Structural Analyses, Sensivity Analyses, and Independent Confirmatory Analyses of the IGNITOR Magnet System

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Abstract---Ignitor has been the first experiment proposed and designed to reach ignition conditions in magnetically confined plasmas.It is a compact ,high field machine based on the physics developed primarily by the Alcator series of experiments. Each refinement of IGNITOR has drawn from a common set of "tools": Bitter plate copper magnets; bucking/wedging interactions of the CS and TF coils; and passive and active preload mechanisms to offset vertical tension in the inner leg and tension in the horizontal leg. Elements of the IGNITOR design are statically indetterminant. Examples of multiply redundant load paths used in other reactor designs are cited. Despite a large body of historical work confirming the structural feasibility of IGNITOR, it still is erroneously perceived as more challenging than other tokamak designs. Past US analyses are recalled: US contributions from independently derived models are described and are compared with the latest IGNITOR project analyses. Differences in modeling philosophy are presented, and results are compared. Recent US analyses employ non-linear path dependent friction of a 2 coil segment. Sensitivity studies of fit-up tolerances and, uncertainties in material properties are presented. While there are some small differences in results, these analyses independently confirm the benefits of the major structural elements used in IGNITOR.

I. INTRODUCTION

The structural analysis and design of IGNITOR has extended over more than 10 years. IGNITOR has been studied in the US many times [3],[2], and there are many investigations of the "robustness" of its structural features. The goal of these studies was usually to find a cheaper way to obtain better structural performance. The Ignition Studies Project, early CIT analyses, and DIGNITOR (IGNITOR Scale-up) studies[2], are a few of these studies. The current Next Step Option (NSO)/FIRE effort also revisited IGNITOR designs, and has borrowed some features.

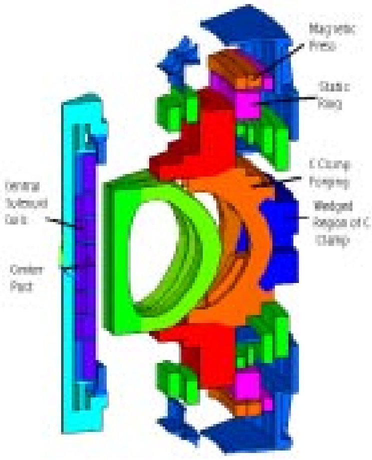

Fig. 1 Expanded View of IGNITOR

An expanded view of IGNITOR's magnet and structural components is shown in Fig. 1. While IGNITOR is conceptually similar to it's 1981 arrangement, some variations in the basic machine arrangement have been considered. Each refinement of IGNITOR has drawn from a common set of "tools". These are discussed in the following notes generically, and it is not intended for this to be an consistent explanation of the current evolution of IGNITOR. The discussion is based on US work on IGNITOR and IGNITOR-like reactors starting in 1981 with the compression device and ending in 1990 with DIGNITOR which was a DOE sponsored study of a scaled-up version of IGNITOR. The present IGNITOR parameters are shown below.

Table I
IGNITOR Parameters

Major Radius Ro	1.32	Minor Radii a X b	.47 X .86m
Aspect Ratio	2.8	Elongation K	1.83
Triangularity δ	.43		
Vacuum Toroidal Field Bt	13 T	Number of TF Coils	24

Work presented here, like many previous US efforts, is intended to study the structural features used in IGNITOR. The analyses are done without benefit of full integration into the IGNITOR team and many details had to be inferred. There is a good reference that describes the engineering design of IGNITOR [1] and is the source of much of the information needed to construct the structural model. PF Scenarios and TF coordinates were also provided[4],[5]. While there are some small differences in results, this analysis independently confirms the benefits of the major structural elements used in IGNITOR.

II MODELING IGNITOR

IGNITOR uses multiple load paths to support the large Lorentz loads which develop in the coils. This necessitates use of global simulations of the electromagnetic, thermal and structural behavior of the tokamak. IGNITOR has been criticized for it's use of multiple load paths, but this is more the rule in tokamak design than the exception. Cased TF coil windings share two poloidal hoop direction load paths: winding pack and case. Similarly, in wedged cased TF coil designs the toroidal hoop is multiply redundant. Out-of-plane support is multiply redundant in all tokamaks the author is familiar with. An early example is TFTR in which the OOP load is shared by the Inner Support Structure (ISS) and the outer shear compression panels. Precision of the TF

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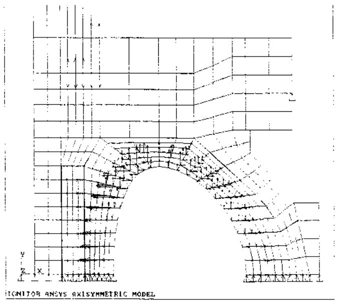


Fig. 2 Early US Axisymmetric Model [3]

case nose fit-up with the ISS was also important in determining load share.

The IGNITOR Project Group has used a combination of two dimensional and three dimensional programs to model IGNITOR. In the recent US study, two large 3D models are employed. A linear model provides relatively quick turn-around. A non-linear model is intended to include frictional effects. Both models are 3 dimensional models of a 2 coil cyclic symmetric sector. Both models employ the same geometric model with changes in element types, and real constants to used to make the switch in solution type.

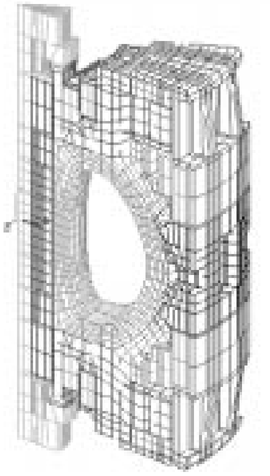


Fig. 3 IGNITOR Structural Model

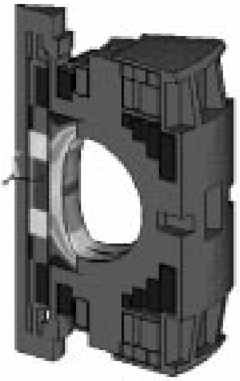
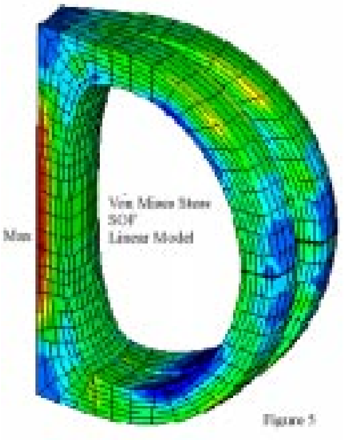


Fig. 4 EOF Coil Temperature Distribution

The linear model employs links instead of gap elements at interfaces between the TF and CS. The usefulness of the linear modeling has been demonstrated for all but CS vertical and shear stresses. The winding pack is connected to the C-Clamp with links that model zero sliding friction. Tensions develop in the links when gaps would have opened. This is fixed at some locations using the ANSYS EKILL feature, eliminating the gaps which open. The IGNITOR Model includes temperature distributions based on ANSYS current diffusion analyses, results from which are shown in Fig. 4. , where the dark areas are warmest. Peak temperatures are adjusted for those published which includ nuclear heating in ref [1]. In the Non-Linear model,Gap elements are used to model all the interfaces in the model. This requires careful model generation to ensure the gap alignment is correct. Eight node bricks are used for the bulk of the model with an occasional plate element. In Past US studies [3] a 3D model was also used, but sensitivities of material properties, preloads, clamp wedged regions and gaps were studied with a simple 2D axisymmetric model, Fig. 2, that allowed non-linear path dependent friction, but only handled in-plane frictional effects. The present model, Fig. 3, also has been run with full path dependent friction. This larger model with 7 load steps, 40 substeps and 2 to 4 equilibrium iterations, runs about a week on a fast workstation. The differences in the two models illustrates the advances in computer speed and size.

III. MATERIAL PROPERTIES AND ALLOWABLES

In the US Program, S_m, the Primary Membrane stress is to be compared with the average stress in CS/PF or TF Build. It is defined as the lesser of 2/3 Yield or ½ Ultimate (for Ductile Materials). The Primary Membrane + Bending allowable is $1.5S_m$. This is essentially the yield stress based on the 2/3 criteria, and should be compared with max linearized stress in CS/PF or TF build (radial variations are interpreted to be like bending stresses). IGNITOR uses ETP 99.9 copper with a yield=374 (77° K longitudinal), 387(77° K transverse), ref[1], p3-10, yield=336 (292° longitudinal), 340(292° K transverse), ref[1],p3-10. Peak stresses in the TF typically occur on the CS side early in the pulse before the coil heats up. The coil is subcooled to 30° K allowing the use of the better allowables. For the TF, the IGNITOR Project Group uses a membrane +bending allowable of 375 MPa at 77°, and 335 MPa at RT. A total stress allowable of 430 MPa at 77° is also used. IGNITOR is a low cycle machine. The fatigue allowable is taken as twice the yield.



IV. COMPARISON OF RESULTS

The peak Von Mises in the coil is at the peak bending allowable for the copper planned for use in the IGNITOR TF Coils.

Table II
Peak Von Mises Stress in all of the TF, (MPa), US-MIT

Pre	SOF	EOF	Rev Shear
204	370 (@ 32°K)	316 (@33°K)	294

Table III
Comparison of Stress Components , Outer Radius (Plasma Side) of the TF, (MPa), IGNITOR Project Team, and US-MIT

	Time	SX	SY	SZ	VM	Tor
Ref[1] Table 5.111	EOF	-34	-78	190	250	
US-MITR#7	EOF	-36	-100	150	200	32.4

The reverse shear scenario produced lower stresses in the coil than the baseline scenario.

Table IV
Comparison of Stress Components , Inner Radius (Central Solenoid Side) of the TF, (MPa)

	Time	SX	SY	SZ	VM	Tor
Ref[1] Table 5.111	EOF	-269	-126	-1	233	
Titus R#7	EOF	-274	-170	0	221	24

The ring load in the IGNITOR Project models and the US/MIT model are similar, 200 vs. 240 MN. In discussions with the IGNITOR Project Team, a larger magnetic press was being investigated, this possibly explains the difference in the loading.

Table V
Static Compression Ring Load Loads, at Cool Down (CD) and End of Flat Top (EOF)

	Time	Ring Ave Hoop	Ring Load (MN)*
Ref[1]	CD		201
R#7	CD	307	248
R#7	EOF	480	387

*Exclusive of Magnetic press Main Ring =2*pi*ΔR*ΔZ*average sigma hoop, where ΔR=.288, and ΔZ=.4467 (In Titus's Model)

V Sensitivity To Modulus And Gap Variations

A usual concern expressed about bucked and wedged coil systems, is that material property uncertainties make prediction of load share between coils very difficult. The most likely candidate for introducing uncertainty is the toroidal modulus of the TF coil. Vertical and radial moduli of the TF are not as effected by the inclusion of the insulation layer, but the toroidal direction includes the insulation layer in the wedge pressure load path. It also includes the effects of fit-up between the TF coils. In the following study, the toroidal modulus of the TF is varied from the "nominal" of 98 Gpa. The result is a small change in the Von Mises stress. Start of flat top (SOF) stresses are used in this comparison Results of earlier US analyses, Figure 6, show a slightly higher hoop stress sensitivity to the modulus variation, but still much lower than the percentage change in modulus. Also in the earlier analyses, the radial fit-up gap between the CS and TF was investigated.

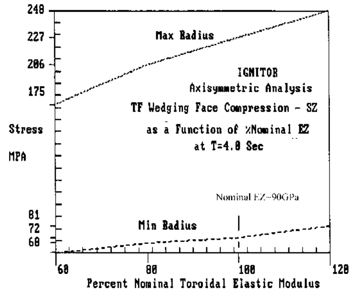
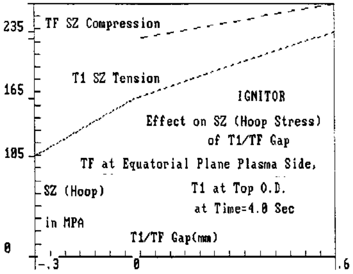


Fig. 5 Effect of Modulus Variation

In the present IGNITOR design, the bore formed by the TF array into which the CS is fit, is machined after assembly.

Figure 6



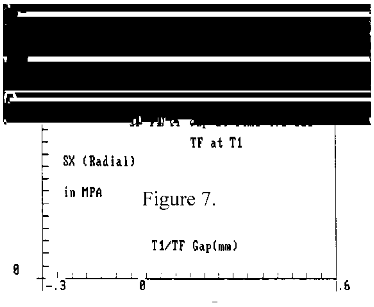


Figure 7.

Tolerances of 1/10mm are expected. This is much smaller than the range of the sensitivity study, and the radial gap is not expected to vary the stress state of the machine significantly.

Table VI
TF Stresses vs. Toroidal Modulus Variations

% Nom. Etor.	Min Radial	Min Hoop	Max Vert	Von Mises
125%	-253	-224	190	363
100%	-261	-190	191	369
75%	-271	-153	192	374

VI. Out oF plane Behavior

In IGNITOR, the TF bore follows the poloidal flux lines very closely, but the high field nature of the machine and it's optimized design makes it necessary to demonstrate acceptable behavior during operational variations. The US IGNITOR Working Group investigated a reverse shear scenario, which was found to be less severe structurally than the nominal scenario. Bucked designs like JET and the ITER EDA, and bucked and wedged designs like IGNITOR impose some portion of the OOP torsional load in the TF central column, on the central solenoid as well, as witnessed by JET's CS "wind-up" problem. Two regions of the Tokamak Support OOP Forces: the TF inner leg array behaving as a continuous torque tube or shell, and the wedged C-Clamp array behaving as a external torque frame. The inner leg carries the torque via friction developed by the wedged faces of the TF coil.

Fig. 9 Current "Hugs" inner TF Bore, Poloidal Field vectors are either small or parallel to the TF current vectors.

A. Shear Margin Calculations

There are two types of shear capacity needed in the TF coils of IGNITOR. At the wedge faces where the TF segments come together, only friction is available to support shear.

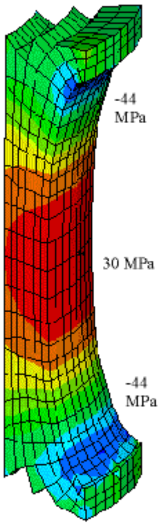


Fig.10 TF Inner Leg Torsional Shear, Bonded Wedge Faces

The interior of the coil winding pack is held together by the insulation shear capacity which depends upon a shear/compression augmentation factor (similar to friction), and bond between the conductor and insulation layers. In the shear margin calculation, the total shear at a radial-vertical plane is computed via SRSS and compared with the shear capacity, either frictional or insulation shear. In figure 11, the white area in the left hand pair of plots, represents the region which satisfies the bond criteria. In the left hand pair the white region represents the area which satisfies the frictional slippage criteria. This indicates that there is essentially no area where bond criteria are violated, but there are some regions over which there is some frictional slippage. The IGNITOR Project Team evaluates the frictional capacity at poloidal "stations" around the TF inner leg and shows there is enough average frictional capacity to keep the coil from significant slippage. In both the US and European analyses some small amount of slippage is indicated.

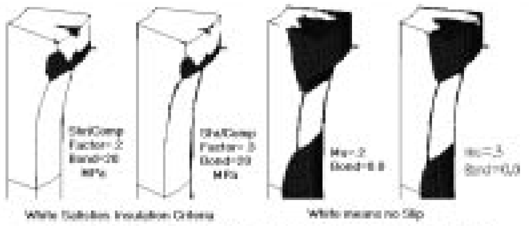


FIGURE 11 TF Inner Leg Shear Margin Results - IGNITOR - US/MIT/PSFC Model

VII. Effects Of Modeling Friction At The TF Wedge Face

The goal of this analysis is to model coil to coil, and coil to C clamp frictional interactions. Introduction of path dependent friction modeling was done in a couple of stages. Run #7 was linear, #8 was linear, and added CS to TF torsional coupling, and #6 was the first non-linear run which employed friction gaps at all the interfaces except the TF wedge face interface. In runs 9 through 12, TF wedge face friction was modeled with gaps that are coupled across the TF faces. With the addition of the TF wedge face friction, a slight amount of slipping occurred, consistent with the shear margin results and added about 35 MPa to the TF Von Mises. This is a displacement limited stress, in that the frictional capacity is ultimately large enough to restrain the toroidal twist of the central column. The max torsional shear in the TF inner leg went up over the linear model results, but the bond criteria is always more demanding than the frictional slippage criteria, and the insulation will be within allowables.

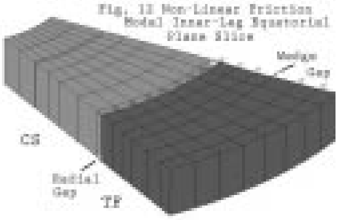


Fig. 12 Non-Linear Friction Model Inner-Leg Equatorial Plane Slice

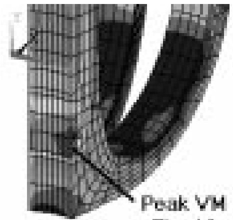


Fig. 13

Table VII
EOF Non-Linear Model Results

	Wedge Face Friction, µ	TF VM MPa	TF Tor. Shear , MPa
Ref[1] Table 5.111		250	
R#8	∞	316	29.8
R#6	∞	370	<29
R#10	.3	408	49.8
R#11	.35	407	50.0
R#12	.5	403	50.5

. The usual friction coefficient used in these analyses is .3. The wedge faces planned for IGNITOR could be treated to improve the coefficient, but in these analyses, increasing the wedge face friction coefficient did not have a strong effect.

Torsional shear in the central solenoid is induced by the toroidal twist of the TF. In the linear model this effect is small. The non-linear model which modeled slippage of the TF wedge faces, showed an increase in torsional shear at the TF parting plane. This "scuffing" shear amounted to 27 MPa, significant, but not unacceptable.

VIII. Conclusions

Agreement with the IGNITOR project team analyses has been obtained. IGNITOR demonstrates acceptable behavior with reasonable uncertainties in material properties and fit-up tolerances. Structural response to a reverse shear scenario yielded lower stresses in the machine than for the nominal scenario. Frictional slippage of the TF wedge faces has been simulated, and acceptably small increases in TF Von Mises stresses resulted.

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