

Nuclear Powered Gas Turbines Potential Power Source of the Late 1990's

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Nuclear fission power is a misunderstood and under used energy source. Even though the splitting of certain heavy elements results in the liberation of vast quantities of energy with a very small volume of fuel, the overriding tone in the majority of current technical literature and popular media is that the risks may not be worth the rewards. Even knowledgeable people dismiss the potential of fission power by waving their hands and vaguely stating "It is too expensive." or "The public will not stand for it." or "They still do not know what they are going to do with the wastes." or even "Nuclear power plants are not as efficient as fossil fuel plants." Currently, each of these statements happen to be true, but they are not natural truths. They are the product of people and attitudes, not physical or technical limitations. Improvements in the applications of already developed technology can make each one of the difficulties associated with nuclear power less problematic. If no action is taken, the use of nuclear fission reactors will eventually cease in the United States. This will lead to greater dependence on dirtier fuels that are being consumed faster than they are being discovered.

In the United States, there has not been a commercial nuclear power plant ordered since 1978. No public utility is willing to take the heavy financial risk involved in a reactor project. They have difficulty obtaining regulatory approval to start the plant, they cannot predict how long it will take to construct the plant,

and, even if the plant is completed and certified, they cannot predict whether or not they will ever be allowed to operate the plant. Opponents of nuclear power point to these facts and gleefully claim that nuclear power has failed in the marketplace. Large, pressurized or boiling water reactors that are custom built over many years simply cannot succeed in today's market. Fortunately, the heat produced by fission is a highly concentrated energy source that lends itself to use in a compact heat engine.

It is technically possible to combine nuclear reactors with gas turbine engines to produce a light weight, efficient and powerful source of energy. Gas turbines currently supply power to virtually every commercial airplane, many naval vessels and they are increasingly being used by electric utilities as peak load generators. Gas turbines have an extremely high power to weight ratio, they can be started rapidly, they have proven to be durable, and they have a reasonable thermodynamic efficiency when operated at design load. Since they depend upon a continuous heat input, they are particularly well suited to a modification that replaces the combustion chamber with a high temperature gas cooled reactor.

This is not a new idea. As early as 1958 the U. S. Air Force operated a prototype engine as part of the Aircraft Nuclear Propulsion (ANP) Program. The engine operated without problem, but the program died in 1959 as a result of political problems and lack of an effective proponent of the program within the

Department of Defense.¹

During the same time that the Air Force was working on the nuclear powered aircraft, Admiral Rickover was fighting to maximize the funding that his pressurized water nuclear power program received. Not only did he feel that his system was the best one for submarines, he also pushed for it to be adopted as the standard plant for the budding commercial nuclear power industry. Rickover was a man of considerable persuasive talents and one who was unlikely to admit that a nuclear power plant developed outside his personal control could possibly be better than his was. He knew about the ANP and some of his own people may have suggested that the engines have merit. There was even some talk of trying to use the technology on submarines.² Given the state of gas turbine technology in 1958, Rickover probably made the correct choice. The jet engines built then had operating lives measured in 100's of hours, obviously not enough for extended seagoing deployments or for commercial power applications. Rickover won the political battle and established the pressurized water reactor as the world wide standard. Unfortunately, even though gas turbine reliability has improved dramatically, the technical merits of the nuclear gas turbine have been largely forgotten.

¹Aircraft Nuclear Propulsion Program, Hearing before the Subcommittee on Research and Development of the Joint Committee on Atomic Energy Congress of the United States, U. S. Government Printing Office, Washington D. C. 1959

²Friedman, N, Submarine Design and Development, Naval Institute Press, 1986. p. 134.

If the advantages of gas turbines are combined with the advantages of atomic fission, a truly valuable alternative energy source would result.

The GCFR/GT (Gas Cooled Fast Reactor/Gas Turbine) power plant tentatively represents the simplest and most economical nuclear power plant that can be designed for operation on a thermal power cycle and employing nuclear fission. The predominant characteristics of this power plant are fuel breeding and the single fluid that functions both as the reactor coolant and the working fluid in the power cycle.³

The engines could be made in many different sizes depending on the application, they would not require complex fuel supply lines, they could be mass produced, and they would be able to be purchased when needed without having to accurately predict energy needs a dozen or more years into the future. It would be foolish to claim that these engines could replace all other sources of power, but they would be particularly useful in providing power for transportation applications. When a power source must propel itself, size and weight are always important to overall economy.

The engine would also be well suited to providing reliable electric power. This is an urgent need. In areas like New York City and South Florida, demand has already outstripped production and minor failures result in rolling blackouts. Even if there is no growth in demand, the electric power grid in the U. S. needs replacement generators to take the place of aging plants. The

³Sorensen, H. A., Energy Conversion Systems, Washington State University Press, 1983.

alternative energy sources available today simply cannot provide the power with enough reliability. Wind and solar power are dependent on the weather, the geographic location and the time of day; geothermal power is dependent on geography; hydro-electric power requires vast amounts of water and land, fuel cells require continuous injection of unstable chemicals and burning fossil fuels and biomass necessarily produces air pollution. Conservation can not do it all either. A clean, relatively inexpensive energy source could lead to impressive gains in productivity and standards of living.

Since nuclear reactors produce their power without combustion, a closed Brayton cycle can be used. There are numerous texts that describe the theoretical cycle in detail. I will concentrate on a proposed real system that shows some of the advantages of the cycle. The inherent flexibility of gas turbine design dictates that this is only one of an infinite number of variations on the concept. Figure 1 is a schematic representation of the proposed design.

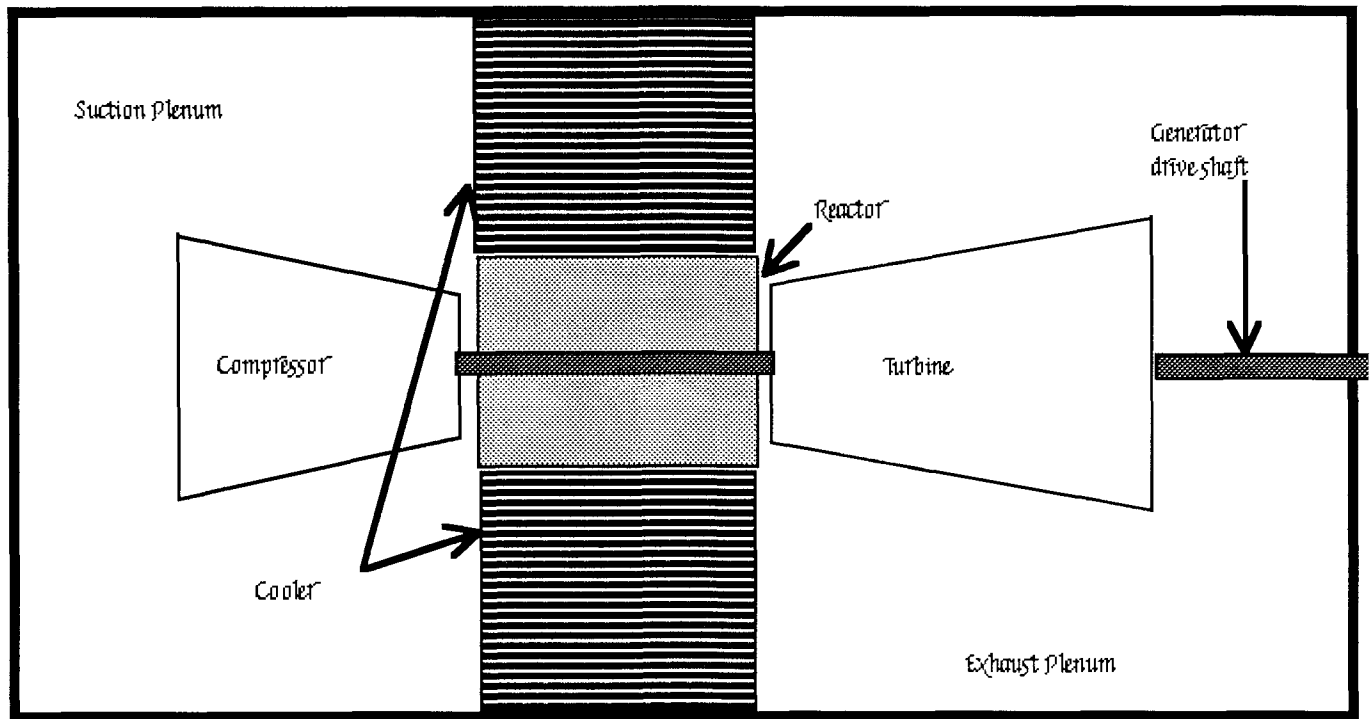


Figure 1

The helium would be compressed and forced through the channels inside the reactor where it would be heated. The hot, pressurized gas would then expand in the turbine and be exhausted into the exhaust plenum. It would then be drawn past the coolers by the suction of the compressor to start the cycle all over again. I have made choices that keep the cycle as simple as possible. I like systems that are inherently stable and require the lowest possible maintenance.

The enclosed volume is initially filled with helium gas at close to atmospheric pressure. Although atmospheric air could be

used, helium is chosen for a variety of reasons. It has a high specific heat transfer coefficient (approximately five times that of atmospheric air) which almost completely makes up for the fact that it has a low molecular weight (approximately one seventh that of atmospheric air). It has a low microscopic cross section for absorption of neutrons, preventing it from affecting the neutron population in the core and preventing it from becoming activated. This feature allows for a vastly reduced shielding weight over pressurized water or liquid metal designs since only the core itself would have to be shielded instead of having to shield large components like steam generators and pressurizers. It is an inert gas so it will prevent corrosion on the surfaces of the engine. It is stable and non flammable, unlike hydrogen which has some of the other beneficial characteristics. Finally, it is inexpensive enough to be used to fill children's balloons. I have chosen to keep the helium pressure low so that there is not a leakage problem and so that there is no need to construct a thick walled pressure vessel to contain the gas. If there is no way for the reactor coolant to leak, one of the greatest worries about current plant designs would be eliminated.

The core that I would use is one that has been designed to use high temperature helium gas as a primary loop in a steam plant. The core consists of numerous fuel rods that are made up of carbide and ceramic coated uranium pellets. These pellets are designed to withstand temperatures up to 2255 °K without melting.

The rods are slender in order to maximize the area available for heat transfer. In order to ensure that the temperature limit is never approached even under the worst case cooling conditions, the gas operating temperature is maintained at 960 °K.⁴

Sea water would be used in the coolers since it is an easily obtained heat sink for shipboard use. The sea water flow could be controlled through the use of variable speed pumps to regulate the inlet temperature to the compressor. This type of cooling system has been in widespread use for many years and the factors involved in its design are well known. Another interesting possibility would be using forced air flow across the enclosure. If the enclosure is made of a corrugated material with a high overall heat transfer coefficient, this would be well suited for land based systems.

A compressor and turbine system would be required which optimizes the performance of the system within the constraints imposed by the reactor core temperature and the assumed temperature of sea water. The selection would also be based on the required power output of the turbine system. I have chosen to require an output power of 30,000 shaft horsepower so that the design can be compared to the LM2500 gas turbines that now power over 100 ships in the US Navy.

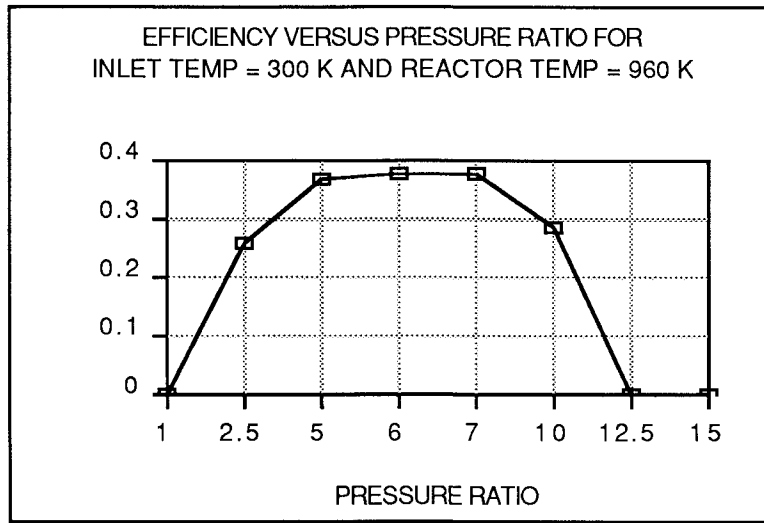
The calculations for the engine performance are straightforward. The equations to analyze the parameters of a

⁴Miller, P., "A Comeback for Nuclear Power? Our Electric Future", National Geographic, Vol 180 No.2, Aug 1991,p. 65

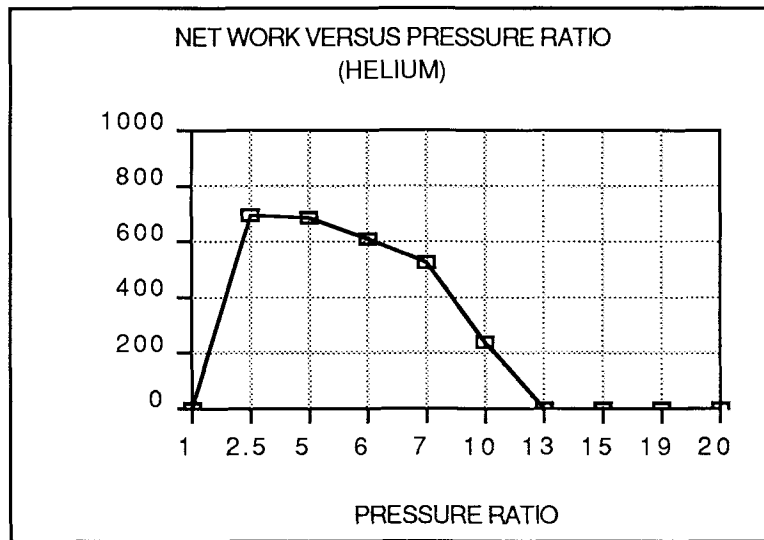
closed Brayton cycle system are available in many standard texts. Helium behaves as an ideal gas, so several simplifications that give good results can be used. The specific heat ratio (k) is assumed to be constant for the range of operating temperatures used. The constant pressure specific heat transfer coefficient (c_p) is considered to be constant.

Although individual calculations are simple, the design of an operating engine involves an iterative process. Changing one parameter (compression ratio, max temp, compressor inlet temperature, compressor efficiency or turbine efficiency) dramatically changes the performance of the engine. When texts discuss ideal Brayton cycles, simple statements about the relationship between pressure ratio and efficiency or max temperature and efficiency are made which are not necessarily so simple in the real world.

The first set of computations involved finding the correct pressure ratio for the compressor. In an ideal cycle, any increase in the pressure ratio would lead to an increase in the efficiency. With a real cycle where the peak cycle temperature is fixed by material constraints, a different result is obtained. The results of the calculation for an inlet temperature of 300°K and 960°K are shown in the below graph. (The assumed compressor efficiency is 90% and the turbine efficiency is 95%. The pressure drops in the reactor and in the cooler are ignored.)



For a real application, the pressure ratio for maximum efficiency is not necessarily the best choice since the power output is also important. The below graph shows the relationship between the pressure ratio and the net work. Assuming that the compressor can create a certain volumetric flow rate, the net work is proportional to the power output if the inlet pressure and temperature are held constant.



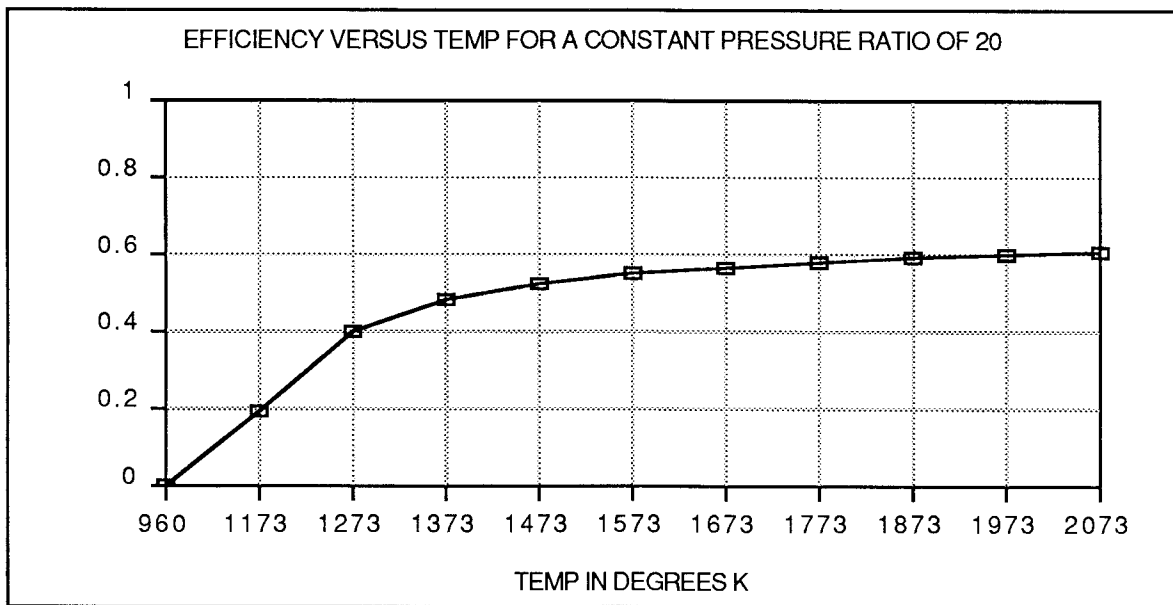
The peak in net work occurs at a lower pressure ratio than the peak in efficiency. However, that choice would lead to a big drop in cycle efficiency. By choosing a pressure ratio that is near the peak in both net work and efficiency, the engine performance can be optimized. It seems that the pressure ratio that gives the highest product of net work and efficiency would give the best results. For my engine design, I would chose a compression ratio of 5:1. Since the pressure rise per stage in real compressors is relatively constant, a low pressure ratio requires a compressor that has fewer stages. For comparison, if the same pressure rise per stage as the LM2500 is assumed (1.192), the compressor would have nine stages to perform its task instead of the 16 stages required in the LM2500. In fact, a simple, one stage centrifugal compressor could be used to produce a 5:1

pressure ratio.⁵

To give the power output equal to an LM2500, the engine would require a volumetric flow rate of 182 liters of helium per second. This is about three times the volumetric flow rate of an LM2500, but it is an easily achievable value. Since heat transfer is directly related to mass flow rate, some observers have suggested that the helium could be pressurized to reduce the required volumetric flow rate.⁶ I would shy away from this approach. The higher system pressures would require heavier boundaries or piping systems and would lead to questions about the safety of the system in the event of a leak. The predicted thermal efficiency of 38% compares favorably with the 36.7% of the standard navy engine. This efficiency is not a limiting efficiency, improved compressor and turbine efficiencies would improve it as would improved reactor materials that allowed higher core temperatures. Some proposed reactor designs already predict temperature limits on the order of 1500 - 2000 degrees K. With peak cycle temperatures this high, the engine efficiency would approach 60%. The below graph gives an illustration at a fixed pressure ratio that takes into account the compressor and turbine efficiencies.

⁵Saarlal, Mado, Steam and Gas Turbines for Marine Propulsion, Naval Institute Press, Annapolis, 1987. p. 141

⁶Gouge, Michael, "HTGR Gas Turbine Power Plant for Submarine Propulsion in the 21st Century", The Submarine Review, July 1991, pp. 86-90



Even though the efficiency is greatly improved over current designs, that is not reason enough to change the entire infrastructure devoted to producing pressurized water reactors. However, the fact that the design is comparatively simple, lightweight, and modular is reason enough to investigate making the switch. The necessary equipment is modern, but not exotic or complex. Many of the nuclear power truisms that are related more to pressurized water steam plants than to nuclear fission would be disproved.

The engines are not yet being produced, but they could be in a short period of time using existing technology. They would immediately reduce the burning of fossil fuels, eliminate the idea that nuclear power plants can never achieve efficiencies of better than 30%, provide an alternative to heavy, space consuming steam

plants in submarines and provide an alternative to surface ship power plants that burn on the order of 12,000 pounds of fuel per hour per engine. They would give utilities a way to produce clean, safe electricity for their customers in a way that would not bankrupt them. Even though there is a finite amount of potentially fissionable material in the world, that amount is extremely large. U-235 and Pu-239 are not the only elements that could be used. Unlike conventional nuclear plants, gas cooled reactors are well suited to breeding new fissionable materials and to using energetic neutrons to fission most transuranic elements. If the core is designed to consume most of the transuranics, even the waste problem is reduced from one of thousands of years to one of a couple hundred years. The technology is available, all that is needed is the will and a few dedicated dreamers.