

Submarine Engines for the Future

By Rodney M. Adams

The nuclear-heated gas turbine—once considered too technically immature for dependable development—has grown up. With the current debate on future submarine propulsion systems, it may be time to reconsider this technology.

USS SALT LAKE CITY (SSN-716) / Y. KAUFMAN

An interesting debate is taking place regarding future propulsion systems for submarines. Participants are lining up behind further experimentation with liquid-metal-cooled reactors, continued use of pressurized water reactors, a return to diesel electric power, or further development of a variety of cycles generally grouped under air-independent propulsion (AIP). Another proposal should be included in the complicated but extremely important debate: the closed-cycle nuclear gas turbine.

Most naval professionals, even those who are nuclear trained, are unaware that a nuclear-powered gas turbine engine is even possible. Those with long memories or an interest in technical history may recall that Admiral Hyman Rickover's team initially evaluated three different systems for submarine use, not just two. Some will claim that Rickover's choice is still the best, but that is an assumption, not a fact.

It might be useful to review the reasons we went nuclear in the first place.

In 1951, when Arleigh Burke forwarded Rickover's plan to build the *Nautilus*, recommending that it become a priority item, we had recently won a war where diesel electric submarines proved their usefulness. We had a large industrial base set up to support them, we had lots of trained operators, and we had a large stockpile of completed ships. The technology was mature, engines were getting more and more reliable, and increases in battery capacity and streamlining were resulting in higher and higher speeds. Not exactly the time to start changing things.

Listen to the words, though, of Captain Edward Beach, a man very experienced in submarines propelled by chemically fueled engines. "Having made 12 war patrols in diesel submarines in the Pacific and experienced all their limitations, including being virtually stationary during depth-charge attack, to me the prospect of a nuclear engine that could drive a submerged submarine fast enough and long enough to overtake, or escape from, any surface ship then in existence was breathtaking. What could we not have done with such a submarine during the war?"¹

Rickover and those who supported his plan knew the limitations of using combustion on board a submarine and saw nuclear fission as a way to eliminate them. Fission requires no external source of oxygen, and there is no possibility of explosion. Unless the core materials are in a specific configuration, there is no significant energy released. In addition, the fuel is very energy dense. One pound of uranium has as much energy stored in it as three million pounds of coal or 240,000 gallons of fuel oil, allowing a tremendous amount of heat energy to be stored on board a ship or submarine. Interestingly enough, a pound of uranium cost about \$10.50 on the world spot market in the summer of 1993.

Consider the tactical and operational advantages of an engine based on a dense fuel source that needs no external oxygen. No longer do submarines on a Western Pacific patrol have to stop in Midway to top off their fuel tanks. No longer do they have to fill ballast tanks with fuel at the start of their mission to have enough on-station time. No longer do they have to lie in wait and hope that fast surface ships cross their paths—they go and get

them. Most important, they no longer have to cower, watching the amp-hour meter with increasing tension, while getting pounded by depth charges. They have the power to attack or evade and live to fight another day.²

There is no doubt that nuclear power has fulfilled its promise for true air-independent power that allows unsupported submarine operations over a full range of speeds for an indefinite period. There are those, however, who want to return to the bad old days of fuel-gauge watching. In a recent *Proceedings* article, a proponent of chemical propulsion discusses submarines that he claims have performance profiles comparable to nuclear submarines.³ Ignoring the fact that he thinks of 23 knots as sprinting and that he overlooks the value of high-speed transits, let's take a hard look at his energy storage numbers.

Assume that the author means kilowatt hours when he writes kilowatts. (A kilowatt is a measure of the rate at which energy is delivered. You cannot deliver "120,000 kilowatts to the shaft over a 28-day mission.") A chemically propelled submarine, he claims, could store 900,000 kilowatt hours in an *Albacore* (AGSS-569)-sized hull. That is less than two days worth of full-power running on a nuclear-powered submarine with a 30,000 shaft horsepower plant. Since the nuclear boat could sustain maximum power for years before running out of fuel, the performance comparison is ludicrous. If the desired patrol area is the Mediterranean and it is surrounded by fuel stations (that can provide liquid oxygen for AIP users), a logical choice might be a chemically propelled sub. If the potential patrol area is an undesignated portion of the Pacific, Atlantic, Indian, or Arctic oceans, a nuclear-powered submarine is the only platform capable of performing the mission.

The U.S. submarine force's decision to go nuclear is even more valid today than it was 40 years ago. If the problem is money, perhaps a better solution would be to figure out ways to reduce the cost of nuclear systems.

Once the choice was made to abandon combustion in favor of fission, many hard engineering decisions still had to be made. There were at least a dozen different research projects going on under the auspices of the Atomic Energy Commission, including pressurized light water, liquid metal, organic coolants, and several different gaseous coolants. In Canada, our close allies were gaining experience in heavy-water-moderated reactors, while in England they were building large reactors cooled by carbon dioxide.

Rickover studied all of the possibilities at Oak Ridge and found a system that he thought could be ready with a major effort in a reasonably short period of time. Cynics might say that he rushed because he knew that he had to do something big to be selected as an admiral and remain on active duty past 1953. Others would contend that Rickover realized that a long-term project would never gain the political support required. He knew he had to have results to show people if his program was to be a success.

Rickover's team evaluated three systems. Pressurized-water primary coolant loops used to make saturated steam won the competition in the early 1950s because it was the most direct technical path available. Liquid-metal-cooled reactors, used to produce superheated steam, made a brief

appearance, but soon were abandoned. Closed-cycle, nuclear-heated gas turbines were dropped before leaving the drawing boards, because they were considered too technically immature for dependable development.

Even at the time, there were those who questioned the decision. It was called a technological leap backward, because the temperatures and pressures in the steam system were significantly lower than those of readily available conventional steam plants.

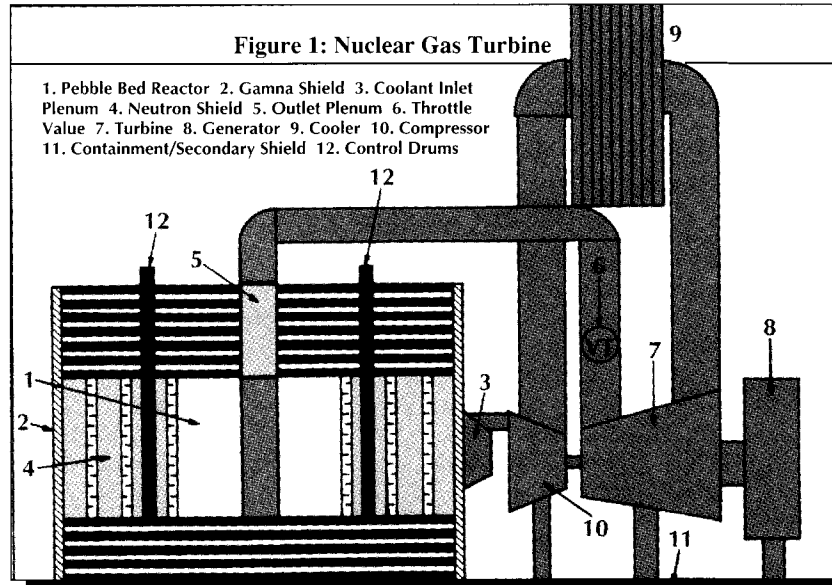
But Rickover understood that efficiency was only one

and waste heat being the only outputs.

The reactor core will be somewhat larger than that required for a pressurized-water reactor, because gas is not as dense a heat transfer medium as water. It will not be too large to fit inside a submarine, however. Using core power densities from proved gas-cooled reactor designs yields an active core size of about 16 to 20 cubic meters, which would fit into a cylinder three meters in diameter and three meters high. Even after allowing for several meters of shielding and foundation, the core would fit easily into a nine- to ten-meter diameter hull.

The compressor should be a centrifugal-flow compressor. It can consist of several stages, if necessary, to get the required pressure ratio of four to about seven for maximum efficiency. Centrifugal compressors can produce stable output over a much wider variety of flows than the axial flow compressors that are normally used in shipboard gas-turbine propulsion systems. The compressor either can be driven directly by the turbine, or it can be driven electrically from the output of a generator attached to the turbine.

The power output of the system can be controlled by directly controlling the flow rate of the gas through the system. Using a throttle valve that would be familiar to operators of steam

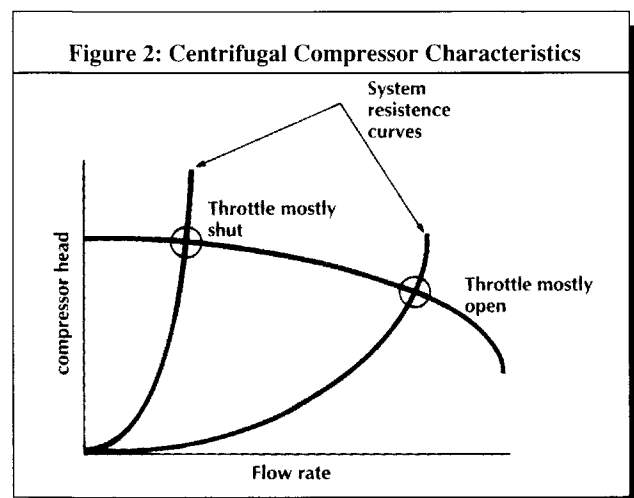


of many measures that could be used to determine the best system design. Naval Reactors cared about pushing submarines; paper designs with nifty ideas could not propel a submarine anywhere. The organization also cared about safety, reliability, sailor-proofing, and a whole host of other concerns—which it met exceptionally well.

Unfortunately, Naval Reactors has been slow to respond to technological change. The nuclear-heated gas turbine has grown up and may now be ready for full-scale development. It is, at least, worth a detailed evaluation and some hard-headed questioning.

There is a strong technological base for nuclear gas turbines that did not exist in the early 1950s when pressurized water reactors were developed. Gas turbines have now proven their utility in marine applications, amassing millions of reliable running hours. Gas-cooled reactors have been operated with coolant temperatures of up to 950°C, with excellent reliability and extremely low coolant activity levels.⁴

Figure 1 shows how the system might look. Here is how the system works: A compressor raises the pressure of a gas—normally helium—that is initially at atmospheric pressure. For the temperatures of interest, the optimum pressure ratio is about five or six to one. The compressed gas flows through an internally moderated nuclear reactor, normally containing graphite, which heats the gas. The hot, compressed gas is expanded through a turbine to produce mechanical energy. The expanded gas is then cooled to bring its entropy back to the starting point and the process starts again. The system is closed, with work



CHARTS REDRAWN BY WILLIAM J. CLIPSON

turbines, the flow rate out of the reactor and into the power turbine can be adjusted to any of a wide range of flows.

If the throttle is opened to allow more flow, the core is initially cooled down. The reduction in core temperatures leads to an increase in the density of core materials, allowing more efficient use of the neutrons in the core and causing power to rise. The core stabilizes at a steady, higher power when the core temperatures are back to the value before the change in throttle position. A reduction in flow follows a similar pattern. Because the mass of the core is relatively large, the temperature changes take place slowly and smoothly. Figure 2 illustrates the response of

the system flow rate to a change in throttle position.

Because the temperatures and pressures in the system remain relatively constant, the overall efficiency of the system remains constant. The throttle valve simply restricts flow by altering the open flow area through it; it does no work and removes no heat. There is little pressure drop through the throttle and it causes extremely small frictional losses.

The power turbine can be an axial flow turbine similar to those used in standard gas-turbine or steam-plant systems. It will be smaller in diameter and have a smaller increase in diameter over the stages than a steam turbine of similar output, because there is a much smaller increase in specific volume with a gas that expands over a five to one pressure ratio than with steam that expands from five hundred pounds to a deep vacuum. The power turbine's response to changes in throttle position will be at least as rapid as the steam turbine's.

The cooler will look like a conventional condenser, with liquid flowing through tubes and a gas flowing across the tubes. Since the reject temperature of the gas coming out of the turbine is several hundred degrees Celsius, it is possible to design an efficient cooler that has air as the cooling medium, if that is felt to be an advantage for surface ships.

If desired for reliability considerations, there could be two or more compressor/turbine sets for the same core. The entire system, including core, piping, and rotating machinery, can be enclosed in a containment boundary.

There would have to be some auxiliary systems, including a purification system to remove any contaminants in the helium loop and a means to supply any needed helium makeup. Because the coolant is a gas, though, there would be no need to routinely charge and discharge fluid to account for temperature differences.

Unlike pressurized-water steam plants that are limited in the temperatures they can use by the characteristics of high-temperature water, gas-cooled plants can be designed to take advantage of improvements in material technolo-

gies that may allow future increases in core temperatures. If, for example, the maximum temperature allowed in the system is allowed to increase from 950°C to 1050°C, there will be an almost 20% improvement in the specific

power output and an increase in maximum efficiency from about 35% to 38%. Since ceramic-materials technology is advancing rapidly, it is reasonable to assume that an advance of this magnitude is well within technological possibility. Figures 3 and 4 illustrate the effects of maximum system temperature on efficiency and specific power output. (Both figures 3 and 4 use degrees Kelvin to put the temperatures on an absolute temperature scale.)

Like Rickover's pressurized-water plants, the plant described here could be called a technological leap backward by those engineers and scientists at the forefront of nuclear gas turbine design. They would point out that the entire system could be pressurized to yield a higher power output with no cost in efficiency. They also might point out that a regenerator would allow recovery of a great deal of wasted heat or that intercoolers could improve the overall performance of the machine. All of those additions may be beneficial at some point; however, the goal of this design is to produce a workable, simple, tough, marine power system that can be deployed with no further research.

Those who are familiar with nuclear-powered steam plants will note the differences between the proposed plant and the ones that actually are operating. The proposed plant has no steam generators, no coolant-pressurizing system, no high-pressure drain system, no main coolant pumps, no

gland-sealing system, and no reserve feed tanks. The length and number of the piping systems are reduced significantly, the pressures in the system are less by a factor of 20 or more, and the maximum system temperature is up by a factor of two on an absolute temperature scale. The coolant is an inert gas instead of a somewhat corrosive liquid whose chemistry must be tightly controlled and whose pressure must be kept ele-

Figure 3: Efficiency vs Pressure Ratio for Various Temperatures (Helium)

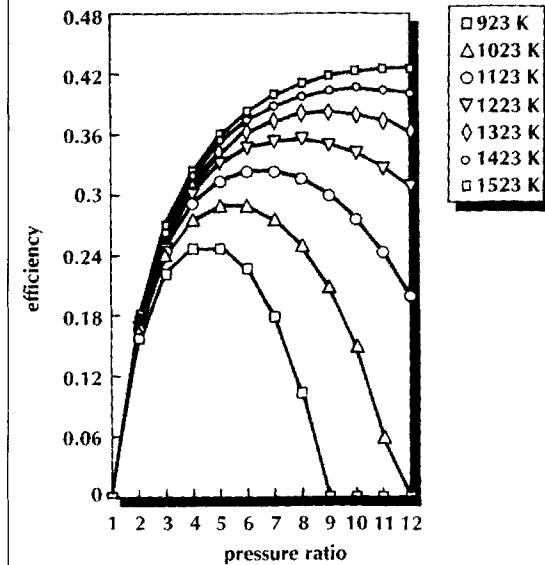
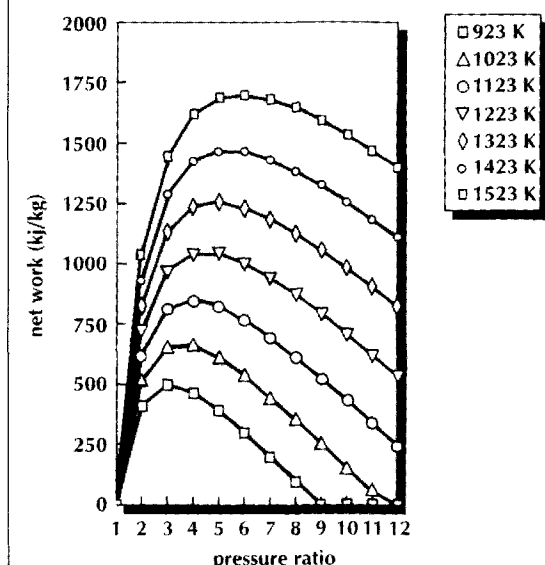


Figure 4: Net Work vs Pressure Ratio for Various Temperatures (Helium)



vated to keep it in liquid form. As a result of the nuclear nature of the coolant, there also is a reduction in coolant activity levels, which allows a reduction in the thickness of secondary shielding.

Some advantages that a system like this could produce include:

- ▶ Reduction in cost. Nuclear-grade materials and construction are expensive. If the quantity of materials, the number of welds, and the number of components are reduced, the cost should be lower.
- ▶ Increase in manufacturing ease. Piping-system construction is difficult and time consuming, especially in confined spaces such as ships and submarines. Reducing piping systems should reduce fit-up time.
- ▶ Increase in thermodynamic efficiency. This is a direct result of the higher cycle temperatures. Even using conservative assumptions, a 30% thermal efficiency is easily obtainable compared to a pressurized-water reactor efficiency of about 20%.
- ▶ Reduction in required manpower. Fewer components means fewer watch stations and fewer logs to keep.
- ▶ Reduction in radiation exposures. Most radiation exposure in pressurized water reactor plants is a result of the effects of corrosive products. Eliminate the source of corrosion (high-temperature water) and the problem is reduced.⁵
- ▶ Increase in power-to-weight ratio. Components such as steam generators, pressurizers, charging water storage tanks, reserve feed tanks, surge tanks, and high-pressure, sound-isolated piping systems are heavy. The reduction in secondary shielding also helps.

Presumably, Naval Reactors has remained informed about developments in gas-cooled reactor operations. They also are well aware of the preference exhibited by the surface Navy for gas-turbine power plants. Presumably, they are aware of what could be done in combining the two technologies.

It is quite possible that the reasons for continuing to build pressurized-water reactors overwhelm the potential benefits of trying a new, risky system. The decision should be made, however, by people who have all the facts at their disposal, who are aggressive questioners, and who can spot the difference between slick presentations and real information at several hundred yards. The active-duty submarine force is full of the right kind of people. Unfortunately,

they have been indoctrinated from the very beginning of their submarine service with a sense of awe for the technical power of the Naval Reactors organization.

Submarine officers are at least as smart and competent as the engineers who populate the Naval Reactors branch. They meet the same high standards of education, and they have a great deal to offer in the way of operational experience. They need to have a real input into the decisionmaking process. Unfortunately, the submarine officer training system is set up in such a way that professional submariners must return to Naval Reactors for permission to continue doing their jobs. This reduces the potential for operator questioning of the technical experts.

Rickover once made a comment about the difference between real reactor plants and paper designs. All good system designs, however, start on paper and get heavily modified on paper (or computers) based on hard-headed choices before metal is ever bent. Even the *Nautilus* started with a paper design. The key is to at some point lock in the design and produce a system that works.

⁵Capt. Edward L. Beach, USN (Ret.), quoted in Foreword to *Rickover and the Nuclear Navy. The Discipline of Technology*. Francis Duncan (Annapolis, MD: Naval Institute Press, 1990), p. xi.

If you need further convincing about the value of nuclear fuel, see Peter Cremer's *U-Boat Commander. A Periscope View of the Battle of the Atlantic* (Annapolis, MD: Naval Institute Press, 1984) and William Y'Blood's *Hunter-Killer. U.S. Escort Carriers in the Battle of the Atlantic* (Annapolis, MD: Naval Institute Press, 1983) about the defeat of the Germans in the Battle of the Atlantic. The German U-boat fleet, a formidable, highly trained force of dedicated sailors and sophisticated machines, was defeated by technical limitations and superior firepower. Specifically, it was beaten when the mid-Atlantic submarine refueling areas were invaded by carrier air power. Code breaking played a role, but the Germans could not stop transmitting their position. It was the only way they could ensure that the milch cows met the patrol boats to provide the fuel needed for continued operations.

⁶G. Santi, "Santa Claus, Diesels, and Elves," U.S. Naval Institute *Proceedings*, October 1993, pp. 92-94.

⁷H. Nabielek, et al., "The Performance of High-Temperature Reactor Fuel Particles at Extreme Temperatures," *Nuclear Technology*, Vol. 84, January 1989, p. 62.

⁸W. A. Simon, et al., "The Fort St. Vrain Power Station Operating and Maintenance Experience," paper presented at the 2nd JAERI Symposium on HTGR Technologies, 21-23 October 1992, p. 8.

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For Men of Stern Fiber

In late 1947, we on board the USS *Bayfield* (APA-33) had been in North China waters for almost six months, teaching Chinese Marines amphibious landings. Because of our long supply line, the food served in the wardroom had become quite monotonous—until one night at dinner we were served a meat dish that could only be described as "fuzzy."

It immediately evoked questions such as "What is this, roast yak hump?" Red-faced, the mess caterer left the table. I thought it tasted quite good, so I ate it.

Later, in confidence, I asked the caterer what it was. Citing his difficulty in obtaining a variety of food and the resulting monotony, he had instructed the galley personnel to use cereal in breading the veal cutlets.

They did. And what did they use? Shredded Wheat!

Lieutenant Commander Robert H. Ehm, U.S. Navy (Retired)