ENERGY CONVERSION - IMPROVEMENTS TO CONSERVE RESOURCES

by

W.W. Brandfon

Head
General Analytical Division
Sargent & Lundy, Engineers

Introduction

For years engineers have striven to raise the efficiency with which fuel energy is converted to other and more useful forms. The resulting benefits to society are many: increased efficiency means lower production costs for industry, lower prices for the consumer, and reduced pollution of air and water for everyone.

By and large the quest for increased efficiency has been successful, particularly in the electric power industry. In 1900 less than 5% of the energy in the fuel was converted to electricity. Today, this figure expressed in terms of thermal efficiency, is around 33%. The increase has been achieved largely by increasing the temperature of the steam entering the turbines and by building larger generating units. In 1910 the typical inlet temperature was 500°F; today the latest units take steam superheated to about 1000°F.

Figure 1 shows the amount of heat necessary to produce a kilowatt hour of electric energy plotted as a function of time since 1920. At that time the heat rate of the most efficient plant was about 20,000 Btu per kWh or approximately 17% net thermal efficiency. In the intervening 50 years, plant heat rates have dropped to as low as approximately 8500 Btu per kWh or close to 40% thermal efficiency for the most efficient coal fired power plants. As shown in this chart, the FPC projects that improvements in efficiency will be minimal up to the end of the century.

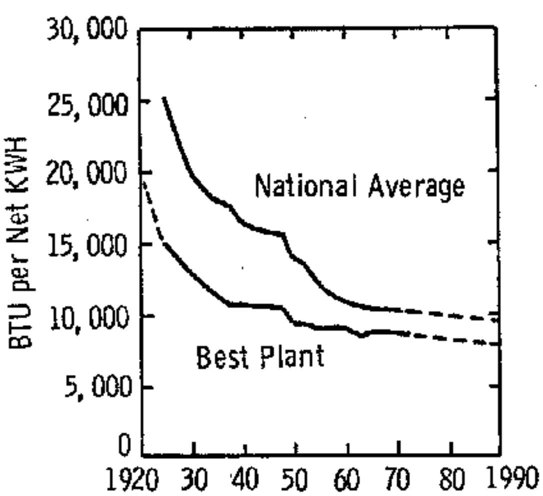

Figure 1 HEAT RATES OF FOSSIL-FUELED STEAM-ELECTRIC PLANTS

The limit has been the ability of available materials to withstand mechanical stress at high temperatures. Because of their massive size, enormous rotational stresses and very high steam temperatures and pressures, today's units operate at very close to the metallurgical and mechanical limits of the materials used in their construction. The difficulty of obtaining additional economic benefits and efficiencies within the present mode of generating concepts, and in addition recent developments in other technological areas have lead to consideration of alternate electric energy systems.

Most of these would eliminate intermediate energy transformation stages and the massive rotational stresses, whereby allowing the use of higher inlet temperatures and making possible the attainment of high overall efficiencies. And in these higher efficiencies lies our hope for conservation of this nation's large but finite fuel resources and the solution to what could become a continuing energy crisis.

The method of computing the maximum theoretical efficiency of a heat engine was set forth by a Frenchman, Sadi Carnot, in 1824. The maximum achievable efficiency is expressed by the difference in entering and leaving temperature of the fluid divided by the entering temperature where all temperatures are expressed in absolute degrees. Practical systems involve internal losses and therefore can only approach theoretical Carnot efficiency. Since all heat engines must ultimately exhaust to the ambient environment, efforts to improve the Carnot efficiency have been directed towards increasing the inlet temperatures. As previously indicated however, the ability of available materials to withstand mechanical stress at high temperatures has limited the efforts to improve the actual operating efficiency.

As shown in Figure 1, fossil fuel steam generating units being installed today have overall efficiencies of up to nearly 40%. Most nuclear power plants operate at lower efficiency because for safety and economic reasons present light water nuclear reactors can not be run as hot as boilers which burn fossil fuel. For the complete cycle of fuel to electricity the overall thermal efficiency of a water moderated and cooled nuclear power plant is somewhere in the vicinity of 30-33%. This means that about 70% of the energy in the fuel used by this type of nuclear plant becomes waste heat, which is released either into an adjacent body of water or, if cooling towers are used, into the surrounding air. For a fossil fuel plant the heat wasted in this way amounts to about 60% of the energy in the fuel.

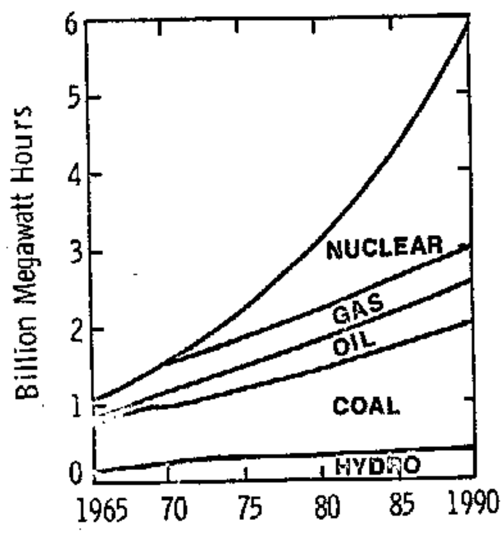

Figure 2 ESTIMATED ANNUAL ELECTRIC UTILITY GENERATION BY PRIMARY ENERGY SOURCES

In this paper, I will attempt to outline very briefly the principles currently used and some projected energy conversion systems which have among their objectives, the conservation of resources through improved efficiency or more optimum utilization. It is convenient to classify these new energy converters into those that may be feasible in the short or near term and those which we may see further out in time - possibly not until the next century. Some we may never see at all as commercial realities. These "near term" systems might include the high temperature gas cooled reactor, the liquid metal fast breeder reactor, and the high temperature gas steam turbine system.

In the category of "long term" systems we will discuss such exotic concepts as MHD, fusion, fuel cells, solar energy, and other forms of energy conversion which to date have progressed a relatively small way down the road towards commercial utilization and are, for the most part, fond hopes in the minds of visionary scientists throughout the World.

"Near Term" Concepts

Most authorities agree that the greatest increase in the generation of electricity will revolve around the utilization of nuclear fuel sources. Figure 2 shows the record between 1965 and 1970. The FPC projection out to 1990 is that while a larger increase in the additional load will be carried by nuclear, a substantial and increasing quantity of our nation's requirements for power will be satisfied with coal as a primary energy source.

HTGR Concept

The generating efficiency advancement

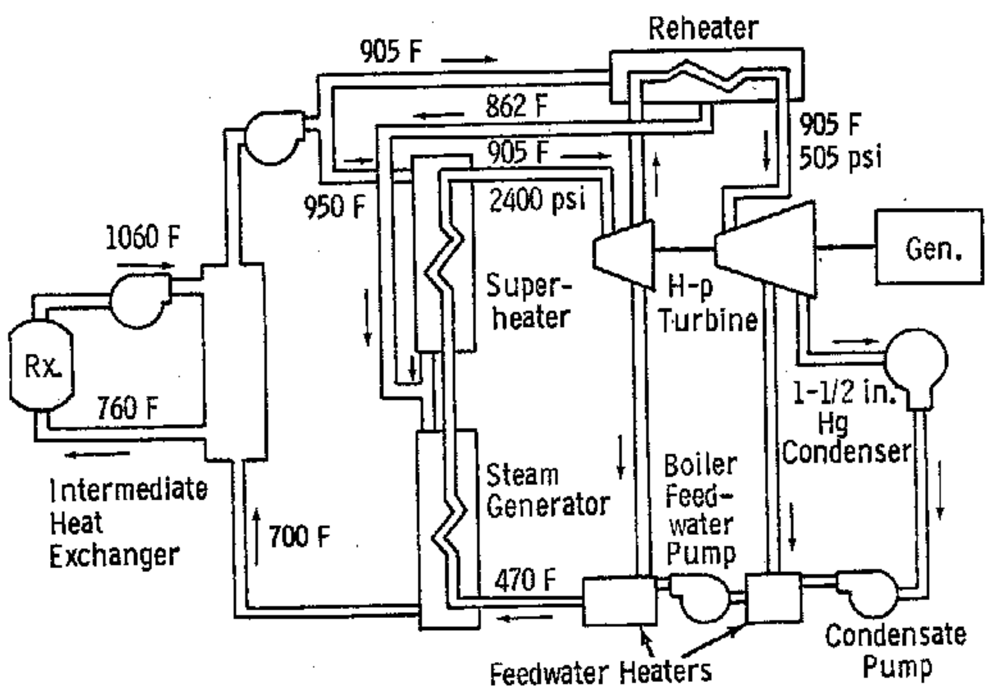

Figure 3

LIQUID METAL COOLED FAST BREEDER REACTOR

(ATOMICS INTERNATIONAL)

which is closest to us is the High Temperature Gas Cooled Reactor (HTGR) now being offered in this country by Gulf General Atomics. One 40 MWe electric unit has been in operation since 1966 at the Peachbottom Station of Philadelphia Electric Company. Another unit, Ft. St. Vrain, rated at 330 MWe, will be operated by the Public Service Company of Colorado. Construction is now complete and the unit is expected to commence commercial operation in 1973. To date Gulf General Atomics has sold eight high temperature gas cooled reactor systems as large as 1100 MWe and are bidding on others. They claim significant advantages for their system, in particular through the safety provided with the use of a prestressed concrete reactor vessel. Another advantage of the HTGR is its high thermal efficiency, approximately 40%. This results from the use of a conventional turbine cycle using pressures and temperatures equivalent to those used in modern fossil plants and compares with a thermal efficiency of about 33% from a light water reactor system, low fuel cost resulting from the use of a uranium-thorium fuel cycle and low sensitivity to the possibility of rising uranium prices.

LMFBR

The next concept which appears to be on the horizon and which could serve to conserve our fuel resources is the Liquid Metal Fast Breeder Reactor (LMFBR). The LMFBR obtains more energy from uranium by converting it to plutonium and then fissioning it. A gram of plutonium fissioned in a fast breeder reactor will provide approximately 50% more Btu's than would the same gram of plutonium if fissioned in a thermal neutron reactor. This occurs because of the greater efficiency of fission in the fast reactor which does not permit as much parasitic absorption of neutrons in plutonium as occurs in thermal reactors. Also, more uranium 238 is fissioned directly by fast neutrons in the fast reactor. In addition, since the LMFBR produces excess plutonium, that plutonium can be used to enrich fuel for the same or other uranium or thorium reactors. Because of its greater fissioning efficiency and its ability to utilize the otherwise useless uranium 238 and thorium, the LMFBR provides energy options which could greatly increase our fuel reserves.

Figure 3 shows the LMFBR system which is being developed by Atomics International. Liquid sodium is heated to above 1060°F in a primary loop and is used to transfer heat to a nonradioactive, secondary sodium loop in a sodium to sodium heat exchanger. Once through steam generators supply 900°F steam to the turbine. Other LMFBR developers are Westinghouse and General Electric. Recently a contract was signed between TVA and Commonwealth Edison whereby the two utilities would cooperate in a joint effort to produce a demonstration breeder reactor by 1980. The reactor will be approximately 400 MWe and be located on the TVA system. Specifications will soon be sent out to GE, Westinghouse and Atomics International for proposals to build the steam supply system, and selection of an architect engineer for the plant will probably also be made shortly.

High Temperature Gas Turbine Systems

If gas turbines can be developed to operate at extremely high temperatures in

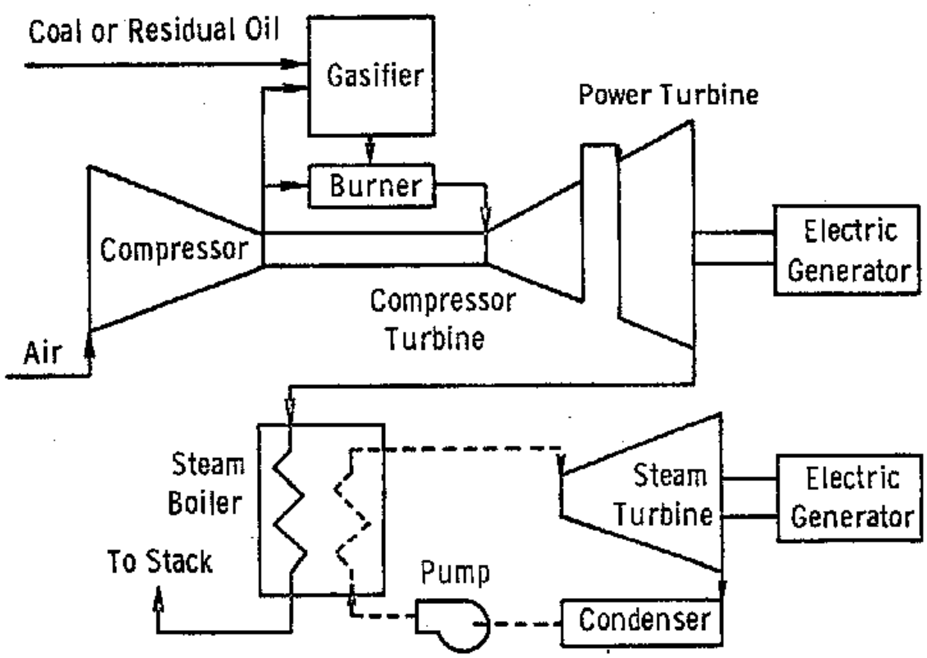

Figure 4 COMBINED GAS-STEAM TURBINE SYSTEM

conjunction with a waste heat steam boiler, the overall efficiency of the power plant could be greatly improved. One study of interest has been developed by United Aircraft Research Laboratories and involves gasification of high sulfur fuel to produce a low heating value fuel gas for use in a combined gas turbine and steam power systems. United Aircraft points to recent and prospective advances in military and commercial aircraft gas turbine technology which they say is applicable to industrial gas turbines. It will yield the high performance, low cost, and long lifetime characteristics desired for base load power generation.

Figure 4 shows a schematic of the power system proposed by United Aircraft. A gas turbine using a gasified coal fuel would exhaust into a waste heat recovery boiler. At the gas turbine inlet temperatures projected for use in this system, it has been determined that the most economical large scale steam system would operate at 2400 psig with 1000°F throttle steam and 1000°F reheat temperatures. Approximately 2/3 of the power would be generated by the gas turbine and 1/3 by the steam system. Proposed technology visualizes a 2200°F turbine inlet temperature and it could possibly be boosted to 3100°F to achieve thermal efficiencies approaching 60%. These high inlet temperatures could be extrapolations of technological advances in gas turbine blade material and blade cooling which would allow the turbine inlet temperatures to increase to the high levels indicated. Research and development engines have already attained turbine inlet temperatures approaching 3000°F. It is interesting that current commercial aircraft engines now operate at temperatures approaching 2400°F on takeoff and over 2000°F during cruise conditions. This increase in temperature is the result not only of better blade materials, but also improved cooling techniques. The actual limiting factor in turbine performance is the metal temperature of the turbine blade which determines the high temperature inlet characteristics. Proponents of this concept, set forth as the "COGAS" power system by United Aircraft Research Laboratories, also claim the advantage of reducing sulfur oxides, particulate and nitrogen oxide emissions and also of reducing or eliminating thermal pollution while serving to conserve our fossil fuel resources.

It should be pointed out however, that current experience with inlet temperature at about 1600°F have not yielded satisfactoril availability of gas turbines.

"Long Term" Concepts

The foregoing descriptions concern energy generation devices that may possibly be achievable before the end of the century. During the remainder of this paper I will discuss some long term improvements to conserve our nation's fuel resources. Some are still in the conceptual stage and several

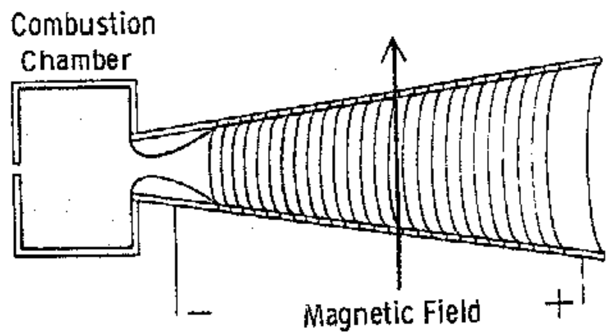

Figure 5
MAGNETOHYDRODYNAMIC TURBINE PRINCIPLE

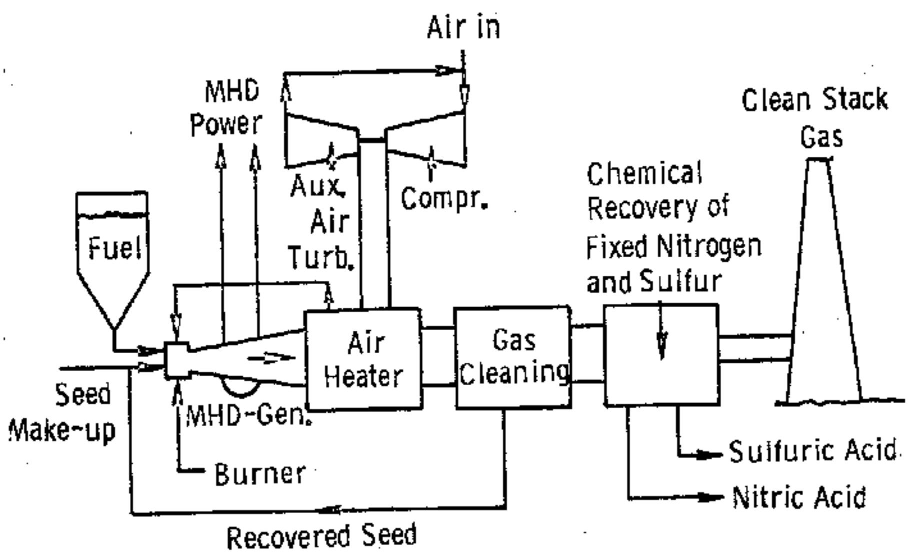

Figure 6 OPEN-CYCLE MHD GENERATION

are realizing limited success in small to moderately sized installations, notably geothermal generation and the fuel cell.

MHD

A possibility for central station application is MagnetoHydroDynamic Power Generation, or MHD. The principle is illustrated in Figure 5. It is accomplished by passing a hot ionized gas or liquid metal through a magnetic field. Substitution of the fluid conducting medium for the rotating metallic conductor of existing turbo-generators enables the utilization of high temperature (4000°F to 5000°F) one stage conversion devices which offer higher overall efficiencies. Though the concept of MHD generation has been known for over 100 years, it is only in the past decade that significant technological advancements have produced systems which offer promise for use in the commercial production of bulk power.

One approach to MHD generation is the open cycle MHD system. It is illustrated in Figure 6, and consists of a high temperature rocket like combustion chamber, a conduit to transmit hot ionized gas through a magnetic field and a high performance magnet to establish the necessary magnetic field. It employs a working gas produced by the combustion of fossil fuels and the addition of compounds (seeding) containing easily ionizable elements which are introduced to increase the electrical conductivity of the gas. The gas is released at very high velocities through the combustion chamber exhaust nozzle and passes through an MHD channel and magnetic field, introducing a DC voltage between electrodes embedded in the channel walls.

MHD open cycle generation, used as a topping unit in conjunction with present steam turbine generation appears to hold the most promise for central station power application. Utilizing the high temperature characteristics of MHD to increase inlet temperatures, and the MHD exhaust heat to supply steam for steam turbine generation, the overall system efficiency is expected to be increased to a range of 50% to 60% and could theoretically provide fuel savings of 20% to 30% over conventional fossil fuel steam electric plants.

Utility companies, manufacturers and research institutions in the United States have been actively involved in MHD investigations since the 1950's, with limited success. Several northeast utilities and the Edison Electric Institute are financing a program to develop an experimental power plant using a simplified liquid fuel MHD generator. The development of a prototype generator fired by clean liquid fuel is expected to produce some technology applicable to base load MHD units. Other work in MHD research is being sponsored by the Office of Coal Research

The Electric Research Council, comprised of representatives from private and public segments of the Electric Power Industry has recently established a task force to make a major review of MHD technology, keep the council advised of developments in MHD and recommend specific research where warranted.

In summary, the technique for generating electricity by moving liquids or gasses through magnetic fields rather than by means of turbines and rotating generators holds the hope of possible increases in power plant efficiencies with significantly lower discharge of heat to cooling waters and reduced emissions of sulfur and nitrous oxides to the atmosphere. Another important benefit could be a considerable extension of our coal reserve as an energy resource. Notwithstanding its great promise, however, MHD has been difficult to develop because of the very high temperatures required by the process, a need for a superconducting magnet, and the need for efficient regeneration of seed. The process requires recovery of the known efficient seeding media (like cesium) to be viable and this has not been made practical yet. There is also a great body of opinion in the US that feels that the MHD process is 25 years too late to be a help.

Fusion

Under very high temperatures, the nuclei of the lightest elements can be made to fuse to form heavier nuclei and in the process release enormous quantities of thermal energy. Controlled fusion offers the possibility of direct conversion of this thermal energy into electricity and an almost infinite source of energy. The sun is an example of natural fusion in which hydrogen is converted to helium and heavier elements. Deuterium, an isotope of hydrogen, is the essential fuel for each 6500 atoms of ordinary hydrogen, and deuterium can be extracted readily at relatively low cost. Thus the world's oceans represent a virtually inexhaustible potential source of fuel and the development of controlled fusion would provide an unlimited energy source. Unfortunately, the conditions necessary to control fusion reactions are extreme. Temperatures of hundreds of millions of degrees farenheit are necessary for the fusion of deuterium nuclei to take place. These temperatures can be created only in a plasma, and ionized mass of electrically charged atoms. Theoretically, sustained fusion, contained somehow in a magnetic field, could convert the energy of the charged particles directly to electrical energy by an interaction between the fluid plasma and the magnetic field. Figure 7 shows the principle of a thermonuclear reaction. Here the nuclei of light elements fuse into heavier elements with the release of energy. High velocity charged particles produced by a thermonuclear reaction might be trapped in such a way as to generate electricity directly.

The principal deterrent to the development of fusion consists of controlling the reaction at the tremedously high temperatures needed. Deuterium fusion occurs at about 500 million degrees fahrenheit. That is hotter than the interior of the sun. Recently a new way to control fusion has been discussed. It involves using high energy lasers to ignite small fuel pellets to fusion temperatures. The containment problem is unsolved,

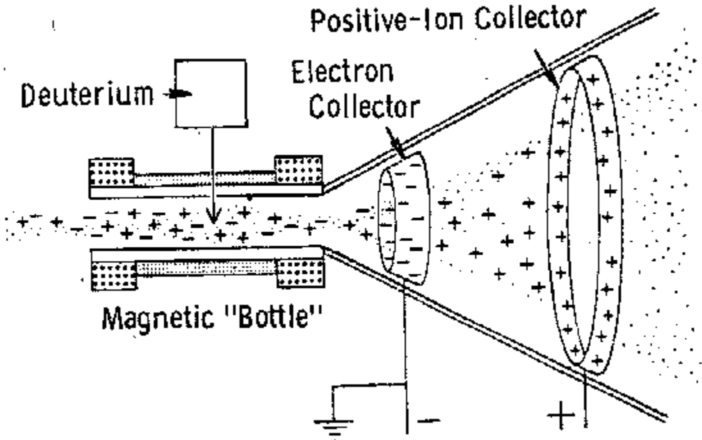

Figure 7 THERMONUCLEAR REACTOR PRINCIPLE

however, and scientists admit only "guarded optimism."

Figure 8 shows another type of fusion reactor plant called a DT or Deuterium-Tritium fusion reactor. This design includes a lithium blanket which acts as a neutron moderator and reacts with nuclear particles to produce tritium.

At present major fusion developmental programs are under way in Russia, the U.S., Great Britain, West Germany and France. Spending in the U.S. has totalled about $400,000,000 and some work is now being done in Princeton, Oak Ridge, Lawrence Livermore Labs, Los Alamos, and the University of Texas. In addition, Gulf General Atomics has done a considerable amount of development on fusion reactors.

According to Dr. Glenn Seaborg, former chairman of the U.S. Atomic Energy Commission,

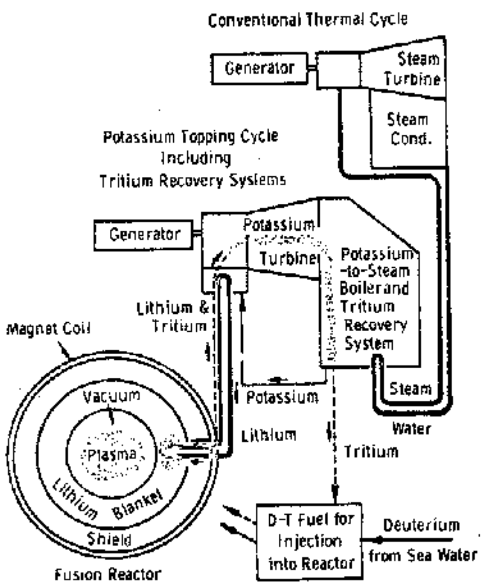

Figure 8 D-T FUSION POWER PLANT

the fusion reactor could have a theoretical efficiency of as high as 90% for a 1000 MWe unit. Small scale tests of the fusion concept are scheduled for the near future, but direct conversion of fusion energy must stil be considered as only a remote possibility.

Fuel Cells

A fuel cell, shown in principle in Figu 9, is a device that converts into electrical energy the chemical energy released from a reaction between a fuel and an oxidizer via an electrolytic medium. Because of the direct conversion of fusion efficiencies as high as 75% are deemed practical. Fuel cell are now in use in the space program which uses a low temperature converter to combine hydrogen and oxygen. The commercial version which could operate on fossil fuels, is a high temperature converter. The cost of suc an arrangement would have to be competitive with alternative power sources and will necessitate the use of the cheaper fossil fuel in high temperature cells. In general, high temperature models are designed to use a variety of impure and inexpensive fuels and air and are less prone to poisioning by sulfur compounds in the gasses produced.

Fossil fuels can usually be broken down, either inside or outside the cell, into a mixture of hydrogen and carbon monoxide and so the high temperature converter must be designed to operate with such a mixture in the presence of other impurities. Figure 9 indicates that fuel cells have the same basi elements as the battery - two electrodes called the anode and the cathode, separated by an electrolyte. In contrast to the batte however, the fuel cell is an open system which requires a continuous supply of reactants for the production of electricity.

Figure 10 shows a type of hydrogen-oxygen fuel cell in which these two elements ar supplied to the anode and cathode respective The hydrogen diffuses through the anode and reacts with an electrolyte, in this case, potassium hydroxide, and gives up electrons. These electrons leave the anode and pass through the external load to the oxygen elec trode (cathode). The hydrogen ions produce by the surrender of electrons move through the electrolyte to the cathode. At the cathode

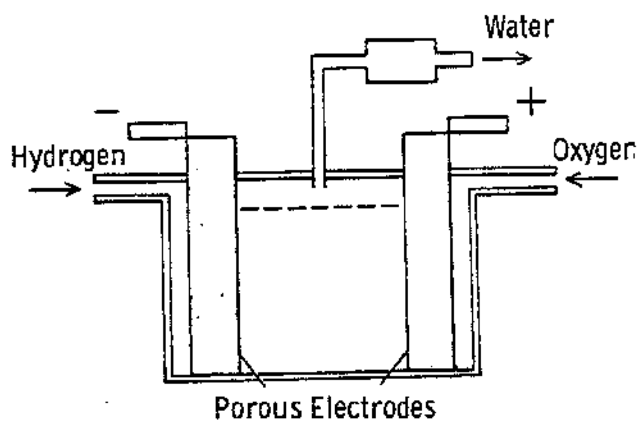

Figure 9 FUEL CELL PRINCIPLE

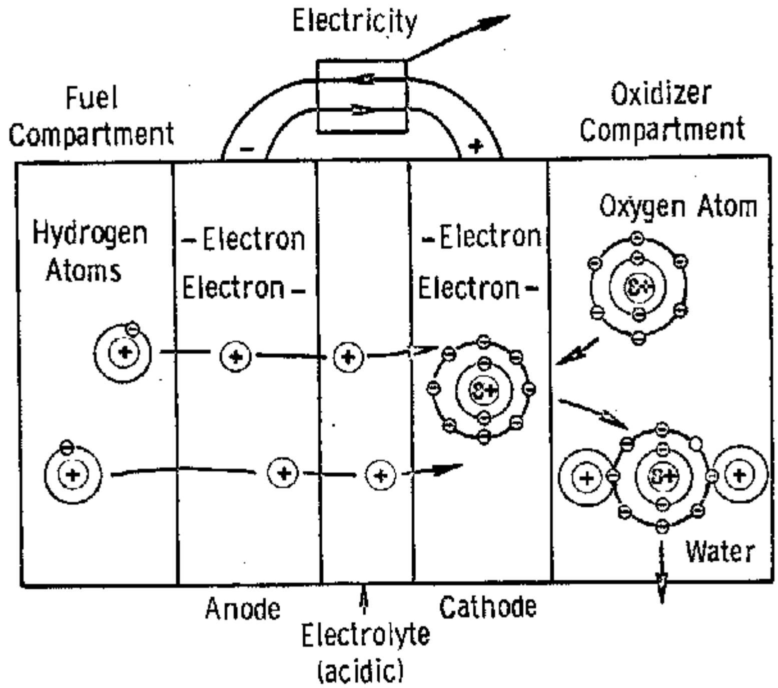

Figure 10 HYDROGEN-OXYGEN FUEL CELL

the hydrogen ions combine with oxygen and the electrons to produce water. In this process the water produced is a by-product and provisions are made for its separation and removal from the electrolyte. Electric current flows through the external load because the anode becomes negatively charged with respect to the cathode.

Fuel cells might be used to store energy during periods of off-peak demand and as generating units during periods of peak demand. In this way, they could be an alternative to pumped storage projects. Fuel cells are also being considered for use in substations where they would provide base load or peaking power to the existing electric power system. This could reduce the need for central station power and transmission lines and consequently reduce the effect of power generation on the environment. Most significantly, the fuel cell holds potential for future use in the transportation field where batteries are presently contemplated, and in the electrochemical industries where low voltage DC power is required. But the outlook for fuel cells in central station application appears remote at best, and extremely costly.

Solar Energy

An unconventional project that is currently under discussion is the possibility of the development of solar energy. NASA has recently awarded a six-month, $200,000 contract to A.D. Little, Inc., to explore the feasibility of using large satellites in orbit 22,000 miles above the earth's equator to beam down electrical energy for power needs on earth. This project proposes to provide earth with 5,000 MW of power and cost approximately $2.5 billion. It would include about 1,000 flights into space of a returnable shuttle to assemble the station in sections. As conceived, the space station would be dumb-bell shaped, with each end weighing about 12,000,000 lbs. The dumb-bells would contain gigantic mirrors to reflect sunlight into a huge panel of solar cells five miles across which would generate power and feed it into a microwave generator for transmission of a beam to earth.

A new type of proposed solar power plant is shown in Figure 11. In this plant sunlight falls on specially coated collectors, which raise the temperature of a liquid metal to 1,000°F. A heat exchanger transfers the heat collected to steam, which then turns a turbo-generator as in a conventional power plant. A salt reservoir holds enough heat to keep

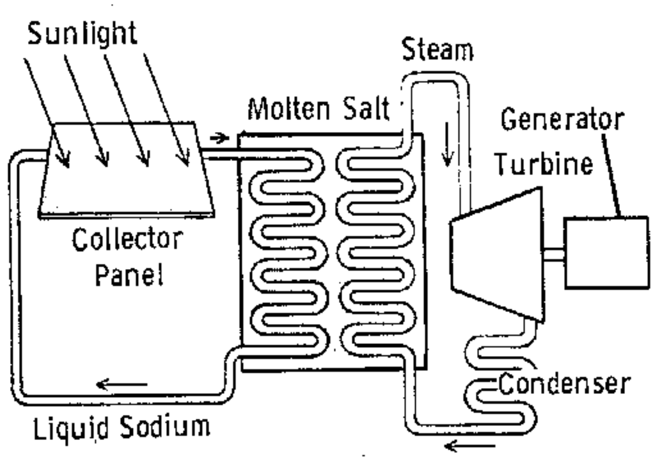

Figure 11 SOLAR ENERGY CYCLE

generating steam during the night, and when the sun is hidden by clouds.

Despite the extensive new interest in solar energy, both by its proponents and by environmentalists throughout the country, even the most enthusiastic solar energy buffs believe that such a station probably could not become a commercial reality before the end of the century.

Other "Long Term" Concepts

Many other exotic and novel forms of energy conversion have been proposed with varying amounts of enthusiastic support by the scientific world. Figure 12 shows the principle of thermionic generation. When a metal is heated, a point is reached where its electrons acquire enough energy to overcome retarding forces at the surface of the metal and escape. This boiling-off of electrons is the principle upon which the thermionic conversion device is based. Thermionic generation is possible with almost any heat source of sufficient temperature and units have been conceived using solar, nuclear and fossil fuels. In general, however, thermionic techniques have been oriented toward space activities, with relatively little effort being concentrated on central station power development.

The thermo-electric generator, shown in Figure 13, is a device which converts heat energy directly into low voltage direct current electricity. A voltage difference is produced between the ends of two joined dissimilar conductors when heat is applied. Usable amounts of electric power are produced by connecting several generators together for use as a single generating source.

Maximum efficiencies using thermo-electric generation, however, appear to be low and most applications have been in the space and military fields and in remote areas. Bell Laboratories is experimenting with a generator which operates at a power level of 160 watts and an efficiency of 2%. This unit is used as a power source for communications equipment in remote areas. It appears to be the consensus of most researchers that there is little promise in this concept for central station power plants in the foreseeable future.

Another source of energy may be the enormous heat within the earth itself. To date, geothermal energy has been developed for commercial use at only one site in the United States. This has been in Sonoma Count[y] California, and was built by Pacific Gas and Electric Company. PG&E expects to have over 600 MWe of geothermal capacity by the end of 1975. Despite the potential of this concept, the U.S. Geological Survey has pointed out that under favorable conditions, geotherm[al] energy may be locally important to several areas in the western states. It probably will be insignificant however, as a factor in future national power capacity.

There are other concepts which have been proposed and investigated with the objective of conserving the nation's resources and generating power more efficiently. Among such concepts are tidal energy, recovery of fuels from waste refuse, and recent studies sponsored by the White House Office of Scienc[e] and Technology. One would investigate a proposal to harness the winds, using windmills located ten or more miles offshore and fixed atop 150-foot steel towers rising from stationery floating platforms or anchored directly to the seabed of the Continental Shelf. These windmills, propelled by steady westerly winds that sweep over the Atlantic, could produce electricity that is used to convert ocean water into oxygen and hydrogen The hydrogen then would be shipped to shore where it could be combined in fuel cells wit[h] readily available oxygen to produce large amounts of electricity. Fresh water might

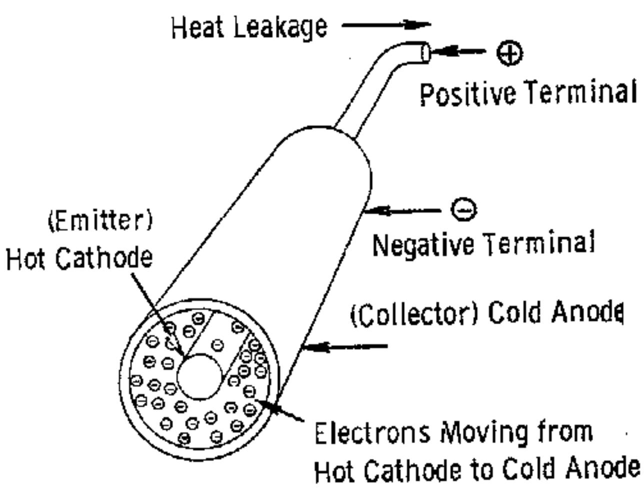

Figure 12 THERMIONIC CONVERTER

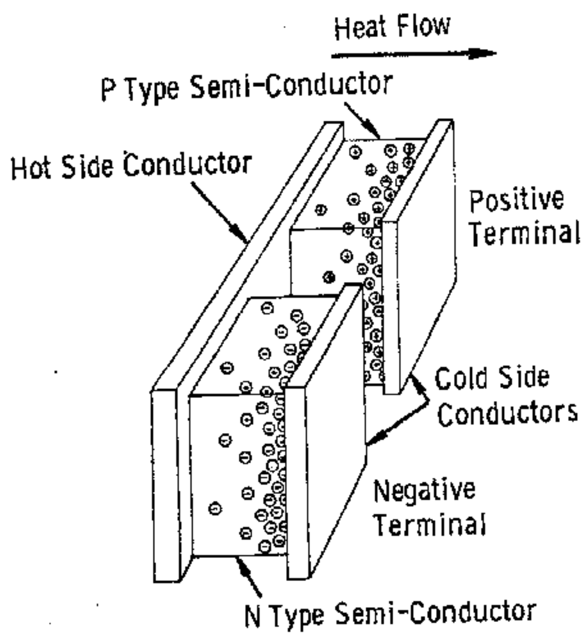

Figure 13 THERMOELECTRIC CONVERTER

be a by-product of this proposed process.

Still another scheme proposes the use of floating heat engines that are fed on one side by warm water from the Gulf Stream surface and on the other side by near freezing water piped upward from the seabed more than 1/2 mile below the surface. The thermal gradient between the two sources of water in the Gulf Stream would produce energy for driving of turbines for the production of electricity. As with the windmill proposal, the ocean-generated electricity would be used to produce hydrogen gas for combination in energy-producing fuel cells ashore.

Such is the scope of proposals which have been studied and which may or may not be further delved into. None of the plans that we have talked about for the long-range may be practical for central station application in the foreseeable future, but each possible way of obtaining energy, both conventional and unconventional by today's terms, is being assessed by scientists under the White House orders to seek new sources of energy. The range of possibilities - from the resources available today to the inexhaustible new forms that are only a hope is enormous.