CHAPTER 1 - INTRODUCTION

Since the early 1960's we have seen the introduction of nuclear powered submarines which seemed at first as though they had all the characteristics needed to completely oust the older diesel electric boats.

This book is about another class of submarines, the Air Independent Propulsion submarines, which are non-nuclear boats with much enhanced endurance. Whereas there are approximately 160 nuclear powered submarines in service there are thought to be between 300 and 400 diesel electric submarines, many of which will become AIP boats over the next twenty five years. I have attempted to write down the main strands of thought that have contributed to the rise of this new phenomenon, and to show why these platforms have military significance.

The diesel electric submarine was gradually developed during the first forty years of the century until it appeared in WW2 as a boat of about 800 tes with diesel engines developing about 2 MW and electric propulsion motors of about 500 kW with batteries with approximately 8000 A-h of capacity. Ref (a). The submarine could remain dived for periods of at most two days, and then only at minimum activity. This type of weapon wreaked heavy damage on N. Atlantic convoys from about 1940 until sometime in late 1943 when Anti-Submarine Warfare measures began to gain the upper hand. Even after 1943 a U-boat was probably superior to a single surface ship in a one-on-one conflict, but the allied forces used co-operative tactics between several surface ships and aircraft to overcome the threat. A key matter in battles with submarines was to keep in contact with the submarine and so to keep it under water until its limited endurance was exhausted, after which it could more readily be confronted.

The need to increase the submerged performance of submarines was high in the minds of German and Japanese submarine designers. They did not think solely in terms of increased endurance. They also considered ways of increasing the underwater sprint speed of the boats. If a boat, once detected could move at say 35 or 40 kts for a short period, it might very well escape from the detection screens of surface vessels and thereafter either simply escape or even return to attack from a new direction.

The designers did not have to start wholly from scratch. Submarine architects had been quite aware of the limitations of their product and there had been some pre-war experiments on making various types of engines run under water. They had not got very far mainly because the admiralty paymasters saw the diesel electric boat as having an obvious development path, and secondarily because there was no convincing alternative propulsion system.

Immediately after the war new work was started on the development of submarines and initially two lines of attack were followed. Both of these originated in Germany. (There was an additional strand of development in Russia, which has only come fully to light in the last few years. I will describe some of the Russian work later.) These approaches were based on a device called a closed cycle diesel, and on something called a Walter turbine. Both of these developments were initiated by an outstanding engineer called Hellmuth Walter. In both cases fuel was burned in oxygen derived from a liquid called hydrogen peroxide. The Germans did not have time to really develop these devices, but they were taken up after the war by several of the allied powers. In the event, these particular devices were not developed for long because they were overtaken by the advent of the nuclear powered submarine and a further period of about fifteen years was to elapse before Air Independent Propulsion started to be taken seriously again. Even then the interest was pretty well limited to engineers and other designers.

I will discuss the early forms of the closed cycle diesel below, and the Cosworth Argo Closed Cycle Diesel in a separate chapter. For now it will be of interest to consider the *Walter turbine*. This device is based on the fact that a light hydrocarbon fuel (petrol, paraffin, diesel oil) is very easily ignited in a stream of pure oxygen. (I have discussed some of the properties of pure oxygen in more detail in another chapter). Walter's idea was to simply mix nearly pure hydrogen peroxide and diesel fuel in a chamber immediately preceding a turbine. The peroxide was passed over some sort of catalyst, usually silver wire, to help it break down to oxygen. Heat was extracted from this fiercely burning mixture in the turbine and so converted to mechanical energy. A sketch of the arrangement is shown in Figure INTRO 1.

With such a device it is not out of the way to think that an 800 te submarine might be driven at 30 kts for a short time. Much has been made about the many fires and explosions that took place while working with this system. It seems that at higher concentrations, a mixture of hydrogen peroxide and water can either explode of its own account or at least induce other things to explode. Perhaps with a longer development period the teeth could have been drawn from this particular problem. Certainly, the idea of an AIP boat with hydrogen peroxide as the oxidiser became rather unpopular. Ref (b). A later chapter is given over to sources of oxygen.

The idea of using HTP was raised again in modern times by Sweden's FFV Ordnance who developed an axial piston motor rather than a turbine to extract the energy. The pistons work against a cam plate. The unit was developed for torpedo propulsion. It produced up to 300 kW from an engine 1m by 0.5 m diameter. A high working temperature of about 800 ºC would make for higher efficiencies than you normally see in steam engines. Ref (d). The British believe that their submarine *HMS Sidon* Ref (e) was sunk by HTP in a torpedo drive exploding, and it would be interesting to know what changes in design philosophy are now proposed in an HTP based torpedo drive.

I consider that the idea of the Walter turbine could be cast into a modern form in which some of the engineering problems which were so hard to deal with in 1944 and 1945 could be lessened. I have briefly discussed this in the later chapter on oxygen sources.

With the advent of the nuclear submarine there was a period of about thirty years in which the heavy hitting countries thought only about the design of atomic powered boats and about the strategy and tactics of deploying them.. It soon became clear that nuclear boats were expensive units that only a few countries were going to have access to. The door seemed to be closed to the submarine world for all but a few key players.

You can't stop people thinking. Sometimes they think best when the situation seems bleak. The submarine designers started thinking about an AIP submarine based not on hydrogen peroxide but on liquid oxygen (LOX) as the oxidant. The technology for manufacturing and storing LOX developed rapidly after the war, as industrial processes were renewed and developed. LOX was starting to be used in large quantities in steel making and by 1965 it was nothing out of the way to see twenty ton tanks of the stuff dotted about factories of various types.

Even in the sixties and early seventies remarkably prescient papers were appearing at Marine Engineering Conferences discussing the options for underwater propulsion. The papers by Morrison, McCartney and Blose (1966) Ref (l) and by Eleanor MacNair (1975) Ref (k), for example, have a ring to them which is readily recognised a quarter of a century later.

Submarine strategists also began to have some dim idea that the nuclear submarine might not be suitable for all roles. It had been specially designed after all for the deep ocean. Either the submarine was carrying missiles or it was shadowing enemy submarines. A great dance in the sea which did not really have anything to do with the second rate nastiness that other lesser nations might be thinking of. Perhaps, the strategists thought, there is still a role for a non-nuclear submarine with improved capabilities. Certainly enhanced endurance under water was something that might be needed.

Even simple sums showed that you could keep a medium sized submarine going for much longer at four knots than the two to three days you might think of for an SSK. A period of two to three weeks soon began to appear as a target. These ideas were gradually refined into the various forms described later in this book.

The following outline calculation is typical of the way an AIP designer might have been thinking twenty years ago :

In a certain German built Type 209 submarine there are 8 off 120 cell units in the battery compartments and they occupy 176 cu m. A 200 kW propulsion motor will keep the submarine going at 9 kts for 23 hours until the battery is 80 % depleted.

Now suppose you remove half the batteries (88 cu metres) and put in place an 8 cylinder diesel engine (2 cu m) and a liquid oxygen (=LOX) tank which might hold 1.5 tes of LOX per m3 of tank. There is thus room for 57 tes of LOX. To get 200 kW at the propeller we might allow some very generous losses and have the diesel generating 265 kW at which power it will be consuming 4.8 te LOX per day. So the submarine will be able to maintain its 9 kts for nearly twelve days.

This argument intentionally misses out many of the subtleties of submarine design. It just sets a ball park figure.

At this level numerous consequential thoughts would have passed through the designer's mind. There would have been no diesel that would work convincingly deep down in the water, so perhaps there was some other prime mover he could use ? How much actual space would be needed for auxiliaries ? Would the system be fully closed like a battery, or would waste material such as carbon dioxide have to be put over the side ? If so, how much space would be needed for buoyancy compensation tanks ? Suppose the underwater patrol speed was reduced to 4 kts could the boat be thought of as staying down for six weeks ? This would be half the standard patrol length of a nuclear missile firing boat. If he had a tank of LOX in the boat, could this be utilised as part of the life support system ? If he were putting CO2 from an engine over the side, could he somehow use the system for getting rid of CO2 from the boat ? Was there a system that did not actually put CO2 over the side ? How much power would be needed for the hotel load ? And so on.

An innovating designer always has to recognise negative strands of thought and find ways of dealing with them. In the matter of submarines, people said we have nuclear submarines with a longer engineering endurance than the crew can survive, what more do you want ? They said there was no suitable heat engine that would run under water, especially at depth, they said that the battery manufacturers would improve the capacity of their batteries. They said the costs would be enormous and no one would back the development. And so on. All these are useful inputs which you have to find some way of rebutting, otherwise you run the risk of making a product that no-one will buy.

After nearly thirty years of work four workable systems have appeared for the propulsion systems : MESMA, Fuel Cell, Stirling Engine and the Cosworth Argo Closed Cycle Diesel. All these systems burn a fuel using oxygen gas derived from a liquid oxygen tank carried in the submarine. I have written about these developed systems in separate chapters.

It is useful to understand some of the factors that were involved in the development of these and other proposed systems. The dictum that *those people who don't understand history are doomed to repeat it* (I think it was Salvador de Madariaga who said it first) translates into engineering and other sciences as *try not to waste money by repeating other peoples' mistakes.* Many very good and inventive people have made contributions to this field and we should try to understand at least the main lines of thought.

Closed Cycle Diesels

Closed cycle diesels have the longest history of experimental investigation of any of the AIP candidates. The earlier devices ran on a recirculating mixture of carbon dioxide and oxygen. They suffered from poor combustion, very poor starting characteristics, they weren't thermally efficient and they made a lot of smoke.

The closed cycle diesel has had a very long gestation period. Its earlier forms all suffered from one or more defects. It will be useful to run over some of the previous embodiments so as to understand the preferred system, the Cosworth Argo-Closed Cycle Diesel, which is discussed in a separate chapter.

Closed Cycle Diesels - 1

The simplest form is as shown in Figure INTRO 2. This system was invented by Kreislauf. *I do not have an original reference to this work and would appreciate being advised on a source reference.*

The diesel breathes a mixture of carbon dioxide (CO2) and oxygen (O2), and it exhausts some different mixture which is routed back to the inlet. Some of the gas is bled off to get rid of the excess CO2 of combustion and oxygen is added to get back to the original mixture. This system encapsulates all the problems with most variants of the closed cycle diesel.

First of all, in getting rid of the CO2 of combustion, you are throwing away also some oxygen since there is no way of easily separating two gases once mixed. As you have to invent some storage method of getting the oxygen into the submarine in the first place, throwing oxygen overboard is absolutely the last thing you want to do.

Secondly, the diesel runs badly because the pressure at the top of the compression stroke is low as compared with running on air. This can be understood with reference to a simple bike pump. Every kid knows that if you put your finger over the delivery nozzle of a bike pump and quickly push the plunger down, the air in the pup gets hot. If you filled the pump with a mixture of CO2 and O2 and did the same experiment, then you would find that the pump still got hot, but not as hot as in the case of air. All gases have a number which we call gamma. The higher gamma, the higher the temperature after a standard compression. All the components of air have gamma=1.4 whereas CO2 has a value of about 1.3. Therefore a mixture of CO2 and oxygen has a lower gamma than air and the gas reaches a lower temperature on compression.

In a diesel you have to have the gas heated to some definite temperature by the end of the compression stroke otherwise when you inject the fuel it won't light. So diesels running on CO2/O2 mixtures are difficult to start. Actually mostly they won't start at all and you have to light a fire (in some sense) in the inlet manifold to get the diesel to go.

Thirdly, diesels running on CO2/O2 have poor combustion. They make a lot of smoke. You can always tell when people have been working on these systems because the workshop has black walls. Furthermore, there is a longer ignition delay with CO2/O2 than with air. The ignition delay is the time interval between squirting in fuel and it bursting into flame. Some of the delay is due to the time needed to physically heat enough of a fuel droplet, but there are other factors are still mysterious.

The net effect of these factors is that the diesel is running very far away from the conditions which the designer intended. Diesels have been developed steadily and continuously for nearly 100 years and the greater part of that work has been in managing the combustion conditions better. It really seems very undesirable to run the diesel under arbitrary new conditions.

Closed Cycle Diesels – 2

The nitro-diesel attempted to get over some of these problems by absorbing the greater part of the CO2 in some sort of chemical. A sketch of a typical system is shown in Figure INTRO 3

In this arrangement the carbon dioxide is absorbed in a solution of potassium hydroxide (KOH). Another candidate was sodium hydroxide but in this case the sodium carbonate which is formed precipitates out at a much lower concentration than the corresponding potassium salt. Although it is relatively easy to get this system to work, the KOH is nasty stuff. You have to use a 50 percent by weight solution, and it is slightly sticky and burns you if it gets on your hands. Also the reaction between CO2 and KOH gives out a lot of heat, so you have to provide means to cool the mixing/absorption vessel. Nevertheless you can remove a lot of the carbon dioxide and the diesel can then be run on the correct air mixture.

At least one small commercial submarine using a KOH scrubber has been made by Bruker Meerestechnik. Ref*(n)* This was a 14.5 m long submarines for underwater observation.

Of course the downside with such a system in a large submarine is that you could not carry enough KOH to have any range at all. Experiments with small engines (say about 60 kW) were carried out both at Newcastle University by Dr Fowler (Ref (s)) and his colleagues and at the CDSS factory in Kettering UK. The combustion and absorption reactions are

$$CH_2 + 1.5\ O_2 = CO_2 + H_2O$$
$$CO_2 + 2KOH = K_2CO_3 + H_2O$$

or, overall,

$$CH2 + 1.5O_2 + 2KOH = K_2CO_3 + H_2O$$

The Newcastle team used a 50% w/w solution which they bought in drums, and they used this to scrub the exhaust until no more than 2% of CO2 remained in the gases at the inlet of the diesel engine. As time went on they found that the KOH had to be pumped round ever faster. They used about 16 kg of solution for every 1 kg of fuel burned. Remembering that a 200 kW diesel engine burns about 0.9 moles fuel per sec or 45 Kg/hour, then some 720 Kg of solution might be needed to keep the engine going for an hour. If we could find 10 m3 of space for KOH solution in our medium sized submarine, the diesel could only be kept running for 10/0.72 = 14 hours, whereas our target is at least two weeks running, which is more than 300 hours. This is not the only problem with a KOH system. The reaction of one mole of carbon dioxide with KOH releases 60 kJ of energy. You soon find the KOH solution becoming hot and starting to boil. You have to install quite a substantial cooling system. So KOH is never going to be a serious contender for proper submarines.

Closed Cycle Diesels – 3

The fact that you could not carry enough KOH in a submarine led to the idea of using a recycle-able absorbent. The usual candidate is something called *methyl ethanolamine.* We abbreviate this mouthful to MEA. The key property of this liquid chemical is that it absorbs carbon dioxide strongly when cold and disgorges it when hot. Therefore you can imagine a plant with two tanks of MEA one absorbing CO2 from the engine and the other being heated up and discharging CO2 overboard.

Unfortunately, you cannot really make this work inside a small submarine. The absorbing towers and associated equipment are too large, it is difficult to stop the toxic chemical leaking out and the problems of installing a small chemical plant in the confined space of a submarine simply can't be overcome. Such plants can be made small enough to scrub out CO2 from the atmosphere of large nuclear submarines; very small amounts of CO2 are involved and even then the plant is quite large and consumes quite a lot of power.

Closed Cycle Diesels - 4

In addition to the problems which have been mentioned above there two other problems that are common to all closed cycle diesels and, to a more or less extent, to some other AIP systems.

The first is in the control of the oxygen content of the mixture, and the second lies in the power needed to pump the carbon dioxide over board.

In a recirculating system from a small diesel the exhaust gas is output at the order of 100 litres/sec. It will probably go into a 100 mm diameter pipe for transport over a nominal 10 metres back to the inlet. The velocity of the gas will be about 12 m/sec and will take something of the order of a second to go from the exhaust back to the inlet. The oxygen which is injected to bring the mixture up to 21 % that the diesel expects is only going to be added quite near to the engine so the oxygen meter has to react in a few hundredths of a second at most.

The second problem is that in a diesel cycle, somehow or another you are going to extract some of the carbon dioxide at a pressure near to 2 Bara and you have then to get it overboard into a pressurised sea at anything up to 50 Bara. There is a considerable power drain in pumping this gas up to sea pressure and it can easily reach up to 30 or 40 percent of the shaft output

Closed Cycle Diesels - 5

There is another diesel cycle called the psychrodiesel Ref (m) See Figure INTRO 4

The psychrocycle embodied an interesting idea to overcome the difficulties of measuring the oxygen content in the gas mixture approaching the diesel inlet. This was a continual problem until zirconia oxygen sensors came onto the market. In the psychrocycle the exhaust gas from the engine was first scrubbed free of its carbon dioxide with potassium hydroxide solution. Then the remaining gas which would be oxygen and water vapour was passed through a “lung” containing water held at a suitable temperature. The water would have its own vapour pressure (which you look up in Steam Tables) and this could be adjusted to give 21% oxygen in the mixture. The diesel would then be running on a mixture of water vapour and oxygen of about the correct constituency.

Of course, the diesel still suffers from the same problem that the CO2/O2 system has, namely that the gamma value of the gases is way below that of the air for which the diesel was designed, so the combustion will be affected, probably adversely, and it will be difficult to start the engine from cold.

The authors of this work also explored another interesting variant. They replaced KOH as the carbon dioxide with a chemical called potassium superoxide KO_2. This material reacts with carbon dioxide to produce oxygen.

$$2KO_2 + CO_2 = K_2CO_3 + 1.5\ O_2$$

so that some or all of the oxygen required to run the engine is carried as this potassium superoxide. In their Table II the authors say that they required 10.6 lbs KO_2/kW-hr or 0.375 lbs/kW-hr, these figures including all tankage and associated equipment. If you convert this these figures to metric values you find that their overall bulk density came in at about 480 kg/m3.

They are using about 10 litres of KO_2 per kW-hr. so a 200 kW engine will use about 2m3/hr. Since a medium sized submarine will have about 40 m3 available for oxygen, you are going to get about 20 hours of continuous operation from the system and it won't match other systems.

It has surprised me that the Japanese have not made more effort in this field. They certainly have a number of small submarines working on CO2/O2 cycles and their university engineering departments seem to continually publish papers on this system. Furthermore, in 1980 Asada and Nagai Ref (p) published a very detailed paper in which many suggestions were made for improving diesel operation under water, including the use of inert gases to control the combustion conditions.

CCD's received a considerable boost when the British motor racing company Cosworth Engineering took an interest in the design. Many of the previous problems with this unit had been resolved by about 1985.

These developments are the subject of a separate chapter.

Stirling Engines

During the 1960's and early 1970's a considerable amount of work was put in, mainly by the Philips company in developing the Stirling Engine. This is an engine which has an external combustion chamber which transfers gas to a working fluid inside the cylinders.

Swedish engineers had the idea to run the combustion chamber at some pressure like 50 Bar (higher than the sea pressure) and just let the waste gases go out into the sea, thus avoiding any pumping losses. This basic premise was developed into the first western AIP system to be installed in service submarines. I have written a separate chapter on this.

Brayton Cycle Systems

The Brayton cycle is one in which energy is extracted by an expansion device from a hot permanent gas. A jet engine is a Brayton device. Thermodynamically Brayton cycles are not very distinguishable from Rankine cycles. The latter usually have a condensable vapour (nearly always steam) rather than a permanent gas as their working fluid.

If you have some chemical reaction that gives out a lot of hot gas, you are probably going to think of a Brayton cycle to get the heat into mechanical energy. Very often a Closed Brayton Cycle (CBC) has a gas turbine in it with the exhaust being poked back into the inlet, oxygen added and CO2 taken out somehow.

At the current time a company called Allied Signal are offering a small Brayton system for powering underwater devices, but from the diagrams in my possession I am not clear how they manage the carbon dioxide of combustion. In an earlier paper in 1992, Ref (f), the author noted that there was a problem of getting rid of CO2 and instead suggested that the fuel should be hydrogen. There would then be no CO2 and the only product would be water. They further suggested using a saturated-unsaturated chemical reaction to get the hydrogen. An example would be to convert cyclohexane into benzene. I don't think such a matter can be managed in a submarine. I have described the problems of storing or making hydrogen in a submarine in another chapter.

Rankine Cycles

Various steam cycles attracted attention because engineers are very familiar with the properties of steam. The French, for example, have cut down their nuclear reactor based Rankine cycle drive and put a burner in place of the reactor to make their MESMA system. There were other systems mooted which tried to use heat sources other than a hydrocarbon-air combination. Some very peculiar chemical reactions can be envisaged. Of those ones that have been analysed, the cost of the fuel soon comes to the fore as a development blocker.

Donaldson, Ref(j), has indicated that work has been carried out on Rankine cycles using working fluids other than steam. He says that the theoretical advantages of such fluids were offset by the poor heat transfer characteristics and most of all by the problems of cleaning the submarines atmosphere if there were a leak.

Dephlagrating Chemicals

The idea here is to take a solid or liquid chemical that can be decomposed into a gas and to use the expanding gas to drive a mechanical device. In America amateur, and not so amateur, rocket enthusiasts use nearly pure hydrogen peroxide as a fuel and they decompose it on an active catalyst immediately before a supersonic nozzle. This system was for example used in the British Black Knight and Black Arrow rockets.

We have seen earlier that hydrogen peroxide is in the technological doghouse as far as navies are concerned, and so we might look to another candidate from the aircraft industry such as IPN. IPN is a mouth saver, standing for *iso*-propyl nitrate. This material (CH3)2.CH.ONO2 decomposes into carbon monoxide methane water nitrogen and various other gases. One mole of IPN gives about 4.54 moles of gases and a lot of heat. There is another chemical called hydrazine N_2H_2 that has been widely studied.

These sorts of technology were developed for aircraft starters and things like this where a reliable short term high energy start was needed which would work under adverse conditions.

However, the problems of dealing with an exhaust which is high in insoluble nitrogen seem to be difficult to overcome in a submarine.

Fuel Cells

In the early 1970's when designers were looking at the various candidates for submarine propulsion, I think fuel cells must have been pretty low down on the list. The idea of taking electrical power from a battery-like device which could be endlessly refilled with fuel was doubtless greedily noted. But the trouble was that at that time there was no really believable device. Notwithstanding this, the fuel cell had its adherents. And they were rewarded, because in the 1980's rapid technological advance was made in fuel cell capability so that they are now a leading candidate for powering AIP submarines. I have put a description of fuel cell developments in two later chapters.

Small Nuclear Reactors

In the 1970's nuclear reactors were still a candidate for 2000 te submarines. Not so much was known about the design of the reactors then and less was known about the dangers. At the moment, writing in 1999, it does not seem very likely that the majority of small submarines will be able to have a nuclear core. This is not a matter of size : The French have the Rubens Amethyst class of attack submarines which are only 2700 tes dived displacement. Admittedly this is at the larger end of the size range expected for an SSK but it certainly shows that you can have quite a small boat with a nuclear drive.

The problem is more one of support and the economics of fleet size. Not all nations have nuclear knowledge of the standard needed to maintain a thing like a submarine. Nor do many nations have fleets of over twelve submarines. Twelve boats is about the minimum number upon which you can justify the provision of all the support facilities. Even then "justification" is something to do with political will rather than economic calculation. The "through life cost" of a nuclear submarine is mind blowing; few countries can face up to it.

However, I think that there is likely to be vigorous development of the nuclear utility in the first half of the 21st century. Fossil fuels will I think (finally) start to rise in price, and I do not see much to fill an energy gap coming from the green designers. I think the nuclear designers will be forced to start thinking out how to make an intrinsically safe reactor instead of concentrating on the safety of pressurised water reactors. Perhaps then there will be some acceptable technology spun off into the maritime sphere.

Enhanced Capability Electrical Storage

In the 1960's and 1970's the battery manufacturers had a fine idea of their own capabilities. There was always going to be some sort of super battery round the corner. In fact, a large submarine lead acid battery in 1945 had a capacity of around about 35 Watt-hours per kg and fifty years later in 1995 the capacity had been raised only to about 55 W-h/kg.

Two other batteries have been developed which have a higher energy density. Firstly there is the sodium sulfide battery which, being built up into a form suitable for submarines, has an energy density of about 140 W-h/kg. It works at 300-370 ºC. This battery has a rather curious construction. Because the failure of the alumina separator would let molten sulphur contact molten sodium with a resultant detonation, the large submarine battery consists of a large number of small cells fixed together.

Secondly there is something called a Zebra battery which is a combination of sodium and a metal chloride. This has an energy density of about 120 W-h/kg but is relatively benign although it works at about 250-300 ºC. Ref (g)

Although neither of the batteries is remotely able to match the performance of any of the main AIP systems, this is not to say that they have had no influence on the design of submarines. The new German 212 for example have Na-S batteries and the Dutch manufacturer RDM, before it was torpedoed by its own government, apparently favoured the use of Zebra batteries.

There is another candidate that has appeared on the electrical energy storage scene. I am not sure about its commercial status at the moment. This is the Aluminium battery, first devised by a man called Solomon Zaronb, and taken up by Alcan Ltd in 1981. This device has an aluminium alloy anode which sits in a plastic pot which is filled with a potassium hydroxide electrolyte. This is surrounded by some sort of carbon weave which keeps the electrolyte in, allows oxygen to enter and supports a catalyst. In operation oxygen enters, and reacts indirectly with the Al anode which is gradually consumed. Eventually you have to replace the anode. The energy density seems very high being about 400 W-h/kg. I feel that this type of device might be better suited to unmanned vehicles, but it all rather depends on how the development goes. [See reference (r)]

In the 1970's there was a considerable uncertainty about the direction in which submarine designers should turn. Although there were plenty of candidate systems none of them seemed to be very strong. Furthermore, there was quite a body of thought that said that if you improved the hull form of the submarine then quite enough extra performance could be achieved. They said that if you took off all the secondary pointy bits, such as a deck mounted gun and side railings, the drag coefficient would fall and the performance would go up remarkably. There was some evident truth in this assertion, you need only look at the shapes of a WW2 Type VIIC and a Type 212 to see this.

When the obvious rebuttal was made that a better hull form plus AIP would lead to an even better submarine, then there was talk that there was no demand for such a submarine. It was said that nuclear boats would always lead in the deep sea role and that close to shore operations did not need the extraordinary range that was now being suggested as being possible.

Another matter occupied the designers for a long time, and this was the relation between the different power units that were now envisaged as being installed in the submarine. Should the underwater speed of the submarine be kept broadly similar and a small AIP used to extend the range of the batteries ? Should a medium sized AIP be installed which would provide all the power for patrol speed propulsion ? Should a very large AIP system be installed replacing most of the batteries and the main diesels ?

Initially, it seemed as though a small AIP unit (say 50 kW) might be able to be fitted sooner than some larger unit like a 250 kW unit. However, in the event this argument fell away and was abandoned. The problem with installing AIP is not really much to do with the AIP itself, it is more with re-arranging the design of the whole submarine. If you have to make this change, the consensus appeared, you might as well put a decent sized unit in.

As more was discovered about the size and workings of the different AIP units, it became clear that you needed to keep a sizeable battery capacity. This provides a sprint capacity for the submarine and avoids having a high power AIP unit running at part power (and lower efficiency) for long periods. Nevertheless, the idea of having a large AIP unit has not been completely abandoned. Papers still appear in which the idea of the "mono" submarine is discussed. A mono submarine has an AIP system that can double as surface propulsion.

In the earlier days attention naturally fixed on the technical details of the AIP propulsion unit. What its performance would be, whether so-and-so's unit was better than someone else's, what range you could get, would it be OK if a mine went off nearby and so on. In latter times it has come to be appreciated that there are other matters which are very nearly as important. For example, if you fitted an AIP unit into a conventional submarine so as to give it three weeks submerged endurance, and went off for trials, you would find that you had to surface after about four days because the air supply had become too degraded to breathe. The air processing units for conventional boats were not adequate, and there was not enough power to run the kit seen in a nuclear submarine. Some of the many problems of integrating an AIP unit into a submarine environment are discussed in a separate chapter. A paper by Donaldson was able to set many of these matters properly into context for the first time. Ref (j)

An American view has been expressed, Ref(h), that non-nuclear submarines could have a more significant role in the next century. I believe that such submarines with their performance enhanced by Air Independent Propulsion and custom built missiles could become very noticeable players.

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(l) T.D. Morrison, J.F.McCartney and J.F. Blose Society of Marine Architects and Marine Engineers, Spring Meeting, Philadelphia (1966) Paper No 5 "Power Plants for Deep Ocean Vehicles"

(m) "Psychrocycle" L.C. Hoffman, M.I. Rudnicki, and H.W. Williams Marine Technology Society Journal v4 n6 Nov-Dec 1970 pp 47-56

(n) Maritime Defence February 1990 p54-55

(p) "Investigations on Recycle and Closed Cycle diesel Engines " Tadataka Asada and Masashi Nagai, Hitachi Company, Society of Automobile Engineers (1980)

(r) These devices were being touted by a company called AlupowerCanada Ltd, 20 Binnington Court, Box 8500, Kingston, Ontario, Canada K7L 5N7

(s) For example see A Fowler, Trans. I. Mar. E. Vol 96 (1984) Paper 47

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