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Influence of the Pre-Discharges on Breakdown Behaviour of the Negative Rod-Plane Spark-Gap at Standard 1.2/50 Impulse Voltages

KURT FESER. Basel. Switzerland

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Influence of the Pre-Discharges on Breakdown Behaviour of the Negative Rod-Plane Spark-Gap at Standard 1.2/50 Impulse Voltages[1])

KURT FESER, Basel, Switzerland[2])

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Dimensioning electric equipment with regard to impulse-shaped overvoltages requires a thorough knowledge of the electric strength of air, to this date still the most important insulating matter in the field of high voltage engineering. Not only the 50 % breakdown impulse voltage is of interest for the optimum design of equipment, but also the dispersion of the breakdown probability. Together with the 50 % breakdown impulse voltage, the latter leads to the determination of the withstand voltage or the 100 % breakdown impulse voltage.

A detailed study of the negative rod-plane spark-gap is going to be done in the following. Behaviour of this spark-gap at atmospheric ovcrvoltages is particularly interesting, as 90 % of all lightnings show a negative polarity [1] . The actual reason of the investigations is due to the considerable dispersion of some measurements on negative rod-plane spark-gaps, as shown in the existing literature ([2] . . . [4]). This systematic dispersion in the 100 . . . 800 kV voltage range is imputed to a physical origin. Knowledge of physical laws brings an efficacious and in the same time an economic remedy.

1. Test arrangement

Two Marx-type impulse generators were available for the execution of tests. The five-stage 1 MV impulse generator having an energy of 12.5 kWs was located in a medium large laboratory [High Voltage Laboratory II (10 X 10 X 6.5) m^3] ([5], [6]). The twelve-stage 3 MV generator, of which only four stages were used in part-stage operation, stood in the High Voltage Hall (23 X 34 X 19) m^3 of the High Voltage Institute of the Munich Technical University [5]. Both tests circuits were arranged [7] so as to stress the object under test with a standard 1.2150 impulse voltage [13].

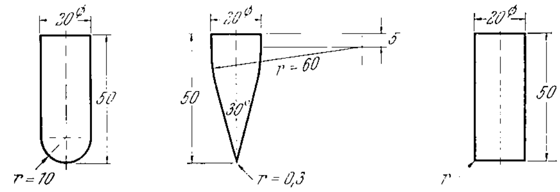
The test object was a vertical spark-gap earthed on one side. The h. v. connexion was a 20 mm brass tube, which could be terminated with various electrode types (fig. 1). The plane electrode was a (2 X 2) m^2 aluminium plate. Further details are described under [7].

The impulse voltage was laid on an oscillograph or an impulse peak voltmeter by means of voltage dividers directly connected to the spark-gap.

2. Test performance and assessment

Voltage values were converted according to well known references [8] to standard conditions (ϑ_0 = 20 °C, b_0 = 760 Torr). A correction of air humidity is not necessary in the case of negative rod-plane spark-gaps. as humidity correction is only made when the positive electrode shows impulse-shaped pre-discharges [7], [9].

Breakdown probability in function of breakdown voltage is obtained by different adjustments to determined voltage values. A determined number of voltage impulses is given on the test object in each voltage range. The ratio obtained by the number of breakdowns to the total number of impulse shots gives the breakdown probability w.



2 cm-hemisphere 30°-pin blunt

Fig. 1. Dimension drawing of various electrode terminations

If measured values have a normal distribution, which is usually the case with air spark-gaps [10], the measurement is clearly characterized by the 50 % breakdown voltage $U_{d\,50\,\%}$ and the standard deviation s. In such a case, these characteristic values may be determined with sufficient accuracy with 5 X 20 voltage impulses [11].

Breakdown process will be influenced under certain physical postulates, to be determined later, by several significant parameters. In such a case, there will be mixed distribution in breakdown probability in function of breakdown voltage. The number of voltage steps and partly also the number of voltage stresses per voltage step had to be considerably increased in these cases. Fig. 2 shows an example of such a mixed distribution, which could not be characterized by any known statistical evaluation. As the distribution did not corre-

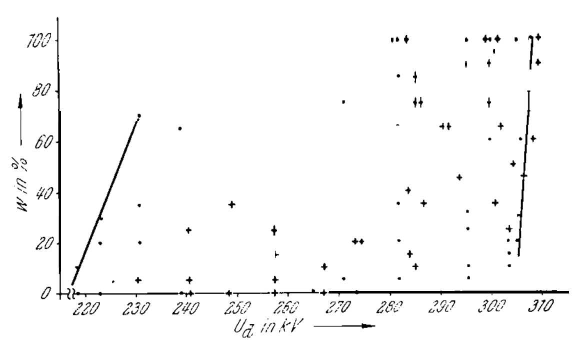


Fig. 2. Breakdown probability of a negative 15 cm rod-plane spark-gap

Impulse shape of impulse voltage: 1.2 50
Electrode shape: blunt
Parameter: R_{da} (• R_{da} = 0, + R_{da} = 260 Ω)
Test arrangement in the H. V. Hall, C_b = 1.5 nF, 40 shots each

[1]) Abridged abstract of the author's dissertation at the Munich Technical University. This paper originated while the author was scientific assistant at the High Voltage Institute of the Munich Technical University. The author expresses his gratitude to the German Research Union for their generous patronage.

[2]) Dr.-Ing. KURT FESER, Emile Haefely & Co Ltd, Lehenmattstraße 353, CH-4000 Basel 28.

spond to any normal distribution, evaluation was effected on linear paper. The mixed distribution was characterized by a front and a rear straight line, intersection points of which with the 50 % breakdown probability line supplied the two characteristic voltage values (U_{d1} and U_{d2}) of fig. 2.

A standard deviation s cannot be determined in these cases.

The sequence of impulse shots was between 10 s and 20 s for all measurements.

3. Test results

Figures 2, 3 and 4 show characteristic examples of the measured breakdown probability w in function of breakdown voltage. These measurements were performed on a blunt electrode, as considerable dispersion occurs precisely on such an electrode form, as shown in the existing literature ([2] . . [4]).

A triggered release of impulse voltage can be achieved for about 70 % of the static breakdown voltage with the aid of firing impulses [12]. Oscillogram checks have shown that the impulse voltage curve at a determined trigger adjustment is practically independent of the firing gap spacing.

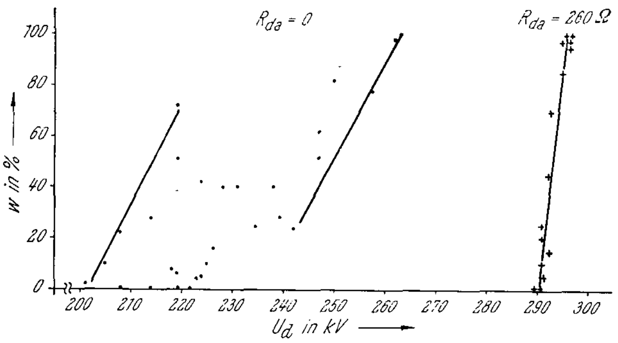


Fig. 3. Breakdown probability of a negative 15 cm rod-plane spark-gap

Impulse shape of impulse voltage: 1.2150
Electrode shape: blunt
Parameter: R_{da}
Test arrangement in H. V. Laboratory II, C_b = 1.44 nF, 40 shots each

Fig. 2 shows furthermore that dispersion of breakdown probability at a certain voltage adjustment can be reduced by means of an outer damping resistor R_{da} placed between the load capacitance and the spark-gap, eventhough there is no influence of the resistance on the voltage applied to the spark-gap.

Distribution shown in fig. 2 is characterized by an entirely unsystematic dispersion. Breakdown probability has been determined for each measure point by 40 shots. An imaginary 50 % breakdown impulse voltage U_{d1} of 227 kV results for the front limit line and a 50 % breakdown impulse voltage U_{d2} of 307 kV for the rear limit line. The noteworthy point of fig. 2 is the fact that several different breakdown probabilities can be measured for one determined breakdown voltage. For instance, every breakdown probability between 0 % and 100 % can be measured for a 282 kV breakdown voltage. The different breakdown probabilities at equal impulse voltage amplitude are obtained by the various possible adjustments of the firing spark-gap of the impulse generator.

It was possible to corroborate this surprising and unexplainable result by measurements performed on the same spark-gap with the aid of another impulse voltage circuit (fig. 3). There again, there resulted this unsystematic dispersion of breakdown probability and an evident influence of the damping resistor is noticeable, implving an increase of breakdown voltage value with a surprisingly slight dispersion.

It is most interesting to make a further comparison of figures 2 and 3: if the damping resistor is not taken into consideration, there is coincidence of the lower limit lines, while the upper limit lines coincide if the damping resistor is taken in account.

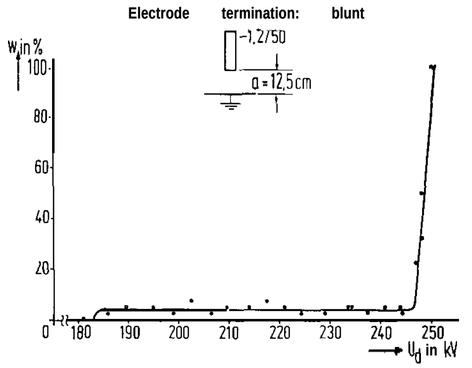


Fig. 4. Breakdown probability of a negative 12.5 cm rod-plane spark-gap

Impulse shape of impulse voltage: 1.2150
Electrode shape: blunt
Test arrangement in H. V. Laboratory II, C_b = 1.44 nF, 40 shots each

These measurements show, from a statistical point of view, that under certain test conditions a significant influence parameter is completely suppressed with this spacing of a = 15 cm and an outer damping resistor.

If there is no resistor, there will be a part suppression of the second parameter, responsible for an increased breakdown voltage (fig. 3). Both these influences determine the breakdown behaviour in the High Voltage Hall (fig. 2). Even with different spacings, breakdown probability will be influenced by several significant parameters, so that mixed distribution will result.

Measurement at a 12.5 cm spacing with the 1 MV impulse generator is particularly instructive (fig. 4). Only one or two of the 40 shots applied at every voltage adjustment lead to breakdown in the 186 kV to 246 kV voltage range. Determining the withstand voltage value according to VDE 0433, Part 3/4.66 [13] would, in this particular case, lead to a completely erroneous result. According to [13] and also to [14], a voltage can be considered as being a withstand voltage, if 5 impulse shots applied at this particular voltage do not cause a breakdown; or, should breakdown occur, it will not occur again at 10 further shots applied. With a breakdown probability of 6.67 %, there would result, for this arrangement, a withstand voltage of some 246 kV, which value would be about 31 % higher than that of the actual withstand voltage.

Fig. 5a) shows what happens if the 50 % breakdown impulse voltages are evaluated for every spacing according to the statistical methods shown, and if the values obtained are drawn up versus the spacings. It will be seen that a dispersion of about 50 % is possible in a spacing range between 15 and 20 cm. In a spacing range of 5 cm $\leqq a \leqq$ 55 cm, breakdown probability on a blunt electrode termination cannot be reproduced with a normal distribution. Several significant parameters influence breakdown behaviour in this transition range.

It is inexplicable that only two transactions known in the corresponding literature mention this considerable dispersion. HYLTEN-CAVALLIUS [2] mentions in a Cigré report two measurements on a 18.1 cm rod-plane spark-

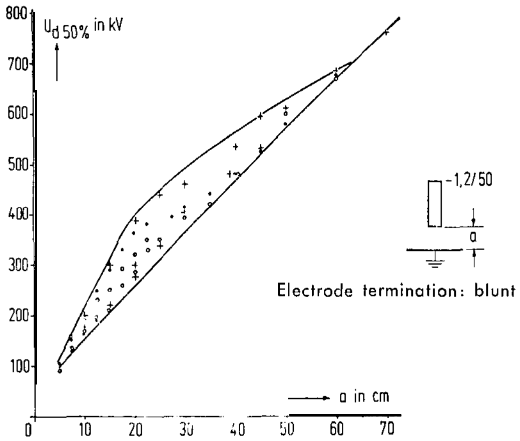


Fig. 5a). 50% breakdown impulse voltages of negative rod-plane spark-gaps versus spacing (at normal conditions)

Electrode termination: blunt
Test arrangement in H.V. Laboratory II: • o
Test arrangement in the H.V. Hall: +

gap. Distribution indicated by this author cannot be evaluated by any normal distribution. If the results are evaluated by means of the two limiting lines, we obtain a very good concordance with our own measurements (U_{d1} = 250 kV, U_{d2} = 350 kV at a = 18.1 cm). MISHRA [3] also mentions distributions which equally point to two distinct breakdown mechanisms. Evaluating a measure according to this procedure (a = 30 cm), there will be found also a confirmation of the transition range

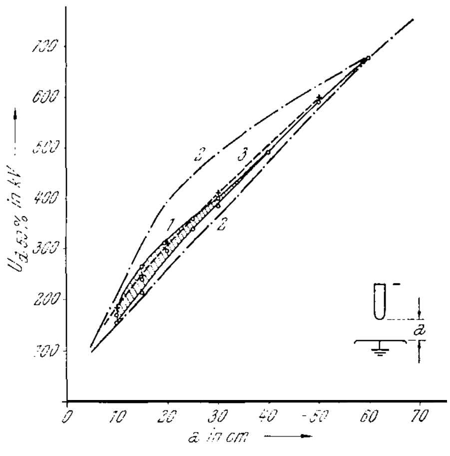


Fig. 5 b). 50% breakdown impulse voltages of negative rod-plane spark-gaps versus spacing (at normal conditions)

Influence of the electrode shape
1 3 cm hemisphere —o—
2 blunt (limit curves of fig. 5 a)
3 30° pin —+—
Test arrangement in H.V. Laboratory II

limits. Both transactions do not investigate the physical origin or the influence possibility of these abnormal distributions.

Cigré report of JOHANSEN and BAKKEN [4] also mentions a strong unsystematic deviation. The reason of this dispersion should, also in this case, be found in the abnormal distributions, as the results had been assessed under the assumption of a normal distribution.

Three methods are basically appropriate for the study of spark formation and thus for the explanation of the physical origin of this considerable dispersion. Physical explanation of the breakdown phenomenon can be obtained by considering not only the voltage curve and the light process in the spark-gap, but also the current flowing across the spark-gap.

4. Breakdown times of impulse voltage in the transition range

Breakdown times of the 50% breakdown impulse voltage for a negative 15 cm rod-plane spark-gap should be in the neighbourhood of 3.4 µs [7].

As shown in fig. 6, it is also the case for the lower 50% breakdown impulse voltage, Up to 295 kV, breakdown time will be between 1 µs and 4 µs and this is, with reference to breakdown probability, the range of the large dispersion. Coming nearer to the limiting lines, breakdowns occur suddenly in the impulse voltage tail after about 15 µs to 20 µs. It is interesting to note that no breakdowns were measured at 300 kV in the 2 µs to about 14 µs transition time. With the increase of the voltage value, both volt-time-curves draw nearer and continue to rise as one single curve as from 355 kV and 2.7 µs. Measurement of breakdown time shows also that two significant parameters are responsible for the breakdown process.

5. Pre-discharge currents and discharge pictures

By rotating the electrode arrangement, it was possible to measure the current directly on the strongly bent electrode by means of the measure arrangement described in [15].

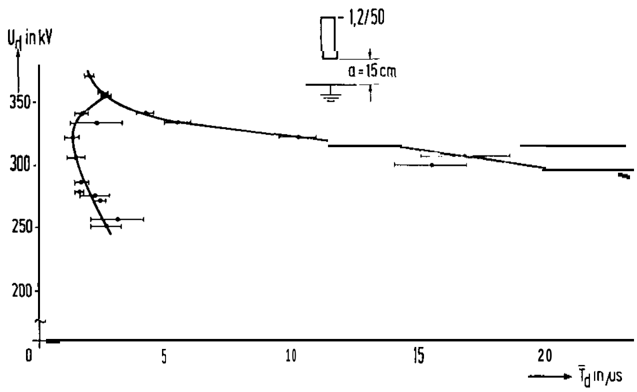


Fig. 6. Volt-time-curve of a negative 15 cm rod-plane spark-gap

Electrode termination: blunt

The rotation of the electrode arrangement did not bring any decisive influence of breakdown probability, as was demonstrated by a control measurement. By means of a camera equipped with a quartz lens, simultaneous pictures were taken both of the current and of the pre-discharge on the strongly bent electrode, as illustrated in fig. 7: two different pre-discharge manifestations may happen in the transition range, both of them influencing in a decisive manner the breakdown process. The lower breakdown voltage of short duration is caused by a canal-shaped pre-discharge (fig. 7), which produces an impulse-shaped pre-discharge current (fig. 7a). Longer breakdown times are occasioned by a diffuse pre-discharge (fig. 7 d), which has a stabilizing effect and prevents breakdown for some time. because of its space-charge distribution. This pre-discharge cannot be observed in the current curve.

6. Influence of the firing characteristics of sphere-gaps of an impulse generator

It was possible to modify the breakdown probability bv re-adjusting the firing gap of the impulse generator and this with a deter-mined voltage setting and a triggered firing of the generator. Under determined conditions (fig. 2, U_d = 282 kV), it was possible to set any desired breakdown probability between 0 % and 100 %. (It is expressly stressed that this phenomenon is repeatable.)

A minimum spacing variation of the firing gap does theoretically exercise but a slight influence on the firing of the impulse generator. According to the sparking laws of TOEPLER [16] and ROMPE & WEIZEL [17], voltage breakdown of a spark-gap depends on the spacing. Breakdown steepness of firing spark-gaps is however decisive for the steepness and level of over-voltage stressing on the next spark-gap [18]. Thus, a modification of spacing allows slight variations, particularly when impulse voltage starts to rise.

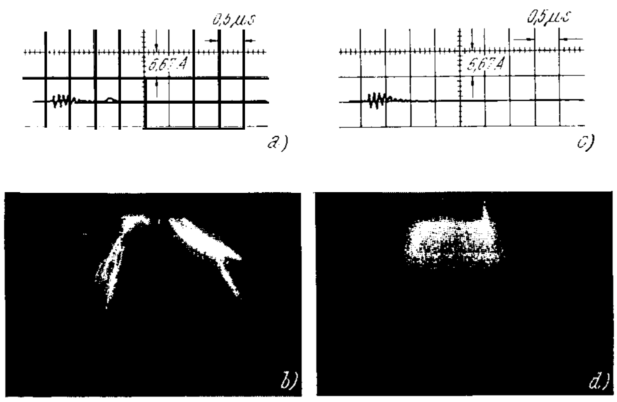


Fig. 7. Pre-discharge currents [a), c)] and discharge pictures [b), d)] in the transition range of the negative 15 cm rod-plane spark-gap at 1.2/50 lightning impulse voltage
Electrode termination: blunt
Parameter: voltage

These slight oscillations at the start of the impulse shape, which cannot be measured with an oscillograph, are the origin of the various breakdown probabilities at a certain voltage setting, as a diffuse pre-discharge is very sensitive in presence of voltage oscillations. This can be confirmed by two measurements:

(1) A damping resistor in the connexion leading to the spark-gap attenuates these oscillations; dispersion of breakdown probability at a determined adjustment gets slighter and a higher breakdown voltage gets thus preference (fig. 2 and 3).

(2) These slight oscillations can be stimulated by a spark-gap in the connexion leading to the spark-gap. With a spacing of only 2 mm of this spark-gap, breakdown probability at a determined voltage setting will increase from 0 % to about 70 % [7].

It is interesting to note that TOEPLER [19] also reports about the influence of a spark-gap at positive d. c. voltage in the neighbourhood of glow corona. The stabilizing glow corona does not appear with a "turbulent" voltage.

Measurements have shown that action of diffuse pre-discharge can be compared with glow corona at positive d. c. voltage:

(I) diffuse pre-discharge leads to a higher breakdown voltage;

(2) diffuse pre-discharge does not originate in case of "turbulence" in the voltage curve;

(3) breakdown duration is considerably higher with diffuse pre-discharge;

(4) a typical transition range builds up in case of a pre-discharge changing into diffuse pre-discharge.

In view of similar behaviour with glow corona, we will introduce for this diffuse pre-discharge the definition "negative glow brush". The canal-shaped pre-discharge is identical with streamer discharge.

So as to obtain a complete picture of the proceedings in the transition range of a negative rod-plane spark-gap, the possibility of influencing pre-discharges in this arrangement will be now examined.

7. Influence of the electrode shape

Position and dimension of the transition range of a negative rod-plane spark-gap will, among other factors, also be influenced by the electrode shape. Transition range with a blunt electrode termination will be particularly pronounced [fig. 5 b)]. As an antithesis, there will be no transition field in this spacing range with a 30°-pin.

Table I shows the influence of various edge radiuses of the blunt electrode on the 50 % breakdown impulse voltages of a 15 cm rod-plane spark-gap (test arrangement in the High Voltage Laboratory II). Conditions contributing to the formation of diffuse pre-discharge are lessened with rounded-off edges.

Table 1

Edge radius in mm	Damping resistance			
	$R_{da} = 0\,\Omega$		$R_{da} = 260\,\Omega$	
	U_{d1}	U_{d2}	U_{d1}	U_{d2}
0.3	214	250	—	293
0,5	215	260	224	302
1,0	225	265	234	295

8. Influence of the source impedance

The source impedance will be essentially due to stray capacitances, to the load capacitance and possible damping resistances. As shown in fig. 3. the damping resistance has a considerable influence on breakdown probability in the transition range. A damping resistance R_{da} = 260 Ω placed between the load capacitor and the spark-gap will encourage the formation of a stabilizing glow brush discharge. An influence of the load capacitance could not be established.

9. Influence of impulse shape of the impulse voltage

Fig. 8 shows, for three different load capacitances, the front duration versus the SO % breakdown impulse voltages.

The higher 50 % breakdown impulse voltage is influenced below 1.5 µs. At about 0.5 µs, distribution of breakdown probabilities can be rendered by a normal distribution. This means that formation of diffuse pre-discharge will not take place if a determined minimum

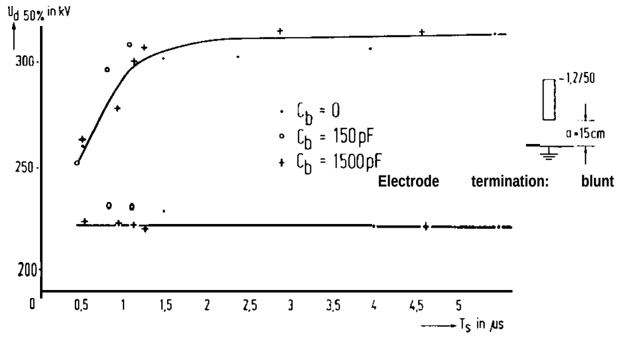


Fig. 8. Influence of front duration on the 50 % breakdown impulse voltage of the negative 15 cm rod-plane spark-gap

front duration is transgressed. Impulse voltage tail has, on the contrary, no influence on breakdown probability distribution. This is understandable, as pre-discharges originate previously in the front of the impulse voltage. Tail duration time of SO µs and of 310 µs have been investigated.

10. Influence of pre-ionisation of the spark-gap

If the cathode of the spark-gap is irradiated by means of a quartz lamp (500 W, wave length 366 nm), it appears that breakdown probability distribution will not be influenced by irradiation. D. c. voltage pre-ionisation of the spark-gap will also show that breakdown probability is not dependent of the pre-stressing with d. c. voltage. Distribution of breakdown voltage with positive or negative d. c. pre-stress with superimposed negative impulse voltage will have nearly the same transition range up to ± 90 kV d. c. voltage, eventhough the insertion voltage of the spark-gap will be transgressed with roughly 40 kV d. c. voltage.

11. Summary

Pre-discharge of the negative rod-plane spark-gap in the transition range varies on the cathode. A diffuse pre-discharge, the negative glow-brush discharge, occurs particularly on blunt electrode terminations, in addition to streamer discharge, which is usual at impulse voltages. This negative glow-brush discharge causes a homogeneization of the spark-gap. In the case of streamer discharges, insertion voltage is transgressed in a determined point, which leads to a partial breakdown; whereas glow-brush discharge is formed by very many simultaneously active single canals [fig. 7 d)] , and their totality causes this homogeneization.

Negative glow-brush discharge is responsible for a higher breakdown strength. A slight undulation of impulse voltage reduces the probability of glow-brush discharge origination. A preliminary resistance attenuates undulation and increases therefore the probability of the negative glow-brush discharge origination.

Negative glow-brush discharge will be influenced by the front duration of the voltage impulse. If front duration is short ($T_s < 0.5$ µs), only canal-shaped pre-discharges will occur.

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