NUCLEAR POWERED GAS TURBINES AN OLD IDEA WHOSE TIME HAS COME

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Abstract

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, rapid response to changing load conditions, independence from fuel supply uncertainities, small total plant volume, independence from oxygen, zero air pollution, relatively low thermal pollution, a high level of plant safety, relative ease of maintenance and operation, reduced long term radioactive waste and acceptable lifetime cost.

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 increase its 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.

The enabling technologies for this engine are modern, high temperature ceramic coated reactor fuels that can maintain fuel integrity even with temperatures of up to 2000°C[1] 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 engine does not need a complex recuperative or inter–cooled cycle for its impressive performance. 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.[2] 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.[3] Exploration for these materials has barely started. The enriched materials in decommissioned nuclear 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.

Much of the conventional wisdom about "nuclear power" is specific to particular plant designs rather than a more general knowledge about how nuclear reactions take place to produce energy in the form of heat. Nuclear power plants do not have to be huge monoliths with mushroom shaped cooling towers. Nuclear power has already been applied in sources as diverse as pacemaker batteries (about the size of a double A battery) that last for 10–15 years, power sources for distant space probes, and engines on board nuclear powered submarines, aircraft carriers and icebreakers.

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.[4] 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.

Historical perspective

The first successful application of nuclear fission for power production was the Nautilus project. This submarine program 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 the 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 devotion to pressurized water reactors was the combination of a gas cooled reactor within a 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.[5]

While Rickover was aware of these developments, he was determined to use mature technology in his program. Gas turbine engines were new and relatively untested. 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.[6] Not only did Rickover influence the course of Naval Nuclear Power, but, with his sponsorship of the Shippingport reactor plant, he established his design as the basis for commerical plants. The basic technology (water cooled and moderated reactors that either directly or indirectly produce steam for a turbine) has not changed in 40 years.

Political and Technological Change

During the 50 years since Fermi's atomic pile there have been considerable changes in technology and politics that affect nuclear power's future course. Reasonable and intelligent people have raised doubts about the current technology and its potential for disaster. Although the risk probability is extremely low, the potential consequences of an accident in a large water cooled plant are enormous.[7] Three Mile Island and Chernobyl convinced the world that the almost impossible can happen. The production of new commercial power plants has virtually stopped in the United States.

This has not eliminated the use of fission power because there are significant benefits that may outweigh the risks. Well run nuclear plants produce electricity at a considerable savings relative to even "cheap" oil or coal. Nuclear fission, unlike the combustion of any carbon based fuel, does not release carbon dioxide or any other pollutants into the atmosphere. There is a growing realization that the earth's atmosphere is a closed system that cannot continue to absorb the waste products of a busy human civilization.

Technology has improved since the days when the Air Force experimented with nuclear powered jet engines. Gas turbines have become a mature power source accumulating millions of hours operating experience and impressive records of reliability, while gas cooled reactors have been successfully operated in the United States and Germany in trial programs and in the United Kingdom on a large scale. The combination of these two technologies could provide a valuable answer to the problem of energy needs in the near term.

Technical Difficulties Associated with Current Plant Designs

The fuel for most reactors has been one of several forms of uranium oxide encased in corrosion resistant metal to isolate the fission products and to protect the fuel from the high temperature water used as coolant. Compared to many industrial materials, this fuel has a 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 the 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. Additionally, since a large decrease in the temperature of the coolant can cause a rapid increase in reactor power, systems and procedures have been developed to protect the core from an injection of cold water while operating.

Judging from nuclear power's amazing safety record, the engineering and training effort has been successful, but it has been costly and is getting reflected in the concern of the general public. Technology that produces intense fear even in a small portion of the population will not succeed in the marketplace.

Finally, the initial choice of low enriched fuel moderated by water to allow for fission by thermal neutrons has influenced the long term waste problem. While the isotopes produced from the fission of the uranium or plutonium will decay to a radioactivity below that of naturally occuring uranium in only 200 years, thermal reactors produce some elements whose half-lives are measured in thousands of years. These actinides are produced when U-238 absorbs a neutron and does not fission. In reactors that are designed to minimize the production of thermal neutrons, this process does not occur.[8]

Advantage of Technological Advances

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 mechanism for isolating 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 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 have a high degree of integrity even at extremely high temperatures and prevent the release of radioactive fission products to the environment. The pellets can be formed into either long thin rods or billiard ball sized spheres in order to be loaded into the reactor.[9]

The considerations for the core specifics are beyond the scope of this paper, but each form has been successfully tested in trial reactors in the United States, the spheres 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.[10] 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. Since helium does not slow down neutrons, the reactors can be designed to operate with fast or semi-fast neutrons to prevent the formation of long-lived actinides.

Gas turbine engines have proven to be a lightweight, compact means of converting the heat energy released from combustion of fossil fuels into mechanical energy. 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 the exhaust products of burning fossil fuel should be less susceptible to corrosion and erosion and should last longer.

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

* 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 the lower system pressure. This scheme is projected to give a nearly flat efficiency response over a wide range of power.[11]

* The engines can be designed for either liquid or dry cooling. Since there is no water required in the cycle, extremely cold ambient conditions will lead to improved efficiency instead of icing problems.

* Since the engines will have efficiencies that are higher than any current heat engines, thermal pollution will be less of a problem.

* There will be no need for frequent fuel deliveries and the purchase of additional fuel can be made in a stable market.

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.

* High quality manufacturing processes will replace much of the on site construction requirements. Large production runs will take the place of individually fitted piping systems.

* Instead of spending large sums of money for exhaust gas scrubbers that add nothing to the output of the power plant, the money could be spent for new plants that could produce less expensive energy.

* The cores can be designed with a strong negative temperature coefficient for stability and ease of operation.

* Unlike water, helium does not get activated in a neutron flux. Using it as the coolant and the working fluid will minimize the contamination of turbine and compressor parts. Modular construction and repair techniques will still be useable. Shielding requirements will be greatly reduced.

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 water cooled reactors has given us an enormous knowledge base relating to reactor physics, radiological controls, personnel training, and materials research. The expertise and the capital necessary exist to make commerically viable nuclear powered gas turbines in the near term. The effort would be an investment that could reap impressive rewards.

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