

Submitted for recognition as an American National Standard

MATERIALS FOR FLUID SYSTEMS OF MARINE VEHICLES

Foreword—This Document has not changed other than to put it into the new SAE Technical Standards Board Format.

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1. Scope—The scope of this HIR is to delineate groups of materials for which there is considerable fabrication and operating experience in the sea water environment. In addition, some of the more promising materials for possible future applications are covered.

1.1 Purpose—The purpose of this Hydrospace Information Report (HIR) is to define materials for use in fluid systems of marine vehicles, including submersibles and advanced surface craft.

This report is more particularly directed to the designer of fluid power and piping systems on board marine vehicles.

1.2 Classification—Material selection should be based on evaluation of properties as affected by the marine environment. See Table 1.

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TABLE 1—MATERIAL PROPERTIES IN MARINE ENVIRONMENT

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1. Mechanical Properties:
 - Ultimate tensile strength
 - Yield strength
 - Shear strength
 - Cyclic fatigue
 - Modulus of elasticity
 - Density
 - Ductility and fracture toughness
 - Bearing properties
 - Lubrication properties
 - Magnetic properties

 2. Susceptibility to Environmental Degradation:
 - Uniform surface corrosion
 - Pitting and crevice corrosion
 - Galvanic corrosion
 - Stress corrosion cracking
 - Corrosion fatigue
 - Erosion and cavitation
 - Hydrogen embrittlement
 - Fretting fatigue
 - Galling and wear
 - Selective phase attack
 - Fluid compatibility
 - Biodeterioration

 3. Acquisition and Maintenance Cost Factors:
 - Raw material cost and availability
 - Fabricability: forming
 - distortion under heat treatment
 - joining
 - machining
 - surface finishes
 - Inspectability
 - Repairability
-

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2. References

2.1 Applicable Publications—The following publications form a part of the specification to the extent specified herein. Unless otherwise indicated the latest revision of SAE publications shall apply.

2.1.1 GOVERNMENT

NAVSHIPS 0900-028-2010—"Material Certification Procedures and Criteria Manual for Manned Non-Combatant Submersibles"
MIL-STD-438—"Schedule of Piping, Valves, Fittings and Associated Piping Components for Submarine Service"
MIL-STD-777—"Schedule of Piping, Valves, Fittings and Associated Piping Components for Naval Surface Ships"
MIL-STD-889—"Dissimilar Metals"
MIL-S-001222—"Military Specification, Studs, Bolts, Hex Cap Screws and Nuts"
Mechanical Properties and Seawater Behavior of Nitronic 50 (22 Cr-13N9-5Mn) by I.L. Caplan, David W. Taylor Naval Ship R&D Center, Bethesda, Maryland, Report 4554, January 1976
Handbook of Hydraulic Systems for Deep Ocean Applications, W. E. Schneider and J. A. Sasse, David W. Taylor Naval Ship R&D Center, Annapolis, Maryland, 21402, February 1981

2.1.2 INDUSTRY

ADA-055-609"Materials Study for High Pressure Sea Water Hydraulic Tool Motors", NTIS, U.S. Dept. of Commerce, Springfield, Virginia 22161
Fink, F.W. & Boyd, "Corrosion of Metals in Marine Environments", MCIC-78-37/March 1978, Battelle's Columbus Laboratories, Columbus, Ohio, September 1977
Johnson, H.A., "Hydrofoil Materials Specification", D321-51313-1, Boeing Marine Systems, Seattle, Washington, October 1977
Padberg, D.J., "Fretting Resistance Coatings for Titanium Alloys", AFML-TR-73-228
Erlwein, D.M., "Chromium Electrochemical Potential Determinations", Boeing Marine Systems, Seattle, Washington, September 1981

2.1.3 PUBLICATIONS

Laque, F.L., "Marine Corrosion", John Wiley & Sons, New York, 1975
"Materials Selector", Materials Engineering, Penton/IPC Publication, Cleveland, Ohio, December 1980

2.1.4 SAE PUBLICATIONS—Available from SAE, 400 Commonwealth Drive, Warrendale, PA 15096-0001.

HIR 1063—"General Environmental Requirements for Marine Vehicles"
HIR 1149—"Hydraulic Fluids for Marine Vehicles"
HIR 1496—"Hydraulic System Design Criteria for Advanced Marine Surface Vehicles"
HIR 1513—"Design Criteria for Sea Water Pumps"
HIR 1528—"Sea Water System Design Criteria for Advanced Marine Vehicles"

3. **Marine Environment**—Exposure of fluid power system components to the marine environment on board marine vehicles varies in severity from application to application. While the working fluid, i.e., hydraulic oil or sea water is the prime consideration, the external environment is also critical. The environment may range in severity from slight moisture condensation in air conditioned cabins to severe salt water spray at air inlets, from occasional wetting down in bilges and on weather decks to continuous immersion in external locations below waterline. Wet/dry cycles are often more adverse than continuous wetting by seawater because of such factors as oxygen and lack of cathodic protection when dry. Corrosion rates double with every 10 °C increase in seawater temperature, and can be accelerated by stray electric currents, such as from welding. Mineral deposits, industrial wastes and marine life such as barnacles and micro-organisms may vary from place to place of operation.

4. **Corrosion**—Of major concern in selecting metals for use in sea water, is corrosion. It takes many forms: general, galvanic corrosion, pitting and crevice attack, stress corrosion, exfoliation, and other forms. Corrosion fatigue can be one of the most rapid modes of deterioration under the combined action of fatigue plus crevice attack. Table 2 illustrates the effect of salt water immersion without protection on endurance limits. Endurance limits are not given for design, only for emphasis on corrosion protection. Sea water velocity effects such as mechanical or fluid impingement may accelerate corrosion or retard it in the case of crevice attack. Selective phase attack occurs in alloys with susceptible constituents. Cavitation attacks all metals and must be prevented by hydrodynamic design.

4.1 **Galvanic Attack**—Because sea water is an excellent electrolyte, severe corrosion often occurs when two different metals are coupled together and immersed in sea water. One metal in the couple may be anodic to the other. The degree of attack depends partly on the relative position of the two metals in the galvanic series for sea water, see Table 3. Usually the greater the difference in potential the greater will be the attack on the anodic member of the couple. Polarization of the surfaces may tend to reduce intensity of the attack with time. Adverse ratio of small exposed anode area to large cathode area accelerates corrosion. A pin hole size flaw in the protective coating of the anode can lead to perforation in a relatively short time.

Metal ions form and electrons are released at the surface of the lower potential metal. The ions, which have a positive electrical charge, go into solution and migrate through the sea water. The electrons, which have a negative electrical charge, pass through the conducting metals to the higher potential.

The electrons are released at the surface of the higher potential metal into the sea water, where they reduce hydrogen ions to atomic hydrogen. The hydrogen is either passed off as gas or is dissolved near the surface of the metal, which results in embrittlement, i.e., leading to future cracks.

The area which is corroding is, by definition, an anode; and the area where reduction is occurring, a cathode. A corrosion cell, then consists of four elements:

1. Anode, seat of corrosion (oxidation)
2. Cathode, seat of reduction
3. Metallic path for electrons from anode to cathode
4. Electrolytic path of current from anode to cathode

The following means may be employed for reducing corrosion rate: (a) isolate the anode from the cathode electrically along the metallic path; (b) isolate the surface of the cathode with nonconductive coating; (c) increase the resistance of the electrolytic path by means of nonconducting piping; (d) connect the anode to a sacrificial anode at a still lower potential; (e) impress a protective current from an external source flowing in the electrolyte to the anode.

Cathodic protection requires metallic and electrolytic conduction paths to all parts to be protected.

TABLE 2—STRENGTH OF METALS IN AIR AND IN SALT WATER

| Metal and Alloy Grade | Yield Tensile Strength (ksi) ⁽¹⁾ | Ultimate Tensile Strength (ksi) ⁽¹⁾ | Percent Elongation in./in. | Percent Reduction in Area | Longitudinal Charpy Vee Notch (ft-lbs) ⁽²⁾ | Fatigue Strength ⁽³⁾ @ 10 ⁸ Cycles Smooth (ksi) ⁽¹⁾ Air | Fatigue Strength ⁽³⁾ @ 10 ⁸ cycles Smooth (ksi) ⁽¹⁾ Salt Water ⁽⁴⁾ | Fatigue Strength ⁽³⁾ @ 10 ⁸ cycles Notch (ksi) ⁽¹⁾ Air | Fatigue Strength ⁽³⁾ @ 10 ⁸ cycles Notch (ksi) ⁽¹⁾ Salt Water ⁽⁴⁾ | |
|--------------------------------|---|--|----------------------------|---------------------------|---|--|--|---|---|----|
| Steels | | | | | | | | | | |
| High Yield Strength, Low Alloy | HY80 | 88 | 103 | 27 | 70 | 100 | 42 | 9 | 20 | 4 |
| | HY100 | 100 | 120 | 22 | 65 | 50 | 66 | 12 | 16 | 4 |
| | HY130 | 140 | 150 | 21 | 65 | 50 | 67 | 9 | 43 | 4 |
| Maraging 18 Nickel | 180 | 191 | 15 | 65 | 60 | 65 | 7 | 35 | 4 | |
| Precipitation Hardened, H-1100 | 17-4PH | 135 | 150 | 17 | 58 | 45 | 60 | 20 | 30 | 10 |
| | J5-5PH | 135 | 150 | 17 | 58 | 45 | — | — | — | — |
| Titanium | | | | | | | | | | |
| Ti-7Al-2Cb-1Ta-1Mo | 110 | 125 | 12 | 30 | 40 | 38 | 40 | 20 | 20 | |
| Ti-6Al-4V | 120 | 135 | 12 | 25 | 20 | 55 | 55 | 38 | 35 | |
| Nickel | | | | | | | | | | |
| Inconel 718 | 147–175 | 160–200 | 12–24 | 15–30 | 50–75 | 84 | 25 | 25 | 20 | |
| Aluminum | | | | | | | | | | |
| 5456 Condition 116 | 46 | 33 | 12 | — | — | 20 | <5 | 16 | <5 | |

1. 1 ksi = 1,000 psi = 6.9 MPa
2. At approximately 20 °C
1 ft-lb = 1.36 N·m
3. Rotating Cantilever Specimens, 1,450 cpm
4. Salt water immersion without cathodic protection

TABLE 3—GALVANIC SERIES IN SEA WATER

| Material | | Volts (Calomel Reference) Max. | Volts (Calomel Reference) Min. |
|--|----------|---|---|
| Graphite | Cathodic | +0.30 | +2.0 |
| Platinum | ↑ | +0.25 | +0.19 |
| Ni-Cr-Mo Alloy C | | +0.09 | -0.04 |
| Titanium | | +0.07 | -0.05 |
| Ni-Cr-Mo-Cu-Si Alloy B | | +0.05 | +0.02 |
| Ni-Fe-Cr Alloy 825 | | +0.05 | -0.02 |
| Alloy 20 Stainless Steels | | +0.06 | -0.04 |
| 316, 317 Stainless Steels, Passive | | +0.00 | -0.10 |
| Ni-Cu Alloys 400, K-500 | | -0.03 | -0.13 |
| 302, 304, 321, 347 Stainless Steels, Passive | | -0.05 | -0.10 |
| Silver | | -0.10 | -0.15 |
| Nickel 200 | | -0.10 | -0.20 |
| Silver Braze Alloys | | -0.10 | -0.20 |
| Ni-Cr Alloy 600 | | -0.14 | -0.18 |
| Ni-Al Bronze | | -0.15 | -0.22 |
| 70-30 Copper Nickel | | -0.18 | -0.24 |
| Lead | | -0.19 | -0.25 |
| 430 Stainless Steel, Passive | | -0.20 | -0.27 |
| 80-20 Copper Nickel | | -0.21 | -0.27 |
| 90-10 Copper Nickel | | -0.22 | -0.28 |
| Nickel Silver | | -0.25 | -0.28 |
| 410, 416 Stainless Steels, Passive | | -0.25 | -0.35 |
| Tin Bronzes (G&M) | | -0.24 | -0.32 |
| Silicon Bronzes | | -0.25 | -0.29 |
| Manganese Bronze | | -0.25 | -0.34 |
| Admiralty Brass, Aluminum Brass | | -0.26 | -0.35 |
| Pb-Sn Solder 50/50 | | -0.27 | -0.36 |
| Copper | | -0.30 | -0.37 |
| Tin | | -0.31 | -0.34 |
| Naval Brass, Yellow Brass, Red Brass | | -0.30 | -0.40 |
| Aluminum Bronze | | -0.31 | -0.42 |
| 316, 317 Stainless Steel, Active, Chrome | | -0.35 | -0.46 |
| Ni Cr Alloy 600, Active | | -0.35 | -0.46 |
| Austenitic Nickel Cast Iron | | -0.43 | -0.54 |
| 410, 416, 430 Stainless Steels, Active | | -0.45 | -0.56 |
| 302, 304, 321, 347 Stainless Steel, Active | | -0.46 | -0.56 |
| Low Alloy Steel | | -0.57 | -0.63 |
| Mild Steel, Cast Iron | | -0.60 | -0.71 |
| Cadmium | | -0.70 | -0.74 |
| Aluminum Alloys | | -0.75 | -1.00 |
| Beryllium | | -0.96 | -0.98 |
| Zinc | ↓ | -0.98 | -1.03 |
| Magnesium | Anodic | -1.60 | -1.63 |

4.2 Crevice and Pitting Corrosion—An O-ring seat in 300 series stainless steels in sea water is a typical example of a crevice, where exposed, and, confined sites of a metal form a corrosion cell. See Figure 1. The exposed sites are oxygenated by running water. The confined site under the O-ring is oxygen starved by stagnant sea water.

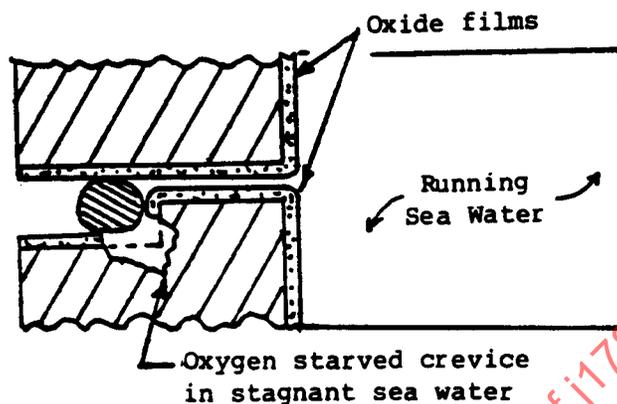


FIGURE 1—CREVICE CORROSION OF STAINLESS STEEL AT AN O-RING SEAL IN SEA WATER

Stainless steel depends upon a thin "passive" oxide film for its corrosion resistance. When immersed in sea water, chloride ions in the water tend to deteriorate the oxide film of the stainless steel. So long as sufficient free oxygen is available, as in a high velocity stream, the oxygen repairs the threatened breaks in the oxide film. The stainless steel remains "passive" and does not corrode. The effect of sea water velocity on corrosion is shown in Figure 2.

In stagnant sea water, however, such as under an O-ring seal, the limited amount of oxygen cannot keep the oxide film repaired. The underlying stainless steel begins to corrode by forming an "active" site. Metal ions form and electrons are released to pass through the metal from the corroding site to another site where they become available for reduction of hydrogen ions to hydrogen atoms. The active site, where corrosion occurs is the anode, the passive site where reduction occurs is the cathode as in a galvanic corrosion cell.

These small sites are parts of the same piece of metal, and therefore the metallic conduction path cannot be interrupted. The use of sacrificial anodes is the preferred method of corrosion protection. An alternative is the use of stainless steels containing approximately 4% or more molybdenum which have more stable oxide films. Figure 3 shows the effect of molybdenum and chromium content on crevice corrosion.

| Alloy | Flow Conditions | | | |
|--------------------------------|-----------------|-----------|----------|------------|
| | Stagnant | Quiescent | Moderate | High Speed |
| Aluminum | | | | |
| 2024, 2219 7178 7079 7075 3003 | XXXXXX | | | |
| 2014 6061 7002 5052 5154 1100 | / / / / | | | |
| 5456 5086 5052 5083 | / / / / | | | |
| 90/10 CuNi | / / / / | | | |
| 70/30 CuNi | / / / / | | | |
| Monel, Ni | / / / / | | | |
| Stainless Steels | XXXXXX / / / / | | | |
| Hastelloy C, Ti | / / / / | | | |

| | | | | |
|-----|---|--|---|---|
| Key | No Attack | Attack Little or Nil | Attack Moderate | Attack Considerable |
| |  |  |  |  |

FIGURE 2—CREVICE CORROSION AND PITTING VERSUS SEA WATER FLOW CONDITIONS

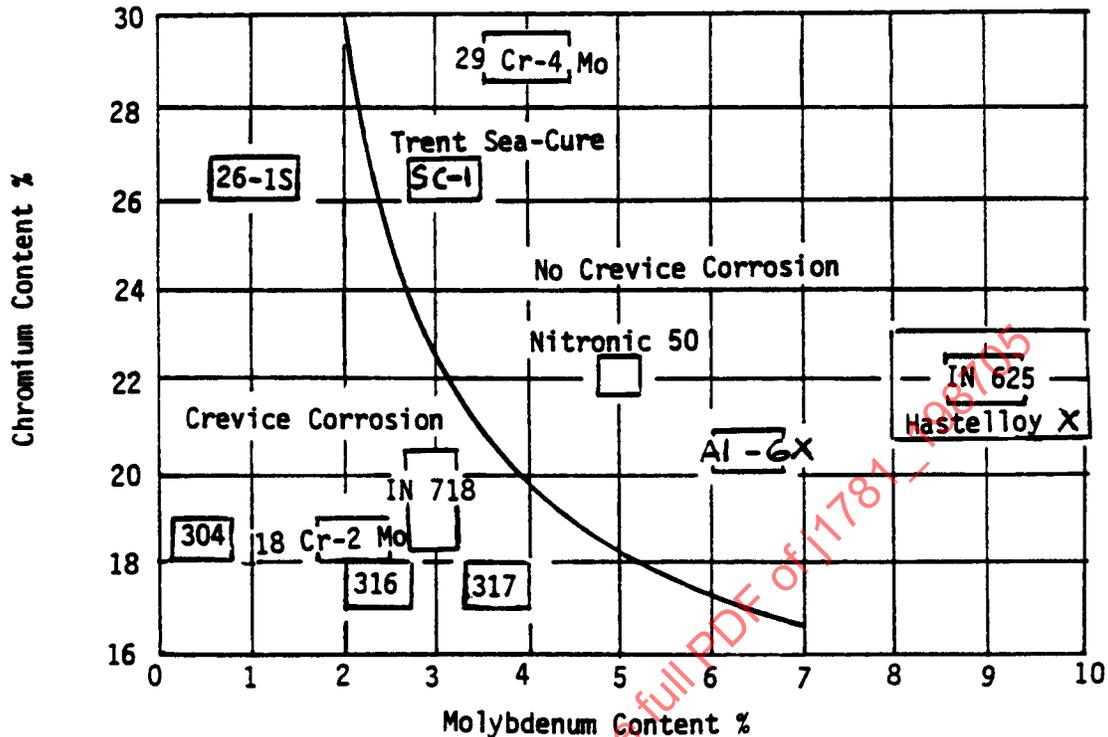


FIGURE 3—EFFECT OF MOLYBDENUM CONTENT ON CREVICE CORROSION

- 4.3 General Corrosion**—Various points of the metal surface become alternatively anodes and cathodes at various times. Low alloy steels are an example. An increase in metal thickness, "corrosion allowance", is an effective though unsophisticated way to approach the problem of general surface corrosion. A complete nonconducting coating system may be adequate in the absence of severe erosion and cavitation. Plating with a sacrificial anode metal such as cadmium is not durable in immersion applications. Zinc flame spraying the hull of the hydrofoil DENNISON was reported very successful. Cathodic protection consisting of sacrificial anodes or impressed current is recommended.
- 4.4 Selective Phase Attack**—Anodic constituents may be removed selectively from an alloy. Brasses and bronzes are susceptible, particularly if they contain more than 15% zinc. Zinc is leached out leaving behind a sponge-like matrix of copper. Aluminum bronzes may experience selective removal of aluminum unless they contain at least 4% nickel.
- 4.5 Exfoliation**—Metal formed by rolling can be selectively corroded at boundaries of successive layers, which become separated by corrosion products. Exfoliation has been observed on aluminum alloys with more than 5% magnesium at sensitized areas due to heat or cold work.
- 5. Design Guidelines for Metals**—From the comments in Section 6 on corrosion, it can be seen that a structural or fluid systems designer must rely heavily on the expertise of materials and process engineers experienced in sea water applications. Specialists will be required to recommend protective coatings, the need for and the type of cathodic protection, and in many instances the desirability of changing alloys to maintain a certain level of corrosion resistance in a given system.

A list of common alloys and their corrosion behavior in sea water is given in Table 4.

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TABLE 4—CORROSION BEHAVIOR OF COMMON ALLOYS IN SEA WATER

| Alloy Type | Alloy Designation | Corrosion Resistance | Remarks |
|---------------------------|---------------------------------|--|--|
| Ti Base | CP Titanium (Commercially Pure) | Excellent | Offers best sea water corrosion resistance of any of the structural alloys. Severe galling problem. |
| | Ti 6Al-4V | Excellent | Highest strength-to-weight ratio alloy. |
| | Ti 3Al-2.5V | Excellent | Tradeoff in toughness of CP for strength of 6Al-4V. |
| Nickel Base | (1)Hastelloy C | Excellent | Limited availability. Difficult to fabricate. |
| | (1)Inconel 625 | Excellent | More easily fabricated than Hastelloy C. |
| | MP35N | Excellent | Relatively new alloy. High cost. |
| | (1)Elgiloy | Very good | Spring alloy, usually satisfactory. |
| | (1)Inconel 718 | Good | High strength level 900–1200 MPa (130-170 ksi) available. Some pitting attack. |
| | (1)Monel 400 | Good | Pits in stagnant sea water 0.13-0.38 mm (5–15 mils) per year. |
| | (1)Monel K500 | Good | Higher strength than Monel 400. |
| Stainless Steel Mo >4% | (1)IN-862 | Excellent | Casting material which is particularly effective resisting pitting and crevice corrosion. |
| | (1)Nitronic 50 Al-6X | Excellent | Wrought materials with good resistance to pitting and crevice corrosion. Can be made into fasteners. Castable. Sacrificial to titanium. |
| | (1)SC-1 Seacure | Excellent | Heat exchanger tubing material. |
| | (1)Alloy 20 Cb | Good | Best resistance to pitting of stainless steels. Excellent in high velocity. |
| | A-286 | Fair | High tensile strength. |
| | 17-4PH | Fair | Susceptible to crevice attack. Excellent in high velocity. Cathodic protection required. Protection of more than –0.8 volt may cause hydrogen embrittlement. |
| | 15-5PH | Fair | Similar to 17-4PH with better toughness. |
| | (1)(Nitronic 40) 21-6-9 | Fair | Similar to 17-4PH. |
| 316 | Fair | May pit in excess of 1.3 mm (50 mils) per year in stagnant water. Should be provided with cathodic protection. Galling problems. | |

TABLE 4—CORROSION BEHAVIOR OF COMMON ALLOYS IN SEA WATER (CONTINUED)

| Alloy Type | Alloy Designation | Corrosion Resistance | Remarks |
|---------------------------|------------------------------|----------------------|--|
| Stainless Steel Mo <4% | 316L | Fair | Weldable variant. Low carbon. |
| | 304 | Poor | Do not use for immersion. |
| Low Alloy Steel | (1)HY80, (1)HY100 | Poor | General surface corrosion must be controlled be controlled by organic coatings. |
| Copper | CuNi 70-30 | Excellent | Will suffer slight corrosion, but is one of the best general purpose alloys for sea water. Outstanding for piping up to 3.7 m/s (12 ft/sec) velocities. Susceptible to erosion corrosion above. Prevents biological fouling. |
| | CuNi 90-10 | Excellent | Offers the same corrosion resistance as CuNi 70-30 up to about 8 ft/sec; actually superior in stagnant water. |
| | Ni-Al-Bronze | Good | Use MIL-B-21230 Alloy 1. (Satisfactory for propellers and many other services) |
| | Alpha-nickel-aluminum bronze | Good | Use MIL-B-24480 and ASTM B150 Alloy C-63200 for wrought material. |
| Aluminum | 5000 Series | Good | 5086 best, 5083 also good. Must be isolated from steel or other cathodic metals. Condensation drip from copper alloys may cause severe pitting even though the aluminum is electrically isolated. |
| | 6061-T6 | Fair-Good | Same remarks as above. Responds well to cathodic protection. |
| | A-356 | Fair-Good | Same remarks as above. It is the preferred casting alloy. |
| | 7000 Series | Very Poor | Do not use for new design. Encapsulate component with paint & seal, provide cathodic protection. |
| | 2000 Series | Very Poor | Do not use. |
| Magnesium | | Very Poor | Do not use. |

1. Trade Name

6. Non-Metallics—Non-metallics cover a wide variety of materials including thermoplastics, composites, glass, elastomerics and coatings.

6.1 Plastics—The term "plastics" covers a variety of organic materials ranging from soft to high strength. The number of plastic materials and their usage for view ports, buoyancy material, gaskets, packings, housings, flexible hose and cable has been expanding at an accelerating rate in the 1970's and will explode in the 1980's. Delrin¹, epoxies, fluorocarbons, polyamids (Nylon¹), phenolics to name a few.

1. Trade Name

The strength characteristics and other properties of plastics are specific to the type of resin, additives and curing used. Technical data may be obtained from manufacturer's literature, handbooks, and a multitude of reports generated from Government sponsored programs in various technical areas.

- 6.2 Composites**—Fiber reinforced plastics provide strength characteristics in the direction of fibers equal to or better than metal. Transverse strength, shear strength and bearing strength, however, are no better than that of the matrix, and allowance must be made for in the design of mechanical or adhesive bonded joints. Water seepage at the ends of the fibers must be eliminated or the structural system may be destroyed.

Glass reinforced plastics (GRP) gained wide acceptance in the 1970's for secondary structures, such as fairings, sea water tanks and piping, because of low cost and corrosion resistance. Impact strength in compression and fatigue life are poor.

Advanced composites such as carbon fiber reinforced plastics have been developed which exceed metals in mechanical properties including strength and stiffness in the direction of the fibers. Graphite-fiber reinforced ¹Teflon is cathodic when coupled to most metal alloys, and may accelerate their corrosion over the contact area.

¹Torlon 4275 is an example of a composite with a combination of ingredients for achieving desired results. It is a polyamide-imide with glass-fiber reinforcing and a ¹Teflon filler for lubrication. Torlon has relatively low swell and is used for vanes in a sea water motor. ¹Vespel is another example: it is used as a hydraulic motor spline adapter to eliminate fretting.

- 6.3 Elastomeric Materials**—Elastomeric materials, of which an increasing number has been developed, are particularly suited for use in applications as insulation, diaphragms, coatings, shells, pottings, shock absorbers, gaskets, O-rings, bladders, storage bags and hose, and reinforcing gas flasks.

Elastomeric compounds that can be readily obtained are nitrile, neoprene, butyl, natural rubber, silicone, polyacrylic and polysulfide rubbers, polyethylene, fluorinated butyl acrylate and fluorocarbon (²Viton) rubbers. The list is being lengthened by the addition of tetrafluoroethylene (²Teflon), polypropylene, polyamids and others, plus their composites, and high strength aramid filaments such as ²KEVLAR. KEVLAR is used increasingly in lieu of glass fibers in dry applications.

- 6.4 Protective Coatings**—In shallow water, coatings are needed against marine growth. At depths of about 1200 to 1800m (4000 to 6000 feet) and deeper, there is very little fouling; hence, in such applications there is a need to cope only with corrosion. Protection of metallic surfaces through the use of coatings consists of covering them with non-metallic materials that are more resistant to the elements of destruction than the underlying metal itself. ²Tufram and ²Nituff finishes applied to aluminum alloys provide sealing of porosities and solid film ²Teflon lubrication. Coating of the anodic metal of a galvanic couple is counterproductive. Flaws in ²Nituff coating of A-356 aluminum sea water valves installed with titanium fittings have perforated in a few months.

²Tiodize and ²Candizing, provide a hard surface for titanium and minimize galling.

- 6.5 Ceramics and Ceramic Coatings**—A new generation of high strength ceramics has become commercially available in solid, bonded powder or flame sprayed coating form. These include, but are not limited to aluminum, chromium, titanium and zirconium oxides, silicon and tungsten carbide and silicon nitride. Compressive strengths are in excess of 2100 MPa (300,000 psi) with flexural strength in the 300-600 MPa (44,000-87,000 psi) range reported. Specific gravities range from 3.2 to 3.8 for non-porous solids. Ceramics resist heat, corrosion, and wear, but their ductility is nil and impact resistance is poor.

2. Trade Name.

The following rules may be applied for structural design:

- a. Minimize or avoid stress concentrations arising from changes in component cross section. Use large radii.
- b. Reduce contact stress of mating parts by promoting good fits using close tolerances and fine finishes.
- c. Avoid unnecessary tensile stress.
- d. Exercise care in the assembly of parts to avoid scratching or chipping of the surfaces. Provide a means to prevent surface damage during service.

7. Applications—The following examples show past and present practice in fluid power system design.

7.1 Hydraulic Tubing—Hydraulic lines have been made of 304 stainless steel, 316L and 21-6-9 on advanced marine craft. Pitting and stress corrosion were encountered in areas exposed to salt spray in tropical climates where hydraulic fluid temperatures exceeded 120°F, and coating was required. In cold climates, 21-6-9 (²Nitronic 40) has been adequate. Aluminum tubing used in the 1960's was not adequate. Aluminum alloy 6061-T6 is used for vent lines. Titanium has excellent corrosion resistance and is light weight. The alloy Ti-3Al-2.5V has high strength to weight ratio and sufficient ductility for tube fabrication. It is the most promising candidate for future surface craft.

7.2 Hydraulic Valves—Navy has used titanium alloy 6Al-4V, copper nickel and ²Nitronic 50 (ARMCO) for valves. On hydrofoils, 6061-T6 valve housing are used in protected locations.

7.3 Hydraulic Actuators and Linkages—Hydraulic actuators of hydrofoils are 17-4PH stainless steel. Low alloy carbon steels were not adequate in locations exposed to spray or splash. Titanium actuators are being considered for fully submerged installations, which would minimize the need for actuator push rods. Push rods are T9-6Al-4V, Inconel 625, or cathodically protected 17-4PH. Actuator and bell crank bearings are generally self-aligning, self-lubricating type. Outer race liners are either Teflon fabric or an injection molded plastic which are galvanically isolating. Balls are 6Al-4V titanium alloy with wear resistant chromium oxide ceramic coating. 17-4PH balls had crevice corrosion.

Chromium plated piston rods have been successful in air and splash zones, but not in fully submerged applications where chromium corrodes. Bronze scraper rings have caused electrolytic attack on chromium plating, which can be avoided by non-metallic ³Teflon scrapers. Cathodic protection is required, with separate jumpers from the piston rod and the hydraulic cylinder to a sacrificial anode. Sacrificial platings, such as cadmium and zinc, are inadequate in submerged and splash zone applications.

Nitronic 50 (ARMCO) is being used in fully submerged mechanisms for deep underwater tools or manipulators.

Ceramic coating or sleeves may be used for improved wear resistance of piston rods in fully submerged applications of future design.

7.4 Sea Water Piping—The U.S. Navy usually requires 90-10 copper nickel for sea water systems in surface ships and 70-30 copper nickel for sea water systems in submarines. See MIL-STD-777 and MIL-STD-438 for a more complete listing of piping and valve materials for shipboard systems of steel hulled vessels.

On aluminum hulls, the use of copper alloys in sea water systems is not recommended because of possible attack by copper ions on aluminum. Sea water piping on hydrofoils has used 3003 aluminum, 316L stainless steel, glass fiber reinforced plastic (GRP) and commercially pure (CP) titanium. 6061 Aluminum was not satisfactory on the HIGH POINT hydrofoil and has been replaced by GRP. Stainless steel is subject to corrosion attack and has been replaced by titanium in all but inactive drain piping. The GRP piping is durable, but mechanical joints were a problem. Titanium is excellent, but not weld repairable in many remote locations. Growth of marine organisms is a problem in tropical waters.

3. Trade Name.