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LAWRENCE LIVERMORE LABORATORY
University of California/Livermore, California

CRYOGENIC ENGINEERING AND FUSION POWER

C. E. Taylor

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CRYOGENIC ENGINEERING AND FUSION POWER

C. E. Taylor

Lawrence Livermore Laboratory, University of California

Livermore, California 94550

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The goal of controlled fusion research is to eventually produce electric power and, after some 20 years of worldwide research effort there has been much progress. We can now outline a reasonable timetable for the U.S. fusion program which leads to the possibility of commercial power in about 30 years;¹ this assumes that a scientific feasibility demonstration will be successful within the next 10 years and serious design studies are now underway on several scientific feasibility demonstration experiments.

There has been increasing interest in making speculative design studies of commercial-scale fusion power plants, mainly to delineate engineering problems and to estimate costs.

Some of these designs are spectacular in scale and present interesting cryogenic engineering applications. The outstanding central feature of fusion systems, other than laser pellet schemes, is that the reacting plasma must be confined by magnetic fields. If such magnets were

¹ Work performed under the auspices of the U.S. Atomic Energy Commission.

to be conventional, such as water-cooled copper, they would consume all or most of the reactor power output. Therefore, it has long been realized that fusion reactors must use either cryogenically cooled or superconducting coils. It is the purpose of this paper to present some of the cryogenic aspects of these reactor designs.

Tokamaks

The most complete design study yet made of a superconducting coil system for fusion reactors has been made by the ORNL group² based on a relatively low field Tokamak. Choice of 79 kG maximum field and Nb-Ti conductor was dictated by the ability to extrapolate present experience to such large sizes with confidence.

This reactor design, shown in Fig. 1, has a coil with 43 circular sections, each 11.2 meters inner diameter and about .5 meters square in cross section, arranged to produce a toroidal field with a 21 meter major center-line diameter. Each coil weighs 78,000 kG and total stored energy is 4×10^{10} joules. It is envisioned that the entire reactor could be housed in an evacuated chamber 165 ft in diameter and 90 ft high built of steel-lined re-enforced concrete. Heat leak could be as low as 1.7 kW, including joints and coil leads, but neutron radiation heating would be about 5 kW, assuming the coil shielding transmits only about 10^{-6} of the neutron energy. However, if refrigerative power of this magnitude is installed, cooldown time would be about 2 months. It is probable that a cost trade-off between refrigerator size shielding thickness and cooldown time might well give a much larger refrigerator for an optimized system.

Although this ORNL design is conservative, it gives reasonable costs and leads me to conclude that present-day techniques for multi-layer thermal insulation, load support using re-enforced epoxy members, steel structural materials, and compound conductor designs can be used for Tokamak coils.

Most reactor coil designs, however, assume significant technology advance in the next two decades and, therefore, utilized higher field designs. It is likely that reactor fields will ultimately be as high as mechanical stresses will allow, and in a 20-30 year time frame, it is reasonable to expect significant developments of practical high-field materials; therefore 150-200 kG fields have been assumed for several speculative designs.

A tokamak coil as visualized by the PPPL group³ assumes fields greater than 150 kG, which demands the use of Nb_3Sn -type mechanically brittle superconductors. They have proposed a coil shape, shown in Fig. 2 which nearly eliminates bending forces and, therefore, results in a lighter-weight structure.⁴ For the design shown in Fig. 2, the coil is about 16 m high, 0.5 m wide, and has a toroidal diameter of about 18 m. This figure illustrates the complex problem of placing a diverter on a reactor. Particles which are continuously diffusing across field lines out of the plasma will eventually strike the vacuum wall and generate a large amount of gaseous impurities. The diverter consists of shaping the magnetic field to allow these particles to strike the wall in a place which is "around the corner" from the main plasma, thus allowing the impurities to be pumped away with only a small chance of returning to the plasma region.

Tokamak experiments to date have used conventional copper coils. However, for the next generation of these devices, because of the large size and cost, the alternative of using superconductors is being considered, both in the U.S. and in Europe. Unlike a future power reactor, physics experiments require a field duration only long enough to observe relevant plasma processes which can be a fraction of a second, therefore, superconductors are not essential and the choice is one of economics, reliability, and predictability. To oversimplify, the choice is largely between investing in superconductors or in conventional power supplies. If one of these huge devices is superconducting, the resulting development will advance the state-of-art much closer to reactor requirements; on the other hand, there is a natural desire to minimize all non-essential risks when building large experiments with costs in the tens of million dollar range.

One interesting alternative which is being studied is to use liquid nitrogen cooled coils in these pulsed systems. The resulting decrease in power supply capitol cost must be balanced against the refrigeration costs and added complexity of thermal insulation.

Another approach to CTR is the LASL theta pinch, an inherently pulsed device.⁵ The plasma is contained in a small diameter (about 60 cm) tube bent into a 112 m diameter torus. The power pulse consists of two stages; first, a fast toroidal field is applied in about .1 μ sec which creates a shock-heated, dense plasma; then a much slower 100-200 kG compression field is applied on a several millisecond time scale which squeezes the plasma to a smaller diameter, heating by adiabatic compression, whereupon thermonuclear "burning" occurs on a millisecond time scale.

The resulting intense neutron burst is absorbed in a blanket located outside the coils and the increase in plasma energy caused by radiation and charged particle production causes an expansion of the plasma.

The compression coil must supply about 6500 MJ to a 114 m diameter reactor and a low-cost energy storage technique is required. Although capacitors are certainly technically feasible and have been almost universally used for fast pulsed fusion experiments, the cost would be impossibly high for a reactor. Therefore, superconducting inductive storage has been proposed. The storage coil need not have a high field but must be efficiently coupled to the compression coil because of the enormous amount of power oscillating back and forth between the coils. This coupling problem is similar to that of a superconducting synchrotron and a solution has been proposed utilizing a time-varying coupling inductance system.⁶

It appears possible, in principle, for the coupling system losses combined with resistive losses in transmission lines and compression coil, to be about equal to the energy added to the coil during each pulse by the expanding plasma which pushes field back into the coil. This represents a direct conversion into electricity of about 7% of the fusion energy. Therefore, the compression coil system may need very little make-up energy.

Such a coupling system may utilize high field superconductors in a mechanically rotating system. Fig. 3 shows a cross-section of the theta pinch reactor.

A major problem, of course, is the design of a conductor with low enough loss when pulsed to remain in the superconducting state. This appears to be within present state-of-the-art. Although a reactor application will probably use a nearly loss-less coupling system, more immediate plasma physics experiments can use the much more simple transfer method of connecting the coil to the load and then opening a shorting switch which is across the storage coil.⁷ This method can transfer a maximum of only 1/4 of the stored energy. The switch may be a superconductor which is driven normal. Of course, all energy deposited in the switch must be removed by a refrigeration system and maximum efficiency is achieved if the switch rises to a high temperature; then for the cooldown cycle, heat is removed at successively decreasing temperatures which poses an interesting refrigeration problem. An extensive development program is underway at LASL on all aspects of magnetic energy storage and transfer. Small (30 kJ) systems have been built and a 300 kJ module is under construction for testing in anticipation of a requirement for a 850 MJ fusion feasibility experiment. Here, as in the case of the next generation tokamak experiments, a decision between superconducting and conventional approaches depends on reliability, predictability, and economics.

Another major approach to fusion power involves the open-ended magnet system on mirror machines. In this type of field, plasma particles can escape by being scattered along the magnetic field lines whereupon they are lost from the main confinement region; this is in contrast to the toroidal systems in which field lines essentially close upon themselves within the plasma and are lost by the much slower process of diffusing

In fact, an energy balance on a mirror reactor shows that the energy carried by the particles escaping along field lines must be recovered at high efficiency if net output power is to be obtained.⁸ Therefore, we visualize a mirror reactor as a steady-state system with an intense stream of particles being accelerated to reaction energies by external sources; this particle stream impinges on the reacting plasma, and is thereby ionized, randomized by collisions, and transposed, supplying both fresh fuel and energy to sustain the plasma in spite of end losses. Plasma escaping out the ends is led along field lines to a low field region. Here the electrons are separated when the field lines are turned abruptly and the ions which are carrying nearly all of the escaping energy in the form of directed kinetic energy, are slowed down by electrostatic fields and ultimately deposit their charge on a high voltage electrode. High recovery efficiencies of the order of 85-90% have been demonstrated in laboratory models and are expected in reactors.⁹

Therefore a mirror reactor consists of a large minimum-B superconducting coil, probably of the "Yin-Yang" shape and a direct recovery system which includes a very large low-field expansion coil. Fig. 4 shows the coil for a 1000 MWe reactor. The most striking feature is that, unlike toroidal machines, the coil is not easily subdividable into many smaller identical sections and the conductors must be wound in three dimensions. In this example for a maximum field at the conductor of 200 kG, the coil weight is 2.8×10^6 kG and, because of the very large forces which are directed toward bending the coils into a single circular loop, a large spherical structural shell is provided.

Structural weight is 55×10^6 kg, stored energy is 4×10^{11} J. Such a huge mass would require at least a month for cooldown using a 30 kW refrigerator. In this case, it is attractive to consider using a warm structure and low cost minimum-conductivity compression material which also serves to minimize heat leak. This reduces cooldown time and structure cost at the expense of more refrigeration power.

There have been two large D.C. superconducting mirror machines constructed, the IMP experiment at ORNL¹⁰ and BB II at LLL.¹¹ The MJ IMP coil system used Nb-Ti circular coils combined with a quadrupole field component produced by Nb₂Sn non-circular coils. BB II used conventional Nb-Ti. However, as in the case for Tokamaks, the next generation mirror experiment can in principle utilize conventional pulsed coils because the plasma pressures of interest have characteristic times of a fraction of a second. Superconducting coils for these large multidimensional minimum-B magnets, using high field materials, will require considerable conductor development and this has been underway at LLL for several years.

Long before a power-producing fusion reactor is built, regardless of which reactor confinement scheme is used, there will be a need for a fusion-device for materials testing purposes. Such a device need not produce net power but it must produce a fusion power density as intense as possible to provide realistic testing of many possible materials.

For example, one of the most pressing problems is to assess radiation damage caused by 14 MeV neutrons at fluxes of about 10^{14} neutrons/cm²/sec. Such a device will require a maximum intensity D.C. field, of

size about 2-3 meters diameter. This application, which must have D.C. coils, may represent one of the next large-scale fusion applications for large high-field coil systems.

The confinement coil systems mentioned herein have stored energies between 15 and 400 G joules. The largest existing superconducting coil at the CERN Bubble Chamber has 0.8 Gj. Discharge of these coils must be controlled to prevent overheating, sparking excessive He coolant pressure, etc. In case of an accident such as loss of refrigeration, the coil must be discharged fast enough to prevent overheating, usually within several minutes, depending on current density and heat capacity. To prevent excessive voltages, this will require subdivision of the coil into electrically isolated sections capable of handling a discharge of a few Gj each.

When such a discharge begins, the coolant will be rapidly heated and provision must be made for rapid venting to keep pressures at reasonable levels. For example, a large volume venting of liquid may be desired. Hollow, internally-cooled conductors appear attractive from this point of view because of the minimum amount of helium within the winding and ability to safely contain this helium at high pressures.

The most difficult cryogenic engineering problems of fusion reactors are mainly those caused by the large size of the superconducting magnets. It seems reasonable to count on extrapolating our existing techniques of low-heat leak supports, superinsulation refrigeration, and structural design. Refrigeration power should be less than 30 kW for a 1000 Mc plant and is not a very significant fraction of total cost. There

will be a need for more practical, rugged, high field superconductors and, in the fusion time scale, their development can reasonably be expected.

When we look ahead 50 years and assume success with fusion, it is conceivable that helium requirements will exceed our expected reserves. The need to extract atmospheric helium, presumably much more expensive than our present supplies, may be an important cost factor in reactor design.

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Fig. 1

Fig. 2

Cross Section of the Princeton Tokamak Reactor Design

Fig. 3
Schematic of a Theta Pinch Fusion Reactor
(Cross Section of a Torus)

Figure 4

- Plan and Cross Section Views of the Livermore Mirror Reactor with Direct Converter