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ENGINEERING ANALYSIS OF TFTR DISRUPTION

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FUSION ENGINEERING DESIGN CENTER

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ENGINEERING ANALYSIS OF TFTR DISRUPTION

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CONTENTS

	Page
LIST OF FIGURES	v
LIST OF TABLES	vii
ABSTRACT	1
1. PURPOSE AND CAPABILITY OF ENGINEERING ANALYSIS	3
2. DESCRIPTION OF MODEL AND PROCEDURE	4
3. CALCULATIONS	6
4. CONCLUSIONS	14
ACKNOWLEDGMENTS	15
REFERENCES.....	15

LIST OF FIGURES

Figure		Page
1	Plasma temperature during current decay	6
2	Torus resistance (normalized)	7
3	Torus outer wall resistance (normalized)	7
4	Thermal disruption time	8
5	Current decay time	9
6	Plasma heat (a), radial position (b), and current (c) at 2.5 MA and 1 keV	10
7	Plasma heat (a), radial position (b), and current (c) at 2.5 MA and 10 keV	11
8	Plasma heat (a), radial position (b), and current (c) at 1.0 MA and 1 keV	12

v/V

LIST OF TABLES

Table		Page
1	Volume (in cm^3) of material vaporized or melted by initial thermal energy	13
2	Volume (in cm^3) of material vaporized or melted by thermal energy added to plasma initial thermal energy by disruption for a 1-keV plasma	13

ABSTRACT

Disruption protection on a reactor-relevant tokamak is a major design problem. It is a configuration as well as a maintenance design driver. Our capability to specify the characteristics of a disruption (which determines the time and magnitude of the induced currents, forces, voltages, and arc erosion) is not sufficient to warrant the risk associated with the construction of a large tokamak fusion device that has a high-conductivity shell.* It is recommended that the next large device include a low-conductivity shell close fitting around the plasma.

This report covers an engineering approach quantifying the currents, forces, and times, as well as plasma position, for the worst-case disruption based on engineering circuit assumptions for the plasma. As the plasma moves toward the wall during the current-decay phase of disruption, the wall currents affect the rate of movement and, hence, the decay time. The calculated structure-induced currents differ considerably from those calculated using a presently available criterion, which specifies that the plasma remains stationary in the center of the torus while decaying in 10 ms.

This report outlines the method and basis for the engineering calculation used to determine the current and forces as a function of the circuit characteristics. It provides specific calculations for the Tokamak Fusion Test Reactor (TFTR) with variations in parameters such as the thermal decay time, the torus resistance, and plasma temperature during the current decay.

The study reviews possible ways to reduce the disruption damage of TFTR by reducing the magnitude of the plasma external field energy that is absorbed by the plasma during the current decay. This absorbed external field energy adds to the plasma thermal energy and increases the melting or ablation of the limiter or wall surfaces. The present TFTR disruption conditions should not encounter a significant increase in disruption magnetic energy until the plasma current is increased above 2.0 MA. The limiter or wall energy that is absorbed from the plasma magnetic field energy is 80 kJ at a plasma current of 1.0 MA. This increases from 340 to 840 kJ when the plasma current increases from 2.0 to 2.5 MA. In addition, about 1800 kJ of thermal energy must be absorbed by the limiter when the plasma temperature suddenly decreases from 10 keV.

*Y.-K. M. Peng and P. Rutherford, *FED-A, An Advanced Performance FED Based on Low Safety Factor and Current Drive*, ORNL/FEDC-83/1, Oak Ridge Natl. Lab., 1983.

1. PURPOSE AND CAPABILITY OF ENGINEERING ANALYSIS

In the early stages of the Engineering Test Facility (ETF) design, the disruption was characterized in a way that allowed the preconceptual design to proceed on divertors, limiters, and first walls. A consensus of the fusion community was utilized through the workshop procedure to characterize the disruption. It was concluded that we should assume a 10-ms decay time for the disruption and that the specified energy (thermal and inductive) would be deposited at specified locations on the surfaces of the wall and limiter. This was the best characterization that could be provided at that time and is essentially the same one that is used for today's design concepts. The characterization should be updated because much more data have been obtained and more is known about disruptions. This report attempts to provide the impetus for this change.

A change is needed because disruption is a major driver in the engineering designs of the first wall surfaces and their structural supports. The maintainability of the limiter is a major configuration consideration. The present characterization does not account for the very fast (approximately 50- μ s) thermal decay time, for the plasma movement during the current decay, nor for the decay time changing as a function of the structure time constant and its position with respect to the plasma (self-inductance and mutual coupling to the plasma). These factors can result in differences in induced structure eddy currents and forces by factors larger than 5, compared to those using the standard characterization.

The Advanced Performance Fusion Engineering Device (FED-A) design was based on a thick (3-cm) conducting shell closely fitted to the plasma. This configuration offers the greatest deterrent to disruptions and disruption damage. However, the engineering designs for FED-A were based on the current decay time of 10 ms.

To provide improved quantization for the worst-case disruption, the following engineering analysis was developed. This procedure has provided results that are in good agreement with the conditions on the Princeton Large Torus (PLT) and Impurity Study Experiment (ISX) machines.¹ In this report, the Tokamak Fusion Test Reactor (TFTR) configuration is analyzed. The TFTR study was completed for the following reasons:

- to qualify this method of calculation for use on future designs such as the Tokamak Fusion Core Experiment (TFCX) and the Engineering Test Reactor (ETR),
- to attempt to quantify the possible TFTR disruption damage and to consider methods to improve the ability of the TFTR to withstand disruption, and
- to provide a design tool for improving the engineering with regard to disruption damage.

The procedure developed is for the worst-case condition. It is applicable to the largest and fastest thermal disruption. It provides for the calculation of the induced voltages, induced currents, and resultant forces. It also provides a basis for determining the likelihood of an arc occurring across bellows or gaps, as well as for calculating the arcing time and coulombs. The arc erosion can then be estimated based on the diffused-arc data obtained on industrial vacuum-switch development with parallel fields.² (A tokamak

poloidal arc should remain in a diffused state for at least 10 ms before it becomes constrictive and produces erosion.)

2. DESCRIPTION OF MODEL AND PROCEDURE

The TFTR coils, vacuum vessel, plasma circuit, and self-inductance and mutual inductances were determined using the ICC code. Values were obtained by simulating the plasma circuit as a hot, well-confined, full-radius ring. Then a second set of inductances was determined with the plasma simulated as a low-temperature (100-eV), small-minor-radius conductor located against the inner wall. The values of the plasma self-inductance and mutual inductances used for each iteration of the computer program were determined from interpolation between these two sets of values as a function of the plasma radius R .

The plasma circuit was simulated as a circular conductor that could vary in major radius R and minor radius a in response to the current and the fields present. The only restraint on the movement was the total system conservation of energy. The vertical field that governs its position could not change faster than the change in energy could be absorbed. It was assumed that the plasma resistivity remained constant during the current decay period. It was, however, changed from a low value (hot plasma) to a high value (cold plasma), simulating the thermal decay. The plasma resistance was then calculated as a function of its major and minor radii. As the plasma moved toward the inner wall, its minor radius was reduced in proportion to the radial movement; that is, the simulation reduced the minor radius by 1.0 cm when the plasma moved 1.0 cm toward the inner wall (scrape-off of uniform magnetic surfaces).

The conservation of magnetic and electrical energy governed the plasma movement or position. As the plasma current decreased and moved inward, its field energy reduced by $\Delta(1/2 LI_p^2)$, but its value could not change any faster than the energy could be dissipated or transferred in the total system, which included all the circuits and structures ($\sum I^2 R t$ and $\sum 1/2 LI^2$). The basic circuit equation was

$$\sum \left(\frac{1}{2} L_{ii} I_i^2 + M_{ij} I_i I_j \right) = E . \quad (1)$$

The derivative, with respect to displacement, was set equal to zero to obtain the following:

$$\frac{d}{dR} \left[\sum \left(\frac{1}{2} L_{ii} I_i^2 + M_{ij} I_i I_j \right) \right] = 0 , \quad (2)$$

recognizing that

$$\frac{d}{dR} = \frac{d}{dt} \times \frac{dt}{dR} \quad (3)$$

Then,

$$\begin{aligned} & \sum \left[\frac{1}{2} \left(\frac{d}{dR} L_{ii} \right) I_i^2 + \left(\frac{d}{dR} M_{ij} \right) I_i I_j \right] \\ & + \sum \left[\frac{1}{2} L_{ii} \left(\frac{d}{dt} I_i^2 \right) \frac{dt}{dR} + M_{ij} \frac{d}{dt} (I_i I_j) \frac{dt}{dR} \right] = 0, \end{aligned} \quad (4)$$

and

$$\frac{dR}{dt} = \frac{- \sum M_{ij} \frac{d}{dt} (I_i I_j) - \sum \frac{1}{2} L_{ii} \frac{d}{dt} (I_i^2)}{\sum \left[\frac{1}{2} \left(\frac{d}{dR} L_{ii} \right) I_i^2 + \left(\frac{d}{dR} M_{ij} \right) I_i I_j \right]} \quad (5)$$

In summary, the disruption process was simulated as a decay in plasma temperature in approximately 50 μ s with a uniform current and temperature distribution. As the current then decayed, the major and minor radii became smaller. The rate at which this occurred was dependent on how fast the plasma-stored magnetic field energy could be absorbed by heating or could be supported by other adjacent circuits.

Because the worst-case condition is required for engineering designs of walls and limiters, the plasma temperature was assumed to drop to approximately 100 eV and remain at this value during the current decay time. The added plasma thermal energy $\sum I_p^2 \Omega t$, which is absorbed from its own magnetic field, produces the increased damage. It was assumed that this energy was conducted away from the plasma to the limiter and wall surfaces in contact with the plasma as fast as it was produced.

By the time the plasma current goes to zero, all of its initial thermal energy has to be absorbed by the wall or limiter surfaces. The additional energy from the magnetic field, which is transferred to the plasma as thermal energy ($\sum I_p^2 \Omega t$), is also deposited on these same surfaces. The ablation and melting energy can only be reduced by reducing the plasma ohmic heating during the disruption. Thus, a fast current decay can result in the

least melting of the surfaces. Engineering damage protection can best be achieved by having low-impedance structures and a high-resistance plasma during the current decay phase of disruption.

3. CALCULATIONS

The 1FTR disruptions were first calculated for the as-built conditions with plasma currents of 1.0, 1.5, 2.0, and 2.5 MA and for initial plasma temperatures of 1 and 10 keV. Variations were then made in the following conditions:

1. plasma temperature (resistivity) during the current decay (Fig. 1);
2. vacuum vessel resistances—(a) increasing and decreasing the vessel resistance by a factor of 2 (Fig. 2), (b) increasing and decreasing the outside portion of the vessel wall (Fig. 3), (c) adding external passive coils to the outside of the vessel (which did not couple well enough to the plasma to have any effect); and
3. varying the thermal decay time [50, 100, and 200 μ s (Fig. 4)].

Fig. 1. Plasma temperature during current decay.

ORNL-DWG 84C-2437 FED

Fig. 2. Torus resistance (normalized).

Fig. 3. Torus outer wall resistance (normalized).

ORNL-DWG 84C-2439 FED

Fig. 4. Thermal disruption time (μs).

Because it is the added magnetic energy that can be affected by engineering designs, it was studied as the important factor. This delta energy, added to the first wall and limiter surfaces ($\sum I_p^2 \Omega t$), was plotted as the common parameter. The current decay times were also plotted (Fig. 5). The decay time varied roughly in proportion to the delta energy. The 10-keV plasma produced a faster current decay time than a 1-keV plasma. This difference results from the larger change in the resistance during the first few microseconds of thermal decay. Curve sets on Figs. 6 and 7 show current decays as a function of time and for the 1- and 10-keV cases. Conditions for a 1.0-MA, 1-keV plasma are shown on the curve set of Fig. 8. (As expected, the current decay is not linear, as now specified for designs.)

Table 1 provides calculated data on thermal energy at various plasma initial temperatures and the volume of material that would be lost for the case of all ablation or all melting. Table 2 provides data on the volume of material that could be vaporized or melted by the added magnetic energy. (A fast dump of energy results in a higher percentage of the total energy going to ablation.) This condition results in less loss of material, assuming melt layers are pulled off the wall during disruption. Table 2 also provides comparative data on other possible first wall and limiter materials (quantifying material loss by ablation and melting) and shows the advantage of graphite and the disadvantage of stainless steel, as compared to SiC and BeO.

ORNL-DWG 84C-2440 FED

Fig. 5. Current decay time (ms).

ORNL-DWG 84C-2441 FED

Fig. 6. Plasma heat (a), radial position (b), and current (c) at 2.5 MA and 1 keV.

ORNL-DWG 84C-2442 FED

Fig. 7. Plasma heat (a), radial position (b), and current (c) at 2.5 MA and 10 keV.

ORNL-DWG 84C-2443 FED

Fig. 8. Plasma heat (a), radial position (b), and current (c) at 1.0 nA and 1 keV.

Table 1. Volume (in cm³) of material vaporized or melted by initial thermal energy

Plasma temperature (keV)	Initial thermal energy (kJ)	Graphite		SiC		BeO		Stainless	
		Vaporized	Melted	Vaporized	Melted	Vaporized	Melted	Vaporized	Melted
10	1800	17.2	<i>a</i>	34.9	187.5	35.9	260.9	36.2	843.9
5	900	8.6	<i>a</i>	17.5	93.8	18.0	130.4	18.1	421.9
2.5	450	4.3	<i>a</i>	8.7	46.9	9.0	65.2	9.0	211.0
1	180	1.7	<i>a</i>	3.5	18.8	3.6	26.1	3.6	84.4

^aNot applicable.Table 2. Volume (in cm³) of material vaporized or melted by initial thermal energy added to plasma initial thermal energy by disruption for a 1-keV plasma

Plasma current (MA)	Disruption thermal energy added to plasma, $\sum I_p^2 \Omega t$ (kJ)	Graphite		SiC		BeO		Stainless	
		Vaporized	Melted	Vaporized	Melted	Vaporized	Melted	Vaporized	Melted
2.5	840	8.0	<i>a</i>	16.3	87.5	16.8	121.7	16.9	393.8
2.0	350	3.3	<i>a</i>	6.8	36.5	7.0	50.7	7.0	164.1
1.5	190	1.8	<i>a</i>	3.7	19.8	3.8	27.5	3.8	89.1
1.0	90	0.9	<i>a</i>	1.8	9.4	1.8	13.0	1.8	42.2

^aNot applicable.

Calculations were also made on arc erosion, assuming arcs would be produced across the bellows when the voltage across a single bellows reached a value of 25 V. It was then assumed that the current would continue flowing until the arc voltage dropped to less than 20 V. For a 1.0-MA plasma, the total coulombs across each gap was 35 A-s. The current flow time was 2.5 s; thus, the arc was assumed to have remained in a diffused state, with essentially no erosion. Extrapolating this calculation to a 2.5-MA plasma, it is estimated that the arc current would flow for 6.25 s. It should remain in a diffused state and not produce erosion.

4. CONCLUSIONS

1. Arc erosion across the bellows during the current decay phase of disruption is not expected to be a major cause of damage, but additional calculations should be completed.
2. The only way disruption damage can be affected in a significant manner is to short out the bellows or to install passive conductors adjacent to the plasma. Shorting out the bellows would have to be done inside the vessel to be effective. This would probably require the addition of rf to assist startup. (Shorting some of the bellows increases the probability of arc damage on those not shorted.)
3. There is essentially no change in the disruption time with variations in the thermal time between 50 and 200 μ s.
4. A higher initial thermal energy plasma results in a faster current decay time. The current decay time for a 2.5-MA plasma at 10 keV was calculated to be 1.5 ms. This fast decay may overstress the insulation on the poloidal field (PF) coils. External passive circuits may be effective in relieving excessive voltage. This should be investigated further.

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