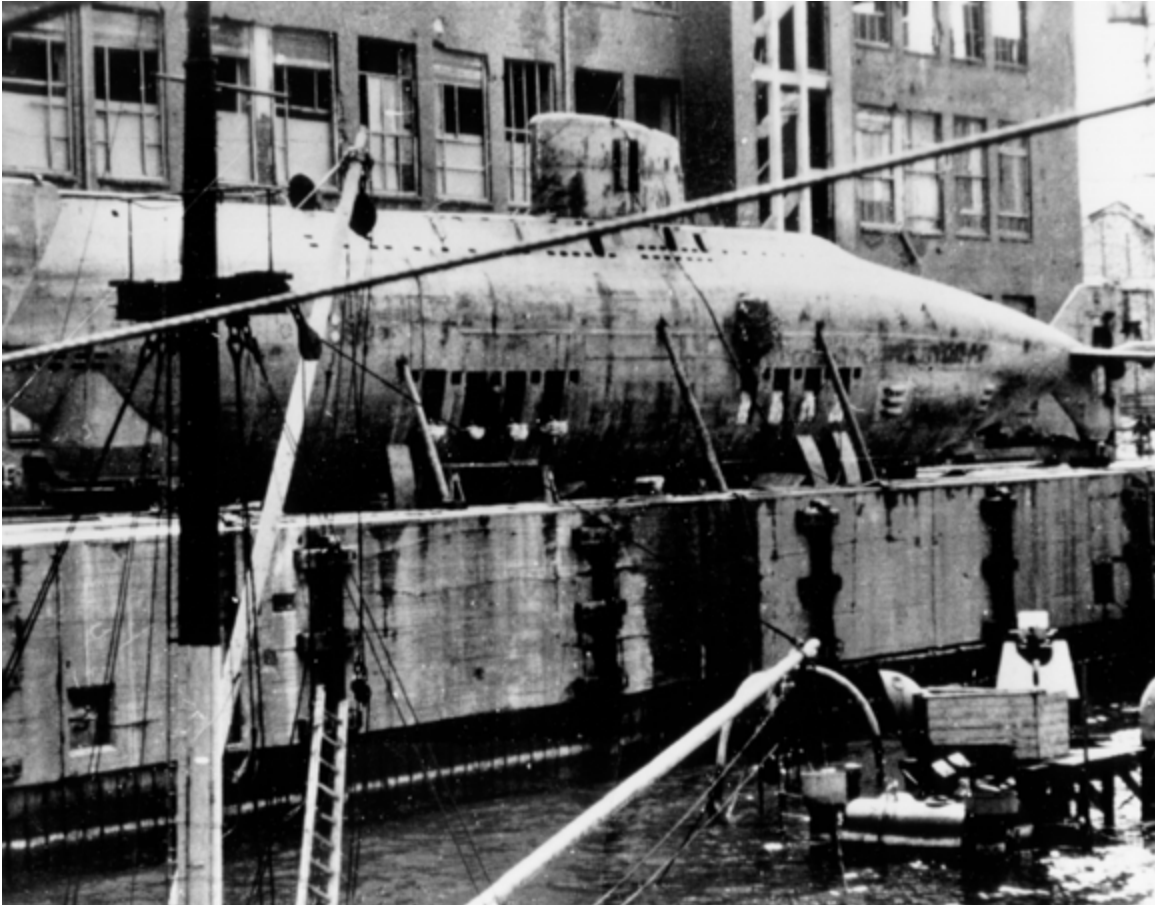


AIR-INDEPENDENT PROPULSION

AIP Technology Creates a New Undersea Threat

by Edward C. Whitman



Walter Type XVIIIB up on the stocks. Pictured above is the German Walter Type XVIIIB *U-1406*, partially dismantled shortly after the end of World War II. *U-1406* was turned over to the U.S. Navy as a war prize and soon disposed of, but the Royal Navy later operated her sister ship, *U-1407*, as *HMS Meteorite* to gain experience in hydrogen-peroxide propulsion technologies.

As interest mounts in "Air-Independent Propulsion" (AIP) for enhancing the performance of small, defensive submarines, a serious new underwater threat is developing in littoral waters. Increasingly, smaller nations unwilling or unable to accept the high cost of nuclear power to achieve greater underwater endurance and longer range are turning to lower-priced and less ambitious alternatives that still offer significant operational advantages over conventional diesel-electric submarines. The best of the latter boats, such as the German-designed Type 209 or the Russian KIL0, can remain submerged on battery at slow speed for periods on the order of three to five days. But now, several AIP schemes in development or already in operation can increase slow-speed endurance to as much as three weeks or a month. While still dwarfed by the potential of nuclear power, AIP offers diesel submarines a remarkable increase in capability.

AIP - The Early History

Despite their initial successes, submarine pioneers were still eager to find some means to free their boats from the necessity of surfacing frequently for access to the atmospheric oxygen demanded by the gasoline or diesel engines that charged the batteries. A number of approaches were tried, but eventually, open-cycle diesel engines, lead-acid batteries, and electric motors for submerged propulsion became the standard submarine engineering plant that served well through two world wars.

In the early 1930s, however, a brilliant German engineer, Dr. Helmut Walter (ca. 1900-1980) of Kiel's *Germaniawerft*, proposed a radical new submarine propulsion plant based on the use of high-purity hydrogen peroxide (H₂O₂) as an oxidant. In Walter's system, hydrogen peroxide from an onboard supply was decomposed using a permanganate catalyst to yield high temperature steam and free oxygen. Into the reaction chamber was injected diesel fuel, which combusted with the oxygen to yield a mixture of steam and hot gas that drove a high-speed turbine. The exhaust and condensed steam were then expelled overboard. Walter's primary design goal was high underwater speed, rather than long endurance, and indeed, his first submarine prototype, the experimental *V80*, reached 28.1 knots submerged in its 1940 trials - at a time when conventional submarines were limited to 10 knots or less. Thus, *V80*, only 76 tons and 22 meters long, also served as an early test bed for studying the dynamics and control of high-speed underwater vehicles.

Later in the war, the *Kriegsmarine* attempted to scale Walter's prototype up to a useful operational size, but although seven Type XVII B H₂O₂ coastal boats were completed before Germany's final defeat, none saw combat. These Type XVIIs displaced 300 tons and were powered by two 2,500 horsepower turbines, in addition to a conventional diesel-electric plant. More ambitious plans to build larger Walter-designed ocean-going submarines, such as the 800-ton Type XXVI and the 1,600-ton Type XVIII were thwarted by the unsuccessful course of the war and the realization that the industrial capacity needed to supply sufficient quantities of hydrogen peroxide could never be achieved. However, the Type XVIII was modified into the highly successful Type XXI "electro-boat," in which larger batteries provided a submerged speed of 17 knots, which could be maintained for 90 minutes. That innovation, and the adoption of the snorkel, yielded a potent combination that strongly influenced the postwar design of conventionally-powered submarines on both sides of the Iron Curtain.

AIP Fallout from World War II

After the conflict, several nations sought to exploit Dr. Walter's revolutionary propulsion concepts. As war prizes, the United States and Britain received the scuttled Type XVII B's, *U-1406* and *U-1407*, respectively, and the latter was resurrected for experimental purposes as HMS *Meteorite*. Additionally, Walter himself and several of his key staff were brought to England and there collaborated with Vickers, Ltd. for several years in the design of more advanced hydrogen peroxide systems. The result was two 1950s-era high-speed boats, HMS *Explorer* and HMS *Excalibur*, whose design was heavily influenced by that of Walter's wartime Type XXVI. While both boats achieved stated design goals for high underwater speed, their highly-concentrated hydrogen peroxide fuel created such a safety hazard that the two boat became known as "HMS Exploder" and "HMS Excruciator." Both were decommissioned in the 1960s.




The Soviet Union built a single, semi-successful exemplar of a Walter-cycle boat, known in the West as "the Whale," but their most serious AIP efforts were focused on a closed-cycle diesel plant based on the German *Kreislauf* system and their own researches prior to the war. Eventually, this led to the 650-ton Soviet QUEBEC class (1956) that used stored liquid oxygen to sustain closed-cycle operation for diesel engines on three shafts. Although 30 were built between 1953 and 1957, their safety record was so dismal that they were known by their crews as "the cigarette lighters" and withdrawn from service by the early 1970s.

Meanwhile, the United States had salvaged a 2,500-horsepower Walter turbine from *U-1406*, as well as a 7,500-horsepower version planned for the Type XXVI, and set them up at the Naval Engineering Experiment Station at Annapolis, Maryland. Subsequently, the Navy funded research on several alternative submarine AIP approaches, including variants of the Walter-cycle and *Kreislauf* systems. Eventually, unacceptable growth in the required size and weight of the corresponding engineering plants - plus the growing prospect in the late 1940s of submarine nuclear propulsion - soon brought these efforts - and those of the British and Russians - to a close. USS *Nautilus* (SSN-571) got "underway on nuclear power" in January 1955.

X-1 – The U.S. Navy's First Midget Submarine

However, in September 1955, the U.S. Navy's first midget submarine, the one-of-a-kind *X-1* (SSX-1), was launched on Long Island with a closed-cycle hydrogen peroxide/diesel plant! Inspired by the success of the British "X-craft" of World War II, *X-1* was intended for shallow-water commando operations. Displacing 36 tons submerged on a length of some 50 feet, *X-1* was powered by a

heavily modified commercial diesel engine with a small battery-powered electric motor as a backup. On the surface, the ambient atmosphere charged the engine, but underwater, the oxygen required for combustion was derived from the catalytic decomposition of hydrogen peroxide in a reaction chamber. Both engine exhaust and water condensate were compressed and discharged overboard. Four hundred gallons of peroxide could be stored in a flexible polyvinyl-chloride bag forward, and the craft could accommodate four crewmembers.

	<p>(left) X-1 Midget Sub. The U.S. Navy's 1955 mini-submarine X-1 used a rudimentary AIP system in which oxygen for underwater operation of its conventional diesel engine was derived from the decomposition of highly concentrated hydrogen peroxide. After a peroxide explosion in 1957, however, its AIP capability was eliminated.</p>
<p>(right) HMS Explorer at sea. One of two experimental Walter-turbine submarines built by the British in the 1950s, HMS Explorer achieved her designed underwater speed, but suffered enough engineering mishaps to earn the nickname, "HMS Exploder."</p>	
	<p>(left) Gotland Class. The Swedish Navy's three Gotland-class submarines each use two Stirling cycle engines as an adjunct to their main diesel-electric engineering plants to provide underwater endurance up to several weeks. This was the first AIP system to enter regular submarine service.</p>

After several engine failures and subsequent design modifications, X-1 finally achieved acceptable performance in February 1957 and undertook a series of operational trials based at the Portsmouth Naval Shipyard. Unfortunately, in May 1957, an explosion in the hydrogen peroxide storage system blew off the whole bow section, and although no one was injured, X-1's closed-cycle capability was never replaced. Instead, the boat was rebuilt with a small, conventional diesel-electric/battery plant, and after being laid up for three years, it was reactivated in late 1960 and subsequently used until 1973 for a variety of research studies in the Chesapeake Bay. Later, X-1 was put on static display at the U.S. Naval Academy in Annapolis, and more recently at the Nautilus Museum in Groton,

Connecticut. Significantly, her former Officer-in-Charge later wrote, "The most important lesson learned from this experimental program was... that high concentration unstabilized hydrogen peroxide has no place on a fighting ship."

Current Efforts in AIP

Although major naval powers like the United States, the United Kingdom, and the Soviet Union turned quickly to submarine nuclear propulsion as soon as it became technically feasible, smaller navies have remained committed to conventional diesel-electric submarines, largely for coastal defense. Many of these have incorporated innovations originally pioneered in the German Type XXI, but more recently, growing demand for longer underwater endurance has generated increasing interest in promising AIP technologies, both old and new. Currently, system developers are actively pursuing the following generic approaches for achieving "closed cycle" operation:

- Closed-cycle diesel engines, generally with stored liquid oxygen (LOX)
- Closed-cycle steam turbines
- Stirling-cycle heat engines with external combustion
- Hydrogen-oxygen fuel cells

Closed-cycle Diesel Engines

Typically, a closed-cycle diesel (CCD) installation incorporates a standard diesel engine that can be operated in its conventional mode on the surface or while snorkeling. Underwater, however, it runs on an artificial atmosphere synthesized from stored oxygen, an inert gas (generally argon), and recycled exhaust products. The engine exhaust - largely carbon dioxide, nitrogen, and water vapor - is cooled, scrubbed, and separated into its constituents, with the argon recycled back to the intake manifold. The remaining exhaust gas is mixed with seawater and discharged overboard. Generally, the required oxygen is stored in liquid form - LOX - in cryogenic tanks.

CCD systems have been developed by a number of firms in Germany, Britain, the Netherlands, and a few other countries. However, except for a 300-horsepower demonstration system refitted onto the German Navy's ex-*U 1* in 1993, no modern CCD systems have entered naval service. England's Marconi Marine recently acquired CCD pioneer Carlton Deep Sea Systems and is marketing a CCD retrofit package for existing conventional submarines, such as South Korea's nine Type 209s. Although one key advantage of CCD systems is their relatively easy backfit into existing submarine engineering plants, there have been no takers. Despite the additional supply complication of needing regular replenishment of cryogenic oxygen and inert gas, there are logistics advantages in retaining standard diesel engines and using normal diesel fuel.

Closed-cycle Steam Turbines

The only steam-turbine AIP under active investigation is the French MESMA system (*Module d'Energie Sous-Marin Autonome*). This is essentially a conventional Rankine-cycle turbo-alternator powered by steam generated from the combustion of ethanol (grain alcohol) and stored oxygen at a pressure of 60 atmospheres. This pressure-firing allows exhaust carbon dioxide to be expelled overboard at any depth without an exhaust compressor.

Basically, the MESMA approach is a derivative of French nuclear-propulsion experience using non-nuclear steam generation. Although MESMA can provide higher output power than the other alternatives, its inherent efficiency is the lowest of the four AIP candidates, and its rate of oxygen consumption is correspondingly higher. The first full-scale undersea application will be in Pakistan's three new Agosta 90B submarines, which will each be fitted with a 200 kilowatt MESMA system for increasing submerged endurance by a factor of three to five at a speed of 4 knots. The first installation is expected to be completed in 2001.

Stirling-cycle Engines

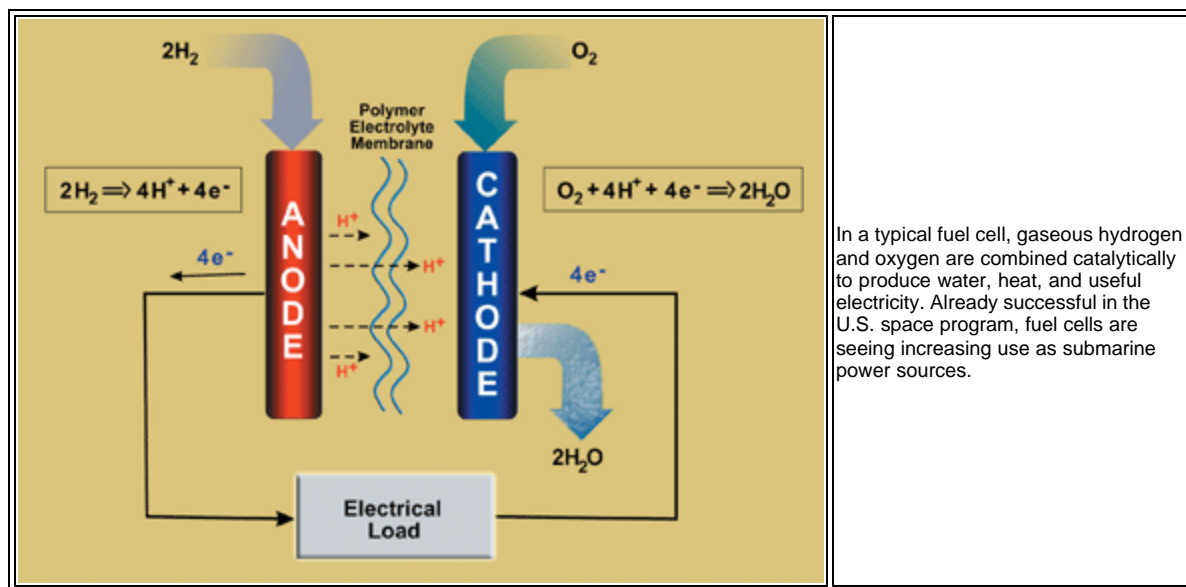
In the Stirling cycle, heat from an outside source is transferred to an enclosed quantity of working fluid - generally an inert gas - and drives it through a repeating sequence of thermodynamic changes. By expanding the gas against a piston and then drawing it into a separate cooling chamber for subsequent compression, the heat from external combustion can be converted to mechanical work and then, in turn, to electricity. Like MESMA, this approach has an advantage over internal

combustion systems, such as the CCD, in that the combustion processes can be kept separate from those that actually convert heat to mechanical work. This provides significant flexibility in dealing with exhaust products and controlling acoustic radiation.

The Stirling-cycle engine forms the basis of the first AIP system to enter naval service in recent times. The Swedish builders, Kockums Naval Systems, tested a prototype plant at sea in 1989, and today, three Swedish *Gotland*-class boats are each fitted with two adjunct, 75 kilowatt Stirling-cycle propulsion units that burn liquid oxygen and diesel fuel to generate electricity for either propulsion or charging batteries within a conventional diesel-electric plant. The resulting underwater endurance of the 1,500-ton boats is reported to be up to 14 days at five knots, but significant burst speeds are possible when the batteries are topped up.

Fuel Cells

In simplest terms, a fuel cell is an electrochemical conversion device that combines hydrogen and oxygen to produce water, electricity, and heat. Fuel cells are already seeing a number of promising applications in the space and automotive industries, and many authorities believe that fuel cells offer the best potential for developing more capable AIP systems in the future. There are several alternative configurations, but for submarine propulsion, so-called "Polymer Electrolyte Membrane" (PEM) fuel cells have attracted the most attention because of their low operating temperatures (80° Centigrade) and relatively little waste heat. In a PEM device, pressurized hydrogen gas (H_2) enters the cell on the



anode side, where a platinum catalyst decomposes each pair of molecules into four H^+ ions and four free electrons. The electrons depart the anode into the external circuit - the load - as an electric current. Meanwhile, on the cathode side, each oxygen molecule (O_2) is catalytically dissociated into separate atoms, using the electrons flowing back from the external circuit to complete their outer electron "shells." The polymer membrane that separates anode and cathode is impervious to electrons, but allows the positively-charged H^+ ions to migrate through the cell toward the negatively charged cathode, where they combine with the oxygen atoms to form water. Thus, the overall reaction can be represented as $2H_2 + O_2 \Rightarrow 2H_2O$, and a major advantage of the fuel-cell approach is that the only "exhaust" product is pure water. Since a single fuel cell generates only about 0.7 volts DC (direct current), groups of cells are "stacked" together in series to produce a larger and more useful output. The stacks can also be arrayed in parallel to increase the amount of current available.

The greatest challenge for fuel-cell AIP systems lies in storing the reactants. Although oxygen can be handled with relative safety as LOX, storing hydrogen onboard as a liquid or high-pressure gas is very dangerous. One solution is to carry the hydrogen in metal hydride accumulators, at low pressure

and ambient sea temperature. (A metal hydride is a solid compound of hydrogen and metallic alloy, in which individual hydrogen atoms occupy interstitial positions in the host metal's crystalline lattice. By manipulating temperature and pressure, hydrogen gas can be absorbed or released at will.) Another, less efficient, approach is to generate gaseous hydrogen from a stored liquid hydrocarbon such as diesel fuel, kerosene, or methanol. This requires an auxiliary device called a "reformer," in which a mixture of hydrocarbon and water is vaporized and superheated under pressure to yield a mixture of hydrogen and carbon dioxide.

Several manufacturers are currently offering fuel cell systems for submarine AIP. Prominent among these is the German *Siemens* firm, which is collaborating with *Howaldtswerke Deutsche Werft* (HDW) and Italy's *Fincantieri* to supply fuel cell installations for the forthcoming 1,840-ton German and Italian *U 212*-class submarines. These will consist of nine PEM fuel-cell modules each nominally rated at 34 kilowatts, to yield a total of approximately 300 kilowatts (400 horsepower). With metal-hydride hydrogen storage, the system is predicted to yield 14 days submerged endurance and the ability to run up to eight knots on the fuel cells alone. *Siemens* is working on a next-generation PEM module rated at 120 kilowatts, and two of these will be incorporated into HDW's 1,860-ton *U 214* boats, planned as export successors to the *U 212* series. Other nations, such as Russia and Canada - the latter with significant under-ice requirements - are also considering fuel-cell modules for either new construction or for upgrading older boats.

Other key advantages here are both higher efficiency and lower specific stored-oxygen consumption than the other alternatives.

An AIP Perspective

Although it is a remarkable tribute to Hellmuth Walter's engineering genius that he fielded a fully functional - if troublesome - 5,000-horsepower AIP system in 1945, the maximum power output of current AIP installations is typically on the order of 400 horsepower (300 kilowatts). In comparison, the conventional diesel-electric plant of the *U 212* class described above is rated at over 3,000 horsepower, and a typical nuclear submarine propulsion plant produces over 20,000. Since the power required to propel a submerged body varies with the cube of its velocity, it should be apparent that at least for the near future, AIP will be valuable primarily as a low-speed, long-endurance adjunct to the under-water performance of conventional submarines. There is little short-term prospect for AIP to become a primary, full-performance alternative to either diesel or nuclear power. Even the phrase "closed cycle" is something of a misnomer, because except for fuel cells, all AIP alternatives require ejecting exhaust gases overboard, which limits both depth capability and stealth.

However, this is not to minimize the dangerous potential for AIP submarines to complicate seriously both coastal defense and assured access to littoral regions. If their distinctive characteristics are exploited by skillful operators, AIP submarines can be used to telling effect for both short- and medium-range missions. AIP dramatically expands the tactical "trade-space" for diesel-electric submarines. If conditions permit, they can transit rapidly on the surface with-out unduly expending the wherewithal for superior underwater performance. Submerged, they can opt for a long, slow, silent patrol that keeps their batteries fully charged and thus capable of powering speed bursts of significant duration. And by carefully husbanding their resources, they can revert again to slow-speed operation and repeat the cycle several times over weeks of submergence. Moreover, AIP technology is evolving rapidly, and some experts predict, for example, that the power output of a typical fuel cell module could well double or triple in the next several years, allowing an even more advantageous trade-off between underwater speed and endurance.

Their tactical flexibility, their small size, their inherent stealth - and the novel operational paradigms AIP submarines introduce to undersea warfare - will make these new boats a dangerous threat to submariners accustomed to nuclear- or conventionally diesel-powered adversaries. The Submarine Force needs to understand this threat - where it's been, where it's going, what it means, and how to counter it.

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TABLE OF CONTENTS