Voyage of the PWR

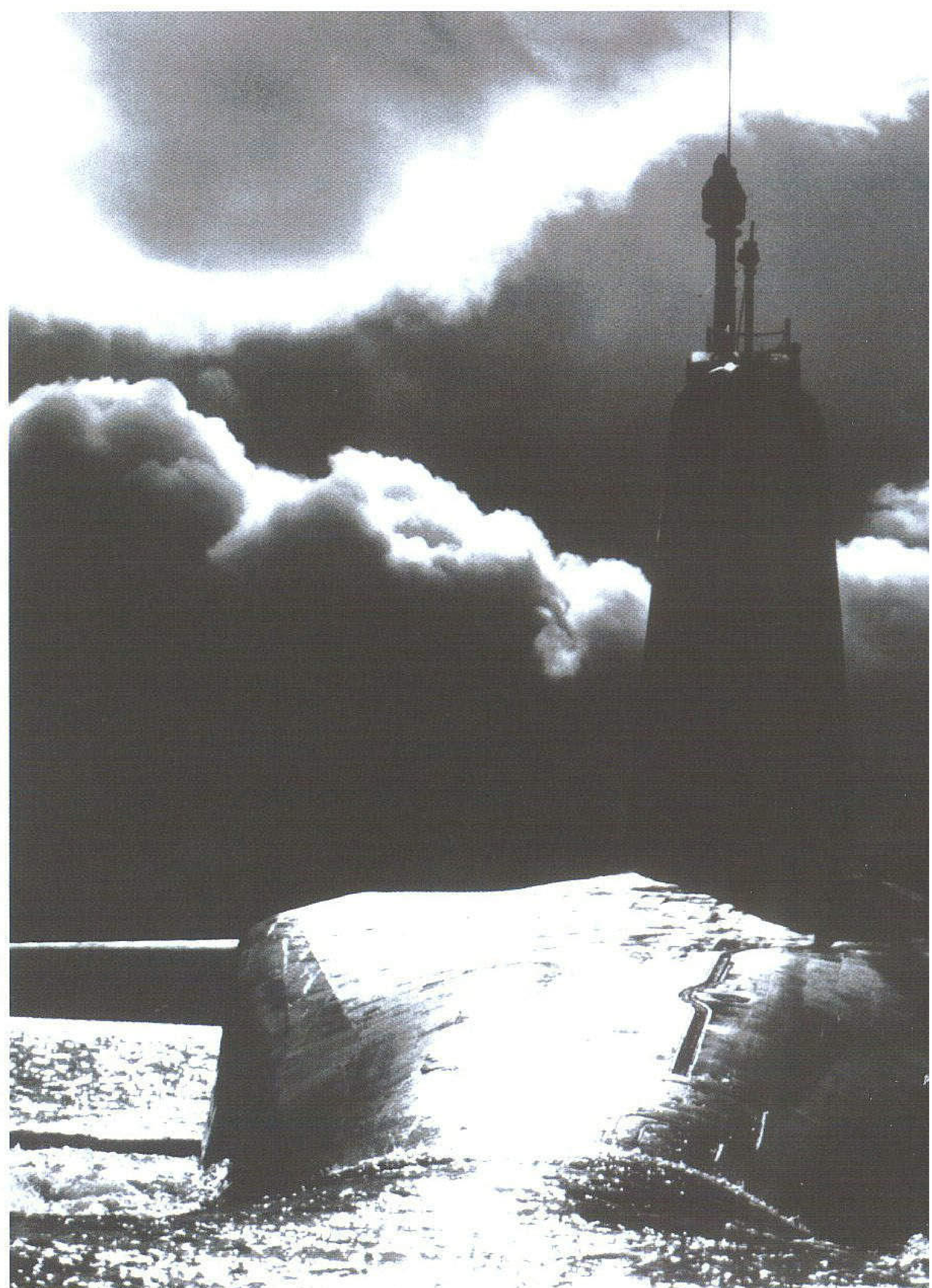
A pocket of nuclear expertise has survived and flourished in the UK throughout the industry's long drought from new power station orders, thanks to Admiral Rickover. ***By David Fishlock***

The PWR has its origins in NSSS development for the US Navy, technology of which was transferred to the UK in the late 1950s. The UK's Ministry of Defence has continued to develop the technology, to an extent that a single fuel core will now last the working life of the submarine. Rolls-Royce is building such cores for the three 'Astute' class 'hunter-killer' submarines under construction.

The PWR was the invention of the US Navy and developed by its scientists and engineers, working closely with American industry, into both submarine power plant and power station. Hyman George Rickover, a well-qualified and experienced electrical engineer, was the visionary responsible for the PWR. Rickover was to have more influence – far more – on the development of atomic engineering than any other single person. He personally drove development of the world's first nuclear submarine, an entirely novel and extremely complex man-o'-war, in an incredibly brief eight years. As sailors say, he ran a tight ship. A pop-eyed, pugnacious, Polish-born sailor himself, he decreed the exacting new standards of quality and reliability expected for the nuclear navy, to which its suppliers were obliged to conform; and the exacting new standards of behaviour expected of nuclear submariners, who could now remain submerged for months instead of hours at a stretch. He was ruthless in ensuring that these new standards were achieved and maintained, and that they were transferred in full to British industry and the Royal Navy. No other nation would ever share this highest of high technologies. But its principles now permeate the nuclear engineering practice of the Western world. The Chernobyl explosion in 1986 revealed to the world just how hugely Soviet standards trailed Rickover's hard-won requirements. In short, Rickover created from scratch a culture of excellence matched by no other activity at the time.

During the Second World War Rickover headed a small task force that studied 'pile' development for the Manhattan Project. His boss in 1947 when the study group he had led was disbanded was Rear Admiral Earle Mills, who made him his special assistant for nuclear matters; no staff, no formal responsibility, no authority, but boundless opportunity for vision and energy. The pair aimed first for Navy endorsement for three principles:

- There was a military need for a submarine with unlimited endurance and high speed submerged.



- Nuclear power alone could meet that need.
- The Bureau of Ships was to be the US Navy's agency for meeting that need.

The US Atomic Energy Commission (AEC) replaced the Manhattan Project as the nation's agent for all things nuclear. In 1948 the AEC set up a division of reactor development. Mills first made Rickover naval liaison officer, then in 1949 head of the Nuclear Power branch of the Navy's Bureau of Ships.

The nucleus of Rickover's team was four naval officers he had led on his study of Manhattan Project piles. They began development of two of the systems to which they had been introduced. At Argonne and Westinghouse's Bettis laboratory they began to develop the PWR; and at General Electric's Knolls Laboratory a system cooled by liquid sodium metal. By the spring of 1949 the PWR had pulled ahead and was selected for the Mark 1 land-based submarine prototype reactor to be built in the Idaho desert. Its coolant, water, was something very familiar to sailors (although not the purity demanded by the new technology). The prototype reactor went critical in March 1953 and reached full power that June. A year earlier president Harry Truman had laid the keel of the 4100-ton *USS Nautilus*, which received its S1W reactor and in January 1955 was "underway on nuclear power," as its captain reported.

The UK's Royal Navy has been ordering a new PWR at the rate of roughly one nuclear steam supply system a year for almost half a century

Rickover had triumphed in an immensely challenging self-imposed task. The fuel can alone presented a huge problem. The engineers had a promising solution, zirconium, but it was rare and costly and contaminated with neutron-hungry hafnium. His solution has benefited the whole nuclear industry. Rickover, small whereas Christopher Hinton was very tall, was a taskmaster out of the same mould. He missed his target date of 1 January 1955 by only 17 days. The US Secretary of the Navy called it the "most important piece of development work…in the history of the Navy."

The following year Rickover, by then both head of Naval Reactors with the AEC and the US navy's assistant chief for nuclear propulsion, expanded his Westinghouse contract to include development of a system for propelling large surface ships. Although later abandoned, the idea lived on as the basis for a power station. One time-saving advantage of his unprecedented – and long-enduring – double role was that he could write letters addressed to himself and respond promptly, thereby keeping both parties well-informed. Every navy using nuclear engines today has chosen the PWR as the staple power plant.

ATOMIC COLLISION

Early in 2005 the US version of this PWR survived a particularly tough test of its robustness, its resistance to shock. The depth charge is the weapon of choice against the submarine, designed to deliver severe shock. The *USS San Francisco*, had the misfortune to run into a rock at full speed, 30 knots (about 38 miles per hour, or 61km/h). A sailor died and almost everyone else aboard was hurt. But the reactor didn't falter. No radioactivity leaked out. It kept the lights burning while the boat surfaced, tremendously damaged by its collision with the seamount. It had decelerated to less than four knots in less than four seconds, the diving officer of the watch reported. But no systems had failed – only crew hurled into violent collision with them.

Rickover's remarkable quest for a reactor that did not rely on air for combustion came to fruition in large degree because of his inexhaustible energy and relentless obsession. But his quest had a spinoff, which he also pursued vigorously, in pioneering development of a land-based power station NSSS.

Submarine reactors have certain essential characteristics not necessarily needed for nuclear power stations, although some contribute to the favoured reactor's popularity. They can be summarised as:

- Compactness – high power density, up to ten times that needed in a power station. This is obtained by using highly enriched uranium fuel, mostly uranium-235, which is very costly. The intrinsic compactness of the PWR makes it smaller and cheaper than competing reactor designs.
- Robustness – military standards of mechanical and thermal shock resistance.
- Flexibility – rapid power change capability; seconds rather than hours for power stations.
- Stealth – low noise signature from pumps *etc*, to avoid detection.
- Cost – although not the main driver, support costs such as refuelling and radiation dose control are important; also core life, since changing the fuel calls for massive surgery on the submarine.

SHIPPINGPORT

When the AEC turned its attention to commercial piles for electricity generation it had the choice of starting afresh or building on Rickover's immense military experience. In April 1953 it proposed that a military project shelved for lack of funds, to build a nuclear-powered aircraft carrier, be explored for civil potential. By July 1953 the civil project was squarely in Rickover's bailiwick. Westinghouse was made lead contractor for the Shippingport project, in which a Pennsylvanian electricity supplier, Duquesne Light Company, would pioneer the new electricity source in partnership with the government. The Shippingport atomic power station would have a single pile producing 60MWe. The pile would be sealed in a cylindrical pressure vessel 33ft (10m) tall, resembling the reactors familiar to the chemical and petrochemical industries. It weighed in at 264 tons – the biggest ever made.

Of crucial importance as it turned out, Shippingport would embody Rickover's design philosophy emphasising safety, conservatism, reliability and redundancy needed for good availability. The project took only four years – Rickover knew how to drive his suppliers. Shippingport reached full power in December 1957, ten years after Rickover had launched his quest for atomic power. It was the world's first commercial atomic power station. (The UK's Calder Hall, 1956, was built primarily to make plutonium and provided electricity and process steam as byproducts). By then, Rickover had equipped the US Navy with over 30 submarine reactors.

The lofty Shippingport pressure vessel was a thick-walled steel pot, the lower half of which was filled by the core, a complex assembly of fuel and control rods to regulate the fission reactions. Water forced at high pressure from beneath the core carried fission heat away continuously to four heat exchangers outside the pot. These raised steam to spin the turbines and generators. Cooling conditions were carefully arranged to avoid boiling and cavitation; voids in the coolant which could cause hot spots and melting in the core. Coolant water had to be extremely pure; free from impurities that could leave heat-resisting residues on the fuel or deposit radioactive 'crud' on equipment outside the pot to complicate maintenance. Very pure water is itself corrosive. The inside of the steel pot had to be given a corrosion-resisting lining. All this and much more had been learned the hard way from the first submarine power plants, of course. Rickover himself coined the name for the pile. As Ted Rockwell, for ten years his technical director, tells it, Rickover revealed that he had landed the Shippingport project to a meeting of his senior staff.

> *We'll call it the Pressurised Water Reactor, or PWR for short, to distinguish it from all those crazy thermodynamic cycles that everyone else wants to build. The only thing Navy about it is that we're going to keep it as simple as possible. Utility operators love automation and gadgets. You know how hard I fought to keep that junk off submarines.*

TECHNOLOGY TRANSFER

In his Thomas Lowe Gray Memorial Lecture to the Institution of Mechanical Engineers in 2005 Vice Admiral Sir Robert Hill reviewed the influence Rickover exerted over the Royal Navy's nuclear propulsion programme in a half century of association between the two navies, starting with his friendship with the late Admiral Earl Mountbatten. It led to the transfer of technology for the NSSS of *USS Skipjack*, the S5W, successor to the *Nautilus* reactor. In was a once-for-all transfer in 1958, after which the Royal Navy was on its own. Rickover specifically rejected any further exchanges, said Hill. We shall see why.

From this technology transfer, which to its chagrin bypassed the UK Atomic Energy Authority, the Royal Navy has developed NSSS for its Valiant, Swiftsure, Trafalgar, Vanguard and Astute classes of submarines.

Rickover laid down precise terms for the transfer. Rolls-Royce would take the lead for the UK, not Vickers Nuclear Engineering (which built the subs). A complete nuclear propulsion system would be provided, including the core, with full supporting documentation and training. The UK could choose the reactor. It chose the S5W, a new system that was to power 98 US submarines. The overall cost of this S5W NSSS, including fuel, turned out to be about £10 million (say about £150 million, or $280 million, at current prices).

Rolls-Royce made the purchase from Westinghouse. UK attempts to negotiate extensions of the bilateral agreement were rejected. Security constraints were very tightly maintained, Admiral Hill reported, "to the extent that even Admiral Horlick's 1982 Thomas Lowe Gray Lecture, *Submarine propulsion in the Royal Navy*, drew heavy censure from the Office of Naval Reactors."

In a talk earlier this year to submariners at *HMS Sultan* at Gosport, where the navy trains its nuclear experts, Admiral Hill offered the opinion that "we'd never have sought and attained the standards of excellence if we'd gone it alone." It was Rickover's devout wish that the UK should be totally independent.

Hill, who had been the navy's director of nuclear propulsion in Bath when its second generation PWR2 was developed, concluded that along with the S5W reactor technology the Royal Naval Submarine Service acquired other important advantages. It got an exceptional plant and achieved Rickover's aim of giving the Royal Navy a step up into the nuclear submarine age. But it also learned "new standards of quality, new shipbuilding techniques, excellence in engineering, and experience of a reliable propulsion plant that was a joy to operate".

Admiral Rickover, believes Hill, instilled a concept that the Royal Navy understood but had never expressed: the concept of true responsibility. As Rickover expressed it:

> *Responsibility is a unique concept: it can only reside and inhere in a single individual. You may share it with others, but your portion is not diminished. You may delegate it, but it is still with you. Even if you do not recognise it or admit its presence, you cannot escape it. If responsibility is rightfully yours, no evasion, or ignorance, or passing the blame can shift the burden to someone else. Unless you can point your finger at the man who is responsible when something goes wrong, then you have never had anyone really responsible.*

Rolls-Royce has 'cradle-to-grave' responsibility for all the Royal Navy's PWRs.

The S5W reactor was the last submarine NSSS designed by Westinghouse, which thereafter concentrated on the burgeoning market for nuclear electricity opened up by the Shippingport success. Rolls-Royce & Associates, as the Royal Navy's contractor was first called, pursued its own R&D programme at Derby and *HMS Vulcan*, Dounreay. Its fuel was enriched by the US government and fabricated into cores at Raynesway, Derby. In the early 1980s British Nuclear Fuels built the A3 gas centrifuge plant at Capenhurst to partially enrich uranium for the Navy, but A3 has since been sold to Urenco. Spent fuel is not reprocessed but stored in ponds at Sellafield.

Steady improvement in reactor design has culminated in the long-life core, according to Rolls-Royce. "The core, with over six times the energy output and over four times the service life of the first core design, will enable the Astute class to operate throughout their service lives without any need to refuel."