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Stop that leak!

The first 100 years of UK submarine engineering

This year sees the 100th anniversary of the Royal Navy's submarine service. I would like to reflect on some of the technological developments and problems that have been part of this century of achievement. The issues have often been of the utmost complexity, demanding the highest standards of engineering judgement, but from a personal perspective in many ways it just boils down to the title of this article.

Like most artefacts, the submarine is an essentially simple idea whose evolution is a history of engineering in itself. The idea is that a more or less neutrally buoyant vessel, equipped with propulsion and a means of making marginal adjustments to its mass, could proceed either on or below the sea surface as its commander decided. It would be very difficult to locate or attack such a vessel while it was below the surface, or even to know whether or not one was in the vicinity. So from the submarine's earliest beginnings, it was the exercise of sea power, and the safeguarding or disruption of all that depended on sea power, which motivated the development of these underwater machines.

For guidance on the engineering problems and solutions posed by the submarine idea, we should recognise that until quite recently virtually every submarine was designed, built and operated with naval functions in mind. Most obviously the purpose of a submarine was to sink surface ships with torpedoes. But the naval employment of submarines ranged far more widely during both World Wars and included protecting friendly shipping, reconnaissance, laying mines, and landing or extracting forces of all types from hostile shores.

Significantly, World War II saw the concept emerge of one submerged submarine attacking another. Since then, the technological developments of nuclear propulsion and the underwater launch of rocket-propelled missiles have made submarines the ideal platform for national strategic deterrence. Anti-ship missiles have greatly enhanced the range from which attacks can be launched on surface ships. Most recently, underwater-launched cruise missiles have enabled submarines to mount precision attacks on land targets at vast ranges. With such a significant list of defence applications it is hardly

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surprising that most cutting-edge submarine engineering has remained a closely guarded secret. I do not intend to breach that security here.

But many of the challenges seem to have an enduring nature and can be described in a relatively straightforward way as a leakage of sea water, electricity, neutrons, information or noise. Whatever the nature of the leak, stopping it invariably requires great attention to detail, particularly if it is to be cost effective.

Historical beginnings

It was in 1863 that three inventors from Louisiana completed the construction of a submersible for the Confederate Forces during the American Civil War. She was shipped by rail to Charleston and put to sea. During her trials she twice sank with the loss of all the crew, including the designer himself. But again she was raised and refurbished, and on 17 February 1864 she successfully attacked the United States' Ship Housatonic using a spar torpedo. The attack was successful but, despite surfacing and signalling to their colleagues ashore, the crew were never seen again and the vessel was only found 130 years later, buried in the seabed.

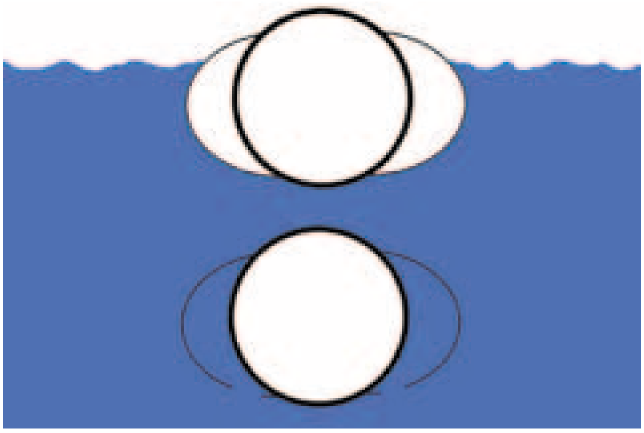
But naval history had been made, and after some thirty further years submarines were once again under construction in the United States. The designer of these new submarines, an emigrant Irish schoolteacher named John Philip Holland, offered a submarine design to the United States Navy which was rejected in 1875 as impracticable. However, the designer continued his experiments and 23 years later, after a great deal of practical development work, Holland launched his sixth vessel. It had all the features of a modern submarine, including torpedo tubes and a periscope, and was demonstrated on the Potomac not too far from the headquarters of the United States Navy – Holland knew where his next market lay.

By 1906, less than 10 years later, the United States had acquired 12 submarines. Despite many famously ungenerous descriptions, these strange new vessels were quickly taken up by nearly all the serious navies of the world, basically purchased, licensed or copied from the Holland design. In 1906 the Russians had 27 in service or planned, the French 45 and the British 35. The submarine contribution to sea power had been securely established.

Basic principles

It may be helpful to outline some basic principles of submarine design. First, the structural watertight boundary of a submarine is called the pressure hull. Generally of circular cross-section and of high strength steel, it is supported by regularly spaced frames. It does not leak and although ensuring that fact is itself an interesting task, with significant construction and maintenance costs, it has no further place in this article.

Around the outside of the pressure hull are a number of so-called ballast tanks, open at the bottom and fitted with a vent valve on top which is operated from inside the submarine. If the vents are opened, the tanks fill with water and the submarine becomes negatively buoyant; close the vents and blow out the water using high-pressure air and the submarine regains positive buoyancy. It is a major concern of submarine designers that these margins of buoyancy are appropriate,

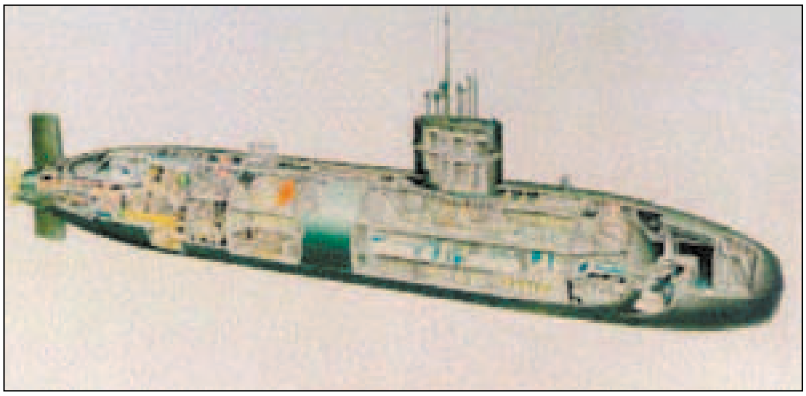


The pressure hull and ballast tanks

and that the vessel has adequate stability while diving and surfacing. Final adjustments are made with lead ballast during the construction phase and operational adjustments (to compensate for sea water density changes and for torpedoes, food, fuel, etc.) are enabled through internal tanks.

Add, in close mutual proximity, hydraulic systems, electrical power storage, generation and distribution, explosives and propellants, toxic chemicals and a nuclear reactor, and

Oil painting of the submersible *Hunley* by Conrad Wise Chapman.



Cutaway view of a Trafalgar Class submarine

you have a modern British submarine such as that shown here; some carry nuclear armed ballistic missiles as well. Keeping all this working and safe – and I assure you, it is kept safe – is in many ways just a matter of stopping leaks. I will start with that most difficult of fluids, sea water.

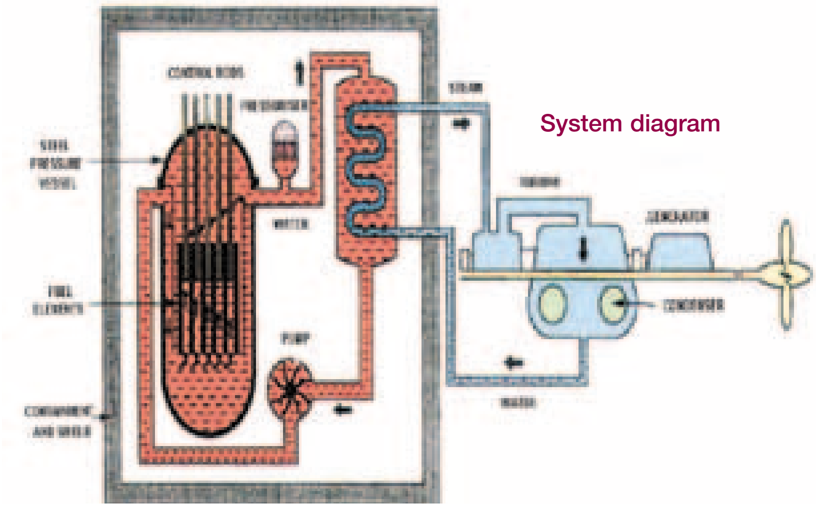
Fluids

As I have suggested, keeping the sea on the right side of the pressure hull is a reasonably straightforward task, or at least it would be, if it were not necessary to penetrate the hull with periscopes, ventilation masts, propeller shafts, hatches, cable glands, mechanical actuators and so forth. Designing a gland that will allow a periscope or other shaft to rotate and slide while never failing to keep out pressure at all depths is not a trivial task. Shipbuilders may claim that leaks are the fault of the gland supplier, or that an inability to turn a periscope derives from an inadequate torque motor. Equipment suppliers may suggest that it is a matter of alignment of various supporting bushes. All this is probably true, and all provides a good argument as to why the paying customer should put matters in the hands of a prime contractor. Be that as it may, from the leakage viewpoint much more interesting than glands is the need to circulate safely large volumes of sea water actually through the submarine for cooling purposes of every type, including the condensers associated with the main steam turbines.

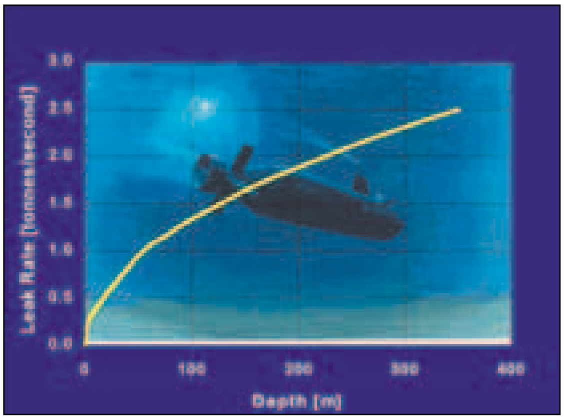
The basic propulsion set-up is shown below. The reactor keeps a primary loop hot; the loop acts as the heating element in a boiler, the steam from which drives a turbine, encouraged by a condenser that sits underneath it. The condensing agent, acting through another heat exchanger, is sea water. The effects of a failure in the associated pipework would be as shown in the graph.

Clearly the submarine designer will seek to minimise the number of pipes, heat exchangers and hull penetrations associated with providing these cooling services. This reduction has been a design trend, but there remains a substantial range of internal mechanical components – valves, pipe bends and junctions, pumps, etc. – which are exposed to external sea-water pressure. Their overall integrity is a paramount concern, not just in the construction phase, but on a through-life basis. The test criterion is nil leakage of any mechanical joints between components, but what of the components themselves: complex shapes that are exposed to the long-term effects of sea water?

The 1960s saw the introduction of Nickel Aluminium Bronze castings for just such components. However, after some 10 years of service, it was found that these NAB components were subject to complex corrosion



System diagram



The effects of a failure in pipework

mechanisms, which could not be reliably detected using non-destructive testing *in situ*. So the solution to the assurance of integrity has generally been to replace the components at a safe life, in order to stop the possibility of leaks or worse.

Of course we try to avoid mechanical joints where these are not the most cost-effective solution and, like Railtrack, submarine engineers are sensitised to the business of searching for cracks. Metallurgic examinations are conducted extensively, for obvious quality assurance purposes, but also to be kept as records should they be needed. We use a variety of techniques for detecting cracks, including radiography, ultrasonics and dye penetration and, when all else fails, the ever-reliable dental putty for taking cast impressions. You could be forgiven for thinking that the march of technology may have left this particular technique in the layby of history, but I assure you that the technicians at the Dounreay prototype submarine reactor plant swear by it and if anybody knows a cheaper, more reliable way of taking three-dimensional records, I have yet to meet him or her.

like Railtrack, submarine engineers are sensitised to the business of searching for cracks

Having introduced the nuclear connection let me explain something of the issue which has temporarily grounded a number of our submarines. However well you design, manufacture, test and inspect the plant, however well you maintain it, however carefully you operate it, there is always a chance that a crack will appear for some reason not foreseen by the designer. But it is both our experience and our intent that such a leak will be detected before anything approaching a catastrophic failure arises. This happened to HMS Tireless last year in the Mediterranean. She did have a tiny primary coolant leak; she shut down the nuclear plant and headed under diesel power for Gibraltar. After a few weeks of analysis, radiography commenced and revealed some incipient underlying cracking. Other submarines have been examined, and in some cases similar cracks have been found. They will be repaired, and – at least as importantly – the mechanism understood before the submarines concerned are returned to service. I am looking forward to finding out why this event was not predicted: helpful prediction is always preferable to detailed post-hoc explanations.

Of course, sea water is not the only fluid that needs to be kept under control. Submarine high-pressure air is kept at about 270 Bar and the hydraulics system runs at about 170 Bar: immense amounts of stored energy, but also both capable of fuelling fires. The Brazilian submarine Tonelero, while nearing completion at Barrow-in-Furness in the 1970s, suffered a fire in the central section of immense severity. The fire was fed by a spray of ignited hydraulic oil that simply kept coming from a disrupted mechanical joint. The submarine's hull was deformed out of circular and the central section had to be replaced to an as-new condition. As a result, construction took six years rather than the normal three or four. Similarly one of the Royal Navy's more testing nuclear submarine incidents was a very serious fire on board HMS Warspite, some twenty years ago, during a visit to the port of Liverpool at a time when the nuclear plant was shut down. Here the luboil system feeding a diesel engine developed a serious leak, spraying oil onto a hot manifold. The fire was extinguished – albeit with some difficulty – and there were no serious casualties. But it took a very long time and a great deal of money to get the submarine back to sea again – a very serious consequence of a rather small leak.

Electricity

The introduction of electricity into submarines relieved the crew of the task of manually cranking the propeller shaft, as they did in the Confederate States Ship in 1864. But of course electricity brought a raft of new leak concerns. Submarines use generators to charge a lead acid battery (and yes, acid leaks are a potential hazard) and the battery drives the shaft motor. This is the life-blood of conventional submarines, but even nuclear submarines have a battery to supply power for hours should the reactor fail and should it not be tactically possible to run a diesel generator. If there is any system which epitomises stored energy it is a submarine main battery. With 220 cells weighing half a tonne each it is not surprising that the short-circuit current is around 47,000 Amps. This means that if you were foolish enough to drop a huge uninsulated spanner across the terminals, it would instantaneously vaporise. This stored energy means that the cleanliness of the battery compartment, as well as the insulation of the generators, is a persistent concern. Neither is high technology; both require immense attention to detail, not least in the atmosphere of a conventional submarine engine room where the smell of diesel fuel gives you a clue as to what must be kept out of the generator windings.

Of course electricity looking for a leak path to earth likes few things better than a sea-water environment. Submarines have a great deal of important cabling outside the pressure hull, generally concerned with the weapon system – by which I mean not just torpedoes and missiles, but also the tactical equipment like sonar and communications that enable weapons to be effectively used. The difficulty here tends to be not so much with the cable run itself – where insulation is effective at great pressure – but with the various connectors and joints that are inevitably needed. Cathodic delamination of the joint between a polyurethane coated transducer assembly and its polyethylene coated cable kept some of our brightest material scientists busy for a year or two. The highest standards of insulation are necessary in order to retain the weakest of sensed noise signals and with something like 2000 transducers in a sonar array, that is quite a quality control challenge. Reliable plugs and sockets for equipment like bridge microphones, which are taken below when dived but vital on the surface, were a persistent challenge for much of my early career. Not for nothing do the Royal Navy's most modern, nuclear-powered attack submarines, the Trafalgar Class, have a straightforward voice pipe between the bridge and the helmsman below. Straightforward, except that it has an isolating cock to prevent leaks.

Spies

Not all leaks are physical, though all can be seen to have physical origins. Information leakage can have consequences just as serious as leaks of electricity or fuel, and perhaps the most famous instance connected with submarine technology took place in the early 1960s.

Harry Houghton and the delightfully named Ethel Elizabeth 'Bunty' Gee both worked at the Underwater Detection Establishment at Portland. They became an item, and although the nature of Gee's involvement is often disputed, both passed papers to the Russians.

For reasons that remain unclear, Houghton and Gee were placed under surveillance, and in early 1962, after nearly a year's surveillance, officers from MI5 and the Special Branch arrested Houghton, Gee, and their controller Lonsdale (in reality Colonel Molody of the KGB) as they met near the Old Vic. Gee was turning over a shopping basket to Lonsdale containing a tin full of microfilm and four large Admiralty files. The developed film produced several hundred photographs of British warships, including specifications for the atomic submarine Dreadnought. The resulting trial caused a sensation, fuelled by all the very best elements of contemporary spy fiction, including one-time pads, microdots, dead letter boxes, miniature cameras and radio transmitters hidden under the floorboards of suburban houses.

Gordon Lonsdale attempting to blend into British society.
From *Spy: 20 years of secret service*, Gordon Lonsdale. Neville Spearman, 1965.

The secrets that Houghton and Gee were convicted of selling to the Soviets related to British submarine detection techniques. Even today it is difficult to gain a clear insight into how much damage the Portland spy ring did, but Houghton and Gee were both sentenced to 15 years' imprisonment following a six-day trial. Their case serves to show that in defence it is not sufficient to solve only the engineering challenges relating to leaks. If the risk of information leakage is not adequately addressed, all the hard-won technological advantages can be undermined.

Weapons

Submarine weapon propulsion systems, whether for missiles or torpedoes, have a remarkable energy density. This must be available the instant it is required, and be absolutely safe and quiescent when it is not. Whether torpedoes are electrically propelled by batteries, or liquid fuelled, this is a considerable safety assurance challenge. We have not always met that challenge and in 1955 this led to the sinking of a submarine, sadly with heavy casualties. After the inevitable initial confusion it became apparent, not least from the extensive damage found by divers in the front sections of the ship, that a weapon had exploded in a torpedo tube. It is not insignificant that the submarine was engaged in the proving trials of a new weapon.

The submarine in question was HMS Sidon and this terrible event took place alongside the depot ship HMS Maidstone in Portland Harbour. 13 men were killed, variously from the force of the explosion, smoke, and toxic gas inhalation. Of course, had the submarine been at sea, the entire crew could have been lost. The Court of Enquiry determined that the safety features of the weapon – a hydrogen peroxide powered torpedo, no less – had failed. A combination of loading drill errors and design weaknesses led to peroxide fuel and lubricating oil bursting from a pipe under excessive pressure, leading to violent combustion.

More recently there has been speculation about the cause of the accident on the Russian submarine Kursk in August 2000. I simply do not know – maybe nobody knows – of a justification for any of the speculation, let alone a proper explanation. But given the stored energy in such a vessel, my money would be on a leak of one sort or another.

Nuclear

Another similarly high-density energy source is the nuclear reactor itself. The heat is generated through neutrons impacting heavy fissile fuel atoms so that these split into two more or less equally sized fragments; these then crash around the other atoms in and around the fuel, creating heat as they slow down. Each fission requires one neutron: if there are too many neutrons creating fissions, the power increases; and if too few, it decreases.

Neutrons both cause and are released by the fission of fuel atoms. Between two and three neutrons emerge at enormous velocity from each fission event, and it is the job of the reactor designer to ensure that the process of further fissions is wholly stable – neither rapidly increasing or decreasing. Rather as ballast tanks are filled with sea water to bring a submarine to more or less neutral buoyancy, so control rods, effectively neutron sponges, are withdrawn from a reactor core until it is just critical: one new fission for each old fission.

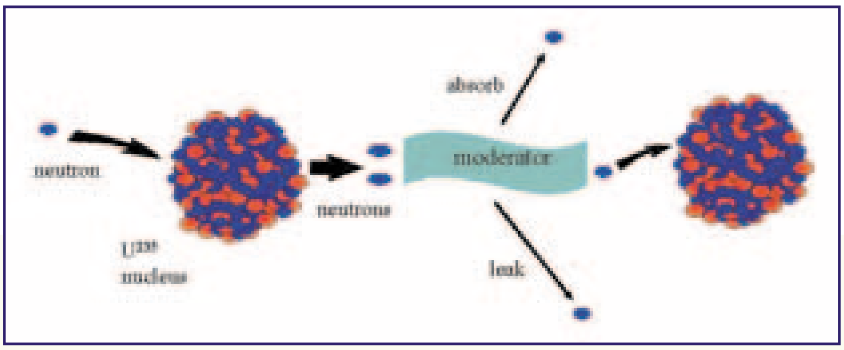
The magic of any pressurised water reactor lies in the arrangements for delivering this single neutron to the next fission. The neutron can only cause fission when it slows down enough after its birth to be captured by a fissile fuel nucleus. During this slowing down process the neutron is either absorbed into other atoms, such as in the control rods, or leaks out of the reactor into a shield tank. The slowing down is achieved by collisions with hydrogen atoms in the molecules of the primary coolant water, which are of more or less equal mass to a neutron and so are hugely efficient in the so-called moderation process. The further a neutron can travel without hitting a hydrogen atom, the more it is prone to leakage or absorption. So densely packed hydrogen atoms, or colder primary coolant, is more efficient at slowing down neutrons than hotter coolant. That means that opening the main engine throttles, which increases the steam demand and lowers the primary coolant temperature, automatically increases the rate of fissions. A pressurised water reactor is, in fact, a self-regulating, load-following power plant. And it all depends on balancing whatever leakage occurs.

Acoustics

I mentioned earlier the importance of noise leakage from a submarine. This is because, underwater, noise is a much more important sensory mechanism than it is in the air. For a start, the speed of underwater sound is much greater; but, just as important, there is not much else which travels long distances through water. I should say that submarines do not themselves generally use active sonar – the source of the pings heard on submarine films – because it is very easy to detect such emissions and this would therefore destroy much of the tactical uncertainty induced by the possible presence of a submarine. Conversely, submarines do like using passive sonar, which listens for noises in the sea, and very much do not like emitting noise themselves. It has been said, indeed, that a modern nuclear submarine at slow speed could create a volume of unnatural quiet in the ocean. We must keep alert to the possibility that such a black hole might itself be detectable.

Conclusion

Anything as complex as a submarine must evolve its design to match its function. Safety will always be a dominant issue, both to assure the vessel's continuing watertight integrity and to control the many types of stored energy on board. Keeping everything in its proper place, including sensitive information, is therefore a continuing concern and one that requires the most capable of engineers and the most cost-effective engineering. The overall technical challenge is enormously stimulating and I am sure that, for those involved, the next hundred years of submarine engineering will be just as exciting as the last, and will in turn support the quiet distinction of the next century of the submarine service. ■



This picture shows a chain reaction: the neutron over on the left-hand side is moving slowly enough that, when it hits the adjacent fuel nucleus, it will interact with it rather than passing straight through. The interaction generates more neutrons. Some of these neutrons will be absorbed by the control rods and be taken out of the system. The rest will pass through the moderator – the very primary coolant water that heats the steam. The neutrons slow down. A proportion of these neutrons interact with further uranium nucleii; the remainder leak away from the system. The balance between these behaviours – absorption, leakage and moderation – determines the reactivity of the core.