AR-009-803

DSTO-TR-0397

A Feasibility Study of Using Oxygen Enrichment for Fuel Cell Air Independent Propulsion

G.A. Clark and M.J. Rowan

DEPARTMENT OF DEFENCE

DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION

Mar-28

A Feasibility Study of Using Oxygen Enrichment for Fuel Cell Air Independent Propulsion

G.A. Clark and M.J. Rowan

Ship Structures and Materials Division
Aeronautical and Maritime Research Laboratory

DSTO-TR-0397

ABSTRACT

It is shown that the output power from a polymer electrolyte membrane (PRM) fuel cell oxygen follows a quadratic relationship with increasing oxygen concentration. Using this information, a potential application of using oxygen enrichment membrane technology for an air breathing fuel cell was investigated. The system chosen was a hypothetical PEM fuel cell powered air independent propulsion system in a conventional diesel electric submarine. A simple model of the system was made using linear programming. The results showed that using existing membrane technology for oxygen enrichment of the incoming air stream, two compressor stages were required whose power requirements were too great for the system. A 30% improvement over existing molecular selectivity in membrane oxygen enrichment technology would allow a single compressor stage, however, 40% of the fuel cell power would still be needed to power the required compressor stage.

RELEASE LIMITATION

Approved for public release

DEPARTMENT OF DEFENCE

DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION

Published by

DSTO Aeronautical and Maritime Research Laboratory
PO Box 4331
Melbourne Victoria 3001

Telephone: (03) 9626 8111
Fax: (03) 9626 8999

AR No. AR-009-803
August 1996

APPROVED FOR PUBLIC RELEASE

A Feasibility Study of Using Oxygen Enrichment for Fuel Cell Air Independent Propulsion

Executive Summary

Ongoing research and development of several technologies worldwide has centred on improving the underwater endurance of conventional diesel electric submarines. Throughout a mission a diesel electric submarine has to frequently recharge the submarine storage battery sets. Battery recharging requires the submarine to surface or snorkel close to the surface to obtain air to operate the onboard diesel generator sets. During battery recharging the submarine is most vulnerable to detection by a number of anti-submarine warfare techniques.

Extending the underwater endurance of a submarine, thereby reducing the frequency and duration of battery charging, increases its operational effectiveness. One viable technology for providing extended underwater endurance is solid polymer electrolyte fuel cells (SPEFC) currently being investigated at the Aeronautical and Maritime Research Laboratory.

Normal operation of an SPEFC AIP system utilises hydrogen and oxygen as the fuel and oxidant respectively to produce DC power when then submarine is fully submerged. However, a SPEFC can also operate on hydrogen and air if configured to do so. Therefore, it has been suggested that the operating effectiveness of a submarine could be further enhanced by incorporating an oxygen enrichment plant (OEP) into the SPEFC system. By doing this a submarine when surfaced or snorkelling to recharge the batteries could operate the SPEFC on hydrogen and air which could be used to supplement part (or all) of the normal power drawn from the batteries or diesel-generator sets for ancillary equipment and the hotel load. The potential advantages being:

- higher chemical to electrical energy conversion with a commensurate lower thermal signature from the submarine
- quieter operation when snorkling or surfaced.

However, fuel cell performance using air as the oxidant is lower than operation with pure oxygen. This report investigates the potential of oxygen enrichment technology to improve fuel cell performance in potential SPEFC AIP systems.

The 5kW SPEFC system located at AMRL was modified to simulate various enriched oxygen conditions of the incoming oxidant stream to determine the effect on output power. It was shown experimentally that power output from the SPEFC increased 60% when operating on hydrogen and oxygen enriched air (50% oxygen) compared with standard hydrogen and air operation. This was 85% of the power obtainable on pure oxygen and hydrogen and at a technically attainable level of oxygen enrichment.

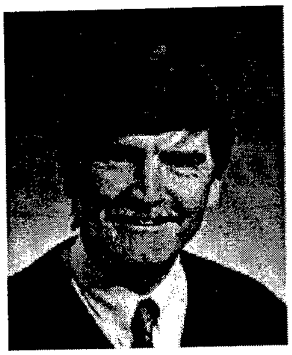
Two conceptual models were developed to determine the system requirements for a submarine of approximately 3300 tonnes displacement. The first model was based on a commercially available dual stage oxygen enrichment plant. The second model was based on a hypothetical single stage plant. Linear programming was used to optimise system performance and operating parameters.

It was shown that with existing dual stage membrane technology it would not be feasible to enrich air on a conventional submarine for purposes of an SPEFC AIP system. Single stage modelling indicated that approximately 40% of the output power from the SPEFC would be consumed during operation. Clearly this is impractical. Hence, the limitations arising from existing and possible future developments of oxygen enrichment membrane technology indicate that it would be inappropriate to apply this technology to an AIP equipped submarine.

Authors

G.A. Clark

Ship Structures and Materials Division



Gregory Clark joined AMRL in 1972 where he initially worked in the areas of metrology, laser research and electronics. After obtaining a bachelor of Applied Science (Physics) from RMIT in 1979 he joined the Explosives Division undertaking experimental and theoretical research into the field of electromagnetic propulsion. In 1986 he moved to the Materials Division researching the defence applications and significance of retro reflection. He is currently a Senior Professional Officer C undertaking experimental and system study work into the application of fuel cells for air independent propulsion and has just completed a Masters Degree in Systems Engineering.

M.J. Rowan

Ship Structures and Materials Division

Martin Rowan graduated B Eng (Footscray Institute, 1984) majoring in Mechanical Engineering. From 1985 he was employed with the State transport Authority of Victoria in the Project Development Section. In 1988 he joined the State Electricity Commission of Victoria and worked in a variety of sections providing engineering services to the power stations and open cut coal mines of the Latrobe Valley. He joined MRL in 1991 as a member of the fuel cell task and the submarine storage batteries task, and is currently a Senior Professional Officer C.

Contents

1. Introduction

Operating effectiveness of military submarines depends greatly on their ability to operate covertly and independently. Significant research and development world-wide is continuing on developing techniques to reduce the detectability of submarines. Minimising a conventional submarine's operating signature is becoming increasingly important as anti-submarine warfare (ASW) systems become more sophisticated.

A conventional submarines vulnerability to detection is greatest during periods when surfaced or snorkelling to recharge the submarine storage batteries. The batteries are recharged using the onboard diesel-generator sets. The diesels emit high temperature exhaust gases and engine noise that are vulnerable to detection by thermal and acoustic sensing devices. In such cases, the submarine is also vulnerable to visual or radar detection.

One way of improving the covertness and evasiveness of a submarine is to increase its underwater endurance capability. In the case of conventional submarines, this could be achieved by installing an air independent propulsion (AIP) system that could provide part or all of the propulsive power whilst submerged[1]. Fuel cells, Stirling engines[2], closed cycle turbines and closed cycle diesels(CCD) have been identified as possible AIP systems for conventional diesel electric submarines. The first two candidates are under active investigation at the Aeronautical and Maritime Research Laboratory (AMRL) to determine their suitability for diesel electric submarines.

Of the six types of fuel cells that are or have been investigated for marine vessel applications, solid polymer electrolyte fuel cells (SPEFC) have been identified as the most suitable fuel cell system for military submarine applications[3]. A SPEFC produces power by electrochemically combining a fuel and oxidant. The fuel, pure hydrogen can be stored on board a submarine in a number of ways, such as liquid hydrogen, gaseous hydrogen absorbed in metal hydrides or obtained by reforming a liquid hydrocarbon such as methanol. Liquid oxygen is the preferred method of storing the oxidant.

It has been estimated that a conventional submarine of 3300 tonnes displacement would typically require an AIP stored energy capacity of 100 MWh [1,4]. It has also been shown in these reports that this amount of energy would provide about a four-fold increase in the submerged endurance.

This paper considers a further enhancement of a conventional submarine equipped with a SPEFC AIP system. As a SPEFC system can operate on either hydrogen and oxygen or hydrogen and air it is suggested that the operating envelop of a SPEFC AIP system would be enhanced if an oxygen enrichment plant (OEP) was incorporated into the AIP system. Thus a submarine with sufficient hydrogen storage could snorkel to obtain air not only for operating the diesel-generator sets but also for the SPEFC.

Consequently, a fuel cell of sufficient power[1] could assist the recharging of the batteries and/or power the submarine near the patrol area with lower thermal and noise signatures than normally produced by the diesel generators recharging alone. Alternatively, it could apply to a mono-boat[2] where the diesel engines have been removed and the submarine is powered solely by a combination of fuel cells and batteries. In this scenario, the fuel cell power would also use snorkelling to obtain oxygen from the air to generate power and recharge the batteries.

The operating characteristics of a SPEFC utilising air instead of pure oxygen has two shortcomings:

- for an equivalent demand for oxygen, the air flow must be at least 5 times the pure oxygen flow due to the lower concentration of oxygen in the air (21% compared to 100% oxygen)
- even with the increased oxidant flow, the maximum continuous power output from the fuel cell is reduced to approximately 40% of the power when operating with pure oxygen [5].

These disadvantages may be reduced if the oxygen concentration of the incoming air stream can be increased by utilising an OEP. However, oxygen enrichment will only prove advantageous if the power required to increase the oxygen concentration of the air is significantly less than the increase in output power from the SPEFC due to the oxygen enriched air stream.

This report presents the results on the performance of a SPEFC when the air flow was enriched in oxygen. The results were then applied to evaluating the benefits of adding an OEP to a fuel cell AIP system installed in a conventional diesel electric submarine of 3,300 tonne displacement and also a hypothetical mono-boat.

2. Oxygen Enrichment System

Maximising the power output from the fuel cell whilst snorkelling can be achieved by enriching the oxygen concentration of the air stream prior to consumption in the SPEFC. Several commercial oxygen enrichment systems are available that are used in hospital and industrial applications for the on site generation of oxygen or nitrogen enriched air from pressurised air lines.

---

[1] Clark[4] has shown that it is possible a install a fuel cell with >1.4 MW of power in a conventional 3,300 tonne submarine. This level of power would be sufficient to recharge at least half the batteries stack whilst also providing submarine hotel and propulsive power.

[2] It should be noted that in a mono-boat the fuel cell stack power would need to be multi-megawatt for a submarine of 3,300 tonnes displacement.

The oxygen (O_2) enrichment system that is readily available and appears to be most suited to a submarine environment is the permeable membrane technique. This enrichment technique is efficient, requiring minimal mechanical components as only pressurised air is required for its operation. Subsequently, it is a technology that appears to be well suited for operation aboard a submarine due to its simplicity and efficiency.

2.1 Technology Description

An efficient method to enrich the oxygen concentration of the air stream is to pass the incoming air through a series of membranes where there is a preferential diffusion rate for oxygen through the membrane over the other gases in the air, viz. nitrogen [6]. A number of commercial oxygen enrichment systems are available that are capable of increasing the oxygen concentrations up to 50% [7,8]. Separation of the different gases is achieved by preferential diffusion of the gas species through the membrane material (Fig 1). A single pass through such membranes can enrich the oxygen concentration in the air to 35% and with a second stage of filtering, a 50% concentration can be achieved. Similarly, if an enriched nitrogen stream is wanted, say for smothering a fire, a single pass will yield an "air" flow with 95% nitrogen with 99.5% obtainable with further filtering [7].

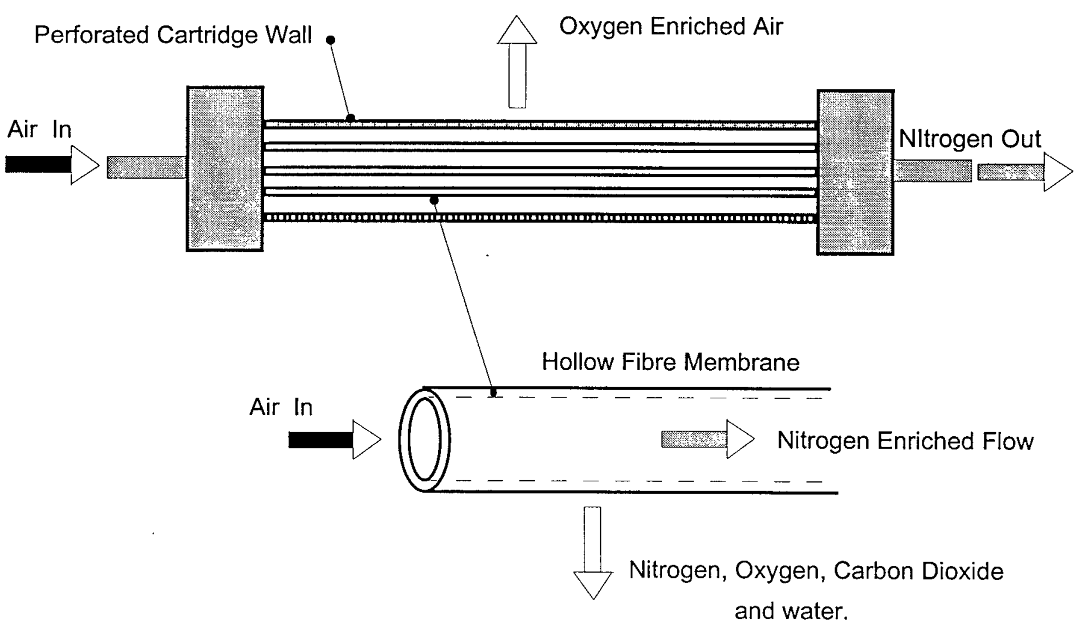


Figure 1. Oxygen/Nitrogen Enrichment using Membrane Technology with a Hollow Fibre Configuration.

Other methods of oxygen enrichment such as pressure swing absorption or continuous magnetic separation [9] are either energy intensive or have not yet become a commercial product.

2.2 Experimental Simulation of Membrane Oxygen Enrichment

As a means of evaluating the potential of using an OEP to increase the operating envelop of a SPEFC system, the existing oxidant supply line to the 5 kW SPEFC purchased by AMRL was modified to provide a variable control on the oxygen-to-nitrogen concentration of the incoming oxidant gas stream supplied to the fuel cell stack. The specifications of the AMRL fuel cell power supply (FCPS) are listed in Appendix 1.

The output voltage and current of the fuel cell were recorded whilst the oxygen concentration in the gas flow was increased from 21%(air) to 100%[3]. The oxygen concentration was measured by a Servomex paramagnetic oxygen sensor whose accuracy was better than 1%. A schematic representation of the experimental arrangement is shown in Figure 2.

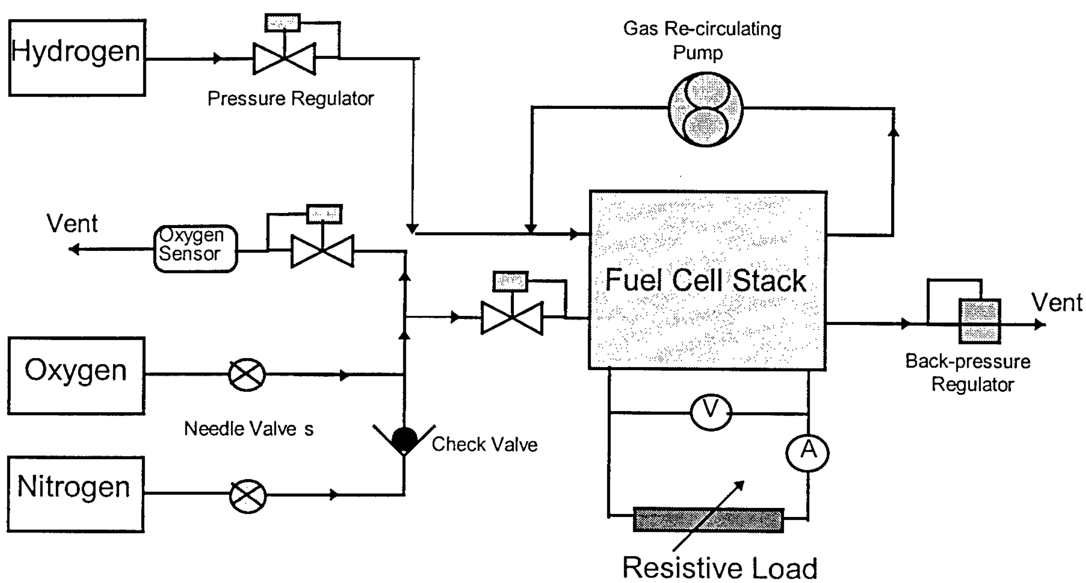


Figure 2. Experimental Oxygen Enrichment System to Simulate Oxygen Enrichment by Membrane Diffusion.

[3] Membrane technology is continually developing and membranes offering higher enrichment concentrations than 50% may become available in the foreseeable future.

The FCPS was operated in a flow through mode for the oxidant flow (Fig 2). In this mode, the oxidant gas had a single pass through the stack . Oxygen not consumed by the stack was exhausted out of the stack and vented to the atmosphere[4]. The internal oxidant pressure of the stack was controlled between the input pressure of 350 kPa and a back-pressure regulator on the oxidant exit of the stack set at 250 kPa. The 100 kPa pressure drop in the stack was due to the flow of the gas through the internal gas manifolding of the stack. The mixture of O_2 and N_2 gas entering the stack was maintained at a constant flow of 68 lpm.

The flow of pure hydrogen was operated in a closed loop mode at a constant pressure of 350 kPa. The unconsumed hydrogen exiting the stack was recirculated back through the FCPS (Fig 2.).

The electrical resistive load for the stack output was decreased in steps from an initial open circuit until the lower voltage limit (0.4V) of any individual cell voltages was reached. Curves of the stack output voltage versus the output current (known as polarisation curves) were obtained for the operating temperature of 50°C. This temperature was chosen instead of the maximum air/hydrogen operating temperature of 54°C as the results could be compared to earlier results of hydrogen/oxygen operation [10].

2.3 Experimental Results of Oxygen Enrichment

Figure 3 displays the effect on the polarisation curve of changing the oxygen concentration. It is clearly seen that the stack voltage increased in the linear resistive region of the polarisation curve with increasing oxygen concentration.

[4] An alternative mode of operation is the closed loop mode. In this mode pure oxygen exiting the stack is recirculated back through the stack. This mode was not used for the enriched air as it would result in the oxygen component of the gas being consumed in the stack with a commensurate increase in the nitrogen concentration as the nitrogen is not consumed.

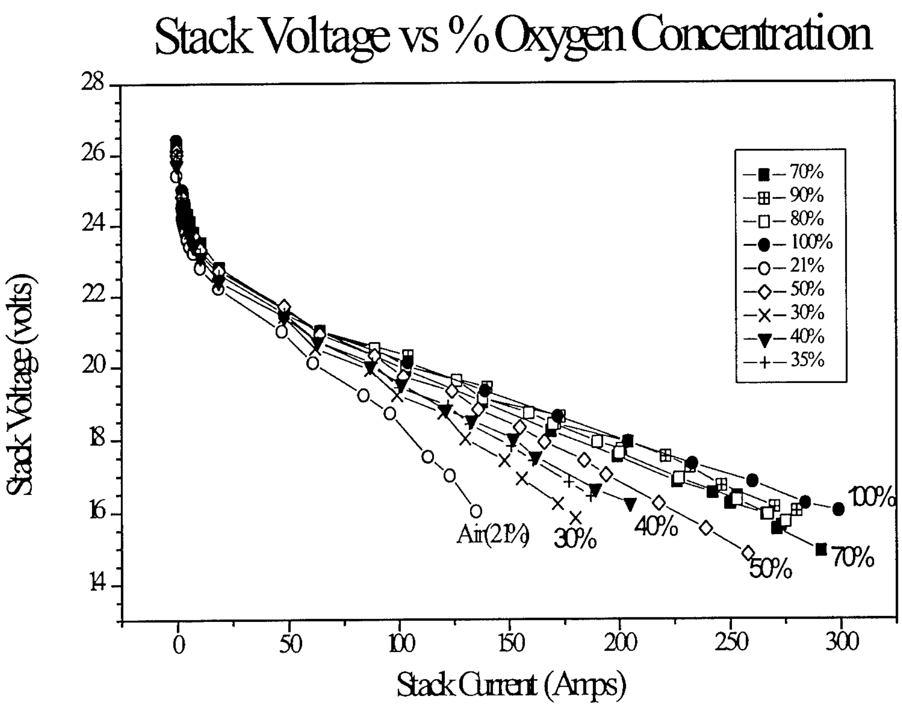


Figure 3. Polarisation curves of the fuel cell at different oxygen enrichment levels.

Using Origin software [11] a multiple regression analysis determined the formula to each curve. The formula was in the form of the Nernst equation: -

$$E = E_o + A\log_{10}(i) + Bi \qquad (1)$$

where,

E is the stack voltage,
E_o is the open circuit voltage,
i the stack current (amperes),
A is Tafel constant (ohms/decade) and,
B is the total system resistance of the stack membranes (ohms)

Table 1 lists the formulae coefficients for the different oxygen concentration.

Table 1. Formulae coefficients for the different concentrations of O_2.

% OXYGEN	E_O (volts)	Tafel constant Co-eff "A" (ohms/decade)	System Resistance Co-eff. "B" (ohms)
100	25.93	-2.201	-0.0147
90	25.51	-1.837	-0.0174
80	25.9	-1.866	-0.0181
70	25.80	-1.972	-0.0194
50	25.55	-1.697	-0.0242
40	25.16	-1.649	-0.0246
35	25.42	-1.732	-0.0258
30	25.32	-1.629	-0.0304
21 (Air)	24.84	-1.375	-0.0398

From the experimental data, the output power was calculated for each level of oxygen at a stack voltage of 17.5 volts. At 17.5 volts the average cell voltage would be 0.7 V which is a typical cell operating voltage for a SPEFC under continuous load.

For purposes of measuring any increase in performance, the polarisation curve of the FCPS operated with 100% hydrogen and 100% oxygen in a closed loop mode at 50°C with reactant inlet pressures of 350 kPa (Fig 4) was used.

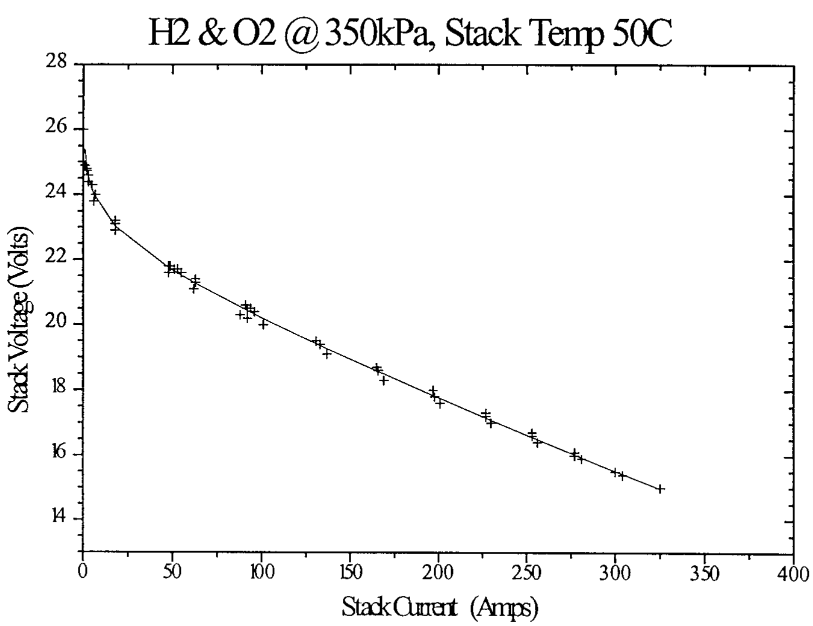


Figure 4. Polarisation curve of FCPS operating in closed loop mode with 100% hydrogen and 100% oxygen at 50 °C, 350 kPa stack pressure.

Output power at 17.5 volts in the closed loop mode was 3.71 kW [Fig 4] which was approximately 5% less than the maximum power obtained with 100% oxygen open loop configuration. This lower level of power may be explained by the fact that the flow in the closed loop mode (<30 lpm) is less than the flow through mode (68 lpm). The greater flow would be expected to account for a slightly higher output power due to the increased turbulence at the membrane walls possibly leading to a greater reaction rate[5], a lower oxygen concentration polarisation or better gas diffusion at the electrode due to product water being swept away or a combination of all three. Figure 5 shows the output power as a function of oxygen concentration for the flow through mode.

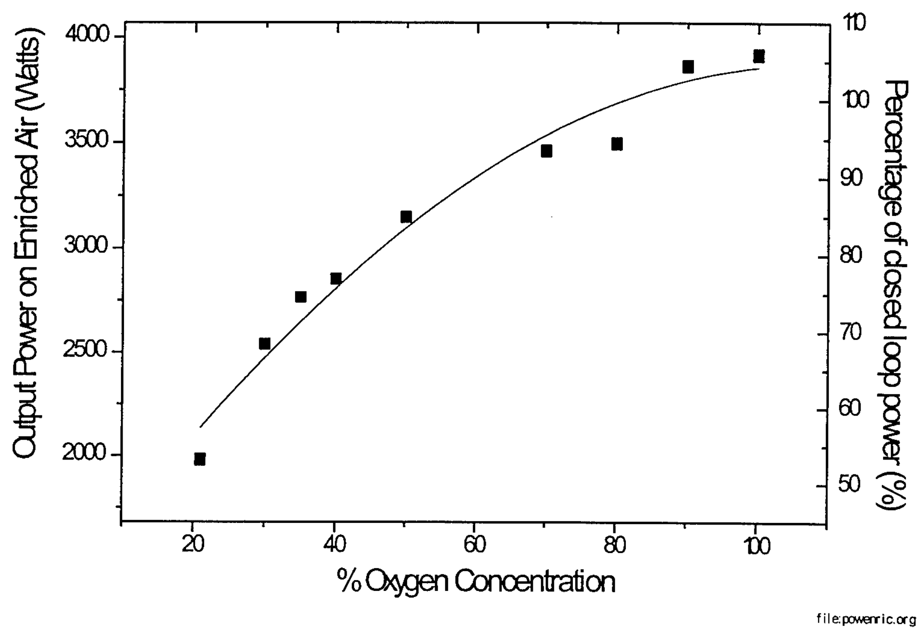


Figure 5. Output power from the fuel cell (@17.5 volts) as a function of oxygen enrichment at 50 °C temperature, 350 kPa stack pressure.

2.4 Experimental Conclusions

The results have shown that enrichment of the oxidant stream above the 21% level of oxygen in the air will produce an increase in the output power of a SPEFC. Figure 5 clearly shows that at the 35% and 50% levels of oxygen (both levels easily obtainable with an OEP) the output power is 75% and 85% of that achieved on 100% oxygen in a closed loop (recirculating) mode compared to 53% when operating on air. Alternatively, there was a 40% and 60% increase in power when operating on 35% and 50% oxygen enrichment respectively over standard air operation.

[5] A higher output power is also evident with the fuel cell stack in closed loop mode (gases continually circulating) than in dead ended mode where H_2 and O_2 are not circulating within the stack.

Equation (2) shows the relationship between power output ("P") and the percentage oxygen concentration ("C") derived from fitting a 2nd order polynomial equation to the results. This equation holds for the operating temperature of 50°C at the specified inlet pressure of 350 kPa and flow of 68 lpm.

$$P = -0.227C^2 + 49.28C + 1199.6 \qquad (2)$$

3. Implications of Oxygen Enrichment for a Conventional Submarine with AIP

The experimental results show clearly the performance advantage of oxygen enrichment for a SPEFC required to operate on air. In practice this increased performance will be reduced by the energy required to supply the pressurised air to the OEP and the fuel cell stack.

However, oxygen enrichment provides the potential for :

- increased operational effectiveness of SPEFC AIP equipped submarines
- the capability of quieter snorkelling with less infra-red signature when recharging of the batteries using diesels and fuel cells
- very quiet snorkelling with a significantly reduced infra-red signature if the fuel cell stack is only used to recharge batteries[6]. The submarine's infra red signature would be reduced due to the lower operating temperature of the fuel cell (~80-90 °C) and the lower amount of waste heat generated[7]. A low noise signature would be achieved by using quiet electric powered turbine compressors.

It has previously been determined that a SPEFC system would fulfil all of the operational endurance requirements of an AIP system for a conventional submarine [1,4]. In the following sections we investigate the requirements of adding a OEP onboard an AIP equipped submarine and the energy requirements for powering the OEP system.

[6] The indiscretion ratio in such cases would depend on the amount of power available to recharge the batteries. Fuel cell power levels would need to be multi-megawatt to equal the diesel generators.

[7] Fuel cells would be operating at approximately 1 MW at 59% efficiency compared to 35-40% efficiency of diesels.

3.1 Modelling Scenario

In modelling the system of oxygen enrichment for a fuel cell equipped submarine we also consider extra storage for the hydrogen fuel. Simple calculations quickly show that it would not be possible to store sufficient hydrogen for the transit out or transit in from the patrol areas based on the Royal Australian Navy mission profiles [12].

As the submarine would not be able to carry sufficient hydrogen for the transit section of an operational tour, the use of OEP would only be advantageous for snorkelling in the patrol areas, eg. near a shoreline or coastal boundary where very long term surveillance was required. As a consequence, snorkelling may be necessary for battery recharging but very low thermal and noise signatures would be desired. For example, an AIP submarine would ideally enter the patrol area with nearly fully charged batteries and operate on a combination of batteries and fuel cell to obtain the maximum endurance approximately four times longer than battery operation alone [1,4].

However, for maximum operational effectiveness a submarine commander would prefer the storage batteries to be at or close to maximum capacity (for that period of the mission) at any time to enable high speed manoeuvring if required. An OEP system combined with a suitably sized fuel cell system may offer the commander the option to recharge his batteries, especially at night, within or very close to the patrol area rather than completely withdrawing from the area.

3.2 Modelling of OEP for an AIP Equipped Submarine

The modelling investigated the requirements of an OEP designed to provide enriched (50% O_2) air to the submarines fuel cell stack. The output power of the stack would assist the diesel charging of the submarines batteries whilst the submarine is snorkelling. Data from commercial equipment for the OEP system and auxiliaries were used in the model.

A fuel cell system operating with an oxygen enrichment system will require a minimum of 1 MW of useable output power to assist in charging the submarines batteries during snorkelling operations. Using an OEP yielding enriched air with a 50% oxygen concentration, a fuel cell will achieve 85% of the power achievable in the normal closed loop AIP operational mode. From this 85% of achievable power, must come the power to run the compressor(s) to pump air through the OEP in addition to the 1 MW to charge the batteries and another 7.5% of the maximum closed loop power to run the fuel cell auxiliaries[13]. Before the required compressor power can be calculated, the general OEP-SPEFC system design must be determined.

3.2.1 System Design

Figure 6 shows a schematic of a hypothetical oxygen enrichment system.

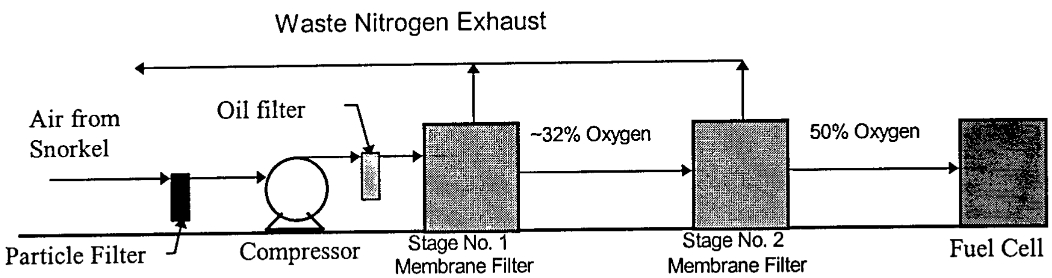


Figure 6. Conceptual oxygen enrichment system for a conventional submarine.

Commercial data on filters [14], compressors [14] and an OEP [7] were used to determine the pressure drops throughout the system[8]. The rotary screw compressor(s) would produce 700 kPa at their nominal flow and this was calculated to be sufficient pressure to feed the fuel cell stack with 350 kPa 50% oxygen enriched air. However, the difficulty with such a system is the required energy to compress the incoming air that is fed into the oxygen enrichment system. The quantity of air required from the snorkel is 7.47 times the flow of enriched air that finally enters the fuel cell stack. Knowing that at the very least, 1 MW of power[9] was required, the required 50% enriched air flow for the fuel cell stack was determined from the experimental gas flow and equation 2. The required incoming air flow would then be over 2700 l/s and require a compressor needing greater than the 1 MW of electrical power generated from the fuel cell stack. Consequently, with the current oxygen enrichment membrane technology it is not a feasible proposition for an AIP submarine system. However, this conceptual model was conducive to modelling using linear optimisation techniques. This allowed the system to be quickly investigated to determine what requirements were needed for the system to be feasible for a submarine.

A major drawback the present system has is that two oxygen enrichment stages are required to attain the 50% enrichment level with each section causing significant pressure drops and requiring significant intake of air in the first stage. The only manner in which an OEP appeared to be feasible was if membrane technology improved so only a single pass was required to achieve 50% oxygen. Although entirely hypothetical, it was considered worthwhile to investigate if such a OEP system would be useful.

The model was modified from the original conceptual system of a double pass through the enrichment membranes to a single pass that would yield 50% oxygen. This would

---

[8] Pressure drops in pipes were ignored as large bore piping would be used with relatively short lengths.

[9] This does not consider auxiliary or compressor power requirements.

require the oxygen enrichment membrane technology to increase from the current 61% diffusion of the available incoming oxygen to 79%. Initially this concept suggests a lowering of the required pressure with a commensurate decrease in the compressor power. However, a membrane with a high selectivity may also require a higher pressure to operate. Therefore, the pressure drop experienced with two stages was left unchanged, but the level of the inlet flow was decreased due to the decreased number of enrichment stages.

Optimising the results for the minimal fuel cell stack power required to provide 1 MW to the batteries on 50% enriched air, a solution was obtained: -

- Fuel cell stack power (O_2 & H_2): 2.56 MW
- Total power on 50% enriched air: 2.18 MW
- Auxiliary power: 0.19 MW
- Power required for compressor: 0.98 MW
- Flow of inlet air: 2,400 l/s
- Flow of 50% enriched air: 800 l/s

The model was extended to investigate a range of battery recharging output powers up to 5 MW. The higher power levels would be relevant to mono-boats where the fuel cell stack would need to have sufficient power to recharge the batteries on their own. Figure 7 shows the results graphically. The compressor power requires approximately 40% of the total power obtained from the fuel cell stack when using 50% enriched air. Therefore a mono-boat of approximately 3,300 tonnes would require nearly 13 MW of fuel cell stack power when using pure O_2 in order to achieve sufficient power from running a hypothetical single stage 50% OEP to charge the submarine batteries[10].

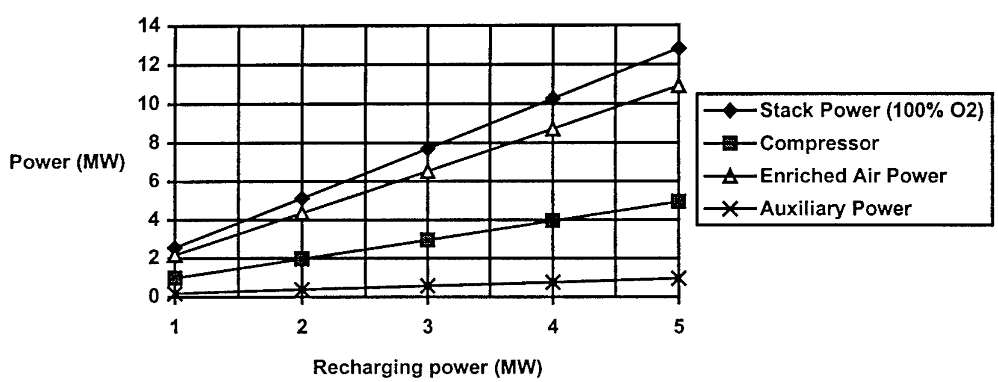


Figure 7. Compressor power, auxiliary power and required fuel cell stack power versus net battery recharging power on 50% enriched air (hypothetical single stage OEP).

[10] Equal to diesel recharging and the same indiscretion ratio.

4. Summary and Conclusions

It has been demonstrated that enriched air supplied to a fuel cell will provide a commensurate increase in the output power of the fuel cell stack. Oxygen enrichment to levels of 35% and 50% that are commercially available, will yield output power levels of 75% and 85% respectively of that obtainable on 100% oxygen. For a given gas flow, pressure and temperature, the output power follows a quadratic relationship dependent on the level of oxygen enrichment.

When oxygen enrichment by current membrane separation technology was applied to an AIP system, the required compressor power level was too great for the system to be viable. Further analysis revealed that the system could be made feasible if the membrane separation technology was improved to allow a single stage of enrichment that would reduce compressor power requirements. However, the membrane technology would have to improve by approximately 30% in its selective molecular diffusion. Even in this case, the compressor power requirements would consume approximately 40% of the SPEFC power output obtained when using 50% enriched air.

As a result of the existing limitations arising from present SPEFC and membrane separation technology it is impractical to consider the application of oxygen enrichment of the air for AIP equipped conventional submarines of 3,300 tonnes displacement.

5. References

1. Brighton, D.R., Mart, P.L., Clark, G.A. and Rowan, M.J.M. (1993). The use of Fuel Cells to Enhance the Underwater Performance of Conventional Submarines. Maritime Technology in the Twenty-First Century Conference, Melbourne University, Melbourne, Australia, 25-27 November 1992.

2. Cocking, J.L., Richards, P.G., and Saulitis, J. (1993). An Overview of Submarine Air-Independent Propulsion and Current Australian Experience with Stirling Engines. Maritime Technology in the Twenty-First Century Conference, Melbourne University, Melbourne, Australia, 25-27 November 1992.

3. P. L. Mart, J. Margeridis, D. Brighton, 'Fuel Cells for Submarine Air Independent Propulsion', *Naval Engineering Bulletin*, Issue 4, January 1991 p. 17

4. Clark, G.A. (1993). Mathematical Analysis of Fuel Cell Air Independent Propulsion Concepts for a Conventional Submarine (U). DSTO-TR-0236, March 1996. CONFIDENTIAL

5. Experience at Materials Research Laboratory (MRL) on the Energy Partners fuel cell has shown the reduction in the maximum continuous power level using air as the oxidant is 37%.

6. Roe, S.P.(1993) Membrane Technology: A Search for Membranes for Submarine Atmosphere Control. MRL Report MRL-GD-0040. Materials Research Laboratory, Melbourne, Australia.

7. A/G Technology Corporation, 101 Hampton Avenue, Needham, MA, USA, 02194-2628. Tel (617) 449-5774, Fax (617) 449-5786.

8. *Membrane air Separation system from Dow produces economical oxygen enriched air stream.*(December, 1985) Dow Chemical USA, 2030 Willard H. Dow Center, Midland, MI 48674, USA.

9. Private communication (Jan'95) with Mr Jack Macknis, Vice President of Lift Feeder Inc. developers of the continuous magnetic separator. 12 Sunnyside Lane, Yardley PA 19067, USA.

10. Clark, G.A., Rowan, M.J., Mart, P.L. and Brighton, D.R. (1993). Poster presented at the 3rd. Grove Fuel Cell Symposium. The Science , Engineering and Practice of Fuel Cells. Imperial College of Science, Technology and Medicine, London. 28th September- 1st October 1993.

11. Origin Software™. MicroCal Software Inc. Northampton, MA 01060, USA.

12. Dovers, W.A.G. (1993). Australia's Maritime Activities and Vulnerabilities. Report by the Strategic and Defence Studies Centre, Canberra, ACT, Australia.

13. Knaack, K., Gruhl, E. and Peterson, U.K. (1991) *Advantages of Air-independent Propulsion Systems for Submarines in Service - The German Approach.* Warship '91 - International Symposium on Naval Submarines 3, Paper 6, 1991.

14 Private communication with Mr Dino Alessio of Champion Compressors Ltd., Princess Highway, Hallam, Victoria, 3803.

15 Chang, Y. and Sullivan, R.S. (1991) *QSB+, Quantitative Systems for Business Plus Version 2.0.* Prentice Hall, Englewood Cliffs, NJ 07632, USA.

Appendix 1

Specifications of the Energy Partners Solid Polymer Electrolyte Fuel Cell.

Membrane:		Nafion 117
Active Area/plate		780.4 cm^2 (0.84 sq ft)
Operating Pressure		288-412 kPa (40-60 psi)
Number of Cells		25
Peak Output Power	(O_2/H_2 operation)	5.5 kW
	(Air/H_2 operation)	3.0 kW
Maximum continuous power	(O_2/H_2 operation)	4.0 kW
	(Air/H_2 operation)	2.5 kW
Maximum Operating Temperature	(O_2/H_2 operation)	71 °C
	(Air/H_2 operation)	54 °C
Hydrogen consumption, (O_2/H_2 operation)		1 litre/s at 5 kW
Oxygen consumption, (O_2/H_2 operation)		0.5 litres/s at 5 kW

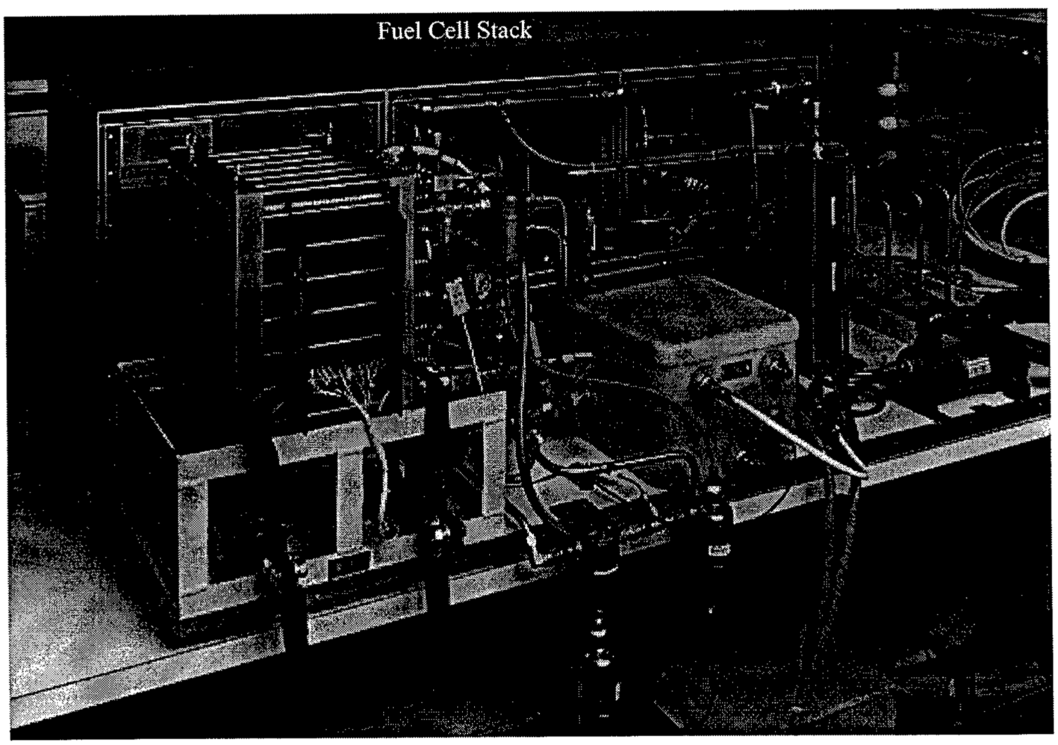


Figure 8. Picture of the MRL Fuel Cell Power System manufactured by Energy Partners, West Palm Beach, Florida..

Appendix 2

Linear programming equations

The linear optimisation was performed using QSB+ software [15].

The linear equations used are listed and described below. Power units are kW and flow in l/s.

Minimise 1POW
Subject to

-0.85*ENPOW + 1*POW <= 0 **(1)**
(1) equates the power on 50% enriched air to be at least 85% of power on 100% oxygen.
-0.3661*ENPOW + 1*FLOW >= 0 **(2)**
(2) relates the power on 50% enriched air to the inlet flow to the fuel cell stack[11].
1*ENPOW - 1*COMP - 0.075*POW >= 1000 **(3)**
(3) The power on enriched air is to be at least equal to 1000 kW after the compressor power and auxiliary power requirements are subtracted.
-1*COMP + 0.4113*INFLOW = 1.94 **(4)**
(4) equates the power of the compressor to the flow of air into the system[12].
-7.47*FLOW + 1*INFLOW =0 **(5)**
(5) equates the inlet flow of air to the final flow of 50% enriched air into the fuel cell stack.

The above equations modelled the double stage enrichment scheme and would not solve due to the large compressor power required. In modelling a single stage of enrichment (to 50%), only equation (5) was changed: -

-3.01*FLOW + 1*INFLOW = 0 **(5)** (single stage of enrichment)

---

[11] This was derived from the known output power of the fuel cell on 50% enriched air at 68 l/m.
[12] This was derived from a linear regression fit to the graph of compressor pumping power versus gas flow at 700 kPa output pressure. The data was obtained from Champion Compressors [14].

DISTRIBUTION LIST

A Feasibility Study of Using Oxygen Enrichment for Fuel Cell Air Independent Propulsion

G.A. Clark and M.J. Rowan

1. DEFENCE ORGANISATION

a. Task sponsor DNER-SM

b. S&T Program

Chief Defence Scientist
FAS Science Policy
AS Science Industry and External Relations
AS Science Corporate Management
} shared copy
Counsellor Defence Science, London (Doc Data Sheet)
Counsellor Defence Science, Washington (Doc Data Sheet)
Scientific Adviser to Thailand MRDC (Doc Data Sheet)
Senior Defence Scientific Adviser/Scientific Adviser Policy and Command (shared copy)
Navy Scientific Adviser
Scientific Adviser - Army (Doc Data Sheet and distribution list only)
Air Force Scientific Adviser
Director Trials

Aeronautical and Maritime Research Laboratory
Director
Chief, SSMD
Research Leader
Task Manager
G.A. Clark
M.J. Rowan

Electronics and Surveillance Research Laboratory
Director

DSTO Library
Library Fishermens Bend
Library Maribyrnong
Library DSTOS (2 copies)
Library, MOD, Pyrmont (Doc Data sheet only)

c. Forces Executive
Director General Force Development (Sea)
Director General Force Development (Land), (Doc Data Sheet only
Director General Force Development (Air), (Doc Data Sheet only)

d. **Navy**

SO (Science), Director of Naval Warfare, Maritime Headquarters Annex, Garden Island, NSW 2000 (Doc Data Sheet only)
Director Naval Engineering Requirements Sub-systems (DNER-SM), CMDR T. Stone, Canberra ACT
Director Naval Electrical Engineering (DNEE), Mr Chris Diener, Canberra ACT
Director Marine Engineering (DME), Mr Bob McDonald, Canberra ACT
Director Submarine Engineering Services (DSEG), Mr Paul Tuck, Canberra ACT
Director General Naval Engineering Services (DGENS), Ms Shireane McKinnie, Canberra ACT
Deputy Director Submarine Warfare Development (Submarines), DDSMWD (Submarines) CMDR David Nichols, Canberra ACT
New Submarine Project, CDRE G. Rose, Canberra ACT
Director of Naval Architechture, DNA, Mr M. Powell, Canberra ACT
Directorate of Submarine Policy and Warfare, DSMPW, CAPT John Diercks, Canberra ACT
Directorate of Naval Warfare, DNW, CAPT B. Adams, Canberra ACT
Maritime Studies Program, DGMSP, CAPT J. McCaffrie, Canberra ACT
Director Naval Architecture, DNA, Mr M. Powell, Canberra ACT

e. **Army**

ABCA Office, G-1-34, Russell Offices, Canberra (4 copies)

g. **S&I Program**

Defence Intelligence Organisation
Library, Defence Signals Directorate (Doc Data Sheet only)

i. **B&M Program (libraries)**

OIC TRS, Defence Central Library
Officer in Charge, Document Exchange Centre (DEC), 1 copy
DEC requires the following copies of public release reports to meet exchange agreements under their management:
*US Defence Technical Information Centre, 2 copies
*UK Defence Research Information Centre, 2 copies
*Canada Defence Scientific Information Service, 1 copy
*NZ Defence Information Centre, 1 copy
National Library of Australia, 1 copy

2. **UNIVERSITIES AND COLLEGES**

Australian Defence Force Academy
Library
Head of Aerospace and Mechanical Engineering
Deakin University, Serials Section (M list), Deakin University Library, Geelong, 3217
Senior Librarian, Hargrave Library, Monash University
Librarian, Flinders University

3. **OTHER ORGANISATIONS**

NASA (Canberra)
AGPS

OUTSIDE AUSTRALIA

4. ABSTRACTING AND INFORMATION ORGANISATIONS

INSPEC: Acquisitions Section Institution of Electrical Engineers
Library, Chemical Abstracts Reference Service
Engineering Societies Library, US
American Society for Metals
Documents Librarian, The Center for Research Libraries, US

5. INFORMATION EXCHANGE AGREEMENT PARTNERS

Acquisitions Unit, Science Reference and Information Service, UK
Library - Exchange Desk, National Institute of Standards and Technology, US

6. ADDITIONAL DISTRIBUTION

Energy Partners (Attn. Dr Mariano Nadal and Dr Frano Barbir), 1501 Northpoint Parkway, Suite 102 Technology Centre, West Palm Beach, Florida 33407 USA (via G. Clark)
Sustainable Power Systems (Attn. Mr Don Alessi Jr), Suite 19, 3866 Prospect Avenue, West Palm Beach, Florida 33401, USA
Dr Frank Vermeulem, Afdeling Energie, VITD Boeretang 200, B-2400 Mol, Belgium
Dr R. Mann, Dept of Chemistry and Chemical Engineering, Royal Military College of Canada, Kingston, Ontario, Canada (via G. Johnston)

SPARES (10 copies)

Total number of copies: 73

Page classification: UNCLASSIFIED

DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION DOCUMENT CONTROL DATA	1. PRIVACY MARKING/CAVEAT (OF DOCUMENT)
2. TITLE A Feasibility Study of Using Oxygen Enrichment for Fuel Cell Air Independent Propulsion	3. SECURITY CLASSIFICATION (FOR UNCLASSIFIED REPORTS THAT ARE LIMITED RELEASE USE (L) NEXT TO DOCUMENT CLASSIFICATION) Document (U) Title (U) Abstract (U)
4. AUTHOR(S) G.A. Clark and M.J. Rowan	5. CORPORATE AUTHOR Aeronautical and Maritime Research Laboratory PO Box 4331 Melbourne Vic 3001

6a. DSTO NUMBER	6b. AR NUMBER	6c. TYPE OF REPORT	7. DOCUMENT DATE
DSTO-TR-0397	AR-009-803	Technical Report	August 1996

8. FILE NUMBER	9. TASK NUMBER	10. TASK SPONSOR	11. NO. OF PAGES	12. NO. OF REFERENCES
510/207/0372	NAV 94/130	DNER-SM	17	15

13. DOWNGRADING/DELIMITING INSTRUCTIONS	14. RELEASE AUTHORITY
None	Chief, Ship Structures and Materials Division

15. SECONDARY RELEASE STATEMENT OF THIS DOCUMENT

Approved for public release

OVERSEAS ENQUIRIES OUTSIDE STATED LIMITATIONS SHOULD BE REFERRED THROUGH DOCUMENT EXCHANGE CENTRE, DIS NETWORK OFFICE, DEPT OF DEFENCE, CAMPBELL PARK OFFICES, CANBERRA ACT 2600

16. DELIBERATE ANNOUNCEMENT

No limitations

17. CASUAL ANNOUNCEMENT Yes

18. DEFTEST DESCRIPTORS

Membranes (Technology); Membranes; Fuel Cells; Diesel Electric Submarines; Linear Programming; Oxygen Generator

19. ABSTRACT

It is shown that the output power from a polymer electrolyte membrane (PRM) fuel cell oxygen follows a quadratic relationship with increasing oxygen concentration. Using this information, a potential application of using oxygen enrichment membrane technology for an air breathing fuel cell was investigated. The system chosen was a hypothetical PEM fuel cell powered air independent propulsion system in a conventional diesel electric submarine. A simple model of the system was made using linear programming. The results showed that using existing membrane technology for oxygen enrichment of the incoming air stream, two compressor stages were required whose power requirements were too great for the system. A 30% improvement over existing molecular selectivity in membrane oxygen enrichment technology would allow a single compressor stage, however, 40% of the fuel cell power would still be needed to power the required compressor stage.