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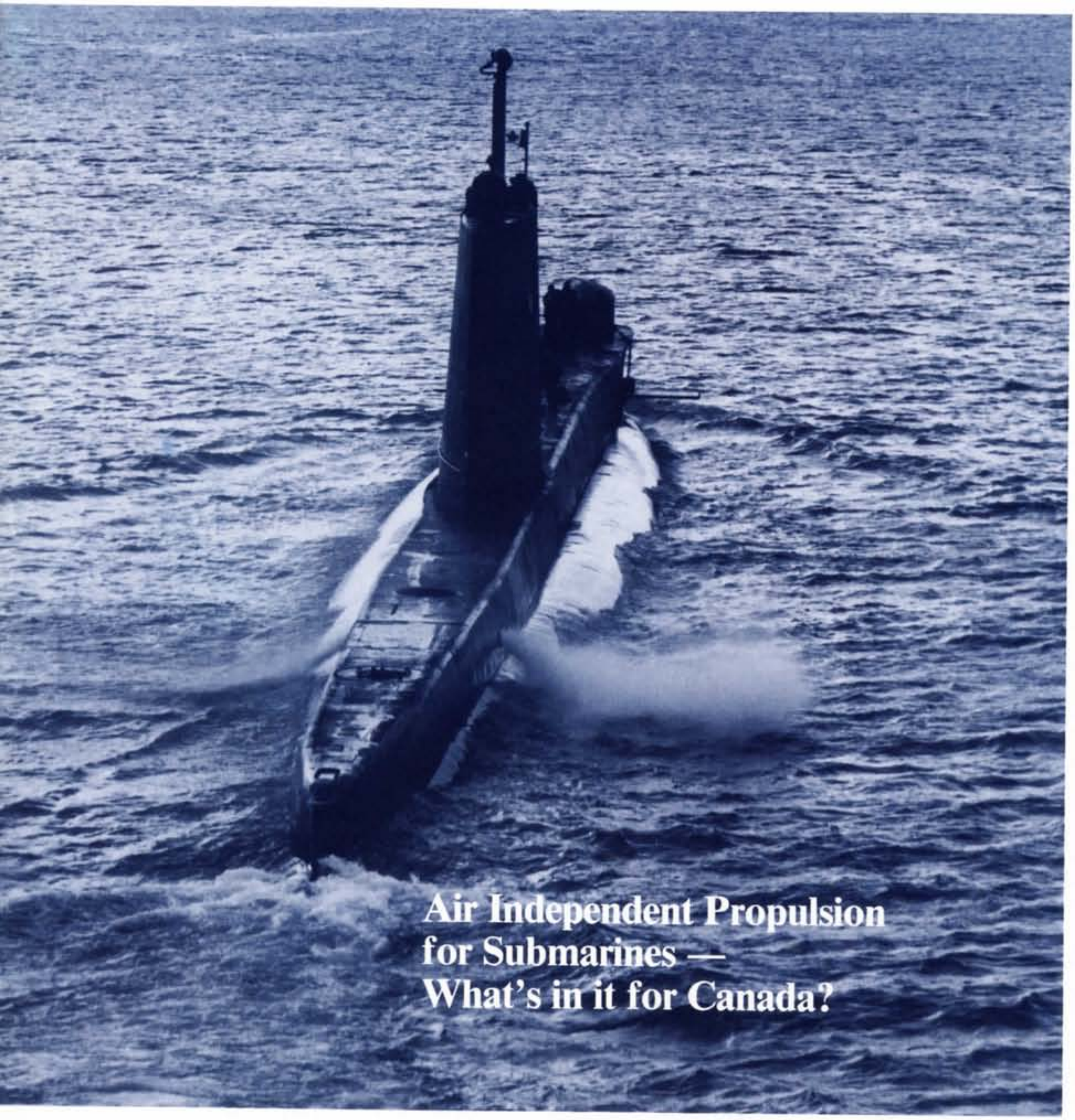
Maritime Engineering Journal

October 1991



Air Independent Propulsion for Submarines — What's in it for Canada?

Canada

Weapon Trials —
This Canadian-developed rocket-boosted target will have a role to play when it comes time to challenge the TRUMP and CPF above-water warfare systems.

. . . page **24**

Maritime Engineering Journal

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OUR COVER
HMCS *Onondaga* leaving Halifax Harbour for exercises in 1979.
(Canadian Forces photo)

October 1991

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Editor's Notes

Equipment Health Monitoring — How much is "good enough?"

In his keynote address to the fifth annual Naval Equipment Health Monitoring Conference in June, Commodore MT Saker (DGMEM) had a blunt message for delegates: quantify the payback from the various EHM programs — or risk losing them.

It was a tough message, but then these are tough financial times for the navy. Virtually every facet of naval engineering support, including EHM, has come under the microscope as engineers and planners strive to maintain an acceptable level of ship availability at the minimum cost. The formula is simple. If an EHM initiative cannot be shown to have a quantifiable payback in terms of increased equipment reliability or reduced maintenance cost, then it probably deserves to be cut.

EHM conference

EHM is a vital part of the navy's overall maintenance system. Intuitively it makes sense, and in practice it works. For example, a recent review of data from the past two years of the Oil and Coolant Condition Analysis Program (OCCAP) proved that the program was successful in anticipating failures. But what we need to know now is how much EHM is necessary — what level of effort in terms of ships' operating time, ships' staff time, shore support time and equipment/process dollar costs is "good enough."

The work of rationalizing the navy's equipment health monitoring programs is now under way. For instance, certain machinery has already been dropped from the Spectrometric Oil Analysis Program (soon to be merged with OCCAP), and a meeting is planned for the fall to determine which equipment should be added to or removed from the Vibration Analysis Program. All of us have a part to play in ensuring we utilize EHM techniques wisely. Make your views known, make sure we all learn from your experiences!

* * * * *

We lead off this issue of the *Journal* with, not one, but *two* articles on air-independent propulsion for submarines. The first, a comprehensive piece by LCdr Karel Heemskerk, considers the various technical options from a Canadian naval perspective. By contrast, the second paper focuses on a single technology — the synthetic atmosphere diesel (SAD) engine. Of note here is that the paper's authors, Professor Graham Reader and Lt Cdr (RN) Gary Hawley, are involved with collaborative research into SADs being conducted by the RNEC (Manadon) and the University of Calgary. The different slants of the two submarine papers make for some very interesting reading.

Also, we are pleased to bring you another ''disaster from the past'' — the story of an engineering incident with a lesson to be learned. In recent months we've had a number of requests for articles such as this, and on this note we urge readers to submit details of incidents from their own experience. Our aim is not to embarrass anyone, so we will not identify specific persons or ships. If you know of an engineering incident in which there is a lesson to be learned, please share it with the rest of us. Who knows? Your story might well save someone from coming to grief either through personal injury or machinery damage.

To complete this issue we present LCdr Richard Houle's overview of trials requirements for the CPF and TRUMP above-water warfare systems, and an article from regular contributor Cdr Roger Cyr on what he figures it will take to support the navy's software in the years ahead. So sit back and relax. We think we've got some good reading for you.

Finally, the *Journal* extends best wishes to three senior officers who have taken their retirement from the navy this summer: **Vice-Admiral Chuck Thomas** (Vice Chief of the Defence Staff — who initially trained and served as a naval engineer), **Commodore Jim Green** (Maritime Command Chief of Staff for Materiel), and **Commodore Ed Murray** (Commandant of the Royal Military College of Canada).

Throughout careers which began in the mid-1950s, these officers have distinguished themselves by their unflagging loyalty and determination. That they should retire with such distinction from influential positions of authority is a fitting testimonial to the depth of their dedication to the naval service of Canada. Bravo zulu and best wishes for an enjoyable retirement.

Captain(N) David W. Riis
Director of Marine and
Electrical Engineering

VAdm C.M.Thomas

Cmdre J.E. Green

Cmdre E.R.A. Murray

Letters

Environmental protection issue well received

At St. Lawrence College, Cornwall Campus, we are always pleased to receive copies of the *Maritime Engineering Journal*. The *Journal* usually provides much in the way of interest and practical examples of work in the marine engineering field that helps with our work in the Marine Engineering Technician Training Plan.

The January 1991 edition was particularly good in this respect with the very interesting and full coverage of environmental protection work. Please could we have a further eight copies for further distribution. — ***Brian E. Keefe, Co-ordinator, Marine Engineering, St. Lawrence College, Cornwall, Ontario.***

Thank you for your letter and the copy of the *Maritime Engineering Journal*. I am glad that you found the article on garbage pollution useful. For my part I was very impressed with your magazine and wonder whether it would be possible to add us to your mailing list. — ***Roger Kohn, Editor,* IMO News, *International Maritime Organization, London, England.***

Many thanks for sending me complimentary copies of the January 1991 issue of the *Maritime Engineering Journal*. I found this to be a most interesting and informative publication.

I would like to send copies of this edition of the *Journal* to a number of people in DFO who, I know, would be interested in the content and in the efforts being undertaken by the navy to improve the level of environmental protection. Could you advise how I should go about ordering 30 copies (that is, if you still have that many available). — ***R.J. Paterson, Oceanography and Contaminants Branch, Department of Fisheries and Oceans, Ottawa, Ontario.***

Thank you very much indeed for the copies of the *Maritime Engineering Journal* containing the article on my little effort in *Protecteur*. I am very proud to have been instrumental in some small way in raising the visibility of our problem. It also provided the ship's company with a certain amount of entertainment watching me at work. I am very strongly in favour of an attack on this problem by everyone, and the more we can encourage individual constructive initiative the better.

The senior staff at MARPAC are most amused at what appears to be a prerequisite for the job of COS READ, here, and I have received many amusing comments. This pleases me very much since clearly many people are reading the *Journal*. I loaned a copy to my father who is a retired naval officer, but he is not sure whether to be proud or horrified! Perhaps this is just a question of the generation gap.

Thank you again for your thoughtfulness. Good luck with future editions. — ***Capt(N) J.K. Steele, Chief of Staff (Readiness), Maritime Forces Pacific Headquarters, FMO Victoria, British Columbia.***

A good "dressing down"

I doubt I'm the first to comment on the caption accompanying the photo of *Fundy*'s engine room on page 25 of the April issue, but here goes anyway.

It would indeed have been *most unusual* for anyone to man an engine room or any other position in full uniform when at sea in 1938, and the CERA in the photo certainly is not dressed in his best bib 'n tucker. He is in fact wearing his *working dress*. For those in Class I uniform this was a serge single-breasted jacket and serge trousers, except when whites were being worn when it was a single-breasted white duck jacket and trousers. Another working rig for Class I was a pair of blue one-piece overalls. There was even a working shirt which, although of the same cut and quality as the dress shirt, featured a blue and white check or striped pattern so that it didn't show the dirt so easily. The Class I best suit featured a double-breasted jacket and was made of better cloth, usually a fine twill or gabardine.

It might also be of interest to note that a Chief ERA and an ERA of the period, who was classed as a CPO and kitted out and paid accordingly, were dressed exactly alike, so there's a good chance he's not the Chief at all.

Also, shouldn't it be "Finished with engine (not engines)?" I can't make out the wording on the telegraph face, but as *Fundy* only had one up 'n downer that would seem to make sense.

Enough stirring of the pot for now. Keep up the good work. — ***David Perkins, Dartmouth, Nova Scotia.***

(Pick, pick, pick. At least we got the telegraph bit right! — Ed.)

Commodore's Corner

By Commodore J.E. Green

Although I am not given to staring out my window overlooking Halifax Harbour — at least, not that anyone would notice — I must confess to watching *St. Croix* for some time in early April as she was being towed out of Dockyard bound for the scrapyard. I recalled being awarded my Boiler Room Watchkeeping Certificate in *St. Croix* (an unspecified number of years ago) and remarked to the other officer present that it was probably appropriate that I would soon be leaving Her Majesty's Service as well. That moment of reminiscence was quickly supplanted by the problem of the moment. Nevertheless, I have spent somewhat more time of late contemplating the intervening years and comparing "those days" with "these days."

These days, as you are all very much aware, are full of uncertainty. The nation, the department and the navy are faced with very serious fiscal problems and some equally serious challenges. These days are indeed difficult and it could be easy to become discouraged or despondent. However, I can assure you that "those days" were no less disconcerting. The disposal of HMCS *Bonaventure*, for example, was, at the very least, traumatic. The boom of the early '70s (the AORs and DDH-280s) was followed quickly by an equally uncertain time. The buzz words of the decade included "freeze on capital," "rust-out" and "what kind of navy are we to have?" Not only were there no ships on the horizon, there were no new ships on the books.

But what of "these days?" While there is much uncertainty as to what ships may or may not be on the books, the ships on (and just over) the horizon are probably the most capable our navy has ever had. Acceptance of *Halifax* will hopefully be history as you read this Corner. *Algonquin* should not be too far behind. CPF and TRUMP will present you with a new set of challenges and opportunities. Those of you who may be preoccupied with the work which remains to be done in those programs would do well to have a chat with the current DGMEM. Commodore Saker will tell you that the problems of the DDH-280s seemed overwhelming at the time and that they "steamed" the propulsion plant in manual for eight months after acceptance.

In short, we have been through some hard times in the past and will be faced with hard times in the future. This would seem to be our lot in life. If I can leave you with any one thought, it is that we naval engineers are a professional and highly dedicated group. Do not lose sight of that simple fact.

Over the last seven years, I am most honoured to have served as PM CPF, contributing to the renewal of our navy, and as COS Mat, doing what I can to help prepare Maritime Command for the arrival of those new frigates. There can be no doubt that the challenges which lie immediately ahead are significant and are made even more difficult by the fiscal reality. I can offer no awe-inspiring solution to those problems. Rather, I would draw one final lesson from the effort *the navy* made in preparation for, and in support of, Operation Friction — with the time you have, and with what you've got, do the best you can. Success will follow. Godspeed.

Commodore Green retired from the navy as the Chief of Staff (Materiel) in July.

Air-independent Propulsion for Submarines: A Canadian Perspective*

By LCdr K.A. Heemskerk, M.Sc., C.Eng., MIMarE

***Modified from a paper by R.G. Weaver and K.A. Heemskerk presented to the C.I.M.E. MARITECH 90 Conference, 30-31 May 1990, Victoria, B.C.**

Abstract

The cost and complexity of nuclear-powered submarines, and general public wariness of anything nuclear are well documented. Yet, they do not alter the fact that SSNs have a tremendous military advantage over their conventional counterparts in that they need not expose themselves regularly to recharge batteries. This edge may not last much longer. Technology now exists, and is improving, which will allow conventional submarines to remain submerged for most of a patrol period. This paper examines and compares the various technical options from a Canadian perspective, provides an assessment of each system's viability for submarine use and outlines a possible way ahead for Canadian work in the field.

Introduction

With the longest coastline of any country on earth and with the nation's economic health very much dependent on sea lines of communication, Canada is a logical candidate for the nuclear-powered submarine (SSN). Indeed, that one of the three oceans bordering Canada is normally icebound makes SSNs a necessity in the view of many strategists.

The Canadian Government's 1989 decision not to proceed with the SSN project, while disappointing, has rekindled Canadian interest in alternative forms of air-independent propulsion (AIP). While nothing on the current technological horizon can match the SSN for speed, under-ice operation or as a vessel of mobility, AIP could improve the SSK as a vessel of position and add an element of under-ice capability with considerable cost savings.

AIP could, in theory, now support a submarine's full range of demands, and entirely replace traditional diesel-electric propulsion in the next generation of submarines. However, studies have concentrated on hybrid systems, incorporating AIP in conjunction with a conventional diesel-electric plant. The AIP power source would simply serve to maintain the charge in the main batteries while the submarine is running at low speeds. The

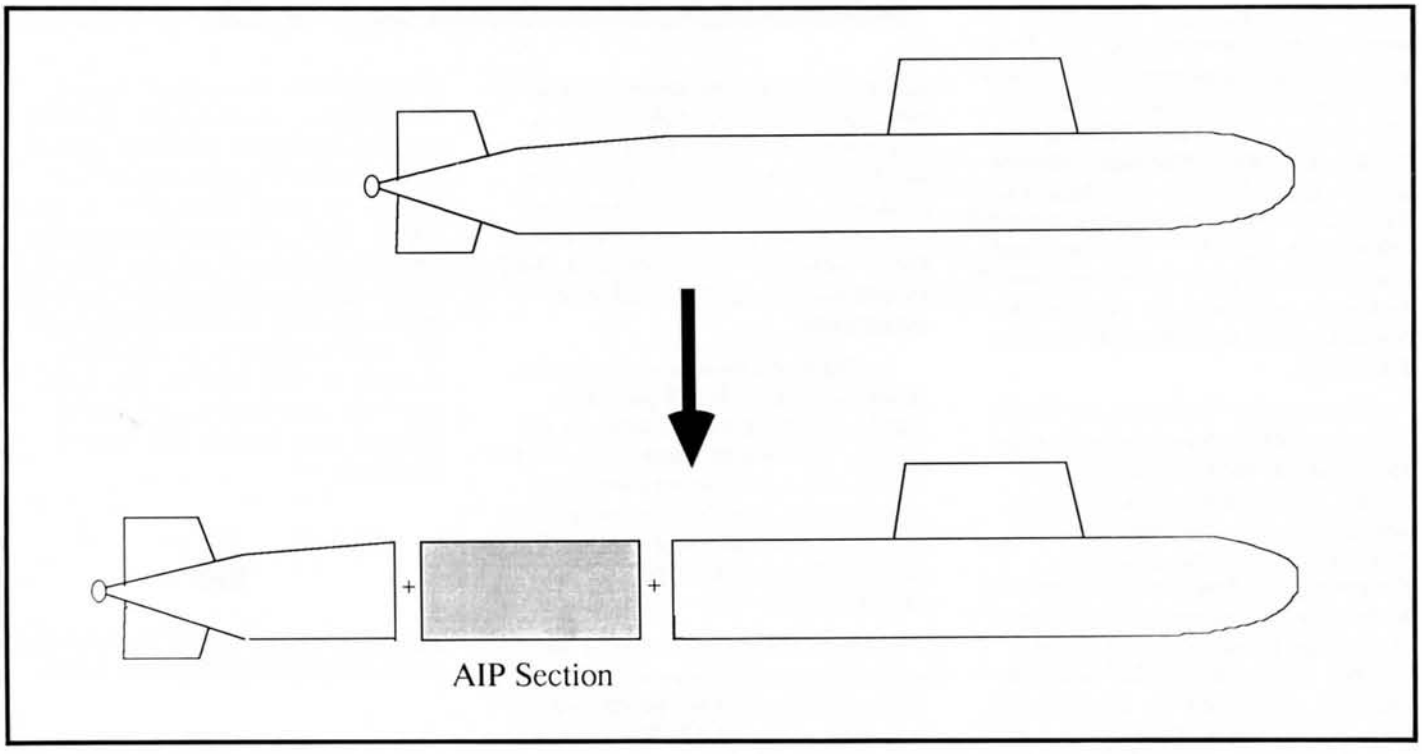

Fig. 1. The hybrid submarine.

system could be thoroughly integrated into a new design, or retrofitted as a "plug" into an existing one. *Figure 1* shows a conceptual installation.

A target AIP output of 300 to 400 kilowatts and an energy store of 100 megawatt hours are viewed as a reasonable minimum for a Canadian boat. This would be sufficient to power a 2,000-tonne submarine at six to eight knots and allow a submerged endurance of about ten days at that speed. The submarine would have its full set of conventional batteries, which would begin to discharge at power levels above the 300- to 400-kW power level.

There are many feasible technical options for AIP. This paper will concentrate on Stirling engines (at sea with the Royal Swedish Navy), fuel cells (trialled at sea with the German navy), closed-cycle diesels (at sea in Italy), metal power cells (under development in Canada), and small nuclear systems (also under development in Canada). Other solutions, such as improved batteries, are outside the scope of this paper.

AIP System Development/System Pros and Cons

Stirling Engines

The Royal Swedish Navy identified the Stirling as its preferred AIP source, and proceeded with full-scale development in conjunction with Kockums Shipyard which installed a Stirling AIP package in a Swedish Näcken-class SSK in 1988. This Swedish plant is based on a four-cylinder engine, the V4-275R. The navy and Kockums are highly satisfied, based on what is now over a year of operational experience since the installation. Indeed, their follow-on submarines (the A-19 class) will be designed to feature this technology. Kockums is also supplying two V4-275R engines to France's Comex Industries for its 500-tonne manned diver lock-out submersible, *Saga 1*.

The Swedish navy selected Stirling technology for a number of good technical reasons (as well as commercial ones). These included low noise level (relative to internal combustion engines), the ability to use diesel fuel, and the maturity of Stirling and LOX technologies relative to other AIP systems.

But Stirling engines have disadvantages as well — in particular, material and combustion problems due to the high pressures and continuous high temperatures employed. The use of low-sulphur fuel, however, helps reduce some of these problems. Also, the Stirling engines available today are somewhat limited in power output. For example, the Stirling V4-275R is rated at only 75 kW; several units would have to be run in parallel to achieve the desired output. Kockums recently announced that it is taking over work on a 600-kW unit previously under development by MAN in Germany.

Closed-Cycle Diesel Engines

The submarine closed-cycle diesel (CCD) effort is very broadly based, with studies being undertaken in all navies with submarines. This paper concentrates on Cosworth of Great Britain and Maritalia of Italy.

The problem in the past with the CCDs has been the rapid corrosion from build-up of combustion products in the recycled exhaust gases, and the fluctuating back-pressures caused by changes in diving depth. The Cosworth Argo system solves both problems by passing the exhaust gases through a seawater scrubber to dissolve most of the condensible gas, and then using a pressure compensating system to discharge the waste overboard. Argon is used to replace the lost nitrogen. Although details are sketchy, it is thought that Maritalia solves the problem by using great volumes of compressed gas stored under pressure in the toroidal hull system, and compressing the exhaust gas back into the hull.

Cosworth is working on Argo development contracts with Rotterdam Dockyard (RDM, Holland) and Thyssen Nordseewerke (TNSW, Germany). RDM's trials are on a 150-kW Mercedes-Benz OM422A diesel, while TNSWs uses a 120-kW OM421A integrated into a mock-up submarine section. Initial results indicate successful closed-cycle operation and change-over between open and closed cycle. Further trials will concentrate on efficiency improvement.

Maritalia has CCDs at sea in mini-submarines, using for gas storage the revolutionary toroidal hull form (a series of pressure vessels formed in toroids). Development and refinement of their hull is continuing. Maritalia's system was installed during the mid-1970s in two experimental mini-subs (120 tonnes and 80 tonnes). One, using an adapted Perkins engine and a Fiat/IVECO 8361, has run successfully at full power at 350 metres. The company has also run Lombardini, GM, Mercedes-Benz and VM diesel engines on closed cycle, logging more than 23,000 operating hours. On the drawing board now is a 48-metre submarine with a diving depth of 400 metres and storage for 100 MWh of fuel and oxygen, for a theoretical range of 4,000 nautical miles at eight knots. The machinery includes two 12-cylinder, 300-kW diesel generators and a 600-kW electric motor.

A big advantage of CCD systems is the ability to start on, or switch over to, outside atmosphere whenever necessary, thereby conserving stored oxygen. Machinery power-to-weight and power-to-size ratios are quite good, and diesel technology is advanced, proven, reliable and readily available.

CCDs do have special problems. Although the problem of recirculating combustion-generated acids (which before had limited cylinder liner and/or valve life to about 500 hours) has now been solved by the use of seawater scrubbers, a way must be found to remove corrosive salt dust. A serious disadvantage for naval submarines would be the diesel's inherent noise level.

Fuel Cells

A hybrid submarine propulsion system has been developed by a German industrial group comprising Ingenieurkontor Lübeck (IKL), Howaldtswerke-Deutsche Werft (HDW) and Ferrostaal, using a Siemens fuel cell. The fuel is hydrogen, stored in an iron-titanium alloy hydride developed in co-operation with Daimler Benz.

The hybrid fuel cell propulsion system and related systems were fitted into the Type 205 submarine *U1* in

(Cont'd on page 11)

Stirling Engines

The Stirling is an external combustion engine operating on a closed regenerative thermodynamic cycle. Invented in 1816 by the Reverend Robert Stirling, the engine today is being developed for use in space, automotive, solar power, underwater and medical fields by General Electric, Kockums (Sweden), MAN/MWM (Germany) and others.

Figure A illustrates the Stirling cycle: during compression (1-2), work is supplied to the gas in the cold cylinder; the compressed gas is moved (2-3) from the cold to the hot cylinder at constant volume, passing over the regenerator where it gains heat and so increases in pressure; in the hot cylinder (3-4) it is heated and expands to perform work; the expanded gas then moves (4-1) back to the cold cylinder at constant volume, passing over the regenerator to transfer remaining heat.

The Stirling cycle can approach the ideal Carnot efficiency since most of the "exhaust" heat is extracted and reused. To maximize efficiency, high gas-operating temperature (about 2000°C) and pressure (30 bar) are used, and so advanced materials technology is essential.

The combustion chamber of a Stirling engine is contained in a pressure vessel at 20 to 30 bar. The exhaust can thus be expelled directly to the sea when submerged at 200 to 300 metres. Below that depth, additional exhaust compression is required to overcome sea pressure, but such compression is of only marginal pressure ratio and so consumes little power. Note that combustion of diesel fuel with oxygen produces an exhaust of 45 percent steam which can be readily condensed. The remainder consists mainly of water-soluble gases.

The Stirling engine uses ordinary diesel fuel stored in conventional tanks, while the liquid oxygen (LOX) oxidant is stored in insulated bottles inside the pressure hull. LOX capacity would be the limiting factor in submerged endurance of a Stirling AIP plant.

As with all the AIP options discussed, the complete Stirling system including LOX tanks, weight-compensating water tanks and auxiliaries could be arranged as an autonomous hull section. All capabilities of the conventional submarine would remain.

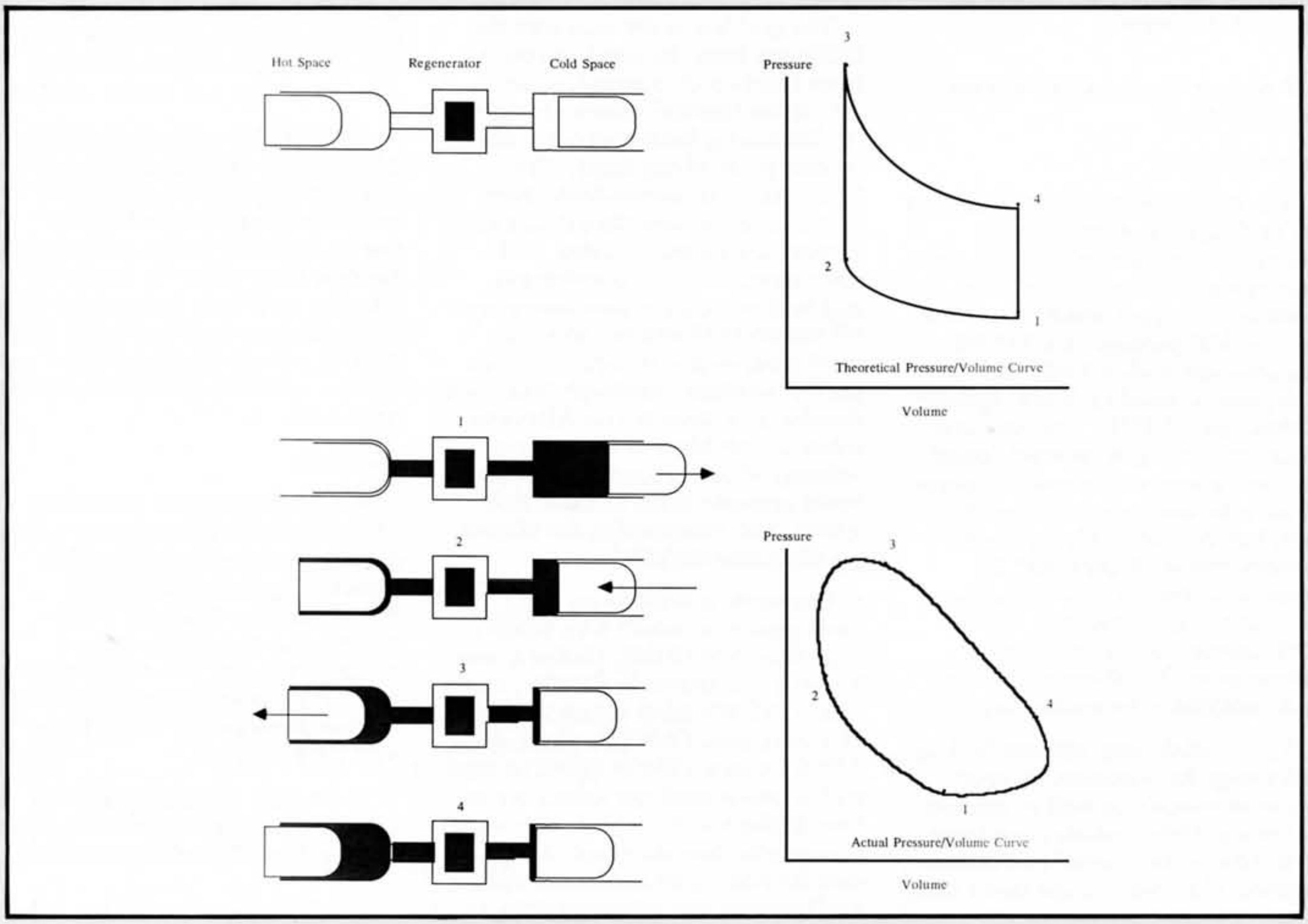

Fig. A. Stirling Engine Principle of Operation

Closed-Cycle Diesels

Cosworth

To obtain air-independence in a diesel engine, the Cosworth Argo system forms a simulated atmosphere by regulating a flow of pure oxygen into an inert gas which is continuously recycled (*Figure A*). The engine is "misled" into thinking it is breathing air.

The working fluid is argon, to which oxygen is added. Exhaust carbon dioxide and water vapour are continuously removed in a seawater scrubber. The turbocharger operates at about 2 to 3 bar, and the scrubber also operates at above atmospheric pressure to ease the task of carbon dioxide absorption.

Cosworth's Argo uses an unmodified turbocharged diesel to drive a 120-kW generator. Associated auxiliaries consume less than ten kilowatts, in part because of an efficient hydraulic water-management system which translates a volume of sea water from depth pressure to scrubber pressure and an equal volume from scrubber pressure to depth pressure. The system is thus independent of operating depth.

Maritalia

Maritalia claims that any diesel can be modified for closed-cycle use. Operation of its compact closed-circuit system is understood to be basically the same as in the Argo, although information is limited. The main difference is the unique and elegant method of storing both the oxygen (air?) and exhaust as gases at approximately 350 bar in the submarine's double-skinned toroidal pressure hull (*Figure B*). The designers claim this hull, using ordinary steel, will enable a submarine to dive to depths equivalent to a titanium-hulled vessel.

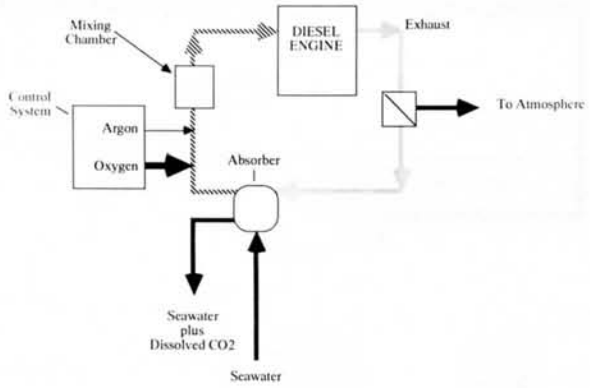

Fig. A. Schematic of the Argo Closed-Cycle Diesel System

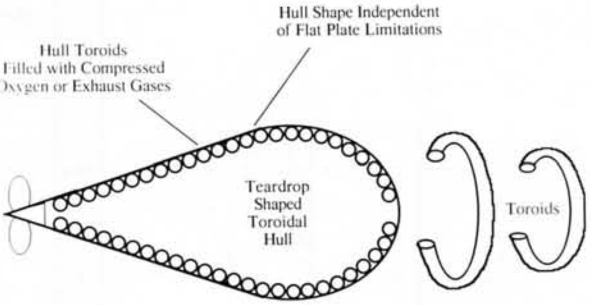

Fig. B. The Principle of the Gas Toroidal Hull

Fuel Cells

A fuel cell is an electro-chemical device which converts chemical energy directly into electrical energy in what is essentially the reverse of electrolysis. The reactants are stored external to the fuel cell and are continuously fed in. The cell consists of an electrolyte and two non-consumable electrodes, usually porous plates, which bring the reactants and electrolyte together. The electrodes also play a catalytic role in facilitating the ionizing reactions.

The fuel cell principle was first demonstrated in 1839, but there were no major developments until almost 1960. Fuel cells have since been developed for space and commercial use, including a 4.5-MW plant in Japan and several 40-kW plants in North America. Japan and some European countries have heavily subsidized development, mainly for land applications.

Reactants required are an oxidant, normally oxygen, and a fuel. Many fuels are theoretically possible, but hydrogen is the ideal since it reacts at any temperature and provides the highest efficiency. Practical problems have obviated the use of complex fuels such as diesel to date, but the tolerance of newer types of cell to gases such as carbon monoxide and dioxide may change this.

Operation of a fuel cell can be demonstrated by considering the reactions in an alkaline electrolyte cell using hydrogen and oxygen (*Figure A*). Hydroxyl (OH-) ions are formed at the cathode which then migrate to the anode where they react with hydrogen to form water and release free electrons. These electrons flow through the load from anode to cathode to take part in another reaction to produce the hydroxyl ions.

Fuel cells are classified by the type of electrolyte used, the three most fully developed being the phosphoric acid, alkaline and solid polymer types. Of these, the latter two are the most suitable for submarine use since they have the highest power/weight and power/volume ratios and efficiency. The solid polymer type is tolerant to pressure differentials between the input reactants and does not share the alkaline cell's propensity to carbon dioxide "poisoning."

Other cells, including metal oxide and molten carbonate types, are considered less suitable for submarine use as they operate at high temperatures (680°C and 454°C, respectively) and require a considerable flash-up time. This is unfortunate since the molten carbonate cell can operate directly on some complex liquid fuels.

Fuel cell output is direct current. Voltage and current would be increased by connecting stacks of cells in parallel and in series, respectively. Fine tuning of the output could be achieved by varying the number of fuel cell plates in the stack.

For a submarine, the oxygen would likely be carried (externally) as LOX. Hydrogen would also be carried external to the hull, as a metal hydride. Although heavy, the hydride is very safe. (It has been described as the equivalent of carrying oxygen as rust). An example of a submarine fuel cell system (based on the German experiment) is shown in *Figure B*, with a general arrangement shown in *Figure C*.

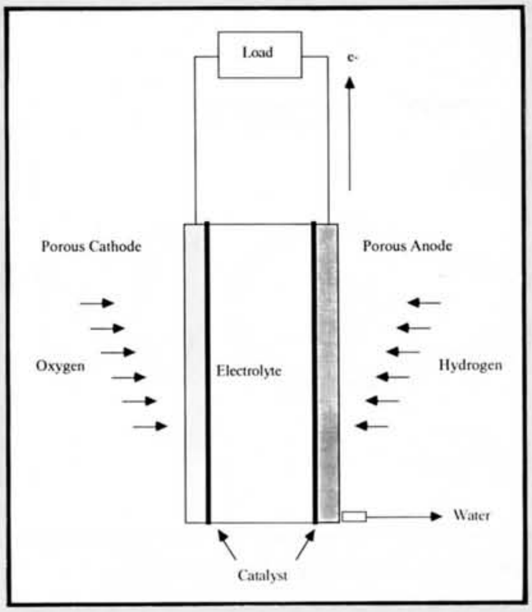

Fig. A. Simple Alkaline Fuel Cell

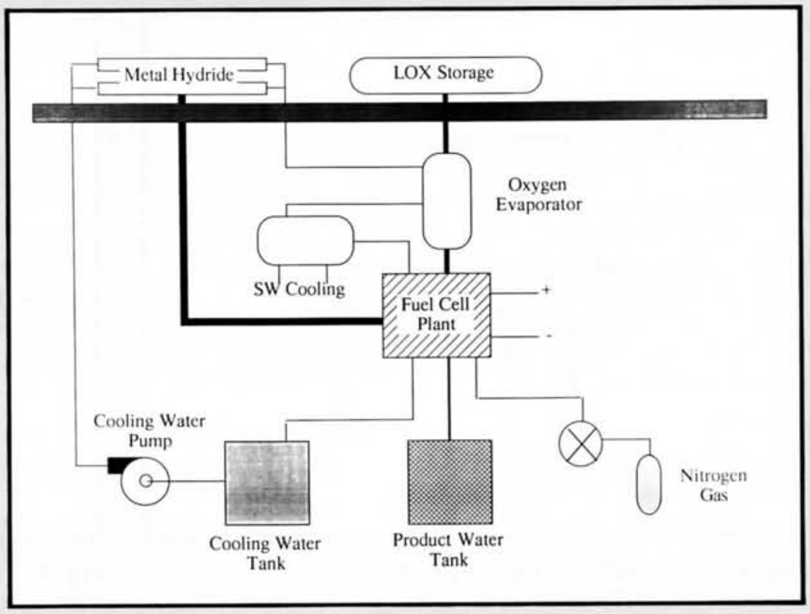

Fig. B. German Submarine Fuel Cell Diagrammatic Arrangement

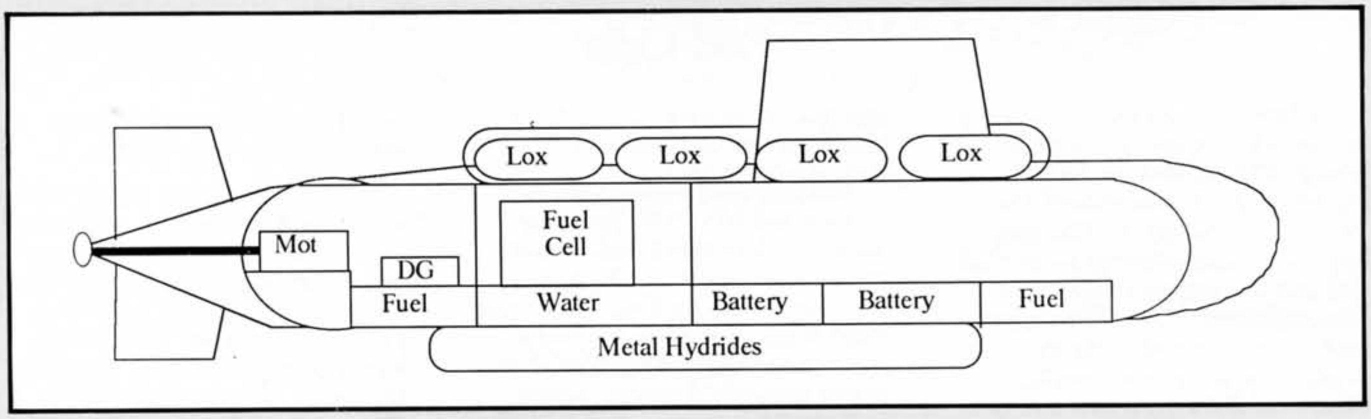

Fig. C. The Hybrid Fuel Cell Submarine

(Cont'd from page 7)

1987. The *U1* had been lengthened by 3.8 metres to accommodate the hybrid system which included 16 fuel cells, each generating 25 kW of power. Sea trials were successful, confirming that hybrid submarines using fuel cells can have several times the underwater range of conventional boats.

A hybrid fuel cell AIP system will be incorporated into the Type 212, Germany's next generation of submarine. The *U1*'s alkaline cells will give way to a solid polymer type to take advantage of the latter's safety and air-breathing capability.

Ballard Technologies of Vancouver has also developed and is marketing an advanced solid polymer cell for land applications. It has definite potential for marine AIP use. Ballard is also developing a practical methanol fuel reformer which would extract hydrogen from liquid fuel, presently methanol.

Since the fuel cell does not use a thermodynamic cycle, Carnot cycle limitations do not apply and overall efficiencies of more than 60 percent (including all parasitic loads) are possible. High efficiency is also beneficial in terms of minimizing infra-red trail. Operation is practically noiseless and the by-products of the reaction are fresh water, easily rendered potable, and low-grade heat, used to extract hydrogen from the metal hydride.

The main disadvantage of fuel cells is the low energy density of the fuel. Also, the fuel used must be pure to prevent contamination of electrodes and electrolyte; even solid polymer cells are poisoned by carbon monoxide. Other disadvantages are the high cost and weight of metal hydrides.

Metal Power Cells

Small aluminum-air power cells have been produced for such applications as telecommunications back-up, emergency lighting, an experimental electric vehicle, etc. Now Alupower Inc., a subsidiary of Alcan International, will market aluminum power cells for underwater applications. Development is still at an early stage, however, with nothing over a kilowatt operating to date.

Most of the advantages of fuel cells apply to the aluminum power cell. In addition, in this case, the need to carry LOX and to use hydrogen as a fuel are avoided. However, in the view of many submariners, the requirement to carry hydrogen peroxide as the oxidant may be a fatal drawback. Considering, though, that nuclear energy has been safely harnessed in submarines, it would be surprising if modern technology could not do the same for safely storing hydrogen peroxide.

Nuclear AIP

Heat from a low-power nuclear reactor could be used to generate steam to drive a turbo-alternator for charging submarine batteries. This small "n" *SSn* would provide SSN endurance (albeit at lower speeds) for significantly less than an SSN price tag.

An Autonomous Marine Power Source (AMPS) is being developed by a Canadian firm, Energy Conversion Systems (ECS), where work is currently at the development stage for a 100-kW plant. A family of designs to deliver anything from 100 to 1,700 kilowatts is planned for the long term. ECS states that a prototype AMPS system could be available for a submarine fit within the next decade.

Other countries, including the U.K. and France, are known to be considering small nuclear power sources suitable for AIP.

The advantage of practically unlimited endurance puts the "SSn" in a class well above the other non-nuclear AIP contenders. However, there are major non-technical disadvantages which will be discussed a little later on in this paper.

Comparison of AIP Options

Efficiency

The fuel cell and aluminum power cell, unencumbered by Carnot limitations, come out well ahead of the rest. Note from *Figure 2* that maximum efficiency for fuel cells is at part load, unlike engines on a thermodynamic cycle. The low efficiency of the nuclear option is irrelevant, of course.

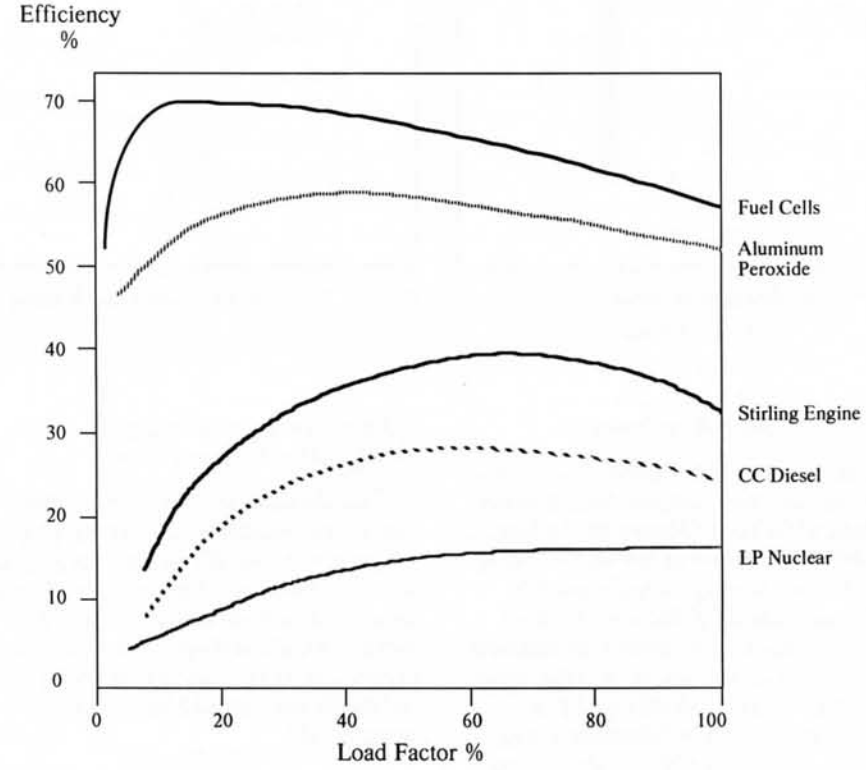

Fig. 2. Efficiency versus Load for AIP Options.

Metal Power Cells

Certain metals in an oxidizing solution act as a sacrificial anode to produce a voltage of practical magnitude. That the anode is consumed differentiates a power cell from a fuel cell.

Aluminum in particular may be made to produce usable power, in what amounts to the reverse of the Hall refining process. The aluminum (normally protective) oxide layer has been overcome with new alloys proprietary to Alcan International.

A schematic of a possible power cell is shown as *Figure A*. In this case the electrolyte is a dilute solution of hydrogen peroxide in an aqueous saline solution. Parasitic reactions do occur, generating a certain amount of both hydrogen and oxygen. The hydrogen peroxide oxidant is consumed and must be continuously refreshed. The aluminum hydroxide product must be continuously flushed from the cell.

To produce a practical submarine plant many individual cells would be stacked in series and in parallel. The plant would include some ancillary systems, such as an electrolyte distribution and recirculation system to supply peroxide and remove the aluminum hydroxide, a precipitator unit to separate and discharge the aluminum hydroxide for storage, and a heat-exchanger to remove waste heat (*Figure B*).

The hydrogen and oxygen created by side reactions in the cells could be used to power an auxiliary fuel cell. Also, some waste aluminum hydroxide might be put to work as a carbon dioxide absorber for the boat's atmosphere control system. Peroxide and hydroxide product would be stored outside the pressure hull.

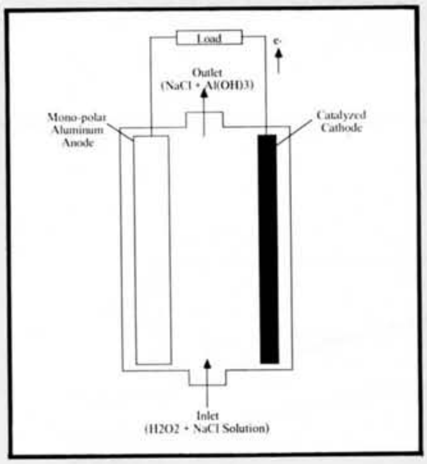

Fig. A. Simple Aluminum Peroxide Cell

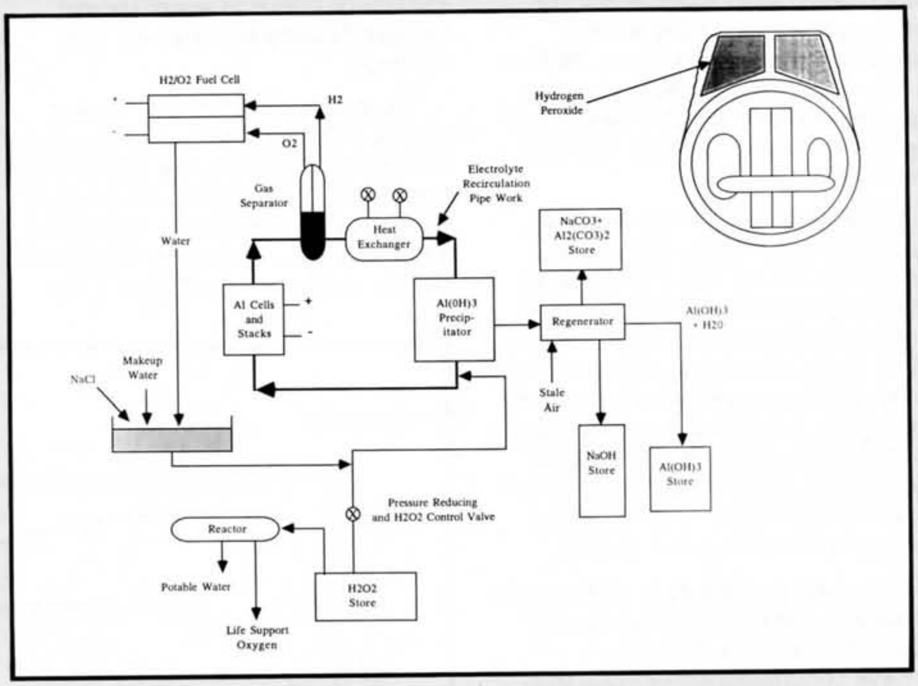

Fig. B. Aluminum Peroxide Power Source

Mass and Space Requirements

The Stirling and closed-cycle diesel engines fare well despite their Carnot-limited efficiency (*Figure 3*). Indeed, a submarine powered by one of these would have a range approximately 1.8 times that of a fuel-cell boat of equal displacement, primarily because the latter is penalized by a large mass of metal hydride. When and if a liquid fuel reformer becomes available, the figures could change a great deal in favour of the fuel cell. Note that the comparison is for the sum of power source, auxiliaries and fuel/oxidant for a given endurance, not simply the machinery itself.

The aluminum power cell comes out exceptionally well in these graphs. Perhaps this should not be surprising since it shares the fuel cell's high efficiency but not its need for heavy metal hydride storage. However, the power cell curves shown are very early estimates and should be treated accordingly.

For practical purposes, the *Mass and Volume vs. Endurance* curve for nuclear AIP is a horizontal line reaching to infinity. For an energy storage requirement above about 400 megawatt hours, it has no competitor.

Cost

Figures are vague at this stage of AIP development, but an AIP premium of about 15 to 20 percent of the cost of the standard conventional submarine is estimated for the non-nuclear options. Fuel cells, power cells and Stirlings should be in the same price range, with CCDs costing somewhat less. The cost of an aluminum power cell system is not yet known but should not be out of line with the other conventional options. Not surprisingly, the nuclear option would be the most costly, particularly for the infrastructure, which would be significantly more complex than for the others.

Safety

The comparison boils down to a choice among various combinations of LOX or 350-bar gaseous oxygen, hydrogen, hydrogen peroxide, methyl alcohol or nuclear energy. Without exception, care and attention will be required; nevertheless, none of these technologies is considered unduly dangerous. Ironically, the nuclear option could well be the safest, given the rigorous safety analysis which would be required for licensing.

Assessed Viability

Several AIP options appear entirely feasible in the short-to-medium term.

Stirling Engines

The Swedish work augurs well for the use of Stirlings in submarines, and there is every indication the Swedes intend to proceed with domestic production and sales initiatives abroad. No insoluble obstacles are envisioned.

Closed-Cycle Diesels

CCDs have only been integrated into mini-submarines to date, but no theoretical reasons are apparent which would prevent success at full scale. However, for naval applications, noise must be considered a major problem; notwithstanding manufacturer assurances, it stands to reason that reciprocating internal combustion engines cannot be quietened to the same extent as can the alternatives. It is a logical hypothesis that the very time one must use the AIP system, one needs to be quiet.

Fuel Cells

Thanks to the German work, marine fuel-cell AIP is now solidly established as viable. Solid polymer cells are considered to hold the most promise at present, but this is definitely a growth industry and major improvements are expected in the next few years.

Aluminum Power Cells

The theoretical advantages of aluminum power cells should provide sufficient incentive for development. The basic principles are sound and a number of electrolyte/oxidant combinations exist from which to choose. Certainly development of large-scale cells is at a very early stage, but optimism is considered warranted.

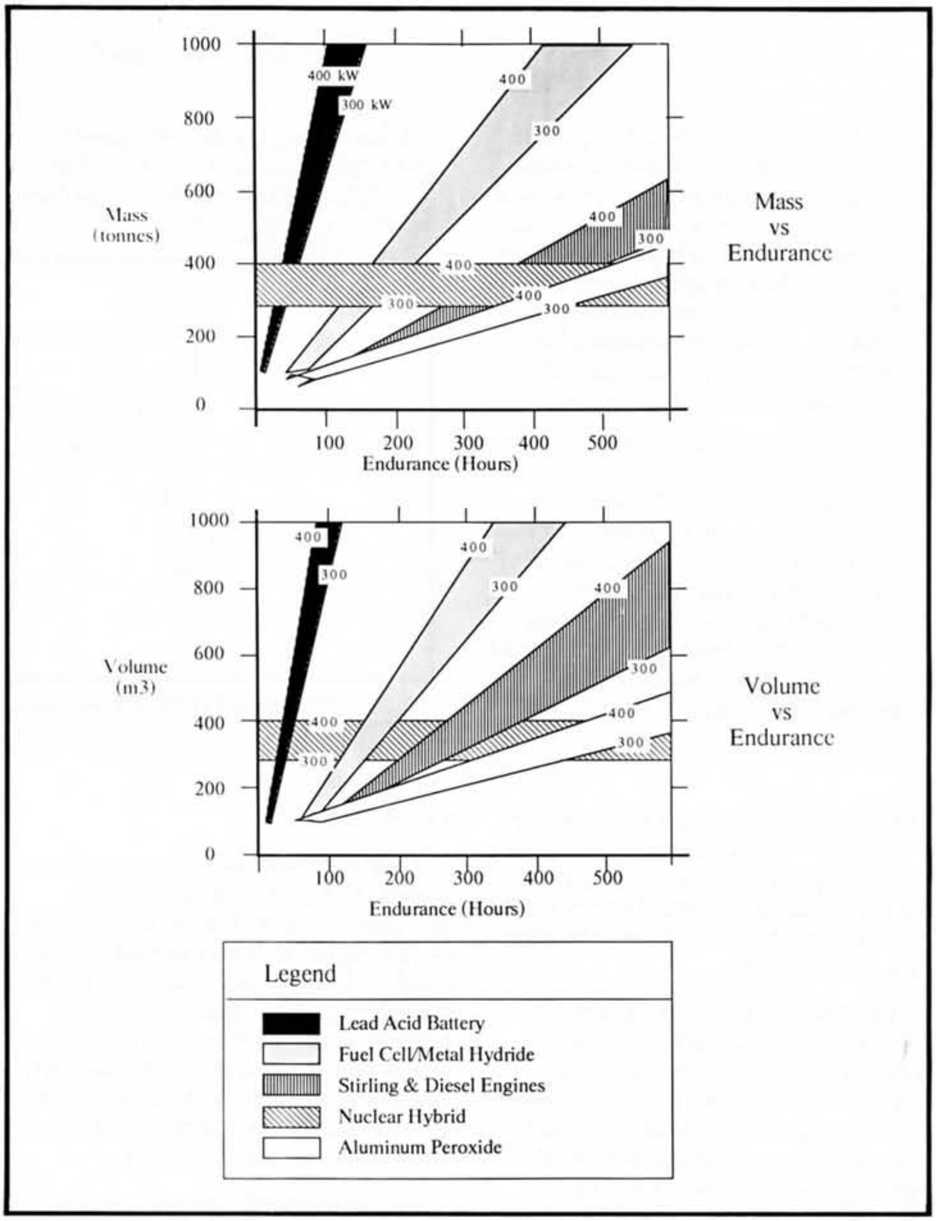

Fig. 3. Mass and Volume versus Endurance at 300 & 400 kW.

Nuclear AIP

Nuclear energy is the purest form of submarine AIP, in that not even a stored or synthetic atmosphere is required. Nuclear battery charging would offer quiet operation and practically unlimited range at a significant cost saving over an SSN. Unfortunately, public unease with anything nuclear would make it very difficult to sell such a project. The inevitable cost premium over other means of AIP (in terms of development, infrastructure and initial procurement) would add to the difficulty.

The Way Ahead for Canada?

Geography must be a central part in any consideration of AIP systems for Canadian submarines. A European submarine could operate on fuel cells from the time it leaves port, while its Canadian counterpart would wish to conserve AIP reactants during the long transit to most of its operating areas. Thus the European sub could use any LOX boil-off, while the Canadian boat would need a cryogenic refrigeration plant, a source of

Small Nuclear

Although there are many possible designs of small nuclear plant, all try to avoid the complexity of a full SSN system. Hence, they aim at using natural primary circuit circulation, large negative temperature coefficients and simplified controls, taking advantage of the buffering effect of the boat's batteries on reactor load transients.

One example is the Autonomous Marine Power Source (AMPS) shown in *Figure A*. This low-temperature, low-pressure, water-cooled reactor is designed for simplicity rather than efficiency. The fuel is a uranium-zirconium-hydride alloy, enriched to 19.7 percent U_{235}. The reactor core is actually immersed in the reserve coolant tank, for added "passive" protection against the classic loss-of-coolant accident. This and other features result in what the developer believes is an exceptionally safe design.

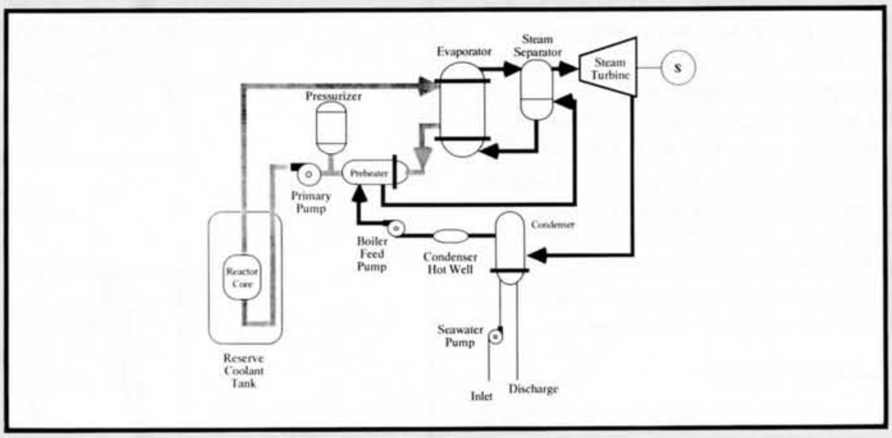

Fig. A. Simplified AMPS Flow Diagram

LOX near the patrol area, or perhaps a different variety of AIP. This is far from suggesting that LOX is unsuitable for Canadian submarines; it merely illustrates the sort of considerations that are necessary.

The Canadian navy will certainly keep abreast of developments in all areas of AIP and keep its options open. In terms of R&D involvement, however, the field can be narrowed. For example, marine Stirling technology is already being actively developed in Sweden, as is the CCD in other countries. Neither requires specific Canadian attention.

If the general public could be persuaded to accept "SSns," then Canadian development effort should concentrate on this technology as it is the only one which gives true air-independence under the Arctic ice. Failing this, and to provide a fall-back position, Canadian R&D effort should be directed into the solid polymer fuel cell and the aluminum power cell. Indeed, there are R&D contracts with both Ballard and Alupower to do just this. For the longer term goal of acquiring fully air-independent submarines rather than hybrids, the Italian toroidal storage concept should be kept in mind.

Conclusion

Given current technology to detect a snorkelling submarine, and the promise of the AIP sources outlined in this paper, it is considered only a small risk to predict that AIP is not only here to stay, but that it will become a standard feature in conventional submarines. A great many AIP systems are currently under development, with an even greater number of nations interested in them.

At the moment, there is no "best" conventional AIP source. The AIP source most appropriate for a particular submarine or customer depends on many factors, including the required operational profile, the speed and endurance, the timing (given the varied development and submarine procurement schedules), the willingness to take technical risk, the proximity to the patrol area and, of course, the available funding.

For the Canadian navy nuclear AIP makes the most sense, but might not be permitted. Of the others, the Stirling engine, the solid polymer fuel cell and the aluminum power cell seem to be the most promising, with the last two being logical candidates for Canadian R&D. The navy is keeping abreast of developments in all areas of AIP, and will keep all options open pending a decision on the number of SSKs (if any) the budget can afford.

Reference

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LCdr Heemskerk was the DMEE 3 submarine systems development engineer until July. He is now MSEO at Naval Engineering Unit Pacific.

Synthetic Atmosphere Diesel Engines for use in Underwater Vehicles

By G.T. Reader, University of Calgary and J.G. Hawley, Royal Navy

The advent of underwater nuclear propulsion in the 1950s heralded a new era in the design and role of the naval submarine. Until that time the submarine had been designed primarily as a surface ship, although improvements in underwater performance had been sought from the mid-1940s onwards. The USS *Albacore* was the most notable exception to this trend since she was designed especially for underwater operation, but the success of the design appears to have been ignored for many years. The hydrodynamic design of the first nuclear boats suffered from the same limitations as those of their conventional cousins but were soon to be improved. The present-day nuclear submarine is a thoroughbred, a truly magnificent beast which is in many ways unrivalled and unchallenged. Yet, for the last ten years or so, arguments have ranged back and forth about SSKs versus SSNs, improved SSKs, the hybrid SSK and so on. Why?

There are many reasons why the conventional boats, at least in terms of numbers, still dominate the military submarine market and why the commercial submarine is exclusively non-nuclear, but the main factor is cost. Not just the cost of building, but that associated with the necessary support infrastructure and the training and retention of personnel. There is also an ever-present political dimension to decision-making when nuclear power and weapons are involved. In an increasingly environmentally aware society nuclear devices are not popular!

The nuclear submarine is a complex feat of engineering which requires a motivated and well-trained crew, a factor perhaps underlined as much by the bad experiences of the Soviets as the good experiences of NATO navies. (Add to this the usual service needs to leadership and discipline, and a fully trained nuclear submariner becomes a very marketable commodity, as the USN has found out to its cost.)

In coastal waters and shallow seas the large nuclear vessel does not have the overwhelming advantage it enjoys in the open ocean. In these environments the SSK can usually hold its own, at least for a few hours. And since the sensor fits of today's SSKs (e.g. the *Upholder* class) are comparable to those of their nuclear contemporaries, there will be other situations in which their performance will be more than acceptable.

The achilles heel of the SSK is its lack of underwater endurance. Present indiscretion ratios are simply too high for the SSK to be able to provide a continual challenge to the SSN. To ameliorate this situation some European navies have turned to the concept of the "hybrid" submarine, in which an auxiliary anaerobic power plant is used to recharge the submarine's batteries while the vessel is submerged at normal operational depths.

Much has been written about this concept, and nuclear protagonists have been vociferously opposed to the idea (especially in the U.K, Canada and the United States). Meanwhile, the Swedes, the Germans and the Italians have carried on with their hybrid developments. The Swedish Stirling hybrid has been accepted into operational service, the German fuel cell plant has performed up to expectations (the new S212 will be powered by such a device), and synthetic atmosphere diesels have been fitted in both commercial and naval underwater vehicles. The United States recently evaluated the performance of such vehicles of Italian design, and the Dutch and Germans are developing the Cosworth (U.K.) and similar synthetic atmosphere diesel systems for a number of applications. Japan has reentered the scene and is once again developing underwater diesels. The Australians have taken options on the Swedish Stirlings. Against this background some countries appear to have adopted the approach of Nero who, as we know, fiddled while Rome burned.

In terms of energy storage capacity and power density the nuclear reactor is unrivalled. If the innovative work of the Canadian ECS group on small, cheap nuclear submarine power plants succeeds, then maybe the concept of low-cost nuclear submarines with displacements of 2,000 tonnes or less will be reexamined. The ECS systems are cited for technical maturity in the late 1990s, but vehicle integration could take a while longer. Perhaps, then, it is time to reconsider some of these air-independent, non-nuclear developments again. It would not be difficult or particularly expensive to retrofit an *Oberon* with a Stirling, synthetic atmosphere diesel or a fuel cell. Indeed, the Royal Navy had a 150-kW recycle diesel unit ready to fit into an "O" boat in the late 1950s, by which time the Soviets had already equipped a Quebec-class coastal boat with a similar unit.

Another factor which is often neglected in discussions on air-independency is that not all naval underwater vehicles are manned submarines of patrol size. The need for new and improved torpedo power plants is usually not addressed at all. Yet, in terms of underwater technology development, there has been an explosion of interest in all types of vehicles. The Italian system examined by the Americans, for example, is the type of vehicle which could be used for swimmer ("à la SEAL") delivery operations. Other vehicles such as the one being developed by DARPA are aimed at unmanned underwater surveillance. There is in fact a wide range of applications other than the manned submarine for which air-independent power plants are required, and the nuclear vs. non-nuclear arguments should not be allowed to distract attention from these developments.

In a paper such as this it is not possible to consider all these applications, or the power plants being developed for them, so we shall concentrate on diesel engine systems. Indeed, the power plant which has received the most attention over the years (and seems to have been reinvented with monotonous regularity) is the closed-cycle diesel. We prefer to use the term *synthetic atmosphere diesel (SAD)* since most of the so-called closed-cycle engines are not in fact closed-cycle, but recycled, and in between there are the semiclosed-cycle systems. To avoid confusion between the different types and variants we have found the generic description of SAD to be most useful and we shall explain why shortly. The heart of a SAD system is the diesel engine, a well-known prime mover and familiar technology in today's navies. A SAD powerpack uses off-the-shelf equipment and this is perhaps its main virtue and attraction.

What is a Synthetic Atmosphere Diesel?

The concept of a SAD system is to operate a diesel engine as a prime mover without access to atmospheric air. Several variants are available, but in all cases part of the exhaust is enriched with oxygen and returned

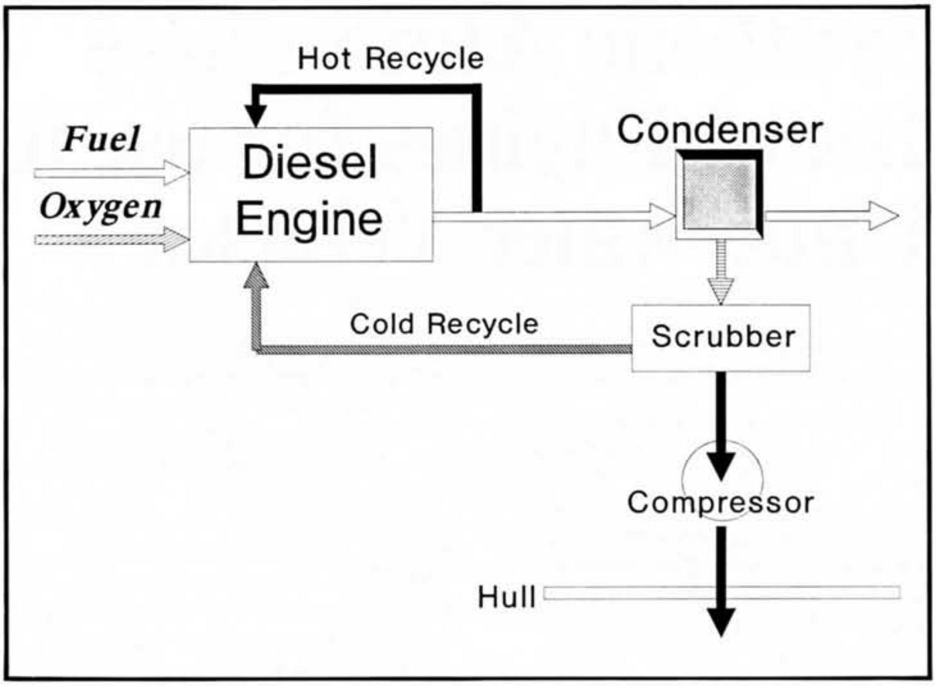

Fig. 1. SAD Concept

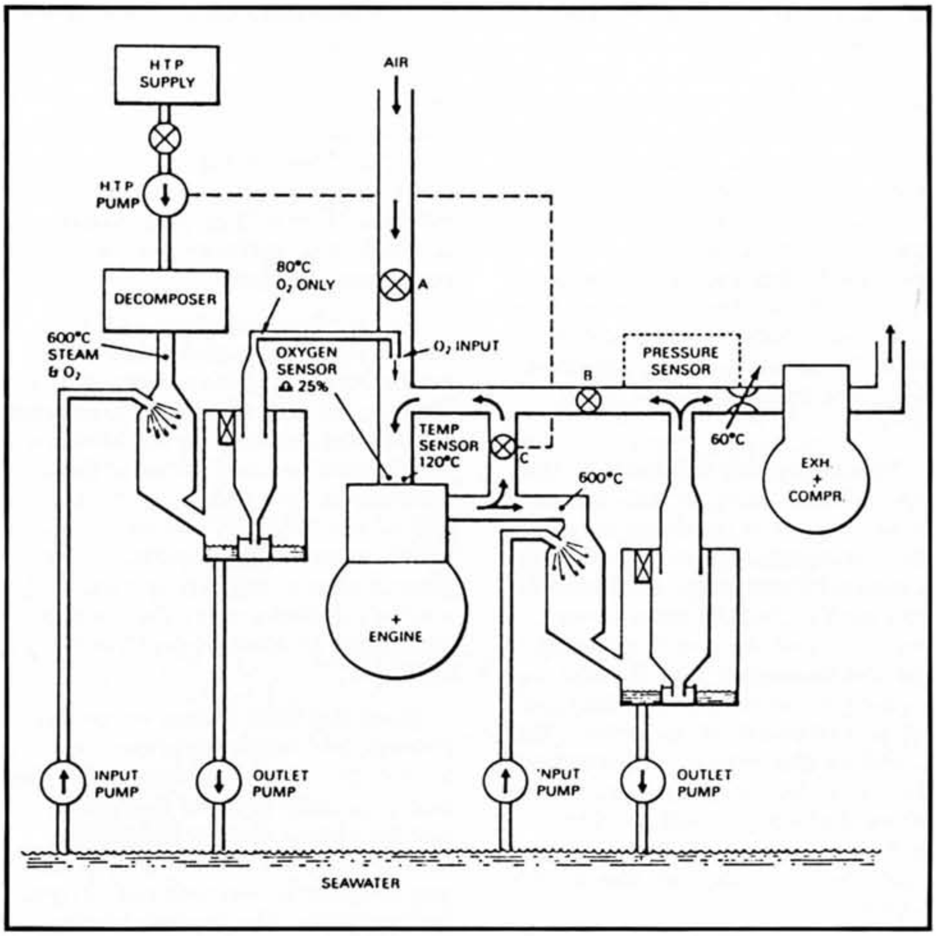

Fig. 2. MOD(N) Recycle Diesel

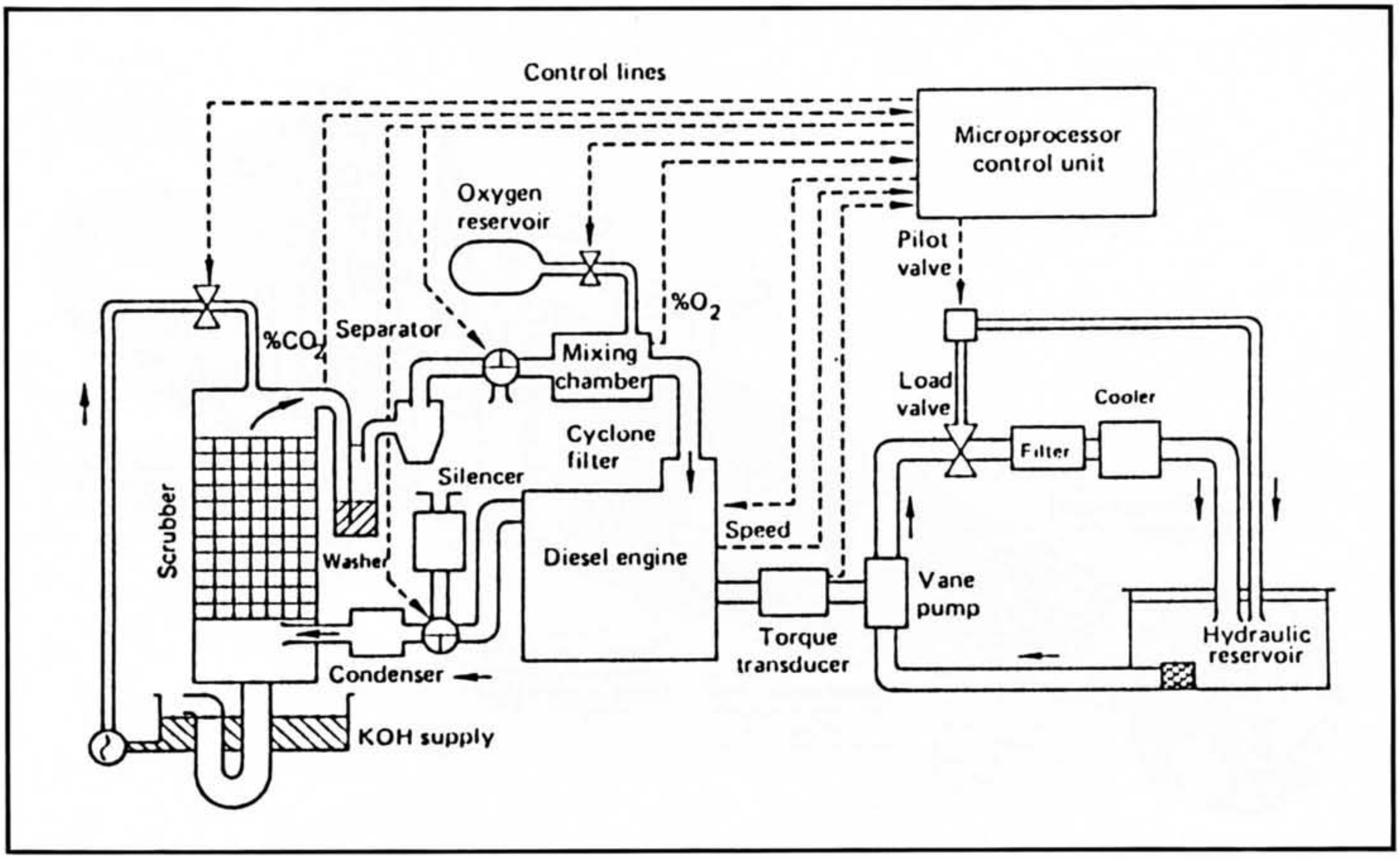

Fig. 3. Newcastle-Cosworth Closed-Cycle Nitro-Diesel

to the inlet (*Fig. 1*). The recirculated exhaust gas is in effect taking over the moderating or diluent role which nitrogen normally plays. Of course if it were possible to run the engine on pure oxygen this would not be necessary. If a hydrocarbon fuel were used, the combustion products would be carbon dioxide and water. After the exhaust has been cooled the water is usually separated, leaving only the CO_2 and excess O_2. Unfortunately, the thermodynamic properties of CO_2 are different from those of nitrogen and in the recirculated mode the compression temperature is not high enough to guarantee ignition. This problem could be overcome by using a high-compression-ratio engine of approximately 50:1. This is not really practical, so usually a hot exhaust bleed system is used to preheat the incoming mixture — experience showing the optimum temperature to be about 120°C (*Fig. 2*).

Although an additional hot recycle helps the engine to operate without misfires and also improves starting, the use of CO_2 alone as the moderating gas results in a level of engine performance 15 to 20 percent lower in terms of bsfc than that in the normally aspirated mode. Furthermore, not all the CO_2 can be recirculated since in a recycle system the pressure would eventually increase above the allowable imep. Thus, the unwanted CO_2 has to be removed from the system and ejected into the surrounding sea water. The backpressure exerted by the sea water is overcome by compressing the carbon dioxide using positive displacement machinery. Unfortunately, as the depth of operation increases, the power drain of the compressor becomes unacceptably high. A SAD system which runs with recycled CO_2 alone is thus depth-limited.

In the 1970s and 1980s Japanese and British research teams experimented with removing the CO_2 from SAD exhausts using chemical scrubbers. Their systems were successful, but the removal of the CO_2 from the exhaust required that another moderating gas be added to the inlet mixture to dilute the fuel-oxygen mixture. The obvious choice for this moderating gas was nitrogen since the resulting mixture is essentially air. Thus the nitro-cycle diesel (*Fig. 3*) was developed by the University of Newcastle and Cosworth Engineering. The scrubbing material used in the Newcastle system was potassium hydroxide. Other types of metallic hydroxides such as sodium or lithium hydroxide could have been used, but the former is very corrosive while the latter is expensive and not readily available outside the United States. These type of chemicals react with the carbon dioxide to form a carbonate slurry and unfortunately cannot be regenerated after use. The amount of chemicals that would have to be carried would pose a major storage problem on long undersea voyages. Other methods of CO_2 scrubbing were therefore sought.

The use of regenerative chemical absorbents — usually of the amine family — is common in atmosphere

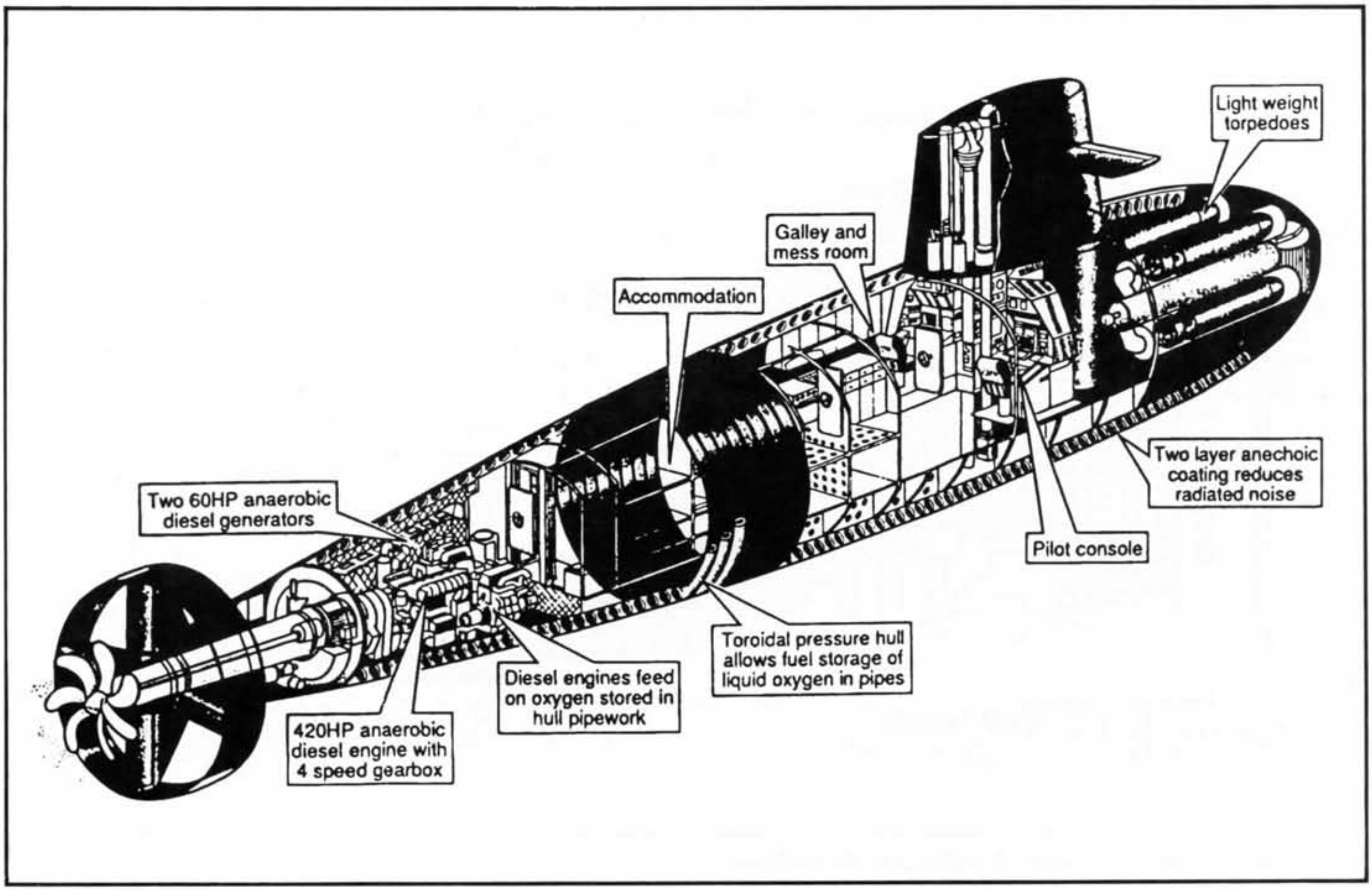

Fig. 4. Maritalia Gst Submarine Concept

control systems. Monoethanolamine (MEA) and diethanolamine (DEA), for example, are used on board nuclear-powered submarines. However, these chemicals are highly toxic, the scrubbing systems using them are bulky and power-hungry, consuming as much as, if not more than, the positive-drive compressors of the basic CO_2 or Kreislauf cycle. Few MEOs wax lyrical about the ease of operation and maintenance of these MEA systems. Nevertheless, the Japanese claim to have successfully developed an MEA system for use with a SAD.

A further alternative is to use water as the CO_2 absorbent. In this case there is a limitless free supply of absorbent, but there is a penalty to be paid for using sea water since it is a relatively poor absorbent compared to the hydroxides and amines. The quantities of sea water that would be required to remove all the CO_2 would be extremely large. To overcome this handling problem, yet still maintain the advantages of using a plentiful supply of absorbent which doesn't have to be stored on board, water scrubbing systems have been designed to extract only part of the CO_2. The remaining CO_2 is recirculated and mixed with argon — hence, the so-called argo-diesel. The use of the higher gamma value argon improves the thermodynamic characteristics of the eventual synthetic atmosphere so that the bsfc is superior to that obtained with a CO_2-only system. The final system is suitable for long-voyage operations.

A water scrubber developed initially by Newcastle-Cosworth and later by Cosworth-Thyssen for a 150-kW SAD takes up less than $10m^3$ and has a mass of 250 kilograms. This system can achieve a bsfc of typically 0.24 kg/kWh with a specific oxygen consumption of 0.84 kg/kWh and a specific argon consumption of 0.038 kg/kWh. If such a system were to be fitted in a seven-metre add-on section to an *Upholder* class, it could extend the submerged endurance of the vessel on a normal patrol by seven to ten days. (This performance is very similar to that claimed for the Swedish Näcken class submarine which is fitted with a Stirling Engine.) The add-on section would contain the SAD generators (two for the sake of safety and the submariners' peace of mind), the oxygen supply, ballast tanks and the extra life-support systems necessary when extended underwater missions are undertaken. The oxygen supply would at the present time be in the form of a cryogenically stored liquid (LOX) or a high-pressure gas (GOX).

The latter is preferred by the Italian company Maritalia which developed the novel submarine design

Fig. 5. *Seahorse*: An Experimental Midget Submarine

concept known as the Gst — *gaseous storage toroidal*. In this system the GOX is stored in high-pressure gas pipes (toroids) which are welded together to form the pressure hull. The U.S. Department of Defense has evaluated midget versions of the Gst submarine (*Fig. 4*).

Applications

To date, SAD systems have been fitted in two types of midget-size underwater craft. The first is the Bruker Meerestechnik *Seahorse*, an experimental four-man submarine with a nominal operational depth of 300 metres (*Fig. 5*). The SAD system used was developed by MAN and is based on a MAN type D2566 ME engine which produces 100 kilowatts at 1,500 r.p.m. The engine can be operated either in open or closed mode and can drive the hydraulic propulsion system or recharge the batteries. Oxygen is carried in the form of LOX and a hydroxide scrubber is used. Argon is the moderating gas and thus the MAN system is a variant of the nitro-diesel and the argo-diesel. Unfortunately, MAN also calls its system the "argo-diesel." The *Seahorse* has undergone some sea and basin trials, but no performance data have so far been published.

Maritalia's small Gst craft, as well as a number of their other SAD-powered underwater vehicles, have been extensively tested. Maritalia — formerly Sub-Sea Oil Services — joined forces in recent years with the major Italian shipbuilder Fincantieri and is working on projects involving O-class size boats with designed submerged endurances of 8,000 nm at five knots, and operating depths over 400 metres. It is believed the Maritialia systems use water scrubbers and that the unwanted exhaust gases can be stored on board so that a wakeless patrol can be undertaken.

In the U.K., Cosworth Deep Sea Systems Ltd. is developing a whole range of SAD systems for a variety of applications, including hybrid power plants for manned submarines, powerpacks for supplying deepwater equipment, and as the main power systems for ROVs, AUVs and robots. In conjunction with Thyssen Nordseewerke of West Germany, Cosworth has been developing over the last two years a 120-kW SAD for use with an add-on submarine module. The engine unit is a Mercerdes-Benz OM421A and has been tested at simulated depths of 500 metres. Cosworth also has a development contract with Rotterdamse Droogdok Mij (RDM) for a slightly larger unit of 150 kW based on a Mercerdes-Benz OM422A.

Within two to three years Cosworth estimates they will be able to develop their argo-diesel systems into the megawatt range for use at depths of 6,000 metres. All their systems use seawater scrubbing and they have accumulated several thousand hours of successful test-bed trials with these units. Cosworth has obvious faith in its systems, for they have built a new factory at Kettering to build their units. Their latest project is a 400-kW SAD incorporating state-of-art noise suppression techniques to make the unit more acceptable from a naval point of view.

In 1980 Japan's Hitachi Shipbuilding announced a 16-kW(e) SAD system they had been working on for some ten years. The system they described appeared to be at a high level of technical maturity. However, not until 1989 was any further information on the Japanese program published and this time it was from Mitsui Shipbuilding — Japan Marine Machinery Development Association. They reported work on a 235-kW prototype long-endurance SAD which used an MEA scrubbing system. These types of power levels would meet the requirements of a manned submarine of up to 2,500 tonnes carrying out a normal patrol.

The Royal Naval Engineering College, Manadon has been researching SADs since 1985 and now have a collaborative program, funded under a NATO grant, with the Department of Mechanical Engineering at the University of Calgary. The objectives of this work are to develop a better analytical model of SAD systems and to collect fundamental system data so that engine and scrubber designs can be optimized. The applications being considered by this group include *Upholder*-size submarines, long-range AUVs and combat swimmer delivery craft.

Thus, worldwide, interest as well as research and development in the SAD is on the increase.

Concluding Remarks

The advantages of SAD systems are:

a. standard off-the-shelf engines are used;

b. the systems can be operated open and closed cycle;

c. navies are familiar with the technology; and

d. response to fluctuating power demand is very good.

The major drawbacks to synthetic atmosphere diesels are noise and the tendency for high engine-wear rates. There is an obvious need for more experimental and analytical work so that SAD system design can be optimized and mission-oriented design undertaken. Apart from basic performance data, more information is needed on scrubber system selection and design and the control of the synthetic atmosphere mixture. Universities could have a significant role to play in SAD system development.

Nevertheless, operational SADs are available. Moreover, they are technically mature enough that they should not be ignored by any navy which has an operational need for extended underwater submarine patrols, but cannot afford the nuclear option.

Acknowledgments

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Professor Graham Reader is the Head of Mechanical Engineering at the University of Calgary. He retired from the Royal Navy in the rank of commander in 1988. His last appointment was as Assistant Dean (Research) of the RNEC.

Lieutenant Commander Gary Hawley, Royal Navy, is a senior lecturer in thermal power at the RNEC and is in charge of the underwater power plant research at the College.

Danger — software ahead!

A personal view of what it will take to support the navy's software.

By Cdr Roger Cyr

Introduction

Software has become the most critical, and talked about, component of all naval systems today. Easily the most fragile and potentially dangerous (especially in view of increasing reliance on full system automation) component of a system, it is considered to be the leading cause of system unreliability. Software is also the component which causes the gravest concerns with respect to maintainability — how it should be maintained and by whom.

One statement continually heard in the software community is that software problems are not technical, but managerial. That is, there are problems with the way the navy manages the software acquisition and maintenance processes. Perhaps, though, the problem is not rooted just with the people who are managing the process. There are also the system engineers to consider, the programmers, the configuration managers, the people who do the validation and verification and, perhaps most important of all, the people whose requirement initiated the acquisition or maintenance process.

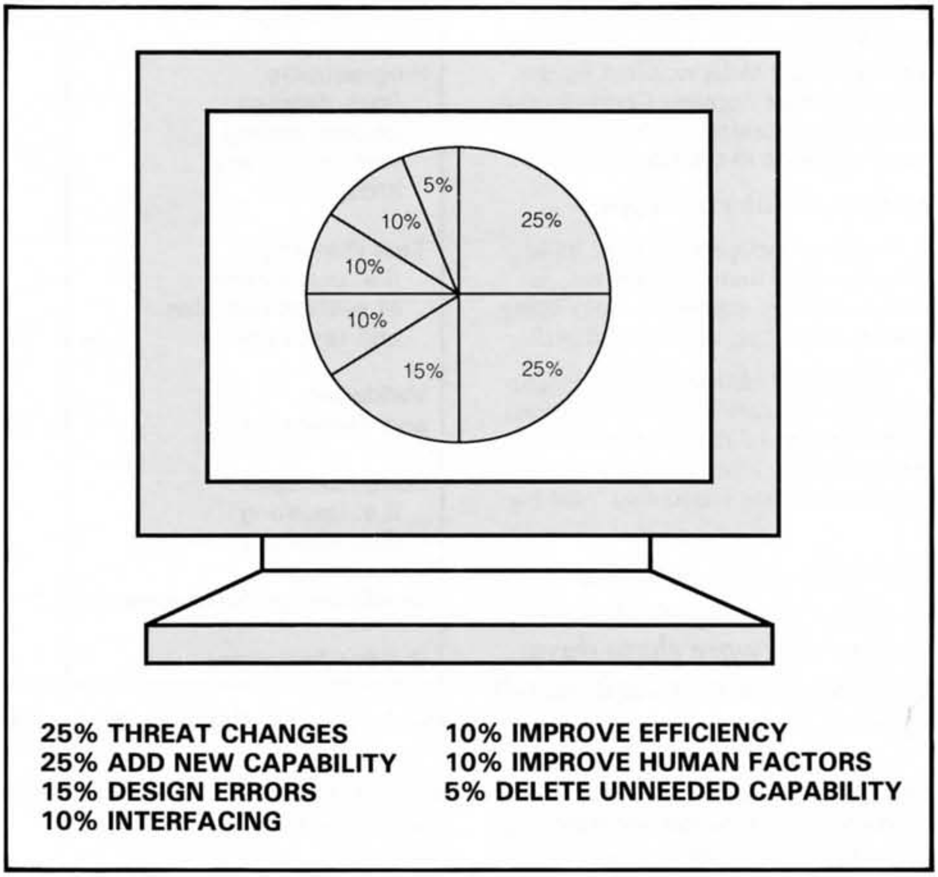


Fig. 1. U.S. Navy statistics showing percentage breakdown of reasons for software changes.

Part of the problem can be attributed to a couple of popular misconceptions regarding software support requirements. The first is that software is an entity, independent of the hardware or system in which it is embedded. Software is but a component of a global system, and to treat it in isolation from the overall system poses grave interfacing problems. The work-breakdown structure of major projects often reflects entirely separate cost centres for hardware and software. As a result, both centres tend to overlook the interfacing requirements of the overall system.

The second misconception is that it requires programming experience to become a software designer or manager. Nothing could be farther from the truth. A basic knowledge of the *structure* is what is needed — not extensive hands-on programming experience.

In terms of software management the navy is going to have its work cut out for it by the Canadian patrol frigate and the modernized Tribal-class destroyer — some 2.5 million source-code instructions. Fifty percent of this will be supported by industry through contracts let by the system life-cycle material managers, but the remaining 1.25 million instructions will have to be supported in-house.

This paper specifically addresses what I see to be the basic philosophy and personnel skills required by the Fleet Software Support Centre to support this substantial inventory of naval software in the years ahead.

Elements of Software Support

From my perspective, four basic elements contribute to effective, in-house software support — they being *system, structure, control* and *skill.*

The *system element* is the recognition that software must be supported in the context of the total system. Barry Boehm, a recognized authority on software, has stated that "the biggest factor in improving software reliability is to have the software process directly involved as a part of the overall system engineering process."

"It takes more than just hitting a few keystrokes to change software these days, and there are no magic words to do it."

The *structure element* is the recognition that the complexity of today's systems software makes it both difficult and costly to change. It takes more than just hitting a few keystrokes, and there are no magic words to do it. Software changes are made for a variety of reasons (*Fig. 1*), but every proposed change must be evaluated for its necessity as well as for its benefit versus cost. Achieving perfection, in itself, is hardly sufficient justification to change a piece of software. Once a decision has been made to proceed with a change, a structured and disciplined approach must be followed.

The *control element* is the recognition that software must be subjected to rigorous configuration control *as a component of a total system under total configuration control.* All changes to the system must be scrupulously controlled and managed by qualified personnel.

The *skill element* is the recognition that we must have in place an infrastructure of personnel who possess the skills needed to effectively perform a full range of software support activities (activities normally associated with software development). The nine basic activities of in-house software support (as defined in the NATO Software Maintenance Concept paper[1]) are described in *Fig. 2.*

SUPPORT ACTIVITY	PERCENTAGE OF TOTAL EFFORT	SKILL REQUIRED
Management (i.e. management of *total* support activity)	6	Software Manager
Requirements Analysis	5	System User
Product Design	11	System Engineer
Programming (incl. detailed design, coding, unit testing and integration)	41	Programmer Analyst Advanced Prog Anal
Test Planning (i.e. preparation of system test plan and test data)	6	System User
Validation and Verification	14	System User
Documentation (i.e. updating user manuals)	11	System User
Configuration Management	3	Programmer Analyst
Quality Assurance	3	Programmer Analyst

Fig. 2. In-house Software Support Activities and Skills

Personnel Skills

From a production standpoint, software is similar to hardware in that different skills are required for the different functions (activities) associated with the development of the product. Making use of the appropriate types and levels of skills ensures production is efficient and cost-effective. It is apparent from *Fig. 2* that each software support activity is but a portion of the overall effort and requires personnel skilled in one or the other of five functional skill categories:

a. System User

b. System Engineer

FUNCTIONAL SKILL	PERCENTAGE OF TOTAL EFFORT	PERSONNEL REQUIREMENT
System User	**36**	**Combat Officer and NCM Operator**
System Engineer	**11**	**Combat System Engineer (CSE)**
Programmer Analyst and Advanced Prog Analyst (*See Note*)	**47**	**CS-2 and CS-3, Contractor, NCM Operator, NCM Technician, Combat Officer, CSE**
Software Manager	**6**	**CS-4, CSE, Combat Officer**

NOTE:

Ideally, all PA and APA requirements should be met by civilian CS personnel. In the event of their unavailability, the requirement should be met by contractor personnel. Failing this, a mix of the military occupations listed above should be used.

Fig. 3. In-house Software Support Personnel Requirements

c. Programmer Analyst

d. Advanced Programmer Analyst

e. Software Manager

System User defines the skills associated with the operation or end use of a system. In the case of naval combat systems these skills are attained through combat officer training and, for NCMs, through operator training. No special software skills are required. System users are required for 36 percent of the activities associated with in-house software support (*Fig. 3*).

System Engineer defines the skills associated with the engineering of a system. These skills, including the required software skills, are attained through combat system engineering (CSE) training. Combat system engineers are required for 11 percent of the activities associated with in-house software support.

Programmer Analyst and Advanced Programmer Analyst define the skills needed for programming, unit testing and integration. Ideally, the activities requiring programmers (47 percent) should be performed by software contractors — a most cost-effective approach. Failing this, they could be performed by Public Service computer specialists (CS-2 and CS-3) or, as a last resort, by a team of naval combat officers, combat system engineers and NCM operators and technicians.

Software Manager defines the skills needed to manage the overall software support activity. The software manager skills will be attained via the Software Manager course. Software managers are required for six percent of the activities associated with in-house software support. These activities should be performed either by a civilian CS-4, a combat system engineer or a combat officer.

Summary

Despite the navy's more than twenty years of experience in software development and maintenance, software continues to be difficult to manage and maintain. The pitfalls are many and our naval systems are being deeply affected by them. Right now, with the requirement to support a whopping 2.5 million source-code instructions for CPF and TRUMP, the navy faces what could well be its greatest technical challenge ever. It is a massive enough undertaking just to contemplate, but the good news is that it can be done — as long as the right machinery is in place to do it.

To begin with, we must maintain a total system perspective and change software only when it is absolutely necessary. The benefits must clearly outweigh the cost. But when we do make a change, be it for an upgrade or whatever, we must exercise disciplined configuration management. This means creating a personnel infrastructure at the outset which can provide the appropriate philosophy, skills and experience to the navy's software development and support process. Anything less than this, and we can surely expect software to remain forever the unstable element of naval systems.

Reference

1. NATO Software Maintenance Concept, Working Paper AC/317(WG/2)WP/24, dated 22 January 1988.

Commander Cyr is the former DMCS 8 section head for naval computer technology. In August he joined the international armaments directorate at NDHQ.

Challenging the TRUMP and CPF Above-Water Warfare Systems

By LCdr Richard Houle

When the TRUMP and CPF ships are delivered, the Canadian navy will embark on its most ambitious trials program ever. Among the most complex of these performance trials will be the above-water warfare (AWW) system trials of three new missile systems, two medium-calibre guns and a close-in weapon system (CIWS). Along with these will be the equipment and integration trials of the various radars, associated electronic warfare sensors and decoys.

To provide a meaningful demonstration of performance, trials must be conducted as realistically as possible. Cost, time and safety constraints will certainly be a factor in this, but the performance and availability of targets and target ranges must also be considered.

To simulate modern threats, aerial targets should be capable of supersonic speed, have a small radar cross-section, have sea-skimming or high-diving capabilities and be manoeuvrable. Surface targets, for their part, should be capable of simulating destroyers and fast patrol boats.

Current in-service aerial targets include towed targets like the radop and Milkcan which use an acoustic miss distance indicator. These targets are cheap, but are slow and require aircraft support. To simulate sea-skimming capability for the CPF CIWS and 57-mm gun trials, the commercially available Hayes TLX-1 target will be rented. The TLX-1 maintains a constant low altitude by using an altimeter.

The rocket-boosted target (ROBOT) developed in Canada will also have a place in the AWW trials. The multistage ROBOT-9 target which is currently available is cheap and expendable, but is restricted in its usefulness by its ballistic trajectory and limited range. The more recent ROBOT-X target (*Fig. 1*) is still under development, but will be available for CPF vertical-launch Seasparrow trials. ROBOT-X is both cheap and recoverable, and is very promising in that it can be programmed to fly various patterns. But with a maximum speed of only 0.85 Mach, it has the disadvantage of being relatively slow. Although this target has reached operational evaluation, it has potential for further development.

Fig. 1. The ROBOT-X Target.

For its Standard Missile trials, PMO TRUMP is planning to use a number of American-made BQM-74 and AQM-37 targets. The BQM-74 is a subsonic programmable target designed to simulate an anti-ship

Fig. 2. The Passive Radar Augmented Projectile

cruise missile. It is capable of low-altitude flight and sustained manoeuvres up to 5.3g and has a longer range than the ROBOT-X. The AQM-37, on the other hand, is a supersonic air-launched drone which can simulate a high-diving target.

To simulate supersonic targets, the Passive Radar Augmented Projectile (*Fig. 2*) will be used. The advantages of the projectile are that it is cheap, its radar cross-section can be adjusted and it can be fired from an existing gun such as the 3''50. It is limited, however, by its ballistic trajectory.

For surface firing, the usual towed targets such as the Larne and high-speed plastic types are still around. But there is also the Barracuda (*Fig. 3*), a remote-controlled surface target being developed in Canada, which offers the speed necessary to simulate a fast patrol boat. By using a variety of radar reflectors its radar cross-section may be adjusted to represent a destroyer-size target as well.

There are also plans to use the CF-18 as a supersonic target for detection, acquisition and tracking trials — but not for live firing trials!

Traditionally, the source of high-performance targets and associated ranges has been through the USN. But due to U.S. Department of Defense budget cuts, American targets and ranges are becoming less available — and this at a time when our needs for highly capable missile systems and the number of platforms carrying them is increasing. Although CPF trials will be conducted off Halifax as much as possible (using the targets mentioned in this paper), there remains some need to use American ranges for some trials. The Harpoon firing trials, for example, will be conducted off Puerto Rico, using American facilities.

It is apparent that no single target or facility can be used to evaluate the complete capability of the CPF and TRUMP AWW systems. What may look like a fairly straightforward process (although destroying a moving target from a moving platform has never been easy) becomes very complicated when it entails accurately assessing the performance of sophisticated AWW systems with limited resources. To accomplish the trials, the navy is going to have to make the most of its on-range time. And one of the best ways of doing this is by "extending" the trials through computer simulation.

While various targets will be used to assess the systems against parameters for target size, speed, altitude and manoeuvrability, extensive data gathering will be undertaken to establish baselines against which software models (*MEJ* July 1990, p.13) can be validated. Computer simulation will then extrapolate how the systems might perform against real threats. The simulations can also be used to evaluate factors such as the tactical environment (e.g. heavy jamming), the suitability of a target to simulate a threat, weapon performance against multiple threats, and the integration of hardkill and softkill, to mention a few.

A number of other activities are being pursued to help the navy achieve satisfactory trials programs for the CPF and TRUMP AWW systems. A portable telemetry receiving station has been developed and acquired for Maritime Command, various target projects are in different stages of development and procurement, and a performance monitoring system is being developed to assist in the data gathering and analysis process.

The hardware is important, but then so too are the people from the various industry and government agencies being considered for the trials support roles. The ships, the weapons, the targets, the ranges, the computers, the trials co-ordinators, the safety numbers — each of them is going to have a critical role to play in challenging and assessing the performance of the CPF and TRUMP above-water warfare systems.

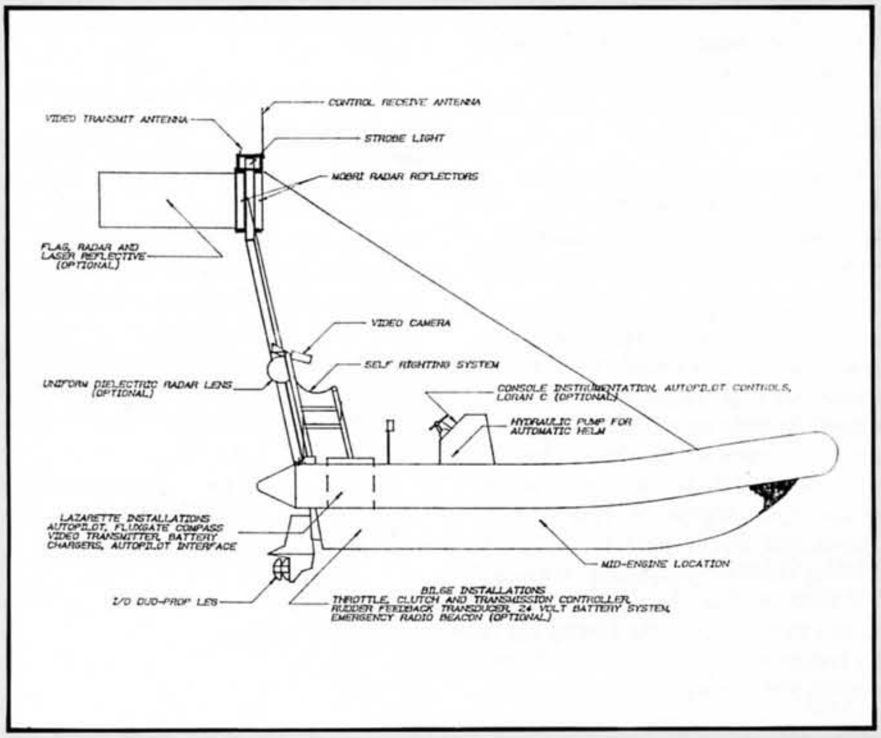


Fig. 3. The Barracuda Target Boat.

Lieutenant Commander Houle is the DMCS 2 trials co-ordinator for above-water warfare systems.

Looking Back:

Engineering Incident — No. 1 Diesel Failure

The events

A DDH 257-class ship was just finishing a short work period. A considerable amount of upperdeck (chipping and painting) work remained to be done, as did some minor engineering jobs.

During the forenoon watch No. 1 diesel alternator was started for the first time after a complete overhaul (6400-hour routine). The watchkeeper was paying particular attention to his job as this was the first run-up. It was to be put on load for trials prior to acceptance. All temperatures and pressures were observed to be normal. After about an hour the lights dimmed and the diesel slowed down. The engine began to smoke and, before it could be shut down, seized solid. The elapsed time from the engine's slowing down to its seizing was about one minute. The CERA and Engineer were notified and an investigation was started.

Machinery damage

Upon opening up the engine it was discovered that another complete overhaul would be required. The failure resulted from the ingestion of foreign material, later determined to be non-skid (that was being chipped from the fo'c'sle) which had been sucked into the engine through the intake, ground up by the blower, and deposited in the cylinders. Within one hour, 6400 hours had been "logged" on a refurbished engine.

Lesson learned

Always inspect intakes and the area around them before starting machinery.

News Briefs

Certificates of merit!

The Assistant Deputy Minister (Materiel), Mr. RD Gillespie, took time on May 22 to present the ADM(Mat) Certificate of Merit to four members of DGMEM. The recipients, seen here in the front row, are: **Jaidev Mahajan** (DMEE 6), **Mrs. Deborah Lidster** (PMO NRMP), **Jack Trudeau** (DMEE 2) and **Andrew Graham** (DMCS 2). In the second row, Mr. Gillespie is flanked on his right by Chief of Engineering and Maintenance MGen WR Oldford, and on his left by Cmdre MT Saker (DGMEM). *(CFB Ottawa photo by Cpl Bournival)*

SHINPADS: The Next Generation

DMCS has released a Request for Proposal for the development of a network-independent interface between the SHINPADS databus and a standard VME multiprocessor computer. Thanks to some special Ada software, the interface will permit seamless integration of standard VME computer components with the current Canadian SHINPADS network.

Development of the Next Generation SHINPADS Node, as the interface is called, is the first part of a three-phase development of the Next Generation Command and Control Technology Project. The follow-on phases will see the development of a distributed, real-time database and an Ada multitasking system.

USN design explored for TRUMP fuel system effluent treatment

In June a Canadian naval engineering team visited the Environmental Protection Branch of the David Taylor Research Center at Annapolis, Maryland. Over the past ten years the David Taylor Labs in conjunction with Johns Hopkins University have experienced considerable success with the design of parallel plate oily water separators.

The Canadian engineers (**Steve Dauphinee** of NEUA, **John Pirquet** of NEUP and **Lt(N) Mike LeGoff** of DMEE 5) spent four days exploring design considerations for using parallel plate equipment to process the large volume of effluent displaced when fuelling the TRUMP water-compensated fuel tanks.

The visit was a direct result of a 1990 NATO meeting on shipboard pollution abatement. During the meeting the USN offered to share with its NATO allies many of the results of its twenty years of R&D in environmental protection.

Naval presence in Quebec

Treasury Board has approved the design phase of a major new naval reserve facility to be constructed at Pointe-à-Carcy, Quebec.

The project, worth approximately $36 million, is the flagship of the third phase of the Naval Presence in Quebec Project (NPIQ 111). The complex will house the new Canadian Forces Fleet School Quebec, the headquarters for the naval reserve and the naval reserve division, HMCS *Montcalm*.

The design phase of the project is worth an estimated $4.0 million and will go to tender this summer. Tendering for construction is scheduled for the summer of 1992.

EHM conference a success

By all accounts the fifth annual Equipment Health Monitoring Conference in Hull, Quebec last June was an unqualified success. Turnout was good for the two-day conference which featured paper presentations, a business meeting and an ongoing display of EHM equipment.

The equipment display, new to the conference this year, gave delegates a chance to see some of the navy's in-service and developmental EHM equipment and techniques in operation. Members of NETE project teams, led by NETE's EHM Section Head **Fumio Motomura**, were well-versed in their presentations of vibration analysis, thermal imaging, data logging, oil and coolant condition analysis and more. The display also showed off some of the latest developments from Canadian industry and the USN.

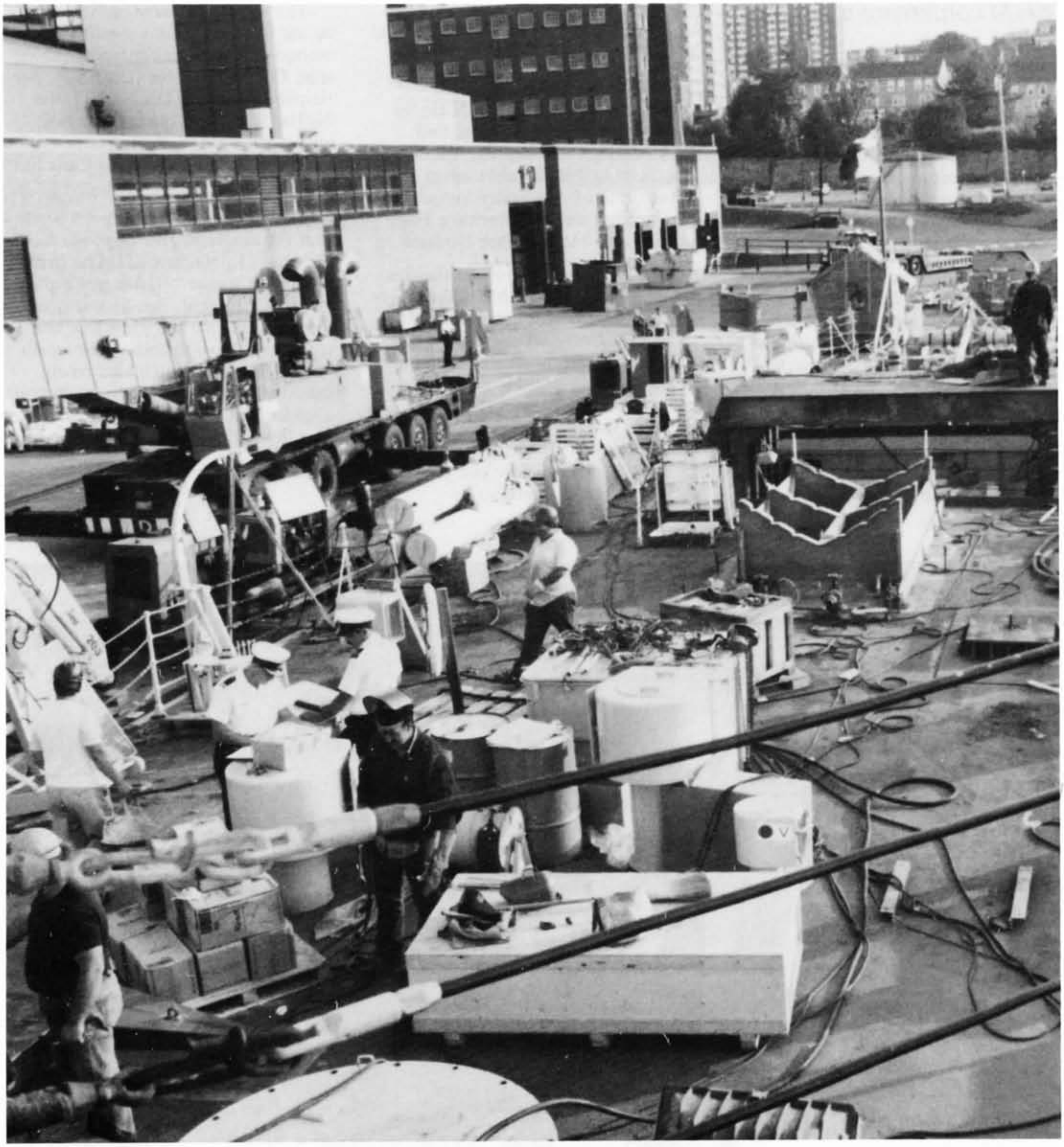
The papers session featured presentations from the USN Equipment Condition Assessment Cell (NAVSSES, Philadelphia), the Naval Engineering Test Establishment, the Directorate of Aerospace Support Engineering and the Maritime Engineering and Maintenance Division.

In his keynote address to the conference, **Commodore MT Saker** highlighted the need for economizing the navy's fleet support operations without causing unacceptable reductions in fleet availability. He urged delegates to consider the cost-effectiveness of EHM in their deliberations. ''DND is facing tough financial times,'' he said, ''and therefore everything, including EHM, needs to be challenged.''

The economy theme carried over to the formal business meeting on the second day. Led by conference chairman **Cdr Bob Gebbie** (DMES 6), participants from NETE, NDHQ, the NEUs, SRUs and other units dealt with a wide range of ''implementation action items'' pertaining to Canadian naval EHM.

Cdr Gebbie later told the *Journal* that the aim is to give ships the tools they need to conduct EHM as first-line maintenance. ''(It) is our top priority,'' he said. But he was quick to point out that the programs and techniques have to show their worth in preventing unanticipated costly machinery failures. ''How much cost *avoidance* is associated with EHM . . . that's the real question,'' he said.

Conference Chairman Cdr Bob Gebbie and Director of Maritime Engineering Support Bob Spittall listen as NETE's Fumio Motomura makes a point. *(Photo by LCdr Steve Mozes)*



Operation Friction

Coming up in our next issue