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# CONFIGURATION DEVELOPMENT AND STRUCTURAL ASSESSMENT OF THE FEDC IGNITOR CONCEPT*

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## ABSTRACT

The Fusion Engineering Design Center (FEDC) performed a design study for a compact ignition tokamak based on the design approach established by Professor Bruno Coppi of the Massachusetts Institute of Technology in his Ignitor concept. His Ignitor concept has two unique features. First, the throat of the copper plate toroidal field (TF) coils is preloaded in the vertical direction to minimize the stress levels in the copper. Second, the net inward radial TF coil forces are balanced by a combination of wedging on the adjacent faces of the TF coils and by bucking against the ohmic heating solenoid coils in the bore of the tokamak. Later Ignitor concepts eliminated the wedging reactions. Both of these features inherently reduce the radial build of the tokamak device.

The FEDC version of Ignitor incorporates both of these unique features packaged in a different configurational arrangement. The FEDC Ignitor features a totally external preload system. The preload is applied directly to the inner leg of the TF coils in the vertical direction only. Horizontal rings are utilized only to react inplane TF coil forces and are not part of the preload system. Modular quadrants of TF coil encasements are utilized to vastly simplify device assembly methods. This design allows the entire core assembly to be constructed in a manufacturing facility and shipped to the site. The improved configuration also results in larger access ports direly needed for diagnostics and radio frequency heating units which may be required. This paper presents the configuration and a structural assessment of the FEDC Ignitor concept.

## INTRODUCTION

The FEDC conducted a design study of the Compact Ignition Tokamak (CIT) device starting with the Ignitor-A design approach developed by Professor Coppi and his European-based design team.[1] The Ignitor device uses a combination of preload applied to TF coil inboard leg plus TF wedging and/or bucking against the ohmic heating (OH) solenoid as the primary approach to minimize the overall device size. The OH solenoid is wound on a central laminated steel core structure, which is also used as a tension member to react a preload to the TF coil inboard leg. The preload is applied by pressure cells located between a removable fitting, connected to the center post, and the top of the machine. External "C-clamp" wedged plates form the main structural element of the device. It is through this structure that the center post preload is applied. The "C-clamp" wedged plates are also prestressed radially inward by a wedge system that reacts the load against compression rings located at the upper and lower outboard region of the device. During operation, the outward force acting on the TF coil outer leg unwedges the "C-clamp" plates and allows the system to react the preload as a downward force on the TF coil inner leg. After further design and structural analysis assessment of the Ignitor-A concept, we concluded that it would be of value to consider an alternate configurational design approach which might offer a simpler load path for the TF coil preload, plus improve the overall device assembly features. The Ignitor-A concept was therefore used as a point of departure from which the FEDC Ignitor configuration has evolved.

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SYSTEM CONFIGURATION

Figure 1 shows an elevation and plan view of the FEDC Ignitor concept highlighting the reactor core and the external preload system that was eventually selected. Three structural preload methods were considered: a picture-frame plate, a thrust cone, and a sand- casting disk. All three concepts were found to be technically feasible and similar in price. The picture-frame plate approach was selected becaused it offered the greatest amount of access around the device. The preload structure is a flat plate about 13 m high and 11 m wide, with a window in the center to accept the tokamak. This "picture-frame" structure is fabricated from 24 plates of Nitronic 33 stainless steel, each 2.54 cm thick. These plates are arranged in two groups of 12 each, separated by 61-cm I-beams and bolted together to prevent buckling. The completed preload structure weighs approximately 454 metric tonnes (one million pounds). The lower part of the preload structure is supported laterally in a floor opening that extends about 4 m below the operating floor into the test cell basement. The upper part of the structure will be supported laterally by seismic restraints. Weight of the entire tokamak, including the external tokamak structure, is carried by the preload structure to the test cell basement.

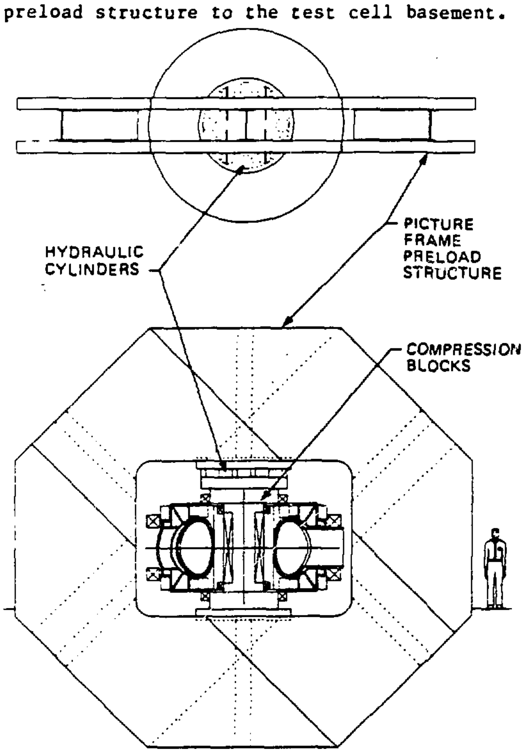

Fig. 1. Plan and elevation view.

The 2.54-cm-thick plates that make up the preload structure will be shipped to the site in 2.4-m-wide finished sections. These sections will then be field-welded into full-size plates and erected as part of the test cell construction sequence.

Upper and lower glass epoxy compression blocks and stainless steel support plates are located between the tokamak and the preload structure. The compression blocks transmit the preload to the TF coil inner leg while insulating the cold coils from the warm support plate and preload structure. A hydraulic assembly is located between the upper compression block and the support plate. This assembly consists of 24 off-the-shelf, double-piston hydraulic cylinders, each capable of exerting a force of 1,050 tonnes with 228 MPa (33,000 psi) hydraulic pressure. The maximum stroke available in the hydraulic system assembly is 2.6 cm, removable as a unit for maintenance outside the test cell.

The details of the reactor core are shown in Fig. 2. It was designed to allow the fitup of the TF coils to meet the requirements of TF wedging or bucking (or the combination of both). The TF coil outboard leg was sized to carry its own in-plane loads; the inboard TF leg was sized to carry the residual tension load (after subtracting preload), plus the wedging/bucking loads. Preload is applied directly to the inboard leg at the top of the device, through an insulation compression block. The outboard half of the TF coil is enclosed in a steel case to support out-of-plane loads. In-plane gaps between the coil and case allow in-plane expansion due to thermal and magnetic loads. The reactor core assembly operates at cryogenic temperatures, while the external frame assembly and hydraulic system operate at room temperature.

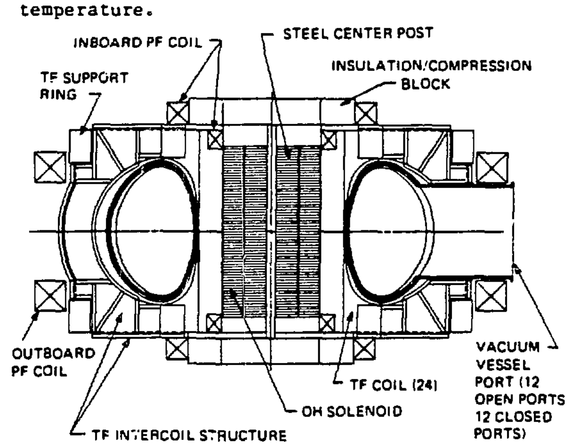

Fig. 2. Reactor core configuration.

To ease the fit-up requirements of an OH/TF bucking and wedging system and enhance the torsional strength of the structure, the reactor was designed in four welded structural quadrants. A core quadrant consists of three structural subassemblies that house the TF coils and form the TF coil intercoil structure (see Fig. 3). An off-the-shelf, heavy-duty, precision positioner is used to assemble one-half of a core quadrant (one-eighth of the device), allowing the TF coil structural assembly to be built up in a horizontal position. Upon completing the half quadrant, the positioner device rotates the piece and sets it upright in the vertical position, on an air-bearing pallet. Two half quadrants are joined together (forming a full quadrant), and a vacuum vessel segment is inserted into the quadrant using an installation fixture. Final machining of all four quadrants is done at the TF-OH interface and at the TF-TF inboard leg interface between quadrants prior to assembling the entire reactor core (see Fig. 4). Twelve large outboard access ports are welded to the vacuum vessel after the entire core module is assembled and the four vacuum vessel interfaces are welded together. A torus quadrant, or the entire torus module, can be assembled at a factory and shipped to the site for final assembly, or the basic components may be shipped for complete assembly at the site.

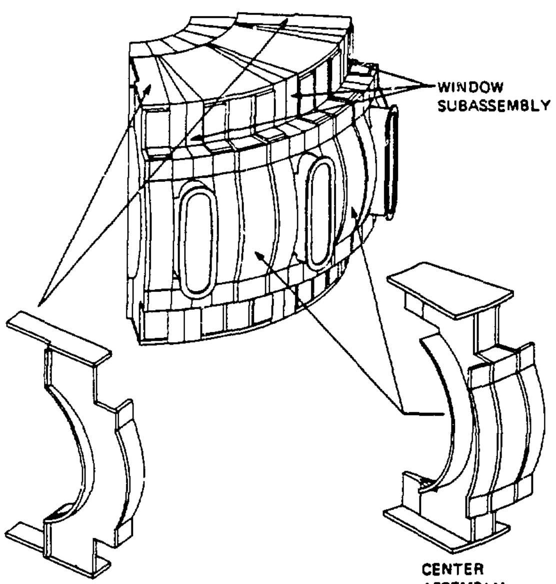


Fig. 3. Reactor core quadrant assembly.

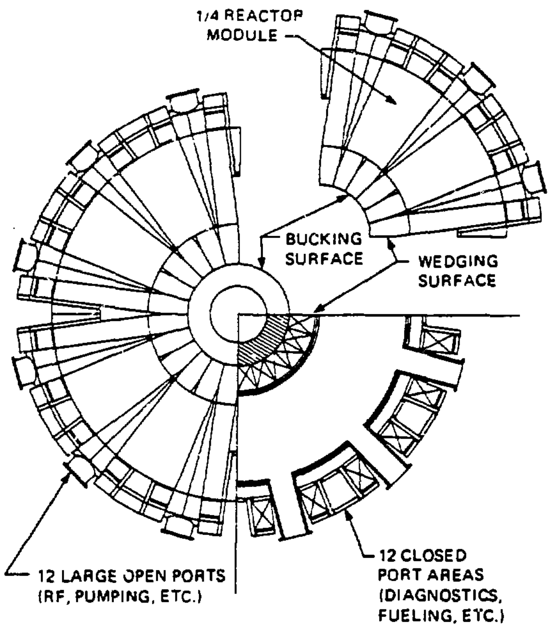


Fig. 4. Reactor core assembly.

The configurational development was done around a 1.08-m-radius device to provide a basis for evaluating of a machine of minimum size. Major machine parameters of the FEDC Ignitor device are listed in Table 1. Subsequent to the definition of the major features of the design, the device size increased to 1.16 m to satisfy the common physics and engineering design guidelines of the U.S. compact ignition study teams.

Table 1. Major Device Parameters

| | |
|---|---|
| Major radius (m) | 1.08 |
| Minor radius (m) | 0.37 |
| Field-on-axis (T) | 12.6 |
| Plasma current (MA) | 8.9 |
| Burn time (s) | 3.2 |
| TF current density (A/cm$^2$) | 10,000 |
| OH current density (A/cm$^2$) | 7,000 |
| Wall loading (MW/m$^2$) | 12.7 |
| Fusion power (MW) | 400 |
| TF peak power (MW) | 490 |

STRUCTURAL ASSESSMENT

The structural evaluation of the FEDC Ignitor consisted of analysis of the toroidal field/poloidal field (TF/PF) coil system and the external preload frame system. These analyses were conducted in accordance with guidelines developed by a working group of materials and structural engineers from the various CIT design groups. The working group was chartered early in the CIT program to establish a common set of allowable stress criteria to be used by each of the design groups.

The guidelines developed were specifically applicable to the copper magnet systems for compact ignition devices in the CIT studies and are generally more lenient than those in the formal codes such as the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (BPVC). The guidelines are considered appropriate only if analysis, test, and quality control programs are fully utilized and provided that the structural behavior of the magnet is monitored throughout the life of the device.

The stress criteria in the guidelines addresses two types of magnet systems—constrained coil and unconstrained coil. The systems have different stress criteria. The FEDC Ignitor is classified as a constrained coil system (i.e., a coil system employing an external structure to react the forces developed within the coil). For a constrained coil, the guidelines stated that the applied stress within the copper magnet material should be determined from the average value of the transverse compression, the average value of the axial tension, and the average value of out-of-plane shear. Note that the criteria specifies an "average" stress through the cross-section rather than simply using peak stresses. These three components are combined to obtain the applied Tresca stress (a maximum shear stress criterion equal to two times the maximum shear stress). The Tresca stress is compared to an allowable stress determined to be the lesser of 0.85 times the 0.002 strain offset yield strength of the material, or 0.7 times the ultimate strength of the material subject to an additional evaluation for cyclic effects. The steel support structures are required to meet the ASME BPVC requiring that the static Tresca stress shall be less than 0.66 times the yield strength or 0.33 times the ultimate strength of the material, whichever is less.

The working group also compiled a set of material properties for the types of copper used by the design groups. The material properties were compiled from various vendor data and laboratory tests by MIT and are shown in Table 2. The FEDC Ignitor uses all three types of copper. The outer and inner PF ring coils are made from C-10100 oxygen-free, high-conductive copper encased in stainless steel. The OH solenoid PF coil is a free-standing coil made of C-17510 beryllium copper. The TF coils are plate coils made of C-15500 silver-bearing copper. The center steel post and the TF coil encasements are assumed to be type 304 stainless steel with the mechanical properties[2] also shown in Table 2.

Table 2. Material Properties/Allowable Stresses in MPa (ksi)

| Alloy | Temperature | Ftu | Fty | Fallow |
|---|---|---|---|---|
| C15500 | 80 K | 531 (77) | 441 (64) | 372 (54) |
| | 293 K | 407 (59) | 393 (57) | 285 (41) |
| C17510 | 80 K | 1020 (148) | 940 (136) | 714 (103) |
| | 293 K | 830 (120) | 760 (110) | 581 (84) |
| AISI 304 | 80 K | 1482 (215) | 676 (98) | 448 (65) |
| | 300 K | 590 (85) | 285 (41) | 188 (27) |

The TF/PF coil system analysis model is shown in Fig. 5. Components in the model include the laminated epoxy fiberglass thermal insulator, center steel post, OH solenoid, upper inner PF coil, TF coil, and steel reaction ring. Since there are 240 TF coil turns in the FEDC Ignitor, the analysis model consists of one TF coil turn and a 1/240 ($1.5^{o}$) radial slice of the remaining components in the model. Only the upper half of the system is modeled since both the configuration and the applied loads are symmetrical about the horizontal midplane. Boundary conditions are applied at the horizontal midplane and at the 0 and $1.5^{o}$ planes in the theta direction (into the page of Fig. 5). The model consists of solid, isoparametric hexa and penta elements of the MacNeal-Schwendler Corporation (MSC) NASTRAN structural analysis code. Magnetic field and forces were calculated using the code EFFI. Temperatures due to both electrical power losses and nuclear heating were determined by computer models at FEDC. Forces and temperatures were applied at the nodes of the OH and TF coils. Preload forces were applied as pressures to the thermal insulator.

Some explanation of the operating scenario of the typical pulse of the device is necessary at this point in order to explain the loading conditions evaluated. Forces are developed in the coils due to electrical current flowing in the magnetic fields generated by the coil system. The current waveforms for all coils (and the plasma) are determined by the system pulse requirements to achieve a specified performance. For the FEDC Ignitor, those waveforms are shown in Fig. 6. With these waveforms and specific coil currents, the coil system can be modeled using the code EFFI to determine the magnetic fields and coil forces for any particular time in the pulse. For this evaluation, the times evaluated are at 0, 3, 4.6, 9, and 10.6 s. Only forces due to the OH and TF coils were included in the analysis since those are the dominant coil forces. These coil forces were combined with the hydraulic pressure preload forces, except for time = 10.6 s, where it is assumed that the preload is removed at the end of burn. The following is a summary of the loading conditions evaluated:

1. time 0.0 s - preload,
2. time 3.0 s - preload + OH forces,
3. time 4.6 s - preload + TF forces (assumed peak TF),
4. time 9.0 s - preload + TF + OH forces + thermal loads for TF and OH coils at end of burn,
5. time 10.6 s - thermal loads for TF and OH coils at end of cycle.

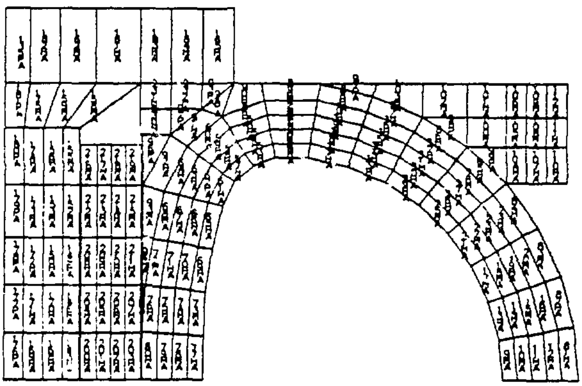

Fig. 5. TF/PF coil system NASTRAN analysis model.

At time = 0.0 s, the hydraulic preload system applies a total vertical load of 223 MN (50 million lb) to the thermal insulation block which transfers the load uniformly to the center steel post, inner PF coil, and the inner leg of the TF coils. At time = 3.0 s, the 17.5-T OH coil has been ramped to the maximum positive current and its radially outward forces are reacted internally and also bucked against the TF coils. This action attempts to unwedge the TF coil throat region. At time = 4.6 s, the OH coil current swings through zero as the TF current is ramped up. For analysis purposes, it was assumed the TF current had reached its flat top value during which the coil is at its peak magnetic field of 20.6 T, producing a vertical separating force of 500 MN. The 223-MN preload reacts 45% of the separating force, the tension in the outboard leg of the TF reacts 50%, and the remaining 5% is reacted by tension in the inboard leg. The net centering forces in the TF coils are reacted by a combination of wedging of mating TF coil faces on the inboard leg and by bucking against the OH coil. By time = 9.0 s, the OH has reached its maximum negative current and its peak temperature of 317 K, while the TF is still at the flat top value and has reached a peak temperature of 312 K in the throat, decreasing gradually around the periphery to an essentially constant temperature of 164 K in the outboard leg. It is during this period that both coils, as well as the reaction ring, reach their maximum stress conditions. At time = 10.6 s, both coils systems have been ramped down to zero and the preload has been bled, leaving only the end of cycle thermal loads in the system with the TF reaching a temperature of 316 K and the OH reaching a temperature of 320 K.

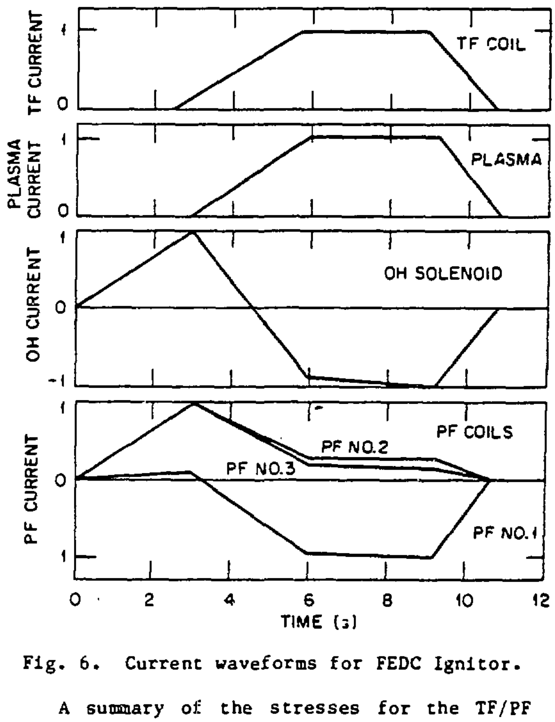


Fig. 6. Current waveforms for FEDC Ignitor.

A summary of the stresses for the TF/PF coil system is shown in Table 3. Note that all stresses are below the tabulated allowable stesses. Also notable is the sizeable margin in the OH coil. This is because the BeCu alloy was chosen due to the temperature match between the OH and TF coils, which prevents separation and preserves the bucking load path, thereby limiting the wedging stresses in the TF coil to acceptable values.

The out-of-plane TF forces are reacted by internal torsional shear stresses in the intercoil structure for the outboard leg and by internal torsional shear stress in the copper TF coil on the inboard leg. Strength of materials methods were used to calculate these torsional shear stresses. A torsional shear stress of 29 MPa (4.1 ksi) was included with the stresses summarized in Table 3 for the TF coil. A torsional shear stress of 138 MPa (20 ksi) was calculated for the stainless steel TF intercoil structure. These values were acceptable. A more detailed analysis can be used to verify these conclusions.

Table 3. TF/PF Coil System Stress Summary in MPa (ksi)

| Loading condition | Component* | | | |
|---|---|---|---|---|
| | TF coil | Ring | OH coil | Center post |
| 1 | 231 (34) | 25 (4) | 45 (7) | 320 (47) |
| 2 | 255 (37) | 62 (9) | 275 (40) | 320 (47) |
| 3 | 193 (28) | 186 (27) | 228 (33) | 317 (46) |
| 4 | 269 (39) | 310 (45) | 400 (58) | --- |
| 5 | 48 (7) | 152 (22) | 76 (11) | --- |
| Allowable stress | 273 (40) | 448 (65) | 571 (83) | 448 (65) |

*Stress values for TF coil are average, while values for all other components are peak.

The structural analysis of the external preload structure was also performed utilizing the MSC NASTRAN computer code. The structure consists of two stacks of 12 plates (2.54 cm thick) that are tied together by bolted I-beams. The analysis model was developed for one plate in the stack with 1/24 of the total load applied. The model shown in Fig. 7 uses plate and shell elements (quad4 and tria3).

The applied loads consisted of nodal forces for the preload of 250 MN and the FEDC Ignitor machine dead weight of 136 metric tonnes, each divided by 24. Gravity load of the structure was combined with the applied loads. A static analysis was performed using these applied loads. The peak major principal stress occurs in each radius of the cutout opening and has a value of 220 MPa (32 ksi). The plate structure is made from Nitronic 33 stainless steel, which has an ultimate strength of 690 MPa (100 ksi) and a yield strength of 379 MPa (55 ksi). Using the lesser of 1/3 of ultimate or 2/3 of yield strength, the allowable stress is 228 MPa (33 ksi).

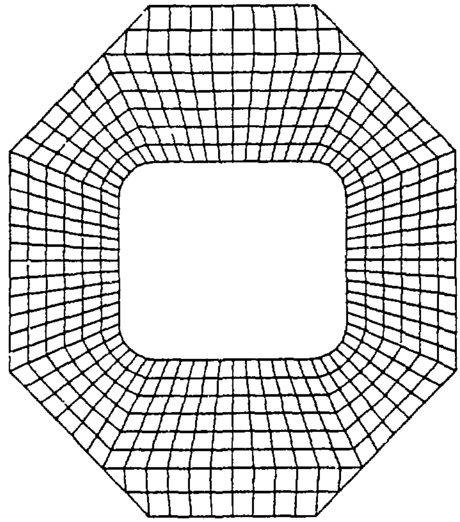

Fig. 7. NASTRAN model for external preload frame.

A buckling analysis was also performed using the buckling solution sequence in NASTRAN. The first mode eigenvalue was 2.73, indicating a factor of safety of 2.73 on the applied loads, which should improve considerably if the I-beam stiffened, double stack of plates were modeled.

CONCLUSION

In summary, the FEDC investigated an alternate configuration of the Ignitor concept. The FEDC Ignitor has the unique features of a completely external preload system, modular assembly concept, and improved access ports openings. The structural assessment concludes that the concept is feasible and meets the guidelines developed for the CIT studies.

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2. N. J. SIMON and R. P. REED, "AISI 304 Stainless Steel - Structural Materials for Superconducting Magnets," National Bureau of Standards, Boulder, Colorado (January 1985).

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