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TOKAMAK ARC DAMAGE

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ABSTRACT

Tokamak fusion reactors will have large plasma currents of approximately 10 MA with hundreds of megajoules stored in the magnetic fields. When a major plasma instability occurs, the disruption of the plasma current induces voltage in the adjacent conducting structures, giving rise to large transient currents. The induced voltages may be sufficiently high to cause arcing across sector gaps or from one protruding component to another.

The vacuum conditions in a tokamak would normally require many kilovolts across the gaps to initiate arc currents. However, voltage breakdown can occur at relatively low voltage if ionized gas is introduced between the electrodes to trigger the arc and especially if the electrodes are hot. In a tokamak, the structures may have hot spots due to radial particle loss and nuclear reactions. When a plasma disruption occurs, the ionized plasma is driven toward the structures by the electromagnetic forces. The heated gaps between the sectors are provided with an ideal source of electrons and ions to trigger arc currents. The key factors governing arc formation and their time behavior are the arc starting voltage, arc sustaining voltage, and the arc discharge mode in strong parallel magnetic fields.

Experimental evidence indicates that the tokamak confining field is likely to maintain the arc current in a diffused state for approximately 10 ms. If disruption-induced currents flow across the gaps long enough, they may become concentrated constrictive arc columns that cause high electrode erosion. As tokamaks increase in size, both the poloidal magnetic field energy and structure time constants increase. Both of these factors are conducive to converting diffuse arcs into constrictive arcs, which may become a major limiting operation factor. This report reviews a tokamak arcing scenario and provides guidelines for designing tokamaks to minimize the possibility of arc damage.

1. INTRODUCTION

Arc damage across vacuum vessel gaps or bellows during a disruption is not a major problem in existing machines. Because of the time constants of the circuits and the field energy required for future machines, arc damage could, however, become a major concern for large tokamaks. Arcing may not be a problem for a Fusion Engineering Device (FED-A) or FED-R design vacuum vessel, but it could be a major problem on the International Tokamak Reactor (INTOR) configuration.

It is an objective to operate tokamaks in a disruption-free mode, but it may be impractical to design for this ideal operating mode. When a major disruption occurs, the thermal and magnetic energy of the plasma circuit must be dissipated rapidly in the limiter or over a longer period of time in passive structure or active circuits. The thermal energy heats, ablates, and melts the structure surfaces in contact with the plasma edge. Voltages are induced in the structures, giving rise to currents that produce voltages across gaps or bellows. If these gaps are heated sufficiently and a source of ions and electrons is introduced, currents flow across the gaps. The main factor in determining if arc current will flow is the density of the ionized gas across these gaps or bellows. The major factor in determining the erosion rate is whether the arc currents remain diffused or develop into constrictive arcs. If they remain diffused, there will be little or no damage; if they become constrictive, damage will occur. Erosion is proportional to the coulombs passed through a constrictive arc. These arcs can result in structure currents and forces being different than those calculated without arcs. The forces and torques being developed in structures may exceed the design values and produce structural damage.

In reviewing the reactor-relevant preconceptual tokamak designs, it was determined that the poloidal plasma field energy will be in the range of hundreds of megajoules (125 MJ for INTOR).¹⁻⁴ If arcs do develop across the torus sectors or limiter blades, a major portion of this energy could be dissipated in arc erosion. The constrictive arc erosion for the INTOR has been calculated to be at least 200 g of material for each major disruption.

The following key questions are addressed for reactor-relevant machines (such as INTOR):

- (1) What voltage is required to develop current flow across gaps?
- (2) What is the minimum voltage to sustain an arc (i.e., the voltage required to support an arc after it has started)?
- (3) What are the parameters associated with calculation of arc damage, and how do such calculations predict the effects of arcing on present machines?
- (4) How can "insulating" structures or field configurations be applied to prevent arcs?

This review is limited to transient toroidal voltages and currents during a disruption. The phenomenon of unipolar arcs is not included.

2. MINIMUM ARC STARTING VOLTAGES

There have been numerous tests that provided engineering data on breakdown and arc voltages in a near vacuum that depend upon the following electrode or environment conditions:

- (1) materials used,
- (2) material temperatures,
- (3) impurities,
- (4) separation distance,
- (5) polarities,
- (6) surface roughness,
- (7) gas pressures,
- (8) types of gases,
- (9) shape geometry, and
- (10) magnetic field intensity.

However, there is very little quantitative data to determine the minimum voltage necessary to start conduction in the presence of hot electrodes and an external source of ionized gas between electrodes, as is the case for a tokamak during a disruption. The source of the information on conditions that would apply to tokamak disruptions is found on an

electrical system subjected to the environment of nearby circuit fault conditions and on special tests to ignite spark gaps, ignition tubes, and similar devices.

It is concluded that in the absence of an ionized gas, the arc initiation voltage for tokamak sector gaps is several kilovolts. It is also well known that 120-V circuits develop arcs across terminals (gaps) with tens of centimeters of spacing when nearby faults occur. Crowbar devices have been reliably fired with less than 100 V across their main electrodes but are initiated with auxiliary electrodes. In the search for specific data for the minimum breakdown voltages, Dr. Raymond Boxman of Tel Aviv University and University of South Columbia has provided a verbal note that he was able to start conduction across terminals with less than 50 V rather routinely. Dr. Allan Greenwood of Rensselaer Polytechnic Institute (RPI), who has had considerable experience with the General Electric Company High Voltage Laboratory,⁵ estimated that arcs could be developed across hot stainless steel electrodes subjected to an ionized gas environment with about 25 V.

In reviewing arc voltage calculations on reactor preconceptual design, the induced voltages across the first wall segments of an INTOR/FED/Tokamak Fusion Core Experiment (TFCX)-type machine following a major plasma disruption have been calculated to be in the range of 20 to 100 V and could be several hundred volts if designs do not provide arc prevention measures.^{6,7} Further quantification of the minimum voltage to prevent the start of an arc is needed but in itself may not be the important driving factor in designing a tokamak to prevent arc damage.

3. MINIMUM ARC SUSTAINING VOLTAGES

Once the arc develops, it continues to conduct current until the current is driven to zero or until the available voltages drop below the point where electrons are emitted. The minimum value of the voltage is a function of the work voltage of the electrode material. The exact values for differing materials at various temperatures, with various

shapes, and under different gas conditions are not known, but an approximate value for stainless steel is estimated to be 18 to 20 V in the absence of an external magnetic field.

If it is not practical to limit the voltage to a value low enough to prevent an arc from developing during a disruption in a tokamak, it would be productive to provide a design that would not support the arc long enough to result in excessive damage. The current would be allowed to flow as a diffused arc but would extinguish before becoming a constrictive arc channel and dissipating a large percentage of the plasma external magnetic field energy. The bulk of the external magnetic energy would be dissipated in I^2R heating of adjacent poloidal passive and active conductors. Additional data are needed to quantify the arc sustaining voltage for the various torus materials and shapes to be used.

The sustaining voltages for ten different cathode materials were measured by Davis and Miller for electrodes about 12.7 cm in diameter separated by 0.5 cm (Table 1).⁸ These measurements were made in the absence of the parallel magnetic fields that exist in tokamaks. Morimiya et al. performed experiments using copper interrupter electrodes in the presence of axial magnetic fields having a strength up to 0.15 T (ref. 9). The cathode was 45 mm in diameter and 5 mm thick; the anode was 80 mm in diameter with a spherical surface radius of 400 mm. Figures 1 and 2 show the voltage drop as a function of magnetic field strength for electrode separation distances of 1 and 3 cm, respectively. These distances are typical of gaps between the modular sectors of a tokamak. The currents are much larger than those given by the data in Table 1 and represent the peak currents in a 10-ms arc. It should be noted that the magnetic fields are weak compared to the toroidal field of a tokamak and that the voltage drop trend increases after passing through a minimum. The minimum voltage is a function of gap between the electrodes, the arc current, and the magnetic field. Experiments having much longer discharge times in the presence of strong axial magnetic fields (5 to 10 T) are needed to determine the arc starting and sustaining voltages during a tokamak plasma disruption.

Table 1. DC volt-ampere characteristics of arcs measured
by Davis and Miller^a

Material	Arc current (A)	Arc voltage (V)
Aluminum	40	19
	250	21
Copper	25	18
	250	22
Graphite	30	15
	250	17
Molybdenum	55	24
	200	27
Silver	45	16
	250	17
Tantalum	100	24
	250	26

^aTwo numbers are given for each material corresponding to the range of arc currents investigated. Note the relatively small change of arc voltage with arc current.

Fig. 1. Arc voltage as a function of arc current and axial magnetic field, 10-mm electrode spacing.

Fig. 2. Arc voltage as a function of arc current and axial magnetic field, 30-mm electrode spacing (ref. 9).

The main criterion is to design the conductivity of the passive torus circuits so that the voltage across all gaps would be less than the minimum arc sustaining voltage before a constricting arc with anode spots develops.

4. ARC CHARACTERISTICS AND EROSION DAMAGE CALCULATIONS

Arc erosion rates are strongly dependent on the arc mode. Low-current diffused arcs have very little erosion, whereas constrictive arcs with anode spots have very high erosion rates.¹⁰ Figure 3 is a physical arc appearance diagram showing the types of arcs in various electrode gap arc current regions. The high-current, small-gap constrictive column arc does the most damage. Intermediate-gap current regions have foot point arcs with anode jets that have significantly lower erosion rates than constrictive column arcs. The transition between foot point arcs and anode spot arcs exhibits noisy arc gap voltages and melting before the hot anode spot develops. The hot anode spot exhibits vaporized metal and high erosion rates.

Data on arc erosion rates as a function of the type of material and the time integral of the arc current (coulombs) have been measured for specific electrode geometrics in the absence of an external magnetic field.¹¹⁻¹⁴ Figure 4 shows typical data for several materials.¹¹ Stainless steel is an alloy of iron, chromium, and nickel that should have erosion rates comparable to nickel. Based on an erosion rate of 80 mg/coulomb, the erosion rate per disruption may be calculated. If the arc discharge current between sectors is given by Eq. (1), the time integral (in coulombs) is given by Eq. (2):

$$I = I_0 [1 - \exp(-400t)] \times \exp(-6t) \text{ A} , \quad (1)$$

$$Q = I_0/6 - I_0/406 = 0.164I_0 , \quad (2)$$

where for $I_0 = 1.6 \times 10^6 \text{ A}$, $Q = 262,400 \text{ coulombs}$. The erosion per sector gap = $80 \text{ mg/coulomb} \times 262,400 \text{ coulombs} = 21.0 \text{ g per sector}$.

Fig. 3. Physical arc appearance as a function of current and electrode gap, for half-cycle, 50- to 60-Hz arcing. Electrode diameter = 100 mm (ref. 10).

Fig. 4. The erosion rate dependence on the number of coulombs (C) transported by a vacuum arc. For tin, multiply the ordinate by 4 and for cadmium, multiply by 2 (ref. 11).

If there are ten sectors, the erosion would be 215 g per plasma disruption. Disruption currents depend on the plasma disruption time behavior. Induced currents calculated in ref. 15 show that I_0 could be $5-6 \times 10^6$ A, resulting in considerably higher erosion than 215 g per disruption.

However, the effects of the strong parallel toroidal field tend to maintain the arc in a diffused state and thereby reduce the erosion.¹⁵ Figures 5 and 6 from ref. 16 show that only modest parallel magnetic fields were needed to prevent arc voltage noise, melting, and anode spots with significant erosion for 10-ms arc discharge pulses. The gaps between the tokamak sectors are in the 1- to 3-cm range, corresponding to Figs. 5 and 6. Long-duration arc erosion experiments (0.1 to 1.0 s) in the presence of strong parallel magnetic fields (5 to 10 T) are needed to determine the type of arcs and their erosion rates for tokamaks.

The field magnitude and arc time are important factors. Dr. Joseph Gorman of Westinghouse provided estimates that with fields in the 5-T range the INTOR/FED disruption arc currents should remain in the diffuse state for 10 ms or more. This magnitude of parallel field vs current scales down to about the same value of time for machines such as the Princeton Large Torus (PLT). The current decay time on the small machines with rather short time constant structures deposits a large percentage of the field energy in the plasma as I^2R heat; this energy is dissipated as thermal energy on structures in contact with the plasma and by radiation to the torus walls. Thus, by the time the plasma current goes to zero, the bulk of the magnetic stored energy has been dissipated. Diffused arcs could develop across bellows or insulating breaks in PLT-sized tokamaks, but they would not produce appreciable erosion. Their effects would be to produce shiny surfaces, as are now contributed to unipolar arcs. These arcs need not flow across the minimum distances between gaps but could flow from one side of a limiter across the bellows or gap and even around the machine to the back side of the limiter. There is not sufficient conduction time to allow the development of constrictive arcs across gaps and thus the production of erosion during a disruption. When time constants of tokamak structures

Fig. 5. Electrode melting and arc voltage noise boundaries, gap length = 10 mm (ref. 16).

Fig. 6. Electrode melting and arc voltage noise boundaries, gap length = 30 mm (ref. 16).

increase such that currents will flow for times that are long compared to 10 ms, then constrictive arcs may develop, and the arc damage can be calculated using data available for arcing without parallel magnetic fields.¹⁰⁻¹³

5. INSULATING TO PREVENT ARCS

Consideration has been given to the design of a system to prevent arcs by providing coated insulated surfaces inside the torus. A practical system that can withstand the forces and temperatures has not been identified for tokamak reactors with modular sectors. Placing carbon blocks, or some material that will not produce undesired effects, on a substrate has been considered, but this type of construction leaves slits or cracks between the blocks of carbon. Overlapping is possible, but this results in a higher probability of cracking the blocks. With the slits and grooves between the blocks, there is a high probability that arc conduction would occur between the insulating or protective blocks.

Another consideration for reducing the probability of an arc developing is to use the toroidal field as a magnetic insulator. High-temperature insulating barriers need to be erected so that arc paths are perpendicular to the magnetic field. This may be effective if no single field line closes by entering and leaving conducting materials or protective blocks. Under relatively tranquil conditions, this might be accomplished, but, under disruption conditions, the field lines near the plasma are not easily controlled such that they remain in the desired configuration.

6. CALCULATION OF ARC VOLTAGE DURING A DISRUPTION

Several reports have been written for INTOR to quantify the voltage that would occur across segment terminals or gaps due to a specified plasma current decay.^{5,6} These results indicate that voltages in the range of 50 to 100 V may be obtained if the torus sectors are not innerconnected at the first wall and the torus sector side and external

walls are made in such a manner as to be good conductors with low inductance. If practical structural designs can be made that result in this low voltage, arcing may not always occur, but such an arrangement would not provide a high degree of self-stabilization for plasma position control. The saddle coil structure would also impede the penetration of any control field.¹⁷ The use of good conducting side walls and external wall structures would be difficult to produce, particularly if toroidal connections were required near the inner radius of the tokamak sectors.

It should also be noted that the plasma will not remain in the center of the torus and always decay in 20 ms, which is the INTOR criterion for disruption. In fact, there is a likelihood of excessive melting of the limiter and the torus first wall if the plasma current decay time is as slow as 20 ms.

Another point in calculating the maximum voltage that can occur between segments is associated with the thermal decay period of disruption. During the start of this phase, there is a high current density in the center of the plasma, and the plasma internal field is nonuniform. Any thermal disruption results in a reorientation of the internal field and current density. This rearrangement results in a very large negative voltage spike in present machines. If there is not a path for current to flow near the outer surface of the plasma, the negative voltage spike will be high. In present machines, this is in the range of several kilovolts. It is probable that current conduction will be started during the disruption period of time and will not deionize before the forward voltage from the decay of the external poloidal field develops.

The disruption voltage between sectors can be reduced sufficiently to eliminate arcing if good electrical connections can be made at the plasma side of the sectors.^{18,19} However, it is difficult to design connectors that will make good contact to carry the high induced currents and yet be able to remove and replace sectors after the assembly becomes highly radioactive. The approach provides for good self-stabilization for plasma position control but impedes the penetration of control or

startup fields. It also provides a good conduction path for any negative voltage spikes that may occur during a thermal disruption of the plasma.

7. CONCLUSIONS AND RECOMMENDATIONS

Although arc damage on present machines is not a major limiting factor on present operations, this should not be expected to be the case for larger devices, unless designs provide for self-consistent electromagnetic considerations. These considerations are startup, shutdown, plasma position control, and plasma disruptions. The sector design must be integrated to satisfy the interactive requirements for all functions, which precludes optimizing the design for one function at the expense of the others.

The small tokamaks such as PLT should not expect to have large arc damage because the disruption-induced structure current decay time is not long compared to 10 ms and, for this case, any gap conduction should remain in the diffused state. As tokamaks get larger, the current decay time in the torus increases, and the diffused arc current flowing between gaps may become constrictive in nature. This can result in major arc erosion.

It may be possible to construct sectors of the torus without internal connectors that have relatively low voltages across their gaps (as now assumed for INTOR). However, it is difficult to design the external connector or saddle coil structure with sufficient strength and conductivity to maintain the voltage across the gaps low enough to prevent arcing. The cost of the position control and active plasma disruption control will be large for this arrangement. This type of torus design will be very difficult to construct if high-current connections are required at the torus removable sector outer wall at its smallest major radius.

The alternative and recommended solution assumed for FED/FED-R/FED-A provides low-resistance connections between the torus segments near the plasma boundary. These are difficult to construct and install. The low-impedance connection may have the additional beneficial effect of

reducing the number of disruptions.²⁰ When a disruption does occur, this alternative will prevent excessive arc damage, minimize forces and torque during disruption, and provide the maximum self-stabilization of the plasma.^{21,22} This latter point will minimize the size of the active position control system.

REFERENCES

1. W. M. Stacey et al., *Conceptual Design*, USA INTOR/81-1, June 1981.
2. W. M. Stacey et al., *Critical Issues*, USA INTOR/82/1, October 1982.
3. C. A. Flanagan, D. Steiner, and G. E. Smith, eds., *Fusion Engineering Device Design Description*, ORNL/TM-7948/V2, Oak Ridge Natl. Lab., December 1981.
4. Y-K. M. Peng et al., *FED-A, An Advanced Performance FED Based on Low Safety Factor and Current Drive*, ORNL/FEDC-83/1, Oak Ridge Natl. Lab., August 1983.
5. J. M. Lafferty et al., *Vacuum Arcs - Theory and Application*, Wiley, New York, 1980.
6. R. J. Thome, R. Pillsbury, and W. Mann, *Sector Gap Voltages and Induced Loads Following Plasma Disruptions in FED/INTOR*, DOE/ET-51013-64, U.S. Department of Energy, December 1982.
7. G. Bronner, *Arc-Over Between Vacuum Vessel Segments*, APD-M-FED 10, December 1980.
8. W. D. Davis and H. C. Miller, *J. Appl. Phys.* 40, 2212 (1969).
9. O. Morimiya, S. Sohma, T. Sugawara, and H. Mizutani, "High Current Vacuum Arc Stabilized by Axial Magnetic Fields," *IEEE Power Engineering Society*, pp. 1723-32, 1973.
10. H. C. Miller, *A Review of Anode Phenomena in Vacuum Arcs*, GEPP-TIS-802, General Electric Co., Neutron Devices Department, St. Petersburg, Fla., 1984.
11. J. E. Daalder, "Erosion and Origin of Charge and Neutral Species in Vacuum Arcs," *J. Phys. D* 8 (1975).
12. C. W. Kimblin, "Erosion and Ionization in Cathode Spot Regions of Vacuum Arcs," *Appl. Phys.* 44 (7), 3074 (1973).
13. E. Burger, J. Cobine, and T. Vanderslice, *Electrode Erosion and Gas Evolution of Vacuum Arcs*, AIEE CP 62-137.
14. P. Barkau, J. Lafferty, T. Lee, and J. Talento, "Transaction on Power Apparatus and Systems Development of Contact Material for Vacuum Interrupters," *IEEE Trans. Power Appar. Syst.* PAS-90, 350-59 (1971).

17/18

15. J. Murray, *Status of FED/INTOR Electromagnetics*, ORNL/TM-8420, Oak Ridge Natl. Lab., 1984.
16. E. Kanenko et al., "Basic Characteristics of Vacuum Arcs Subjected to a Magnetic Field Parallel to Their Positive Columns," *IEEE Trans. Plasma Sci.* PS-11 (3), 169 (1983).
17. J. G. Murray, "FED Control Power," in *Proceedings of the 9th Symposium on Engineering Problems of Fusion Research*, Institute Electrical Electronics Engineers, New York, 1981.
18. S. L. Thomson, *Electrical/Contact Size and Spacing for the FED Shield Wall*, FEDC-M-81-ES-036, Fusion Engineering Design Center, Oak Ridge Natl. Lab., 1981.
19. G. Gorker, *Contact Analysis and Applications Guidelines*, FEDC-M-82-E/M-029, Fusion Engineering Design Center, Oak Ridge Natl. Lab., 1982.
20. Y-K. M. Peng et al., *FED-A, An Advanced Performance FED Based on Low Safety Factor and Current Drive*, ORNL/FEDC-83/1, Oak Ridge Natl. Lab., 1983.
21. G. Gorker, *Torus Sector Electrical Connectors*, FEDC-M-81-ES-101-A4, Fusion Engineering Design Center, Oak Ridge Natl. Lab., 1981.
22. G. Gorker, *Comparison of Electrical Connectors and an Alternate That Uses Conducting Bands and Controlled Arcs*, FEDC-M-82-E/M-040, Fusion Engineering Design Center, Oak Ridge Natl. Lab., 1982.

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