sensor system.

Electromagnetic interference originating in the platform electrical system can seriously affect the transmission and processing of data from sensors. Conducted interference, which affects both underwater and topside sensor systems, is by far the most difficult problem to overcome.

Thermal shock is a serious design consideration. Theoretically, very high temperatures can be attained by sensor packages exposed to solar radiation aboard ship, and the rapid immersion of the sensors in seawater can result in errors due to hysteresis effects on transducers and the stabilization time required of the internal sensor electronics. Differences in the coefficient of materials expansion can lead to permanent mechanical and electrical damage. Further data are required in order to assign realistic upper temperature limits for a proper test for these phenomena.

The wide variation of wave heights and tides which may be encountered does not normally affect the measurements defined in this study. The primary difficulty is that a fixed reference is hard to establish for water-level measurements at sea.

Wind measurements from large structures such as ships and fixed platforms are difficult because of the characteristics of airflow around the massive disturbing structures.

Precipitation is primarily a problem to optical and radiometric measurements by changing the optical properties of the instruments.

In many cases, the transport and storage environment is more severe than operational exposure. Particularly, shock and vibration resulting from the many available transport modes can easily destroy a sensor's mechanical and electrical integrity. Calibrations performed before shipment must be carefully checked prior to deployment. Packaging methods are well-advanced, however, and the prevention of severe mechanical stress in shipment is a well-developed art adequately described in MIL-HBK-304. Environmental extremes to which sensors may be exposed during transport and storage are listed in Table I-1.

Table I-1

PROBABLE ENVIRONMENTAL EXTREMES
IN TRANSPORT AND STORAGE

| Transport or Storage Mode | Environmental Parameter | Probable Extremes |
|---|---|---|
| Hand-carry | Shock (drop) | See Table III-7 |
| Hand truck or fork lift | Shock (drop)<br>Vibration | See Table III-7<br>Frequency, 2 to 10 Hz; double amplitude, 0.25 in. |
| Motor transport (truck) | Vibration (MIL-HBK-304)<br>Temperature | 1 to 200 Hz at 2 g; 200 to 300 Hz at 5 g<br>65°C max. |
| Railway transport | Vibration (MIL-HBK-304)<br>Temperature | 2.5 to 7.5 Hz at 0.75 g; 50 to 70 Hz at 0.5 g<br>65°C max. |
| Air transport (jet cargo craft, delicate-equipment stowage) | Vibration (MIL-STD-810B) Figure III-16<br>Temperature<br>Pressure | 5 to 14 Hz; double amplitude, 0.1 in.<br>14 to 23 Hz, 1 g<br>23 to 32 Hz; double amplitude, 0.036 in.<br>52 to 2000 Hz, 5 g<br>10 to 21°C<br>0.2 atmos. |
| Helicopter transport | Vibration (MIL-STD-810B) Figure III-17 | 5 to 20 Hz; double amplitude, 0.1 in.<br>20 to 33 Hz, 2 g<br>33 to 52 Hz; double amplitude, 0.036 in.<br>52 to 500 Hz, 5 g |
| Ship | Shock<br>Vibration<br><br><br>Temperature (IEEE45) | 5 g<br>5 to 15 Hz; double amplitude, 0.03 in.<br>16 to 25 Hz; double amplitude, 0.02 in.<br>26 to 33 Hz; double amplitude, 0.01 in.<br>50°C max. |
| Small boats (20 knots, 4-ft waves) | Acceleration | 15 g |
| Storage | Temperature<br>Moisture | 50°C max.<br>100% relative humidity with condensation |

## SECTION II
## RECOMMENDATIONS

The prevention of corrosion and fouling overrides all other material considerations because the need for commonality of sensor hardware requires that the designer consider the most serious environmental restrictions — those imposed by the long-term exposure of instruments on deep-ocean buoys. The wide variation in oxygen content and velocities encountered in the underwater environment forces one to consider the probability of severe damage by pitting and crevice corrosion.

There have not been sufficient tests on the survival of metals over the wide range of conditions to be met by the Coast Guard's requirements, but the resistance of some materials to all forms of attack is so notable that their use is strongly recommended for underwater sensors despite the additional cost. Those metals are

- Titanium-6 Aℓ-2Cb-1Ta-1Mo
- Hastelloy C (Union Carbide Corp.)
- Inconel alloy 625 (International Nickel Co., Inc.)

The performance of several other metals is within acceptable limits for noncritical sensor components exposed to seawater. They are

- Carpenter 20 (The Carpenter Steel Co.)
- Incoloy 825 (International Nickel Co., Inc.)
- 90/10 and 70/30 copper-nickel (with small percentages of iron)
- Stainless steel 316

The use of some metals and alloys should be expressly prohibited because of their demonstrated poor performance under certain conditions. Among these are

- Stainless steels 304, 410, 416, 430, 302, 321, and 347
- Aluminum alloys
- Brass
- Bronze
- Monel

Several other metals systems (most notably, hot-dip galvanized mild steel) have been inadequately tested under conditions required of oceanographic sensor configurations and cannot be evaluated at this time.

Sensors that will be exposed to the marine atmosphere or to the splash or tidal zones are not so restricted as to materials because of the ready availability of oxygen. Although crevices will be troublesome, use of stainless steels in the splash and tidal zones and aluminum in the marine atmosphere should be permissible in most cases.

In the submerged environment, coating systems should be concerned primarily with the prevention of marine fouling; however, it is difficult to assemble a sensor package that includes only the recommended metals exposed to seawater. Good practice must be followed when dissimilar metals are used, keeping in mind the principle of relative exposed areas and the galvanic series. In addition, crevices, except those formed by mating two or more surfaces of titanium, Hastelloy C, or Inconel alloy 625, must be sealed. Crevices such as those formed by nuts and boltheads, V-bands, hose clamps, and gaskets can be sealed with Dow-Corning 780 silicone rubber (properly cured), an epoxy-filled boot of heat-shrinkable polyolefin tubing, or a combination of the two. All dissimilar metals should be isolated wherever possible by nonconducting bushings, washers, or gaskets. All exposed metal corners and edges to be painted should have a radius of not less than 0.0625 in. to enhance coating adhesion and thus minimize the probability of coating damage during handling.

The wide variety of available pressure cases and sensors precludes specific directions for coating application; also, this would be overly restrictive for manufacturers. However, the following general guidelines should be followed for underwater sensor packages:

- Titanium Surfaces

  (1) Abrasive-blast to a roughness profile of 0.001 to 0.0015 in. all exposed metal surfaces that can withstand such treatment. Acid-etch all other exposed metal surfaces to be coated.

  (2) Remove oil and grease with Brulin's Scotch Cleaner.

  (3) Apply one coat of Navy Formula 117 (MIL-P-15328) wash primer to all metal surfaces to be coated. Dry-film thickness should be 0.0005 to 0.0007 in.

  (4) Apply three coats of Navy Formula 119 (MIL-P-15929) red-lead vinyl anticorrosive for a final dry-film thickness of at least 0.006 in.

  (5) Apply two coats of Navy Formula 121/63 (MIL-P-15931B) antifouling to a final dry-film thickness of not less than 0.005 in. (A final application must be applied before sensor deployment if more than 30 days have elapsed since the last coat. At least 24 hr of drying time must be allowed before immersion. The final coat can be brush-applied.)

- Neoprene, Rubber, and Nonmetallic Surfaces

  (1) For neoprene, roughen the surface mechanically. Wipe with a solvent and apply three coats of Navy Formula 134 (MIL-P-22299) polyisobutylene A.F. to a final dry-film thickness of 0.006 in. Allow 8 to 16 hr between each coat and at least 24 hr but not more than 30 days of atmospheric exposure before immersion.

  (2) For rubber and other nonmetallic surfaces, roughen the surface mechanically. Wipe with a solvent and apply one coat of Gaco neoprene coating to a dry-film thickness of 0.001 in. Apply three coats of Formula 134 as for neoprene.

The use of sacrificial anodes on the surface of sensors is deemed unwise because improper placement may tend to destroy the effectiveness of antifouling coatings and because protection is unnecessary for approved metals.

Note that quality control in paint formulation can be poor and that the sensor manufacturer must be responsible for assuring that the formulations obtained are to specification and are fresh. The only test of a coating's effectiveness is long-term exposure at sea.

Moisture protection is the primary goal of coating systems in the marine atmosphere. A large number of meteorological sensor manufacturers have developed paint systems that are adequate for protecting exposed sensor hardware. Frequently, the specification of Navy Paint systems will result in degradation of performance of hardware. (A heavier paint coating will increase the moment of inertia of a cup anemometer, for instance.) Because these components are seldom critical in themselves, it is deemed wise to permit the manufacturers to utilize coating systems now in use.

# SECTION III
# ENVIRONMENTAL FACTORS

## 3.1 OPERATIONAL ENVIRONMENT

The concern here is with survival of an instrument package after it has been successfully shipped, calibrated, and deployed. It is meaningless to describe the environment without suggesting methods for increasing survivability, so this has been done wherever possible.

3.1.1 CORROSION. The at-sea deployment of complex measuring equipment exposes to a corrosive environment components and materials developed primarily by technical personnel whose experience is more land- than sea-oriented. There has not been and may never be the effort expended in ocean research as that resulting from our recent successful space efforts, and one is restricted to application of empiricisms resulting from the 2000 years of experience which has been built on the first observation that an iron nail will not survive if asked to hold a copper plate to the bottom of a ship. The empirical knowledge does exist, however, and it is the purpose of this section to remind the designer of the corrosion processes that may take place and to report on the best available preventive measures as they apply to meteorological and oceanographic sensors.

Although marine atmospheric corrosion presents a serious design consideration, long-term immersion imposes the most demanding constraints. Several materials now commonly used for meteorological and oceanographic sensors, it will be shown, are incompatible with the sea and should not be used in combination.

Postassembly protective coatings are only partially successful for the following reasons: certain components must be left uncoated for measurement considerations or to facilitate assembly and disassembly, chips and holidays in paint coatings invariably occur in handling, and there are certain marine organisms which have deleterious effects on coatings.[1] The designer, therefore, should make the best possible use of materials and techniques that presume destruction of the anticorrosive coating. Protective measures can then be used to provide a safety factor and increase the effectiveness of successive coatings that may be applied for biological fouling protection.

Meteorological sensors do not require the same degree of corrosion protection. Since they are not required to maintain watertight integrity under high external pressures, failure of coatings and moderate superficial corrosion are not expected to lead to the instrument's catastrophic failure. Although it is unreasonable to require the use of the exotic materials (such as titanium) for meteorological sensors, good design practice and adequate coating systems are still necessary.

3.1.1.1 Classification of Corrosion Processes. Involved in corrosion are eight basic processes to which different materials and combinations of materials are subject in various degrees.[2]

- Uniform corrosion
- Galvanic corrosion
- Crevice corrosion
- Pitting
- Intergranular corrosion
- Selective leaching
- Erosion
- Stress corrosion

The mechanism of all these forms are not well-known, but the results are obvious and corrective measures are possible in most cases.

3.1.1.1.1 Uniform Corrosion. This is the least insidious form of corrosion because of its familiarity. Involved are oxidation-reduction reactions between surface sites of a metal immersed in an electrolyte (seawater). Frequent shifts of the local sites of these reactions lead to general or uniform corrosion that results in a more or less uniform destruction of the surface.

3.1.1.1.2 Galvanic or Dissimilar-Metals Corrosion. Galvanic corrosion, almost invariably the fault of the equipment designer, results from the improper selection of material combinations or a failure to follow basic rules. A thorough understanding of this potentially severe corrosion form is imperative.

Immersion of two dissimilar metals in seawater results in a source of potential energy — a battery cell. An electrical potential exists between these two metals, so a current will flow if a path is provided. The energy expended by current flow through this conductive path is provided by the oxidation-reduction reactions at the seawater interfaces. The usual battery rules are in full effect; an increase of both bare metal surface areas results in increased current flow. Likewise, any increase of galvanic potential results in an increase of current flow. Where distance is decreased between the metals causing lower internal resistance of the battery, an increased flow of current results. Obvious solutions are to decrease the area in contact with the electrolyte (see 3.1.1.1.2.1 for qualification), use metals which exhibit little or no potential difference, or, best of all, break the external circuit. In practice, all these solutions are difficult; some apparently obvious solutions are even bad practices.

3.1.1.1.2.1 Decrease in Area. Aluminum and stainless steel are commonly coupled in oceanographic equipment. The obvious method to prevent corrosion in such a couple is to protect the aluminum surface, which is normally seen to corrode, and to leave the corrosion-resistant stainless steel bare. This solution is incorrect.[2] Corrosion-preventive coatings are never perfect. Small holidays or perforations are always present, and the relatively large area of the stainless steel accelerates local corrosion of the aluminum.

The stainless steel should always be coated and the aluminum left bare. Even this rule must be qualified, however. An unfavorable anode-to-cathode area should never be permitted to exist. A small aluminum fixture coupled with a large potentially bare stainless steel (cathodic) structure will result in catastrophic wasting of the anodic aluminum. The use of stainless-steel bolts in an aluminum structure would be considered reasonably good practice if the bolts were coated. The use of aluminum fasteners on a stainless-steel structure will result in failure — coated or uncoated.

3.1.1.1.2.2 Galvanic Potentials. The potential of a metal in water is not necessarily a constant. Corrosion-reaction products may accumulate at the surfaces of both anodes and cathodes. For example, titanium is considered a noble (cathodic) metal (between gold and silver in a galvanic series); yet, less noble metals in couple (electrical contact) with titanium are corroded at a lower than expected rate since titanium polarizes readily in seawater. The position of a metal in the galvanic series should be used as a design guide by selecting metals as close together as possible in the series for a given seawater-exposed system. However, no substitute exists for actual corrosion tests that simulate as nearly as possible the expected marine environment.

Relative potential positions of some metals now in marine service are listed in Table III-1.

If metals which differ in galvanic potential must be used in couple, the more noble metal should always be much smaller in exposed area than the anodic metal, and the nobler metal should be coated to further decrease its effective area.

3.1.1.1.2.3 Breaking the Circuit. If dissimilar metals must be used (and there is often no choice), the gross forms of galvanic corrosion can be prevented by carefully and fully isolating the different metals electrically (Figure III-1).

Table III-1

RELATIVE POTENTIAL POSITIONS OF METALS

| Galvanic Potential | Metal |
|---|---|
| Most noble, cathodic, or protected metals | Gold |
| | Titanium |
| | Silver |
| | Hastelloy C (62 Ni, 17 Cr, 15 Mo) |
| | 316 stainless steel (passive) |
| | 304 stainless steel (passive) |
| | Inconel (passive) |
| | Silver solder |
| | Monel |
| | Cupronickels |
| | Bronzes |
| | 316 stainless steel (active) |
| | Copper |
| | Brasses |
| | Tin |
| | Lead |
| | Lead-tin solder |
| | Ni-resist |
| | 304 stainless steel (active) |
| | Cast iron |
| | Wrought iron |
| | Mild steel |
| | Cadmium |
| | Aluminum |
| | 2000 series |
| | 7000 series |
| | 1100 series |
| | 5000 series |
| Least noble, anodic, or corroded metals | Zinc |
| | Magnesium |

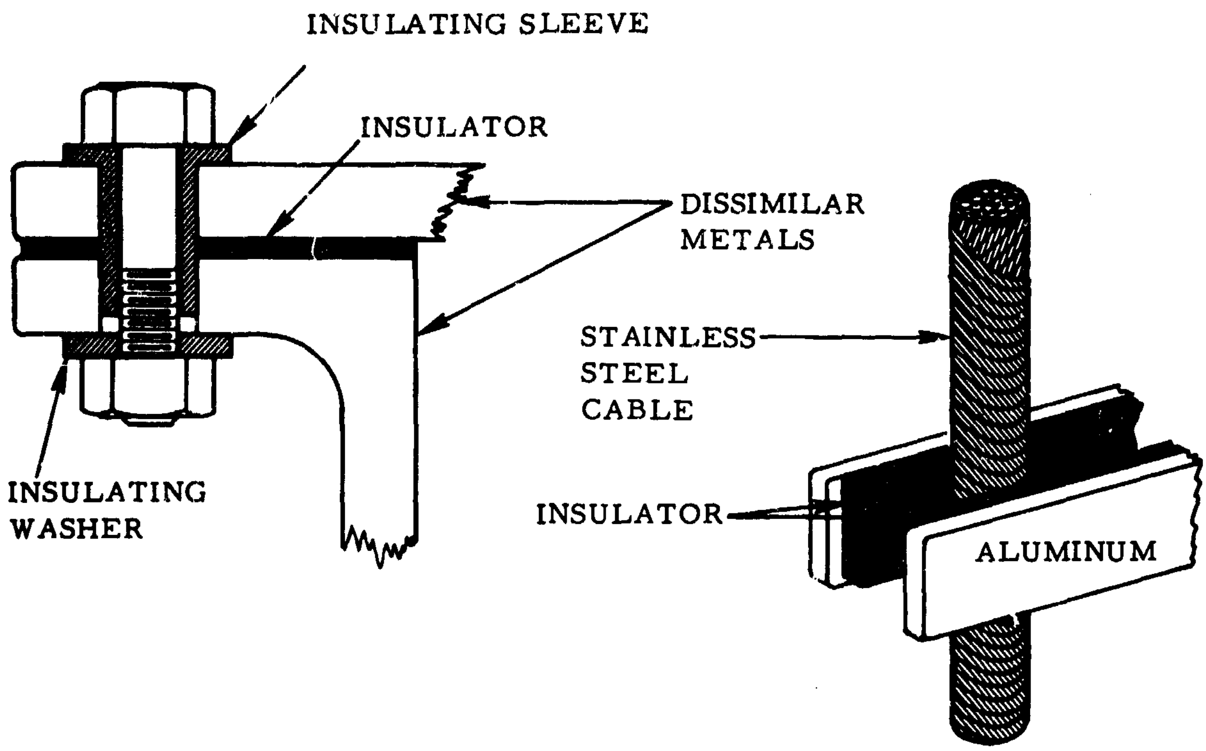


Figure III-1. Examples of Dissimilar-Metal Isolation

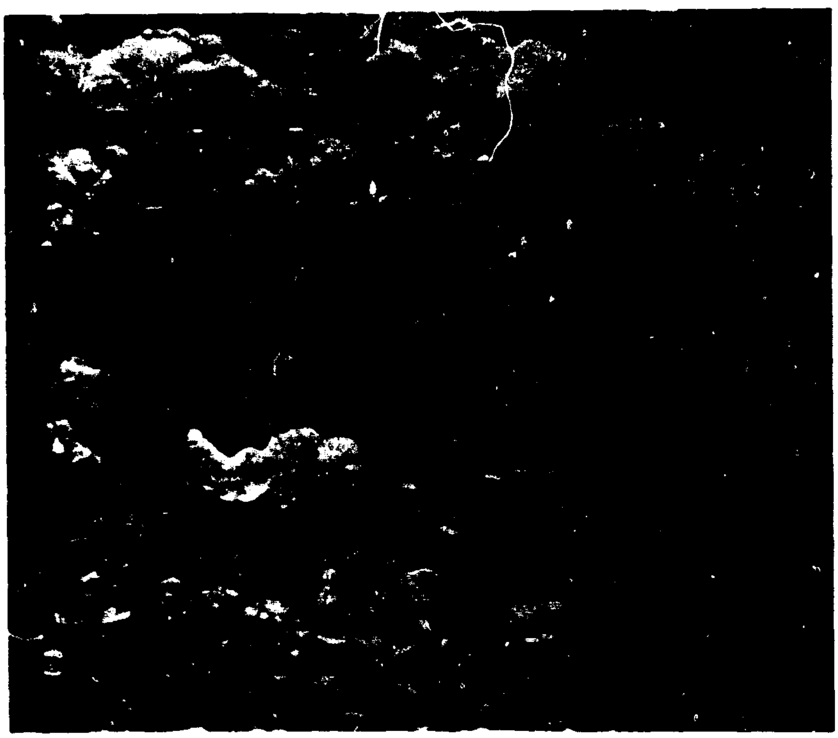

Figure III-2. Galvanic Corrosion of 7075-T6 Aluminum Coupled to 321 Stainless Steel — 751-Day Exposure at 5640-Ft Depth, Pacific Ocean (Official Photograph of U.S. Navy)

Figures III-2 and III-3 illustrate galvanic corrosion where dissimilar metals were not electrically isolated. Captive insulating devices are best whenever possible; loose washers and sleeves are easily lost and almost invariably are replaced in the wrong order (if at all) during reassembly after servicing. Improper replacement of one insulator can completely negate the protection which can be afforded by a complete set. Part of an assembly procedure might well be the determination of ohmic resistance between well-defined points on a structure.

A particularly insidious form of galvanic corrosion is the result of improper selection of protective coating. An antifouling paint with a copper base should never be used in close proximity to aluminum.[3,1] Ionic copper leaching from the paint may precipitate and accelerate galvanic corrosion at a small holiday in the anticorrosion coating on the aluminum, accelerating galvanic corrosion at that point. Direct contact of the copper-based paint to the aluminum surface will also be recognized as a dissimilar-metals couple and, due to the unfavorable anode-to-cathode ratio, small imperfections in the coating will permit rapid substrate corrosion.

3.1.1.1.2.4 Induced Galvanic Corrosion — Seawater Return. A special case of galvanic corrosion may be induced in a sensor package by the impression of two or more different electrical potentials on seawater-exposed system components.[4] A common error is the inclusion of the pressure case of an electronic package in the electrical system (usually as a noise-reduction expedient) without adequate consideration of the relative potentials of all system components including platform hull. In such a case, it must be remembered, an extremely unfavorable anode-to-cathode ratio can exist with attendant rapid acceleration of corrosion. (Impressed voltages may also tend to protect the sensor if correct polarities are observed.) A particularly hazardous condition may be caused by the use of a pressure case on the sensor

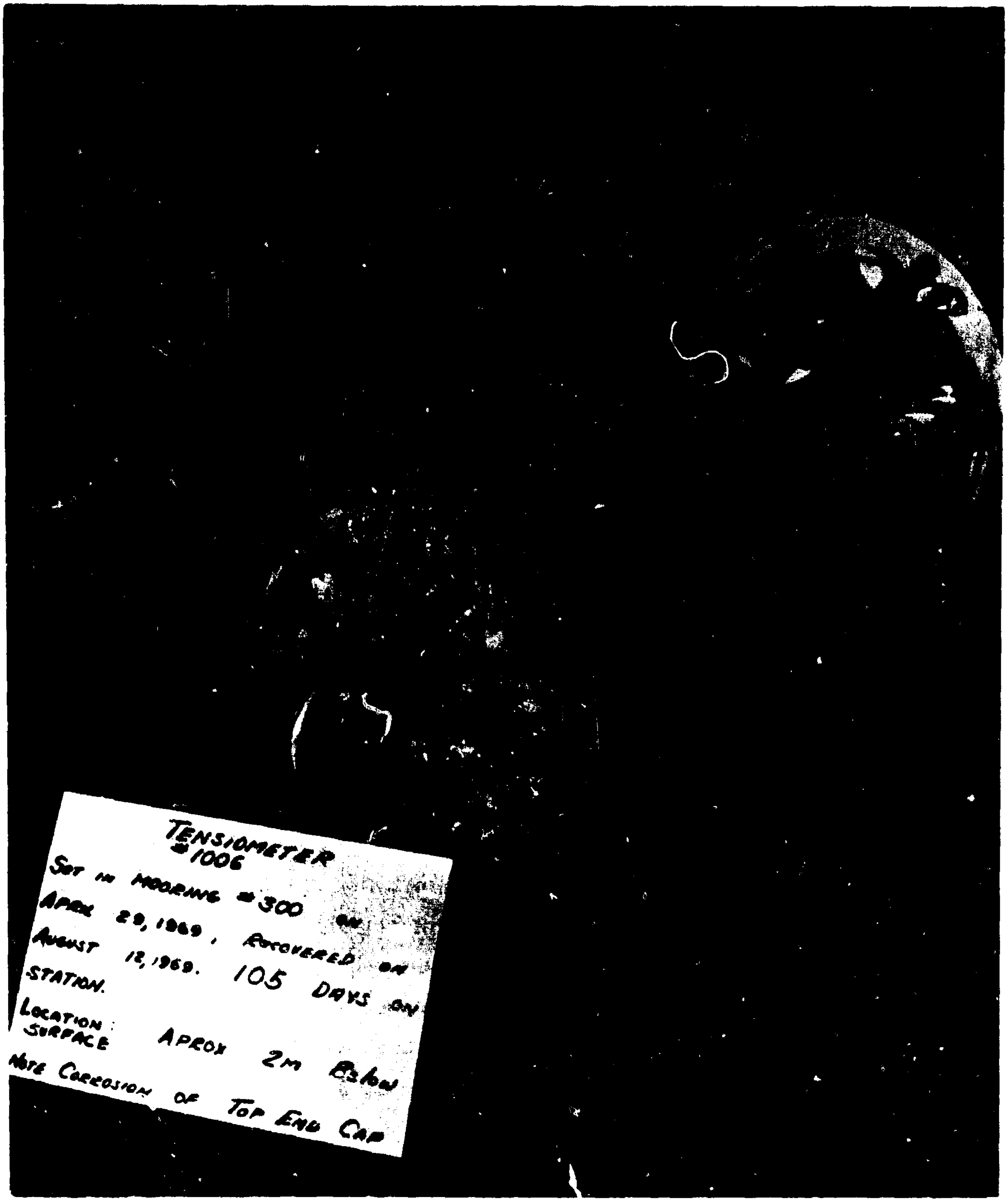


Figure III-3. Galvanic Corrosion of 6061-T6 Aluminum End Plate (Not Electrically Isolated) and Stainless-Steel Hardware (Courtesy of Woods Hole Oceanographic Institution) structure as a seawater return for power. The portion of an aluminum case in contact with seawater, for example, will be consumed at the rate of 4.5 to 5.5 kg/amp-year[5] in the instance of an anodic direct-current potential impressed on the case. The use of alternating potentials may lessen but not alleviate the problem. Coatings may also be "blown off" by the application of relatively low electrical potentials between seawater-exposed systems components.[4]

3.1.1.1.3 Crevice Corrosion. Figure III-4 illustrates crevice corrosion after more than 2 years' exposure in the Pacific. Crevice corrosion is related to pitting in that the same class of metals and alloys is subject to both forms of corrosion.[2] Characterized by intense local attack in small stagnant regions such as gasket and O-ring surfaces and under fastenings (e.g., bolts, V-bands, and hose clamps), crevice corrosion is particularly difficult to treat because the metals which are most severely attacked encompass many of the more commonly used marine materials and the surfaces affected are frequently critical to the structure or to watertight integrity. The metals affected are, as a class, those which depend on the maintenance of an extremely thin oxide film for their corrosion resistance; therefore, oxygen must be readily available so that the film can be kept intact.

The precise mechanism of crevice corrosion is complex and not of real interest here, but generally the shortage of oxygen, local natural formation of acidic solutions, and maintenance of high concentration of metal ions in the crevices may all be involved. For corrosion to occur, crevices must be sufficiently wide to permit seawater entry and sufficiently narrow for existence of a stagnant region. Troublesome crevices are typically a few thousandths of an inch or less in width. In some cases, the high metal ion concentrations in the openings will cause pitting attack just outside the crevices. The bases of some fouling organisms, notably the barnacle, will frequently foster crevice or pit growth.[1]

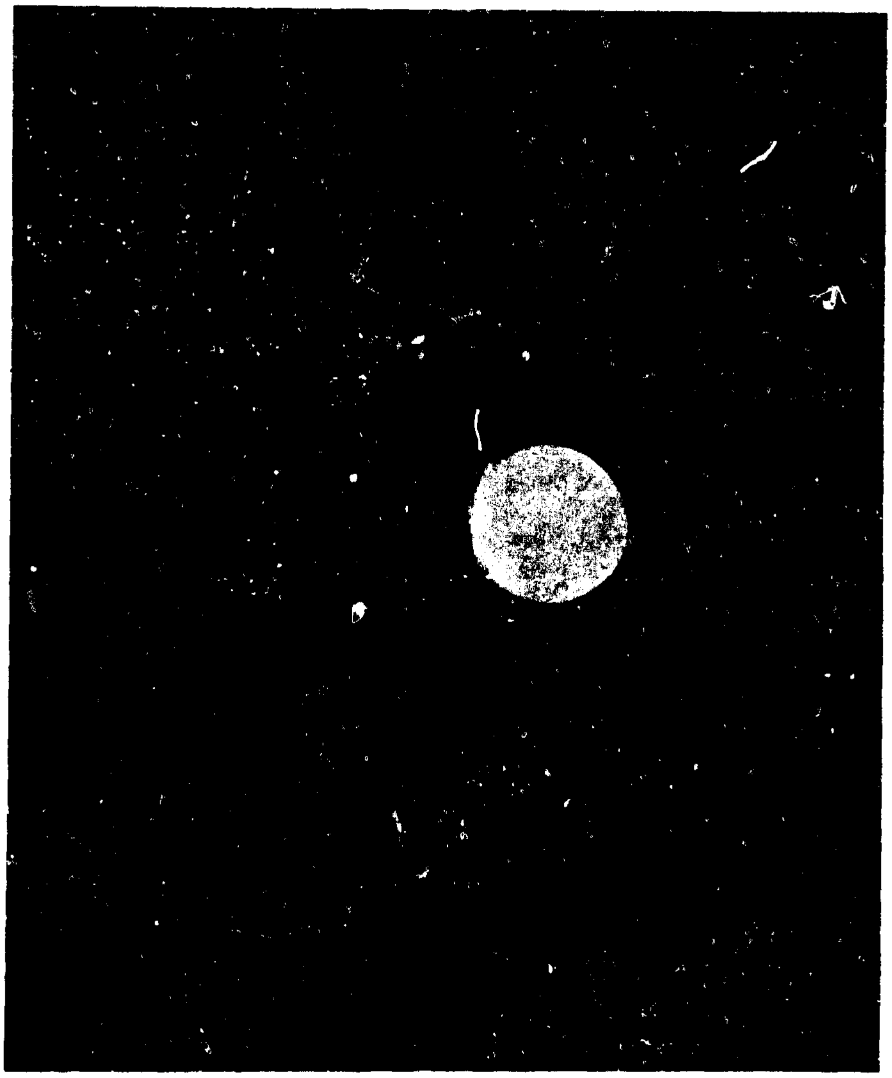

Figure III-4. Crevice Corrosion of 430 Stainless Steel — 751-Day Exposure at 5640-Ft Depth, Pacific Ocean (Official Photograph of U.S. Navy)

Metals subject to crevice corrosion include nickel chromium alloys; nickel copper alloys; monel; 304-, 316-, and 400-series stainless steels; copper; alloy 20; 6061 aluminum; and Incoloy 825. In fact, all stainless steels and aluminum alloys are subject in some degree to this form of corrosion.

Some useful guidelines for the avoidance of crevice corrosion are

- Use of sound, complete, nonporous, welded joints in preference to bolted, gasketed joints and incomplete welds
- Avoidance of stagnant regions in the original design
- Use of titanium or Hastelloy C for critical fittings or surfaces
- Prompt disassembly and complete flushing, drying, and lubrication (certainly before long-term storage) of all surfaces which might entrap seawater or salts

3.1.1.1.4 Pitting. Pitting is a form of corrosion closely related in mechanism to crevice corrosion but differing in that the attacked metal surface need not be so obviously exposed to stagnant conditions. However, low water velocities definitely contribute to the severity of the condition.

The same metals involved in crevice corrosion are subject to this form of destruction, which is characterized by the formation of deep holes or pits (Figure III-5). This is a particularly insidious form of corrosion due to the fact that the depths of the holes often exceed the widths; furthermore, the holes are often covered by corrosion products. Perforation of the metal is the usual result.

Pits generally form on the upper horizontal surface of equipment and grow in the direction of gravity.[2] Fewer pits will normally start on vertical surfaces and only rarely will pits be found growing upward from bottom horizontal surfaces. The pits usually start slowly, but the process of pit growth is autocatalytic in that the relatively heavy metal chlorides and the high concentration of hydrogen ions in pits tend to accelerate the growth of the holes. The process is thought to start by means of a temporary high concentration of $C\ell$ ions at a point on the surface and, of course, this condition can occur more readily in a low-velocity flow of seawater.

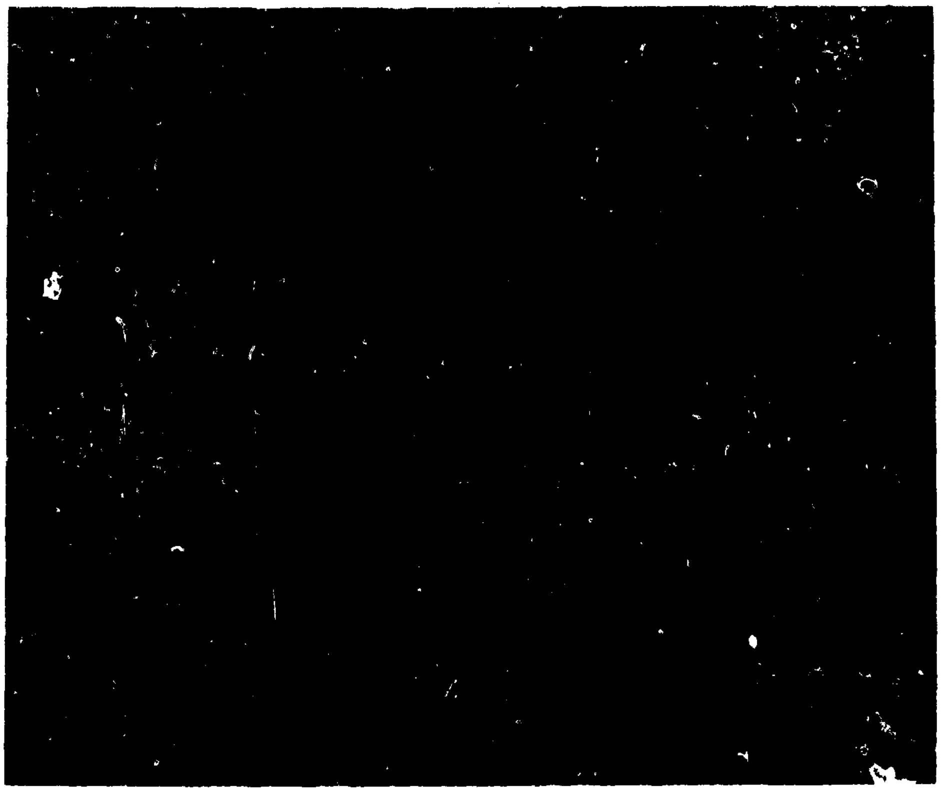

**Figure III-5.** **Pitting of 6061-T6 Aluminum — 751-Day Exposure at 5540-Ft Depth, Pacific Ocean (Official Photograph of U.S. Navy)**

The obvious pitting preventive is to utilize those metals or alloys displaying the greatest pitting resistance. Several materials are listed here in the order of decreasing resistance to this form of attack:

| | |
|---|---|
| Excellent resistance | Titanium<br>Hastelloy C or Chlorimet 3<br>Inconel alloy 625 |
| Acceptable | Hastelloy F<br>316 stainless steel<br>Durimet 20<br>Nionel |
| Unacceptable | 304 stainless steel<br>6061 aluminum |

3.1.1.1.5 Intergranular Corrosion. This type of attack is notable in some materials currently found (albeit improperly) in oceanographic sensor packages — notably 304 stainless steel and some aluminum alloys. Depletion or enrichment of alloying elements at grain boundaries as the alloy cools naturally or is heat-treated or welded causes the formation of effective galvanic cells, and localized attack can occur at or near the boundaries. Small amounts of iron in aluminum, the higher zinc concentration at boundaries in brass, and chromium depletion due to the presence of carbon in stainless steels are examples of situations in which intergranular corrosion may occur.

The most familiar manifestation of intergranular corrosion is the sugary-surface appearance of type 304 stainless steel in a narrow band near a welded joint, which results from a welding temperature that reaches a critical range over a narrow region and increases the sensitivity to intergranular corrosion by formation of chromium carbide. The effective lowering of metallic chromium in the stainless steel causes this portion of the metal to become anodic to the balance of the alloy. High-strength aluminum alloys such as Duralumin (Aℓ-Cu) are also prone to this type of attack.

The problem can be prevented in welding stainless steels by use of low-carbon alloys such as 304L, 316L, 347 or 321, or by quench-annealing the structure after welding.

3.1.1.1.6 Selective Leaching. The most familiar form of this type of corrosion is the formation of a weak spongy copper mass from yellow brass. This can occur in a general form throughout the entire metal or remain localized in regions known as plugs.

In the process of corrosion, the zinc is removed from the alloy; the process, therefore, is also known as dezincification in the case of brass. Aluminum bronzes and some alloys containing iron, cobalt, chromium, and nickel are also subject to selective leaching in some environments, but brass is the most important marine metal involved. Muntz metal (40 percent zinc) and naval brass (37 percent zinc) are more prone to leaching than is red brass (15 percent zinc); some improvement has been achieved by the addition of tin to 70 percent Cu/30 percent Zn brasses to form admiralty metal and by the further addition of small amounts of arsenic, antimony, or phosphorus as inhibitors to admiralty. Metals subject to selective leaching also favor crevice corrosion; thus, it is important to avoid the use of these metals on sealing surfaces and critical parts such as fasteners.

3.1.1.1.7 Erosion Corrosion. Except for copper and brasses, the velocities encountered in the natural ocean environment are not sufficient to contribute to this type of corrosion. In fact, the water motion may actually increase the resistance of the more acceptable metals such as Carpenter 20 or 316 stainless steel by exposure of the surfaces to a steady supply of oxygen, permitting immediate repair of the passive oxide films. Corrosion films on copper and brass, however, are readily swept away at 1- or 2-m/sec velocities, and the solution rates of these metals may be increased significantly by seawater velocities. The corrosion mechanisms involved are the simple ones of mechanical wear and abrasion.

3.1.1.1.8 Stress Corrosion. Stress-corrosion cracking requires the application of moderate-to-high tensile stress in a corrosive medium. The stresses may be those applied in-situ or residual stresses resulting from forming and fabrication. Characterized by a virtually unattacked surface, stress-corrosion cracks can propagate within a metal at the rate of several inches per hour. The process, which is poorly understood, can affect aluminum alloys, brass, stainless steels, and some titanium alloys — all in combination with seawater as the corrosive medium.

A special case of stress corrosion is corrosion fatigue, which is probably one mechanism of failure of wire ropes including those made of titanium alloy. Corrosion fatigue refers to the tendency of metals to fracture under repeated cyclic stressing in a corrosive environment. In seawater, austenitic stainless steels can only be expected to maintain 70 to 80 percent of their normal fatigue resistance. Those metals most subject to pitting can also be expected to exhibit corrosion-fatigue characteristics inasmuch as the presence of pits tends to increase stress concentration and initiate cracks.

The existence of eight corrosion processes, any or all of which might be acting to destroy a deployed sensor package, emphasizes the need for the designer's careful consideration of the exposed metals system. Discussions with designers of sensor hardware reveal many misconceptions regarding the resistance of metals to these processes, so it is hoped that this brief review will enable the specifier and designer of instrument systems to avoid more effectively some of the pitfalls of design.

Physical or mathematical modeling of metals systems, it has been suggested, might yield useful data on corrosion behavior. Electrical currents induced in a cable by differences in oxygen and ion concentration and temperature differences as a function of depth and currents induced by motion of the array in the earth's magnetic field are some of the unknown factors that might be investigated. The complexity of the problem makes computer treatment attractive, but the paucity of information on the variability of parameters might render a model study difficult or useless.

3.1.1.2 Corrosion Zones. The corrosion behavior of metals may vary considerably between and within each of the four zones considered here. Figure III-6 shows this variation for ordinary steel.[2] Although similar presentations of data are not available for other sensor-system materials, one can assume, with a knowledge of the eight basic corrosion processes, that this function will change shape radically between metals. Monel, for example, can be expected to pit catastrophically in quiet seawater, but it has been quite successfully used as a sheathing in the splash zone on an offshore drilling platform.[6] The characteristics of each corrosion zone are discussed briefly in the following.

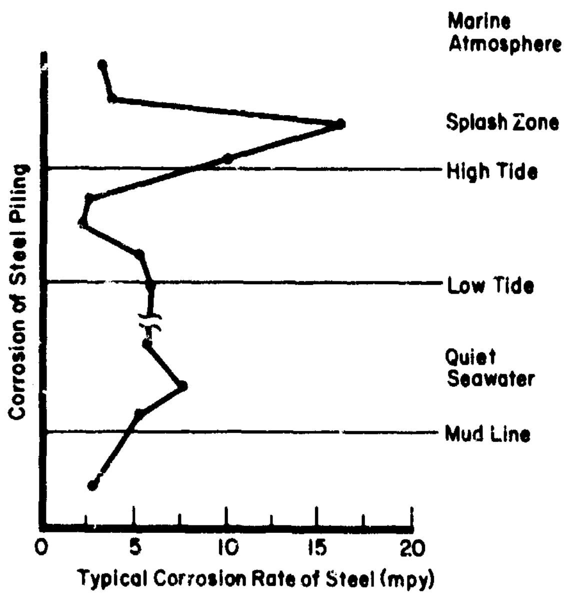


Figure III-6. Corrosion of Ordinary Steel in the Sea (after Fontana and Greene, Corrosion Engineering, 1967, McGraw Hill Book Co., New York, N. Y.)

3.1.1.2.1 Marine Atmosphere. One of the most important factors affecting corrosion in the marine atmosphere is the high relative humidity and the presence of hygroscopic salts — either sea salt or the products of corrosion. Atmospheric corrosion is rapidly accelerated above a certain critical relative humidity; this depends on the salt involved but is usually about 70 percent.[7] There is also a wide variation in the amount of corrosion with location, the values obtained at Kure Beach, North Carolina, being considerably different from those obtained in a tropical environment such as Nigeria.[6,8] Elevation above the sea surface, as well as orientation and degree of shelter can also be expected to cause variations. A maximum corrosion rate has been found (for mild steel) at a height of 25 ft above the beach surface in the Nigerian tests.[8]

The ready availability of large quantities of oxygen makes the marine atmospheric regime quite different from the totally immersed environment, since materials that readily form passive oxide films perform more suitably in the relatively high-oxygen atmosphere. Crevices in this type of environment can be expected to be almost as troublesome as in quiet seawater, however, since the hygroscopic salts tend to retain water in stagnant regions.

3.1.1.2.2 Splash Zone. In Figure III-6, one can see that the splash zone is a severe test for steel inasmuch as rust films have little opportunity to dry and develop protective characteristics.[6] The high concentrations of dissolved oxygen in the seawater in this zone, as well as the more severe erosive action of the waves, account for the higher rates of attack.

Again, the high oxygen content can be expected to aid in the formation of the passive oxide film on the stainless steels, and similar materials (with the probable exception of aluminum) should be suitable to the splash zone and the marine atmosphere.

3.1.1.2.3 Tidal Zone. In the tidal zone, a new factor of differential aeration must be considered. Surfaces in this zone are wetted by highly aerated seawater as the tide rises; below the low tide level, however, surfaces remain in contact with relatively low concentrations of oxygen. The cell that is established causes the tidal-zone surfaces to be cathodic to the submerged surfaces, and they are thus protected.[6]

3.1.1.2.4 Below Tidal Zone. In the always immersed environment, there must be protection against marine-fouling organisms, hydrostatic pressure, and the relatively low oxygen content of the water. All of these considerations result in a sensor-package metals system for the below-tidal zone, which may differ considerably from the other three zones. Inasmuch as coatings are used on the metals, one must also consider the effects of the coatings and coating imperfections on metals that are totally immersed in an electrolyte. Discussion of this complex zone is expanded in subsequent sections of the report.

3.1.1.3 Marine-Service Materials. The present status of corrosion research and testing precludes a thorough treatment of metals. Although there has been extensive testing on copper and nickel alloys at the Naval Civil Engineering Laboratory and International Nickel Company, the results apply only under test conditions (flow rate, depth, oxygen concentration, etc.). General Dynamics-Convair anticipates a testing program on hot-dip, galvanized, mild steel as applied to instrument-package use; the results could well be of great value to hardware designers. Meanwhile, some of the materials in use today, as well as the more commonly considered "exotic" metals and alloys, are discussed briefly in this subsection. Table III-2 presents the properties of marine-service materials.

3.1.1.3.1 Titanium. This section is not intended as an exhaustive guide to the use of titanium, although this material has been given the most extensive coverage of all of the marine-service materials. General properties, corrosion resistance, and welding and machining techniques are considered only in sufficient detail to allow a decision on the practicality of titanium's use as the environmentally exposed material on oceanographic and meteorological sensors. A fabricator should utilize the detailed information available from the Titanium Metals Corporation (TIMET) and Reactive Metals, Inc. (RMI).

3.1.1.3.1.1 General Properties. Titanium very naturally emerges as the most desirable metal for use on sensors that will be immersed for long periods. Commercially, pure titanium as well as two alloys, 6Aℓ-2Cb-1Ta-1Mo and 6Aℓ-4V, combine excellent resistance to all forms of corrosion with an attractively high strength-to-weight ratio and a magnetic relative permeability of unity. On the negative side, its relatively low elastic modulus complicates machining; its tendency to react with other elements at high temperatures necessitates special precaution in welding, and its relatively high cost has prompted manufacturers to use other materials that are only marginally suitable.

Cost factors as great as 4:1 over stainless steel for raw material and 8:1 over stainless for fabricated parts have been quoted.[9] The fact remains that very few materials processed into complex shapes can survive the marine environment, and all of these materials are costly.

Three basic metallurgical types of titanium are available. The alpha alloys, including 6Aℓ-2Cb-1Ta-1Mo, have single-phase crystal microstructures promoting good weldability. The high aluminum content increases strength characteristics and oxidation resistance at elevated temperatures. The alpha alloys have medium strength, good notch toughness, and good resistance to high temperature creep; they are not heat-treatable. The 2-phase alpha-beta alloys, including 6Aℓ-4V, are heat-treatable and some, such as 6Aℓ-4V, are weldable. Strength is medium-to-high and forming qualities are good, but high temperature creep properties are not as good as those of the alpha alloys. The beta alloys are highly heat-treatable and, therefore, are capable of high strengths. Creep resistance and formability are fair, but the ductility of welds is less than that of the base metal.

Aluminum is added to these alloys to increase strength. The maximum limit for aluminum content should be 6.5 percent if the good stress-corrosion resistance of the metal is to be retained. The beta stabilizing elements — vanadium, columbium, tantalum, and molybdenum — can increase fracture toughness or permit heat-treating.

In general, the alloy 6Aℓ-2Cb-1Ta-1Mo (formerly designated 0.8 Mo) features a high fracture toughness, excellent weldability, and immunity to stress-corrosion cracking. The cost is somewhat higher than the more readily available 6Aℓ-4V, which also has good creep resistance if the loading is kept below the proportional limit. There is some evidence that 6Aℓ-4V may be susceptible to stress-corrosion cracking, although almost complete immunity in seawater can be obtained at some sacrifice in tensile strength.[10] Specifications of 6Aℓ-4V ELI (extra low interstitial oxygen content) will result in an alloy with better fracture toughness and better weldability.[11]

# Table III-2

## PROPERTIES OF MARINE-SERVICE MATERIALS

| Material | Major Elements | Density (lb/cu in.) | Thermal Expansion Coefficient (°F x 10⁻⁶) | Young's Modulus (psi x 10⁶) | Yield Strength (psi, 0.2% set) | Creep Resistance | Corrosion Resistance | Machinability | Weldability | Available Forms | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Aluminum 6061-T6 | Al, Mg, Fe, Si, Zn, Cu | 0.098 | 12.[illegible] | 10.0 | 40,000 | | Good resistance to marine atmospheric corrosion | Excellent | Inert-gas, electric arc, welding lowers mechanical properties | Sheet, plate, strip, wire, rod, bar, extrusions, tube, pipe | Data: 1952 Alloy Digest Al-3 |
| Aluminum 5086 | Al, Mg | 0.096 | 13.[illegible] | 10.3 | 17,000 - 57,000 depending on temper | | Good resistance to stress and pitting corrosion | Excellent | Plate rated good by Aircomatic welding | Sheet, plate | Data: 1955 Alloy Digest Al-28 |
| Aluminum 6061-T6 | Al, Mg, Fe, Si | 0.098 | 13.0 | 10.0 | 31,000 | | Good resistance to marine atmospheric corrosion | Good | Oxyacetylene, metal arc, carbon arc, inert-gas arc, resistance | Pipe, extrusion, tube | Data: 1956 Alloy Digest Al-42 |
| Aluminum 11[illegible] | Al, 99% | [illegible].098 | 1[illegible].2 | 10 | 5,000 - 22,000 depending on temper | | Good resistance to marine atmospheric corrosion | Good; may be gummy | Torch, inert arc, electric resistance methods | Bar, rod, wire, plate, sheet, extrusion, forgings | Data: 1956 Alloy Digest Al-44 |
| Cupro-Nickel [illegible] | Cu, Ni, Fe, Mn, Zn, Pb | 0.323 | 9.[illegible] | 18 | 29,000 (0.5%) hot-rolled | | Resistant to erosion, corrosion and pitting | 20% of free cutting brass | Metal arc, inert-gas shielded arc, brazing | Sheet, strip, plate, rod, bar, tube | Not heat-treatable, hardened by cold-working<br>Data: 1959 Alloy Digest Cu-77 |
| Cupro-Nickel [illegible] | Cu, Ni, Fe, Mn | 0.32 | 9.0 | 22 | 36,000 (0.5%) | | Good resistance to stress corrosion and fatigue and to pitting | | Gas-shielded arc, metallic arc, resistance | Tubes | Data: 1963 Alloy Digest Cu-133 |
| Berylco 717C | Cu, Ni, Fe, Mn, Be | [illegible].310 | 9.0 | 22 | 84,000 (aged) | | Good resistance to stress corrosion, fatigue, erosion, and pitting | 20% of free cutting brass | Tungsten inert-gas process | Castings, prealloyed pigs | Age-hardenable casting alloy<br>Data: 1967 Alloy Digest Cu-178 |
| Chlorimet 3 | Ni, Mo, Cr, Fe, Si, C | 0.32 | 7.06 | 24.5 | 50,000 solution annealed | | Excellent resistance to pitting | Machines at low cutting speeds | Atomic hydrogen, heliarc, metallic arc | Castings | Data: 1955 Alloy Digest Ni-19 |
| Monel | Ni, Cu, Fe, Mn | 0.319 | 7.8 | | 25,000 - 40,000 annealed, rod and bar | | Excellent, with adequate oxygen supply | Satisfactory; slow speeds required | Gas, metallic arc | Rod, bar, wire, forgings, plate, sheet, strip, tubing, castings | Data: 1956 Alloy Digest Ni-21 |
| Hastelloy C | Ni, Mo, Cr, Fe, Tu, Mn, Si | 0.323 | 7.02 | 28.5 | 45,000* cast, annealed | 28,000 psi 0.0001 %/hr at 1200°F | Excellent resistance to all forms of corrosion | Machines readily at low speeds | Heliarc; anneal after weld | Castings, bars, sheet, tubing, wire, welding, rod | *Yield strength may be increased to 105,500 by aging<br>Data: 1956 Alloy Digest Ni-23 |
| Hastelloy F | Ni, Fe, Cr, Mo, Cb, Co, Mn | 0.295 | 8.1 | 29 | 48,000 bar-stock, annealed | 12,000 psi 0.00102 %/hr at 1200°F | Resistant to pitting and stress corrosion | Difficult | Metallic arc, inert-gas shielded arc, resistance | Bars, rods, sheet, strip, plate, tubing, wire | Data: 1956 Alloy Digest Ni-30 |
| Nimonel | Ni, Fe, Cr, Mo, Cu | 0.294 | 7.18 | 29.5 | 35,000 | | Good resistance to pitting | Machines readily when annealed | Metal arc | Sheet, bars, rods, plate, pipe, tubing | Data: 1959 Alloy Digest Ni-54 |

## Table III-2 (Contd)

| Material | Major Elements | Density (lb/cu. in.) | Thermal Expansion Coefficient (1°F x 10⁻⁶) | Young's Modulus (psi x 10⁶) | Yield Strength (psi, 0.2% set) | Creep Resistance | orrosion Resistance | Machinability | Weldability | Available Forms | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Inconel Alloy 825 | Ni, Fe, Cr, Mo, Cu | 0.294 | 7.8 | 28.3 | 35,000 mill-annealed | | Good pitting resistance, stress-corrosion resistance | Machines readily in annealed condition | Metal arc, inert gas, resistance | Sheets, bars, plate, pipe, tubing | Not hardenable by heat treatment<br>Data: 1965 Alloy Digest Ni-109 |
| Inconel Alloy 625 | Ni, Cr, Mo, Fe, Cb, Co | 0.305 | 7.1 | 29.8 | 42,000* solution-annealed | 28,000 psi 0.0001%/hr at 1200°F | Resistant to pitting and stress corrosion; exceptional fatigue strength | Low cutting speeds required | Excellent; no postweld thermal treatment required | Bars, rod, sheet, strip, forging, tubes | *Cold-working may increase yield strength by 400%; nonmagnetic; solution-annealing recommended<br>Data: 1967 Alloy Digest Ni-121 |
| Armco 17-4 pH | Fe, Cr, Ni, Cu | 0.282 | | 28.5 | 95,000 annealed, 170 000 hardened | | Not subject to intergranular corrosion | Comparable to 410 S-ST at 280 - 320 Brinnell | Inert gas, shielded arc | Bars, forgings, castings, wire | Magnetic<br>Data: 1953 Alloy Digest SS-7 |
| Carpenter 20 Durimet 20 Alloy 20 | Fe, Ni, Cr, Cu, Mo, Si | 0.287 | 9.4 | | 30,000 cast, 35,000 wrought | | Some pitting; subject to intergranular corrosion if not annealed | Comparable to 18-8-Mo S-ST | Comparable to 316 S-ST; torch, electric arc | Castings, wire, rod, bar, strip, sheet, plate, pipe, tubing, billets | Not hardenable by heat treatment (austenitic); best corrosion resistance requires quench after anneal<br>Data: 1957 Alloy Digest SS-63 |
| AISI Type 316 S-ST | Fe, Cr, Ni, Mo, Mn, Si | 0.29 | 9.2 | 29 | 30,000 annealed, 50,000 or more cold-rolled | 12,700 psi 1%/10⁴ hr at 1200°F | Good pitting resistance; subject to intergranular corrosion after welding | Difficult; 45% of AISI B 1112 steel | Arc, gas, resistance, atomic hydrogen; always anneal after weld | Sheet, strip, plate, bars, tubing | Hardens by cold-working only (austenitic)<br>Data: 1961 Alloy Digest SS-114 |
| Titanium MST-6Al-4V | Ti, Al, V | 0.160 | 5.2 | | 120,000 | 50,000 psi* 0.18%/300 hr at 650°F | Excellent resistance to all forms of corrosion | Slow speeds required | Resistance or fusion welding; protect from atmosphere | Bar, rod, forgings, sheet, plate | *Good resistance to creep and fatigue; most readily available alloy<br>Data: 1955 Alloy Digest Ti-7 |
| Titanium MST Grade III | Ti 99.5% pure | 0.162 | 5.0 | 15.5 | 72,000 | | Very slight uniform attack | Slow speeds required; tends to seize | Inert gas, electric arc | Sheet, strip, plate, bar, flats, wire, billets | Produced by 'S' method of melting; work hardens rapidly, nonmagnetic, good fatigue resistance<br>Data: 1957 Alloy Digest Ti-11 |
| Titanium [illegible] 6Al-2Cb-1Ta 0.8 Mo | Ti, Al, Cb, Ta, Mo | 0.162 | 5.0 | 17.0 | 95,000 | | Good general corrosion resistance | Slow speeds required | Resistance or fusion welding, inert-gas shielding | Billet, bar, plate, sheet, wire, extrusions | High impact resistance; developed for use in deep-submergence vehicles<br>Data: 1967 Alloy Digest Ti-53 |
| Alumina Ceramic Coors AD-94 | 94% $Al_2O_3$ | 0.131 | 3.9 to 5.5 | 41 | 28,000 Brazil test | Unknown | Inert | Easily machinable before firing | | | |
| Glass 7740 Borosilicate Corning | Silica sand | 0.081 | 1.8 | 9.1 | | Does not creep | Excellent | | Fusion, epoxy cement | Blown, pressed ware; plate; tubing; rods; panels | |
| Filament-Wound Glass Fibers (typical) | Glass epoxy | 0.076 | | 20 (maximum) | | Unknown | Unknown | Poor; tends to break fibers | | Cylinders | Wicks due to micro voids; surface preparation for coating difficult |

3.1.1.3.1.2 Corrosion Resistance. Titanium, a highly reactive metal, depends for its corrosion resistance on an extremely thin, tenacious surface film of titanium dioxide. Pitting and crevice corrosion, the most serious limitations to the use of stainless steel in relatively quiet seawater, are not a concern with titanium or the two alloys discussed here. Uniform corrosion is generally considered nil, and erosion resulting from high-velocity seawater or suspended sediments should also be nil. Some titanium alloys have been shown to be susceptible to stress-corrosion cracking. The alloy 6Aℓ-2Cb-1Ta-1Mo (0.8 Mo) has been extensively tested by Navy laboratories for use in deep submersibles and has been found to be immune. Although some formulations and treatments of 6Aℓ-4V can possibly cause susceptibility to cracking in seawater, the balance of cost, availability, and lack of significant tensile stress in most oceanographic sensors strongly suggests use of the alloy properly processed and annealed after fabrication. Unalloyed titanium is also thought to be immune to stress corrosion, and its use is recommended in applications where high strength of the alloys is not required. Pure titanium is considerably lower in cost than the alloys.

Hydrogen embrittlement, although not strictly a form of corrosion, is a concern with many metals (titanium included). The initial cause of embrittlement is the penetration of atomic hydrogen into the crystal structure of the metal. The hydrogen reacts with titanium to form brittle hydrides. Cracking from embrittlement is more likely to occur in the higher-strength condition of the metal and at high stress levels. Hydrogen contamination may occur by the application of a current which makes the metal cathodic or by solution of the gas during the welding or melting processes. Stress corrosion is a distinctly different process more frequently associated with metals that are anodic to other metals in a galvanic system but not confined to this constraint.

3.1.1.3.1.3 Welding. Titanium, when hot, readily absorbs or combines with most other elements. Most of these combining elements result in a gain in strength and a significant loss in ductility and toughness. When titanium is welded, therefore, it must be completely protected from external contaminating elements by scrupulous attention to cleaning of the work and work area and by shielding of the weld puddle and surrounding hot regions of metal, including the back, by inert gases. Shielding must be continued, even after the weld has been completed, until the hot metal has cooled to ≤ 600°F.

Normal fluxes are inadequate to protect titanium from contamination; in fact, fluxes may actually contribute to a loss of weld ductility by alloying with the metal.

Of all the elements that will combine with titanium, oxygen has probably the most important effect. The metal normally has a very thin self-healing surface oxide film that provides its outstanding corrosion-resisting properties. When heated, however, titanium dissolves its own oxide. The oxygen diffuses into the metal, resulting in reduced ductility and toughness.

Aluminum is also a reactive metal but does not dissolve its own oxide; thus, the only damage that can be done by oxygen in welding aluminum results if the oxygen is entrapped in the weld puddle. When welding aluminum, therefore, only the weld puddle must be protected from oxidation whereas, in titanium, all hot metal must be protected.

Grinding, machining, and sandblasting techniques similar to those used to clean other metals can also be used to clean titanium, but metal grits should be avoided.[11] The use of chlorinated solvents such as tri-chlorethylene should be avoided inasmuch as deposits remaining after cleaning may cause cracking when the alloy is later heated.

The equipment used for welding may be either the gas tungsten arc or the gas metal arc, but the inert gas shielding must be more extensive and the power source should be capable of breaking the arc while maintaining gas flow for 10 to 30 sec before and after the weld. A properly executed weld should have properties comparable to the base metal as shown on the following page.

| | Ti-6Aℓ-4V | | Ti-6Aℓ-2Cb-1Ta-1Mo | |
|---|---|---|---|---|
| | Base | Weld | Base | Weld |
| Ultimate tensile strength, ksi | 124 | 131 | 127 | 132 |
| Yield strength, 0.2%, ksi | 110 | 115 | 107 | 116 |
| Elongation, % | 13 | 8 | 13 | 11 |
| Reduction of area, % | 26 | 19 | 29 | 27 |
| Charpy V-notch, ft-lb | 30 | 33 | 33 | 38 |
| Dynamic tear test, ft-lb | 1500 | 2000 | 2500 | 2100 |

Contamination causes approximately 99 percent of weld cracks. Weld color, as follows, is a good indication of the quality of the job but should not be used as conclusive proof of quality:

| | |
|---|---|
| Silver | Generally a good weld |
| Straw | Normally acceptable |
| Blue | Not usable in pressure applications |
| Purple | Only usable in noncritical applications |
| Powdery | Unacceptable for any use |

Dye checks reveal minute cracks; X-ray tests are valid indicators of porosity; and hardness tests show excessive oxide adsorption.

3.1.1.3.1.4 Machining. Titanium can be economically machined if the metal's special physical characteristics are taken into account. Like stainless steel, the low thermal conductivity inhibits the dissipation of heat and requires the proper use of coolants. The relatively low elastic modulus of the metal requires rigid setups, sharp and properly ground tools, slower speeds, and heavier feeds. The commercially pure grades of titanium are comparable in difficulty of machining to 18-8 stainless, with the alloys generally somewhat more difficult.

Turning is the least difficult of machining operations, but detailed instructions on speeds, feeds, and tool shapes have been developed. Drilling can be successfully accomplished with ordinary high-speed drills, although spiral drill points give better results. Milling, grinding, and sawing techniques are also well-developed. Tapping is probably the most difficult operation of all, but the use of interrupted threads on the tap or a 65 percent thread will give good results. Recommended coolants for machining operations are 5 percent sodium nitride in water or a 5 to 10 percent solution of soluble oil in water.

3.1.1.3.1.5 Surface Preparation and Antifouling Coating. Evidence to date indicates that there is no reason to avoid the use of standard Navy paint systems on titanium and its alloys; as a matter of fact, there are some data to support a beneficial effect on those alloys that are subject to stress-corrosion cracking.[12]

Experienced in coating titanium are the Naval Applied Science Laboratory in Brooklyn, New York, the Navy Paint Laboratory at Mare Island,[13] and the Naval Civil Engineering Laboratory at Port Hueneme.[14] NASL, with short-term exposure experience and the Navy Paint Laboratory, with 1-year exposure experience, believe that the most satisfactory coating system is as follows:

- Surface Preparation
  - (1) Sandblast with 8-20 mesh flint at 90 psi (the nozzle normal to the surface and at 1- to 2-in. distance) to a 140-μin. roughness. (Avoid metal grit.)
  - (2) Airblast to remove particles.
  - (3) Clean the surface with toluol.
- Paint System

  1 coat of formula-117 wash primer (MIL-P-15328)<br>
  4 coats of formula-119 vinyl red lead anticorrosive<br>
  2 coats of formula-121 vinyl antifouling paint (MIL-P-15931B)<br>
  Final coating thickness, 11 mils

Application of coating, although not necessary for the corrosion protection of titanium itself, is certainly required for protection from fouling. In addition, a good coating system, even if incomplete, reduces the effective surface area of the titanium and thereby tends to protect the less noble metals in the sensor system.

3.1.1.3.2 Hastelloy C, Chlorimet 3. These similar alloys of nickel, chromium, and molybdenum offer extremely attractive corrosion resistance. The wrought Hastelloy C displays the inertness and the strength characteristics of the titanium alloys. Both are essentially immune from all forms of corrosion attack. Here again, material cost is high and the alloys are not readily available in forms permitting efficient fabrication of sensor packages.

3.1.1.3.3 Inconel Alloy 625. This nickel-based alloy with high molybdenum content should find increased acceptance by instrument manufacturers. It is comparable to Hastelloy C and titanium in its resistance to all forms of corrosion.

3.1.1.3.4 Stainless Steels. The misleading name of this group of alloys has led to widespread use by instrument manufacturers. Most of the stainless steels should be avoided in oceanographic instrument use because of their susceptibility to pitting and crevice-corrosion attack. The more acceptable alloys, subject to a lesser degree to these forms of corrosion, are alloy 20 (also known as Carpenter 20 in wrought form and Durimet 20 cast) and, in noncritical applications, 316. The use of type 304 should be avoided entirely in direct seawater-exposure applications. For use in the marine atmosphere and at the air-sea interface, the restrictions can be somewhat relaxed because of the more ready availability of oxygen to maintain the passivity of the surfaces. Crevices should still be avoided whenever possible.

3.1.1.3.5 Copper-Nickel Alloys. The 70-percent Cu/30-percent Ni and 90 percent Cu/10-percent Ni (both with small percentages of iron) are attractive alloys for use in seawater because of their good resistance to pitting and crevice corrosion.

3.1.1.3.6 Berylio 717C. The addition of approximately 1/2 percent beryllium to the 70-30 copper-nickel alloy improves strength characteristics and maintains high resistance to corrosion and pitting. The annealing and age-hardening of berylio 717C yields castings twice as strong as the standard alloy meeting Mil-C-20159. The extra strength is obtained at a reasonable cost, so this alloy is attractive for oceanographic use.

3.1.1.3.7 Brass. The use of brasses for long-term seawater immersion should be avoided. High-zinc brasses are subject to selective leaching corrosion. Even the inhibited admiralty brass is subject to fabricator or vendor substitution by uninhibited brass with very little possibility of detection. The low-zinc (red) brasses and admiralty are susceptible to erosion corrosion at moderate water velocities and in the splash zone. Manganese bronze (a brass), which has been used by at least two sensor manufacturers, has exhibited slight to extensive selective leaching properties in INCO tests.

Admiralty brass is used extensively for meteorological instrumentation and is the standard material specified by the Weather Bureau for anemometers.

3.1.1.3.8 Aluminum Alloys. Although there has been widespread use of aluminum alloys in oceanographic instrumentation, experience shows several disadvantages in their use. The 2000 series is subject to general and intergranular corrosion. The 5000 and 6000 series, though exhibiting good general corrosion resistance, are subject to pitting attack in a low-oxygen environment. The 7000-series (high-strength) alloys tend to delaminate due to structural microcracks. All alloys are highly electronegative and, therefore, are difficult to use in conjunction with other metals. The use of the more effective copper or mercury-based antifouling paints is extremely hazardous and leads to increased local galvanic attack. The common practice of anodizing or Martin-hardcoating often leads to accelerated local corrosion (resembling pitting) when aluminum is used in combination with more noble metals such as stainless steels in fully immersed applications.

Aluminum is considered a suitable material for use in the marine atmosphere if it is suitably protected with a coating system. In this application, anodizing promotes adhesion of coatings and is not likely to cause accelerated local corrosion as it might during total immersion. The 5000 and 6000 series are considered best for marine atmospheric exposure. Pitting will remain a problem in crevices and on gasketed surfaces or at lapped joints.

3.1.1.3.9 Monel. This nickel-copper alloy should not normally be considered for seawater exposure in oceanographic instruments because of its poor resistance to pitting in relatively quiet water. There is a history of successful use of this metal at the air-sea interface and in the marine atmosphere — primarily because of the ready availability of oxygen.

3.1.1.3.10 Nonmetallics in Marine Service. Oceanographic sensors may utilize a great number of nonmetallic substances in direct exposure to seawater. Several of these materials are currently being evaluated for use as underwater housings. Those showing the most promise are the ceramics, glass, and plastics (both thermoplastic and thermosetting as well as the filled thermosetting resins). The ceramics, both alumina and beryllia, are polycrystalline materials combining high compressive strength, extreme hardness, high chemical resistance, and excellent insulating properties. Compared with most metals, the ceramics exhibit better corrosion resistances but are brittle, relatively weak in tension, and subject to damage by thermal shock. Quantity production of environmentally exposed instrument cases can be relatively inexpensive. Coors Porcelain Co. has a proprietary process for bonding rubber to ceramics, which might be employed to attain increased mechanical protection and antifouling properties by the use of biologically toxic elastomers such as NOFOUL.®

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There is insufficient information at the present time on several properties of ceramics:

- Thermal and physical shock resistance
- Paint adhesion
- Creep
- Fatigue in pressure cycling
- Corrosion in seawater

There has been considerable experience in the use of glass in the marine environment and, indeed, glass spheres and other engineering shapes are readily available commercially (e.g., Corning). Some advantages of glass are

- Very high compressive strength of $3 \times 10^5$ to $5 \times 10^5$ psi
- No creep
- High resistance to corrosion in seawater
- Nonmagnetic
- Transparent (uncoated)

Disadvantages of glass include the following:

- Glass has relatively low tensile strength of $20 \times 10^3$ to $50 \times 10^3$ psi, and strength may be seriously degraded by small imperfections, particularly scratches
- Resistance to mechanical shock is poor
- Complex glass structures are difficult to fabricate
- Glass to metal, glass to glass, and cemented seals are difficult to make, require considerable skill in assembly, and may be limited in the number of pressure and temperature cycles that they can withstand without failure
- Penetrations are relatively complex

- Construction and maintenance can be very difficult, particularly in the polar-access fused hemispheres
- Antifouling protection is more difficult because of relatively poor adhesion; sandblast or other abrasive surface preparation may cause a severe loss of tensile strength

There are two basic types of plastics — thermoplastic and thermosetting. By applying heat, the thermoplastics can be formed and reformed repeatedly without changing chemical composition or structure. These plastics creep or flow when subjected to long-term or repeated stress. The strain that results from this moderate stress application is normally reversible by the application of heat. Thus, the thermoplastics are said to possess an "elastic memory." Plexiglas is one of the most useful of the thermoplastics.

Thermosetting plastics undergo a chemical change during cure and cannot be reformed by the application of heat without losing their properties. Typical thermosetting resins are epoxy and polyester resins. The thermosetting plastics are usually used in conjunction with filler materials or fibrous reinforcing substances such as glass. Glass-reinforced epoxy has poor fatigue resistance. In addition, considerable creep strain may result from the application of moderate stress well below the yield point. There is also evidence of some loss of material strength after long-term seawater immersion. One of the techniques of combining glass with thermosetting properties involves mandrel winding, under tension, of glass filaments that have been dipped in thermosetting resin. The resulting structure may be 80 to 90 percent glass. Normally, glass-reinforced plastics are not entirely waterproof and tend to "weep" under high pressure.

3.1.1.4 Anticorrosion Coatings. The prevention of corrosion by application of coatings is considered in conjunction with antifoulants. In subsection 3.1.2.5, paint systems are treated as one topic.

3.1.1.5 Cathodic-Protection Systems. Cathodic protection refers to the techniques of impressing an external current on a metallic surface in an electrolyte as a means of decreasing or halting the corrosion process on the surface. Two methods are commonly used: the sacrifice of an anodic metal electrically coupled to the protected metal or impressed current from an external source on usually nonsacrificial electrodes. Both systems are quite practical for long-term seawater exposure of relatively simple metal systems, but the impressed-current system suffers several drawbacks in systems of any complexity.

Probably the most important argument against the use of impressed current is the need for close automatic control of protected surface potential — normally accomplished by continuously sensing surface voltage with respect to a nearby Ag-AgCℓ reference cell and feeding the data back to control circuitry for adjustment of electrode current. Protection of each metal in a system requires a different minimum potential with respect to the reference cell, and excessive potentials lead to destruction of coating systems. The "distance effect" also comes into play in that surfaces at various distances from the anode receive different amounts of protection; therefore, close spacing of impressed current anodes is imperative to afford protection to all surfaces, even in a simple metal system (which is unlikely). This method is eliminated from consideration on deep-ocean buoys because of the logistics of supplying sufficient power to a long string of sensor packages for the adequate (but not excessive) protection of all. Adequate control and power can be supplied from navigational buoys and fixed platforms, but the designer must consider the entire metals system (including the platform) and indeed must also consider cathodic-protection systems already extant on present fixed platforms for structural protection.

Application of sacrificial anodes to sensor packages is quite practical, and aluminum and zinc alloys capable of long-term protection of the coupled surfaces are available. The process of corrosion of sacrificial anodes is self-regulating in that they corrode (or provide current) at the rate required by the protected exposed surfaces. There is little danger of "blowing off" a coating by impression of excessive potentials. There is one great danger, however: the designer must take great care not to "protect" the coatings applied for antifouling protection. Antifouling coatings depend for their effectiveness on the solution of metallic ions that are toxic to fouling organisms. A conductive metal-based antifoulant can be effectively prevented from discharging toxic ions to the seawater by coupling to a sacrificial anode, thereby completely nullifying the coating's effectiveness. One should remember that copper, mercury, and tin form the basis of most marine toxics and that sacrificial anodes are generally highly anodic with respect to these metals.

A great deal of the practical information useful to the ocean-systems designer must be gleaned personally from scattered sources. Fontana and Greene are particularly thorough in describing all the corrosion processes.[2] Brown's treatment of corrosion and DeHart's materials survey are also helpful.[15,16] Both Fred M. Reinhart of the Navy Civil Engineering Laboratory and J. R. Saroyan of the Navy Paint Laboratory have been extremely helpful in supplying information for this report.[4,17]

3.1.2 MARINE FOULING. This discussion limits consideration of marine biological fouling to those sessile or attached organisms that can be expected to adversely affect oceanographic sensors; free-swimming species and free-floating grasses and flotsam that normally affect measurements only temporarily are not discussed. The frequently mentioned term "fishbite" is so poorly documented and understood that any treatment of the topic would be purely subjective and might well be misleading; fishbite, it is believed, will not present a serious problem to Coast Guard proposed systems.

The consideration of meteorological sensors in a system also necessitates concern for a different type fouling — that from birds, bird guano, salt spray, and salt incrustation. These are treated briefly.

3.1.2.1 Types of Fouling Organisms. Nearly 2000 species of animals and plants are recognized as marine-fouling organisms; this includes 615 types of plants and 1361 different animals. The most important foulers beneath the air-sea interface are barnacles, tunicates, hydroids, algae, bacterial slime films, bryozoa, and mussels.

3.1.2.1.1 Bacteria and Algae. Usually, the first biological community to form on a submerged surface are bacteria and algae (such as diatoms), which produce slime films. This formation occurs within a few hours of implantment. Organic and inorganic detritus, silt, and other particulate matter soon become incorporated in the film.

3.1.2.1.2 Barnacles. Under the proper conditions of season or water temperature favorable to reproduction, the barnacle is nearly as prompt as the slime film in finding attachment to surfaces. Barnacles are arthropods, related to crabs and lobsters, and are characterized in the adult stage by their hard, encasing, calcareous shells with four movable plates which open for feeding. They form a particularly tenacious attachment to all surfaces not toxic to them (including rough, smooth, hard, and soft surfaces). The barnacles form attractive attaching surfaces for other fouling organisms.

3.1.2.1.3 Mussels. Mussels are mollusks related to the clam and oyster; mollusks are distinguished by paired shells or valves joined by a ligament. The mussel attaches to a surface by means of a clump of tough threads (byssus) protruding through an opening in the shell. Fouling from this organism is frequently very severe, particularly in temperate coastal waters.

3.1.2.1.4 Hydroids. Hydroids are a colonial form attaching by rootlike stolons to a surface (Figure III-7). The stolons spread over the attachment surface and give rise to additional colonies. The actual feeding and sexual polyps occur at the free ends of stemlike structures that may reach full mature length in a matter of weeks. The fouling density continues to increase as new colonies are formed at the surface; eventually, a thick mass of growth may weigh several lb/sq ft and extend 6 to 12 in. Hydroids can be recognized as straight or branching growths, each thread terminating in an expanded tip. There are more than 2000 known species of the hydroid, but less than 300 are reported as foulers.

3.1.2.1.5 Tunicates. Tunicates, which appear as rounded, soft, flabby masses, may occur singly or in colonial forms that spread over a surface. The simple tunicates may be an inch or more in diameter and are commonly called sea squirts. The colonial tunicates form extensive jellylike masses composed of many individuals that retain their own inhalant siphons but may form common exhalant siphons with several nearby individuals.

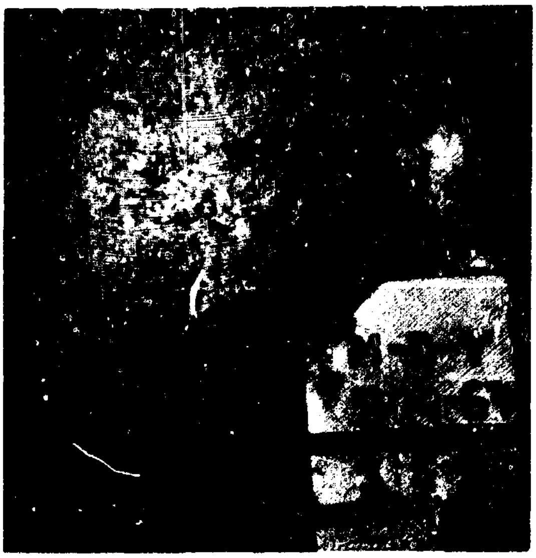
3.1.2.1.6 Bryozoa. The bryozoa are another colonial form, with various species taking on several characteristic patterns of growth. Some species grow in chainlike branching lines; others spread in roughly circular patches resembling the flat bases of dead barnacles or flat coral patches. These two groups are known as encrusting bryozoa. Erect bryozoa grow outward from the surface in fan or bushlike patterns and may be mistaken for hydroids, except for the fact that the branch tips are not expanded. At least one species of encrusting bryozoan, subovoidea, is quite resistant to copper antifouling toxics.

3.1.2.1.7 Birds and Guano. Above the air-sea interface, birds must be considered a fouling creature because of the adverse effect they may have on measurements. Sea birds include albatross, petrels, cormorants, auks, pelicans, gannets, and terns (including gulls). The excrement of these sea creatures, sometimes including dead bodies, is valuable commercially as fertilizer; Peruvian guano deposits contain 11 to 16 percent nitrogen, 8 to 12 percent phosphoric acid, and 2 to 3 percent potash.[18]

FLOAT P-46

- Unprotected; out 14 wk
- Hydroid
- 44 m

COMPARE WITH P-17-P
OUT SAME TIME AND DEPTH



25 MI OFF PANAMA CITY, FLORIDA

FLOAT P-17-P

- Protected; out 14 wk
- 44 m
- No growth on band
- Note zone of inhibition around band

**Figure III-7. Protected and Unprotected Floats**

3.1.2.2 Geography of Fouling. Fouling organisms are by far most abundant in coastal waters and, except for bacterial slimes and the occasional occurrence of a few species of barnacles, the problem is usually limited to regions within a few tens of kilometers from waters that are ≤ 200 m deep. The use of deep-ocean buoys may present a special case, however, since they may be towed to their mooring sites from continental waters, carrying with them a nucleus of colonies of coastal organisms. Although the attrition of animals whose larvae stage is free-floating can be expected to be severe, forms such as hydroids, gooseneck barnacles, and encrusting bryozoa may well find an attractive environment. Fouling would probably be much less of a problem if deep-ocean buoys were transported on deck to the implantment site.

Separate coastal regions support distinctive combinations of species of organisms. The general trend shows increasing numbers of species and increasing severity of fouling toward the tropics. The fouling growth of some animals is frequently severe in colder and, in fact, in Arctic waters, although reproduction tends to be more seasonally limited. From Newfoundland to Cape Hatteras, the mussel dominates most fouling communities, although occasionally the dominant forms are barnacles or hydroids. South of Cape Hatteras and in the Gulf of Mexico, fouling communities show greater diversity; the mussel may be lacking entirely. More tropical forms — including a large barnacle, oysters, and some coralline algae — may occur in the Bahamas and between Cape Kennedy and the Florida Keys. Tunicates and goose barnacles are also common. On the Pacific Coast, several mussel species are important foulers from Puget Sound to San Diego; found there also are barnacles of several species, with the large barnacles commonly found on the Florida coast also occurring on the Pacific Coast, particularly south of San Francisco.[1]

Marine birds tend to concentrate in regions of high productivity.[19] One of the most striking examples of this is the bird population off the west coast of Peru. The birds may reach a density of 5,600,000/sq mi and consume an estimated 1000 tons of fish daily. This high-productivity region (the result of upwelling and a ready supply of nutrients) accounts for the accumulation of guano, Peru's major industry.

It is futile to consider in detail the many biological provinces that occur throughout the world. The fact is that fouling is prevalent in all coastal waters and, except for limitations placed on reproduction by seasonal temperature changes in the water, the problem is severe everywhere in the world. Inasmuch as little or no fouling can be tolerated in most measurement systems, it is more important to describe the reasons why fouling must be prevented.

3.1.2.3 Effects on Measurement. The effects of fouling on most instrument systems can be considered so serious that absolute fouling protection is mandatory if the sensor data are to be meaningful.

Today's current meters are almost universally mechanical in that the angular velocity of one of several rotor forms is sensed. Differential pressure or lift provides the force necessary to overcome bearing friction at the threshold and then maintain rotation roughly proportional to current speed. A change in form drag on either side of these bodies causes a change in the proportionality constant necessary to recover current-speed data from rotational counts per unit time. Probably even more serious is the potential increase in frictional drag which may occur from fouling growth in small clearances such as are found between magnets and reed-switch speed pickups or around bearings themselves. The use of light as a rotational sensor has often been considered as an expedient for overcoming small clearance problems (and the additional drag and nonlinearity caused by magnetic forces), but fouling growth can easily cause serious light attenuation.

Current direction is usually sensed in one of two ways: by a vane orienting a compass housing (or sometimes an entire sensor-package housing) and by sensing the position of a separate pivoted vane with respect to a housing and the position of a compass with respect to the same housing. The latter method is subject to complete stoppage by fouling growth. An additional complexity is required to sense the direction of two transducers (vane and compass), although the directional response may well be more suitable for measuring rapid changes in direction. Pressure transducers commonly have diaphragms that are free-flooding and subject to fouling growth which might conceivably clog or stiffen, thus changing calibration.

Complete antifouling coating protection can probably overcome all of these mechanical effects, but more difficult to treat are the electrical and optical effects.

Measurement of electrical conductivity, which is the best known and most common method used for determining salinity in-situ, depends on precise geometric knowledge of the transducer. The relation used is

$$\sigma = G\left(\frac{\ell}{A}\right)$$

where

$G$ = conductance (number actually read)

$\ell$ = effective cell length

$A$ = effective cell area

$\left(\frac{\ell}{A}\right)$ = cell constant which is determined experimentally in seawater calibration

$\sigma$ = specific conductivity which is related nonlinearly to both salinity and temperature

The most important (but not the only important) part of the conductivity cell is the most constricted part of the seawater path. In most conductivity cells, the most constricted path is the hole through the center of two concentric toroidally wound transformers. The rest of the seawater current path linking the two transformers is the effectively infinite surrounding sea. The following example illustrates how essential the careful control of the cell's geometry is.

For a 3-in. long, 3/4-in. diameter center hole (neglecting the relatively minor contribution of the rest of the path), one can roughly calculate the cell constant:

$$\frac{\ell}{A} = \frac{3}{\pi \times (0.375)^2} = 6.78$$

For a specific conductivity of 50.00 mmho/cm, G would have been adjusted to read 50.00 by use of a multiplier (k = 6784):

$$G = k\sigma \frac{A}{\ell} = 6784 \frac{0.05}{6.78} = 50.00$$

If one forms a 3-mil nonconducting surface on the inside of the hole, such as might be an approximation to a light barnacle growth, then

$$\frac{\ell}{A} = \frac{3}{\pi \times (0.372)^2} = 6.9$$

Rather than a 50.0 mmho/cm reading, one has

$$G = k\sigma \frac{A}{\ell} = 6784 \frac{0.05}{6.9} = 49.28$$

This is a serious error for deep-ocean work.

Conductive biocidal coatings or nonconductive coatings that leach toxics and change dimensions should not be used, particularly on cell holes.

Measurements of pH and dissolved oxygen depend on electrochemical sensors that cannot be directly coated with antifoulants. Organisms which attach to diffusion membranes or pH electrodes modify the local environment so that the seawater parameters of interest are not being measured; indeed, the accumulation of protein on a pH electrode can destroy its measurement capability. Mechanical or thermal means are probably the only feasible ones for fouling protection.

Tide and wave gages that pierce the sea surface are affected by the filtering effects of encrusting organisms; hence, their ability to measure short waves decreases and calibration changes are caused by capillary wetting of surfaces above the changing air-sea interface. Also, the additional drag on wires or capacitive probes might well cause catastrophic damage to the sensors because of combined wave-orbital motion and surface-current velocity.

Optical effects on underwater sensors that depend on fixed light paths for measurment are obvious, and sensor windows must be protected by surrounding toxic coatings. This expedient does not overcome light attenuation resulting from silt deposition, which is a purely mechanical process. Fouling growth can also cause serious attenuation and pattern changes in sound transducers; it causes severe calibration changes in sound-velocity meters by changing sound-path length and severely attenuating sound signals by changing reflector surface characteristics.

In the marine atmosphere, the fouling concerns are birds, bird guano, and salt incrustation from spray. Guano accumulation can be expected to be detrimental to the measurement of cloud cover and solar radiation by occlusion of the protective transparent lens. Salt spray tends to accumulate on mirror surfaces in dew-point sensors, is caught and collected as precipitation, becomes encrusted on solar radiometers (decreasing the output),* and causes errors in transmissivity determinations.

*A test conducted by Convair on an Eppley pyranometer calibrated at 7.00 mv/langley showed a decrease in output of 0.5 to 0.6 mv (0.07 langley) at solar radiation level of 8.8 mv (1.25 langleys) as a heavy sea-salt crust was formed; this is an error of approximately 5.6 percent.[20]

Techniques have been devised or suggested for overcoming most of the effects of salt spray. Most common of the suggestions (from Weather Bureau personnel) involves the use of a retractable device or a periodically opened sensor, but there is no assurance that this expedient will prevent salt buildup. At least one short-range transmissometer purges the light sensor's surface with a continuous flow of dry gas. Obviously, this technique cannot be used for dew-point sensing.

Some work has been done to discourage birds from using platforms as perches. The NEL tower near San Diego originally used imitation owls with some success; more recently, tape-recorded gull distress calls have been broadcast from the tower (for 3 min every hour), nearly ridding it of gulls.[21] Birds have been discouraged from perching on Convair "Monster" buoys by the use of a discone antenna resembling a cage or trap.

3.1.2.4 Effects of Fouling on Corrosion. Some fouling organisms, notably barnacles, not only very firmly attach to surfaces but actually plow beneath corrosion-protective coatings. The obvious effect is the destruction of the coating integrity. A more subtle effect is the rapid accelerations of pit growth in metal surfaces as a result of metal ion concentration, acid formation, and differential oxygen concentrations beneath the base of the animal's shell.

This study has not revealed the effects of bird guano on either metals or coatings, but one should note that the material can contain rather large percentages of phosphoric acid. Coatings used for the protection of meteorological sensors which are generally made of aluminum should be able to withstand long-term exposure to the constituents of guano.

### 3.1.2.5 Coating Systems for Protection from Corrosion and Fouling.

Corrosion protection may be afforded a metallic substrate by the barrier nature of a coating, excluding water and oxygen from the surface, or by the inclusion of inhibitive chemicals or anodic metal particles that provide a measure of cathodic protection. Antifouling coatings are formed by loading coatings with biological toxics such as cuprous oxide and mercuric or organo-tin compounds.

The effective barrier-type anticorrosive coatings are usually materials of high molecular weight. Only those materials possessing low water permeability are acceptable for this use. Table III-3 shows the wide variation in permeabilities of commonly considered films.[22] These permeability values are given for applications near the sea surface. At high hydrostatic pressures, values of permeability normally decrease.

Inhibitive coatings include chemical treatments such as phosphates and chromates and wash primers, including Navy Formula 117 (Mil-P-15238). Cathodic protection is afforded by coatings of zinc or aluminum or by zinc-rich coatings.

3.1.2.5.1 Surface Preparation. The first important step in coating application is surface preparation. Abrasive blast cleaning is by far the preferred method of preparing both metal and nonmetal surfaces (except rubber). This step removes old paint, rust, and millscale and produces a rough profile to provide more "tooth" for an increase in mechanical adhesion of coatings of as much as 2000 percent. Typical of present poor practices in mechanical (wire brush) abrasive preparation is the use of steel bristle on aluminum surfaces, particularly on welds; small steel particles are imbedded in the aluminum, which can initiate corrosion and lead to violation of protective coatings.

Table III-3
PERMEABILITY OF MOISTURE THROUGH ORGANIC COATINGS
(after Burns, 1939)

| Coating | mg of $H_2O$/0.01-in. film/sq in./24 hr |
|---|---|
| Cellophane (not moistureproof) | 300 |
| Cellulose acetate | 300 |
| Vinyl acetate | 115 |
| Vinyl chloroacetate | 27 |
| Linseed oil | 80 |
| Long oil varnishes | 36-48 |
| Long oil varnishes plus aluminum powder | 14 |
| Single-pigment paints | 29-56 |
| Nitrocelulose lacquers | 15-87 |
| Orange shellac | 16 |
| Asphalt coatings | 5 |
| Polyamide-epoxy | ≤1 |
| Vinyl copolymers | ≤1 |
| Vinyl-alkyds | ≤1 |
| Polyurethanes | ≤1 |

An abrasive that leaves a minimum of occluded particles should be selected. For metal surfaces in general, Mil-A-21380B is a good basic guide. A roughness profile of approximately 20 percent of coating thickness is desirable. Oil and grease from handling can be removed with an alkaline or emulsifier cleaner such as Brulin's Scotch Cleaner (Brulin Company, Oakland, Calif.). For steel, phosphate, phosphate-chromate, or Formula 117, wash primer can then be used.

Delicate aluminum parts such as anemometer cups probably cannot be safely blasted with abrasives; in the case of delicate topside aluminum sensor components, coating adhesion can be improved by anodizing or Martin-hard-coating. All other aluminum surfaces should be treated with a chromium conversion coating.

3.1.2.5.2 Coating Application. Careful surface preparation is useless if subsequent coating application is faulty. A holiday may result in severe localized corrosion. Improper or incomplete application of an antifouling paint can result in gross fouling attachment. The performance of the painter is critical. Spraying distance should not exceed the point at which a continuous wet film of coating is obtained. Spraying from too great a distance usually results in a porous film that is not an effective water barrier. Some coatings are difficult to apply and require special techniques.

For economic reasons, the recommended number of coats is frequently not observed. A good paint job requires, at the very minimum, three coats. Multiple coats provide more complete coverage, offsetting to some degree imperfect painting techniques, and permit maximum solvent release for coatings that contain slow evaporating solvents. Contrasting colors are frequently used for alternate coats as a quality control on the coverage of each coat.

Experience has shown that an effective barrier is provided only by the application of certain minimum film thicknesses. Actual dry-film thickness measurement is the only acceptable method of determining whether adequate protection has been achieved. If a thickness gage is not available to the manufacturer, small metal coupons can be placed in appropriate places during the spraying operation and later removed for film-thickness measurement by micrometer or optical comparator. (Simple optical comparators are inexpensive and easy to use.) Table III-4 lists typical wet- and dry-film thicknesses.[22]

Table III-4

TYPICAL WET AND DRY THICKNESSES
(after Saroyan, 1969)

| Paint | Spray Passes | Wet Film (mils) | Dry Film (mils) | Percent Dry Film Is of Wet Film |
|---|---|---|---|---|
| Navy Formula 119 | 2 | 10 | 1.9 | 19 |
| Navy Formula 119 | 3 | 12 | 2.5 | 21 |
| Navy Formula 119 | 4 | 16 | 3.5 | 22 |
| Navy Formula 121 | 2 | 8 | 4.0 | 50 |
| Navy Formula 121 | 2 | 7 | 3.2 | 46 |
| Navy Formula 121 | 3 | 9 | 4.2 | 47 |
| Epoxy | 2 | 3.6 | 1.3 | 36 |
| Epoxy | 2 | 4.5 | 1.5 | 33 |

Proper and responsible supervision of cleaning, surface preparation, and coating operations is imperative. Too little attention has been given in the past to corrosion and fouling protection. Although it is recognized that each manufacturer's seawater-exposed materials system is unique, the survival of costly equipment and the waste of ship and mantime is at stake — not to mention the loss of valuable scientific data. Manufacturers must develop and maintain materials and coating standards.

For underwater sensor surfaces where recovery and overhaul are expected at intervals of not more than 1 year, the thickness of anticorrosive coatings should be 6 to 8 mils (dry film). The following is a standard Navy specification for an anticorrosive coating:

- Surface treatment: Formula 117 wash primer (Mil-P-15328)
- Anticorrosive: zinc chromate vinyl primer, Formula 120 (Mil-P-15930) for aluminum and stainless steel, followed by anticorrosive primer Formula 14N (Mil-P-19453)

Antifouling coatings should be applied for a minimum thickness of 4 mils. Efficient antifoulants are Navy Formula 121/63 (Mil-P-15931B), which is nonconductive if it contains less than 3 percent metallic copper, and Formula 134, which was developed for use on rubber surfaces and is readily adaptable for other nonmetallics and metal surfaces.

Several "exotic" coatings approved under Mil-P-23236 can also be used. This specification covers four different classes — epoxy, coal-tar epoxy, zinc silicate, and urethane. The zinc silicate is not satisfactory for seawater-immersion service unless top-coated with epoxy, vinyl, or coal-tar epoxy. Anticorrosive and antifouling paint applications, it should be noted, require minimum and maximum drying times, so the paint manufacturer's recommendations should be followed explicitly. For maximum effectiveness, the final coat of antifouling paint should be applied not less than 24 hr and not more than 30 days before immersion. It is recognized that this last requirement may cause hardship and that final application may be necessary at sea before sensor deployment.

Fouling protection of elastomeric materials on sensor structures has been particularly troublesome in the past. Two systems developed for the Navy are mentioned here for reference; the system for use on natural rubber is patented, but unrestricted use for U.S. Government purposes is permissible.

For both applications, the surface should be roughened mechanically and wiped with solvent; then,

- For neoprene:

  3 coats of Formula 134 (Mil-P-22299) polyisobutylene A. F.

  dry film thickness: 2 mils each coat (6 mils total)

  drying time: 8 to 16 hr between each coat and at least 24 hr but not more than 30 days' atmospheric exposure before immersion

- For natural and other rubbers:

  1 coat of neoprene coating (1.0 mil) (Gates Engineering Company)

  3 coats of Formula 134 (Mil-P-22299), 2 mils each coat (6 mils total)

  drying time: 8 to 16 hr between each coat and at least 24 hr but not more than 30 days' atmospheric exposure before immersion

There has been extensive effort to devise methods for protecting radar antennas (consisting of aluminum plumbing and stainless-steel hardware) exposed to stack gases and marine atmosphere.[22] It is readily apparent that these methods can be used directly on marine-atmosphere exposed meteorological sensor components. These same protection methods are suggested by Saroyan for coating underwater aluminum structures.[22] In this procedure, the aluminum is cleaned by abrasive blasting or chemical means and subjected to a series of processes such as

- Mild alkaline cleaner (Diversey 202, Diversey Corp., Chicago, Illinois, or equivalent)
- Deoxidizer (Deoxidizer No. 1, Amchem Products Inc., Niles, California, or equivalent)
- Chromium conversion coating (Alodine 1200S, Amchem Products, Inc., or equivalent)

The aluminum is further protected with three coats of an epoxy coating system, after which electron-irradiated heat-shrinkable polyolefin components (Rayclad Tubes Inc., Redwood City, California, or equivalent) are installed over the critical joints of dissimilar metal contacts and hard-to-protect surfaces. An epoxy adhesive is used between the boot and the surface. The stainless-steel hardware is cadmium-plated (0.0005 to 0.001 in.) and treated with a chromium conversion coating such as Iridite IP (Allied Research Products Inc., Baltimore, Maryland, or equivalent).

The protection of underwater sensors involves several unique problems. Several regions such as electrochemical sensing transducers, lights and light sensors, bearing surfaces (both underwater and topside rotors), and possibly conductivity heads (especially the torus hole) cannot be directly protected. An efficient antifoulant such as Formula 121/63 can be expected to afford some protection from the attachment of fouling organisms for distances of a centimeter or two, depending on flow rate; this should afford attachment immunity to bearings, windows, and cell surfaces if they are kept small and in close proximity to coatable surfaces. The practicability of actually coating conductivity cells entirely is unknown, but certainly any investigation of this problem should utilize only those antifoulants which are nonconductive. Coatings that contain lampblack in their recipes, as well as all inorganic zinc coatings, are conductive. In general, inorganics containing little or no metallic particulate matter are nonconductive.[17]

Other difficult regions are those surfaces forming metal-to-metal seals (closures); they must be periodically opened for servicing. It is recommended that a chamfered edge be provided wherever possible for a "final" predeployment seal with an RTV silicone rubber such as Dow-Corning 780, followed by an epoxy-filled boot of heat-shrinkable polyolefin tubing. This type of seal may later be cut open for servicing.

Aluminum alloys are particularly difficult to protect when in combination with other metals that will undoubtedly be used in a sensor package. The best corrosion protection can be afforded by use in all critical regions of those materials that do not corrode in combination with efficient coating systems that give complete protection from fouling. By far, copper-based antifoulants are the best. Mercury-based paints are hazardous to use because free mercury in the compounds tend to amalgamate with some alloys, particularly stainless steels. Tin-based antifoulants — most safely used on aluminum structures — are the least efficient of the three.

The information contained in the preceding is based on work performed during the past 30 years by the Navy Paint Laboratory at Mare Island. John R. Saroyan, noted coating specialist with the laboratory, has contributed heavily — both by personal communication and by publications referenced in this report.[3,17,22] The author recognizes that a great number of coatings are available on the market today — some with glowing claims for their effectiveness. A recent paper describes a product manufactured by B. F. Goodrich called NOFOUL;® this product is being evaluated by the Applied Sciences Division, Office of Research and Development, Coast Guard, and exposure tests to date look good. R. D. Parkhurst suggests that this material be seriously considered for corrosion and antifouling protection. However, the only coating systems that have been given full consideration are those which have been proven effective over the years by extensive test programs. The author can see no reason why sensors that will be procured by government agencies should not make use of the very valuable experience of the Navy Paint Laboratory.

3.1.3 TEMPERATURE. Temperature ranges encountered in the open ocean do not normally exceed the range of -2° to +30°C. Very near the surface and in inshore waters, 30° may be exceeded. In certain parts of the Red Sea, temperatures may exceed 42° on the surface and 56° in deep holes, and reference can be found to a lower extreme of -3°, although this is exceptional.

Marine atmospheric temperatures normally have a much greater range than that of the water itself, although the sea temperature tends to modify boundary-layer temperatures, making them less extreme than temperatures over a continental mass. It is more meaningful to assign to a locale an air temperature that is exceeded a certain percentage of the time rather than to fix a limit that will never be exceeded; thus, Table III-5 presents data on dry-bulb temperatures that are equalled or exceeded 99 percent of the time during the coldest three consecutive months and dry-bulb temperatures that are exceeded 1 percent of the time during the warmest four consecutive months. Two examples are shown for each of four ocean basins.[23]

Table III-5

TYPICAL MAXIMUM AND MINIMUM TEMPERATURES AT MARINE-DOMINATED LOCATIONS

| Location | Temperature (higher 99% of time during four coldest consecutive months) (°C) | Temperature (higher 1% of time during four warmest consecutive months) (°C) |
|---|---|---|
| Atlantic Ocean | | |
| Keflavik, Iceland | -10 | 15 |
| Bermuda | 12 | 31 |
| Caribbean Sea | | |
| Grand Bahama | 8 | 32 |
| Port au Prince, Haiti | 17 | 36 |
| Mediterranean Sea | | |
| Nicosia, Cyprus | 1 | 39 |
| Valetta, Malta | 6 | 33 |
| Pacific Ocean | | |
| Wellington, New Zealand | 2 | 24 |
| Manila, Phillipine Islands | 23 | 34 |

Although the range of temperatures found within the ocean is not normally considered extreme for electronic equipment, the rate of change is of concern. Shipboard deployment of sensors typically involves a single package dropped or lowered through the water column. Measurements are taken as rapidly as the fall rate and sensor response permit so that an investigator can obtain as much data as possible. Vertical gradients in temperature and drop rate determine the required time constant for a transducer to be used from shipboard; all three factors dictate the measurement sampling interval. Therefore, instruments for use on shipboard are subject to a peculiar environmental situation which is controllable to some degree by an onboard scientist or winch operator. (One must also be aware of the step-function transition from atmospheric to ocean temperature, however, and this will be discussed later under the heading "Thermal Shock.") The infinite variety of thermal structures in the sea precludes pinning down an expected gradient; indeed, whether the investigator is considering microstructure or macrostructure, the gradient need not be monotonic. Each measurement program has specific goals, so sensor drop rate and time constant must be tailored to these goals and to regional considerations.

An array of underwater sensors suspended from a moored deep-ocean buoy will typically have a periodic vertical motion of several meters. If this motion occurs in a steep gradient of, say, $0.05°/m$, the temperature sensor then effectively also measures depth variations and there is seldom a satisfactory method of determining whether the measured changes are actually true temporal changes at a given depth. It may well be an advantage to use a slowly responding temperature transducer in this case so that this type of "noise" can be filtered mechanically. Of course, the end use of the data will dictate the decision. Horizontal changes in temperature (as water is transported past a sensor) are nearly always quite slow, especially at great depth. Horizontal changes in bottom water are on the order of hundredths of a degree per year. Except for special cases such as the measurement of internal waves at mid-depths, frequent measurements are seldom made.

Navigational-buoy water-temperature sensors are typically mounted near the surface in nearshore waters. Temperature variations can be expected to follow a seasonal pattern near the surface, with extremes of -2° to as high as 35° and short-term time changes that depend on the mixing processes of the buoy-marked estuary and local shelf waters. Again, specific goals must be applied to determine time constants and sampling interval.

A fixed-platform system will be subjected to a small-scale version of the deep-ocean water column, but temperature changes will be more rapid than in the deep ocean because of interfacial and coastally induced turbulence and the mixing processes associated with shallow-water waves and tides.

It is important to emphasize that an adequate description of time-varying changes in the ocean is the aim of a measurement program and that transducers must be capable of measuring processes at the speed of interest. The absolute range of temperatures that will be encountered will not be excessive, however, for most sensor packages.

One important effect of temperature is to change the viscosity of fluids. More than a twofold increase occurs in the viscosity of seawater in its transition from a temperature of +30° to 0°C. A more important effect is the change in viscosity of damping fluids such as those used in magnetic compasses and vane-followers. Very careful selection of damping fluids is required if severe aliasing of direction data by an underdamped or overdamped direction sensor is to be prevented. In order to evaluate the effects of turbulence and array motion, direction responses of instruments should be tested at the temperature extremes that may be encountered in the environment. Again, the best cure for potential errors is nearest the source of the measurement and is achieved by properly matching direction transducer response times to the expected environment.

The measurement of atmospheric temperatures has its own peculiar set of problems. Near the air-sea interface, strong temperature (and dew-point) gradients may exist, making measurement difficult on a moving platform. Under certain conditions, sea spray may reach the sensors and change the apparent temperature, either directly or by evaporative cooling. The most serious difficulty, however, results from radiation: direct solar radiation, sea-surface reflected radiation, or that radiated from the platform structure. A radiation shield is imperative but never results in complete shielding. Although an air-temperature sensor can be calibrated quite accurately in a liquid bath, there is no guarantee by this calibration method that actual use will enable the transducer to couple adequately to the air or decouple adequately from radiation influences.

3.1.4 HYDROSTATIC PRESSURE. Pressures encountered at great ocean depths are more easily placed in perspective by considering the forces exerted by a water column. Seawater weighs approximately 64 lb/cu ft; at 6000-m water depth (19,700 ft), this corresponds to a force, exerted on all surfaces of a body, of 19,700 x 64 = 1,260,000 lb/sq ft (8857 psi).

One can assume that underwater equipment will be designed to withstand pressures below yield stress (and cyclic hydrostatic loading) for the material and form chosen. For long-term pressure application, however, an insidious element enters: plastic flow or creep. Failure (of a pressure case, for example) may occur at pressures well below yield stress simply because the dimensions may slowly change outside of design tolerance. For example, an effective O-ring seal between a cylindrical case and a flat endplate may open beyond permissible limits because of plastic deformation of the endplate; O-ring seals depend on the maintenance of close tolerances and smooth surfaces, and a significant dimensional change may cause failure either directly or by permitting crevice corrosion to occur. Indeed, failure may not occur at depth but on recovery as the pressure is released from a deformed or corroded seal surface. Flooding is catastrophic at any time.

Two processes leading to distortion are usually in simultaneous operation within a material: they are both thermally actuated and are known as grain boundary sliding and dislocation climb. At or near absolute zero (0°K), the atoms can be regarded as permanently fixed in the crystal lattice; at the upper extreme, the approach to melting temperature permits a rapid exchange of places between atoms. Under stress at moderate temperature, grain boundaries behave like a viscous fluid, and creep strain results. Strain resulting from dislocation barrier jumps also occurs because atomic mobility, which increases rapidly with temperature above absolute zero, permits atomic vacancies to diffuse and remove rows of atoms. Dislocations can thereby be effectively displaced and can then move on. Dislocation climb is the more important process at high stress levels, whereas grain boundary sliding predominates at lower stress levels.

Creep-strain failure of a pressure case would not normally be expected to occur by rupture. The vessel seals would probably fail by distortion beyond design tolerance, but the result would be the same as far as the enclosed electronics is concerned. Rupture failures result from one of two modes of intercrystalline fracture. One mode is the growth of cracks originating along the lines of intersection of three or more grain boundaries where stress concentrations are particularly high. The other process, which is most likely to occur at low or moderate stress levels over long periods, is the growth of voids along grain boundaries that are normal to the direction of tensile stress; the growth and coalescence of these voids eventually result in cracks.

Several materials are notably more creep-resistant than others. Some materials have been developed especially for creep resistance — usually involving control of grain size or the introduction of hard second-phase particles in solid solution. These materials include SAP (sintered-aluminum powder) and the complex alloy, Nimonic 90. Materials more commonly considered for oceanographic use include titanium 6Al-4V alloy, which shows excellent creep-resistance, and glass, which does not creep.

Creep is primarily a phenomenon associated with tensile stress. Very little information exists on the creep behavior of materials under compression, but it is difficult to envision a closed structure in which tensile stress is not present. This property of materials must be a serious consideration in the design of vessels and devices to be used at high pressures over long periods of time.

Some of the more serious aspects of the high-pressure environment can be overcome by applying techniques that minimize pressure differentials inside and outside an enclosure. This is generally accomplished by filling a pressure case with a fluid closely approximating the compressibility of seawater and mechanically coupling the ambient pressure to the inside by means of a bellows, piston, or diaphragm. Additional problems are created, however — particularly with complex electronic circuitry. Aside from the obvious increase in the degree of difficulty in servicing, electronic components are often adversely affected. Carbon resistors can be expected to change radically in value under pressure. Capacitors sealed with air entrapped may collapse at relatively low pressures. Certain magnetic materials will exhibit large changes in characteristics. Many semiconductors will fail under pressure unless their cases are protected from collapse. Although it may be inferred from this that the design is more difficult for pressure-equalized environment, it has been demonstrated that proper component selection can place this technique well within the realm of practicability as a valuable design method.

3.1.5 SENSOR MOTION. The motion of the sensor platform or the sensor's self-motion can be expected to influence meaningfulness of measurements. Involved to some extent on several platforms are the measurements of current velocity, water temperature, wind velocity, air temperature, barometric pressure, precipitation, solar radiation, and waves. This discussion is not intended as a detailed analysis of platform motion but should serve as a reminder to the instrument specifier of the difficulties he may encounter with traditional measurement methods.

For underwater measurements from a moving platform, the difficulty arises from an inability to accurately fix on the instruments in space, to maintain the position chosen, or to adequately describe the motions imparted to a sensor array. There is only one good fixed reference at sea — the bottom — and this reference is often distant by several kilometers from the point at which one wishes to make measurements. Accuracy of current measurements, therefore, are constrained by the distance from the reference point, by the compliance of the moor, and by the turbulent horizontal motion of the sea that keeps an instrument string in constant motion. Ocean currents are not steady but continuously change in direction and speed. Furthermore, this motion is not vertically isotropic but may vary radically in speed (and direction) with depth. Therefore, the prediction of the motion of a sensor array can yield only statistical approximations. The alternative to motion prediction is to reduce the array compliance so that motions imparted to the sensor are small with respect to the scale and magnitude of the water motion or measurement of the array motion with respect to the earth's surface. This measurement is generally made by using sensor-mounted accelerometers and is complicated by errors introduced by integration of the usually small accelerations encountered at low frequencies.

In meteorological measurements, the problems concern only one important part of the system — the platform itself to which the sensors are affixed. The platform is normally closely coupled to surface phenomena such as waves and wind. Again, it is important to make measurements at a fixed point — either horizontally or vertically — and in a fixed direction (such as with solar radiation). The motions and accelerations encountered, although not destructively severe, can render meaningless the measurements of wind velocity, temperature, pressure, precipitation, and radiation.

### 3.1.5.1 Motion Description.

3.1.5.1.1 Buoy Motion. There has been no significant amount of work on the nonlinear analysis of buoy motion. Nearly all fluid-dynamics analyses have been concerned with objects moved through a stationary fluid. The magnitude of the motions of these bodies moved through stationary (although turbulent) fluids is generally much greater than the motion of the fluid itself, so turbulence can be ignored. A moored buoy, however, must operate in the real world where turbulence is a fact and (to many investigators) a noise. It is only in the major ocean currents that the relatively small-scale turbulent contribution is small with respect to the major flow. There have been considerable analyses of the motion of ships, but the work is only marginally useful to the description of the motion of a buoy system. Almost all studies of buoy motion have been conducted with linear approximations because of the extreme complexity of the problem.

The major contributors to buoy motion are

- Wave action on the surface float
- Horizontal drag on buoy, mooring line, and sensor packages
- Rotational motion imparted by large-scale turbulent features
- Strumming resulting from Karman vortex shedding

Waves impart to a surface-following buoy a vertical motion that is transmitted in a complex manner to a compliant moor. Waves tend to be random in nature; only in the major features can periods be assigned. The buoy designer must be aware of the expected major wave periods if he is to avoid resonances in the moor that may greatly amplify vertical motions imparted at the surface. If this amplification is avoided, one can expect an approximately linear decrease of vertical motion of the moor with depth. In the wave itself, and extending to depths which depend on the wave features, vertical orbital motion predominates.

Horizontal drag on the system is imparted by the water current and wind and is proportional to the square of the fluid velocity; hence, changes in velocity are reflected on the buoy system as a nonlinear force function. Induced motions are primarily horizontal; only in the case of a submerged buoyant member does vertical motion become important.

Large-scale turbulence (the rule rather than the exception) additionally complicates the motion by inducing a rotational component. Oceanic turbulence is primarily a horizontal feature and, as with the irrotational drag above, the motion induced in the array depends on the scope and compliance of the moor but is often measured in kilometers with velocities of tens of centimeters per second. As with translational motion, the absolute distances traveled by a sensor can be expected to decrease approximately linearly from the surface layer to the bottom.

Vortices shed by features of the moor are quite predictable for a steady flow (unreal), and the frequency of the motion thus imparted to the buoy string depends on the effective cross-sectional area of the sensor (or cable), the fluid velocity, and the kinematic viscosity of the water. The motions induced by vortex-shedding are usually small in oceanographic sensor systems normally deployed but complicate the measurement of small-scale features and lead to mechanical fatigue of system components.

Pitch, roll, surge, heave, and rotation of the platform itself depend strongly on hull form. A spar buoy, for instance, is poorly coupled to the surface waves and tends to remain fixed with respect to the vertical. Pitch, roll, surge, and heave are of small importance in the case of a spar, and rotation can also be minimized. This hull form is generally considered more suitable than a surface-follower for measurements requiring a relatively well-fixed vertical reference such as waves, temperature gradients, and wind profiles.

3.1.5.1.2 Fixed-Platform Motion. Motion problems of fixed-platform arrays are much less serious than those of buoys (or ships). Wind as well as water speed and direction may be more clearly defined on a fixed platform because the sensor arrays can be fixed in space and constrained against rotation, thus avoiding the vagaries of geomagnetic direction transducers. Furthermore, the distance between top and bottom constraints on underwater sensors permits the use of a relatively stiff array. No significant vertical motion should be imparted, and the horizontal and rotational motion can be constrained within the mechanical deflection limits of supporting cables and the torque arm supplied by guide cables.

3.1.5.1.3 Ship Motion. When an underwater sensor package is lowered from a ship, the motion imparted can be at least as complex as that to which a buoy sensor is subjected. However, some control may be exercised by ship propulsion or a winch operator. The following are motions that can be expected:

- Wave action on the ship may be amplified by the lever arm formed by the distance between the boom and the ship's center of motion. This verticle motion of the ship can be either damped by the downline and sensor package or amplified by resonance effects. Indeed, many instrument packages have been lost by failure to consider the magnitude of the forces which can be induced by ship motion.

- Horizontal drag on the cable and sensor package tends to lift the sensor from the desired depth; additionally, ship's wind and current set can either decrease or amplify the problem.

- Rotational motion of the sensor string about its own axis or about a turbulent eddy axis can further complicate the determination of absolute velocity of water motion at depth.

- Meteorological sensors, usually mounted on a ship's mast where wave motion is greatly amplified by the height of the installations, will frequently be seriously biased by the motion.

### 3.1.5.2 Effects on Measurements.

#### 3.1.5.2.1 Buoy Measurements

3.1.5.2.1.1 Ocean Sensors. The primary deleterious effects of the motion of the underwater sensors are felt by current meters, which can only measure velocity with respect to the sensor package. Vertical motion imparted to a current meter in a shear field will complicate a measurement intended to describe the variation of velocity with time in the horizontal plane. (One presumes that the current meter, which is intended to measure the horizontal components of velocity, will not respond to vertical components but this is not always true.) Small-scale motion of a sensor array will appear as noise or as aliased data in the measurement of gross motional scales.

Primarily, mechanical speed and direction sensors are subject to inertial effects which may completely mask larger, slower motion features. Mechanical aliasing can occur (as with the Savonius rotor) because of omnidirectional sensing characteristics or because of rotor inertia. (The Savonius rotor is better coupled to the fluid during a speed increase than during a speed decrease.)

The measurement of water temperature is also subject to the effects of sensor motion. Unwanted vertical-array motion in a strong temperature gradient can present an entirely false picture to an investigator who is interested in the relatively small horizontal variations of temperature.

The difficulty of measuring waves from a moving platform is well-known. Wave-amplitude measurements require double integration of vertical acceleration, which frequently generates large errors, or the measurement of pressure from an auxiliary damped platform, which can introduce an undesirable filtering effect dependent on pressure-sensor depth. The measurement of wave direction presently requires proper combinations of acceleration, pitch, roll, and direction information.

3.1.5.2.1.2 Meteorological Sensors. Wind-speed measurement is often biased by the motion of the platform because of the accelerative asymmetry of cup anemometers[24] and because of errors introduced by pitch (axial inclination).[25] The first effect is most pronounced at low wind speeds and higher mast levels. The second effect should be a function of angle alone. Wind-direction measurement by vanes also suffers from platform motion. At low wind speeds when the vane is poorly coupled to the wind itself, apparent air motion induced by platform roll moves the vane. In addition, a vane must be well-balanced about its vertical axis. Biaxial drag body (square law) anemometers have been developed to obviate some of the difficulties in measuring wind velocity from moving platforms.

Air-temperature and dew-point measurements are complicated by the fact that large temperature and humidity gradients can occur near the air-sea interface. Vertical sensor motion, therefore, is of concern. Barometric pressure will change on the order of 0.1 mbar for each meter of height; 0.1 mbar is the accuracy requirement on all platforms.

The most commonly used precipitation gages (tipping bucket and weighing type) are unsuitable for use on moving platforms because they are acceleration-sensitive. A radiometer must be kept vertical within approximately 5° to prevent unrealistic measurements resulting from earth radiation.

3.1.5.2.1.3 Directional Heading. Directional information (platform heading) must be carefully considered. The improper selection of damping fluid for a magnetic compass can cause large errors in indicated direction.

3.1.5.2.2 Fixed-Platform Measurements. Inasmuch as proper design of a sensor suspension can reduce motion of the array to insignificant values, motion is not considered a measurement limitation.

3.1.5.2.3 Ship Measurements. Ships are not normally constrained in any manner with respect to a fixed reference point except within the limits of navigational aids. One is tempted to state that current measurement from a ship at sea is impossible; however, it is done to some degree of accuracy almost every day.

One technique is the measurement of relative velocities between two or more major ocean features, such as the measurement made between the very slow-moving deep oceanic water and the Cromwell current, with both measurements being made simultaneously from a single sensor cable. Another method involves a relatively taut-moored buoy as a reference, the maintenance of a zero-wire angle on a sensor string by ship maneuvering, and a plot of ship's position with respect to the "fixed" buoy. These are complicated expedients indeed and only serve to make possible the measurement of the ocean's gross features.

Wind-velocity measurements can also be biased by the relative motion of the ship while steaming (and errors in measuring this relative motion) and by the frequently violent motion of a mast (the usual mounting position of the anemometer).

All of the other vagaries of measurements from buoys apply as well to ships. The instrument specifier is cautioned to consider carefully all of the effects of motion on the system.

3.1.6 STRUCTURAL PROXIMITY EFFECTS. Sensors to be mounted on or near each of the several types of platforms are subject to special cases of measurement-environment modification. Some can be dismissed rather quickly, but other underwater and topside measurements require considerable thought and planning by an investigator. Among the latter are current velocity as well as chemical and optical parameters, wind velocity, temperature, barometric pressure, precipitation, and radiation. A good example of the modification of wind environment is shown in Figure III-12, subsection 3.1.12.

3.1.6.1 Buoy Effects. In underwater measurements, the most serious effect of a buoy system is the fouling community that lives and propagates on the mooring line above the 400-m level. Hopefully, the buoy hull will be adequately protected from all but micro-organisms, but this study has not revealed an adequate protective coating for either metal-sheathed or plastic mooring lines as they will be used in this application. The presence of these organisms can be expected to influence measurements of chemical parameters such as pH and oxygen by their own modification of the local chemical environment. These effects are naturally felt more seriously under conditions of low water velocity. Additionally, fouling growth can be expected to infect unprotected sensor surfaces such as light ports and electrochemical sensor membranes. The effects of the increase in the cross-sectional area of a mooring line will also be seen as an increase in form drag, but it is impossible to assess the function precisely since some organisms, notably hydroids and erect bryozoa, may well tend to decrease drag by providing an effective natural fairing.

Navigational buoy sensors have, in the past, been hull-mounted and directly subjected to the motions of the hull. In addition, the hull itself perturbs the flow. Theoretically, this flow perturbation extends to infinity, but a frequently used rule-of-thumb is that the influence of a modifying body is small at a distance of five times the effective diameter. Navigational buoy hulls draw a bit more than 1 m, so an extension of a current sensor to a distance of 5 m below this draft would seem to increase the effective-accuracy capability of a hull-mounted current meter. However, this rigid hull extension also tends to amplify the effective sensor motion due to hull pitch and roll, and an omnidirectional current sensor (such as the Savonius rotor) will sense this motion as an increased current speed. Only a properly designed directional sensing system can resolve this difficulty.

All of the deleterious effects of fouling growth can be expected to influence a sensing array, much as on the deep-ocean buoy but more seriously because of the extremely high continental-shelf fouling populations. The measurement of ambient light will also be made difficult by the shadowing effect of the buoy hull, and measurement of ambient noise will be rendered impossible by the acoustic coupling of the buoy electrical generating system to the water. Above the air-sea interface, the primary influence is from the buoy structure. Advection of a fluid over a boundary or past a perturbation causes a disturbance in the boundary layer. The effects of the disturbance grow downstream at different rates for different parameters. The diffusion speed for momentum (velocity) effects is different from that for, say, temperature.[26]

One can see, then, that measurement of any parameter near a structure (within approximately 20 diameters)[26] will be influenced by the structure. Some of these perils are

- Changes in the turbulent motion of the wind, which may cause errors in velocity measurement
- Temperature effects, both from changes in the normal temperature profile by advection past the buoy and by heat added by radiation from the platform and by exhaust from onboard generators
- Changes in air pressure caused by the flow past a structure
- Precipitation-direction changes caused by vertical (upward) motion around a disturbing structure
- Radiation from the buoy, influencing the measurement of reflected radiation or albedo

3.1.6.2 Ship Effects. Ship-deployed underwater sensors should see relatively little environmental modification by the platform except possibly at the surface where the ship's cooling water discharge will modify downstream temperatures. The interpretation of near-surface measurements traditionally requires a great deal of common sense because of the difficulty on a rolling ship of maintaining a precise shallow depth, defined as the surface, and because of the sharp temperature and salinity gradients that may frequently be found near the surface. Above the surface, the influence of the platform is again more evident than underwater.

Although the stream lines past a simple structure can be easily visualized, a ship's superstructure is not simple; rather complex airflow may result (especially from a beam wind). Violent updrafts can make the measurement of wind velocity and precipitation extremely unreliable. Because of the flow up and over an obstruction, one may also be measuring a parameter at some level other than that of the instrument. Other measurement hazards to consider, similar to difficulties encountered on a buoy, include:

- Heat generated by and reflected from the platform, making temperature and radiation measurements difficult
- Light (and radiation) shadowing effects
- Pressure reduction on the lee side of obstructions

The BOMEX project widely used bow-mounted boom extensions for mounting instruments in order to minimize the effect of the structure on air-sea interface measurements.

3.1.6.3 Fixed-Platform Effects. An underwater sensing array suspended from a fixed platform is subjected to all of the environmental influences of the local platform fouling population, platform shadow effects, and ambient noise as just discussed. The most notable difference is the large structure extending to the bottom. Even a casual examination of Figure III-8 reveals the difficulty of making meaningful current measurement near the tower structure.

Figure III-8. Buzzards Bay Entrance Light Station Showing Heavy Mussel Fouling. Cables are part of cathodic-protection system

Figure III-9 shows guide and data cables for a presently installed oceanographic measurement system. The cables enter the water at a distance of approximately 3 m from the tower leg; tower-leg diameter is a nominal 36 in., but this is effectively increased to 42 in. by heavy mussel fouling.

The vortices shed in the wake of the tower structural components and the wave surge produce an extremely complex water motion. Probably, a better choice of velocity sensor location can be made, first assessing the mean tidal-current direction and the variability of the direction. Possible choices are dead center of the platform structure, which would tend to decrease directional bias, or well away from the structure (either by long boom or independent moor), which would naturally increase deployment and maintenance difficulty.

Figure III-9. Buzzards Bay Entrance Light Station Illustrating Proximity of Tower Leg to SWORD Array

For the meteorological suite, the large tower structure, which is well-removed from the air-sea interface, is difficult to assess. The gross effects of the platform will be similar to those on buoys and ships, but it is possible (and probably desirable) to use large existing radiobeacon antennas to remove the instruments as far as possible from the bulky superstructures.

### 3.1.7 ELECTRICAL POWER

3.1.7.1 General. Power-source instability is one frequent difficulty in operating oceanographic data systems. The best method of overcoming this is to have a separate power source for the data system so that it will not be affected by transients generated by the switching of heavy loads often encountered on ships, fixed platforms, and navigation buoys. This is not always practical, however, so oceanographic sensors must be designed to operate from a common source if voltage and frequency instability may be present.

A number of power sources in use or in development show promise, particularly for remote unattended operations. These include

- Batteries
- Fuel cells
- Nuclear-energy sources
- Chemical combustion
- Internal-combustion engines
- Combination sources

It is beyond the scope of this work to cover all of these potential power sources. The primary source of power for many applications (fixed platform, ship, and navigation buoy) is the internal-combustion engine driving a single- or 3-phase 60-cycle alternator. This power source also is one most subject to voltage and frequency instability, so the requirements are based on an internal-combustion engine driving a 60-cycle alternator.

3.1.7.2 Operating Limits. The power source can be expected to furnish steady-state line-voltage variations of ±10 percent and frequency variations of ±5 percent from a nominal primary power input of 115 vac at 60 Hz. Voltage changes of ±20 percent and a frequency change of ±5 percent of nominal from any point within the steady-state limits previously given, recoverable to the final steady-state value within 2 sec, can also be expected. As a rule, momentary impairment of operations during these changes is permissible, but the changes should not cause failure of any component or prevent resumption of normal operation or require the equipment to recycle when the steady-state value has again been reached.

3.1.7.3 Transients. In applications in which oceanographic sensors are used on platforms that are primarily aids to navigation, the power source can be subjected to large fluctuations in load demand.

Figure III-10 shows the current vs time for a 1000-w incandescent filament lamp as used in a Class-II load for Coast Guard EOE-3 Purchase Description No. 198. This purchase description states in paragraph 5.3 "... For a sudden load change from no load to full load to no load, the maximum overshoot or undershoot is 10 percent of the rated voltage."

Even if the alternator itself cannot exceed 10 percent of rated voltage, however, the sensor designer and manufacturer must be aware that other systems on the platform can insert noise spikes on the power line when subjected to this rapid voltage change. The presence, magnitude, and duration of such noise spikes can vary from platform to platform, and quantitative values are impossible to describe. The designer must be aware, however, that spikes with rise times in the nanosecond range, duration in the microsecond range, and amplitudes of up to 100 per nt of rated voltage are possible. Care must be taken to isolate the sensor circuits and protect them from damage caused by such spikes and to specify the limits to which the sensor can be subjected without being damaged.

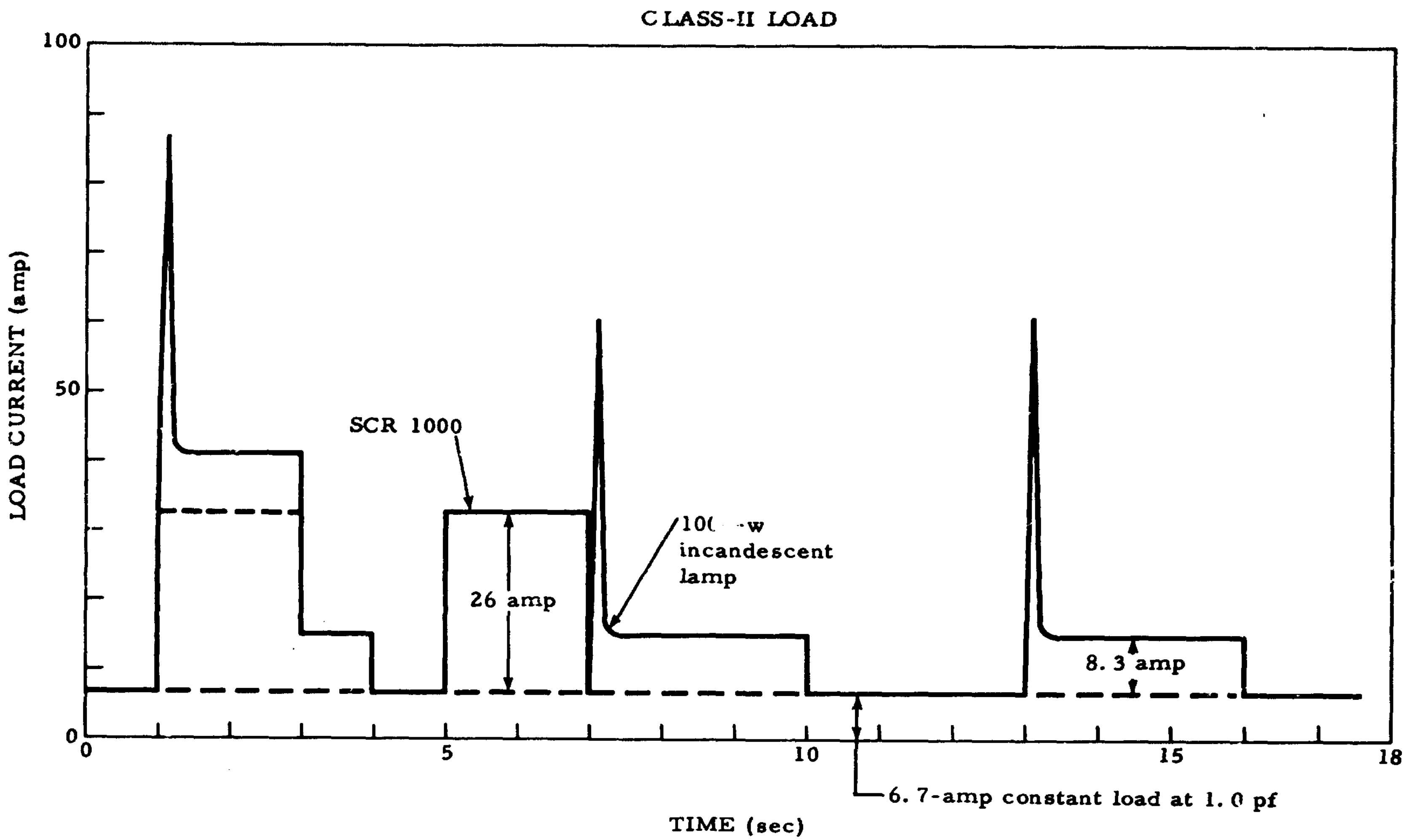



Figure III-10. Current Vs Time, Class-II Load (1000-w Incandescent Filament Lamp)

3.1.8 ELECTROMAGNETIC INTERFERENCE. Electromagnetic interference can seriously disturb the operation, transmission, and reception of signals by communications equipment and electronic sensors. The interference sources should be located and measures taken to reduce this interference to levels that do not significantly interfere with the desired signals.

Interference is often difficult and expensive to analyze completely and correctly; thus, the task is often left until the system has been constructed and activated, and the analysis is then made part of the troubleshooting procedure — an approach that is not recommended.

The procedure of locating and compensating for interference sources is an integral part of the system-design procedure. In some cases, very little or no compensation or protection will be necessary, but generally the electromagnetic interference will be a significant design problem.

Interference can be classified by the method of transfer as either conducted or radiated (Figure III-11). Radiated interference can be analyzed using electromagnetic-field theory, while conducted interference can be analyzed using conventional circuit theory.

Radiated interference is of concern when dealing with systems that are above the surface of the ocean. Specific examples of sources of radiated fields affecting buoys and platforms are

- Communication transmitters
- Mercury-vapor and carbon-arc lights as well as other navigational aids
- Power generator and powerline transients which may result from infrequent but heavy loads
- Lightning and atmospheric static

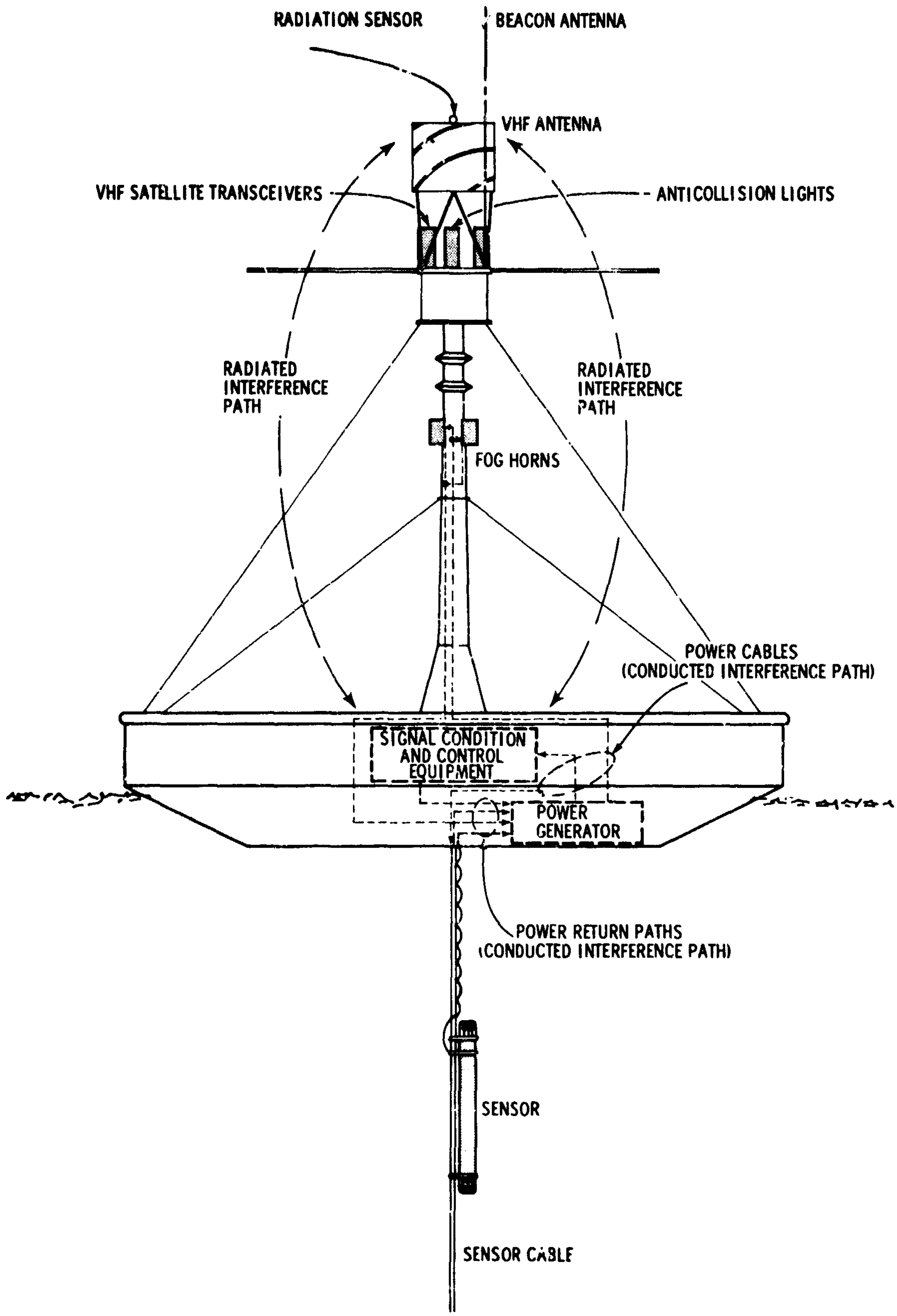



Figure III-11. Examples of Conducted and Radiated Interference

Basically, any $\frac{di}{dt} \neq 0$ will create an electromagnetic field. By shielding the source or receiver or by reducing the radiation by reducing $\frac{di}{dt}$, one can control this radiated interference. Radiated interference should not be a serious concern to underwater sensor systems.

A relation illustrating the penetration of electromagnetic radiation in a medium is that for "skin depth" (δ) — distance that attenuates the field intensity by 8.6 db for seawater:

$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}}$$

$$\omega = 2\pi f$$

$$\mu = 4\pi \times 10^{-7} \text{ henry/m (permeability)}$$

$$\sigma \doteq 4 \text{ mhos/m (seawater conductivity)}$$

Therefore,

$$\delta \doteq \frac{252}{\sqrt{f}}$$

One can see that, at 1 MHz,

$$\delta \doteq 0.25 \text{ m}$$

and, at 10 kHz,

$$\delta \doteq 2.5 \text{ m}$$

Attenuation of electromagnetic radiation at frequencies above 100 Hz is so severe that interference at these frequencies does not normally occur. At the lower frequencies below 100 Hz, the greatest source of noise is natural geomagnetic radiation originating in lightning strikes and other unknown sources. This more or less constant background level is about 40 db below 1 gamma at 10 Hz and varies approximately as $f^{-1.2}$ with frequency.

Conducted interference is of concern when designing both subsurface and surface systems. Typical sources of conducted interference affecting systems on most platforms are

- Motors
- Switches
- Digital systems
- Power generators

Significantly aiding in the reduction of conducted interference are the filtering effects of power-supply leads, the proper selection of ground paths, and isolation of power sources.

Although a strict set of rules cannot be specified for controlling electromagnetic interference, control can be stated as being based on five principles:[27]

- Circuit Design

  Design for maximum desired signal and minimum spurious signal

- Component Selection

  Use, where possible, components that are not, in themselves, sources of unwanted signals

- Placement

  Locate sensitive components the maximum distance from spurious signals and route leads to prevent coupling where possible

- Shielding

  Use shields (both at source and receiver) where the above methods are not effective

- Grounding

  Establish a grounding procedure that minimizes interference

An excellent source for detailed information on the problem of interference is the 2-volume "Interference Reduction Guide."[28]

3.1.9 THERMAL SHOCK. Assessment of the higher absolute values of temperature involved in the consideration of thermal shock is difficult. The energy absorbed by a body from impinging solar radiation will be transferred to the surrounding medium by reradiation, convection, and conduction. The highest temperature will be reached if the object is shielded from wind-convective currents and if conduction is negligible. In this situation, the equation at equilibrium is

$$P = \underbrace{\epsilon_T \sigma A \, (T^4 - T_o^4)}_{\text{radiation}} + \underbrace{hA(T - T_o)}_{\text{natural convection}}$$

where

$P$ = power transferred from body (w)

$\epsilon_T$ = total thermal emissivity of the surface

$\sigma$ = Stefan-Boltzmann constant = $5.67 \times 10^{-12}$ ($w/cm^2 \, °K^4$)

$A$ = surface area ($cm^2$)

$T$ = surface temperature of the body (°K)

$T_o$ = ambient temperature (°K)

$h$ = convective heat-transfer coefficient ($w/cm^2 \, °K$)

This equation indicates that the equilibrium temperature T is a function of surface area, surface thermal emissivity, and convective heat-transfer coefficient.

The metals and finishes that are used will greatly influence the temperature attained by a body. Thermal emissivities of surfaces may vary from near blackbody values ($\epsilon_T = 1$) to values exhibited by highly polished metal surfaces, which will be on the order of 0.02 to 0.2 for $\epsilon_T$ (Table III-6). Materials with a lower total thermal emissivity naturally attain higher temperatures.

Table III-6

LOW-TEMPERATURE TOTAL EMISSIVITIES

| Surface Type | Emissivity $\epsilon_T$ |
|---|---|
| Silver, highly polished | 0.02 |
| Aluminum, highly polished | 0.08 |
| Nickel, polished | 0.12 |
| Copper, polished | 0.15 |
| Monel, oxidized | 0.43 |
| Brass, polished | 0.60 |
| Copper, oxidized | 0.60 |
| Steel, oxidized | 0.70 |
| Black gloss paint | 0.90 |
| White lacquer | 0.95 |
| Gray paint | 0.95 |
| Lamp black | 0.95 |

The convective heat-transfer coefficient h is a complex function of fluid properties and the geometry of the situation. The accurate prediction of h is difficult.

It is suggested that a relatively simple study would reveal the upper limits of the temperature involved. Such a study should include temperature measurement of the instrument-package form, with materials and finishes actually used, and be conducted using several measured values of solar radiation; additionally, the test package should rest on an optically white surface and be shielded from the wind. Actual upper temperature limits could then be extrapolated from the test results.

We are unable to assign an actual upper temperature limit but can assume that it will be on the order of 75°C. Surface water temperature under these ambient conditions will probably be ≥ 20°. A rapid temperature change of 55°, as the package is immersed, can easily present difficulties to an oceanographic sensor system. During calibration, sensors are routinely cycled over the temperature measurement range, say -5° to +35°. Hysteresis may be noted during this cycling, but a 40° range is not the worst-case condition in actual practice. As noted, a system deployed at sea might well experience a greater temperature range and hysteresis effects could be considerably more serious.

The time that a sensor package requires to reach thermal equilibrium is also a consideration. The seawater-exposed transducer may well have a relatively short time constant, but enclosed electronic components are seldom as well-coupled thermally to the sea and may require stabilization times of considerably longer duration.

Finally, differences in the coefficient of expansion of package or component materials may cause physical (and hence, electrical) damage to components or momentary failure of watertight seals.

3.1.10 WAVES AND TIDES. Ocean waves are created primarily in the exchange of energy between air and water. The resulting waves may be classified as long waves that occur where the water depth is shallow with respect to wave length or as surface waves that occur when the water is deep relative to wave length. The period of surface waves at sea rarely exceeds 13.5 sec.[19] A measurement of more than 18 m has been made of a wave height (crest-to-trough), but wave heights are generally in the 0- to 10-m range.

There have been many attempts to construct a simple relation describing the highest wave heights that can result from a given wind velocity. The equation[19]

$$H = \frac{0.3}{g} W^2$$

where

H = wave height (m)

g = acceleration of gravity ($m/sec^2$)

W = wind speed (m/sec)

is dimensionally correct, and the constant 0.3 has been selected to correspond with observations.

Difficulty in measuring surface-wave characteristics from floating platforms is encountered because a fixed reference is not readily available.

Tides are waves with a very large period; they are caused by the attractive force of the sun and moon (astronomical tides) and by variations in atmospheric pressure, wind velocity, and temperature (meteorological tides). Each tide is a sum of partial tides, each related to one of the factors just mentioned.

Tide measurements at sea are extremely difficult because of the difficulty in relating measurements to the bottom reference level and because of the relatively slow variation in tide level. The largest known tides occur in basins such as the Bay of Fundy where spring tides range to 15.4 m.

Waves may cause mechanical damage to meteorological sensors mounted near the water surface; they also may cause errors in measurement due to sensor motion.

3.1.11 FLOTSAM. Floating debris and ice constitute a minor hazard to instruments mounted on buoys and platforms. Floating debris may be rafted onto a buoy or platform and damage sensors located near the air-sea interface or it may affect measurements made by these sensors, particularly wave sensors.

Although large floating debris and ice can seriously damage buoys, platforms, and associated sensors, normal good engineering practice makes most transducers capable of withstanding the forces generated by flotsam collision.[29]

3.1.12 WIND. Wind directly affects most meteorological sensors and measurements by creating pressure differentials, by causing sensor (or buoy) motion, and by convective heat transfer. Wind also indirectly affects measurements by creating waves and currents as discussed in a previous subsection. Maximum wind velocities, occurring during severe tropical storms, will be approximately 80 m/sec; this figure may be slightly exceeded at times by short-duration wind gusts. The maximum winds that will be encountered will vary with location.

The buoy, platform, or ship obstructs normal wind flow. An excellent example of this is in Figure III-12, which shows the ratio of measured airflow around Argus Island tower to the calculated airflow if the tower were not present.[30] Disturbances caused in this manner were previously discussed in subsection 3.1.6.

Wind creates a significant horizontal force on any buoy or platform. This force can result in the motion of buoys and sensors, especially those mounted at the top of structures (masts). Some aspects of this problem have been discussed in subsection 3.1.5.

Another result of wind is rime frost which grows into the wind on surface exposed to fog particles of supercooled water droplets. Rotational anemometers are especially susceptible to this form of icing due to the relative velocity of the cups and the airstream.

Wind may also cause convective cooling of any temperature-sensing device or — at high velocities — may cause frictional heating of the device, although errors so caused are normally quite small.

3.1.13 PRECIPITATION. It is estimated that precipitation in the form of rain, snow, sleet, and hail averages 81.2 cm/year over all of the ocean surfaces.[29] Measurement of rainfall at sea is difficult; most rainfall data for oceans are extrapolated from island and coastal stations, and accuracy of such extrapolations is uncertain. Precipitation in any form affects the accuracy of an optical measurement such as visibility or global radiation. Ice encrustation of a pyranometer is a good example.

Precipitation also affects the mechanical measurement of wind velocity because accumulation on the sensor changes the moment of inertia of the rotational device.

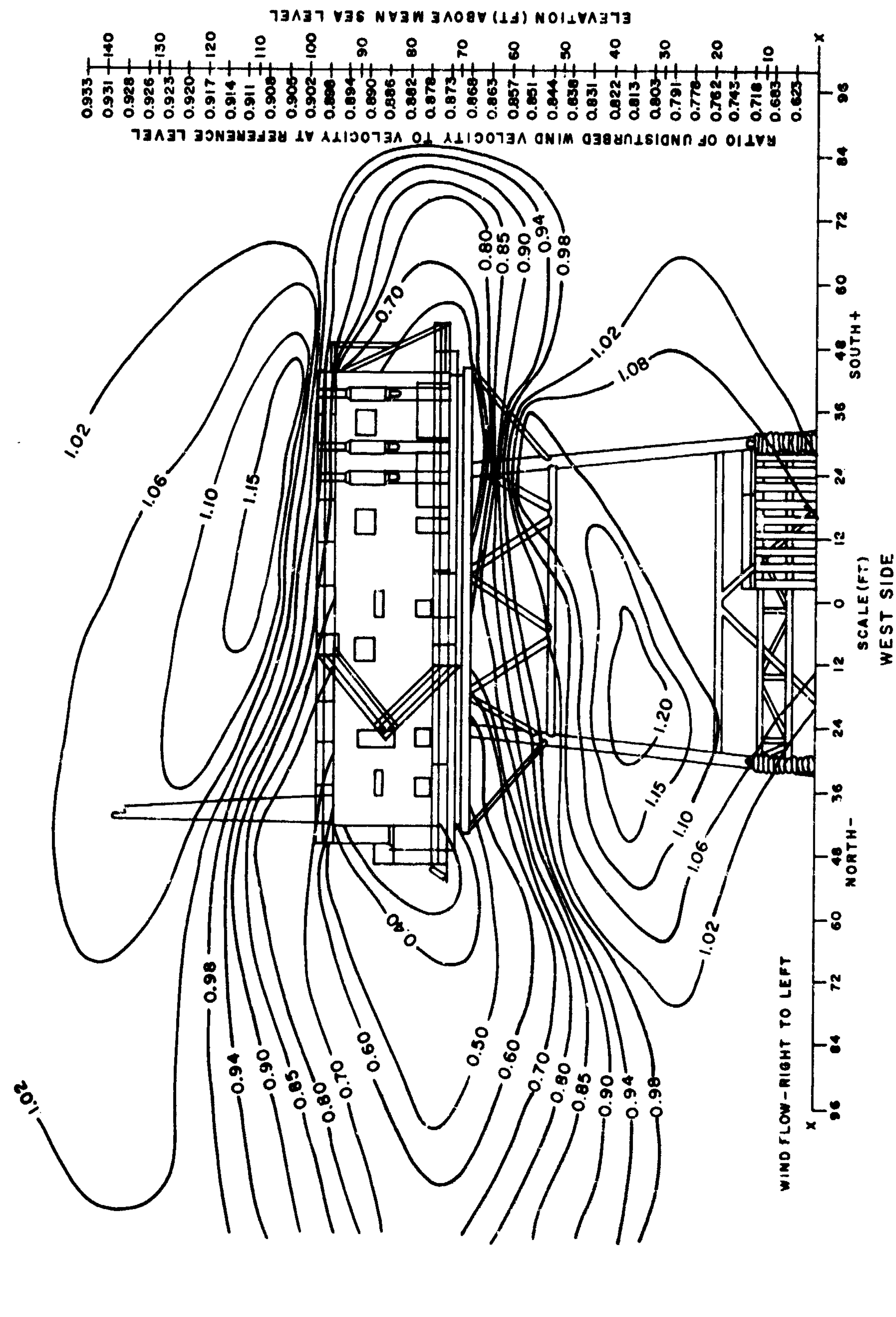



Figure III-12. Ratio of Observed to Theoretical Undisturbed Airflow (after Thornthwaite et al, 1962)

Instruments such as pyranometers or dew-point devices that are affected by precipitation or salt spray and must be exposed to obtain a measurement should be mounted sufficiently high to guarantee that salt spray does not reach the sensor. The problem of protecting exposed sensors from precipitation and icing is difficult to solve. Heating can be supplied to prevent icing but this is probably expensive and does not completely solve the precipitation problem.

All electronic and mechanical equipment that requires no direct exposure to the atmosphere should be enclosed, sealed, and desiccated or purged with dry gas so that moisture (in the form of precipitation or salt spray) will not come in contact with it. All surfaces that must be exposed to the elements should be protected in the manner outlined in this subsection if possible.

## 3.2 TRANSPORT AND STORAGE ENVIRONMENT

3.2.1 ORIGINAL SHIPMENT. A manufacturer must have responsibility for the effective packaging and safe shipment of instrumentation. The manufacturer is assumed to be in the best position to judge the transport and storage survivability of his equipment from his own plant to delivery to the Coast Guard. Obviously, it is impossible to foresee the almost infinite variety of hazards that packaged or crated equipment may experience during shipment, and acceptance should be based on proof of safe delivery. Equipment's mechanical and electrical integrity must be maintained, and shipment must not have deleterious effects on calibrations that may have been performed prior to shipment. Obvious hazards are mechanical shock and vibration during transport, as well as temperature and moisture extremes that may be met in shipment and storage enroute.

3.2.1.1 Hand-Carry. Normally, packaged or crated equipment is handled by people who do not consider the often delicate nature of scientific instruments. Labels such as FRAGILE, THIS SIDE UP, and DELICATE EQUIPMENT are often disregarded. One must assume that packages may be dropped, bumped, shipped upside down, or, in general, carelessly handled.

3.2.1.2 Hand Truck or Fork Lift. Equipment will be placed none too gently aboard these short-distance transporters and subjected to accelerations caused by the operation of relatively small, hard tires on an often rough surface. Drop and bump are also hazards here.

3.2.1.3 Loading Dock or Warehouse. Packaged equipment, it should be assumed, will be exposed to full sunlight or precipitation for extended periods; this can cause excessive heat, warpage, soaking, and deterioration of the strength of many packages. One must also assume that, in shipment, intermittent storage will be encountered in which there is no attempt to either heat or cool the enclosure.

3.2.1.4 Truck. Normally, one can expect temperatures as low as the regional extremes and probably considerably higher inside a vehicle exposed to sunlight. Vibration and accelerations for extended periods can be expected.

3.2.1.5 Rail. The same comments apply for rail as for truck transport, but higher-frequency accelerations can be expected because of the lack of soft suspension filtering of surface irregularities. Repeated shocks should be anticipated because of rail-car coupling practices and roadbed irregularities.

3.2.1.6 Air. Vibrations and accelerations will be of a different nature. Temperatures will rise at least as high as ground-level extreme and may drop to extremely low levels encountered at high altitudes. Low pressure at high altitudes should also be considered.

3.2.1.7 Ship. Rough handling can again be expected with this mode of transport. Dockside equipment is normally rugged and crude, while paving, planking, or deck surfaces are almost always very irregular. Vibrations and accelerations during loading and unloading will be of high amplitude, and drops and hard impacts should be expected. Extremes of heat, cold, humidity, and precipitation should also be anticipated.

3.2.2 POSTDELIVERY TREATMENT. The equipment is expected to be uncrated and inspected for acceptance test by the U.S. Coast Guard. Operational tests and calibration checks or full calibration will be performed in Government facilities. (This mode, rather than direct shipment uncrated, is expected to provide the most severe handling conditions inasmuch as the integrity of the packaging is now violated and because handling will be more extensive.) Transport from the Government acceptance facility to storage or the point of use will be in either uncrated or repackaged mode. The same modes of transport as before can be used, but packaging is not likely to be as effective in providing protection as originally. Storage will normally be in a warm atmosphere subject to the dry-land temperature extremes and salt-air environment. Additional transport modes will be as follows.

3.2.2.1 Small Boat. Equipment will be hand-carried from a landing to a moving platform. Ease and certainty of grasp become important along with size, weight, and rolling stability on a moving deck. Engine vibrations will be encountered. Upon arrival at the measuring platform, transfer must be made by hand to a buoy (very difficult), a ship, or by crane hoist to a tower. Drop, bump, and impact are almost inevitable. Temperature extremes range from extremely high on deck in direct sunlight to very low ambient.

3.2.2.2 Helicopter. For shipboard or fixed platform delivery, no additional environmental extremes should be encountered with this mode of transport. Storage spaces must be assumed to encompass the full range of the atmospheric marine environment. Additionally, long periods of machinery vibration must be withstood.

3.2.3 SHOCK AND VIBRATION. Equipment subjected to transport experiences complex combinations of shock and vibration. This mechanical punishment may result from an almost infinite variety of situations. The purpose of this section is to define the terminology, describe in some detail the sources of the accelerations, and set reasonable limits as they apply to sensor hardware.

During a hand-carry operation, the principal form of abuse that one can expect is the result of accidental droppage. Human limitations and industrial practice place limits on expected drop height as a function of weight. For example, a small light package (less than 20 lb) might well be tossed from man to man while being loaded on a truck. The Dow Chemical Company has estimated that the effective drop height resulting from mishandling in this "transport" mode is 42 in.[31] Similarly, one man might hand-carry a 21- to 50-lb package but would be unlikely to throw it in loading. The results of this reasoning are summarized in Table III-7.

Table III-7

PREDICTED DROP HEIGHTS

| Weight (lb) | Probable Handling Mode | Probable Drop Height (in.) |
|---|---|---|
| 0-20 | Hand-to-hand toss | 42 |
| 21-50 | Carried by 1 man | 36 |
| 51-250 | Carried by 2 men | 30 |
| 251-500 | Light equipment handling | 24 |
| 501-1000 | Light equipment handling | 18 |
| 1001- | Heavy equipment handling | 12 |

Depending on the type of packaging and the object's weight, the accelerations that may be encountered in a hand-carry operation can be predicted: a 40-lb package might undergo a 36-in. drop; if the surface area of the bottom side were 80 sq in., the static stress would be $\frac{40}{80} = 0.5$ psi. If it were then packaged in 3 in. of polyester urethane, for example, a 58-g acceleration, as interpolated from Figure III-13, could be expected.

MIL-HBK-304 contains curves for a variety of packing materials and drop heights.[32] The packaging designer can make good use of this reference to insure that sensors withstand anticipated drops.

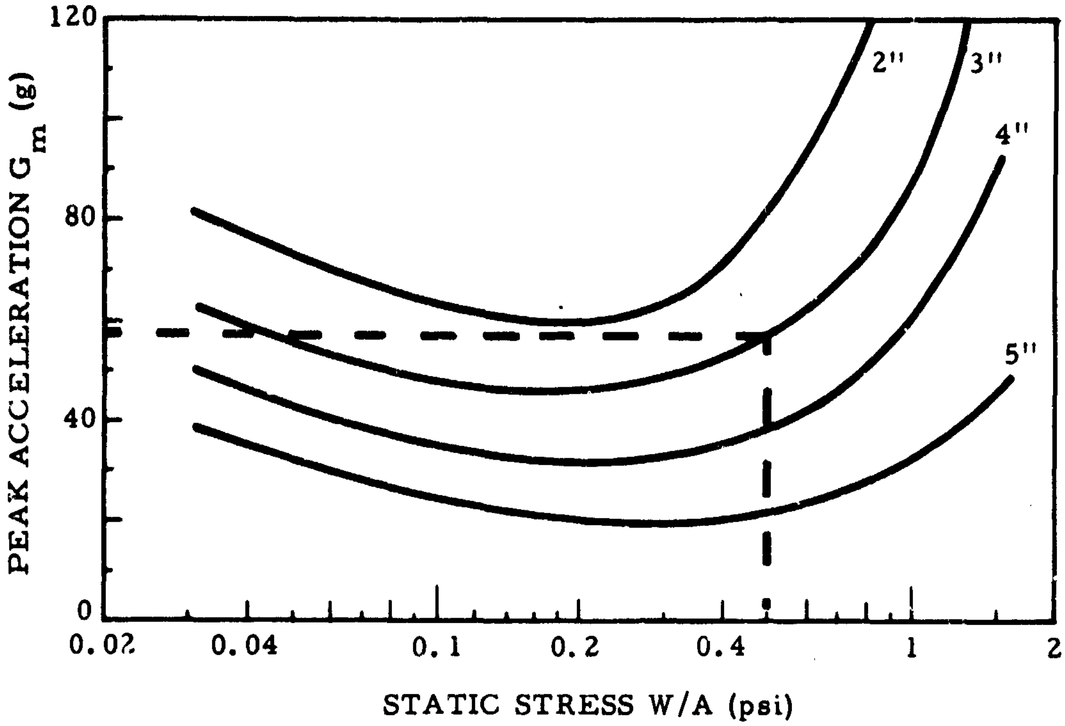



Figure III-13. $G_m$ - W/A Curves for Urethane Foam (Polyester Type, 4.0 pcf) for 36-In. Drop Height (from MIL-HBK-304, 1964)

During rail transport, the principal source of both vertical and lateral vibration and shock is the movement of the car wheels along the rails. The resultant vibrations, varying with car speed, are amplified through the spring suspension system to the car bed. By truck transport, shock and vibration may come from a variety of sources including wheel impact, wheel shimmy, engine vibration, and drive-shaft whip. These effects vary, depending on truck speed and roadbed condition.

If the equipment package is to be shipped by air, vibration must be considered. It can be traced to the following causes:

- Propeller vibration (piston-type cargo craft)
- Aerodynamic vibration
- Engine vibration
- Impact of tires

The remaining transportation mode is ship transport. The principal sources of vibration of cargo ships while underway are

- Pressure fields generated by propeller blades beating against the hull
- Imbalance of the propeller drive shaft
- Hydrodynamic buffeting of the hull

These accelerations must be thoroughly examined to assure that the equipment can withstand the abuses.

A shock is defined as a sudden, severe, nonperiodic excitation of a system and is almost always complex in nature. This complexity of shock is difficult to precisely reproduce in the laboratory; rather, certain characteristics of the complex shock are selected and used as maximum conditions which are laboratory-reproducible. Characteristics commonly used are amplitude of shock, frequency range, pulse duration, and peak value. When these critical values are known, the next step is to select a simple shock pulse to apply to the system. Three basic types of reproducible simple shocks are half-sine, sawtooth, and rectangular. The sawtooth pulse, because it tends to excite all resonant frequencies over a broad spectrum, is generally recommended for use when the limits to be approximated lie within a wide spectrum of frequencies. The amplitude and duration of the pulse are selected to approximate the critical values experienced in the complex shock under simulation. In this way, by using simple laboratory-reproducible shock pulses, one can make a good estimate of whether a given transportation shock will lie inside the tolerance limits of the equipment as packaged for shipment.

Vibration is encountered along with shock in most transportation modes and, here again, critical values of amplitude in designated frequency ranges can be applied to the equipment package in the laboratory. Although each situation must be examined for critical values, some of the values have been approximately determined and can be used for initial packaging-design criteria.

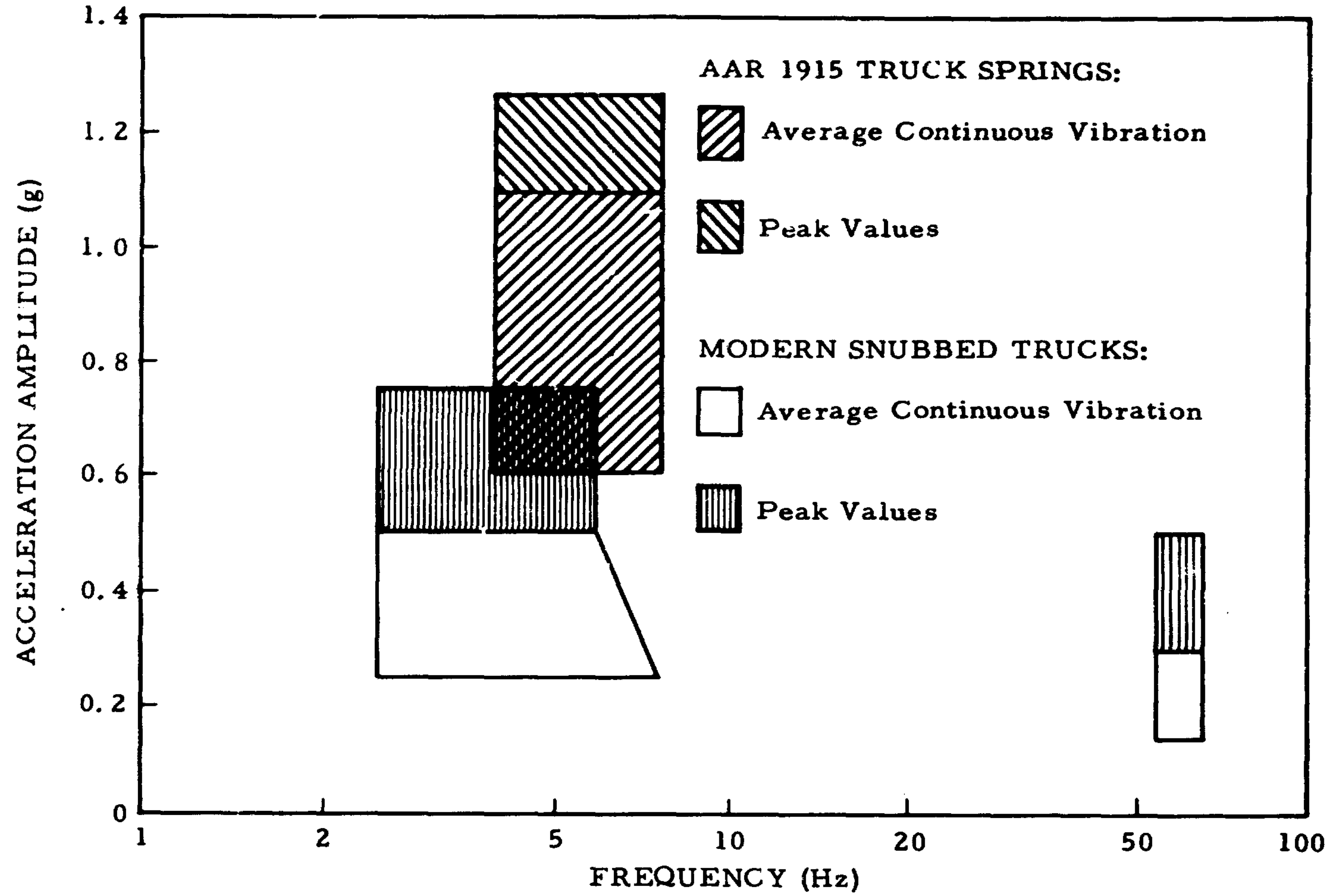



Figure III-14. Ranges of Predominant Frequencies and Corresponding Acceleration Amplitudes in Railroad Cars (from Shock and Vibration Handbook edited by Harris and Crede. Copyright 1961, McGraw-Hill Book Co. Used by permission)[32]

In hand-carry, hand-truck, or fork-lift modes, the weight of the object is known. A reasonable drop height should be selected and the maximum expected acceleration determined from MIL-HBK-304.

In truck transport, high speeds over rough roads could produce peak accelerations as high as 5 g over a frequency range of 1 to 300 Hz (although most peaks will be < 2 g between 0 and 200 Hz). Under normal operating conditions, cargo peak accelerations range to 0.4 g through a frequency range of 2.5 to 5.0 Hz.

The principal forcing frequencies related to rail shipment range from 2.5 to 7.5 Hz and from 50 to 70 Hz, with maximum amplitudes of 0.75 and 0.5 g, respectively[32] (Figure III-14).

During taxi operations, air-shipment accelerations will vary from 0.2 to 0.5 g in the range of 1 to 3 Hz. In flight, packages resting on cargo decks should be expected to experience accelerations of 4 g in the range of 8 to 500 Hz for piston-engine cargo aircraft[32] (Figure III-15) or significantly higher frequencies in jet aircraft[33] (Figure III-16). A package transported by helicopter experiences vibrations in a lower range of frequencies than those imparted by a jet aircraft[33] (Figure III-17).

Specifications for ruggedized electronic equipment aboard ship have anticipated maximum shocks of 5 g and vibrations of ±0.03 in. (5 to 15 Hz), ±0.02 in. (16 to 25 Hz), and ±0.01 in. (26 to 33 Hz). U.S. Coast Guard experience in designing small boats has shown that accelerations to 15 g can be expected for a 20-knot speed in 4-ft waves. Shipboard accelerations as high as 0.3 g within the frequency range of 2 to 20 Hz should be anticipated.

Figure III-18 shows a composite of accelerations that anticipates any mode of transport.

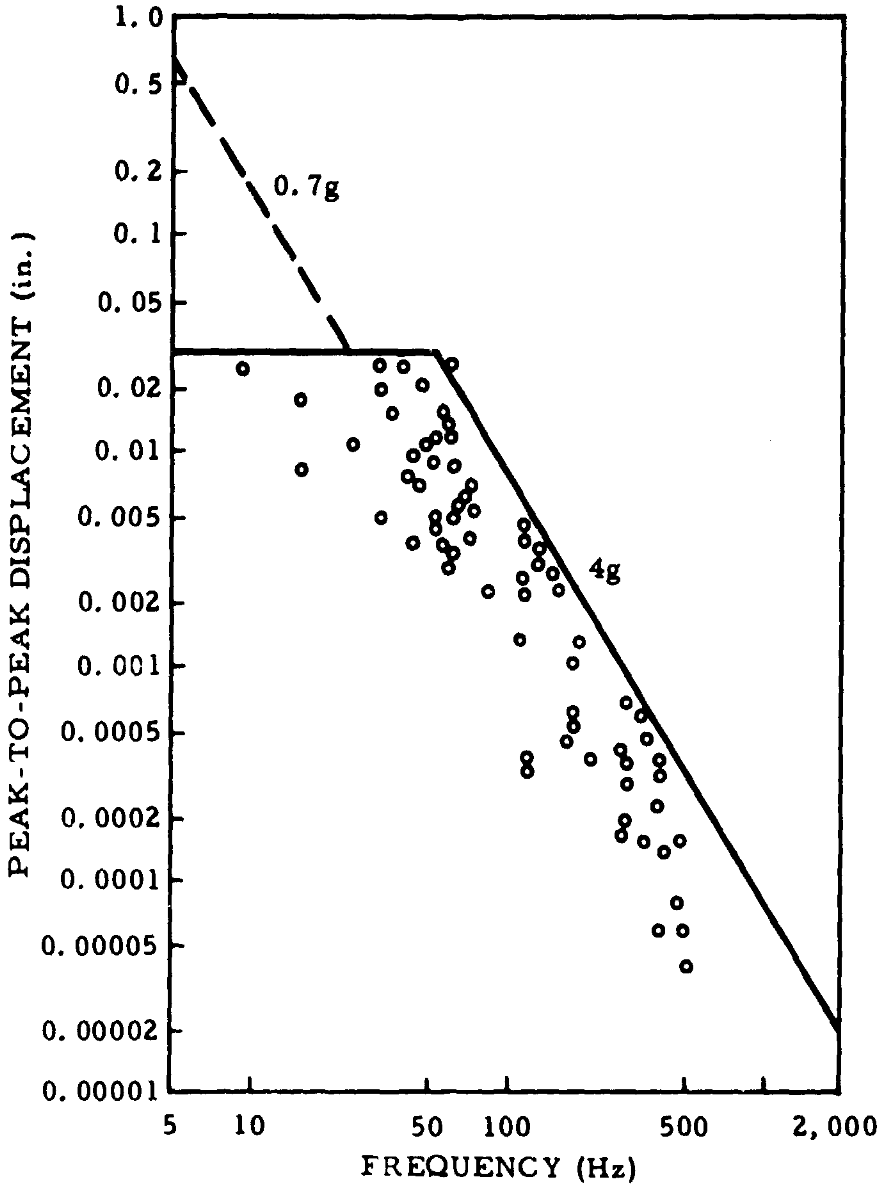



Figure III-15. Displacement and Frequency Data for Vibration on Cargo Decks of Cargo Aircraft (from Shock and Vibration Handbook edited by Harris and Crede. Copyright 1961, McGraw-Hill Book Co. Used by permission)[32]

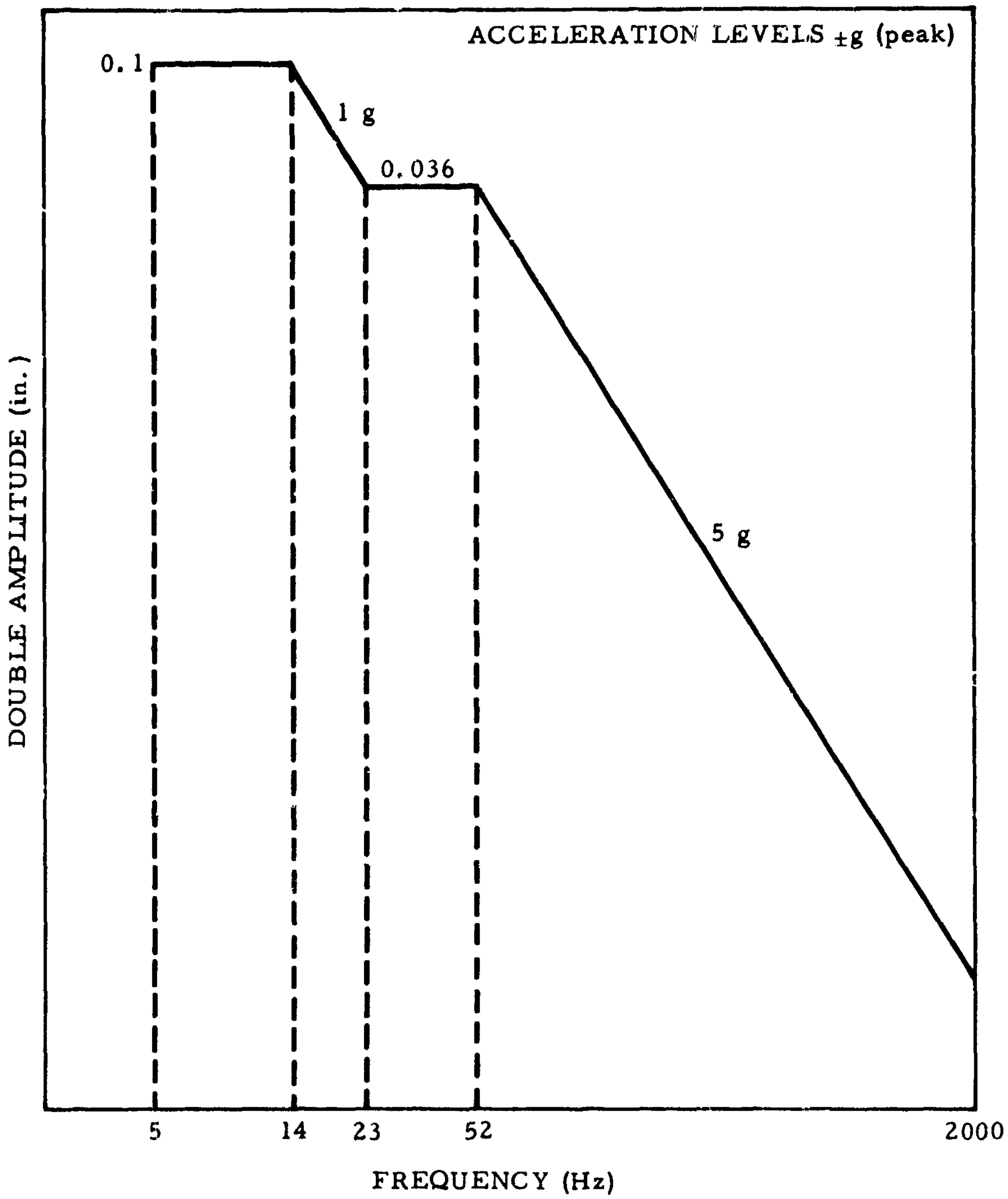



Figure III-16. Vibration Test Curve (Sinusoidal) Aircraft with Maximum Frequency of 2000 Hz (after MIL-STD-810B)

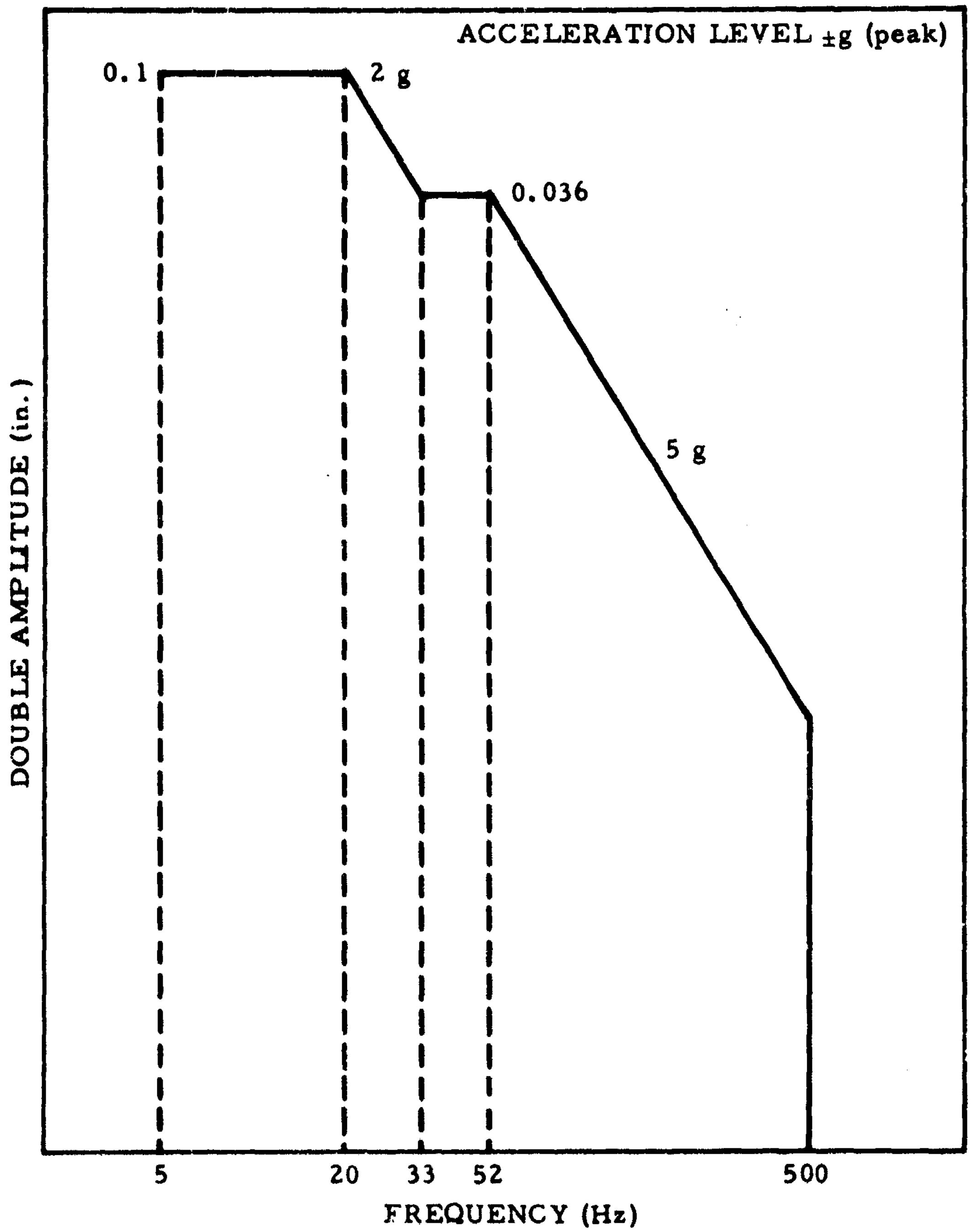



Figure III-17. Vibration Test Curve (Sinusoidal) Aircraft and Helicopter with Maximum Frequency of 500 Hz (after MIL-STD-810B)

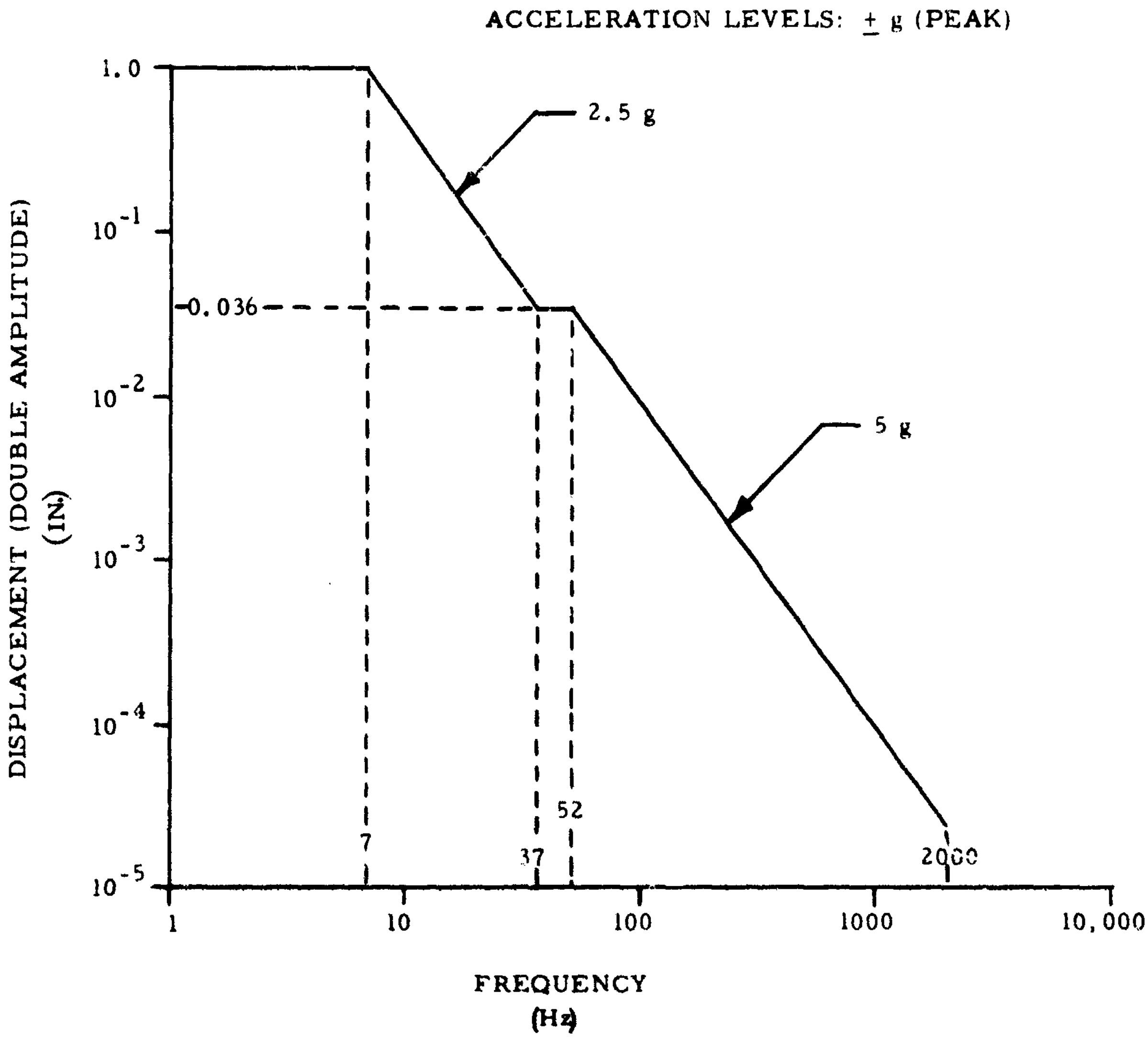



Figure III-18. Vibration Test Curve, Composite of Accelerations Anticipating Any Mode of Transport

3.2.4 OTHER ENVIRONMENTAL FACTORS. Each of the several transport modes involves exposure to different extremes of temperature and moisture. Truck and rail transport are essentially the same as far as these environmental factors are concerned. Air transport may additionally bring in low pressure and extremely low temperatures. Shipboard environments may naturally differ from other transport modes, and warehouse and loading platforms involve another set of factors. Prior knowledge of the transportation mode to be used should enable manufacturers to anticipate the environmental extremes to be encountered, and tests need not encompass all feasible transportation router.

3.2.4.1 Truck and Rail. Landbound vehicles, normally enclosed but with no provision for heating or airconditioning, can be expected to experience low temperature extremes corresponding to ambient conditions. It is senseless to attempt to assign a value to the expected low temperature inasmuch as delivery rates and season will determine the extreme encountered; also, assignment of a value may well place an undue burden (and expense) where it is not needed. High temperatures can be more easily estimated, and an experienced consensus anticipates a maximum temperature of 65°C in enclosed vehicles exposed to sunlight. Long-period exposures to such high temperatures may well lead to serious deterioration of electrochemical devices, such as batteries, and to oil leaks as well as damage to plastics and some elastomers. This damage would not normally be expected in the operating environment but must be anticipated in shipment.

3.2.4.2 Air Transport. During air shipment, cargo may be exposed to high-altitude ambient pressures and to extremely low temperatures. An aircraft flying at 30,000 ft experiences a pressure of 0.224 atmosphere. Temperatures may range lower than -40°C. Possible damage to electrochemical sensors should dictate to manufacturers that air shipment be made in pressurized and heated air-cargo carriers.

3.2.4.3 Ship Transport. Temperatures would not normally be expected to be of a wide range in an enclosed cargo space aboard ship, but long exposure to a tropical environment may lead to damage similar to that encountered in truck and rail shipment. Moisture would not be expected to damage underwater sensors themselves but may cause deterioration of packaging materials, making subsequent handling hazardous.

## SECTION IV

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13. ABSTRACT


Task 2 describes the operational, transport, and storage environments for oceanographic and meteorological field instruments. The study resulted in recommendations for environmental protection and called attention to areas needing further work in order to accomplish adequate sensor protection at sea.


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| Hydrostatic pressure | | | | | | |
| Pressure | | | | | | |
| Sensor motion | | | | | | |
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