THE MECHANICALLY SUPERCHARGED VALENTA DIESEL ENGINE

BY

COMMANDER M. P. N. SESSIONS, M.A., C.ENG., M.I.MECH.E., R.N.,
LIEUTENANT-COMMANDER C. H. LEONARD, M.SC., M.I.MECH.E., R.N.
(*Sea Systems Controllerate*)
LIEUTENANT-COMMANDER C. R. ENGLISH, M.SC., M.I.MECH.E., R.N.,
(*H.M.S. Nottingham*)

Introduction

The Type 2400 UPHOLDER Class submarine is to be powered by two 16 cylinder mechanically supercharged Paxman Valenta diesel engines[1]. The first two production engines were delivered to the shipbuilder after 7,000 hours of development test running had been achieved in an endeavour to ensure that this particular engine has a trouble-free introduction to service. This programme has been the most ambitious diesel engine development for submarines sponsored by MOD(PE) since the development of the ASR1 in the early 1950s.

Historical Background

The development of the Paxman Valenta engines commencing in 1960 has been described by M. F. Clover[2]. In the early 1970s studies were undertaken to find the successor prime mover for conventional submarines to replace the ASR1, used in the PORPOISE and OBERON Classes, which some die-hards wanted to retain. Paxman Diesels Ltd. carried out a study on mechanically supercharging an 8 cylinder Valenta. At the same time they undertook trials to determine the effects of intake depression and back pressure on a turbo-charged Valenta as one or two foreign navies used turbo-charged engines for small inshore submarines. Advantages of a turbo-charged engine include better and flatter specific fuel consumption, greater commonality with surface fleet engines, and a quieter exhaust. Among the many disadvantages are the inability to develop the specific net power, the greater air mass flow requirements, excessive variation in power output with varying back pressure, rematch needed for surface conditions, and excessive exhaust temperatures. The strict R.N. specification for snorting sent exhaust temperatures rocketing to over 650°C during the trials, without the engine being able to develop the power of a mechanically supercharged engine. TABLE I shows the effects of

TABLE I—*The Effect of Charge Air System on BMEP and s.f.c.*

	BMEP (bar)	*% Max BMEP*	*s.f.c.* (kg/kW hr)
Exhaust turbo—Surface	17	100	0·221
Exhaust turbo—Snort			
theoretical	10	66	0.255
best achieved (trials)	7.6	49	0.28
Mechanically supercharged—snort	17 (gross)		
	13 (net)	76 (net)	0.28
Naturally aspirated	4.9	32	0.285

Note: for a mechanically supercharged engine,
gross output = engine output + blower power
net output = engine output to generator.

alternative air charge systems on Brake Mean Effective Pressure (BMEP) and Specific Fuel Consumption (s.f.c.).

Early debate centred on whether the submarine fit should be four 8 cylinder engines, three 12 cylinder engines, or two 16 cylinder engines. Later the selection was between two 16 cylinder units at 1350 r.p.m. and two 18 cylinder units at 1,200 r.p.m. and, although a novel formula for reliability was used to try to settle that argument—namely reliability α (no. of cylinders + 2) $\times$ (crankshaft speed)^3—the decision was taken to remain with the 16 cylinder engines which were already in use in the INVINCIBLE Class (CVS).

By 1978 the requirement had hardened into a 16 cylinder engine capable of developing 1.5 MW under full snort conditions. It was designated the 16RPA 200 SZ. A study was undertaken by Vickers Shipbuilding and Engineering Ltd. into various engines available. A summary of the contenders is given in TABLE II.

TABLE II—*Some Characteristics of the Competitors*

		Paxman	*Pielstick*	*MTU*	*ASR1 (uprated)*
Power	kW(brake)	1500	1020	1170	1420
Engine speed	r.p.m.	1350	1300	1400	920
BMEP(net)	bar	12·5	9·0	9·6	10·5
Blower power	kW	400	265	186	230
Specific weight	kg/kW	5·9	7·35	7·5	15·3

A detailed description of the engine was given by W. R. Dingle and M. F. Clover[3] and some of its more interesting features are discussed below. FIG. 1 shows a side view of a prototype. The comparative size of this engine and the ASR1, of similar power output, is indicated in FIG. 2.

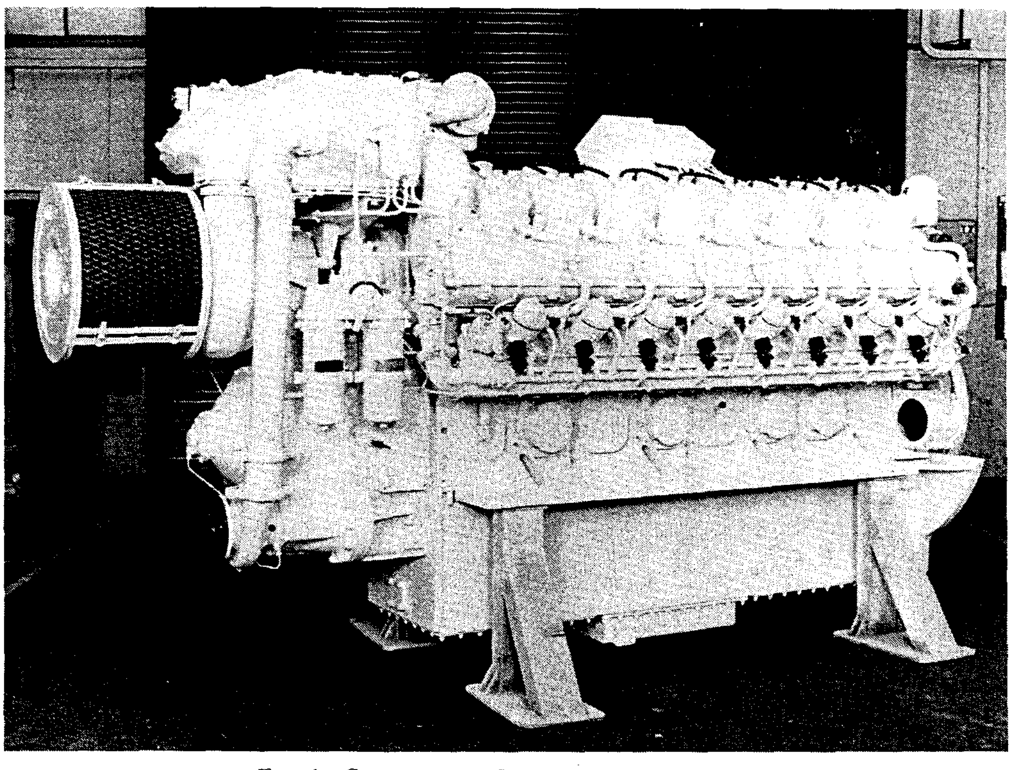

FIG. 1—SIDE VIEW OF VALENTA 16RPA 200 SZ

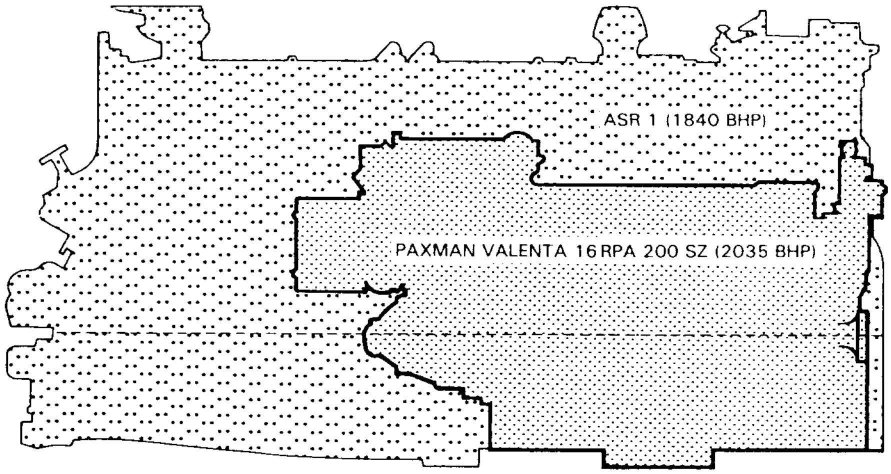

FIG. 2—COMPARISON OF VALENTA 16RPA 200 SZ AND 16 CYLINDER ASR1

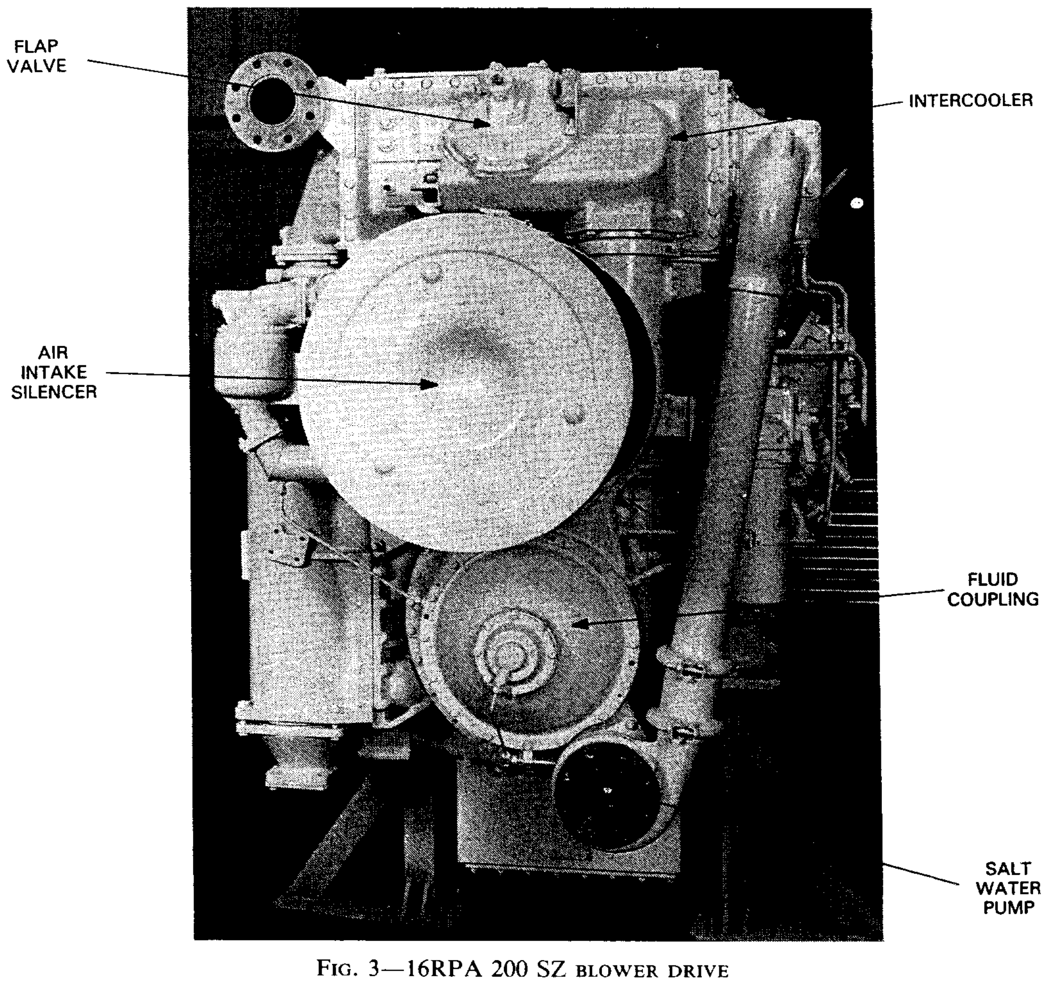

FIG. 3—16RPA 200 SZ BLOWER DRIVE

Special Design Features

The Blower

Most notable of the special design features of the 16RPA 200 SZ is the supercharger or compressor and its mechanical drive mounted at the free end of the engine (FIG. 3). The drive is via a toothed coupling with crowned splines mounted inside the double viscous damper unit (FIG. 4). The output shaft drives a splined disc which in turn drives a fully floating annulus of an epicyclic gear.

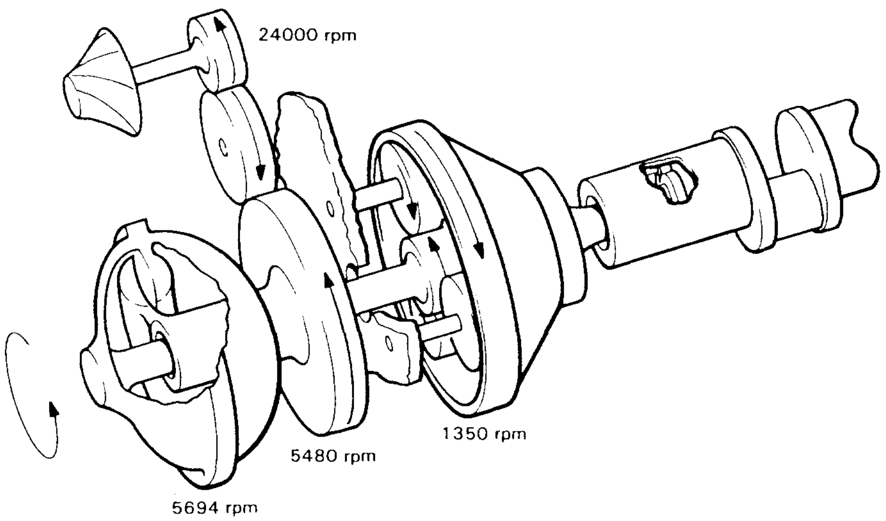

FIG. 4—SUPERCHARGER DRIVE

Star gears of the spur type, with plain bearings run on spindles supported at both ends for rigidity, drive the floating sun gear and the shaft to the fluid coupling input. The 'controlless' coupling reduces inertia effects on run-up and run-down and isolates torsional vibrations both ways, although it is an energy loss.

A single train of spur gears, with one idler, takes the drive from the fluid coupling to the supercharger, increasing the speed to 24,000 r.p.m. The impeller, diffuser, lobed type plain bearings, the delivery casing and the air inlet filter are standard parts from a Napier NA250 turbo-charger.

The drive is lubricated by engine oil supplied from the end of the main rail. Special care is taken to ensure that all gears and splines are well lubricated, especially the sun gear, while at the same time stagnant areas have to be avoided to prevent carbon from being centrifuged out of the oil.

A series of design checks was made which incorporated recommendations from Vickers Gearing, Ricardo, Hygate Gears, Michael Neale & Associates, various bearing manufacturers, and Fluidrive. Many small improvements were made as a result.

Salt Water Pump

Unusually, the salt water pump is driven off an external gear cut on the epicyclic annulus gear because there is nowhere else to site this pump.

Water Removal

Water removal from the cylinders is accomplished ingeniously by fitting air-operated plungers on the cylinder head covers to 'sprag' or open the air inlet valves (FIG. 5). At the same time slow turning capability has been developed for the air starter motor. Prior to every engine start, the crankshaft will be turned over with the air inlet valves spragged to ensure that no water is present in the engine before full starter motor air is applied.

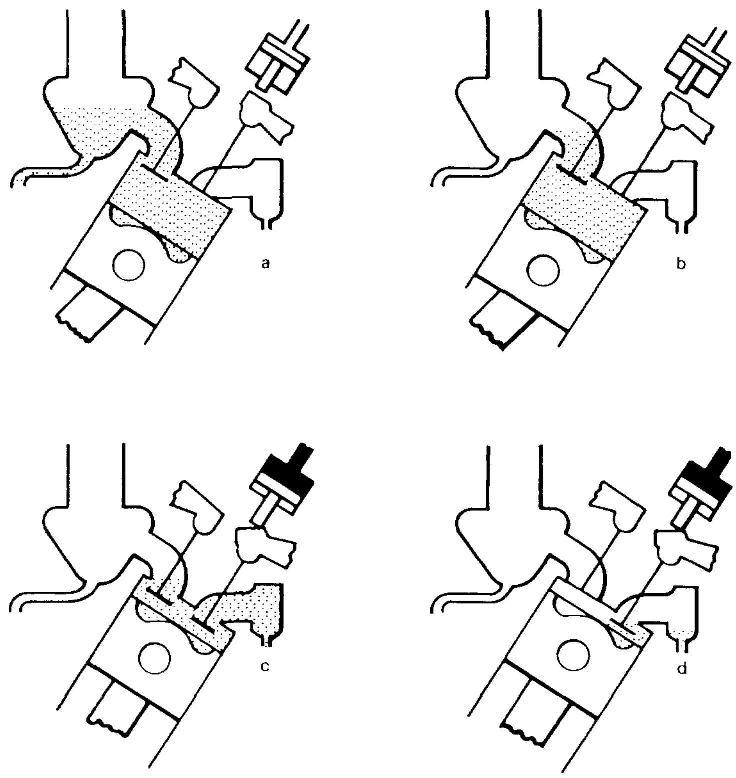

FIG. 5—OPERATION OF INLET VALVE'S SPRAGGING GEAR
(a) ENGINE FLOODED
(b) EXHAUST MANIFOLD DRAINED THROUGH EXHAUST MANIFOLD DRAIN
(c) SPRAGGING GEAR OPERATED, WATER BEING PURGED THROUGH INLET MANIFOLD DRAIN
(d) ENGINE CLEAR OF WATER

Emergency Flap Valves

As a consequence of the *Warspite* fire, an emergency air induction flap valve has been positioned between the supercharger and the intercooler and is released to shut on engine overspeed, and at emergency and normal stops. An air bleed valve has to open each time the flap valve closes, to prevent supercharger surge. The flap valve has to be reset manually.

Camshafts

The cam profiles are different to those in a turbo-charged engine because there is no requirement for exhaust valves to open early to provide energy for the turbo-blower. Overlap between inlet valves opening and exhaust valves closing was originally 15°, following naturally aspirated engine practice, but this was increased to 60° to provide a better trapped air fuel ratio with some purging of the cylinder and better exhaust colour. However, blower power increased as well.

Torsional Vibration Measurements

Because there is no means of fitting an AEL damper tester or similar device on the free end of the crankshaft, external teeth are incorporated into the free end dampers and proximity probes fitted to enable torsional vibrations to be picked up and analysed.

Crankcase Breather Oil Mist

The crankcase breather oil mist is fed through a Myson Brooks electrostatic precipitator before discharging into the compartment. Oil drains into the sump, while discharged gases are sucked into the engine by the flow of combustion air past the engine.

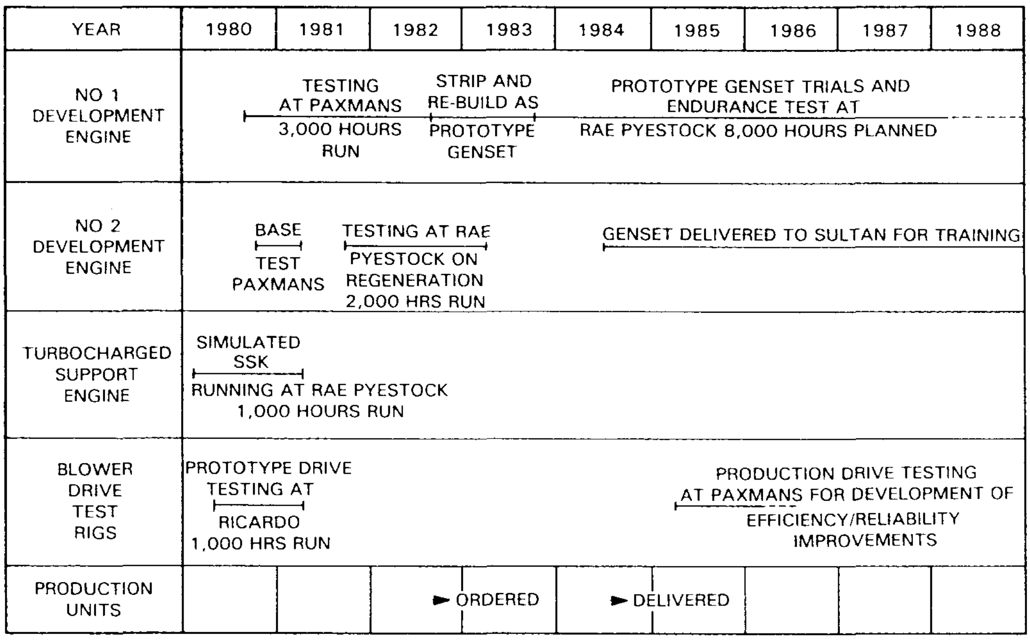

FIG. 6—PAXMAN 16RPA 200 SZ DEVELOPMENT PROGRAMME

The Development

The original plan called for just one development engine in 1978 but due to the short time between engine ordering and the declaration of modification state zero, this was increased to two engines, one of which was to be sited at Pyestock. The programme was further expanded with the use of a supercharger test rig when a 6 cylinder Valenta engine became available. FIG. 6 is a bar chart showing what has been achieved. In order to gain experience, each blower drive contained some alternative parts in areas such as roller bearings, where doubt existed.

The Blower Test Rig

A supercharger was connected to the free end of a straight 6 cylinder Valenta (FIG. 7). This ran for a 1,000 hour test at Ricardo Consulting Engineers, Shoreham-on-the-Sea, in 1980 and 1981. The air discharge from the compressor was throttled. One interesting problem was that the direction of rotation of the engine had to be reversed because in the rig the supercharger was at the wrong end of the engine.

There were no failures of the drive in this 1,000 hour test, so confidence could be placed in the reliability of the supercharger and its drive at an early stage. Close scrutiny revealed a number of problem areas, notably sludging in the fluid coupling, a sticking oil pressure reducing valve, and excessive power loss from the drive partly due to oil churning. Improvements to the design for maintenance were recommended.

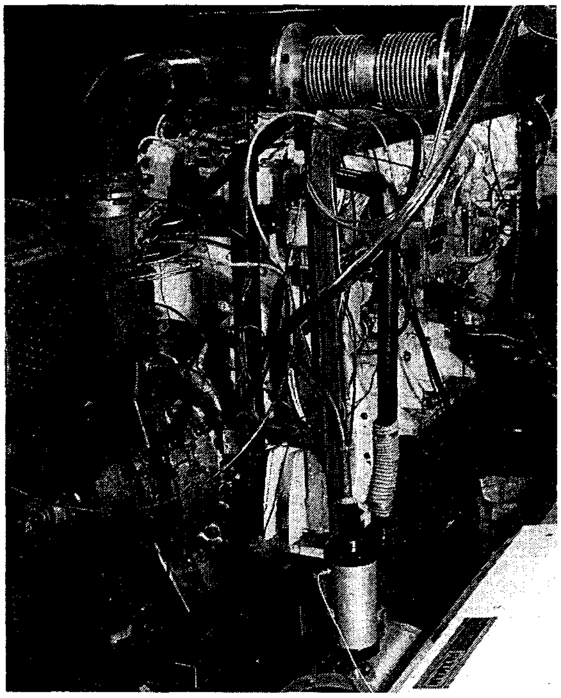

FIG. 7—BLOWER TEST RIG AT RICARDO

First Development Engine

The first development engine started running in August 1980. It was coupled to a brake and was to be used for performance testing followed by endurance testing. Its first run was made exciting when the engine attempted to pump its sump contents out through the breather. A number of ancillary items were found to be inadequate, but the main design was sound except for oil churning which led to high oil temperatures in the drive and damage to the intercooler fins which were not strong enough.

The engine continued endurance running to reach 2000 hours by December 1981. Several different cycles were used, one being the 'shop' cycle which overloaded the blower by some 10–15% over what will be experienced in service, while other cycles included accelerated submarine snorting cycles, involving applying full load immediately after start-up, and running for half an hour followed by a crash stop.

By October 1982 the engine completed its scheduled 3000 hours running without major problems. Opportunity was taken during the later stages of the running period to carry out a limited programme of alternative component evaluation aimed at extending component life and hence the time between engine overhauls.

One problem not solved during this period was the treatment of crankcase breather gas. A prototype arrangement controlling the flow of crankcase gases into the engine was fitted but there was insufficient time to develop the design to overcome some shortcomings. An alternative method using an off-engine device was therefore specified for production engines, as described above.

Much performance work was completed during the 3000 hours running. Initially this work was concentrated on engine performance at its design snort and surface condition. This was then expanded to establish the optimum and limiting engine performance over a wide range of conditions, and involved investigations of combustion, ignition timing, alternative engine speeds, ratings and snort conditions, camshaft design, diffuser build, compression ratio, and air inlet temperature.

The variation of engine power with engine speed over different snort conditions produced particularly interesting results (FIG. 8). The lower specific fuel consumption at the reduced engine speed, resulting from less supercharger power consumption and reduced inlet depression, may prove operationally attractive at sea.

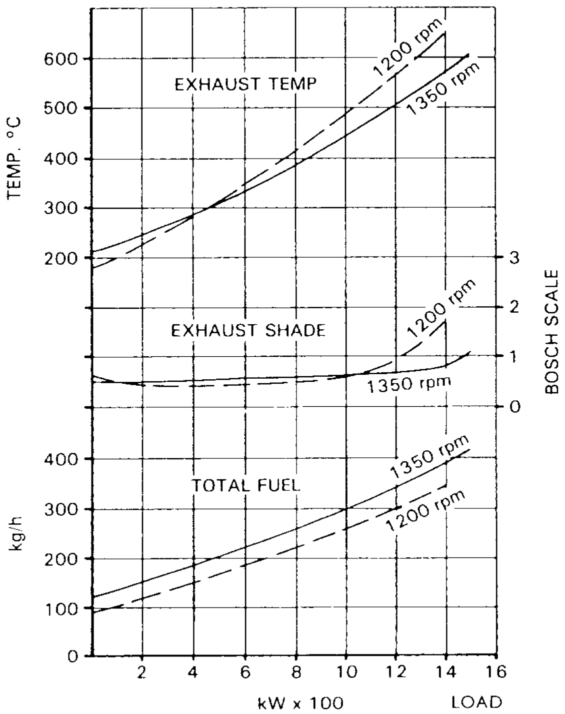

FIG. 8—ENGINE PERFORMANCE AT 1200 AND 1350 R.P.M.
intake 680 millibar abs.
exhaust 1610 millibar abs.

The Second Development Engine

The second development engine was destined to go to RAE after it had undergone 75 hours testing in the production cells at Paxman Diesels. It was fitted with a slave a.c. generator with a rectifier to produce d.c. which was converted to 50 Hz a.c. for feeding into the RAE's grid. This was the first time that energy recovery on a development test engine had been attempted in a MOD establishment.

An auto watchkeeping controller was also fitted to enable the engine to run unattended, allowing it to complete 2000 running hours in just over a year. This running period was specified as endurance running, but some performance work and shipbuilder's trials were undertaken during it.

This engine was replaced by the first development engine, rebuilt to the specified production standard build complete with its silencer, coupled to a prototype generator and mounted on 'vee' configuration mounts. Provision of a prototype submarine hull and back-up valve, a representative inboard exhaust system and a prototype engine control panel allowed comprehensive testing of the entire submarine diesel generator system while continuing the endurance testing of the diesel engine.

The engine control panel not only provides the normal start, stop and surveillance functions, but also controls the spragging gear, the slow turn for purging, the exhaust hull and back-up valves and an air blow system for water clearance of the exhaust mast. In order to determine correct settings and prove the exhaust system, a special water tower was erected to provide 'sea' at the appropriate height above the engine. Snort trials, water clearance from the mast, engine trials, and control timing trials were all successfully completed using this system.

A number of boat-orientated trials are still under way at RAE, Pyestock. These will be followed by the completion of the planned 8000 hours endurance test with the engine running on a typical operational cycle.

Development Problems

Numerous problems were thrown up in this comprehensive programme. Some of the more significant and interesting ones are described below.

Smoke

The mechanically supercharged engine is unique in that its air fuel ratio is worst at full power under full snort conditions. The level of smoke emission was a contractual issue, so significant effort went into trying to reduce smoke. Amongst the methods tried were:

(*a*) A 60° camshaft.
(*b*) Various types of injectors.
(*c*) Larger compressor impeller.
(*d*) Compressor washing, because fouling is so critical.
(*e*) Compression ratio variation.
(*f*) Spill by-pass fuel pumps.

Solution (*f*) was finally chosen as being the most successful.

Fluid Coupling Slip

The fluid coupling first used was made of aluminium. During overspeed tests the fluid coupling failed without an adequate safety margin and the unsuitability of this coupling was confirmed when cracked vanes were observed on the rig test. The solution was to fit a coupling milled from steel similar to that used for the Godfrey drive on the ASR1. Unfortunately when the engine oil is cold the coupling functions satisfactorily for about 10 seconds and then the compressor speed drops dramatically (FIG. 9). Another 5 minutes elapse before the compressor picks up speed again as the oil warms up. However, with repeated starts or under normal engine standby conditions with the sump oil heated to 40°C, this problem does not occur.

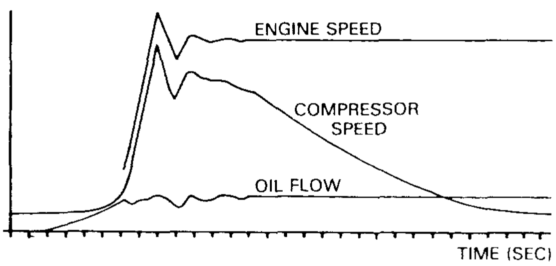

FIG. 9—16RPA 200 SZ COMPRESSOR: CHARACTERISTICS OF STEEL FLUID COUPLING

High Temperature in the Supercharger Drive

The drive proved to be more inefficient than originally designed. The oil and drive casing temperatures were excessive. Many measures had to be taken to reduce the oil temperature including:

(*a*) reducing oil supply to all rolling element bearings;
(*b*) improving drainage from casings, to ensure no gear train or fluid coupling churns oil;
(*c*) incorporating baffles to prevent oil from splashing on to gears.

Pistons

This engine is fitted with oil cushion pistons. Early on there were some polishing or rubbing problems with the pistons, as well as evidence of oil cushion breakdown. This was overcome by a change in piston profile below the top ring and by improving the quality of the piston rings.

In the surface fleet, Valenta engines are no longer fitted with oil cushion pistons, for the sake of commonality with commercial engines. The oil cushion was retained for the Type 2400 engine as it provides added engine protection in the event of water ingress into the cylinder.

Sludging in the Fluid Coupling

The high centrifugal forces experienced in the fluid coupling cause a build up of sludge around the inner surfaces of the coupling. This problem has been alleviated to some extent by the addition of drilled plugs which allow a controlled flow of oil through the coupling.

Impeller Rubbing

Rubbing has occurred between the compressor impeller blades and volute casing on a number of occasions. Design clearances should prevent this rubbing and these have just been increased to try to overcome the problem. The rubbing has not caused any catastrophic failure, nor does it affect engine output.

Future Developments

Trials are in progress on a second blower drive rig at Paxman Diesels Ltd. A blower and blower drive built to production standards is being driven by a Type 22-09 depot spare turbo-charged Valenta 12 engine, adapted to drive the supercharger at its free end. Work on this rig is aimed at improving drive efficiency and reliability. A more efficient compressor impeller is being procured for trials on this rig and at RAE, Pyestock.

Reliability

The engine development project followed the new procedures initiated in MOD(PE) to improve availability, reliability and maintainability (ARM). New ground was broken in terms of specifying diesel engine reliability targets and trying to validate these targets. ARM reviews were held with the Company. FIG. 6 demonstrates some of the activities that went towards improving the engine's reliability.

A key factor for determining the reliability of the Valenta base engine was feedback from British Rail, where 3 000 000 Valenta engine hours had been accumulated in 5 years compared with 1 000 000 hours in 15 years for the Ventura. Intensive reporting was initiated for Valentas in CVS, with data fed back to Paxmans to effect the more minor improvements. This data has shown that the Valenta is almost four times as reliable as the Ventura. The unknown area remains the blower drive which has yet to achieve sufficient running as a production unit to enable its reliability to be quantified. The planned 8 000 hour endurance test should provide the necessary confidence in the drive.

The engine control system reliability has caused some concern. Instrumentation junction boxes have had to be mounted on-engine due to compartment constraints. This has caused numerous spurious signals related to loose and vibrating connections. Mounting arrangements have been improved but not yet proven.

Conclusion

While there are still problems outstanding, the ambitious joint Paxman, RAE, and MOD(PE) development programme will mean that the Type 2400 mechanically supercharged Valenta diesel engine should be an order of magnitude more reliable on first introduction than either the ASR1 in *Porpoise* or the Venturas in nuclear submarines.

Acknowledgements

Acknowledgements are due to Paxman Diesels Ltd. for provision of photographs, data and figures, and to colleagues at Foxhill and RAE, Pyestock for assistance.

Any views that are expressed are those of the authors and do not necessarily represent official MOD(PE) policy.

References

1. Bullard, J. P., *et al.*: The Type 2400 'Upholder' class submarine; *Journal of Naval Engineering*, vol. 28, no. 3, Dec. 1984, pp. 414–423.
2. Clover, M. F.: The Paxman Valenta diesel engines: *Journal of Naval Engineering*, vol. 24, no. 3, Dec. 1978, pp. 235–251.
3. Dingle, W. R., and Clover, M. F.: Paxman Valenta mechanically supercharged diesel engines for submarines; *Royal Institution of Naval Architects Symposium on Naval Submarines, London, 17–20 May 1983*, paper no. 10.