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CONCEPTUAL DESIGN STUDY FOR THE ORMAK-F/BX FACILITY

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Summary

Consideration is being given in the U. S. to a large, injection-heated tokamak that could attain the zero-power Lawson Criterion with H plasma in the late 1970's. The facility would be designed for subsequent replacement of some internal components and addition of shielding and containment to permit D-T burning experiments. An 8-manyear conceptual design study is to be accomplished in FY-1974 at Oak Ridge, This project is called ORMAK-F/BX for Oak Ridge Tokamak Feasibility and Burning Experiments. The F/BX reference design is now evolving. Conservative projections of plasma behavior indicate that the toroidal field coils must be about 5-meter bore diameter. Superconducting NbTi has been chosen for the TF coil windings and the plasma driving system will use an iron core and return yokes.

Rationale and Concept

Plans for the development of fusion power have generally shown as the next major device after the demonstration of scientific feasibility a plasma test reactor[1] that would involve actual fusion, with appreciable burnup and alpha particle heating.[2] In 1972 a group at ORNL conceived the idea of a tokamak facility designed so that after serving for demonstration of scientific feasibility it could be adapted, at a fraction of the cost of a new

*Operated by Union Carbide Corporation for the USAEC.

facility, for ~~limited~~ D-T burning experiments that possibly could ~~could, however,~~ provide much of the information expected from a plasma test reactor. It was recognized that evaluation of the practicality, risks, benefits, and costs of this scheme would require a significant effort ~~design studies~~. Therefore a conceptual design study has been funded by USAEC-DCTR in FY-1974 and is being conducted at Oak Ridge.

The basic strategy visualized for the facility is as follows. One would conservatively design and build a set of toroidal field coils large enough to demonstrate scientific feasibility, with enough space left over in the toroidal field for the inclusion of radiation shielding and, perhaps, some unspecified innovative experiments. The facility (buildings, cells, etc.) would be designed to accommodate equipment for tritium handling, radiation shielding, and radioactive maintenance, but these features would not necessarily be installed until after scientific feasibility had been demonstrated with hydrogen plasmas. Then the additional investment (which should be less than half the original facility costs) would be made. The original set of TF coils would be retained, having been built large enough for significant D-T burning experiments.

Goals

The basic objective in the first phase of the operation would be to produce, study, and understand hydrogen plasmas at conditions well beyond those in previous devices; specifically, at conditions that meet the zero-power Lawson criterion.

In the D-T burning phase of operations, objectives in the areas of physics and technology can presently be stated rather generally as (1) study and understanding of plasma with appreciable effects of alpha particles, and

(2) experience in design, operation and maintenance of a tokamak with tritium, radiation, and induced radioactivity. Efforts to define more sharply the goals and criteria for the burning experiments are underway. Reaching ignition will not be a criterion, although this may turn out to be possible if plasma losses do not increase as much with temperature as is now assumed. It is not expected that ~~fusion rates and~~ neutron fluences will be high enough to yield useful information on radiation damage.

Guidelines for ORMAK-F/BX Study

Since the concept was an outgrowth of the ORMAK program at ORNL, it came to be called ORMAK-F/BX; the F/BX standing for Feasibility and Burning Experiments. No deliberate attempt was to be made, however, to pattern the device after the existing ORMAK. Instead the conceptual study would begin with fundamental considerations and develop a reference design meeting the basic requirements.[34] About 8 manyears of scientific and technical effort, drawn from the Union Carbide organization that staffs ORNL and the other Oak Ridge plants are to be devoted to the study. By July 1974, the goals are to establish design criteria, to choose a reference design, to assess the practicality and assurance of success, and to estimate manpower, resources, costs, and schedule for design, development, construction, and operation. These results, if favorable, would serve as a basis for further design and, ultimately, construction of an F/BX facility.

Requirements on Design

A basic ~~design~~ precept in the conceptual design is conservatism, both in design methods and technology dependence, to provide the greatest assurance that the facility will be able to fill the important role visualized for it in the CTR program.

In the area of plasma physics, the reference design is based on encountering the high losses associated with trapped-ion effects before Lawson-criterion conditions are reached.[4,5] The reference design also assumes that plasma impurities will be equivalent to $Z_{eff} = 3$ and that in the feasibility experiments the stability factor, q(a), must not be less than 4. Another assumption is that the maximum toroidal field (at the coil bore) will be limited at the outset to 75 kG. These design bases and decisions lead to large plasmas; on the order of 1.7-m minor radius and 5.5-m major radius for the scientific feasibility experiments.

Conservatism in physics specifications inevitably imposes unprecedented demands on technology. One such area is plasma heating, where 5 to 10 MW must be delivered into large plasmas. Another is the toroidal field coils, which must have a bore diameter about 5 m or larger (to allow for 50-75 cm of internal shielding). For the burning experiments, a long pulse is desirable and the reference design requires that the equipment be capable of maintaining the fields and plasma current for 100 sec (assuming that plasma losses will turn out to permit a pulse this long).

A most formidable task, widely recognized but little explored, is that of maintaining and disassembling a tokamak after it has become radioactive. This task is being addressed from the earliest stages of F/BX design, as indeed it must be if maintenance during the D-T burning phase of operations is to be practicable.

Early Results of Study

At this writing the ORMAK-F/BX study is still in its early stages. Nevertheless, some important points have been developed and a few key decisions have been made. Some of these are described below, although it must be emphasized that all are subject to change as the study progresses.

Toroidal Field Coil Material

It has been decided that in the F/BX reference design, the conductor materials in the toroidal field coils shall be NbTi in the form of multiple filaments imbedded in a rectangular matrix of copper or aluminum; (or alloys thereof); the operating temperature, current density, and magnetic field intensity shall be limited so that the NbTi operates in the superconducting mode.

Material of this type has already been developed and there is every reason to expect that sturdy coils meeting F/BX requirements can be successfully fabricated. The decision to go this way in the reference design is basically a judgement that, all things considered, the chances of timely development and construction and reliable operation of F/BX are better with TF coils of this material. In the course of reaching this decision, elementary considerations were used first to narrow the choice to cryoresistive coils (copper cooled with liquid nitrogen) or superconducting NbTi. Water-cooled coils were ruled out because of the high power and the length of the F/BX pulse; several hundred megawatts for 100 seconds appeared prohibitively expensive to supply.

In the comparison between cryoresistive coils and superconducting coils, the following considerations favored the latter.

a. Operation of superconducting coils is steady-state, but resistive coils must be pulsed. The probability of mechanical failure is likely to be greater for the very large, pulsed coils, in which thermal and stress cycles must be repeated tens of thousands of times.

b. Plasma information can be developed more rapidly because the repetition rate of experiments can be higher with superconducting TF coils. In this case the rate is not limited by the TF coils but by other components ~~the ohmic heating windings~~ which can be designed for a higher repetition rate than would be permitted by resistive TF coils.

c. The power required for a superconducting magnet system (including refrigeration) is on the order of 1 MW; for a cryoresistive system, power is higher by a factor of 10 to 100. The smaller power supply is significantly less expensive, probably more reliable, and produces less environmental impact.

d. If ~~experience shows an~~ early experiments show a strong incentive to increase the toroidal field, this is less difficult with superconducting coils. (If the structure is designed for the higher stresses, the permissible field with NbTi can be increased 25% by reducing the temperature from 4K to 2K.)

e. Superconducting windings can operate at a higher current density, permitting thinner coils and improved access to the plasma.

f. Experience with superconducting development and operation will have greater applicability in future devices.

g. The capital costs of the toroidal field system (including magnets, refrigeration, power supply, and protective system) are about half as large with superconducting coils as with cryoresistive coils.

One point favoring cryoresistive coils has to do with shielding in the burning experiments, where the neutron power may be several megawatts. Nearly all of this will be deposited in the shield, but some will heat the TF magnets. ~~This~~ Any heat is simpler to deal with at liquid-nitrogen temperature than at liquid helium temperature because of the extremely low heat capacities at the lower temperature. Consequently a somewhat thicker shield is probably necessary for superconducting coils. (Radiation damage is not expected to be a decisive factor in F/BX.)

Development costs are another point favoring cryoresistive coils, but This point has turned out not to be very weighty, ~~however~~. In the first place, these costs are on the order of one-tenth of the capital costs of the TF systems. Secondly, there is not so much difference as was once supposed. (Cryoresistive coil development costs are now estimated at about half those for superconducting coils.) We once viewed cryoresistive coils at a straightforward scaleup. Then we recognized that constraints of space and power practically demanded asymmetric coils, which entailed much more development. Furthermore this development would not be applicable to tokamak power reactors, where superconducting TF coils ~~are essential.~~ will be an economic necessity.

Plasma Driving System

The plasma current in F/BX will be around 3 megamperes. An important requirement in F/BX is that the system used to create and maintain this current not produce stray magnetic fields that would compromise data acquisition. It now appears that this can be accomplished most effectively and economically by using a system with an iron core and return yokes. Because of the rapid flux change in the early stages of a pulse, the material must be laminated to limit eddy currents; it turns out that standard transformer steel is well suited for this application. The iron parts for F/BX are massive (close to 4000 tons total), so the central core and six return yokes are composed of several parts to facilitate disassembly and assembly of the device.

The primary windings could be located inside the toroidal field coils, to reduce energy requirements, or outside, to ease the assembly and space problems and to move further from the radiation source in the D-T burning experiments. In the latter case they might be superconducting coils, cooled along with the structure holding the toroidal field coils. This choice is presently being weighed.

Vacuum Enclosures

The primary vacuum enclosure is the plasma liner. In the F/BX reference design the liner is of thin metal, not corrugated and without a ceramic section. The secondary vacuum enclosure is required to prevent collapse of the liner and to reduce inleakage. The location of this enclosure profoundly affects the layout, assembly, and maintenance of the device.

Two locations for the secondary enclosure were considered initially in the F/BX study. One was a "bell jar," which would enclose the iron transformer core and yokes, the toroidal field coils, and everything inside them. The second was a toroidal shell between the plasma liner and the toroidal field coil bores. In the course of exploring the implications of these two concepts, we conceived of a third. This is an enclosure that contains the toroidal field coils and everything inside, but not the transformer core and yokes. Such a scheme has advantages from the standpoint of penetration design and maintenance strategy and is now being given most serious consideration.

We anticipate that regardless of the topology of the secondary vacuum enclosure, it will be desirable to can the toroidal field coils to provide an independent vacuum in their thermal insulation. The primary objective here would be to avoid a large thermal cycle and excessive turnaround time when any of a large class of maintenance jobs is required.

Assembly and Maintenance

A practical, basic consideration in facility layout and design of machine internals is the procedure for assembling the primary system. Various schemes have been conceived and layout drawings made to study their feasibility. In any case it is expected that large subassemblies (probably one-sixth) of the toroidal field coils, liner, shield, and other coils will be prepared in a building adjoining the operating area. Each subassembly, weighing around 250 tons, would be mounted on a platform which could be lifted by an air cushion and thus serve as a transport vehicle. A heavy crane would be required to move other items, notably the parts of the transformer yokes.

A tokamak is a complex device, and radiation compounds the difficulty of maintenance. The goals in F/BX are to ensure the practicability of any repair that might conceivably be required and to reduce to the practicable minimum the downtime required for normal maintenance. To this end, maintainability is to be considered in the design of every subsystem. In addition, a maintenance system, consisting of strategies, detailed procedures, special tools, devices, and facilities must be conceived and developed. At the outset of this effort, maintenance tasks are being categorized according to the effects on system vacuum and temperatures. In the case of the burning experiments, the possibilities for personnel exposure to tritium or to radiation from induced radioactivity are also being considered.

A Layout

An impression of the magnitude of F/BX is conveyed by Fig. 1, which is a half-section through the torus in one of the configurations that is being investigated. At the left is a 3.4-m-diameter iron core, capable of providing 25 volt-seconds to the plasma. The bore diameter of the TF coil shown here is 5m and the diameter of the plasma liner is 3.4m. (The indicated dimensions were selected to begin layout studies before optimization calculations were completed, but are believed to be reasonably close to those that will be required.) This particular configuration is one in which the ohmic heating coils are of superconducting material, located in the thermal envelope surrounding the bucking rings that resist the centering force of the toroidal field coils. The base structure is an air-cushion vehicle, brought into alignment and supported by jacks.

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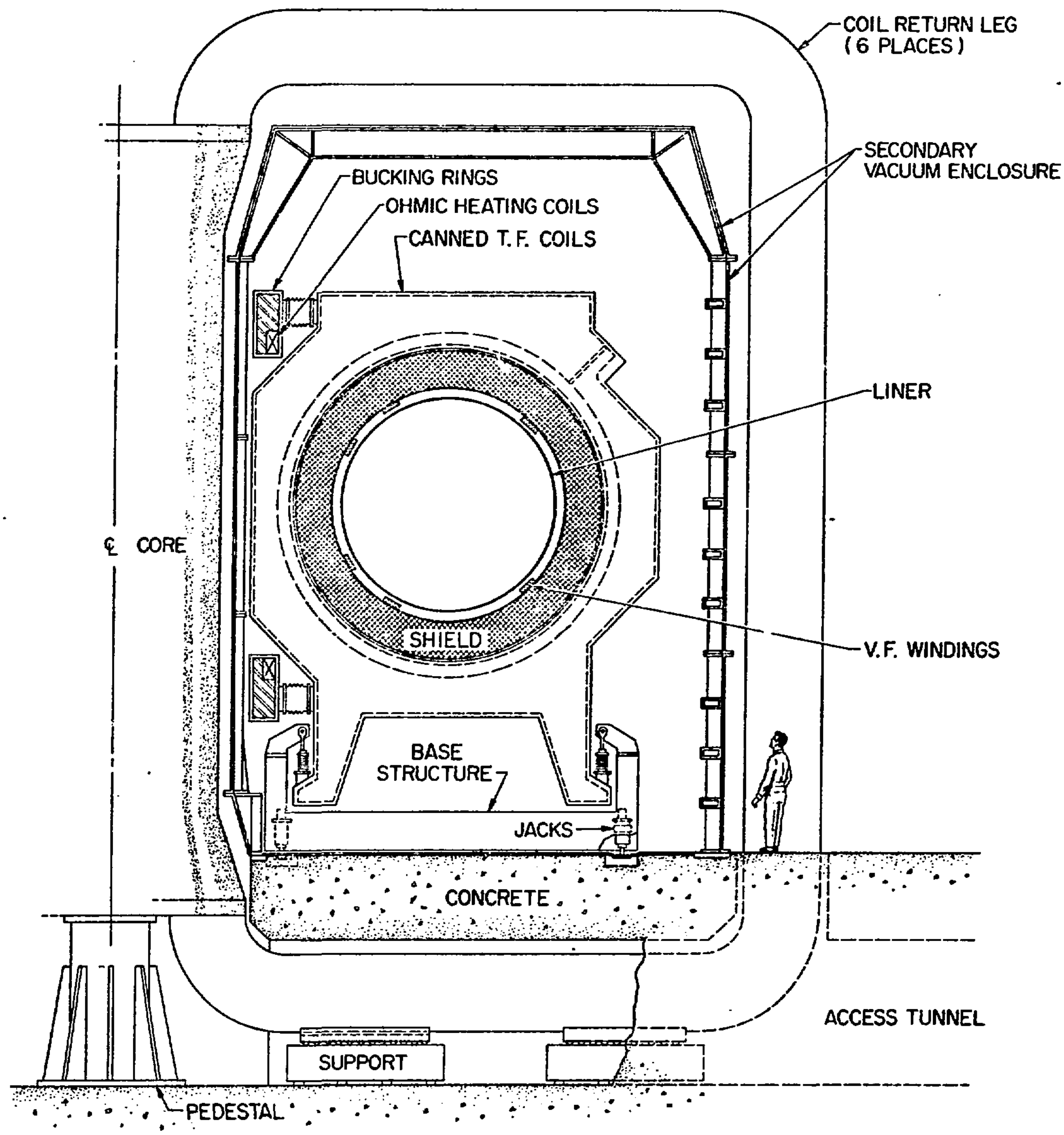

BURNING EXPERIMENT