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Major Plasma Disruptions in TNS

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Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22161
Price: Printed Copy \$5.25; Microfiche \$3.00

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Contract No. W-7405-eng-26

FUSION ENERGY DIVISION

MAJOR PLASMA DISRUPTIONS IN TNS

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Date Published: February, 1979

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Prepared by the
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ACKNOWLEDGMENTS

The work outlined in this report was carried out as part of the Oak Ridge National Laboratory (ORNL) Instrumentation and Controls Study for the Tokamak Fusion Reactor. Gratitude is expressed to Don Steiner of the Fusion Energy Division (FED) of ORNL for his insight and interest. Invaluable assistance in the form of computational expertise and interest in the project was provided by T. J. Huxford of Union Carbide Corporation Nuclear Division (UCC-ND) Engineering and J. K. Ballou of FED. Others with whom discussion provided beneficial insight were A. T. Mense, J. R. McNally, Jr., and Martin Peng, all of FED; W. M. Wells of UCC-ND Engineering; and P. B. Mohr of Lawrence Livermore Laboratory. Wayne Houlberg of FED also provided input which forms part of this work, and special thanks go to him.

SUMMARY

Evaluation of the instrumentation and control of a power producing tokamak fusion reactor such as The Next Step (TNS) requires an assessment of the consequences of a major plasma disruption during reactor operation. The most important consequence of a disruption will be damage to the first wall from thermal and magnetic stress. Severe temperature gradients will cause thermal stress, placing a limit on the number of disruptions that can occur before the integrity of the wall is lost, and eddy currents induced in the wall will interact with the magnetic energy of the plasma and the $\vec{B}_T$ field to create mechanical forces. Consequences to the ohmic heating (OH) coils, their power supplies, and other coils must also be taken into account.

The two most important parameters for the assessment are the plasma disruption time, τ_D , and the uniformity of the plasma energy deposition on the wall. Neither of these two parameters can be calculated definitively, but the distribution of energy on the first wall is the more uncertain.

The analysis described in this report is based on the parameters of TNS. For this device, the plasma disruption time is estimated to be $\tau_D = 24$ msec, with 185 MJ of thermal energy and 191 MJ of magnetic energy stored in the plasma. Uniform energy deposition has been assumed for the analysis.

Given these parameters, the principal results of the analysis are as follows.

1. The maximum Joule heating (I^2R) in the wall is about 2.85×10^9 W/m³; the fraction of the plasma magnetic energy going into Joule heat is about 30%. The rest of the magnetic energy is distributed to other components in the tokamak blanket region and is eventually felt as Joule heat.
2. The maximum current induced in the wall, assuming a steady-state plasma current of 5.6×10^6 A, is about 1.7×10^6 A. This result is based on a constant mutual inductance between the wall and the plasma of 9.64×10^{-6} H.

3. The maximum surface heat flux, assuming the plasma spreads out uniformly in the poloidal direction with a constant velocity, is about $3.85 \times 10^8 \text{ W/m}^2$.
4. The temperature rise in the first wall (which is made of 316 stainless steel) is roughly 400°C from a starting temperature of 104°C , indicating that wall failure due to thermal fatigue will occur after about 450 disruptions. (This result was based on the empirical data for wall failure given in Sect. III of the ASME Boiler and Pressure Vessel Code.)

The following qualitative conclusions can be drawn.

1. If $\tau_D = 100 \text{ } \mu\text{sec}$ (as has been assumed in the past but is now thought to be unlikely, due to recent theoretical results on the nonlinear interaction of tearing modes), some of the first wall will ablate and perhaps $40 \text{ } \mu\text{m}$ of the steel will melt.
2. The nonuniformity of the energy deposition will be enhanced by the fact that the tokamak is a torus rather than a cylinder, by the fact that the torus is noncircular, by the fact that the plasma is not centered in the torus, by magnetic ripple in the $\vec{B}_T$ field, and by instabilities formed by the coupling of magnetic islands in the plasma.

1. INTRODUCTION

Large fusion reactor systems used as commercial power producing devices must be reliable, maintainable, and economical and must have a reasonable lifetime. They must also be controllable, especially if the burntime is long enough to require fueling and helium removal. The instrumentation and control of a fusion reactor require a knowledge of the behavior of the parameters to be controlled, instruments to measure each parameter, and a control strategy for changing the parameter to the desired value. Parameters requiring control may include ion density, electron and ion temperature, plasma position, and perhaps others. The parameters to be controlled may change as operation progresses from startup through burn to shutdown.

During the burn and shutdown phases of reactor operation, roughly 200 MJ of thermal energy and 200 MJ of magnetic energy are stored in the plasma. If the plasma in a fusion reactor goes into a disruptive instability during the burn cycle so that the plasma is lost in a very short time (100 μ sec-25 msec), this energy is released to the first wall and other components.

Several questions come to mind:

1. Can the plasma be protected from a major disruption by operation within a particular set of parameter values?
2. If a disruption does occur, what damage will be done to the reactor itself? How many disruptions could be tolerated? What is the probability per cycle of a disruption?
3. What component failures will lead to a major plasma disruption? For example, if an equilibrium field (EF) coil power supply fails, will this lead to a major plasma disruption?
4. If it becomes evident that a major plasma disruption is imminent, can any action be taken to ameliorate the potential damage?
5. Will long burn pulses magnify the likelihood of a plasma disruption because of impurity buildup in the plasma?

In this report we partially answer, in a preliminary way, the second question posed above. Our primary concern is the consequences to the

first wall; we also briefly consider mechanical forces on coils, the need for protection of magnet power supplies, and the possibility of controlling an incipient disruption.

It is possible that control of the fusion reactor may consist of determining those operating parameters for which plasma instabilities do not arise. This possibility is complicated by the fact that the device will be very complex, with a delicate interaction between the operating parameters. For example, when heat is added via neutral beams, particles are also added and the plasma composition may be changed. This inability to change only one parameter at a time makes the control difficult but challenging.

Background information and a method of attacking the problem are given in Sect. 2. Analysis of the temperature in the first wall based on various models is considered in Sects. 3 and 4. In Sect. 5, we present some preliminary thoughts on the effects of a disruption on other components, the case of nonuniform energy deposition, and the possibilities of control. Recommendations and conclusions are given in Sect. 6.

2. PLASMA DISRUPTION IN A TOKAMAK

2.1 BACKGROUND INFORMATION

2.1.1 Previous Work

Little comprehensive work has been done on the aspects of disruption in power producing tokamaks. The Electric Power Research Institute's report on its fusion reactor control study¹ notes that "abort control is one of the most difficult control problems of a power reactor" but contains little quantitative work. Similarly, the scoping studies by General Atomic Company and Argonne National Laboratory (ANL) reported in Ref. 2 contain very little quantitative work; the report does provide a useful bibliography and some insight into various shutdown scenarios. In Ref. 3, the ablation of material from the first wall was investigated as a function of time and wall area involved; results showed that maximum ablation for stainless steel, assuming uniform energy deposition, was 35 μm for the ANL Tokamak Experimental Power Reactor.

2.1.2 Theory

The theory of the plasma disruption process itself is in a state of development.⁴ Both minor (internal) and major (external) plasma disruptions can apparently be understood via the interaction of tearing (resistive kink) modes in the magnetic field. The most important interaction is probably that of the $m = 3, n = 2$ and $m = 2, n = 1$ modes, where m and n are the poloidal and toroidal mode numbers of the poloidal flux function, respectively. The model used is a phenomenological one based on solving a reduced set of MHD equations. Its practical applications include a method of scaling the plasma disruption time from one tokamak to another and an indication of the factors which may be useful in avoiding a plasma disruption.

2.1.3 Disruption Phenomena

Observation and control of the following phenomena may permit the prevention of a plasma disruption.

1. The safety factor, $q(r)$, is sometimes flat before a major disruption. (Since the low order helical flux functions are involved, an asymmetry in the energy deposition on the first wall is expected.)
2. An $m = 2$ precursor oscillation, as observed in the x-ray and voltage loop signals, often precedes a disruption.
3. A negative voltage fluctuation occurring at the limiter signals the onset of a disruption.
4. The disruption appears to be poloidally asymmetric, so an odd m component of the helical flux function is most likely involved.

The smooth shutdown of a power producing tokamak will probably require feedback control, which can be developed once the shutdown physics is more thoroughly understood. Control of an incipient disruption will depend upon the length of time between the detection of trigger signals and the start of the actual disruption. Even if incipient disruptions can be controlled, it is still necessary to determine the consequences to the system, since the failure of components may drive the plasma into a disruptive instability.

2.2 THE DISRUPTION TIME

The time scale of the major disruptive instability is not accurately known for TNS. However, a scaling law developed by Carreras et al.⁵ can be used to estimate the disruption time as follows. If plasma diamagnetic effects are ignored, τ_D is proportional to $S^{2/5} \tau_R$, where S is the ratio of the resistive skin time, $\tau_R [\equiv a^2/(\mu \bar{n})]$, and the time for Alfvén waves to propagate around the torus in the toroidal direction, $\tau_{HP} [= R_o (\mu_o \rho_o)^{1/2} / B_{\phi o}]$; ρ_o is the mass density; and $B_{\phi o}$ is the constant toroidal magnetic field. This can be written as

$$\tau_D = C [\bar{R}_o^2 \bar{m}_i \bar{n}_i \bar{B}_{\phi o} \bar{a}^6 (1/\bar{V}^3)]^{1/5}, \quad (2.1)$$

where C depends upon $q(r)$ and its derivative and the other parameters are defined in Table 2.1, which gives their values for the Princeton Large Torus (PLT) and TNS. The observed disruption time in PLT is

Table 2.1. Parameters used in scaling
the disruption time τ_D for TNS

	PLT	TNS
Major radius, R_0 (m)	1.3	5.0
Ion mass, $\bar{m}_i$ (proton masses)	2.5	2.5
Ion density, $\bar{n}_i$ (10^{13} cm $^{-3}$)	10	13
Toroidal field, $\bar{B}_{\phi 0}$ (T)	5	5.3
Minor radius, $\bar{a}$ (m)	0.45	1.25
Voltage at limiter, $\bar{V}$ (V)	2-4	0.05-0.1

$\tau_D = 500$ μ sec; from this value and the scaling law of Ref. 5, a disruption time of $\tau_D = 24$ msec is projected for TNS, roughly 48 times the value for PLT. This extrapolation is shown in Fig. 2.1 (adapted from Ref. 5).

If the disruption time is longer than anticipated, it will have two beneficial consequences. First, control may be possible; second, even if control is not possible, the damage done to the first wall will decrease as the disruption time increases.

2.3 SCOPING THE PROBLEM

Order of magnitude calculations are given in this report, and uniform energy deposition has been assumed for all analyses (see Sect. 5.4). The logic followed is shown in Fig. 2.2.

Figure 2.2 also indicates that the lifetime of the first wall can be estimated if the probability per burn cycle of a major plasma disruption can be estimated. It is perhaps too early to attack this problem, because the operating parameters of TNS have not yet been completely determined, and estimating the probability of an abort given a set of assumed parameters is a very difficult problem.

Figure 2.3 indicates the impact on the wall lifetime of the thermal energy released by a major plasma disruption, and Fig. 2.4 shows the possible effects on components of the magnetic energy stored in the

Fig. 2.1. Scaling law for obtaining the disruption time for TNS.

plasma. Of course, the magnetic energy will give rise to eddy currents that cause Joule heating in the wall, thus adding to the thermal load.

The sequence of calculational steps for analyzing the impact of a major plasma disruption on the first wall is shown in Fig. 2.5. All the blocks shown have been considered, but not all have been analytically formulated. Obviously, lumped parameter models can only provide rough estimates of quantities such as temperature, eddy currents, etc. Distributed parameter models require the solution of partial differential equations, which is difficult and time-consuming. Certainly an accurate assessment of the temperature in the wall, the possibility of melting, and other important aspects of a disruption will require distributed parameter modeling.

Fig. 2.2. Methodology for analyzing the consequences resulting from a major plasma disruption.

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Fig. 2.3. Possible consequences to first wall resulting from thermal energy stored in the plasma.

Fig. 2.4. Possible consequences to first wall and other components resulting from magnetic energy stored in the plasma.

Fig. 2.5. Model evolution for calculating the impact on the first wall of a major plasma disruption.

Currently, it is felt that the use of lumped parameter models to discern trends, perhaps modeling some components with partial differential equations, is the most efficient method of determining the consequences of a plasma disruption. It is recommended that the work for the coming year be directed along these lines. Not shown in Fig. 2.5 is the linking that can be done between the distributed and lumped parameter models. The judicious linking of various models should provide valuable insight into the disruption problem.

3. LUMPED PARAMETER MODELS

3.1 PLASMA DISRUPTION MODELS

A complete model for the time and space distribution of the ions and electrons during the disruption does not exist, and the model of Ref. 4 does not completely describe the disruption process from beginning to end. Thus, a description of the plasma as it disrupts and strikes the first wall is desirable. In the analysis that follows we use two models for the surface heat flux on the wall. The heat flux is assumed to be uniform in space but to have a time dependence as given below.

3.1.1 The Constant Velocity Model

Assume that the plasma has a parabolic spatial distribution in both density and temperature, as shown in Fig. 3.1. Then if the plasma moves radially outward as shown, the surface heat flux that strikes the wall as a function of time can be obtained as follows.

The thermal energy of the plasma is given in terms of the density and temperature by the relation

$$E_{pt} = \frac{3}{2} (n_i T_i + n_e T_e) V_p , \quad (3.1)$$

where V_p is the volume of the plasma. Table 3.1 gives typical values for these quantities for TNS.⁶

The total thermal energy of the plasma, E_{pt} , deposited on the wall during a disruption time τ_D is calculated as follows. Writing the ion distribution as

$$n(r) = n_{\max} [1 - (r/a)^2] \quad (3.2)$$

and the temperature distribution as

$$T(r) = T_{\max} [1 - (r/a)^2] , \quad (3.3)$$

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PLASMA MOVES OUTWARD RADIALLY
AT CONSTANT VELOCITY

PARABOLIC DENSITY
PROFILE

PARABOLIC TEMPERATURE
PROFILE

Fig. 3.1. Constant velocity model for the plasma disruption.

Table 3.1. Typical parameter values for TNS

Quantity	Value
Average ion density, n	$1.3 \times 10^{20} \text{ m}^{-3}$
Average ion temperature, T_i	13.0 keV
Minor radius, a	1.25 m
Major radius, R_o	5.0 m
Elongation, σ	1.6
First wall area, A_w	348.6 m ²
First wall thickness, δ_w	$1.65 \times 10^{-3} \text{ m}$
Plasma volume, V_p	227.4 m ³
Plasma resistance, R_E	$3.0 \times 10^{-9} \Omega$ at 13.0 keV
Toroidal field at wall, $B_{\phi w}$	7.7 T
Steady-state plasma current, I_{po} (I_{10})	$5.6 \times 10^6 \text{ A}$
Thermal energy in plasma, E_{pt}	$1.85 \times 10^8 \text{ J}$
Neutron wall loading, q_n''	$2.38 \times 10^6 \text{ W/m}^2$
Self-inductance of plasma, L_{11}	$12.2 \times 10^{-6} \text{ H}$
Mutual wall-plasma inductance, L_{12}	$9.64 \times 10^{-6} \text{ H}$
Self-inductance of wall, L_{22}	$9.75 \times 10^{-6} \text{ H}$
Steady-state surface heat flux, q_{to}''	$5.94 \times 10^5 \text{ W/m}^2$

we obtain

$$E_{pt} = 3V_p nT = 3n_{\max} T_{\max} \int_0^a [1 - (r/a)^2]^2 (2\pi R_o) 2\pi r dr \quad (3.4)$$

(assuming the electron and ion densities and temperatures to be the same). The energy in a ring at radius r and thickness dr is

$$dE_{pt} = 3n_{\max} T_{\max} [1 - (r/a)^2]^2 (2\pi R_o) (2\pi r dr)$$

or

$$\frac{dE_{pt}(r)}{dr} = 12\pi^2 n_{\max} T_{\max} R_o r [1 - (r/a)^2]^2 . \quad (3.5)$$

If we assume that the ring is moving radially outward at a constant velocity v , the rate at which the energy is striking the wall is ($dr = vdt$)

$$\begin{aligned} \frac{dE_{pt}}{dt} &= \frac{dE_{pt}}{dr} \frac{dr}{dt} = 12\pi^2 n_{\max} T_{\max} R_o v \cdot vt [1 - (vt/a)^2] \\ &= P_o (t/\tau_D) [1 - (t/\tau_D)^2]^2 , \end{aligned} \quad (3.6)$$

where P_o is some constant and we used $a = v\tau_D$. P_o is determined by noting that

$$E_{pt} = \int_0^{\tau_D} \frac{P_o}{\tau_D} t [1 - (t/\tau_D)^2]^2 dt$$

or

$$P_o = 6E_{pt}/\tau_D . \quad (3.7)$$

The surface heat flux due to the disruption is thus

$$q''_{wo} = \frac{6E_{pt}}{A_w \tau_D} \quad (3.8)$$

and the surface heat flux for the constant velocity is

$$q''_{wt}(t) = \begin{cases} q''_{to} , & t < 0 \\ \frac{6E_{pt}}{A_w \tau_D} \left(\frac{t}{\tau_D} \right) \left[1 - \left(\frac{t}{\tau_D} \right)^2 \right]^2 + q''_{to} \exp(-t/\tau_D) , & 0 \leq t \leq \tau_D \\ q''_{to} \exp(-t/\tau_D) , & t > \tau_D . \end{cases} \quad (3.9)$$

It may be noted that the energy confinement time for the plasma may be estimated from the relation

$$\tau_E = \frac{E_{pt}}{q_{to}'' A_w} . \quad (3.10)$$

3.1.2 The Gaussian Surface Heat Flux Model

The constant velocity model described in Sect. 3.1.1 can only be an approximate formulation of the heat flux when the plasma disrupts, since it assumes that all the heat energy goes to the wall with all the particles clinging to the first wall. In fact, there will probably be a fair amount of heat energy left in the vacuum chamber even after the plasma disruption is over. Even if nothing is done it would take some time before there is a thermal equilibrium between the remaining gas in the tokamak and the wall temperature. Therefore, it was decided that a Gaussian model for the plasma disruption would also be considered. This has two advantages. First, the heat deposition rate does not go to zero after a time τ_D , and second, a comparison can be obtained between the two models to see how sensitive the results are to the surface heat flux.

The surface heat flux on the first wall is assumed to be

$$q_{wt}''(t) = q_{wo}'' \exp - [(t - \tau_D/2)/\tau_D]^2 + q_{to}'' \exp -(t/\tau_D) , \text{ for } t \geq 0 . \quad (3.11)$$

Again using the fact that

$$E_{pt} = P_o \int_{-\infty}^{\infty} \exp -[(t - \tau_D/2)/\tau_D]^2 dt ,$$

we obtain

$$q_{wo}'' = \frac{P_o}{A_w} = \frac{2E_p t}{A_w \sqrt{\pi} \tau_D} . \quad (3.12)$$

Notice that at $t = 0$, i.e., at the beginning of the disruption, the plasma has already started dumping some energy on the wall.

3.2 MODEL OF CONSEQUENCES TO THE FIRST WALL

The first wall, being the component closest to the plasma, will be most directly affected by the plasma disruption. As the plasma current dies away and the heat flux strikes the wall, eddy currents will be induced into the first wall and will add to the total heat load. However, they may have the beneficial effect of lessening the temperature gradient in the wall.

3.2.1 Assumptions

The interaction of the plasma disruption with the wall is initially treated as though no other component of the reactor were involved. The heat load on the wall is due to the surface heat flux and the induced eddy currents generating a $I_w^2 R_w / V_w$ volumetric heat rate.

Several assumptions are made in this calculation.

1. Eddy currents are induced uniformly in the wall.
2. The surface heat flux is spatially uniform on the first wall.
3. The mutual plasma-wall inductance, L_{12} , and the plasma self-inductance, L_{11} , are constant during the plasma disruption process and then become zero when the plasma current goes to zero.
4. The Biot number is small;

$$Bi = \frac{\text{surface convection heat transfer rate}}{\text{internal conduction heat transfer rate}} = \frac{h_x \delta_w}{k_w}$$

is less than unity. This means that the temperature profile in the wall is nearly flat.

5. The Fourier modulus is large, $Fo \gg 1$, and is defined as

$$Fo = \frac{\alpha_w \tau_D}{\delta_w^2} = \left(\frac{\text{distance temperature wave travels}}{\text{wall thickness}} \right)^2,$$

where α_w is the wall thermal diffusivity.

It is obvious that every one of these assumptions will be violated at least some time during the disruption.

Figure 3.2 is a schematic diagram of the physical system to be simulated. There are four primary equations in the model. The energy balance equation for the wall is

$$\frac{dE_w}{dt} = q'_{wt} A_w + q'_{wE} V_w - U A_w (T_w - T_o). \quad (3.13)$$

The voltage balance equation for eddy currents in the wall is

$$L_{22} \frac{dI_2}{dt} + R_2(T_w) I_2(t) = V_2. \quad (3.14)$$

The voltage induced in the wall by plasma decay current is

$$V_2 = -M_{12} \frac{dI_1(t)}{dt}. \quad (3.15)$$

The plasma current as a function of disruption time is assumed to be of the form

$$I_1(t) = I_{10} \exp -(t/\tau_D). \quad (3.16)$$

In these equations, V_2 is the voltage induced in the wall, $R_2(T_w)$ is the wall electrical resistance, which changes with wall temperature, $V_w = A_w \delta_w$ is the volume of the wall, $q'_{wE}(t) = I_2^2(t) R_w(T_w) / V_w$ is the volumetric heat generation rate, I_{10} is the steady-state plasma current,

U is the overall heat transfer coefficient, T_o is the temperature of the coolant, and E_w = total thermal energy of the wall. Details of the model are given in the Appendix.

Fig. 3.2. Schematic diagram for analysis of the plasma-wall interaction.

3.2.2 Results and Observations

The quantities of interest are the maximum temperature in the wall (the temperature is assumed to be uniformly distributed across the

thickness of the wall), the fraction of the magnetic energy stored in the plasma that goes into Joule heating in the wall, the relative importance of the heat load from Joule heating and the surface heat flux.

Two quantities must still be defined mathematically. The fraction of the magnetic energy stored in the plasma which is converted to heat energy in the wall, F_E , is defined as

$$f_E = \frac{\int_0^\infty I_2^2(t) R_2(T_w) dt}{\frac{1}{2} L_{11} I_{10}^2} = \frac{\int_0^\infty I_2^2(t) R_2(t) dt}{1.91 \times 10^8 \text{ J}} \quad (3.17)$$

The fraction of magnetic and thermal energy that goes into heating the wall, f_T , is

$$f_T = \frac{(1/t_{\max}) \int_0^{t_{\max}} \{C_{w0} V_w [T_w(t) - T_1]\} dt}{E_{pt} + (1/2) L_{11} I_{10}^2} \quad (3.18)$$

(This might better be defined by changing $t_{\max}$ to τ_D .) Table 3.2 lists the values of quantities of interest obtained using this model. Figures 3.3-3.5 show temperature, current, and magnetic and thermal power densities, respectively, as a function of time. Figure 3.6 shows the rate of temperature change in the first wall due to three energy exchange processes.

The lumped parameter model is expected to give indicative but not highly accurate results. The temperature variations of the thermodynamic properties have been included in the model. However, it is expected that the induced wall current $I_2(t)$ is a little larger than the actual current, since other components have not been included, and eddy currents will also be induced in these components which will affect the current induced in the first wall.

The model could be improved in at least two significant ways. The first is to account for the nonconstant inductances as the plasma is disrupting. The second is to include other components, especially the equilibrium field (EF) coils interior to the toroidal field (TF) coils.

Table 3.2. Results of lumped parameter model ($T_i = 377\text{K}$)

	$\tau_D = 10^{-4} \text{ sec}$		$\tau_D = 2.4 \times 10^{-2} \text{ sec}$	
	Constant velocity	Gaussian	Constant velocity	Gaussian
Maximum temperature, K	502	550	464	498
Time of maximum temperature, sec	0.0135	0.0126	0.024	0.043
Maximum current, A	5.31×10^6	5.30×10^6	1.65×10^6	1.65×10^6
Time of maximum current, sec	4.54×10^{-4}	5.4×10^{-4}	0.0175	0.0175
Maximum Joule heating, W/m^3	2.94×10^{10}	3.20×10^{10}	2.85×10^9	2.82×10^9
f_E	0.782	0.781	0.308	0.311
f_T	0.289	0.289	0.152	0.151

Fig. 3.3. Average wall temperature as a function of time with an initial temperature of 377K, $\tau_D = 24$ msec. The dashed line is for the Gaussian model calculation; the solid line, for the constant velocity model calculation.

Fig. 3.4. Current induced in the wall as a function of time. $T_i = 377K$, $\tau_D = 24$ msec. The dashed line is for the Gaussian model calculation; the solid line, for the constant velocity model calculation.

Fig. 3.5. Densities of magnetic energy (squares) and thermal energy (circles) vs time. $T_i = 377K$, $\tau_D = 24$ msec. The dashed line is for the Gaussian model calculation; the solid line, for the constant velocity model calculation.

Fig. 3.6. The rate of temperature change in the first wall due to three energy exchange processes; surface heat flux (squares), heat transfer (circles), and eddy currents (triangles). $T_i = 377K$, $\tau_D = 24$ msec. The dashed line is for the Gaussian model calculation; the solid line, for the constant velocity model calculation.

3.3 PLASMA-WALL-EF COIL MODEL

The plasma disruption will induce eddy currents not only in the first wall but also in the coils. Since the plasma disruption occurs on such a short time scale, there will be a magnetic field "pulse" that radiates outward from the plasma. It will take time for this pulse to penetrate the first wall and affect the other coils. This time delay can produce some significant changes in the induced currents. To model the interaction between the plasma, the wall, and the poloidal field (PF) coils, we make the following assumptions.

1. All inductances are constant during the disruption time.
2. No temperature dependence is taken into account for resistances, etc.
3. The time for the magnetic field to penetrate the first wall, τ_2 , is given by

$$\begin{aligned}\tau_2 &= \frac{\mu a \delta_w}{2\eta_{ss}} \\ &= \frac{(4\pi \times 10^{-7})(1.25)(1.65 \times 10^{-3})}{2(2.88 \times 10^{-7})} = 4.5 \times 10^{-3} \text{ sec} .\end{aligned}\tag{3.19}$$

4. The plasma resistance is chosen to simulate the disruption time τ_D . This means that

$$R_1 = \frac{L_{11}}{\tau_D} = \frac{12.2 \times 10^{-6} \Omega}{\tau_D} .\tag{3.20}$$

The plasma resistance is actually much smaller than this, but during the disruption phenomenon L_{11}/R_1 is not the dominating consideration. We arbitrarily choose R_1 as indicated so that the plasma decay time matches that observed.

We now apply Kirchhoff's laws to each circuit element. The electromotive force (emf) relation for the plasma is

$$L_{11} \frac{dI_1(t)}{dt} + R_1(t)I_1(t) = L_{12} \frac{dI_2}{dt} + \dot{\phi}_{13} ,\tag{3.21}$$

where we make the provision that it takes time for the $\vec{B}$ field due to the change in the plasma current to penetrate the first wall and influence the PF coils. This is the reason for the $\dot{\phi}_{13}$ term. The time lag is accounted for by the approximation

$$\tau_2 \dot{\phi}_{13} + \phi_{13} = L_{13}I_3 .\tag{3.22}$$

The first wall voltage balance yields

$$L_{22} \frac{dI_2}{dt} + R_2 I_2 = L_{12} \frac{dI_1}{dt} + L_{23} \frac{dI_3}{dt} \quad (3.23)$$

and, for the PF coils,

$$L_{33} \frac{dI_3}{dt} + R_3 I_3 = \dot{\phi}_{31} + L_{23} \frac{dI_2}{dt} + V_3 . \quad (3.24)$$

The magnetic flux, $\dot{\phi}_{31}$, is the flux in structure 3, the PF coils, due to a change in the plasma current I_1 . Therefore we have

$$\tau_2 \dot{\phi}_{31} + \phi_{31} = L_{13} I_1 . \quad (3.25)$$

The parameters in the model and the initial conditions are given in Table 3.3. One further condition was imposed on the solution: L_{1i} ($i = 1, 2, 3$) goes to zero for all time $t > t_1$ where t_1 is chosen so that $I_1(t_1) = 0$. This means that once the plasma current achieves zero, there is no longer any self-inductance or mutual inductance associated with the plasma.

3.4 WALL ABLATION MODEL

The wall ablation problem requires a sophisticated heat conduction code that accounts for the heat of fusion and of vaporization. We derive a very simple estimate of the amount of ablated material based purely on the conservation of energy.

If the total plasma energy, E_{pt} , goes into the surface instantaneously, then the mass of material that is ablated, m_A , is given by

$$E_{pt} = \Delta h_T m_A , \quad (3.26)$$

Table 3.3. Parameter values used
in the model

Parameter	Value
L_{11}	$12.2 \times 10^{-6} \text{ H}$
L_{12}	$9.64 \times 10^{-6} \text{ H}$
L_{13}	$2.016 \times 10^{-4} \text{ H}$
L_{22}	$9.75 \times 10^{-6} \text{ H}$
L_{23}	$2.016 \times 10^{-4} \text{ H}$
L_{33}	0.381 H
$I_1(0)$	$5.6 \times 10^6 \text{ A}$
$I_2(0)$	0 A
$I_3(0)$	$6.9 \times 10^4 \text{ A}$
V_3	4000 V
R_1	$12.2 \times 10^{-6} \Omega/\tau_D$
R_2	$6.98 \times 10^{-4} \Omega$
R_3	$58 \times 10^{-3} \Omega$
τ_2	$4.5 \times 10^{-3} \text{ sec}$

where Δh_T is the change in enthalpy from the initial (steady-state) temperature to 3090K including the heats of vaporization and fusion.

The change in enthalpy is

$$\Delta h_T = (h_{1700} - h_{377}) + h_{\ell s} + (h_{3090} - h_{1700}) + h_{\ell v} = 9456.5 , \quad (3.27)$$

so that

$$m_A = \frac{E_{pt}}{\Delta h_T} = 19,563 \text{ g} .$$

The volume is m_A/ρ , so knowing A_w we obtain

$$x_A = 7 \times 10^{-6} \text{ m} .$$

This result assumes uniform energy deposition.

Table 3.4 lists some important properties of 316 stainless steel, the expected wall material for TNS.

Table 3.4. Properties of stainless steel

Property	Value
Melting point	1700K
Boiling point	3090K
Heat of fusion	64 kcal/g
Heat of vaporization	1770 kcal/g

4. DISTRIBUTED PARAMETER MODELS

4.1 MODEL OF TEMPERATURE DISTRIBUTION IN THE FIRST WALL

A one-dimensional analysis of the temperature profile was made with the HEATING5 code,⁷ a finite difference code which solves the transient problem by an implicit (Crank-Nicolson) technique or by Levy's modified explicit method. The temperature gradient in the first wall during the plasma disruption is found and then used to obtain the thermal fatigue resulting from the disruption.

Three contributions to the heat load in the first wall are considered:

1. the surface heat flux impinging on the wall as the plasma disrupts;
2. Joule heating due to the eddy currents induced on the wall;
3. neutron flux interacting with the stainless steel and causing a heat load internal to the wall. The neutron flux heating contribution is terminated after the steady-state temperature distribution is achieved.

The very high energy electrons (>1 MeV) can also contribute to the internal energy generation, but these are neglected, as are any gamma rays (x rays) emanating from the plasma. Disruption times of 100 μ sec and 24 msec are considered. Because the temperature gradient is very steep, the wall was divided into two regions for the 100- μ sec case. The region close to the plasma had many more nodes than that near the coolant.

4.1.1 Assumptions

We assume that the internal heat generation due to Joule heating is spatially uniform. The time dependence of the Joule heating is obtained from the lumped parameter model. The boundary conditions on the first wall (indicated in Fig. 3.2) are that at the front surface ($x = 0$) the expression

$$q_T'(t) = -k(T) \left. \frac{\partial T(x,t)}{\partial x} \right|_{x=0} \quad (4.1)$$

is satisfied and at the back surface the water coolant (at a bulk temperature of 20°C) carries the heat away from the wall. The heat transfer coefficient is chosen as 6222 W/m²-°C. The temperature distribution is obtained from the heat conduction equation,

$$\frac{\partial}{\partial x} \left[k(T) \frac{\partial T(x,t)}{\partial x} \right] + q_{wE}'''(t) = C_p \rho \frac{\partial T(x,t)}{\partial t} . \quad (4.2)$$

HEATING5 first obtains the steady-state distribution. The profile is essentially linear, with the front surface at 131°C and the rear surface at 87°C. The steady-state profile includes the term⁸

$$2.38 \times 13.1 \exp(-x/0.385) \text{ MW/m}^3 , \quad (4.3)$$

where we assume that the neutron wall loading is 2.38 MW/m².

The solution of Eq. (4.2) in cylindrical geometry indicates that the thermophysical properties of stainless steel can vary with temperature. For $\tau_p = 24$ msec, no phase change is necessary, but for $\tau_p = 100$ μ sec, the stainless steel not only melts, it also vaporizes.

If melting occurs, the boundary conditions between the liquid region (l) and the solid region (s) are

$$-k_l \frac{\partial T_l}{\partial x} \bigg|_{x_{ls}} + k_s \frac{\partial T_s}{\partial x} \bigg|_{x_{ls}} = h_{sl} \rho \frac{dx_{ls}}{dt} , \quad (4.4)$$

where h_{sl} is the latent heat of fusion (64 kcal/g-K) and x_{ls} is the melting boundary, which is moving as the heat is deposited.

If vaporization is taken into account as well (HEATING5 can only accommodate one phase change), then in place of Eq. (4.1) the boundary condition at the liquid-vapor interface, x_{lv} , which is in motion, is

$$q_T'''(t) = -k_l \frac{\partial T_l}{\partial x} \bigg|_{x_{lv}} + h_{lv} \rho \frac{dx_{lv}}{dt} , \quad (4.5)$$

where the latent heat of fusion, h_{lv} , is 1770 kcal/g.

4.1.2 Results and Observations

Figures 4.1-4.3 indicate the results of HEATING5. For the 100- μ sec case, about 4 or 5 μ m of the wall ablate and about 40 μ m melt. For the 24-msec case, the wall neither melts nor ablates. In fact, the difference between the maximum and the average wall temperature is about 407°C.

Thermal fatigue estimates for the stainless steel have been made, and about 460 aborts could be tolerated [less the fatigue due to the normal thermal cycling (see Sect. 5.5)].

The maximum wall temperature for the 100- μ sec case was $\sim 5400^\circ\text{C}$, achieved at the surface at 70 μ sec. The maximum depth of wall melting was 35 μ m, if the latent heat of fusion was included in the calculation, and occurred 100 μ sec after the plasma disruption began. If the latent heat of fusion is ignored in the calculation, 40 μ m of the wall melts.

The heat of vaporization cannot be conveniently included in the HEATING5 code, so the 100- μ sec runs are correct up to 3090K but not beyond that temperature.

Fig. 4.1. Temperature profile in wall for $\tau_D = 24$ msec, constant velocity surface heat flux, including Joule heating.

Fig. 4.2. Wall temperature profile for $\tau_D = 100 \mu\text{sec}$, constant velocity surface heat flux.

Fig. 4.3. Solid-liquid interface as a function of time. $\tau_D = 100 \mu\text{sec}$, constant velocity surface heat flux.

One other fact to be noted is that the internal heat generation rate due to eddy currents changes the wall temperatures by roughly 1% of the temperature change due to the surface heat flux. This can also be observed from the lumped parameter models. Therefore, the temperature distribution is not sensitive to the eddy current heat generation rate.

The 100- μsec heat pulse causes ablation of material from the surface. Classical heat conduction may not be applicable to this situation due to the possible formation of a "virtual limiter," i.e., a cold plasma or sheath protecting the wall (to some extent) from the incident heat flux (see Sect. 5.6). This question should be investigated further.

4.2 ANALYTICAL ESTIMATE AND COMPARISON

Behrisch⁹ has made an analytical estimate of the temperature distribution in the first wall assuming a semi-infinite solid. The temperature

increase ΔT of the surface of the first wall due to dumping a total energy E_{pt} on the area A_w in a time τ_D is

$$\Delta T = \frac{E_{pt}}{A_w} \frac{1}{\sqrt{\tau_D}} \sqrt{\frac{4}{\pi C_w k_w \rho_w}}. \quad (4.6)$$

If the universal "depth" unit u is used instead of x , where

$$u = \frac{x}{\sqrt{\tau_D}} \sqrt{\frac{\rho_w C_w}{4k_w}}, \quad (4.7)$$

the temperature profile is given by

$$T(u) = T(0) [\exp(-u^2) - 2u \int_u^\infty \exp(-e_s^2) de_s]. \quad (4.8)$$

For the 24-msec disruption time, ΔT is about 535K according to Eq. (4.6); for $\tau_D = 100 \mu\text{sec}$, ΔT is 8291K. Of course, these analytical estimates do not take into account melting, latent heat of fusion, latent heat of vaporization, or changing material properties. The results of HEATING5 and of Ref. 9 are compared in Table 4.1. (The analytical results are taken from graphs in Ref. 9.)

Table 4.1. Comparison of the temperature increase, ΔT , at the surface of the first wall

	$\tau_D = 24 \text{ msec}$	$\tau_D = 100 \mu\text{sec}$
ΔT		
Analytical value	$\sim 450\text{K}$	$> 2400\text{K}$
HEATING5 value	456.73K	3854K

5. OTHER CONSIDERATIONS

Thermal consequences to the first wall have been of primary importance because the wall's proximity to the plasma makes it particularly liable to damage. However, there are other important aspects of a plasma disruption. Some of these are briefly addressed in this section.

5.1 FORCE FIELDS

The forces on the first wall and the poloidal field (PF) coils will be impulsive but may be massive. They result from the $\vec{J} \times \vec{B}$ terms, where $\vec{J}$ is the current density and $\vec{B}$ is the field. If we take Newton's second law for a body,

$$\rho_m \left[\frac{\partial \vec{v}}{\partial t} + (\vec{v} \cdot \text{grad}) \vec{v} \right] = \vec{J} \times \vec{B} - \text{grad } P, \quad (5.1)$$

where ρ_m is the mass density and P is the pressure, and apply it to the first wall, we can see that the current density induced in the first wall by the plasma disruption must be obtained. After this is done, then the net force can be calculated by calculating the $\vec{J} \times \vec{B}$ component. Of course, this will vary from point to point on the wall. It may be mentioned that the only components of the forces on the first wall are those normal to the wall.

The emf induced in the wall, E_2 , is obtained as

$$E_2 = -M_{12} \frac{dI_1(t)}{dt}. \quad (5.2)$$

The current density is then obtained by writing

$$J_2(t) = (E_2/R_2) \frac{1}{\delta_w 2\pi a} \quad (5.3)$$

if the wall is circular and of radius a . The resistance of the wall, R_2 , depends upon the wall material, temperature, and dimensions.

5.2 POWER SUPPLY PROTECTION

The protection of the power supply from feedback of the voltage pulse induced in the ohmic heating (OH) coils may be a significant problem. The time duration and the height of the voltage pulse will depend primarily upon the mutual inductance of the coils and the plasma, the disruption time, and the magnitude of the plasma current. Various protection devices may be used to prevent damage to the power supplies. These include fuses, switches activated by rapidly changing voltage, etc.

5.3 SHOCK WAVES

Depending upon the plasma disruption time, the plasma disruption-first wall interaction may be more adequately treated in the context of "detonator" or shock waves than that of the heat conduction equations. The 24-msec case can certainly be treated by classical heat conduction, but the same may not be true for the 100- μ sec disruption time. The Fourier modulus, F_0 , for 100 μ sec is about

$$\frac{0.0413 \text{ cm}^2/\text{sec} \times 10^{-4} \text{ sec}}{0.165 \text{ cm}^2} = 1.5 \times 10^{-4} .$$

This means that the disruption is over before the heat pulse has penetrated more than 1% of the distance through the wall. Thus, for the 100- μ sec pulse, it may be necessary to treat the plasma disruption as a shock phenomenon.

5.4 NONUNIFORM ENERGY DEPOSITION

All the calculations to date have assumed a uniform energy deposition on the wall. However, there are several factors which will tend to make the deposition nonuniform.

1. The vacuum vessel is toroidal, so more heat will probably be deposited on the interior of the first wall.
2. The center of the plasma will not be at the center of the first wall.
3. The first wall will most likely be D-shaped rather than circular. If the D is constructed of "flats," this accentuates the nonuniformity.
4. The magnetic islands that form in the plasma create regions of ergodicity formed by the coupling of magnetic modes. The thickness of the ergodic regions will determine the particle transport so that the energy deposition will depend upon the nonuniform thickness of these regions of ergodicity.
5. Magnetic field nonuniformities (such as TF ripple) will probably lead to nonuniformities in the energy deposition.

As mentioned in the fourth point above, rapid particle transport (plasma disruption) is associated with the ergodic field line region. If the energy deposition on the wall is directly proportional to the thickness of the ergodic region, surface heat fluxes, $q_{wt}'(\theta, t)$, may differ by a factor of three. The surface heat flux now depends on the poloidal angle θ as well as time. Quantification of this factor is an essential task that must be addressed.

5.5 WALL LIFETIME

The number of major plasma disruptions that can be tolerated before the wall fractures can be estimated from the temperature gradients obtained by HEATING5. The maximum thermal stress, σ_{MAX} , is given by¹⁰

$$\sigma_{MAX} = Kn \frac{E\alpha\Delta T}{1 - a\mu}, \quad (5.4)$$

where K is a stress concentration factor due to surface irregularities; n is a factor depending upon the amount of constraint imposed; $a = 0, 1$, or 2 , depending upon the number of directions constrained; μ is Poisson's ratio; E is Young's modulus; α is the linear temperature coefficient of thermal expansion; and ΔT is the temperature change in the wall due to the plasma disruption.

Table 5.1 provides the values of these parameters for the disruption in TNS. The number of cycles permitted before failure was obtained from Ref. 11. The temperature coefficient of expansion is given by

$$\alpha = 1.7887 \times 10^{-5} + 2.3977 \times 10^{-9}T + 3.2692 \times 10^{-13}T^2 \quad (5.5)$$

where α is in (degrees Celsius)⁻¹ and T is in kelvins.

A summary of the analysis procedure can be found in Ref. 12. Available data on thermal fatigue and component failure are collected in Ref. 11.

The curves for allowable stress amplitude, S_a , vs the number of cycles before failure, N, can be used to determine N after S_a has been obtained. For this case, S_a is $1/2 (\sigma_{MAX})$. A safety factor of ten is given in the curves.

In the case of TNS, the ordinary cyclic operation is a factor as well as the fatigue due to the plasma disruption. The cumulative fatigue damage may be estimated by the cumulative lifetime usage factor, U (how much of the life of the wall has been used),

$$U = \frac{P_1}{N_1} + \frac{P_2}{N_2}, \quad (5.6)$$

where P_1 is the number of burn cycles anticipated during the lifetime of the tokamak, P_2 is the number of major plasma disruptions anticipated in the lifetime of the device, N_1 is the number of burn cycles that would cause wall failure, and N_2 is the number of plasma disruptions to cause wall failure. For safe operation, the cumulative use factor U should not exceed 0.80.

5.6 THE VIRTUAL LIMITER

The thermal analyses performed thus far have assumed classical heat conduction with conventional boundary conditions. However, Sestoro¹³ postulates the existence of a "virtual limiter," which is formed as follows.

Table 5.1. Thermal stress limits on the first wall
(constant velocity model)

Quantity	τ_D	
	24 msec	100 μ sec
T_{MAX}	588°C	5688°C ^a
$\bar{T}$	181°C	759°C
ΔT	407°C	4929°C
α (at $\bar{T}$)	$1.904 \times 10^{-5} \text{°C}^{-1}$	$2.071 \times 10^{-5} \text{°C}^{-1}$
K ($1 \leq K \leq \infty$)	1	1
n ($0 \leq K \leq 1$)	1	1
E	26×10^6 psi	26×10^6 psi
a	1	1
μ	0.30	0.30
σ_{MAX}	2.88×10^5	3.79×10^6
S_a	144 ksi	1895 ksi
N (number of cycles for fracture)	450	1

^aWall melts so that fatigue analysis no longer applies.

When the plasma goes into a disruption, the plasma energy is carried from the center of the plasma to the wall and to the cold, impurity-rich plasma periphery. The cold periphery absorbs the energy and reemits it as bremsstrahlung, recombination, and deexcitation radiation, which the wall must absorb along with its share of the plasma energy. This will heat the wall to a very high temperature (if τ_D is small) and vaporize some wall material, which enters the cold plasma periphery and may prevent further wall erosion by greatly increasing the cold plasma's absorption of energy. This cold, dense, high Z plasma screening the wall from the hot interior plasma is the virtual limiter.

As the disruption continues, the vaporized material will spread out. The time scale of this spreading is a significant factor in the assessment of the damage to the first wall in the event of localized energy deposition. The amount of vaporized material necessary to protect the wall from direct plasma particles can be calculated using the stopping power of the virtual limiter with respect to the hot plasma particles. This amount has been investigated for the Joint European Torus (JET) but not for TNS. The time-dependent behavior of the virtual limiter has not been investigated, and this is certainly an area where some study should be done.

5.7 CONTROL POSSIBILITIES

It appears that the plasma disruption time for a TNS-type machine will be on the order of 24 msec. This time scale is long enough to permit consideration of some control possibilities.

The control possibilities fall into three general areas:

1. The device may be operated so that the likelihood of a disruption occurring is very small. This necessitates measurements of the temperature and density profiles as well as other parameters. The reactor operator would have to maneuver fueling controls, helical winding coils (to cause field lines to become ergodic), etc. so that the plasma could never enter the region of parameter space where disruptions are likely.

2. An incipient abort signal (such as the voltage spike at the limiter) could be detected and action taken to ameliorate the damage to the first wall. For example, valves may be opened to flood the chamber with cold gas and protect the walls. Perhaps other protective options are also open.
3. A control system could be designed to detect an incipient abort signal and prevent the abort. Perhaps the hard shutdown can be controlled sufficiently to transform it into an ordinary or soft shutdown.

The last two possibilities do not exist if $\tau_D = 100 \mu\text{sec}$.

6. CONCLUSIONS AND RECOMMENDATIONS

The following conclusions are derived from the analysis.

1. It is likely that the plasma disruption time τ_D will be longer than previously anticipated. Instead of 100 μ sec, it is probable that the disruption time will be 24 msec or even longer for TNS.
2. For $\tau_D = 24$ msec, the temperature rise in the first wall (316 stainless steel) will be roughly 400°C, so that about 450 disruptions could be accommodated before wall failure due to thermal fatigue. (This estimate assumes a uniform energy deposition.)
3. The eddy currents are much more important in force considerations, power supply protection, etc. than in contributing to the heat load through I^2R (Joule) heating. It seems that less than 10% of the temperature change in the wall will be due to the induced eddy currents.
4. The temperature rise is not very sensitive to the shape of the heat pulse that strikes the wall. It is primarily due to the disruption time, τ_D , and the total thermal energy in the plasma, which determines the pulse height.

The following recommendations seem appropriate at this time.

1. Further study should be done on forces induced in coils, the first wall, etc. The need for power supply protection must be quantified so that a recommendation can be made as to the best way to protect the OH supplies.
2. Further analysis should be done on the thermal consequences to the first wall, with special attention directed to the case of nonuniform energy deposition. Perhaps initial parametric studies can be made, and this should be done primarily for the 24-msec disruption time.
3. Initiation of control mechanisms could begin assuming the 24-msec case. It is even possible to start examining hardware requirements for gas puffing for first wall protection.

4. The preliminary results of this report should be improved by consideration of more detailed models (accounting for both latent heat of fusion and vaporization) and should also be improved and updated as MHD disruptive theory evolves.
5. Fusion devices currently under construction (such as Doublet III) should be analyzed in terms of consequences of a disruption to the first wall, with the idea of recommending experiments to be performed. For example, thermocouples could be put into the wall for temperature measurements, and attempts to measure the heat pulse and the non-uniformity of the disruption could be considered. This would be of direct concern for this analysis but would also be of concern to theorists who study MHD disruptions.

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APPENDIX

LUMPED PARAMETER MODEL OF THE PLASMA AND WALL
DURING A MAJOR PLASMA DISRUPTION

Section 3.2.1 of the report provides the basic framework for calculating the wall temperature during a major plasma disruption. For completeness, the balance equations are rewritten as

$$\frac{dE_w(t)}{dt} = q_{wt}'A_w + q_{wE}''V_w - UA_w(T_w - T_o) , \quad (A.1)$$

$$L_{22} \frac{dI_2(t)}{dt} + R_2(T_w) \cdot I_2(t) = V_2 , \quad (A.2)$$

$$V_2 = -M_{12} \frac{dI_1(t)}{dt} , \quad (A.3)$$

$$I_1(t) = I_{10} \exp (-t/\tau_D) . \quad (A.4)$$

The thermal energy in the wall is

$$E_w(t) = C_{ww} V_w \rho_w [T_w(t) - T_i] , \quad (A.5)$$

so that

$$\frac{dE_w}{dt} \cong C_w V_w \rho_w \frac{dT_w}{dt} . \quad (A.6)$$

The heat capacity and density of the 316 stainless steel wall are given¹ as

$$C_w(T_w) = 459.2 + 0.13286 T(K) \text{ J/kg-K} \quad (A.7)$$

and

$$\rho_w(T_w) = \begin{cases} (8.0842 - 4.2086 \times 10^{-4}T - 3.8942 \times 10^{-8}) \times 10^3 \text{ kg/m}^3, \\ \quad T_w < 1700K; \\ (7.4327 + 3.9338 \times 10^{-5} - 1.8007 \times 10^{-7}T^2) \times 10^3 \text{ kg/m}^3, \\ \quad T_w \geq 1700K . \end{cases} \quad (A.8)$$

All the temperatures in these relations must be in kelvins.

The thermal conductivity is

$$k_w(TK) = \begin{cases} 9.248 + 1.571 \times 10^{-2}T \text{ W/m-K}, & T < 1700K; \\ 12.29 + 3.248 \times 10^{-3}T \text{ W/m-K}, & T \geq 1700K . \end{cases} \quad (A.9)$$

The electrical resistivity is

$$\eta_{ss} = 1.8 \times 10^{-7} [1 + 3 \times 10^{-3}(T - 300K)] \Omega\text{-m} . \quad (A.10)$$

The electrical resistance of the wall is

$$R_w = \eta_{ss} \frac{R_o}{a \cdot (\text{minimum of } \delta_w \text{ or } \delta_e)} , \quad (A.11)$$

where δ_e is the electrical skin depth,

$$\delta_e = \sqrt{\frac{2\eta_{ss} \tau_D}{8\pi^2 \times 10^{-7}}} . \quad (A.12)$$

The overall heat transfer coefficient U is given² by

$$U = \frac{1}{R_{th} A_w + (1/h_x)} , \quad (A.13)$$

where the thermal resistance is

$$R_{th} = \frac{\delta_w}{4\pi^2 a k_w (RK) R_o} \quad (A.14)$$

so that $A_w R_{th} = 4.17 \times 10^{-5} \text{ m}^2\text{K/W}$.

The film coefficient h_x is obtained using the Dittus-Boelter relation

$$Nu = 0.023 Re^{0.8} Pr^{0.3} ,$$

so that for a coolant tube 0.0254 m in diameter we have

$$h_x = \frac{k_w}{d} Nu = 6222 \text{ W/m}^2\text{-K} , \quad (A.15)$$

where we use a Reynolds number of 79,935 and a Prandtl number of 1.90.

The overall heat transfer coefficient is thus 4939 W/m²-K.

The initial conditions for the two differential equations are chosen so that $I_2(0) = 0$, $T_o = 293\text{K}$ and $T_w(0)$ is obtained by solving

$$q'_{to} A_w = UA_w [T_w(0) - T_o] ,$$

or $T_w(0)$ is 377K. [$T_w(0)$ is also called T_i .]

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