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Engineering Status of the Fusion Ignition Research Experiment (FIRE)

by

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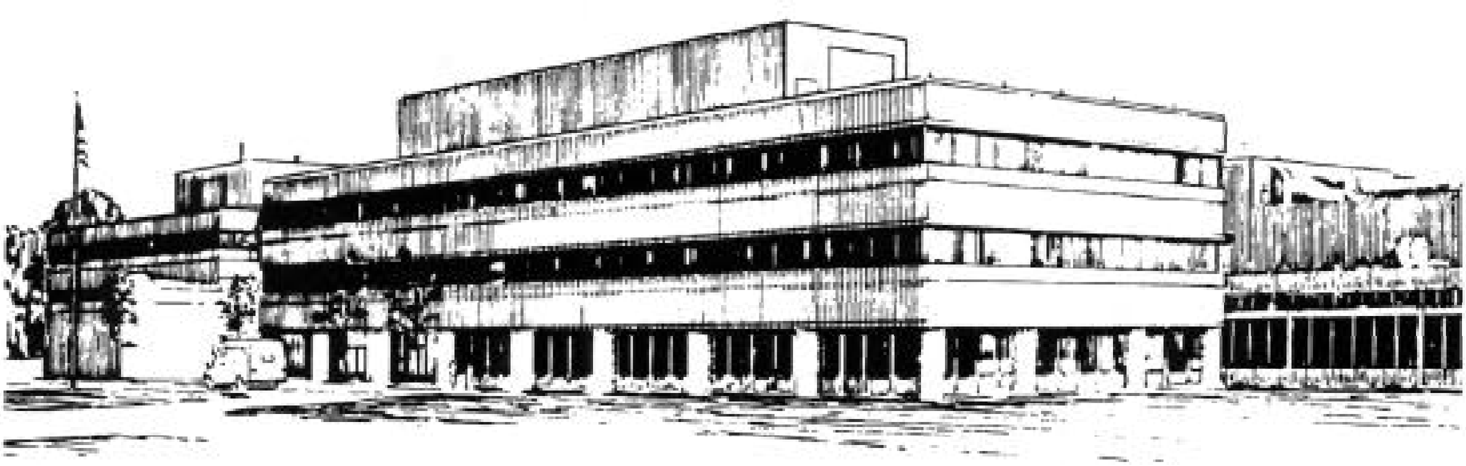

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ENGINEERING STATUS OF THE FUSION IGNITION RESEARCH EXPERIMENT (FIRE)

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ABSTRACT

FIRE is a compact, high field tokamak being studied as an option for the next step in the US magnetic fusion energy program. FIRE's programmatic mission is to attain, explore, understand, and optimize alpha-dominated plasmas to provide the knowledge necessary for the design of attractive magnetic fusion energy systems. This study began in 1999 with broad participation of the US fusion community, including several industrial participants. The design under development has a major radius of 2 m, a minor radius of 0.525 m, a field on axis of 10T and capability to operate at 12T with upgrades to power supplies. Toroidal and poloidal field magnets are inertially cooled with liquid nitrogen. An important goal for FIRE is a total project cost in the $1B range. This paper presents an overview of the engineering details which were developed during the FIRE preconceptual design study in FY99 and 00.

I. FEATURES AND DESIGN GOALS

Details of FIRE are shown in Figs. 1 and 2. This design configuration was driven by several major choices made early in the study:

- A highly shaped plasma with internal active feedback control coils and space for wall stabilization;
- Double null divertors;
- Cryo cooled copper resistive magnets. This permits a compact, high field design which is important to the achievement of cost goals.
    - Wedged copper TF coils. Beryllium copper is used on the inner leg; the remainder is oxygen free copper.
    - Copper segmented solenoid and copper ring coils.
- Double walled vacuum vessel with internal steel / water shielding.

The major goals set for FIRE are given in Table 1. The baseline design meets or exceeds these objectives.

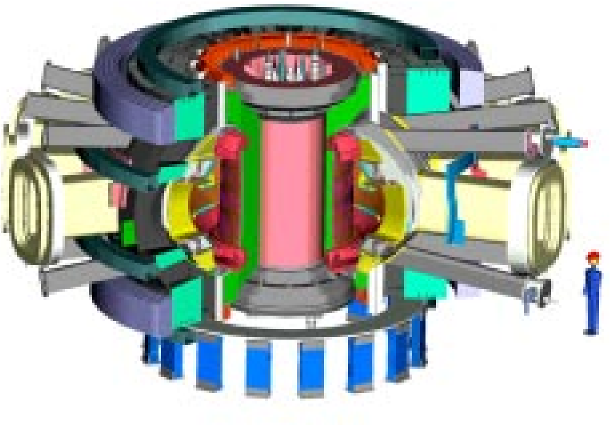

FIG. 1. AN ISOMETRIC VIEW OF THE FIRE TOKAMAK

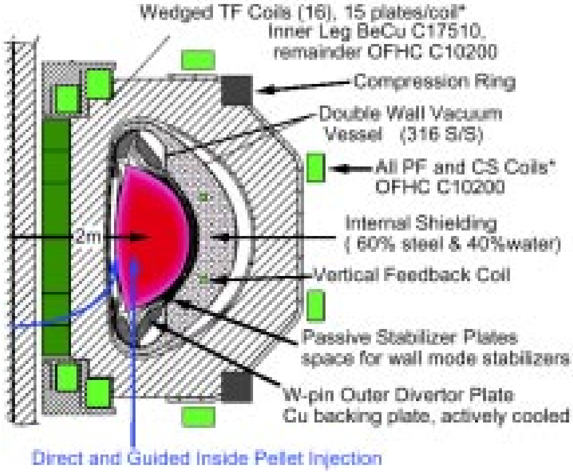

FIG. 2. AN ELEVATION VIEW OF FIRE

R(m); a(m)	2.0; 0.525
κ_{95}; δ_{95}	~1.8; ~0.4
q_{95}	>3
B_t (T)	10 (12)*
I_p (MA)	6.44 (7.7)*
Flattop time (s)	~20 (12)*
TF Ripple (%)	0.3 (edge)
Fusion power (MW)	100-200
ICRF power (MW)	30
Design life (full power / 2/3 power)	3,000 / 30,000

*Upgrade higher field mode

TABLE 1. MAJOR DESIGN GOALS

II. ENGINEERING SYSTEMS

A . TOROIDAL FIELD (TF) COILS AND STRUCTURE

The TF system consists of (16) partially cased wedged coils constructed of radially oriented copper plates insulated with glass epoxy (see Fig. 3). The plates in the inner legs are made of C17510 BeCu copper; the plates in the balance of the coil are made of C10200 oxygen free copper. Torsional shear developed by the interaction between the TF coil currents and PF coil fields crossing them are reacted by friction generated between the wedged turns. Centering forces supply the wedge pressure at the equatorial plane. A large pair of compression rings, shown in Figs. 1 & 2, assures adequate wedge compression at the upper and lower inner leg corners. At 10 T the TF system is capable of 18.5 s flat top pulses with DT and 26 s with DD. At 12T, the TF system is capable of 12 s with DT and 15 s with DD. Each turn has LN_2 passages which achieves re-cooling the coils to 80K between pulses (i.e., 3 hrs.) This passage is drained during shots to avoid activated nitrogen.

B. CENTRAL SOLENOID AND POLOIDAL FIELD COILS

The central solenoid consists of a free standing five segment solenoid. The outer poloidal field coils consist of 4 symmetric pairs of ring coils. All are fabricated of C10200 copper and are cooled with LN_2 via passages between coil layers.

C. VACUUM VESSEL (VV)

The VV is a double walled stainless steel vacuum vessel with steel / water shielding between the walls. This, in conjunction with port shield plugs, decreases the dose rate on the TF coils and permits hands on maintenance outside. The vessel is fabricated in quadrants of 316 stainless steel. Each quadrant has a large midplane port, angled ports above and below the mid plane, and vertical ports top and bottom. Since carbon is not used, high temperature bakeout is unnecessary. The vessel operates at 100 C. The field joint between quadrants uses splice plates to accommodate assembly tolerances and to permit accessing of the outer weld joint. This type of joint has undergone full scale testing using remote welding equipment as part of the ITER R&D program.

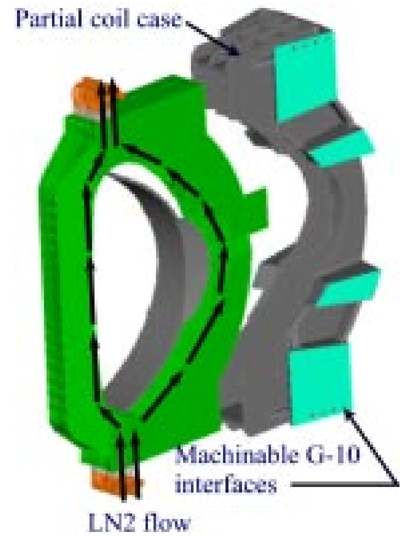

FIG. 3. TF COIL AND CASE DETAILS

D. DIVERTOR AND PLASMA FACING COMPONENTS

The FIRE divertor components are shown in Fig. 4. The outer divertor plate and baffle are actively cooled; the inner divertor plate and first wall armor are conduction cooled to the copper clad vessel walls. The peak operational heat loads are expected to be 20-25 MW/m^2, 6 MW/m^2, and 3 MW/m^2 for the outer divertor, baffle, and inner divertor regions. Each outer divertor and baffle ring is assembled of 16 modules designed to be remotely handled. The inner divertor plates are common in design with the first wall and consist of beryllium coated copper tiles attached to the clad vessel walls by spring washer loaded quarter turn fasteners. This attachment method permits the tiles to be individually replaced in the event of disruption damage with the planned in-vessel remote manipulator. The outer divertor module design builds upon the fabrication technologies developed for ITER. The high heat flux material, so-called “tungsten brush”, consists of tungsten rods bonded to water cooled copper alloy plates. They have been tested at 25 MW/m^2.

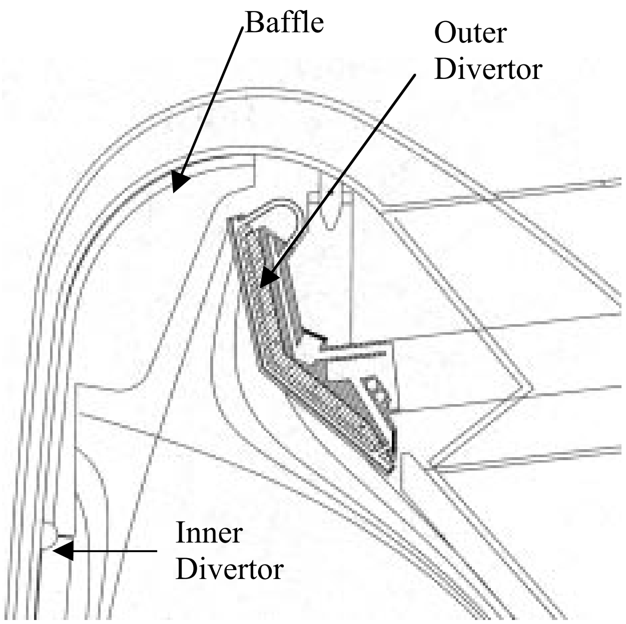

FIG. 4. FIRE DIVERTOR

E. THERMAL SHIELD

FIRE will be enclosed in an insulating thermal shield which provides an insulating environment for the LN_2 cooled magnets. The shield consists of a foam spray insulated thin stainless steel shell supported by a stainless steel structure. Penetrations will be sealed with rubber/fabric bellows which are designed to accommodate the relative motion between the VV and shield.

F. ION CYCLOTRON HEATING (ICH)

Plasma transport calculations indicate the need for 30 MW of ICH heating. This power is delivered by four two-strap antennae located in four of the main horizontal ports. With a 6 cm gap to the plasma, 30 MW can be delivered at 150 MHz and a limiting voltage of 35 kV. At 100 MHz, full power requires a gap $\leq$ 3.5 cm.

G. FUELING AND PUMPING

FIRE is fueled by a combination of gas puffing and pellet injection to achieve and maintain the burning plasma. Gas will be puffed from three sets of injectors located at the outside mid-plane, vertically, and from the inside lower quadrant. Tritium rich pellets will be used for core fueling; deuterium rich pellets will be used for edge fueling. Pumping is provided by a set of refrigerated duct D-T cryo condensation/diffusion pumps backed by turbo pumps. A total of 16 cryopumps (8 top, 8 bottom) are located at alternating divertor ports.

H. TRITIUM

On site tritium inventory has been set at 30 g to permit operational flexibility without introducing additional restrictions. This can be reduced if a tritium reprocessing system with daily reprocessing is added.

I. POWER

A 10 T pulse will require 13.7 GJ of energy; the TF will require a peak power of 490 MW, and the PF 250 MW. At 12 T the TF energy is approximately the same because of temperature limits in the magnet, but the PF energy requirements increase. The total energy in this case is 15.2 GJ, with peak powers of 815 MW for the TF and 360 MW for the PF.

J. CRYOPLANT

Liquid nitrogen will be provided by large (520,00 gallon) liquid nitrogen storage tanks located on site. These tanks are sized for a two day supply at 4 shots/day. The tanks will be replenished by a new on-site (or near site) air liquefaction plant with pipeline delivery. The magnets are kept cold except during maintenance periods. Only 50 cool downs are anticipated during the life of the machine.

III. NEUTRONICS

A. ACTIVATION, DECAY HEAT, AND RADIATION EXPOSURE

The shielding provided by the double walled vacuum vessel and port plugs permit hands on maintenance outside the magnets at the midplane within a few hours of shutdown. The dose rate at the top of the machine drops to an acceptable level within one day after shutdown. The dose rates behind the vacuum vessel and divertor remain high .

B. SHIELDING

The average nuclear heating for the walls for 200 MW fusion power DT pulses is 3 MW/m^2. The insulation dose is 1.5 x 10^{10} rads for 3,000 full power pulses (5 TJ of fusion energy) plus 30,000 DD pulses (0.5 TJ of fusion energy). This peak end of life value occurs at the TF magnet surface on the inboard mid plane. Experimental data indicates that polyimides and bismaleimides exhibit only a small degradation in shear strength at a dose of 10^{10} rads and will probably be acceptable. Newly developed insulations, such as cyanate esters are being investigated. These may have suitable radiation properties in addition to being easier to process.

IV. FACILITIES, REMOTE HANDLING, AND SITING

Conceptual layouts have been developed for FIRE's facilities, assuming a new, "green field" site. The test cell design was greatly influenced by remote handling requirements. Components that require remote handling include those located in the vessel interior and in the ports. These parts will be removed from the vessel or port and transferred to handling casks using a cantilevered boom mounted remote handling system. The test cell size is ~39m x 39m. and is determined by the space required to maneuver and dock remote handling casks at ports. The casks would transfer the component to the hot cell where they are refurbished or processed as waste. The hot cell concept is based on the expectation that some port mounted components can be repaired and returned to the tokamak. The hot cell processes are expected to include divertor repair, tritium recovery from beryllium, size reduction by sawing or cutting, and encapsulation of radioactive material for subsequent shipment to a waste repository.

V. COST ESTIMATES

An important goal for FIRE is for the project cost to be in the $1B (FY 99) range. Preliminary cost estimates have been prepared and are currently being internally reviewed. Preliminary estimates indicate a project cost of approximately $ 960.0 M (before contingency) and $1.193.0 B (FY 99), including an average contingency of 24.6%.

VI. FUTURE DIRECTIONS

Activities are underway and will continue in FY 2001 which may result in improvements to the guidelines currently being used to develop FIRE. Discussions with the Next Step Options Physics Advisory Committee (NSO-PAC) at their meeting in August and with the US Fusion Community indicate a desire for increased physics performance to offset a range of more pessimistic physics assumptions. Several options are being studied which may permit the operating performance to be improved without significant impact on FIRE's costs. Physics studies include operating modes which exploit the higher field capability of the baseline (or bucked and wedged TF design described below) and / or optimization of the plasma geometry by reducing the aspect ratio and increasing its triangularity. Engineering studies will include consideration of a combined bucked and wedged TF coil design which would reduce peak stresses in the TF coil sufficiently that they could be made entirely of oxygen free copper with a conductivity of 100% IACS. This has a number of significant advantages: the lower system resistance would reduce TF power requirements by ~46%. This would reduce power and cryogenics capital equipment costs, in addition to reducing operating costs. The temperature excursion during a pulse would be reduced, which would reduce thermal stresses. Alternatively, the reduced heating could be used for longer pulse durations. TF coil manufacturing costs will be lower with the oxygen free copper. On the negative side, the bucked and wedged configuration will probably be limited to a peak field of ~11.5T and the machine assembly will be more difficult due to the need to maintain more precise fit up tolerances to achieve the proper balance between wedging and bucking. Consequently, the bucked / wedged configuration will be evaluated in FY 2001 as part of the design options study to determine if it should be adopted.

AKNOWLEDGEMENTS

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