ENGINEERING OF THERMONUCLEAR POWER PLANTS*

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STATUS OF FULL-SCALE FUSION REACTOR POWER PLANT STUDIES

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Introduction

The difficult plasma physics problems have almost completely dominated the thermonuclear reactor program all over the world. Only in the past few years, and then only in a small way, has there been any effort to evolve a conceptual design for a full-scale fusion reactor plant. Typical studies made in the United Kingdom,¹ the U.S.S.R.,² and the U.S.A.³ indicate that the engineering problems, although difficult, appear tractable if favorable solutions can be found to the plasma physics problems. It must be emphasized that no firm design could possibly be worked out at this time. The purpose of these design studies has been to provide a basis for attempts to answer some basic questions such as -- if we can obtain a stable plasma, can one build the cryogenic magnets required to confine it at a reasonable cost? What new technology would be required and what would be the cost of the development program for that technology? What is the point in developing such a power plant -- are its advantages sufficient to justify the cost of the whole development program? What are the environmental implications of a fusion reactor complex?

Typical Conceptual Design

In an effort to answer these questions several conceptual designs have been evolved. One of these that appears to be well suited for use with either the magnetic mirror or the toroidal type of magnetically confined plasma will serve to illustrate the problems involved and a set of possible solutions. Further, it will indicate some of the many points in common

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which fusion reactors have with fission reactors as well as major differences. From this we can surmise something of the time and cost required to develop a prototype fusion reactor if and when reasonable solutions are found to the plasma physics problems.

To illustrate the problems, the D-T (deuterium-tritium) fusion reaction is assumed. The plasma temperature required for the D-T reaction is roughly one-tenth that for the D-D or D-³He reactions, and hence it appears less difficult to obtain a suitable plasma with the D-T reaction. On the other hand other fuel cycles have certain advantages, for example, the D-D cycle has the advantage that it does not make it necessary to breed. Although the D-T reaction requires fueling with tritium and yields a very penetrating 14 MeV neutron, both the D-D and the D-³He reactions are accompanied by reactions that generate both tritium and neutrons. Thus in any case the fuel cycle will entail handling material containing a substantial fraction of tritium, and the rate of emission of 14 MeV neutrons will be at least one-tenth that for a D-T plasma.⁴ D-D and D-³He reactions could lead to radiation damage effects and structural activation within a factor of 2 of the corresponding values for the D-T fuel cycle.

It should be noted that the use of a pulsed system such as a θ -pinch or a laser-ignited pellet device raises difficult stress, metal fatigue, energy storage, and other special problems peculiar to those systems^{5,6} and time does not permit going into these. The pulsed systems, however, appear to give less difficult problems with fueling and ash removal.

Figure 1 shows a cross section through the magnet and plasma region of a magnetic mirror or toroidal type of fusion reactor. Note that in the center we have a plasma at a temperature of hundreds of millions of degrees Fahrenheit, a vacuum wall that encloses a liquid lithium blanket region which operates at somewhere between 1000 and 2000°F (i.e., at or above the fuel temperature of an IMFRR), then some thermal insulation, a water-cooled shield region which operates at perhaps 200 or 300°F, and finally a cryogenically-cooled superconducting magnet which would operate at -453°F. Thus we have nearly as extreme a set of temperature conditions as man can produce. This drawing also indicates something of the whole complex of difficult design conditions that must be satisfied if one is to have a commercially viable fusion reactor. One of these, for example, is

Fig. 1. A Representative Fusion Reactor

the requirement that we interpose about 6 ft of blanket and shielding material between the plasma and the cryogenic magnets in order to protect them from radiation heating. This in turn means that, to keep the magnet costs in dollars per kilowatt to a reasonable level, the useful volume in the plasma region should be a large fraction of the total volume enclosed by the magnets. Thus we must go to a large machine, that is, a plasma region with a minor diameter of perhaps 16 ft and a cryogenic magnet diameter of around 30 ft. This in turn means that, if we build a toroidal type of machine, the overall diameter of the doughnut will have to be over 100 ft. As a consequence, the minimum size of an economically attractive machine of this type appears to be quite large with a power output something like 500 to 1000 MW(e).

A large diameter for the plasma region is beneficial from the standpoint of the plasma physics. A diameter of only 5 or 10 ft might prove acceptable, but a larger diameter will reduce losses to the walls.

If the thermonuclear reactor makes use of a deuterium-tritium fusion reaction, it is essential that the reactor be designed to breed tritium. This in turn has led to the use of a lithium blanket surrounding the plasma so that the neutrons emitted by the fusion reactions are slowed down and absorbed in such a way as to produce more tritium than would be consumed in the fusion reaction.⁷ Fortunately, it has been found that, with the sort of lithium blanket contemplated in Fig. 1, it should be possible to operate with a tritium inventory of only 1 to 10 kg and get a good breeding ratio so that the doubling time for the tritium may be as little as a month. In short, it appears much easier to breed tritium in a fusion reactor of this type than it is to breed fissionable material in a fission breeder reactor.

The use of the lithium blanket does raise problems, however, in that metallic lithium, the most attractive material for breeding tritium, is compatible with only a few structural materials. Stainless steel could be used, but it is subject to corrosion by lithium if the temperature is raised above about 900°F. As will be discussed later, there is a very strong incentive to employ higher temperatures in order to improve the thermal efficiency of the power plant and reduce the amount of waste heat that would have to be rejected from the thermodynamic cycle. With niobium

it would be possible to operate at much higher temperatures, and this would make it possible to reduce the waste heat to less than half the amount currently rejected from the best fossil fuel-fired plants. Fortunately, the program for nuclear electrical power sources for space applications has nicely validated the use of lithium in niobium at temperatures up to 2200°F.⁸ Further, work for the Air Force at Battelle on structures suitable for hypersonic aircraft has led to the rolling of niobium sheets in 3 ft widths and the fabrication of these sheets into shell structures suitable for aircraft wings and fuselages.⁹ As a consequence, the feasibility of fabricating niobium into the type of structure shown in Fig. 1 has been demonstrated, although it is clear that structures of this type will be expensive and will require stringent quality control measures.

Another major problem associated with the blanket region is radiation damage to the vacuum wall.⁷ This problem may be more severe than the radiation damage problem in a fast breeder reactor because in this instance we would like to have the vacuum wall last for 20 years to avoid replacing large radioactive parts, whereas in the fast breeder reactor the relatively small fuel elements would be replaced at intervals of a year or less. The extensive radiation damage work currently underway in the Fast Breeder Reactor program will prove enormously helpful to the fusion reactor effort, but additional work will be required because the initial neutron energy in fission reactors is only 1 or 2 MeV whereas in fusion reactors it is about 14 MeV. This may induce radiation damage mechanisms that we have not yet been able to envision. As a consequence of these uncertainties it may be necessary to employ a relatively low power density, and this appears feasible although it does yield a higher capital cost.

The huge superconducting magnets with cryogenic cooling for a reactor of the type represented in Fig. 1 present a new and difficult set of problems peculiar to fusion reactors. These magnet rings are over twice as large as the largest built to date (that for the hydrogen bubble chamber at Argonne), and will present some very difficult fabrication problems. In addition, the magnetic forces acting on these coils are of the order of 10,000 tons and pose extremely difficult structural problems. These problems have appeared so difficult as to raise questions as to whether an economically interesting solution could be achieved. Several recent

studies^{10,11} indicate that, while these magnets will indeed be expensive, the capital cost per kilowatt of electrical output for a large fusion reactor will be acceptable, i.e., \$60/kW(e).

At first thought it appeared that the cryogenic refrigeration system required for the superconducting magnets would be terribly expensive. Fortunately some similar refrigeration systems built under the space program provide a firm basis for estimating the floor space requirements and cost of such systems. For example, the 65 ft diameter, 125 ft high space chamber at the NASA Manned Space Flight Laboratory at Houston employs a cryogenic refrigeration system whose capacity would be adequate for cooling the cryogenic magnets of a 500 MW(e) fusion reactor for about \$2,000,000.¹²

The conceptual design of Fig. 1 does not show any means for coping with two major plasma physics problems of fusion reactors; namely, provisions for fuel injection and heating on the one hand and removal of unburned plasma on the other. Several methods for fuel injection and heating to the required plasma temperature have been proposed, and some of these look promising, but it is difficult to tell at this stage whether any of these would be suitable for an economically attractive plant. The problems presented by unburned plasma removal appear to be even more difficult in toroidal machines, whereas in magnetic mirror machines the problem appears to be one of excessive losses out through the end regions. Some sort of a divertor or pumping will be required to remove a portion of the plasma continuously from the toroidal machines. In either type the helium would then be removed from the unburned deuterium and tritium, and the latter would be recycled while the helium would be a useful by-product. A few arrangements for divertors have been proposed, but it is not clear that any of these can be incorporated in an engineered design that would satisfy all of the requirements for a sound, reliable, economical, commercial power plant. This points up the fact that not just one but several scientific advances will be required before one can design a prototype thermonuclear power plant. That is, it will not be sufficient to get a stable plasma; it will also be necessary to get a satisfactory system for fuel injection and heating as well as a satisfactory system for removal of unburned plasma, and these must be of a character such that they will fit into an economically attractive engineered design.

If one turns from the reactor proper to the rest of the plant, there appear to be a number of reasonably straightforward ways in which the heat energy developed in the blanket region can be employed to produce electricity. If the blanket region is made of stainless steel and cooled with lithium at about 900°F, it would be possible to raise steam at perhaps 800°F to drive a conventional steam power plant and obtain an overall thermal efficiency about equal to the 40% of the best fossil fuel plants. The steam generator could be similar to that for an IMFBR, and the rest of the steam plant would be conventional. A second approach would be to employ the heat in a gas turbine cycle, in which case there would be a strong incentive to make use of a high temperature blanket region to obtain a good thermal efficiency. Commercial gas turbines are now operating with turbine inlet temperatures of around 1700°F. With niobium as the structural material in the blanket and a 1700°F turbine inlet temperature, it should be possible to obtain an overall thermal efficiency for the gas turbine plant within a few percentage points of that obtainable with current fossil fuel-fired steam plants. Figure 2 shows a schematic diagram for a gas turbine plant of this type.¹³

A third and still more attractive approach, although novel, would be to employ a potassium-steam binary vapor cycle.³ With this system it would be possible to get an overall thermal efficiency of around 58% as opposed to the 40% thermal efficiency of current fossil fuel-fired plants. This would reduce the waste heat rejection per kilowatt of electricity by more than a factor of 2, and would reduce the fuel consumption by about 30% as compared to a conventional 1000°F steam cycle. Figure 3 shows a schematic diagram of such a power plant. Note that this type of plant also shows promise for obtaining a high thermal efficiency, reduced fuel consumption, and reduced heat rejection for both fission reactor and fossil fuel-fired power plants.^{14,15}

In attempting to choose between the various thermodynamic cycles that might be employed with a fusion reactor, one finds that the tritium recovery problem becomes an important consideration. The tritium will tend to diffuse through the walls of the heat exchanger between the lithium system and the thermodynamic working fluid so that the latter will become

Fig. 2. Flow Sheet Showing Pressures and Temperatures in a Helium Gas-Turbine Cycle Coupled to a Thernonuclear Reactor

Fig. 3 Conceptual Layout for a Thernonuclear Power Plant Designed to Produce 5000 Mw(t) and 2800 Mw(e) Using a Potassium-Steam Binary Vapor Cycle. The vacuum wall is shown as 30 ft in diameter and 60 ft long. The building shown is 330 ft by 600 ft.

heavily contaminated with tritium. If a simple steam cycle is employed, the tritium will mix with the steam and this will present a major problem because there is no economically feasible way of separating the radioactive tritium from the normal hydrogen in the water of the steam system. However, for either the gas turbine or the potassium vapor cycle system it appears that there are effective processes that could be employed to remove the tritium and maintain an extremely low tritium concentration in the working fluid.^{13,16} Further, the equipment required for either system would be neither bulky nor expensive.

The availability of fuel reserves is a timely question. Deuterium is obtained from water at a cost of about \$150/lb, which would give a fuel cost of about 0.003 mills/kWhr for a fusion reactor plant. The amount of deuterium in sea water is enormous — enough for 3×10^{12} yr if one supplied the entire world with all of its energy at 15 times the present world rate of energy consumption. For the same rate of world energy consumption the known reserves of lithium are sufficient for only about 200 yr.¹⁷ However, the probable reserves are at least ten times greater, and the amount of lithium in sea water gives another factor of over 1000.¹⁷ It appears possible to extract lithium from sea water at no more than the cost required for the isotope separation process used for deuterium, and, if so, the cost would still amount to only about 0.003 mills/kWhr, or roughly 1% of current costs for fossil fuels. Further, one can expect that within less than a century it will be possible to develop an economically attractive system based on the D-D reaction.

Environmental Problems

The first step in appraising the environmental problems of thermonuclear power plants is to attempt to envision the worst sort of accident that could conceivably occur. In the first place, the amount of fuel present in the plasma (about 2 grams) is so small that there is no way in which a nuclear explosion could occur.¹⁸ Further, there is absolutely no way in which the fuel or any of the other elements in the power plant could come together to form a critical mass that could yield a nuclear explosion.

In turning to the question of environmental contamination, the first and most important point is that the only radioactive materials present in a fusion reactor will be tritium and activated structure rather than the whole gamut of fission products with all the uncomfortable unpleasanties that these imply. The only volatile radioactive material in the system will be tritium, and it appears that the reactor can be designed so that all of the tritium produced will be burned — there will be no residual for burial. The product of the fusion reaction is helium, and this is inert. The only waste radioactive material produced will be the induced activity in the structural material.

Table 1 was prepared to give some perspective by showing the relative amounts of radioactive materials, both volatile and non-volatile, for both fusion and fission reactors.^{18,19,20} From the standpoint of the volatile radioactive materials (which are really the controlling consideration from the standpoint of an accident) the tritium of the fusion reactor represents a biological hazard potential that is lower by a factor of about a million than that represented by the radioactive iodine in a fission reactor. If a D-D or D-³He fuel cycle were employed, the inventory of tritium might be reduced by as much as a factor of ten, but it would still be large because of side reactions.⁴ If niobium is employed as a structural material, it would represent a biological hazard potential about 3% of that represented by the plutonium in a fast breeder fission reactor. It may be possible to employ vanadium rather than niobium as the structural material in a fusion reactor, in which case a further reduction by a factor of 300 in the biological hazard potential could be effected.

It should be emphasized that the concentration of the activity in the fusion reactor structural material would be very much lower than that in the fuel of a fission reactor, and, as a consequence of the reduced power density, simple thermal radiation and thermal convection would be sufficient to remove the heat, and hence the fusion reactor can be designed so that afterheat could not cause a meltdown. Further, the niobium is a refractory material with a melting point of 4500°F.

Although less spectacular than the major accident problem, the problems of containing volatile radioactive materials under routine operating conditions are still very difficult. This will be particularly true for

Table I. Principal Radioactive Inventories of the Reference Fusion Reactor (RFR)
and a Liquid Metal Fast Breeder Reactor (LMFBR)

<u>Inventory</u>	<u>Activity (curies per watt of thermal power)</u>	<u>Maximum Permissible Airborne Concentration (μcuries/cm³)</u>	<u>Relative Biological Hazard (Activity $\div$ MPC)</u>
<u>RFR</u>			
³ H (combined in H ₂ O)	$1.20 \times 10^{-2}^a$	2×10^{-7}	6×10^4
<u>Niobium as the Blanket Structure</u>			
⁹⁵ Nb	1.55×10^{-1}	3×10^{-9}	5.2×10^7
Total Niobium Structure	7.14×10^{-1}	-	2.4×10^8
<u>Vanadium as the Blanket Structure</u>			
⁴⁸ Sc	4.20×10^{-3}	5×10^{-9}	8.4×10^5
Total Vanadium Structure	5.51×10^{-2}	-	$8.6 \times 10^5^b$
<u>LMFBR</u>			
¹³¹ I (on crops)	3.16×10^{-2}	1.4×10^{-13}	2.3×10^{11}
²³⁹ Pu	6.04×10^{-5}	6×10^{-14}	1.0×10^9
Total Plutonium Isotopes	1.82×10^{-2}	-	8.3×10^9

^aThe specific activity of tritium is approximately 10^4 curies per gram.

^bImpurities within the vanadium might increase this number by a factor of two.

the tritium in fusion reactors because the various isotopes of hydrogen are very elusive and tend to diffuse through metal walls if their temperature is raised above about 600 or 800°F. As a consequence, a special set of techniques must be employed to keep the leakage of tritium from the reactor system to an extremely low level. Past experience with fission reactor plants indicates that this can be done, but that it will require the most effective techniques available for maintaining leak tightness, e.g., those that have been employed in the development of liquid alkali metal and molten salt systems to yield leakage rates below 0.0001%/day.

It appears possible to design a fusion reactor plant economy so that all of the tritium produced will be burned, and hence there will be no problem associated with the disposal of surplus tritium. However, the induced radioactivity in the structural metal will pose a disposal problem. Fortunately, the metal will have a low level of activity, its half life will be shorter than plutonium even if niobium is used, and the metal is refractory. Some notion of the relative difficulties of disposing of the radioactive niobium from a fusion reactor plant as compared with the transuranic elements from a fission reactor plant¹⁹ is indicated in Table 2. Clearly the fusion plant represents a much less difficult set of problems, particularly if a material such as vanadium could be employed rather than niobium. (Stainless steel or molybdenum would yield activities only a little lower than given by niobium.)

As a consequence of their greatly reduced hazard potential, it appears possible that, after extensive operating experience, fusion reactors could be located close to major population centers. This would not only reduce the problems of electrical transmission lines, but would also facilitate the use of the waste heat from the thermodynamic cycle for industrial processes and urban district heating systems. Note that in some of the district heating systems in the U.S. there is as much demand for low temperature steam in the summer for driving absorption air-conditioning systems as there is in the winter for building heating. Thus, the waste heat from the thermodynamic cycle can be used to good advantage in either the winter or the summer, and a reasonably good balance can be obtained between the requirements for electrical power and the requirements for low temperature

Table II. Long-Lived Activities in the Blanket Structure of the RFR and in the Spent Fuel of an IMFBR

<u>Nuclide</u>	<u>Mean Life (yrs.)</u>	<u>Activity Generation Rate [curies/W(th)-yr]</u>	<u>Accumulated Activity @ 1000 yrs. [curies/W(th)]</u>	<u>Maximum Permissible Airborne Concentra- tion^a (μcuries/cm³)</u>	<u>Relative Biological Hazard (Activity @ 1000 yrs. + MPC)</u>
<u>RFR with Niobium</u>					
^{93m} Nb	19.6	8.8×10^{-3}	0.17	4×10^{-9}	4.2×10^7
⁹⁴ Nb	2.9×10^4	2.9×10^{-6}	2.9×10^{-3}	4×10^{-10}	7.2×10^6
<u>RFR with Vanadium</u>					
Long-Lived Activities Due to Activation of Impurities in Vanadium					$\sim 5 \times 10^3 - 5 \times 10^4$
<u>IMFBR Spent Fuel</u>					
⁹⁰ Sr	40.4	6.7×10^{-4}	2.7×10^{-2}	3×10^{-11}	9.0×10^8
¹³⁷ Cs	43.4	9.3×10^{-4}	4.0×10^{-2}	5×10^{-10}	8.0×10^7
⁹⁹ Tc	3.0×10^5	1.2×10^{-7}	1.2×10^{-4}	2×10^{-9}	6.0×10^4
²³⁸ Pu	128	9.0×10^{-7}	1.2×10^{-4}	7×10^{-14}	1.7×10^9

^aMaximum permissible airborne concentration for continuous exposure as discussed in text.

heat in an urban complex. This should make possible marked savings in fuel as well as a tremendous reduction in the amount of heat rejected to the environment.³

Development Program

In summary it appears from the very limited conceptual design studies carried out to date on full-scale thermonuclear power plants that, if and when good solutions can be found to the plasma physics problems, it should be possible to design and build economically attractive full-scale thermonuclear power plants. However, it is also clear that these plants will entail some extremely difficult technology problems, and that much time and effort will be required for their solution. Fortunately, a great deal of work that has been carried out and is being carried out in the fission reactor program will also be applicable to thermonuclear reactors. On the other hand, there will also be many special problem areas such as those represented by cryogenic magnets which will be peculiar to thermonuclear reactors and will require major efforts to obtain economically viable solutions. Table 3 summarizes these technology areas.

Many of the uncertainties associated with a number of special problems common to most of the concepts for full-scale fusion reactor plants might be reduced substantially by a modest technology evaluation and development program that is being initiated. This includes the construction of a roughly full-scale superconducting magnet coil (about 50 such coils would be required for a reactor), construction and testing of a small-scale pilot plant for the tritium removal system, investigation of the compatibility of vanadium with lithium, investigation of radiation damage to niobium and vanadium, investigation of the magnetohydrodynamic problems associated with pumping metallic lithium through a strong magnetic field, and studies of environmental impact problems.

Table 3. Major Areas of Fusion Reactor Technology

Technology from Fission Reactor Programs

1. Neutronics ~ nuclear cross-sections, codes
2. Radiation damage, creep, and fatigue effects
3. Liquid metal handling, equipment, instrumentation
4. Metallurgy of refractory metals, materials compatibility
5. Hydrogen diffusion
6. Systems for removing hydrogen from inert gases and alkali metals
7. Gas turbine, potassium vapor, and MHD power cycles
8. Shielding
9. Cost estimating data
10. Maintenance of radioactive equipment
11. Waste disposal
12. Power plant control

Special Technology

1. Plasma engineering
2. Plasma instrumentation
3. Fuel injection, heating, and recovery
4. Divertor (for ash removal and vacuum wall protection)
5. Superconducting magnets and cryogenics
6. Radiation damage from 14 MeV neutrons
7. Pumping metals through strong magnetic fields
8. High temperature thin shells in large sizes
9. Direct electrostatic energy conversion
10. Energy storage and transfer

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