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ION PRODUCTION RATES IN SF_6 AND THE RELEVANCE THEREOF TO GAS-INSULATED SWITCHGEAR

J. Kindersberger[1], N. Wiegart[2], and S.A. Boggs[3]

[1]Technical University of Munich, Munich, West Germany
[2]Brown Boveri Research Center, Daettwil, Switzerland
[3]Ontario Hydro Research Division, Toronto, Canada

INTRODUCTION

Breakdown of SF_6 is of commercial interest as a result of the large amounts of SF_6-insulated switchgear installed world wide and is of technical interest as a result of the excellent dielectric strength of the gas caused by its high electronegativity. Previous studies in the area of positive surge breakdown area have centered on the concept of "critical volume". The basic idea has been that probability of breakdown depends on the volume stressed above the minimum breakdown voltage and the electron production rate [1-2]. These concepts are semi-empirically based and have been derived under relatively homogeneous field conditions. As such, one has no reason to think that the concepts have any fundamental or universal validity.

The present work was undertaken as part of a joint effort, led by BBC, to develop a more thorough formalism to predict positive surge breakdown of SF_6 for a wide range of geometrical conditions, including highly inhomogeneous fields. Such a formalism requires that the fundamentals of breakdown be understood, starting from the ion density and field-dependent electron detachment rate. This approach, along with clarification of the leader breakdown mechanism [3,4,5], has allowed direct computation of breakdown voltage (accurate to roughly 10%) as a function of geometry and pressure [5], for a wide range of geometrical configurations.

In support of this program, the Technical University of Munich (TUM) and Ontario Hydro undertook measurements of the ion production rate in SF_6, the time to achieve zero-field equilibrium ion concentration, and the zero-field equilibrium ion density. From these data, a number of fundamental parameters can be determined, including the ion recombination rate, ion mobility, etc. As well, the time constant for reaching zero-field equilibrium is an important parameter of experimental interest, as this determines the time between voltage applications which is necessary to assure equilibrium experimental conditions. The ion production rate is a fundamental parameter which determines,

along with the recombination rate and electric field, the concentration of negative ions within a high voltage system.

EXPERIMENTAL CONDITIONS

Figure 1 shows the experimental configuration employed for the measurements. A section of commercial gas-insulated bus duct was used as the test chamber. A steel cylinder was inserted to act as the ion collector. To determine the time to equilibrium, all ions were swept out of the chamber, after which the ion concentration was allowed to build for a specified time after which the ions were again swept out and measured as a function of time. As the time between sweeps was increased, the ion current approached a maximum value, the equilibrium value. If the "dead time" after sweep voltage application, during which amplifiers saturate as a result of displacement current, can be made sufficiently short, the measured current as a function of time represents the ion concentration as a function of radial position. The Technical University of Munich was successful in making measurements with a dead time of only 300 ms. While measurements of this type are useful for determining the equilibrium ion concentration, the radial distribution thereof, and the time to equilibrium, the ion creation rate can only be determined from such measurements by fitting the theory for the equilibrium distribution (including an ion recombination rate) to the data.

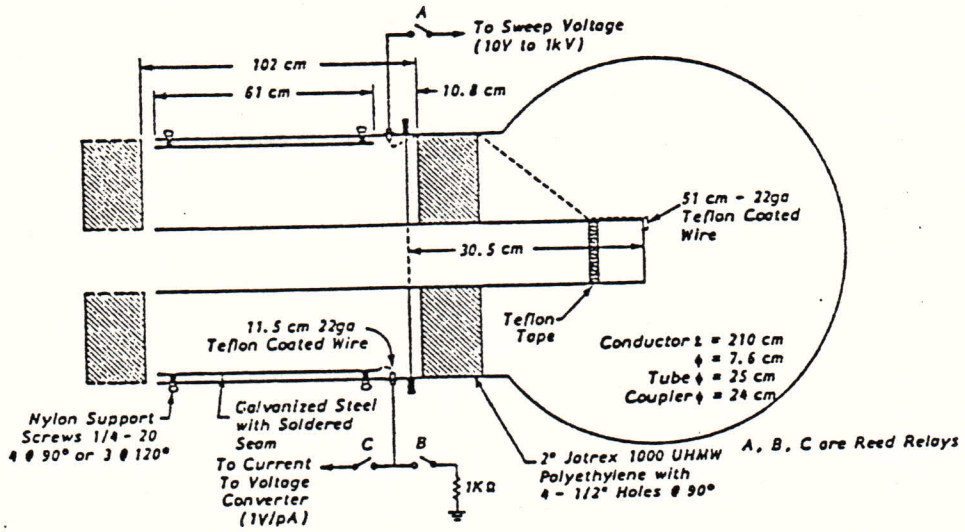

Figure 1. Experimental Configuration for Measurements

The ion creation rate can be determined much more directly by measuring the steady-state ion current when a relatively large potential is applied between the conductor and collecting electrode. Such measurements are difficult, as the ion current is very small relative to that which occurs if the ions are swept out

after the ion concentration is allowed to build to equilibrium. However, such measurements determine the ion creation rate directly and are insensitive to most experimental artifacts which could affect the zero field equilibrium ion concentration.

The currents measured varied from the 100 fA range in the case of steady-state current measurements up to 10 pA range, in the case of measurements in which the ions were swept from the gap after zero-field equilibrium ion concentration was reached. The large volume required for these experiments tended make apparatus highly microphonic, and extreme care was necessary to achieve adequate isolation. As well, the high voltage bias supply had to be extremely stable, as even a small ripple would result in a displacement current much larger than the ion current of interest.

EXPERIMENTAL RESULTS

Ion Production Rate

TUM and Ontario Hydro carried out experiments in which the steady state ion current was measured independently and in experimental configurations of differing dimensions. The calculated "Natural Rate of Ion Production" is shown in Figure 2. The agreement is remarkable, especially given that the ion production rate should depend, to some degree, on the shielding (provided by the building, enclosure, etc.). Most of the TUM measurements were carried out on the ground floor; when measurements were carried out on the top (4th) floor of the laboratory, the ion production rate was found to increase by 25% with the reduction in shielding. When the limited 4th floor data of TUM are compared with the data from Ontario Hydro (which were taken in a single story building) the measured ion production rates agree to within a few per cent.

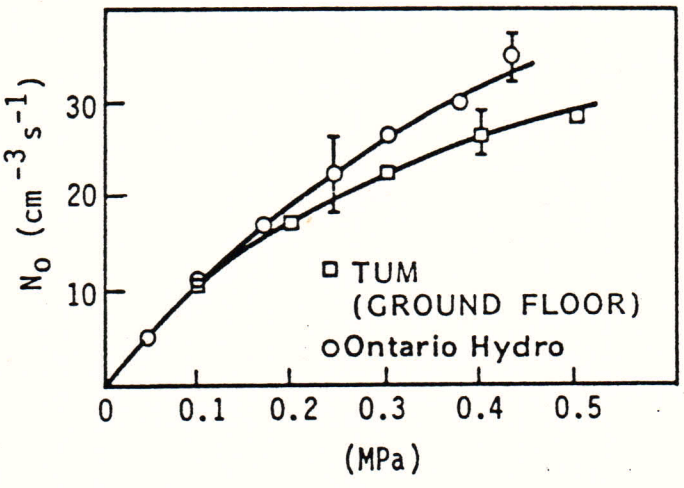

Figure 2. Natural Ion Production Rates in SF_6

One might have expected the rate of ion production to increase in proportion to the gas density; however, both measurements at TUM and Ontario Hydro indicate that the rate of ion creation increases less then linearly with pressure for pressures above 100 kPa. The results of measurements at TUM on coaxial geometries of differing dimensions suggests that secondary radiation from the chamber walls causes this phenomenon. Experiments at the Hahn-Meitner Institute in Berlin [6] resulted in a strictly linear dependence when an artificial radiation source was employed to produce ionization.

Figure 3 shows the equilibrium ion densities which resulted from measurements at TUM and Ontario Hydro. These data were generated through the analysis of the current waveform resulting from applying a sweep field to the apparatus after equilibrium ion concentration had been achieved. From measurements of the ion production rate and total charge at zero-field equilibrium along with the theoretical charge distribution for coaxial geometries [5,7], the maximum ion concentration was determined. As this concentration depends on the equilibrium between production and recombination, it should be essentially independent of coaxial test cell dimensions for gap distances >5 cm. For smaller gaps, the equilibrium is not reached as a result of diffusion to the walls. In the absence of macroscopic gas motion and contact potential differences which might increase ion losses to the enclosure, the equilibrium ion concentration depends on the rates of ion production and recombination through coupled differential equations [8]. As the production rate is known from steady-state ion current measurements, the recombination rate can be determined, if one assumes no perturbations from turbulence. Such a determination results in a recombination coefficient (Table 1) roughly 70% greater than that quoted in the literature [9].

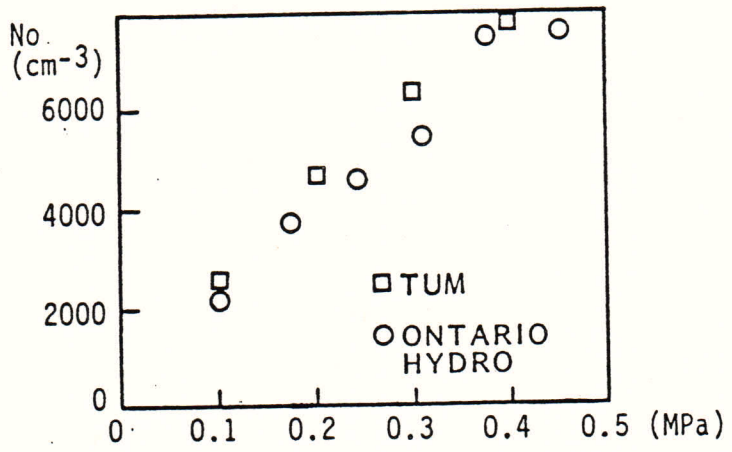

Figure 3. Zero-field Equilibrium Ion Densities

The TUM measurements also facilitate determination of the ion mobility [10] and diffusion coefficient from the duration of the sweeping current pulse. Values for the various constants as determined by the measurements are shown in Table 1.

DATA ON NEGATIVE SF_6 IONS

Quantity	Unit	Value (100 kPa)	Lit.Value	Remarks
Mobility	$m^2/V\text{-}s$	0.36 E-4	0.6 E-4 [10]	B,K
Diff. Coeff.	m^2/s	2.84 E-9	-	K
Rec. Coeff.	m^3/s	1.7 E-12	1.0 E-12 [9]	K
Ion Density	$1/m^3$	2 E+9	-	B,K,Fig 3
Ion Pr. Rate	$1/m^3 s$	1 E+7	-	B,K,Fig 2

(B - Boggs, experiment at Ontario Hydro; K - Kindersberger experiment at TU Munich)

The time required to reach zero-field equilibrium ion concentration in a test piece is important to experimentalists who wish to conduct statistical experiments in which all voltage applications are equivalent. This time is relatively independent of testpiece geometry for testpieces larger than a threshold size, as the ion concentration in mid-gap of such a testpiece is dominated by the ion creation and recombination rates and relatively independent of the proximity of the walls. The threshold size corresponds to distances of roughly 2 cm from the nearest conducting surface. Analysis of the ion sweep waveforms taken as a function of time after sweeping the ions from the apparatus indicates a time constant for the approach to equilibrium ion concentration in the range of 2.5 minutes. If each voltage application were to perturb the ion distribution substantially, a period in the range of 10 minutes between voltage applications would be necessary to assure that each experiment was carried out with the zero field equilibrium number of ions in the apparatus.

CONCLUSIONS

As negative ions are the source of electrons which initiate positive surge breakdown in SF_6, knowledge of the ion creation rate and concentration is essential to a probabilistic understanding of the reliability of gas-insulated substations. The measurement of the parameters which determine the negative ion concentration is an essential step toward such an understanding. The present work

was a small part of a larger project which had as its goal the development of means by which positive surge breakdown (at a given probability) of SF_6 could be predicted to within 10% accuracy for arbitrary surge waveforms and arbitrary geometries, including those which are highly inhomogeneous. Thanks to the efforts of one of the co-authors and his institution (N.W. at BBC), this goal was achieved, and the details of the method will be published under separate cover [5]. The results of this work place design engineers in a position to predict with reasonable accuracy the probability of breakdown of an arbitrary stress enhancement in an SF_6 insulated system for arbitrary surge waveforms. The logical extension of this work is to predict ion concentrations for operating switchgear, subject to the continuous power frequency voltage. Another logical extension is to assess the degree to which a given impulse test sequence assures the in-service reliability of a section of SF_6 switchgear as a function of the imperfections which might exist within the system, i.e., for a given imperfection (stress enhancement) what is the probability of a given test sequence detecting that imperfection, and if it is not detected, what is the probability of failure in service.

A corollary to the above considerations is that the efficacy of any (surge) test would be greatly improved if the ion concentration can be increased. This might be effected by adding a small amount of tritium to the SF_6 used for factory tests. The addition of 1 ppm of tritium would increase the probability of surge breakdown by a factor of roughly 100 (for low probabilities), i.e., increase the equilibrium ion concentration by a factor of 100. This would result in a very substantial increase in the efficacy of a factory surge test, as each surge applied with the tritiated SF_6 would become roughly equivalent to 100 surges in pure SF_6. As the TLV for SF_6 is 1000 ppm, the concentration of tritium in the working environment should not go above 1 ppb for a tritium concentration of 1 ppm.

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