

Submitted for recognition as an American National Standard

**(R) HYDRAULIC SYSTEM DESIGN CRITERIA FOR HIGH PERFORMANCE MARINE
SURFACE VEHICLES AND SMALL SUBMERSIBLE VEHICLES**

FOREWORD—This Document has also changed to comply with the new SAE Technical Standards Board format.

This recommended practice is intended as a guide toward a standard practice. Because it covers such a wide variety of vehicles it is intended for use as a guide in the development of a detailed system specification or as a supplement to a design specification.

1. Scope

1.1 Scope—This Hydraulic Recommended Practice (HRP) provides hydraulic design considerations and criteria with emphasis on features distinctive of lightweight, high performance surface craft and small submersible vehicles.

1.2 Field of Application—This Recommended Practice applies to fast, high performance, lightweight craft such as hydrofoils, surface effect ships (SES) and to small manned and unmanned submersibles where light weight is paramount and aerospace technology can be applied.

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

AMS 4943—Titanium Alloy Tubing, Seamless, Hydraulic, 3.0Al - 2.5V, Annealed

AMS 4944—Titanium Alloy Tubing, Seamless, Hydraulic, 3.0Al - 2.5V Cold Worked, Stress Relieved

AMS 4945—Titanium Alloy Tubing, Seamless, Hydraulic, 3.0Al - 2.5V, Texture Controlled, 105,000 psi
(724 MPa) Yield Strength

AMS 5561—Steel Tubing, Welded and Drawn, Corrosion and Heat Resistant, 9.0Mn-29Cr-6.5Ni-0.28N
High-Pressure Hydraulic

ARP584—Coiled Tubing, Corrosion Resistant Steel, Hydraulic Applications

ARP994—Recommended Practice for the Design of Tubing Installations for Aerospace Fluid Power
Systems

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SAE J1779 Revised OCT92

AS4059—Aerospace-Cleanliness Classification for Hydraulic Fluids
ARP4146—Coiled Tubing - Titanium Alloy, Hydraulic Applications
HIR1063—General Environmental Considerations for Marine Vehicles
HIR1149—Hydraulic Fluids for Marine Vehicles
HIR1514—Design and Specification Guide for Hydraulic Pumps Used on Advanced Surface Craft and Submersible Vehicles
HIR1622—Noise Control in Fluid Power Systems of Marine Vehicles
HIR1694—Materials for Fluid Systems of Marine Vehicles
HRP4382—Diagrams and Associated Tables for Hydraulic Systems of Marine Vehicles
HIR4544—Specifications and Standards for Marine Hydraulic Systems and Components

2.1.2 ASTM PUBLICATIONS—Available from American Society for Testing and Materials, 100 Barr Harbor Drive, West Conshohocken, PA 19428-2959.

ASTM F 303—Standard Practices for Sampling Aerospace Fluids from Components
ASTM D 1744—Water in Liquid Petroleum Products by Karl Fischer Reagent

2.1.3 ISO PUBLICATIONS—Available from International Organization for Standardization, 1 rue de Varembe, 1211 Geneva 20, Switzerland. (Also available from American National Standards Institute, 11 West 42nd Street, New York, NY 10036.)

ISO 4406—Hydraulic fluid power - Fluids - Method of coding level of contamination by solid particles

2.1.4 NATIONAL FLUID POWER ASSOCIATION (NFPA) PUBLICATIONS—Available from the National Fluid Power Association, Inc., 3333 North Mayfair Road, Milwaukee, WI 53222.

NFPA T2.6.1—Method for Verifying the Fatigue and Establishing the Burst Pressure Ratings of the Pressure Containing Envelope of a Metal Fluid Power Component

2.1.5 DEPARTMENT OF DEFENSE PUBLICATIONS—Available from Standardization Documents Order Desk, Building 4D, 700 Robbins Ave., Philadelphia, PA 19111-5094.

2.1.5.1 *MILITARY STANDARDS*

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-2193—Hydraulic System Components, Ship

MS 18282—Relief Valve Operating Characteristics Versus Maximum Operating Pressure for Liquid Service

MS 18283—Relief Valve Operating Characteristics Versus Maximum Operating Pressure For Steam and Gas Service

2.1.5.2 MILITARY SPECIFICATIONS

MIL-H-5440—Hydraulic Systems, Aircraft, Design and Installation Requirements for
MIL-H-8775—Hydraulic System Components, Aircraft and Missiles, General Specification for
MIL-F-8815 —Filter and Filter Elements, Fluid Pressure, Hydraulic Line, 15 Micron Absolute and 5 Micron Absolute, Type II Systems, General Specifications for

MIL-C-15730—Cooler, Fluid, Naval Shipboard, Lubricating Oil, Hydraulic Oil and Fresh Water
MIL-P-17869—Pumps and Motors, Power, Oil Hydraulic (Naval Shipboard Use)
MIL-P-19692—Pumps, Hydraulic, Variable Delivery; General Specifications for
MIL-F-24402—Filters (Hydraulic), Filter Elements (High Efficiency), and Filter Differential Pressure Indicators

MIL-F-24402—Filters (Hydraulic), Filter Elements (High Efficiency), and Filter Differential Pressure Indicators

MIL-F-24702—Filter Elements, Hydraulic, Disposable, General Specification for (Metric)

MIL-C-24714—Connector Tubes, Hydraulic Component, General Specification For

MIL-H-83282—Hydraulic Fluid, Fire Resistant, Synthetic Hydrocarbon Base, Aircraft

2.1.5.3 OTHER DEFENSE PUBLICATIONS

"Handbook of Fluid-Filled, Depth/Pressure Compensating Systems for Deep Ocean Applications" by Thomas H. Mehnert, compiled by the David Taylor Naval Ship Research and Development Center, Annapolis, Maryland (DITC No. AD 894-795)

"Handbook of Hydraulic Systems for Deep Ocean Applications" by William E. Schneider and John Sasse, compiled by David Taylor Naval Ship Research and Development Center, Annapolis, Maryland (DITC No. ADB062-769L)

NAVSEA P-9290.1—System Certification Procedures and Criteria Manual for Deep Submergence Vehicles

2.1.6 OTHER PUBLICATIONS

American Bureau of Shipping, New York, Guide for the Classification of Manned Submersibles, 1968

Skaistis, Stan "Noise Control of Hydraulic Machinery" 1988, Marcel Dekker, Inc. New York

Wilcox, Wayne K., Selection Parameters for Hydraulic System Filters with a Comparison of Aircraft and Marine Applications," Naval Engineers Journal, Sep 1987 Vol. 99, No. 5 pp 62–70.

3. Requirements

3.1 **Function**—The function of the hydraulic system is the actuation of craft attitude and directional controls and of other utilities at a significant power level and in a controlled manner. On hydrofoils, hydraulic systems may actuate the hydrofoil control surfaces, the rudder, the bow thruster steering nozzles and thrust reversers, retract the foils and the anchor, and start the propulsion engine. On surface effect ships, hydraulic systems may actuate the rudder, the steering nozzles, and thrust reversers, vary the propulsor inlet, control the lift for the lift fans, control the cushion doors, the cushion differential pressure valves, the propulsor closure valves, and power winches and other equipment. On submersible vehicles hydraulic systems are typically used to power maneuvering, propulsion and trim control systems. Winches and manipulator arms are often powered hydraulically on submersible vehicles.

3.2 System Arrangement—This HRP applies, but is not limited, to aircraft type central hydraulic systems, used on advanced marine vehicles. The primary function of the system is to extract mechanical power from each propulsion or ship service prime mover and distribute hydraulic power to the users. Electric motor driven pumps and if bleed air is available, air driven pumps may also be used.

The hydraulic power generation and distribution system shall fail operational/fail safe. Unless otherwise required by the detail specification, the following guidance is applicable. Loss of one hydraulic system shall not cause the vehicle to go out of control. Loss of two systems shall not prevent safe return of the vehicle to port. Separate systems and separate controls should be used to achieve redundancy. A system can be subdivided into two or more closed hydraulic loops, each with a separate reservoir and pumps. Different power sources should be used to obtain redundancy; the primary pump can be driven by the propulsion engine and the secondary pump by the ship service plant. The use of hydraulic fuses and reservoir level monitoring may be used to enhance safety.

The hydraulic distribution system shall have redundant lines or crossover or power transfer equipment and fault isolation valves so that operation can easily be restored after a major leak. Dual power supply shall be provided for all vital functions on manned vehicles. In addition, manual backup control is recommended where it can increase safety, as for hullborne steering. On military vehicles additional system isolation and replenishment features may be required for survivability. On unmanned vehicles, redundancy may be reduced.

3.2.1 HYDRAULIC POWER PLANT PACKAGE FOR SUBMERSIBLES—The hydraulic system power plant should be designed, where possible, as a package unit capable of being readily removed from the vehicle for repair and test. All of the power package hydraulic systems components, including the electric motor, can be contained in the reservoir package and designed to operate submerged in the system fluid. The entire system shall function properly when subjected to external pressures up to the ambient sea pressure at the maximum expected vehicle depth.

3.3 Pressure Level—System pressure level shall be selected on the basis of minimum equipment weight, maximum reliability and least life cycle cost. Higher pressures tend to minimize weight but the number of components rated above 21 MPa (3000 psi) is limited and development costs may be significantly greater for higher pressure systems. For intermittent duty subsystems, such as engine start subsystems, high pressures, up to 35 MPa (5000 psi), are often used to minimize weight. Variable displacement pressure compensated pumps are often used for pressure regulation of central hydraulic systems where the maximum operating pressure of the system is the pump cutout pressure. MIL-H-5440 provides guidance for setting of regulators, pump unloading valves for 10 MPa (1500 psi) and 21 MPa (3000 psi) design pressures. The function of pressure relief valves is to limit the magnitude of transients or protect the system in the event of compensator or regulator failure.

3.3.1 PRESSURE COMPENSATION—On submersibles, hydraulic systems must often work against very high ambient sea pressures. A common method of overcoming the problems of this high external pressure is to pressure compensate the system. This is a method of keeping the internal pressure in the reservoir and return side of the system slightly above the sea pressure by referencing the system operating pressure to sea pressure. The "Handbook of Fluid-filled, Depth/Pressure Compensating Systems for Deep Ocean Applications" provides descriptions of various types of pressure compensated systems (see 2.5.3).

3.4 Pressure Definitions and Pressure Test Requirements

3.4.1 RATED PRESSURE—The rated operating pressure of a component is the maximum safe operating or working pressure of a component based on an established number of fatigue cycles or a burst test requirement and does not necessarily preclude the use of the component in applications subject to infrequent transient pressures.

- 3.4.2 **MAXIMUM OPERATING PRESSURE**—This is the maximum calculated pressure developed under operating conditions considering, but not limited to, factors such as rapid valve closing, overhauling, and suddenly applied loads and relief valve response time.
- 3.4.3 **FATIGUE PRESSURE RATING**—Components which have an expected service life of one million or more pressure cycles with a magnitude in excess of 50% of their rated operating pressure are to be subjected to impulse fatigue tests to ensure a fatigue pressure rating at their operating pressure. See NFPA T2.6.1 for recommended verification test procedures.
- 3.4.4 **PROOF PRESSURE**—The proof pressure is the hydrostatic test pressure to which components and piping are subjected prior to system delivery to verify integrity and the absence of leaks. For parts not covered by a specification or standard, the contracting or design activity shall specify the required proof pressure. The following guidance shall be used in determining the minimum proof pressure:
- The proof pressure should be at least 150% of the rated operating pressure.
 - For suction ports the proof pressure shall be not less than 200 kPa gage (29 lb/in²g).
 - For pressure and cylinder ports the proof pressure shall not be less than the maximum calculated pressure under conditions of hydraulic shock considering, but not necessarily limited to, such factors as rapid valve closing, overhauling and suddenly applied loads, and relief valve response time.
 - For return ports the proof pressure shall be at least 135% of the maximum return line pressure considering maximum flow rates and minimum fluid temperatures. If a stop valve is installed in a return line, the requirements for pressure and cylinder ports shall also apply upstream of the stop valve and the proof pressure must be at least equal to that developed with full flow through any relief valve protecting the return line.
 - For unbalanced cylinders and other components which can be subjected to pressure multiplication, the proof pressure for ports subjected to the multiplication shall be not less than the nominal system pressure times the multiplication factor based on area ratios.
 - For submersible vehicles, all components which may be subjected to submergence pressure shall be subject to an external proof pressure of at least 135% of the pressure at the maximum operating depth of the vehicle. Components always compensated to sea pressure may have the compensating pressure applied during the external proof test.

Proof pressure requirements similar to those defined above are specified in MIL-STD-2193 for Navy ship hydraulic components along with burst and fatigue pressure requirements. For systems built to aircraft hydraulic system requirements, proof and burst pressures are identified in MIL-H-5440. While the requirements are similar, there are differences. In order to permit utilization of both aircraft and Navy ship hydraulic components, either standard may be applied to the extent it does not conflict with requirements herein.

- 3.4.5 **SYSTEM TIGHTNESS TEST**—For components, piping, tubing and fittings which are proof tested prior to installation, a proof test is not normally required after installation if a tightness test is conducted at system operating pressure.
- 3.5 Pressure Regulation**—Constant pressure systems are recommended for primary controls where fast response is required to control high speed marine vehicles. Constant pressure systems are best suited for central hydraulic systems serving multiple actuators. Variable pressure hydraulic systems with open center directional control valves, servo pump controlled systems, and hydrostatic drive systems are normally limited to single purpose utility applications.

The minimum cracking pressure of relief valves shall be at least 110% of the maximum normal operating pressure but above any pump ripple pressures. See MS 18282 and MS 18283 for guidance on relief valve operating characteristics and settings. When adjustable relief valves are used, means should normally be provided to protect against inadvertent adjustment. This can be done by lockwire or by using in-line valves which must be disconnected from the line for adjustment. Since back-pressure at the outlet of the relief valve is usually additive to the setting, care must be exercised in systems where back-pressure may be significant.

- 3.6 Temperature and Other Environmental Considerations**—Ambient temperatures must be considered in selecting system fluid and sizing piping and components. HIR1063 provides guidance on various environmental operating conditions for marine vehicles. When seawater is used for cooling, seawater temperatures range from -2 to 29 °C (28 to 85 °F) on the open sea and 35 °C (95 °F) in the Persian Gulf.

If operation in Arctic regions is required, the hydraulic system should be capable of starting with a temperature of -40 °C (-40 °F). While maximum performance is not required at cold temperatures, the cold temperatures should not significantly increase the time for the vehicle to get underway. The equipment should be designed for a nonoperating temperature of -54 °C (-65 °F) to assure that no damage will occur during shipping and storage.

Other temperatures to be considered are:

- a. Maximum dew point of compressed air used for pressurization should be as dry as the ambient temperature, typically -29 °C (-20 °F).
- b. Maximum safe fluid temperature where personnel may touch uninsulated piping ($+52$ °C (125 °F))
- c. Minimum flash point of the system fluid (see 3.8)

- 3.7 Cleanliness**—Cleanliness is essential for reliable operation of any high performance hydraulic system. Aerospace experience shall be applied rigorously. The marine environment itself poses a hazard to maintenance of cleanliness by the possibility of seawater leakage into the system. Craft attitude control actuators should be capable of tolerating normal contamination without hard-over failure. For this reason, critical components, such as servovalves, should be of types which are tolerant of contamination and possess chip shearing capability. The following guidelines should be followed in regard to cleanliness:

- a. Chlorinated solvent shall not be used to clean hydraulic systems or components. Should chlorinated solvent contamination be suspected, the fluid should be tested by the gas chromatographic technique and should not contain more than 200 ppm total chlorinated solvent. Excessive solvents can be removed by techniques such as vacuum dehydration.
- b. No free, undissolved water should be permitted in the hydraulic fluid since it may affect the fluid properties and characteristics and it may result in corrosion. For the commonly used MIL-H-83282 fluid, water contamination should be limited to 300 ppm. For most other fluids, the Navy limits water contamination to 500 ppm. Total water content may be determined by Karl Fischer Reagent Method ASTM D 1744.
- c. Fluid cleanliness levels should be established based on component requirements for long life and reliable performance. Cleanliness requirements can be specified based on the cleanliness classes identified in AS4059 or ISO 4406. Generally, fluid cleanliness should be AS4059, Class 7 or cleaner for particles above 5 μm in size at delivery and after servicing. This level of cleanliness requires a carefully planned program of flushing, clean oil supply, component cleanliness, filter maintenance and periodic monitoring of system cleanliness. If in-service cleanliness deteriorates two or more classes, serious deficiencies in maintenance or design are most likely present and corrective action is necessary. The cleanliness class required depends upon the contamination sensitivity of individual components; electrohydraulic servovalves often require AS4059 Class 5 cleanliness.

- d. Component cleanliness can be controlled by invoking AS4059 cleanliness levels and a method for sampling from ASTM F 303. Component cleanliness shall be maintained during assembly, test and installation. System cleanliness shall be maintained throughout system fabrication.
- e. To minimize seawater contamination, hydraulic reservoirs and return lines may be pressurized higher than the water pressure acting on the system cooler and submerged actuators. See 3.3.1 for further information.
- f. Reservoirs which are vented to atmosphere can be protected with particulate and moisture control devices. Such devices are capable of controlling particulates in the air well below the filtration rating of system filters. Devices are available which are capable of reducing the moisture content of incoming air by 80%. The pressure losses due to air flow through protective devices should be low enough to not cause an adverse affect on the system during intake or exhaust.

3.8 Hydraulic Fluid—Factors governing the selection of hydraulic fluid for marine vehicles and the physical properties of some of the commonly used fluids are described in HIR1149. Fluids shall be selected using these factors with full consideration given to viscosity changes that will occur over the operating temperature and pressure ranges of the system. Seawater has not been an acceptable fluid for vehicle hydraulic systems. Rust inhibitors operating on the water coagulation principle are used in some preservative fluids. Failure to drain fluid from components containing preservative fluid with these inhibitors can result in the clogging of filters.

3.9 Hydraulic Diagrams—Hydraulic diagrams and associated tables should be prepared in accordance with the requirements of HRP4382.

3.10 Components—Component selection can be from those covered by Military Specifications for both aerospace and marine hydraulic components, commercially available hydraulic components, and specially developed and tested hardware. For Navy ships, components must usually comply with MIL-STD-2193 which provides general requirements, including testing, for shipboard hydraulic components. Aerospace components generally comply with the requirements of MIL-H-8775. Factors limiting applicability of aerospace components to marine use are maximum available size, lack of corrosion resistance, electrical insulation, and other special requirements as described in this report, in HIR1063 and MIL-STD-2193. Many of these limitations also apply to commercially available components. HIR4544 provides a listing of hydraulic component specifications and standards which may be suitable for use in marine vehicles. The suitability of a particular component must be evaluated by the designer for his specific application.

3.10.1 PUMPS—Aircraft hydraulic pumps per MIL-P-19692 of the variable displacement, pressure compensated type are often used because of their low energy requirements during periods of low usage. MIL-P-17869 covers various types of pumps qualified for Navy shipboard use. In many cases it may be necessary to design and procure a pump to suit the requirements of the system. HIR1514 provides guidance for selecting and preparing a detailed specification for hydraulic system pumping components on marine vehicles. This document allows one to set forth the pump environmental and performance considerations, establish service life and reliability requirements, and define the specific evaluation tests to qualify it for the particular application.

It is often desirable to be able to reduce the load during start-up of the ship service unit. This may be accomplished by bypassing pump output to return or depressurization of the pump compensator. Pumps should be installed with a positive static head, if possible, to avoid air locks and cavitation. This is particularly important when using high speed aircraft type pumps. Inlet pressurization may be obtained by means of a boost pump or by a pressurized reservoir.

Warning plates shall be installed adjacent to and readily visible at each fluid filling opening of each reservoir. Each plate shall indicate the type of fluid to be used in the reservoir. For example, "USE ONLY MIL-H-83282 FLUID."

Pumps and motors for deep submersibles shall be constructed of materials that will resist salt water contamination of the hydraulic fluid. Shaft seals should be designed to withstand vacuum filling of the component if required. Care must be taken in the selection of pumps and motors to ensure that no uncompensated volume occurs during any part of the operating cycle.

- 3.10.2 RESERVOIRS—Reservoirs should be constructed of corrosion resistant materials compatible with the hydraulic fluid. The use of coatings to obtain corrosion protection is not recommended. The hydraulic reservoir shall have sufficient capacity to accommodate hydraulic actuator differential volumes, accumulator volumes, thermal expansion of the fluid plus a leakage reserve adequate for the longest service interval. A relief valve is required for overpressure protection of the reservoir. The relief valve should be designed to handle both air and hydraulic fluid.

Reservoir pressurization is often necessary and may be obtained by means of a bootstrap piston with start-up accumulator or by directly pressurizing the reservoir with a compressed gas, usually air. When pressurizing with air, care should be taken to provide clean, dry air. If the air source contains moisture, it will be necessary to provide a means of removing the moisture to prevent condensation within the reservoir. The reservoir must be designed to minimize air entrainment in the fluid. Dissolved air can come out of solution in portions of the hydraulic system where pressure is reduced below reservoir air pressure. Separated free air can cause reduced bulk modulus and other problems.

Reservoirs for submersibles: If the electric motor is not compatible with the system fluid or electrical arcing could cause fluid contamination, the hydraulic reservoir should be designed to have two separate pressure compensated compartments. One compartment containing dielectric oil should house the electric motor to drive the pump while the other compartment should be filled with system fluid and house the pump and associated components. (See HIR1149 for guidance in selecting dielectric oil and system fluid.) A mechanical shaft seal should be provided which will preclude the interchange of fluids between the compartments.

Reservoirs, except for shallow diving vehicles, should be located outside of the pressure hull. The reservoir installation shall be designed for ease of cleaning and maintenance of components contained therein. Means should be provided for removing water from the hydraulic system fluid by recycling fluid from the reservoir through test connections of compensator connections to an external purification unit. The number of external connections should be kept to a minimum.

Reservoir compensation for submersibles: Each compartment of the reservoir should be pressure compensated to maintain the hydraulic system pressure above sea pressure at all times. A readily removable cover plate(s) should be provided in the outer shell of the vehicle to permit ready access to the compensator(s) for inspection and system filling. The compensator(s) shall be arranged to provide compensation to all portions of the system. Subcircuits of sections of the system that may be isolated by the closing of valves during normal operation should contain separate pressure compensating/relief features such as relief valves and check valves.

- 3.10.3 FILTERS—As a minimum filters shall be installed in the discharge lines of all hydraulic pumps, with the possible exception of hand pumps. Return line filters are recommended for systems serving more than one compartment or more than five actuators. Systems employing pumps and motors with case drains shall employ either case drain filters or return line filters to filter case drain flow. Last chance (secondary) filter/strainers should be installed when necessary to protect contamination sensitive components.

For detailed recommendations regarding filter selection, including filter location, use of filter bypass relief valves, filtration efficiency, dirt capacity, element condition indicators, maintenance practices, and operating costs see reference 2.6, Wilcox. For military applications filters per MIL-F-8815 or MIL-F-24402 are often used. In general, filtration efficiency must be sufficient to provide fluid cleanliness compatible with the contamination sensitivity of components down stream of the filter. Return line filters and suction strainers with apertures 300 μm square (50 mesh/linear inch) are considered preferable to the use of pump suction filters. Disposable filter elements are preferred and for military applications it is usually necessary to use filter elements qualified to a military specification. MIL-F-24702 is a general filter element specification incorporating standard industry tests which can be used as a guide to develop a specification for any configuration element to suit a particular application.

All filters should be equipped with an indicator or differential pressure gage to indicate when servicing is required. Indicators are not required for strainers and last chance filters. Flexible transparent covers for pop-up indicators should be considered to protect the mechanism from contamination and corrosion. Large capacity filters are usually more cost effective but weight considerations may override this consideration, especially on deep submersibles. In any event, sufficient dirt capacity should be provided to limit servicing to no more frequently than once a week. Filters shall be located so that they are readily accessible for servicing without significant loss of fluid.

- 3.10.4 **TEMPERATURE CONTROL**—Fuel, air, and seawater are possible heat sinks for control of hydraulic fluid temperature. Selection criteria include availability, fouling, and corrosion. Marine air contains salt spray which is extremely corrosive and as a result can rapidly impair heat transfer. Seawater cooled fluid coolers are available which resist fouling and corrosion. MIL-C-15730 is applicable to the shell and tube coolers used on Navy ships. Plate-fin and immersion type coolers are lighter weight but often less maintainable. Sandwich-plate types that are easy to clean and have high efficiency should be considered but are generally pressure limited to approximately 1500 kPa (220 psi) and 105 °C (221 °F).

For submersible vehicles, supplemental cooling units are not usually required. Cooling of the hydraulic package can usually be accomplished by locating the hydraulic reservoir in direct contact with sea water. However, supplemental cooling may be required for long periods of operation without vehicle movement or if operation of the system is required when not immersed in the water.

- 3.10.5 **RELIEF AND FLOW CONTROL VALVES**—Relief valves must be sized to permit the full output of the pump or system to pass through the valve without developing pressures that would exceed the proof pressure of lines and components. Generally, the minimum reseal pressure should not be less than the nominal system operating pressure to ensure that the system can return to normal operating conditions without a decrease in operating pressure.

Means shall be provided to control overhauling loads and the pressures they generate. Use of pressure compensated flow control or counter balance valves should be considered. Relief valves are sometimes used between an actuator and a blocked center directional control valve to limit the pressures that can be developed due to overhauling loads. However, there may be poor control of the load once the relief lifts (cracks), particularly if the relief valve is oversized.

- 3.11 **Hydraulic Lines**—Hydraulic tubing (either customary U.S. or metric units) is preferred over piping (NPS) but piping may be used for larger diameters if tubing is not available. In larger sizes, piping may be less costly than tubing but incur significant weight penalties. For lines up to 1-1/2 in (38 mm) outside diameter, installation per ARP994 is recommended. Mixture of piping and tubing should be minimized to facilitate logistic support.

3.11.1 LINE MATERIALS—Hydraulic lines should be designed on the basis of service pressures, durability, compatibility with the hull material, standardization, and lightweight. Copper ions leached onto aluminum hull plating can cause severe damage. Aluminum thin walled tubing often is not durable in the shipboard environment. The preferred materials are stainless steel and titanium. Among the stainless steels, the alloy 21Cr-6Ni-9Mn (AMS 5561) is preferred over AISI 304 on the basis of strength to weight ratio. However, AISI 304 is recommended when shipboard replacement of tubing is required since it is easier to fabricate. Pitting of 21-6-9 tubing was a severe problem in the tropics on Boeing JETFOILs where the fluid temperature exceeded 50 °C (120 °F). The problem was solved by applying two coats of epoxy resin base zinc chromate to the tubing and installing heat shrinkable polyolefin sleeves sealed with polysulfate rubber at all joints. However, for new designs titanium tubing and titanium alloy fittings should be used since the coating of the stainless steel tubing is labor intensive for initial installation and maintenance. Among the titanium alloys, 3Al-2.5V (AMS 4943, AMS 4944, and AMS 4945), is preferred for strength and ease of fabrication.

HIR1694 provides guidance on the selection of materials and their corrosion resistance. For Navy submarines and surface ships respectively, MIL-STD-438 and MIL-STD-777 identify the materials and specifications for piping, valves, and fittings. For sea water service rated piping to military specifications, the piping may be used in contact with sea water at the rated service pressure. For non sea water service rated piping used in contact with sea water, a corrosion allowance shall be added to the required minimum wall thickness. The corrosion allowance normally added is 1.25 mm (0.05 in) for nonferrous materials and 1.65 mm (0.065 in) for ferrous materials.

3.11.2 CONNECTIONS—Where it is necessary or desirable to remove hydraulic line sections from the craft for maintenance or replacement, such sections should be installed with mechanically assembled joints. The number of mechanical joints shall be held to a minimum by means of manifolds and modules, and by permanently swaged, welded, or heat recoverable couplings. Heat recoverable couplings are cryogenically stored fittings that shrink to form an interference fit when warmed to ambient temperature. The use of brazed joints is generally not recommended due to their susceptibility to melting during a fire. Where fire is unlikely, brazing can provide reliable joints in small diameter lines. Use ARP994, HIR4544, MIL-STD-438, and MIL-STD-777 as applicable for guidance in selection and installation of tubing and fittings.

The use of mechanical joints in sea water should be minimized since the joints often result in sea water contamination of the system. A technique that can be used to minimize the possibility of sea water contamination is to use double seals, with a leakoff between the seals. This leakoff can be piped to a location where any leakage can be monitored. On submersibles where monitoring is not possible, the leakoff can be connected to the compensation system. If a seal fails it will be compensating system fluid rather than sea water which leaks into the system.

Fitting installation shall be in accordance with manufacturer's recommended practice. Fittings with national pipe threads (NPT) shall not be used.

For subplate mounted components, the use of short connector tubes with diametrical seals are preferred to face seals. Connector tubes used on Navy ships must be in accordance with a MIL-C-24714 specification sheet. If face seals are used, utmost caution is required as to flatness, smoothness, lack of steps, and inherent stiffness in mating parts to ensure a satisfactory seal. Gaskets molded into metal washers may also be considered.

Flexible connections should be used for mounting components subject to motion, vibration, or frequent removal such as pumps, motors, and actuators. Tube coils, flexible hoses, and swivel joints may be used for this purpose. Coiled tubing in accordance with ARP584 for stainless tubing or ARP4146 for titanium tubing is preferred. The specifications and standards for many flexible hose types are listed in HIR4544.

Galvanic isolating fittings or hose are required where dissimilar metals are exposed to seawater.

3.11.3 PENETRATIONS—Penetration through watertight boundaries require watertight sealed unions or fittings. This includes the hull, weather decks, and watertight subdivisions. Firewall penetrations should have means for shutting off the flow of combustible hydraulic fluid to the fire zone. Within the zone, fire sleeves should be provided on hoses or coiled tubing used. Care must be exercised to avoid the introduction of elastic loads on bulkheads or tubing, as well as to avoid mechanical vibration coupling.

3.12 Hydraulic Noise Control—Airborne noise control is necessary where intelligible speech communication is a vital factor. Also Occupational Safety and Health Act (OSHA) standards apply for hearing protection. In military vehicles, structure borne and fluid borne noise must be minimized to prevent detection of the vehicle. A few noise control techniques are briefly summarized herein. For more complete coverage see HIR1622 and Skaistis (2.6).

3.12.1 REQUIREMENTS—HIR1622 identifies OSHA, U.S. Navy, U.S. Army, and some commercial requirements for airborne noise limits. Also referenced are Military Standards for performing noise tests on equipment and acceptance criteria.

3.12.2 LINES—Hydraulic lines shall be installed and restrained to avoid resonance with the fundamental pump frequency. Quarter wavelength organ pipe resonance shall be avoided. The support spacing shall be per MIL-H-5440 as a guide, with supports located close to all 90° bends and fittings. Hydraulic line supports shall be cushioned to isolate vibrations. Multiple lines shall be supported by clamp blocks. Clamps secured by two bolts or two anchor points and cushioned are preferred to clamps with single point support for lines in vibration areas. Ample clearance should be provided to prevent abrasion with structure. Clamps should be installed so they do not preload the tube. In general, hydraulic lines should not be used to support components. However, small components may be supported by the lines provided that line supports are located close to the component. Lines between bulkheads should be designed with some bends to accommodate bulkhead deflection during operation.

Fluid velocities should be limited as described in ARP994 to control noise and reduce velocity surges. Closed end lines should be avoided to eliminate possible standing wave generation. Hydraulic transients shall not exceed the hydrostatic proof test pressure. For quick closing valves the increase in pressure due to valve closure can be determined by Equation 1:

$$P_{ic} = \rho c v_o \quad (\text{Eq. 1})$$

Where:

P_{ic} = pressure increase due to instant closure

ρ = mass density of the fluid

c = velocity of sound in the fluid

v_o = velocity of the fluid in the line

Using typical values for r and c

$P_{IC} \approx 50 v_o$ where v_o is the velocity in ft/sec and P_{IC} is in psi

or

$P_{IC} \approx 1150 v_o$ where v_o is the velocity in m/sec and P_{IC} is in Kpa

The above analysis applies where the valve closure time (T) is less than the time (T_c) for one round trip of the pressure wave within the line. T_c is commonly called the critical closure time. For times greater than T_c the pressure increase for valve closure will be less than that for instant closure.

- 3.12.3 VALVES AND ACTUATORS—Valves producing step function changes shall be avoided for continuous modulation to minimize noise, vibration, and fatigue. Directional control valves controlling flow rates larger than 20% of pump capacity shall have a slow actuation consistent with system needs. Actuators controlling inertial loads larger than steady state forces shall have end snubbing.
- 3.12.4 NOISE SUPPRESSION DEVICES—Pump ripple dampers are sometimes needed to reduce noise reaching manned compartments. It may be necessary to provide return line accumulators on some long lines as determined by analysis or test. Control surface actuation frequencies ranging from 1 to 3 Hz have been found to induce line surges (banging).
- 3.12.5 ACCUMULATORS—Accumulators are used to store hydraulic energy. This stored energy provides an emergency source of power and can be used to reduce pump size and response requirements for transient loads.

3.13 Component Corrosion Protection

- 3.13.1 Protective painting is adequate for components internal to the vessel such as pumps and filters. Components exposed to salt spray or to seawater require careful material selection and possibly cathodic protection. Refer to HIR1694.
- 3.13.2 Hydraulic actuators exposed to seawater should be built of seawater corrosion resistant stainless steel; for example vacuum arc remelt 17-4PH or 15-5PH. Hard chrome plate is not a suitable corrosion protection means in a seawater environment. Use of corrosion resistant alloys in sliding contact should be avoided to prevent galling. Screw threads may have a dry film lubricant. Rod bushings may be aluminum nickel bronze to avoid galling. Scrapers should be PTFE. Trim may be 316 CRES. Lockwires shall be monel. The exterior surface of the actuator may be polished to a smooth finish or may have an epoxy and polyurethane coating.
- 3.13.3 Consideration must be given to the fact that the hydraulic actuators may be immersed in seawater in some applications.

In a continuous submerged installation it is possible to protect a piston rod of a utility actuator by grounding 17-4PH piston rod and cylinder to an aluminum anode with separate grounding straps.

In a dry/wet cycle it is possible to protect a push rod and seal installation from corrosion and wear by a combination of materials and finishes. One material which has been used is 6Al-4V titanium with plasma sprayed chromium oxide coating ground and lapped to a mirror finish (0.2 μ m or 8 μ in). The seal holder can be floated in a rubber (40 durometer nitrile has been used) bushing to accommodate lateral deflections.

3.13.4 Oil coolers circulating seawater may be copper nickel. If so, they shall be galvanically isolated from the hull and shall have a sacrificial anode. Titanium may be used without anodes.

3.14 Bearings—Actuator bearings exposed to seawater shall not depend on grease lubrication which may be washed away. For example, self-aligning spherical bearings may have a titanium ball with a ceramic coating to offer a sliding surface which resists pitting by seawater corrosion. AISI 440C stainless shall not be used. The bearing race may be reinforced plastic, with tetrafluoroethylene (TFE) or other dry film lubricant. Fatigue life shall be the sizing criterion. Clearance should be allowed for swelling of plastic in contact with water.

3.15 Electric Indicators—Advanced marine vehicles generally require remote automatic sequencing of mechanisms and remote infinitely variable positioning of hydrodynamic control surfaces. All of the controls which are electrical require protection from seawater to avoid shorts to ground and mechanical corrosion damage to working parts.

It is essential to keep wiring dry. Means of excluding moisture by simple passive means have been disappointing in the past. In order to be effective, future designs shall be equal to or better than the examples quoted herein:

- a. Utility actuators can and should be controlled by means of remote controlled valves located inside the machinery compartments. Rotary position switches may be used in protected locations. Some position-sensing switches however, may have to be in exposed locations. To avoid corrosion, the switches should be magnetically actuated and should have no external working parts. Reed switches or variable induction type proximity sensors may be used. Switches should be sealed to the end of watertight cables to avoid shorts. Control valves remotely operated by solenoids or electric motors should have manual overrides on manned vehicles.
- b. Infinitely variable positioning actuators require a position transducer. In protected locations any convenient linear or rotary transducer may be used. In exposed locations a linear transducer housed inside the cylinder end cap and within the hollowed out piston rod is recommended. Servovalves should likewise be housed under a hard cover or in a cavity in the actuator body external to the hull. A pressurized conduit should be used to connect the electrical actuator cavities to a sealed junction box inside the hull. The conduit should be pressurized with dry compressed air to a pressure of 50 KPa (0.5 atmosphere) above ambient. Pressurizing air must continuously be replenished to make up for unavoidable air leakage. Care shall be taken that the pressurizing air does not become a source of water condensation. Dedicated air dryers are needed for reducing dew point below minimum ambient temperature. Hydraulic fluid can drip through imperfect seals into electrical cavities and may have to be drained periodically.

3.16 Solenoids—Solenoids for control valves shall be designed for operation in the system fluid or be dry coil solenoids enclosed by welded or brazed housings capable of preventing external fluid intrusion. On submersible vehicles, solenoids are usually required to operate satisfactorily when immersed in sea water and subjected to a pressure equivalent to at least 135% of the ambient pressure at the operating depth of the vehicle. Unpotted coil insulation must be compatible with any compensating and system fluid which may be present.

3.17 Life Requirements and Service Provisions—The life requirements for hydraulic system components must be based on the mission and life requirements of the vehicle. For submersible vehicles, maintenance generally cannot be performed during the mission. Even the maintenance that can be performed between missions may be severely limited to minor tasks such as lubrication and filter element replacement for submersible vehicles. In general, components should be designed to have a life at least equivalent to the major overhaul schedule of the vehicle.

Consideration should be given in the design of hydraulic systems of marine vehicles to system checkout and servicing with:

- a. On-board auxiliary power
- b. Shoreside hydraulic service cart (water and particulate removal)
- c. On-board electric pump

Hydraulic filters should have indicators activated by differential pressure drop to signal the need for maintenance. MIL-F-24402 filters are equipped with interchangeable gage indicators, mechanical pop-up indicators, or mechanical pop-up indicators equipped with electrical switches for remote indication but may be too large for many submersible vehicles.

Hydraulic reservoirs located within the vehicle shall normally have local sight gauges and fluid sampling valves in addition to any remote level indicators installed.

Hydraulic pump pressure status shall be displayed by a remote indicating light.

Hydraulic accumulators shall have gas pressure indicating gauges if recharging the accumulators can be accomplished during the mission. Accumulators without gas pressure indicating gages should have provisions for connection of a gage.

Sufficient pressure test stations and vents shall be provided for system checkout and air removal. The system should be designed so that entrapped and entrained air will be bled back to the system reservoir as the system is operated. Readily accessible vent(s) should be installed for venting this air. Provision should also be made for ease of bleeding and, if necessary, vacuum filling during the initial charge of the system or using an air separator to remove air from the fluid during operation. Air removal is particularly important on submersible vehicles with pressure compensation (see 3.3.1). If air is present in the system, the volume of fluid required in the reservoir to achieve compensation is increased. With too much air it may not be possible to obtain full compensation. Vacuum dehydration is an effective means of reducing the air content of the service fluid.

Drains shall be provided at system low spots unless an alternative means of draining is available. Means shall be provided for detecting and removing water from the system. Connections on the reservoir or the compensator should be provided to permit the connection of an external purification unit for removal of water.

There shall be provisions for isolating damaged branch lines. Shutoff valves in pressure lines should be used in combination with check valves in return lines. Automatic shutoff and volumetric or rate fuses should be used with caution regarding unwarranted shutdown.

To aid in servicing, double seals with leak offs may be used for mechanical joints in seawater so that the failed seal can be readily identified (see 3.11.2).

3.18 System Support—Advanced marine vehicles having high performance hydraulic systems require adequate logistic support. Servicing equipment should be provided to remove moisture and solvents as well as solid particle contaminants from the hydraulic fluid. Equipment may range from drain and refill to purifiers including a vacuum/spray dryer, depending on economic reasons. Operation from remote facilities requires operations and maintenance information, spare parts, clean test benches, and standard mechanics tools as well as special tools. Use of special tools should be held to a minimum. Information shall include labels, placards, technical manuals, detailed procedures, and directives.