26 Apr 1974

Prospects for Nuclear Fusion Power

William C. Gough

PROSPECTS FOR NUCLEAR FUSION POWER

William C. Gough
U.S. Atomic Energy Commission
Washington, D.C. 20545

ABSTRACTS

The prospects for fusion power are discussed including the need for fusion, its environmental advantages, and the research results that form the basis for present confidence that the program will succeed. The steps remaining before commercial fusion power will be available are outlined. Exploratory ideas for second generation fusion electric power plants, and non-electrical applications of fusion technology and reactors are briefly covered.

* * * *

The closest thing to a single solution for the world's many problems would be an unlimited supply of cheap, clean energy. The world could then feed and house its growing population, alleviate the mineral shortages that produce international tensions, clean up the long suffering environment, and enjoy a stupendous number of other benefits. [1]

The exciting thing is that cheap, clean energy is not an idle dream. Scientists right now are converging on the remaining technological obstacles that still keep us from this powerful solution to so many problems.

The source of this fantastic power is the process known as thermonuclear fusion. All of the stars, including our sun, create their vast energies by the fusion process. On earth, hydrogen bombs, which depend on fusion reactions, have convincingly demonstrated the potency of this source of energy, but many people do not realize that the same power that can be used for such horrifying destruction can equally well be used for human betterment.

Fusion does not depend on fossil fuels, which are limited and dwindling, but on fuels that are extremely abundant. Certain types (or isotopes) of hydrogen can be joined, or fused together, with a tremendous release of energy. For instance, the world as a whole has 8,300 Q of known and probable reserves of lithium, one likely fusion fuel when converted to the hydrogen isotope tritium. [2] Seawater contains another 21 million Q of lithium. Q is a unit of heat measurement equal to a billion billion BTU, or British Thermal Units. The entire world now consumes about a fifth of a Q each year. The situation is even more favorable when we consider deuterium, a hydrogen isotope that is also a fusion fuel. The oceans contain 7.5 billion Q of deuterium, enough to run the earth for billions of years. The procurement of deuterium from the oceans, where it occurs as one part in every 6500 parts of hydrogen, is comparatively easy and the water can be returned virtually unchanged to the oceans. Figure 1 summarizes this data.

ENERGY USE

	Q (10^{18} BTU)
U.S. ELECTRIC GENERATION	0.015
U.S. ENERGY CONSUMPTION	0.06
WORLD ENERGY CONSUMPTION	0.17
10^{10} PEOPLE AT U.S. PER CAPITA CONSUMPTION	2.9

FUSION ENERGY RESERVES

KNOWN AND INFERRED U.S. LITHIUM RESERVES	500
PROBABLE WORLD LITHIUM RESERVES	8,300
LITHIUM CONTENT OF SEA WATER	21,000,000
DEUTERIUM CONTENT OF SEA WATER	7,500,000,000

Figure 1

Fuel costs for fusion are almost completely negligible. Essentially every nation of the world possesses these fuels. Thus fusion would eliminate for all future generations what has been a major cause of international tension and wars; the conflicts over the energy resources that are essential for the survival of industrial societies. [3]

The fusion process is relatively clean in sharp contrast to the polluting combustion of fossil fuels. Fusion does not release carbon dioxide or other combustion products into the atmosphere and it does not burn the earth's oxygen or hydrocarbon resources, which could be used as raw materials for many chemicals if they were not burned for heat. The extraction of fusion fuels from the land or seas would present a negligible impact upon the environment.

Another important advantage of fusion is that no radioactive wastes are produced from the burning of the fuel, although radioactivity is produced in the structure of the plant due to the neutrons generated in most fusion fuel cycles. For a given fuel mixture, the extent of this induced radioactivity depends upon the structural materials used. This selection is up to the reactor designer, and studies have shown that the amount of this radioactivity can be kept relatively low. In addition, the plant must be carefully designed to prevent leakage of tritium fuel from the reactor. Tritium, however, is one of the least toxic radioactive materials. Some common fusion fuel cycles are given in Figure 3 as well as the reactions required to produce or "breed" tritium.

FUSION FUEL CYCLE

Reaction		IGNITION TEMPERATURE
$D + T \longrightarrow He^4 + n$	$+ 17.6$ Mev	50,000,000°C
$D + D \longrightarrow He^3 + n$	$+ 3.2$ Mev	300,000,000°C
$D + D \longrightarrow T + H$	$+ 4.0$ Mev	
$D + He^3 \longrightarrow He^4 + H$	$+ 18.3$ Mev	500,000,000°C
$H + Li^6 \longrightarrow He^3 + He^4$	$+ 4.0$ Mev	900,000,000°C

TRITIUM BREEDING

$n + Li^6 \longrightarrow T + He^4 + 4.8$ Mev

$n + Li^7 \longrightarrow T + He^4 + n - 2.5$ Mev

Figure 2

The fusion process is also remarkably safe. A fusion reactor is inherently incapable of a "runaway" accident. In fact, the fusioning hydrogen gas or "plasma" is so tenuous that there is never enough fuel present at any one time for a dangerous nuclear excursion to occur.

Since no solid material can exist at the temperature range required for a useful energy output from fusion (about 100 million degrees C) the principal emphasis has been on the use of magnetic fields to hold the hot gas or plasmas from the walls. These invisible magnetic fields are hundreds of times stronger than what people usually experience using a household magnet. Other methods such as the use of electrostatic fields or inertial confinement (as when a solid pellet is ignited to fusion temperatures by a high power laser) are also being researched. [4]

The first fusion reactors will very likely operate using the deuterium-tritium (D-T) fuel cycle since the plasma physics conditions are easier to achieve than in any other fusion fuel mixture. Figure 3 and 4 are conceptual designs of DT fusion reactors.

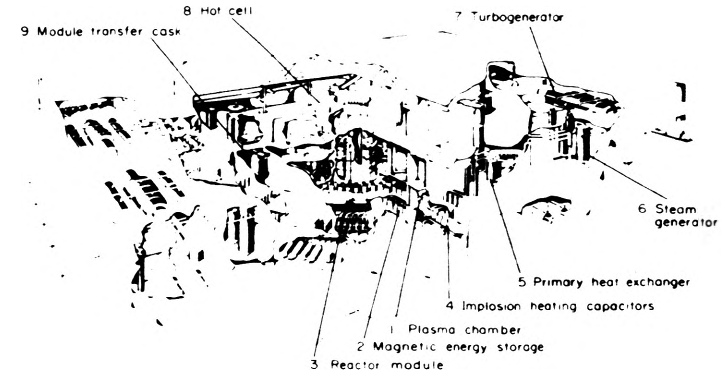

Figure 3—Conceptual design of a theta pinch fusion power plant done jointly by the Los Alamos Scientific Laboratory and the Argonne National Laboratory.

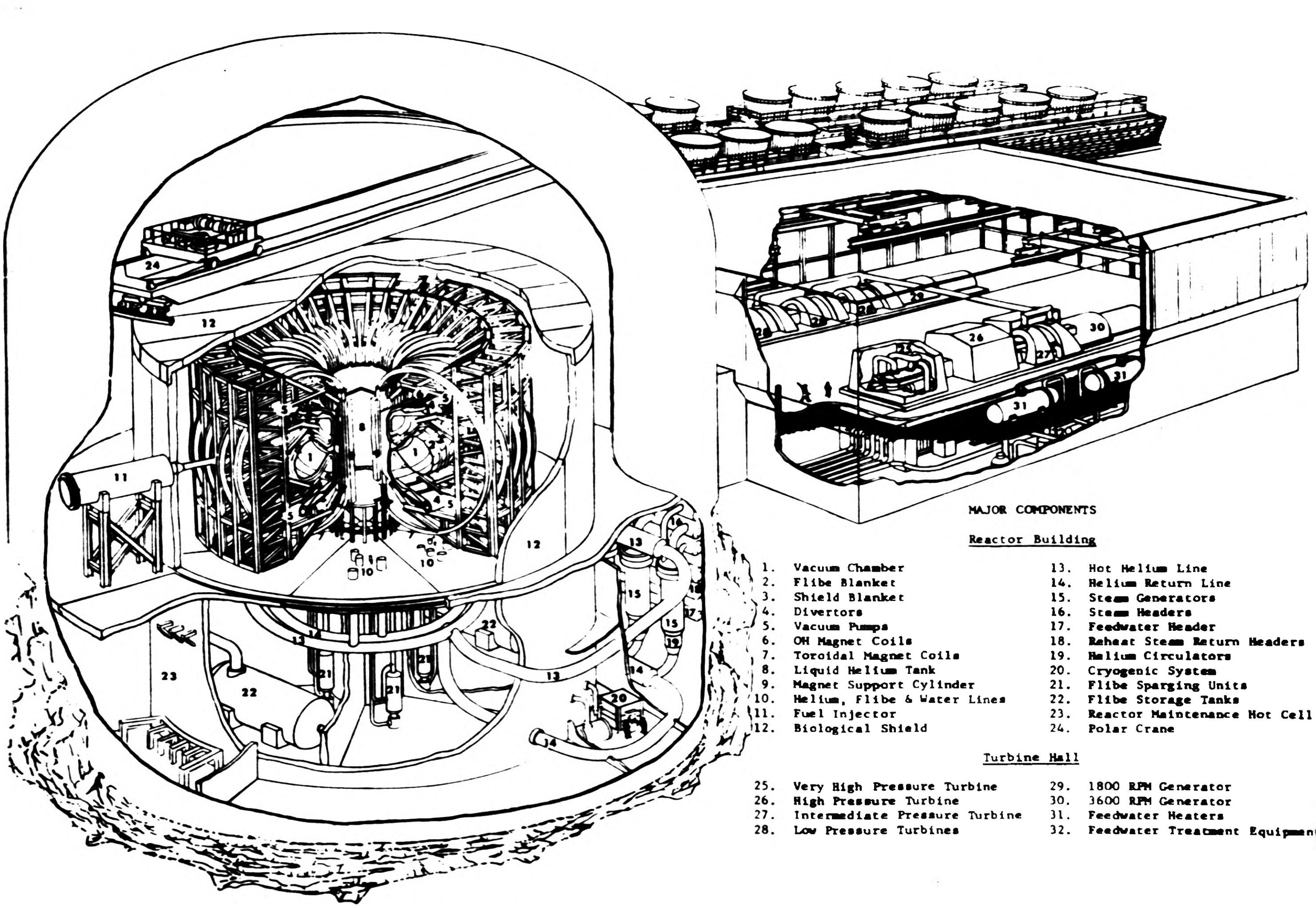

Figure 4—Conceptual design of a tokamak fusion power plant done by the Princeton University Plasma Physics Laboratory. 2,100 megawatts of electricity is produced at 40% efficiency.

The waste heat from such plants will about equal that produced in the most efficient fossil fuel or fast breeder power plants of similar size planned for the future. Figure 5 illustrates thermal energy conversion from a fusion reactor.

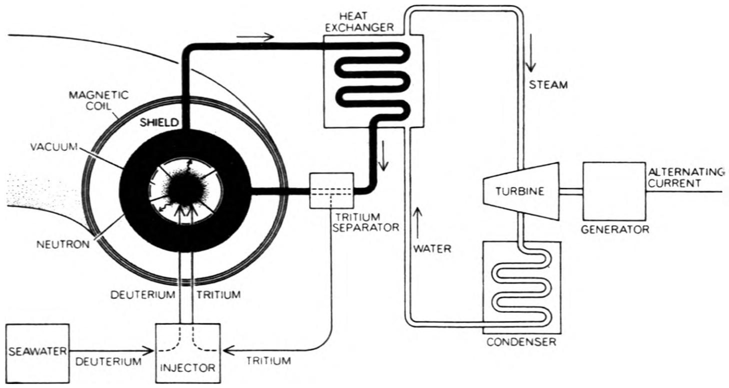

Figure 5—THERMAL ENERGY CONVERSION would be most effective in a fusion reactor based on a deuterium-tritium fuel cycle, since such a fuel would release approximately 80 percent of its energy in the form of highly energetic neutrons. The reactor could produce electricity absorbing the neutron energy in a liquid-lithium shield, circulating the liquid lithium to a heat exchanger and there heating water to produce steam and thus drive a conventional steam-generator plant. The reactor core could be either linear or toroidal. Alternately, helium could be used as coolant with the lithium in a solid compound. (From "Prospects of Fusion Power" by Gough and Eastlund. Copyright 1971 by Scientific Americas, Inc. All rights reserved.)

The environmental advantages and safety of fusion reactors may permit the siting of fusion power in urban areas where a good use could be found for the waste energy, such as the heating of buildings or the processing of sewage. As one moves towards the more advanced fusion fuel cycles the need for making tritium fuel from lithium in the reactor disappears and the number of neutrons produced progressively becomes less and less until it is insignificant.

As the fusion energy increasingly becomes available as charged particles rather than neutrons, the production of electricity directly from the ultra-high temperature fusion plasma at extremely high efficiencies becomes possible. Advanced fuel cycles and direct energy conversion are considered possibilities for second generation fusion reactors. At present, very limited work is underway on such possibilities due to the expensive and high risk nature of such research and development. Figure 6 illustrates direct energy conversion from a fusion reactor.

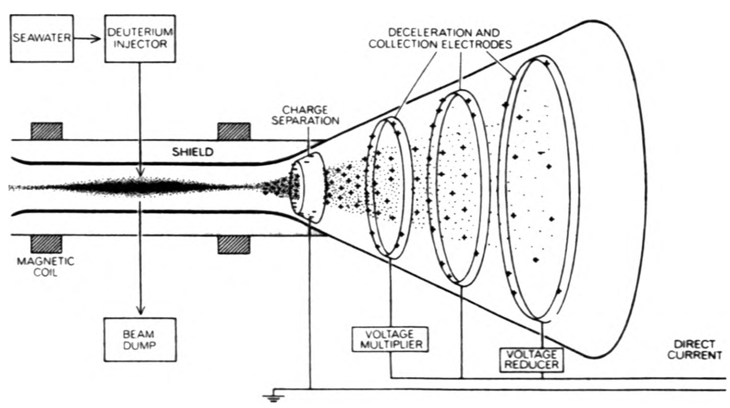

Figure 6—Direct energy conversion would be more suitable for fusion fuel cycles that release most of their energy in the form of charged particles. The energetic charged particles (primarily electrons, protons, and alpha particles) produced in the core of a linear fusion reactor would be released through diverging magnetic fields at the ends of the magnetic bottle, lowering the density of the plasma by a factor of as much as a million. A large electrically grounded collector plate would then be used to remove only the electrons. The positive reaction products (at energies in the vicinity of 400 kilovolts) would finally be collected on a series of high-voltage electrodes, resulting in a direct transfer of the kenetic energy of the particles to an external circuit. (From "Prospects of Fusion Power" by Gough and Eastlund, Copyright 1971 by Scientific American, Inc. All rights reserved.)

Over the last few years, the fusion program has entered a period of transition as we prepare to undertake the massive effort required to turn a laboratory research program into a major new energy source. Pictures of some fusion laboratory experiments are shown in Figures 7, 8, and 9.

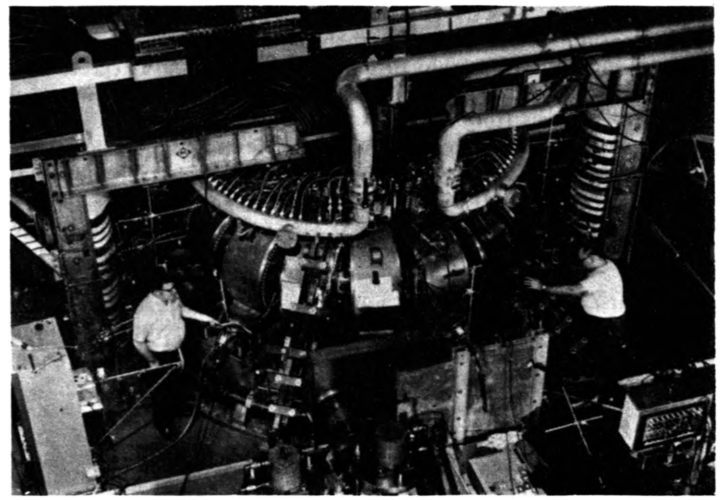

Figure 7—The Symmetric Tokamak (ST) at the Princeton University Plasma Physics Laboratory in New Jersey was the first tokamak in the United States.

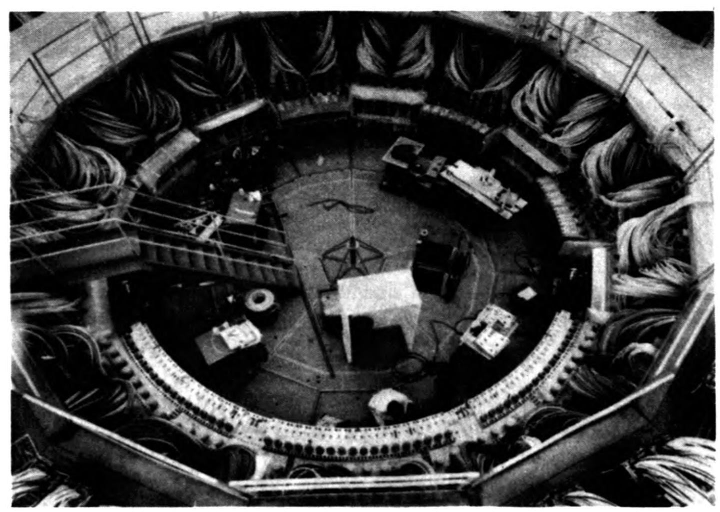

Figure 8—The Scyllac torus experiment at the Los Alamos Scientific Laboratory in New Mexico is a theta pinch device 25 meters in diameter.

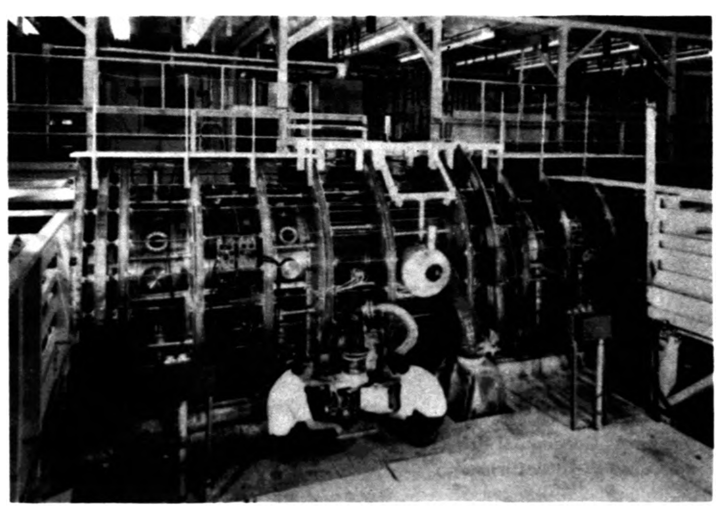

Figure 9—The 2X-II mirror experiment at the Lawrence Livermore Laboratory in California has produced plasma over 50,000,000 °.

In a day when people spend hours of their time waiting for energy at the local gas station, a natural question is when will the abundant cheap energy from fusion be available? Unfortunately, fusion will not be here in time to relieve the present energy crisis which results from having energy in the wrong form for existing technologies. You just can't burn rocks in your gas tanks even though we still have plenty of energy in the form of coal and uranium in the United States. The clearest warning for the present crisis came in 1970 when the rate at which we were finding domestic oil reserves failed, for the first time, to exceed the rate at which we were consuming oil. The current energy situation results from the inaction on the part of this nation to take anticipatory steps for example research and development work on coal gasification and liquification.

The present energy problems are a precursor to move serious but equally predictable future crises. Ones that will involve the closely interrelated questions of energy supplies, material availability, and environmental degradation. Plentiful fusion energy would be a major factor in averting a future crisis so that you and your children could experience a good standard of living in a healthful environment. The development of a major new technology like fusion energy is expensive and the lead time is long, yet it may be needed sooner than many people are willing to admit.

To appreciate the steps remaining before commercial fusion power will be available to you let us look back and see how far we have already progressed. The inception of the fusion power program was in 1952 over twenty years ago. The accomplishments to date have been significant. The technologies for creating and studying million degree plasmas were developed, a new field of physics for understanding fusion plasma has evolved, experts in this new field of physics are now graduating from American universities, the barriers that appeared to exist for achieving the temperature, densitites, confinement conditions necessary for a fusion reactor have all been broken in individual experiments, and recently fusion experiments with designs heavily dependent upon the new theories have operated as predicted. In fact, small amounts of fusion energy have been produced under controlled conditions in our laboratories—but far less than the amounts necessary to achieve net power. We now believe that there is no basic law of physics that keeps us from economic fusion power. Although many years of hard work have gone into these accomplishments, the cost to the American taxpayer has been less than the cost of a single moon shot.

Our next goal on the road to fusion power is to achieve all three of the essential fusion conditions—temperature, density, and confinement time—in a single experiment that produces net energy. There are many possible pitfalls ahead since physics and engineering uncertainties remain to be better understood. Yet we are confident that with adequate funding, solutions will be found to any problems that arise. We project that the much larger "energy breakeven" experiment will operate in the 1980-82 timeperiod. Recent analyses have indicated that by tailoring the plasma in the experiments in certain ways, "breakeven" conditions might be achieved in the late 1970's using the smaller experiments now under construction. An intensive effort to evaluate this possibility is now underway. [5] Figure 10 shows the "breakeven" plasma conditions for both the tailored "two component" case and the familiar Lawson criteria.

In addition to the plasma physics challenges that may lie ahead as we move towards fusion power conditions, extensive engineering developments must be carried out—for example in materials, superconducting magnets, plasma heating technology, neutronics, and tritium chemistry. [6] Such work will enable experimental fusion power reactors (20-100 million watts electrical) to be operated in the mid and late 1980's and a demonstrated fusion power reactor to be operated about the year 2000.

The engineering and materials development for these long lead time systems will cost billions. The Presidents' fiscal year 1975 budget request to Congress included a five year plan for the fusion program totaling $1.2 billion. A number of this magnitude needs to be put into perspective. For example, this amount is $200 million less than the cost of the new 2300 mega-watt electric power plant planned by Consumers Power Company for Quanicassee, Michigan. Even assuming a greatly reduced growth rate in the use of energy in the United States, more than 500 such nuclear fission power plants each as large and each at least as expensive will be needed by the year 2000. This is in addition to the large number of fossil fuel plants scheduled. The present budget of the AEC's Division of Controlled Thermonuclear Research is $56.8 million and it is anticipated that this budget will increase considerably next year.

The specialized manpower required for the initial stages of a rapidly expanding fusion program exist. There are now an estimated 1500 plasma physicists in the United States; the fusion power program employs only about 300. Engineers, chemists and physicists trained in the space, weapons and nuclear fission reactor programs have the necessary backgrounds to perform the projected tasks in fusion materials research, tritium studies, component development, and system engineering.

'BREAK-EVEN' PLASMA CONDITIONS FOR FUSION POWER

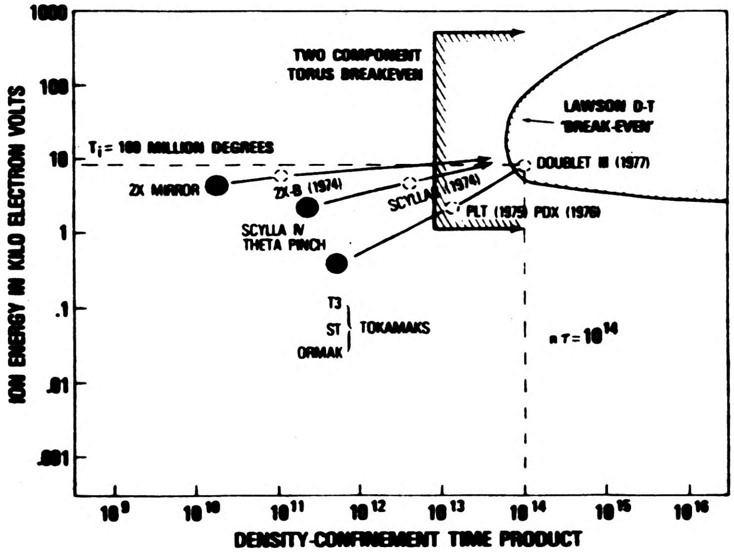

Figure 10

Fusion technology can do more than lead to a system for producing electricity. Fusion will also provide a unique means of producing large quantities of electromagnetic radiation, energetic charged particles, and high energy neutrons, which will yield important benefits to mankind. [7]

A strategy for a liveable long-term future might include:

1. A stabilized world population.
2. A closed materials economy where wastes are converted into new raw materials.
3. New industrial and agricultural processes, (including recycling) that avoid the undesirable byproducts resulting from today's widespread use of energy in the form of chemical compounds.
4. An abundant energy source that is highly compatible with the earth's environment.

Besides meeting need number 4 (abundant energy), fusion technology may help us to meet needs two and three by creating high temperature plasmas that are ideal for converting energy to forms that can be tailored to do specific jobs.

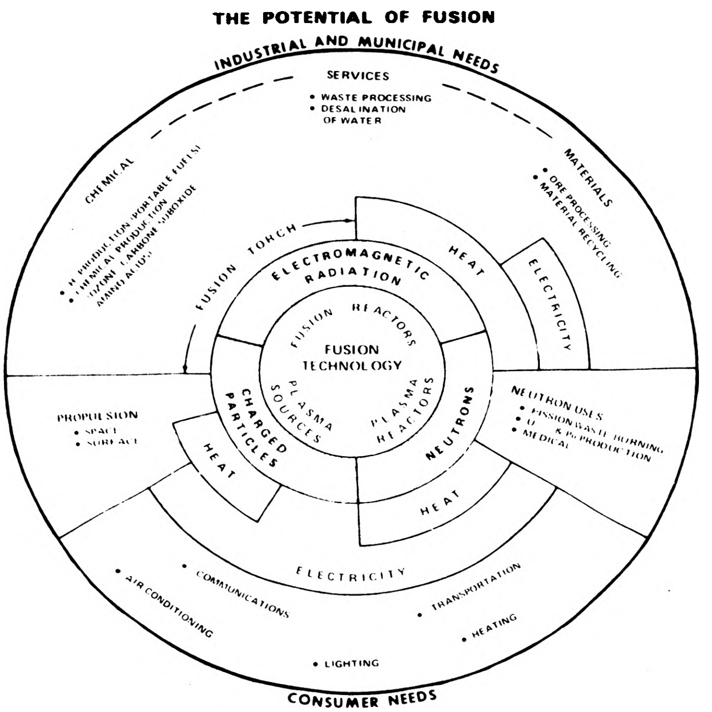

Figure 11—This chart suggests the many ways in which fusion technology will meet human needs. In the center of the wheel, three stages in the development of fusion technology are indicated:

1. *Plasma sources,* where little or no fusion energy is generated. This stage is approximately where scientists are now.
2. *Plasma reactors,* which operate at ultrahigh temperatures and produce fusion energy but no net power; that is, more energy has to be put into the system than can be taken out. This stage will be reached with the coming large-scale fusion experiments.
3. *Fusion reactors* producing net power. This is the goal of the current fusion power program. At this stage, a relatively small amount of power put into the system will generate a large amount of fusion power.

All three stages make available three primary forms of energy:
1. High-intensity radiation, ranging from X-rays through ultraviolet to infrared.
2. Ion and electron kinetic energy associated with the plasma.
3. High energy neutrons.

All three of these primary forms of energy can be converted to heat or electricity for many applications, or they can be used directly, as in the case of neutrons which burn up fission waste.

Recognizing the unique potential of fusion plasmas, my colleague, Dr. Bernard J. Eastlund, and I put forth the concept of the "fusion torch". [8] The general idea is to use the ultrahigh-temperature plasmas, quite possibly directly from the exhaust of a fusion reactor, to vaporize, dissociate and ionize any solid or liquid material. [9]

The fusion torch might eventually make possible the steady-state economy, in which all wastes become raw materials for new products. More immediately, such techniques offer the possibility of processing low-grade mineral ores or producing portable liquid fuels by means of the plasma system.

The fusion torch could be used to transform the kinetic energy of a plasma into ultraviolet radiation or X-rays by the injection of trace amounts of heavy atoms into the plasma. The large quantities of electromagnetic energy generated in this way could be used for many purposes desalting seawater, heat, and producing hydrogen. Such new industrial processes should be less likely to pollute the environment than traditional methods. Industrial processes based upon fusion technology are just starting to emerge and could come into widespread use during the next ten years.

Fusion reactors operating on deuterium-tritium fuel would produce large quantities of neutrons. Although one usually thinks of moving directly from nuclear fission reactors to pure fusion reactors, we could possibly move through a stage where fusion-fission are combined in a single system to form a hybrid reactor. [10] Such systems involve the coupling of neutrons from fusion reactors with nuclei of uranium or thorium to produce a multiplication of energy and thus less stringent conditions for net power. In addition to generating electricity, the hybrid could provide fissionable material for existing nuclear fission power reactors during the years when pure fission power is phasing into our total energy producing system. Another use for the neutrons from fusion would be to reduce the problem of fission wastes. From recent studies it appears that fusion reactors can potentially transmute most of the high level wastes from a fission economy into stable or short half-lived ash. However, the problem is extremely difficult and it will require considerable effort to assess fully the practicality of these ideas." [11]

The fusion program in the United States involves government laboratories, private industry, and universities. In addition to the federal government, the public utilities are now funding a small but growing program in fusion research. The U.S. fusion program represents about one fifth of a close cooperative worldwide endeavor to meet a major problem of mankind. The world fusion effort can be divided into four parts—the largest is in the Soviet Union, followed by Euratom nations, then the United States and finally the rest of the world (principally Japan, Sweden, Australia and Canada). The cooperative nature of this program has been spearheaded by world conferences sponsored by the U.N.'s International Atomic Energy Agency. An expanded exchange of U.S. and Soviet scientists to work in each others' laboratories is now being undertaken to augment the already extensive mutual exchanges that exist between the U.S. and western nations. One can envision the time when space communications technologies are used to accelerate the world fusion power effort. This could be accomplished by connecting via satellite the twenty major world fusion centers so that remote terminals in all laboratories would have access to central fast computers and TV communications would link the top world fusion scientists so they could interact directly, continually and quickly. In the United States next year we have planned a large computer facility with interconnecting links to all major U.S. fusion laboratories.

There is no substitute for energy—you must have it to be a strong person, a strong nation, or a strong and healthy world. Indeed energy is a weapon, as increasing numbers of persons are beginning to realize—and fusion energy is truly a weapon for world peace and betterment.

REFERENCES

1. William C. Gough, and B. J. Eastlund, "The Prospects of Fusion Power", *Scientific American,* Vol. 224, No. 2, (February, 1971).

2. *Controlled Thermonuclear Research*—Part I&II, Congressional Hearings (Subcommittee on Research, Development, and Radiation of the Joint Committee on Atomic Energy) Nov. 10-11, 1971, (U.S. Government Printing Office, Washington, D.C. 1972).

3. William C. Gough, *Why Fusion,* WASH 1165, (U.S. Government Printing Office, Washington, D.C., June 1970).

4. William C. Gough, "CTR Engineering Systems Study Review Meeting," AEC Headquarters, Germantown, Maryland, September 19 and 20, 1973, WASH-1278.

5. Robert L. Hirsch, "Fusion Power Research and Development: The Scene Today" paper presented at the 140th Meeting of the American Association for the Advancement of Science, San Francisco, California, Feb. 24 - March 1, 1974.

6. "Technology of Controlled Thermonuclear Fusion Experiments and the Engineering Aspects of Fusion Reactors", proceedings of conference held at the University of Texas, Austin, November 1972, AEC Report No. CONF-721111.

7. William C. Gough, "The Promise of Fusion Power," *The Futurist*, Volume VII, No. 5, October 1973.

8. Bernard J. Eastlund and William C. Gough, "The Fusion Torch–Closing the Cycle from Use to Revise," U.S.A.E.C. Report WASH-1132, May 15, 1969.

9. Zeinab A. Sabri, Design of a Fusion Reactor–Torch System; *IEEE Trans on Plasma Science*, April 1974 to be published.

10. B. R. Leonard, Jr., "A Review of Fusion-Fission (Hybrid) Concepts", *Nuclear Technology*, Vol. 20, Dec. 1974.

11. W. C. Wolkenhauer, B. R. Leonard, Jr., and B. F. Gore, "Transmutation of High-Level Radioactive Waste with a Controlled Thermonuclear Reactor," Battelle Pacific Northwest Laboratories Report BNWL-1772, Sept. 1973.