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Tokamak Fusion Test Reactor**

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University of California

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TESTS OF VACUUM INTERRUPTERS FOR THE TOKAMAK
FUSION TEST REACTOR

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ABSTRACT

The Tokamak Fusion Test Reactor (TFTR) project at Princeton University requires the insertion of a resistor in an excited ohmic-heating coil circuit to produce a plasma initiation pulse (PIP). It is expected that the maximum duty for the switching system will be an interruption of 24 kA with an associated recovery voltage of 25 kV. Vacuum interrupters were selected as the most economical means to satisfy these requirements. However, it was felt that some testing of available systems should be performed to determine their reliability under these conditions.

Two interrupter systems were tested for over 1000 interruptions each at 24 kA and 25 kV. One system employed special Westinghouse type WL-33552 interrupters in a circuit designed by LASL. This circuit used a commercially available actuator and a minimum size counterpulse bank and saturable reactor. The other used Toshiba type VGB2-D20 interrupters actuated by a Toshiba mechanism in a Toshiba circuit using a larger counterpulse bank and saturable reactor.

Both of these systems successfully completed 1000 interruptions without failure and indicated a very low contact erosion rate. Both appear to satisfy the needs of TFTR with respect to reliability and to have such low erosion rates that this feature is not expected to be a limitation on lifetime.

PART I - WESTINGHOUSE INTERRUPTERS

I. INTRODUCTION

This report covers the first part of a series of tests performed by the Los Alamos Scientific Laboratory (LASL) for Ebasco/Grumman (E/G). In these tests the performance of type WL-33552 vacuum interrupters was investigated in circuits like those to be used in the ohmic-heating subsystem of the Tokamak Fusion Test Reactor (TFTR). The circuit used is similar to one proposed by Westinghouse for TFTR. The interrupter features special electrodes designed to have a long life and the use of an axial magnetic field to provide long life and high reliability. The axial field is supplied by a coil external to the interrupter. Two interrupters are used in series to enhance their individual reliabilities. The circuit features a very small capacitor to supply the counterpulse current and a special way of using the capacitor. It is 70 μf instead of a more normal 400 to 500 μf . It is charged to a fixed voltage which is determined by the maximum current to be interrupted. This voltage can then be used to interrupt any current up to the maximum. This mode has been demonstrated in earlier experimental work. It is a change from the normal mode in which the capacitor voltage is varied with the current to be interrupted.

The purpose of the tests reported here is to determine the actual reliability and lifetimes of the interrupter's circuit under the conditions anticipated for TFTR. These include a maximum current of 24 kA, a current-carrying interval of about 100 ms that develops a $\int I^2 dt$ value in the switch of $6 \times 10^7 \text{ amp}^2 \text{ s}$, and a maximum recovery voltage of 25 kV sustained for 15 ms. These conditions could all be met with simple modifications to our normal test circuit except for the large $\int I^2 dt$ requirement. To meet it, extensive modifications were made that allowed a homopolar generator to be connected momentarily to the interrupters under test. The homopolar heats them to simulate the extended current-carrying time of TFTR.

Because the use of vacuum interrupters in TFTR-like circuits is fairly unusual, the tests performed included experimentation and unilateral decisions by LASL about some of the circuit features, for example, the size of certain components and the timing of certain events. They also included extensive diagnostic provisions to detect malfunctions or failures of the various components. At times failures were purposely caused to gain experience in their detection and interpretation. Because of these features of the tests, some of the results reported below were taken with component values or timings which were not optimum and did not give highly reliable interruption. In addition there was not sufficient time to explore the full range of variables, thus better operating conditions might exist outside of the range explored. Immediately below are presented the circuit and component values used in the majority of the tests, a description of measurements routinely taken, a listing of the tests actually performed, and the results with interpretations of them.

II. CIRCUIT AND COMPONENTS USED

The standard LASL circuit used to test single interrupters is shown in Fig. 1. It generates voltage and current waveforms in the interrupter which are shown in Fig. 2. The details of this circuit and its operation are described elsewhere.¹ These waveforms are unacceptable for E/G's purposes for several reasons: 1) the interrupter's conduction time, from S1 to S3 of Fig. 2, is only 5 ms or so, much less than the 100 ms of interest, 2) the recovery voltage, VC2, is imposed on the interrupter for less than 1 ms, not the 15 ms of interest, 3) the magnitude of dV/dt is considerably less than that anticipated for the TFTR circuit, and 4) the interrupter recovery voltage, VC2, has a short interval of reversed polarity, near S3, which must somehow be avoided in TFTR. To correct these performance deficiencies, LASL has made extensive changes in its circuit. The resulting circuit, used in most of the tests with two interrupters in series, is shown in Fig. 3 and the values of its components are given in Table I. The features of the circuit are explained below.

TABLE I

VALUES OF CRITICAL COMPONENTS	
C1	1440 μf
C2	71 μf
C3	1.9 μf
CD	250 $\mu\mu f$
R1	1000 Ω
R3	100 Ω
RD	1 M Ω
RL	1.5 Ω
LSR	10 gapless tape-wound cores total flux = 0.08 Wb
LSR	30 small gap tape-wound cores total flux = 0.12 Wb
L	140 μH air-core inductor
LAF1 and LAF2	8 turns of 4-0 cable connected in two parallel sets of 4 turns each. Field at center is 210 mT at 24 kA.

Fig. 1. Conventional LASL test circuit.

Fig. 2. Typical traces of voltage, current, and electrode motion.

Fig. 3. LASL test circuit as modified for E/G tests.

A. Components VI3, VI4, and HP

The homopolar generator, HP, is capable of generating 10 kA at 7 V or 20 kA at about 4 V. It is connected to the interrupters being tested, VI1 and VI2, by two auxiliary interrupters, VI3 and VI4. Largely because of the resistance of the four series-connected interrupters, only 10 kA can be generated in this circuit by HP. Interrupters VI3 and VI4 can be closed and opened quickly upon command. Thus they can be used with HP to heat VI1 and VI2 to any degree desired and can then be opened just before the normal test sequence is initiated to disconnect HP completely from the normal test circuit.

This use of VI3 and VI4 and HP is not in all respects a perfect simulation of the conditions expected in TFTR. In particular, the heating current is not the full 24 kA of TFTR, and, in addition, there is a short (~ 4 -ms) period just before interruption during which the interrupter current falls to zero. Previous experiments¹ have shown that the 4-ms zero current period has no serious consequences. The effect of the mismatch of current levels is unknown.

B. Components VI5, LSR', R3, C3, and LAF5

Originally the recovery voltage was intended to be maintained at 25 kV on the test interrupters by connecting a solid state diode (provided by E/G) in series with L of Fig. 1. The duty on this diode is severe because the voltage rises across it very rapidly when it ceases to conduct. The diode was inadvertently damaged thus another auxiliary interrupter, VI5, was used in its place. Because of the severe duty, this interrupter was assisted in every way conceivable, i.e., with an externally powered axial field coil, LAF5; with a saturable reactor LSR', and with a snubber circuit composed of R3 and C3. In spite of these auxiliaries, VI5 was still found to restrike with a 5 to 10% probability.

C. Component R1

Ignitron S3 presents a new problem in the modified circuit. Normally, it ceases conduction shortly (~ 1 ms) after its current has dropped close to zero. In the new circuit, however, the ignitron must conduct during the whole 15 ms of maintained voltage on the test interrupters. The insertion of R1 provides a "keep-alive" current of 25 A.

D. Components RL and C2

To simulate the TFTR circuit better, C2 was reduced from 180 μ F to 70 μ F and RL (1.5 Ω) was inserted. In TFTR $RL = 1.0 \Omega$, but because L of our test circuit is much smaller than the inductance of the ohmic-heating coil of TFTR, RL had to be increased to 1.5 Ω to provide the desired recovery voltage. This causes dV/dt to be somewhat too high.

E. Special Diode

TFTR will use a combination of series inductance and a diode to remove the reverse-voltage spike mentioned above. In our circuit the inductor, L, and ignitron, S2, perform this function. To guide E/G in the design of their circuit, a special inductance-diode combination has been tested to determine the circuit parameters required to satisfy TFTR's needs. These measurements and the parameters determined are discussed further below.

Fig. 4. Axial field coils mounted on vacuum interrupters.

F. Components LAF1, LAF2, CD1, CD2, RD1, and RD2

Axial field coils LAF1 and LAF2 are used with the Westinghouse interrupters WL-33552 under test. Figure 4 shows these 8-turn coils surrounding their respective interrupters. Also shown are the actuators and saturable reactors arranged as they were used in these tests.

CD and RD are used to divide the recovery voltage equally across VI1 and VI2, to provide a test point (TP5) to signal the failure of a single interrupter, and to identify the faulty one.

III. MEASUREMENTS ROUTINELY PERFORMED

A. Electrical

Oscilloscopes were used to measure the voltage or current found at test points TP1 through TP6. Test points 1 and 2 are low resistance current monitors; TP3 is a Rogowski coil current monitor; the rest are high voltage probes. TP5, TP4, and TP6 could be used respectively to measure the arc voltage across VI1, VI1 and VI2 together, and VI1, VI2, and VI5 together. More important, the timing of their contact partings could be identified and measured by using these three test points. Figure 5 showing three closely-spaced voltage jumps (labelled 1, 2, and 3) as each interrupter opens, is an example of the voltage at TP6. TP4 was also used to determine the overall success of an attempted interruption. Figure 6 shows the voltage at TP4 after a successful interruption. TP5, in contrast, gave information about the success of each of the separate series interrupters. Figure 7 shows the voltage at TP5 when the upper interrupter has failed (labelled F). TP1, TP2, and TP3 could be used to verify a failure and to distinguish between a failure of VI1 and VI2, VI3 and VI4, or VI5. Figure 8 shows the output of TP3 for a successful interruption. Shown are the end of the HP current, the 4-ms current

Fig. 5. Arc voltage showing closely spaced openings of VI1, VI2, and VI5. The trace covers 8 ms.

Fig. 6. Recovery voltage across VI1 and VI2. The trace covers 40 ms. The peak recovery voltage is 26 kV.

Fig. 7. Recovery voltage at the midpoint of VI1 and VI2 when VI2 has failed. The trace covers 20 ms.

Fig. 8. HP and normal test currents through VI1 and VI2. The trace covers 20 ms. The test current is 25 kA.

Fig. 9. Slow scan of HP current. The trace covers 2 s. The peak current is 10 kA.

delay from 1 to 2 as VI3 and VI4 open, and then the normal-test-sequence current waveform concluding in a successful interruption at 3. Figure 9, showing the complete HP current waveform, gives the output of TP2 on a slow scan.

A large number of system failures were observed during the tests and only a much smaller number of interrupter failures. These system failures are discussed later; but at this point, the importance, during the tests, of correctly identifying the source of a failure should be emphasized. In most cases, this determination was made unequivocally. This was possible because of the excellent instrumentation, a good understanding of the circuit, and experience gained in preliminary experimentation.

B. Other Measurements

The oscilloscope traces described above provided values for currents, voltages, and the times at which various events occurred. Also, routinely measured were the spacing of the electrodes of VI1 and VI2, from which erosion data could be obtained, and the temperature of the stems of VI1 and VI3. The opening speeds of VI1 and VI2 were measured twice during the tests.

IV. TESTS PERFORMED

The test circuit and component values are shown in Fig. 3 and Table I. Where possible they duplicate the values specified by Westinghouse in its proposal to E/G. To the extent possible, the tests were performed following E/G specification PPPL-1108 as revised on March 1, 1978 and further modified in ongoing discussions. In particular, the conditions of Table II were met in most of the tests.

TABLE II

<u>EBASCO SPECIFICATIONS</u>	<u>TEST CONDITIONS</u>
Commutation time, $\leq 500 \mu s$	50 μs
Recovery voltage peak, 25 to 27 kV	25 to 26 kV
Recovery voltage rise time, $\leq 500 \mu s$	80 μs
Recovery voltage period, 15 ms	40 to 400 ms
Dwell time, $\geq 50 \mu s$, and as short as possible	30 μs
Arcing gap, ≈ 7 mm	~ 7 mm .

The other important parameters listed in paragraph 11.1.5 of PPPL-1108 were routinely recorded or are calculable from recorded data.

The tests were conducted in 13 sets, where enough tests were performed in each set to provide data of some statistical value, and, where, usually, only one significant parameter was changed between sets. A total number of tests in excess of 1000 were performed at full current and with I^2t heating to provide the crucial data on reliability and erosion. Table III lists the different sets and the pertinent information for each. In the table, Δt is the interval between shots, t_{arc} the arcing time, B_{ax} the axial field, V_s a sustained recovery voltage, I^2t the integrated value of the square of the heating current, and "failures" lists the number of double and single interrupter failures observed. The results of the tests will be discussed in the order shown in the Table.

TABLE III

TESTS PERFORMED

Test	Δt (Min)	t_{arc} (ms)	I^2t ($\times 10^7 A^2s$)	V_s	B_{ax}	C_2 (μf)	RL (Ω)	Failures (Double/Single)	Tests at 24 kA
A WL-33552A	2	6.0	0	No	Yes	187	∞	0/0-1	87
B WL-33552B	2	6.0	0	No	Yes	150	∞	0/0	176
C A & B in Series	2	5.0	0	Yes	Yes	150	∞	0/0	315
D A & B in Series	2	5.0	6	Yes	Yes	71	1.5	2/3	26
E A & B in Series	2	5.0	0	Yes	Yes	71	1.5	0/1	38
F A & B in Series	2	7.0	0	Yes	Yes	71	1.5	0/0	20
G A & B in Series	2	7.0	6	Yes	Yes	71	1.5	0/1	90
H A & B in Series	2	7.0	0	Yes	Yes	71	1.5	0/0	15
I A & B in Series	2	7.0	6	Yes	Yes	71	1.5	0/0	192
J A & B in Series	2	7.5	6	Yes	Yes	71	1.5	0/1	315
K A & B in Series	3	7.5	10	Yes	Yes	71	1.5	0/0	105
L A & B in Series	2	4.8	6	Yes	Yes	71	1.5	0/0	54
M WL-33552B	-	-	40	-	Yes	71	1.5	-	2

A. Single WL-33552A

Currents were increased in 5-kA steps from 5 to 30 kA. At each level a variety of counterpulse voltages were used. No failures were seen. Finally 87 tests were performed at 24 kA. One failure was observed among these 87. The jitter in contact opening time was ± 0.3 ms. No contact erosion was seen, instead a gradual growth, due probably to contact roughening, was noted.

B. Other Single WL-33552B

Currents were increased from 5 to 30 kA in 5-kA steps. Finally 176 shots were fired at 24 kA. No failures were observed. Jitter and erosion comparable to A above were seen.

C. Two WL-33552 in Series

Recovery voltage was sustained for 15 ms or more for the first time by use of VI5. Current was increased from 5 to 25 kA in 5-kA steps. A current of 30 kA could not be reached due to equipment limitations. Finally, 315 tests were fired at 24 kA. No failures of any kind were observed, but for 200 of these tests some of the instrumentation was disconnected so that a single interrupter failure would not have been observed. Some second zero interruptions were seen, indicating that the interrupters were operating fairly close to their limit. Little erosion was noted; in fact, an apparent growth of the electrodes was measured due, presumably, to surface roughening.

D. Two in Series, HP on, and C2 Reduced to 70 μ F

Twenty-six tests were fired at 24 kA. Many restrikes were observed. Two were simultaneous restrikes of both interrupters; three were restrikes of single interrupters. Earlier experience and subsequent findings indicate that these restrikes were caused by a combination of events including an arcing time which was too short, the deleterious effects of the extra I^2t contact heating, and extra-large jitter in opening time caused by a broken anchor in the actuator, discovered about 100 tests later. See I below.

E. Repeat of D With HP Off

One single interrupter restrike was observed out of 38 tests at 24 kA. This indicates that I^2t heating was not the only cause of trouble in D.

F. Repeat of E With 7-ms Arcing Time

No restrikes of any kind were observed in 20 tests at 24 kA. This indicates that a short arcing time was part of the trouble in D.

G. Repeat of F With HP on at $I^2t = 6 \times 10^7$

One single interrupter restrike was observed out of 90 tests at 24 kA. The broken mechanical link was then found and repaired. This indicates that I^2t heating doesn't cause trouble.

H. Repeat of F With HP Off

No restrikes of any kind were observed in 15 tests at 24 kA.

I. Repeat of H With HP On

No restrikes of any kind were observed in 192 tests at 24 kA. Thus the many restrikes observed in D were eliminated by lengthening the arcing time and fixing the broken link.

J. Repeat of I With Arcing Time of 7.5 ms

One single interrupter restrike was observed in 315 tests at 25 kA.

K. Repeat of J but $I^2t = 10 \times 10^7$

No restrikes of any kind were observed in 105 tests.

L. Repeat of J With Arcing Time Reduced to 4.8 ms

No restrikes of any kind were observed in 54 tests.

M. Fault Test

A fault test was performed at the maximum current of our system. The maximum current was achieved by connecting a second bank of capacitors, C1, in parallel with the first and discharging them both simultaneously from their maximum voltage through VI2. VI1, VI3, VI4, and VI5, as well as LS1 and LAF1 were removed from the circuit interrupter. VI2 was not purposely opened during this test but did so spontaneously because of magnetic popping forces. The interrupter's voltage waveform, shown in Fig. 10, reveals this popping by the periodic addition of the arc voltage to the normal resistive part of the total voltage drop. The peak current reached during two fault tests of this type was 86 kA, and the duration was about 50 ms. Figure 11 shows a representative current waveform.

The fault test was relatively uneventful. The interrupter was lightly welded shut after both of these tests. It could be broken loose with a moderate manual pull. High potential tests showed that the vacuum integrity was unaffected by the fault test. The stationary stem was badly bent due to mechanical forces exerted on it by the leads to the interrupter. These had not been designed to resist the magnetic forces developed during the fault test. Figure 12 shows the bent stem after the interrupter's envelope was removed.

V. SPECIAL DIODE TESTS

The test circuit of Fig. 1 was modified for these tests by dividing inductor L into two parts, (L1 = 30 mH, L2 = 110 mH) and connecting a diode from their midpoint to ground. Figure 13 shows this part of the circuit and various test points, TP7 through TP11, used to monitor the voltages and currents. Test point TP9 is a current monitor, and the others are voltage monitors. The diode used was manufactured by Semtech Corporation² to meet the current, voltage, and energy dissipation specifications. Physically it is about 0.6 m long and 0.15 m x 0.22 m in cross section.

Fig. 10. Interrupter voltage during fault test. The trace covers 100 ms. The peak voltage is 80 V.

Fig. 11. Interrupter current during fault test. The trace covers 100 ms.

Fig. 12. Vacuum interrupter after envelope was removed.

Fig. 13. Modified circuit for diode tests.

Tests were performed with this diode in the circuit of Fig. 13 to establish those parameters of the diode which would be important to its use in the TFTR circuit. Its purpose there is to suppress reversed-voltage spikes introduced by the vacuum interrupters. Since the test circuit already limits these spikes through the action of inductor L and the ignitron pair S2, there was no need to use the Semtech diode as a part of the normal test circuit at the full current level of 24 kA. Instead, most measurements were performed near 5 kA but with an unusually large counterpulse voltage. This combination produces large spikes but is unlikely to overstress the diode. This cautious approach was stimulated by earlier experience with another diode which was damaged when operated near its design limits because of a faulty circuit element.

To indicate the nature of the spike to be suppressed, Fig. 14 shows a typical trace of the voltage measured at TP8. The offending spike at the beginning of the trace has two distinct parts, the first due to LdI/dt , where L is the stray inductance in the interrupter leg of the circuit (a few microhenries) and dI/dt is the rate of change of the counterpulse current in that leg. The second part of the spike is initiated by the interruption of the current at its first zero. After interruption, the voltage at TP8 rapidly rises to the voltage on C2. This residual voltage is a small fraction (say 10%) of the voltage originally present on this capacitor. In the TFTR circuit it will be approximately 1 kV, and the whole spike will last about 50 ms.

Figure 15 shows the voltage measured at TP10. This voltage differs from that shown on Fig. 14 due to the filtering action of the combination LSR/C2 followed by that of L1/D. Measurements, not shown, confirm that LSR/C2 has little effect on the waveform other than to remove some of the sharp leading edges of the spikes. The L1/D combination is wholly responsible for the marked reduction in the area of the spikes. The desired information concerning the parameters of the diode can be extracted from the shape of traces such as these.

Figures 16-18, for example, show on expanded traces the diode current and the voltage at TP10 and TP11, i.e., at both ends of the diode. Figure 18, the voltage at the lower end, is the voltage to be expected across a pure inductor of value ~ 0.7 mH. This inductor is made up of an approximately 0.3-m length of 4-0 cable connecting the diode to ground. The difference between Figs. 17 and 18 is caused by the impedance of the diode. Analysis of this difference leads to an equivalent circuit for the diode composed of a series connection of a perfect diode, an inductor, a resistor, and a battery. The values found for the parasitic components are ~ 1 mH, 40 m Ω , and 100 V. Their combination accounts for the peak voltage of 224 V at 5.4 kA shown in Fig. 17. It would generate a peak voltage of several hundred volts if it were used in TFTR at 24 kA with a normal counterpulse and with the filter inductor that was used in these tests.

This peak voltage could be too high for certain uses. It could be reduced either by increasing the value of L1 or by reducing the parasitic components in the diode. Certainly when connecting D into the TFTR circuit, care must be taken to reduce its lead inductance to well below 1 mH.

Fig. 14. Voltage across interrupter. The trace covers 1.0 ms.

Fig. 15. Voltage across diode. The trace covers 1.0 ms.

Fig. 16. Current through diode. The trace covers 0.5 ms.

Fig. 17. Voltage across diode. The trace covers 0.5 ms.

Fig. 18. Voltage across ground lead to diode.
The trace covers 0.5 ms.

VI. DISCUSSION OF RESULTS

A. Reliability of Interrupters

As mentioned in the introduction, these tests were performed under a variety of conditions, timings, and component values. Some conditions are favorable for reliable interruption and some are not. Two tasks are undertaken in this part of the report. These are, first, to discriminate between the favorable and unfavorable conditions and then to evaluate the reliability of interruption and the lifetime of the vacuum interrupters under the favorable conditions.

From all 1435 of the tests with the WL-33552 vacuum interrupters listed in Table II, two restrikes were observed of the complete interrupter, i.e., simultaneous restrikes of both series interrupters, and seven restrikes of single interrupters. These restrikes were not distributed randomly, however. Most of them occurred in series D which included only 26 tests. Clearly something was wrong during this series. It appears that the reliability was adversely affected by a combination of three factors - short arcing time, homopolar heating, and a broken actuator link. If this series is omitted because of unfavorable conditions and the rest of tests A to L retained in the data base, no complete failures were observed but a total of four single interrupter failures out of 1407 tests. On the other hand, a short arcing time appears to be the major harmful affect. If instead of omitting only run D, all data are discarded for arcing times of 5 ms or less, that is runs C, D, E, and L, then there are no complete failures, and a total of three single interrupter failures occurred out of 1000 tests.

It must be recognized that the data presented above include two quite different subsets: series A and B in which a single interrupter was tested at 25 kV, and series C through L in which two interrupters were tested in series

at a total voltage of 25 kV. From series A and B one can derive a probability of 1/263, i.e., 0.4% that a single interrupter will fail. From the remaining series a probability of 3/2288, i.e., 0.13%, or 2/1474, i.e., 0.14% can be found for a single interrupter failure, essentially independent of which series is discarded for unfavorable conditions. Although the difference between 0.4% and 0.13% is large and indicates that, as expected, the failure rate at 25 kV/interrupter is greater than at 12.5 kV/interrupter, the data have too much probable error to justify this conclusion. Other information indicates that the dependence of reliability upon voltage is quite small. We, therefore, chose to lump all of our data together and find an average failure rate for a single interrupter of 0.16%. Now if two interrupters are connected in series, the combination will fail only if both fail. The probability of this appears at first to be the square of 0.16%, i.e., 2.5 parts per million, but the conclusion is wrong and pessimistic. The reason for this involves the ability of a single interrupter in a series pair to recover rapidly its insulating properties after a failure. This recovery occurs because of the circuit configuration used. A single failed interrupter can conduct only for a limited time, t_0 , before the voltage across it drops to zero and the remaining unfailed interrupter sustains all of the voltage. This time t_0 is determined by the size of the capacitor in parallel with each interrupter. After t_0 , the interrupter current is zero and after an additional deionization time, t_1 , the interrupter can withstand its normal voltage without reigniting. A combined failure of both interrupters will occur then only if the second interrupter fails within a time, $t_0 + t_1$, after the first.

One can calculate the probability of such a combined failure and compare it with the square of the probability of a single failure to show their difference.

Let $p \equiv$ probability/sec for failure of a single interrupter

and $P1(.015) \equiv$ probability that a single interrupter fails in a 15 ms interval.

$$\text{Then } P1(.015) = p \times 1.5 \times 10^{-2}.$$

Now $P2(.015) \equiv$ probability of a combined failure in 15 ms.

$$P2(.015) = 2P1(.015)P1(t_0+t_1) = 2p^2 \times 1.5 \times 10^{-2} \times (t_0+t_1) .$$

$$\text{Thus } \frac{P2(.015)}{P1(.015)^2} = \frac{2p^2 \times 1.5 \times 10^{-2} (t_0+t_1)}{p^2 (1.5 \times 10^{-2})^2} = 2 \frac{(t_0+t_1)}{1.5 \times 10^{-2}} .$$

If $t_0+t_1 = 75 \mu s$, which appears to be easily achievable, $P2/P1^2 = 0.1\%$.

Now the selected data, which show zero combined failures in about 1000 interruptions, are not sufficient to distinguish between these two models. It appears, however, that the combined failure rate will be less than 2.5 parts per million and far below 0.1%, the failure rate which must not be exceeded to meet the needs of TFTR.

Most of the data was taken with $\int I^2 dt$ heating values of $6 \times 10^7 \text{ A}^2\text{s}$ or more. The reported failure rate of 0.2% thus corresponds to this amount of electrode heating. The data taken without heating are insufficient to allow an independent failure rate determination. Other data, however, suggest that the effect of this amount of heating on the failure rate is small.

B. Erosion of Interrupter Contacts

A plot of the erosion results is not shown because the measured erosion is very small and in most cases of negative sign, i.e., indicating growth not erosion. Instead, x-ray images were made of the electrodes, and finally, one interrupter was broken open to provide an unobstructed view of the electrodes. Figure 19 shows a photograph of the electrodes of this interrupter. There has clearly been pitting of both electrodes, extensive melting of their surfaces, and a net transport of a small amount of electrode material from the perimeter of the cathodes to the perimeter of the anodes. A fine metallic ridge has built up around the anodes which has, in some cases, broken loose or transferred to the cathode. The average thickness of the electrodes has not changed within $\pm 0.01 \text{ in.}$, the precision of the original measurement. This erosion rate is much less than that of conventional interrupters previously measured. Some very minor spattering of melted material onto the shield structure is apparent. It appears that a projected contact life of ten thousand operations is feasible before a significant change in electrode shape or build up of spattered or evaporated deposits will occur. A periodic reversal of anode-cathode roles would probably extend this life significantly.

Performing typical interruptions on a two-minute cycle caused the outer extremity of the stationary stem of VII to reach an average temperature of 100°C . This temperature was approached with a time constant of several hours. When the standard I^2t ($6 \times 10^7 \text{ A}^2\text{s}$) preheating cycle was eliminated and interruption proceeded normally otherwise, the stem temperature increased only half as much. This shows that the electrode heatings during arcing and during the preheating phase were of similar magnitude. Calculations of these heat

Fig. 19. Electrode surfaces of opened bottle.

depositions with an arc voltage of 50 V and an electrode resistance of 100 m Ω confirms this rough equality. As a consequence, an I^2t value of 6×10^7 A²s is expected to be critical. Below that value the I^2 heating does not contribute significantly to the total heat developed in the electrodes and thus would not be expected to affect the reliability of interruption. Above that value the I^2t heating would have a significant affect on electrode temperature and might have a significant affect on interruption. Other measurements made at LASL, indicate that 6×10^7 is a low value and that much higher I^2t values can be tolerated without significant changes in reliability. The effect on contact melting and erosion due to the I^2t heating is unknown but may be significant.

C. Actuator Performance

Five Ross actuators³ were used to open and close VII through VI5. The reliability and maintainability of these actuators were of constant concern. During the tests the following failures were observed:

1. A microswitch and its leads failed causing unusually slow electrode separation.
2. A mechanical hinge pin became loose completely inhibiting the opening of VI2.
3. An anchor bolt broke causing a large increase in opening jitter and an unusually slow electrode separation of VII.
4. A clamp on a stationary stem loosened increasing the heating of that electrode on VI2.
5. A mechanical connection to the moving stem loosened increasing the opening jitter of two different interrupters.
6. A microswitch adjustment shifted causing VII to bounce closed regularly after a successful interruption.

High speed photographs were taken of the motion of the actuators for VII and VI2. From these actuator photos, conclusions could be drawn concerning the opening speeds of the electrodes of these two interrupters. Maximum speeds of 2.6 m/s were found for VII and 1.6 m/s for VI2. Corresponding electrode spacings were 0.6 and 0.4 cm at a 4-ms arcing time and 1.4 and 0.9 cm at a 7-ms arcing time. The large difference between these results for the two interrupters is not understood. Their actuators and drivers were checked for malfunctions and were readjusted to similar mechanical and electrical specifications with no affect. Both actuators were quite old and have had several parts replaced due to wear. This wear and refitting somehow may have caused the large differences observed.

Previous measurements with other interrupters have shown that electrode gaps of 0.7 mm or more are desirable for low restriking probability. Thus the several failures observed with arcing times of 4 to 5 ms appear to be caused mainly by insufficient gaps.

D. System Reliability

The overall system reliability during the tests was very poor compared to the reliability found for the interrupters. Part of this was related to components such as VI5, which sees extremely severe duty and which would not be included in the switch used in TFTR. Other sources of failure, however, would cause trouble in TFTR and will be mentioned here to emphasize the attention which must be paid to their design and construction to avoid similar troubles. These troubles were of three types - ignitron prefires, electrical pickup, and mechanical shocks caused by the large magnetic forces. Ignitron prefires became progressively worse above 10 kV but could be avoided or greatly reduced by cooling the cathodes and heating the anodes. Electrical pickup can be reduced by care in grounding and shielding, but this care must be exercised from the initial design phase. Pickup problems were largely created by circuit changes introduced to meet the various E/G specifications. Mechanical shock problems can be reduced by using large conductors with bolted or soldered connections liberally supported and insulated from ground.

E. Special Diode

No trouble is expected with this diode as long as (1) the inductance, L_1 , in series with it is large enough, (2) the lead inductance of the diode is kept small, and (3) the diode is protected against faults of various kinds in the rest of the circuit that might cause its destruction.

VII. CONCLUSIONS

When tested in its proposed circuit under the proposed mode of operation, the WL-33552 interrupters behaved about as expected. When conditions were unfavorable, i.e., when the arcing gap was too short, interruption was unreliable. When operated with an adequate electrode gap (7 mm) the interrupters opened 24 kA at 25 kV with a failure rate of 0.2% or so for a single interrupter. No failures were observed for two interrupters in series. The measured erosion rate was very low (≤ 0.1 mm/1000 shots) but some electrode material melted or otherwise migrated to the perimeter of the electrodes and to the anode. The rate of spattering of electrode material to the shield or insulating structures was very low. I^2t heating values of 6 or 10×10^7 A²s appear to have no significant affect on reliability and probably no effect upon erosion.

The fault test was performed at 85 kA, well below the value of interest to E/G. Its very mild consequences, however, lend some credence to the opinion that no serious explosions will accompany a full fault.

PART II - TOSHIBA INTERRUPTERS

I. INTRODUCTION

The purpose of this segment of tests was to determine the reliability and erosion rate of two, series-connected Toshiba type VGB2-D20 vacuum interrupters. As in the Westinghouse tests, the interrupter was specified to operate at 24 kA with a recovery voltage of 25 kV. In this set of tests, however, there was to be no external I^2t heating, so that the total heating, primarily during the arcing interval, was approximately $8 \times 10^6 \text{ A}^2 \text{ s}$. These tests also differed from those conducted on the Westinghouse interrupters in that the counterpulse bank and saturable reactor were specified by Toshiba at values considerably larger. This subjected the vacuum interrupter under test to lower values of dI/dt and dV/dt . Both the total and midpoint voltages across the series interrupters were monitored for 30 ms following interruption. This allowed detection of double or single interrupter restrikes during this period. Erosion rates were also measured for both interrupters during all the standard tests.

In addition to the above tests, a set of extended tests on a single-interrupter Toshiba interrupter were performed to determine the upper-limit interruption ability. Toshiba International imposed, for these tests, certain constraints on the critical parameters. The extended tests section of this report discusses these in detail.

II. STANDARD TESTS

Figure 20 is a schematic of the circuit used in the standard tests. It differs from the circuit used in the Westinghouse tests in that there is no homopolar generator for I^2t heating, the counterpulse capacitor and saturable reactor are changed, and the test interrupters have internal axial-field coils. Current is initiated by discharging the 2760- μF capacitor through the 200- μH inductor, the blocking circuit, the 407/110- μH saturable reactor, and the Toshiba vacuum interrupters. The series ignitrons on the left prevent voltage reversal on the 2760- μF capacitor and thereby initiate an exponential decay after current peak is reached. All three vacuum interrupters are then opened and the 450- μF counterpulse capacitor is discharged. This drives the current in the Toshiba interrupters to zero where interruption occurs. The remaining energy in the 200- μH inductor then transfers to the counterpulse capacitor where it is held by the blocking circuit. The 1-k Ω resistor maintains the voltage across the test interrupters by keeping the ignitrons conducting.

The 407/110- μH saturable reactor was designed to meet the specifications in Fig. 21 supplied by Toshiba.

Firing sequences were controlled with a digital delay generator through fiber-optic cables. The control cabinets and digital oscilloscopes are shown in Fig. 22.

Figure 23 is a photograph of the Toshiba interrupter installed in the facility for tests.

Fig. 20. Circuit for standard Toshiba tests.

Fig. 21. L-I characteristics of saturable reactor for standard tests.

Fig. 22. Control cabinets with digital delay generators and digital oscilloscopes.

Fig. 23. Toshiba interrupter in test facility.

A. Definition of Critical Parameters

The instructions for operation of the interrupters, supplied in Toshiba document number KDPU-0005, revised July 25, 1978, include a list of specifications under which the interrupters were to be operated. The critical parameters included in these specifications are displayed in Fig. 24.

Table IV compares the Toshiba specifications with those experimentally obtained in the standard tests. The only specification exceeded in the test circuit was $di/dt|_m$ due to facility constraints. As will be seen later in the results, this had no effect on the reliability of interruption in the standard tests.

B. Testing

Initially, approximately 150 single-interrupter tests were run at currents less than 24 kA. The purpose of these initial tests was twofold. First of all, the facility and its components had to be checked at low current levels. This included verification of ignitron and breaker timings, establishment of proper voltage-current relationships, and adjustment of the data acquisition equipment. The initial low-current tests also helped to condition the vacuum interrupters by absorbing stray gasses that might be present in the vacuum chamber.

TABLE IV
COMPARISON OF TOSHIBA SPECIFICATIONS
WITH THOSE EXPERIMENTALLY OBTAINED

<u>Parameter</u>	<u>Definition</u>	<u>Toshiba Specification</u>	<u>Experimental Value</u>
I_{INT}	Interruption current, kA	24	24
$\frac{di}{dt} _m$	Mean rate of current fall, A/ μ s	<96	130
$\frac{di}{dt} _Z$	Mean rate of current fall near current zero, A/ μ s	<26	26
V_P	Peak recovery voltage, kV	<25	24.6
V_N	Peak inverse voltage, kV	<25	3.9
$\frac{dV}{dt} _P$	Rate of rise of recovery voltage V/ μ s	<300	103
$\frac{dV}{dt} _N$	Rate of rise of inverse voltage, V/ μ s	<300	108
T_{ARC}	Arcing time, ms	8	8

The interrupters were then connected in series, and the current was gradually increased in another series of tests. This procedure of increasing the current in several discrete steps was followed every time the facility had been inoperative for a period of several hours or more to condition the ignitrons for full voltage. Figure 25 shows the current waveform for a typical 24-kA interruption. The second picture is a magnification of the current just prior to interruption and illustrates the effect of the saturable reactor. Figure 26 includes the corresponding voltage waveforms for a typical interruption. The second picture shows the inverse voltage in detail.

Another measurement taken routinely during the standard tests was of displacement versus time for the moveable contact of Toshiba interrupter No. 1. This was to help detect any changes in the actuator movement due to wear or loosening of parts. A displacement transducer with a 25-kHz excitation frequency provided the displacement curve shown in Fig. 27. The displacement curve remained constant throughout the standard tests indicating a very consistent actuator movement.

C. Circuit Idiosyncracies

Two circuit idiosyncracies were observed during the standard tests; both affected the recovery voltage characteristics. The first occurred when the 1-k Ω resistor failed to hold the counterpulse ignitrons in a conducting state after current interruption. The voltage on the snubber capacitor across the interrupter then decayed through the 1-k Ω resistor with a 7.5-ms time constant. In a normal test sequence this time constant is approximately 500 ms. This abnormality is referred to as a "voltage droop" and is pictured in Fig. 28.

The second abnormality occurred when the blocking circuit failed to hold the voltage on the counterpulse capacitor. The capacitor voltage would then oscillate with the 200- μ H inductor for one-half or more cycles until the blocking circuit did interrupt. The result was an oscillatory recovery voltage such as that pictured in Fig. 29. In both types of abnormalities the peak recovery voltage is the same as in a normal shot.

D. Results from Standard Tests

Table V gives a summary of standard tests performed on the Toshiba interrupter.

TABLE V

SUMMARY OF STANDARD TESTS ON TOSHIBA INTERRUPTER

Description of Test Condition	Type	Interruption Current (kA)	V _P (kV)	V _N (kV)	$\frac{dV}{dt} _P$ (V/ μ s)	$\frac{dV}{dt} _N$ (V/ μ s)	$\frac{di}{dt} _M$ (A/ μ s)	$\frac{di}{dt} _Z$ (A/ μ s)	No. of Shots	No. of Failures
Startup	Single	5-24	6-25	<3.9	<103	<108	<133	<26	153	0
Startup	Series	5-23	6-24	<3.9	<103	<108	<133	<26	194	0
Oscillatory Recovery	Series	24	25	3.9	103	108	133	26	58	0
Decaying Recovery	Series	24	25	3.9	103	108	133	26	143	0
Flat Recovery	Series	24	25	3.9	103	108	133	26	944	0

Fig. 24. Critical test parameters.

(a)

(b)

Fig. 25. Current waveforms for typical 24-kA interruption.
 (a) Full current waveform.
 (b) Magnification near current zero.

(a)

(b)

Fig. 26. Voltage waveforms for typical 24-kA interruption.

(a) Full voltage waveform.

(b) Magnification of inverse voltage.

Fig. 27. Displacement vs time for Toshiba interrupter No. 1.

Fig. 28. Voltage droop across interrupter.

Fig. 29. Oscillatory recovery voltage, one-half cycle.

As can be seen, there were no failures to interrupt on any of the 1145 series-connected, full-level tests. In addition, the midpoint voltage between the two interrupters was carefully monitored during the course of testing and revealed that there were no single-interrupter restrikes. Both the full and midpoint voltages were observed for 30 ms after interruption.

E. Erosion

Erosion measurements were routinely made at the beginning of each day's testing on both vacuum interrupters. This was accomplished by inserting a depth micrometer through guide plates mounted above each moveable contact. The micrometer armature was lowered until it came in contact with the coupling attached to the stem of the moveable electrode. The net erosion as a function of the total number of 24-kA shots is plotted in Fig. 30. Minor indications of growth or erosion are probably a result of slight changes in the seating of the moveable electrode. The major trend indicates an initial erosion rate of approximately 0.2 mm/1000 shots for the first 600 shots. Following this, there appears to be an abatement of erosion. The earlier tests in which an interrupter was cut open after a similar series of tests, have shown a net migration of material from one electrode to another. Thus, erosion in the normal sense of the word is not directly applicable to the process which takes place between the electrodes of a vacuum interrupter. The failure mechanisms of vacuum interrupters are still not well known, but it is generally felt that their lifetime is not proportional to the thickness of the electrodes.

Fig. 30. Erosion of Toshiba interrupters.

III. EXTENDED TESTS

Single-interrupter tests were run on a Toshiba interrupter to determine its maximum interrupting capabilities. The parameter $di/dt|_Z$ was kept below 100 A/ μ s for currents below 40 kA and below 50 A/ μ s for currents between 40 and 45 kA. Fig. 31 is a schematic of the circuit used for these extended tests.

The circuit is similar to the previous one except it lacks a blocking interrupter. Instead, the 100- μ H inductor is allowed to ring with the counterpulse capacitor for one-half cycle. This results in a sinusoidal shaped recovery voltage waveform. At the end of the one-half cycle the 0.01-ohm resistor is inserted parallel to the inductor. This quickly damps out any further ringing of the L-C circuit. It should also be noted that the saturable reactor has been changed and that the counterpulse and snubber networks are adaptable to either a 40- or 60 kV configuration.

A. Testing

Figure 32 shows a typical recovery voltage waveform for the extended tests. The second photograph shows an expanded view of the inverse voltage.

A total of 51 tests was made with the circuit of Fig. 31 at currents ranging from 35 to 45 kA. Peak recovery voltages were from 24 to 33 kV. Six failures were observed, all at currents in excess of 40 kA. Figure 33 shows the voltage waveform for one such failure. Although this failure occurred after the voltage peak, most failures took place prior to the peak. Occasionally the interrupter would restrike on the inverse voltage but recover sufficiently to hold off the forward recovery voltage. Figure 34 illustrates this phenomenon which is referred to as a second-zero interruption.

Another set of extended tests was performed utilizing second-zero interruption with an ungapped saturable reactor identical to that used in the tests of Westinghouse interrupters. This reactor has the advantage of a very high unsaturated-to-saturated inductance ratio as well as being simple to construct and modify. The counterpulse essentially drives the interrupter current slightly through zero and then reapproaches the zero crossing with a very low di/dt . Figure 35 shows a typical current waveform for this type of interruption. Here the inverse current is 250 A, and di/dt prior to the second-zero crossing is 10 A/ μ s.

Fig. 31. Circuit for extended tests.

(a)

(b)

Fig. 32. Recovery voltage waveform for extended tests.
 (a) Full voltage waveform.
 (b) Expanded inverse voltage.

Fig. 33. Voltage restrike after 45-kA interruption.

Fig. 34. Restrike on inverse voltage (expanded view).

Fig. 35. Second current-zero interruption with ungapped saturable reactor.

Fig. 36. Probability of interruption for single Toshiba interrupter.

A total of 26 tests was made in the above described way with currents ranging from 35 to 47 kA. Four failures were observed, all above 42 kA. These failures involved restrikes on the voltage rise from 6 to 18 kV. Successful recovery voltages ranged from 25 to 33 kV peak.

B. Results from Extended Tests

Table VI is a summary of the extended test results taken on a single Toshiba interrupter. From these data, the performance of the interrupter appears to be fairly independent of the type of saturable reactor used. By combining the results of tests with both types of saturable reactors, the probability of interruption curve shown in Fig. 36 can be constructed.

TABLE VI
SUMMARY OF EXTENDED TESTS ON TOSHIBA INTERRUPTER

Description of Test Condition	Type	Interruption Current (kA)	V _P (kV)	V _N (kV)	$\frac{dV}{dt} _P$ (V/μs)	$\frac{dV}{dt} _N$ (V/μs)	$\frac{di}{dt} _M$ (A/μs)	$\frac{di}{dt} _Z$ (A/μs)	No. of Shots	No. of Failures
Gapped Saturable Reactor	Single	35	24	6	120	3000	380	37	10	0
	Single	33-37	30-33	5	490	290	430	43	11	0
	Single	40.-42.5	24-25	4	130	110	390	43	22	3
	Single	42.5-45.0	25-26	3	200	100	410	40	8	3
Ungapped Saturable Reactor	Single	34-37	25-26	-	340	-	1200	10	10	0
	Single	40.-42.5	29-30	-	390	-	1300	10	1	0
	Single	42.5-45.0	30-31	-	430	-	1300	10	12	2
	Single	45.0-47.5	31-32	-	440	-	1300	10	3	2

From this graph, the 90% and 50% success points are 41 and 46 kA, respectively. This is in general agreement with previous findings at LASL for similar sized interrupters with internal axial fields. It must be noted that this is a conservative estimate for the maximum ratings because of the following reason. Due to the decaying nature of the current waveform, the interrupter must be opened on approximately one and one-half times the current it is required to interrupt. If the arc at this higher current is not diffuse, then it is possible to form an anode spot. This anode spot would increase the restrike probability upon application of a recovery voltage due to thermoionic emission. Thus it is possible that a higher rating might be found if the device were tested with a flat current waveform.

IV. CONCLUSIONS

A total of 1145 tests was made on two series-connected Toshiba interrupters at 24 kA and 25 kV. No failures to interrupt occurred during any of these tests. In addition, no single interrupter restrikes were observed. The contact erosion rate was monitored and found to be 0.2 mm/1000 shots for the first 600 tests. During the remaining tests there appeared to be no further erosion.

Extended tests were performed to find the upper-limit interruption ability on a single interrupter. The 90% and 50% reliability points are 41 and 46 kA, respectively. These points are valid for recovery voltages between 24 and 33 kV.

PART III - OVERALL CONCLUSIONS

Two interrupter systems were tested for over 1000 interruptions each at 24 kA and 25 kV. One system employed special Westinghouse interrupters in a circuit designed by LASL. This circuit used a commercially available actuator and a minimum size counterpulse bank and saturable reactor. The other used Toshiba interrupters actuated by a Toshiba mechanism in a Toshiba circuit using a larger counterpulse bank and saturable reactor.

Both of these systems successfully completed 1000 interruptions without failure and indicated a very low contact erosion rate. Both appear to satisfy the needs of TFTR with respect to reliability and to have such low erosion rates that this feature is not expected to be a limitation on lifetime.

The superiority of the Toshiba system, i.e., no single vacuum interrupter failures versus three single interrupter failures for the Westinghouse interrupters, can be attributed to three major sources: a different circuit which imposes lower stresses on the Toshiba interrupters, a better Toshiba actuator which performs more reliably and predictably, and a larger vacuum interrupter with somewhat better characteristics. The relative contributions of these three factors are unknown.

The many problems encountered with the Ross actuator indicate that extensive development work should be spent on it before its further use is considered.

References

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