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Air-independent Stirling engine-powered energy supply system for underwater applications

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SYNOPSIS

Underwater operations, offshore as well as military, depend on the supply of large amounts of energy. The ability of the Stirling engine to utilize any heat source of sufficiently high temperature allows it to be combined with high-density storage, resulting in considerably increased endurance under water as compared with conventional systems. Silent, vibrationless operation is another attractive feature, not least in military applications. Heat is generated in an air-independent combustion system using hydrocarbon fuels and pure oxygen. Within a development program for the Royal Swedish Navy, where Kockums is the main contractor responsible for system integration, a number of air-independent Stirling power modules are being manufactured and tested for installation in an operational Swedish submarine. A prototype system has already been successfully run in a submarine test section at Kockums. United Stirling AB is currently involved with Comex of Marseilles to provide two Stirling underwater engines for installation in Saga I, a 500 t manned diver lock-out submarine. Another programme with the Royal Swedish Navy is aimed at the development of an air-independent propulsion system for an untethered autonomous remotely operated vehicle. The energy system will be based on a well proven Stirling engine concept adapted for underwater operation.

INTRODUCTION

Air-independent energy supply systems combined with high density energy storage allow considerably increased endurance when submerged without surface support, which is of vital importance for most military and offshore underwater operations.

The combat efficiency of a military submarine is dependent on its capability to stay submerged and hidden for a long time, and the development of advanced surveillance and detection systems will require a minimum of exposure, e.g. during a snorting/recharging phase, as well as silent, vibrationless propulsion machinery and low infra-red emissions.

Offshore operations for the exploration of oil wells and mineral sources in arctic regions or in deep water require long endurance, air-independent energy supply systems. Commercial submarines or habitats with such systems are used for long-term support of saturation divers or the release and control of robots, allowing work to be performed whatever the weather conditions on the surface.

Autonomous remotely operated underwater vehicles (AROVs), i.e. small unmanned submarines and for military offshore operations, also depend on propulsion systems with high energy density storage, allowing long-range operations under water.

Military AROVs, controlled through signals and/or equipped with artificial intelligence, are being developed for surveillance missions, tactical probe missions or weapon delivery. The ability to stay hidden with virtually no emissions is another important requirement of such vehicles.

The offshore industry is looking for systems that can replace currently used diving techniques, which are expensive and, in many cases, hazardous. For this reason autonomous vehicles for survey applications both in open water and under ice, e.g. the inspection of pipelines or hydrographical investigations, are being developed.

Vehicles in use now, with power supplied through an umbilical or by lead–acid batteries, have restricted operating ranges and need support from surface vessels. The need for air-independent systems possessing increased endurance under water compared with conventional battery systems and the ability to maintain silent operation has motivated the development of advanced concepts such as the Stirling energy system, which is currently under production at United Stirling AB, Malmö (USAB). Air-independent Stirling-engine-based systems, using oxygen and hydrocarbons as reactants, can provide

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considerably increased endurance when submerged combined with vibrationless and silent operation of the vehicle with virtually no emissions.

ORGANIZATIONS

United Stirling AB

United Stirling AB started its Stirling activities as a licensee to NV Philips in 1968 and has since been working on the development and commercial applications of Stirling engine systems in a number of areas. The major part of the company activities are today concentrated on air-independent Stirling engine systems for underwater applications. USAB has recently merged with Kockums Marine AB, and Fig. 1 shows the ownership structure.

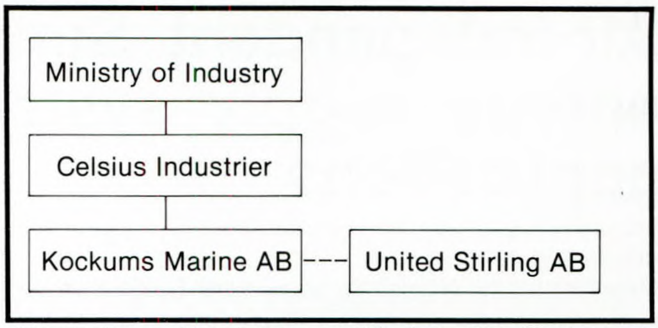

Fig. 1. Ownership structure of Kockums Marine AB and United Stirling AB

The initial development at USAB was based on single-acting displacer engines, with a rhombic drive mechanism. However the general complexity and disadvantages in weight, dimensions and manufacturing costs encouraged USAB to concentrate its attention on the double-acting engine concept. A number of such engines have been built, forming the basis of the USAB main engine programmes, two of them with 4-cylinder double-acting cluster configurations, nominated 4-95 and 4-275, and another based on a single-acting dual-cylinder V-configuration, nominated the V160 engine.

The USAB engines have an overall performance equivalent to those of advanced diesel engines in the medium power range. Total testing time for all USAB engines on dynamometers and in demonstration programmes exceeds 290,000 h, while maximum testing time for an individual engine exceeds 18,000 h. Additionally, separate component testing is being performed on specific components such as seals, piston rings, regenerators and heaters. More than 100,000 h of separate component testing have significantly contributed to improved overall engine reliability.

From 1978 to 1987, as a subcontractor to Mechanical Technology Incorporated (MTI), USAB was working within an automotive Stirling engine (ASE) programme, totally funded by the American Department of Energy. The main objective of this programme was the transfer of Stirling engine technology to the U.S.A., offering the automotive industry an alternative energy converter. As a part of this technology transfer, USAB designed, built and tested new generations of Stirling engines, contributing to the creation of a practical 60 kW passenger car Stirling engine. This engine is also considered to be attractive for a number of stationary applications within the energy conversion area.

During 1983–87 USAB had a technical and commercial co-operative agreement with McDonnell Douglas (MDC) within the solar application area, aiming for the introduction of complete solar Stirling modules for electric power generation. USAB was responsible for the energy conversion unit, including adaptation of the engine to solar heat supply, whilst MDC was responsible for the development of the solar concentrator and system integration. As a result of this co-operation, a new solar-powered electric generating plant, more efficient than any other solar energy system currently in operation, was demonstrated. Early in 1986 USAB granted MDC an exclusive license for a 25 kW solar Stirling engine, based on the 4-95 concept.

The underwater applications of the Stirling engine have been studied and developed since the early 1970s. These are considered to be an area for early commercial introduction, characterized by attractive system features, low production volume, tailored system design and hence insensitivity to the relatively high cost for the complete system.

The Stirling power module V4-275R, integrated with a liquid oxygen system, is currently being incorporated in the design of submarines for the Royal Swedish Navy and the offshore company Comex in France. In addition, design and construction of an air-independent propulsion system for AROVs, based on a converted 4-95 Stirling engine, is proceeding in a cost-sharing contract with the Royal Swedish Navy, also sponsored by SIND (The Swedish National Industrial Board).

Kockums Marine AB

Kockums Marine AB operates under Celsius Industries (formerly Swedyards), a government-owned marine and industrial group with more than 15,000 employees (see Fig. 1). Design and construction of various naval ships is a speciality of Kockums and fits well into the general high-technology profile of the shipyard.

On the naval side, Kockums is today concentrating on submarines and has, in addition to being the leading shipbuilding yard, been the development and design authority for Swedish submarines for the last 30 years.

In recent years Kockums has produced submarines in the *Hajen* (1955), *Dracken* (1960), *Abborren* (conversion 1962), *Sjöormen* (1967) and *Näcken* (1980) classes and is currently engaged in the construction of the four submarines of the *Västergötland* class. Additionally, a submarine rescue vehicle, the URF, was delivered in 1978. The *Västergötland* construction will result in a squadron of highly capable, modern conventional submarines, characterized by low detectability, long endurance and high fire power. The design of the next generation of submarines, the type A19, is now taking place.

The submarines developed and designed at Kockums are very advanced and confirmation of this was given by the Royal Australian Navy (RAN) order for submarines, gained in competition with leading shipyards all over the world. The RAN arrived at this decision after a thorough evaluation process, starting with a request for project proposals from a number of shipyards capable of providing the design and then implementing the construction. From this group two candidates were selected to carry out extensive project definition studies before Kockums was selected as the main contractor.

Six submarines were ordered with another two as an option. The order also includes an option of air-independent Stirling engine systems for installation in the submarines. In these circumstances it was natural for Kockums to acquire United Stirling in order to integrate United Stirling's knowledge of these engines with Kockums Marine's knowledge of system development.

THE UNDERWATER STIRLING ENERGY SYSTEM

Basic Stirling principles

The Stirling engine is an externally heated engine with a closed operating cycle. In terms of compression and expansion it works similarly to a conventional internal combustion engine but differs in two fundamental ways: the power pistons operate in a closed helium (or hydrogen) working gas system and heat is continuously transferred to the cycle via a heat exchanger.

The simplest descriptive model of the Stirling process consists of two pistons, one operating in a cold and one in a hot space (see Fig. 2). The working gas, which is enclosed between the pistons, moves continuously back and forth between the hot and the cold space and is continuously heated or cooled. The gas passes through a regenerator, which stores heat when the gas moves from the hot to the cold side and gives off heat when the gas moves in the opposite direction. The two pistons are mechanically linked to each other in order to achieve the proper volume variation.

Fig. 2 illustrates what is happening during the four different phases of the Stirling cycle. Compression takes place when most of the working gas is in the cold space and pressure is low. Expansion occurs when most of the gas is on the hot side and pressure is high. The difference between the theoretical and actual pressure/volume curves is due to the fact that realization of the practical Stirling engine entails continuous piston movements and continuous heating and cooling.

Most Stirling engines are now based on the double-acting principle, i.e. the pistons have two functions: they move the gas back and forth between the hot and the cold sides and they transmit mechanical work to the drive shaft.

The arrangement of a 4-cylinder double-acting Stirling engine (four separate working gas cycles) is shown in Fig. 3. The pistons in a double-acting Stirling engine are thermodynamically co-ordinated. Each operates simultaneously in two

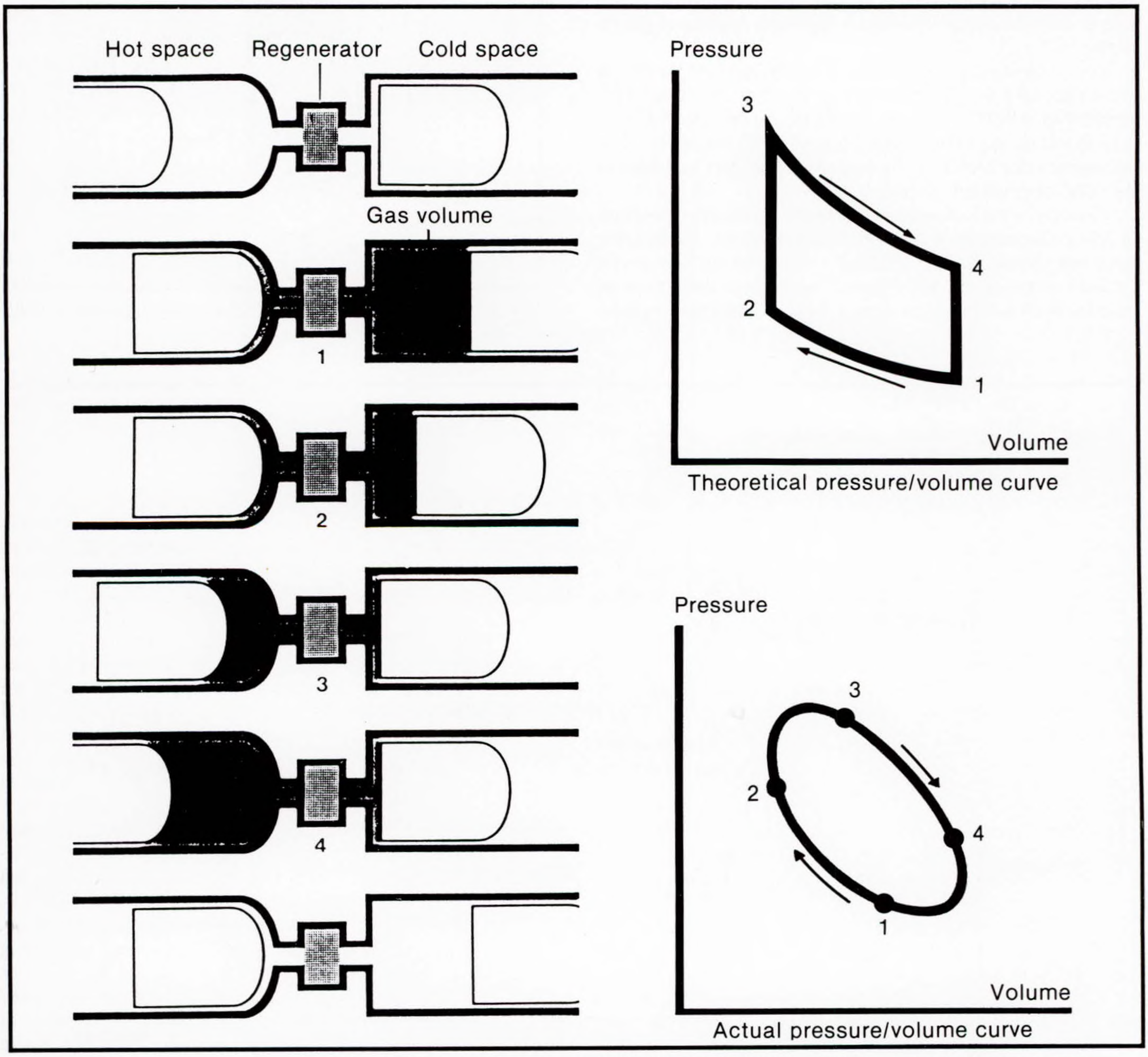

Fig. 2. Schematic diagram of the Stirling engine process with theoretical and actual pressure/volume curves

cycles. The hot upper surface of one piston is co-ordinated with the cold undersurface of an adjacent piston. The operating principle for two adjacent pistons in a double-acting Stirling engine is shown in Fig. 4, which also illustrates the corresponding phases in the actual pressure/volume diagram.

For high efficiency the Stirling thermodynamic cycle requires the working gas to be at a high temperature and high pressure. Hence the availability of advanced materials technology is necessary for high-performance Stirling engines. The technology was established in the late 1960s, after significant development work had been carried out by NV Philips in The Netherlands.

Characteristics of the underwater Stirling system

Heat for operation of the Stirling engine is generated in an air-independent combustion system, using hydrocarbon fuels, e.g. diesel, and pure oxygen. Combustion pressure is constant and set to 20–30 bar, allowing operation down to 200–300 m without the use of an exhaust gas compressor. Combustion products are water and carbon dioxide, which is easily dissolvable in ambient water. The first underwater Stirling engine is shown in Fig. 5.

For control of the pressurized combustion of diesel oil using pure oxygen, which produces an adiabatic flame temperature of 4000 °C, exhaust gas recirculation (see Fig. 6) is used to reduce the flame temperature to an acceptable level. A microprocessor monitors the engine and process variables in the basic operational modes.

Cooling of the exhaust gas allows the combustion products to leave the vehicle at a very low temperature, minimizing infra-red radiation. The Stirling cycle ensures low cyclic torque variations and low levels of noise and vibration compared with those of reciprocating internal combustion engines. The overall emissions from the Stirling system are consequently very low, which is important in military applications.

The underwater Stirling engine

Basic engines. Two Stirling engine concepts, the V4-275R and the 4-95, are presently used as basic engines in underwater Stirling systems.

The V4-275R basic engine (Fig. 7). This engine was designed with underwater applications in mind, using a V-configuration to eliminate output shaft gears and minimize

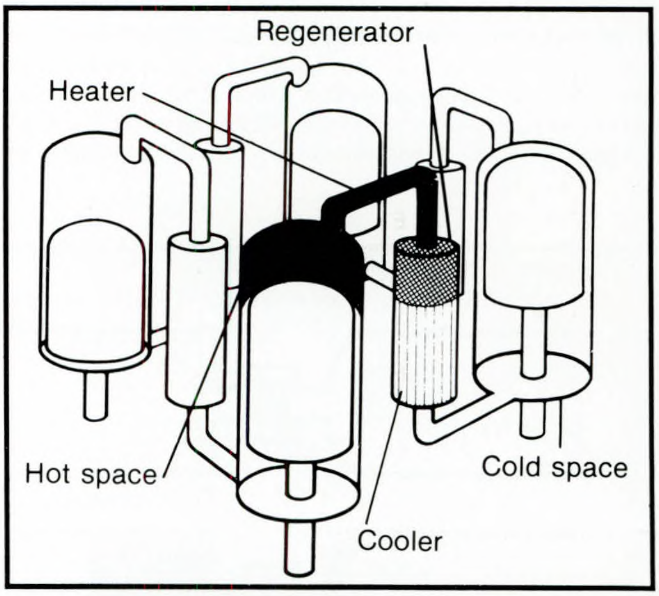

Fig. 3. Arrangement of a 4-cylinder double-acting Stirling engine

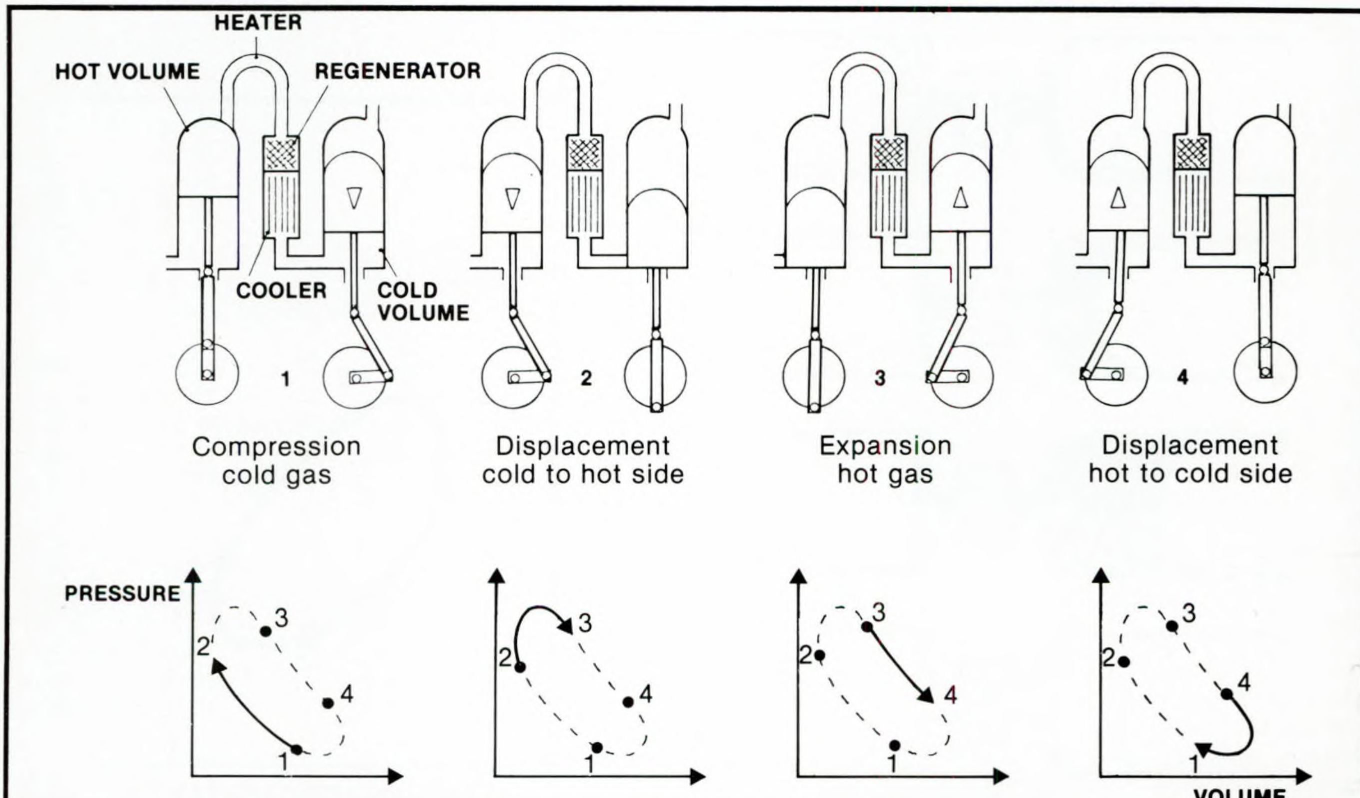

Fig. 4. Principles of operation of the double-acting Stirling engine

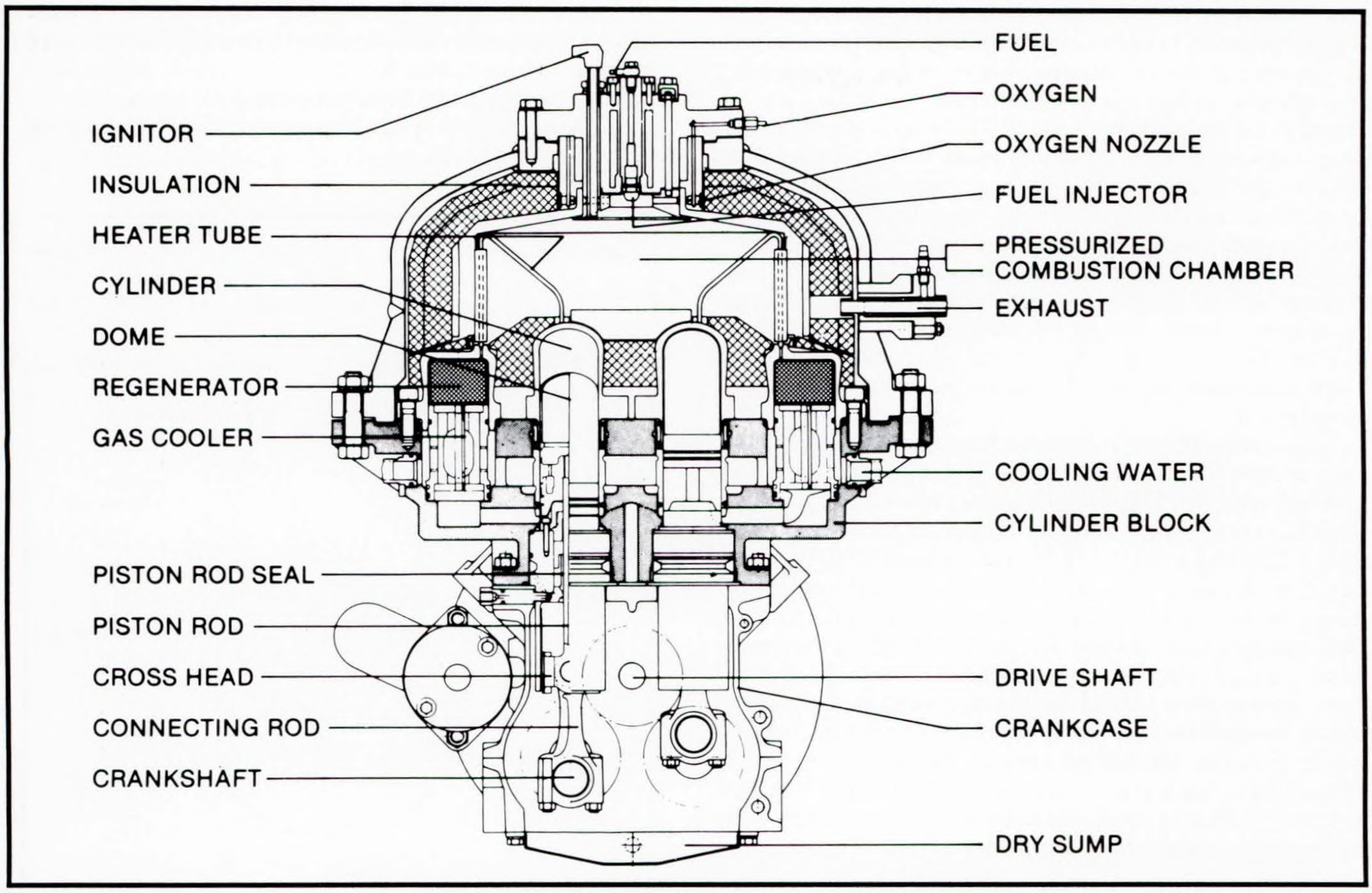

Fig. 5. Cross-section of the first underwater 4-95 Stirling engine

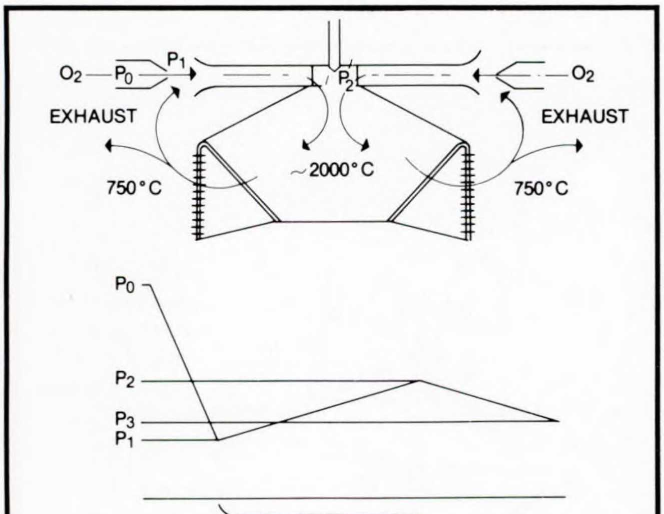

Fig. 6. Basic principles of the combustion gas recirculating system

noise and vibrations. The V4-275R designation means four cylinders, each one with a swept volume of 275 cm^3. The letter R stands for annular regenerators and coolers. The engine design is characterized by division into three main parts: crankcase, cylinder block and heater.

The crankcase is split into a 2-part bedplate configuration and contains the crankshaft and two balancing shafts. The cylinder block contains the specific Stirling engine parts: coolers, cylinder and crosshead liners and check valves. It also serves as the bottom end of the pressure vessel for the combustion system. The heater, which is located on top of the cylinder block, contains the regenerators and is surrounded by the upper part of the pressure vessel for the combustion system (Fig. 7).

The 4-95S basic engine concept (Fig. 8). The 4-95S engine is a U4-configuration with four parallel cylinders, each with a swept volume of 95 cm^3, and two crankshafts. Basically it is a converted 4-95 Mark II solar engine, originally with the crankshafts synchronized via gears to one output shaft. To minimize noise and vibrations the gears are replaced by a synchronous belt.

The engine (see Fig. 8) is characterized by three major parts: the crankcase with crankshafts, the cylinder blocks with coolers and cooling ducts, cylinder liners, and check valves for power control and the heater, consisting of four heater quadrants with cylinder tops, regenerator housings with regenerators and heater tubings.

Fastening the combustion pressure vessel directly to the cylinder block would have required a reinforced block with increased width. Instead it is fastened with bolts to a thick plate, inserted between the crankcase and the cylinder block with spacing sleeves to unload the block. This allows the basic 4-95 engine to be used with a minimum of modifications. In the future, however, a wide cylinder block will be used with the pressure vessel bolted directly to it.

Combustion system. The underwater combustion system is characterized by two main features: combustion at high pressure equal to the surrounding water pressure and combustion of pure oxygen and a hydrocarbon fuel, e.g. ligroin or diesel oil.

The combustion chamber (see Figs. 7 and 8) is surrounded by a pressure vessel where the combustion pressure during operations is always maintained at 20–30 bar, independent of the actual diving depth. A back-pressure valve in the exhaust line prevents the surrounding water pressure from influencing the combustion chamber pressure. Depending on the selected combustion pressure the engine can operate submerged down to 200–300 m with direct overboard discharge of combustion products with no need for either an exhaust gas compressor or a dissolving system. Deeper operating depths, to say 600 m, will be achieved by adding exhaust gas compression with a pressure ratio of only 2:1 and hence very low power consumption.

The combustion of a hydrocarbon, e.g. diesel fuel, with pure oxygen results in an adiabatic flame temperature of approximately 4000 °C, which is too high for existing metallic materials. A thermic ballast for heat absorption is provided with the Stirling combustion gas recirculation (CGR) system (see Fig. 6), where the exhaust gases, carbon dioxide and steam, are recirculated by a set of ejectors. The reduction of the static pressure created when oxygen is supplied via the ejector nozzles is used to develop a return flow of exhaust gases which have already been cooled by passage through the Stirling engine heater. This gives a flame temperature below 2000 °C, which is normal for Stirling engines and permits the use of conventional materials. The exhaust gases released from this system contain only combustion products and no diluent. They consequently represent a small flow and can be exhausted overboard.

Control system. The two main parts of the engine system, the basic engine and the combustion system, each have a control and safety system integrated in a microcomputer program. The main task for the basic engine control is to adjust the working gas pressure, and consequently the shaft power, to a level where the heat absorption capability of the engine balances the heat input from the combustion system.

The main task of the combustion control is to set the supplied fuel flow to match the desired power level and adjust the supplied oxygen flow continuously in order to achieve a constant oxygen excess. In addition to these control routines the system also involves sequences for start, stop, power variation and an extensive safety protection arrangement. The main control principles are as follows.

1. The power level is determined by the fuel flow, which is set manually or automatically.
2. The actual fuel flow is measured and the correct oxygen flow is set by the oxygen flow control valve to a value which gives an oxygen excess of 10%.
3. The working gas pressure in the Stirling engine is adjusted to a level which balances supplied heat and absorbed heat.

Pressure control. The engine power output is varied by manual or automatic adjustment of the supplied fuel flow. The pressure control routine in the microprocessor program balances the heat given off by combustion of the fuel with the heat absorbed by the Stirling cycle by altering the internal working

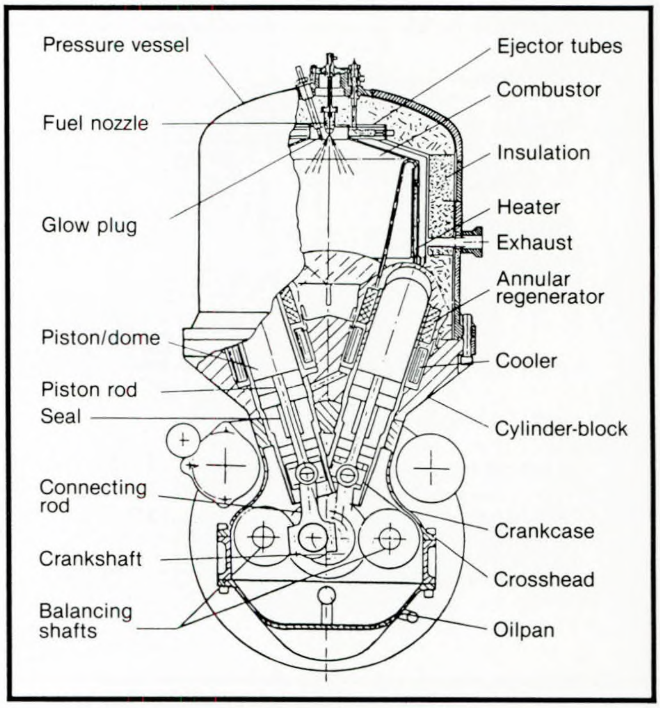

Fig. 7. Cross-section of the underwater 4-275 Stirling engine

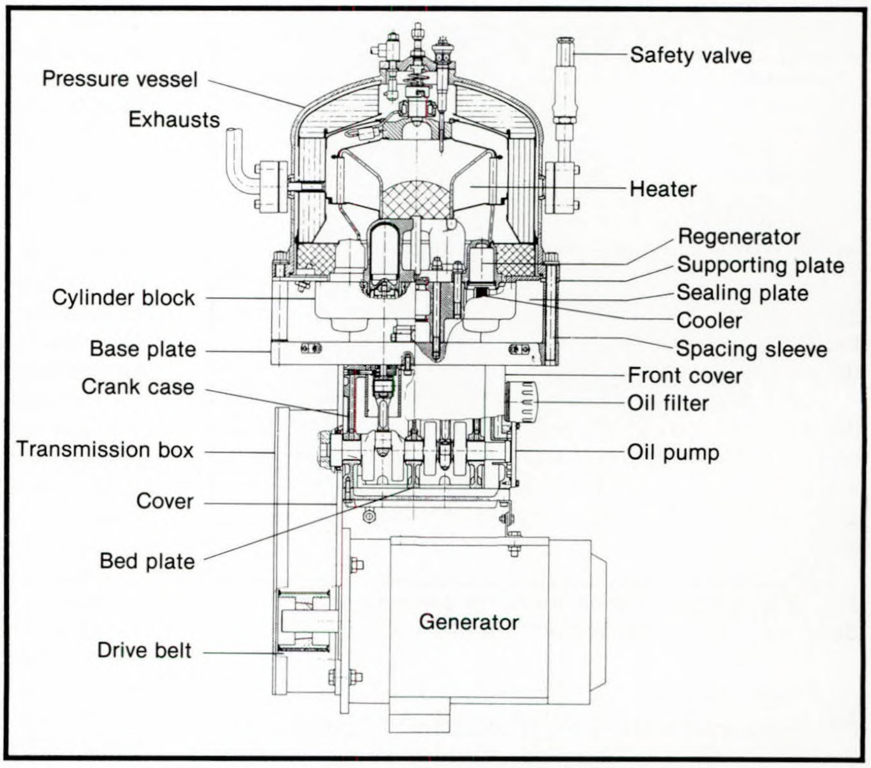

Fig. 8. Operating set of the underwater 4-95S Stirling engine

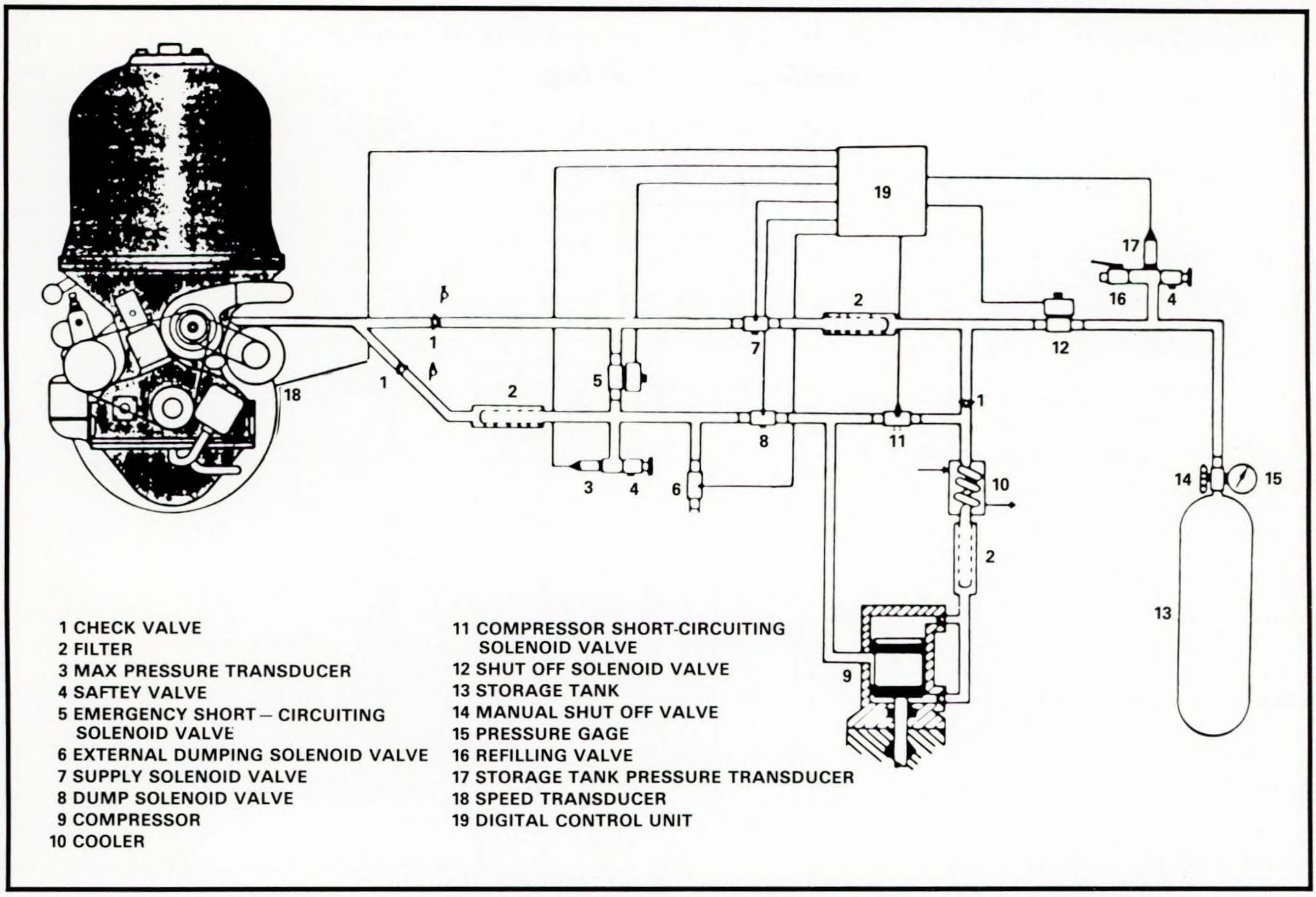

Fig. 9. V4-275R pressure control system

Table 1. Characteristics of the V4-275R engine

Continuous power at 2200 rev./min	H_2 100 kW He 75 kW
Oxygen consumption	H_2 820 g/kW·h He 950 g/kW·h
Speed range	1500–2600 rev./min
Diving depth (without exhaust gas compressor)	200–300 m
Weight	600 kg
Size (l x w x h)	0.8 x 0.8 x 1.2 m

Table 2. Characteristics of the 4-95S engine

Continuous power at 1800 rev./min	H_2 10–25 kW He 10–20 kW
Oxygen consumption	950–1100 g/kW·h
Speed range	1000–3200 rev./min
Diving depth (without exhaust gas compressor)	150–300 m
Weight	450 kg
Size (l x w x h)	0.7 x 0.6 x 0.9 m

gas pressure. A set of thermocouples reads the temperature of the heater tube wall and the highest of these readings is fed into the microprocessor and compared with the set value.

If the temperature is increasing, working gas is supplied to the engine to increase its heat absorption capacity and *vice versa*. In the case of rapid loss of load the resulting overspeed will be handled by short-circuiting of the Stirling cycles, which gives an instantaneous loss of engine power. The rotational speed of the system is controlled by the generator.

The main components of the pressure control system (see Fig. 9) are short-circuit valves (5 and 11), supply valve (7), dump valve (8), compressor (9) and storage bottle (13).

Engine specifications. The specifications of the V4-275R and the 4-95S engines are given in Tables 1 and 2.

Oxygen storage system

Oxygen could be stored either in gaseous (GOX) or liquid (LOX) form, the latter requiring less tank volume and weight, yet at the price of increased system complexity. The difference in volume and in dry weight between a GOX and an LOX tank decreases with smaller oxygen storage. A lower limit for an LOX system is considered to be 300 kg of oxygen, approximately corresponding to 250 kW·h energy storage.

For the larger V4-275R engine an LOX system is chosen, while the choice between LOX and GOX for the 4-95S engine is dependent on the required endurance under water of the AROV.

The LOX system. The LOX system tank and piping arrangements are shown in Fig. 10. The tank is bunkered with LOX at atmospheric equilibrium. The tank pressure is maintained at a level slightly above the engine combustion pressure, using either the natural heat leakage to the tank or a special pressurizing loop external to the tank where LOX is heated and fed back to the tank as gaseous oxygen, thus increasing the tank pressure to the required level.

The GOX system. The gaseous oxygen is assumed to be stored in 20 to 50 litre standard bottles at 200 bar.

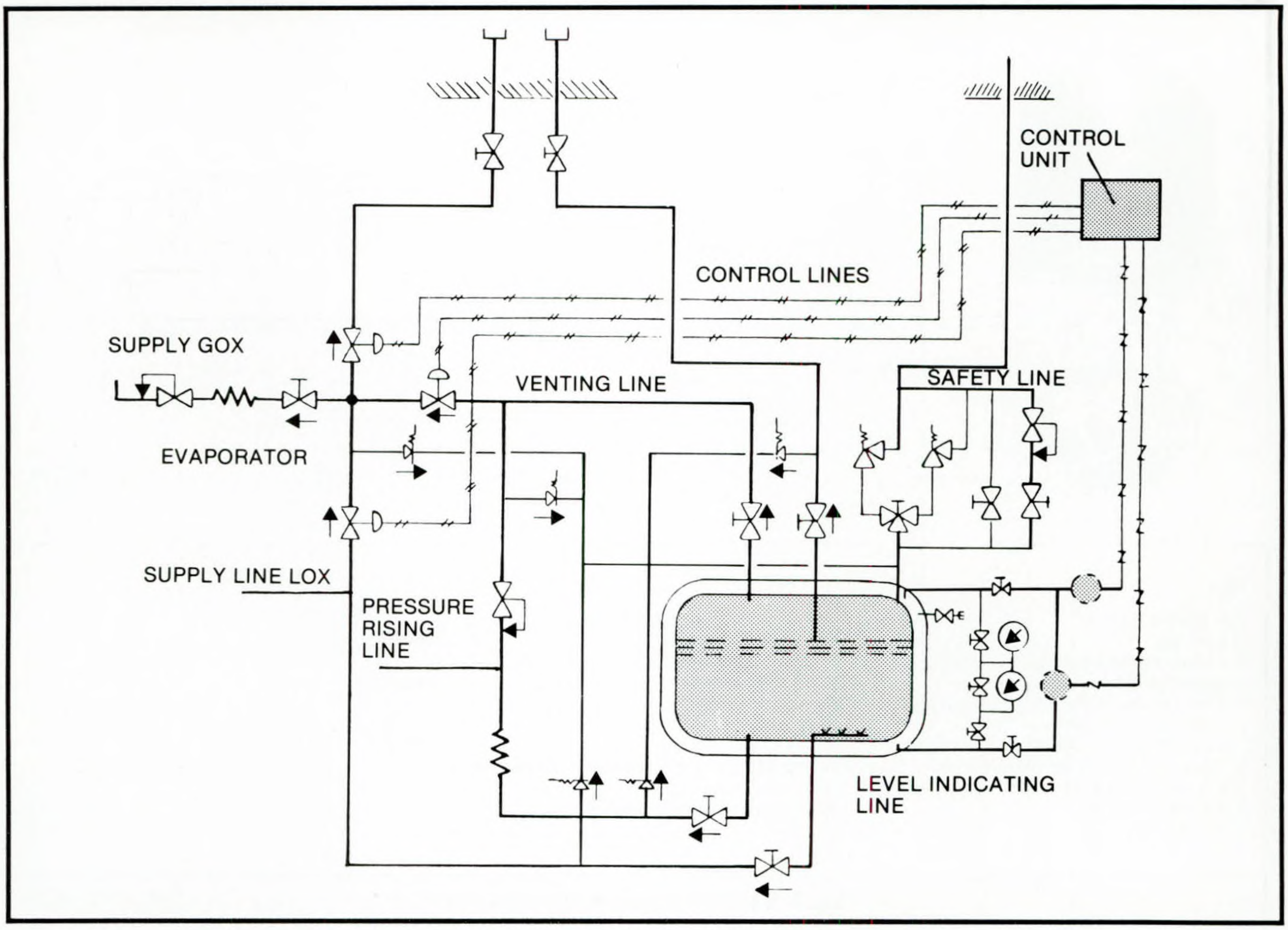

Fig. 10. LOX system for the Stirling test plant

APPLICATIONS IN MANNED SUBMARINES

Military applications

Tactical background. Of critical importance for the combat efficiency of the conventional submarine is the capability for long submerged endurance, calling for the longest possible intervals between successive snorting/recharging phases. The recharge energy is provided by the submarine's diesel generator plant and the induction air is led to the diesel engines through a snort mast penetrating the surface. The exposed snort mast will therefore indicate the submarine's location for quite a substantial period of time. In addition, the diesel engine emits a structure-borne noise which is difficult to attenuate and easily detectable. Consequently, the snorting submarine is vulnerable to detection and thus attack.

Surveillance and detection systems are undergoing rapid development, and it can be anticipated that the threat of environment for the snorting submarine will be increasingly severe. However, improving the submerged endurance simply by adding more batteries will quickly lead to an unacceptable growth of submarine size because of the poor energy density of the batteries.

Conventional developments are therefore concentrated on improvements of battery energy density. Such developments have a certain technical potential but substantial improvements are not expected.

The introduction of an 'energy dense' and air-independent power conversion system offers the potential for a significant improvement of the submerged endurance. Future operational conditions of conventional submarines are summarized in Table 3.

Table 3. Future operational conditions of conventional submarines

Future combat environment		
	Intensive radar scanning	
	Recharging of batteries via snorting	
		Hazardous
		Outside combat area
		Minimized
Future submarine propulsion		
	Hybrid systems	
	Conventional + air-independent	
		Reduced snorting
		Increased operations within combat area
Air-independent systems		
	Fuel cells	
	High-energy batteries	
	Closed-cycle diesel systems	

The submarine engine system. The normal submerged cruising mode of the conventional submarine is silent, economical and for low-speed surveillance. From Swedish Navy evaluations and predesign work it was found that a suitable

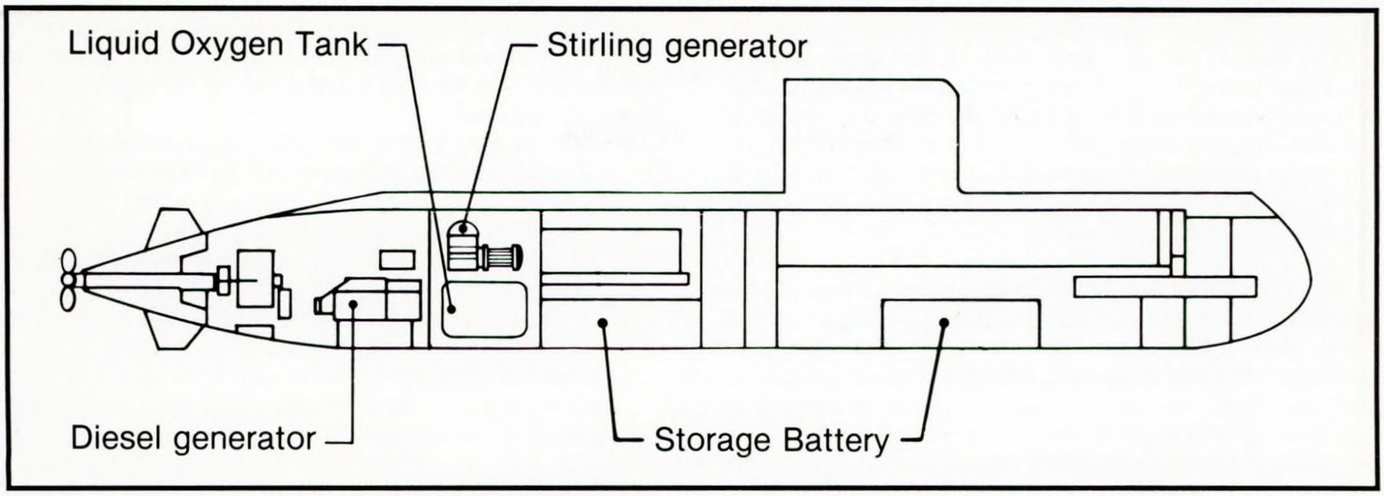

Fig. 11. Naval submarine with an integrated Stirling section

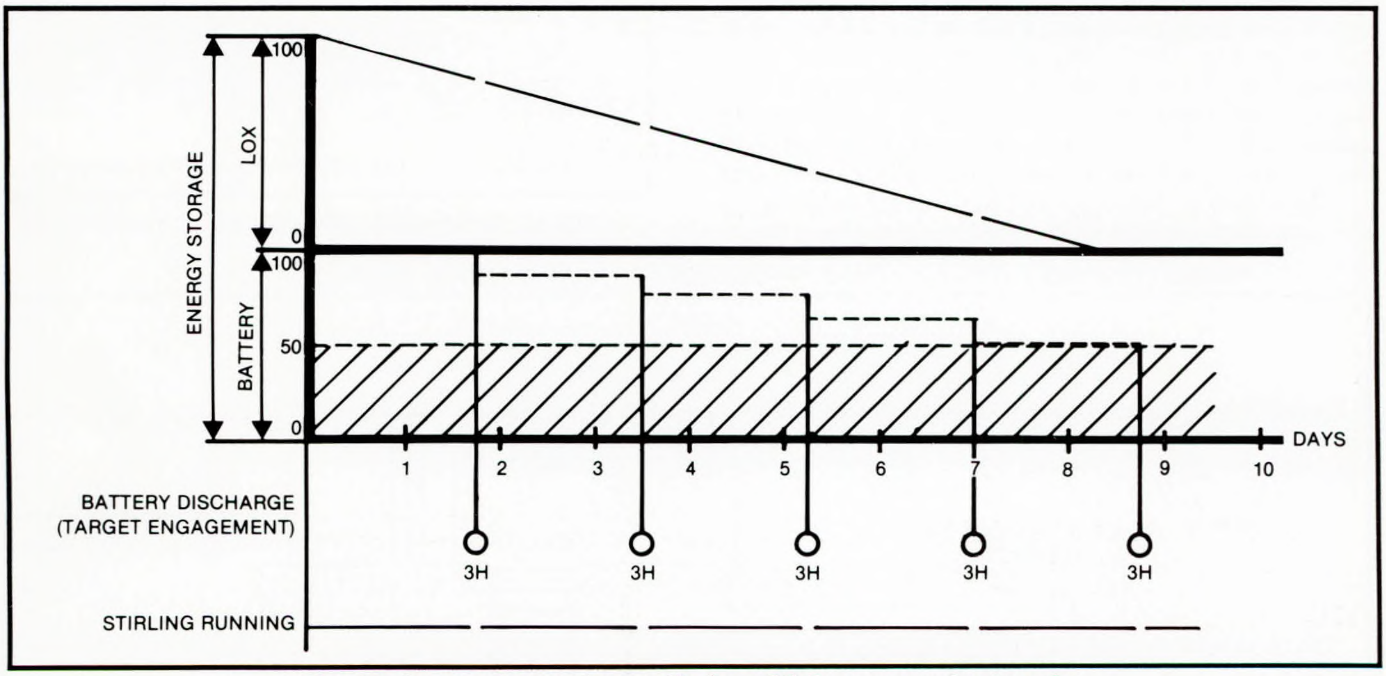

Fig. 12. Assumed operating profile for a Stirling-powered submarine

concept could be a hybrid power conversion system, meaning the addition to the well established conventional battery system of an air-independent component at a power level sufficient for an appropriate air-independent submerged cruising mode. The air-independent power conversion component can be designed for low power generation, since this will be sufficient to support this particular mode, while the battery energy storage will be used for modes requiring higher power outputs such as offensive and escaping manoeuvres.

The add-on concept is appropriate as a first-generation hybrid system, and also covers the case under which a conventional submarine, already in commission, could be retrofitted with an add-on hull section containing the entire air-independent system (see Fig. 11). An add-on system for a 1000 t conventional submarine uses two Stirling generator sets of approx. 70 kW each with auxiliaries and an LOX system. The power level is sufficient to support the quiet, economical running mode including the related auxiliary power requirements.

When the Stirling system is running, the batteries are kept on-float and supply energy only when the power requirements exceed the Stirling system's capability. Fuel oil is provided to the engine from the ordinary bunker oil supply on board and oxygen is stored in one or more LOX storage tanks. The submerged endurance will mainly depend on the amount of stored oxygen. Therefore the LOX tank sizes will define the dimensions of the add-on hull section. An appreciation of the current energy density is given from the relationship that an increase of the submarine length by some 10% will more than double the submerged low-power endurance.

The submerged endurance of a hybrid-powered submarine. Fig. 12 illustrates a fictional operational profile of a conventional submarine having an air-independent Stirling system sufficient for low-speed propulsion. The submarine will commence operations with full oxygen storage and the battery fully charged. The operation starts with the add-on system running (no battery discharge) until the second day, when a target is engaged during 3 h of battery running (discharge).

Upon completion of target engagement the power conversion returns to the add-on system for the next surveillance period, prior to a new target engagement phase, and so on.

The battery is consequently discharged in steps, and is in this example discharged down to the tactical reserve level of 50% after about 9 days. By this time the oxygen is consumed and the submarine reverts to the conventional mode. However, this hybrid submarine would have been in the operational area for 9 days and conducted four target engagements without exposing the snort mast.

The Royal Swedish Navy Stirling programme – initial feasibility study and current activities. The Royal Swedish Navy and Kockums have for an extensive period of time performed tests and studies of air-independent energy conversion systems for submarines. A number of projects and prototype tests have been carried out using heat engines (the closed-cycle diesel engine and Stirling engine), fuel cells and high energy density batteries.

At an early stage of the naval programme a feasibility study of a 1000 t attack submarine was conducted showing at least a 5-fold increase in submerged endurance time with a Stirling engine/LOX system compared with a lead–acid battery alternative (see Fig. 13). In this study the total weight of the submarine would be unchanged, since one-half of the battery was replaced by an LOX tank. The current design of a Stirling add-on machinery module, described below, will keep the full battery capacity on board and will result in a larger submarine.

The Stirling technology was then identified as having the best near-term potential as an air-independent power source and was subsequently selected by the Royal Swedish Navy for full-scale system development. The decisive factor supporting this decision was the established technical maturity of major system components.

1. The standard Stirling engine was at a commercial stage after a substantial and successful development period in Sweden.
2. The basic underwater technology had been verified within a Swedish programme for underwater power generation.
3. The LOX system technology for handling and storage was well developed and available in Sweden, as was a means of transporting and storing liquefied oxygen.

An underwater engine development program based on the well proven 4-275 standard Stirling engine was initiated in

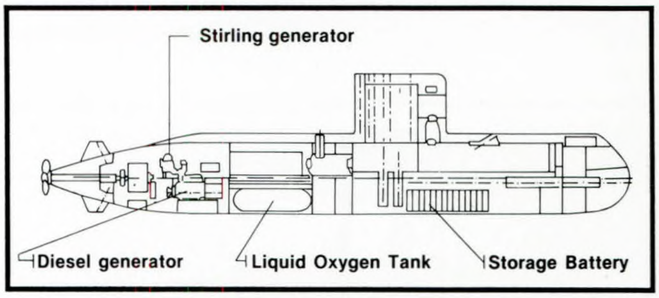

Fig. 13. Naval submarine with hybrid machinery

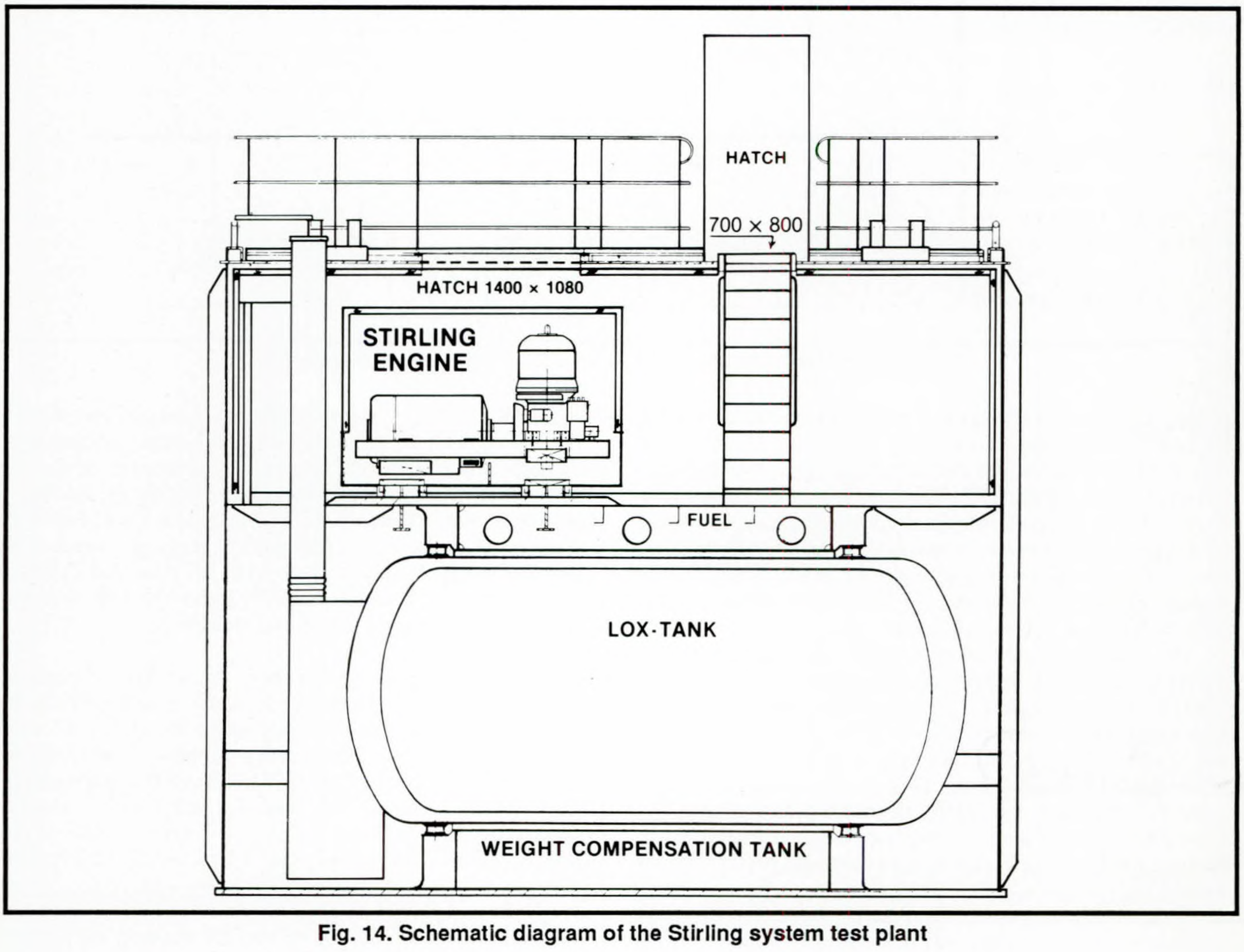

Fig. 14. Schematic diagram of the Stirling system test plant

1982, intended for integration with an LOX system, using well established cryogenic technology from the AGA Cryo Company in Sweden. Since mid-1985 the Stirling engine system has been successfully tested in a full-scale submarine test section (see Figs. 14 and 15).

The next step was installation of the energy system in an operational Swedish submarine. This phase, having Kockums as main contractor responsible for system integration, started recently with cutting the submarine to add an extra hull section, where the Stirling system is now being installed. Functional tests with the Stirling machinery will start this year and be continued by sea trials and evaluation in the operational submarine, supported by USAB/Kockums.

Offshore applications

Background. The offshore industry has the need to carry out work in deep water and often under harsh environmental conditions. Exploration of underwater gas or oil wells, mineral sources, etc. often requires surface-independent energy supply systems with long endurance under water.

Examples of work operations of immediate interest for the offshore industry are:

1. maintenance of oil wells and sea bed-based production systems;
2. qualified seismic investigations of mineral sources (e.g. metal nodules);
3. geologic sampling by drilling;
4. underwater welding;
5. maintenance of natural gas and oil pipe lines;
6. control of robot vessels and remotely controlled manipulators and repair of sea bed-based production units.

Commercial submarines or different types of habitats are used for deep water operations to provide diver support at the sea bed. Long endurance under water is important, not least for saturation diving. With air-independent Stirling systems, work at deep water can be performed continuously for a minimum of 2 weeks, independent of the weather conditions on the surface.

The Saga I submarine Stirling programme. The current Stirling underwater technology at USAB originates from a programme that started in 1979–80 for modification of the 4-95 engine (see Fig. 5) in a joint project with Comex Industries, aiming for a power source of extensive endurance for manned submersibles.

Within the 4-95 project certain 'key functions' for a successful underwater modification of the standard engine were demonstrated with satisfactory results.

1. Overpressure combustion.
2. Combustion gas recirculation.
3. Oxygen control system.
4. Exhaust valve design.
5. Arrangement analysis versus pre-set energy density objectives.

This program was more or less a pilot project for the current USAB program with Comex which covers the installation of two V4-275R engines integrated with an LOX system in Saga I.

Saga I is a 300 t manned diver lock-out submarine, which is under final construction at Comex in Marseilles. Basically it is a mobile underwater habitat (see Fig. 16), situated in an autonomous, long-range submarine with the capability to release divers and various tools at a depth of up to 450 m or robots up to 600 m. Saga I uses a hull that was built 10 years ago but was never completed, which has an atmospheric compartment 12.6 m long and a diver lock-out section 5 m long.

Comex launched the project in 1982 and is now in partnership with IFREMER, the French National Agency for Ocean Development.

Fig. 15. Stirling system test plant

On the surface, power is provided by a diesel engine. When submerged, Saga I is powered by two V4-275R engines with a maximum rating of 75 kW installed inside the pressure hull (see Fig. 16). The oxygen storage, manufactured by AGA Cryo in Gothenburg, consists of two LOX tanks with a total capability equivalent to 10,000 kW·h located outside the pressure hull allowing the submarine to remain submerged for up to 14 days.

The combustion pressure is 30 bars, allowing initial submerged operation down to 300 m (with an exhaust gas compressor down to 600 m).

The two V4-275R Stirling engines were delivered to Comex late in 1987 and have recently been installed in Saga I. After initial testing of the system, sea trials will start with support from USAB/Kockums.

APPLICATIONS IN AUTONOMOUS UNMANNED UNDERWATER VEHICLES

Autonomous unmanned underwater vehicles are today commercially available and operating in a number of applications, mostly military. Free-swimming vehicles

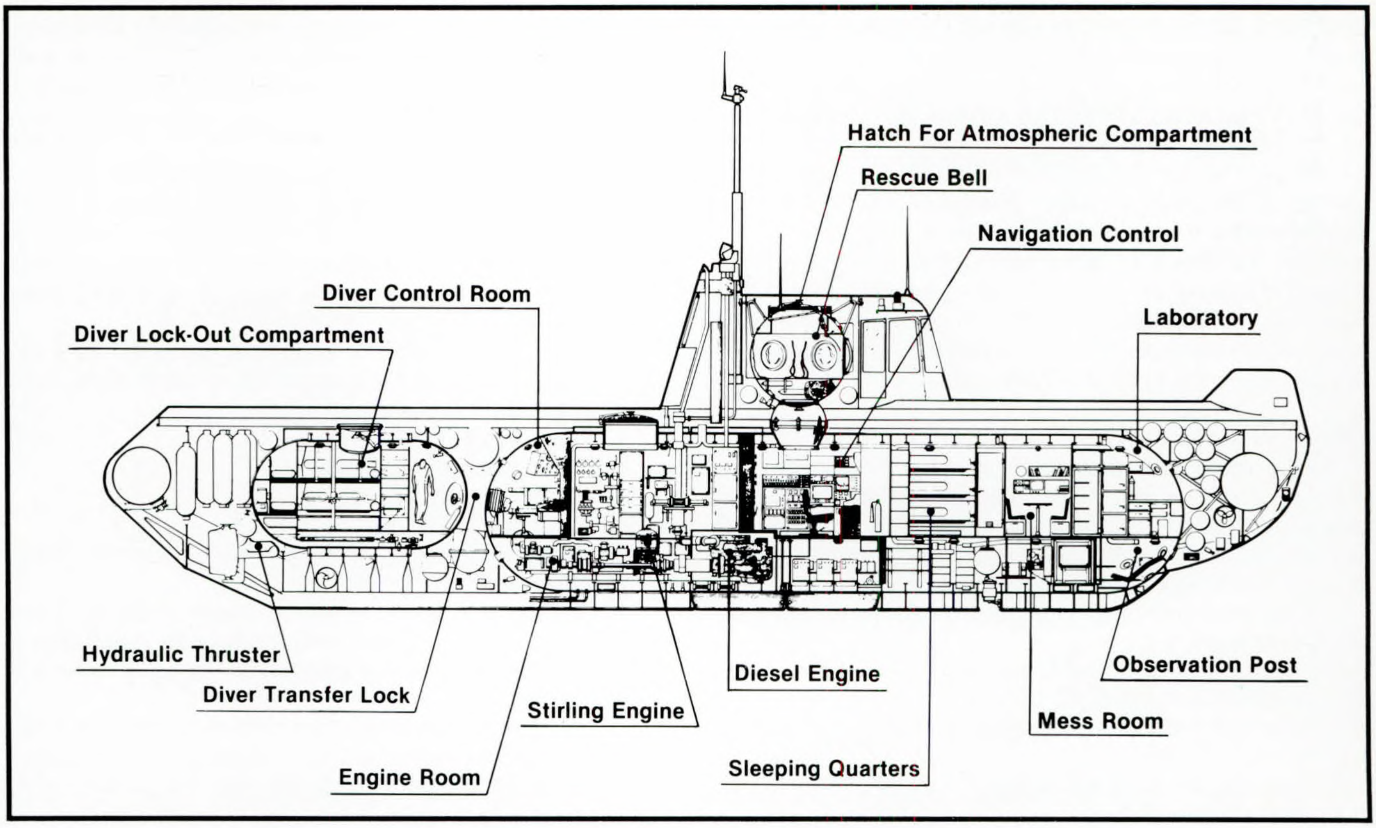

Fig. 16. Interior arrangement of Saga I submarine

currently in production are powered by different types of electric batteries, which are either heavy with low energy density or extremely expensive, e.g. silver–zinc batteries, but still with a limited operating range. Very advanced vehicles may be powered by fuel cells.

Using high energy density thermal propulsion machinery like the Stirling energy system will considerably increase the endurance and operating range of the AROV. Furthermore this will open new marketing opportunities based on observation and data collection.

Military applications

Tactical background. Unmanned, remotely controlled underwater vehicles are even now standard equipment in most modern navies all over the world.

The most common application today is mine hunting, where the vehicle is used to identify mines and, if necessary, blow them up. ROVs are also used for search operations, e.g. recovery of lost torpedos, replacing divers in deep water. Other missions that could be performed by free-swimming AROVs include:

1. patrolling assignments, including information processing;
2. sensor/weapon delivery vehicle for short-range operations;
3. carrier of test/exercise equipment for naval use.

Using a long-endurance Stirling propulsion system, the AROV would be able to perform extensive reconnaissance and surveillance operations.

A traditional ROV, having little or no artificial intelligence, needs a lot of communication capacity. Initially a fibre-optic link could be used for control and transmission of data, but this would limit the operating range. To benefit fully from the extended endurance of a Stirling AROV, the next step would be the introduction of a hydroacoustic communication system. Combined with pre-programming of the vehicle, it would then be possible to perform considerably extended surveillance and reconnaissance missions, with only supervisory assistance from the operator.

Future developments in communications and artificial intelligence is potentially very great and AROVs equipped with advanced artificial intelligence will be able to execute long-range missions, where the operating distance is limited only by the endurance of the energy supply system. Examples of long-range tactical operations include:

1. covert surveillance, where the objective is to stay hidden while determining the location of enemy forces;
2. tactical probe missions to unmask active defences by drawing a reaction to penetration by the unmanned vehicle;
3. weapon delivery.

High energy density, allowing long-range operations and excellent covertness (with almost no emissions), are important qualities of the Stirling system, making it most suitable as a military AROV propulsion system.

AROV programme for the Royal Swedish Navy. A cost-sharing contract with the Royal Swedish Navy, supported by the Swedish National Industrial Board (SIND), for the development of an AROV propulsion system has been awarded to USAB.

The goal is to demonstrate the operation of a complete prototype Stirling energy system in a pod submerged in water by the end of 1989. Major tasks are the design and construction of the system, installation in the pod and functional testing under water with evaluation of system characteristics.

The energy conversion unit of the AROV is basically a generating set (see Fig. 8) powered by a 4-95S underwater engine operating at 1500 rev./min in the 5–15 kW power range. A 15 kW synchronous a.c. generator with rectifiers provides electricity for the propulsion machinery and the auxiliary systems. Synchronization of the two engine crankshafts and transmission of power to the generator is made with a curved-tooth belt drive, allowing low noise and vibrations.

The combustion system runs at 17.5 bar constant pressure, allowing diving depths down to 150 m without the need for an exhaust gas compressor. Fuel is ligroin with GOX as oxidizer. Installation of the 4-95S Stirling energy system is made in a pod of 800 mm internal diameter.

The energy storage requirement is naturally dependent on the actual application and type of mission to be performed. Oxygen storage corresponding to 90–180 kW·h for propulsion and auxiliary systems is considered to be sufficient for most of today's missions.

Thus a GOX system was chosen for the AROV, each module consisting of seven 50 litre standard bottles, operating at 200 bar. The amount of oxygen stored in one module of 1.5 m length is approx. 100 kg, corresponding to 90 kW·h energy storage.

Offshore applications

Unmanned remotely operated vehicles are today frequently used in the offshore sector for inspection and maintenance work, e.g. in connection with drilling support, platform cleaning and inspection, pipeline inspection and repair, etc. Apart from relieving divers (mostly at depths beyond 55 m or the limit for air-diving) from hazardous work operations, they have the advantage of requiring less surface support. Energy is supplied to the ROV by an umbilical connected to a surface vessel. Major drawbacks are limited operating lengths and diving depths, and risks for tether entanglement in underwater structures or in the propeller of the surface ship.

Free-swimming AROVs using conventional batteries have the disadvantage of a limited operating range. However, using a Stirling energy supply system with an extended operating range would open entirely new operational areas, both industry and science oriented, for the AROV.

Systematic survey missions are considered to be ideal work tasks for untethered AROVs with a long operating range, and offshore companies will need them for the exploitation of subsea oil and gas sources, as well as for inspection of pipelines and cables on the sea bed. Another use is for marine geology, where AROVs may be used for systematic exploration of nodule deposits on the sea bed.

Scientifically oriented uses are oceanography, including bathymetric mapping and acoustical/optical images, and marine biology, where AROVs could be used for inspection of poisonous or radioactive waste dumped in deep water, monitoring of water quality, etc.

Finally a number of surveillance and search operations could be performed, e.g. coastguard activities, customs control, rescue operations, retrieval of lost objects, wreck inspections, etc.

CONCLUSIONS

The short-term solution for the surface-independent supply of large quantities of energy to underwater systems is likely to be based on closed-cycle heat engines, among which the Stirling engine embodies several features which have been recognized for many years. External combustion, high efficiency, low noise and vibration levels and the feasibility of integration with thermic reactions of high specific energy make the Stirling engine an appropriate energy converter for underwater systems requiring extensive surface independence.

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