ANALYSIS OF HYDRAULIC SYSTEMS IN THE FLEET

BY

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Introduction

The use of hydraulics as a means of transmitting power has been a feature of the engineering specialization of the Royal Navy throughout this century. In general these early hydraulic systems were slow moving, low pressure with a water/oil mixture as the fluid, and used mainly for powering gun mountings and steering gear. In more recent years, however, hydraulic systems have found more diverse uses powering controllable-pitch propellers, stabilizers, upper-deck machinery, as well as the traditional gunnery and missile launcher systems. Such systems use high-pressure mineral oil as the fluid, incorporate many finely toleranced components, and are required to perform their functions in the most adverse environmental conditions. The aim of this article is to present the major areas of concern based on reports received from a number of systems employed on a more general engineering nature, as opposed to those dedicated to weapon systems, and for whom the marine engineering specialization has responsibility.

Systems Reviewed

Hydraulics have found an increasing role and have made a considerable impact since the introduction of gas-turbine-propelled warships. The following systems are typical of those found in service today:

Controllable-pitch propeller systems as fitted in Type 42 destroyers.

Type 21 and 22 frigates.

Steering systems.

Stabilizer systems.

Upper-deck hydraulic systems for powering such equipment as capstans, winches and boat davits.

The CPP, steering, and stabilizer systems are in continual use at sea whilst the upper-deck systems are used periodically during evolutions such as refuelling and towing. The reliability of these systems in service is assessed by the number of defects that have been reported rendering the system unavailable. Additionally, many other defects of a smaller nature have occurred on systems in service, but have not been reported because a repair has been effected in a short time at sea by ship's staffs. TABLE I shows the number of defect reports received over a three year period on the hydraulic systems being reviewed. Two particular systems, the CPP and the Type 21 steering gear, stand out as being prone to failure. A further break-down of the actual defects reported on these systems given TABLES II to IV shows that the pump

TABLE I—*Non-availability of systems reported by OPDEF, October 1978 to October 1981*

System	*No. of Defects Reporting Non-availability*	*No. of Systems in Service*	*Total Time System Unavailable (Days)*
Type 21 CPP	24	16	2462
Type 42 CPP	31	12	1535
Type 21 Steering Gear	14	16	422
Type 22/Type 42 Steering Gear	3	16	93
Stabilizers T21, T22, T42	10	48	1249
Upperdeck Hydraulics T21, T22, T42	17	16	1730
Aux. Hyd. System HUNT Class MCMV	16	2	801

TABLE II—*Defects reported with Type 42 CPP system*

Reason for Defect Report	*No. of OPDEFs*
Downel Pump	14
Pump Actuator/Servo Assembly	7
O/T Tube Extension	2
Oil Heater	1
Oil Cooler	1
Neoprene Bag in Accumulator	1
Propeller Pitch Feedback Mechanism	1
Hub Pressure System Leak	1
Defective System Control Valve	1
Agouti	1
Salt-Water Contamination of System	1

TABLE III—*Defects reported with Type 21 CPP system*

Downel Pump	10
Pump Actuator/Servo Assembly	9
Defective System Control Valve	2
Hub Pressure System Leak	1
Salt-Water Contamination	1
Excessive Particulate Contamination	1

TABLE IV—*Defects reported with Type 21 steering gear*

Defective Pump	4
Defective Pump Servo	4
System Component Failure	3
Mechanical Steering Mechanism	2
Excessive Particulate Contamination	1

and its associated servo mechanism has caused most concern. Whilst pumps generally stand out as a weak area in the hydraulic systems reviewed, there have been other shortcomings in design, documentation, and personnel. TABLE V itemizes the areas that have caused most concern.

TABLE V—*Areas of concern with hydraulic systems*

1. Environmental conditions
2. System cleanliness
3. Ability to assess system state
4. Ability to flush system
5. Ease of maintenance
6. Swash-plate pumps
7. Filtration
8. Pipe systems and couplings
9. Isolating valves
10. Flexible hose policy
11. Tanks
12. High usage of OM33
13. Filling arrangements
14. Poor documentation
15. Hydraulic expertise

Environmental Conditions

Most marine engineering hydraulic systems are sited in adverse environments such as machinery space bilges or in exposed positions on the upperdeck. The complexity of machinery spaces often means hydraulic systems are in close proximity with other systems and equipments. Thus components are subjected to leakage from other fluids, mainly lubricating oils, diesel fuel, and sea water, as well as heavy traffic from personnel who have frequently to clamber over pipe systems both for monitoring and maintenance purposes. Damage to components can also result from the need to move other equipments in and out of machinery spaces. On the superstructure, system pipework and control valves are exposed to a salt-laden atmosphere, with badly sited pipes often being trodden upon by personnel moving around the upperdeck. With many components inaccessible, particularly in machinery spaces, it is an almost impossible task to ensure that system cleanliness standards are upheld when carrying out routine maintenance or repairs.

System Cleanliness

It is likely that over a period in service, hydraulic systems will become degraded due to particulate contamination as a result of wear in components, erosion within the system, and dirt entering the system from external sources. Particulate contamination is undesirable in modern hydraulic systems because its presence leads to reduced reliability, short component life, poor system performance and a high maintenance load. For a high availability, therefore, it is desirable that systems should be able to accept some measure of contamination.

TABLE VI—*Particulate contamination levels in R.N. hydraulic systems*

System	*Contamination Level Post Refit or Building*	*Maximum Permitted Contamination Level in Service*
4·5-inch Mk 8 Gun	RN 2000	RN 6300
Type 21/42 CPP	RN 2000	RN 6300
MCMV Main Hydraulic System	RN 2000	RN 6300
Type 21 Steering Gear	RN 6300	RN 15 000
GWS 30 Launcher (Seadart)	RN 6300	RN 15 000
Seacat Launcher	RN 6300	RN 15 000
RESOLUTION Class Missile Handling System	RN 6300	RN 15 000
Type 22/42 Steering Gear	RN 15 000	RN 21 000
MCMV Aux. Hydraulic System	RN 15 000	RN 21 000
Type 21/22/42 Upper-deck Hydraulic System	RN 15 000	RN 21 000

All service hydraulic systems have been allocated a R.N. cleanliness standard dependent on the level of contamination they will accept; and these levels are monitored by the comparison slide method. The lower the number, the higher the quality of systems oil required. TABLE VI gives the cleanliness standards of a number of R.N. hydraulic systems. The CPP system and the MCMV main hydraulic system stand out as requiring the highest cleanliness standards of any hydraulic system in the surface and submarine Fleets. Only the 4·5 inch Mk 8 gun-mounting has a similar standard for a totally weapon-dedicated system. As the MCMV main hydraulic system has only recently entered service, an assessment of its reliability cannot be made at this stage. However, the effect on one Type 42 destroyer whose CPP system contamination level exceeded the required cleanliness standards resulted in that ship being non-operational for a total period of six months. The Type 21 steering gear, whose system cleanliness requirements are of the same order as most weapon handling systems and submarine services, has required the incorporation of a significant modification. Because of a considerable loss of operational time, this modification was installed specifically to enable the system cleanliness standards to be maintained.

The penalties of designing systems with high cleanliness standards are:

Components are expensive to produce because of the fine machining required.

An unnecessary burden is imposed on ships' staffs and support authorities who are required to maintain these high cleanliness standards.

Support is generally costly and time-consuming, particularly flushing.

Reduced availability if contamination levels fall outside tolerance limits.

There are other factors that should be taken into account if such systems are unavoidable and these are discussed in some detail, along with other system shortcomings, under subsequent relevant headings. However, in the case of the CPP system and the Type 21 steering gear, it seems that both have been designed with excessively high cleanliness standards for the function for which they are required.

Ability to Assess System State

Routine checks on hydraulic fluids are usually done by a junior rating, who should have done the one-day hydraulic sampling course at H.M.S. *Sultan*, using a millipore sampling kit. Particulate contamination is assessed by comparing the prepared slide against a known master slide, whilst water contamination is assessed using the Visi-Cross method. As well as the

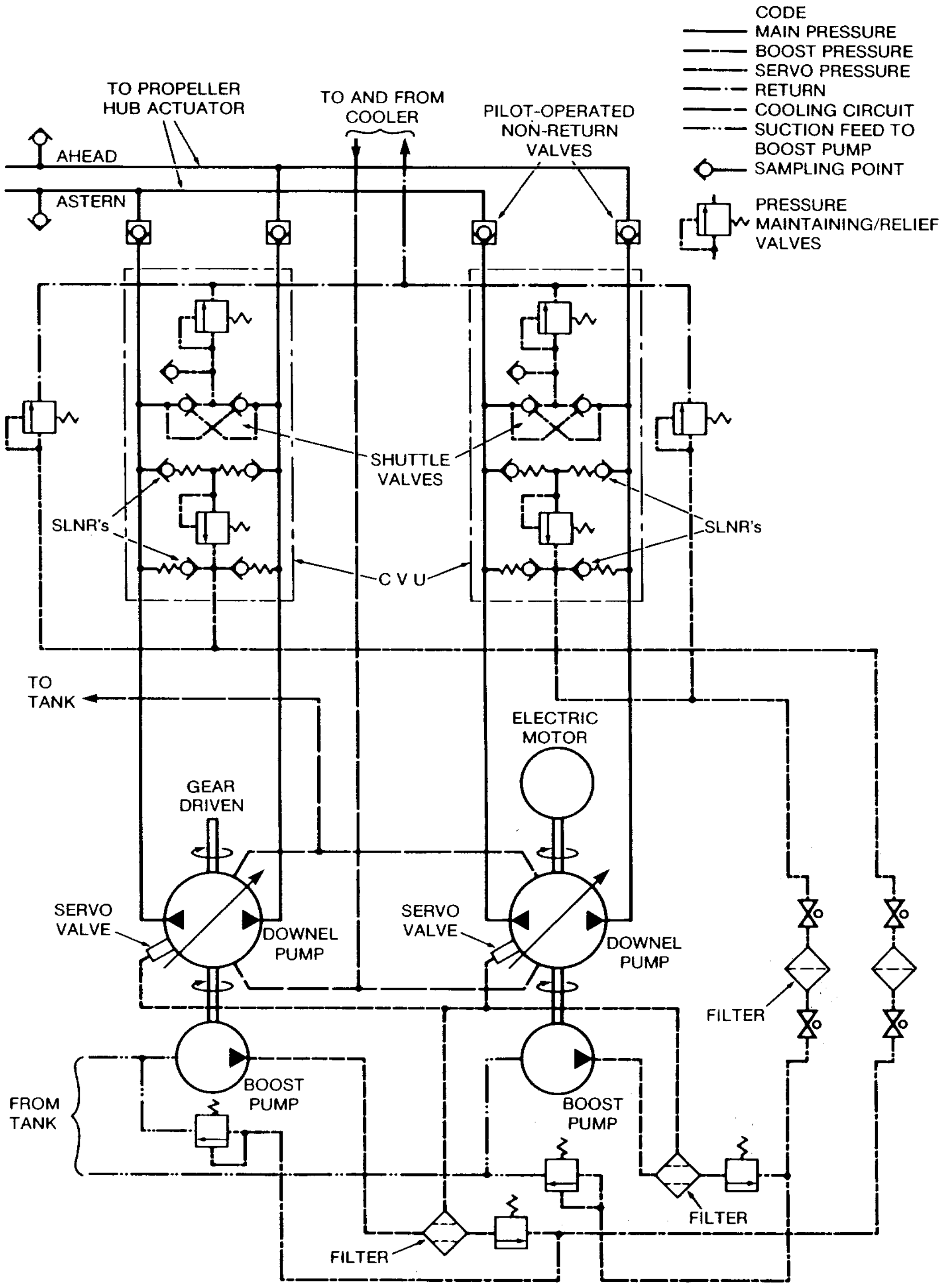

FIG. 1—SIMPLIFIED CPP HYDRAULIC SYSTEM

relatively inexperienced staff who monitor standards, two major deficiencies have been experienced. No provision was made to enable the sampling kit to be attached to a pressurized system. Thus, prior to a sample being taken, the system has to be shut down to enable the kit to be 'snapped on' to the connector. The more serious deficiency, however, particularly with the CPP system and Type 21 steering gear is the lack of sampling points. Guidance to designers in BR 3038 specifies sampling points should ideally be sighted in the following positions:

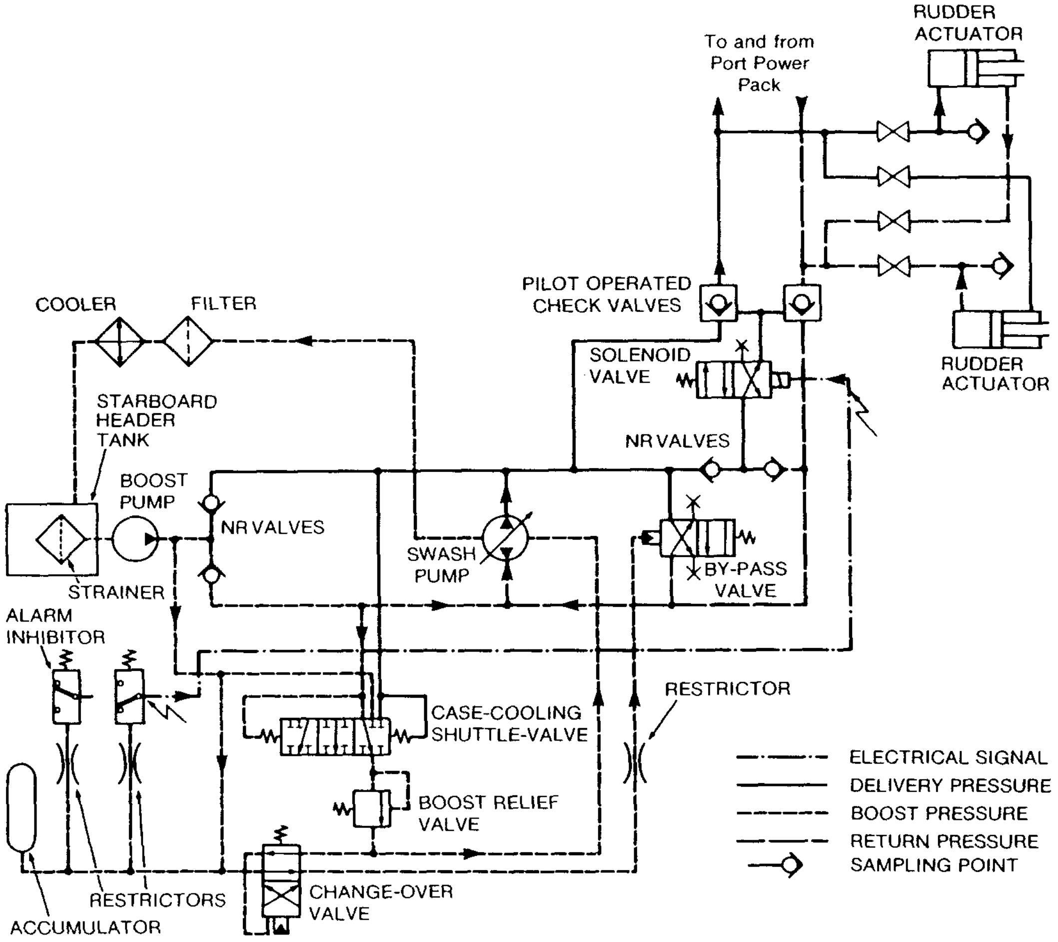

FIG. 2—TYPE 21 FRIGATE STEERING GEAR SHOWING HYDRAULIC POWER PACK ON LOAD

Immediately upstream of contamination-sensitive components.

Upstream of filters.

Return line to replenishment tank.

After a sharp bend.

The CPP system, despite its complexity, is provisioned with just one sampling point. The positioning is such that it is sited prior to the oil entering the shaft, after the gear-driven and motor-driven pump discharges have merged, and on what is effectively a dead leg (FIG. 1). A second sampling point sited on each composite valve unit (CVU) is not only inaccessible in some ships, but also is positioned such that it is only in circuit when up to one gallon of oil is being dumped whilst the propeller is being moved from ahead to astern. The Type 21 steering gear likewise has just one sampling point sited on the rams, which again is effectively a dead leg (FIG. 2). Thus the state of the two least contamination-tolerant systems under review cannot be adequately monitored. In comparison the 4·5 inch Mk 8 gun-mounting has approximately fifty sampling points!

Ability to Flush System

It is inevitable that hydraulic systems will from time to time require to be flushed and it is, therefore, essential that adequate provision be made for this evolution. Whilst the upperdeck hydraulic and stabilizer systems have sufficient flushing connections, in the less contamination-tolerant CPP and Type 21 steering systems little thought appears to have been given as to how

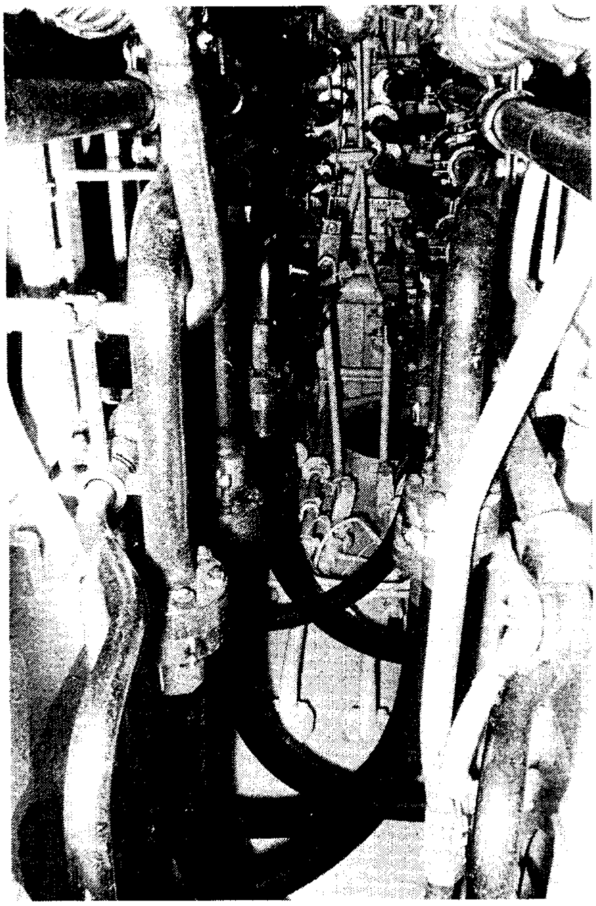

FIG. 3—CPP HYDRAULIC SYSTEM: THE 'SNAKE PIT'

they may be effectively flushed should they become contaminated in service.

Both systems have a number of dead legs and parallel paths, require extensive dismantling and removal of system components and, in the case of the CPP system, require the ship to be dry docked. It is arguable whether, with the bore size of the pipe to be flushed and with all papallel legs in the system eliminated, it is possible to achieve turbulent flow anywhere in the CPP system with the maximum flowrate of 200 gal/min available from the flushing rig. The recommended flushing routine laid down in the system BR would involve a ship being non-operational for a good many weeks and, because of the need to spring pipes back into position on reassembly, there is every possibility of new debris being introduced. Whichever method of flushing of the CPP system is used, and each ship appears to adopt a different one, the procedure is costly, time-consuming, and never totally effective. No provision has been made for flushing the Type 21 steering gear with an external rig. Use of the system pump is advocated, but as the failure of this pump may well have caused the system to be contaminated, it is not considered good engineering practice to fit a new pump to flush a dirty system. The solution to both problems is clear: either have systems that are more contamination tolerant or make adequate provision to enable an effective flush to be carried out if and when the need arises.

Ease of Maintenance

Because of their position in the ship, no marine engineering hydraulic system is easy to maintain, but the CPP system in the Type 42 destroyer is particularly inaccessible as illustrated in FIGS. 3 and 4. Pumps and their associated servo units, as well as some system control valves, are sited in the bilge. Filters are hidden behind a mass of pipework and the access into the replenishment tank is a mere 8 inches from the deckhead (FIG. 5). Reports on other systems have indicated that other general problem areas are insufficient isolating valves, badly-sited filters, and, in the case of upper-deck machinery, cranage is often required to remove an entire equipment in order to repair a leaking seal. If systems are to have a high availability, components must be readily accessible, such that they can be easily repaired *in situ* or replaced.

Swash Plate Pumps

With the exception of the upper-deck hydraulics, all the other systems reviewed use swash-plate pumps. As already indicated this has proved a particularly weak area with the CPP and Type 21 steering-gear systems. The

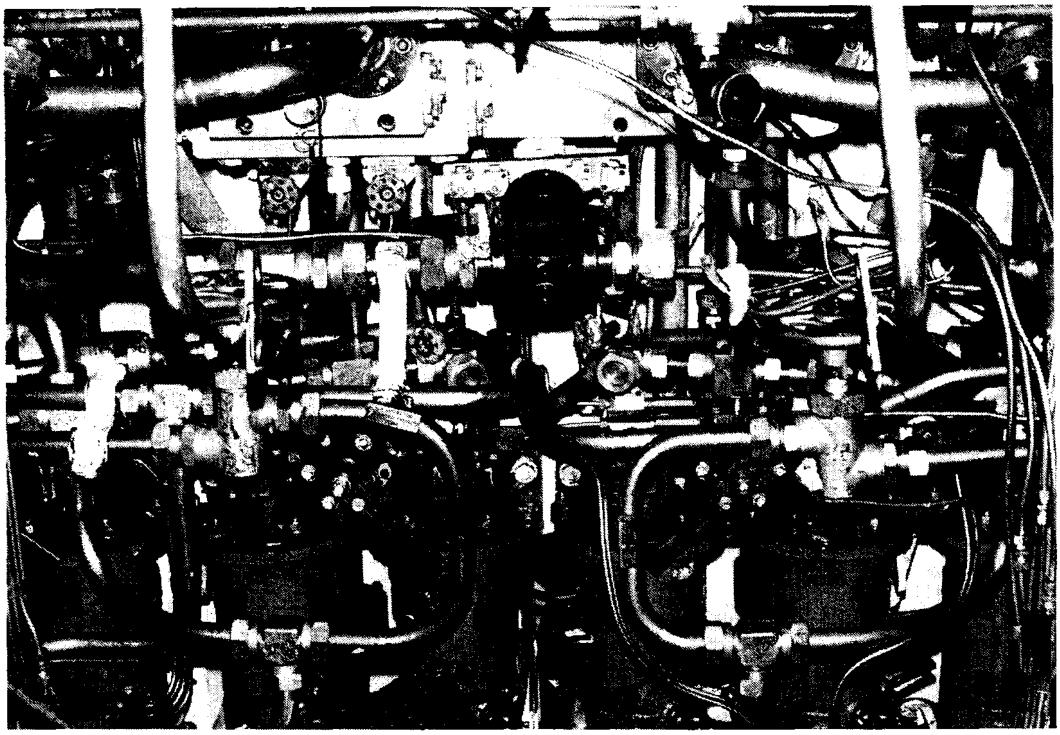

FIG. 4—CPP HYDRAULIC PIPEWORK SHOWING POSITION OF FILTERS

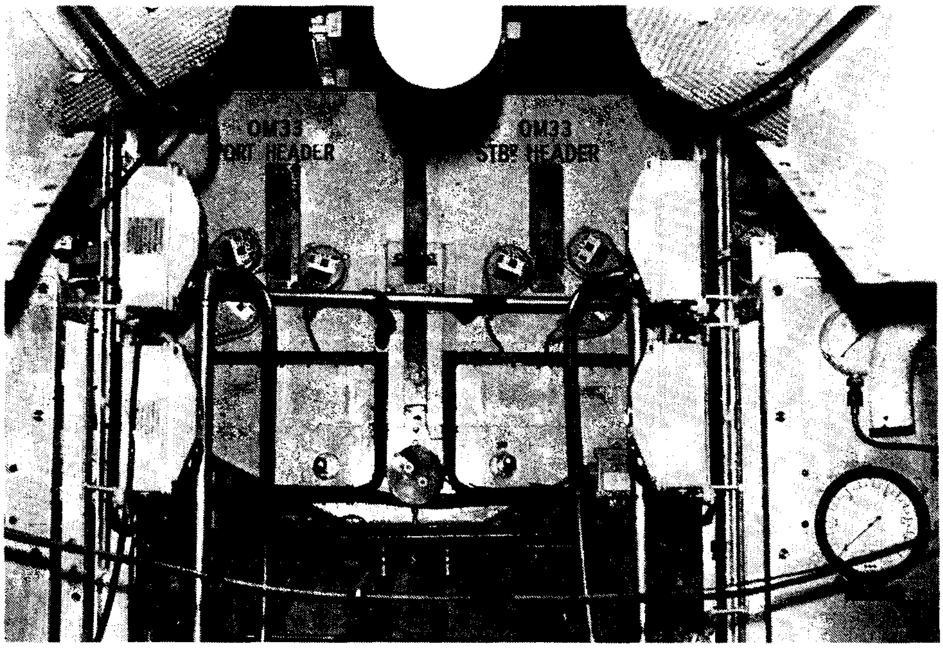

FIG. 5—TYPE 42 CPP SYSTEM HEADER TANK

pumps and the servo system associated with them have been equally prone to premature failure. The most likely cause of failure, although not substantiated, has probably been some form of particulate contamination fouling the fine clearances found within the pump. It is not known exactly how many of these pumps have failed in service, but during the last three years a total of twenty-two CPP pumps have been issued and no fewer than twenty pumps have been supplied for the Type 21 steering gear over the same period. In the latter case this is equivalent to replacing each pump in service twice during that period.

One particular phenomenon associated with the CPP pump has been 'Port Plate Lift Off'. Movement of the pump barrel away from the ported plate causes the main hydraulic system oil to leak directly across into the pump cooling system and thereby collapsing main system pressure. Although in itself not a pump failure, any debris within the fluid would prevent re-seating taking place if trapped between the barrel and the ported plate and has probably been a cause for rejection of some pumps. Another identifiable cause has been the failure of the ball joint/slipper arrangement by which the pistons connect to the swash plate, suggesting partial or total piston seizure. It is not known why both the CPP pump and the Type 21 steering gear pump have failed so frequently in comparison to the VSG pump used in the stabilizers and Type 22/42 steering-gear systems. Nor it is known why the latter pump is able to operate in a much dirtier environment than the two former. It is submitted, however, that along with other system components in the CPP and Type 21 steering gear, these particular pumps are too finely toleranced for the purpose for which they are intended. For systems that are in use 24 hours per day and on which the entire function of the ship depends, the pumps in particular should have a long life and be able to accept a greater degree of contamination than is presently the case. To this end perhaps a screw-type pump would have been better suited for the purpose, particularly for the CPP system.

Filtration

The *Hydraulics Manual* (BR 3038) states that full-flow filtration usually provides the greatest measure of protection to system components and also advises the positioning of filters immediately before components with fine clearances. Most service hydraulic systems follow a familiar pattern of siting filters on the supply to servo systems and on return legs to replenishment tanks. This has proved adequate for the stabilizer, upper-deck hydraulics, and the Type 42 steering systems. However, lack of filters in the more complex CPP and Type 21 steering systems has probably been a contributory cause in many of the reported failures.

The Type 21 steering system shown in FIG. 2 has just one filter and this is positioned on the return leg to the tank. Neither the pump servo (where clearances are in the order of 0·0001 of an inch), the swash-plate pump itself, nor any other system component has been afforded any protection from particulate contaminants. Needless to say, debris has been a cause at one time or another of many system components jamming, which in some cases led to a total loss of steering and in one case ended in a fatality. Such was the frequency of 'sticking' components in one ship that a hammer was permanently stowed in the compartment to 'shock' offending items in an effort to free them. Had filters been positioned in the main pump supply and return lines (as is now the case) and in the supply to the pump servo, considerable savings would have been made on pumps in particular. In the event the system has been unreliable to the extent that one Captain remarked that the steering gear 'had introduced a new dimension into ship handling'.

The positioning of filters in the CPP system is such that adequate provision is made for the boost and servo supplies. However, no filters are fitted in the main hydraulic supply and return lines, or to any of the components linked to these lines. It is ironical that a possible suitable filter element has been provisioned as an Emergency Filter Pak. This filter which can be fitted across the main hydraulic lines for cleaning up system oil has by the very nature of its title been condemned to an almost unknown ship's fitting, bolted on a bedplate in a corner of the machinery space bilge. No filtration has been provided in this system for the pump cooling or return line to the replenishment tank, despite the extensive pipework involved. With the likelihood of

'Port Plate Lift Off' this is a potentially vulnerable area.

Positioning of filters particularly in systems which are not contamination tolerant is obviously of great importance if cleanliness standards are to be maintained. Of equal importance is the ability to detect a choked filter if a system malfunction is to be prevented. Often reports have been received of filters being positioned such that warning devices are not easily sighted. The use of 'pop up' indicators in particular have proved ineffective as a means of alerting watchkeepers of a potential problem in a hydraulic system. Most watchkeepers are junior ratings monitoring and recording many different systems and equipments of which a hydraulic system may be just one. A differential pressure gauge is a more familiar and effective means of assessing the cleanliness state of a filter.

Pipe Systems and Couplings

The materials most commonly used for hydraulic pipework in R.N. hydraulic systems are either copper nickel or Tungum. Likewise the Keelaring coupling is the most frequently used joint for connecting lengths of pipe. The *Hydraulics Manual* advocates the maximum use of continuous pipework in order to prevent leakage. However desirable, such a policy is not always practicable because of the need to remove at intervals components for repair or flushing and, in some cases, sections of pipe to aid removal of equipments from other services. Disturbance of one coupling for whatever reason often affects the security of other couplings, particularly those either side of the one being broken, and this aggravates the inherent fire risk ever present with these couplings. The extensive use of Keelaring couplings has imposed an enormous maintenance load on ships' staff because of the need periodically to check the torque setting on each coupling nut. Many couplings are badly sited or totally inaccessible: this is particularly the case with the CPP system where there are upwards of 200 coupling nuts and where such a task is almost impossible. In the HUNT Class MCMV the enormity of such a task requires base support. Although the Keelaring coupling has exhibited shortcomings in service, it is only fair to point out that when evaluated and tested against other mechanical couplings it has proved to be equal or better for ship hydraulic systems.

In the CPP system where pipe runs are extensive and the bore size is large, a successful flush of the system is impossible. As the flushing routine requires the removal of the majority of system components, the selective use of breakaway couplings would have been justified. This would also have been advantageous for other maintenance purposes where the repair policy is based on upkeep by exchange. For upper-deck systems which extend the length of the ship, the use of brazed joints or cryofit couplings is believed to be a more suitable alternative to Keelaring couplings.

Isolating Valves

In the event of a system component breaking up, it is essential that facilities exist to isolate loops if the spread of contamination is to be avoided. With steering systems and CPP systems a high availability is required as both are in continual use at sea. The CPP systems have two pumps both capable of driving the same actuator, yet there is no provision for isolating a pump loop if it should become defective or contaminated. It is known that pump failures in the non-defective loop have taken place within hours of an initial breakdown in the other loop. A CPP pump failure can lead to the spread of debris through the main hydraulic system and through the shared pump cooling loop. In a Type 21 frigate, a similar pump failure on the steering system could result in a total steering failure. Besides being able to isolate defective system loops, valves would serve as a useful aid to fault diagnosis. In complex systems where several components can give similar symptoms when defective, the ability to isolate sections would enable maintainers to pinpoint the offending item more quickly and thus reduce downtime. Poor positioning of isolating valves, however, can and does have an adverse effect. In the Type 22 frigate and HUNT Class MCMV, isolating valves positioned downstream of the flushing valve has meant complete depressurization of entire sections to enable maintenance to be carried out on one loop. Such an evolution adds to the initial work because on repressurization, leakage has frequently occurred in a number of Keelaring couplings.

For a warship to be effective, systems must be readily available. Invariably most systems are duplicated but the utilization of this duplication to increase availability is dependent on being able to isolate sections for either routine maintenance or repair.

Flexible Hoses

Flexible hoses are an integral part of any hydraulic system; however, their use should be restricted because of the contamination they can create and their susceptability to sudden failure. A survey is in hand to identify the number of hoses fitted in each system. Whilst the number of hoses is not expected to be excessive, they are of different sizes and have various different end fittings. No attempts have yet been made to standardize hose size, length, or end fittings, consequently some systems do require considerable support with regards to spares. The present upkeep policy for flexible hoses is such that they are inspected externally every six months and, depending on their siting and function, are required to be changed at either four or eight year intervals. Implementation of this policy is dependent on knowing the cure date of the rubber from which the flexible is manufactured. This policy has proved difficult to implement because:

(*a*) The indelible markings showing the rubber cure date on the hose have often disappeared because of wear and tear, even before a ship enters service.

(*b*) The positioning of flexible hoses often makes such inspections extremely difficult.

(*c*) Spare hoses in support of such a policy have in some cases not been patternized nor are they readily available.

Replenishment Tanks

The advice given in the *Hydraulic Manual* on reservoirs is that they should be sighted high above the pump inlet, have a wire-mesh screen or a vertical baffle to prevent aeration, and fluid indicators should be fitted with spring-loaded shut-off cocks. To meet the requirements of the latter, most hydraulic systems have had tanks modified accordingly since acceptance into service. The replenishment tanks fitted in the hydraulic systems in Type 42 destroyers have been the subject of most defect reports. The steering gear tank is sited between the rudder heads and inboard of the two pumps. It is impossible to see the oil level in the tank as it is fitted with a high and low level viewing port only. By leaning across the moving tie bar connecting the two rudders, a watchkeeper can only hazard a guess as to the tank contents level by shining a torch in through the high level port. A modification to this arrangement is still awaited. As already stated, the access lid for the CPP header tank is sited in the top of the tank a mere eight inches from the deckhead (FIG. 5). Internally the tank is webbed, baffled, and has a wire-mesh screen bolted over the pump suctions; it is, therefore, impossible to clean effectively. To remove the tank involves not only breaking into both CPP systems but also would probably require half the machinery control console, sited above the tank, to be dismantled. The replenishment tank is often the best means operators have to make a quick assessment as to the system cleanliness state. Being the low pressure point in the system, contamination will tend to migrate to the tank. Gauge glasses give an indication of the oil state, simply from its appearance, whilst a sampling connection on the lowest point of the tank is often the best way of detecting water in the system. However, it is essential that, in the event of contamination within the system, the tank should be capable of being cleaned.

High Usage of OM 33

OM 33 is universally used in R.N. hydraulic systems in the Surface Fleet. Whilst fulfilling most requirements, it does, however, have two disadvantages: these are that it is inflammable and it has a low saturation level when in contact with water. It is also relatively expensive and hence usage is an important factor to be taken into consideration. TABLE VII shows the usage of OM 33 for a one year period which, at £60/drum, represents a sizeable outlay in support. Most of this oil is lost from the CPP system, mainly through minor leaks. Large quantities have also been used for flushing CPP systems when little, if any, is recovered.

In gas-turbine-propelled ships, OM 33 is stored in quantity at the specified cleanliness standard for the system for which it is intended. As the vast majority of oil stored is eventually used in the CPP system, the cleanliness standard required is RN 2000. Oil is supplied at a RN standard of approximately 15 000; however, most Naval Bases 'double-filter' the oil such that it is supplied to ships at RN 2000. Whilst supplies are readily available at Naval Bases, ships deployed rely on an accompanying Royal Fleet Auxiliary to support their needs. Double filtered oil is not carried and oil supplied does require filtering before being struck down for storage. The recent introduction into service of the Fawcett Filter Pak has eased this problem although it is time-consuming and imposes limitations on the ship until all the oil embarked has been 'struck down'.

TABLE VII—*OM 33 consumption figures over a twelve-month period*

Ship	*Consumption* litres	*Equivalent Drums* 45 gallons
Amazon	12 853	64
Ambuscade	3790	18
Antelope	12 047	60
Arrow	9034	45
Active	16 648	83
Alacrity	24 246	121
Ardent	7998	40
Avenger	5703	29
Broadsword	8836	44
Battleaxe	13 423	67
Sheffield	3696	18
Coventry	4488	22
Newcastle	31 148	155
Glasgow	9075	45
Cardiff	4963	25
Birmingham	23 444	117
Brecon	4396	23

Filling Arrangements

The filling arrangements are adequate but only since the recent introduction into service of the Fawcett Filter Pak. Oil is embarked from 45-gallon drums and pumped direct into a filling line which then discharges to a central storage tank. Transfer to hydraulic services inboard is by use of a small centrifuge. The biggest 'hurdle' that has had to be overcome has been to impress on ships' staffs the higher cleanliness standards required for embarking hydraulic oil over those for other fluids. The ready availability of double filtered OM 33 has been a major factor in ensuring that oil embarked has been at the high cleanliness standard required.

Poor Documentation

The initial lack of expertise of hydraulic systems amongst personnel was not helped by the poor documentation available. Books of Reference (BRs) gave scant and often inadequate descriptions of systems and components whilst some system diagrams were inaccurate. Even now system BRs continue to exhibit shortcomings with amendments taking anything up to three years to be incorporated. The omission of flushing routines in particular is a serious shortcoming. The Engineering School at H.M.S. *Sultan* produced a number of dockets with simplified descriptions and diagrams which have enabled operators and maintainers to 'muddle through'. The problem really has only been overcome by the experience and expertise that has been acquired over a period of years.

Support for hydraulic systems has been hampered by lack of information in spare parts catalogues and this has seriously reduced system availability. In particular many items were not patternized or provisioned. Flexible hoses for some CPP systems have still to be patternized and this after some seven years of service! Modification states of the Type 21 steering-gear pumps were not well documented and on one occasion this led to no less than four pumps being transported abroad to repair a defective system. It is essential that documentation in support of a system or equipment precedes the introduction into service of that system/equipment.

Hydraulic Expertise

There was no tradition of hydraulic engineering within the marine engineering branch of the Royal Navy. Consequently both operators and maintainers were largely unprepared to deal with many of the systems introduced in recent years. In particular there has been a general lack of awareness as to the significance of good hydraulic hygiene. Practices that had previously been acceptable for years when repairing/maintaining other systems were detrimental when applied to hydraulics, thus a protracted process of training, based largely on experience gained, has evolved. Only recently has that expertise become available at the Training Establishment, where it can now be passed on to those about to join ships.

The hydraulic specialist section who would normally advise on hydraulic system design was not established at the Ministry of Defence Ship Department until as late as 1973. By this time the Type 42 destroyer was in an advanced state of build and the first Type 21 frigate was undergoing sea trials. The design of an open-circuit CPP hydraulic system subsequently is understood to have overcome many of design shortcomings of the present CPP system and will it is hoped be fitted in later Type 42 destroyers and Type 22 frigates.

Conclusion

Over the last decade, the number of hydraulic systems fitted in ships has grown considerably from what had previously been a source of power for gunnery and steering systems. The complexity of some systems combined with the high cleanliness standards required has imposed an unnecessarily heavy workload on operators and on maintainers, many of whom were largely unprepared to deal with such systems. Little consideration appears to have been given to the need for accessibility and exchangeability of system components whilst the use of swash-plate pumps stands out as an area of major weakness. Some systems are over complicated for the function for which they are required and in many areas the situation has been aggravated by poor support. Essential documentation has not been readily available and advice on flushing is still unavailable or impracticable for some systems.

Whilst a great deal has been learnt over this period, considerable time, energy, and cost could have been saved had systems been more contamination tolerant. For naval engineering it is suggested that the principles of design must be *simple, robust,* and *easy to maintain.* These principles have not been applied to some hydraulic systems in service today and the resulting legacy is the continual attention they will require, particularly as their years in service lengthen.