

CHAPTER 2 - STIRLING ENGINES

The Stirling engine is a device with an external combustion chamber surrounding a cylinder containing a piston. Cool gas is pumped into the cylinder where it expands and forces the piston down. Gas is then sucked out, re-cooled and used again. Often, cylinders are arranged in a circular pattern, cool gas from one cylinder being passed to the hot space of the next. Two web sites describing Stirling Engines and giving many other links and references are given at Reference (a).

The Stirling engine was in quite wide use in the second half of the nineteenth century, but after this it began to lose out to the internal combustion engine which soon came to have a power to weight ratio superior to the Stirling.

“Stirling Engine” covers a wider range of mechanism than “internal combustion engine”; there are an astonishingly wide range of different constructions which can be understood to be Stirling engines.

The Phillips Company in Holland decided around the end of the second world war to see if they could not re-engineer the Stirling engine using modern techniques. They had an eye on low electrical power generators for use in remote regions. Phillips found that this market gradually weakened over a twenty year period, perhaps because the advent of the transistor, and they eventually sold a lot of the business in about 1968 to other companies including United Stirling AB of Sweden.

The Swedes have a long history of submarine making. They launched their first boat, the *Hajen*, in 1904. It had a displacement of 107 tes. The Swedish navy tend to buy boats that are on the small side because of their need to operate effectively in the Baltic Sea. In the cold war period there was a need to be able to cause as much difficulty for Russian boats as possible in the event of hostilities.

Large areas of the Baltic are unsuitable for submarine operations and about half the remainder has a depth of between 18 and 46 metres. Conditions for active sonar are bad with a thermocline at about 12 metres and anti-submarine warfare in the Baltic is difficult. On the other hand a combination of varying salinity and temperature make for good ranges for passive sonar. These conditions tend to make suitable operating conditions for smaller boats. The boats need only moderate endurance because they are never far from port. A 12 day patrol is the sort of period a boat expects to be at sea. The boats have a minimal crew as two watches only are required on the short patrol. The lack of strong tides makes for good navigational accuracy. In the early nineties there were over 75 submarines from five countries operating in the Baltic making it one of the most submarine-dense areas in the world.

Swedish engineers had begun considering options for Air Independent Propulsion very early. Their pioneering efforts were not without their reverses. It had been intended that the Sjoörmen class, eventually delivered in 1967-68, was to have AIP. Technical difficulties prevented this ambition being realised. Per Dahlander from Kockums, writing a long time after the event, said that he thought that the early technical targets were far too ambitious. They wanted the AIP

engine to supply power throughout the whole range of both submerged and surfaced performance. The battery was to be largely removed, only a small reserve being retained.

At this time the Swedes were considering not only the Stirling Engine, but Lithium batteries and variants on the diesel fuel/hydrogen peroxide motor they used in their Type 61 torpedoes. This must have been a Walther turbine which I have touched on in another chapter. They also considered various closed cycle diesel engines (doubtless of the Riccardo-Vickers type). It seems that by the middle sixties they had decided that the only technology that they could get to work well would be the Stirling Engine.

In the late 1970's there was a change in Swedish defence policy. Rather than preparing to defend against a coastal invasion, they would have a more flexible policy. This in turn called for a more sustained submerged endurance in the operational area to provide a greater degree of surveillance and readiness. Notwithstanding the probable unpopularity of AIP that must have resulted from the inability to create an AIP unit for the Sjöormen class, the engineers turned again to updated forms of the Stirling engine.

The idea was that they would modify the combustion chamber of a Stirling engine to run at some pressure like 60 Bara and discharge the products of combustion directly to the sea. The submarine could then run perfectly well at all depths down to that value equivalent to the pressure in the combustion chamber.

In 1984 new studies of an add-on section containing a Stirling Engine were started. By December of the same year a whole section was ordered from Kockums. This section, called the Kraftmyggan or "power mosquito", actually floated in a dock. It was delivered in 1985 and a team from the Swedish navy experimented with it for about two years until 1987 when it was decided to fit the section in the Naecken Class (A14) boat *Naecken*. In 1987 the submarine was cut into two parts, the 8.5 metre long section added, the internal services re-connected, and the boat was re-launched. The following sea trials and evaluations went so successfully that by the autumn of 1989 the system was no longer thought of as being experimental.

Some of the papers published at the time refer to one of the more irritating problems as that of keeping the environment in the boat sufficiently free of carbon dioxide. This was not waste CO₂ from the Stirling engine, but CO₂ from human exhalation. It was difficult, it appears, to get enough soda lime canisters into the boat to deal with the greatly increased submarine endurance. You might think that this matter of breathable air quality is one of those trivial things that are soon solved, but it was still causing comment at Naval conferences in 1996 and I don't believe that it has really been solved. I have discussed this some more in a chapter on integration problems.

The engines, type V4-275R, were made by Kockums company, and were supposed to deliver 75 kW shaft power. So far as I understand the matter, the continuously available power was less than 75 kW, perhaps closer to 60 kW. It proved impractical to mount several units on a common

shaft, so the uprating of power demands a multiplicity of separate engines. The Nacken Class has a submerged displacement of a little over 1000 tes and might require only something like 60 kW at 4 kts plus a hotel load of a nominal guessed 60 kW.

It is reported that the specific fuel consumption is 250 gm/kW-hr, the oxygen consumption at 65 kW is 950 grams/kW-hr, the dry weight of the engine is 750 kg and the envelope dimensions L*W*ht are 800*800*1400 mm or 0.896 cu m. The working gas inside the engine is helium and it is at a mean pressure of about 100 Bara. This calls, in turn, for storage facilities and a mechanism for purging the helium from the engine when it is not in use, and replacing it with nitrogen. When the engine is to be re-started the helium is put back.

The size of the engine is noteworthy. A Volvo diesel engine giving about the same shaft power, the Volvo TMD31, weighs 375 kg and has dimensions 1070*620*708 mm or 0.469 cu m. So the Stirling engine looks a bit bulky at first sight. However, remember that the Stirling will run under water whereas the diesel will not; it has to have other equipment added. So, installing a Stirling engine in a submarine would seem to be sensible from the point of use of installed volume.

It is believed that the exhaust has 10 % oxygen in it, and that this is a result of having to run the combustor with extra oxygen to try to keep some of the heat transfer surfaces clean. Putting oxygen overboard is something which is undesirable. You have to modify your submarine and put a LOX tank in it to provide oxidiser for the fuel and it seems bad in principle to have to throw away oxygen. I believe also that a good quality, low sulphur, fuel has also to be used as part of the tactics to keep the heat transfer surfaces clean, but whether this means a quality above NATO standards I am not sure.

There is another reason for believing that the exhaust has oxygen in it. Combustion of fuels is usually carried out with excess oxygen; in a diesel or a spark engine, usually 21% oxygen goes in and about 15% comes out. In theory you can burn all the oxygen, but in practice it doesn't work like this and there are notable amounts of oxygen in the exhaust.

Adding the 8.5 m section into a boat which was originally 49.5 m in length reduced the maximum submerged speed by 0.1 kt and increased the power requirement by 10 %. The turning circle was increased a little, and the handling was marginally worse. The section was designed to be neutrally buoyant.

Following these trials the Swedish navy installed Stirling systems in three of their Gotland (A19) class boats, the *Gotland*, the *Upland* and the *Halland*. These submarines were commissioned in 1996 and 1997. They are rather bigger than the Nacken Class at about 1250 tes and are said to be able to proceed at 5 kts submerged for "several weeks". Janes Fighting Ships 1998-99 says that "space has been left for two more (ie four) Stirling engines" Space is at such a premium in submarines that I find this hard to accept. I understand that there is an export submarine, the type T96, being offered for sale.

No-one can deny that the Swedish engineering establishment has created a workable AIP system which works satisfactorily. They have fitted the system in four of their boats. They were well ahead of all other western countries in carrying out work on AIP systems. However, they have

been surprisingly unsuccessful in selling this system to external customers in spite of the fact that their export departments are self evidently very active.

Sweden sold one very elderly Sjöormen submarine to Singapore in 1995, as far as I understand it, for training and familiarisation. Then the Singaporean navy purchased four second hand

Västergötland Class (A17) submarines. But, they ordered them without the Stirling engine. There is a note on their web site (<http://web.eas.org.sg/~ngwh97/gotland.html>) that there is an option to change to Stirlings later. Since the boats did not have Stirlings already installed the boats would obviously have had to cut and stitched, but it is not a big job as these things go.

It may be that the Singaporeans did not think they needed the longer endurance. People working with AIP tend to think that a submarine without AIP is like strawberries without the cream, but you have to remember the operational circumstances. In the Atlantic where submarines are continually duelling with highly technical ASW frigates submerged endurance is a *sine qua non*. On the other hand if, lets say, you are wanting to keep an eye on a South American country with only a small navy and twenty year old sonar sets, then AIP might not be worth the expense. Nevertheless it's a funny thing that the Singaporeans did not buy Stirlings.

We thought that the Australians intended to install Stirling Engines in at least one of their Collins Class submarines. Since Kockums have purchased a substantial interest in the Australian Submarine Corporation, this would hardly be an unreasonable thought. Rumour has it, on the other hand, that the whole Stirling project has now been rejected for the Australian navy. Other rumours say that the Stirling engines are difficult to control at depth.

Every AIP system at the moment is surrounded by rumours. Some of these are based on fact and others are made up by salesmen. Although we all listen eagerly to the rumours we must not let ourselves be blinded by them. What is clear about the Swedish Stirling system is that it is the first system to be installed in a Western Navy, it works very well and gives a small submarine a considerable submerged endurance. It certainly appears to be very well suited to the Baltic Sea operations to which it would have been addressed initially.

There appear to me to be some limitations and deficiencies in the Stirling system :

Firstly, I believe that it is going to be difficult to apply it to larger submarines. This may explain why the very large (3000 te) Australian Collins Class submarines don't have Stirling propulsion. Stirling engines do not have many applications other than in submarines and you cannot go out and buy units "off the shelf". You have to put in multiples of 60 kW and remember that this is 60 kW shaft. A 2400 te submarine might need as much as 200 kW electrical after all parasitics have been allowed for, so you could be into between four and six separate power units each with an electrical generator. I doubt that it is an option to develop a larger Stirling engine for the limited numbers likely to be involved. You have to remember also that Stirling engines have a rotten engineering history. In spite of great efforts by companies like Philips, the potential high efficiency which initially attracted engineering and commercial interest was never realised. No niche market could be found and the developmental content of the engines is therefore small.

Secondly, I firmly believe that a trail of bubbles is left behind the submarine. This trail is at least two boat lengths in extent and greatly increases the signature of the submarine. I have discussed this matter of bubbles in a separate chapter.

Thirdly, as I've mentioned above, I believe that there are noticeable amounts of oxygen in the exhaust and that this is necessarily thrown overboard, substantially reducing the range of the submarine. I suspect that the reduction is considerable.

Having said this, it must be recognised that Sweden was the first Western country to take AIP seriously, they have their system installed in several submarines and they have more than thirty years hands-on experience. They are serious players in this game.

Ref (a)

w.apawn.com/search.php?title=stirling_engine
w.worldhistory.com/wiki/S/stirling-engine.htm

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