The TFTR Ohmic Heating (OH) System will apply 140,000 volt impulses upon the OH coils to start the plasma. In order to reduce the voltage stress to ground on the OH coils to 12 kV without changing the magnetic field induced by the OH system in the plasma, six d-c current interrupters will be applied to six entry points in the OH coil system. And in order to impart a nearly rectangular shape to these impulses, the voltage determining elements will be nonlinear resistances placed in parallel with the interrupters.

These nonlinear resistors, made of semiconducting material, are not normally used in repetitive or continuous duty, and their proper functioning is crucial to the reliable operation of the system.

The system described herein, presented for the Preliminary Design Review for the TFTR Pulsed Energy Conversion System, at Princeton University, on August 16, 1977, is being revised owing to the impact of revisions to the Toroidal Field Coil System, and to refinements to the OH System design.

INTRODUCTION

The OH System inductively couples with the plasma by means of the OH coils, which are concentric with the toroidal vacuum vessel’s major circumference, forming a transformer in which the plasma is the one-turn secondary winding. The basic functions of the OH system are to (1) provide sufficient emf to ionize the gas in the vacuum vessel to initiate the plasma, (2) induce a current in the plasma, that heats the plasma by means of the I/R power loss, and (3) provide flux — up to 13 volt-seconds — as necessary during operation to compensate for the effect of injecting the neutral beam, maintain the plasma current, and terminate the experiment.

REQUIREMENTS

The OH System provides several functions during each of two basic modes of operation: Experimental Power Discharge, and Vacuum Vessel Discharge Cleaning.

Experimental Power Discharge

1. Current Buildup: Six seconds before the Toroidal Field (TF) current reaches its "flat top" level, the OH converter (see figure 3) begins raising the current in the OH coils. During the six seconds the OH current raises linearly from 0 to 20 kA, inducing a constant one volt per turn in the OH coils. The OH current reaches 20 kA just as the TF current reaches "flat top."

2. Plasma Initiation: Resistances, inserted instantaneously into the OH circuit for 5 to 15 milliseconds, drop 140 kV, inducing 250 V per turn in the plasma. This accelerates free electrons and ionizes the gas to form the plasma.

3. Current Takedown: During this third interval, the voltage is reduced sufficiently to prevent "runaway electrons" but kept high enough to maintain the plasma and to bring the OH current to zero in 50 milliseconds or less. This induces current that ohmically heats the plasma.

4. Current Reversal: The OH capacitors (see figure 3), assisted by the OH converter, raise the current in the forward direction to 8 kA in 75 milliseconds or less. This induces more current that further heats the plasma.

5. Neutral Beam Injection: At this point, the neutral beams of deuterons that heat the plasma further, must be contained by raising the current in the equilibrium field coils. This would induce an undesirable "skin current" in the plasma, were the OH current not reduced to compensate. Accordingly, during this interval, the OH current is taken nearly to zero in about 0.2 seconds.

6. Plasma Buildup and Termination: The plasma current is taken to its maximum value, maintained, and taken to zero, by means of the OH converter.

Vacuum Vessel Discharge Cleaning

Discharges at full power will repeat every 300 seconds. At lower power, they can occur as often as every 60 seconds. During each burst, the OH System provides the six functions enumerated below.

1. Current Buildup: Six seconds before the Toroidal Field (TF) current reaches its "flat top" level, the OH converter (see figure 3) begins raising the current in the OH coils. During the six seconds the OH current raises linearly from 0 to 20 kA, inducing a constant one volt per turn in the OH coils. The OH current reaches 20 kA just as the TF current reaches "flat top."

2. Plasma Initiation: Resistances, inserted instantaneously into the OH circuit for 5 to 15 milliseconds, drop 140 kV, inducing 250 V per turn in the plasma. This accelerates free electrons and ionizes the gas to form the plasma.

3. Current Takedown: During this third interval, the voltage is reduced sufficiently to prevent "runaway electrons" but kept high enough to maintain the plasma and to bring the OH current to zero in 50 milliseconds or less. This induces current that ohmically heats the plasma.

4. Current Reversal: The OH capacitors (see figure 3), assisted by the OH converter, raise the current in the forward direction to 8 kA in 75 milliseconds or less. This induces more current that further heats the plasma.

5. Neutral Beam Injection: At this point, the neutral beams of deuterons that heat the plasma further, must be contained by raising the current in the equilibrium field coils. This would induce an undesirable "skin current" in the plasma, were the OH current not reduced to compensate. Accordingly, during this interval, the OH current is taken nearly to zero in about 0.2 seconds.

6. Plasma Buildup and Termination: The plasma current is taken to its maximum value, maintained, and taken to zero, by means of the OH converter.

Figure 2 is a profile of the current in the OH System during this mode, wherein a 300-400 kA deuterium plasma "aggressively" cleans the vessel's inside wall of impurities deposited either from the atmosphere before pumping or as a result of previous Experimental Power Discharges. Bursts of high energy deuterons drive
A past.

The nonlinear resistors will be of the varistor type that is used as the energy absorbing material in surge arrestors. Silicon Carbide ("Thyristor type") has been commonly used for this purpose in the past. A new material - zinc oxide - has superior electrical, mechanical and thermal properties.

INTERACTIONS WITH AUXILIARY COMPONENTS

Auxiliary components - such as power converters and reversing capacitors - connected in parallel with the varistors, will function normally if the voltages applied by these components are low enough to remove the current from the varistors. The current in a varistor drops rapidly when the voltage falls below its surge rating, so that it "disconnects itself from the circuit and does not overheat or load the auxiliary component. This allows us to leave the varistors solidly and permanently connected to the coil system, provided the exponent \( a \) - in the empirical equation \( I = kE^a \) that describes the relationship of voltage and current - is large enough.

An \( a \) of 20 or greater describes a varistor whose current will fall from 20 to 1 kiloampere or less if the auxiliary component reduces its voltage from 23 to 20 kilovolt, and this is deemed satisfactory in this application. This is characteristic of the new zinc oxide material, but not of silicon carbide, whose \( a \) typically falls in the range 3.5 to 4.

DERATING AND ECONOMIC CONSIDERATIONS

Varistors are being used as surge arrestors to normally absorb 100 J/cc per "shot". In this service they may show a change in their characteristics after a few shots. The most probable change is an increase in current at low voltage. In silicon carbide this is caused by decomposition that leaves carbon tracks in the material; in zinc oxide the cause is not well understood, but it is assumed to be associated with changes in the semiconductor junctions at the grain boundaries. Silicon carbide discs undergo progressive changes in their voltage drop when they are pulsed, and different discs, particularly if they come from different batches, change in different ways. Zinc oxide is claimed to be very stable in comparison. It is necessary to derate silicon carbide for this repetitive application. It is prudent to do so for zinc oxide as well.

The table shows the thermal behavior and characteristics of varistor material at its maximum ratings.

<table>
<thead>
<tr>
<th></th>
<th>SiC</th>
<th>ZnO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature coefficient, °C/J/cc</td>
<td>.39</td>
<td>.24</td>
</tr>
<tr>
<td>Temperature rise, °C</td>
<td>80</td>
<td>24</td>
</tr>
<tr>
<td>Energy absorption, J/cc</td>
<td>135</td>
<td>100</td>
</tr>
<tr>
<td>Estimated Cost, c/cc</td>
<td>9.5</td>
<td>40</td>
</tr>
</tbody>
</table>

The nonlinearity is rated much more conservatively than silicon carbide. This may account for part of the instability attributed to silicon carbide, because the temperature of zinc oxide is allowed to rise only one third as high. It is interesting, therefore, to compare the cost based upon equal temperature rises.

<table>
<thead>
<tr>
<th></th>
<th>SiC</th>
<th>ZnO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature coefficient, °C/J/cc</td>
<td>5.6</td>
<td>9.6</td>
</tr>
<tr>
<td>Temperature rise, °C</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Energy absorption, J/cc</td>
<td>.23</td>
<td>.4</td>
</tr>
<tr>
<td>Estimated Cost, c/cc</td>
<td>.07</td>
<td>.07</td>
</tr>
</tbody>
</table>

The cost figures are very uncertain at this time, because the development of the zinc oxide material is in a very early stage. The cost depends strongly upon the allowable temperature rise - that is, upon how much the material is derated from its one shot surge rating. We have had recommendations that vary from 5 to 1 down to no derating at all, the latter based upon the assertion that no electrical degra-
tion will occur if the heat is removed fast enough to keep the peak temperature below 100°C or so. However, there may be mechanical wear owing to mechanical scrubbing between the device and its heat sink. This phenomenon, termed "thermal fatigue", has been observed in silicon controlled rectifiers in welding applications.11, 14

Two designs are presently being considered: one that uses zinc oxide at 24°C rise for protection only, silicon carbide at 10°C rise to absorb the coil energy; and one that uses zinc oxide for both functions. The former design costs about 1¢ per joule. The latter, more elegant design, costs between 0.4¢ per joule (at no derating, 24°C rise) and 2¢ per joule (at 5 to 1 derating, 5°C rise). The total energy in the OH system is about 35 megajoules.

### TECHNICAL CONSIDERATIONS

#### Voltage Droop

In general, the voltage will droop somewhat as the current falls off. The lower the exponent α, the greater the droop. Assuming the current falls from 20 to 8 kA during a 15 millisecond pulse, the droop will be as shown in the table.

<table>
<thead>
<tr>
<th>Exponent α</th>
<th>1</th>
<th>3.5</th>
<th>4</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>(5 msec)</td>
<td>16</td>
<td>6.2</td>
<td>5.4</td>
<td>2.2</td>
</tr>
<tr>
<td>% Droop (10 msec)</td>
<td>30</td>
<td>13.6</td>
<td>12.0</td>
<td>5.0</td>
</tr>
<tr>
<td>(15 msec)</td>
<td>43</td>
<td>23.0</td>
<td>20.5</td>
<td>8.8</td>
</tr>
</tbody>
</table>

#### Current Sharing

Varistor material comes in the form of a disk whose area is, in general, much less than required for this application. The table shows the ranges of the characteristics of the two materials. It is desirable to use the lowest practical voltage gradient, which is characteristic of large grain-size material; this requires fewer parallel disks. It is not practi-

<table>
<thead>
<tr>
<th>Voltage</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>SIC</td>
<td>130</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ZnO</td>
<td>100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-repetitive</td>
<td>80</td>
<td>24</td>
<td></td>
</tr>
<tr>
<td>Repetitive</td>
<td>17</td>
<td>20</td>
<td></td>
</tr>
</tbody>
</table>
| Contributions to fabricate very large disks because nonuniformities in the mix can lead to current hogging. It is more practical to carefully match stacks of smaller disks to achieve an equal current distribution. Balancing transformers will also be used as a backup means to assure that the current partitions itself equally.

The voltage and current coefficients of varistor materials are as follows:

<table>
<thead>
<tr>
<th>Voltage coefficient</th>
<th>[ \frac{dv}{dt} \cdot \frac{\text{Z}/\text{C}}{\text{Volts}} ]</th>
<th>20,000 Volts</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIC</td>
<td>-0.04</td>
<td>-1.3</td>
</tr>
<tr>
<td>Current α</td>
<td>80 to 60</td>
<td>3.8</td>
</tr>
<tr>
<td>Current coefficient</td>
<td>-( \frac{dv}{dt} \cdot \frac{\text{Z}/\text{C}}{\text{Volts}} )</td>
<td>0.8 to 2.4</td>
</tr>
</tbody>
</table>

Although zinc oxide has a very low temperature coefficient of voltage compared with silicon carbide, its high exponent α can make its current sensitivity nearly the same. Any tendency toward hogging current will be aggravated if the stacks of varistors retain a thermal "memory" of previous shots. Therefore, it is prudent to cool them as close to ambient temperature as is possible, between shots.

### DYSFUNCTIONS IN THE OH INTERRUPTERS

If one or more OHI's fail to interrupt, larger than normal voltages will be impressed upon the OH coils. The worst case, occurring when 2 or 3 adjacent OHI's fail to interrupt, or are reclosed leaving the remaining OHI's open, causes a potential of twice normal from coil to ground. The principle that has been adopted is that this case is not treated as a fault, and that the OH system will tolerate this dysfunction. In fact, this sets the electrical potential level of the surge arresters at 23 kV.

### REQUIREMENTS OF THE AUXILIARY COMPONENTS

The OH converter and the capacitor bank designs are undergoing revisions at the time, owing to the impact of revisions of the TF system upon the OH system, and to refinements to the OH system. The design parameters of the OH system are listed below:

<table>
<thead>
<tr>
<th>Coil Parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>No. Turns</td>
<td>550</td>
</tr>
<tr>
<td>Current</td>
<td>20,000 Amperes</td>
</tr>
<tr>
<td>Inductance</td>
<td>0.17 Henrys</td>
</tr>
<tr>
<td>Resistance</td>
<td>0.1 Ohms</td>
</tr>
</tbody>
</table>

### Power Supply Voltage

- **Current Buildup**: 3,300 Volts
- **Plasma Buildup**: 5,300 Volts
- **Neutral Beam Injection**: 15,900 Volts
- **Discharge Cleaning**: 12,500 Volts
- **Current Reversal**: 21,200 Volts
- **OHI Reversal Bank**: 27,300 Volts
- **Discharge Cleaning Low Bank**: 97,500 Volts

### Capacitance

- **Capacitance**: 0.0134 Farad
- **Capacitance**: 0.0006 Farad
- **Capacitance**: 0.24 Farad
- **Capacitance**: 0.24 Farad

### Resistance

- **Resistance**: 0.1 Ohms
- **Voltage**: 20,000 Volts

Referring to figure 3, the 6 kV 20 kA OH Converter performs the Current Buildup and Plasma Buildup and Termination functions. The 10 kV 8 kA OH Interrupter and its associated varistor, together with the converter, prevent skin currents during Neutral Beam Injection. The OHI capacitors, in two configurations, perform Current Reversal and High Bank Discharge.
functions. And the EFC capacitors, borrowed from the equilibrium field compression bank, perform the low
Bank Discharge function. It is not necessary to use the motor-generator flywheel system during Discharge
Cleaning, because the capacitors store sufficient energy for the purpose, and their charging supplies
do not exceed the capabilities of the 60Hz mains.1,2,3

CONCLUSIONS

The design work on the OH System has led to the following conclusions:

1. It is technically feasible to operate the TFTR OH
system at a relatively high impedance level in order to
bring the operating current within the range of pre-
sent d-c interrupters. The high interruption voltage
that this entails can be achieved by providing six
entries to the system, thereby reducing the normal
operating voltage to normal insulation levels. It is
necessary to carefully coordinate the operation of the
six interrupters and to allow for the possibility of
dysfunctions of one or more interrupters.

2. It is technically feasible to use zinc oxide or
silicon carbide nonlinear resistors to determine the
250 volts per turn that initiates the plasma. How-
ever, a repetitive or continuous application is not
considered normal by the manufacturers of this materi-
als, and there is no information on the behavior of the
material in this application. Therefore, a very
conservative approach must be taken that involves the
following considerations:

a. Allowance must be made for progressive changes
or deterioration in the characteristics of this
material, particularly silicon carbide, which is
known to undergo considerable change in its elec-
trical characteristics under use. Zinc oxide
material is said to be very stable under these
conditions, except for its leakage resistance at
very low currents, which is of no interest in
this application; nevertheless, this material is
very new, and the effect of 300,000 operations
has not been even considered, much less tested,
and therefore it is only prudent to allow for
changes in this material as well. Provisions
must be made for balancing the currents that flow
in parallel paths, and to monitor for changes in
characteristics between paths.

b. The material must be cooled so that its tem-
perature rise is lower than that for its normal
operation as an arrester.

c. The material must be cycled as much as is
possible without causing excessive mechanical
stress from thermal gradients. If possible, it
should cool nearly to ambient temperature be-
 tween shots.

d. Samples of the material must be tested in
conditions that simulate its expected use, with
careful measurements taken to detect any vari-
aitions in its electrical characteristics, and
visual inspection for mechanical changes, such as
wear on the surfaces of the disks, from dif-
ferential expansion between a disk and its
heat sink.

e. Finally, an alternative method for operating
the OH system must be available in the event of
failure of the varistor, in the form of linear
resistors that can be switched into the circuit.

ACKNOWLEDGMENT

The work described herein was performed pursuant to
Princeton Plasma Physics Laboratory's Subcontract
No. 258 under ERDA Contract No. EV76-C-02-3093 with
Princeton University. The authors would like to
acknowledge the contribution of helpful suggestions
by Dr. F. von Roehm, and analyses and recomenda-
tions by Drs. B. Cheo and Z. Zabar, and computer
simulations by S. Ghoshroy.

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