ATMOSPHERE CONTROL SYSTEMS IN NUCLEAR SUBMARINES

BY

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Introduction

Credit for building the first submarine is usually given to Cornelius Van Drebble, who in 1620 built a submarine that carried James I for a short trip under the Thames at a depth of 12–15 ft. Robert Boyle[1] referred to Drebble's achievement and attributed Drebble's success largely to 'the completion of a liquid that would speedily restore to the troubled air such a proportion of vital parts and would make it again, for a while, fit for respiration.' This is probably the first reference to a submarine atmosphere control system, and highlights the important part played by atmosphere control systems in allowing submarines to meet their operational objectives.

The introduction of the submarine into regular naval service commenced with the First World War. Gradual advances were made in propulsion systems that were matched by developments in relatively simple atmosphere control systems that provided oxygen and removed carbon dioxide using consumable chemicals.

A breakthrough in propulsion technology was made by the Germans in World War II when the Walther closed cycle turbine was introduced into the Type XXIV U-boats. These submarines had high underwater speed and could remain totally submerged for longer periods than conventional submarines of the time. The Type XXIV never became operational and the German's unfinished task was continued by the Royal Navy. In all, three Royal Navy submarines using Walther cycle turbines were operated successfully, but emphasis was placed on propulsion system development, and the atmosphere control systems were based on well-proven technology, with allowance made for extra supplies of consumable chemicals.

The Walther cycle submarine was technically obsolete by the time it became operational because of the development of the nuclear submarine. Until the advent of nuclear power the submarine was really only a submersible. Regular access to the atmosphere was needed to allow diesels to recharge batteries, and the atmosphere was revitalized at the same time.

The nuclear reactor does not need air to release its energy, and long periods of submergence became a reality and an operational requirement. Long submergence required system designers to provide an environment that would provide 100 or more men with an internal source of healthy breathable air for periods up to 90 days at frequent intervals during their lifetime. The composition of the air must be such that they suffer neither discomfort nor short- or long-term health problems.

Much technological effort has gone into the development of regenerative atmosphere control systems. Undoubtedly the designer's task has been served by the increased power available in nuclear submarines, but as with any other fuel source high energy efficiency is an important design criterion.

Atmosphere Control Systems

The policy regarding the assessment of safe levels for atmospheric contaminants is embodied in five main principles:

(*a*) Determine what is present.

(*b*) Set the Maximum Permissible Concentration (MPC) for specific continuous exposure times. MPC_{90} represents the maximum permissible for 90 days.

(*c*) Develop equipment to eliminate contaminants or control levels within the required MPC. (e.g. 90 day, 24 hour, or 1 hour exposure levels.)

(*d*) Exercise strict materials control at all phases of the submarine's life.

(*e*) Continually review the atmospheric spectrum.

Normal atmosphere consists of nitrogen (78%), oxygen (21%), carbon dioxide (0.03%) and argon (0.93%), plus minor traces of other gases. When men live and work in a closed space, the main effects of their respiration are the depletion of oxygen and an increase in carbon dioxide levels. In addition the atmosphere is contaminated by numerous compounds in the form of gases, dust, and aerosols. In a typical submarine atmosphere there are currently in excess of 200 identifiable compounds, with many more suspected but not positively identified. Major contaminant groups requiring to be controlled are detailed below, together with the main sources of contamination:

(*a*) Carbon dioxide	Crew respiration.
(*b*) Carbon monoxide	Smoking, oil-soaked lagging, cooking.
(*c*) Hydrogen	Batteries, hydrogen from the electrolyser as an impurity in the oxygen.
(*d*) Freons	Chilled water plant, fire-fighting agents.
(*e*) Organic vapours	Oil leaks, cooking, paints, polymers, solvents.
(*f*) Dust and aerosols	Running machinery, wear debris, smoking, cooking.

When compounds have been identified, their effect on the health and performance of the crew is assessed by the Institute of Naval Medicine, which specifies the respective MPC exposure levels. For the vast majority of compounds an MPC is readily established, but for some compounds extensive investigations are required before it can be declared.

TABLE I—*Submarine Atmosphere Control System Equipments*

Primary Role		*Equipment*	*Secondary Role (removal)*	*Undesirable By-products*
production	*removal*			
Oxygen		Electrolyser; high pressure caustic electrolysis of water	None	Water vapour, potassium hydroxide, hydrogen
	Carbon dioxide	Monoethanolamine (MEA) scrubber using absorption/distillation process	None	MEA, ammonia, water vapour
		Molecular sieve scrubber using temperature swing regeneration	Freon Carbon monoxide Organics Hydrogen	Dust
	Carbon Monoxide Hydrogen	Catalytic burner operating at high temperature (200°C+) Catalytic burner operating at ambient temperature	Organics Microbiological Viral Ammonia MEA	Hydrogen chloride, hydrogen fluoride, nitrous oxides, dust
	Dust	Particulate filters	None	None
	Moisture	Air conditioning plant	None	Freon, organics
	Aerosol	Electrostatic precipitators	Microbiological Viral	Ozone
	Vapours, Odours, Organics	Charcoal filters	None	Dust, light organics
	Freon	Catalytic burner	None	None

Real-time analysis equipment is not fitted to submarines for other than the main atmosphere constituents (O_2, CO_2, H_2, Freon, CO), but a mass spectrometer has been developed which will greatly enhance on-board analysis capability. Atmospheric contaminants that cannot be analysed on board are controlled by closely specifying the type and quantity of materials that are allowed during build, at sea, and during refit. All submarines undergo an Air Purification Trial after build and refit, during which scientific staff from the Admiralty Marine Technology Establishment undertake a detailed analysis of the atmosphere. Throughout a commission the submarine will also obtain 'grab samples' using captive sampling techniques for subsequent laboratory analysis.

In 20 years of operating nuclear submarines the Royal Navy has established a comprehensive inventory of contaminants and has developed a range of equipment to deal with the specific contaminant groups. The atmosphere control system consists of individual equipments each designed with a primary role, and some with important secondary roles. Equipments must be designed to ensure that no unacceptable by-products are exhausted into the atmosphere, or, if this is unavoidable, the effect on the system must be analysed and techniques developed for removing this secondary contamination.

The unique nature of the task demands specialized equipment; proven technology is utilized where feasible, but there have been occasions where innovative techniques have been developed and introduced into service. TABLE I summarizes the equipments in service, and Martin and others[2] describe the design and operation of the equipments.

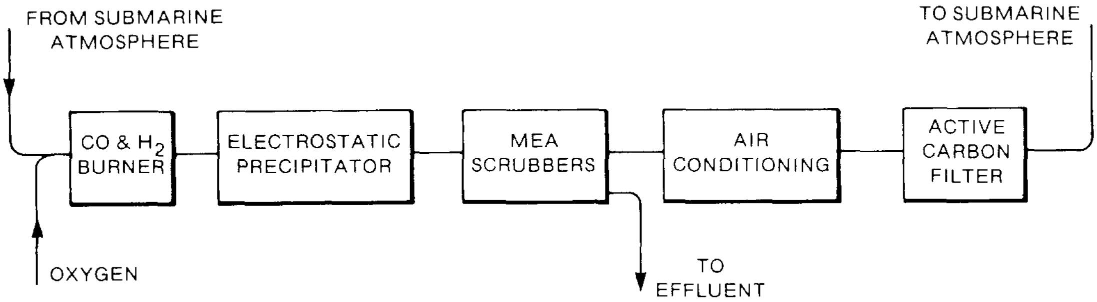
The idealized air flow paths for typical systems utilizing monoethanolamine scrubbers and temperature swing molecular adsorbers (TSMA) incorporating low temperature catalytic carbon monoxide and hydrogen burners are shown in FIG. 1. The individual equipments are not linked by trunking. They have different air throughput requirements and each contributes separately to the purification of the atmosphere. Their relative locations in the boat ensure that the air generally follows the idealized route shown in the diagram. An equipment's performance can be affected by the relative position within the overall submarine ventilation system. A total system approach is essential if satisfactory performance is to be achieved. Cross-contaminants, or inadequate air distribution arrangements can adversely affect overall system performance, even though individual equipments may perform perfectly during development tests.

There are relatively generous power and space allocations available to designers of nuclear submarine systems compared to their counterparts in the conventional submarine projects. However, it is still important to provide compact, highly efficient and reliable equipment. The following section describes the development of the Solid Polymer Electrolyte (SPE)* electrolyser. It demonstrates the nature of the development programme to provide an equipment suitable for the demanding environment.

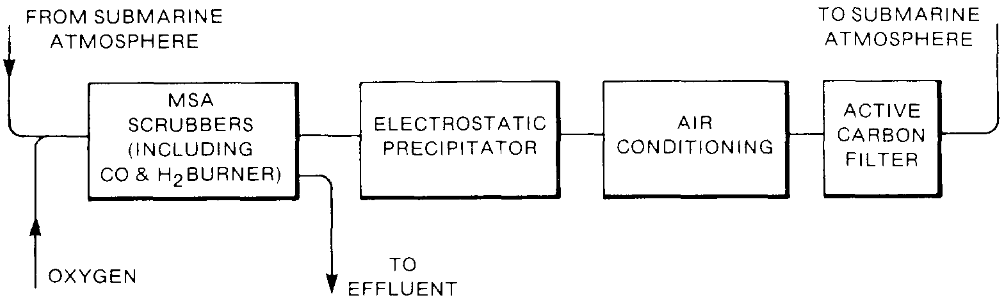
Development of the Solid Polymer Electrolyte Electrolyser

With the exception of H.M.S. *Dreadnought,* all Royal Navy nuclear submarines are fitted with electrolysers for producing oxygen. The first electrolyser was developed by CJB Developments Ltd. and entered service in H.M.S. *Valiant.* This electrolyser—the high pressure electrolyser (HPE)—has been the basic unit fitted to R.N. submarines. Successive equipment marks have been introduced, but the principle of operation of all HPEs remains the same. The latest Mark V HPE, to be fitted in the new TRAFALGAR

*SPE is a registered trade mark of The General Electric Company of America.



SYSTEM WITH MEA PLANT



SYSTEM WITH MSA PLANT

FIG. 1—IDEALIZED AIR FLOW PATHS
Note: Individual equipments have particulate filters at inlet or outlet depending on specific requirements

Class, represents the development peak for the caustic high pressure electrolyser. In 1973 Director General Ships conducted studies into advanced oxygen generation systems. The aim was to review technical developments and to assess their suitability for submarine use. The background for the study stemmed from the realization that although the HPE was successful it was a complex and costly equipment that demanded high standards of maintenance, and had the potential for creating a hazardous situation.

Many different systems were studied and discarded as being unsuitable for development. The most promising new system was a water electrolyser that could operate over a pressure range from atmospheric to above 124 bar, and which dispensed with a conventional electrolyte, requiring only demineralized water in the process circuit. At the heart of this development was the Solid Polymer Electrolyte (SPE). The SPE was developed by General Electric Company of America who were using the material in spacecraft fuel cells.

The advantages of an electrolyser using the SPE compared to the HPE (see also TABLE II) were:

(*a*) Greater safety —cell membrane resists high differential pressures and prevents gas mixing. No caustic electrolyte.
(*b*) High reliability—greatly simplified control and process system.
(*c*) Reduced maintenance load.
(*d*) Smaller, less weight.
(*e*) No large nitrogen purge system.
(*f*) Reduced capital and support costs.

TABLE II—*Comparison of SPE and HPE characteristics*

Parameters	*Mk V HPE*	*SPE*
Output	100	120
Size	100	63
Weight	100	44
Production cost	100	78
Through life cost	100	42
Cooling water	100	74
Power requirement	100	93
Maintenance	100	20

The SPE Cell

The HPE—the predecessor of the SPE—operates at 124 bar and uses a caustic (potassium hydroxide) solution which is electrolysed in a cell stack comprising a number of bipolar cells in series. Each cell consists of an annular chlorinated polyether cell frame with a woven asbestos diaphragm moulded into the periphery and completely covering the inner area. On each side of the asbestos diaphragm are positioned the anode and cathode electrodes and inter-cell separator sheets. The diaphragm allows for free circulation of the electrolyte whilst providing a high resistance to gas flow and it serves to prevent oxygen and hydrogen mixing and forming an explosive mixture. It is essential to control the differential pressure across the diaphragm whilst simultaneously controlling total system pressure under all output conditions. The control system is necessarily complex.

The SPE is a sheet of tough, flexible, fluorocarbon polymer which is impervious to the contra-passage of gas through the material. The polymer has the sulphonic ion electrolyte in solid solution within the carbon polymer lattice. Electrolysis takes place within the material using water that has permeated the membrane. Unlike the HPE which has two separate streams of potassium hydroxide solution each kept separate using asbestos cell diaphragms, the SPE electrolysis water is circulated only to the oxygen electrode (anode). Excess anode water is supplied to provide cooling, and to sweep away the oxygen produced from the electrode surface.

A further significant difference between the SPE cell and the HPE cell is that the SPE membrane has flexible electro-catalyst bonded to its surface. This feature reduces cell voltage drop, increases efficiency, and produces a compact lightweight cell. FIG. 2 details schematically a typical SPE cell.

Pilot Phase

In 1975 CJB Developments Ltd. were awarded a contract to commence development of an SPE electrolyser. The Pilot Phase objectives were to investigate the relationship between process parameters, and particularly to examine critical aspects that were known to affect performance on the HPE. The critical areas were:

(*a*) Pressure control.
(*b*) Feedwater supply and purity.
(*c*) Gas purity and analysis.
(*d*) Gas/water separation.
(*e*) Control system.
(*f*) Purge system.
(*g*) Cell performance and degradation.
(*h*) Safety system.

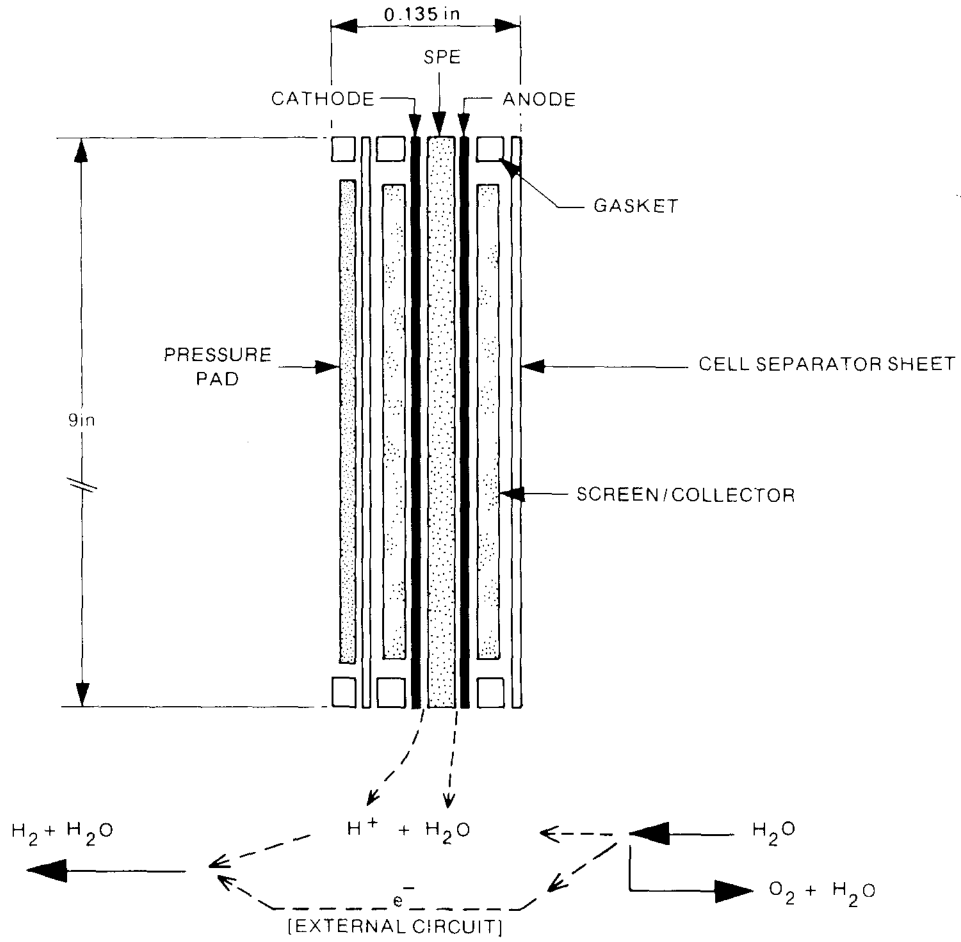


FIG. 2—SPE CELL DIAGRAM

A 0·34 m^3/hr six cell pilot rig was commissioned and successfully operated for 100 hours. Results indicated that in the pressure range 0 to 124 bar conversion efficiency was virtually constant, but that system complexity increased as operating pressure increased. The optimum route was to develop a low pressure electrolyser with the oxygen side pressure at atmospheric, and the hydrogen side pressure at 10 bar.

Breadboard Prototype

Production of a fifty-eight cell 2·8 m^3/hr breadboard plant built to commercial standards commenced in 1977. The process system is shown in FIG. 3. Starting at the inlet, demineralized water supply (the make-up cell reaction water) is delivered via an electrically-operated valve (2). The valve operation is intermittent, with demand signals received from a high-low level sensor in the oxygen separator (3). Make-up water mixes with the water from the separator and is then circulated to the heat exchanger (5) by means of the circulating pump (4). From the heat exchanger the water passes through a de-ionizer (6), a flowmeter (8), and filter (9) before entering the cell stack oxygen side. In the cell stack the water provides anode feed and cell cooling. The oxygen/water mix is separated at the oxygen separator and the oxygen (99.8 per cent pure) is delivered to the submarine ventilation system. Apart from the initial filling of the plant no water is supplied to the hydrogen side. There is an ionic water transfer across the cell membrane from anode to cathode at eight times the electrolysis rate. Water is transferred

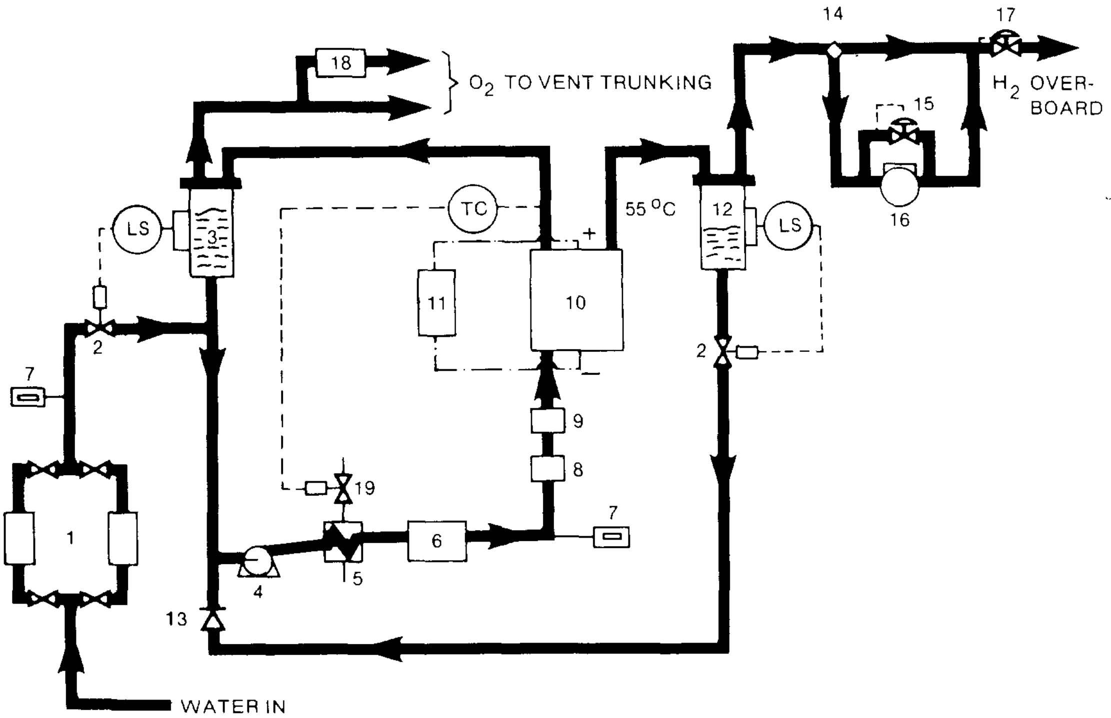


FIG. 3—LOW PRESSURE SPE PROCESS DIAGRAM

Key
1. De-ionizer
2. Solenoid valve
3. Oxygen separator
4. Circulating pump
5. Heat exchanger
6. In-line de-ionizer
7. Conductivity cell
8. Flowmeter
9. Filter
10. Cell stack
11. Transformer/rectifier unit
12. Hydrogen separator
13. Check valve
14. Discharge selection valve
15. Pressure maintaining valve
16. Hydrogen compressor
17. Pressure regulating valve
18. Oxygen analyser
19. Temperature control valve

TC. Temperature controller
LS. Level switch

from the hydrogen separator (12) via the intermittent operation of the valve (2) which is controlled by signals from a high-low level sensor in the hydrogen separator. The oxygen side operates at 0·2 bar, slightly above atmospheric in order to facilitate gas discharge. The hydrogen side operates at 10 bar.

The breadboard plant operated successfully for 3100 hours and was virtually trouble-free. There were minor problems with gas/water separation, gas analysis and de-ionizer design, but these were solved early in the programme and the remainder of the time was spent in establishing the design definition for a naval system. An interesting period began when at 2400 hours an external water leak already present in the fifty-eight cell stack increased in severity and could not be controlled by increasing the tension on the tie bolts. The stack was stripped and two cells were found to have developed small pinholes in the inter-cell separator sheets. Subsequent investigations showed the pinholes had been caused by corrosion induced in the hydrogen side during shut-down when fuel cell conditions were created due to the high capacitive charge on an open circuit cell stack slowly leaking away. Changes were introduced to increase the cell-stack open circuit resistance and to modify the separator sheet coating material. Subsequent tests on single and multiple cell rigs have demonstrated that the problem has been resolved.

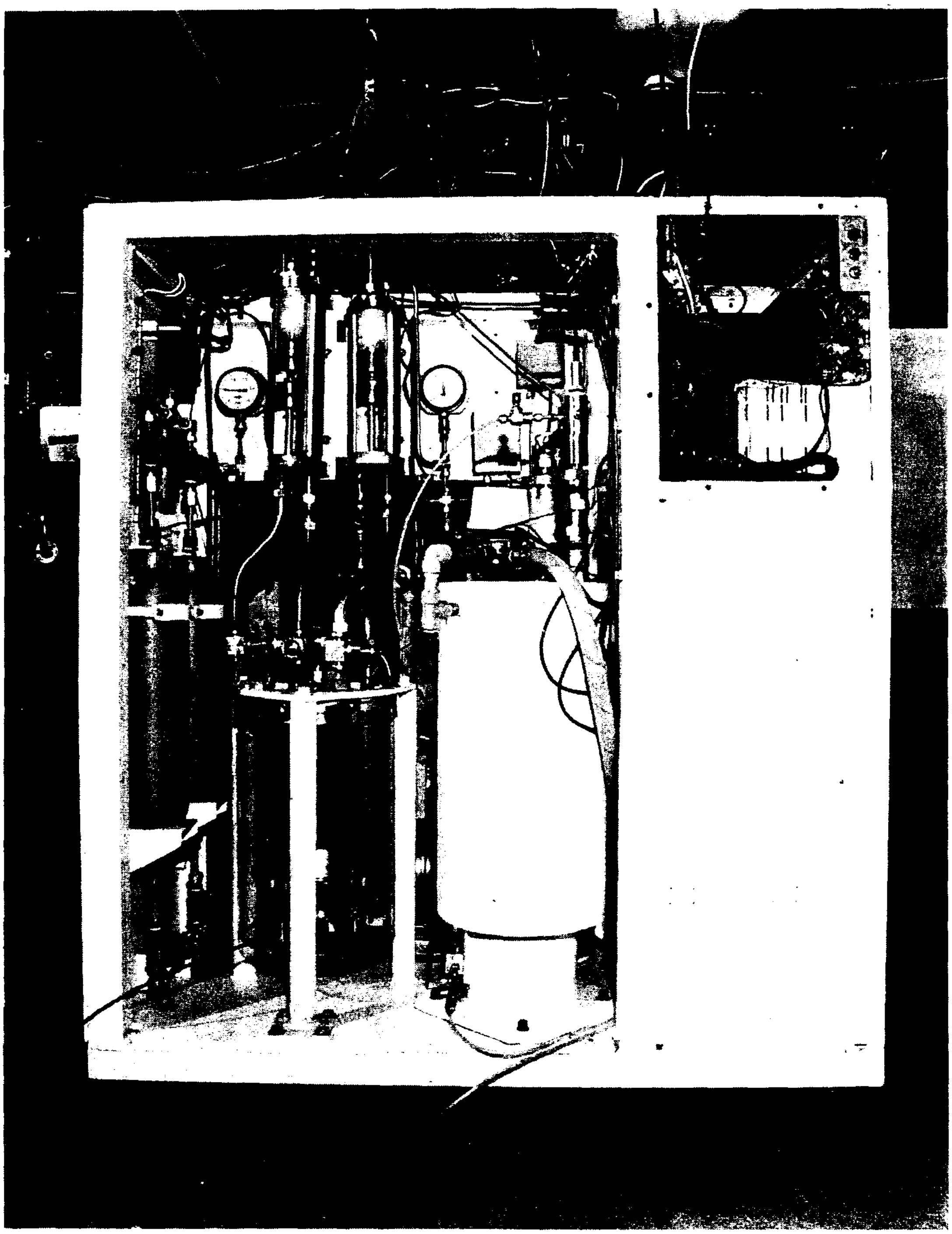


FIG. 4—BREADBOARD PROTOTYPE SPE ELECTROLYSER

FIG. 4 shows the breadboard plant. It demonstrated beyond doubt the feasibility of producing a naval electrolyser and in 1979 production of the naval prototype began.

Naval prototype

The data and operating experience acquired from the earlier programme phases were used to produce a Development Specification that detailed the Ministry of Defence requirements for the production system. The Development Specification contained details of gas output rates, noise, shock, vibration, availability, reliability and maintainability targets, quality assurance requirements, environmental characteristics, and support requirements. The task before the project team was to integrate the breadboard results into the naval system and to demonstrate that the Development Specification could be achieved (FIG. 5).

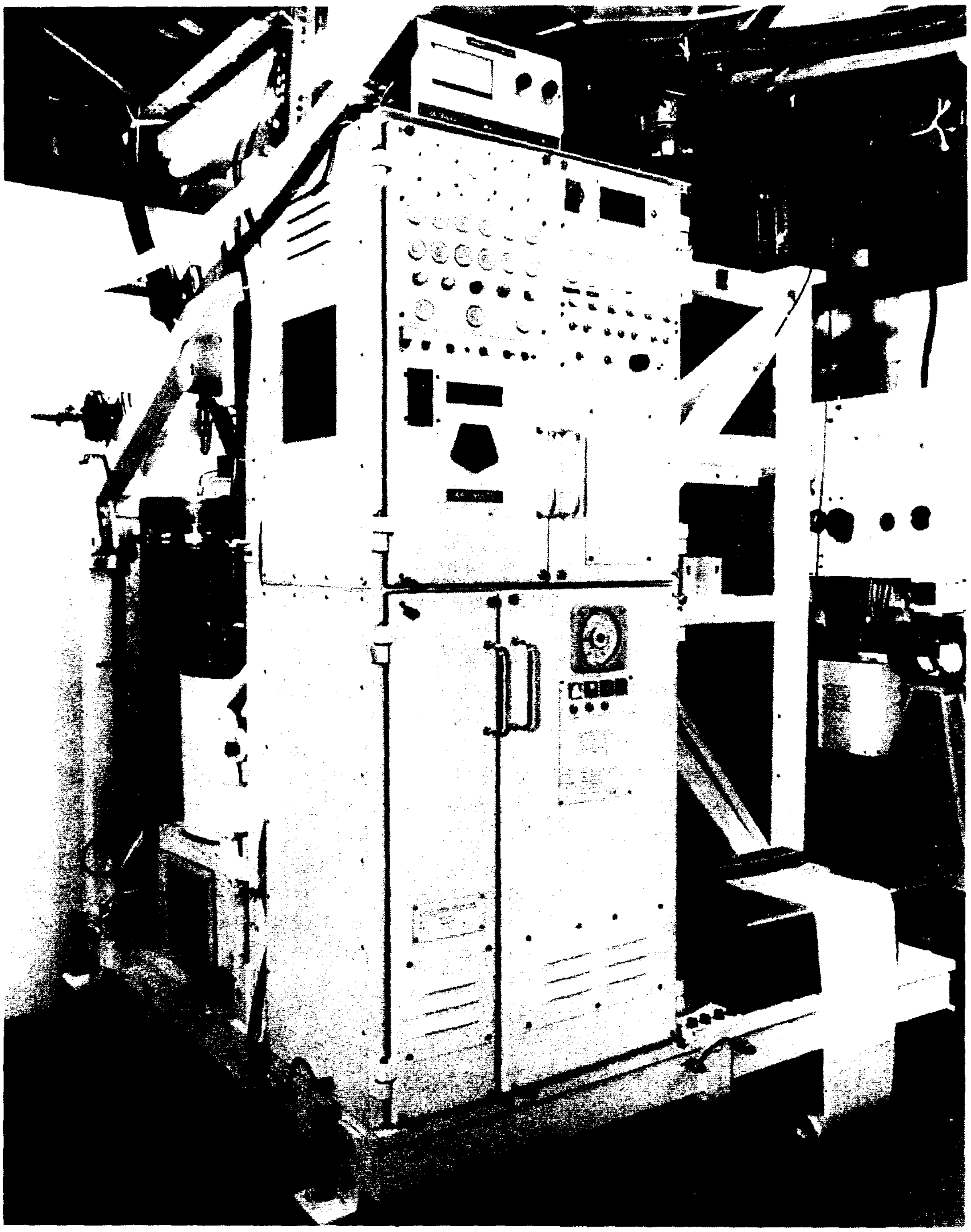


FIG. 5—MAIN FRAME ASSEMBLY OF THE NAVAL PROTOTYPE ELECTROLYSER

The first obstacle encountered was the selection of suitable components. For many applications components already in service were not suitable, and selecting suitable commercial alternatives capable of meeting the requirements was a time-consuming and costly exercise. There were occasions, too many in fact, where the project had to assess a component's suitability for use when the manufacturer was unable to provide the confidence sought. Considered risks were taken, sometimes involving vital sub-systems, but the principle adhered to throughout was that the benefits of SPE should not be diminished by the incorporation of in-service type-approved components where these would compromise the design.

In any development activity it is important to ensure that successful prototype performance can be repeated in production units. Quality assurance needs to be given adequate consideration at all stages. The development team have an obligation to think the project right through to in-service support. For the SPE electrolyser the components have mostly been supplied by Defence Quality Assurance Board approved contractors against defined performance specifications.

The naval plant has an oxygen output greater than that of the breadboard and sufficient to meet future requirements. The plant is modularized to provide flexibility of installation, to improve on-board accessibility, and to facillitate the upkeep by exchange of defective units. The plant consists of:

(*a*) Main Frame Assembly (MFA)—one common structural assembly on a single bedplate housing two independent electrolyser process and control systems.

(*b*) Transformer Rectifier Unit—a free-standing air-cooled direct current supply with an input from the 440V 60Hz 3 phase system (one for each system on the MFA).

(*c*) Hydrogen Discharge Assembly—one common bedplate housing two independent discharge systems.

The power supplies, controls, and process and discharge systems are dedicated to each electrolyser for normal operation. The capability to cross-connect between particular assemblies has been incorporated.

The HPE requires up to forty minutes to complete a pressurize-depressurize cycle. The SPE electrolyser can be pressure-cycled in less than three minutes with oxygen being discharged within fifteen seconds of start-up. The ease with which it can be restarted after a stoppage has allowed a simple but comprehensive control system to be incorporated. The reduction in pre-start checks, compared with HPE, and the use of simple circuit interlocks has allowed straightforward manual operating routines to be adopted for stop, start, and output variation. This apparent step back in concept has received wide support from operational personnel. There are twenty measured parameters which will prevent start-up, or initiate shut-down if pre-programmed levels are exceeded. The control logic displays the initiating failure cause to the operator. A plant simulator is integrated into the logic system to allow operators to follow fault-finding routines at a slower pace than normal logic sequencing will allow.

Availability, Reliability, and Maintainability

Successive HPE development electrolysers were accepted from the manufacturer after completing a 2500 hour trial each. The equipment was then tested further at AMTE Haslar for periods up to 10 000 hours. Throughout the development of the SPE electrolyser, Availability, Reliability and

Maintainability (ARM) characteristics were continuously reviewed. It was decided that the naval prototype would be performance tested solely at the contractor's works. The endurance trial was aimed at allowing the contractor to demonstrate that the Development Specification for ARM performance was attainable. The defence expenditure moratorium in 1980 had a positively beneficial effect on the testing policy. The dilemma was to allow sufficient testing time to enable ARM performance to be determined whilst keeping testing costs to a minimum. A Planned Reliability Growth Programme (PRGP) was selected that would enable technical and financial progress to be monitored against the time-controlled achievement of availability and reliability targets.

The Duane reliability model was selected as the most suitable. There are more refined reliability prediction models but, looking to the future service application, the data input to the Duane model is more easily obtained from normal Service sources. Codier[3] and Green[4,5] describe the Duane model, which shows that an empirical relationship exists between cumulative mean time between failures (MTBF) and the testing time for development programmes where a continuous effort is made to improve reliability by the introduction of modifications. Hill[6] shows that a similar principle can be adopted to plot cumulative Mean Time to Repair (MTTR), and the combination of instantaneous values for MTBF and MTTR can be used to compute instantaneous availability using the formula:

$$\text{Availability} = \frac{\text{MTBF}}{\text{MTBF} + \text{MTTR}}$$

The HPE performance of MTBF = 200 hours and MTTR = 6·5 hours was used as a basis for setting target levels for the SPE electrolyser at 700 hours and 2·5 hours respectively. In setting the targets account had to be taken of the economic consequences of reaching too far, and the relationship between shore-based test results and in-service capability. For HPE a shore-based test would yield an MTBF twice that exhibited by an operational unit, the inverse applying to the MTTR. This difference was not expected to be so significant for the simpler SPE electrolyser. In a 3100 hour test the breadboard plant achieved a cumulative MTBF of 212 hours, equivalent to 406 hours achieved instantaneous MTFB ($MTBF_I$) with a reliability growth factor of 0·47. The naval prototype was basically the same process system with different components. Failure modes were expected to be more difficult to correct, but failure frequency would be reduced. Assuming a conservative factor of 0·2 (low reliability growth) the required MTBF of 700 hours was estimated to be achievable within 5000 hours' testing. An MTBF of 700 hours combined with an MTTR of 2·5 hours gave an availability of 0·996 which was operationally acceptable, and most importantly kept the test programme within the tight cost constraints.

The plant was considered to have failed when it did not meet any one or more of the following criteria:

(*a*) Plant delivers demanded output.

(*b*) Plant accepts changed control demand.

(*c*) Plant reacts safely to alarm condition.

The plant has completed 5000 hours endurance testing and has demonstrated:

$$MTBF_I = 659 \text{ hours}$$
$$MTTR_I = 0{\cdot}941 \text{ hours}$$
$$\text{Availability} = 0{\cdot}9986$$

The Duane reliability plot shown in FIG. 6 compares predicted reliability growth with achieved reliability growth. The achieved $MTBF_I$ of 659 hours falls slightly short of the target level, but the value is sensitive to interpretation of the plotted result. The MTTR of 0·94 hours betters the target and this assures that overall availability at 0·998 is better than forecast.

The design has been produced to allow for minimum on-board maintenance. Required maintenance envelopes for the assembly modules were specified at an early stage in the development. No module has access on more

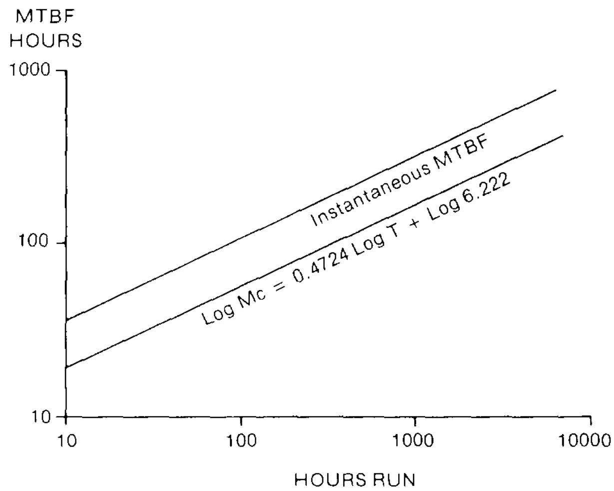


FIG. 6—DUANE RELIABILITY PLOT FOR NAVAL PROTOTYPE

than two sides and the maximum allowance for access is 0·6 m from the front. If side access is allowed a maximum of 0·45 m has been specified. A full Maintenance Evaluation has been conducted by Director Engineering Support (Navy) personnel and all maintenance tasks were confirmed to be feasible within the authorized envelope.

The results achieved during the endurance trials show the plant to have an overall performance that meets the specification and is significantly better than the HPE. On completing endurance trials the naval prototype was despatched to the National Gas Turbine Establishment (now the Royal Aircraft Establishment) at West Drayton to undergo full environmental testing.

Environmental Testing

The environmental testing was divided into four parts:

(*a*) *Vibration Tests:* The vibration tests attempt to induce resonances in the units at the various forcing frequencies found in submarines. Few problems were encountered and all were cured with minor stiffening.

(*b*) *Shock Tests:* The shock tests showed some minor problems and tripped the plant. The plant was immediately restarted and produced full output.

(*c*) *High Temperature/Humidity Tests:* These tests attempt to create the most extreme conditions found in a submarine. Unfortunately the test facilities currently available cannot produce the most extreme conditions. The plant performed satisfactorily under the worst conditions achievable.

(*d*) *Electro-Magnetic Compatibility:* The plant will operate satisfactorily in the EMC environment found in submarines and will not produce any unacceptable emissions.

Summary

Modern submarines submerge for long periods with no contact with the earth's atmosphere. This forces us to consider the effects of many atmospheric contaminants and to provide methods of controlling the effects of occupation of the submarine and restoring its atmosphere.

The development of the SPE electrolyser shows the typical processes involved in producing a piece of equipment for the harsh naval environment. The successful conclusion of this programme has provided a considerable improvement in oxygen production equipment for the submarine fleet (see TABLE II).

Other items of atmosphere control equipment can benefit from new technology, and various other development programmes are in hand. The SPE electrolyser programme has been described as a typical example.

The endurance and environmental trials have shown that the prototype design will meet its objectives. The production design is therefore much the same as the naval prototype. The design is now fixed and the first production plant is complete.

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