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ENGINEERING DESIGN OF A FUSION TEST REACTOR (FTR) AND FUSION ENGINEERING RESEARCH FACILITY (FERF) BASED ON A TOROIDAL THETA PINCH

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Abstract

ENGINEERING DESIGN OF A FUSION TEST REACTOR (FTR) AND FUSION ENGINEERING RESEARCH FACILITY (FERF) BASED ON A TOROIDAL THETA PINCH.

This paper describes two advanced toroidal theta-pinch devices which are being proposed for future construction. The Fusion Test Reactor (FTR) is being designed to produce thermonuclear energy (at 20 MeV/neutron) equal to the maximum plasma energy ($Q = 1$) and to demonstrate α-particle heating. The Fusion Engineering and Research Facility (FERF) is being designed to test materials in a fusion environment where the average 14-MeV neutron flux from the plasma is $\gtrsim 5 \times 10^{13}$ n/cm$^2 \cdot$s over large surface areas. These devices employ the staged theta-pinch principle where the heating is accomplished by rapid (~ 0.1 μs) implosion and expansion followed by a slow compression of the plasma. The rapid implosion injects as much heat as possible at as large a plasma radius as possible so that the plasma remains stable even after further compression. The final compression to ignition requires the transfer of a large amount of magnetic energy which implies a long transfer time (~ 1 ms) for realistic voltages in the driving circuit.

Throughout the heating and burn cycle the plasma must remain in equilibrium and stable to the dominant MHD-modes. A sufficiently large plasma radius guarantees stability against the $m = 1$ modes. These equilibrium and stability conditions and the requirements on thermonuclear burn determine the design parameters for either machine. The design parameters must also be consistent with economic limitations and technological feasibility of components. In addition to these requirements, the FERF must provide a steady and reliable source of fusion neutrons.

THEORETICAL CONSIDERATIONS FOR FTR AND FERF

Equilibrium and Stability

The equilibrium and stability conditions for high-β, toroidal plasmas are taken from the sharp-boundary MHD theory of Freidberg [1]. For equilibrium,

$$f_o\delta_o + f_2\delta_2 = \frac{1}{h^2 aR\delta_1} \qquad (1)$$

and for $m = 1$ stability,

$$\left(\frac{a}{b}\right)^4 \geq g_o\left(\frac{\delta_o}{\delta_1}\right)^2 + g_2\left(\frac{\delta_2}{\delta_1}\right)^2 + g_1\ (ha)^2 \qquad (2)$$

where R is the major radius, b is the inner radius of the implosion coil and a is the plasma radius; the parameter h is the wave number of the $\ell = 0$, 1 and 2 perturbations of the plasma, and δ_o, δ_1, and δ_2 are the magnitudes of these perturbations normalized to a. The quantities f_i and g_i are functions only of β [1]. A similar theory including only $\ell = 0$ and 1 perturbations was previously given by Freidberg and Ribe [2]. Stability is improved by letting $R \to \infty$, $\delta_1 \to \infty$, and $b \to 0$; the finite values of these three quantities are determined by economic and technological considerations. The largest value of R permitted by economics is approximately 40m. The smallest allowed value of b is determined by the finite thickness of the plasma sheath and is taken to be 10.5 cm. In the absence of supporting experimental data for larger δ_1, the value was set at 1.5, although larger values reduce the machine size and costs substantially. By eliminating h between Eq. (1) and Eq. (2) and by varying δ_o and δ_2 to minimize a, the minimum allowed value of a is given by

$$\check{a} = b \left[\frac{3^{3/2}}{2} \frac{g_1 b}{\delta_1^{\,2} R} \left(\frac{g_0 g_2}{g_2 f_o^{\,2} + g_o f_2^{\,2}} \right)^{1/2} \right]^{1/5} \tag{3}$$

For $\beta = 0.8$ the minimum plasma radius equals 3.14. This value of $\check{a}$ corresponds to $\delta_o = 0.12$, $\delta_2 = 0.10$, $\lambda = 2\pi/h = 3.4$ m. Any heating and burn sequence has to maintain $a > \check{a}$ as well as satisfying the requirements for thermonuclear burn.

Compression and Burn

A computer code has been developed which models the plasma compression and burn to determine the plasma stability and Q-value. The model includes α-particle production and heating, electron-ion energy equilibration, and bremsstrahlung losses [3]. Less important effects such as classical diffusion and more realistic density profiles will be included in the future. The required input for these calculations are the normalized plasma radius and ion temperature after implosion, $x_{SH} = a/b$ and T_{SH} respectively, and a functional form for the time dependence of the compression field, B(t).

Implosion Heating and Staging

Unlike the compression phase a strong interaction between the driving circuit and the plasma behavior is incurred during the implosion and staging phase. Strong technological limits are placed on the implosion circuit by the sub-microsecond time scale of the implosion phase and the necessity for maintaining the implosion field for hundreds of microseconds during the rise of the compression field. These considerations require the computer code to simultaneously model the behavior of a realistic implosion circuit and the plasma.

Initially the NET-2 circuit code [4] was used to model both the circuit and the plasma during implosion and staging, and modeling of the plasma by this code can be done only approximately. Because the Q-value and plasma stability predicted during the compression phase is sensitive to the values of x_{SH} and T_{SH}, a more sophisticated model is needed to describe the behavior of the plasma during the implosion phase. A computer simulation has been developed which describes the plasma behavior but does not include an external circuit [5]. A more advanced simulation is being developed [6] which includes the external circuit as well as anomalous electrical resistivity, electron heating, and ion isotropization.

ENGINEERING DESIGN OF THE FTR

The theta-pinch FTR is an 80 m diameter, 0.2 m minor diameter toroidal device with plasma parameters to meet breakeven (Q = 1) conditions when operated on DT. The FTR involves a number of technological departures from present-day toroidal theta pinches;the magnetic field is produced by a high-voltage, implosion-heating bank, which "stages" into a slow compression supply consisting of switched superconducting magnetic coils and a capacitor "transfer" bank to allow high transfer efficiencies. As presently envisioned, a 150 MJ capacitive energy store will initially be used to generate the 50 kG compression field. These capacitors will eventually serve as transfer elements for the superconducting inductive store in the second phase of operation. To minimize the refrigeration costs associated with the superconducting energy store, the repetition rate is once every 15 minutes. On the average 4 DT discharges/d will be made ($\sim$1000 DT discharges/y), each of which requiring nominally 15 mg of tritium.

General Aspects of the FTR

Figure 1 illustrates the general arrangement anticipated for the FTR facility. The functions of vacuum wall, primary tritium barrier, and end-fed implosion heating coil will be performed by a copper/insulator composite now under development at LASL. A magnetic material will provide a return path for the implosion-heating field between the concentric implosion coil and the multiturn compression. coil. Current feedplates are anticipated approximately every 1/4 helical wavelength. These components and the associated pulse-forming and staging capacitor bank will be located within a leak-tight, toroidal cell. The FTR discharge tube will be modularized into $\sim$1/4 wavelength segments and will also support a primary radiation shield (to reduce neutron activation of the cell air and the implosion-heating/staging capacitors). Provisions are made for semi-remote replacement of the discharge tube modules and limited personnel access to the FTR cell after a DT discharge. Implosion heating power supplies and triggers, crowbar switches, high-voltage interrupters, transfer capacitors, superconducting energy store, tritium handling facilities, and plasma diagnostics will be located immediately adjacent to the FTR cell.

Electrical Aspects of the FTR

Thermonuclear burn calculations indicate that $\sim$50 kG compression fields will be required for periods of $\sim$30 ms to obtain $Q \geq 1$ and to maintain plasma equilibrium and stability. The circuit shown in Fig. 2b is being considered for generating the required time-dependent compression field, This circuit contains a superconducting storage coil which is energized while the interrupter switch is opened and the stored magnetic energy is resonantly transferred to the compression coil by means of the transfer capacitor. When the transfer is complete the crowbar switch is closed resulting in a 50 ms L/R decay time. The voltage rise during transfer and the current in the storage coil (which must be interrupted by vacuum breaker) are determined by the stored energy in a module and the transfer time. With 375 kJ per module transferred in 1 ms, the current-voltage product is 20 kA times 60 kV. Vacuum breaker technology and the current carrying limit of ac superconducting wire indicate that 20 kA is the largest current one should use; hence, the peak voltage during transfer is 60 kV. The long L/R times required by the field decay, and the energy and current in a storage module both require a high inductance multi-turn compression coil.

The short time scale of the implosion requires that the low inductance coil have less than one turn. Hence, separate coils must be used for implosion and compression. The implosion coil is located concentrically inside the multi-turn compression coil and a magnetic material is placed between the two

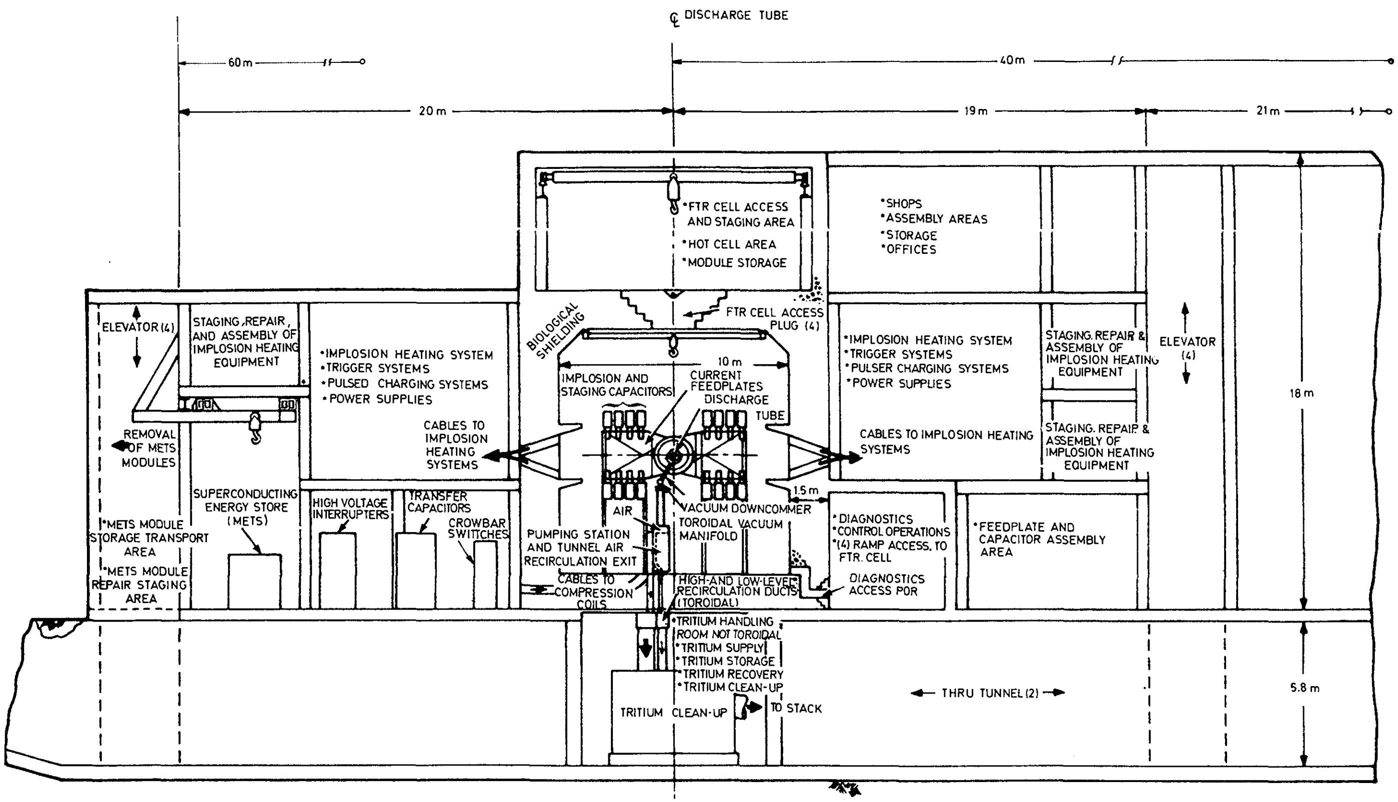

FIG. 1. Elevation view of proposed FTR experimental facility. All rooms and power supply components are drawn to a realistic scale.

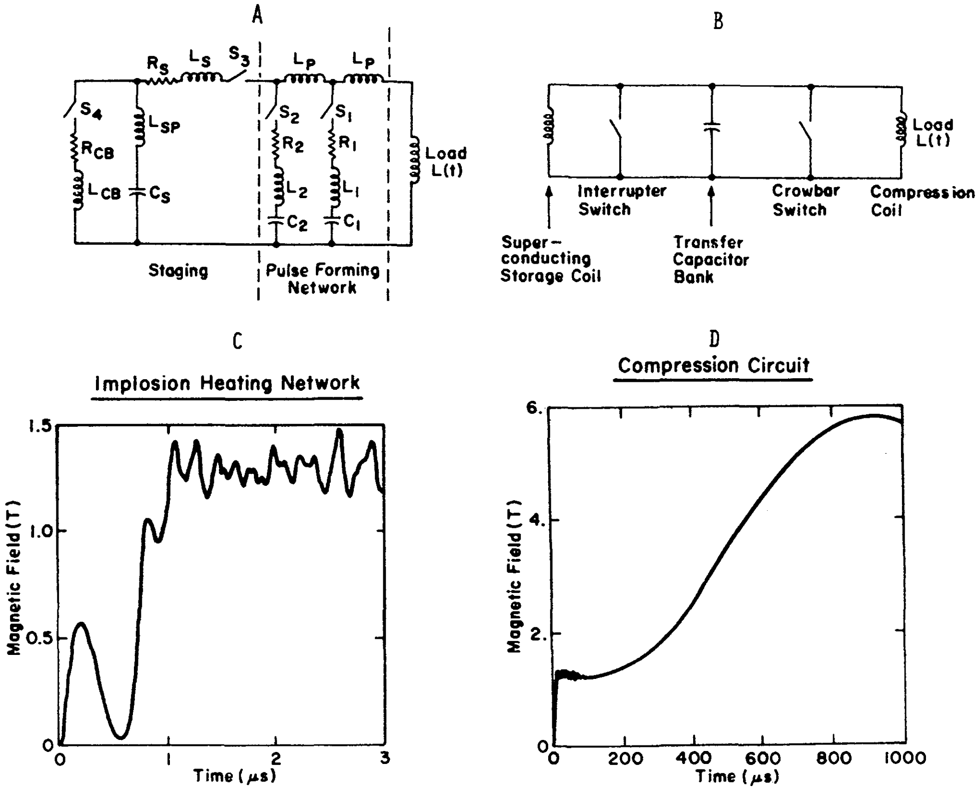

FIG.2. Implosion heating, staging and compression circuits for the FTR.

coils to minimize magnetic coupling. The results of a simple implosion calculation for the realistic circuit depicted in Fig. 2a is shown in Fig. 2c. The first pulse is produced by closing S_1 followed by closing the staging bank switch S_3 at about 400 ns. The current from the staging bank C_3 rises in about 1 μsec. The sharp risetime of the second pulse is achieved by closing the second switch S_2 at about 600 ns. The crowbar switch S_4 is closed at peak field at about 1.2 μs .

As noted previously the effectiveness of compressional heating depends sensitively on x_{SH} and T_{SH}. More realistic calculations, which combine non-linear circuit analyses with the results of plasma simulation models, are being developed to examine both the double-bounce scheme depicted in Fig. 2c and the single-bounce implosion technique.

Radiological Aspects of the FTR

Central to the FTR design depicted in Fig. 1 are the precautions associated with the handling of gram quantities of tritium and the intense neutron fluxes anticipated during a DT burn. The major portion of the 2.3 g tritium inventory will be stored in a vault beneath the FTR cell. Each ~15 mg quantity of tritium required per discharge will be released from and subsequently collected on uranium beds; these beds will contain only a few weeks tritium supply based on a schedule of 4 DT discharges/d. Tritium injection and recovery will be via the cryogenically pumped vacuum system. A low-level and a high-level tritium clean-up system will operate respectively on routine and accidental tritium releases.

For every percent DT burned the FTR will yield $\sim 10^{19}$ (14 MeV) neutrons. Component activation, radiation damage to organic materials, air activation, and the biological hazard associated with these neutron intensities represent some of the design considerations upon which the system depicted in Fig. 1 is based. The primary shielding surrounding the FTR torus is selected to reduce air and capacitor activation as well as to shield maintenance personnel from long-lived radiations emanating from the vacuum-wall and magnetic coil assemblies. Although almost a year's operation (4 DT discharges/d) is required before the damage threshold is reached in the implosion-heating/staging capacitors, anticipated neutron fluxes at the vacuum wall preclude the use of organic vacuum seals. Long-term activation of the FTR modules is associated primarily with copper (conductors) and iron/nickel (ferrite); although the use of aluminum conductors is being considered, the long-term activation of modules will necessitate remote handling.

FERF DESIGN

A FERF (Fusion Engineering Research Facility) is needed to study materials radiation effects and to test reactor components under realistic fusion reactor operating conditions prior to the building of power reactors. Such a facility

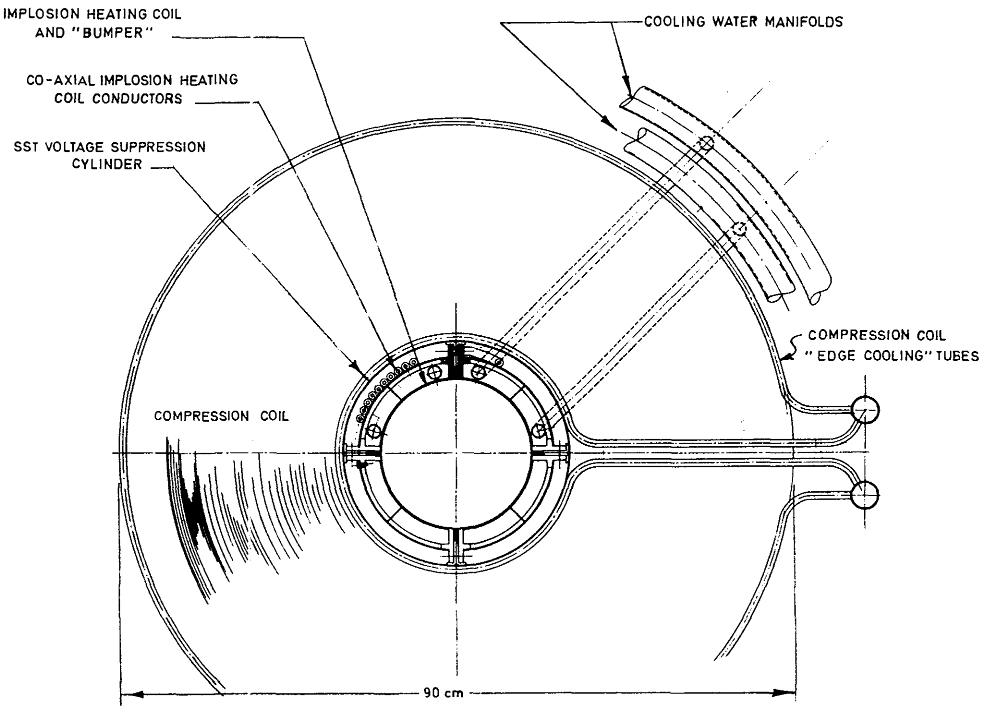

FIG.3. FERF-module cross-section.

is essentially a fusion reactor, and although it must simulate, at least in model scale most of the effects expected in a reactor, it will consume rather than produce electrical power and tritium. The facility must be large enough to accept hundreds of creep, fatique, rupture, embrittlement, sputtering, blistering, etc. materials experiments along with test reactor modules. At the same time it must provide a sufficiently intense environment that simulated lifetime tests can be accomplished in less than several years.

The design selected for the theta-pinch FERF is similar to the Reference Theta Pinch Reactor (RTPR) [7] in many respects. However, choices for dimensions, energy-storage systems, magnetic coil circuits and other parameters have been altered from the RTPR to emphasize economics and near term technology. The design uses water-cooled, aluminum implosion heating and compression coils. (Fig. 3) Modular assembly of these coils within an aluminum-lined, concrete shielded tunnel permits remote handling of the active core or experimental elements for replacement or repair. The fuel stream is processed by cryogenic rectification and titanium gettering to remove helium, protium and other impurities from the circulating DT mixture. Experimental areas are available both within and external to the DT plasma chamber. Beam ports originate in the plasma chamber, penetrate the shielding and terminate in the experimental area of the facility. Within the chamber alternate modules designed for specific radiation damage or engineering testing may be used. Remote handling methods are available for replacing both standard and test core modules. A hot cell facility is coupled with the handling systems for replacing, servicing, processing and testing the standard or test modules. These module handling facilities are shown along with an arrangement of the shielding, beam tubes and vacuum ports in Fig. 4.

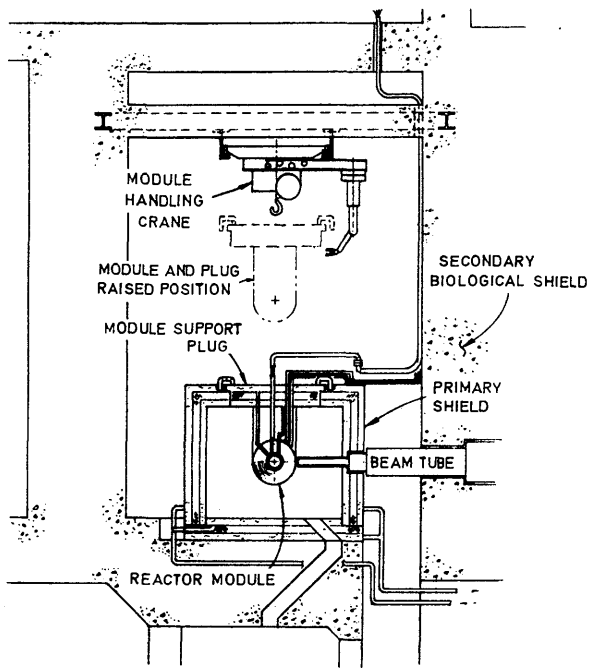

FIG.4. Module handling arrangement.

TABLE I. DESIGN PARAMETERS

R	major radius	35 m
b	minor radius	10 cm
ϕ(r = 10 cm)	average 14 Mev neutron current	6.7×10^{13} n/cm^{2}sec
β	plasma beta	0.9
δ_1	amplitude of $\ell = 1$ modulation $\div$ a_o	1.5
δ_o	amplitude of $\ell = 0$ modulation $\div$ a_o	.362
λ	wavelength of $\ell = 0$, 1 modulations	4.1 m
a_{sh}	plasma radius after implosion heating	7.6 cm
a_o	minimum plasma radius	3.8 cm
E_θ	implosion heating electric field	3.7 kV/cm
B_s	implosion heating magnetic field	25.3 kG
B_o	compression magnetic field	80 kG
R_I	inside radius of compression coil	13 cm
ΔR	thickness of compression coil	17.7 cm
ℓ	implosion heating coil length	0.50 m
R_p	coil load impedence (7)	0.2 ohm
L_L	coil inductance and associated co-axial leads	27 ph/m
J	first wall, 14 MeV neutron current (average)	6.7×10^{17} n/m^{2}s
J_R	compression field rise time	85 ms
J_C	cycle time	1 ms
COST	Implosion energy store installation	43 M$
	5 year operation*	24.4M$
	Compression energy store**	79.6M$
	5 year operation*	91.4M$

* power (1.14×10^5 $/MW-yr) and one complete replacement of capacitors

** calculated for conventional capacitors @ 6¢/J

Plasma Systems

The operating parameters are chosen to obtain the desired neutron flux while satisfying the requirements of plasma stability, implosion heating, high-voltage technology, plasma cooling, and fuel replenishment. The minimum minor radius, compatible with the requirements of implosion heating, was selected to obtain the smallest possible machine. The major radius, compression magnetic field, minimum plasma radius, $\ell = 0$ plasma displacement, and pitch number of the helical field are selected to satisfy the requirements for toroidal equilibrium, wall stabilization of the $m = 1$ mode, and finite gyroradius stabilization of the $m > 1$ modes [2]. The parameters of the design are given in Table I.

The rather fat ($a/b = 0.38$) plasma is obtained with a shock electric field less than predicted [8] due to alpha particle heating during a slow compression. Implosion heating is driven by a four-gap coil with 60 kV/gap. The insulation of the co-axial leads and the gap is connected by bonding a sleeved joint many insulation thickness long while the conductors are oven brazed to the respective sides of the gap. The caluclated risetime of the current (L_L/R_p) is 80 ns.

Thermonuclear burn is calculated with the DT burn code [3]. A sinusoidal field pulse shape is employed that affords reversible energy transfer by LC resonance of the compression coil with the homopolar capacitors used for energy storage. The slowly rising compression field dictates a new approach to staged heating. Before ionization, the compression field is allowed to rise to B_s. Then, the implosion coil is energized in ~100 μsec to that the field inside it is nulled and the flux transferred to an annulus between the implosion and compression coils. Ionization, which was avoided during the flux transfer by the relatively long time involved and the presence of the field, is accomplished during the null window created in the slowly rising field. Implosion heating occurs when the current in the coil is interrupted, which is accomplished by energizing the coil through a self-disrupting plasma switch of the type now under investigation for inductive energy transfer [9]. Then the field is immediately supported by the compression coil.

The dimensions of the coil structure are cost optimized by a computer program that includes the cost of compression field energy (1¢/J for homopolar generator/capacitors [10]), implosion energy storage (50¢/J), "window" energy storage (6¢/J), and operating expenses (5 years) including power (1.3¢/kwh) and capacitor replacement costs are given in Table I.

Neutronics

The neutronics calculations were carried out by a four region, one-dimensional cylindrical model. The reactor module includes the plasma chamber and coil regions (aluminum and water) (45cm maximum radius). The primary shield is 42 cm thick and consists of 2 cm aluminum as a tritium barrier, 28 cm of water, 10 cm of lead, and 2 cm of iron. The biological shield is 2.5 m of borated concrete. The experimental space includes all open space around the coils, the space between adjacent modules and inside the beam tubes. The total energy deposition in the system is 17.86 MeV per DT neutron (82.4% in the two coils, 17.4% in the primary shield, and .2% in the biological shield). The total neutron flux attenuation in the system is about 10^{15}. The maximum gas (H, He, D, T) production rate of 1155 ppm/y occurs at the inner surface of the implosion heating coil. Magnesium was found to be produced at a high rate from the AL(n,n'p) reaction (1100 ppm/y at the first wall). The total activity at shutdown is 5.4×10^8 Ci which decays in 10 days to about 200 Ci. Most of the short-lived activity is due to Na^{24} (half-life 15 hours) produced

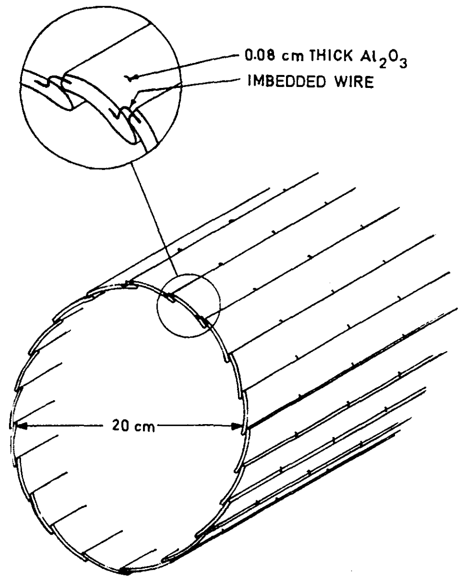

FIG.5. First-wall plasma bumper.

by the Al(n,α) reaction. The longest-living radioactive isotope generated is Al^{26} with a half-life of 740000 years and represents the main concern with respect to long-range biological hazards. (.2 km^3/W_{th}).

Cooling

Temperature oscillation due to gamma ray and bremsstrahlung radiation from each reactor pulse will not cause significant thermal shock or stresses. The energy in the plasma at the end of burn, however, can cause unacceptably large thermal fatigue effects. It is planned to allow this plasma energy to be slowly transferred to the wall, by the use of a gas blanket [7]. A conservative 10 milliseconds transfer time results in about an 80 K temperature rise of the alumina insulator surface facing the plasma after the plasma energy, (486 j/cm) is transferred to the wall. This temperature oscillation each pulse (one second) may limit the first wall lifetime to unacceptably short times. To give a margin of safety, a "First Wall Bumper" is proposed for use here [11]. The bumper is a radiation cooled liner (figure 5) inserted between the plasma and the implosion heating coil. Its function is to absorb the energy from the plasma, intercept high energy particles, and reduce the thermal stress in the composite first wall. More details of the bumper system are given in References [11] and [12].

Tritium Handling and Containment

The main fuel stream of the FERF is processed by a cryogenic distillation system similar to that designed for the theta-pinch RTPR [7]. A two-column separation system including catalyzers, thermal equilibrators, heat exchangers and Joule Thompson expanders are used to separate the helium and about 95% of the protium (from DD reactions and (n,p) reactions with structural materials) from the partially burned ash from the plasma chamber; the DT isotopomers are recycled to fuel storage. The protium and traces of DT are oxidized to water, scrubbed in molecular sieve traps and processed for storage/ disposal.

Tritium containment for the FERF appears to be more manageable than for the RTPR [7], because the FERF has no blanket system and no high temperature heat exchangers. The aluminum-liner construction greatly facilitates tritium containment because the tritium permeability of aluminum is extremely low over the operating temperature range of the inner structure (20 to 100°C). Tritium losses by permeation into the coil-coolant (water) and the shield structure is less than 10^{-5} Ci/d.

Materials

Aluminum is used for the basic metal for FERF to minimize the induced radioactivity. Pure aluminum has excessive void swelling rates of 2% by volume per year, but other low strength aluminum alloys look promising. Because of this low strength the stresses, particularly the cyclic stresses, must be kept to low levels. A preliminary stress calculation for the FERF coil indicated that it should be possible to keep the stress below 35 MPa (5000 psi) for an 80 kG coil.

The greatest unresolved materials problem for the FERF design are the effects of the gas produced inside the metal by the radiation and void swelling. The void swelling problem present in aluminum at room temperature may reduce the dissolved gas concentration in the metal by providing a high density of sinks for the gas atoms, but the swelling rate may be increased when the voids are stabilized by the gas atoms and when the gas atoms can increase the nucleatinn rate of the voids. A definitive answer to whether the swelling rate in aluminum can be kept to an economically acceptable rate below about 1% by volume per year by alloying, even with the anticipated high rate of gas production in the metal, cannot be given without improved experimental evidence. Such data should be available within a few years from heavy ion irradiation with simultaneous gas injection experiments.

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