The long shadow of Admiral Hyman Rickover (Part 2)

by CM Meyer, technical journalist

This is the seventh in a series of articles being published in Energize tracing the history of nuclear energy throughout the world, and Part 2 of the series on Admiral Rickover.

"Shielding was also more difficult with the sodium-cooled reactor. As a result, the pressurised water reactor (PWR) would become the standard for the nuclear navy and for most civilian power plants" (Wicks, 2004: 5)

In 1870, the writer Jules Verne published a science fiction novel ("20 000 Leagues under the Sea") about a submarine that could obtain almost indefinite electrical power from the elements present in seawater. Run by the enigmatic captain Nemo, the submarine traveled unconquered for some 20 000 leagues, sinking whatever shipping Nemo wished to attack before finally being sucked down into the sea in a huge, fictional whirlpool near Norway.

The Nautilus and the Seawolf: water versus sodium cooled reaction.

But by the end of 1955 science fiction had become science fact. Two submarines had actually been built that could run and produce electrical power almost indefinitely using four elements that are present in sea water: uranium, sodium, and water (containing the elements hydrogen and oxygen). The "Nautilus" used a reactor powered by uranium that was cooled and moderated by water. Its sister ship, the "Seawolf" differed in that it used liquid sodium as a coolant.

The reactor developed for the Nautilus submarine was a PWR, and used water under high pressure both as a coolant and a moderator.

The "moderator" in a reactor has a crucial function: it must slow down neutrons very considerably from about 1/30 the speed of light (the approximate speed at which they are emitted from a uranium-235 (U235) atom when it splits, roughly 10 000 km/s) to about 2,2 km/s. At this lower speed, the neutron is more likely to be absorbed by the next nucleus of U235 it smashes into, and cause that nucleus in its turn to split and release more neutrons, thereby continuing the controlled chain reaction by which nuclear energy is released. Much of this energy is in the form of heat, caused by the fission products smashing into the uranium in the fuel. Reactors using moderators are called 'thermal' reactors.

The PWR in Rickover's programme was successful for several reasons. Firstly, because highly enriched uranium (HEU) with a far higher percentage of U235 (about 80%) was used as fuel than in a normal nuclear reactor (about 5%), considerably less fuel was needed than in normal reactors. Very roughly, this meant that something like 100 kg of fuel was needed for the submarine's reactor, compared with tons of fuel needed by more conventional reactors. (The first Chelyabinsk-40 production reactor used 150 tons). The final result was a very compact reactor that also allowed for enough heavy shielding to adequately shield the crew of the submarine from radiation. Water, sealed in very thick steel, was pumped through the core, heated, and then passed through a heat exchanger where a secondary stream of water was heated to produce steam, drive turbines and generate electricity. The thick steel also served to keep the water under the necessary high pressure.

Secondly, unless the thick steel piping and housing were somehow to fail (and cause a massive steam explosion), there was little that could easily go wrong with this type of reactor. The rate of reaction could be controlled by control rods that were moved into or out of the reactor core. Moving control rods into the core meant more neutrons were absorbed, and the reaction rate slowed. Pulling the rods out meant fewer neutrons were absorbed and the reaction rate increased. But unlike the water-cooled reactor at Chernobyl (known as the RBMK model), the primary coolant was sealed by thick steel into a primary circuit and re-circulated through the heat exchanger and then again through the reactor. If there was a leak of the coolant – water – this would go into the water tank that surrounded the whole reactor.

The Seawolf submarine used liquid sodium in its reactor. This turned out to have more disadvantages than advantages. The main advantage was that the sodium coolant could carry more heat than the water coolant of the Nautilus, generate more steam, and thus, from simple thermodynamics, result in a more efficient production of energy.

But should the reactor spring a leak, and if even a few drops of molten sodium came into contact with water, it would be enough to cause a major explosion. The molten sodium would also be highly radioactive (as would any liquid metal coolant). Persistent problems with corrosion were also encountered (Ref. 9;10). For these reasons, even though the Seawolf was operated satisfactorily for nearly two years and completed its sea trials, the concept was dropped, and its sodium-cooled reactor was replaced by a PWR (Ref. 3;4).

This lesson was not lost on Rickover, who saw to it that the power plants used for all nuclear submarines and surface ships in the US Navy (and later the first civilian power plant he designed and developed at Shippingport in the USA) were PWRs. The primary factor was safety, not economics. As a submariner, Rickover never forgot the importance of safety and having a safe, dependable design. So far it has paid off: none of the approximately 200 nuclear-powered submarines, cruisers and aircraft carriers that Rickover was responsible for, has ever been known to abort a mission because of reactor failure(Ref. 2:7).

However, the same cannot be said of the Soviet navy, especially in the strange story of the ill-fated Alpha-class submarines. Here, like the civilian power plant programme before Chernobyl, considerations other than safety were accorded priority.

Stranger than fiction: Project 645 and seven Soviet submarines

"The submarine suffered a major accident with one of its reactors in 1968, and nine members of the crew died. In this accident, one of the reactors of the submarine was

severely damaged after a pipe in the reactor compartment was contaminated by corrosion particles from the liquid metal coolant" (Rawool-Sullivan et al, Ref. 14;165)

In the movie "The Hunt for Red October", a Soviet Alpha-class interceptor submarine suffers a reactor failure, with catastrophic consequences for its crew. But the real story of why the Soviet nuclear navy, like the US Navy, also eventually came to rely largely on PWRs for their nuclear-powered submarines - and not the LMC (liquid-metal cooled) reactors as used in the Alpha submarines - is even stranger than fiction.

The first design proposal for Project 645 read like science fiction. The submarine would be capable of reaching 45 knots under water (fast enough to escape from any torpedoes fired at it), able to dive to more than a kilometre deep, be largely automated and have a crew of only "15 to 17 personnel" (Ref.14; 163). Because of the advanced equipment, the whole crew would be officers except for the cook (Ref.15; 4)! And to reach these incredible speeds, the submarine would be powered by not one but two reactors, both to be cooled by liquid metals (a mixture of lead and bismuth). And like

The world's first nuclear-powered submarine, the Nautilus, under way. Photo: US Navy Submarine Force Museum.

In 1957, some two years after the Nautilus first put to sea, the first Soviet nuclear submarine was launched successfully. Like the Nautilus, this nuclear submarine used a PWR. But immediately after this success, Project 645 was started. It was to develop a radically new Soviet submarine that was decades ahead of the Nautilus in concept. It called for a special interceptor (with a similar role to a jet fighter aircraft) that could race towards its target and intercept it before it could escape.

the reactors, most of the technology and automation on the ship would be radically new and complex. Not the least of this was the double hull, to be made of titanium, because a steel hull would have made the submarine too heavy to achieve its required performance.

In short, magnificent technically and decades ahead of its time, the submarine design was focused on power generation but not on safety. In fact, this was exactly the sort of design that the far more cautious Rickover would have rejected. And when the US Navy developed a counter to Alpha-class submarines, the Seawolf class (not to be confused with the original Seawolf) still used PWR reactors, and deliberately avoided many of the more advanced features of the Alpha class.

As Rickover would have predicted, the actual results of Project 645 were far more sobering. The main problem was that if the reactor temperature fell below about 123°C, the liquid lead-bismuth coolant (about 44% lead and 56% bismuth) would congeal, causing the reactor to seize up and essentially "freeze" itself" (Ref.14;163). This meant the reactor had to be kept running continuously to prevent the coolant freezing. In the case of the Alphas, this soon meant that the reactor had to be kept running continuously for the entire working life of the submarine, making refueling impossible and maintenance very difficult.

K-27, the prototype built under Project 645 suffered "a major accident with one of its reactors in 1968" that killed nine crew members . Despite this, experience gained was used to build seven Alpha class submarines under a new project, Project 705.

The results soon vindicated Rickover's decision to reject the original Seawolf in 1957: liquid-metal coolants and submarines do not mix. Three of the seven Alpha-class submarines suffered reactor failures, and a fourth, in a freak accident, collided with a whale. One submarine (K-123), suffered not one but two reactor accidents. The first reactor was removed in 1982, following an unspecified accident, and a new reactor installed. In a second accident, liquid metal from the primary cooling circuit of the replacement reactor "leaked out and contaminated the entire reactor compartment" (Ref. 14; 168). It took 8 - 9 years to correct the problem, and the submarine was recommissioned in 1991.

By the end of 1995, the last Alpha class submarine had been decommissioned, and the dream of a new generation of Soviet submarines based on liquid metal cooled reactors had come to an ignominious end (Ref. 4), (Ref. 5).

References

See end of the third article on Rickover in the next issue of Energize for references on the three Rickover articles. ❖