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Experimental study on the similarity of gas discharge in low-pressure Argon gaps

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Through experiments and theoretical analysis, we investigated the similarity of gas discharge in low-pressure Argon gaps between two plane-parallel electrodes. We found that the breakdown voltages depended not only on gap length and the product of gas pressure and gap length, but also on the aspect ratio of the gap, i.e. $U_b = f(pd, d/r)$. When we considered similar discharge gaps, the radius r , gap length d and gas pressure p fulfilled the conditions of $p_1 r_1 = p_2 r_2$ and $p_1 d_1 = p_2 d_2$. In this situation the reduced field E/p was also constant. The voltage-current characteristic curves of similar gaps were approximately the same, which is a novel experimental result. Comparison of the discharge physical parameters of the scaled-down gap and prototype gap shows that the proportional relations can be derived from the similarity law. Our experimental results provide some instructions on extrapolating two similar gaps and their discharge properties. Application of the similarity law is straightforward when we scale the discharges up or down if they are too small or large.

I Introduction

Paschen's famous law states that the breakdown voltage of a gas gap does not depend individually on the gap length d and gas pressure p , but depends on their product pd ; i.e. $U_b = f(pd)$ [1–9]. According to Townsend Paschen's law is a unique case, with a uniform electric field, of a more general similarity theorem which can be used for breakdowns in non-uniform fields if they are dependent on ionisation by electron collision with neutral particles [2, 3, 10, 11]. Von Engel has discussed and summarised the similarity theorem successfully [6, 12–14]. He specified that under certain conditions similar discharges can be produced in gap-

that have the same geometrical shape but different linear dimensions. It is also notable that the similar discharges have all the physical properties, such as density of the charged particles and current density, in the correct proportions, and also display similar voltage-current characteristics [2, 10, 15–19].

It is also possible to use the known properties of the discharge in one gap to derive the characteristics of the discharges in another geometrically identical gap due to the similarity of gas discharge; this is useful in cases where experimental studies may not be practical or even possible [2, 10, 16, 20]. One pre-condition for such an experiment is to verify that there is a similar discharge in the specified geometrically similar gaps. Progress with similar discharge has been made recently in micro-discharge situations with the huge glow discharge of the International Thermonuclear Experimental Reactor (ITER) and the picoseconds pulse discharge [2, 5, 10, 21, 22].

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In this paper we have used experiments and theoretical analysis to investigate the similarity of gas discharge in low-pressure argon gaps between two plane-parallel electrodes. The results show that the breakdown voltages of these gaps depend not only on the product of gas pressure (p) and gap length (d) but also on the aspect ratio of the gap; i.e. $U_b = f(pd, d/r)$. Theoretically, it has also been proved that $U_b = f(pd, d/r)$, the non-uniform electric field between plane-parallel electrodes, is a special case of the similarity theorem of gas discharge [2, 10, 16]. The experiments show that similar glow discharges exist only in two gaps with a limited scaled-down factor k . Similarly, the theoretical analysis shows that processes such as stepwise ionisation and inelastic collision of the second kind violate the similarity of the discharge as k increases. The voltage-current ($V - I$) characteristics of the glow discharge region studied in similar conditions also confirm the similarity in the gas breakdown.

II Conditions for similar discharges

The first necessary condition for similarity discharges in two geometrically similar gaps is that the product of gas pressure (p) and gap length (d) for these two gaps should be the same [2, 10, 19], i.e. $p_1 d_1 = p_2 d_2$, which ensures that the total number of collisions for one electron to cross the gap is the same [23]. The second condition is that the reduced field in these two gaps should be the same [2, 19, 24–27]; i.e. $E_1/p_1 = E_2/p_2$ for the uniform electric fields or $E_1(p_1 x_1)/p_1 = E_2(p_2 x_2)/p_2$ for the non-uniform fields at the corresponding points where $p_1 x_1 = p_2 x_2$, thus ensuring that the average energy of the electrons is the same [16, 23, 28].

One additional condition is required for the similarity discharges in two geometrically similar gaps: the discharges in these two gaps should be dominated by the physical processes allowable for a similar discharge, known as allowed processes [2, 29]. Many physical processes are happening in the gas discharge, such as stepwise ionisation, ionisation by single collision, diffusion, photoionisation, Penning ionisation, recombination and electron attachment [2, 10, 30]. In appendix 1 of his book von Engel has shown how to test whether a process is forbidden or allowable for a similar discharge. An al-

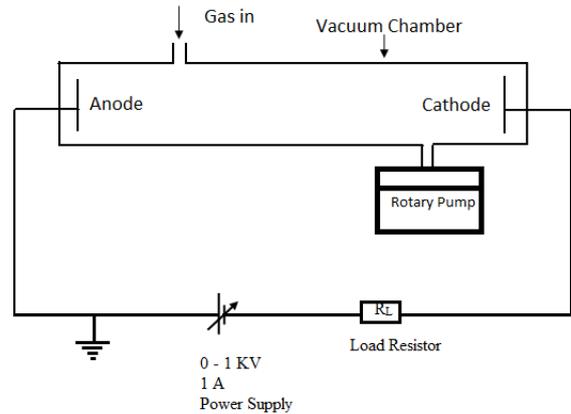


Figure 1: Experimental setup.

lowed process is any process in which the change rate of particle density fulfils the conditions stated in Eq. (1) [2, 29, 31]. Otherwise it is a forbidden process that is not forbidden for gas discharge, but not allowed for similar discharge [2, 10, 29]. It is not possible to distinguish whether a discharge is dominated by forbidden or allowed processes, and this is not controllable.

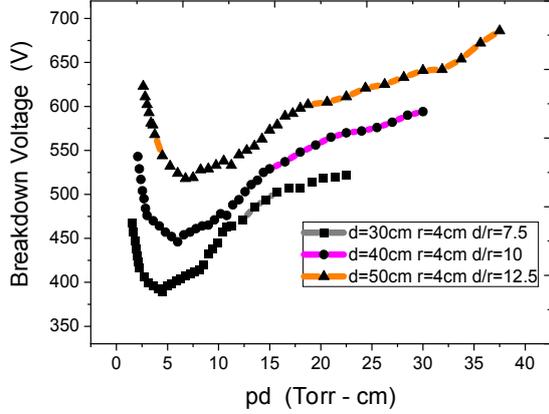
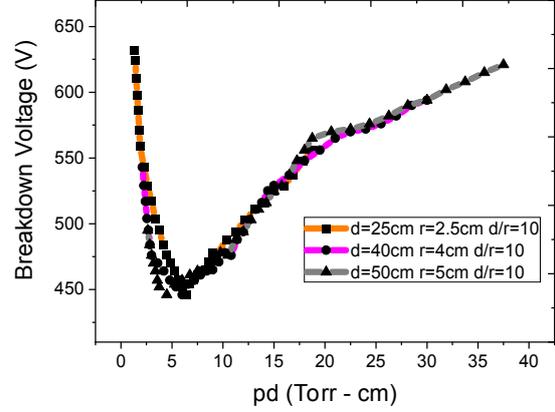
$$\left(\frac{dN}{dt}\right)_{gap1} = \frac{1}{k^3} \left(\frac{dN}{dt}\right)_{gap2}, \quad (1)$$

where k is a scaled-down factor or the ratio of the linear dimension of gap 1 to 2 [2, 10, 32]; N is the particle density.

III Experimental setup

The setup consisted of a cylindrical vacuum chamber made of stainless steel, about 30 cm in diameter and 80 cm in length. An aluminium stand was placed at a height of about 100 cm from the ground, on which the chamber was mounted horizontally. A digital pirani gauge (model IVDG – 1000) was also attached to the aluminium stand, showing the pressure inside the vacuum chamber in millibars. A rotary pump was connected to the cylindrical chamber to evacuate the pressure inside the chamber. A gas inlet was used to fill the chamber with gas.

A glass discharge tube was placed inside the vacuum chamber. The electrodes (anode and cathode)


 Figure 2: Paschen's curves for constant electrode radius (r) and varying inter-electrode distance (d).

 Figure 3: Paschen's curves for the same d/r values.

were placed inside the discharge tube using a Wilson fed through arrangement from the end of the glass tube. This arrangement enabled us to change the separation during the experiment. The electrodes were made of stainless steel of about 1 mm thickness and a diameter of a few centimeters (5 cm, 8 cm and 10 cm, see Table 1).

Thin circular mica sheets of about 7 cm diameter were placed around the electrodes to prevent field lines beyond the electrodes. We used a DC voltage supply that varied over a range of 0 to 1000 V, with a maximum output current of 1 A. To measure and limit the discharge current we connected a resistor (variable) in series.

Table 1: Parameter values are chosen for similarity verification.

Gap	d [cm]	r [cm]	p [mbar]	d/r	a
Gap 1	50.0	5.0	0.20	10	1.00
Gap 2	40.0	4.0	0.25	10	1.25
Gap 3	25.0	2.5	0.40	10	2.00
Gap 4	25.0	5.0	0.20	5	1.00
Gap 5	20.0	4.0	0.25	5	1.25
Gap 6	12.5	2.5	0.40	5	2.00
Gap 7	5.0	5.0	0.20	1	1.00
Gap 8	4.0	4.0	0.25	1	1.25
Gap 9	2.5	2.5	0.40	1	2.00

IV Similarity in gas breakdown

In 1928 Townsend revealed that the breakdown voltage U_b for a longer gap was higher than that for a shorter gap, even with an equal value of pd [5, 11, 28, 33–36], i.e. $U_b = f(p, d) \neq f(pd)$. Consequently, Paschen's curves for the gaps with different d values do not superimpose onto each other. In this paper, this phenomenon was investigated by measuring the breakdown voltages of low-pressure Argon gaps between two plane-parallel electrodes. A schematic representation of the experimental set up is shown in Fig. 1. A DC voltage was used in the electrodes. Figure 2 shows typical results with different d/r ratios, where r is the radius of the electrodes. From Fig. 2 we see that as d/r increases the Paschen's curves move to the right and upwards. In Fig. 3 we observe that the curves with an equal value of d/r superimpose onto each other. From the experiments we conclude that the breakdown voltage of these gaps depends on two factors: the product of gap length and gap pressure, and the aspect ratio of the gap, i.e. $U_b = f(pd, d/r)$. The electric field that exists in the gap between two parallel electrodes is determined by d/r , and in the case of a non-uniform electric field breakdown voltage would be a function of not only pd but also d/r .

The value of E/p is the same for the same value of d/r , and when the d/r value is different the field distributions are also different [16]. In fact, the distribution of the electric field is a function of d/r . A

mathematical expression is obtained by the polynomial fit of the profile of the electric field [35,37,38].

$$\frac{E}{E_{av}} = f\left(\frac{x}{d}, \frac{d}{r}\right) \text{ or } \frac{E}{p} = \frac{U}{pd} f\left(\frac{px}{pd}, \frac{d}{r}\right), \quad (2)$$

The breakdown criterion, the self-sustained condition for Townsend discharge can be expressed as

$$\begin{aligned} \gamma \left[\exp\left(\int_0^d \alpha(x) dx\right) - 1 \right] &= 1 \\ \text{or } \int_0^d \alpha(x) dx &= \ln\left(1 + \frac{1}{\gamma}\right), \end{aligned} \quad (3)$$

where γ is the coefficient of a second electron emission from the cathode by ion bombardment; α is the electron impact ionisation coefficient and is a function of the reduced field E/p , i.e.

$$\alpha = A p \exp\left(\frac{-B}{E/p}\right), \quad (4)$$

where A and B are constants. By substituting (2) into (4), and then into (3), we obtain

$$A \int_0^{pd} \exp\left[\frac{-B}{\frac{U_B}{pd} f\left(\frac{px}{pd}, \frac{d}{r}\right)}\right] d(px) = \ln\left(1 + \frac{1}{\gamma}\right).$$

Now, dividing both sides by A and substituting $px = y$

$$\int_0^{pd} \exp\left[\frac{-Bpd}{U_B f\left(\frac{y}{pd}, \frac{d}{r}\right)}\right] dy = \frac{\ln\left(1 + \frac{1}{\gamma}\right)}{A},$$

$$\int_0^{pd} \exp\left[\frac{-Bpd}{U_B f\left(\frac{y}{pd}, \frac{d}{r}\right)}\right] dy = f\left(U_B, pd, \frac{d}{r}\right),$$

$$f\left(U_B, pd, \frac{d}{r}\right) = \frac{\ln\left(1 + \frac{1}{\gamma}\right)}{A}. \quad (5)$$

From Eq. (5), theoretically, we prove that the breakdown voltage is a function of d/r and pd . The same results are also observed in our experiments. From Eq. (5) we see that, for any two gas gaps, if $p_1 d_1 = p_2 d_2$ and $d_1/r_1 = d_2/r_2$, the breakdown voltage for these two gaps will be the same, i.e. $U_{b1} = U_{b2}$. Substituting these three equations ($p_1 d_1 = p_2 d_2$, $d_1/r_1 = d_2/r_2$, $U_{b1} = U_{b2}$) into Eq. (2), we know that the reduced field E/p in these two gaps at the corresponding point $p_1 x_1 = p_2 x_2$ will be equal, i.e. $E_1(p_1 x_1)/p_1 = E_2(p_2 x_2)/p_2$. Here, $U_b = f(pd, d/r)$ is also a special case of the similarity theorem, with non-uniform electric fields between plane-parallel electrodes [39,40], and extends Paschen's law to this special case. It should be indicated that $U_b = f(pd, d/r)$ also applies to the uniform electric field where $d/r \rightarrow 0$, and it reduces to Paschen's law.

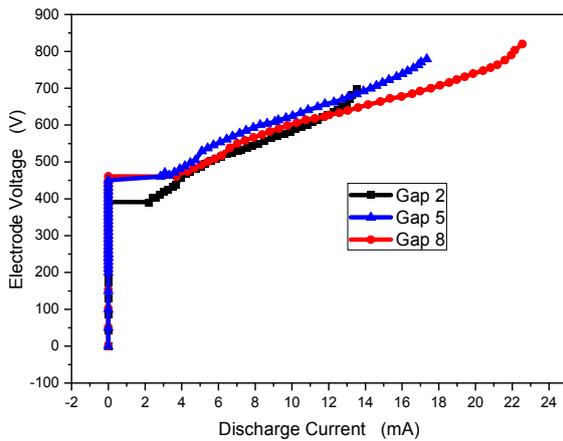


Figure 4: $V-I$ characteristic curves for different gaps.

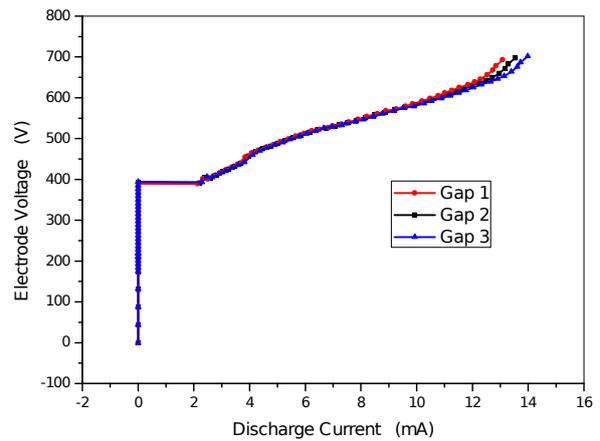


Figure 5: $V-I$ characteristic curves for similar gaps.

V Voltage-current characteristic curves of the similar gaps

The voltage-current ($V-I$) characteristics of DC glow discharge plasma can be obtained either by gradually increasing the external voltage or by lowering the external resistance [3, 4, 28, 37, 41–47]. External high resistance can be introduced to limit the amount of discharge current produced [47]. The operation region of glow discharge can be identified by studying the voltage-current characteristics. The nonlinear nature of glow discharge plasma can be analysed by studying the $V-I$ characteristic [48, 49]. Moreover, the $V-I$ characteristic is the primary step that enables us to find out whether two discharge gaps are similar or not.

The distance between the electrode (d), electrode radius (r), gas pressure (p), and external resistance (R) were kept fixed and the applied voltage (V_A) was varied in equal steps over a wide voltage range. High resistance was introduced into the circuit to limit the amount of current produced. For each voltage applied, the corresponding voltage across the resistor (V_R) was measured. The discharge current ($I = V_R/R$) and electrode voltage ($V = V_A - V_R$) were calculated at each step and the forward characteristics obtained. After reaching the maximum voltage, the voltage was reduced in equal steps as before, the discharge current and electrode voltage were calculated and the reverse characteristics obtained. Placing the discharge current (I) on the x -axis and electrode voltage (V) on the y -axis gives the typical $V-I$ characteristics, as shown in Fig. 4 and Fig. 5.

For any two gaps arranged to fulfil the relationships $p_1 d_1 = p_2 d_2$, $p_1 r_1 = p_2 r_2$ and $E_1/p_1 = E_2/p_2$, the gaps are said to be similar [16]. Along with the physical quantities mentioned, the voltage-current characteristic is approximately the same. Experimentally, the validity of this similarity law for $V-I$ characteristics of a large discharge tube is verified here for three discharge gaps satisfying the above similarity relation. The external resistance chosen for all the three cases is 10 k Ω . In a physical system, the occurrence of hysteresis refers to the parametric dependence of a state on its history. Hysteresis is a clear sign of nonlinearity in the system [43, 47]. The jump phenomenon and hysteresis in discharge current are very well known phenomena in gas discharge, due to the variation in discharge

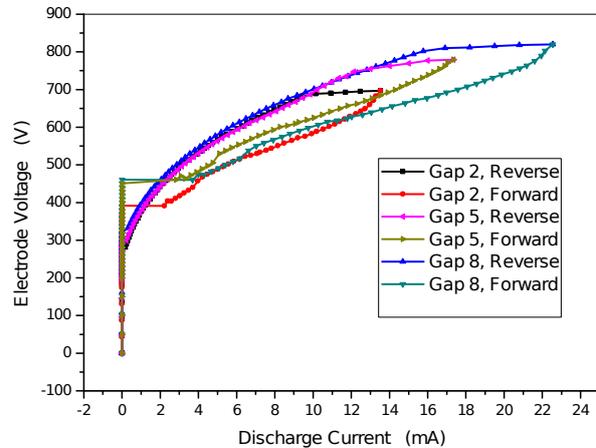


Figure 6: $V-I$ characteristic and hysteresis for different gaps.

voltage [43]. A gradual increase in discharge voltage causes a sudden increase in discharge current. This is called the jump phenomenon. The current increases gradually with an increase in voltage, confirming the operation of glow discharge plasma in the abnormal region [4–6]. After reaching an applied voltage of 900 V, the voltage is decreased in steps of 10 V. The characteristic curve does not retrace through the forward path. There is a decrease in the amount of current discharged in the reverse direction. The current lags behind the voltage and hysteresis is observed; the jump phenomenon can also be observed in the reverse direction. The $V-I$ characteristic and hysteresis for gaps having different d/r is shown in Fig 6. Figures 7, 8 and 9 show the $V-I$ characteristic and hysteresis for similar gaps and confirms the similarity experimentally.

When $p_1 d_1 = p_2 d_2 = p_3 d_3$, the total number of collisions undergone by one electron to cross the gap will be the same for the three gaps. The electric field in a gap between two plane-parallel electrodes can be obtained using the ratio d/r ; the distribution of the electric field is a function of the d/r ratio. The E/p ratio for the three gaps is found to vary almost constantly, by making the d/r ratio constant. The E/p ratio signifies the energy gained by the electron between two consecutive collisions [23]. By fixing the parameters E/p and pd , the electron multiplication rate of the gaps becomes fixed [23]. The rate of electron multiplication de-

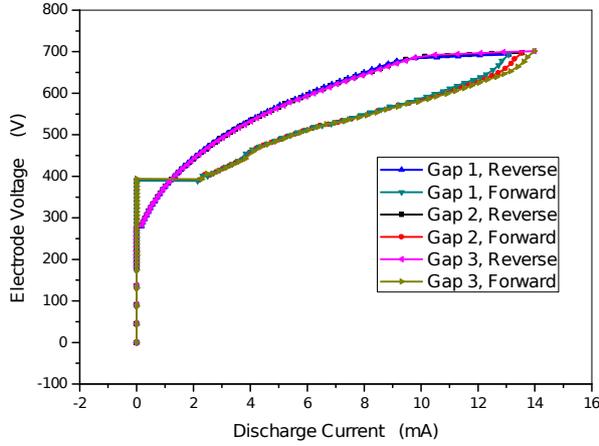


Figure 7: $V-I$ characteristic and hysteresis for similar gaps ($d/r = 10$).

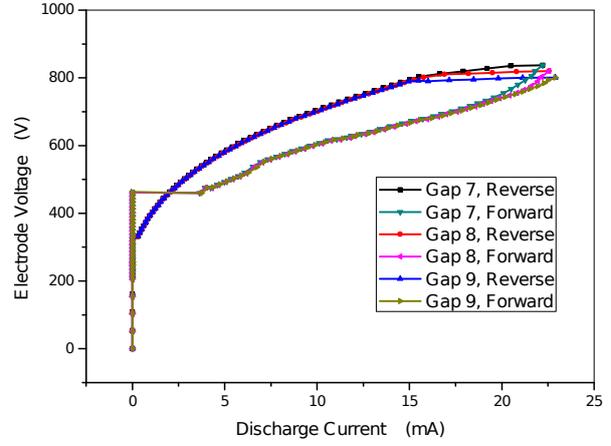


Figure 9: $V-I$ characteristic and hysteresis for similar gaps ($d/r = 1$).

termines the rate of ionization, which in turn determines the rate of discharge current [23]. For voltage varying constantly for the three gaps, the discharge currents produced become equal, as the ionization rate due to electron multiplication is the same. The three curves overlap, and the occurrence of forbidden processes in this gap can be discarded.

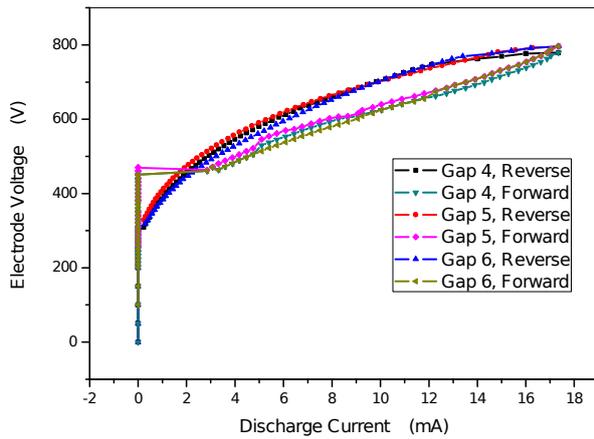


Figure 8: $V-I$ characteristic and hysteresis for similar gaps ($d/r = 5$).

VI Conclusions

In a special case, $U_b = f(pd, d/r)$ is the breakdown voltage between two plane-parallel electrodes with low-pressure gaps, and is the non-uniform electric field between plane parallel electrodes which is connected with the similarity theorem of gas discharge. Similar glow discharge was observed only in two Argon gaps which had a limited scaled-down factor k , and in the case of forbidden processes such as the inelastic collision of the second kind and the step-wise ionisation which tend to violate the similarity of the discharge as k increases [2, 10]. From the experiments we observe a clear cathode fall layer, a positive column between the electrodes, and a negative glow zone. These findings indicate that the discharge is a typical glow discharge [6, 37]. The comparison of discharge physical parameters between the scaled-down gap and prototype gap enables us to find the proportional relations derived from the similarity law. The same voltage-current characteristic curves of the two similar gaps are also obtained.

Studies have been carried out on DC glow discharge at low pressure for more than 100 years; the mechanism of the discharge is well studied. The area of DC glow discharge has many applications, but some of the issues remain unsolved. The glow discharge cleaning of the International Thermonuclear Experimental Reactor (ITER) is considered one of the unsolved problems. In the case

of ITER, a huge tokamak device, the fusion reaction takes place inside a toroidal chamber. The fusion reaction should be stopped after a period of operation, and once stopped the inner wall of the toroid needs to be washed with DC glow discharge plasma. This cleaning involves inserting small electrodes that function as the anodes for the glow discharge on the inner wall. The inner wall serves as the cathode for the glow discharge because it is electroisolated from the small anodes. The question before designers of ITER is whether the DC glow discharge plasma made up of small anodes can uniformly cover the huge wall of the toroid. Unfortunately, it is not possible to showcase the full-scale experiment at present. In this paper, we tried to answer the ITER designers' question using a scaled-down experiment, and investigated whether the glow discharged plasma consisting of small anodes can uniformly cover the wall of the scaled-down chamber or not. The affirmative answer obtained from the scaled-down experiment can be extrapolated to ITER.

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