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The Princeton Reactor Studies Program*

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ABSTRACT

The history, composition, and philosophy of the Princeton Reactor Studies Program are described. The problems besetting a realistic fusion power station are summarized, and the principal features of a reference design for a first generation reactor are presented. Current program results are related to needs for experimental work and their possible effects on future reactor studies.

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I HISTORY OF PROGRAM

The Princeton Reactor Studies Program was undertaken in July of 1971. Its first objective was to generate a conceptual design of a complete fusion power station in considerable detail and in an entirely self-consistent manner. This first phase is being completed now in the closing months of 1972.

To supplement the talents of Plasma Physics Laboratory personnel it was felt essential to call upon people experienced in the field of nuclear fission, from the electrical manufacturing industry and from the electrical utilities. These people were recruited both from within the United States and abroad. Approximately 18 people have contributed to about eight man-years of effort that will be reported in a full description of the model.¹

Considered as a first-generation plant, the reactor was intended to be as simple as possible, but nevertheless be of commercial interest. A Tokamak plant generating a nominal 5000 MW_{th} and 2000 MWe was selected as shown in Fig. 1.

II CHARACTERISTICS OF THE PRINCETON REFERENCE DESIGN

A. The Principal Parts and Problems of a Toroidal Reactor

1. The Plasma

At the center of the reactor lies the plasma, its central core at a temperature approaching half a billion degrees, but at so low a density (10^{14} ions, cm^{-3}) that its pressure is only 20 atmospheres. The gas is primarily a mixture of equal numbers of deuterium and tritium atoms

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(that are completely ionized), but also contains some helium (the ash of the reaction) and some impurities. The major radius of the plasma is about 10 meters, its minor radius a little over 3 meters. The density distribution is parabolic. Density and temperature profiles are shown in Figs. 2 and 3. A continuous flow of fuel takes place through the plasma, the average residence time being 2.8 seconds, during which about 2.9% of the fuel charge burns. For these conditions to be possible, it will be necessary that the diffusion coefficient be not much greater than $5000 \text{ cm}^2/\text{sec}$, a value already achieved in the laboratory. The primary problem and so-far unanswered question is whether these values can be retained as plasma temperatures are increased by at least a factor of ten over the levels achieved to date.

2. The Injector

A major unknown is precisely how to inject the fuel into the machine with any hope of carrying it to the center. No experiments have yet been carried out on this important and crucial matter. Laboratory plasmas formerly were not energetic enough to give significant results, but this situation has now changed, and it should be possible to pursue this question. Means suggested have been the acceleration of high velocity streams (more likely a sequence of high velocity droplets or pellets) by electrostatic means. The incoming fuel tends to be ionized by the plasma and immobilized by the magnetic field very promptly after penetration.

3. The Divertor

There is a continual flow of fuel through the plasma at about thirty-five times the consumption rate. This fuel must be collected for processing and be prevented from touching the wall in the main reaction chamber to avoid excessive erosion of the wall and contamination of the reactor gas. The divertor performs this function as well as playing the role of a very effective pump. It is basically a magnetic device that peels an outer layer of magnetic flux from the outer portion of the central region and guides the plasma into an external volume. Figure 4 shows the machine cross section and details of the Christensen divertor.

4. The Vacuum Wall

In order to prevent the entry of contaminants into the low density plasma, an ultra high vacuum environment must be provided. The wall will be in an intense radiation field and will need to be cooled to remove the heat deposited by bremsstrahlung and synchrotron radiation on the first surface and deposited by neutrons and gamma rays throughout the metal. The neutron flux through this wall will be as intense as any anticipated in a fission reactor and will be of a harder spectrum, the rate of production of radiation damage to this wall being estimated to lie between two and five times that expected in a fast breeder. Void production and swelling should not be a severe problem, but the embrittlement produced by (n, α) reactions may be of great importance, possibly second only to the basic one of plasma confinement, in determining the success or failure of economic fusion power.

5. The Blanket

In The DT fusion reaction,

eighty percent of the energy released by fusion is carried by the neutrons, a particle not affected by the magnetic field. The only way to collect this energy is to convert it to heat by slowing the neutrons by collisions in solid material. This is one function of the blanket. If this were its only function, material selection would be a simple problem, but the other function of the blanket is to make use of these neutrons to breed the fuel tritium, which does not occur in nature, from lithium, which is abundant. In contradistinction to the fission process, a DT fusion event produces only one neutron, yet it consumes one triton; so the problems of neutron economy require careful design of the blanket. Some neutron losses are inevitable; so neutron multiplication is required in the blanket, and materials that are strong absorbers of neutrons must be avoided. In this particular model the lithium is present in the form of lithium beryllium fluoride, a salt.

6. The Shield

The neutrons and gamma radiation that escape the blanket must be shielded for protection of the plant operating personnel and others in the surroundings and must be prevented from delivering heat to the cryostats that maintain the superconducting coils near liquid helium temperature. The cost of refrigeration at this low temperature is, of course, very high, and it is an economic necessity to prevent the entry of heat to as high a

degree as possible. Thus the bulk of the shield lies between the blanket and the coil structure, and a rather modest biological shield is needed outside the coils.

7. The Coolant

Several cooling media have been suggested for removing heat from the inner regions of the blanket. Water (steam) is considered undesirable because of the presence of tritium in the system, which would easily enter the steam cycle (as HTO) and lead to difficult tritium inventory and safety problems. Molten salts, liquid metal (lithium), and helium are the most popular choices. The electrical conductivity of liquid metal and even molten salt is sufficient to present awkward problems of pumping in a high magnetic field, and even the purest helium will have enough oxygen contaminant to produce a severe corrosion problem for any refractory metals used in the structure. In this model helium is chosen with enough oxygen added to assure the oxidation of the tritium leakage for collection on a desiccant, and stainless steel is chosen as the structural material for compatibility.

8. The Magnet

It is essential that the large volume, high magnetic fields necessary for a fusion reactor be generated by superconducting coils. The power needed for normal magnets would be far too large a load on the plant for economic operations. The power output of a given machine varies as B^4 ; so there is strong motivation for as high a field as possible. Three con-

siderations dominate the design problems: a) In a toroidal magnet the field strength varies inversely as the major radius. Therefore the field at the superconductor itself must be substantially higher than the useful field strength at the center of the plasma, b) The useful current density in available superconductors decreases sharply at high field levels, implying that the cost of materials rises rapidly as the design value climbs, and c) Magnetic forces rise as B^2 . At the 160,000 gauss maximum level chosen for this model (the upper limit of the current state of the art), magnetic pressure is equivalent to 17,000 psi. The shape of the magnet shown in Figs. 1 and 4 is chosen to eliminate large bending moments and avoid the need for reinforcing hoops to prevent deformations.

9. The Fuel Cycle

The fuel cycle consists of the primary loop of injector-plasma-divertor-vacuum pumps-liquifier-DT makeup-injector, with associated systems to recover tritium from the helium coolant and the molten salt breeding medium. The former process is accomplished by maintaining about 50 ppm of oxygen in the helium coolant, which is sufficient to oxidize the tritium to water for easy removal by a desiccant. The molten lithium beryllium fluoride is continuously circulated from the blanket through a desorber (about fifteen minutes to circulate the entire blanket inventory) where pure helium strips the entrained gas. This helium is in turn passed through potassium fluoride beds where the TF (formed in the salt when tritium is bred) forms potassium acid fluoride, KTF_2 , from which the tritium is easily recovered.

10. The Heat Cycle

Figure 5 presents the details of the essentially conventional steam system of the plant. A steam generator contains the superheater and reheaters and receives helium at 1150°F from the blanket. Most of this is returned to the blanket at 680°F , but 10% is delivered to the first two feed water heaters before return to the reactor at 166°F . Steam is delivered to the three high pressure turbines on one shaft at 1000°F . Small steam turbines driven by exhaust steam from the very high pressure stage power the 10 MW cryogenic refrigeration plant and the 240 MW helium circulators.

B. Operating Characteristics

This system delivers approximately 2000 MWe at an overall efficiency a little over 40%. It burns about 2 pounds of fuel per day (1.2 pounds of T_2 and 0.8 pound of D_2). The latter is available now from heavy water separated from natural water in the neighborhood of \$30/pound of heavy water or \$150/pound of deuterium. The tritium would be manufactured in the plant from about 2.8 pounds of lithium available at about \$10/pound. Thus the total fuel cost for a day's operation would be \$120 for deuterium and \$28 for lithium equivalent to 0.003 mills/kWh, a completely negligible fuel cost.

III THE POTENTIAL ADVANTAGES OF A FUSION SYSTEM

A. The Environment

The plant would contain a significant inventory of tritium, a dangerous, radioactive gas. The bulk of the inventory will be in fuel storage for the injectors, occupying a small volume and capable of protection with high safety

factors at small cost against the usual seismic, fire, and explosion hazards. Leakage rates will apparently be easily controllable within reasonable environmental standards.

There will be no radioactive waste per se to be disposed of. However it is to be expected that activated inner portions of the plant will eventually need to be replaced. When this is done, the removed, radioactive material can be stored on site until the activity has decayed to the point where the material can be refabricated into useful components.

Since a heat cycle is essential to tap the DT fuel source, waste heat is an essential feature of such a power station. The inherent safety of these systems would allow their location in regions of high population density and provide a potential market for the waste heat, an advantage not available to remotely located power plants.

B. The Economy

As noted above, fuel is essentially free for a fusion reactor. Operation and maintenance costs should be about the same as for fossil fueled or nuclear fission plants, near half a mill per kilowatt hour. The cost of fusion power will be dominated by the capital costs of the plant, a figure not subject to very accurate estimates at the moment since the full details of the plant are not known. If capital costs can be limited to \$300 per kilowatt, the cost of fusion power should be limited to less than six mills per kilowatt hour.

C. Aspects of the Unique Fuel Situation

There are other rather surprising consequences of the fusion fuel situation other than its negligible cost. The necessary fuel inventory of the plant is rather low - about sixteen pounds of tritium. This low inventory results in an extremely small required breeding ratio (B.R.) for reasonable fuel doubling time. For example, for a tritium burning rate, r , of 400 pounds per year, the doubling time, τ_2 , given by

$$\tau_2 = \text{Inventory} / (\text{B.R.} - 1)r ,$$

if desired to be three years, requires a breeding ratio of only 1.02.

Another aspect of negligible fuel costs is the effect on the system planners' attitude towards plant efficiency. A potential saving in fuel costs is no longer the motivation; only the desire to reduce waste heat. Since thermal pollution is perhaps the least threatening of all the pollution problems facing us; an increase in efficiency, although desirable, is probably not worth very much increase in capital costs.

IV FUTURE WORK

A. Experimental Needs

1. Plasma Confinement and Heating

This central problem for fusion power has been and is continuing to be the prime focus of research attention for the world-wide effort. With the outstanding results achieved this year with the ATC experiment, the path seems clear towards achieving ignition conditions and a demonstration

of scientific feasibility. However these have not been achieved yet, and the question is still open. The transport coefficients must be determined for reactor grade plasmas before serious design can begin.

2. Injection and Diversion

The range of high velocity droplets or jets in energetic plasmas has been investigated only theoretically and needs experimental verification. The low temperature plasma problems of the divertor may be crucial.

3. Radiation Damage

As soon as the scientific feasibility of fusion power is demonstrated (by achieving the Lawson criterion), a host of engineering problems will demand answers before the economic feasibility is demonstrated. Among the materials problems, the most pressing will be those of radiation damage. This includes:

a) Sputtering. Bombardment of the wall with ions, especially the heavier ones, knocks wall atoms out of the metal. Erosion rates in some places may reach a level approaching a millimeter per year.

b) Void Formation. This is an effect discovered in the fission industry in 1967. The coalescence of voids into bubbles causes swelling of the metal and possible loss of structural integrity.

c) Embrittlement. The production of helium in the metal via (n, α) nuclear reactions embrittles it. The helium is not soluble in the metal and accumulates on grain boundaries inhibiting slippage in strain and reduces the elongation to fracture to a few percent when the helium concentration reaches a hundred parts per million. Brittle metals are subject to cracking under thermal or mechanical shock.

d) Insulation. Few insulators are known that do not turn to powder under the influence of the radiation levels that must be present in a fusion reactor; some glasses may turn out to be satisfactory.

Some experiments are already underway on these important questions, and the fission industry work is helpful in many ways, but there are no sources of 14 MeV neutrons of sufficient intensity to duplicate the expected conditions. There are proposals for special accelerators with high density deuterium gas targets formed by shock waves from supersonic jets that could produce an intense neutron beam when bombarded by accelerated tritons, that would simulate the neutron flux in a fusion reactor, but a fusion materials test reactor may be needed to give completely satisfactory answers to these open questions.

4. Other Materials Problems

Compatibility of the structure and tubing (stainless steel, niobium, vanadium, zirconium, molybdenum, nimonic PE16, or other), the breeding medium (metallic lithium, lithium beryllium fluoride, lithium nitrate, lithium nitrite, lithium hydride), the coolant (helium, lithium, lithium beryllium fluoride, potassium, steam) are problems that may well be answered before they are needed in the fusion industry by similar applications in the fission industry. The liquid metal fast breeder reactor program is exploring much ground that would need to be covered by the fusion effort had it come first.

B. Reactor Studies

A power plant, whether fossil, fission, or fusion, is an intricate and complex set of systems. In a study program for hypothetical reactors it is easy to concentrate on a few aspects of the problem rather than the whole package, and this can lead to serious error. Our approach to try to avoid this problem has been to set as our first objective a self-consistent complete reference design. When this has been accomplished, we shall turn to the next phase of our studies. This will be to examine variations on the reference design. These will include, as examples: a regular cyclic form of operation; the use of alternate apparatus for ignition, cooling, control, structure, etc.; the use of alternate fuel cycles; the question of how small a demonstration reactor might be; plus several others.

In each case, the reference design will serve as a standard against which to measure the effects of the changes implied by the alternate model. By this procedure we hope to avoid some of the serious errors that can be made by studying only one aspect of a problem.

If the momentum that has been developed in controlled thermonuclear research within the last few years is maintained, the proof of scientific feasibility will be at hand around the end of the decade, and an important transition will take place in the fusion power development program. It is none too soon to prepare for this transition, and the various reactor studies groups now in existence should be setting the stage promptly for the fusion power engineering to come.

Reference

- ¹A Fusion Power Plant, R.G. Mills, editor, to be published (1973).