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FORESEEABLE THERMAL, MECHANICAL, AND MATERIALS ENGINEERING*
PROBLEMS OF FUSION REACTOR POWER PLANTS

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ABSTRACT

The engineering problems that will be posed by full-scale fusion reactor power plants are illustrated by examining a representative conceptual design. The temperature extremes that must be accommodated run from 4°K in superconducting magnets to 10^8°K in the plasma. These temperature differences lead to difficult problems with differential thermal expansion, high heat fluxes, and stringent thermal insulation requirements. The magnetic fields that must be provided run from 25 kG to 100 kG, and these fields induce forces on elements of the structure of the order of 20,000 tons. The walls of the chamber containing the plasma must withstand intense radiation by 14 MeV neutrons and 1 to 50 keV ions. Unusual fluid flow and heat transfer problems include two-phase boiling flow of helium in the cryogenic magnets, magnetohydrodynamic effects on the flows of red hot lithium and boiling potassium in a high magnetic field. These and many other problems must be solved in such a way as to give a reliable, safe system at a reasonable capital cost, and this must be done with materials whose resistance to corrosion and nuclear, physical, and fabrication properties meet all of the requisite boundary conditions.

INTRODUCTION

Major efforts to develop fusion reactors have been underway in the U. S., the UK, and the U.S.S.R. for over 20 years, and more recently have been initiated in several other nations, yet no one has yet demonstrated experimentally that a controlled thermonuclear reaction can be obtained on anything like the scale required for a full-scale fusion reactor. However, progress in recent years has been encouraging,¹ and it now appears not only that the plasma physics problems probably can be solved, but that it may be possible to build a full-scale electric

power plant that would produce electricity at fuel costs of only 0.006 mil/kWhr, or about 1% of the cost of the basic fuel for fission reactors. Further the potential supply of fuel for fusion reactors is enormous — there is sufficient heavy hydrogen in the world's oceans so that if only half of it were employed, it would serve to provide all of the world's energy needs at 10 times the level anticipated for the year 2000 for a period much longer than our sun is expected to last.² Inasmuch as water is available to everyone, a practicable fusion power system would eliminate competition for the world's limited reserves of fossil fuel and thus should help greatly to reduce international tensions. Further, inasmuch as the product of the fusion reaction is helium there would be no long-lived fission products. There would, of course, be activated structure as a consequence of the copious production of neutrons, and it would be necessary, at least for the first few generations of nuclear power plants, to employ tritium with deuterium as the fuel, and this will introduce some difficult radiological safety problems in handling the volatile, radioactive tritium. However, conceptual design studies indicate that it may be possible to keep the inventory of volatile radioactive material in a fusion reactor sufficiently low that it will represent a biological hazard potential about 1 millionth that in a fission reactor, and, by proper design, activation of the structure might be kept sufficiently low so that the inventory of non-volatile radioactive material would be of the order of 1% of that in a fission reactor.³ Thus, there is a whole set of extremely important incentives to obtain viable engineering solutions to the design of fusion reactors assuming that the plasma physics problems can be resolved satisfactorily.

BASIC CONCEPTS

Half a dozen different basic concepts for confining the high temperature plasma of a fusion reactor are under active development.⁴ Although some of the problems of these different concepts are quite specialized and peculiar to only one or a few concepts, most of the problems to one degree or another

are common to all types that currently appear promising. Thus, for the purpose of this paper, it seemed in order to simplify this presentation by choosing just one of these concepts to illustrate the engineering problems involved in the development of a full-scale fusion power plant, and, because it is receiving the most attention all over the world, the tokamak type of fusion reactor was chosen for this purpose. The tokamak uses a set of magnet coils arranged as in Fig. 1 to form a toroidal cavity in which an ionized plasma of deuterium and tritium can be confined by a magnetic field.⁶ The plasma can be heated part way to the ignition temperature by pulsing a secondary poloidal field so that a current is induced in the plasma which acts as the single turn secondary winding of a transformer. See Fig. 1. However, the electrical resistance of the plasma falls off so rapidly at ion temperatures above about 1 keV that an additional means must be employed for heating the plasma further. Currently one of the most promising approaches appears to be the use of neutral beams injected into the plasma with energies of the order of 40 keV. When the plasma temperature reaches around 10 to 20 keV, the fusion reaction rate should become sufficiently high so that the reaction will be self-sustaining, and the energy output will exceed the energy input.

REPRESENTATIVE ENGINEERING DESIGN

A cross section through the torus of a representative conceptual design for a full-scale fusion reactor power plant of the tokamak type is shown in Fig. 2. Note that the plasma temperature is estimated to be 160,000,000°K. The plasma is surrounded by a 1000°C lithium blanket designed to absorb over 99% of the fusion energy released by the plasma. The energy from the D-T fusion reaction is divided between a 14.3 MeV neutron and a 3.7 MeV alpha particle. The bulk of the energy from the 14.3 MeV neutrons is converted into heat as the neutrons penetrate deeply into the blanket, but the energy from the 3.7 MeV alpha particle induces x-ray and synchrotron radiation which is converted into heat in the metal wall separating the lithium from the plasma. This wall is also subject to severe radiation damage from the 14 MeV neutrons

as well as the possibility of sputtering damage from ions that escape from the plasma in spite of the confining magnetic field. Thus, it is the most critical structural element in the reactor.

Choice of Lithium for the Blanket

Lithium was chosen as the blanket material because only one neutron is produced per fusion and this neutron must be used to generate tritium. There is no significant natural supply of tritium, but it can be produced by absorbing neutrons in ^6Li to give tritium plus helium. To generate it in fission reactors would be prohibitively expensive. Inasmuch as each fusion reaction destroys one tritium atom and produces only one neutron, neutron losses through parasitic captures must be offset by employing a blanket material in which the process of slowing down 14 MeV neutrons will be accompanied by sufficient $n, 2n$ reactions to breed an adequate supply of tritium. Either lithium or beryllium could be employed to accomplish this, but the world's supply of beryllium is far too limited to make it a viable candidate. Thus one has no choice but to employ lithium in one form or another. Analysis quickly discloses that heat removal from the first wall is a vital problem, and that liquid metallic lithium is an outstandingly good coolant. Thus, liquid lithium was chosen as the blanket material for the design considered here. The problems of pumping the liquid metal through the strong magnetic field can be greatly eased by making the passages essentially parallel to the lines of magnetic force as in the design shown in Fig. 2. This problem will be discussed further later in this paper.

Choice of Structural Material for the Blanket

The choice of liquid lithium poses problems in selecting a structural material to contain it. Stainless steel can be employed, but extensive experience indicates that above about 500°C solution type corrosion and mass transfer present serious difficulties. Fortunately, extensive experience under the space power plant program in the U.S. has demonstrated that niobium is compatible with lithium at temperatures up to over 1000°C giving no difficulty with corrosion

or mass transfer.⁶ Further, niobium has a much higher strength at elevated temperature than stainless steel. This will permit heating the working fluid of the thermodynamic cycle to a higher temperature than would be possible with stainless steel, and thus will yield a system with a higher overall thermal efficiency than any power plant built to date.⁷ If the proper techniques are employed, niobium can be formed, machined, and welded using methods similar to those employed for stainless steel.⁸ It is ductile and the limited data available indicate that it has excellent resistance to fast neutron damage for fission spectrum neutrons.⁹ Analysis indicates that it should have good resistance to radiation damage by 14 MeV neutrons,^{10,11} but this problem can be resolved ultimately only by testing, and no really good way of doing this has yet been envisioned. Of course, the same uncertainty prevails with respect to the resistance of any other structural material to damage by 14 MeV neutrons.^{10,11}

It happens that niobium is also an excellent choice from the standpoint of possible sputtering damage as a consequence of ions escaping from the plasma and striking the surrounding walls. Sputtering tests run with beams of deuterium ions have shown that niobium is roughly 10 times as resistant to sputtering as most other materials.¹²

Tritium generation in the blanket poses a number of different problems. The best way of coping with these is to make use of a tritium recovery system that maintains a very low concentration of tritium in the lithium -- of the order of 1 ppm.³ If this can be done, the inventory of volatile radioactive material can be kept very low, the capital investment in the tritium inventory will be small, and hydrogen embrittlement of the structural material can be avoided. It happens that niobium at elevated temperatures is almost as permeable to hydrogen as palladium, and this property can be employed to give what appears to be a very attractive tritium recovery system.¹³

In the balance it appears that niobium is an excellent choice as the structural material for the blanket because of its high strength at elevated temperatures, its good resistance to fast neutron damage, its excellent resistance to sputtering by high energy ions, its excellent compatibility with high

temperature liquid lithium, its high permeability to hydrogen at high temperatures, its good ductility, and its good fabrication characteristics. Its principal disadvantage is that fast neutrons interact with niobium atoms to raise electrons to excited states, thus giving a substantial amount of troublesome long-lived activity. However, the level of this activity is only about double that given by stainless steel or molybdenum. While not mentioned previously, molybdenum appears at first to be a good candidate, but it is far less resistant to fast neutron damage than niobium, and brittleness in the weld zone makes it unsuitable for welding. Vanadium appears to be an interesting candidate because it would give a much lower level of residual activity than niobium¹⁴ but there is little information to show whether it would be sufficiently compatible with lithium, its strength at elevated temperatures is inferior to that of niobium, and there is little experience in fabricating it.

Magnet Shield

The power required to drive the helium refrigeration system for the superconducting magnets runs about 1 MW per kilowatt of heat removed at 4°K. Although the 1 m thick lithium blanket serves to absorb over 99% of the energy in the 14 MeV neutrons emitted from the plasma, much further attenuation of this neutron flux is necessary to avoid imposing an excessive heat load on the refrigeration system for the superconducting magnets. To accomplish this it is necessary to introduce a magnet shield about 1 m thick between the blanket and the superconducting magnets.¹⁵ At first thought the magnet shield might be made of lead and water, but consideration of possible accidents leads to the conclusion that it would be desirable to avoid having water and molten lithium in close proximity. As a consequence it appears best to make the magnet shield of a solid, relatively inert material such as graphite, alumina, magnesia, or possibly lithium hydroxide. Calculations of the neutron attenuation rate in these materials indicate that lithium hydroxide would give a thinner magnet shield than lead and water, whereas a graphite shield would have to be thicker. Inasmuch as the cost of the superconducting magnet coils increase more rapidly than linearly with the bore, there is a strong incentive to minimize the thickness of the magnet shield. The final

choice will depend on a combination of material cost, fabrication, and handling considerations.

Note that the magnet shield will have to be cooled, but that the heat load is small and the heat fluxes are low so that it could be cooled readily with a gas such as helium. Thus there need be no water near the lithium.

Effects of Choice of Torus Minor Diameter

One can see intuitively when examining Fig. 2 that if the radial thickness of the blanket and magnet shield must be about 2 m, it will be necessary to go to a plasma region diameter of at least around 5 m if one is to make use of a reasonably large fraction of the volume of the magnetic field generated by the magnet coils. Plasma physics relations indicate that, as the size of the plasma region is increased there is a reduction in the strength of the magnetic field required to contain the plasma. Further, the cost of the magnets increases as the square of the magnetic field because the permissible current density in the superconductor is approximately inversely proportional to the strength of the magnetic field and the number of ampere turns required increases linearly with the strength of the magnetic field.¹⁶ Space does not permit a proper discussion of this vital set of problems, but Fig. 3 indicates the manner in which both the magnetic field and the cost of the magnet, magnet shield, and blanket will vary with the minor diameter of the plasma region.¹⁷ Note that the minimum cost is obtained with a plasma region minor diameter of around 5 m. However, if one also takes radiation damage problems into consideration and makes use of the best information available on the permissible fast neutron fluence to niobium before serious embrittlement takes place, it appears that to obtain a ten-year life for the blanket structure it will be necessary to limit the power output per unit of area of the first wall to not more than about 1 MW/m^2 . If one uses this value and considers the effect of torus size on the reactor cost per kilowatt of electricity produced, one obtains a set of curves similar to those in Fig. 4. A review of Figs. 3 and 4 indicates that the larger the minor diameter, the lower the unit cost per kilowatt of electricity, and that this type of reactor is suited only to units of power outputs exceeding around 1000 MW(t).

Magnet Coil Design

It is evident from the previous section that enormous magnet coils are required — the magnet field will have to be of the order of 40 kG and the magnet bore must be of the order of 10 m. If ordinary water-cooled copper coils were employed, the power required for the magnet would be roughly equal to the entire electrical output of the plant. As a consequence, some sort of cryogenically-cooled coils must be employed, and the evidence is accumulating that it will be best to use superconductors.

In designing superconducting coils it has been found that it is essential to provide sufficient copper intimately associated with the superconductor so that in the event the magnet quenches — i.e., goes from superconducting to normal — there will be sufficient copper present to carry the electrical current without the magnet destroying itself. This can be accomplished by combining the copper and superconductor intimately either in the form of two thin tapes metallurgically bonded together or in the form of small filaments of superconductor embedded in copper. Conductors of the latter type can be formed by drilling a set of holes in a block of copper, placing rods of superconducting material such as NbTi in the holes, and drawing the slug down until the superconductor filaments are reduced to a diameter of 10 μm . The latter construction makes it possible to twist and braid the conductors to obtain microfield characteristics that are especially desirable from the magnet design standpoint.

The electromagnetic forces acting on the conductors in the coil produce a net force acting radially outward that is equivalent to a pressure of around 1 or 2 kg/mm^2 . In most superconducting coils built to date this hoop tension force has been accommodated by interleaving strips of stainless steel with the superconductor when winding the coil so that the stainless steel carries the hoop tension loads. However, when the magnet coils are arranged in the form of a torus, the magnetic field lines are closer together in the portion of the torus close to the polar axis of the torus and this leads to a pronounced asymmetry in the radial forces acting on the coil. Figure 5 shows a typical polar diagram for the magnet coil of a tokamak. Note in Fig. 5 that there is

a net force acting inward toward the pole of the torus. This force is very large indeed — of the order of 20,000 tons. To accommodate this it is necessary to provide some additional structure, and one way of accomplishing this is to make use of two massive compression rings, one to support the upper portion of the magnet and one below it. See Fig. 6. Note in Fig. 6 that a reinforcing ring has been placed around the magnet coil to carry the bending loads associated with the severe asymmetries in the radial force distribution indicated in Fig. 5. A polar diagram for the bending moment distribution in this reinforcing ring with allowance for the reactions at the large compression rings is shown in Fig. 7.

While not immediately obvious, it is also necessary to design the magnet structure to accommodate an accident condition in which one or more of the coils quenches, and its contribution to the magnetic field falls off to zero. If this occurs, the resulting asymmetry in the magnetic field produces powerful tangential forces acting on the magnet coils adjacent to the quenched coil or coils, and forces them away from the quenched coils. The magnitude of this lateral force is also of the order of 20,000 tons, and structure must be provided to accommodate it.

It should be noted at this point that the thermal inertia of the magnet system is extremely large — so much so that it will be very expensive to provide sufficient refrigeration system capacity to cool the magnet system from room temperature to operating temperature in less than several weeks.¹⁶ Thus, there is a major incentive to minimize the weight of structure closely associated with the superconductor. At first thought one might be inclined to provide thermal insulation between the superconductor and the surrounding structure, but this is not practicable because of the large amounts of differential thermal expansion that would be entailed and the fact that there is no known thermal insulation that would be sufficiently effective to keep the heat load on the cryogenic coils to an acceptable level and yet would be capable of carrying loads of the order of 1 or 2 kg/m². Thus the entire structure supporting the magnet coil must be operated at the same temperature as the superconductor, i.e., around 4°K, and this includes the structure designed to carry the tangential loads on coils if one or several coils were to quench.

A promising way to accommodate all of these requirements is indicated by the magnet structure shown in Fig. 8. The magnet coil would be wound on a channel-shaped bobbin around which would be shrunk a circular box beam. Inasmuch as the superconducting windings must be cooled by liquid helium, the bobbin would be attached and sealed to the reinforcing ring by electron beam welding. Note that there would be substantial shear forces acting on this weld as a consequence of the bending moments indicated in Fig. 7. In this design the lateral forces acting on the magnet in the event one coil quenches would be accommodated by extending the inner portion of the box beam tangentially outward to meet the corresponding member of the adjacent coil along the half of the coil closest to the pole of the torus. Thus, tangential forces on the superconducting coils in that inner region would be transmitted directly in compression to the adjacent coils. To minimize the amount of surface area requiring thermal insulation, gaps would be left between magnet coils for the 180 deg sectors on the side away from the pole of the torus. The tangential force on the outer half of the coil would be carried in bending and torsion of the box section of the reinforcing ring which projects from the inner structure as a semicircular cantilever beam. It should be mentioned that, initially, the possible magnitude of this tangential load was not appreciated, and an I section beam was employed, but further analysis led to the proportions indicated in Fig. 8. Note that the tangential force distribution around the perimeter of the coil is similar to the radial force distribution shown in Fig. 6.

In attempting to choose a material for the magnet structure, it was decided that it would be best to employ an austenitic stainless steel. These alloys are non-magnetic, they retain good ductility down to 4°K, their strength at 4°K is about double that at room temperature, and their coefficient of thermal expansion is close to that of the Cu-NbTi conductor in the magnet windings.

Coil Winding

The magnet coils are wound of flat Cu-NbTi conductor having a width of 1 to 2 cm and a thickness of perhaps a millimeter to possible two centimeters.

To obtain the desired characteristics in the fine structure of the magnetic field, the conductors are wrapped much like a roll of confetti tape to form pancakes. The pancakes are spaced about a millimeter apart to provide liquid helium coolant passages between pancakes to assure good cooling of every element of the coil. The design of the passages is conditioned primarily by the requirement that any tendency to form local hot spots as a consequence of joints or faults in the superconductor must be countered by adequate cooling, hence the critical condition is analogous to the burnout heat flux problem in a boiling water reactor. The major problem is in designing these passages to include the sufficient structure to cope with the enormous lateral forces that act to draw adjacent pancakes together. It might be noted that the design of Fig. 8 was based on an allowable stress in the stainless steel structure of 80,000 psi at 4°C , and provides for both radial and lateral loads of 1 to 2 kg/mm² on the individual conductors. The conductor pancakes would be wound on the bobbins with a tension on the conductor slightly less than the yield point. A thin plastic tape would be interleaved with the conductor to serve as electrical insulation and, by heat treating, as a bonding material to give a rigid assembly.

Reactor Assembly

If one turns from the problems implicit in the cross section of Fig. 2 to the overall problems of the complete reactor assembly, one encounters a number of additional boundary conditions. Figure 9 helps to give an idea of these problems. The design of Fig. 9 contemplates putting the reactor together in sub-assemblies each of which would represent one sextant of the torus. In the lower right foreground the assembly of one such a sextant is being initiated with the erection of the magnet coils. In the lower left foreground the blanket assembly for a sextant is being threaded into the magnet and magnet shield assembly for that sextant. Note that the structure supporting the various elements of a complete sextant assembly must be designed to accommodate the large amounts of expansion of the hot blanket assembly relatively to the approximately 120°C magnet shield and the contraction of the 4°K magnet coils in going from isothermal

conditions at room temperature to operating conditions. The problems are complicated by the requirement that these massive elements must withstand the shaking forces of an earthquake as well as their own weight and the large electromagnetic forces acting on the magnet coils. Further, the magnet coils, which weigh about 60 tons each, must be supported through very high quality thermal insulation with little heat loss through the support structure. In the design considered here the loads would be carried by thin webs of titanium that would extend diagonally through the thermal insulation around the coils. These webs would carry the gravity loads in tension and the shaking forces of an earthquake would be absorbed in shear with the multiplicity of individual webs acting much like the support skirt at the base of a large tank. The magnet shield assembly would be supported independently of the magnet coils by a set of struts extending downward to the floor between the magnet coils. The blanket assembly would be supported from a set of links attached to the rugged inner wall of the magnet shield. This suspension would be designed to accommodate differential thermal expansion between the blanket assembly and the magnet shield. Note that there would be gaps between adjacent sextants of the blanket and the magnet shield to accommodate thermal expansion. These gaps would also serve as ducts for the blanket coolant pipes, the neutral beam injectors, and the vacuum pumps for the plasma region.

Creep Buckling

A major problem in the design of the blanket structure is the accommodation of the pressure differential between atmosphere and the vacuum in the plasma region. A simple toroidal shell having a circular cross section and operated at high temperature with atmospheric pressure outside the shell and a vacuum inside would be subject to creep buckling and implosion unless its wall thickness were of the order of many centimeters, and this would lead to excessive parasitic losses of neutrons. It would be possible to make use of an extensive set of reinforcing ribs and webs, but it was decided to follow a quite different approach in the design of Fig. 9. In this layout the magnet shield material would be

enclosed in a rugged tank that would constitute the vacuum wall, and all of the space inside the toroidal cavity formed by this tank would be evacuated to the pressure level desired in the plasma region, i.e., around 10^{-5} mm. Thus, the structure for the lithium blanket region need accommodate only the pressure differential between the pressure maintained in the lithium and the high vacuum of the plasma region. It appears quite practicable to keep this pressure differential to about 0.1 atm.

The detailed design of the blanket segments is a little more complex than implied by the cross section of Fig. 2. It is advantageous to introduce graphite into the blanket region partly to reduce the inventory of lithium and thus reduce the capital investment, partly to effect better attenuation of the neutrons and thus reduce the thickness of the blanket and magnet shield region required, and partly to improve the neutron economy.¹⁸ As a consequence, the blanket region in the design of Fig. 9 makes use of a layer of graphite in the central portion of the blanket as shown in Fig. 10. In appraising the stresses on the various elements of this design, note that the wall adjacent to the plasma is a simple circular arc and hence it is in simple tension under the pressure differential between the lithium and the vacuum of the plasma region. The radial walls and the circumferential walls adjacent to the graphite are mutually supporting. Thus, only the outer circumferential wall of the blanket segment is under a substantial stress that stems from the hoop tension associated with the overall pressure differential between the lithium and the vacuum in the region between the blanket and the magnet shield tank. This wall can be made as thick as desired without introducing either a serious parasitic loss of neutrons or producing a large amount of neutron activation of the structure.

Magnetohydrodynamic Effects

The total pumping power associated with both the conventional resistance of the fluid flow system and the magnetohydrodynamic effects must be kept to a small fraction of the reactor power output. Unless the streamlines in the fluid flow are maintained essentially parallel to the lines of force in the magnetic field along the bulk of the flow path and the fluid velocity is kept low,

the additional pumping power stemming from electromagnetic effects will be unacceptably high. This imposes a major limitation on the blanket design and presents some challenging problems to the designer.

Consideration of magnetohydrodynamic problems led to the design shown in Figs. 9 and 10. This design was based on the flow path indicated in Fig. 11, which shows a section on a plane through a minor radius of the toroidal blanket.¹⁰ Lithium in the inner blanket annulus circulates clockwise following the lines of force of the toroidal field up to the end of the racetrack-shaped circuit for that sextant, then flows radially outward, and then turns and flows counterclockwise through the outer lithium annulus along lines of force to a similar return bend at the other end. A cascade of turning vanes in each 90 deg bend should minimize the eddy losses in the turns and provide a good velocity distribution for the flow into the straight sections between the turning vane cascades. It is in the radial flow regions that there would be a substantial magnetohydrodynamic effect and a large resistance to flow as a consequence of the electric current generated in the moving conductor represented by the liquid metal stream. However, it is possible to turn this magnetohydrodynamic effect to good advantage by imposing a counter emf more than sufficient to off-set that generated by the flow so that this region will operate as an electromagnetic pump. By providing for good electrical contact between the end regions of adjacent rings, electric current to produce the desired pumping effect can be introduced through a pair of bus bars on one side of the torus as indicated in Fig. 11. By using this arrangement at one end of each sextant, the pressure rise required in each EM pumping region can be kept to about 0.1 atm and the current required for each region would only be about 9,500 A. The total voltage required for the complete set of segments in the toroid will be about 7.8 V. This gives a pump efficiency of about 5%, and a pumping power-to-heat removal ratio of about 0.05%.

The heat generated in the first wall, the graphite, and the lithium must be removed by circulating the liquid lithium through a heat exchanger. A subtle hydrodynamic effect stems from the drastic reduction in the eddy diffusivity in a conducting fluid as a consequence of its flow through a strong magnetic field. Because of this effect the principal mechanism for lateral transport of heat

across the streamlines will be simple thermal conduction; in spite of the high Reynolds number, heat transport by eddy diffusion will occur at a relatively low rate. This will greatly reduce the heat transfer coefficient in the high heat flux regions at the first wall, at the wall adjacent to the graphite, and along the heat exchanger walls if the heat exchanger is placed inside the magnetic field as in the design of Figs. 9 and 10. Analyses indicate that the good thermal conductivity of lithium coupled with a relatively low power loading of $\sim 1 \text{ MW/m}^2$ gives a reasonable temperature distribution throughout the blanket.²⁰

It has been suggested that magnetohydrodynamic effects might inhibit nucleate boiling in the potassium boiler tubes shown in Fig. 9. Analyses indicate that the bubble dilation rates to be expected will be too low to yield pressure differentials of the order of surface tension forces, hence a strong magnetic field ought not have an appreciable effect on nucleate boiling in potassium. A recent experiment in fields up to 50 kG has confirmed this conclusion.²¹

Summary

Irrespective of the type of fusion reactor chosen, the design engineer is confronted with a host of challenging problems that have much in common with applied mechanics problems in other fields. It is hoped that this paper has given some insight into the character of a representative set of these problems, and that it will stimulate work on solutions that will contribute to development in this extremely important area.

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Configuration of the U.S.S.R. Tokamak Fusion Experiments.

Fig. 2. Section through the minor diameter of a toroidal fusion reactor showing the plasma, blanket, magnet shield, and magnet regions.

Fig. 4. Effects of design power output on the total cost of the magnet, blanket, and magnet shield assembly using both the cost per kilowatt electrical and the wall radius giving the minimum cost at each of a series of typical wall heat loadings.

Fig. 5. Radial force on the magnet coil reinforcing ring as a function of azimuthal position. The polar axis of the torus is to the right of the diagram.

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Fig. 7. Bending moment in the coil reinforcing ring as a function of azimuthal position. The polar axis of the torus is to the right of the diagram.

THERMOSETTING
RESIN .0127 mm

INSULATION
(MYLAR) .254 mm

SUPERCONDUCTING
RIBBON

COOLANT PASSAGE

1.02 mm

1.02 mm

0.5-cm

2 cm

ENLARGED DETAIL (NTS)

7.5

PARTIAL SECTION THROUGH BOBBIN

scale - 1cm=1cm

2.5

2

ENLARGED DETAIL (NTS)

ROUGH BOBBIN

3

TOROIDAL FUSION REACTOR (1000 MWI)

Fig. 9. Conceptual design of a 1000 MW(t) toroidal fusion reactor of the tokamak type showing the latter stages of construction.

Fig. 10. Section through a segment of the blanket showing the main structural elements.