CHAPTER 9 - INTEGRATION

In earlier chapters we have considered some of the characteristics of the various fully engineered AIP systems. How then might a potential customer decide between the systems ? He must consider all those matters that are consequent upon the installation of a system in his submarine. We lump all these matters under the heading of "integration".

In the earlier days of AIP, published papers tended to have rather loud headlines : "Fuel cells are more efficient" or "Closed Cycle Diesel uses standard equipment", as manufacturers tried to convince customers that their system was the only possible one to consider. Nowadays, we have come to see that there is a considerable convergence between the performance of the different systems and that a much more considered approach must be taken to selection of systems.

The essence of "integration" can be seen by considering what will happen if you install an AIP system in a submarine giving say a increase in submerged endurance to two weeks. A conventional diesel electric submarine is only designed to stay submerged for two days at the very most, after this it comes near to the surface to snort. During this time the atmosphere in the boat is completely changed and you start again for another short period of fully submerged travel. Whatever you do, your (badly) modified boat must surface long before its engines' endurance is reached because the atmosphere in the boat has too high a level of carbon dioxide.

Now the control of carbon dioxide in a submarine is by far from being a trivial problem. The level of CO_2 in the ordinary atmospheric air we breath is only 0.03 percent. In a submarine, for a period of three weeks, the level may be allowed to rise higher than this, but still not to the 1% level. So, in controlling the level of CO_2 you are having to remove a very minority component from a mixture of other gases. This scenario is one that chemical engineers try to avoid. It is intrinsically difficult and usually involves large towers being erected in whatever plant they are trying to create.

In a conventional submarine, for the short inter-snort period, the level of CO_2 is just allowed to rise a bit. In an emergency situation canisters of soda lime are deployed. These are tubes containing a mixture of caustic soda and calcium oxide. These absorb carbon dioxide by reaction, but they cannot be regenerated at a later time. If you want your submarine to stay down for three weeks, you either have to use a substantial amount of space as soda lime canister storage or you have to fit a chemical reactor plant similar to that used in a nuclear submarine. Such plants might consume 30 or 40 kW. This is no problem in a nuclear boat but is a substantial matter in a non nuclear boat where the total hotel load might only be 30 kW. Suddenly instead of subtracting 30 kW from your 200 kW power source you are having to subtract something more like 70 or 80 kW; perhaps a third or more of the installed AIP power. Of course, if you knew the figures in advance there's not a problem, you just size things accordingly. But if you forgot it, your entire boat design will fail.

I have referred to this matter of carbon dioxide control in another connection in the Chapter on New Roles, as there is an interesting operational matter that arises.

There is another type of canister which is based on potassium superoxide, KO_2. CO_2 is absorbed and oxygen is regenerated. So far as can be determined with partial hindsight, these are the type of canisters used by the remnants of the crew of K-141, (the Russian submarine *Kursk*) as they tried to maintain themselves in the rear compartments of the boat. It appears that survivors lived

for a day or two at least until one of the men dropped a canister into the sea water. This appears to have cause a flash fire and asphyxiated the group.

(Incidentally, I recently visited the Kursk Memorial in St Petersburg as it is close to my mother-in-law's grave, and I was very put out to see that there was no crew listing. Only the crew members domiciled in St Petersburg were listed. Most of these men were the officers, so the impression is given that a memorial is erected to the officers only)

Effects on the signature of the submarine

Thermal signature

An SSK, driven by diesels on the surface and by batteries under water, has a small or zero submerged thermal signature. Unless the boat is being driven extremely hard, over about ten knots, the batteries do not give out heat; if anything they are endothermic. All AIP systems on the other hand are exothermic and, for a 200 kW system, put a nominal 200 kW of heat overboard into the sea. This is enough to heat up the water near the submarine by one to two degrees Celsius and the weapon designer has to consider whether this would lead to an increased detection risk.

It seems to be obvious that in deep water there is no increased risk. A nuclear submarine disposes of far more heat than this as the heat from the steam passes through the seawater condensers and straight out to the sea. The megawatt of heat is quite insufficient to allow the submarine to be detected once it is submerged to more than fifty metres. You have to remember that in any case finding a submarine in blue water is an exercise akin to finding a needle in a haystack.

The question about thermal signatures revolves around the detectability of an AIP submarine in relatively shallow waters and the truth is that I don't think anyone has considered the problem deeply.

Acoustic signature

I believe that some forms of AIP emit bubbles and this would seem to considerably increase the visibility of the boats to acoustic devices. I have already considered some of the matters involved in the chapter on disposal of carbon dioxide.

Effects on the performance of the submarine

The retrofitting of AIP to an existing submarine involves cutting the boat and adding a new section. A plug we call it. The boat is longer and so it will require more power to propel it at a given speed and we have seen from the published accounts of the Swedish *Naecken* that the top speed might be reduced by 0.1 kts. This hardly seems significant for a boat which will have an underwater sprint speed of more than 12 kts.

This submerged top speed of a submarine will not be affected by the type of AIP installed. Such sprints are carried out on battery, which for short periods can produce much more power than any reasonably sized AIP installation. On the other hand, in installing the AIP unit, some battery capacity might be removed. If so, then the time the boat can travel at its top speed will be reduced.

A more serious consideration might lie in the stability of the entire boat, especially in a case where the plug might not be neutrally buoyant. Although one would normally try to make such a plug neutrally buoyant, the designer might deliberately make it heavy in order to get some extreme range. Then you have a heavy bit in the middle of a lengthened boat. If *I* did this, I would be looking very carefully at the behavior of the design under extremes of turn.

The most important matter to consider is the efficiency of the AIP system because this determines the underwater performance of the AIP boat. Many interpretations of efficiency have been put forward. In the early days the efficiency of the prime mover was emphasised. Then more complicated criteria began to appear based on some sort of average patrol. I cannot see why we can't take the submerged endurance at 4 kts as one universal measure of efficiency. Really, we are trying to see how far the boat will go on one LOX-tank-full's worth. In studying manufacturers' statements, be careful to see that all power units that are driven off the AIP are in fact included in the power balance sheet. Thus, you have to consider all continuously operating devices like pumps. In addition there are often intermittently operating units which pump out small holding tanks and such like.

Finally, never forget that every submarine has a hotel load, which includes power for essential instruments, lighting and a varying portfolio of other functions dependent upon what the boat is doing, but which includes cleaning exhaled carbon dioxide from the breathable atmosphere. The hotel load may very well alter if you cut a submarine, install an AIP plug section, and refit.

Effects on the structure of the submarine

The designer will try to make a plug that is neutrally buoyant and probably will try to control the centre of buoyancy as well. In doing this he will have to struggle with matters that are the daily grist to the designers mill : How to arrange heavy items of equipment with awkward shapes into some arrangement that is compatible with the overall design of the submarine. He has to allow passage for through services, make sure there is a walk way, put the ships services in place, check the weight distributions, and allow room for any planned maintenance operations. In addition the designer will have to see what new effects, arising from the particular AIP prime mover, might have to be considered in the design.

Weight and Volume

In considering the matters of the weight and volume, the key thing to keep in mind is that all components (however minor) must be considered. In earlier days of AIP, many very optimistic sets of figures were produced which listed only the main components were considered. Sometimes even some of these, particularly the weight compensation tanks, were omitted.

All AIP systems seem to be surrounded with small items such as pumps, holding tanks, instrument boards, transducers, sound isolation equipment including the supporting rafts, electrical conversion units, starter apparatus and so on through quite a long list of items. One of the bigger items is usually the LOX storage with its evaporators and heat exchangers and its associated compensation tanks.

As a rule of thumb, weight seems to be the limiting factor in small submarines (less than 600 tes) while volume starts to become progressively important as the size is increased to the 1000 – 2500 te range. You have to remember additionally that equipment is not necessarily designed to be optimally sized for all values of delivered power. The manufacturer will perhaps have only designed a "standard plant" delivering say 200 kW net. Larger power levels can easily lead to a great increase in both weight and volume, because units have to be multiplied.

A strict comparison of weight and volume of two systems can only really be made by a purchasing customer. No one manufacturer has access to a competitor's data.

Filling Systems

All AIP systems as presently envisaged will have a LOX tank inside the boat. This LOX tank has to be filled periodically, sometimes in less than ideal conditions. You cannot willy-nilly allow large quantities of liquid oxygen to fall on steel plate, because the steel plate might be harmed. It might crack straight away, or it might lose strength or elasticity which might affect its load bearing capability. Gross spillages might cause a fastener such as a nut and bolt to become loosened or cause some local shrinkage which might result in a fastener not being able to be undone at some later stage. Spillage of LOX might also have untoward chemical effects such as the sensitization of otherwise harmless materials such as lubricating grease so that they become ignition sources.

Some AIP systems also require hydrogen to be brought to the boat and this also has its associated dangers not least of which is the possibility of it coming into contact with large quantities of pure oxygen.

So filling systems are an important area where careful design must be used to safeguard the structure of the boat.

Electrical Systems

The AIP system has to made compatible with the overall electrical system of the boat. The boat is always predominantly DC because it has a massive battery at its heart but it can have provision for different amounts of AC. Designers like to have AC motors because they can look in catalogues and buy an AC motor (and other equipment) for just about any duty. DC motors, on the other hand, are relatively rare, are slightly bigger, need more maintenance and are more expensive.

However, sometimes there is not enough AC power in the boat for a particular configuration to work. For example, in specifying a Closed Cycle Diesel set for a Russian submarine some years ago, we found that there was not enough AC provision in the boat to start the CCD set. The

CCD has to have various circulating pumps and other equipment activated before the diesel generator can be started and there was not enough power to do this. Therefore the AC motors which we would have preferred to use, had to be exchanged for DC units.

So far as we understand the matter at the moment, Closed Cycle Diesels, MESMA and Stirling systems will use some fairly standard arrangement of multiphase alternator and transformer rectifier unit to produce DC power to go into the boat's electrical skeleton. A fuel cell on the other hand is believed to require DC-DC conversion equipment which is expensive, demanding of volume and not very efficient. Whereas Stirling and diesel engines have a nominal thermal efficiency of 30% and a steam cycle say 25%, the fuel cell has a thermal efficiency of more like 50% at low powers. However by the time the source power has been converted into a form usable in the boat, and the system is running at full power, the superiority of the fuel cell has been much lessened and the integrated efficiency of MESMA, Stirling and CCD seems to be similar.

Access

You have to think which parts of the AIP system can be removed at which stage of maintenance. We are relatively familiar with dealing with the problems of an SSK or a nuclear submarine, but the provision of AIP brings new problems in its wake. It is important not to end up in a situation where expensive dockyard work needs to be carried out merely because some matter of access had not been thought out in advance.

It is not long since a crank shaft in the diesel of a British nuclear power submarine broke and had to be replaced between planned maintenance schedules. You might think that, just in the way of things, submarines with AIP in them might suffer a number of unforeseen failures. Therefore you need to see what can be disassembled while in the boat, which new components can be carried in the boat, and which replacement parts could be brought down a hatch and moved through the submarine into the AIP compartment.

Perhaps it doesn't strictly come under "access" but a designer should also consider very carefully the spares list. In moving to AIP, one is also moving away from the traditional machinery used in submarines and corrections must be made accordingly.

Beyond this, one must then consider what can be done in the harbor by means of soft patches on the boat, and what might require the submarine to be cut into two.

Other aspects of integration

Can the submarine AIP system work on the surface ?

I mentioned this earlier as "up-down capability" The question should be considered to include working near the surface and to mean breathing air rather than oxygen. Naval department engineers often want to know whether the AIP system could be used as an emergency to move the boat on the surface in the event of damage.

A Closed Cycle diesel, for example, can be used on the surface, but only if the purchaser has stipulated that he wants to use it in this way. In this case some means of switching in the turbocharger, not in use for submerged closed cycle work, would have been designed in.

At another extreme, I suspect that a fuel cell designed to run on pure oxygen will behave poorly if it is fed with air.

Is the AIP system depth independent ?

This question is to do with power consumption; do you expend more power on auxiliaries as the boat goes deeper ? You also have to find out whether in extreme cases the system might stop working. By "depth" we mean the range of depths accessible to the submarine which for the size of submarine we are talking about is 500 metres. In reality, I think only a very few non nuclear boats go below 300 m.

Whatever the properties of earlier designs, I think that all current systems will work down to the design depth of the submarine. A hydride fuelled fuel cellis completely depth independent. Closed cycle diesels are certainly depth independent down to 500 m. Stirlings and MESMA have burners working at some pressure which is fixed at something like 60 Bar which is higher than the sea pressure when the boat is at deep dive depth. There are currently no reformer based designs, but one assumes that when they appear they will have their heat source running at 60 Bara.

Can the system be made as a plug for retrofitting ?

We think most systems can be made as a plug, but it seems at the moment that a hydride fuel system is not going to be offered in this form. The German submarine consortium has been at pains to put both the LOX and the hydrogen outside the pressure hull. This does not mean that a hydride system could not be manufactured at some later time as an in-hull system. Perhaps the Germans have just opted for a very safe configuration until such time as more experience has been built up.

Costs

Most people reading this book will know that many items of military equipment are not sold to the customer for their true cost. Sometimes units are sold cheap as part of some bigger deal, or they are actually given away for political reasons. Deals may only go ahead when, maybe, money has moved sideways. Sometimes submarines are even sold when neither the seller or the buyer wants the deal.

As engineers we may look on at these manifestations of international dealing with some interest ,or not, as the taste takes us. But what we must not forget is that inside the submarine factory we must still do the costing very well. The end customer may or may not pay the commercial price for the submarine, but someone has to pay the factory. We still have to get the steel and pay the designers and all the others.

As with weights and volumes of systems, only a paying customer can really judge the relative costs of systems. No one manufacturer can know in detail what his rival is charging. Having said this, you would think that fuel cells were going to be relatively expensive for a while. There is no mass market for 100 kW fuel cells and so they tend to be very expensive. Equally, for all that there seem to hundreds of people writing articles about hydride storage, very few people actually use them and so there is another expensive customized item in the boat.

Making the systems for some extreme size of boat can cause costs to rocket. The manufacturers offer some standard size of AIP system. Nearly always, a departure from this size causes a price hike because of the extra design and testing costs that lie on top of the unit price. Some systems probably can't be scaled. It is difficult for me to think of 60 kW Stirling engines being assembled in banks to give 1 MW of submerged power. On the other hand both MESMA and the Closed Cycle Diesel could easily do this.

It is certainly true that the costs of a closed cycle diesel also start to increase quickly when the boat is made smaller. You have to design special one-off components, and it is very difficult to explain to the customer (who often is commercial) why you want £2m dollars for a car engine.

One of the worst things for the AIP manufacturer is when a war department wants you to put your system in a torpedo. We were once asked to produce an outline design for a high speed torpedo to catch a Russian Alpha submarine. This was, we were told, capable of doing 40 kts at over 1000 metres depth. We made some designs for a closed cycle petrol engine and then drew out the system as having an engine from a car called the Ford Cosworth Sierra which was at that time being sold in the UK as a high performance road car. (It was especially in demand by theives, who would steal the car, rob something or another more or less in broad daylight, and then outpace the pursuers, finally adding insult to many injuries by selling the car on.) We estimated that the torpedo propulsion unit would do a good deal more than the 60 kts hunt speed required. But fitting everything into the torpedo envelope looked as though it be a nightmare. Fortunately, when we gave the customer the price, we did not hear from him again, and we went back to fighting about who should have the redundant engine in their car.

I think both Closed Cycle diesel and MESMA would be very happy indeed if a market developed for larger submarines. Both systems naturally lend themselves to a larger size of boat, and the costings don't look silly. In designing a power plant for a submarine oil tanker in 1995, we added a few million pounds on to the calculated price and told the customer that we had put this figure in "for unforeseen contingencies". He seemed to think this was quite a wise precaution. He wasn't actually much interested in the price, since the cost of the power plant was small compared with the whole submarine.