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Experiments with Vacuum Interrupters Used for Large DC-Current Interruption

R. W. Warren*

*Industrial Staff Member. Westinghouse Research Laboratory, Beulah Road, Churchill
Boro, Pittsburgh, PA 15235.

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scientific laboratory
of the University of California
LOS ALAMOS, NEW MEXICO 87545

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EXPERIMENTS WITH VACUUM INTERRUPTERS USED FOR LARGE DC-CURRENT INTERRUPTION

by

R. W. Warren

ABSTRACT

Vacuum interrupters have been tested in circuits similar to those used in theta-pinch and tokamak fusion devices. The effects on performance of auxiliary circuit components and axial magnetic fields have been determined, and limits to lifetime caused by mechanical and electrical wear have been measured. Results show that the upper reliable limit of interruption is independent of the auxiliary components but quite dependent on interrupter size and on the axial field.

I. SUMMARY

More than a dozen vacuum interrupters have been examined to determine their ability to interrupt large dc currents and to successfully sustain the resulting large voltage transients. The importance of auxiliary circuit components such as saturable reactors and R-C "snubber" elements has been assessed as has the effect of varying the electrode gap, its opening speed, and other system variables. The following general rules have been formulated governing P , the probability of a successful interruption of a current, I_0 , and I_{cp} , the counter-pulse current used to create an artificial current zero at which interruption may occur.

(1) P does not depend strongly on I_{cp} if I_{cp} is large enough to achieve a current zero and if the saturable reactor is also large enough.

(2) P does not depend strongly upon I_0 until the arc voltage becomes noisy. P then drops rapidly with further increases in I_0 .

(3) I_m , the upper limit to I_0 , varies roughly linearly with the diameter of the arcing electrodes.

(4) I_m is independent of circuit elements and operational parameters such as saturable reactor, snubber circuit, and opening speed and gap, over a wide range.

(5) There is no significant variation of I_m among the vacuum interrupters produced by different manufacturers.

Table I gives I_m , the upper limit to the interruptible current for all of the interrupters measured at a reliability of 50 and 90%. The last two columns of Table I show the large increase in I_m and the decrease in arc voltage which occurred for those interrupters operated in a strong axial magnetic field. This improvement is substantial and its documentation an important result of this report.

II. INTRODUCTION

Many approaches to fusion require storage and rapid transfer of large amounts of energy, posing problems not only for the storage systems but for the transfer circuitry. Power levels are extremely high

TABLE I
VACUUM INTERRUPTER CURRENT INTERRUPTION RELIABILITY

Interrupter ^b	Nominal Diam (in.)	Electrode Diam (cm)	Maximum Current (I _m , kA)		Axial Field	
			Reliability		(% Increase in I _m)	(% Decrease in Arc Voltage)
			50%	90%		
A1	4	2	6	5		
A2	4	2	8	7	10	15
A3	4	5	13	12	25	50
B1	4		6	5		
A4	5	7	17	14		
A5	5	7	18	15	70	10
A6	5	8	16	14		
A7	5	9	19	17	80	10
A8	7	10	24	22		
A9	7	12	26	24		
Prototype 1	7	10	>37	>37	*	
Prototype 2	7	13	15	13	>100	50
C1	8	11	28	26		

*Interrupter has an internal axial field coil.

^bA, B, and C refer to three different manufacturers.

because the energies involved in reactor-size devices are typically $\sim 10^7$ J and transfer times range from 1 to 10^{-5} s. A major concern is the switching required in these systems, particularly any *interrupting* switch. The use of solid state thyristor switches or "plasma valves" of various kinds is attractive because of their anticipated long life. However, they are prohibitively expensive when compared with the mechanical switches which are now used. But mechanical switches cannot achieve the goal of millions of operations required for reactor applications. Because of this cost-performance split, other switching components and concepts which may be inexpensive and may provide a long operating life should be examined. This report describes the beginning of such an examination of vacuum interrupters.

During the last several years the Los Alamos Scientific Laboratory (LASL) has been pursuing research on current interruption with commercial vacuum interrupters for use in an inductive energy storage and transfer system for the Scyllac Fusion

Test Reactor (SFTR).¹ More recently, development has been applied to the Tokamak Ohmic Heating (TOH) circuitry. To meet the requirements of SFTR, i.e., 500 MJ energy storage to be delivered to the coil in 1 ms, a system of modules was developed. The maximum current and voltage for these modules were set rather arbitrarily at 26 kA and 60 kV, which were felt to be the highest current and voltage that the various components could easily sustain. These limits and the transfer time of 1 ms determined the 400-kJ module size. A diagram of the circuit of one module is shown in Fig. 1A, where L_o is the load coil, L_s is the superconducting coil, and HP is a generator which raises the current in L_s and switch S_1 to 26 kA in several minutes. At this time S_1 is opened and the current is transferred to the circuit containing L_o and C_s . If L_o and C_s have the correct values, all of the energy originally stored in L_s is transferred to L_o in 1 ms. If S_1 is closed when this transfer has been accomplished, the energy can be held in L_o for a time given by its L/R decay constant.

One of the difficulties with this circuit is the need for a switch S_1 which can successfully interrupt a 26-kA current and withstand a 60-kV recovery voltage. Vacuum interrupters were selected as probable candidates for S_1 , but because they were developed for ac uses, little was known about their performance in this unusual application. Accordingly, a special apparatus was set up to test the interrupters and their possible auxiliary components.

This report discusses the interrupter circuit, functions of its components, and progress made on this test program. An important feature of this program has been a gradual broadening to include interrupter tests for other applications. Tokamaks, in particular, need interrupters for their ohmic heating systems with ratings as large or larger than those of SFTR.

III. PROGRAM PLAN

The primary purpose of the experiments is to investigate the performance of standard vacuum interrupters. Performance is evaluated by examining (1) the reliability of interruption vs current, (2) the operating life of an interrupter, and (3) the dependence of these properties on the variables under our control.

These variables include the following important parameters:

- (1) the magnitude of the counterpulse current,
- (2) the type of interrupter, i.e., size and manufacturer,
- (3) how the interrupter is operated, i.e., opening speed and electrode spacing,
- (4) temperature,
- (5) the presence of magnetic fields,
- (6) the properties of the saturable reactor component, and
- (7) the properties of the snubber component.

Because the measurements are quite time-consuming, an orderly testing approach is required to arrive at useful results in the shortest time. The following plan was used.

1. Choose a "standard" interrupter and operate it under the simplest circuit conditions, that is, no snubber, no saturable reactor, and the simplest environmental conditions (room temperature and no magnetic field). Choose a standard electrode opening speed and gap.

2. Vary I_{cp} , the counterpulse current, over a wide range and determine $P(I_{cp})$, the probability of interruption.

3. Vary I_0 , the interrupter current, and repeat step 2, that is, establish $P(I_0, I_{cp})$ under standard conditions.

4. Vary the moving electrode's speed and gap at counterpulse and determine their effects on $P(I_0, I_{cp})$ over a limited range of I_0 and I_{cp} where P is near 50% and thus particularly sensitive to change.

5. Install the snubber circuit and saturable reactor separately and test their effects on $P(I_0, I_{cp})$ over a limited range of I_0 and I_{cp} and for the new standard speed and gap determined to be optimum in step 4.

6. Test samples of all commercially available interrupters over a wide range of I_0 and I_{cp} and for the standard speed and gap and for an optimum standard saturable reactor and snubber circuit determined in step 5.

7. Investigate effects of different electrode temperatures on P for the standard interrupter under standard conditions.

8. Investigate effects of magnetic fields on P .

9. If necessary, investigate interrupter performance under combinations of nonstandard conditions.

10. Evaluate the lifetime of the standard interrupter under standard conditions.

The following sections go into considerable detail in discussing our results for each part of this plan. These sections are organized to follow the order of the plan.

IV. CIRCUIT DESCRIPTION

A full diagram of the test circuit is shown in Fig. 2, which differs from Fig. 1A for four reasons. First, the basic operating mode is somewhat different. In Fig. 1A, the energy originally present in L_s is transferred in part to C_2 and then to L_e where it is trapped by reclosing switch S_1 . In Fig. 1B, which is a modified form of Fig. 1A, the energy originally in L_s can be transferred to C_2 and then back into L_s where it is trapped by closing switch S_2 . This circuit modification eliminates one major component, L_e , but does not change the requirements on S_1 , the interrupter. The test circuit includes this modification.

Fig. 1.
Progressive modification of energy transfer modules.

Fig. 2.
Test circuit.

Second, in Figs. 1A and 1B, a dc generator was used to pump energy into L_s over a time of several minutes. This was made possible by the superconducting nature of L_s . Figure 1C shows a further modification of Figs. 1A and 1B; energy is delivered to nonsuperconducting L_s from the capacitive energy storage subsystem composed of capacitor C_1 and ignitrons I_1 and I_2 , instead of from HP. Figure

1C is a simplified form of the real test circuit shown in Fig. 2. In the circuit shown in Fig. 2, C_1 is charged through switch J_1 over several minutes by the 25-kV power supply; ignitron I_1 is fired, initiating an LC oscillation with a 4-ms period involving the components C_1 , L_s , L_{sr} , and switch S_1 . After a quarter period, C_1 is discharged and the current in L_s reaches its maximum. I_2 then fires automatically so

that the current in L_o decays exponentially through I_2 and S_1 with a time constant of ~ 100 ms. This 100-ms interval is adequate to allow completion of our experiments that concentrate on the opening of switch S_1 and its successful interruption of the current.

The third difference between Figs. 1A and 2 is the extra equipment shown in Fig. 2 which assists in the interruption or serves some other purpose. The 15-kV supply and ignitrons I_3 and I_4 , for example, allow C_2 to be charged before the interruption is to be accomplished. At the time of interruption, I_3 is triggered, generating a counterpulse current I_{cp} through S_1 of the opposite sign from I_o , the current being interrupted. If the magnitude of I_{cp} and I_o are approximately equal, the net current through S_1 is very small and is easy to interrupt. L_{ar} is a saturable reactor which helps to hold the net current near zero for long times. R_v and C_v are parts of the snubber circuit which also helps to extinguish the arc that forms when S_1 opens. Ignitron I_6 and resistor R act as the final "dump" for the energy originally in C_1 . R_{C1} and J_2 , as well as R_{C2} and J_4 , provide a means of removing energy from capacitor banks C_1 and C_2 in an emergency. The shorting balls, SB_1 and SB_2 , provide assurance that C_1 and C_2 are uncharged at the end of an experiment.

The fourth difference between Figs. 2 and 1A is the provision made in Fig. 2 for measurement of the crucial current and voltage parameters. This includes several low-impedance ($1/4$ -m Ω), low-

inductance shunts (frequency response to 10^6 Hz) which can be placed at various points in the circuit to allow current measurements, and various voltage probes (frequency response to 10^6 Hz) used similarly. The kinds of signals commonly observed and often presented in the following discussions are shown in Figs. 3-7. Figure 3 shows the current through the interrupter on a long time scale, i.e., 20 ms or so. The quantities in the inset (I_p , I_o , and dT) are, respectively, the peak current, the current at interruption, and the overall time interval displayed in Fig. 3. Figure 3 shows, at t_o , the sinusoidal current rise after I_1 fires; at t_1 , the exponential decay after I_2 fires; at t_2 , the firing of the counterpulse; and after this, sometimes, the occurrence of restrikes.

Figure 4 shows the voltage across the interrupter on a similar time scale. V in the inset is the overall voltage interval displayed, i.e., 250 volts full scale. On it can be seen at t_o the cosinusoidal voltage variation corresponding to the sinusoidal current rise; at t_1 , a transient when I_2 fires; at t_2 , a step in voltage when the interrupter S_1 opens, followed by an approximately exponentially increasing voltage, full of noise, which is the arc voltage; and at t_3 , the off-scale energy-transfer voltage transient.

Figure 5 shows the current near t_2 , counterpulse time, on an expanded time scale of 100 μ s or so. On it can be seen at t_{2a} the initiation of the counterpulse, and at t_{2b} , the first current zero. Sometimes a second current zero occurs as seen at t_{2c} on Fig. 5. Figure 6 shows a vertical expansion of Fig. 5. Figure 7 shows

Fig. 3.
Interrupter current vs time.

Fig. 4.
Interrupter voltage vs time.

Fig. 5.
Current near counter-pulse time.

Fig. 7.
Voltage near counter-pulse time.

Fig. 6.
Expanded trace of Fig. 5.

the interrupter voltage near t_3 on a similarly expanded time scale. On it can be seen at t_{3a} the voltage jump caused by the counterpulse current; at t_{3b} , a drop in voltage caused by the first current zero; and at t_{3d} , a sudden drop in voltage caused by the end of the counterpulse. The voltage then begins a sinusoidal increase as the energy is transferred into C_2 with a time constant of ~ 1 ms.

To keep all of these times straight, a list of them is presented here:

t_0	I_1 fires, current flows out of C_1
t_1	I_2 fires, beginning of exponential decay of current
t_2	interrupter opens, arc voltage rises rapidly
t_3	I_3 fires, counterpulse started
t_{3a}	I_3 fires, initiation of counterpulse
t_{3b}	first current zero
t_{3c}	second current zero
t_{3d}	end of counterpulse.

V. EXPERIMENTAL PROCEDURE

A. The Standard Interrupter Setup

The largest interrupters made by GE, Westinghouse, and ITT-Jennings are shown in Fig. 8. The family of Westinghouse interrupters, i.e., the 4-in., 5-in., and 7-in. sizes are shown in Fig. 9. We have chosen as our standard interrupter the most common 7-in. Westinghouse interrupter #WL-23231. A view of one electrode and the inside of this interrupter is shown in Fig. 10. This interrupter is normally mounted on an actuator mechanism which is powered by an electronic driver circuit, all of which can be triggered by an electric pulse to open

Fig. 8.

Family of largest interrupters, made by General Electric, Westinghouse, and ITT-Jennings (from left to right).

Fig. 10.

Inside of 7-in. interrupter.

Fig. 9.

Family of different sized interrupters made by Westinghouse.

and a different electrical pulse to close. The actuator and driver are standard components purchased from Ross Engineering Corp.*

Figure 11 shows a 7-in. interrupter mounted on the actuator. The opening speed can be varied to a maximum of ~ 2.5 m/s by changes in the driver circuit. The electrode gap opens to a maximum of ~ 1.5 cm. The standard opening speed and gap were chosen to be 2.5 m/s, and 0.7 cm.

*Ross Engineering Corporation, 559 Westchester Drive, Campbell, CA 95008.

The opening speed is usually measured by an optical technique. A narrow beam of light is passed from the source to a photocell. The beam is intercepted by a lightweight "comb" mounted on the moving electrode. This comb alternately passes and interrupts the beam and generates electrical pulses in the photocell. Figure 12 shows a scope trace of these pulses, and Fig. 13 shows a resulting plot of electrode displacement vs time. The instant of electrode separation is simultaneously determined by a simple resistance measurement between the electrodes. Occasionally the electrode motion is measured with a linear potentiometer. This allows a higher spatial resolution of the motion but slows it down due to the extra mass added to the moving electrode by the potentiometer and its clamp.

When the two capacitor banks have been charged to the desired potential four pulses are delivered; three to the ignitrons I_1 , I_3 , and I_5 , and one to the driver. First I_1 is triggered to initiate the current in L_5 and S_1 ; then the driver is triggered to open the interrupter. Ignitron I_3 is triggered to generate the counterpulse, and finally I_5 is triggered to trap the energy in L_3 and damp it out in R . The delay between these events is ~ 1 ms before the interrupter opens, ~ 3 ms before the counterpulse is generated, and 1 ms before the energy is trapped back in L_5 . Figure 3, a slow-speed trace of the current through S_1 , shows two of these events, the initiation of the

Fig. 11.
Interrupter and its actuator.

current at t_0 and its interruption at t_3 . Figure 4, a trace of the voltage across the interrupter on the same time scale, shows t_2 , the time when the interrupter opens. Finally, much faster sweeps show details of the counterpulse current and voltage and the interruption phenomenon. Figures 5, 6, and 7 show such traces.

All of the various wiggles and bumps shown in Figs. 3-7 have a significance which should be un-

Fig. 12.
Photoelectric record of electrode motion.

Fig. 13.
Electrode position vs time.

derstood. The sinusoidal current rise of Fig. 3, for example, results from the ringing of the LC circuit composed of C_1 and L_s . The exponential decay shown in Fig. 3 is governed by the magnitude of L_s , its resistance, and the voltage drops across ignitron I_2 and the arcing interrupter. The overall sinusoidal shape of Fig. 7 is determined by the ringing of the LC circuit composed of L_s and C_2 . The cosinusoidal voltage curve at the beginning of Fig. 4 is a result of

the sinusoidal current shown in Fig. 3 and the inductance of the interrupter and its leads through which this current passes. The jump at time t_2 is proportional to the arc voltage. It reveals some of the arcing phenomena and differs from interrupter to interrupter and for the same interrupter under different operating conditions. Finally, the details of Figs. 5 and 6 are closely related to circuit and arcing phenomenon. In Fig. 5, for example, the shape of the counterpulse current's leading edge is determined by C_2 and the stray inductance in the circuit. The total current passes through zero twice, once at t_{2b} and once at t_{2c} . Interruptions are commonly observed at both the first and second current zero and are occasionally observed at third and higher zeros. An interruption at either the first or second zero is considered to be successful. The only difference from the circuit point of view is a slight delay in the generation of the voltage wave of Fig. 7 in the case of a second zero. As will be discussed later, this delay becomes even smaller if saturable reactors are used in the circuit.

B. Determination of $P(I_{cp})$

The voltage on C_1 is adjusted to produce a desired current I_0 through S_1 at time t_2 when the counterpulse is generated. The voltage on C_2 is adjusted to produce a desired counterpulse current I_{cp} . Delay times t_3 , t_4 , and t_5 are adjusted to the standard

settings and the apparatus is set into operation. The resulting interruption is monitored on four oscilloscope channels and recorded as successful or not. In general two different kinds of failures are observed. In Type A failures, the arc fails to interrupt at all, i.e., the current through S_1 continues without any significant voltage appearing across it. In Type B failures, the arc current reignites only after a large voltage has appeared across S_1 . I_{cp} is varied and successful interruptions at the first (Type 1) or second (Type 2) zero are distinguished from Type A or B failures. Figure 14 shows a typical result for a given I_0 , where P , the probability of interruption, is plotted against I_{cp} . If $I_{cp} < I_0$, no interruption occurs. We label this region "O." If I_{cp} is slightly greater than I_0 , interruptions are all successful and at the first zero, i.e., Type 1. If I_{cp} is further increased, successful Type 2 interruptions become more numerous. Finally, with high enough values of I_{cp} , failures of both Types A and B occur. On Fig. 14 we have designated two special points, the values of I_{cp} at which P is 90% and 50%. These points will be discussed below.

C. Determination of $P(I_0, I_{cp})$

The above measurements were repeated at different values of I_0 until the maximum interruptible current I_m was covered. Figure 15 shows the results for standard conditions, where I_{cp} is plotted vs I_0 .

Fig. 14.
Probability of interruption vs counter-pulse amplitude.

Fig. 15.

Probability of interruption vs I_o and I_{cp} .

and contours of constant P are shown. The straight line at 45° represents the condition where $I_{cp} = I_o$. If $I_{cp} < I_o$, no current zeros and, therefore, no interruption occurs. An interesting feature of these curves is that as I_o approaches I_m , the range of I_{cp} that leads to a successful interruption grows steadily smaller. For the interrupter shown in Fig. 15, $I_m = 24$ kA when $P = 50\%$ and 22 kA when $P = 90\%$.

D. Dependence of P on Opening Speed and Gap

Adjustments were made in I_o and I_{cp} until I_o was near its upper limit I_m and P was near 50%. P is then especially sensitive to small variations in any independent variable. The gap was then varied, keeping the opening speed and I_o and I_{cp} constant; and P was measured. A dependence of P on gap was found for several different interrupters. A typical example is shown in Fig. 16. As the gap was increased P increased until a critical gap g_o was reached. For larger gaps, P fell to a much lower value. This experiment was repeated with an opening speed lower than standard by a factor of 1.4. Exactly the same dependence on gap was noted. Thus the gap appears to be a crucial parameter in determining P , not arcing time. In Fig. 16 the overall variation in P with gap size is large, but it corresponds to a change in I_m with gap size of only 20% or so.

Fig. 16.

Probability of interruption vs arc gap.

P gradually increases as the gap increases because the recovery voltage is applied across a larger gap, producing a smaller field and, therefore, a lower restrike probability. We found that as the gap at counterpulse is increased, more and more failures are of Type B and these restrikes occur at higher and higher voltages, i.e., the restrike tends to occur at a critical field.

The drop in P when the gap size exceeds g_o requires a more complex explanation. The voltage across the arcing interrupter was examined and traces like those shown in Fig. 4 were obtained. For short arcing times (short gaps) the trace is quite smooth. For long times (long gaps) it is very noisy. The noise always starts at a time which corresponds to a gap equal to g_o . Thus, an important correlation has been established; whenever the gap exceeds g_o , the voltage becomes noisy and P drops to low values. It is believed that the onset of noise signifies the formation of a constricted arc and an anode hot spot. The hot spot, in turn, assists in the reignition of the arc and, thus, explains the drop in P when the gap exceeds g_o .

E. Saturable Reactor

A saturable reactor minimizes the net current flowing through switch S_1 for a time δt long enough to allow a significant recombination of the plasma left over from the much higher currents carried just before the counterpulse. This critical time δt is in the range 10 to 100 μs for vacuum interrupters. The

desired value of net current is as low as possible. The standard reactor was chosen as one composed of several laminated gapless cylindrical cores wound from a 4-mil strip of silicon steel. The dimension of each core is 1-in. i.d. and 4-in. o.d. by 4-in. long. The flux rating of one core is 0.008 Wb. The time before a single core becomes saturated, t_s , is calculated to be 4 μ s from the relationship $V\epsilon = \phi$, where V is the counterpulse voltage applied to a reactor (~ 2 kV) and ϕ is its flux rating (0.008 Wb). To achieve the 10- to 100- μ s critical time, from 2-25 cores are necessary. A standard of 10 cores was chosen. These cores are arranged in the circuit by simply threading the insulated lead from L_s to S_1 through the stack of reactors once.

This arrangement is shown in Fig. 17, where six such cores are shown on the right side of the picture. The left side shows a stack of split "C" cores with the same flux rating. A secondary winding is shown threading these C cores. The use of multiple turns threading the reactors would not extend δt but would have some effect on the net current before and during saturation.

A demonstration of the behavior of our standard saturable reactor is shown in Figs. 5, 6, 18, and 19, which show the current through S_1 . S_1 is not opened for these tests, thus no interruption occurs. Figure 18 shows the case where I_{cp} is slightly too low to bring the net current to zero. The net current then has a sinusoidal oscillation whose frequency is determined by C_s and the stray inductances. The saturable reactor is completely saturated at all times contributing no inductance to the circuit. Figure 5 shows a case where I_{cp} is slightly larger. The saturable reactor has unsaturated at t_{sb} and become saturated again at t_{sd} . It holds the net current to a low value for almost 70 μ s. Figure 6 is a vertical expansion of Fig. 5 by a factor of 16 to show the detailed shape of the net current. Finally, Fig. 19 shows what happens when I_{cp} is excessively large. In this case the saturated core is driven by the counterpulse through the unsaturated region back into saturation in the opposite direction and then the core traces its path. The intermediate saturated interval generates the "blip" seen in Fig. 19.

The only unexpected behavior demonstrated by these measurements is the "reversed" slope of the net current shown most clearly in Fig. 6. In an ideal inductor, i.e., one with infinite permeability and no

Fig. 17.
Two stacks of saturable reactors.

hysteresis or eddy currents, the top of the curve of Fig. 6 should be perfectly flat with a current of zero. Thus the deviations from flatness must be due to one of those nonideal properties mentioned above. Because these deviations are quite obvious in the measurements, and because they are expected to have important effects upon interruption, their source has been investigated in considerable detail.

The differences between the effects of finite permeability, hysteresis, and eddy currents can be most readily demonstrated if their separate effects are examined in a situation such as that shown in

Fig. 18.
Interrupter current with I_{cp} very low.

Fig. 19.
Interrupter current with I_{cp} very high.

Fig. 19, i.e., when the counterpulse is much too large.

If finite permeability is considered alone, the B-H curve of the core can be illustrated by Fig. 20; consequently, the expected counterpulse curve looks like Fig. 21, where the slopes of the two "flat" parts are of the opposite sign but the same magnitude, and the curve is symmetrical about its peak.

If hysteresis is considered alone, the B-H curve looks like Fig. 22 and the expected counterpulse curve looks like Fig. 23.

A combination of finite permeability and hysteresis will give a curve as in Fig. 24, where the slopes of the "flat" parts still have opposite signs and the same magnitude, but where the symmetry around the peak has been lost.

Eddy current effects cannot be illustrated with a B-H curve because currents induced in the iron core must be considered. Before the counterpulse, I_0 creates a saturated flux in the iron. As I is decreased by the counterpulse, the core eventually comes out of saturation and a flux change occurs in the iron. This generates an emf in each lamination and a resulting eddy current, I' , proportional to the conductivity of the iron, in each lamination. Figure 25 illustrates this current. Now consider the iron as a perfect magnetic material characterized by an ideal B-H curve; the *total* current linking the iron must be zero whenever it is unsaturated. Thus, during this period the interrupter current must be reversed slightly to cancel I' and keep the total linked current at zero. Because of the resistance of the lamination, I' will not persist but will die out in such a way as to produce a counterpulse current curve of reversed slope like that shown in Fig. 6. It can be shown that whenever eddy current effects dominate, the slope of the flat parts of the curve will have a constant negative slope.

The magnitude of these eddy current effects can be emphasized by using thick laminations; the effect of finite inductance by using air gaps in the iron; and the effect of hysteresis by using a "hard" iron with a large coercive force. Figures 26-28 illustrate cases where these three effects have been separated fairly well from each other. These measurements were made under identical conditions on almost identical cores. Figure 26 shows a measurement in good agreement with the treatment of eddy currents given above. For this test the standard gapless core was wound of 4-mil-thick magnetic material. In contrast, Fig. 27 shows agreement with Fig. 23, i.e., an almost pure hysteresis effect. For this test the lamination was only 2 mil thick and should, therefore, show only one-fourth of the eddy current effect of the 4-mil strip. Finally, Fig. 28 shows a combination of hysteresis and finite

Fig. 20.
B/H curve showing saturation and finite permeability.

Fig. 21.
Hypothetical interrupter current for B/H curve of Fig. 20.

Fig. 22.
B/H curve showing saturation and hysteresis.

Fig. 23.
Hypothetical interrupter current for B/H curve of Fig. 22.

Fig. 24.

Hypothetical interrupter current showing finite permeability and hysteresis.

Fig. 25.

Eddy currents in iron laminations.

Fig. 26.

Interrupter current showing eddy currents.

Fig. 27.

Interrupter current showing hysteresis.

permeability. For this test the core was wound with 1-mil strip, the thinnest available. The properties of such a thin strip, for example, its permeability, suffer because of the difficulty of rolling it so thin.

The distortion illustrated in the above paragraphs can also be controlled by external manipulations. If air gaps are purposely introduced into the cores, for example, results, as shown in Fig. 29, typical of finite permeability are readily achieved. The vertical scales of Figs. 27-29 are all the same. In a similar way, extremely large eddy current effects can be introduced by threading a secondary winding through the cores and connecting it to a resistor. By this means the negative slope of Figs. 6 and 26 can

be readily increased to any desired value. Suffice it to say that by using either the natural properties of different cores or introducing external variations, the shape of the counterpulse can be controlled over wide limits. Important effects upon P would be expected to arise from this shape.

Measurements of the dependence of P on (1) the flux rating of the core and (2) the details of the inductor used are now presented. The discussions begin with the standard 0.08-Wb inductor composed of ten cores. Measurements were made of $P(I_0, I_{cp})$, and Fig. 30, a graph of the results, was plotted. There are three distinct regions in this plot; Region I where interruption is successful and no "blip" occurs in the current trace, Region II where interruption is successful and a blip is seen, and Region III where

Fig. 28.

Interrupter current showing hysteresis and finite permeability.

Fig. 29.

Interrupter current showing the effect of air gaps.

interruption fails. The upper boundary of Region I corresponds to the value of I_{cp} at which the saturable reactor is just driven completely through its unsaturated region. This upper boundary can be raised or lowered by using more or fewer cores; however, the effect on I_m of changing the number of cores is insignificant. Thus, the major beneficial effect of using cores is not to increase I_m but to extend the range of I_{cp} for a successful interruption. It was also seen that for these tests interruptions made at high currents rarely occur at the second zero. Thus,

Fig. 30.

Probability of interruption vs I_0 and I_{cp} when saturable reactors are used.

it is reasonable that the exact shape of the counterpulse is not important but only the length of time that it holds the interrupter current and voltage near zero. If this time δt is greater than, roughly, 20 μs , and if $I_0 < I_m$, the arc interrupts successfully.

Next, P was obtained for six different inductors, all with the same flux value. They were composed of the gapless 1-, 2-, and 4-mil cores discussed above and of the split 4-mil cores, each with spacers of thicknesses 1, 5, and 35 mils in each gap. The counterpulse pulses were quite different in shape for these six cases. Figure 31, for example, shows the counterpulse current for the split core with two 35-mil spacers. It should be compared with Fig. 5 for the standard reactor. In spite of these large differences, P showed almost no dependence on the shape of the counterpulse. Our conclusion from these measurements is that P is determined almost solely by the behavior of the interrupter and that the reactor parameters are quite unimportant as long as $\delta t \geq 20 \mu s$.

Fig. 31.

Interrupter current with gapped saturable reactor.

Fig. 32.

Interrupter voltage when interrupter is not opened.

F. The Snubber Circuit

Measurements have been made of P with and without the snubber circuit and with various values for R . Details of the current and voltage traces depend upon these parameters and upon whether interruption occurs at a first or second zero.

As an illustration of the effects seen, Figs. 32, 33, and 34 show, respectively, the voltage across the interrupter when the interrupter was not opened, when it was opened but no snubber circuit was used, and when it was opened and the standard snubber was used.

Figure 32 shows only an inductive voltage pulse generated by the fast-rising counterpulse current. For Figs. 33 and 34, the arc was successfully interrupted at the first current zero which occurred on the traces at the vertical fiducial mark. The snubber attenuates the sudden jump in voltage which occurs exactly at interruption time. The currents observed during the voltage traces of Figs. 33 and 34 are very similar. Figure 35 shows an example where, after its first zero, the current reaches a peak of about 100 A and then decays exponentially with a time constant of 20 μ s or so. This current presumably represents the collection of the plasma residue which was present shortly before interruption when the arc current was much larger, i.e., 9 kA.

Fig. 33.

Interrupter voltage with no snubber; first current-zero.

In the case of interruption at the second zero, Figs. 36 and 37 show the corresponding voltage traces with no snubber and with the usual one. Again the snubber is effective in eliminating the initial rapid rise in voltage after interruption at t_{3c} . In this case the sudden change is downward, and a period of time can be noted between the first zero at

Fig. 34.
Interrupter voltage with snubber; first current-zero.

Fig. 35.
Interrupter current near current zeroes.

Fig. 36.
Interrupter voltage with no snubber; second current-zero.

Fig. 37.
Interrupter voltage with snubber; second current-zero.

t_{3b} and the second zero at t_{3c} during which a low-current 150-V arc burns. A trace of the current observed during a second current zero interruption is shown in Fig. 38. The reversed-slope trace is typical of a saturable reactor dominated by eddy current distortions.

The details of operation of the saturable reactor have more effect on a second-zero interruption than a first. As Figs. 37 and 38 show, the arc current after

the first zero flows in a reversed direction. The interrupter voltage adjusts itself to maintain this current. If a standard reactor is used, the current then drops linearly to zero at which time interruption occurs. The interrupter voltage then follows the dictates of C_2 and the snubber circuit. If a different reactor had been used, the current trace, Fig. 38, would have been quite different and in most cases, P would have been lower.

Fig. 38.

Interrupter current near current zeroes.

If R is set equal to zero, the voltage and current curves are very similar to the above, except that a strong, weakly damped oscillation occurs in the current curve which causes the current to pass rapidly through zero perhaps three or more times during the flat-top time. Curves with $R = 0$ and $R = 2.3\Omega$ are shown in Figs. 39 and 40 to illustrate this effect. The interrupter was not opened, thus the counterpulse circuit oscillated through three major cycles on these traces.

Our major finding is that through all of these variations of the snubber circuit, P , the probability of interruption is unchanged.

VI. RESULTS FOR DIFFERENT INTERRUPTERS

At this point in the investigations all of the commercially available interrupters were tested under standard conditions to determine $P(I_0, I_{cp})$. Tests were also conducted occasionally under nonstandard conditions. From the results, four generalizations and two useful numbers were obtained. The generalizations are:

(1) P does not depend strongly on I_{cp} as long as I_{cp} is large enough to achieve a current zero and the saturable reactor is large enough to suppress a blip.

(2) P does not depend strongly upon I_0 until the arc voltage becomes noisy. P then drops rapidly with further increases in I_0 .

Fig. 39.

Interrupter current showing ringing of snubber circuit.

Fig. 40.

Interrupter current without ringing of snubber circuit.

(3) I_m , this upper limit to I_0 , varies roughly linearly with the diameter of the arcing electrodes.

(4) I_m is independent of circuit elements and operational parameters, i.e., saturable reactor, snubber circuit, opening speed and gap, over a wide range of variation.

(5) There is no significant variation of I_m with interrupters from different manufacturers.

The useful numbers are I_m (50%), and I_m (90%), the currents which can be interrupted with a 50% and 90% reliability for each different interrupter (see Table I).

Figure 41 shows the linear manner in which I_m (50%) and I_m (90%) vary with electrode diameter.

VII. EFFECT OF MAGNETIC FIELD

There have been several reports³ of an improvement in the interruption of 60-Hz arcs through the use of axial magnetic fields. To investigate this effect for dc arcs, a 39-turn solenoid of 4-0 cable was wound which completely encloses the vacuum bottle, as shown in Fig. 42. The snubber is on the right. The coil was wound so that its impedance, $\sim 10\text{ m}\Omega$, would match a 10-V, 1-kA power supply which was available. With this combination, a maximum field of about 0.8 kG can be generated and maintained for several seconds without overheating the coil.

So far six interrupters have been tested with an axial field, five with this externally applied field and one special interrupter with an internally generated

Fig. 41.

Maximum interruptible current for different interrupters.

Fig. 42.

Arrangement of field coil around interrupter.

field. The data from these interrupters are shown in Table I. This latter interrupter, called Prototype 1 in Table I, was built by Westinghouse Electric Corp. Prototype 2, also specially built by Westinghouse, has no internal field structure, but contains electrodes of a novel configuration. Its performance is shown in Fig. 43. The arc voltage is plotted vs magnetic field with I_0 as a parameter. The open points indicate successful interruptions and the solid points, restrikes. The dotted line roughly indicates the boundary between successful interruptions and failures. The restrikes occur at progressively lower voltages as the experimental

EFFECT OF AXIAL FIELDS

Fig. 43.

Arc voltage versus axial field and arc current.

conditions shift farther from this line. The rating of this interrupter with no axial field is 13-18 kA; with a 0.4-kG field the rating is above 30 kA. At higher fields, it appears that the rating would continue to improve.

The arc voltage is plotted vs field because of the high sensitivity of the arc voltage to the field. Figures 44 and 45 show the arc voltage vs time for, respectively, an interruption with no field and with a field of about 0.5 kG, both carrying the same current. The vertical fiducial is the time when arc voltage shown in Fig. 43 was measured. Clearly, the magnetic field has not only reduced the arc voltage but has also eliminated the noise and reduced the slope of the voltage curve. The same correlation between appearance of noise and failure to interrupt (discussed earlier) appears here. The major effect of the field is therefore identified as a suppression of the anode hot spot. This phenomenon has been directly observed by others.⁴

Two unexplained phenomena are the different magnitudes and the lack of correlation of the field's effect on I_m and on the arc voltage. As shown in Table I, the improvement in I_m varies from 10% to over 100% in a regular way, while the reduction in arc voltage varies from 10 to 50% randomly.

The reductic arc voltage and the presumed absence of an spot when an axial field is used increase I_m and are expected to reduce electrode erosion. The magnetic field can be generated in three

Fig. 44.

Interrupter voltage without axial field.

Fig. 45.

Interrupter voltage with axial field.

ways: by an external coil fed by an independent power supply, by an internal coil as accomplished with Prototype 1, or with an external coil fed by I_0 . The versatility and relative ease of these methods, as well as the large improvements in I_m and the assumed reduction in erosion, make the use of axial fields very attractive. This technique presents an obvious means of extending interrupter performance in almost any conceivable application. Other

interrupters are to be tested at still larger fields to explore these effects further.

VIII. LIFE TESTS

A. Mechanical

Since the number of operations demanded from vacuum interrupters can be many thousands or, for some future uses, millions, we have begun to assess the possible lifetime of standard components. Obviously, testing systems in a realistic way for these numbers of cycles can be a time-consuming operation. Synthetic tests of various kinds for different vulnerable parts of the system have, therefore, been devised.

The first vulnerable component was thought to be the bellows of the interrupter. Accordingly, interrupters have been opened and closed repeatedly on a standard actuator in a 10-s cycle. Three 7-in. interrupters were cycled in this way while carrying no current. After each operation a high voltage was applied across the open interrupter. A significant current would indicate a vacuum leak. A bad leak could also be detected by a change in the 25-lb force attributable to the vacuum helping to hold the electrodes closed.

The first interrupter tested was cycled to 74 000 operations. There was no problem with the interrupter during the test. The rest of the actuating system, however, gave many problems. Among these were (1) at 10 000 cycles a nut holding the moving stem loosened, (2) at 15 000 cycles the high-voltage test circuit burned out, (3) at 28 000 cycles a microswitch in the actuator failed, (4) at 29 000 cycles the latching solenoid in the actuator burned out, and (5) at 36 000 cycles the connectors to a microswitch sheared off and an aluminum link, which was showing serious wear, was replaced with a steel link. These problems were not considered serious because the actuator had not been specifically designed for life testing.

The second interrupter was tested successfully to 10 400 cycles. A spring and another microswitch failed during these shots. The third interrupter was tested successfully for 10 900 cycles, and no new problems were encountered.

At one time an interest arose in cooling electrodes by passing LN_2 to them through the stems. Doubts

were raised about the ability of the interrupters to withstand the thermal stresses associated with this treatment, so a standard 7-in. interrupter was totally immersed in LN_2 to see what would happen. Initially this was done very gingerly, suspending the bottle in the cool vapor over the liquid for several hours before immersion, etc. The submergence was so uneventful, however, that the final tests were made by plunging a warm interrupter directly into LN_2 . No failures of any sort were observed after repeated tests of this kind. Mechanically, these interrupters are very resistant to thermal stress damage.

B. Electrical

Erosion of the electrodes by the electric arc is now expected to be the serious life-limiting process. Estimates made from experience with 60-Hz applications indicate that a 10 000-operation life expectancy is an optimistic guess. The normal testing procedures for $P(I_o, I_{cp})$ give some information about this kind of erosion limit, but there are complications. In determining P , there are at least four types of interruptions: (1) successful ones, (2) unsuccessful ones because of a counterpulse which is too small, (3) unsuccessful ones where the arc restrikes immediately at a low voltage, and (4) unsuccessful ones where the restrike is delayed to a high voltage and the restrike current is very large. In the normal operation of an interrupter, however, most interruptions will be type 1, i.e., successful ones. In the determinations of P , the mixture of interruption types that occurs gives a larger erosion than would occur if they had all been successful.

Because of this, a special erosion test was made on fresh units in which erosion from successful interruptions could be separated from that due to other types. The erosion measurements were based on observations of the positions of marker points on each electrode's stem. As the electrodes eroded these marker points moved closer together. Although the measurements were complicated by thermal expansion and by stretching of the stem, separate erosion rates for successful and unsuccessful interruptions were obtained at 20 kA. In one kind of interrupter, these rates were 0.015 mm/shot and 0.08 mm/shot, respectively. Thus, as few as

several hundred successful interruptions would exceed the allowable erosion of this interrupter and end its life. In another kind of interrupter, these rates were at least an order of magnitude lower, allowing a useful life of several thousands of operations. These two types of interrupters contain electrodes made of very different materials. This probably accounts for the markedly different erosion rates.

IX. FUTURE WORK

A. Refine Ratings of Existing Interrupters

The easy measurements on vacuum interrupters have now been made. We want to make four more important but difficult and time-consuming sets of measurements on conventional interrupters.

1. Determine the dependences of P on recovery voltage and its time derivative. Preliminary measurements indicate that these dependencies are weak.

2. Determine the effect on P of the heating of the interrupter caused by an extended passage of current, e.g., a current ramp to 20 kA for 5 min. No substantial experimental information on this effect exists, but it is believed to be small for theoretical reasons.

3. Determine the erosion rate of interrupters used with axial fields.

4. Determine I_m when the current is low enough so that $P = 99\%$ or more. To make this determination, the number of interruptions must be about 1000 for a 99% determination and 10 000 for 99.9%.

During this very large number of operations we can evaluate simultaneously I_m (99%), I_m (99.9%), erosion, and other related lifetime concerns. A knowledge of I_m (99%) and I_m (99.9%) is particularly important for switch applications where the reliability of operations must be very high. Conventional wisdom has it that vacuum interrupters cannot achieve P values as high as 99% due to a fundamental limitation. If true, a series arrangement of interrupters to improve reliability will be needed.

B. Increasing Ratings of Existing Interrupters

Conventional 7-in. interrupters are to be tested to their limits with an impressed axial field. Conventional interrupters are to be connected in parallel and series combinations to achieve higher ratings. Some of these multiple-interrupter arrangements will include axial field interrupters.

C. New Designs of Interrupters

The design and manufacture of better interrupters, in particular, better axial field interrupters, is to be promoted, and these new devices are to be tested.

D. Early Counterpulsing

The feasibility of a new⁵ approach to interruption with early counterpulsing is to be investigated. With this technique, the counterpulse reduces the current through the interrupter to very low values *before* the interrupter is opened. Very little arcing or erosion should occur. This is the only technique that appears to be able to achieve an erosion rate so low that lifetimes significantly longer than 10 000 operations might be anticipated.* To permit this new technique to be used, interrupters and actuators of much higher speed must be constructed. The feasibility of this goal is being investigated through interactions with several developers and manufacturers of interrupters and actuators.

X. INTERRUPTER MEASUREMENTS AND DEVELOPMENT WORK PERFORMED ELSEWHERE

All tokamaks need large interrupting switches to operate their ohmic heating circuits. It is to be expected, therefore, that work paralleling that

*Similar work is being done at Hughes Research Laboratory by W. Knauer.

described above would be performed wherever tokamaks are being built e.g., Russia, Europe, and Japan. Some of the work in Europe involves vacuum interrupters⁸ and some air-blast interrupters.⁹ The most advanced work on vacuum interrupters appears to have been performed by Toshiba⁷ in Japan for JT-60. They use axial magnetic fields as an essential feature.

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