BIPOLAR HVDC TRANSMISSION SYSTEM STUDY BETWEEN ±600 kV AND ±1200 kV POWER SUPPLY STUDY FOR INSULATOR POLLUTION TESTS

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ABSTRACT

The aim of the project was to determine the required capacity (stiffness) of a dc power supply to be used for flashover tests on contaminated insulators.

The present state of the art was based on a survey of the literature which showed that neither the loading effect (maximum leakage current) of the contaminated insulators nor the necessary rectifier parameters have yet been clearly determined. The following theoretical investigation revealed the critical factors influencing the flashover voltage. Extensive laboratory studies were performed in IREQ's small fog chamber, where the flashover voltage of heavily contaminated insulators were measured by the clean fog method in which the contaminated and dried insulators were installed in the fog chamber and energized. Then clean fog is applied and the voltage maintained until the flashover occurs or until the leakage current reduces to a few mA. The voltage and the leakage current are recorded by a magnetic-tape recorder. The test is repeated several times to determine the dependence of the 50% flashover voltage on the rectifier parameters. The majority of the contamination tests were performed at the heavy pollution level of about 0.5 mg/cm^2 of equivalent salt (NaCl) deposit density.

The major conclusions of the investigation are as follows:

- The flashover voltage of contaminated insulators depends on the following parameters of the rectifier: dynamic voltage drop, smoothing capacitance, resistance on the ac and dc side.
- The maximum current before the flashover can be 4 ~ 4.5 A. This value is significantly higher than was quoted in the literature.
- The dc pollution test requires a rectifier able to provide a current impulse with a peak value of 4 ~ 4.5 A, a duration of 0.2 ~ 0.6 s and a charge of 0.2 ~ 0.5 C, with a dynamic voltage drop of less than 5 - 10% and less than 10% voltage fluctuation.

With these conclusions, the objective of the project is achieved and the required rectifier capacity is defined.

A further conclusion is that the most economic rectifier for this purpose is a half-wave, cascade rectifier with a high-speed control circuit. Development of the high-speed control circuit is suggested as a continuation of this work.

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Section 1

SUMMARY OF THE PROJECT RESULTS

The objective of the project was to determine the required capacity (stiffness) of a dc power supply to be used for flashover tests on contaminated insulators. For this purpose the rectifier parameters were adjusted over an appropriate range and the variation of the 50% flashover voltage as a function of the power supply parameters was measured; this measurement was then used to determine the effect of the rectifier parameters. In addition, the nature of the leakage current of the contaminated insulators was studied to determine the expected maximum loading of the rectifier.

In order to establish the present state of the art, a survey of the literature was conducted from which it may be concluded that:

- The negative polarity voltage should be used for the tests because it gives a lower flashover voltage than the positive ones;
- The voltage drop cannot be compensated economically by a capacitor;
- The transient voltage drop of the rectifier at maximum current is the major factor influencing the flashover voltage. This voltage drop may be controlled by a high-speed regulator although only one circuit suitable for medium voltage is described briefly and without details in the literature.

Consequently, the literature survey justifies further research work in the following areas:

- The nature of the leakage current during dc pollution tests using the clean-fog method, which is used exclusively in the USA and in Canada;
- The effect of rectifier parameters on the dc flashover voltage of insulators using the clean-fog method.

The following theoretical investigation used a simplified model to calculate the effect of source resistance, a parameter which was not considered in previous studies.

The results of the calculation show that:

- The minimum voltage capable of producing flashover and the critical arc length increase linearly with the source resistance.

- The maximum current corresponding to the critical arc length or the minimum flashover voltage is independent of the source resistance but depends on the pollution level. The current measured just before flashover should therefore be more or less constant and independent of the rectifier parameters.

- The critical factor influencing the flashover voltage is the dynamic voltage drop of the source at maximum current, which occurs just before flashover. The dynamic voltage drop is the voltage drop produced by a suddenly-appearing load current pulse.

- The current before flashover is expected to augment at an ever-increasing rate. The maximum current before flashover increases with the level of pollution. The maximum expected pollution level should therefore be used for the experimental investigations.

- The theory does not provide any quantitative values and, moreover, supposes a simplified voltage source. Therefore, experimental study is required to obtain values for the leakage current and to determine the effect of the rectifier parameters on the flashover voltage.

Extensive laboratory studies were undertaken to obtain qualitative values for the necessary rectifier parameters. These parameters were varied over an appropriate range and the 50% flashover voltage of artificially polluted insulators was measured by the clean fog method. The measuring technique may be described briefly as follows: the insulators were polluted by dipping them in a salt slurry and were then dried. The insulator chain was installed in the small fog chamber and energized. Then clean fog was applied and the voltage was maintained constant until the insulator flashed over or until the leakage current decreased to a low value (a few mA for example). This test was repeated several times using the up-and-down method.

More than 90 tests were performed in all and the effect of 12 parameters was studied. All the tests except one were performed at the pollution level of 0.5 mg/cm^2 of equivalent salt (NaCl) deposit density.

The results of the tests to determine the nature and loading effect of the leakage current are as follows:

- The leakage current during the test comprises current impulses. The maximum current impulse may have a peak value of 4 ~ 4.5 A, which is much higher than that quoted in the literature. The duration of this current impulse is 0.2 - 0.6 s and its charge is 0.2 - 0.5 C.
- The peak value of the impulse seems to be independent of the rectifier parameters but higher values were measured when flashover occurred than when the insulator withstood the test.
- The shape of the current pulse is influenced by the smoothing capacitance if its value is smaller than 3 μF.
- The most probable value of the leakage current is significantly less than the maximum value.
- The average value of the current is estimated to be about 100 - 150 mA during the last part of the test.

The experimental results enabled the effects of the rectifier parameters on the 50% flashover voltage to be determined. These effects are outlined below:

- The transient voltage drop of the rectifier is a measure of the error in the flashover test and should be less than 5 - 10%.
- The smoothing capacitor does not influence the flashover voltage if its capacitance is larger than 3 μF in the case of a rectifier with a short-circuit current rating of more than 62.5 A at 50 kV. However, it does influence the fluctuation of the voltage and the capacitance value selected should therefore be such that it does not reduce the voltage fluctuation of more than 5 - 10%.
- Increasing short-circuit current of the rectifier reduces the 50% flashover voltage although this effect is negligible for values over 30 A.
- Increasing the ac resistance produces a nearly linear increase of the flashover voltage and should therefore be kept near to zero.

- The dc resistance does not seem to influence the 50% flashover voltage but its value should be kept at a minimum (a few hundred ohms) although a certain resistance is necessary to limit the discharge current of the capacitor during flashover.

- A comparison of half-and full-wave rectifiers shows that saturation occurs in the transformer in the case of half-wave rectifiers because of the premagnetizing effect of the dc component of the current. This raises doubts about the feasibility of applying half-wave rectifiers in pollution tests.

Finally the test results permit a definition of the required rectifier parameters and thus the objective of the project is fulfilled. The results may be summarized as follows:

- The dc testing of polluted insulators calls for a rectifier able to provide slow-rising triangular-shaped current impulses with the following maximum values:

  peak value: 4 - 4.5 A
  duration : 0.2 - 0.6 s
  charge : 0.2 - 0.5 C
  time interval between pulses:
  not less than: 0.1 s
  average
  current : 0.15 - 0.2 A

  The dynamic voltage drop of the rectifier should be less than 5 ~ 10% and the fluctuation (ripples) of the voltage should be less than 10% during the impulse.

- Considering the voltage range of 1000 kV and above, the required rectifier should be rated in the range of 1000 kV x 4 A = 4000 kVA = 4 MVA. Such a unit is rather expensive. Furthermore, analysis of the nature of the leakage current shows that the duration of the larger current pulses is 0.2 - 0.6 s. This suggests that a high-speed control circuit with a 5 - 10 ms time constant and a well-damped step response curve could reduce the rectifier capacity by an estimated factor of 3 - 5.

- The price of the half-wave rectifier is considerably lower than the full-wave one but the simple half-wave rectifier showed saturation. This suggests that the ideal circuit would be a single-phase rectifier in a cascade connection supplied from a high-frequency source (120 - 400 Hz) and provided with a high-speed regulator to compensate the voltage drop for a load impulse up to 5 A.

Section 2

OBJECTIVE OF THE PROJECT

The objective of this project is the determination of the required capacity (stiffness) of a dc power supply to be used for flashover tests of contaminated insulators. For this purpose the stiffness of the power supply shall be adjusted over an appropriate range of short circuit capacities of the ac supply, smoothing capacitances, and series impedances, and the variation of the 50% flashover voltage as a function of the power supply parameters shall be measured together with the leakage current and the test voltage.

The project calls for two test series:

- The first test series will utilize a 400 kV, 5A single-phase rectifier and a 200 kV, 1 MVA high voltage transformer. The tests shall be performed over a range of 10 test parameters. To achieve these parameters, the ac short-circuit current capability shall be changed from 2 amperes to 20 amperes, the series resistance shall be changed from 0 to 1000 and 10,000 ohms, and the smoothing capacitance varied from 0.2 to 5 microfarads.
- The second test series will be performed utilizing the 400 kV, 125 mA cascade rectifier with 0 external capacitance and five values of external capacitance ranging from 0.1 to 6 microfarads.

Section 3

PRESENT STATE OF THE ART

The project started with a survey of the literature dealing with the voltage source requirements for contamination tests. Several papers were found dealing with the required ac source [4,5,6,7,9,10,11,12,13] but only a few papers discuss the dc source requirements [1,2,3,8]. However, the study of the results dealing with the ac source requirements resulted in a better understanding of the problem. In the case of the ac source, the steady state short circuit current of the system is considered to be the major criterion for selection of the test circuit. Forrester et al [4] showed the relationship between the flashover voltage and the short circuit current. The IEC [5,12] developed a recommendation which gives the required short circuit current as a function of the X/R ratio.

Kolossa [6,11] showed that the flashover voltage depends on the transient voltage drop of the source. The flashover voltage is not influenced significantly if the transient voltage drop is less than 5% at the maximum leakage current. Measurement of the transient voltage drop is difficult. Therefore, measurement of the steady state voltage drop was suggested, with a permissible value of 3% at the maximum leakage current. The analysis of the test circuit shows that the inductance of the circuit primarily influences the transient voltage drop.

Verma [9] showed that the leakage current has no high frequency component, but that there is a phase shift between the voltage and the current within each half cycle. The report [9] presents an equation to calculate the voltage drop. This equation gives the voltage drop as a function of (R/X) and (I/I_{short}).

Niklas et al [13] point out that the lowest transient voltage drop and the highest possible short circuit current are desirable. However, an extremely high short circuit current may change the insulator surface and this, in turn, leads to an increase of the flashover voltage. A new meter for obtaining a more precise measurement of the transient voltage drop is described. The voltage of the voltage divider is rectified and fed to a biased differential amplifier. The dc bias voltage partially compensates the voltage of the transformer and allows amplification of the voltage drop. The new equipment makes possible the measurement of voltage drops of less than 1%. A slightly modified version of the circuit may be used for dc tests.

Schneider [14] performed a test series with a very powerful transformer and found a 8-10% decrease of the flashover voltage when the short circuit current was increased from 30A to 95A. These results are in opposition to the IEC recommendations [12], which suggest that the flashover voltage is independent of the test circuit parameters if the short circuit current is larger than 10A.

Annestrand [11] developed a new test method for polluted insulators under dc conditions. A single-phase rectifier rated at 200 kV, 60 mA with a smoothing capacitor of 1.7 μF were used for the tests.

Poland et al [2] reported that a more powerful rectifier is required for pollution tests. The BPA developed a rectifier rated at 550 kV and 1.5A with a smoothing capacitor of 0.35 μF. This system can be connected in series. When the voltage is increased to 825 kV, the current rating is unchanged but the smoothing capacitor is reduced to 0.23 μF.

Nakajima et al [8] reported that the dc tests require a very stiff power source. The insulator flashover voltage depends on the instantaneous voltage drop, which must be reduced to a minimum (1%). Saturation was observed during the test with the single-phase rectifier. Furthermore, the effect of the smoothing capacitance is presented. It is shown that a small value of the capacitance reduces the leakage current before flashover and this, in turn, reduces the flashover voltage. The flashover voltage - capacitance curve shows that the capacitance influences the flashover voltage for values up to 60 μF.

Flashover produces a sudden discharge of the smoothing capacitance. This current should be limited to 100A by a resistance connected between the capacitance and the test object in order to avoid damage to the insulator surface.

Sorms (3)(16) investigated the nature of the leakage current during dc tests performed using the salt-fog method (the salinity was 100 S/ℓ). It was found that the leakage current impulse before flashover carries a charge of 100 - 200 mC and its amplitude may be of the order of 1 ~ 1.5 A. An inverse relation — shown in Fig. 1 — was found between the peak value and the duration of the leakage current.

Analysis of the results leads to the conclusion that 1) the voltage drop of the rectifier should be between 1 and 4% during the test 2) the voltage drop cannot be compensated economically by a condenser, since the 100 - 200 mC charge of the leakage current impulse calls for 20 - 40 μF if the permitted voltage drop is 5%. The paper presents a control circuit which holds the dc voltage constant to within 5%. The circuit diagram is shown in Fig. 2. The details of the circuit are not given but its operational principle is clear from the diagram. The phase angle of the thyristors is controlled by the dc voltage. The voltage drop reduces the firing angle and increases the output voltage of the rectifier as shown in Fig. 3. The condenser influences the ripples but does not affect the voltage regulation. In the case of flashover, the ac current operates an overcurrent protection which removes the firing impulse within 10 μs.

The flashover voltage of insulators has been measured by different authors under dc conditions. The results obtained show that the negative polarity of the flashover voltage is lower than the positive one. Furthermore, the ac flashover voltage is higher than the negative polarity dc value.

The survey of the literature leads to the following conclusions:

- The dc flashover tests of polluted insulators should be performed using a negative polarity voltage
- The transient voltage drop at maximum current is the major factor influencing the flashover voltage of polluted insulators during both ac and dc tests
- Only one measurement was found dealing with the nature of the leakage current. This measurement was made using the salt-fog test which is not used in North America. No sta-

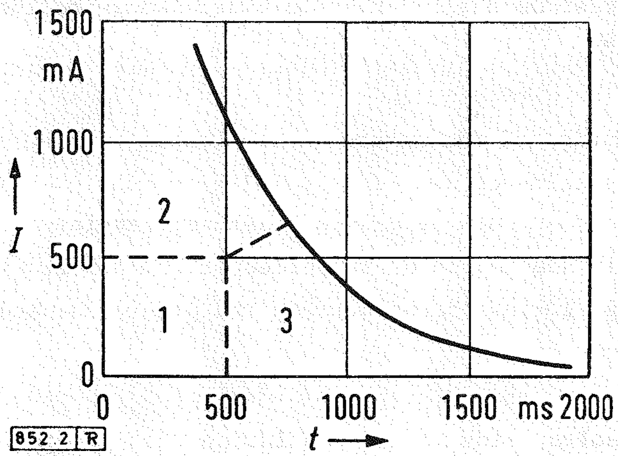

FIG. 1 Relation between the peak value and the duration of the leakage current

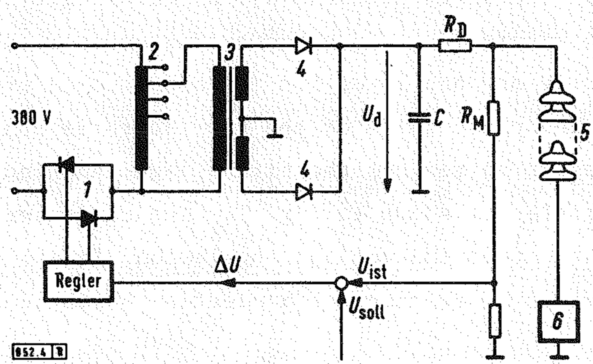

FIG. 2 Diagram of the test circuit

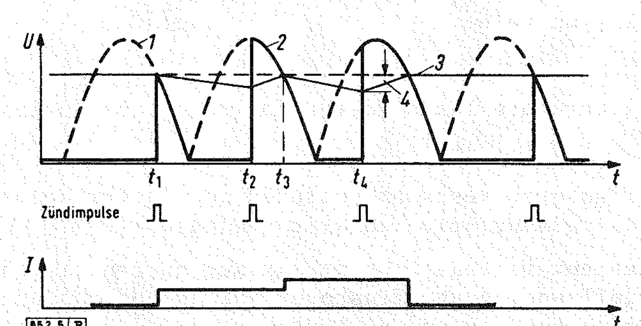

FIG. 3 Voltage drop caused by the current through the polluted insulators

tistical evaluation of the leakage current impulses is presented. Rather, conclusions are drawn by analyzing a sample of the results. Accordingly, the current impulse peak value is in the range of 1 ~ 1.5A, its duration is between 400 and 2000 ms, and its charge is about 100 - 200 mC

- The voltage drop cannot be larger than 3 - 5%. The effect of different rectifier parameters on the flashover voltage has not been studied, although some studies show the effect of the smoothing condenser
- For the case of a full-wave rectifier, it has been demonstrated that a fast-acting control circuit can compensate the voltage drop. However, the details of this circuit are not presented and the application of a full-wave rectifier is not economical for voltages higher than 400 - 500 kV.

Consequently, the literature survey justifies further research work in the following areas:

- The nature of the leakage current during dc pollution tests using the clean-fog method, which is used exclusively in the USA and in Canada
- The effect of rectifier parameters on the dc flashover voltage of insulators using the clean-fog method
- Development of a circuit to compensate the voltage drop of a rectifier circuit supplied by a single-phase transformer in order to make the flashover voltage of the insulators independent of the rectifier parameters over a practical operation range.

This final report presents the results of the EPRI-sponsored research work at IREQ in the first two areas.

Furthermore, this report deals briefly with possible solutions in the third area, suggesting these as a basis for an extension of the research work.

Section 4

THEORETICAL CONSIDERATIONS

It is desirable to review the theory of the flashover mechanism [7,10] in order to predict the expected current-voltage relation before flashover and to evaluate the possible effects of source impedance on the flashover voltage. After Nasser [7], the major phases of contamination flashover are summarized and illustrated schematically on Fig. 4.

The phases of flashover — quoted from Nasser [7] — are as follows:

- Heating of surface layer causes increase in conductivity and current (Fig. 4 a)
- Continued heating leads to local drying of surface layer (Fig. 4 b, c)
- Further heating causes dry zone formation by lateral local drying (Fig. 4 d)
- Onset of partial arcs across the dry zones is a distinct behavioral feature of contaminated insulators. Local concentrated heating causes the partial arcs to change position laterally across the same dry bands (Fig. 4 d, e, f)
- Arc extinction and onset of glow and streamer discharges across dry zones where highest potential gradients prevail. This phase is responsible for the intensive radio noise emitted from contaminated insulators. This phase is not shown in Fig. 4
- -- Many partial arcs may merge to form one single arc bridging a large portion of the insulator and propagate by thermal action in various directions (Fig. 4 j). Arc extinction and return to phase 5 may occur

  -- The fast sweep of the arc endpoints along the wet conductive leakage path leads to completion of the arc and to flashover (Fig. 2 m). The last portion of the bridged leakage path does not exhibit a dry path.

During the last phase (6 a, b), the dry zone on the insulator surface is bridged by an arc, while the rest of the insulator is covered by a resistive

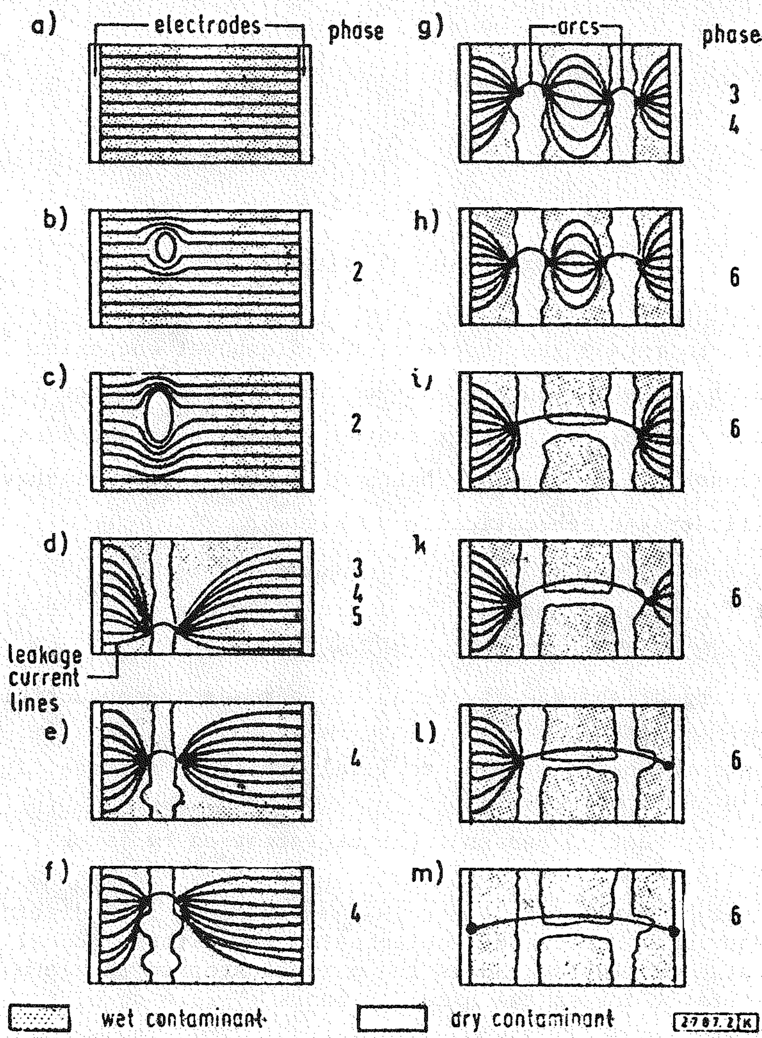

FIG. 4 Major phases of contamination flashover[7]

layer. The voltage across the insulator will be divided between this layer and the arc. An exact calculation of the variation of voltage with arc length is rather complicated. However, the effect of the source impedance can be estimated using the simplified model shown in Fig. 5.

If a current I flows through the circuit of Fig. 5, the applied voltage will be the sum of the voltage drops across the source resistance, the surface layer resistance and the arc.

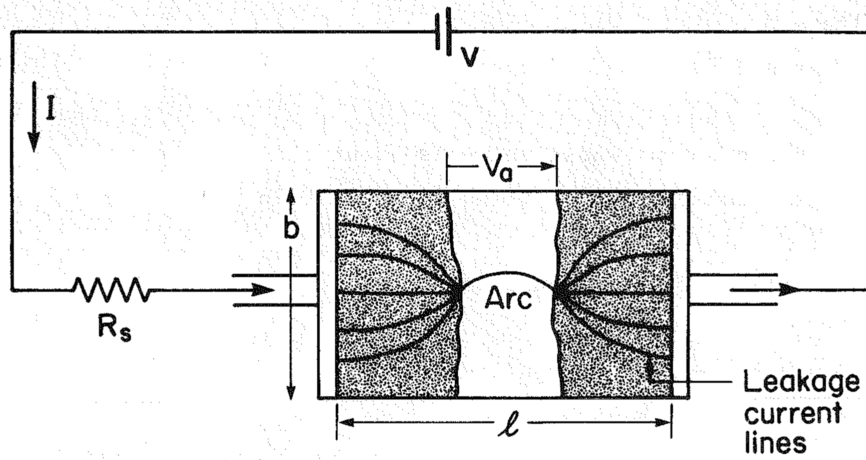

FIG. 5 Simplified insulator model

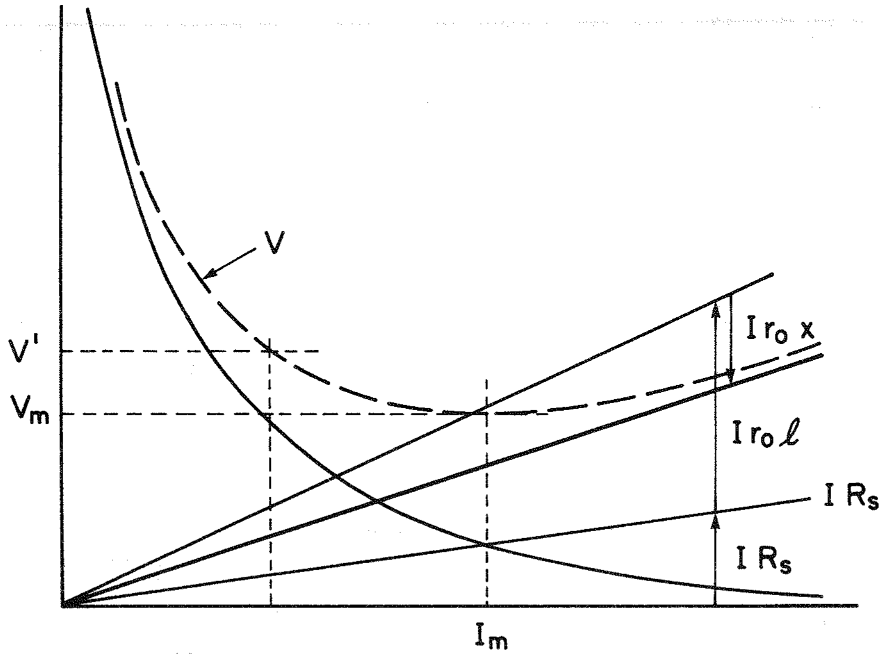

FIG. 6 Voltage in function of current in the circuit of Fig. 5

The voltage drop across the source and the surface layer resistance is:

$$I\, r_o\, (\ell - x) + R_s I$$

where r_o is the resistance of the wet surface layer per cm.

ℓ is the leakage distance

x is the length of the arc

I is the current

the arc voltage drop is:

$$V_a = A\, I^{-n} x$$

where A is a constant whose value is about 63

n is a constant whose value is about 0.76

The voltage equation of the circuit is:

$$V = A\, I^{-n} + I \left[R_s + r_o\, (\ell - x) \right] \quad \ldots \qquad (1)$$

Several analyses of the pollution phenomenon have been presented during recent years. These studies consider natural conditions, when the insulator is supplied by a very powerful source ($R_s = 0$). The present study, however, considers laboratory conditions, where $R_s \neq 0$. The source impedance influences the phenomenon and an analysis for a source with a finite resistance is not known to the author.

However, the method used by several authors may be followed.

The sum of the voltage drops in equation (1) as a function of the current for a given arc length x is shown schematically in Fig. 6. If the actually ap-

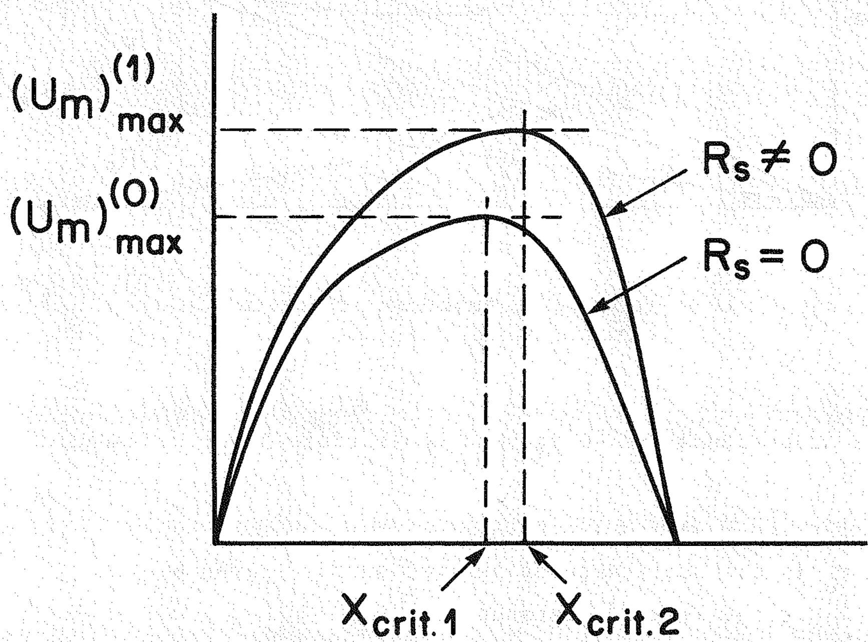

FIG. 7 Representation of the U_m (x) function and effect of the source resistance R_s

plied voltage drops below the minimum V_m, the arc will be extinguished. In the case of higher voltages, the arc may extend, thus modifying both the arc and the resistance layer characteristics. This produces a new V-curve with a different minimum value. If this value is higher than the applied voltage, the arc extinguishes. Otherwise, it develops further. The criterion for flashover is that the supply voltage be larger than V_m for every x. The minimum voltage can be calculated by differentiating V with respect to I and equating this to zero. We obtain

$$I_m = \left[\frac{A\ n\ x}{R_s + r_o\,(\ell - x)}\right]^{\frac{1}{1+n}} \quad \ldots. \tag{2}$$

and, by substitution into equation (1),

$$U_m = (1 - n)\ (Ax)^{\frac{1}{1+n}} \left[\frac{R_s + r_o\ (\ell - x)}{n}\right]^{\frac{n}{1+n}} \quad \ldots. \tag{3}$$

The U_m (x) function is plotted for different values of R_s on Fig. 7. It can be seen that:

- The function has a maximum value at $x = x_{crit.}$ (critical arc length).
- The maximum value increases with increasing source resistance.
- The critical arc length increases linearly with increasing source resistance.

The maximum value of U_m and the critical arc length can be calculated by differentiating U_m (x) with respect to x and equating the result to zero, giving

$$\frac{dU_m}{dx} = (1 + n)\left[\frac{n}{1+n}\left(-\frac{r_o}{n}\right)\left(\frac{R_s + r_o\ (\ell - x)}{n}\right)^{-\frac{1}{1+n}} (A\ x)^{\frac{1}{1+n}} + \frac{1}{1+n}\ A\ (A\ x)^{-\frac{n}{1+n}} \left(\frac{R_s + r_o\ (\ell - x)}{n}\right)^{\frac{n}{1+n}}\right] = 0 \quad \ldots. \tag{4}$$

The value of x determined by equation (4) gives the critical arc length, $x_{crit.}$

$$x_{crit} = \frac{R_s}{r_o}\ \frac{1}{1+n} + \frac{\ell}{1+n} \quad \ldots. \tag{5}$$

The maximum voltage corresponding to x_{crit} is:

$$(U_m)_{max} = A^{\frac{1}{1+n}} \left[R_s \, r_o^{-\frac{1}{1+n}} + \ell \, r_o^{\frac{n}{1+n}} \right] \quad \ldots \qquad (6)$$

The current corresponding to the maximum voltage is

$$I_m = \left(\frac{A}{r_o} \right)^{\frac{1}{1+n}} \quad \ldots \qquad (7)$$

Analysis of equations 5, 6, 7 shows that:

- Flashover of the insulator requires a higher voltage than $(U_m)_{max}$.
- The minimum voltage that can cause flashover increases linearly with the source resistance.
- The critical arc length increases linearly with the source resistance.
- The maximum current corresponding to the critical arc length, or to the minimum flashover voltage, is independent of the source resistance. It depends only on the pollution severity and the arc constants. Consequently, the current measured just before flashover should be more or less constant, for a fixed pollution level.

An investigation of the simplified theory of the mechanism of flashover of polluted insulators leads to the following conclusions:

- The critical factor influencing the flashover voltage is the dynamic voltage drop of the source at maximum current, which occurs just before flashover; the dynamic voltage drop is the voltage drop which is produced by a suddenly-appearing load current pulse.
- The current before flashover is expected to increase at an ever-increasing rate. The maximum current before flashover increases with the level of pollution. Therefore, the maximum expected pollution level should be used for the experimental investigations.
- The theory does not provide any quantitative values and, moreover, supposes a simplified voltage source. Therefore, experimental study is required to obtain values for the leakage-current and to determine the effect of the rectifier parameters on the flashover voltage.

Section 5

EXPERIMENTAL STUDY

During the experimental study, the flashover voltage and leakage current of heavily polluted insulators were measured using different rectifiers.

The following conditions were studied:

1) Series C: Tests with cascade rectifier (Fig. 9)

Tests C1	$D = 0.5$ mg/cm^2,	$C = 0.18$ μF
Tests C2	$D = 0.5$ mg/cm^2	$C = 2.92$ μF

2) Series H: Tests with half-wave rectifier (Fig. 10)

Tests H1	$D = 0.5$ mg/cm^2, $C = 3.075$ μF, $R_{AC} = 0$ Ω, $R_{DC} = 300$ Ω
Tests H2	$D = 0.5$ mg/cm^2, $C = 12$ μF, $R_{AC} = 0$ Ω, $R_{DC} = 300$ Ω

3) Series F: Tests with full-wave rectifier (Fig. 11)

Tests F1	$D = 0.5$ mg/cm^2,	$C = 3.075$ μF	$R_{AC} = 0$ Ω	$R_{DC} = 300$ Ω
Tests F2	$D = 0.5$ mg/cm^2,	$C = 12$ μF	$R_{AC} = 0$ Ω	$R_{DC} = 300$ Ω
Tests F3	$D = 0.5$ mg/cm^2,	$C = 0.262$ μF	$R_{AC} = 0$ Ω	$R_{DC} = 300$ Ω
Tests F4	$D = 0.5$ mg/cm^2,	$C = 3.075$ μF	$R_{AC} = 3000$ Ω	$R_{DC} = 300$ Ω
Tests F5	$D = 0.5$ mg/cm^2,	$C = 12.0$ μF	$R_{AC} = 3000$ Ω	$R_{DC} = 300$ Ω
Tests F6	$D = 0.5$ mg/cm^2,	$C = 3.075$ μF	$R_{AC} = 6000$ Ω	$R_{DC} = 300$ Ω
Tests F7	$D = 0.5$ mg/cm^2,	$C = 3.075$ μF	$R_{AC} = 0$ Ω	$R_{DC} = 3000$ Ω
Tests F8	$D = 0.1$ mg/cm^2,	$C = 3.075$ μF	$R_{AC} = 0$ Ω	$R_{DC} = 300$ Ω

4) Short circuit and loading tests on different rectifiers

In the presented list: D is the equivalent salt deposit density, C is the smoothing capacitance, R_{AC} is the resistance on the "AC side" of the smoothing capacitance and R_{DC} is the resistance on the "DC side" (Figs. 10-11).

TEST METHOD AND CIRCUIT

A) Test arrangement

The tests were performed in the small fog chamber at IREQ. The chamber dimensions and the test arrangement are shown on Fig. 8. During the first test series, the chamber was supplied by steam fog which is generated by a boiler and blown into the chamber through a pipe system with several regulated openings.

- Steam temperature in the pipe near the opening: 100°C
- Steam pressure at the boiler: 3.8 ~ 4 lbs/square inch
- Steam flow: 0.25 $lbs/h/m^3$ is 100% generation rate for IREQ's facility
- Average droplet radius (about): 8 μm
- Standard deviation of fog droplet distribution (estimated): σ = 4 μm.

During the test, it was found that the temperature of the small fog chamber was about 50°C at the end of the test. This temperature is too high to represent natural conditions. Therefore, the remainder of the test was performed using warm fog resulting in a maximum room temperature of about 35°C. The warm fog is generated by fog nozzles which atomize the water by forcing it through an orifice using high-pressure air. A vertical fog stream is produced by fans. The measured parameters are:

- Water temperature near the fog nozzles: 65 - 75°C
- Water input: 30.6 mℓ/min per m^3 of fog chamber volume
- Air pressure: 25 psi
- Fog temperature: variable
- Velocity of fog stream: with fan: 0.5 - 1.5 m/s; without fan: > 0.1 m/s
- Average fog droplet radius: 18 μm
- Standard deviation of fog droplet distribution: σ = 12 μm.

The chamber was supplied through the bushing by a rectifier.

B) Rectifiers

The tests were performed using three different rectifiers, with negative polarity dc voltage:

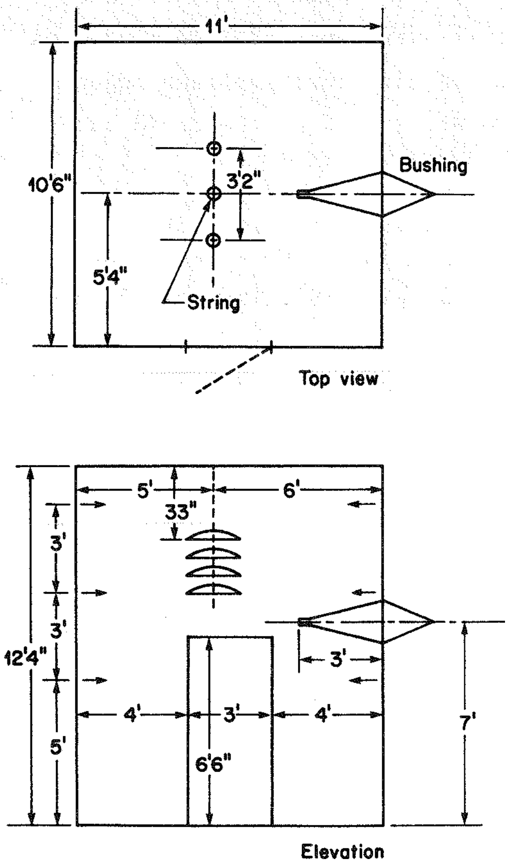

FIG. 8a Small fog chamber

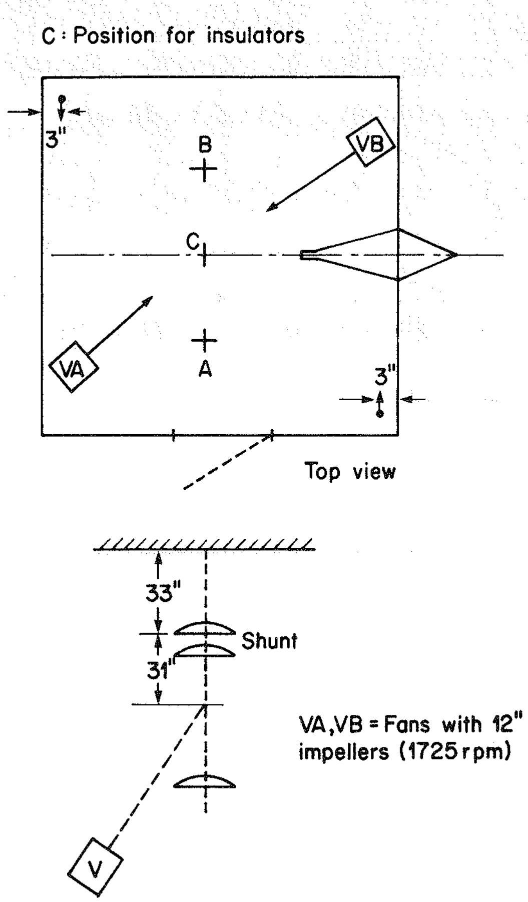

FIG. 8b Small fog chamber

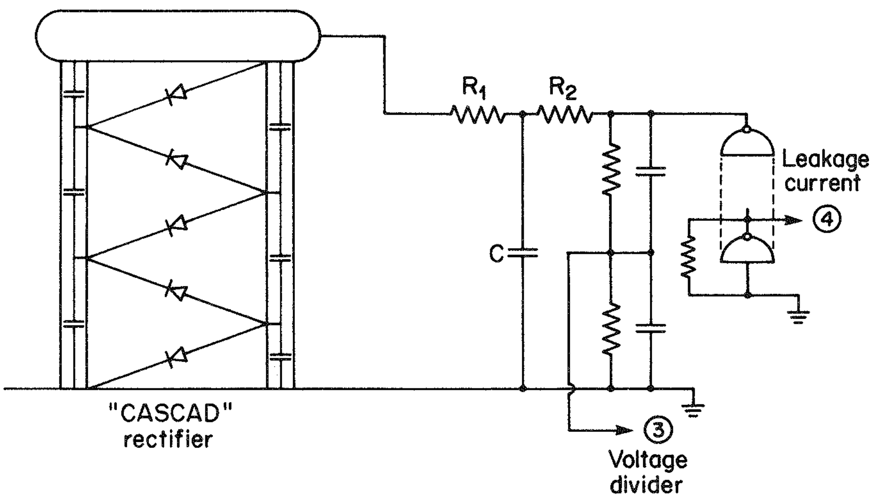

FIG. 9 Cascade rectifier

Cascade rectifier (ASEA)(Fig. 9). The rectifier is rated at 1200 kV and 125 mA, and is able to supply a current impulse with an amplitude of 250 mA for 0.5 sec. The rectifier is equipped with an electronic voltage regulator which keeps the test voltage constant to within ±5% at the rated current.

Half-wave rectifier (Fig. 10). This system is rated at 200 kV and 5 A. The voltage is manually adjusted by a 1 MVA voltage regulating transformer.

Full-wave rectifier (Fig. 11). The system is rated at 100 kV and 5 A, but is supplied by a 65 kV, 667 kVA transformer.The voltage is manually adjusted by a 1 MVA voltage regulator.

C) Measuring circuit

The high voltage part of the measuring circuit is shown on Figs. 9, 10, and 11. During each test, the following parameters were measured:

DC voltage. The dc voltage was measured through a resistive divider, which supplied a dc amplifier. The output voltage of the amplifier was recorded directly on a Visicorder, and on magnetic tape recorder. The latter enables faster replaying of the voltage and current in order to study the details of the voltage and current curves.

Insulator leakage current. The leakage current was obtained from a shunt which was connected in parallel with the last insulator. The shunt voltage is connected to a protection circuit (Fig. 12), which short circuits the shunt in case of flashover. The protection circuit contains a thyristor and a gap. The latter provides back-up protection.

The leakage current and the peak current were recorded directly on a Visicorder, on a magnetic tape recorder. The measurement of the peak leakage current using a sampling-type leakage current detector gives the envelope curve of the leakage current and enables comparison of the test results with the leakage current measurements performed under natural conditions. The leakage current has been measured by IREQ using similar equipment at several test sites in Newfoundland.

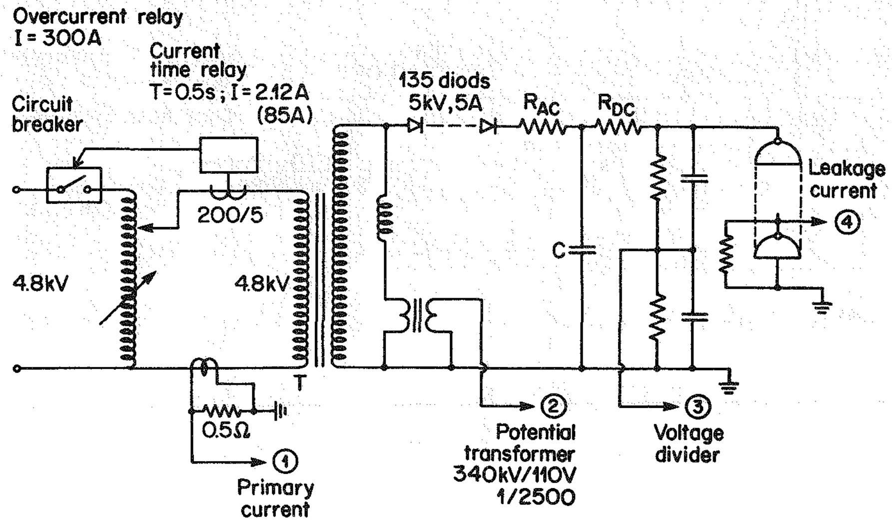

FIG. 10 Half-wave rectifier

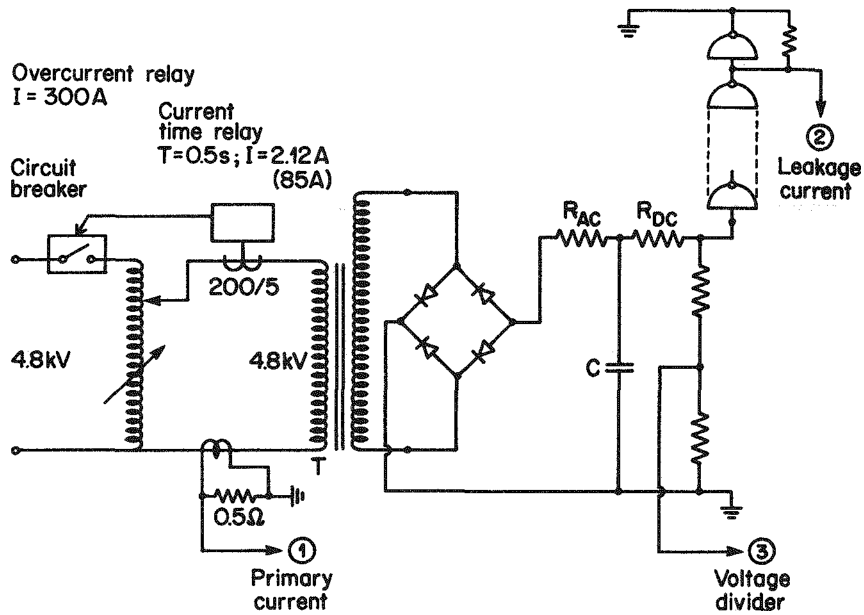

FIG. 11 Full-wave rectifier

The leakage current contains current impulses. The rectifier must provide these current impulses without significant voltage drop. In order to evaluate the performance of different supply circuits the peak leakage current-voltage drop relation, and the charge of the "leakage current impulse (Q) - voltage drop" relation were determined.

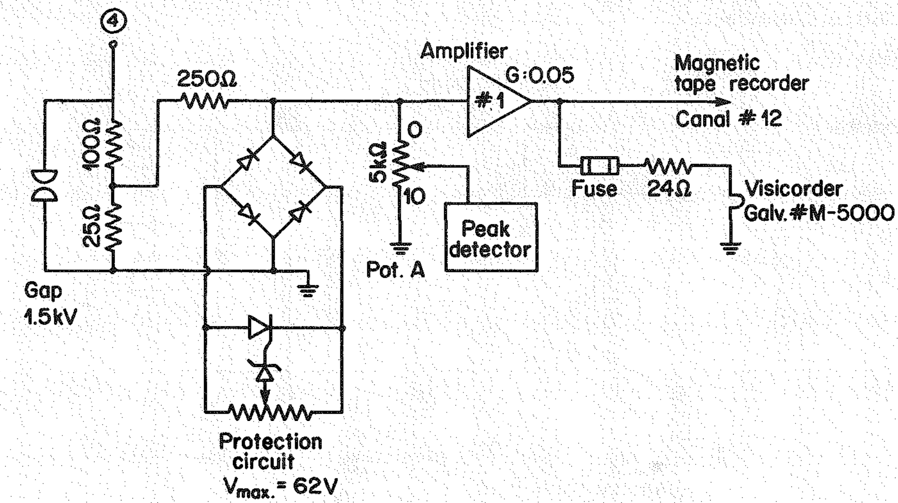

FIG. 12 Leakage current measurement

Furthermore, in order to determine the nature of the current pulses which occur during the pollution tests, a computer program was developed to determine the histogram and cumulative distribution (curves) of the:

- Peak leakage current
- Current impulse charge
- Voltage drop
- Time duration of the current impulses

<u>AC voltage</u>. It was measured using a voltage transformer and recorded on the Visicorder and on magnetic tape.

<u>AC current</u>. It was measured by means of a current transformer inserted on the low voltage side of the transformer. The current was recorded on the Visicorder and on a magnetic tape.

<u>Deposit density on the insulator surface</u>. Before each test the pollution was washed down from 2-3 insulators using distilled water, and the resistivity of the resulting solution was measured. From this the equivalent NaCl salt deposit density, which is a measure of pollution severity, was calculated.

D) Insulators and pollution severity

The literature indicates that the insulator shape influences the leakage current before flashover. This fact implies that the rectifier performance will be influenced by the shape of the insulator. However, the effect of insulator shape on the leakage current does not seem to be very large. Furthermore, only a few types of insulator are used for dc. This suggests that the insulators used for the Pacific Intertie should be used for the present project, since they represent typical conditions: EPRI accepted this suggestion, and the NGK-DC-type insulators (catalog No. 6A-12136B) were used for the tests.

The data of the tested NGK long-leak insulator are as follows:

- Type: NGK

- Diameter: 29.2 cm
- Height : 14.6 cm
- Leakage distance: 48.95 cm
- Arcing distance: 23.5 cm
- Surface : Top : 1007 cm^2
  Bottom: 1943 cm^2
  Total : 2950 cm^2
- Form factor : 0.945

Theoretical investigation shows that the tests should be performed at the maximum pollution level. The data obtained from the Los Angeles Water Power indicate that the maximum pollution level on the Pacific Intertie is about 0.25 mg/cm^2. Based on this and on other data, it seems to be safe to select a 0.5 mg/cm^2 pollution level for the tests. EPRI agreed that all the tests except one be performed at this pollution level.

E) Test method

The tests were performed using the clean-fog method, in accordance with the recommendations of IEC Publication 60-1 (1973).

A short description of the test method follows:

- The 22 insulators are polluted using the dipping method in which they are submerged in a suspension suggested by the IEC.

- The insulators are dried by a forced air stream produced by a fan.

- The deposit is washed down from four insulators in order to determine the pollution severity.

- Nine or six insulators are installed in the fog chamber and energized using a negative polarity dc voltage.

- If the leakage current is negligible (less than 1 mA), clean fog is applied. The voltage is maintained constant until flashover occurs or until the leakage current decreases to a low value (a few mA for example) and the discharge activity on the insulator surface ceases.

- After the test, the insulators are cleaned and repolluted using the procedure described above.

The test is repeated several times using the "up-and-down" method which consists of repeating the following procedure:

- If the insulator chain flashes over, the test is repeated using a 5% lower voltage.

- If the insulator chain does not flash over, the test is repeated using a 5% higher voltage.

Section 6

TEST RESULTS

FLASHOVER TESTS ON POLLUTED INSULATORS

The test results are divided into 3 parts corresponding to the three different types of rectifier used.

- Cascade rectifier

The test results are shown in Table 1. A typical oscillogram (Test no. 9) is shown on Figs. 13 a, b. Fig. 13a shows the dc voltage and leakage current during the test. Fig. 13b shows an enlarged view of part of the oscillogram of Fig. 13a, facilitating the study of the details of the leakage current and voltage drop.

- Half-wave rectifier

The test results are shown in Table 2. A typical oscillogram is shown on Fig. 14. The oscillogram presents the leakage current (1), dc voltage (2), ac voltage (3) and ac current (4) just before flashover.

- Full-wave rectifier

The test results are shown in Table 3. A typical oscillogram is shown on Figs. 15 and 16. The oscillogram of Fig. 15a gives the variation of the leakage current (1) and dc voltage (2) for a complete test, during which the insulator flashed over. Fig. 15b presents an enlarged view of part of the oscillogram before flashover. The identification of the traces is the same as for Fig. 14. Fig. 16a gives the variation of leakage current (1) and dc voltage (2) when the insulator does not flash over. Fig. 16b presents an enlarged view of part of oscillogram 16a. The traces on the oscillograms are marked dc leakage current (1), dc voltage (2), ac current (3). The variation of the maximum leakage current measured by the peak detector is shown in Fig. 17 for a test during which the insulator flashes over.

TABLE 1

TESTS PERFORMED WITH CASCADE RECTIFIER

Test No.	No. of Insulators	Deposit density mg/cm^2	Test voltage kV/unit	Leakage current max. mA	Voltage drop max.	C µF	R_2 Ω	Flash-over yes	Flash-over no	Observation
1	9	0.31	0.3	29.2	–	–	–	–	–	Leakage current measurement
2	9	0.65	0.3	37	–	–	–	–	–	——— . ———
3	9	0.525	0.3	21.2	–	–	–	–	–	Leakage measurement; disturbance in the fog system
4	3	0.525	0.3	23.3	–	–	–	–	–	Leakage current measurement
5	3	0.525	0.3	20.8	–	–	–	–	–	Leakage current measurement; disturbance in fog system
6	9	0.5	11	850*	80-100%	–	1,500	X		The circuit is too weak for the test
7	9	0.469	11	850*	80%	–	0	X		The circuit is too weak for the test
8	9	0.469	8.89	2.09A	80%	0.18	800		X	——— . ———
9	9	0.586	11	3.13A	80%	0.18	800	X		——— . ———
10	9		11	?	23%	2.92	800		X	
11	9	0.533	8.89	?	?	2.92	800	X		

* The measuring system saturated at 850 mA

TABLE 2

TESTS PERFORMED WITH HALF-WAVE RECTIFIER

SERIES NO.		H 1 $V_{50\%}$ = 6.97 kV/unit							
Test No.		5	6	7	8	9	10	11	12
Number of insulators		9	9	9	9	9	9	9	9
Date		10-3-76	10-3-76	11-3-76	11-3-76	12-3-76	12-3-76	15-3-76	15-3-76
Concentration (solution)	g/l	105	105	105	105	105	105	105	105
Temperature of the solution	°C	24.5	24.5	24.0	24.0	21.0	21.0		
Salt deposit density — Top	mg/cm^2	.678	.678	.668	.668	.666	.666	.668	.668
Salt deposit density — Bottom	mg/cm^2	.487	.487	.494	.494	.482	.482	.476	.476
Salt deposit density — Total	mg/cm^2	.549	.549	.556	.556	.547	.547	.544	.544
Temperature int. before	°C	24.5	24.5	22.7	24.0	21.0	21.2	19.5	19.0
Temperature int. after	°C	28.0	22.0	23.0	27.0	21.0	25.0	21	20.5
External humidity	%	11	14	15	15	12	13	16	15
Total voltage	kV DC	60	70	66	60	64	60	64	64
Voltage per unit	kV DC	6.66	7.77	7.33	6.66	7.11	6.66	7.11	7.11
Results Δ: flashover 0: withstand	Δ ou 0	0	Δ	Δ	0	Δ	0	Δ	Δ
Duration of the voltage	min.	30	4.25	5.5	30	6	30	6	8.5
Maximum current	Amp.	2.17	3.14	3.25	1.76	3.85	1.41	4.2	4.0
Voltage per unit before flashover or min. value	kV	4.11	5.22	4.67	4.33	4.41	4.78	4.29	4.3
Current impulse duration before flashover	s	-	-	0.28	-	0.26	-	0.42	<0.6
Fog type		WARM FOG							
Test parameters		HW, R_{AC} = 0 Ω, R_{DC} = 300 Ω, C = 3.075 μF							

TABLE 2 CONTINUATION 1

SERIES NO.			H 2			$V_{50\%}$ = 6.97 kV/unit				
Test No.			13	14	15	16	17	18	19	20
Number of insulators			9	9	9	9	9	9	9	9
Date			16-3-76	17-3-76	17-3-76	18-3-76	18-3-76	20-3-76	19-3-76	23-3-76
Concentration (solution)		g/l	105	105	105	105	105	105	105	105
Temperature of the solution		°C	23.9	23.2	23.2	23.0	23.0	23.9	23.9	21.0
Salt deposit density	Top	mg/cm^2	.673	.676	.676	.644	.644	.644	.644	.637
	Bottom	mg/cm^2	.474	.481	.481	.466	.466	.463	.463	.430
	Total	mg/cm^2	.542	.549	.549	.526	.526	.522	.522	.500
Temperature int. before		°C	22.8	21.8	20.5	21.8	22.3	23.1	23.0	20.1
Temperature int. after		°C		21.2	25.2	-	-	-	-	-
External humidity		%	13	16	16	13	12	16	16	20
Total voltage		kV DC	60	64	60	64	60	64	62	62
Voltage per unit		kV DC	6.66	7.11	6.66	7.11	6.66	7.11	6.89	6.89
Results Δ: flashover 0: withstand		Δ ou 0	0	Δ	0	Δ	0	Δ	0	Δ
Duration of the voltage		min.	14	7.5	30	6.75	30	7.5	20	6
Maximum current		Amp.	1.0	-	-	1.15	1.33	2.1	1.15	3.56
Voltage per unit before flashover or min. value		kV	5.55	-	-	5.83	5.23	4.44	5.48	4.0
Current impulse duration before flashover		s	-	-	-	-	-	0.25	-	0.66
Fog type			WARM FOG							
Test parameters			HW, $R_{AC} = 0\ \Omega$, $R_{DC} = 300\ \Omega$, C = 11.45 μF							

TABLE 2 CONTINUATION 2

SERIES NO.			H 2 cont.	H 1 cont.		
Test No.			21	22	23	24
Number of insulators			9	9	9	9
Date			23-3-76	24-3-76	24-3-76	26-3-76
Concentration (solution)		g/l	105	105	105	105
Temperature of the solution		°C	21.0	21.5	21.5	21.7
Salt deposit density	Top	mg/cm²	0.637	0.640	0.640	0.666
	Bottom	mg/cm²	0.430	0.429	0.429	0.458
	Total	mg/cm²	0.500	0.502	0.502	0.530
Temperature int. before		°C	19.2	21.3	20.5	23.0
Temperature int. after		°C	21.0	21.8	23.0	24
External humidity		%	20	25	23	25
Total voltage		kV DC	62	62	62	62
Voltage per unit		kV DC	6.89	6.89	6.89	6.89
Results Δ: flashover 0: voltage		Δ ou 0	0	0	0	Δ
Duration of the voltage		min.	30	30	30	5.5
Maximum current		Amp.	1.19	0.98	1.80	4.48
Voltage per unit before flashover or min. value		kV	5.3	5.22	4.67	4.22
Current impulse duration before flashover		s	-	-	-	-
Fog type			WARM FOG			
Test parameters			HW, SAME AS NOS. 5-12			

TABLE 3

TESTS PERFORMED WITH FULL-WAVE RECTIFIER

SERIES NO.		F 1			$V_{50\%} = 6.53$ kV/unit				
Test No.		25	26	27	28	29	30	31	32
Number of insulators		9	9	6	6	6	6	6	6
Date		26-3-76	30-3-76	30-3-76	31-3-76	31-3-76	31-3-76	31-3-76	2-4-76
Concentration (solution)	g/ℓ	105	105	105	105	105	105	105	105
Temperature of the solution	°C	21.7	22.3	22.3	23.2	23.2	23.2	23.2	23.2
Salt deposit density — Top	mg/cm^2	.666	.681	.681	.687	.687	.687	.687	.631
Salt deposit density — Bottom	mg/cm^2	.458	.490	.490	.515	.515	.515	.515	.459
Salt deposit density — Total	mg/cm^2	.530	.571	.571	.573	.573	.573	.573	.519
Temperature int. before	°C	22.6	23	22.5	22.5	22	22.2	22.5	22.5
Temperature int. after	°C	23.2	22.3	24.0	24.2	24.8	23.0	24.2	23.2
External humidity	%	23	19	22	24	24	30	30	27
Total voltage	kV DC	2.7	2.7	7.8	40	36	38	40	38
Voltage per unit	kV DC		300 V	300 V	6.67	6	6.33	6.67	6.33
Results Δ: flashover 0: withstand	Δ ou 0	Leakage current	Leakage current	Leakage current	Δ	0	0	Δ	0
Duration of the voltage	min.				4.5	25	25	6	25
Maximum current	Amp.	-	-	-	-	-	-	-	-
Voltage per unit before flashover or min. value	kV	-	-	-	-	-	-	-	-
Current impulse duration before flashover	s	-	-	-	-	-	-	-	-
Fog type		WARM FOG							
Test parameters		HW, $R_{DC} = 300\ \Omega$, $R_{AC} = 0$, $C = 3.075\ \mu F$							

TABLE 3 CONTINUATION 1

SERIES NO.		F 1, $V_{50\%}$ = 6.53 kV/unit					
Test No.		33	34	35	36	37	38
Number of insulators		6	6	6	6	6	6
Date		2-4-76	2-4-76	2-4-76	2-4-76	2-4-76	2-4-76
Concentration (solution)	g/l	105	105	105	105	105	105
Temperature of the solution	°C	23.2	23.2	23.2	22.0	22.0	22.0
Salt deposit density — Top	mg/cm^2	.631	.631	.631	.631	.631	.631
Salt deposit density — Bottom	mg/cm^2	.459	.459	.459	.462	.462	.462
Salt deposit density — Total	mg/cm^2	.519	.519	.519	.521	.521	.521
Temperature int. before	°C	22	22	22.5	22.0	22.0	22.0
Temperature int. after	°C	24	24	23.5	23.6	24.0	24.0
External humidity	%	25	25	27	26	28	26
Total voltage	kV DC	40	42	40	38	40	40
Voltage per unit	kV DC	6.67	7	6.67	6.33	6.67	6.67
Results Δ: flashover 0: withstand	Δ ou 0	0	Δ	Δ	0	Δ	Δ
Duration of the voltage	min.	25	6	6	25	7	5
Maximum current	Amp.	-	3.84	2.87	1.6	2.1	3.51
Voltage per unit before flashover or min. value	kV	-	5.43	5.2	5.1	5.08	5.45
Current impulse duration before flashover	S	-					
Fog type		WARM FOG					
Test parameters		F.W. R_{DC} = 300 Ω, R_{AC} = 0, C = 3.075 µF					

TABLE 3 CONTINUATION 2

SERIES NO.			F 4 $V_{50\%}$ = 7.5 kV/unit								
Test No.			39	40	41	42	43	44	45	46	47
Number of insulators			6	6	6	6	6	6	6	6	6
Date			05-04-76	05-04-76	07-04-76	07-04-76	07-04-76	08-04-76	08-04-76	08-04-76	08-04-76
Concentration (solution)		g/l	105	105	105	105	105	105	105	105	105
Temperature of the solution		°C	22.0	22.0	25.0	25.0	25.0	23.0	23.0	23.0	23.0
Salt deposit density	Top	mg/cm^2	0.631	0.690	0.690	0.690	0.690	0.637	0.637	0.637	0.637
	Bottom	mg/cm^2	0.462	0.498	0.498	0.498	0.498	0.462	0.462	0.462	0.462
	Total	mg/cm^2	0.521	0.557	0.557	0.557	0.557	0.523	0.523	0.523	0.523
Temperature int. before		°C	22.2	22.0	24.0	23.6	22.0	23.0	22.5	20	22.5
Temperature int. after		°C	22.8	24.0	24.5	24.2	23.5	24.0	24.8	22	24.2
External humidity		%	16	16	18	14	16	15	14	14	16
Total voltage		kV DC	40	60	48	44	46	44	46	44	46
Voltage per unit		kV DC	6.67	10	8	7.33	7.67	7.33	7.67	7.33	7.67
Results Δ: flashover 0: withstand		Δ ou 0	0	Δ	Δ	0	Δ	0	Δ	0	Δ
Duration of the voltage		min.	25	4	4.5	25	6.5	25	7	25	6
Maximum current		Amp.	0.7	-	2.9	2.4	-	2.14	0.83(?)	1.06	-
Voltage per unit before flashover or min. value		kV	4.35	-	5.33	3.83	-	4.33	5.33	5.38	-
Current impulse duration before flashover		s	-	-	0.42	-	-	-	-	-	-
Fog type			WARM FOG								
Test parameters			FW, R_{DC} = 300 Ω, R_{AC} = 3000 Ω, C = 3.075 μF								

TABLE 3 CONTINUATION 3

SERIES NO.			F 6			$V_{50\%}$ = 8.5 kV/unit			
Test No.			48	49	50	51	52	53	54
Number of insulators			6	6	6	6	6	6	6
Date			08-04-76	08-04-76	09-04-76	09-04-76	09-04-76	12-04-76	12-04-76
Concentration (solution)		g/ℓ	105	105	105	105	105	105	105
Temperature of the solution		°C	23.0	23.0	22.0	22	22	22.0	22.0
Salt deposit density	Top	mg/cm^2	0.637	0.637	0.637	0.637	0.637	-	0.630
	Bottom	mg/cm^2	0.462	0.462	0.468	0.468	0.468	-	0.462
	Total	mg/cm^2	0.523	0.523	0.525	0.525	0.525	0.521	0.521
Temperature int. before		°C	23.0	22	22.5	22	22.2	22.5	21.5
Temperature int. after		°C	24.0	24.0	23.5	24	24.2	23.0	22.5
External humidity		%	16	15	14	14	14	14	15
Total voltage		kV DC	50	54	52	50	52	50	52
Voltage per unit		kV DC	8.33	9	8.67	8.33	8.67	8.33	8.67
Results Δ: flashover 0: withstand		Δ ou 0	0	Δ	Δ	0	Δ	0	Δ
Duration of the voltage		min.	20	4.5	5	25	5.5	25	7
Maximum current		Amp.	1.80	2.24	3.30	1.69	4.19	-	1.3
Voltage per unit before flashover or min. value		kV	4.28	5.22	5.58	4.9	5.39	-	5.83
Current impulse duration before flashover		s	-	0.31	0.3	-	0.24	-	0.22
Fog type			WARM FOG						
Test parameters			FW, R_{DC} = 300 Ω, R_{AC} = 6000, C = 3.075 μF						

TABLE 3 CONTINUATION 4

SERIES NO.		F 7 $V_{50\%}$ = 6.5 kV/unit							
Test No.		55	56	57	58	59	60	61	62
Number of insulators		6	6	6	6	6	6	6	6
Date		12-04-76	13-04-76	13-04-76	14-04-76	14-04-76	14-04-76	20-04-76	20-04-76
Concentration (solution)	g/l	105	105	105	105	105	105	105	105
Temperature of the solution	°C	22.0	22.0	23.0	23.0	22.0	22.0	24	24
Salt deposit density — Top	mg/cm²	0.630	0.630	0.640	0.640	0.644	0.644	0.731	0.731
Salt deposit density — Bottom	mg/cm²	0.462	0.462	0.461	0.461	0.467	0.467	0.504	0.504
Salt deposit density — Total	mg/cm²	0.521	0.521	0.522	0.522	0.528	0.528	0.586	0.586
Temperature int. before	°C	24	24.5	24.5	23.0	23.0	23	24.0	23.2
Temperature int. after	°C	25.0	25.5	25.0	24.2	25	25	25.0	25.0
External humidity	%	15	15	15	11	12	12	30	38
Total voltage	kV DC	46	44	40	38	40	38	40	38
Voltage per unit	kV DC	7.67	7.33	6.67	6.33	6.67	6.33	6.67	6.33
Results Δ: flashover 0: withstand	Δ ou 0	Δ(?)	Δ(?)	Δ	0	Δ	0	Δ	0
Duration of the voltage	min.	5	5.5	8.5	25	8	25	6.5	25
Maximum current	Amp.	4.2	4.3	-	-	4.30	1.00	-	0.93
Voltage per unit before flashover or min. value	kV	2.83 (?)	2.5 (?)	-	-	1.35 (?)	5.03	-	5.03
Current impulse duration before flashover	S	0.32	0.42	-	-	-	-	-	-
Fog type		WARM FOG							
Test parameters		FW, R_{DC} = 3000 Ω, R_{AC} = 0, C = 3.075 μF							

TABLE 3 CONTINUATION 5

SERIES NO.			F 2	$V_{50\%}$ = 6.5 kV/unit				
Test No.			63	64	65	66	67	68
Number of insulators			6	6	6	6	6	6
Date			20-4-76	20-4-76	20-4-76	20-4-76	20-4-76	20-4-76
Concentration (solution)		g/ℓ	105	105	105	105	105	105
Temperature of the solution		°C	24	24	23.0	23.0	23.0	23.0
Salt deposit density	Top	mg/cm^2	.731	.731	.671	.671	.671	.671
	Bottom	mg/cm^2	.504	.504	.474	.474	.474	.474
	Total	mg/cm^2	.586	.586	.539	.539	.539	.539
Temperature int. before		°C	23.0	23.2	23.5	23.2	22.6	23.0
Temperature int. after		°C	24.0	25.0	24.2	24.6	24.5	24.6
External humidity		%	38	37	38	38	36	36
Total voltage		kV DC	40	38	40	38	40	38
Voltage per unit		kV DC	6.67	6.33	6.67	6.33	6.67	6.33
Results	Δ: flashover 0: withstand	Δ ou 0	Δ	0	Δ	0	Δ	0
Duration of the voltage		min.	6.5	25	3.5	25	6	25
Maximum current		Amp.	2.73	1.04	1.78	0.8	3.51	1.82
Voltage per unit before flashover or min. value		kV	5.36	5.41	5.36	5.54	5.45	5.28
Current impulse duration before flashover		s	0.4	-	0.44	-	0.6	-
Fog type			WARM FOG					
Test parameters			FW. R_{DC} = 300 Ω, R_{AC} = 0, C = 12 μF					

TABLE 3 CONTINUATION 6

SERIES NO.			F 5 $V_{50\%}$ = 6.89 kV/unit							
Test No.			69	70	71	72	73	74	75	76
Number of insulators			6	6	6	6	6	6	6	6
Date			21-04-76	21-04-76	21-04-76	21-04-76	21-04-76	21-04-76	22-04-76	22-04-76
Concentration (solution)		g/l	105	105	105	105	105	105	105	105
Temperature of the solution		°C	23.0	23	23	23	22	22	23.0	23.0
Salt deposit density	Top	mg/cm²	0.638	0.638	0.638	0.638	0.623	0.623	0.644	0.644
	Bottom	mg/cm²	0.459	0.459	0.459	0.459	0.461	0.461	0.477	0.449
	Total	mg/cm²	0.533	0.533	0.533	0.533	0.515	0.515	0.538	0.538
Temperature int. before		°C	22.5	22.2	22.0	20.9	21	21	23	24
Temperature int. after		°C	23.0	23.8	22.0	22	22	22	24.8	25
External humidity		%	40	38	43	40	40	40	50	49
Total voltage		kV DC	46	44	42	38	40	42	42	42
Voltage per unit		kV DC	7.67	7.33	7	6.33	6.67	7	7	7
Results	Δ: flashover 0: withstand	Δ ou 0	Δ	Δ	Δ	0	0	0	Δ	Δ
Duration of the voltage		min.	7	6	7	15	25	25	6	8
Maximum current		Amp.	1.9	1.82	-	(?)0.26	2.13	2.66	2.0	1.65
Voltage per unit before flashover or min. value		kV	5.4	5.5	-	-	4.33	4.17	5.34	5.45
Current impulse duration before flashover		s	0.22	0.2	-	-	-	-	0.26	0.23
Fog type			WARM FOG							
Test parameters			FW, R_{DC} = 300 Ω, R_{AC} = 3000 Ω, C = 12 µF							

TABLE 3 CONTINUATION 7

SERIES NO.		F 3 $V_{50\%}$ = 6.67 kV/unit						
Test No.		77	78	79	80	81	82	83
Number of insulators		6	6	6	6	6	6	6
Date		22-4-76	22-4-76	22-4-76	22-4-76	23-4-76	23-4-76	23-4-76
Concentration (solution)	g/l	105	105	105	105	105	105	105
Temperature of the solution	°C	23.0	23	22	22	23	23	23
Salt deposit density — Top	mg/cm^2	.644	.644	.644	.644	.654	.654	.654
Salt deposit density — Bottom	mg/cm^2	.477	.477	.461	.461	.467	.467	.467
Salt deposit density — Total	mg/cm^2	.538	.538	.542	.542	.530	.530	.530
Temperature int. before	°C	24	24	24	23	22	22	23.5
Temperature int. after	°C	24.5	25	25	25	24	24.5	25
External humidity	%	52	52	50	50	48	48	48
Total voltage	kV DC	40	38	40	38	40	42	40
Voltage per unit	kV DC	6.67	6.33	6.67	6.33	6.67	7	6.67
Results Δ: flashover 0: withstand	Δ ou 0	Δ	0	Δ	0	0	Δ	0
Duration of the voltage	min.	9	25	6	8	25	6	25
Maximum current	Amp.	2.47	1.40	3.70	3.0	-	-	-
Voltage per unit before flashover or min. value	kV	6.16	3.33	3.0	1.86	-	-	-
Current impulse duration before flashover	S	0.3	-	-	-	-	-	-
Fog type		WARM FOG						
Test parameters		FW, R_{DC} = 300 Ω, R_{AC} = 0 Ω, C = 0.262 μF						

TABLE 3 CONTINUATION 8

SERIES NO.		F 8 $V_{50\%}$ = 10.25 kV/unit					
Test No.		84	85	86	87	88	89
Number of insulators		4	4	4	4	4	4
Date		23-04-76	23-04-76	23-04-76	23-04-76	23-04-76	23-04-76
Concentration (solution)	g/l	18	18	18	18	18	18
Temperature of the solution	°C	23.0	23.0	23.0	23.0	23.0	23.0
Salt deposit density – Top	mg/cm^2	0.1145	0.1145	0.1145	0.1145	0.1145	0.1145
Salt deposit density – Bottom	mg/cm^2	0.083	0.083	0.083	0.083	0.083	0.083
Salt deposit density – Total	mg/cm^2	0.0934	0.0934	0.0934	0.0934	0.0934	0.0934
Temperature int. before	°C	22.5	22	22.5	22.0	22	22.5
Temperature int. after	°C	23.0	23.0	23.0	23.0	23.0	23.0
External humidity	%	42	40	40	39	39	38
Total voltage	kV DC	60	50	40	44	40	44
Voltage per unit	kV DC	15	12.5	10	11	10	11
Results Δ: flashover, 0: withstand	Δ ou 0	Δ	Δ	0	Δ	0	Δ
Duration of the voltage	min.	3	4	15	5.5	15	7
Maximum current	Amp.	3.10	2.9	0.51	1.47	0.42	2.96
Voltage per unit before flashover or min. value	kV	8.83	7.33	6.0	6.33	6.11	5.98
Current impulse duration before flashover	s	0.084	0.26	-	0.36	-	0.58
Fog type		WARM FOG					
Test parameters		FW, R_{DC} = 300 Ω, R_{AC} = 0 Ω, C = 3.07 μF					

TABLE 3 CONTINUATION 9

SERIES NO.			F 8 cont			
Test No.			90	91	92	93
Number of insulators			4	4	4	4
Date			24-04-76	24-04-76	24-04-76	24-04-76
Concentration (solution)		g/l	18	18	18	18
Temperature of the solution		°C	23.0	23.0	23.0	23.0
Salt deposit density	Top	mg/cm²				
	Bottom	mg/cm²				
	Total	mg/cm²	0.0976	0.0976	0.0976	0.0976
Temperature int. before		°C	22.5	22.5	24	23
Temperature int. after		°C	23.5	23.5	24	24
External humidity		%	34	34	32	32
Total voltage		kV DC	42	40	42	42
Voltage per unit		kV DC	10.5	10	10.5	10.5
Results Δ: flashover O: withstand		Δ ou O	Δ	O	Δ	Δ
Duration of the voltage		min.	5.5	15	5	4.5
Maximum current		Amp.	2.10	0.42	1.78	1.0
Voltage per unit before flashover or min. value		kV	5.7	6.03	6.2	6.0
Current impulse duration before flashover		s	0.21	-	0.3	0.2
Fog type			WARM FOG			
Test parameters			Same as Tests Nos. 84-89			

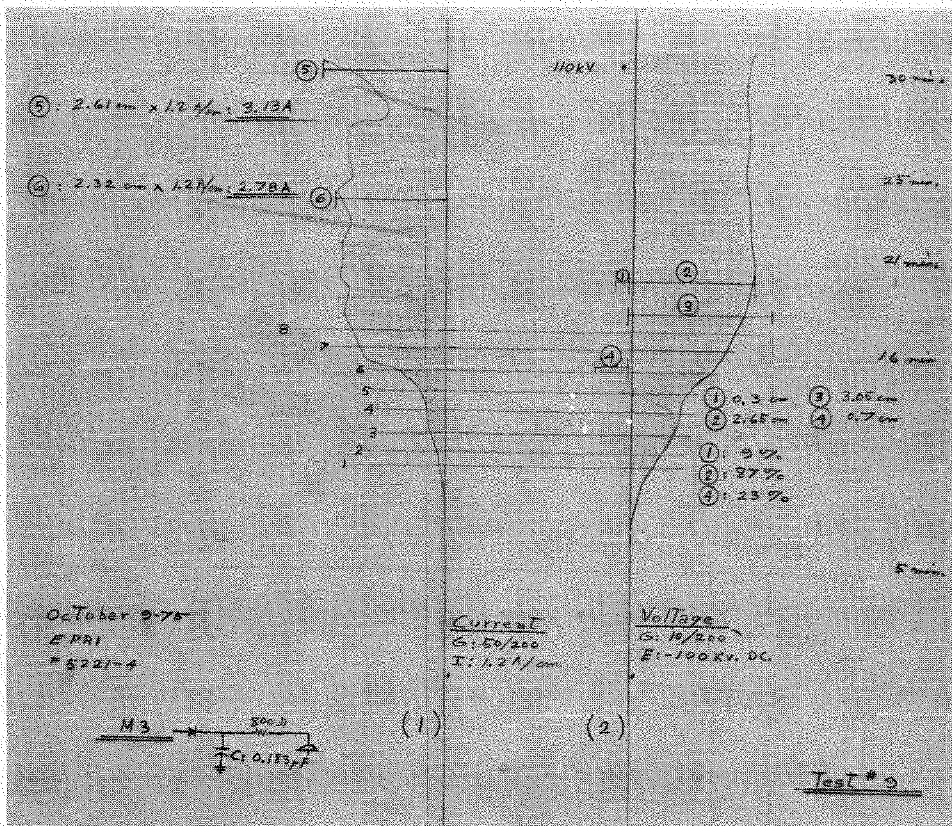

FIG. 13a DC voltage and leakage current of a test with cascade rectifier

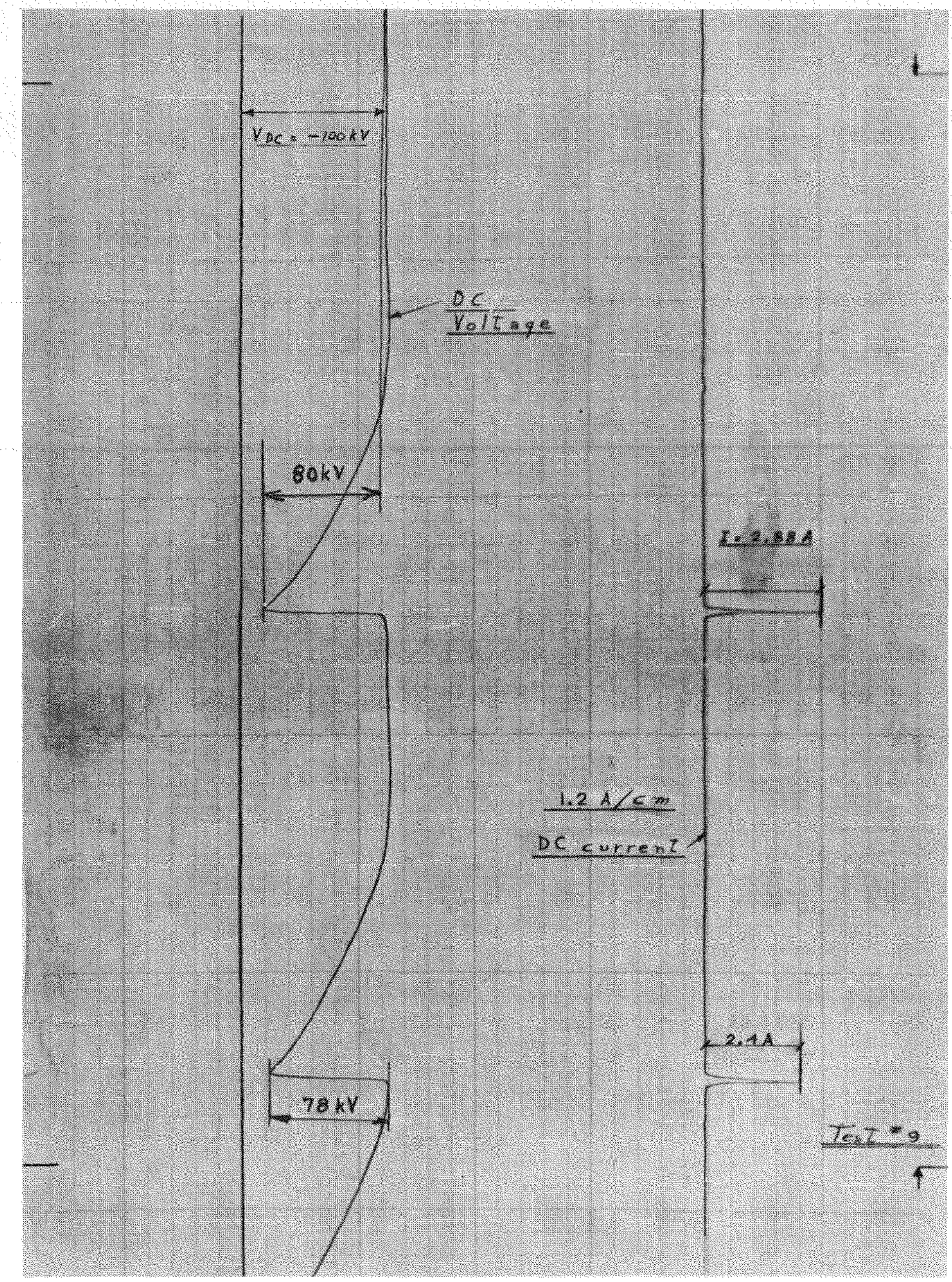

FIG. 13b Enlarged part of Fig. 13a

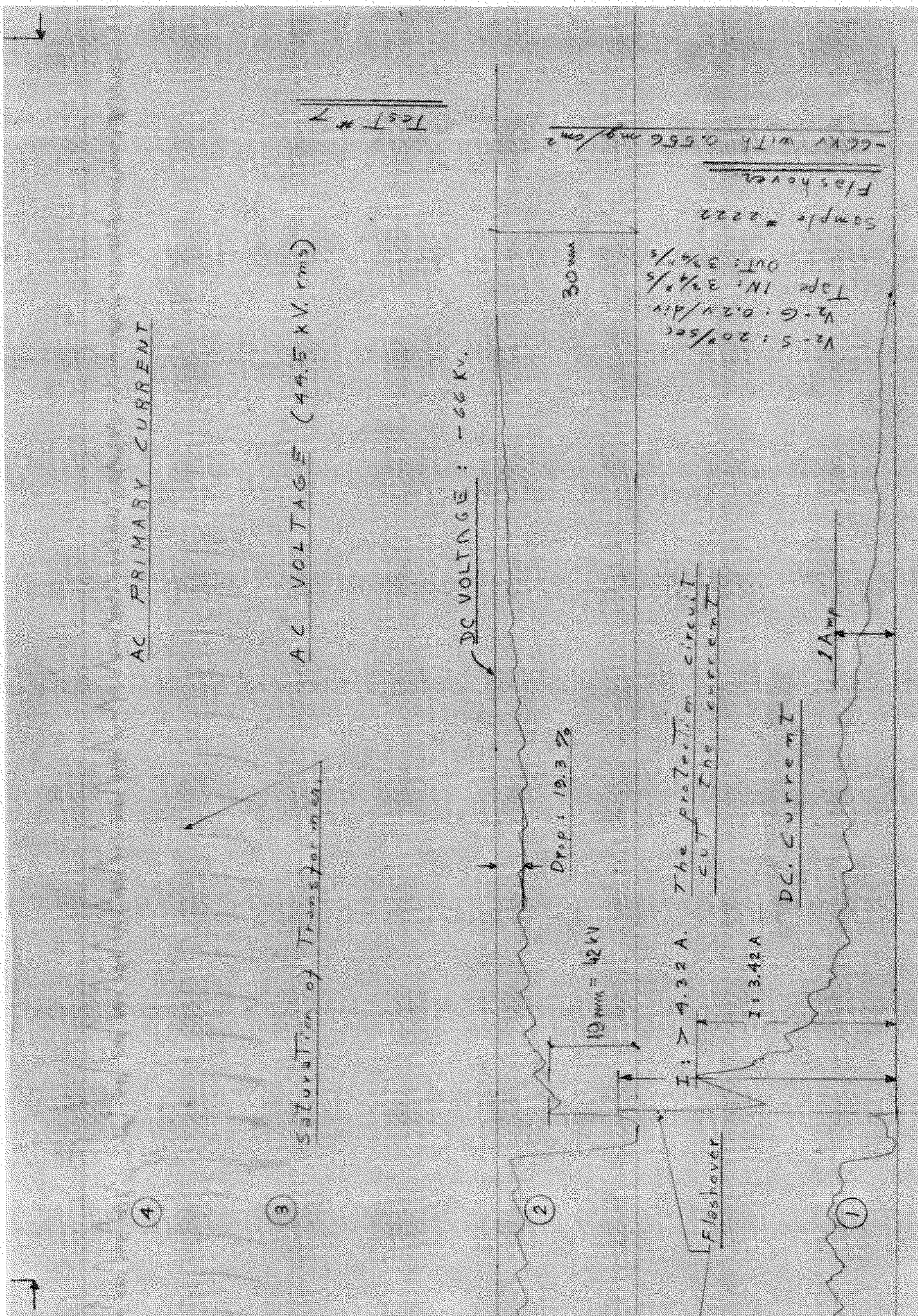

FIG. 14 Voltage and current before flashover test with half-wave rectifier

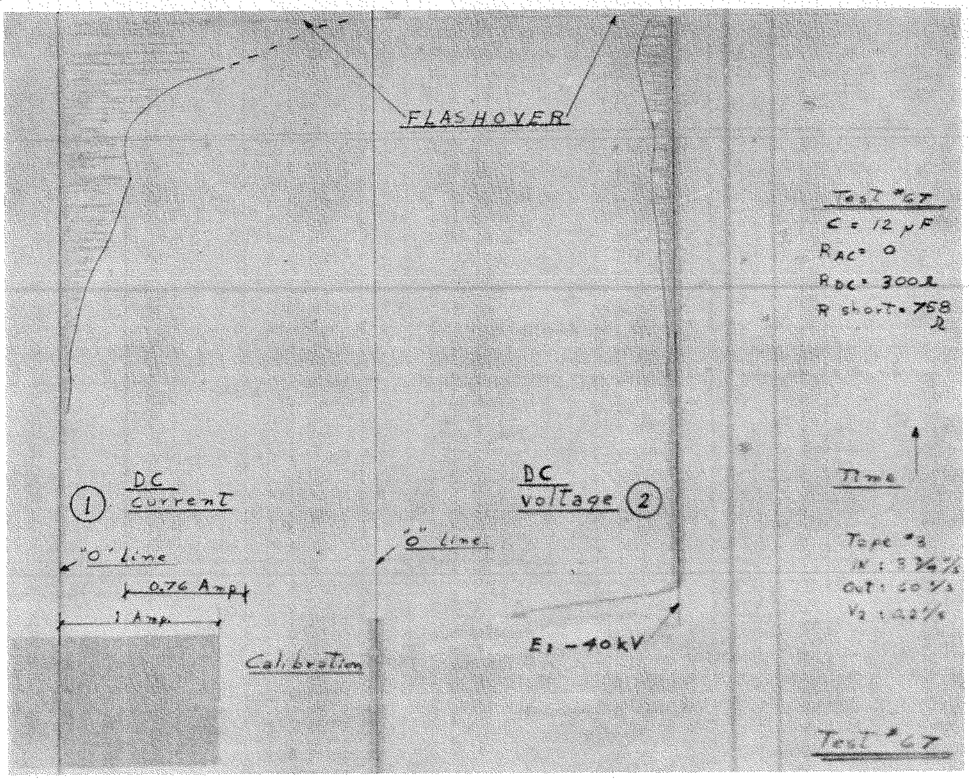

FIG. 15a Test with full-wave rectifier (flashover)

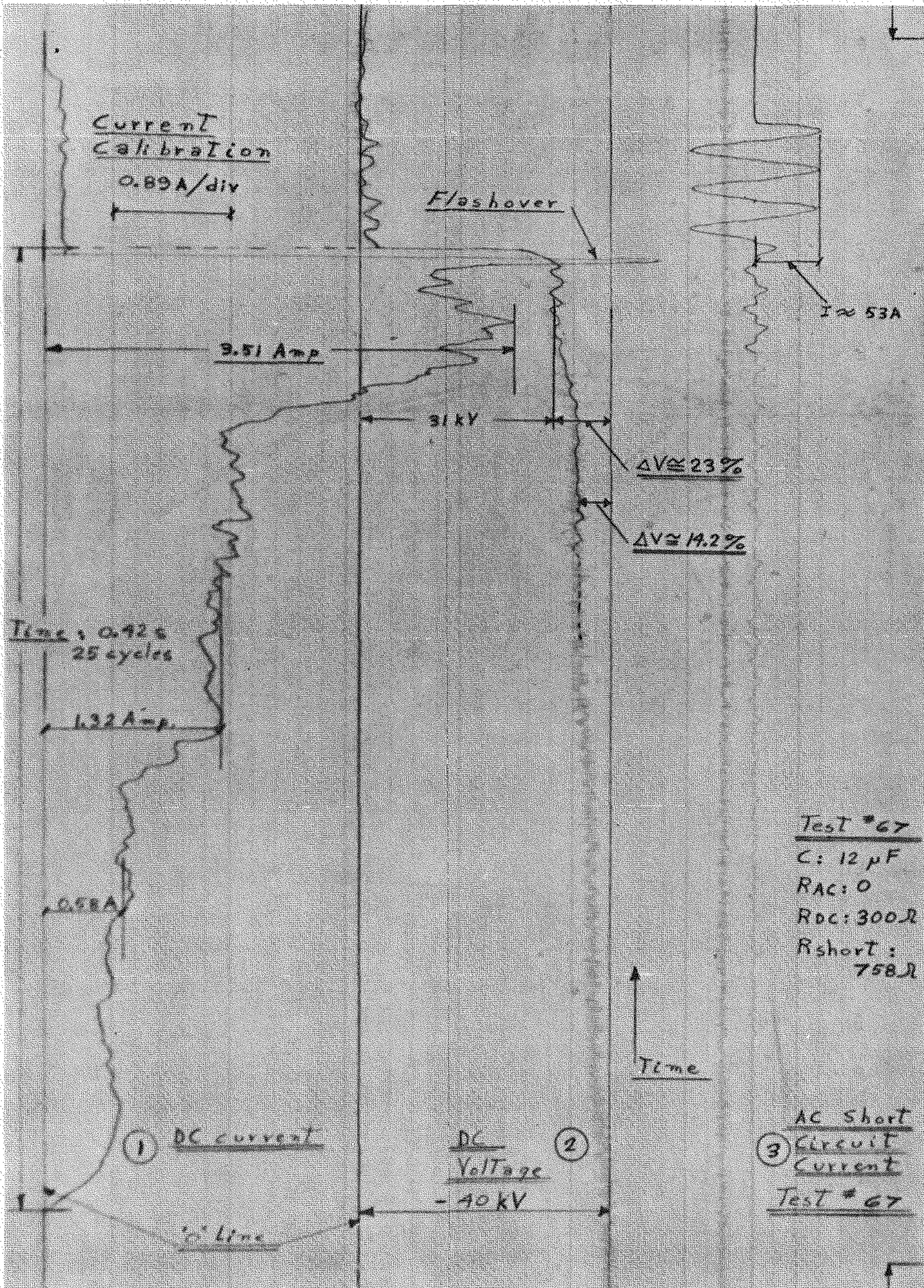

FIG. 15b Test with full-wave rectifier, voltage and current before flashover

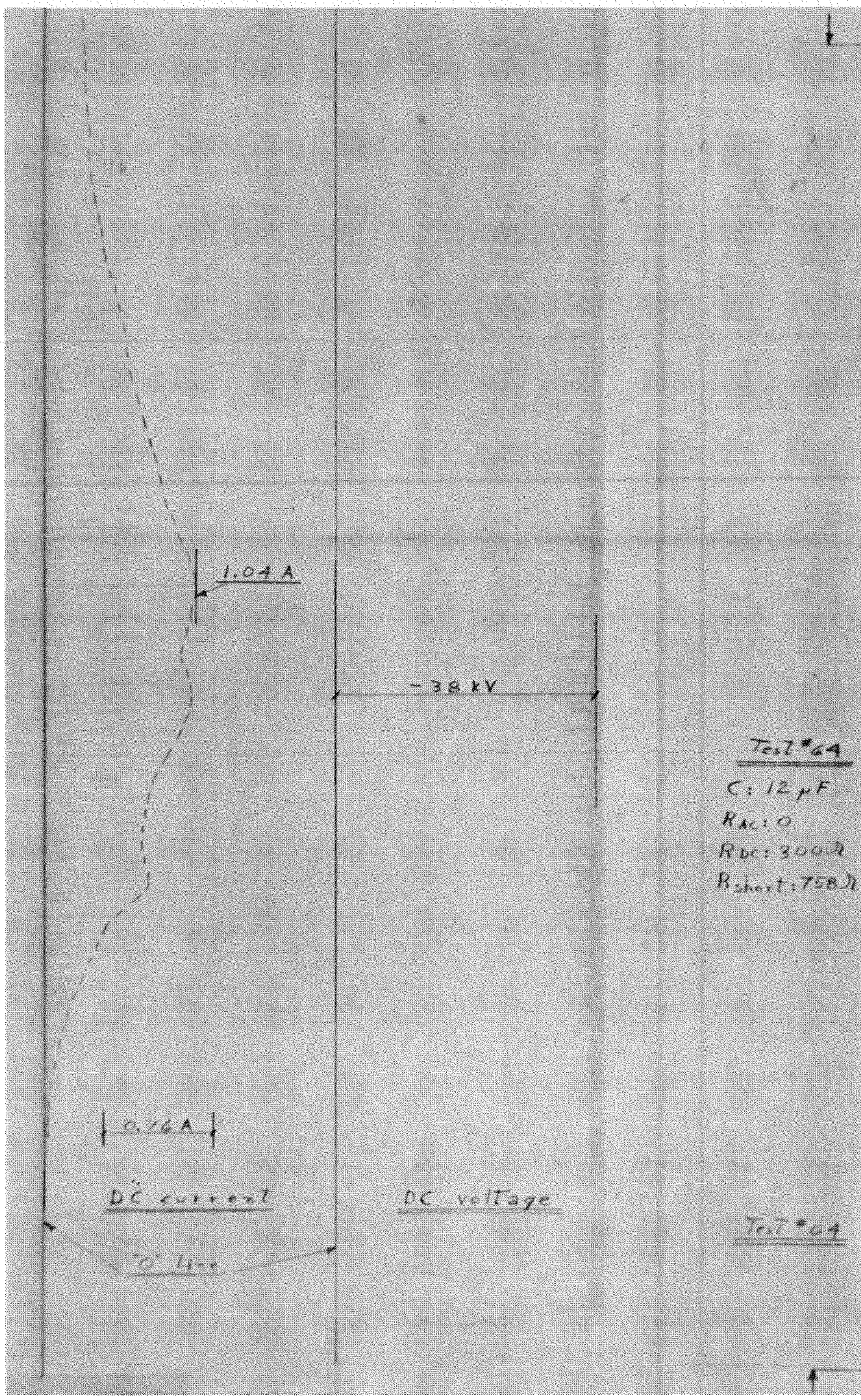

FIG. 16a Test with full-wave rectifier (withstand)

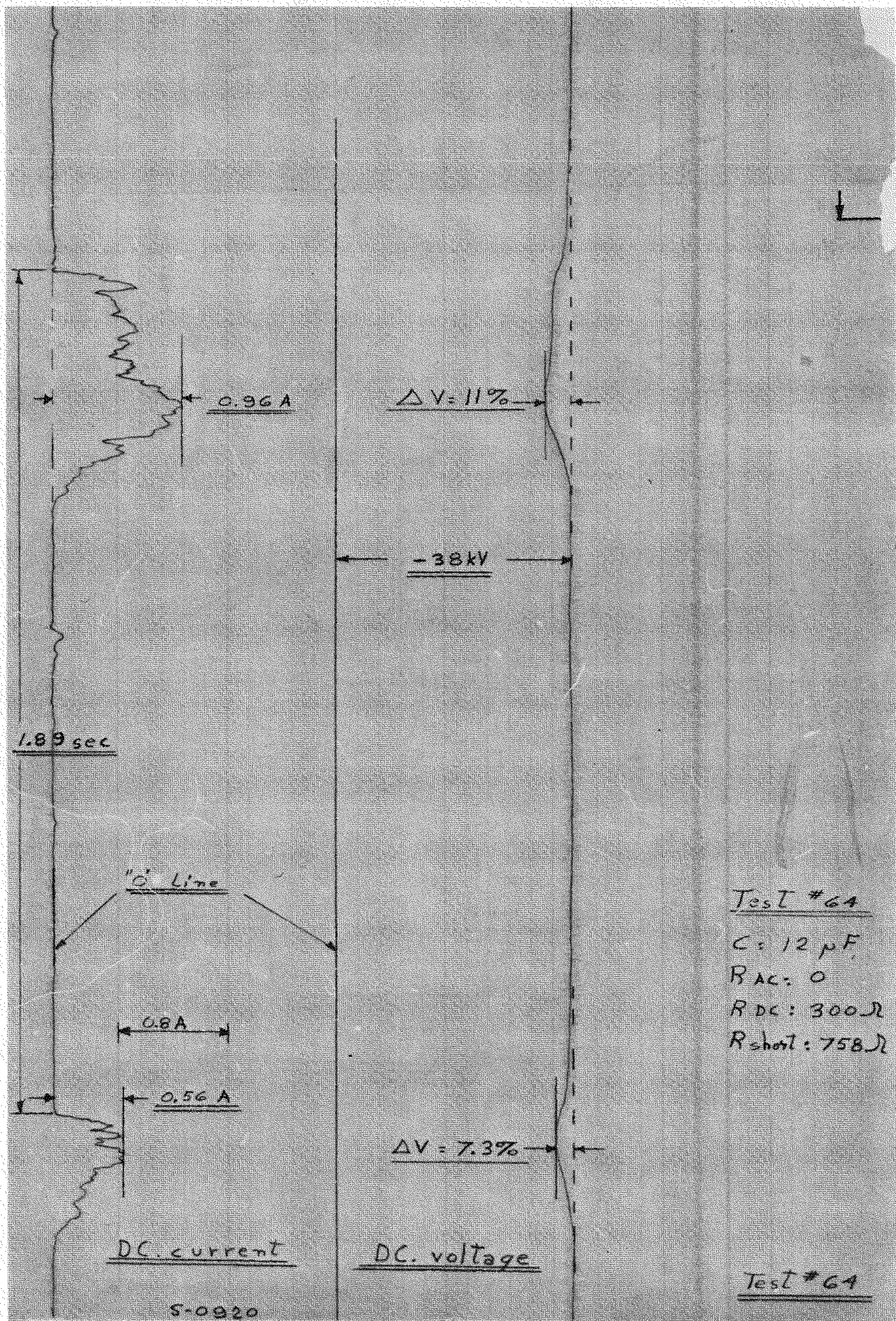

FIG. 16b Test with full-wave rectifier; enlarged part of oscillogram of Fig. 16a

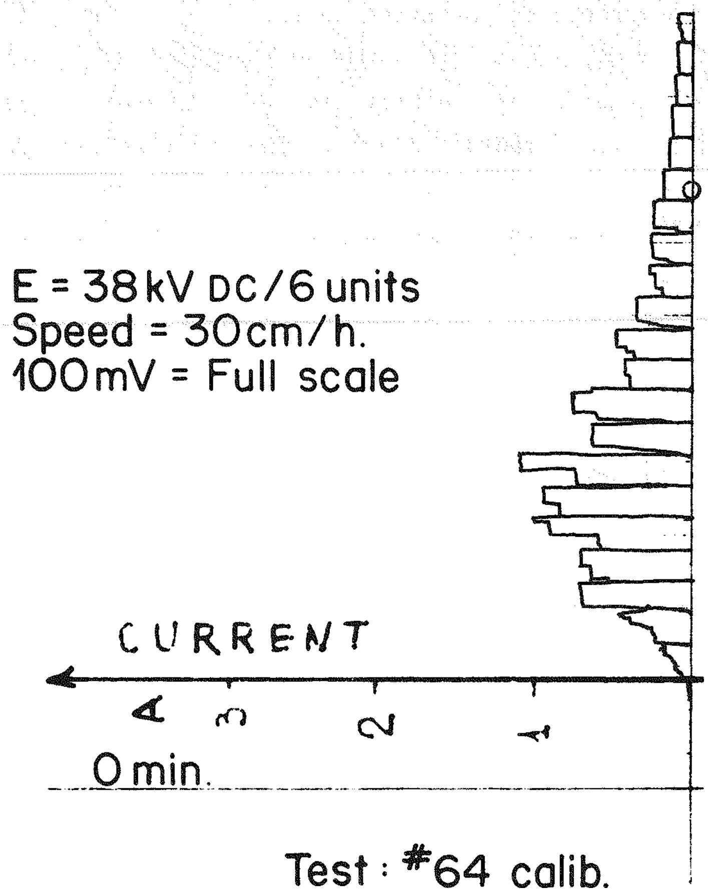

FIG. 17 Variation of maximum leakage current (measured by peak detector)

SHORT CIRCUIT AND LOADING TEST OF THE RECTIFIERS

The behavior of a rectifier is generally determined under steady-state conditions. For comparison, the steady-state parameters of the rectifier were determined, although it can be seen that these parameters do not describe fully the rectifier behavior during pollution tests.

The steady-state parameters of the rectifier were determined from the short circuit and loading measurements. The rectifier voltage was adjusted to the desired value without load, and the load resistance or the short circuit was inserted in the circuit by the flashover of a gap. The overcurrent protection system (or the operator) switched off the circuit after 0.5 ~ 1 second. This time was sufficient to obtain the steady-state value. During the pollution tests and the short circuit and loading tests, the current on the low voltage side of the rectifier transformer was measured.

- Cascade rectifier

The results of the flashover tests showed that this rectifier is too weak for pollution tests. The major parameters of this rectifier are given in the specifications supplied by ASEA. Therefore, a more precise measurement of the rectifier parameters was not performed.

- Half-wave rectifier

The results of the short circuit tests were not conclusive because of saturation.

The results of the loading test are shown in Table 4. A typical oscillogram with the voltage and current is shown in Fig. 18.

The oscillograms revealed that the saturation produces a heavy voltage drop even in the case of moderate loading.

- Full-wave rectifier

The results of the short circuit tests on the full-wave rectifier are summarized in Table 5.

TABLE 4

RESULTS OF LOADING TESTS WITH HALF-WAVE RECTIFIER

DC current in mA	AC at low voltage peak A	DC voltage kV max.	DC voltage kV min.	Voltage drop (fluctuation)	LOAD TEST
622	140	50.2	26	50%	
625	140	49.76	26.6	47.7%	
1830 (?)	289	100 kV*	40 kV	60%	*
756	125	51*	25.16	50.66%	
168 (?)		20 kV	0		short circuit

* During the loading, the maximum voltage increased about 5 - 10%.

TABLE 5

RESULTS OF SHORT CIRCUIT TESTS ON THE FULL-WAVE RECTIFIER

No	R_{AC} Ω	R_{DC} Ω	V_{DC} kV	$\hat{I}_{short}$ (DC) A	$\hat{I}_{AC}$ (low voltage) side A	$\hat{I}_{short}/\hat{I}_{AC}$
1	1800	300	24	10	301	30.1
2	1800	300	40	16	483	30.18
3	0	0	25	30	905.4	30.18
4	0	0	42	55	1660	30.18
5	0	0	22	26.2	785	29.96
6	0	0	27	34.2	1026	30

The short circuit current-voltage function is shown in Fig. 19

LEAKAGE CURRENT TESTS

Depending on the test method, the pollution level is defined either by the equivalent deposit density or by the surface conductivity.

The equivalent deposit density is calculated from the measured conductivity of the solution obtained by washing down the pollution from the insulators. The surface conductivity is calculated from the minimum resistance of the insulator using the form factor of the insulators.

The minimum resistance is calculated from the low voltage leakage current measurement. The dry, polluted insulators are installed in the fog chamber. The fog is applied and the insulators are energized to 300 V/unit for 30 sec. every 2-5 minutes. The voltage and current are measured and the insulator resistance is calculated.

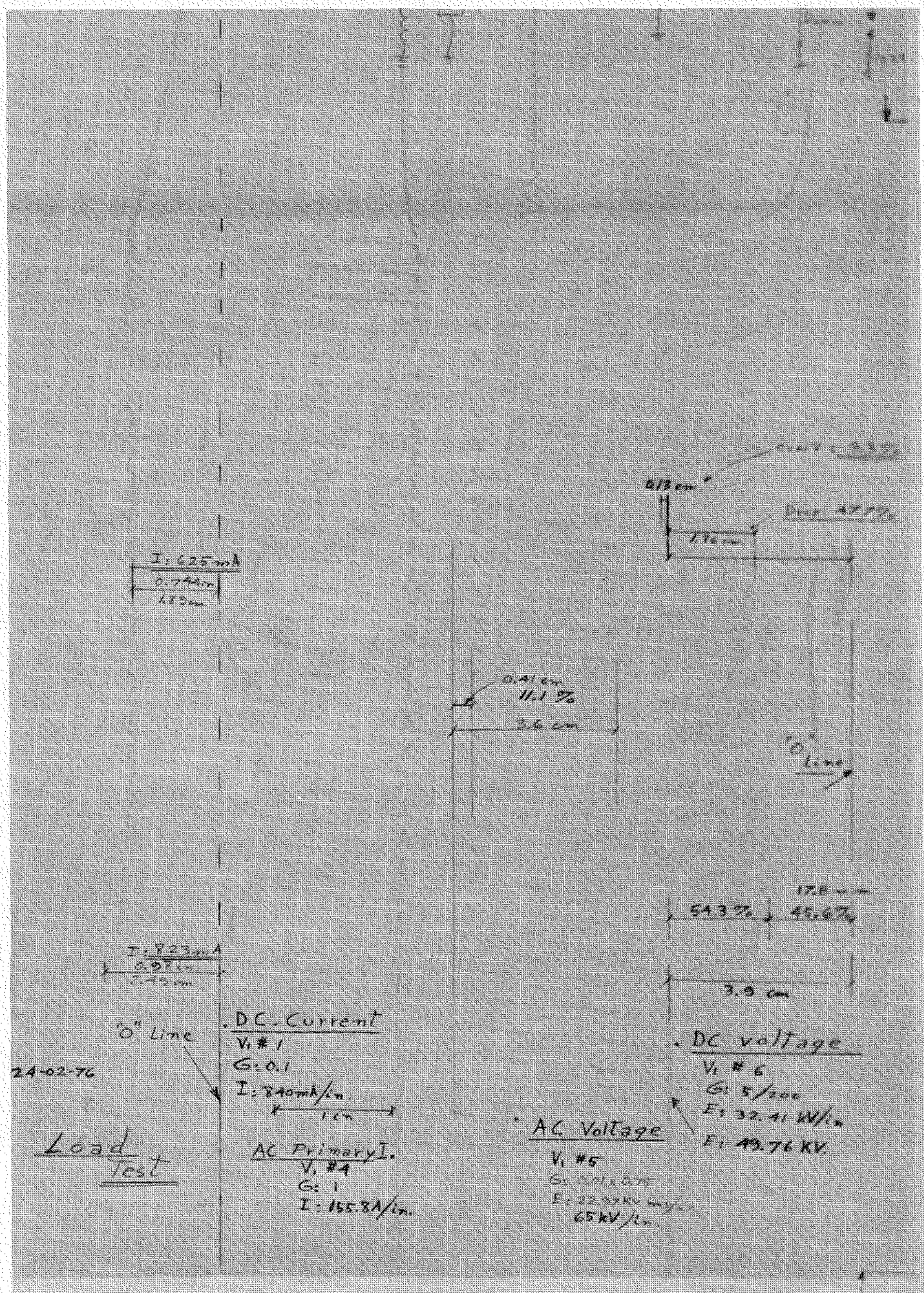

FIG. 18 Loading test on half-wave rectifier

There were several tests performed during the study. The test results are given in Table 6.

TABLE 6

RESULTS OF SURFACE RESISTIVITY OBTAINED BY LEAKAGE CURRENT MEASUREMENT

Equivalent deposit density mg/cm^2	Minimum resistance per unit kΩ	Lowest surface resistivity* kΩ	Test No.		
0.31	10.3	10.9	Table 1	1	STEAM
0.65	8.1	8.57	Table 1	2	STEAM
0.525	14.15	14.95	Table 1	3	STEAM
0.525	12.87	13.62	Table 1	4	STEAM
0.525	14.42	15.26	Table 1	5	STEAM
	13.8	14.62	Average of tests 3-5		
0.530	failure of equipment		Table 3	25	WARM FOG
0.571	8.57	9.069	Table 3	26	WARM FOG
0.571	7.50	7.94	Table 3	27	WARM FOG
0.571	8.04 kV	8.51	Average of tests 26-27		

* The lowest surface resistivity is determined by dividing the minimum resistance by the form factor f of the insulator. In the case of the insulator tested the form factor was 0.945.

Section 7

DISCUSSION AND EVALUATION OF TEST RESULTS

The test results were evaluated with the following aims in mind:

- Determination of the parameters of the rectifiers used for the tests
- Determination of the nature of the leakage current during the dc pollution tests
- Determination of the effect of the rectifier parameters on the dc flashover voltage of polluted insulators

RECTIFIER PARAMETERS

Half-wave rectifier, steady state conditions. Fig. 18 indicates that the loading causes the dc current to increase rapidly from zero to 0.823 A, after which the current starts to decrease. The steady state value of 0.625 A is reached after 5-7 cycles (83 ~ 117 ms). There is a small 60 Hz fluctuation in the current.

The loading produces a sudden drop in the dc voltage (54.3%). However, after a few cycles, the rectifier restores the voltage, furthermore the load current increases the fluctuation of the dc voltage. Interestingly, the maximum voltage is about 3.3% higher than the no-load voltage. The fluctuation is 47.7%. The ac voltage shows a saturation which reduces the negative peak value by about 11%.

The dc voltage fluctuation of a single phase rectifier without transformer saturation can be calculated using equation 8

$$V_{fluct} = \frac{I_{dc}}{fC} \qquad (8)$$

In the case under discussion, C = 3 μF and I_{dc} = 0.625 A. Using these values the expected voltage fluctuation is 3.47 kV, which corresponds to 6.98% (no-load dc voltage of 49.76 kV).

It can be seen that the actual fluctuation is 47.7% much larger than the calculated one. This is due to the effect of saturation.

Table 4 shows that doubling the voltage nearly tripled the current, but increased the fluctuation by only about 10%; the increase calculated from Eq. 8 should be much larger.

These results indicate that the half-wave rectifier, because of saturation, represents a weak source, and that the parameters of such a source are difficult to define. However, this circuit represents an attractive solution for extra high voltage. Therefore, a few tests were performed with the half-wave rectifier to determine the feasibility of the method, but the majority of the tests was performed with the full-wave rectifier.

Full-wave rectifier steady-state conditions. The short circuit test indicates that there is no saturation of the full-wave rectifier circuit and analysis of the results indicates:

- The short circuit current increases linearly with voltage (Fig. 19).
- The short circuit current can be calculated with sufficient accuracy from the current of the transformer, as measured on the low voltage side. This current was measured during each test. Using these results, the short circuit currents for the different test series (F1 - F7) are plotted in Fig. 20.
- The rectifier circuit can be characterized by the short circuit resistance (R_{short}). The short circuit resistance of the circuit used for tests F1 - F8 is indicated on Fig. 20 and presented in Table 7.

It can be seen that:

- The condenser does not affect the short circuit current. The rectifier short circuit resistance is about 810 Ω in the case of F1, F2, F3, and F8. The observed (about ±6.5%) deviation of the measured values is due to measuring errors.

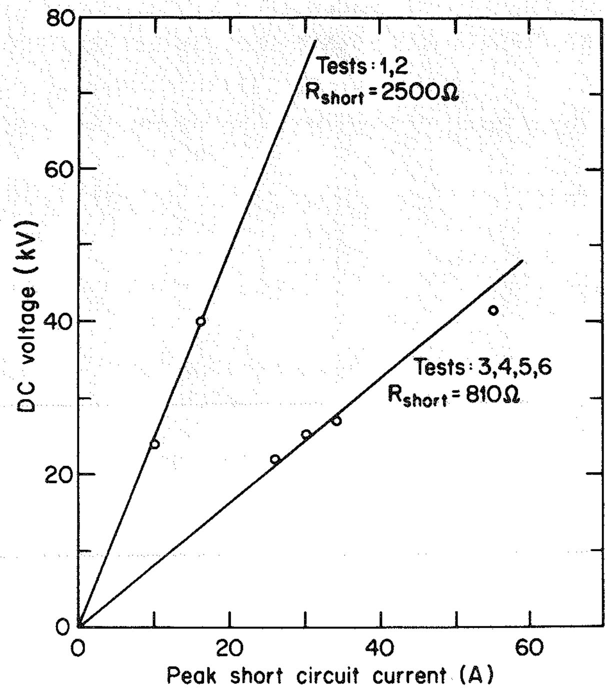

FIG. 19 Voltage - short circuit current relation for full-wave rectifier

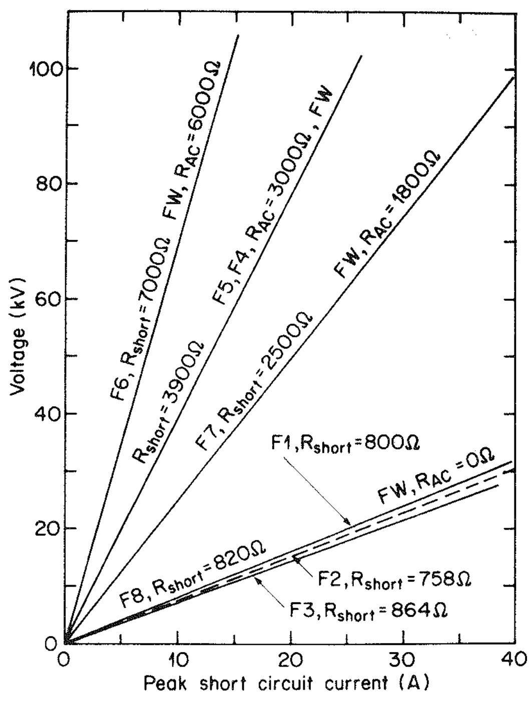

FIG. 20 Short circuit current of full-wave rectifier

TABLE 7

VALUES OF THE SHORT CIRCUIT RESISTANCE FOR THE TESTS F1 TO F8 WITH THE FULL-WAVE RECTIFIER

NUMBER OF TEST SERIES	R_{short} Ω
F1	800
F2	758
F3	864
F4	3900
F5	3780
F6	7000
F7	2500
F8	820

- F4, F5, and F6 show that the ac resistance is simply to be added to the rectifier short circuit resistance e.g. in the case of F4, R_{AC} = 3000 Ω and the rectifier short circuit resistance is 800 Ω. The expected new short circuit resistance is 3800 Ω; the measured value is 3900 Ω.
- The dc resistance R_{DC} = 3000 Ω increases the rectifier resistance, but only 2500 Ω was measured. This is in contradiction to expectation. The circuit must be studied further.

The equivalent resistance facilitates the calculation of the expected average voltage drop under steady-state conditions:

$$\Delta V_2 = V_o - V = I\,R_{short} \qquad (10)$$

where: I is the dc current; V_o is the no-load voltage; R_{short} is the short circuit resistance; V is the voltage at load of I

The maximum current is of the order of 3 - 4 A. Therefore, the voltage drop is in the range of 2400 - 3200 V, which is about 6 ~ 8% at 40 kV in the case of circuits F1, F2, F3, and F8. The voltage drop will increase to 7500 ~ 10000 V, or 18 - 25%, for circuit F7 and it will be about 11340 ~ 15600 V, or 28 ~ 39%, for circuits F4 and F5. In the case of circuit F6, more than 28 kV, or 70%, is expected. This calculation is valid only under steady-state conditions; the dynamic voltage drop of the rectifier must be studied separately. However, the steady-state behaviour of the circuit gives a fair technical description of the circuits used for the pollution tests.

NOTE: The dynamic voltage drop is the voltage drop produced by a suddenly-appearing load current pulse.

The full-wave rectifier in circuits F1, F2, F3, and F8 represents a fairly powerful circuit. However, if a resistance is connected in series with the circuit (F4, F5, F6, F7) the voltage drop is expected to become prohibitively large.

ANALYSIS OF RECTIFIER BEHAVIOUR DURING THE POLLUTION TESTS

For each test the dc leakage current and the dc voltage were recorded and oscillograms similar to those shown on Figs. 15 a, b and 16 a, b were obtained. Analysis of these oscillograms shows:

- The leakage current contains irregularly shaped impulses with widely varying amplitudes (10 mA - 3 A) and durations (3 - 30 cycles). The time between the individual impulses varies between: 0.1 - 0.5 s. The leakage current impulses generally increase slowly - steps can be observed on the rising part of each pulse. After reaching its maximum value the current decreases rapidly. Physically, this behaviour corresponds to the gradual extension of the arc and, after reaching a certain length, its extinction. In some cases, the arc immediately re-ignites after extinction, thus producing a double pulse. Furthermore, 60 or 120 Hz fluctuations can be observed on the current pulses. The amplitude of the fluctuations depends on that of the voltage fluctuations, and its value can be decreased by the use of a smoothing capacitance.

- The current pulse discharges the condenser and produces a sudden dynamic voltage drop which increases the voltage fluctuation. Between the leakage current pulses there is no current (the rectifier is in a no-load condition). The dc voltage fluctuation during this phase is negligible.

  (the time between the current pulses is generally sufficient to restore the rectifier voltage to the no-load value. However, in some cases the time is not sufficiently long, resulting in an excessive voltage drop).

  A dynamic voltage drop can be observed on the oscillogram of Fig. 14 (half-wave rectifier, with a 3 μF smoothing capacitance, Test 7). The current increases to 0.8 - 1 A and stays constant for about 6 - 8 cycles. This current produces a 19.3%, or 12.73 kV, voltage drop. The voltage fluctuation is about 6.16 kV or 9.3%. The rectifier is supplied by a 1 MVA 200 kV, 5 A transformer.

- Short circuit measurements show that the combined transformer and supply impedance is 3448 Ω at 200 kV. The voltage drop of the transformer at 1 A should therefore be about 3.45 kV or 5.2% referred to 66 kV. The measured voltage drop due to saturation is about 14.5% at 1 A dc. The expected voltage fluctuation is calculated using equation below. The value for 1 A is:

$$\Delta V = \frac{I}{f\ C} = \frac{1}{60.3E-6} = 5.54\ kV,$$

which is smaller than the measured value. This difference may also be explained by saturation.

Increasing the value of the condenser reduces the voltage fluctuation and the voltage drop, e.g. for Test 18 the shape of the current impulse is similar to that of Fig. 14, at 0.9 A the voltage drop is only 9.1%. The corresponding voltage fluctuation cannot be measured but is estimated to be less than 4%.

- The full-wave rectifier can be investigated using the results of Test 67 (R_{AC} = 0, R_{DC} = 300 Ω, C = 12 μF, R_{short} = 7.58, F 2), Fig. 15 b. For a current of 1.32 A, the voltage drop is about 14.2%, or 5.7 kV. The ripples, which are of the same magnitude as the noise, have an estimated amplitude of less than 6-7%.

The calculated voltage drop for a current of 1.32 A is 1.32 x 758 ≈ 1000 V or 2.5% which is less than the measured value of 20%. This result shows the difference between the steady-state and the dynamic voltage drop of the rectifier.

The expected amplitude of the ripples is calculated using the following equation

$$\Delta V = \frac{I_{dc}}{2f.C} = \frac{1.32}{2.60.12E-6} \simeq 916\ V \text{ or } 2.29\%,$$

which is of the same order as the measured value.

Reduction of the capacitance to 3.02 μF will increase the voltage fluctuation, e.g. during Test 35 a 15% fluctuation and a 12.4% voltage drop were measured at a current of 1.2 A.

The calculation gives a 6.6 kV or 16.6% voltage fluctuation, in good agreement with the results of the measurement. Decreasing the value of the condenser to 0.1 μF produces a 120 Hz variation of the current with a minimum value of almost zero. The voltage also varies with a frequency of 120 Hz, and its amplitude varies between 110% and 70% of the nominal value when the current varies between 0.5 and 1.5 A.

The voltage across the insulator can no longer be considered dc rather it is a dc voltage with a superimposed large ac component.

- This analysis suggests that the condenser value is determined by the permissible value of the voltage fluctuation. The effect of the voltage fluctuation cannot be separated from the effect of the voltage drop. However, it is suggested that the voltage fluctuation is mainly responsible for the dependence of the flashover voltage on the value of the smoothing condenser.

- A comparison of the steady-state and the dynamic behaviour shows that the dynamic voltage drop is much larger than the steady-state value. Therefore, the expected pollution behaviour of a rectifier can be estimated only by a test involving sudden dynamic loading.

  A study of the oscillograms indicates that the voltage drop has different values for the same peak current because of the different shapes of the current impulses. This suggests a statistical evaluation of the leakage current.

STATISTICAL EVALUATION OF THE LEAKAGE CURRENT

In order to determine the "voltage drop-rectifier parameters" relation, the leakage current and voltage drop recorded on the magnetic tape were analyzed by computer. The computer determined the peak value of each current impulse and the integral of the current impulse (which represents its charge), together with the voltage drop produced by the current impulse. The values obtained were plotted and typical results are shown on Figs. 21 and 22.

Fig. 21 shows the correlation between voltage drop and peak value of the leakage current impulses.

Fig. 22 shows the correlation between the voltage drop and the charge of current impulse.

The figures show that there is a significant spread in the measured values, but that in each case, an average curve and a boundary of the values can be determined. These curves are marked in Figs. 21 and 22. For the following analyses, only the average curve will be used. In order to discriminate against noise which was observed on the magnetic tape and to avoid the disturbance produced by flashovers, the computer was programmed to select only current impulses of amplitude between 1.5 A and 50 mA of duration longer than 20 ms and carrying a charge of less than 0.08 C.

Current pulses larger than 1.5 A generally occur just before flashover. These pulses are studied individually and the results are presented in Fig. 38.

Two tests from each series were analyzed by this method - one test involved insulators which flashed over and the other involved no flashover. The curves show the behaviour of the rectifier under different load conditions, and the

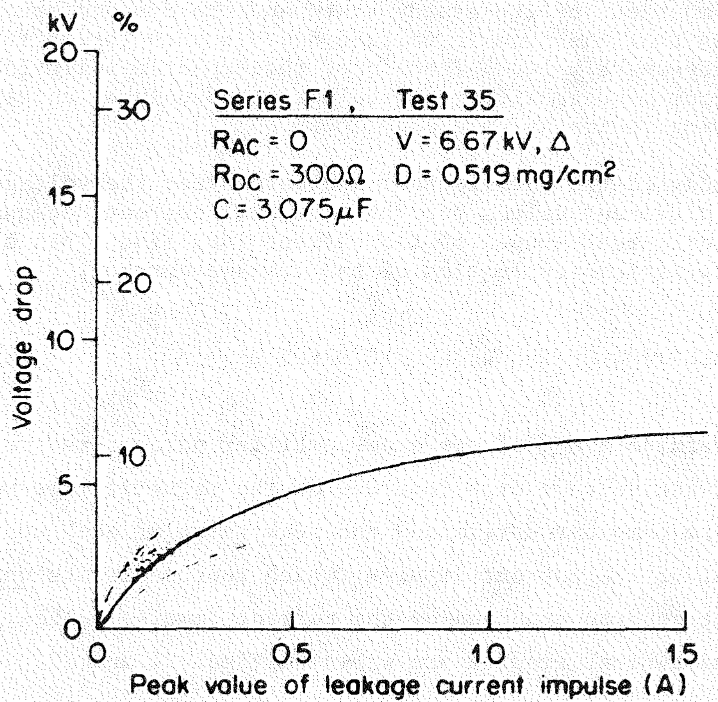

FIG. 21 Correlation between voltage drop and charge

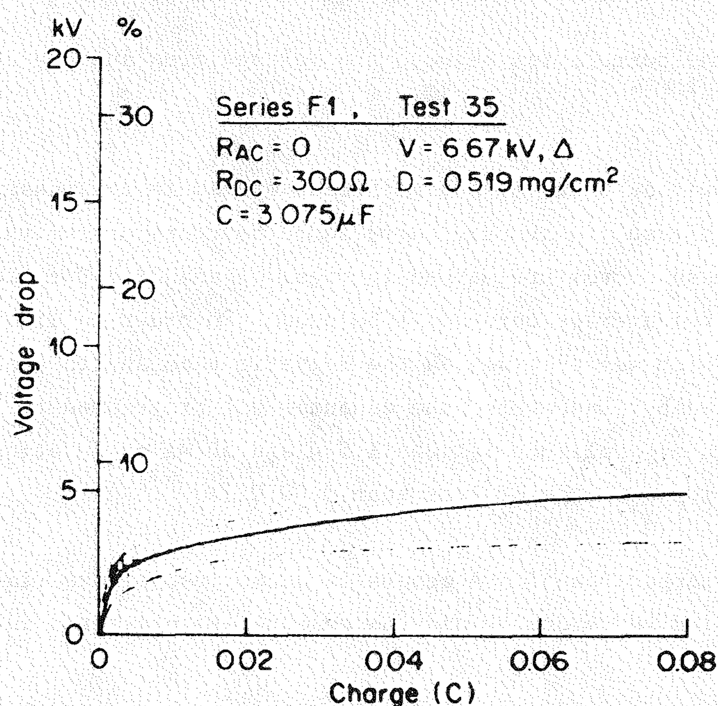

FIG. 22 Correlation between voltage drop and charge

influence of the rectifier parameters. All the average curves obtained are shown in Figs. 23 - 31 where the curves are arranged according to the rectifier parameters.

Fig. 23 shows the difference between the half- and full-wave rectifiers.

Figs. 24-26 show the variation of the voltage drop as a function of leakage current for different values of the rectifier parameters.

Figs. 27-29 show the voltage drop as a function of the charge of the leakage current impulses for different values of the rectifier parameters.

Figs. 30-31 show the effect of pollution severity.

a) <u>The dynamic rectifier characteristics</u>

On Figs. 21 and 22 each point represents a measured value. It can be seen that several different voltage drop values occur for each current or charge value. In other words, the rectifier "voltage drop-current" or "voltage drop-charge" curves are not single-valued functions. Analysis of the oscillograms suggests that this phenomenon is caused by:

- The different durations and shapes of the current pulses, causing varying voltage drops for pulses of the same peak current value. The durations and amplitudes of the current pulses show a statistical distribution, as shown in the previous report, causing a corresponding spread in the voltage drops.
- The time intervals between succeeding current impulses are distributed statistically. If the time interval is less than three times the rectifier time constant, the voltage drop will be influenced by the time interval between the current pulses, since there will then be too little time to allow the rectifier to recover.
- Measuring error. The magnetic recording introduces about 5-6% noise. This factor is considered to be insignificant, however, because it is largely eliminated by the programming method.

The shapes of the "voltage drop-current" curves of the rectifier are shown in Figs. 23-26. It can be seen that the relation is non-linear. If the rectifier is powerful, e.g. in Fig. 25, curve F1 shows saturation and the voltage drop

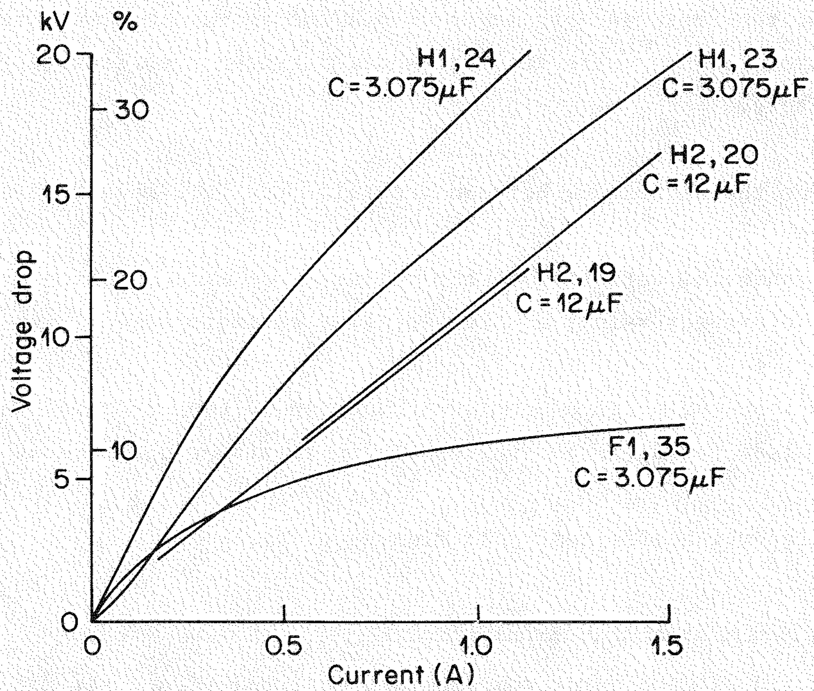

FIG. 23 Effect of rectifier connection on voltage drop - current function H: half-wave, F: full-wave

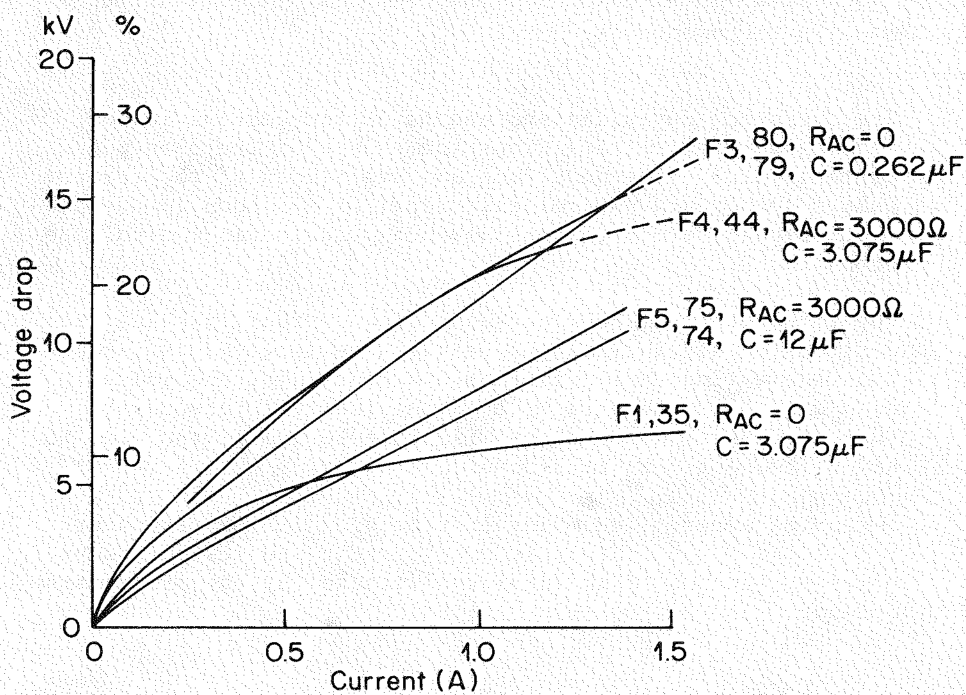

FIG. 24 The smoothing condenser effect of voltage drop - current function

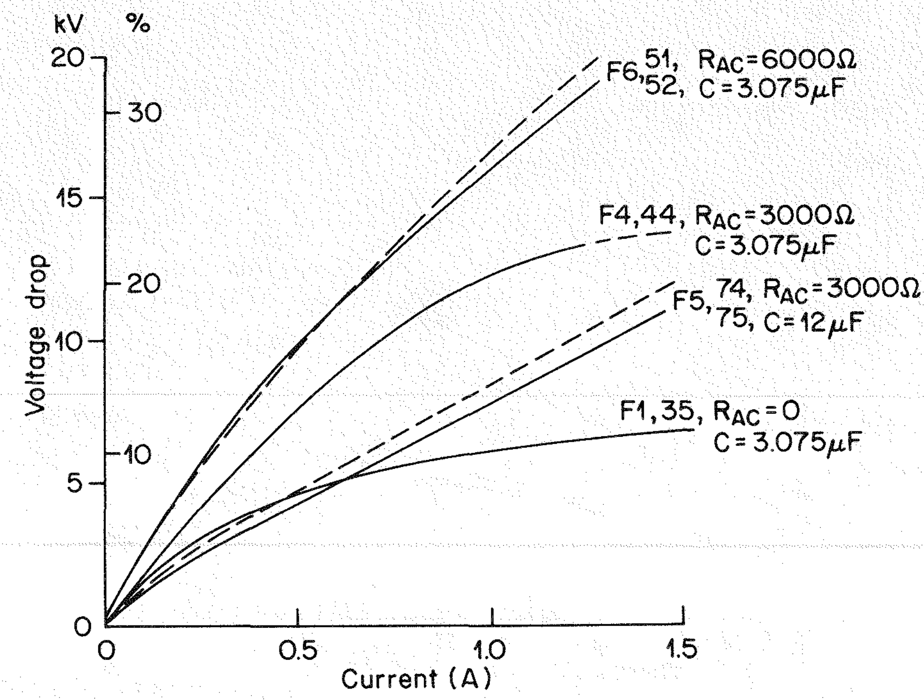

FIG. 25 Effect of ac resistance on voltage drop - current function

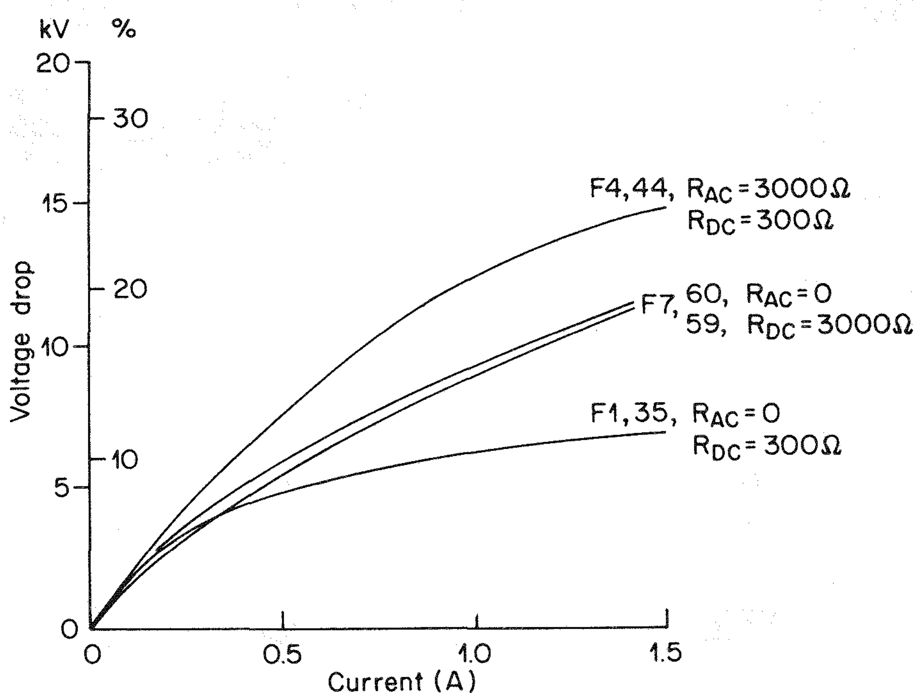

FIG. 26 Effect of dc resistance on voltage drop - current function

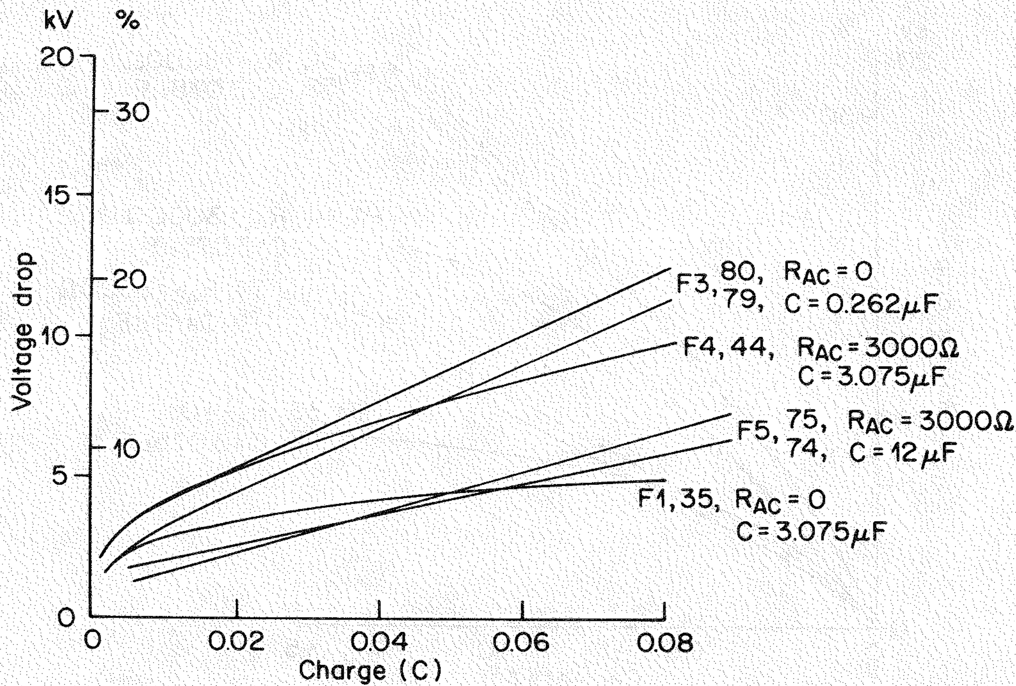

FIG. 27 Effect of condenser on voltage drop - charge function

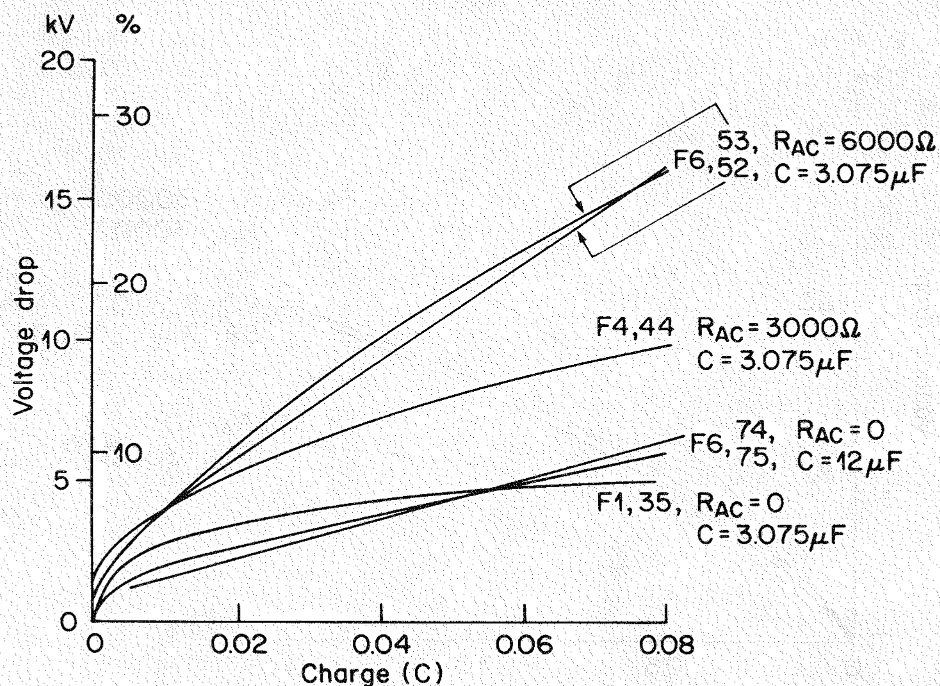

FIG. 28 Effect of ac resistance on the voltage drop - charge function

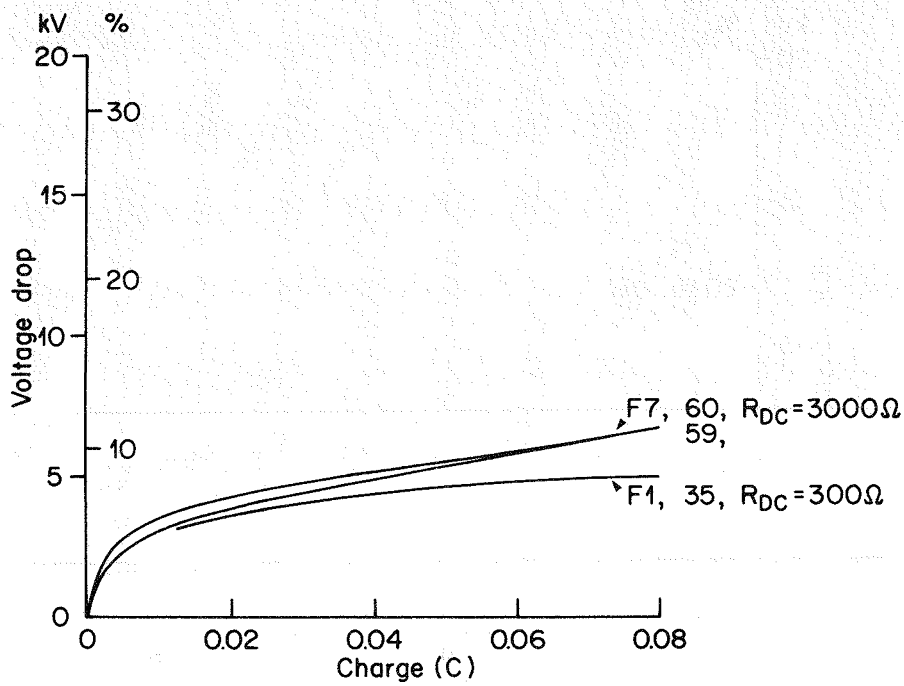

FIG. 29 Effect of dc resistance on the voltage drop - charge function

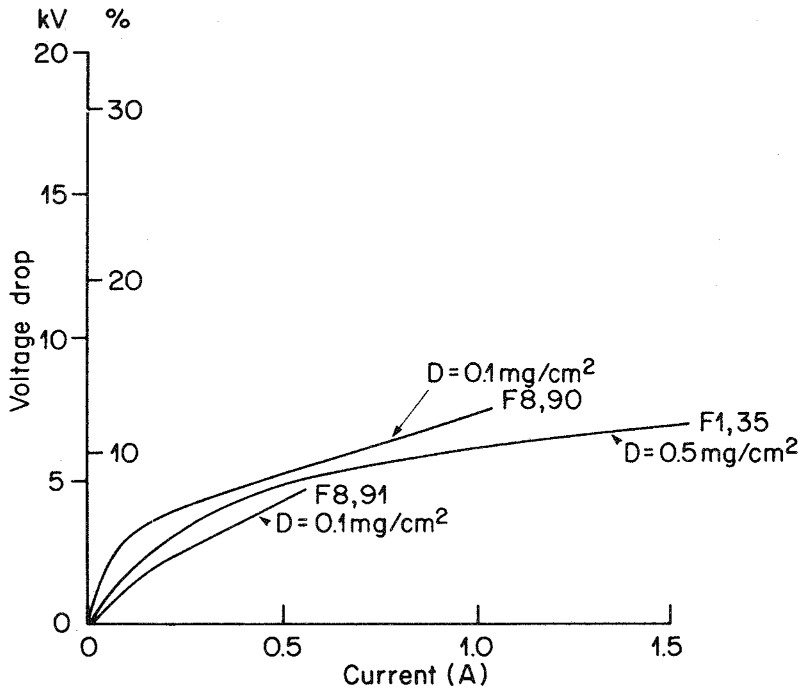

FIG. 30 Effect of pollution on the voltage drop - current function

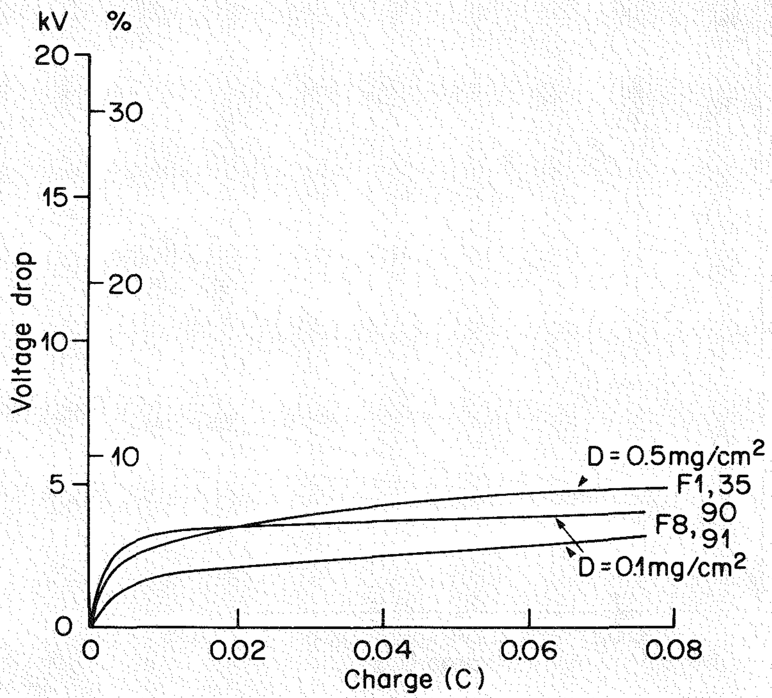

FIG. 31 Effect of pollution on the voltage drop - charge function

becomes more or less independent of the current. The rectifier in the case of curve F1 is the most powerful connection used for these tests (R_{AC} = 0, R_{DC} = 300 Ω, C = 3.075 μF).

As the power of the rectifier is reduced e.g. by a series ac resistance, the curves become more linear e.g. F6, when a 6000 Ω resistance is connected in series with the rectifier the characteristic is nearly linear.

The shapes of "voltage drop-charge" curves of the rectifier are shown on Figs. 27-31. It can be seen that, in the case of test series F1 and F7, when there is no ac resistance in the rectifier circuit, the curves show saturation, and that the voltage drop does not depend significantly on the charge when the latter exceeds 0.04 C.

However, when the rectifier power is reduced by an ac resistance, the voltage drop increases more or less linearly with the associated charge (e.g. F3, F4, F6) when the latter exceeds 0.02 C.

One explanation may be that the current pulses carrying small charges and having a short duration may drain the condenser, producing the initial 4-6% voltage drop. The pulses carrying more charge have a longer duration, and the rectifier is able to recharge the condenser.

If the rectifier is powerful, it recharges the condenser quickly, resulting, we believe, in saturation. If the rectifier power is reduced by an ac resistance, however, the recharging time will be longer, resulting in a more or less linear dependence of the voltage drop on the charge.

THE EFFECT OF THE RECTIFIER PARAMETERS ON THE FLASHOVER VOLTAGE

Cascade rectifier

The oscillogram of Fig. 13 a shows that the leakage current impulses increase gradually as the wetting progresses. After the application of fog the leakage current produces a voltage drop and an overvoltage subsequently occurs. This can be seen more clearly on Fig. 13 b. This oscillogram indicates that even a moderate current (100 - 150 mA) produces a large (30 - 40%) voltage drop.

This indicates that the time response of the voltage regulator in the rectifier is not sufficiently fast to compensate the sudden voltage drop produced by the current pulse. The overvoltage indicates that the voltage regulator overcompensates the voltage drop after a certain delay.

Towards the end of the test, when the leakage current impulse reached 800 mA, a series of arcings or flashovers occurred. This large current pulse paralyzed the control system and the voltage fell almost to zero.

The approximate relation between the current and the voltage drop, as derived from the oscillograms, is given in Fig. 32. It can be seen that:

- The voltage drop of the cascade rectifier is very high, even without the dc resistance of 15 kΩ.
- Use of a condenser reduced the voltage drop and, as shown on oscillograms not presented here, the overvoltage as well. However, current impulses larger than 800 mA produced a sudden discharge of the condenser and the voltage dropped practically to zero.
- After the current impulse the rectifier recharges the condenser and restores the voltage, generally before the next

current impulse occurs. However, the large 12 μF capacitance increases the time required to restore the voltage, so that the next impulse may occur before the full voltage is reached.

- The 50% flashover voltage of this insulator chain is between 11 kV/unit and 8.89 kV/unit but, due to the limited capacity of the power supply, it is difficult to judge whether or not flashover occurred.

The results lead to the conclusion that the measured leakage current pulses have higher peak values and longer durations than would be expected from consulting the available literature. Consequently, the present cascade rectifier set, even when equipped with an additional condenser, does not meet the test requirements. However, a more powerful version of this circuit, with a better (faster) control would be an ideal solution.

Half-wave rectifier

The oscillogram of Fig. 14 shows the voltage and current before flashover. It can be seen that the dc current increases slowly up to 4 A. Simultaneously, the voltage decreases. The voltage drop at 1 A is about 19.3%, which corres-

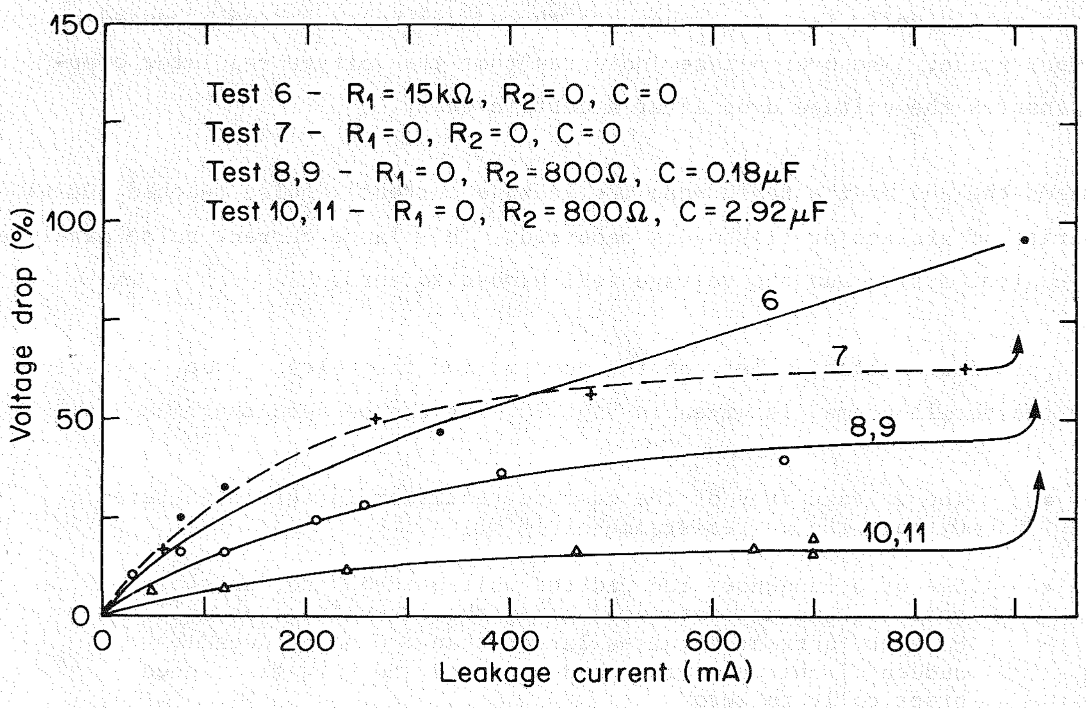

FIG. 32 Voltage drop - current characteristic of cascade rectifier

ponds to 12.7 kV. The current before flashover decreases and suddenly starts to increase very rapidly. The peak before the increase is 3.42 A. As the current increases the voltage collapses and flashover occurs. The voltage before the flashover is 40.7 kV; the voltage drop is about 38%. The current is estimated to be about 4.32 A.

It can be seen that after flashover, the arc extinguishes and repeated flashovers occur. This is due to the delay in the operation of the protection system on the ac side.

The leakage current produces saturation in the transformer. Thus effect can be observed on the transformer-voltage and the primary-current oscillograms. This saturation is responsible for the excessive voltage drop observed during the current pulses. The short-circuit current of the transformer was measured and it was found to be 29 A at 100 kV using the IREQ standard supply.

The results of Table 2 are summarized in Table 8.

TABLE 8

SUMMARY OF THE RESULTS OBTAINED WITH THE HALF-WAVE RECTIFIER

Series	$R_{AC}(\Omega)$	$R_{DC}(\Omega)$	C μF	$V_{50\%}$(kV)	I_{max}(A)	V_{min}/ kV/unit average
H 1	0	300	3.075	6.97	4.2	4.51
H 2	0	300	11.75	6.97	4.48	4.97

It can be seen that the condenser does not influence the 50% flashover voltage. The maximum current before the flashover was between 1 - 4.5 A. The voltage just before the flashover varied between 4.11 - 5.83 kV. Neither of these quantities seems to depend on the value of the condenser.

An evaluation of the results leads to the conclusion that the saturation observed during the tests with the powerful single-phase rectifier raises doubts about the feasibility of using this equipment for such tests.

The saturation can be avoided by:

- Application of a powerful cascade rectifier
- Application of a high-speed voltage regulator which would increase the transformer voltage to compensate the voltage drop, and if the transformer had a third low-voltage winding, it could be loaded during the off-load cycle, thus reducing the effects of the saturation.

Full-wave rectifier

The oscillograms on Fig. 15 a, b show a test (Test 67) during which the insulator flashed over and Fig. 16 a, b presents a test (Test 67) during which the insulator withstood the voltage.

It can be seen that in both cases the leakage current impulses increase with progressive wetting. In the case of flashover the current decreases, after which a gradually increasing current impulse occurs (Fig. 15 b), which finally leads to flashover. In these impulses three steps can be distinguished - the first of about 0.58 A, the second of 1.32 A, and the third of 3.51 A. After the third step the current decreases and suddenly increases up to flashover. The current pulse produces a more or less steadily increasing voltage drop. The voltage before flashover is V_{min} = 30 kV, which corresponds to a 25% voltage drop.

In the case of withstand, the current decreases after reaching the maximum value. This is probably due to the washing effect of the fog. The variation of the peak current can be observed very well on Fig. 16 a. Fig. 16 b shows magnified views of two voltage impulses. It can be seen that the current pulse produces a voltage drop, but that the rectifier restores the voltage between the two impulses. The frequency of the impulses is about 0.5 - 2 Hz. The maximum current is about 1 A.

Using the full-wave rectifier as the dc voltage source, the 50% flashover voltage was plotted as a function of different rectifier parameters. The results are shown in Fig. 3.

Fig. 33 shows the effect of a smoothing condenser for ac resistance values of 0 and 3000 Ω.

Fig. 34 shows the effect of the short circuit current.

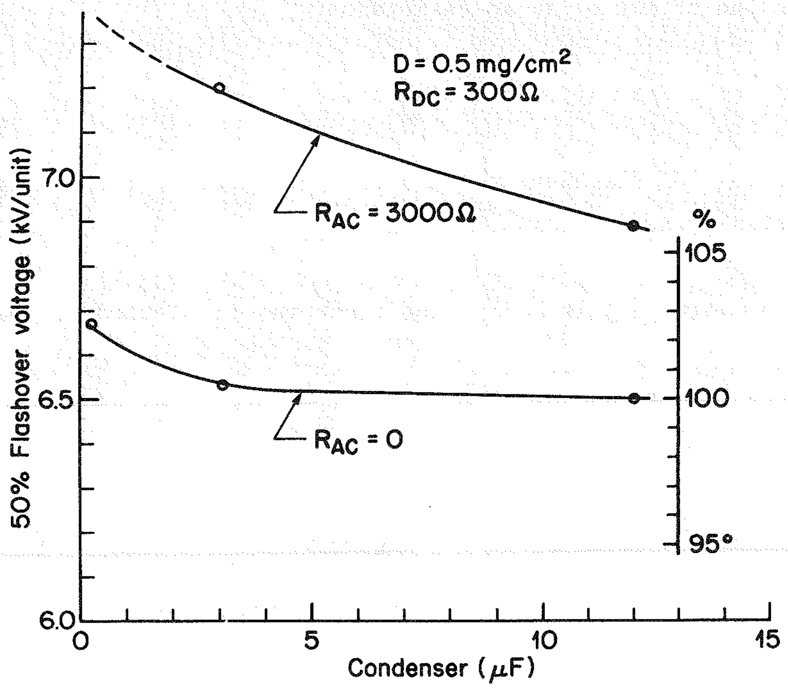

FIG. 33 The 50% flashover voltage in function of capacitance

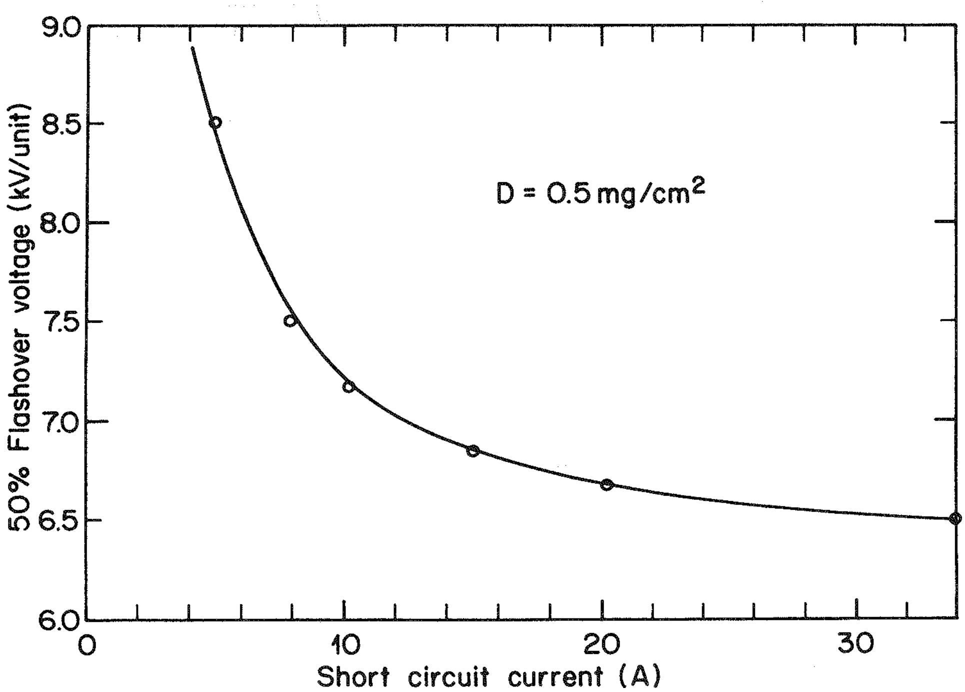

FIG. 34 The 50% flashover voltage versus short circuit current

Fig. 35 shows the effect of an ac resistance.

Fig. 36 shows the effect of a dc resistance.

Fig. 37 shows the 50% flashover voltage as a function of the voltage (V_{min}) just before flashover.

In Fig. 38, the voltage just before the flashover is plotted for each test.

Analysis of the results shows:

- Effect of smoothing capacitance. Fig. 33 shows that for values below 3 μF the smoothing capacitance influences the flashover voltage, but for higher values the flashover voltage is independent of the capacitance if the rectifier short circuit current is larger than 62 A at 50 kV;

  if the rectifier short circuit current is reduced, e.g. by a 3000 Ω resistance, the flashover voltage increases significantly and shows a dependence on the capacitance. Fig. 24 shows that the voltage drop for C = 0.262 μF is significantly higher than for C = 3.075 μF (curves F3, F1) if R_{AC} = 0 Ω.

  Fig. 27 shows the same phenomena. Surprisingly, however, the effect of the charge is much less significant than that of the current.

- Effect of the ac resistance. The ac resistance reduces the short-circuit current of the rectifier. Fig. 35 shows that the 50% flashover voltage increases linearly (at least in the region studied) with the ac resistance. The lack of saturation near zero resistance suggests that the application of a more powerful rectifier may further decrease the flashover voltage. This problem needs further study, however.

  Fig. 27 illustrates these results, showing the significant increase in the voltage drop caused by increasing the value of the ac resistance. It should be noted that, even in the case of R_{AC} = 0, the maximum voltage drop is almost 11%; which also suggests that the application of more powerful units may reduce the flashover voltage.

  A similar effect is shown in Fig. 28 as a function of the charge.

- Effect of the dc resistance. Fig. 36 shows that increasing the dc resistance from 300 Ω to 3000 Ω does not significantly affect the 50% flashover voltage. On the other hand, Figs. 26 and 29 indicate that increasing the dc resistance increases the voltage drop; in Fig. 26, for example, at 1 A

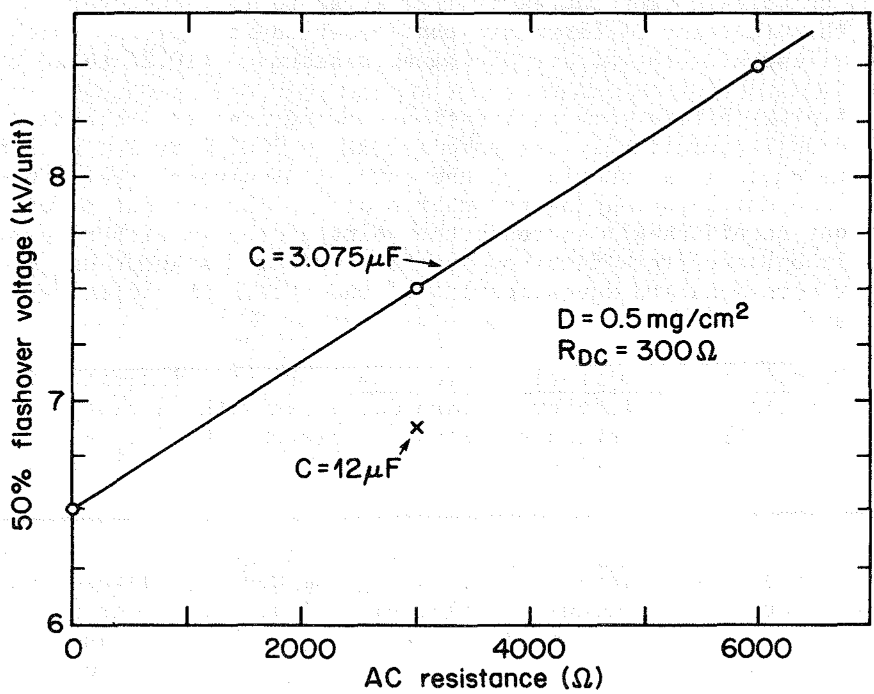

FIG. 35 50% flashover voltage versus ac resistance

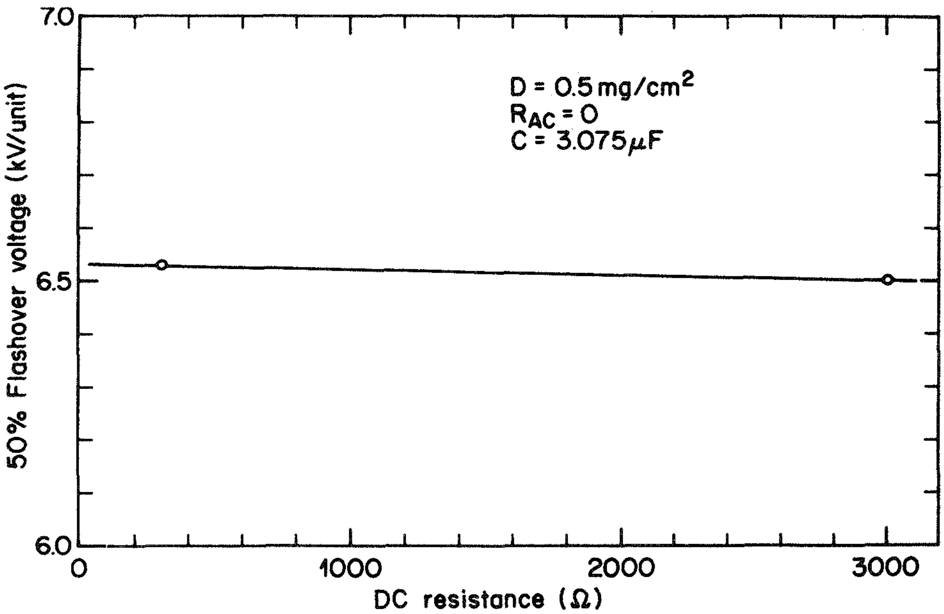

FIG. 36 50% flashover voltage versus dc resistance

- the voltage drop increases from 10.2% to 15%. However, this increase is less than that observed in Fig. 25, which illustrates the effect of the ac resistance (10.2% to 20.2%).

  Fig. 29 offers some explanation showing that the voltage drop is practically the same for R_{DC} = 3000 Ω or 300 Ω when measured as a function of the current impulse charge. Consequently, increasing the charge of the current pulse does not significantly increase the voltage drop in either case. In spite of this finding, further tests are suggested for a more accurate investigation of the effect of the dc resistance.

- Effect of the short-circuit current. Fig. 34 indicates that the 50% flashover voltage decreases with increasing rectifier short-circuit current. However, the diagram shows that the effect of the short-circuit current is not significant for values above 30 A in the examined case.

- Effect of the voltage drop. The voltage just before flashover or the minimum voltage during the test was determined from the oscillograms and plotted against the number of tests as shown in Fig. 38. The average value of these voltages was calculated and the results are summarized in Table 9 and plotted in Fig. 37.

TABLE 9

VOLTAGE DROP ASSOCIATED WITH DIFFERENT TEST CIRCUIT PARAMETERS

Series No.	R_{AC}	R_{DC} (Ω)	C (μF)	V kV/unit	5 %	D mg/cm^2
H 1	300	0	3.075	4.57	8.4	
H 2	300	0	11.07	5.13	12.8	
F 1	300	0	3.075	5.25	3.3	
F 2	300	0	12.0	5.4	4.6	
F 3	300	0	0.262	3.58	2	0.5
F 4	300	3000	3.075	4.76	14	
F 5	300	3000	12	5.03	12.1	
F 6	300	6000	3.075	5.2	10.5	
F 7	3000	0	3.075	?	?	
F 8	300	0	3.075	6.45	14.6	0.1

As depicted in Figs. 37 and 38, the pre-flashover voltage for tests F1, F2, F4, F6, is within a narrow range, which suggests that whatever the circuit configuration the flashover requires more or less the same voltage

The tests performed with the half-wave rectifier indicate a lower voltage before flashover. Furthermore, the voltage before flashover cannot be determined for test series F3 because the 0.22 μF capacitor was too small to maintain a smooth dc voltage. For test series F7, the large dc resistance reduced the current and made evaluation impossible. However, considering only test series F1, 2, 4, 6, it may be concluded that the pre-flashover voltage may be the most important factor in the flashover process. The minimum flashover voltage of a polluted insulator may be equal to the average of the voltages measured before flashover. During the test the no-load voltage of the rectifier is measured by a voltmeter and used as a flashover voltage. However, the actual voltage before flashover is reduced by the voltage drop. The accuracy of the measurement therefore increases with the reduction of the difference between the no-load voltage and the pre-flashover voltage, in other words, the reduction of the dynamic voltage drop.

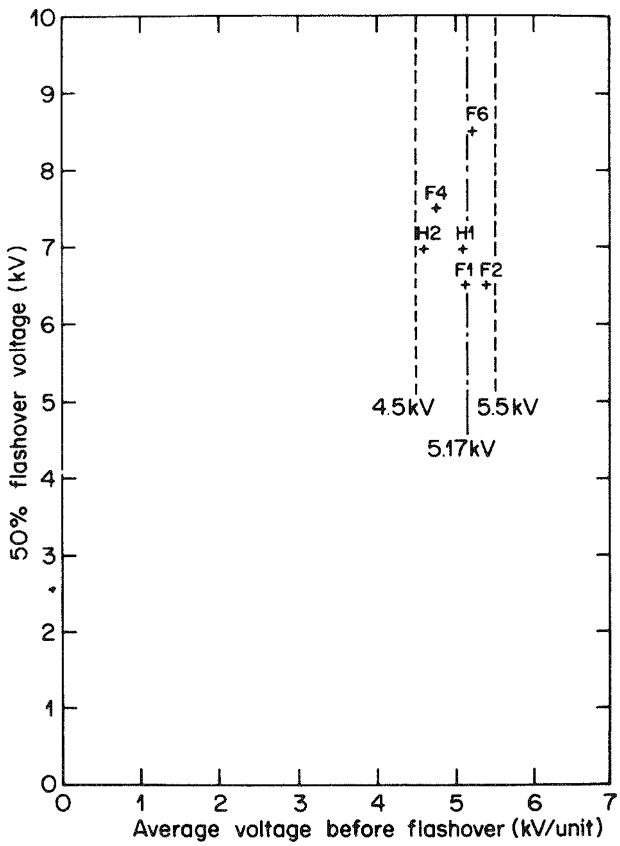

FIG. 37 50% flashover voltage versus average of the voltage before flashover

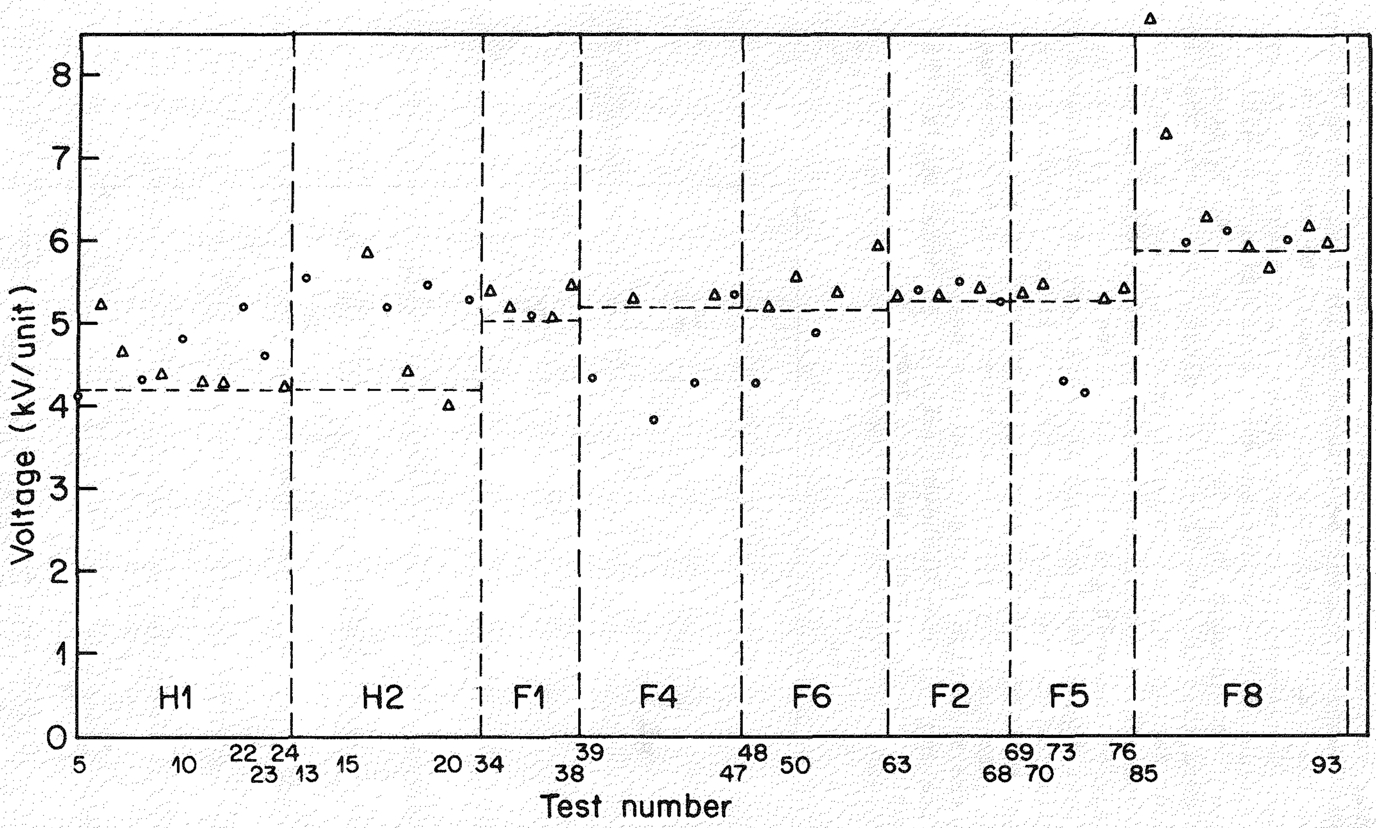

FIG. 38 The voltage just before the flashover

The statistical nature of the flashover produces a significant spread in the test results which already limits their accuracy; a voltage drop of 5 - 10% therefore seems to be acceptable at the expected maximum leakage current.

- Effect of the pollution severity. It is well-known that decreasing the pollution severity increases the 50% flashover voltage. The test results show that when the deposit density decreased from 0.5 to 0.1 mg/cm^2, the 50% flashover voltage increased from 6.53 kV to 10.25 kV (57%).

  Fig. 30 shows that the pollution severity does not affect the dependence of the voltage drop on the leakage current. This was not unexpected as the same rectifier was used in both cases.

  Similar results may be seen in Fig. 31. These last two figures possibly provide some proof that the measurements and the evaluation method are correct because they provide results which are to be expected from physical principles.

COMPARISON OF FULL- AND HALF-WAVE RECTIFIERS

Analysis of the oscillograms shows that, during the test, saturation occurs in the transformer for the case of the half-wave rectifier because of the premagnetizing effect of the dc component of the current. No saturation was observed in the case of the full-wave rectifier.

Comparison of the results of series H1 with those of series F1, and those of H2 with F2 (Table 2) shows that:

- If C = 3.075 μF, the 50% flashover voltage is 6.73% higher for the half-wave rectifier than for the full-wave rectifier.
- If C = 12 μF, the 50% flashover voltage is 7.2% higher for the half-wave rectifier than for the full-wave rectifier.
- Fig. 23 shows that the average voltage drop for the half-wave rectifier is significantly higher than for the full-wave rectifier. This explains the difference in the flashover voltage; at 1 A, for instance, the voltage drop is 2.56 times higher in the case of the half-wave than in that of the full-wave rectifier.

NATURE OF THE LEAKAGE CURRENT

The expected shape of the leakage current was described previously and discussed in detail. This section presents the statistical analysis of the leakage current just before the flashover and the leakage current impulses during each

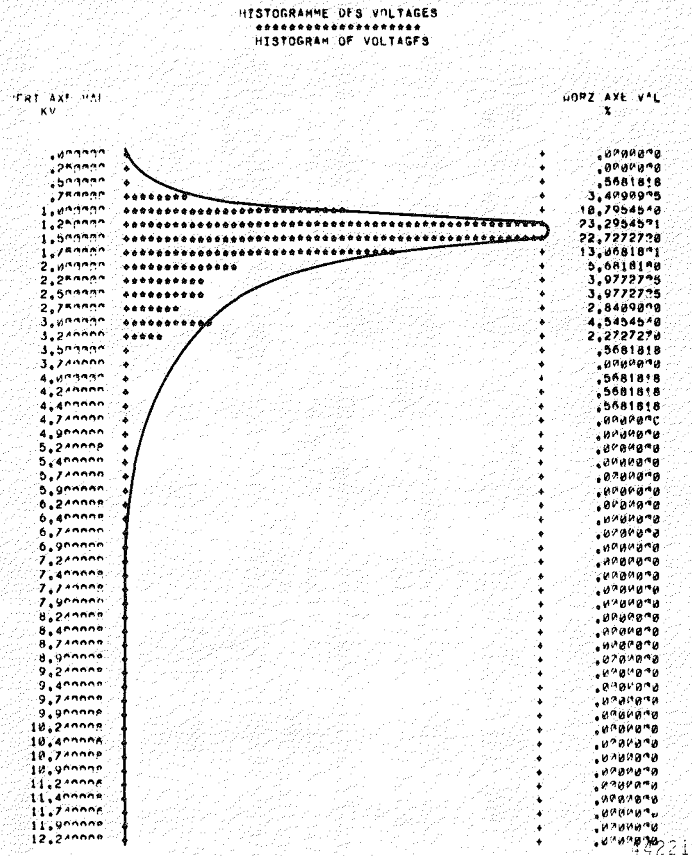

FIG. 39a Histogram of voltages

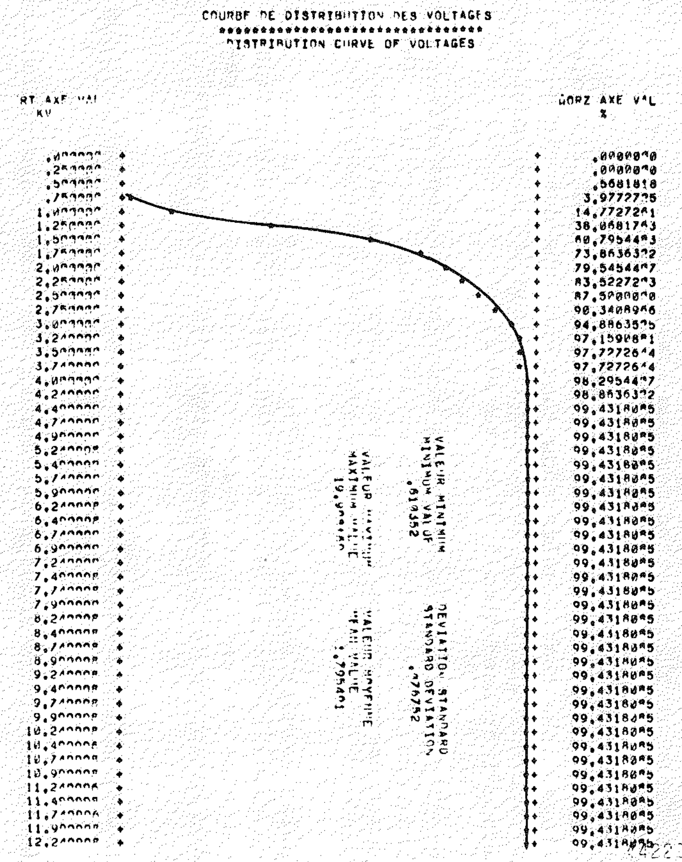

FIG. 39b Distribution curve of voltages

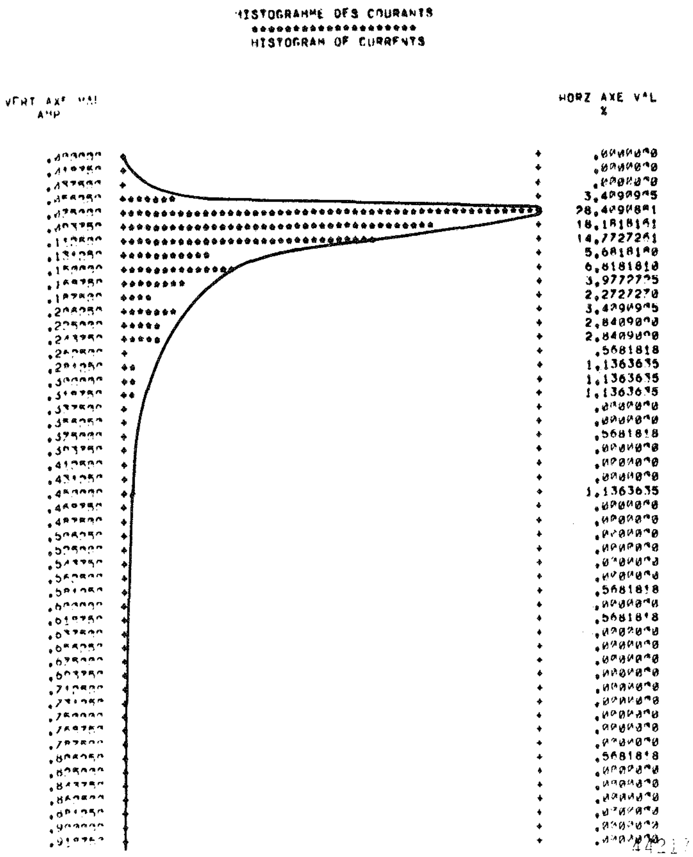

FIG. 39c Histogram of currents

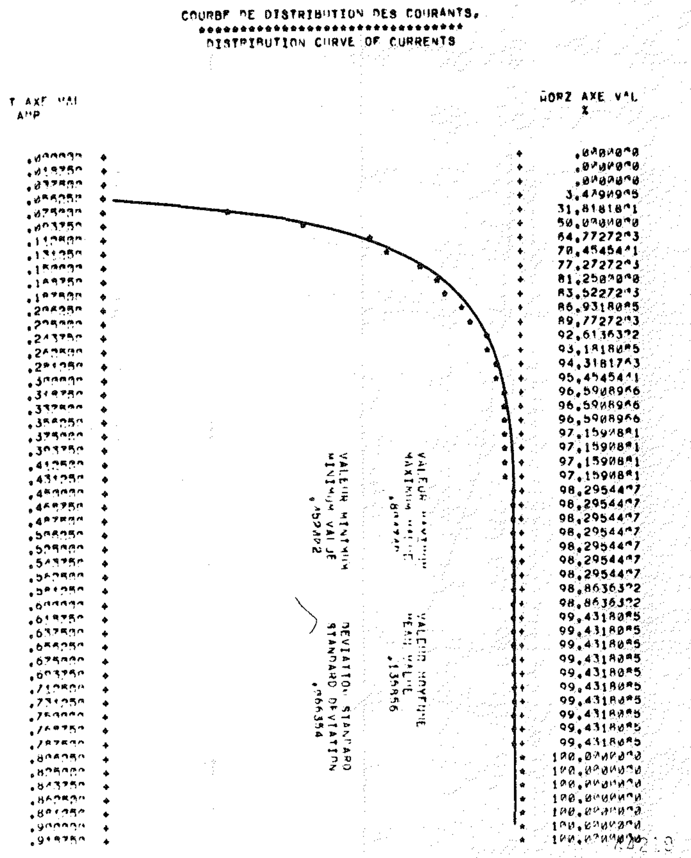

FIG. 39d Distribution curve of currents

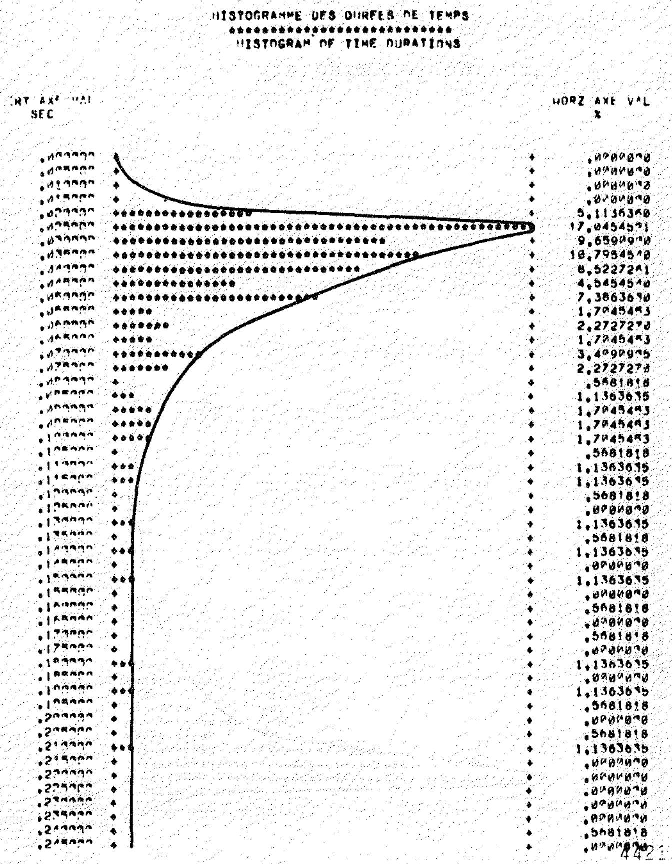

FIG. 39e Histogram of time duration

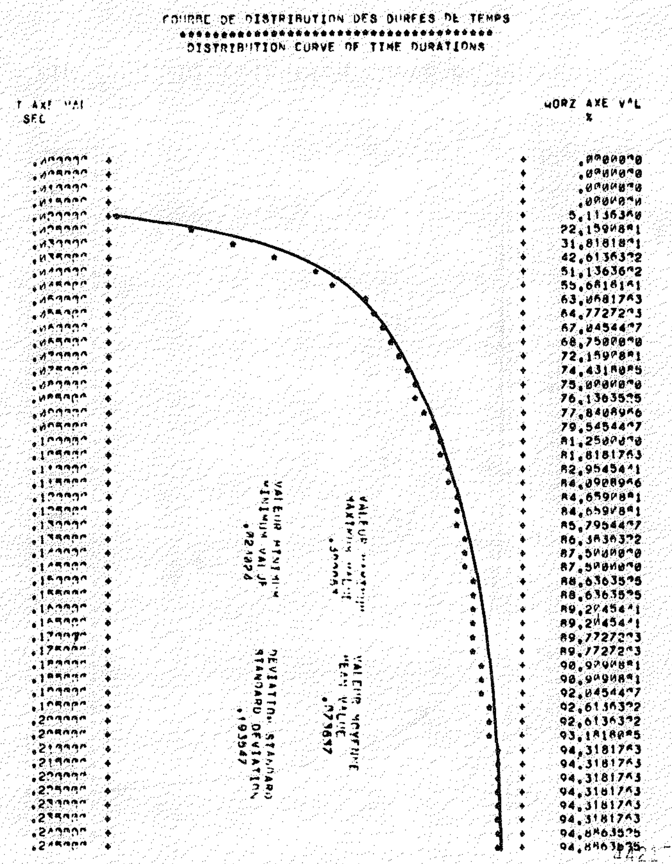

FIG. 39f Distribution curve of time durations

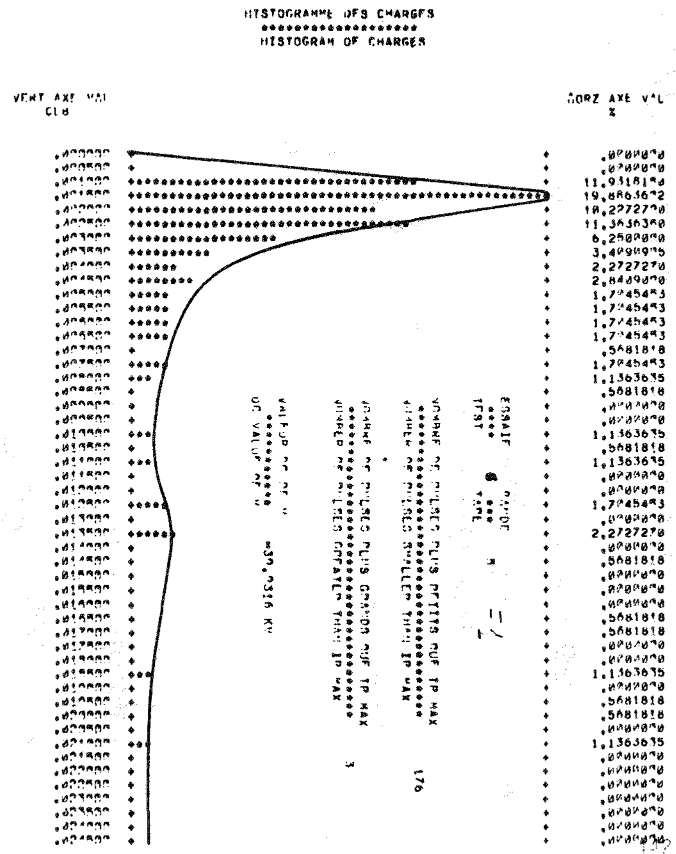

FIG. 39g Histogram of charges

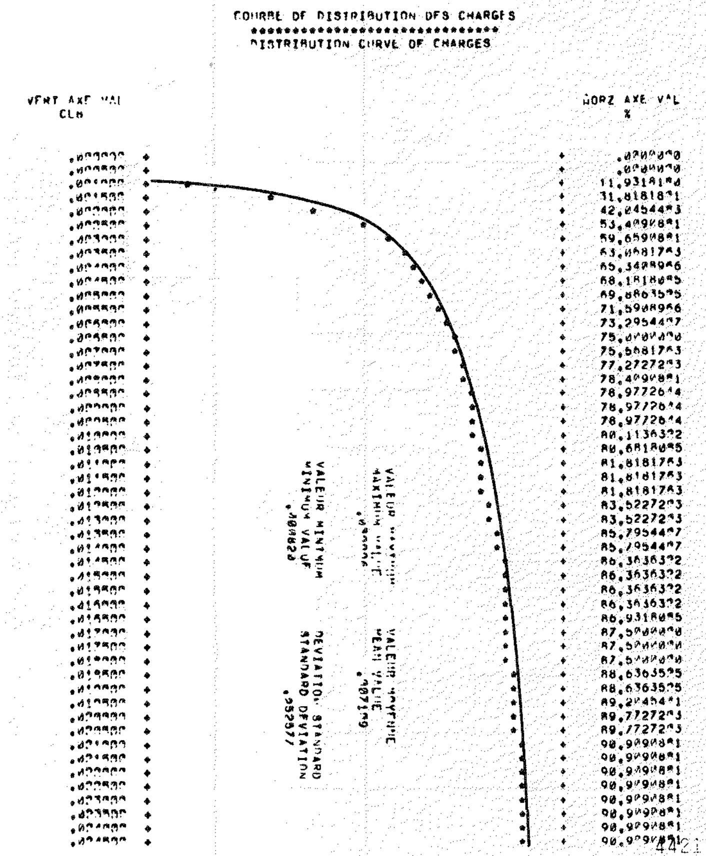

FIG. 39h Distribution curve of charges

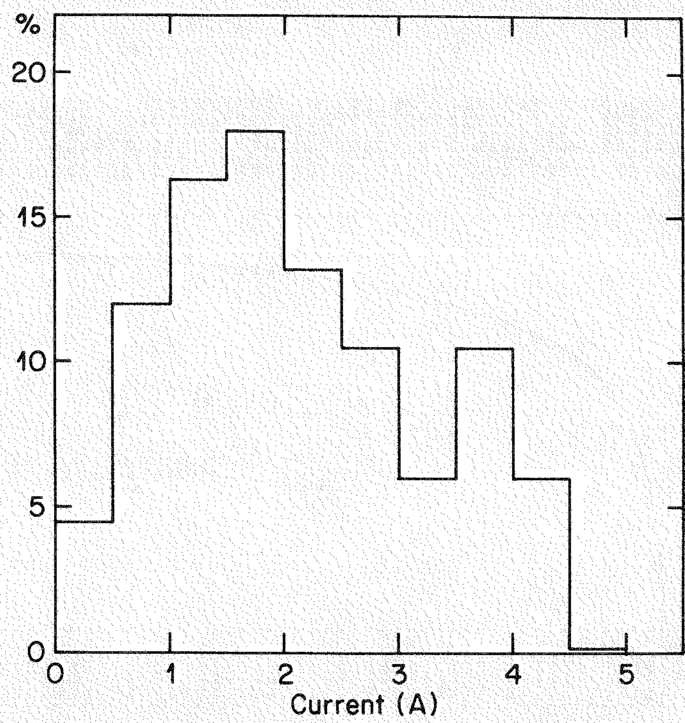

FIG. 40 Histogram of maximum leakage current

test. The computer compiled the histogram and cumulative probability curve of the leakage-current pulse: a) peak value; b) duration; c) charge. Typical histograms and cumulative probability curves are shown in Fig. 39.

Maximum expected leakage current

The maximum leakage current that occurred just before flashover (or at some other time during the test) was measured. It should be noted that it is rather difficult to determine the leakage current before flashover owing to the rapid change in the current (Fig. 15 b). Hence, engineering judgment was used to read the appropriate value from the oscillogram. The values are presented in Table 2; the histogram of the leakage current is shown in Fig. 40.

The most probable value is seen to be in the range of 1.5 ~ 2 A (about 18% of all the measured values), but in 6% of the tests, the leakage current just before flashover was in the range of 4.0 ~ 4.5 A.

Comparison of the values of Table 2 shows that the maximum leakage current is generally higher when flashover occurs than when the insulator withstands the test.

Fig. 15 a shows that the leakage current increases slowly before flashover. This current can be represented by a triangular-shaped current pulse. The duration of the current pulse (time interval between 5% of the maximum current to flashover) is in the range of 0.2 ~ 0.6 s, the most frequent value being about 0.35 s. The charge of the pulse was determined in some cases by graphic integration and was found to be in the range of 0.2 ~ 0.5 C; a typical value is 0.3 C.

The current-pulse shape is not influenced by the short-circuit power of the system; however, it depends on the smoothing capacitance because it modifies the voltage fluctuation which in turn causes fluctuation in the leakage current. This effect was not observed for capacitances greater than 3 μF although the dc resistance modifies the shape of the current pulses. In a circuit with high dc resistance, the current will rise similarly as in a circuit with low dc resistance but will not fall suddenly as in a circuit with low dc resistance.

Statistical evaluation of the leakage current

The cumulative distribution curves for each test series were traced and compared. Fig. 41 shows typical series of curves showing the cumulative distribution of the peak value of the leakage current for test series F1. It can be seen that an envelope curve can be drawn encompassing all the measured values. Note that the distribution curves in this case are near to each other. Similar diagrams were prepared for each case and compared; unfortunately the spread of other measurements is larger than that shown in Fig. 41, which makes evaluation of the effects of different parameters somewhat difficult.

The effect of pollution on the cumulative distribution curve of the leakage current is shown in Fig. 42 where the increasing pollution severity can be seen to flatten the cumulative distribution curves.

A similar effect may be observed in Fig. 43 which shows the effect of the ac resistance on the cumulative distribution of the voltage drop. The average values of the charge, duration and peak of current pulses and of the voltage drop are summarized for each test series in Table 10.

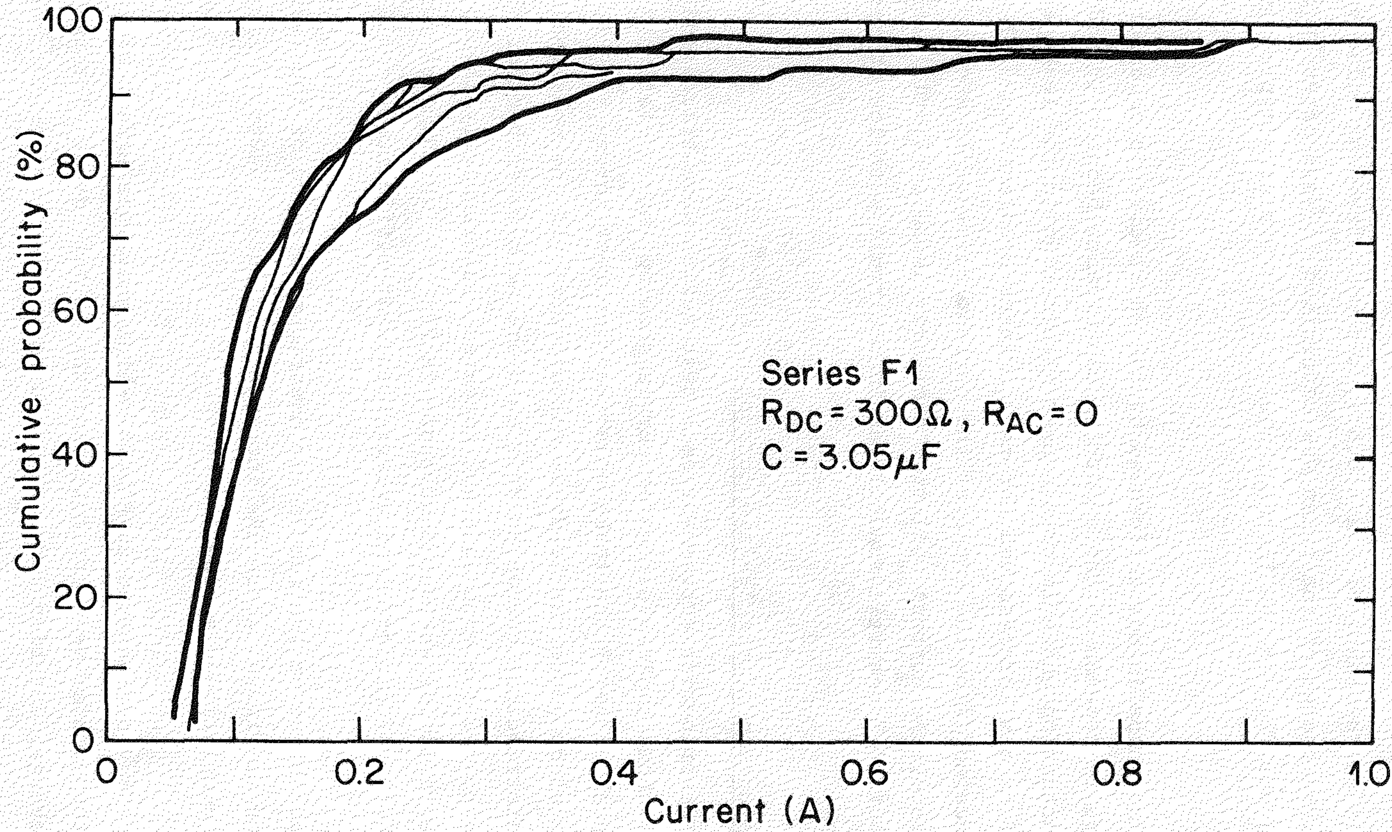

FIG. 41 Cumulative distribution of leakage current for test series F1

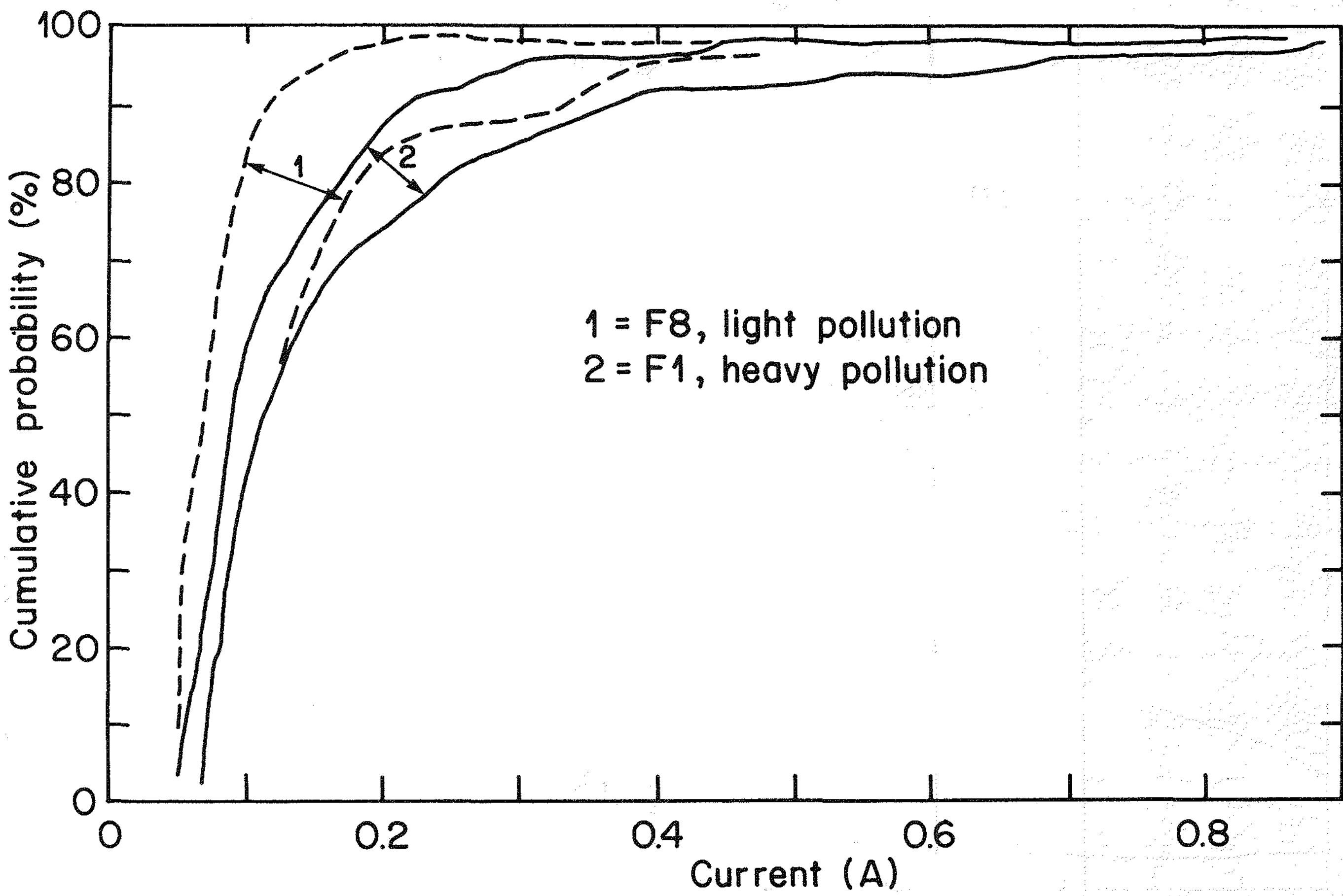

FIG. 42 Effect of pollution on the cumulative distribution of leakage current

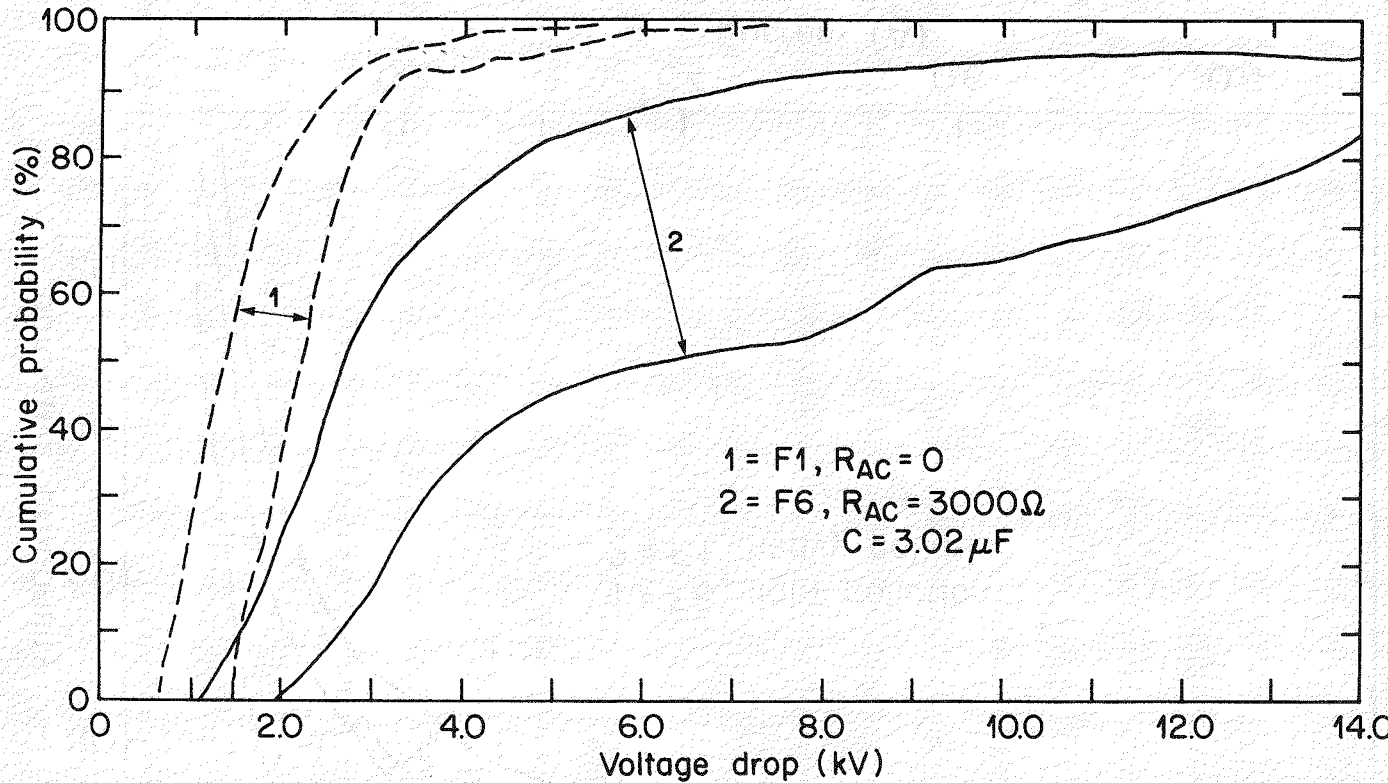

FIG. 43 Effect of ac resistance on cumulative distribution of voltage drop

<u>TABLE 10</u>

VOLTAGE DROP ASSOCIATED WITH DIFFERENT AMPLITUDE AND DURATION OF LEAKAGE CURRENT IMPULSES

TEST NUMBER	CHARGE mC			TIME ms			CURRENT mA			VOLTAGE DROP kV			$R_{DC}/R_{AC}/C$
	Δ	0		Δ	0		Δ	0		Δ	0		
H 1	10	8.27	9.23	89.3	75.9	83.2	193	162	179	6.85	5.89	6.56	300/0/3.075
H 2	10.2	11.2	10.6	91.6	96.3	93.6	180	211	192	4.63	4.74	4.67	300/0/11.75
F 1	-	-	8.58	-	-	79.4	-	-	174	-	-	4.33	300/0/3.07
F 2	9.12	7.26	8.19	80.6	70	75.3	177	150	164	4.76	4.99	4.88	300/0/12
F 3	7.05	7.8	7.43	68	75	72	196	176	186	19	8	13.7	300/0/0.262
F 4	6.7	9.2	7.78	63.8	81.1	71	161	208	181	12	12.7	12.3	300/3000/3.07
F 5	10	5.3	7.6	83.6	63	73.3	205	118	161	7	7	7	300/3000/12
F 6	12.4	8.6	11.13	86.3	65.5	80.7	272	191	245	10.7	8.3	9.9	300/6000/3.07
F 7	14	6.5	9.93	95.5	45	85.17	194	142	177	-	-	6.8	3000/0/3.07
F 8	9.65	5.67	8.45	110	77.6	100	138	99.5	127	5.5	5.3	5.46	300/0/3.07

Δ Flashover
0 Withstand

Comparison of the values given in Table 10 permits the following conclusions:

- The effect of pollution may be obtained by comparing F1 and F8 which reveals that the charge is not affected by the pollution severity; however, the average duration of the current pulses is shorter (about 20%), their average amplitudes being 31% higher at higher pollution levels than at lower ones.

- The effect of the ac resistance may be obtained by comparing F1, F4 and F6. It can be seen that the charge and duration of the leakage-current pulses are apparently not influenced by the dc resistance. The average amplitude of the leakage current increases with increasing of ac resistance.

- The dc resistance does not seem to influence the average current-pulse parameters but the average voltage drop increases with the increase in dc resistance.

- The variation in the smoothing capacitance influences neither the average duration, nor the average charge of the current pulses but the average amplitude of the current impulses decreases slightly with increasing capacitance. The average voltage drop is more or less the same at 3 μF and 12 μF but significantly higher (about 3 times) at 0.2 μF.

Section 8

CONCLUSIONS

The research work comprised a survey of the literature, theoretical investigations and laboratory studies. The major results of this investigation may be summarized as follows:

- DC testing of polluted insulators calls for a rectifier able to provide a slow-rising triangular-shaped current impulses with the following maximum values:

  peak value: 4 - 4.5 A
  duration : 0.2 - 0.6 s
  charge : 0.2 - 0.5 C
  time interval between the pulses:
  not less than: 0.1 s
  average current: >0.2 A

  The dynamic voltage drop should be less than 5 ~ 10% and the voltage fluctuation (ripples) less than 10% during the pulses.

  Thus the major objective of the project has been achieved. However, the test results afford further conclucions, which are summarized below.

<u>The literature survey revealed that</u>

- The dc flashover tests of polluted insulators should be performed using a negative-polarity voltage.

- The transient voltage drop at maximum current is the major factor influencing the flashover voltage of polluted insulators during both ac and dc tests.

- Only one measurement was found to deal with the nature of the leakage current. This measurement was made using the salt-fog test, which is not used in North America. No statistical evaluation of the leakage-current impulses is presented. Rather, conclusions are drawn by analyzing a sample of the results. Accordingly, the current impulse peak value is in the range of 1 ~ 1.5 A, its duration between 400 ms and 2000 ms and its charge about 100 mC - 200 mC.

- The voltage drop cannot be larger than 3% - 5%. The effect of different rectifier parameters on the flashover voltage has not been studied although some studies show the effect of the smoothing condenser.

- For the case of a full-wave rectifier, it has been demonstrated that a high-speed control circuit can compensate the voltage drop. However, the details of this circuit are not presented and the application of a full-wave rectifier is not economical for voltages higher than 400 kV - 500 kV.

Consequently, the literature survey justifies further research work in the following areas:

- The nature of the leakage current during dc pollution tests using the clean-fog method, which is used exclusively in the USA and in Canada

- The effect of rectifier parameters on the dc flashover voltage of insulators using the clean-fog method

- Development of a circuit to compensate the voltage drop of a rectifier circuit supplied by a single-phase transformer in order to make the flashover voltage of the insulators independent of the rectifier parameters over a practical operation range.

The results of the EPRI-sponsored research work at IREQ in the first two areas are presented in this final report.

<u>The study of the flashover mechanism showed that</u>

- Flashover of the insulator requires a higher voltage than $(U_m)_{max}$.

- The minimum voltage that can cause flashover increases <u>linearly</u> with the source resistance.

- The critical arc length increases <u>linearly</u> with the source resistance.

- The maximum current corresponding to the critical arc length, or to the minimum flashover voltage, is independent of the source resistance. It depends only on the pollution severity and the arc constants. Consequently, the current measured just before flashover should be more or less constant, for a fixed pollution level.

An investigation of the simplified theory of the mechanism of flashover of polluted insulators leads to the following conclusions;

- The critical factor influencing the flashover voltage is the dynamic voltage drop of the source at maximum current, which occurs just before flashover.

- The current before flashover is expected to increase at an ever-increasing rate. The maximum current before flashover increases with the level of pollution. The maximum expected pollution level should therefore be used for the experimental investigations.

- The theory does not provide any quantitative values and, moreover, supposes a simplified voltage source. Therefore, experimental study is required to obtain values for the leakage current and to determine the effect of the rectifier parameters on the flashover voltage.

The experimental study enables different conclusions to be drawn with regard to specifying the rectifier parameters, and provides qualitative values of the effects of parameters.

The findings are summarized as follows:

Study of the nature of the leakage current

- The leakage current comprises current impulses whose amplitude, duration and charge vary randomly during the test. However, the envelope curve of the peak current tends to increase as wetting progresses. Flashover occurs near the maximum current or, if the insulator does not flash over, the amplitude of the current pulses reach a maximum value and subsequently, decreases because of the washing effect of the fog.

- The leakage-current pulse is slow-rising pulse which suddenly collapses when the arc extinguishes. The pulse may be approximated by a triangle.

- The most probable peak value of the largest leakage-current pulse when the insulator withstands the voltage or when the current, just before the flashover, is in the range of 1.5 - 2 A but 6% of the values are in the range of 4 ~ 4.5 A;

- The duration of a current pulse is in the range of 0.2 - 0.6 s and the charge around 0.2 - 0.5 C.

- The pulse amplitude seems to be independent of the rectifier parameters but higher values were measured when flashover occurred than when the insulator withstood the tests.

- The shape of the current pulse is influenced by the smoothing capacitance if less than 3 μF.

- The most probable value of the peak leakage current increases with the pollution severity.

- The statistical evaluation of the leakage current showed that the average value is in the range of 0.2 A.

- Further statistical evaluation of the leakage-current pulses revealed that the variation of the rectifier parameters does not influence the leakage-current values significantly although small irregular changes were observed.

Study of the effect of the rectifier parameters on the 50% flashover voltage

- The voltage across the insulator just prior to flashover is more or less independent of the rectifier parameters; its value being about 4.6 ~ 5.4 kV/unit under heavy pollution conditions.

- During the test, the no-load voltage of the rectifier is measured and used as flashover voltage. Hence the transient voltage drop (no-load voltage - pre-flashover voltage) is the measure of the error of the flashover test. Its value should be limited to about 5 - 10%.

- The smoothing capacitor does not influence the flashover voltage if its capacitance is larger than 3 μF but, in the case of a rectifier with a short-circuit current rating of more than 62.5 A at 50 kV, it does influence the fluctuation of the voltage; the selected capacitance value should therefore be such that it reduces the voltage fluctuation by less than 5 - 10%.

- The increasing short-circuit current of the rectifier decreases the 50% flashover voltage although this effect is negligible for values of more than 30 A.

- Increasing the ac resistance produces a nearly linear increase of the flashover voltage and should be kept near to zero.

- The dc resistance does not seem to influence the 50% flashover voltage but its value should be kept at a minimum (a few hundred ohms). This resistance is necessary to limit the discharge current of the rectifier during flashover.

- Comparison of half- and full-wave rectifiers shows that saturation occurs in the transformer in the case of half-wave rectifiers because of the pre-magnetizing effect of the dc component of the current. Furthermore, the voltage fluctuation is larger in this rectifier than in the full-wave one which requires a larger smoothing capacitance.

- A statistical evaluation of the voltage drop of the rectifier is necessary because of the different durations and the variable spacings of the current impulses during the testing of polluted insulators,

- The flashover voltage - peak current and charge characteristic shows saturation in the case of powerful rectifiers.

Evaluation of the rectifiers available in IREQ

- Cascade rectifier, 1200 kV; rated 250 mA continuous and 500 mA short-term loading. This rectifier is not powerful enough to test polluted insulators even in the case of light pollution.

- Half-wave rectifier, 200 kV; 5 A continuous rating; the saturation observed during tests with this powerful half-wave rectifier raises doubts about the feasibility of using this equipment for such tests. However, if the transformer had a third low-voltage winding, it could be loaded during the no-load cycle, thus reducing the saturation effects.

- Full-wave rectifier, 120 kV; 5A, short-circuit current 62.5 A at 50 kV; smoothing capacitance larger than 3 μF. This powerful rectifier is suitable for pollution tests on heavily polluted insulators if operated at voltages higher than 50 kV. However, at lower voltages, the dynamic voltage drop becomes too large.

SUGGESTIONS CONCERNING RECTIFIERS FOR POLLUTION TESTS

From the list of required rectifier parameters at the beginning of section 7, it can be seen that the average load current is rather low but has to be able to provide large current impulses at a fairly low repetition rate. The tests showed that, in most cases, the rectifier was able to restore the no-load voltage between the current impulses.

Two possible solutions can be foreseen:

- Powerful multi-(3-phase) phase rectifier

- Rectifier with high-speed control which maintains the voltage up to about 5 A current

Considering the voltage range of 1000 kV, this multi-phase unit should be rated 1000 kV x 4 A = 4 MVA which would be prohibitively expensive. The high-speed control seems therefore the most feasible solution.

The tests showed the advantages of the full-wave rectifier connection although the price of a full-wave rectifier in the 1000 kV range is very high because it needs a floating transformer or a transformer with two high-voltage windings and two bushings. The simple half-wave rectifier used in most high-voltage laboratories showed saturation.

This analysis suggests that a half-wave rectifier in a cascade connection seems to be the ideal solution. This circuit is free from saturation and can be supplied with high frequency (120 - 400 Hz), which may reduce the capacitor requirements. Furthermore a high-speed control circuit, with a flat characteristic up to 5 A, would reduce the power requirement by an estimated factor of five. The control circuit and rectifier time constant should be in the range of 5 - 10 ms and should have a well-damped step-function response curve. The cascade rectifier control may use a pair of thyristors connected in parallel in the opposite direction. The gate signal of the thyristor should be controlled by the output voltage of the rectifier.

Section 9

SUGGESTIONS FOR FURTHER WORK

The results presented in this report suggest an extension of the project to cover the following points during the next year:

- Determination of the circuit elements of a cascade rectifier suitable for pollution testing (supply rating; transformer, capacitors)
- Development of a high-speed control circuit to compensate the voltage drop of a cascade rectifier. The system should be suitable for extra-high-voltage applications
- Further study of the effect of the voltage drop and short-circuit current to verify the estimated permissible transient voltage drop of 5 - 10%. This calls for measurement of the 50% flashover voltage (when using a rectifier with less than 5% voltage drop) for three different voltages and two different pollution levels. The required number of tests would be 30 (3 series).
- Further study of the nature of the leakage current of polluted insulators under dc voltage. This would involve the measurement of the 50% flashover voltage of the same insulator chain at very low pollution levels (D = 0.03 mg/cm^2). This study would require about 10 tests (one series).
- Further study of the effect of the dc resistance in order to explain the contradiction found during this investigation. This would mean measuring the 50% flashover voltage at R_{DC} = 0 R_{DC} = 1000 Ω R_{DC} = 6000 Ω. This study would require about 3 x 10 tests (3 series).

Section 10

REFERENCES

1 Annestrand, A., Schei, A., "A Test Procedure for Artificial Pollution Tests on Direct Voltage", Direct Current, Vol. 12, No. 1, Feb. 1967, p. 1-8

2 Poland, M.G., Scarborough, W.E., Hill, H.L., Renner, P.E., BPA'S, "Extra High Voltage DC Tests - I Contaminated Insulator Tests", IEEE Trans. Power Apparatus Syst. (USA), Vol. PAS-86, No. 10, Oct. 1967, pp. 1146-52

3 Sorms, R., "Gleichspannüngsgnelle zur Prüfung Verschmutzter Insolatoren", ETZ-A Bd. 89 (1968), H. 21

4 Forrest, Lambeth, Colombo, Kucera, Hurley, Limbourn, "International Studies of Insulator Pollution Problems," CIGRE Report 33-12 (1970)

5 IEC Report on artificial pollution tests for H.V. insulators to be used on a AC systems, IEC TC 36 (CO) 43, Feb. 1971

6 Kolossa, I., "Zusammenhange Zwischen den für Fremdschichtüberschläge Wasgebenden Kenngrossen von Hochspannüngsanlagen", Teil 1 und 2, Archiv für Technisches Messen, Blah. Z, 734-30, 4 Dez. 71/Jan. 72

7 Nasser, E., "Contamination Flashover of Outdoor Insulation", ETZ-A, Bd. 93 (1972), H 6

8 Nakajima, Y., Seta, T., Nagai, K., Horie, H., Naito, K., "Performance of Contaminated Insulators Energized by DC Voltage", CIGRE Report 33-07 (1974)

9 Verma, M.P., "Test Circuit Data for Pollution Tests", Presented on CIGRE 33-74 (WG-04) 15 IWD, Working Group Meeting 1974

10 Verma, M.P., Pedersen, A., Kolossa, I., Niklasch, H., Kristiansen, K.E., Rasmussen, J.K., "A New Criterion Common for Different Pollution Procedures Providing the Link Between Service and Test Conditions", WG Document CIGRE Sc 33-74 (WG-04) 18 IWD

11 Kolossa, I., "Contribution to Dimensioning of AC Sources for Pollution Tests", Presented on the CIGRE 33-75 (WG-04) 3. IWD Working Group Meeting 1975

12 IEC Report 507 (1975)

13 Niklasch, H., Petrusch, N., Ozwirk, W., "Data of the Pollution Test Circuits at the FGH and the Voltage Drop During Tests", WG Document CIGRE SC 33-76 (WG-04) 4 IWD

14 Schneider, H.M., "Circuit Characteristics of Contamination Test Equipment and its Influence on the Flashover Voltage", WG Document CIGRE SC 33-76 (WG-04) 3 IWD

15 Remhold, G., "Ultra High Voltage DC Power Supply for Large Current", Haefely Publication 1975 or in German SEV Bulletin, No. 14, July 19, 1975.

16 Hirsch, F., Rheinbaben, H.V., Sorms, R., "Flashovers of Insulators under Natural Pollution and HVDC, IEEE Transaction, Vol. PAS-94, No. 1, Jan/ Feb. 1975.