

NUCLEAR POWERED GAS TURBINES. AN OLD IDEA
WHOSE TIME HAS COME.

by
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Modern warships in the U. S. Navy are propelled by one of two types of engines. Small to medium sized surface combatants use gas turbine engines for their high power to weight ratio, ease of maintenance and operation, rapid response and relatively low cost. Aircraft carriers and submarines use pressurized water nuclear reactors due to their unlimited endurance (years between refuelings), high total power production, and lack of dependence on oxygen or need for exhaust. This situation has been accepted for lack of better alternatives.

It is possible, by combining proven technologies, to produce a closed cycle gas turbine engine in which the gas is heated by a nuclear reactor. The characteristics of the engine would include rapid start capabilities, high power to weight ratio, independence from fuel supply lines, small total plant volume, independence from oxygen, zero air pollution, a low thermal signature, a high level of plant safety, relative ease of maintenance, and acceptable lifetime cost. This is not a perpetual motion machine or something out of science fiction, it is achievable in the near term.

Brief Technical Description

The engine operates on the well known Brayton cycle that is used in all gas turbine engines. The major difference is that the cycle is closed. The working fluid that shows the most promise is helium. A compressor raises the pressure of the helium. The reactor heats the pressurized gas to give it more internal energy. The turbine turns the hot, pressurized gas into mechanical work by accelerating the gas through nozzles and directing it onto rows of spinning blades. When the useful work has been extracted, the gas is cooled to bring it back to the starting point of the cycle and the process continues. Figure 1 is a T-S diagram of the cycle. Figure 2 is a schematic diagram of the proposed system.

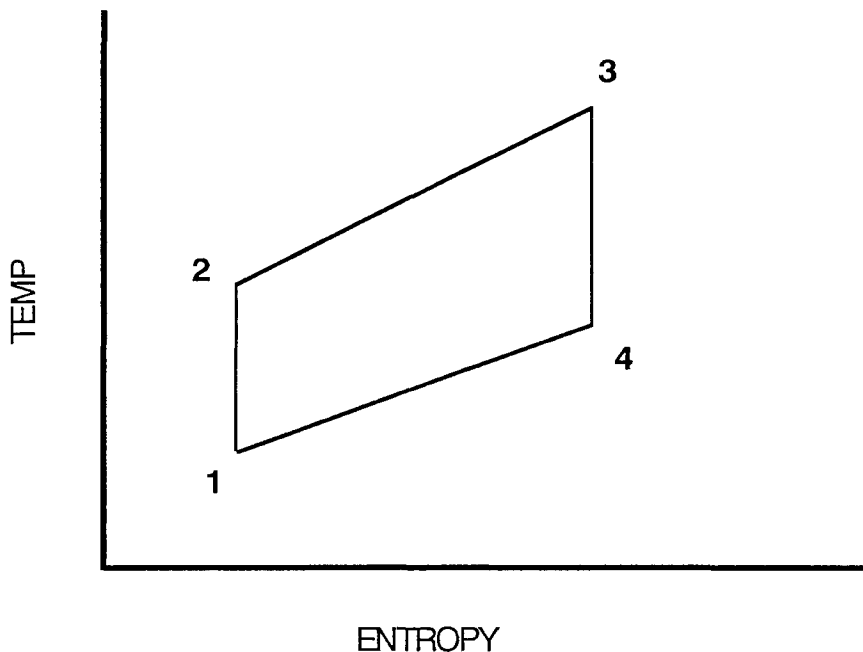


Figure 1

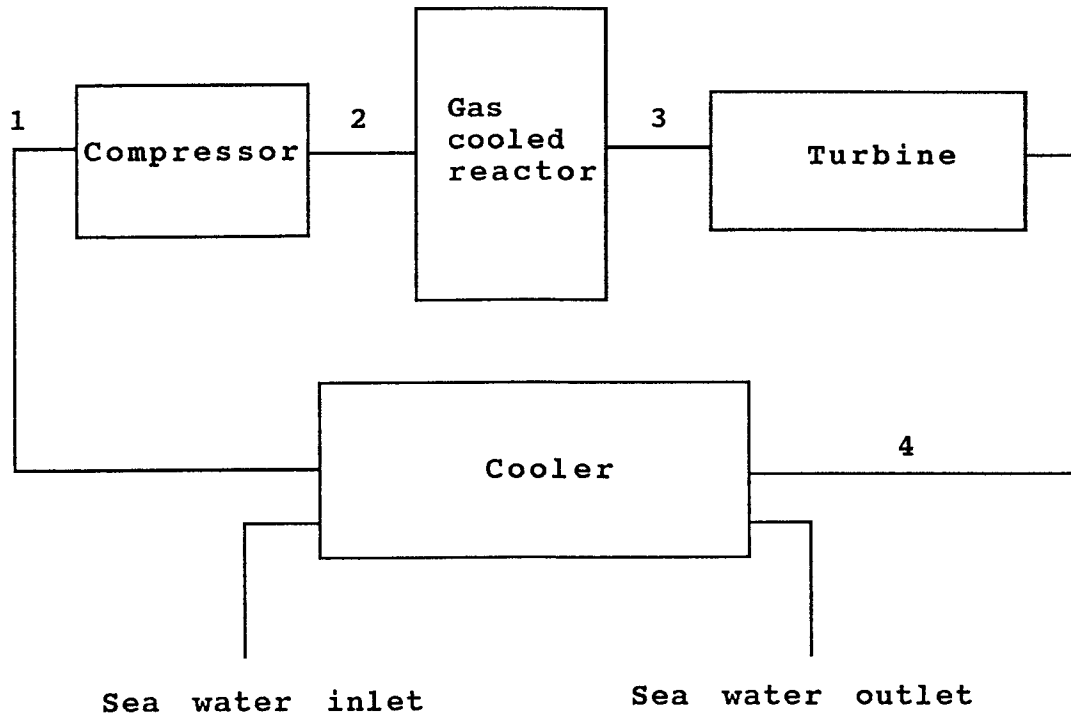


Figure 2

The enabling technologies for this engine are modern, high temperature ceramic reactor fuels that can maintain fuel integrity even with temperatures of up to 2000°C and high efficiency compressors and turbines that can operate reliably with turbine inlet temperatures of 1000°C. With current limitations on core exit temperature, turbine inlet temperature, compressor and turbine efficiencies and postulated cooler effectiveness, the engines have the potential to reach thermodynamic efficiencies in excess of 40%. This is a large increase over current nuclear powered steam plants that have max efficiencies of 30%. Additionally, improved efficiencies are possible as materials are developed to allow higher temperatures.

Nuclear Power Myths

Amid all of the negative press concerning nuclear fission, much information has been obscured. The fissioning of heavy elements like uranium and plutonium is a highly concentrated form of energy that leaves a very small volume of waste product behind. It requires no oxygen and produces no exhaust gas that must be discharged. One gram (there are 454 grams in a pound) of uranium-235 when fissioned will release 7,300 kilowatt hours of energy. For comparison, that is the same amount of energy that is released from burning 13 barrels of oil or 3 tons of coal.¹ The waste products from that gram of uranium weigh less than a gram, with the mass difference being directly converted into heat energy.

Contrary to some reports that uranium resources are too limited to make much of a difference in the long term, the total energy available from proven uranium resources in the United States is more than ten times that of coal.² Exploration for these materials has barely started. Additionally, the enriched materials in decommissioned nuclear

¹Duderstat, James and Kikuchi, Chihiro, Nuclear Power, Technology on Trial, University of Michigan, 1979, p. 99

²Duderstat, p. 10

warheads could be readily converted into reactor fuels, giving a new meaning to the idea of beating swords into ploughshares. One way of completely destroying the explosive potential of these materials is to break each atom in half for the production of useful energy.

Finally, though the question of how best to handle the waste generated from the plants is not resolved, this is not as large a problem as many people think. The total volume of the high level waste produced in the United States projected through the year 2000 would fit into a cube measuring 15 meters on a side. When compared to the fact that a single 1000 KW coal fired plant requires the removal of thirty three train car loads of ash every single day, it is obvious that the problem is rather tightly bounded.³ The wastes have been safely stored in temporary areas for many years and there are many technically sound proposals for permanent storage. Part of the reason that permanent storage arrangements have not been completed is that the "spent" fuel rods are potentially valuable, with a large amount of fissionable material that can be recycled with available technology.

The mental picture that most people have of nuclear energy production is of enormous plants with huge cooling towers or a maze of piping with complex indication systems on board aircraft carriers, cruisers and submarines. These images are directly related to the fact that current nuclear power plants use pressurized water to make steam. The images have little to do with the fission process itself. The steam produced in the secondary of pressurized water reactors is handled in the same way as steam produced in boilers fueled by a variety of carbon based fuels. The steam system is what produces much of the complexity, size and weight of the plants.

Historical perspective

The Nautilus project began only 8 years after Enrico Fermi achieved the first self-sustained chain reaction. Captain Hyman G. Rickover, a determined engineer who wanted to rapidly apply the potential of nuclear power to the problem of underwater propulsion, was the driving force behind the Nautilus. He made decisions for Nautilus based on following the course of least technical risk in order to make the project work. He and his team succeeded admirably, launching an operating nuclear powered submarine a mere 13 years after the very first chain reaction. This was an amazing feat and the quality of the effort has enabled the basic design to remain intact during the 37 years since the Nautilus reported "underway on nuclear power."

Unfortunately, a crash program requires that some sacrifices be made. Investigating interesting possibilities takes time and resources away from the primary effort. One casualty of Rickover's single-minded determination to apply nuclear power was that proposed alternatives to his pressurized water reactors were squelched. One of those alternatives was the combination of a gas cooled reactor with a then infant gas turbine engine. In 1958, the Air Force operated a nuclear powered gas turbine as part of their Aircraft Nuclear Propulsion program and in 1961 the Army operated a small, closed cycle nuclear gas turbine designed to supply power to remote bases or communications sites.⁴

While Rickover was aware of these developments, he was determined to use mature technology in his program. He was an influential man in those times of technological confrontation with the Soviet Union and he convinced Congress, industry, and the American people that his way was the only way.⁵

The centrally controlled Navy Nuclear Power program has produced admirable successes including an unmatched safety record, a large number of highly trained people and a strong base of knowledge. However, it has also produced a high cost power plant that no one else in the United States will buy, a fragile industrial base that is totally dependent upon a single customer and a feeling among the general population that the program may not be worth the expense. Additionally, it has produced a system where few people are willing to challenge the status quo.

During the 42 years since the beginning of Naval nuclear power there have been considerable advances in technology and politics that affect the future course of nuclear power. Gas turbine engines have become a mature power source accumulating millions of hours of operating experience and impressive records of reliability, while gas cooled

³Duderstat, p. 110

⁴McDonald, Colin F. "Turbine Power Plant Possibilities With a Nuclear Heat Source-Closed and Open Cycles", 90-GT-69, paper presented at the Gas Turbine and Aeroengine Congress and Exposition-June 11-14, 1990.

⁵Duncan, Francis, Rickover and the Nuclear Navy, The Discipline of Technology, Naval Institute Press, Annapolis, 1990, p. 13-16

reactors have been successfully operated in the United States and Germany in trial programs and in the United Kingdom on a large scale. On the political side, the superpower confrontation seems to be over and there is an increased interest in reducing the costs of providing for the national defense. There is a growing realization that nuclear fission is less harmful for the environment than burning fossil fuels. Finally, there is a growing understanding in the Navy of the benefits that can be obtained from innovation and new ideas.

ANTI-NUCLEAR POWER ARGUMENTS IN THE NAVY

The following are some of the standard arguments that have been used against nuclear power for shipboard use.

- * The plants have a low power to weight ratio and complicate ship design.
- * They are extremely costly and hard to justify in an era of relatively cheap oil.
- * The plants require a long time to build and test.
- * It takes a nuclear powered ship a long time to go from cold iron to steaming conditions.
- * Operation and maintenance of the plants requires a highly trained, specialized and expensive work force.
- * A large volume of internal space must be dedicated to the engineering plant on a nuclear powered ship.

All of these "facts" are true, but they are not facts about nuclear power, they are facts about pressurized water steam plants. Nearly two decades ago the rest of the maritime world decided to stop building more steam plants. For the last decade or so, only submarines and aircraft carriers obtained enough advantages from nuclear power to overcome the disadvantages. Both programs are now in jeopardy due to their high cost and changing defense priorities. As a result, nuclear plants and their components are increasingly being produced at low and inefficient production rates.

Advantages of Technological Advances

The fuel for most reactors has been a ceramic fuel encased in corrosion resistant metal to protect it from the high temperature water used as the coolant. Compared to many industrial materials, this fuel has a relatively low melting point. The combination of fuel and coolant chosen in the early days of nuclear power has placed limitations on the highest temperature available in the cycle and on thermodynamic efficiencies. Additionally, the combination has had an impact on nuclear power's cost and perceived safety.

The enormous engineering effort to design against the possibility of fuel melting has driven the cost of nuclear power. Due to the large change in thermodynamic properties that occurs if high temperature water loses pressure and changes phase from water to steam, nuclear power plants require carefully designed systems and procedures to prevent the loss of coolant. They also need several redundant means of removing heat from the core in the event that power is lost to the pumps that normally circulate coolant.

Judging from nuclear power's amazing safety record, the engineering and training effort has been successful, but it has been costly and is getting more so. Not all of the costs are measured in dollars, they are also measured in the amount of time that leaders on nuclear powered ships spend in duties related to their engineering plants.

When high temperature water is removed from the equation, the opportunity for a completely different fuel appears. The basic ingredients of fissile material are the same, but the means to isolate the fission products is different. Fuel designed for use in a gas cooled reactor is formed into small pellets that are encased in several layers of a high integrity ceramic coating. A certain amount of extra space is included inside each pellet to allow for the fact that some fission products are gases and will have a higher volume requirement than the original material. These pellets can be formed into either long thin rods or billiard ball sized spheres in order to be loaded into the reactor.⁶

The considerations for the core specifics are beyond the scope of this article, but each form has been successfully tested in trial reactors in the United States, the spheres

⁶McDonald, C. F., "The High Temperature Gas-Cooled Reactor - A Versatile Nuclear Heat Source for Space, Terrestrial, Mobile, Subterranean and Undersea Power Applications", Proceedings of the 23rd Intersociety Energy Conversion Engineering Conference, July 31- Aug 5 1988. p. 545

at Peach Bottom in Pennsylvania and the rods at Fort Saint Vrain in Colorado. Due to its ability to withstand high temperatures, cores using the new type of fuel can be designed to maintain integrity even without forced cooling. Through the heat transfer mechanisms of radiation and conduction the fuel reaches an equilibrium temperature before it gets hot enough to fail. This characteristic eliminates the possibility of meltdowns. Since high pressure is not needed to keep the coolant in a single, predictable phase, most of the components in the system can operate at atmospheric pressure. This minimizes the potential for leaks.

Gas turbine engines have proven to be a lightweight, compact means of converting the heat energy released from combustion of fossil fuels into the mechanical energy required to push ships and aircraft and to produce electricity. When operating at peak loads, they have a better fuel efficiency than other alternatives. When using an inert gas that is heated in a reactor, several synergisms can be realized that will make the gas turbines even better.

- * A turbine operating in inert helium instead of in the corrosive environment of the exhaust products of burning fossil fuel should last longer.

- * Problems associated with incomplete combustion, fuel nozzle clogging, soot formation, and air pollution will be eliminated.

- * A closed cycle plant will be insulated from environmental considerations like salt spray, sandstorms, and ambient air temperature.

- * A closed Brayton cycle operating with a constant temperature power source can use inventory control of the coolant for power level changes. With this scheme, if the power demand goes down, some of the gas can be bled off the discharge of the compressor to lower the system pressure. This scheme is projected to give a nearly flat efficiency response over a wide range of power.⁸

- * The engine gives ship designers the ability to locate the engine wherever it is most convenient. The enormous volume of intake and exhaust ducting is eliminated as is the need for exhaust gas cooling.

- * There is no high temperature exhaust to provide a bright infrared target. Waste heat will be rejected to the ocean in the form of a slightly warmer wake.

- * Fuel handling, storage and treatment systems can be eliminated, saving a great deal of weight. The potential exists for a core that lasts the life of the ship.

Tactically, the ships would have greatly improved flexibility and resistance to changes in the external world. No longer will ships have to refuel every few days, subjecting them to the hazards of operating in close proximity to other ships at constant courses and speeds. Training time will no longer be dictated by quarterly fuel budgets or events that temporarily limit the availability of fossil fuels. The need for foreign naval bases will be limited to the resupply of weapons and spare parts, things that are needed much less frequently than fuel. Fast surface combatants will be able to race across oceans to respond to contingencies without waiting for slower oilers to keep up.

For submarines the benefits would be equally impressive. They would be able to deploy faster from a shutdown condition. Overhauls could be shortened based on the reduced propulsion plant maintenance. Hull sizes could be reduced at the same time that power is increased, leading to higher speed capabilities. Weight formerly dedicated to the propulsion plant could be put into the hull to increase operational depth capabilities without resorting to exotic materials.

Cost Picture

The following characteristics of the engine should result in substantial cost savings.

- * A system with fewer components should be less expensive. This engine greatly reduces the number of parts involved when compared to either fossil fueled gas turbines or pressurized water nuclear plants.

- * Eli Whitney and Henry Ford showed that complex manufactured products using standardized designs for large scale production in factories can be made cheaper and with higher overall quality than equipment that requires an artisan for each piece. These engines could propel ships, both commercial and naval and submarines. They might even be eventually adaptable for aviation applications. The potential market is enormous.

- * The complex infrastructure devoted to the distribution of fossil fuels to a geographically dispersed fleet can be reduced.

⁷McDonald, C. F., p.544

⁸Fruttschi, H. U., "Rapid Positive Load Changes by Gas Injection in Closed Gas Turbine Cycles," ASME Paper 78-GT-8

* The need for exhaust gas scrubbers to meet environmental regulations will be headed off before it imposes a burden on the fleet.

* The potential small size of the overall unit make it possible that it can be retrofitted into existing ships. There may be no requirement to build ships from the ground up to take advantage of these engines.

* Ships and submarines will reduce the amount of their precious internal volume dedicated to the propulsion plant. In any transportation application, the size and weight of the engine plays a large role in the overall economy of the vehicle.

* The engines would require a lower manning level than current nuclear plants. Both operations and maintenance will be simpler. This will reduce payroll costs per platform and again increase the volume of internal space available for other applications.

* Compared to water, helium experiences low activation in the reactor, minimizing the contamination of turbine and compressor parts. Modular construction and repair techniques will still be useable. Shielding weight will also be greatly reduced.

* Although quality and dedication to reactor safety will continue to be the hallmarks of Navy Nuclear Power, the inherent stability built in to the plant design should reduce the required oversight and lead to significant savings in administrative costs.

Conclusion

The technology is modern, but all of the components have been thoroughly tested. Gas turbines are well understood and manufactured by many companies for such diverse applications as aircraft and ship propulsion, peak load generators, and natural gas pipeline pumps. The United Kingdom, Germany and the United States have operated sufficient numbers of gas cooled reactors so that any difficulties associated with them are well understood.

The long term success of the pressurized water reactor has given us an enormous knowledge base relating to reactor physics, radiological controls, personnel training, and materials research. The United States has the expertise and the capital necessary to make nuclear powered gas turbines for shipboard propulsion in the near term. The technology can be applied to other programs, helping the United States to regain it's prominence in an industry it once dominated. The program would be an investment that could reap impressive rewards.

4/6/92

R. L. Kiang

Comments on LCDR Adams' course project report entitled "NUCLEARED POWERED GAS TURBINES - AN OLD IDEA WHOSE TIME HAS COME".

This report is well written. The idea of combining a closed cycle gas turbine with a gas-cooled reactor is an interesting one. I enjoyed reading the entire report. My comments should not be construed as a judgement of the quality of the work as a term paper (that job belongs to Prof. Wu), but rather as suggestions for future improvements should LCDR Adams decides to pursue this matter further.

To me, the biggest shortcoming of this report is the lack of quantitative information. Phrases like "rapid start capabilities", "high power to weight ratio", and "fewer components" would have a lot more weight to them if they are backed by numbers. I fully realize that numbers are hard to come by, at times, but that's what scientific research is about.

The discussions at the top of p.5 talk about converting nuclear warhead material to reactor fuel. My rather limited knowledge about nuclear warhead tells me that either pure U-235 or Plutonium is the common fission material. The fuel in a commercial nuclear power plant is only 3% U-235; and that is why a reactor will never have a nuclear detonation. It is not clear to me how much modification is needed before the warhead material can be used as reactor fuel. "break each atom in half" does not mean a lot to me.

I am not familiar with the fuel used in a gas-cooled reactor. An identification of the high temperature ceramic clad fuel pellets would be very helpful. You also need to convince me that such fuel rods or spheres can maintain its integrity without forced cooling. Quotation of some experimental data would help.