THE INSTITUTE OF MARINE ENGINEERS
76 Mark Lane, London EC3R 7JN *Telephone: 01-481 8493 Telex: 886841*

TRANSACTIONS (TM)

ROYAL NAVAL HYDRAULIC MACHINERY

ISSN 0309-3948
Trans I Mar E (TM)
Vol. 98, Papers 9 and 10
(1986)

Contents

Refitting Hydraulic Machinery

J. R. Corless CEng, FIMarE, MIMechE, RCNC
HM Dockyard, Devonport

SYNOPSIS

Failure to achieve clean environmental conditions is the cause of the majority of breakdowns in hydraulic equipment. The failure may result in plant stoppage through mechanical failure, or degradation of performance through excessive leakage. In repair processes, therefore, the first precaution must be to ensure that no further contamination can take place and then thoroughly clean all the parts before re-assembly. Where replacements are not readily available, components which have deteriorated can be built up by chrome plating, or cleaned, honed and fitted with oversize pistons or valve spools. During the testing of the refitted components, hygienic conditions must be maintained in the test circuit while fluid flows, pressures, temperatures, leak-offs and power outputs are measured as proof of performance. During re-installation the same stringent cleanliness controls must be maintained. These can be checked by using field sampling equipment and analysing the result. Finally the system is flushed to remove any dirt that has escaped the previous surveillance. A range of flushing rigs has been provided to ensure that the flushing velocity is kept high enough to maintain turbulent flow conditions throughout the system.

INTRODUCTION

In order to achieve the high-performance characteristics which distinguish hydraulic machinery from other power plants, high standards of dimensional accuracy and surface finish are applied during manufacture. It is essential that these are maintained during repair, and hence strict control of the environmental conditions is imperative.

Mr J. R. Corless joined the Royal Corps of Naval Constructors after 23 years service in the Royal Navy. In 1973 he was appointed to Devonport Dockyard where he has been the Mechanical Engineer Line Manager in the Submarine Division and until recently in charge of the Workshop responsible for the repair and overhaul of all hydraulic equipment sent in from refitting ships.

FAILURE OF HYDRAULIC COMPONENTS

From experience gained during the repair of hydraulic equipment for the Royal Navy, it has been found that the majority of breakdowns in hydraulic systems are caused by deterioration of hydraulic hygiene inside the hydraulic circuit. Solid contamination causes scoring and wear, which can result in one of three types of failure:[1]

1. Catastrophic failure, where a component ceases to operate, often disintegrating and causing further contamination in the process (Fig. 1).
2. Intermittent failure, where contaminating particles prevent regular operation. For example a valve is prevented from seating by dirt trapped beneath it, but because the dirt is soft compared with the valve seat it is washed away without trace when the valve re-opens. This sort of failure is very difficult to diagnose and results in low confidence in the reliability of the system.
3. Degradation failure, where corrosion or erosion causes increased internal leakage leading to low efficiency or sloppy control. The sort of failure often degenerates into catastrophic failure.

Failure is more likely to occur when the particle size is greater than the critical size specified for the system. This often causes scoring or seizure in piston pumps and spool valves. Failure also occurs because of silting of small particles leading to clogging of the fine passages in control valves, erosion of the sharp control edge of spool valves and ovality in piston pump barrels. Thus wear products produce more contamination and open up diametrical clearances permitting even larger particles to enter. This further degrades the performance of the system.

It is most important, therefore, on first commissioning the system that samples of the hydraulic oil are regularly analysed to ensure that the cleanliness remains within the specified range. In the RN most systems operate either between classes 2000 and 6300 or between classes 6300 and 15 000. All systems are filled with oil filtered to class 2000 and must be flushed if during operation the standard deteriorates beyond the upper limit. An abbreviated table of these standards is shown in Fig. 2 and they have been explained more fully in Ref. 2.

Working as we do in a marine environment, the importance of water contamination cannot be overlooked. Entrained water, usually accompanied by dissolved air, will cause rusting and pitting of steel surfaces. The resultant particles, and the reduced lubricating properties of the fluid, will cause increased wear to moving parts resulting in further contamination.

Hydraulic oils usually have good demulsifying properties, so where flow velocities are low the entrained water will separate and lie in these dead legs causing some of the rust inhibitors to be washed out of the oil, so aggravating the corrosion in those areas. On the other hand, where flow velocities are high, larger quantities of water will cause the oil to emulsify with a consequent increase in viscosity. This will cause sluggish operation of the system and choking of the filters.

For these reasons the water content of oil in RN hydraulic systems is checked regularly, and the oil is changed if contamination exceeds 500 ppm.

In submarine systems, where many hydraulic components have sea water on one side of the seal and hydraulic oil on the other, water can enter when the water pressure exceeds that of the oil. It has not been practical to change the oil during service when the water content reaches the level specified above, so a special hydraulic fluid has been developed which will hold up

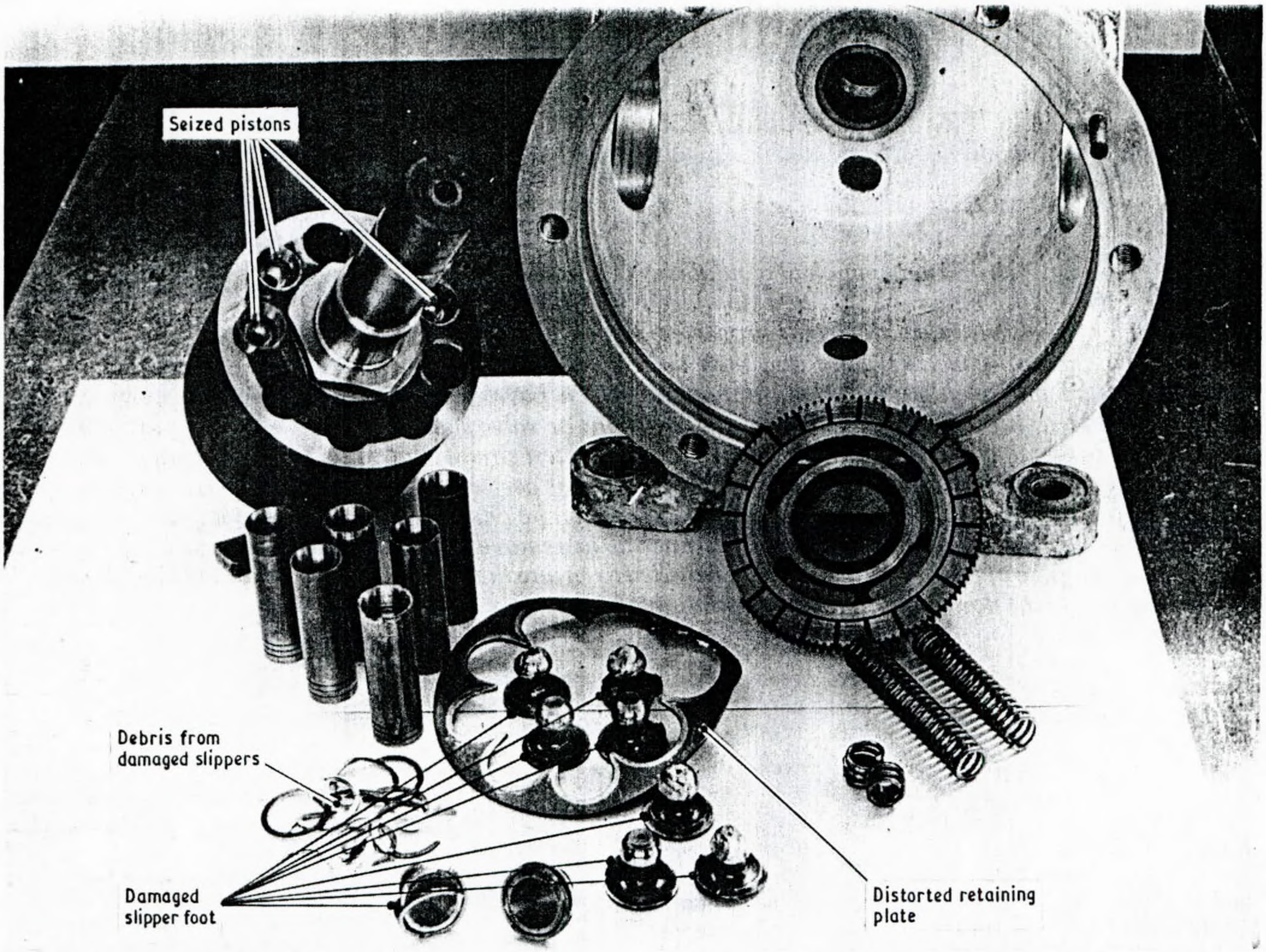

FIG. 1: Catastrophic failure of an axial piston pump. Overheating of the pistons, probably caused by dirt in the oil, resulted in piston seizure. As the pump continued to rotate the slippers were forced against the seized piston distorting the retaining plate and breaking off the lips on the feet of the individual slippers. This caused further debris, some of which entered the system causing further contamination

to 10 % by volume of sea water in an emulsion without detriment to its viscosity or lubricating properties.

REFITTING HYDRAULIC SYSTEMS AND COMPONENTS

When removing a defective component, contamination must not enter the system through the exposed ends. Before any pipes or threaded connections are detached, the external surroundings must be clean and any dirt-making operations must be stopped while the system is open. The relevant part of the system must be isolated and depressurised. Hydraulic systems under pressure are reservoirs of large quantities of energy so an escaping spray of oil from a broken joint could be a potential fire hazard as well as a danger to the eyes and exposed skin of those in the vicinity. After removing the defective unit, the ends of all open pipes and ports must be capped or plugged. Any caps used for this purpose must be robust and have a flanged end sufficiently large to prevent the pipe being reconnected with the cap or plug left in the circuit.

Finally care must be taken in removing any old 'O' seals from their grooves. Several examples of damage caused by the careless use of screwdrivers, scribers or other such implements to remove the old seals have been encountered. If such burrs and scoremarks are not removed the life of the replacement seal will be considerably reduced.

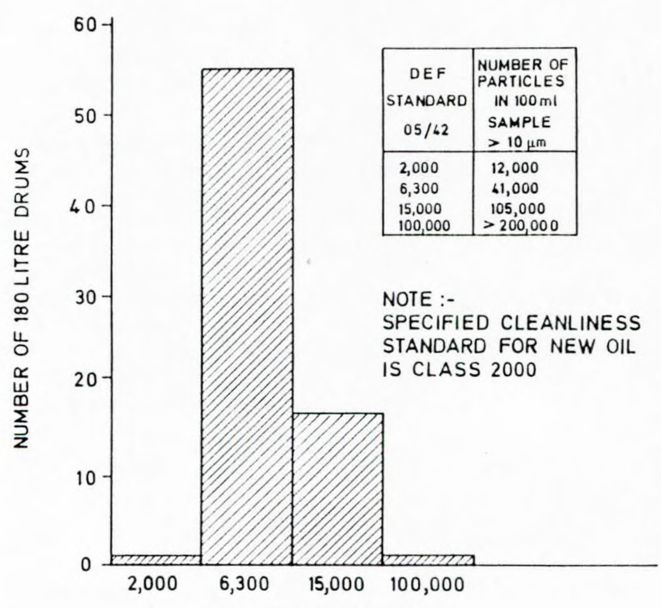

FIG. 2: Analysis of cleanliness of new oil drum contents prior to issue (Oct. 1983). Out of 74 drums tested, only one was sufficiently clean to issue without flushing. From Ref. 2

The defective unit is then wrapped in polythene and boxed for transport to the workshop, where it is unpacked and cleaned externally. After stripping, the constituent parts are cleaned and degreased and taken to a temperature-controlled room where they are examined for damage and then measured. Critical dimensions are compared with those on the relevant inspection chart, and if they are within the permitted limits and the unit shows no sign of pitting or scoring it is passed to the refitting benches for preparation for re-assembly. Any parts rejected after inspection are replaced by spares, or, if these are not available, they are repaired.

It is often more economical to repair sub-components than replace sub-assemblies and to this end manufacturers supply oversize parts to compensate for wear. Worn pump barrels can be reclaimed by grinding and lapping plunger bores and fitting a suitable oversize piston from a standard range of replacements. Similarly control valves can be refitted with matched spools and sleeves, or individual spools or sleeves fitted from oversize spares machined to suit. Scored valve plates of axial piston pumps have been recovered by lapping, to remove grooves between the inlet and exhaust ports, providing that afterwards the case-hardened surface is intact.

Using similar techniques other repair processes can be devised. In one particular instance, a hoist control valve was sent in for repair because no replacement was obtainable. The valve consisted of a ported block, in which directional control was achieved by lateral movement of a spool and speed control by rotating the spool so that a scroll uncovered varying areas of the pressure port. After stripping it was discovered that the spool was undamaged but deep axial scores in the bore of the block linked the pressure and return ports. A repair procedure was then developed.

First the block was bored oversize to allow a sleeve to be shrink fitted. To achieve this the mating surfaces were lapped to a high standard of finish and the sleeve chilled in a flask of liquid nitrogen. It was then fitted and bored to size. Finally the ports were drilled in the sleeve. The first attempt failed because insufficient thickness had been left in the sleeve wall to prevent it distorting when the ports were drilled, and pressure therefore leaked across the back. When the operation was repeated the sleeve wall was left as thick as possible and the ports were drilled in stages. Finally the sleeve inner diameter was bored, ground and honed to the required size.

The most common defects encountered are deep scores on the bores of actuator cylinders and on the bores of hydraulic accumulators. Some axial scores on ram rods and circumferential grooves on pump spindles in way of shaft seals have also been found. In these cases reclamation can be accomplished by grinding the bore or shaft to remove the score marks and then building up the surface by hard chrome electroplating. The thickness of the chrome deposit must allow for a minimum chrome thickness of 0.1 mm after machining to finished size. Heavy deposits of chromium are not recommended, however, as they are brittle, and so an underlayer of nickel is used when large deposits are required to regain the original size.

There is no limit to the amount of nickel that can be deposited, and combined coats have enabled 0.75 mm to be reclaimed in the Dockyard, with as much as 12.5 mm being achieved commercially. Electroplating can either be carried out in a conventional tank or by an *in situ* procedure developed by Selectron Ltd. Their method is particularly useful for building up external surfaces on spindles or spool valves which can be mounted in a lathe, and, because high current densities can be used, the rate of plating is about 60 times faster than the tank process used in the Dockyard (Fig. 3).

The Selectron process can also be used to build-up lateral score marks. Afterwards the circularity and surface finish have to be restored by hand or by using other portable machine tools.

Air-loaded accumulators often become defective because of longtitudinal scores in the bore. Where these are light they are removed by honing. Oversize pistons are then required if beyond the limits of the seal. If the scores are very deep the cylinders are ground to remove the damage, and since they are too large for the Dockyard plant they are sent away to Unochrome Ltd to be 'Fescolised', a proprietary electroplating process using nickel and chromium, which builds up the bore to enable it to be ground and honed back to its original size.

When all dirt-making operations have been completed the components are once again cleaned and de-greased before passing into a clean room for assembly, if necessary wrapping them in polythene for transit or if assembly is likely to be delayed. These controlled assembly areas are enclosed and built in such a way as to enable them to be cleaned easily and kept clean. The ventilation air is filtered and the humidity controlled to between 35 and 45% at 20 °C, which is dry enough to prevent rusting of steel parts while they are waiting to be assembled and yet sufficiently moist to avoid causing sore throats to those working there (Fig. 4).

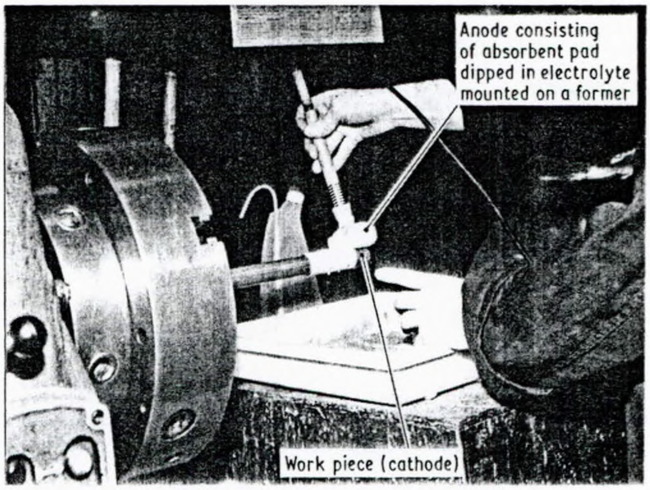

FIG. 3: Recovery of a damaged spool valve sleeve by the Selectron electroplating process. The work piece is connected to the negative supply of a power pack through the lathe. The positive supply lead is shown connected to the anode, wrapped in absorbent material soaked in a suitable electrolyte. Metal is deposited from the liquid in the pad on to the work piece at a rate of up to 0.05 mm/min

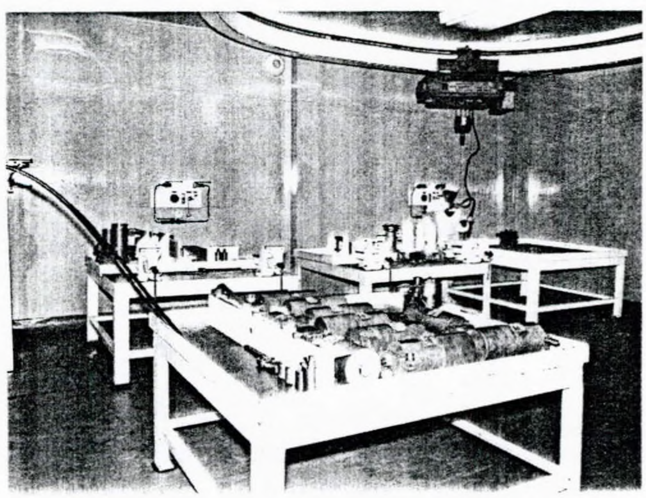

FIG. 4: Hydraulic clean room (photograph taken from the air lock). The room conforms to the British Standard definition of a 'Controlled Clean Area' with smooth walls, easy to clean floors and stainless-steel-topped test benches. Fitter wears clean lint-free overalls

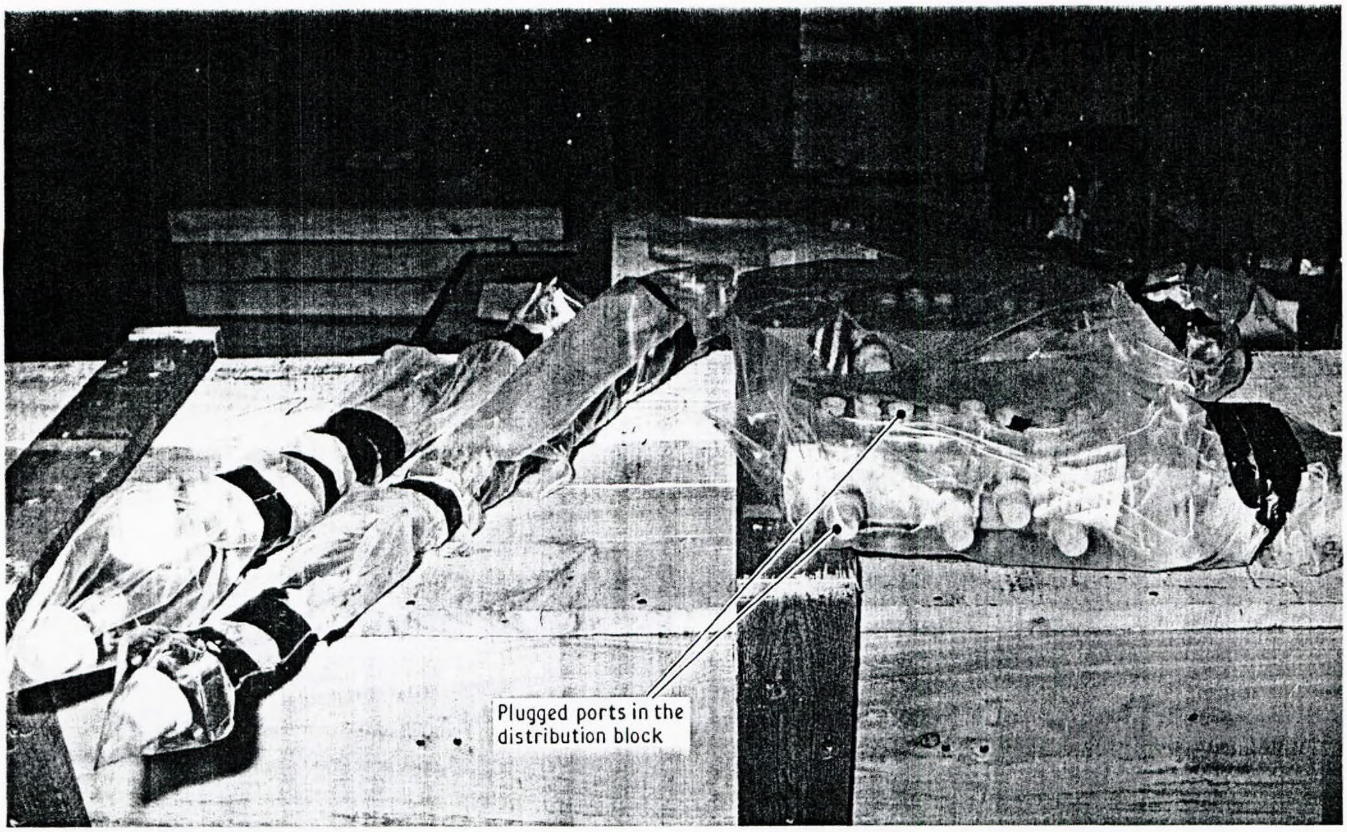

FIG. 5: Repaired hydraulic components wrapped ready for return to the ship for re-installation (note plugged ports in the distribution block)

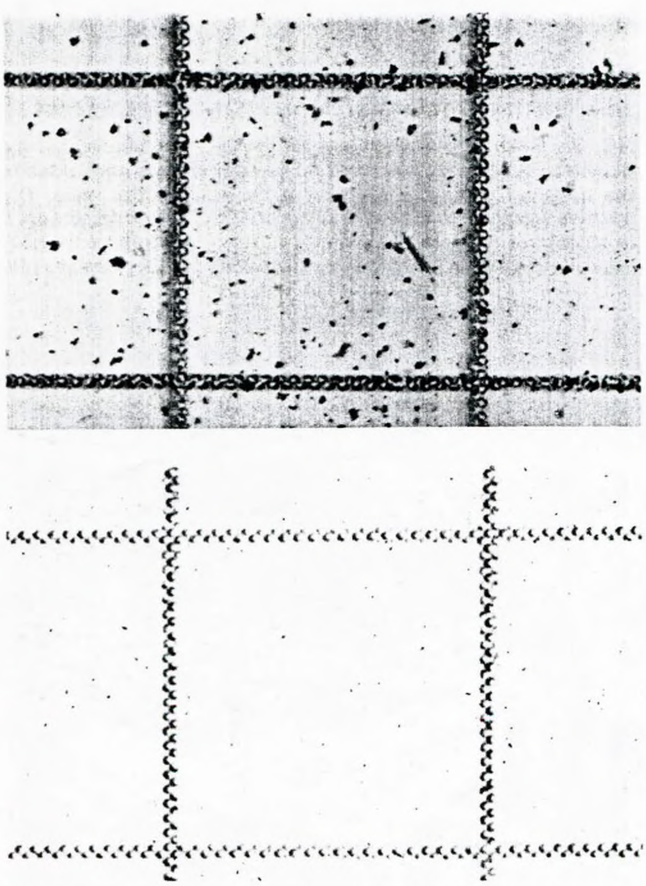

FIG. 6: Upper, unacceptable contamination found in new equipment on receipt from the manufacturer (grid about 3 mm square). Lower, acceptable standard for service (Class 6300) (grid about 3 mm square)

The assembly process is carried out on clean stainless-steel-topped benches, which are wiped down at the beginning of each work period, and the fitter concerned wears clean white lint-free overalls. On completion of the assembly it is ensured that all openings in the equipment are plugged and the whole is bagged in polythene for transport to the work site or test bay (Fig. 5).

It is important to realise that new components from the manufacturer are to be treated as 'dirty'. Contamination has often been discovered in the form of swarf, shop dirt, dust, fibres, sand (especially core sand), moisture, weld splatter, corrosion particles and paint chippings in spares received from store (Fig. 6).

Pipework is particularly susceptible to being the cause of built-in dirt, largely because of the erroneous belief of the manufacturer and the pipework installer that cleanliness does not have to be worried about because the pipework is going to be flushed on completion of assembly. Flushing is not an infallible method of removing contamination, and so the highest standards of cleanliness must be observed at all stages, and new pipes must be cleaned as soon as they are completed.

In the Dockyard two cleaning methods are specified: chemical cleaning or, for carbon steel pipes only, vacuum abrasive cleaning.[3] If the pipes are not going to be put back into service immediately they are flushed with preservative oil to the cleanliness standard specified for the relevant service. Further flushing or cleaning should not be needed until after installation in the system, provided the pipe ends are sealed whilst in store.

TESTING HYDRAULIC VALVES AND MACHINERY

The test procedure for refitted hydraulic components is usually carried out in two parts. First a pressure test is carried out using the hydraulic fluid specified for the system (of which the component is a part) at a specified temperature to ensure a standard viscosity. This proves the adequacy of the envelope of the components and the efficiency of the seals. Secondly flow tests are carried out, if required, to set up the restrictors in the control blocks or to prove the volumetric efficiency of the actuators.

Pumps are tested in a loading rig, where the rig pressure is controlled by the setting of the relief valve. The rig prime mover is a variable-speed electric motor. The pump is first run-up light and then loaded to the required pressure. Pressure and flow readings are made periodically and the pump casing leak-off is collected and measured. Throughout the test the temperature of the hydraulic fluid is monitored and the pump discharge oil is passed through a cooler to maintain the temperature in the circuit within the prescribed limits. Some trials require heat runs to be carried out for 4 or 8 h to prove that there is not untoward build-up of temperature in the pump.

For weapon equipments, a maximum temperature of 60 °C anywhere in the circuit is specified. This is to ensure that, even at local hot-spots, the oil never reaches a temperature at which carbonization occurs, which would cause solid contamination of the hydraulic circuit.

In particular, when testing axial piston pumps, the casing leak-off quantity is a good guide to the condition of the pump. At low pressures, if the leak-off is excessive it can mean that there is inadequate sealing between the valve plate and the cylinder of the pump. At high pressures, excessive leak-off usually occurs because of excessive clearances of the pistons in their barrel.

Where the pump is part of an automatically controlled system, the servo-unit of the pump has to be proved. In the Dockyard a test rig has been designed to represent the pump loading, reproducing the duty cycle on a cam connected to the operating lever of the servo-control valve (Fig. 7). During testing the swash plate displacement and the corresponding pump flow are recorded continuously on an X–Y plotter.

Motors are tested in a similar manner using a hydraulic pump as the 'A' end and measuring the output of the motor against a dynamometer. Pressures, temperatures, flow rates and leak-offs are measured as before, with the motor operating against a specified load.

Having taken all these precautions during strip-out, repairing and reassembling the equipment, care must be taken that they are not negated by using dirty oil during testing. The standard of cleanliness of the test circuit must be at least as high as that required where the item will operate, and regular samples must be taken and analysed to confirm that this standard is being maintained.[2] Again strict control must be exercised to ensure that discipline is maintained during connecting and disconnecting and that after testing all openings are plugged or capped, operating ram exposed surfaces are protected and the item sealed in a polythene bag before being transported to its installation site.

Finally similar precautions must be taken during re-installation, otherwise all the time and expense lavished on the equipment, to ensure the elimination of built-in dirt, will have been wasted.

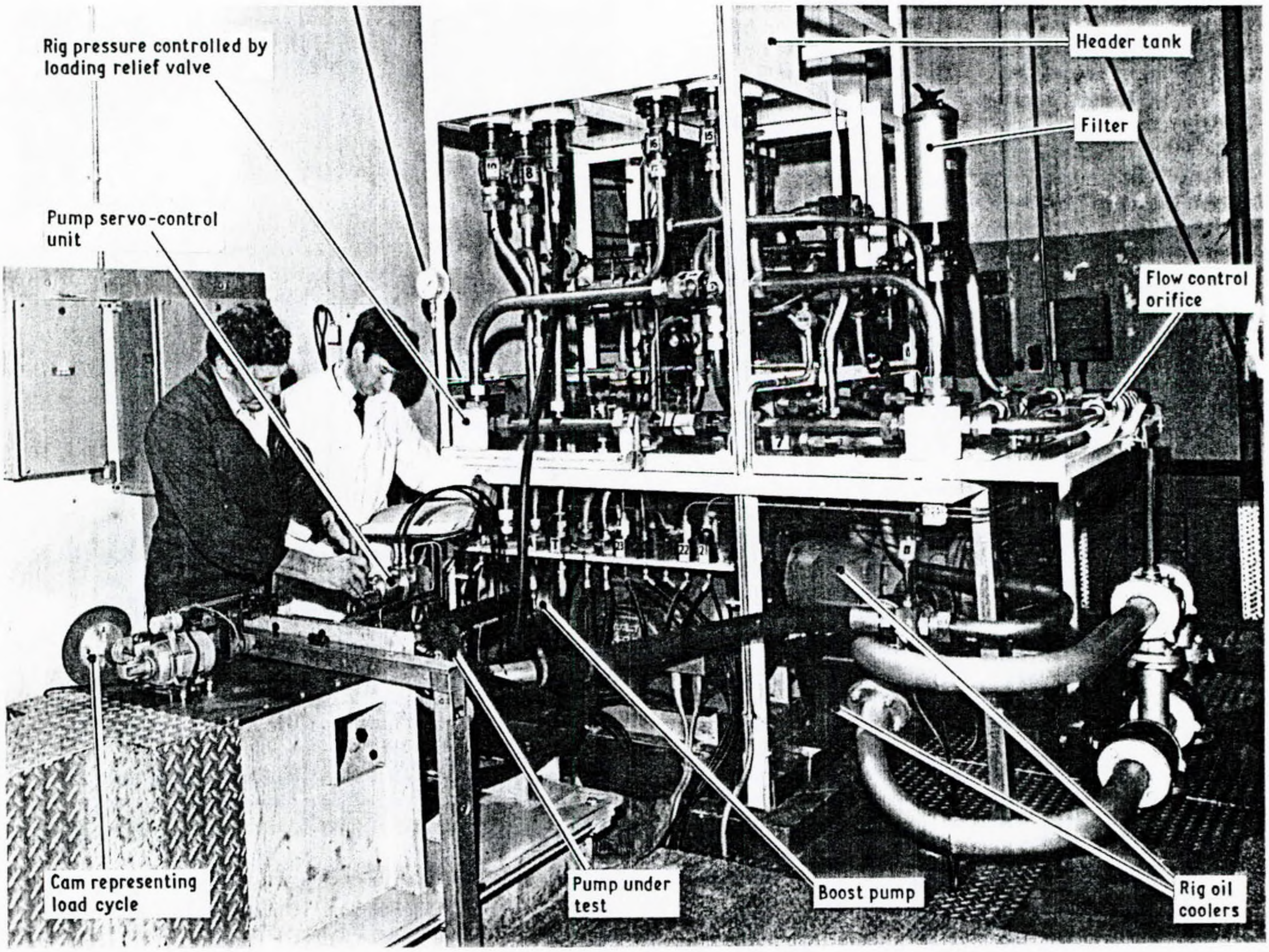

FIG. 7: Test rig for a pressure-compensated axial piston pump, showing loading circuit and cycling cam arrangement in the process of being connected to the pump servo-control valve

RE-INSTALLATION OF THE REFITTED COMPONENT

The most effective way of preventing dirt causing damage to newly refitted components of warships' hydraulic systems is to adopt the following procedure:

1. Complete the installation of pipe work and dirt-tolerant components before sensitive items are put into place. Pipe ends should remain capped until the last possible moment.
2. Complete the hydraulic circuit using jumpers to take the place of sensitive components. Fill and pressure test the system and flush until the required standard of cleanliness is reached.
3. On completion of the above prepare the area for the installation of sensitive items.

If sufficient care is taken during the installation of the refitted component, further extensive flushing is not necessary. To ensure this, however, strict embargoes should be placed on any operation such as welding, painting, chipping, drilling or grinding which could contaminate the oil from dirt in the atmosphere.

As a further precaution, when dirt-sensitive equipment is being installed temporary clean areas can be constructed, as during its removal, and access can be controlled. Such persons who do enter are not allowed to smoke or take food into the area. Finally it should be stressed that protective caps must be left on all components and pipework until the last possible moment and that mating parts should be clean and dry.

When fitting new or repaired equipment, the specified tightening torques must not be exceeded. This is particularly important where Keelaring couplings are fitted, as the hardened collet will bite too deeply into the pipework and start a stress raiser that could result in subsequent failure by fatigue. If the system is to be painted, it is important that the area of pipework in the vicinity of any coupling should be left bare and protected by mastic tape where exposed to the weather.

The environmental conditions prevalent during the period when machinery is under repair are usually much more damaging than those experienced during normal operation. The air is usually laden with dust, fumes and moisture, and the machinery is often left with its normal protection impaired. Some of the more vulnerable sources of dirt ingress are:

1. Reservoir access covers and air breathers. These are often removed for cleaning the tank and for replenishing the hydraulic fluid. It is important to check that the covers are replaced securely after use. If they are not, contaminated air will be drawn in during the venting operations, which often follow the replacement of hydraulic rams and actuators.
2. Cylinder seals. These are fitted with wiper rings to remove fine contaminants from the piston rod, which is exposed to the atmosphere. These are not 100% effective, as if they were they would wipe the rod dry with subsequent wear on the seal itself.

The most common source of contamination occurs when replenishing the system with new oil. Even though the oil drums are lined with polythene, there are sufficient defects in the lining to permit corrosion of the drum material. In the Dockyard it has been found that it is necessary to re-filter stored oil every six months to maintain the standards required.[3]

It is recommended therefore that oil is filtered during each transfer process, so that as much contamination as possible is removed before it enters the system and is ground down to finer particles. A small 'Filterpak' has been developed for this purpose consisting of a 16 l/min pump discharging through a 10 μm filter. Before filling the system, the area surrounding the filler cap should be wiped clean before the cap is removed. All pistons should be placed in the retracted position where possible and the reservoirs of filter assemblies filled separately.

Before starting up for the first time, the system must be bled. Variable displacement pumps are run up in the neutral position and the level of oil in the reservoir checked. Each directional control valve should now be operated in turn until all rams are in the extended position, while bleeding from the ends of the pistons until all air is expelled. Indications of a good bleed are:

- No fluid–air foam in the tank.
- No unusual noises in the hydraulic system.
- No jerky movements of piston rods, motors etc.

REMOVAL OF CONTAMINATION FROM THE SYSTEM

In spite of all the precautions taken during repair and reinstallation, some contamination will remain in the circuit and this can only be removed, before it causes damage or wear to sensitive components, by flushing the system through selected flow paths. System flushing should be carried out before sensitive items are installed to avoid damage to the fine finishes on their surfaces and also to avoid the loss of pressure head in forcing the oil through their restricted passages. These components should be jumpered out and the flow paths chosen to produce a circuit with as little fluid resistance as possible. The reason for this precaution is that a flush will not be effective unless turbulent flow is maintained during the process, as it is the fluid eddies and high velocity at the pipe wall which are the most effective in lifting off the dirt and keeping it in suspension in the fluid until it is retrieved by the flushing filter.

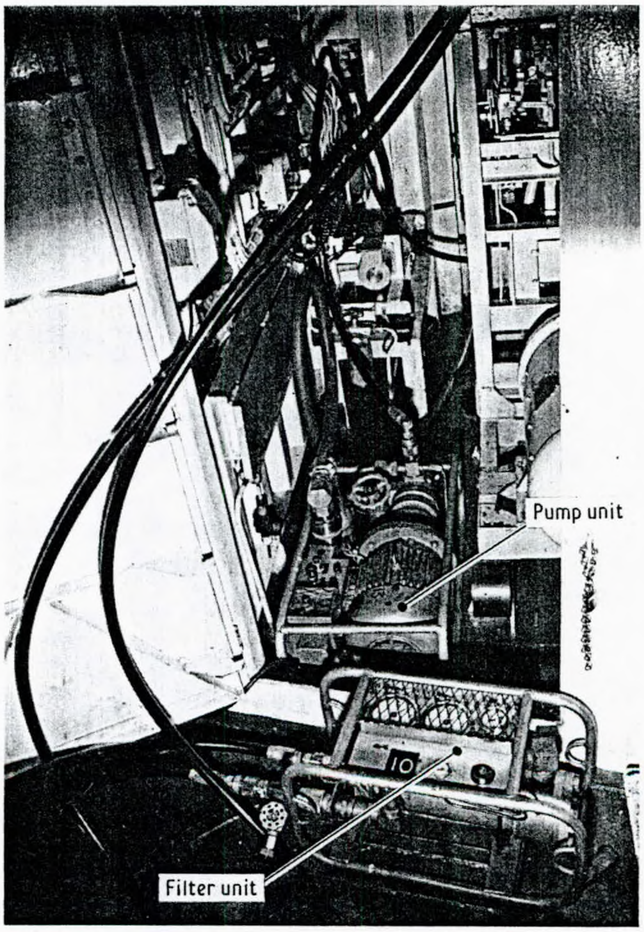

FIG. 8: A 72 l/min Partikon (Thermal Control Co. Ltd) split flushing rig in use in the gun bay of a frigate. The rig consists of separate pump and filter units, making it easier to transport and operate in confined spaces where larger integral rigs are unmanageable

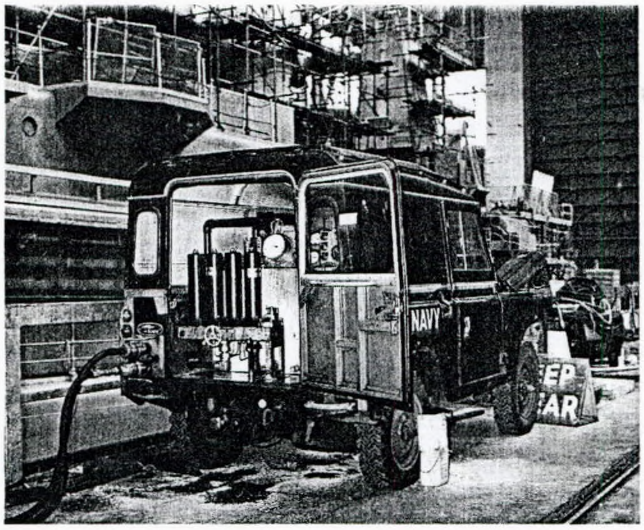

FIG. 9: A 270 l/min Landrover-mounted integral flushing rig in use on a frigate hydraulic ring main

First, as mentioned earlier, the velocity of the flushing oil must be kept sufficiently high to maintain turbulent flow through the pipes. To do this the oil is kept warm, to reduce its viscosity, by keeping the pipe runs between the flushing rig and the system to be flushed as short as possible. This is achieved by using a rig of 'split' design where the component parts are separate compact pump units and filter modules connected by flexible hoses, enabling them to be taken close to the system being flushed. An example of this type of equipment is illustrated in Fig. 8, where it is being used to flush the hydraulic system in frigate's gun bay.

However, in some ships, such as submarines, the access hatches may be too small or the congestion inside the hull too great to permit the pump unit to be brought on board. In these cases the flushing rig is left on the dockside and the connecting pipes to the ship are contained in lagged service trays to prevent heat loss.

The next stage is to examine the layout of the pipe system, and select individual flushing paths to keep the overall fluid resistance as low as possible to maintain turbulent flow. This means that some of the small-bore runs are very short. Also, since it is difficult to flush dirt particles uphill through vertical legs in the system, the flushing flow path is chosen to avoid them. Where this is not possible, a filter unit is fitted at the bottom of such legs.

The split design of the flushing rig is particularly suitable for this purpose, as more than one filter module can be used, if necessary placed at a position in the circuit where it is most effective.

Also, as it is important to avoid recirculating dirty oil through parts of the system already flushed, flow paths are chosen to flush branch lines into the main supply and return lines. The branch lines are then isolated and the main runs are flushed back towards the reservoir.

The reservoir is the most difficult component to flush effectively as the flow velocity through it is inevitably low. A separate tank module is therefore substituted for it during the flushing process, and the system reservoir is opened for manual cleaning.

Lastly a flushing filter with a high dirt-holding capacity and high collapse properties is selected to minimise the number of filter changes necessary during the flushing operation. Filtering in stages using first coarse and then finer filter elements is not economical and it is better to try and remove the dirt in as few passes as possible. To do this a filter element capable of a filtration efficiency of about 99.6% (B5 = 250: B10 > 3000) is used, enabling the element to be changed easily without compromising the cleanliness of the system.

Large filter elements are more economical than small ones, and manufacturers' literature claims that if the area is quadrupled then the life can be increased by eight times, with the cost being increased by little more than three times. This leads to the cost per flush with a large filter element dropping to 40% of the cost using a small one.[4]

In carrying out the flush of the flow path it is important that all components which have been cleaned separately during repair are by-passed during the preliminary flushing until the pipe system has been cleaned to an acceptable level.

FLUSHING RIGS

Since the size and complexity of hydraulic circuits in the Royal Navy vary from the ring-main system in a destroyer or submarine to small compact power packs for a ship's steering gear or stabilisers, it follows that no one flushing rig will be efficient over the whole range. Some rigs only have to produce sufficient flow energy to overcome the resistance of the system pipework to maintain turbulent flow, but others have to do this at sufficient pressure to enable some of the system actuators to be 'stroked' during the flushing operation. To meet this need a range of flushing rigs, varying from 22 l/min at 24 bar to 900 l/min at 138 bar, have been produced.

As stated above, the most widely used type has been the split rig, which is chosen for its versatility and ability to be transported close to the system to be flushed. It enables a choice of high- or low-pressure pumping unit to be used, it can be connected to filters placed in the most effective position in the circuit using more than one filter if necessary, and it can be coupled directly to the system reservoir or use a separate reservoir of its own. Its main disadvantage is the necessity to have electric cables carrying high current or voltages (110 V, 50 Hz, 3 phase at 40 A, or 415 V, 50 Hz, 3 phase at 21 A), which have to be led from the shore supply breaker to the flushing site. In such circumstances the cable must be armoured or some earth-leakage protection device or safety breaker must be used.

The split rig can only be used if there are suitable electrical power supplies nearby. Unfortunately this is often not the case, particularly in commercial ports or on sites where small units have to be repaired. In circumstances such as these the Royal Navy have had a mobile flushing rig developed. The pumping unit is mounted on a long-wheelbase Landrover with the power take off adapted to accommodate the pump drive. The filter bank is mounted at the rear of the vehicle and the unit controlled through the rear door (Fig. 9). The rig will deliver about 270 l/min at 69 bar.

On all flushing rigs provision is made for taking an oil sample from a self-sealing coupling at the inlet to the filters, and this sample is analysed to determine the cleanliness standard of the system.[3]

CONCLUSION

Hydraulic components are costly and down-time in system operation is expensive, so a little effort in keeping the system clean can save much more than the cost of a single failure.

REFERENCES

1. J. B. Spencer and C. Balmer, 'Effective contamination control in fluid power systems'. Sperry Vickers (1977).
2. D. L. Kitch, 'Hydraulic system cleanliness – design manufacture and operation and maintenance aspects'. *Trans. I. Mar. E. (TM)*, Vol. 86, pp. 156–168 (1974).
3. J. R. Corless, 'Contamination control during the repair of hydraulic machinery'. I. Mech. E. Conference Paper C240/84 (1984).
4. *Filtration News*, Pall Industrial Hydraulics Corporation, No. 2 (1982).