Application of streamer criteria for calculations of flashover voltages of gaseous insulation with solid dielectric barrier

APPLICATION OF STREAMER CRITERIA FOR CALCULATIONS OF FLASHOVER VOLTAGES OF GASEOUS INSULATION WITH SOLID DIELECTRIC BARRIER

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Abstract: The streamer inception criterion is applied to sphere-sphere gaps employing a dielectric barrier in dry air. For such an arrangement, an optimal location of the barrier should exist, where the breakdown voltage becomes maximum. This barrier effect is usually thought of being caused by charging of the barrier. In recent publications the streamer criterion was applied to the shortest path in air circumventing a barrier. There it was evaluated on the undisturbed electrical background field. Here, we consider charging of the barrier due to a pre-breakdown streamer. The approach of applying the breakdown criterion to the undisturbed electrical field is compared to its application on different model charging conditions of the barrier at the moment just before breakdown. The dependence of the breakdown voltage on barrier position is examined and its magnitude is compared with experimental values of the AC breakdown voltage. Apparently, charges have to be considered, when using the streamer criterion for a quantitative prediction of the barrier effect.

1 INTRODUCTION

The evaluation of the electrical withstand performance of high voltage gas insulated equipment is an important step in design. To avoid too many testing loops by try-and-error, a simple calculation method would be desirable. But by today, there is no general method that would allow for a satisfactory calculative prediction of the breakdown voltage (BDV) of arbitrary electrode configurations. Empirical relations are usually utilized for well known configurations. Numerical simulations of electrical gas discharges based on e.g. particle-in-cell, Monte Carlo or drift-diffusion models, provide in principle possibilities to simulate the discharge process. Practical use of these approaches, however, is still very limited or even impossible due to the complexity of the numerical problem, especially when realistic 2D and 3D geometries are to be analyzed.

The streamer breakdown criterion has been used for many years as an engineering approach to calculate the BDV for homogenous field cases. The criterion can be supplemented by a propagation electric field criterion [1] [2] to extend its application to a range of inhomogeneous electric field situations. Some authors [3] have even proposed to apply the streamer criterion to situations, where a solid dielectric barrier is placed in the gas gap between the electrodes. A good correlation to experimental BDV has been reported [3], when evaluating the criterion along the shortest path in gas between the electrodes. Experimental studies have shown, that there exists an optimum position of the barrier, at which the BDV is maximum [4] [5]. In the present paper, several models are discussed to find an evaluation method of BDV of sphere gaps with a dielectric barrier in the gas gap using the streamer criterion, supplemented by propagation electric field criterion. As will be shown below, the assumption of charge deposition on the barrier surface facing the energized electrode resulted in a BDV trend as expected and observed in experiments.

2 TEST SETUP

The test employed a sphere gap configuration, which was centred axially inside a grounded cylindrical vessel. The high-voltage electrode was a spherical copper electrode with a diameter of 20 mm and the grounded electrode was a copper sphere with a diameter of 150 mm. The electrode gap could be varied from 10 mm to 50 mm. The enclosing steel vessel had a diameter of 500 mm and a height of 600 mm, and was equipped with an optical window for visual inspection. The vessel was filled with synthetic air at a pressure of 1.5 bar abs. Solid dielectric barriers made from polyamide with dimensions of 200 mm x 200 mm x 3 mm could be placed between the electrodes.

The AC peak breakdown voltage (BDV) was measured with and without barriers. The barrier position ξ, as defined in (1), was set for each gap length to 1/3, 1/2 and 2/3.

$$\xi = \frac{\text{Barrier position from the energized electrode}}{\text{Total inter electrode gap}} \quad (1)$$

As can be seen from Figure 1, the BDV increased with reduced distance of the barrier from the high voltage electrode. The maximum of the BDV is expected to be found for ξ in the range of 0.1 to 0.3 [4], [5], [6], [7], not tested here.

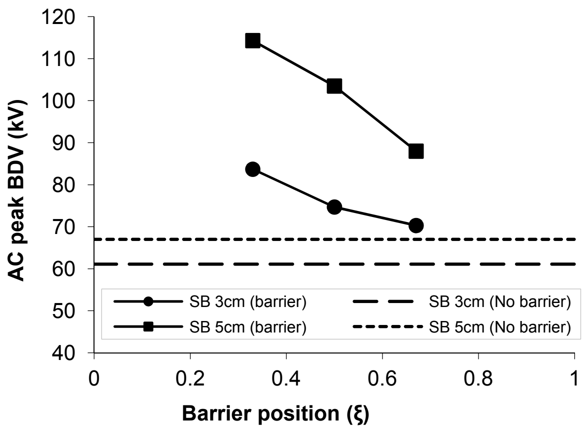

Figure 1: AC peak BDV at a gap length of 30 mm and 50 mm, with and without barrier for synthetic air at a pressure of 1.5 bar absolute.

2.1 Streamer criterion

The streamer criterion [8] [9] [10] is evaluated along the most critical path between the electrodes. The criterion is given by

$$\int_x \alpha_{eff}\, dx = K \,, \tag{2}$$

where x is a coordinate on the critical path between the electrodes, α_{eff} is the effective ionization coefficient of synthetic air [11] [12], and K is the ionization constant. We used $K = 9.15$ according to recent publications [13] [11].

2.2 Propagation field criterion

The streamer criterion (2) has been formulated based on a static and homogenous electric field condition [11]. The criterion (2) can be still successfully applied in inhomogeneous field conditions, when introducing additionally a criterion for the minimum electric field strength that is required for the propagation of a streamer [1] [2], at least for field utilization factors greater than 0.2. The field utilization factor is defined as

$$\eta = \frac{U}{d \cdot E_{\max}} \,, \tag{3}$$

where U is the applied voltage, d is the gap length, and E_{max} is the maximum electric field strength at the electrode surface.

The propagation field strength in air depends on the applied voltage waveform. Here, a propagation field strength of 0.7 kV/mm is considered for AC voltages. Application of the additional criterion means, that

$$E_{avg} \geq E_{prop} \,, \tag{4}$$

where E_{avg} is the average electric field along the breakdown path and E_{prop} is the propagation field strength.

In the all of the following evaluations both criteria, the streamer criterion and the propagation field criterion, needed to be satisfied to obtain the BDV. For simplicity this extended scheme is referred to as the streamer criterion.

3 NUMERICAL MODEL

The test configuration was modelled in Ansys Maxwell in 2D, using axis symmetry. The square shaped dielectric barrier was thereby approximated as a disc of 100 mm radius. The electrostatic boundary conditions were set as indicated in Figure 2. In the experiments, discharge traces on the barrier always pointed from the centre of the barrier to the shortest distant part of the edges and not diagonally to the corners, which indicated, that such a geometrical simplification is acceptable.

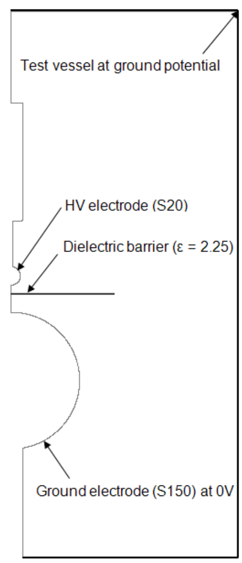

Figure 2: 2D axis symmetry model of the electrode configuration at 30 mm gap length with a dielectric barrier

3.1 Model 1 – non-charged barrier

In model 1 the barrier is assumed to stay electrically non-charged by the streamer breakdown. The barrier then only acts as a simple geometrical obstacle for the streamer to propagate. Two breakdown paths were considered:

Path 1: the shortest possible path in gas between the electrodes

Path 2: from the electrodes to the barrier along the axis line and circumventing the barrier along its surface

Both breakdown paths are as indicated in Figure 3, in an enlarged view of the electrode gap, as shown in Figure 2.

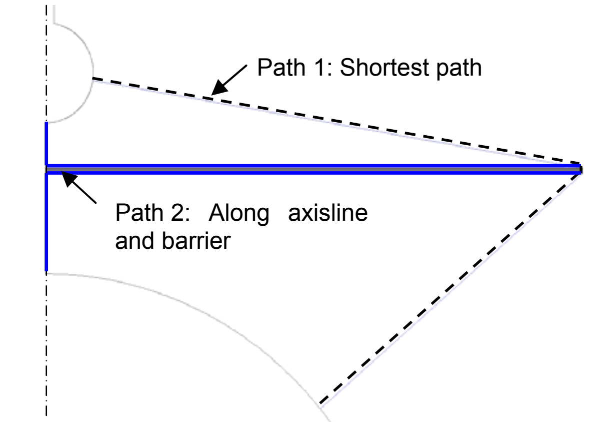

Figure 3: The two modelled breakdown paths

Figure 4 shows the electric field distribution along path 1 and path 2, for a dielectric barrier positioned at $\xi = 0.3$. As expected, the electrical field strength far from the electrodes is much lower than it is near the electrodes.

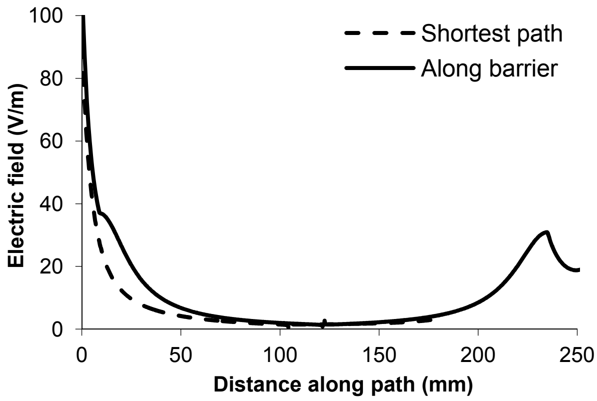

Figure 4: Electric field strength along path 1 & 2, calculated for one Volt.

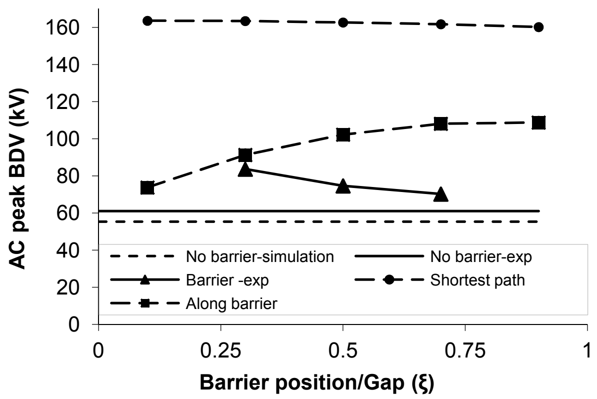

Figure 5: BDV versus barrier position at a gap length of 30 mm, evaluated for Path 1 and for path 2 and experimental results.

To find the streamer breakdown voltage, the applied voltage must be increased not only as much as to satisfy the streamer criterion, but as much as to make the average electric field along the breakdown path higher than the propagation electric field strength. Figure 5 shows the resulting BDV evaluated at different positions of the barrier.

For path 1 the BDV level remains nearly constant for all barrier positions, unlike reported recently [3]. For path 2 the BDV rises with increasing ξ, in contrast to our experimental values and to [4], [5]. Obviously this model is not suitable to predict the BDV of a barrier in the gap satisfyingly.

3.2 Model 2 – streamer channel connection

In model 2 we assume, that before the actual breakdown occurs a pre-breakdown streamer channel is connecting the energized electrode and the barrier with a constant potential gradient of $E_{Str} \sim 0.45$ kV/mm [8], [9]. Breakdown is assumed to occur, when the streamer criterion is fulfilled in the gap between the barrier and the earthed electrode.

Charges accumulating on the barrier will increase the electric potential on the barrier. Two simple potential distributions on the barrier surface are considered here:

Case 1. linearly decreasing from the centre of the barrier, reaching zero potential at the barrier edge

Case 2. Uniform distribution

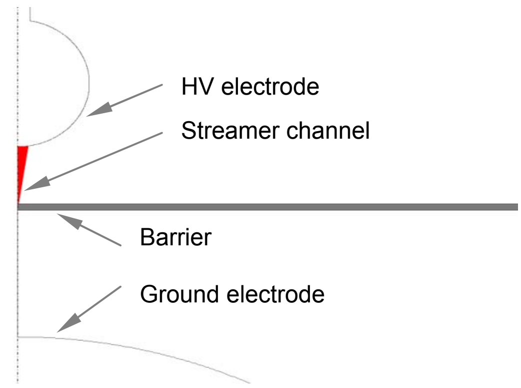

Figure 6: Streamer breakdown to the barrier according to Model 2.

The potential on the barrier surface is chosen such as to satisfy the assumed potential gradient along the streamer channel. Then the streamer criterion is applied to a path along the axis line between the barrier and the earthed electrode. The BDV is evaluated using

$$V = \Delta V + V_{gap}, \quad (5)$$

where V is the applied voltage between the electrodes, ΔV is the voltage drop due to the streamer channel between the energized electrode and the barrier, and V_{gap} is the potential difference required to cause a streamer breakdown between the barrier and the earthed electrode. Since we assume constant E_{Str}, ΔV increases little with ξ, while the required voltage for breakdown V_{gap} at a shorter gap distance between the barrier and the earthed electrode decreases much stronger.

The BDV results for case 1 and case 2 of model 2 are shown in Figure 7. It can be seen, that both assumed potential distributions on the barrier give rise to approximately the same BDV. No maximum in BDV with barrier position is observed, though. At large ξ the BDV is strongly underestimated. Therefore model 2 also does not appear to be able to predict the BDV satisfyingly, even though the magnitude of the BDV for barrier locations near the middle of the gap is in good agreement with our measurements.

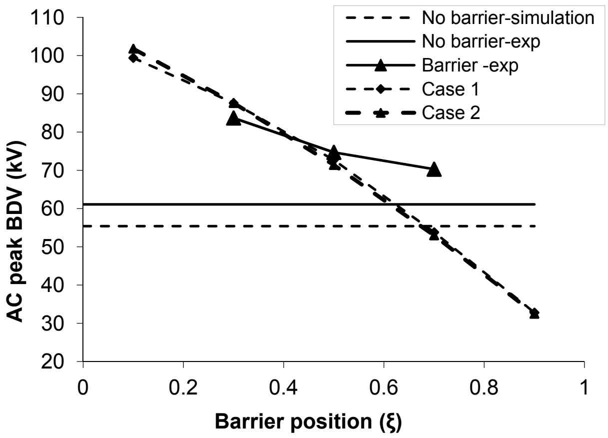

Figure 7: BDV results for both cases in model 2 as compared to experiments, with and without barrier.

3.3 Model 3 – ionization and two gaps

In the experiment, at BDV a spark discharge is observed. Just before sparking we assume, that ions could drift towards the barrier, depositing a charge. In model 3 we assume, that the barrier is charged by positive ions due to a first streamer. Applying (2) along several field lines, it is possible to obtain an estimate of the total ionization along each field line during such a streamer pre-discharge, as shown in Figure 8.

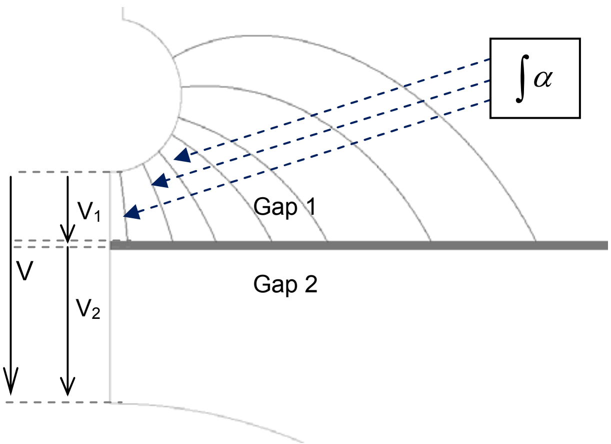

Figure 8: Evaluation of charge density along radial direction of the barrier.

These charges are then assumed to drift along the field lines, depositing on the barrier. The resulting charge density distribution is shown in Figure 9. These charges change the electric field distribution. Consequently, a further increase in voltage is needed to cause a new streamer inception. Breakdown is supposed to occur, when the streamer criterion is fulfilled in each separate gap at both sides of the barrier.

To obtain the charge distribution, we raise the voltage until (2) yields $K = 9.15$ for the central field line (axis line). Then K is evaluated for other field lines, as indicated in Figure 8. From this a charge distribution on the barrier is obtained for each position of the barrier, as shown in Figure 9.

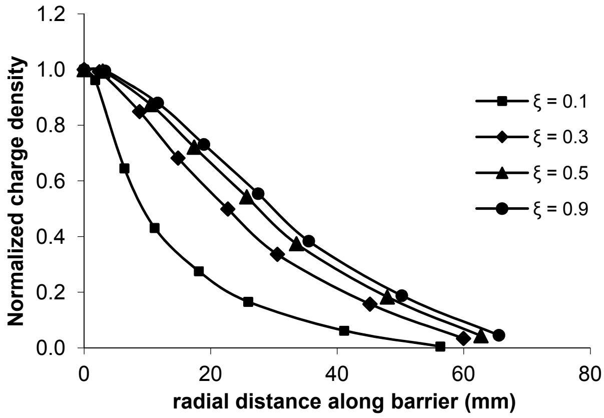

Figure 9: Normalized charge density distribution at inception voltage (55 kV) for different barrier positions.

It can be seen, that the charge distribution along the radial direction of the barrier represents a bell shaped curve, which is pronounced the more, as the barrier is positioned closer to the energized electrode.

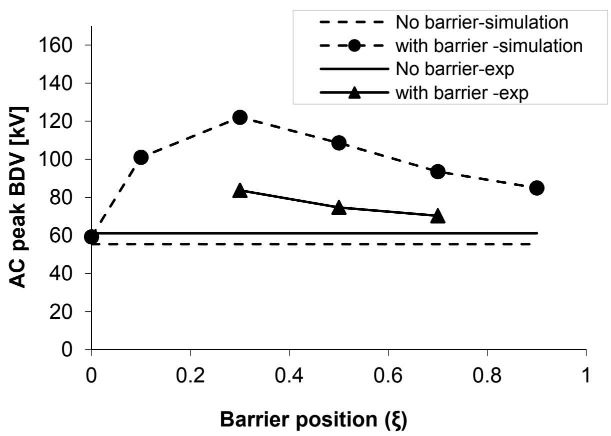

Figure 10: BDV simulation results (Model 3) compared with experiments (with/without barrier).

Figure 10 shows the comparison of BDV results from model 3 with experiments. It can be observed, that the BDV shows a maximum at a position near to the energized electrode, in qualitative agreement with [4], [5]. The magnitude of the BDV, however, is overestimated by about 50% as compared with experiments. We conclude, that the charge density distribution and its magnitude on the barrier surface must be considered, in order to predict the BDV of the electrode gap, but the model still needs corrections.

3.4 Model 4 – ionization charge and continuous discharge path

In model 4 we finally combine model 3 with model 1. Like in model 3 the charging of the barrier is evaluated. But rather than assuming the streamer breakdown to occur in two separate gaps, as shown in Figure 8, the streamer criterion shall be satisfied along path 2 of model 1, Figure 3.

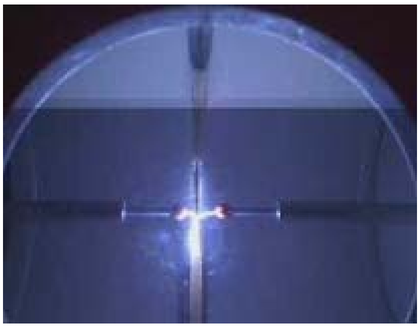

Figure 11: Breakdown path along barrier surface as observed in a experiment (electrodes - 20mm spheres, still image from a video).

The assumption of such a critical path has also been supported by the observations from experiments, like the one shown in Figure 11. Sparking started straight towards the centre of the barrier and from there surrounding the barrier. It is interesting to mention, that at later re-strikes during the following periods of the 50 Hz voltage application, the arc often did not connect to the barrier anymore but was bypassing the barrier, similar to Path 1 in figure Figure 3. Such behaviour in the late discharge stage is probably due to massive charging of the barrier and the air space in the gap. Obviously is also affected by heating of the gas in the spark channel. But here the focus shall be on the first breakdown.

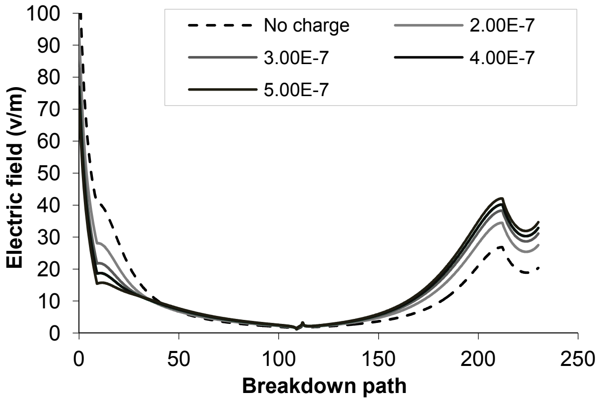

Figure 12: Electric field distribution along the breakdown path for different values of the charge density at the centre of the barrier.

The electric field distribution along the breakdown path 2 is shown in Figure 12. Like in model 1, the criterion for propagation of the streamer is determining the BDV due to the low field values on the path around the barrier.

The breakdown condition was found by scaling up the normalized charge distribution in steps and each time applying the streamer criterion. The lowest voltage, at which the criterion was satisfied while the potential on the barrier due to surface charge was lower than the applied voltage, was taken as the BDV.

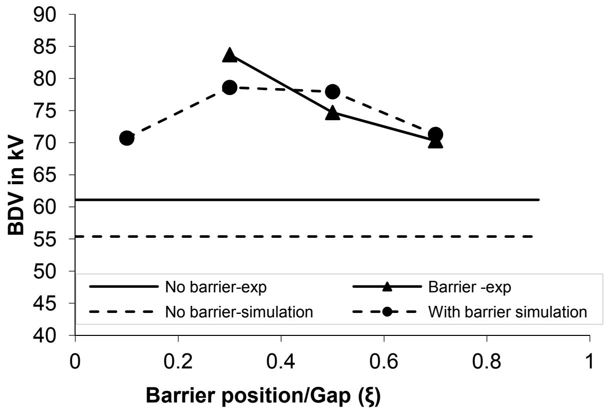

Figure 13: BDV simulation results (Model 3) compared with experiments (with/without barrier).

Figure 13 finally shows the comparison of the BDV as obtained using model 4 with those obtained from experiment. Not only the magnitude of BDV is in good agreement with measurement, but also an expected maximum of the BDV at barrier positions near the energized electrode was found from model 4. So far, model 4 seems promising for use of BDV prediction.

4 DISCUSSION

While considering the charging of barrier surface, only deposition of positive ions was considered when modelling the critical condition before breakdown. There is a potential for refinement in the estimation of charge density distribution on the barriers and of the magnitude of charge required for breakdown. It is not clear yet whether accumulation of electrons at the opposite surface of the barrier has to be considered, too. In addition to surface charges, positive space charge in the gap might be of relevance.

In recent publications [14] [15] it was shown, that the growth of a first and a second positive streamer develops on a ns time scale, when ions can be considered static. Spark breakdown then occurred delayed by one µs [14], time enough for ions to move. From that finding one could conclude, that the charge deposition should be derived in two or more steps, in order to cover pre-breakdown discharges. Then again, (2) does also not account for all ionization processes, like photo-ionization.

Due to such uncertainties our approach was not targeting a quantitative accurate charge calculation, but a qualitative best estimate for the charge distribution.

In [14] two different breakdown paths initiated by a secondary streamer were shown. At higher pulse voltage a direct and straight secondary streamer showed. But at a breakdown at the lowest possible voltage in a gap without barrier, a leader like secondary discharge growth was observed, that bypassed the space charge of the first streamer. One could argue that the barrier effect is inhibiting the lower voltage breakdown level, thus leading to our observation. For small barrier diameter this might not hold anymore.

5 CONCLUSION

A systematic study of strategies to apply the streamer criterion to sphere gaps with a dielectric barrier in the gas gap has been undertaken to predict the BDV in synthetic air. Calculated BDVs were compared with experiments and the methods were assessed for the ability to predict an optimal position of the barrier with respect to the energized electrode. Barriers have been considered as geometrical obstacle only as well as being a collector of charge on their surface.

It has been shown that the application of the streamer criterion simply on the shortest path between electrodes is not sufficient to predict BDV of barrier configurations. We conclude that charge accumulation on the barrier surface and its effect on the background electric field need to be taken into account, when evaluating the BDV by employing the streamer criterion together with the propagation field criterion. Such evaluation seems promising, when breakdown occurs around a barrier without puncture.

If a streamer-type criterion is applicable to gas gaps with barriers, as supposed in this work, the proper definition of the critical initial condition for breakdown needs yet to be clarified. With model 4 in this work a sound first approximation could be demonstrated, though.

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