COMPRESSED AIR SYSTEMS

AN UPDATE

BY

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Introduction

Compressed air may not be the most glamorous of naval engineering topics but nevertheless is of some passing interest to the submariner wishing to surface his boat, to the gas turbine MEO starting his engines, and to a WEO for conditioning his radar waveguides. It also has considerable impact on warship upkeep.

This article updates a previous one by (then) Commander J. T. G. Bowen[1] in June 1980 and outlines current developments in compressed air systems as sponsored by Section ME213 of the Sea Systems Controllerate (formerly D161c of Ship Department). It covers improvements to in-service equipments, new equipments due to be introduced into service, lessons from the Falklands campaign, miscellaneous system improvements, and developments in upkeep. If it appears to cover lots of little points then that is the way with compressed air systems.

COMPRESSORS

The heart of any compressed air system is the compressor. Improvements to in-service compressors and introduction of better machines is vital and is a major part of the work of the Section.

Existing HP Compressors

TC Series/R80/4000 Models

Present compressors in the Fleet are mainly the old TC series and the more recent R80/4000 machines of Compair (Reavells) manufacture. These were specially designed for R.N. service and use expensive shock-resistant and sea water corrosion resistant materials. The R80/4000 has particularly low noise and vibration. Only limited development testing was possible before these designs had to be accepted into service and they have been described[1] as 'monument[s] to Mechanical Engineering'. They have a less than wonderful reputation for reliability, with stage valves, relief valves, cooler, plungers, lubrication, drainage, and bursting discs contributing to a MTBF of 50 to 200 hours running and excessive repair times.

Readers at sea will be relieved to learn that improvements are in the pipeline for 1984. Stage valves (FIG. 1) will be available that use bowed washer springs instead of helical coil springs, leading to improved fatigue life and reduced likelihood of valves breaking up and causing consequential damage to the compressor. Valve life of

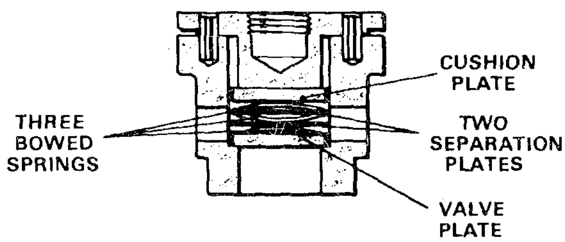

FIG. 1—TC/R80 IMPROVED 4TH STAGE VALVE USING BOWED SPRINGS

1000s of hours should be attained regularly and the requirement for attention will be indicated by gradual deterioration in performance rather than the sudden and often very damaging clatter that is the bane of the present compressor maintainer. Relief valves will be superseded by better proprietary items, successfully used on the new VHP36 compressor, and made of stainless steel with a ball valve lid.

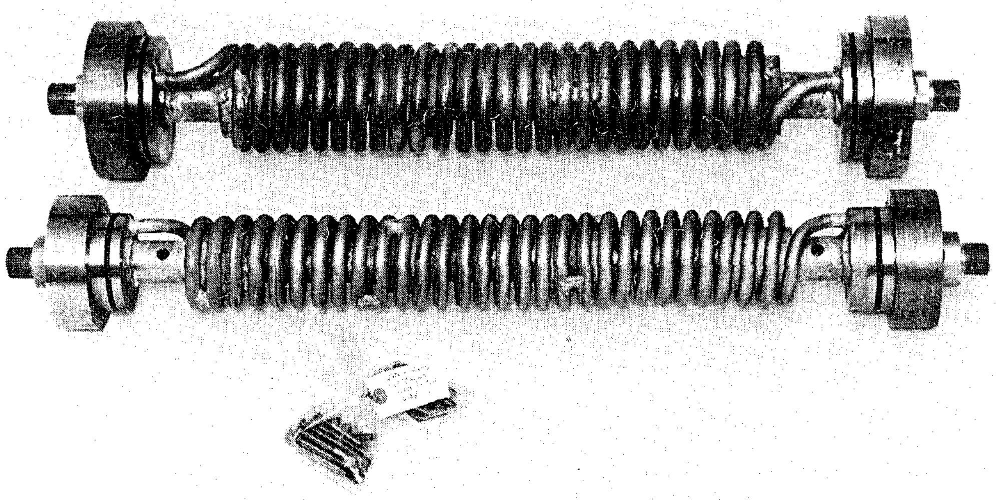

FIG. 2—TC/R80 SERIES IMPROVED 3RD AND 4TH STAGE COOLERS

Improved high pressure coolers (FIG. 2) are under trial in H.M.S. *Birmingham*, using an all-brazed coiled design that minimizes the possibility of air leakage and improves heat transfer. A drawback may be difficulty in cleaning the air side but initial results are most encouraging. Plungers of freer fit and supplied with conventional piston rings in a matched liner will reduce the incidence of plunger seizure on first running a refurbished machine, the cause of much bitter frustration as the last weekend of an AMP approaches. Changing the third and fourth stage oil lubrication feeds from direct into the cylinder to the air inlet passage reduces the pressure required to be developed by the oil pump and reduces the temperatures experienced by the small bore delivery pipe. Modification parts will be made available and significant reductions in blockage problems and more consistent lubrication are expected.

Good drainage of these compressors is vital and attention to this aspect pays dividends. The material of the diaphragms fitted in automatic drain valves has been improved and dramatic reductions in spares usage have been noted since. Some compressors still have drain valves operating in series but modification kits are available (DCI RN 541/83) to convert them to the superior parallel operation. The present design of bursting disc is the cause of frequent inadvertent washing down of deckplates, the copper material failing through a combination of corrosion and fatigue. The use of Melinex-lined and PTFE-coated bursting discs appears more successful and they may be made available after testing is complete.

Dunlop IC754

Mine Counter-Measure Vessels are fitted with the Dunlop IC754 HP air charging compressor, a lightweight machine selected for its low magnetic signature but really designed for intermittent light duty rather than the arduous duty of the vessel's main compressor. It is hardly surprising that failure rates are high. The use of synthetic compressor oil Anderol 500 (now OX-95) and various modifications have alleviated the situation but the real answer will be to replace the machine with a more rugged, continuously rated one.

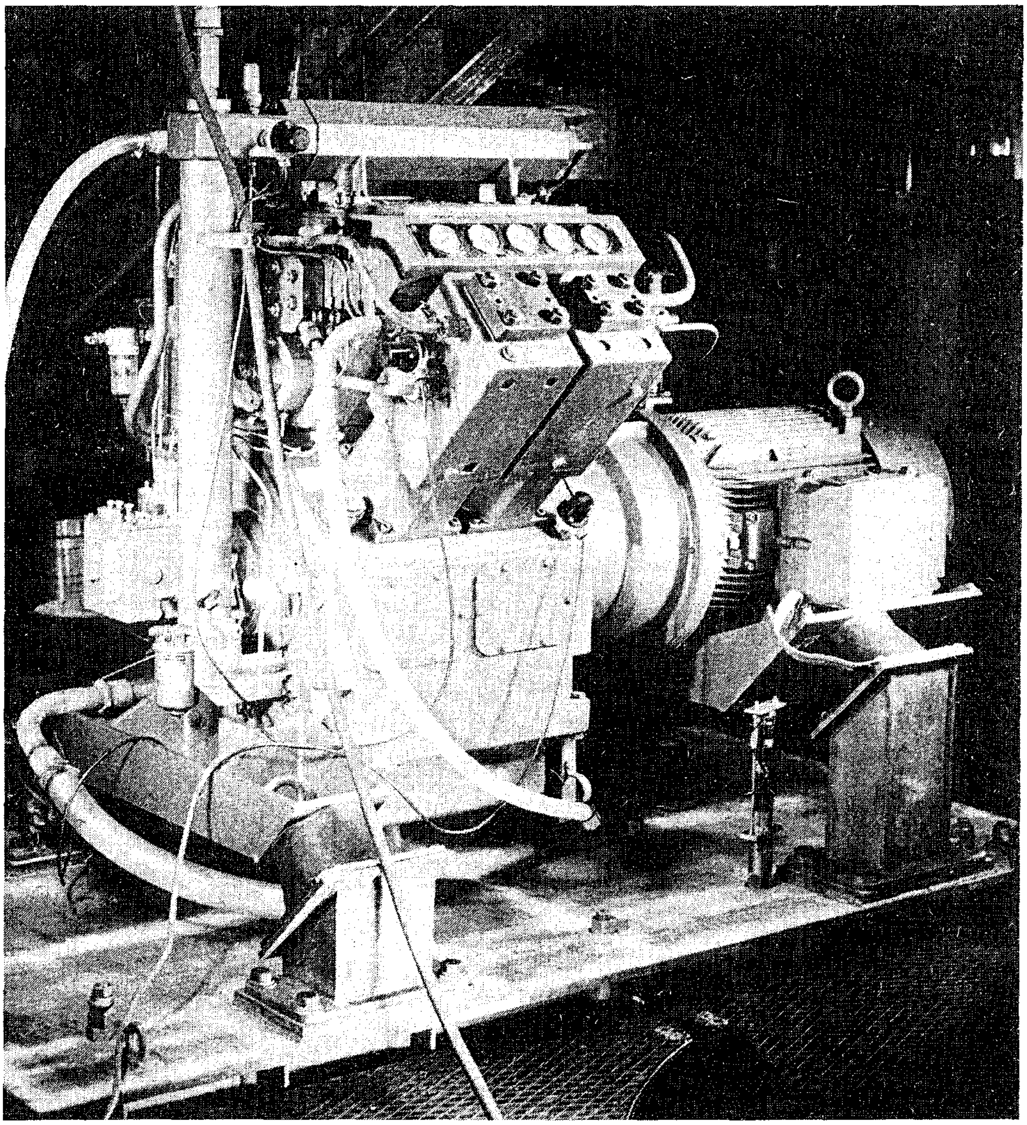

FIG. 3—COMPAIR NAVALIZED VHP36 HP AIR COMPRESSOR

New HP Compressors

The Type 2400, the first Type 23 frigate, and probably the Trident SSBN will use the Compair VHP36 HP air compressor (FIG. 3). This machine is a slightly navalized version of a successful commercial machine and has that rare combination of being both cheaper and more reliable than earlier naval compressors. Instead of the hundreds of running hours spent in development of the early TC and R80 machines, the R.N. will benefit from hundreds of thousands of hours of commercial running experience and 8000 hours development running at NAMD Haslar.

The compressor is manufactured mainly from SG (spheroidal graphite) Iron castings and has a 90° V-4 cylinder arrangement. When mounted on its special rubber mounts the machine has been proved to meet shock and vibration targets, and costs a fraction of previous special naval compressors. A comparison of the VHP 36 cast crankshaft in FIG. 4 with the older R80 crankshaft in FIG. 5 illustrates how costs have been kept down.

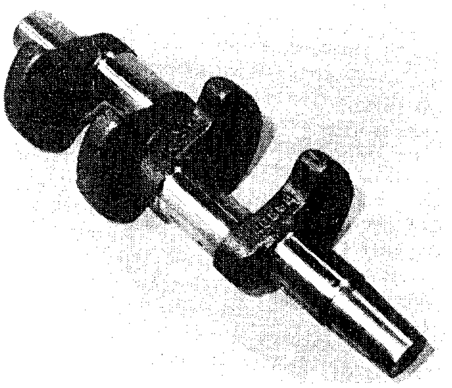

FIG. 4—VHP36 CRANKSHAFT

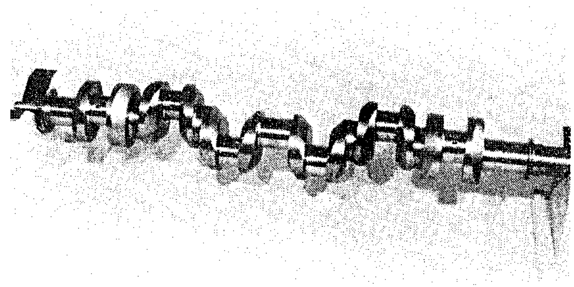

FIG. 5—R80/4000 CRANKSHAFT

The concentric valve arrangement[1,p.295] has proved to be very reliable in commercial service and on trial at NAMD Haslar. No valve has broken up during trials and the limitation appears to be carboning and gumming when standard naval oils OMD-113, OM-100 or OEP-69 are used, requiring some cleaning after 500 hours in service. The use of synthetic compressor oil, OX-95, has been shown to permit valves to last for several thousand hours' operation before attention is required, but whether the logistic and storage problems of yet another oil is worth the reduced valve maintenance has still to be decided.

A strong competitor for HP compressors in the future Fleet is the Hamworthy TH series of machines, an example of which is on trial at NAMD Haslar (FIG. 6). However it is some years astern of the Compair VHP36 both in terms of development and numbers sold commercially. The unit is similar to the VHP36 in that it is of SG Iron construction and employs concentric valves, but the four stages are arranged in a horizontal flat four configuration. An ingenious yoke links the opposing pistons (FIG. 7), with advantages in piston alignment and lubrication so that injection of oil into the high pressure stages is not required. This eliminates some of the cost and complication of previous styles of compressor. As with the VHP36, excellent valve life and ease of maintenance is being demonstrated on trial.

For MCMVs the William and James 'Triquad' (FIG. 8) is being introduced into service in 1984 to replace the Dunlop machine. The name reflects the combination of stages and cylinders that is possible to match output and pressure to requirements. Again the machine is a slightly navalized version of a successful commercial machine and was selected for having a reasonably low basic magnetic signature. Extensive shore and sea trials have demonstrated the machine's impressive reliability.

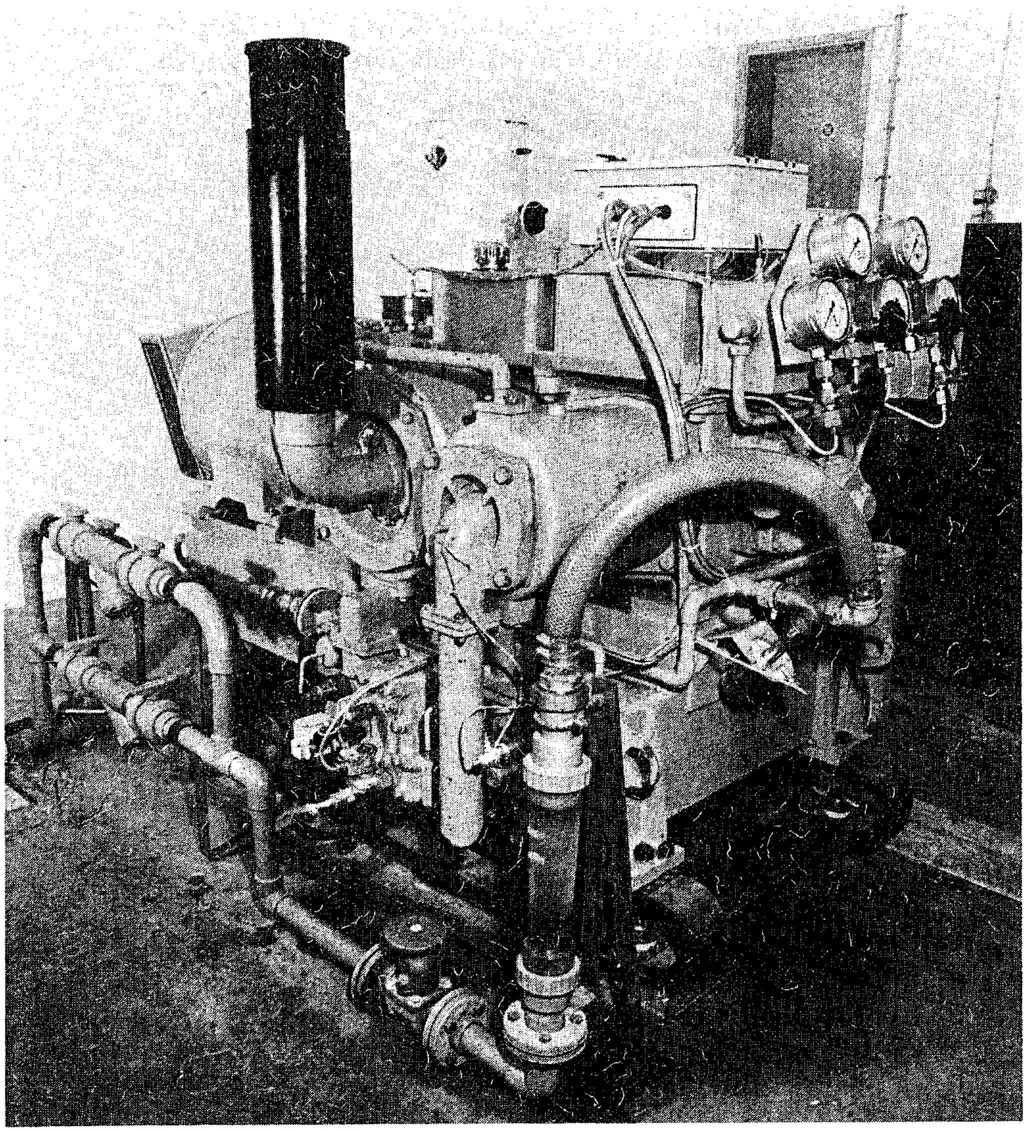

Fig. 6—Hamworthy 4TH HP air compressor

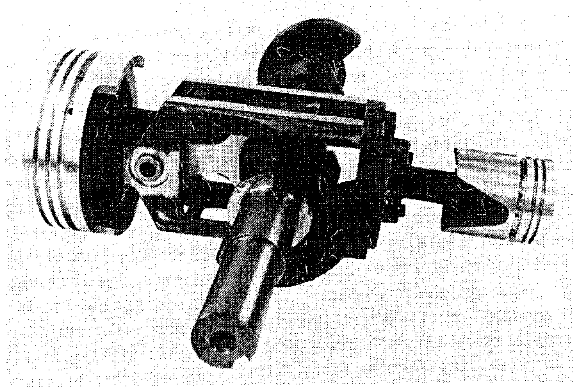

Fig. 7—Hamworthy horizontally opposed pistons and yoke

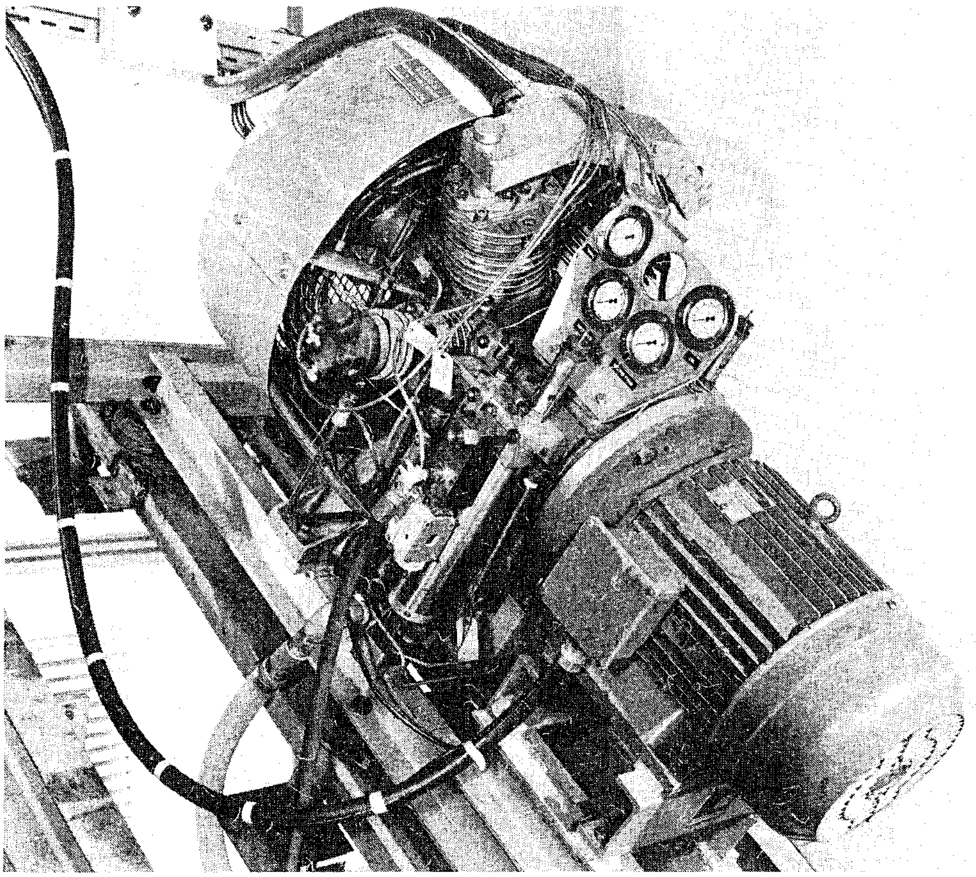

FIG. 8—WILLIAMS & JAMES 'TRIQUAD' MINIMUM MAGNETIC HP AIR COMPRESSOR (ON 40° HEELING TRIAL)

LP Compressors

The William and James Model 262 is the standard LP air compressor at sea at the moment. Other versions of this machine are used for Agouti special service air supplies and in old classes of ships. It is a two-stage oil-free machine built from expensive fabrications and bronzes and specially designed for R.N. use in 'monumental' style to meet stringent air quality, shock, and corrosion specifications.

The complex cylinder head and oil-free piston assemblies have not proved as reliable as hoped; repairs are lengthy and require considerable attention to detail for success. It has been difficult to determine the underlying cause of the high incidence of piston failures as many modes are possible and usually the piston is extensively damaged, disguising the cause in the effects. However it is believed many failures are associated with the steel springs backing the carbon segmental piston seals machining and fretting the aluminium piston, leading to slackening of the piston assembly over some 1 to 2000 hours running and then final failure. Well chamfered aluminium spring rings, soon to be introduced, will reduce this effect but the real cure may be a completely new style of piston perhaps taking advantage of modern materials such as PTFE. Improved cooling of the machine, especially when running unloaded, has been demonstrated in trials following a clever and simple suggestion from H.M.S. *Battleaxe*, and again a modification will be forthcoming.

Much of the complexity and inherent unreliability of this style of compressor stems from the requirements to produce oil-free air. However the advent of suitable oil-removing filters now permits the use of 'oily' compressors for the task and opens up the possibility of using a machine selected from the most competitive sector in the compressor industry, that of providing 7 to 8 bar air, with obvious procurement and reliability advantages for the Fleet.

The ultimate incentive arrived with the Falklands campaign and the urgent necessity to fit LP air compressors in Type 42 destroyers to relieve some of the load from the unreliable and difficult-to-maintain HP air compressors. The machine selected was the commercial Hydrovane 42 PUAS rotary vane, oil-lubricated compressor similar to smaller machines fitted on auxiliary boilers but packaged with a GEC 'Alpak' electric motor, an aftercooler to reduce moisture, and coalescer oil-removing filters to achieve the necessary air quality (FIG. 9). The first unit was made up and installed in four days and the literally 'back of an envelope' working drawing used at that time is preserved in the file!

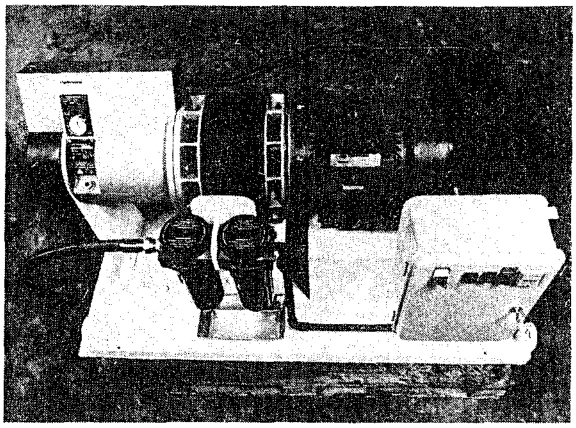

FIG. 9—HYDROVANE/ISIS 42 PUAS LP AIR COMPRESSOR

Provided these compressors are given regular oil changes and the machine's oil cooler (concentric with the motor coupling) is kept clean on the air side, 30 000 running hours can be expected before any sort of overhaul is necessary. The unit has limited shock resistance but this is overcome by using X mounts.

Proper As & As have been approved now and all Type 42 destroyers, Type 21 frigates, H.M.S. *Bristol*, and some LEANDERS will have Hydrovane LP compressors fitted by the end of 1984. To date some 80 000 running hours have been accumulated across the Fleet with no major defects reported and savings of 33% to 75% of HP compressor running hours achieved. Indeed the cost of a Hydrovane unit is usually recovered in the first year of operation from the spares saved on HP air compressors.

As with any rush measure there has been a delay in providing full spares and documentation support but this will be available soon. Meanwhile the machine's good reliability and the supply of maintenance spares direct from the manufacturer are keeping things going for the present.

The advisability of using simpler more reliable LP compressors to supplement HP compressors applies to submarines also. Development trials are in progress to prepare a 'Fluidaire' rotary vane oil-lubricated compressor. The unit selected is identical in principle of operation and general configuration to Hydrovane units but is better matched to the pressure and output required.

Submarine LP Blower/Special Service Air Compressors

Some large size submarines will require large LP blowing compressors for surfacing, discharging at a pressure that is beyond the stretch of existing blowers. Similarly the Type 23 frigate and the new Replenishment Auxiliary (AOR) require large compressors for their extensive noise-reducing special service air systems, as gas turbine bleed will not be available.

A promising compressor for these duties is the Nash liquid ring CL machine. Successful trials have been completed at NAMD Haslar for a Type 23 unit and trials of the submarine unit are due to commence late in 1984. As expected the simple rugged design provides excellent reliability but the sealing water requirements demand careful design of the installation.

COMPRESSED AIR SYSTEMS

Falklands Experience

The Falklands campaign has taught (and retaught) us many lessons. The following areas are receiving attention in new design and in-service air systems:

(*a*) Whilst machinery space important consumers were generally adequately served with high integrity air supplies, weapon systems and sensors often had primitive and vulnerable supplies dependent on long single spurs. Future surface ship designs will have local compressor and drier sets dedicated to sensors and backed up by 'no break' alternative supplies of air. Lightweight compressors of the Hydrovane type make this possible without adding too much top weight. Some improvements have been possible with existing designs of ship.

(*b*) Pipe systems sometimes were poorly routed and had too few isolating valves so that action damage was unnecessarily disruptive. Vertically disposed air ring mains offer some advantage over the more traditional horizontal ring mains in frigate sized ships and will be used in the Type 23.

(*c*) Compressor availability was less than satisfactory, with 'all HP' ships particularly prone to serious degradation. As already discussed, LP compressors generally will be used in future ships.

(*d*) Breathing apparatus recharging facilities were sometimes insufficient and poorly positioned for use in smoke. Future designs and existing ships are receiving additional facilities.

(*e*) It was found that compressors could so easily ingest smoke and contaminate the whole of the air system, especially breathing apparatus recharging facilities. Alternative suctions will be provided in existing designs and in new designs routine suction will be from immediately behind AFUs. Consideration is being given to linking compressor shut down with ventilation crash stop controls so that compressors will not be left running inadvertently.

(*f*) Whilst LP air system repairs are fairly simple to achieve with worm drive clips ('Jubilee' clips) and plastic hose, first aid repairs to large sections of HP systems were beyond even the most ingenious damage control parties because of the high pressures and lack of suitable equipment. Ships will be provided soon with HP air damage control kits consisting of Keelaring couplings and PTFE-lined stainless steel braided hoses enabling shattered systems to be breached quickly and effectively. No doubt peacetime ingenuity also will find the hoses useful for all sorts of maintenance, repair, and overside services.

(*g*) Interestingly there were few reports of escaping air adding significantly to combustion, but nevertheless improved facilities for dumping air in emergency will be incorporated in new designs. However this is not easy without compromising system integrity and resistance to action damage.

Breakable Couplings

The search for better breakable couplings continues but, despite claims by many manufacturers and extensive Ministry evaluations, the Keelaring coupling still represents the most cost-effective all-round coupling for surface ships. A few types of breakable couplings avoiding the use of elastomeric seals and relying on metal-to-metal sealing, such as the Dylo, are being evaluated and show promise, but the coupling stubs require brazing or welding to pipework and accurate alignment of pipework at build.

Permanent Couplings

There is little doubt that welding offers the best hope for maximum reliability in permanent coupling of pipes and valves in air systems, but development is costly. The Cryofit coupling is out of favour as it is prone to stress corrosion failure and requires a heat shrink plastic sleeve for protection, but the ease with which it can be applied in congested areas and pipe runs means it will be used for some time yet as the alternative to welding.

A new coupling, the Permanswage, combing Cryofit style gripper teeth and seals in a swaged-on sleeve has shown considerable promise and may well be approved shortly as a replacement to the Cryofit. It is easy to fit, requiring only a portable hydraulic swaging tool and is not prone to stress corrosion cracking.

Filters

A primary cause of contamination in air systems and of failure to meet air quality standards for diving gear and breathing apparatus charging, is the oil carried over from HP air compressors. Evaluation trials are underway to select an oil-removing coalescer and activated carbon filter set that can be inserted at compressor discharge. It is hoped such units can be made available to the Fleet late in 1984.

Driers

All compressors will produce air saturated with moisture at discharge pressure and temperature. Any subsequent cooling or expansion of the air will cause moisture to condense and in extreme cases to freeze. For this reason it is important to ensure the compressor final cooler is as effective as possible. The moisture causes corrosion in steel fittings, particularly HP air reservoirs, and erosion in valves. Freezing can cause valves to fail completely. The additional cost, weight, space and maintenance of driers is now accepted as well worthwhile to avoid system moisture problems and all HP and LP air system in future major warships will have driers of the twin dessicant tower reactivating type.

One disadvantage of dry air is that CO and CO_2 removal for breathing air purposes is more difficult. The traditional soda lime column requires some moisture present for the necessary chemical reaction but work is in hand to evaluate and select a suitable molecular sieve clean-up pack for breathing air in future ships.

Hoses

HP air hoses of the traditional rubber/steel reinforced type, especially those used at compressor discharge and for overside services, have a high failure rate and limited shelf life. The slightly porous nature of the inner sealing tube causes air to percolate out under the outer protective rubber sleeve and, despite pricking, causes bubbles and bulging. This is more alarming than actually dangerous but nevertheless total failures have occurred and the situation is unsatisfactory and expensive.

The introduction of PTFE-lined, stainless steel braided hoses with unlimited shelf life has solved the problem and most ships should be fitted with these hoses now.

Ships' Whistles

A noisy sideline is sponsorship of ships' sound signal appliances (the technical term for sirens, fog-horns, etc.). Unfortunately many ships of the Fleet require to be equipped with uprated whistles to meet the latest IMO standards in much the same way as navigation lights were uprated some years ago. The price to be paid is that bridge personnel are likely to be deafened by the new whistles as well as blinded by the new lights.

Submarine whistles require improvement and a new design is at sea in H.M.S. *Splendid* for evaluation. Unfortunately the potential of the new design cannot be realized to the full as the whistle must be buried in the fin and not allowed to produce flow noise when submerged. Consideration was given to providing a portable whistle but this was eventually discounted because of stowage problems and because it would be yet another underarm load for the bridge party.

Surface Ship Special Service Air Systems

The trend in special service air systems is to provide much greater quantities of air via extensive and sophisticated systems from dedicated compressors, as gas turbine bleed may not be available in some ships. Whether this trend will continue much more depends on performance and cost comparisons with rival schemes to reduce self noise and radiated noise, such as acoustic tiles. Discharging the vast quantity of air out into the sea is easy in comparison with preventing it being drawn back into sea water cooling systems!

HP AIR STORAGE RESERVOIRS

Generally two sizes of storage reservoir are fitted in HP air systems, of 258 litres (9.1 cu. ft.) and 106 litres (3.75 cu. ft.) internal volume. Both versions are of seamless, solid drawn steel construction and have evolved steadily from a design dating back some 60 years. Better materials and quality assurance techniques have permitted the working pressure to increase from 2000 lbf/in^2 in the 1920s to 276 bar (4000 lbf/in^2) in 1960. Similarly the periodic recertification interval increased steadily to the 6 years presently demanded by BR3000, but the actual recertification test procedure involving removal from the warship and testing in a dockyard facility remains virtually unchanged from the earliest days. As a complication identical cylinders fitted ashore were, until recently, subject to the Factories Acts and required recertification every 26 months.

As everyone involved in the operation and upkeep of warships will testify, periodic recertification (or proof testing) of HP air crylinders is of major significance in upkeep programmes. The business of removing up to 100 cylinders every 6 years, for periodic recertification is obviously most disruptive and very expensive. The problem is likely to become worse as successive defence policies demand fewer and shorter periods for upkeep. Generally too there is well found suspicion that recertification techniques are unnecessarily old-fashioned and recertification periodicities unnecessarily cautious.

Accordingly the problem is being attacked on three fronts:

(*a*) Development of safe *in situ* recertification techniques and equipment involving less disruption in the ship.

(*b*) Research and collation of evidence to permit safe extension of recertification interval.

(*c*) Changes in cylinder design to facilitate *in situ* testing and extension of test interval.

In Situ Recertification Techniques and Equipment

The present recertification procedure conducted in dockyard test shops every 6 years is as follows:

(*a*) Remove cylinder from ship, unsweating end fitting if necessary.

(*b*) Clean exterior by shot-blasting or similar process.

(*c*) Clean interior by 'rumbling', a process involving rotating the cylinder loosely packed with steel boiler punchings.

(*d*) Conduct careful visual examination of internal and external surface for cracks, excessive corrosion, and neck thread damage.

(*e*) Water pressure test to $1 \cdot 5 \times$ working pressure (414 bar) measuring any permanent volumetric expansion of the cylinder by use of a water jacket.

(*f*) Represerve ready for issue.

There is much that is unsatisfactory in this procedure. The internal cleaning process, 'rumbling', tends to peen over any corrosion pits or cracks but it can be argued that it improves the fatigue resistance of the surface. Generally cleaning by shot-blasting or water jet is to be preferred. The visual inspection is carried out using the simplest of equipment, a lamp and the eyes of an experienced inspector. The water pressure permanent expansion test is very insensitive. Calculations and tests reveal that massive thinning of the cylinder over vast areas would be necessary before even slight bulging could be produced and detected. Indeed no cylinder has ever been rejected on this criteria in the history of testing cylinders in dockyards.

Despite these unsatisfactory aspects it could be argued the present test has achieved its purpose of preventing any cylinder failing in service. However, an equally satisfactory if not superior procedure is thought to be possible *in situ*.

Schemes ranging from the most Heath Robinson to sophisticated electronic equipment have been tried but most of them foundered because of the difficulty in gaining suitable access to the cylinder.

The scheme presently favoured uses acoustic monitoring equipment to detect stress wave emissions from any subcritical crack growth during *in situ* pressure testing. This is a very elegant means of performing the test and trials conducted ashore and in H.M.S. *Bristol* are promising. However the method requires a fairly clean cylinder, reasonable access, and absence of noise interference caused by flow in adjacent pipe systems. So far the high pressure water jet cleaning equipment employed as a preliminary to the stress wave test has defied attempts to adapt it to work in cylinders mounted in any position other than vertical, as is the case with so many submarine cylinders. Work continues in this area as this general technique will provide probably the best long-term answer.

Currently in favour for the short term is the simpler approach of conducting a careful *in situ* visual examination, using suitable equipment such as endoscopes and with defined rejection criteria, and finishing off with an *in situ* water pressure test involving minimal hazard to operators and adjacent equipment. The difficulty lies in ensuring adequate standards of internal cleanliness to permit inspection to take place. Investigation shows that many cylinders in normal service are clean enough and water/detergent flushes can be helpful for modest contamination, but it will have to be accepted that more severe contamination or rusting will necessitate removal of the cylinder.

This interim procedure is likely to be approved in 1984 and will provide worthwhile reductions in upkeep effort for many ships. It is emphasized there is no completely satisfactory solution for existing designs of ships and submarines as testing in place was not envisaged in their design and as a result cylinders are often inaccessible or have to be removed anyway for structural survey or representation. Future classes will incorporate *in situ* testing as part of the design requirement wherever possible.

Extension of Recertification Periodicity

The evidence shows that no cylinder has ever failed in service, no cylinder has failed the shop pressure test, and the very small proportion that have been rejected at inspection were generally over 20 years old and suffered either from neck thread wear or corrosion as a result of the sweating/unsweating process or else had internal corrosion caused by obvious abuse such as lack of drainage or internal non-ferrous drain pipes in contact. No cracks have ever been detected. Cylinders from conventional submarines appear to suffer the worst external deterioration, probably as a combination of age, the severe environment of the mounting position in ballast tanks, and the less satisfactory external paint schemes applied early in the life of the submarines.

To support the statistical case a series of trials and investigations has been conducted at ARE Holton Heath and elsewhere into the fatigue, corrosion, and crack propagation properties of the cylinders. Pneumatic burst tests were predictably and impressively devastating (FIG. 10) but hydraulic burst tests were found also to demand respect. Fatigue and corrosion rate trials (FIG. 11) were of a more routine and long-term nature. By relating

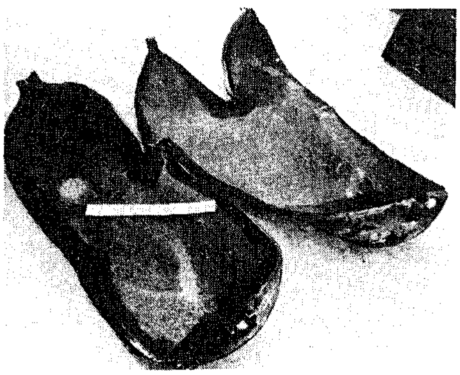

FIG. 10—206 LITRE HP AIR CYLINDER AFTER PNEUMATIC BURST TEST

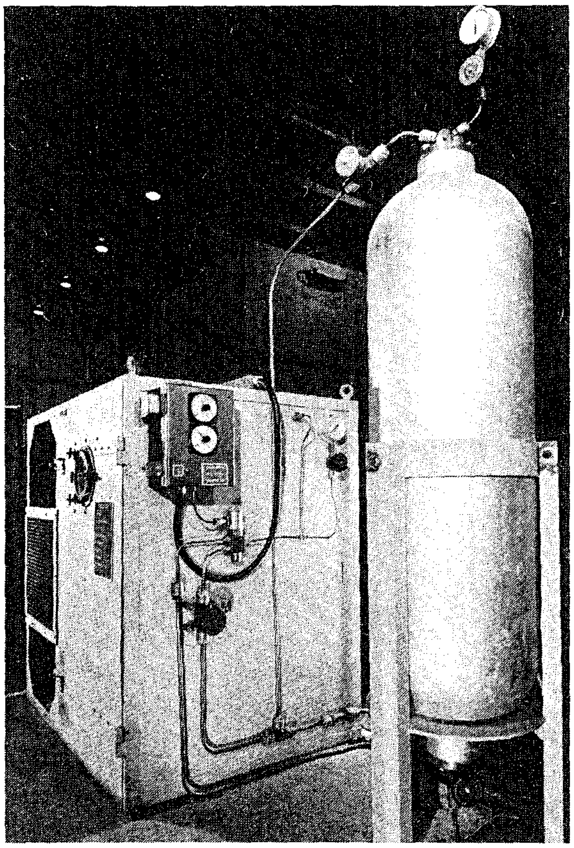

FIG. 11—NAMD HASLAR HP AIR CYLINDER PRESSURE CYCLING TEST RIG

the properties determined in these tests to the environment and operating conditions of the cylinders in service it has been possible to predict safe periods between recertification. An essential part of this was the determination of numbers and depth of pressure cycles experienced by cylinders in service. The co-operation of ships' staff in compiling the necessary data during 1983 is acknowledged.

From all this data it has been shown that after a proof test, growth of cracks from just subcritical to critical proportions is most unlikely, even in a corrosive environment, in the life of surface ships and nuclear submarines. The same study demonstrated that conventional submarines, because of the greater extent of pressure cycling in service, run a slightly higher risk of fatigue cracking, and any extensions in recertification periodicity could not be so dramatic.

Accordingly, regulations are being amended to permit:

(*a*) A much extended periodicity between full recertification for nuclear submarines and surface ships.

(*b*) Some extension of periodicity for conventional submarines.

(*c*) Introduction of *in situ* inspections midway between full recertification.

(*d*) Full certification *in situ* where possible.

Currently full recertification at 20 years and inspections at least every 10 years is proposed for nuclear submarines and surface ships, and a 14 year/7 year cycle for conventional submarines.

Cylinders Fitted Ashore

A certificate has been obtained from the Health and Safety Executive exempting standard naval HP air storage reservoirs fitted ashore from the requirements of the Factories Acts (i.e. recertification every 26 months) but bringing them under the Health and Safety at Work Act and the present 6 year test cycle demanded by BR3000. There is no intention at present to extend the recertification periodicity beyond 6 years for these cylinders.

Changes in Cylinder Design

Resistance to Internal Corrosion

Many types of internal coatings have been tried on a test rig subjecting reservoirs to pressure cycling and extremes of likely environmental conditions. Most coatings, including epoxy resins, plastic films, paints, etc., failed in months rather than providing 25 years protection. Difficulty in adequately preparing the internal surface of the cylinder or detachment due to the strain cycling were the general causes of failure. However in the end simple metal spraying with zinc and aluminium proved excellent and there is sufficient confidence now to approve the scheme for all cylinders delivered during and after 1984.

Access

Wide neck cylinders with 100 mm bores have been standard in new construction for some years now[1]. The design permits much easier access for *in situ* cleaning and inspection and for the application of internal coatings. However the present submarine plug/'O'-seal end fitting is not ideal, as metal spraying of the throat is not possible and corrosion can prevent the plug from resealing once disturbed. The Wills ring seal in surface ships is having some teething problems associated with torquing down the studs. Work continues in order to develop a satisfactory end fitting that will seal for 25 years immersed in sea water and subjected to either internal or external pressure, and yet that can be disconnected and reconnected in a foolproof manner in the working conditions found in the bottom of a ballast tank.

Curved HP Air Reservoirs

The Trident SSBN requires vast quantities of stored air and gas and, despite the large size of the submarine, space is at just as much a premium as ever. For this reason curved reservoirs will be fitted conforming to the curvature of the hull and tucked in between frames. Basically these will be longer (5 m) versions of standard 258 litre cylinders and bent in much the same way as large steam pipes for aircraft carriers. It is hoped that metal spraying of internal surfaces will be possible despite the size of cylinder.

Summary

It is hoped this article has illustrated useful improvements to in-service equipment and better systems for future warships. The revised recertification procedures for HP air cylinders will be a significant reduction in the upkeep effort for all warships.

Reference

1. Bowen, J. T. G.: Hull systems design—atmosphere control and compressed air systems; *Journal of Naval Engineering*, vol. 25 no. 3, June 1980, pp. 285-300.