Voltage (60 Hz) Breakdown Strength vs. Temperature of Octafluoropropane (C₃F₈) Gas Exposed to Uniform and Non-uniform Electric Fields

Edward J. Roman

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VOLTAGE (60 Hz) BREAKDOWN STRENGTH VS. TEMPERATURE OF OCTAFLUOROPROPANE (C\textsubscript{3}F\textsubscript{8}) GAS EXPOSED TO UNIFORM AND NON-UNIFORM ELECTRIC FIELDS

BY

EDWARD J. ROMAN

A thesis submitted in partial fulfillment of the requirements for the degree Master of Science, Department of Electrical Engineering, South Dakota State University 1970
This thesis is approved as a creditable and independent investigation by a candidate for the degree, Master of Science, and is acceptable as meeting the thesis requirements for this degree, but without implying that the conclusions reached by the candidate are necessarily the conclusions of the major department.

Thesis Advisor

Date

Head, Electrical Engineering Department

Date
Acknowledgment

The author extends his sincere thanks to Professor M. L. Manning for his many helpful suggestions, as well as aid during the tenure of this thesis. The author also wishes to thank L. C. Whitman who was of assistance in the selection of a thesis topic. The helpful suggestions of H. Graetzer are acknowledged. Credit is given to the author's wife who was so patient with her help in the first typing and editing of the thesis. The financial support given to the author by the Center for Power System Studies was most sincerely appreciated.
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INTRODUCTION

A. General Background of Gaseous Insulation

Gaseous insulation is at least as old as air itself. In the early days of the electrical industry air was depended upon extensively as an insulating medium. Air, in fact, is not too bad as an insulator and today it is still used for this purpose. Air is noninflammable, non-explosive, plentiful and it has good dielectric characteristics.

Over the years, however, there was a need for insulating mediums which had higher dielectric strength than air. Solid and liquid insulating mediums gained wide use because of the higher dielectric strengths. However, solid and liquid insulating mediums possessed some undesirable characteristics. Solids were heavy and bulky, and sometimes interfered with mechanical motion. At times, they also blocked the necessary heat dissipation from a device and readily transmitted noise. Some liquids created a fire hazard or large pressure surges on arcing. They too were heavy and good transmitters of noise.

Gaseous insulation really began to make its mark as a useful insulating medium with the development of apparatus that had more stringent operating gradients. The need to insulate higher voltages with lighter and more compact equipment helped to encourage the use of gaseous insulation. Since there was a need for gaseous insulation, other gases were used in the place of air. Hydrogen was one such gas. It, of course, had the distinct disadvantage of being flammable as well as explosive. Nitrogen was another gas. It was a stable and inert gas,
but its dielectric strength was slightly lower than that of air. Other
gases such as neon, argon, xenon, helium, and krypton were used where
spectral emission features were important.¹

Recently, new gases have come into use as gaseous insulating
mediums. These gases are the so-called electronegative gases. These
gases have this name as a result of their apparent capacity to capture
free electrons. Their molecules seem to have an affinity for free
electrons and thus form heavy negative ions which are relatively immo-
bile.¹ Since free electrons are important in the formation of an arc,
these gases have the property to prevent these arcs from occurring by
capturing the necessary free electrons needed for the formation of the
arc.

One popular electronegative gas is sulfur hexafluoride, SF₆. SF₆
was demonstrated to have good insulating qualities and in 1940 the
General Electric Company was assigned a patent on the use of SF₆ as a
gaseous insulation.

Gases formed by the partial or complete replacement of the hydro­
gen atoms by fluorine and/or chlorine atoms in hydrocarbon molecules
constitute a large family of electronegative gases.¹ Of particular
interest are the so-called three and four carbon members of perfluoro­
carbons. They are applicable from temperatures of 200 to 250°C.²

One of these perfluorocarbon gases of interest is perfluoropropane,
C₃F₈, sometimes designated octafluoropropane.

B. Desired Characteristics of Insulating Gases

Although a high dielectric strength is important when selecting a
gas as an insulating medium, many other characteristics are important. Probably, the second most desirable characteristic is the extent to which the gas can act as a cooling agent. The following list gives some of the characteristics desired of insulating gases:

1. High dielectric strength at lower pressures
2. Good heat transfer characteristics
3. Non-toxic
4. Non-flammable and will not support combustion
5. Minimum decomposition and toxicity under conditions of arcing
6. Low boiling point to insure safe starting conditions
7. Plentiful and economical
8. Chemical and thermal stability under operating and environmental conditions in the presence of structural materials.

Octafluoropropane gas, C₃F₈, meets all of the above requirements relatively good.

C. Octafluoropropane

Octafluoropropane is a three carbon perfluorocarbon or fluorinated hydrocarbon. It has the following molecular structure:

\[
\begin{align*}
| & | & | \\
F & C & C & C & F \\
| & | & | \\
F & F & F
\end{align*}
\]

Its physical and chemical properties are:

Molecular Weight \(188.02\)

Normal Boiling Point \(-36.7°C\)
Freezing Point ........................................... -160°C
Critical Temperature ................................. 71.9°C
Critical Density ........................................ 0.6 g/cc
Critical Pressure ......................................... 26.4 atmos.
Vapor Pressure at 21.1°C (70°F) ................. 114.8 psia
Thermal Stability ........................................ No detectable decomposition through at least 500°C (932°F).
Chemical Stability ...................................... C₃F₈ is one of the least reactive compounds known and the most heat stable under normal operating conditions. At 275°C (527°F), it has negligible reaction with materials of construction.
Flammability ............................................. Non-flammable and will not support combustion.
Toxicity .................................................... Toxicological tests show it to be non-toxic.
Specific Heat (calculated-ideal gas)
at 90°C ................................................. 39.60 calories/gram-mole-°C
Heat of Vaporization (calculated) at
20°C ....................................................... -3.610 Kcal/gram-mole
Coefficient of Thermal Conductivity
(calculated) at 70°F .................................. 3.6 x 10⁻⁵ cal/sec-cm-°C
Some tests have been conducted to determine the electrical properties of $C_3F_8$. M. L. Manning in a paper titled *Experience with the AIEE Subcommittee Test Cell for Gaseous Insulation* gives results of various tests made on $C_3F_8$ as well as other gases. With a $3/4''$ sphere to grounded plane electrode system, under a rapidly applied 60 Hz test, the ratio of breakdown voltage strengths of $C_3F_8$ to those of air varied from 1.87 at a 0.1'' gap spacing to 2.25 at a 0.5'' gap spacing. One minute withstand, 60 Hz tests using the same electrode system showed that the ratio of breakdown voltage strengths of $C_3F_8$ to those of air varied from 2.09 at a 0.1'' gap spacing to 2.25 at a 0.5'' gap spacing. These tests were conducted at a temperature of 23°C and at atmospheric pressure.

Members of the halocarbon family or the so-called perfluorocarbons are subject, to some extent, to decomposition when under the influence of corona or an arc. Decomposition products may be toxic and corrosive. Corona can cause the gradual breakdown of $C_3F_8$ gas and as a result fluorides would be released which in turn may combine with moisture and produce corrosive compounds. Due to the above conditions a device using $C_3F_8$ gas should be designed to have corona-free operations.

Octafluoropropane has been used in dry type transformers. Other possible uses are in pressurized wave guides and choppers. It seems its use could be extended to many devices.

D. Area of Investigation

The author chose to investigate the voltage breakdown strength of
C₃F₈ as a function of temperature of the gas. The types of tests applied were the 60 Hz rapidly applied and one-minute withstand tests. The investigation was made both with and without a weak source of irradiation present near the cell. Two types of electrode systems were used: 3/4" sphere to grounded plane which represented a uniform field, and a point to grounded plane which represented a non-uniform field.

Figure 1 shows a tree diagram of the various types of tests made. Each type of test made shown in Figure 1 represents tests made at seven different temperature levels. The temperature levels were: room temperature, (23°C - 30°C), 50°C, 80°C, 110°C, 140°C, 170°C and 200°C.
Fig. 1. A Tree Diagram of the Problem

* Tests were repeated
REVIEW OF LITERATURE

Much has been published on various studies made in connection with gaseous insulation. Messrs. G. Camilli, J. J. Chapman, R. E. Plump, J. D. Cobine, C. N. Works, and T. W. Dakin, as well as others, have written articles on the subject.6

Some articles are of particular importance to research on the breakdown strength of $C_3F_8$ as a function of temperature. Such articles are those written on studies of the voltage breakdown strength of $C_3F_8$ gas, of studies related to Paschen's law, and of studies on the investigation of the effects of temperature on the breakdown strength of gas.

M. L. Manning5 discussed tests on four types of gases, namely: sulfur hexafluoride ($SF_6$), perfluoropropane ($C_3F_8$), nitrogen ($N_2$), and air. Four types of electrical systems were used. Electrode system A was a 3/4" diameter brass sphere to a 1-3/4" diameter brass plane, electrode system B was a 1/2" square brass rod to a 1-3/4" diameter brass plane; electrode system C was a 3/4" diameter brass sphere to a 1" square projected brass rod; and finally electrode system D was a 1/2" square brass rod to a 1" square projected brass rod.

The bottom electrode was grounded through 0.9 megohms of resistance for all of the 60 Hz voltage tests.

The results showed that with a 3/4" sphere to grounded plane electrode system, under a rapidly applied 60 Hz test, $C_3F_8$ had breakdown voltage strengths from 14.4 KV at a 0.1" gap spacing to 44.3 KV at a 0.5" gap spacing. The same test ran on air showed breakdown voltage
strengths from 7.7 KV at a 1.0" gap spacing to 19.7 KV at a 0.5" gap spacing. This means that the ratio of breakdown voltage strength of C₃F₈ to that of air for this test varied from 1.87 at a 0.1" gap spacing to 2.25 at a 0.5" gap spacing. One minute withstand, 60 Hz tests using the same electrode system showed that the voltage breakdown strength varied from 13.8 KV for C₃F₈ and 6.6 KV for air at a 0.1" gap spacing, to 42.3 KV for C₃F₈ and 18.8 KV for air at a 0.5" gap spacing. This means the ratio of breakdown voltage strength of C₃F₈ to that of air for the one-minute withstand test varied from 2.09 at a 0.1" gap spacing to 2.25 at a 0.5" gap spacing.

The results also showed that for the rapidly applied test on the 3/4" sphere to grounded plane, the breakdown voltage strength of SF₆ was slightly higher than that of C₃F₈ at each gap spacing tested. The same situation was shown for the one-minute withstand tests.

It was also shown that when the rapidly applied and the one-minute withstand tests were made with a 1/2" square rod to grounded plane the breakdown voltage strength of C₃F₈ was higher than that of SF₆. This is just the reverse relationship between the breakdown values of C₃F₈ and SF₆ as that in the above described 3/4" sphere to grounded plane tests.

All of the above tests were conducted at a temperature of 23°C and at atmospheric pressure.

The results also showed that when using the 3/4" diameter sphere to plane electrode system and applying a 60 Hz voltage test, the voltage breakdown strength of nitrogen was slightly higher than that for
air for all gap spacings between 0.1" and 0.5". This was true for both the rapidly applied and the one-minute withstand tests. On the other hand, similar tests conducted using a 1/2" square rod to plane electrode system showed that the voltage breakdown strength of air was higher than that of nitrogen at all gap spacings used for both the rapidly applied and one-minute withstand 60 Hz voltage tests. This is opposite to the relationship of the breakdown values of air and nitrogen obtained when using the 3/4" sphere to plane electrode system.

Rapidly applied and one-minute withstand 60 Hz tests using the 3/4" sphere to 1" square projected electrode system and the 1/2" square rod to 1" square projected electrode system were made on the four types of gases. The results of these tests showed that for all tests the voltage breakdown strength of nitrogen was slightly higher than that of air at all gap spacings. One exception to this was the rapidly applied 60 Hz voltage tests using the 1/2" square rod to the 1" square projected plane. The voltage breakdown strength of air was equal to or greater than that of nitrogen between 0.4" and 0.5" gap spacings. For the 3/4" sphere to 1" square projected electrode system the breakdown value of SF6 was slightly higher than that of C2F8. For the 1/2" square rod to 1" square projected electrode system, the reverse was true.

M. L. Manning indicated that upon comparing the results from the tests using various electrode systems, gases have electric strengths which vary with the electric field used in the tests. He also indicated that this suggests the desirability of using more than one set of electrode systems in the test cell during tests.
M. L. Manning and E. D. Padgett studied the breakdown strength of C₃F₈, SF₆, air and nitrogen inside a test cell with and without a directly grounded bottom electrode. All the 60 Hz voltage tests used a 3/4" sphere to plane electrode system. The results showed that when using a directly grounded bottom electrode, the breakdown strengths of C₃F₈ and SF₆ were approximately the same for both the rapidly applied and one-minute withstand 60 Hz voltage tests. At 0.1" gap spacing the breakdown strength for the two gases was approximately 11.0 KV and approximately 41.5 KV at 0.5" gap spacing. The breakdown strengths of air and nitrogen for the same test were the same between a gap spacing of 0.25", where they were both approximately 13 KV and a gap spacing of 0.5" where the strengths were both approximately 16 KV.

When the bottom electrode was connected to the ground through a high impedance some different results were obtained. The breakdown voltage of C₃F₈ was much higher. The results for the one-minute withstand test showed that the breakdown voltage of C₃F₈ gas varied from approximately 27 KV at 0.1" gap spacing to approximately 52 KV at 0.45" gap spacing. The breakdown strength of SF₆, on the other hand, varied from approximately 20 KV at 0.1" gap spacing to 45 KV at 0.45" gap spacing. The breakdown strength of C₃F₈ was higher than that of SF₆ under conditions of a high impedance ground. The breakdown strength of nitrogen was somewhat higher than that of air. All tests were made at normal temperature and pressure.

L. C. Whitman discussed the positive and negative impulse voltage breakdown values of C₃F₈ gas. Two electrode systems were used: a 1" diameter brass sphere to a 1-3/4" diameter square edged brass plane,
and a 3/32" diameter tungsten rod, with a 25 degree sharp point, to a 1-3/4" diameter square edged brass plane. All of the tests were made at a pressure of 28.35 in. of Hg \( \pm 10 \) in. of Hg and a temperature of \( 80^\circ F \pm 10^\circ F \).

His test results showed that the voltage breakdown of \( C_3F_8 \) for the 1" sphere to plane electrode system with a positive impulse voltage varied from 27 KV at a 0.1" gap spacing to 100 KV at a 0.65" gap spacing. For the point to plane electrode system, the breakdown voltage for the same test varied from approximately 18 KV at a 0.1" gap spacing to approximately 83 KV at 1.0" gap spacing. The sphere to plane electrode system had higher breakdown values than did the point to plane electrode system and had a steeper curve of breakdown voltage vs. gap spacing.

Similar tests on \( C_3F_8 \) gas using a negative impulse voltage showed that the breakdown voltage values were approximately 25 KV for the sphere to plane electrode system and approximately 17 KV for the point to plane electrode system at a 0.1" gap spacing. Breakdown voltage values were approximately 97 KV for the sphere to plane electrode system at a 0.55" gap spacing and 89 KV for the point to plane electrode system at a gap spacing of 0.75".

Similar tests were run for air. The results show that for the sphere to plane electrode system, the breakdown ratio of \( C_3F_8 \) to air for positive impulse voltages varied from 3.3 at a 0.05" gap spacing to 2.5 at a 0.35" gap spacing, and finally a ratio of 3.0 at a 0.75" gap spacing. For the same electrode system, only with a negative polarity, this ratio varied from 2.6 at a 0.5" gap spacing to a low of
2.54 at a 0.25" gap spacing, to 2.7 at a 0.63" gap spacing.

The breakdown ratio of $C_2F_8$ to air for the point to plane electrode system with a positive impulse voltage applied was also given. This ratio varied from approximately 10.5 at a 0.5" gap spacing to a low of 2.2 at a 0.8" gap spacing, and finally to 2.35 at a 1.0" gap spacing. The breakdown ratio of $C_2F_8$ to air for the same electrode system using negative impulse voltages varied from 4.85 at a 0.4" gap spacing to 2.5 at a 0.9" gap spacing.

F. J. Campbell discussed the considerations of Paschen's law as observed experimentally at higher pressures. Paschen's law states that the voltage breakdown of a gas in a uniform field is proportional to the product of the electrode gap spacing and the pressure of the gas. F. J. Campbell implied that the temperature of the gas remained constant, which meant that the product of gap spacing and pressure is then equal to the product of gap spacing and gas density.

F. J. Campbell compared curves of the breakdown voltage vs. pressure times gap spacing for air, $H_2$, and $N_2$, under uniform field conditions. It was shown that for each gas a minimum breakdown voltage was observed and that this breakdown was the lowest for inert gases. At very low values of pressure times gap spacing the breakdown values were higher than at the minimum point. Electrons traveling in the gas between the electrodes hit very few atoms. At very high values of pressure times gap spacing, the breakdown strengths are again higher because excited electrons would lose most of their energy through collision with density packed molecules.
He stated that in a uniform field the sparkover voltage of a gas increases linearly with pressure (Paschen's law) up to above 10 atmospheres. At this point the factors which contribute toward electrical instability become sensitive enough to cause an increase in ionization between the gap. Above 10 atmospheres Paschen's law is not followed as there is a gradual diminution in the rate of breakdown voltage with pressure.

F. J. Campbell explained why oxygen and many other polyatomic gas molecules which contain oxygen, sulfur, fluorine, chlorine, and bromine (electronegative gases) have higher breakdown voltage strengths. The electronegative gases have the ability to capture the free electrons in the gap. He states that the higher breakdown strength of a mixture of CO₂ and N₂ is accounted for by the electronegativity of the CO₂ gas.

A. H. Sharbrough, D. R. White, P. K. Watson, T. H. Lee, and Allen Greenwood made an investigation into the breakdown strength of nitrogen gas at high temperatures through the use of a shock tube. The gas under study was heated and accelerated with the use of a shock wave. A pair of electrodes extended into the gas. After the shock front had passed, a voltage pulse was applied across the electrodes to test the breakdown strength of the heated gas. The electrode spacing and gas density behind the shock front was maintained at constant values for all the tests, while the shock strength was varied.

Paschen's similarity law says that the breakdown potential strength of a gas in a uniform field should remain constant if the product of the electrode spacing and the gas density remain constant. This indicated that any observed change from the law should be indicative of an effect.
of gas velocity or temperature. The effect of temperature here is understood to mean the effects other than the dependence of density on temperature.

Temperatures in excess of 4,000°K and gas velocities as high as 2,500 meters per second were reached during these experiments. Above 1,500°K breakdown values with marked deviations from similarity behavior were observed and at 4,000°K the voltage breakdown strength was as low as 50 percent of the breakdown values at room temperatures.

Since these tests were conducted on a gas in a dynamic state, it was found that at a given temperature the breakdown potential decreased with increasing time after the passage of the shock front. This was attributed to a changing degree of ionization with time. Thus their measurements were made under nonequilibrium conditions.
BASIC THEORY

In this section various equations will be presented. A list of the symbols used in the equations and what they represent is given below.

\( \alpha \) = Townsend's first ionization coefficient.

\( \alpha_b \) = value of \( \alpha \) for the conditions of breakdown.

\( \gamma \) = probability that the positive ions in the gas will produce electron emission at the cathode.

\( \epsilon \) = base of the natural or naperian logarithms = 2.718.

\( \lambda \) = mean free path of an electron.

\( \sigma \) = the total number of electrons per square meter under steady state conditions.

\( \sigma' \) = number of electrons per second per unit area near the cathode that are accelerated toward the anode.

\( \sigma'' \) = number of electrons emitted from the cathode each second (including those produced by the \( \gamma \) process).

\( \sigma^+ \) = density of positive ions.

\( \sigma^- \) = number of negative ions that reach the anode.

\( \chi \) = the probability that electrons emitted at the cathode will not diffuse back to the cathode.

\( d \) = distance between cathode and anode.

\( E \) = electric field strength.

\( e \) = charge on the electron.

\( F \) = some function.

\( f' \) = some function similar to \( F \) and \( f \).

\( f \) = some function similar to \( F \) and \( f' \).

\( J \) = current density

\( J_0 \) = \( e \sigma' \)
\( J_a \) = current density at the anode.

\( N_0 \) = number of ion pairs formed per unit volume per second by a source of irradiation.

\( P \) = pressure of gas.

\( V_b \) = the breakdown potential, in a uniform field, corresponding to \( \approx b \).

\( x \) = displacement toward the anode.

\( Z \) = number of attachments per electron per cm of drift.

J. S. Townsend and his co-workers introduced the first general theory of electrical breakdown between 1900 and 1920.\(^{11}\) A more comprehensive theory was presented in the streamer theory by Loeb and Meek in 1936.\(^{12}\) The Townsend theory describes breakdown phenomena at lower pressures (far below atmospheric pressure), and the streamer theory is used to describe activities at higher pressures.\(^{12,13}\)

A. Pre-spark Volt-ampere Characteristics

Gas placed between two electrodes has basic volt-ampere characteristics. A typical gas tube volt-ampere characteristic is shown in Figure 2, which is obtained by increasing the anode-to-cathode voltage from zero up to higher voltages until breakdown of the gas occurs.\(^{11,13}\) The characteristics are shown for uniform electric field conditions, constant external irradiation, and for a pressure of several microns (1 micron = 10\(^{-3}\) mm H\(_2\)O).

Between points O and A the current is space-charge limited. External sources of ionization such as x-rays, \( \beta \) and \( \gamma \)-rays or photons of light cause a few ions to be present in the gas in this low voltage region.\(^{11}\) Thermal ionization may also contribute to the production of electrons. As the voltage becomes higher and higher in
Fig. 2. Pre-Spark Volt-Ampere Characteristics of a Gas between Two Electrodes.
this region, more ions and electrons reach the electrodes and are neutralized. This recombination process reduces the number of charged particles in the gas. The rate of increase of current with voltage then decreases with increasing voltage in the region between 0 to A.\textsuperscript{13}

If the voltage is again raised, a point is reached where the rate at which charged particles arriving at the electrodes equals the rate of production of these particles. This is called the saturation current density region. This is the region between A and B.\textsuperscript{11,13}

If the voltage is increased and approaches point B, some of the free electrons acquire energies high enough to cause ionization of atoms in neutral molecules upon collision with them. These collisions form more electron-ion pairs and the new electrons may themselves make ionizing collisions. With the increased level of production of electron-ion pairs, the current will increase again as shown above point B in Figure 2.\textsuperscript{11,13} This is called the $\infty$-process.

Townsend introduced the quantity $\gamma$, which is called Townsend's first ionization coefficient. If $\sigma_-$ is the number of electrons per second per unit area near the cathode that are accelerated toward the anode, and $x$ is the displacement toward the anode, then:

$$d\sigma_- = \gamma \cdot d\sigma_- \quad (1)$$

is the number of ion pairs formed per second by the electrons which make the ionizing collisions in a volume of unit cross-section and a depth $dx$. The coefficient $\gamma$ has units of electrons/meter/primary electron.\textsuperscript{11,13}

If there exists a constant source of $\sigma_-$ electrons near the
cathode, the total number of electrons per square meter under steady state conditions, and at a distance x from the cathode is:

\[ \sigma_-(x) = \sigma_0 \varepsilon^x \]

This equation indicates that an avalanche of electrons will occur. The current density at a point x from the cathode is:

\[ \mathbf{J}(x) = e \sigma_0 \varepsilon^x = \mathbf{J}_0 \varepsilon^x \]

where \( e \) is the charge on the electron. The current at the anode would then be:

\[ \mathbf{J} = \mathbf{J}_a = \mathbf{J}_0 \varepsilon^d \]

where \( d \) is the distance between the cathode and anode electrodes.

If there also exist some source of irradiation such as x-rays, that cause \( N_0 \) ion pairs per unit volume per second to form throughout the gas instead of only near the cathode, equation (1) must be modified. This irradiation of the gas will cause an increase in the electron density in the gas. The number of ion pairs now formed would be:

\[ d\sigma^- = (\alpha \sigma^- + N_0)dx \]

Integration of this with the condition of zero electron density at the cathode yields:

\[ \alpha \sigma^- + N_0 = A \varepsilon^x \]

where if \( x = 0 \), \( \sigma^- = 0 \), then \( A = N_0 \). Since this is the steady state...
case, the steady state electron concentration at a point $x$ is:

$$\sigma^{-}(x) = \frac{N_o}{\infty} (\epsilon^x - 1)$$

(7)

and the current density is:

$$J^{-}(x) = \frac{e N_o}{\infty} (\epsilon^x - 1)$$

(8)

Townsend's first ionization coefficient $\alpha$ can be calculated in terms of $P$ and $E$, where $P =$ pressure and $E =$ electric field strength. Let $\lambda$ be the mean free path of an electron, in the field direction, between its collisions with atoms. The mean energy gained by an electron is $Ee\lambda$, between each collision. The number of ionizing collisions made per centimeter in the field direction is $\alpha$, and depends on the energy, $Ee\lambda$, and on the number of encounter per cm. The number of encounter is directly related to the gas pressure at a constant temperature. Thus:

$$\alpha = Pf'(Ee\lambda)$$

(9)

where $P =$ pressure, $E =$ electric field strength, $e =$ charge on an electron, $\lambda =$ mean free path, and $f'$ is some unknown function.

It can be reasonably assumed that $\lambda$ is proportional to $(1/P)$ at a constant temperature. So:

$$\alpha = PF(Ee/P),$$

(10)

where $F$ is a function similar to $f'$. Since $e$ is a constant it can be written:
where \( f \) is similar to \( F \).

If the voltage is further increased to point \( C \), other processes take place that aid in ionization. Positive ions make some inelastic collisions in the gas, and this process is called the \( B \) process. The probability of this happening, however, is small. A more important process at this point is the process of the emission of electrons from the cathode and is called the \( \gamma \) process. It is made up of three basic processes, namely the emission of electrons due to:

1. Impact of cathode by positive ions (\( \gamma_i \) process)
2. Photons striking the cathode (\( \gamma_p \) process)
3. The action of neutral atoms in a metastable energy level striking the surface of the cathode (\( \gamma_m \) process).

The additional supply of electrons due to the total \( \gamma \) process can be included in the equation of current density. Let \( \sigma' \) be the number of electrons emitted from the cathode each second, including those produced by the \( \gamma \) process. As before, \( \sigma \) is the number of electrons produced in the area of the cathode from natural irradiation, etc. Then \( \sigma' - \sigma \) is the density of electrons produced by the \( \gamma \) process per second and is proportional to the total number of positive ions formed in the volume of gas, between the electrodes (sensitive volume) of unit cross-sectional area. Let \( \sigma^+ \) be the density of the positive ions and it should be equal to the number of electrons at any point. Using equation (2)

\[
\sigma^+ = \sigma = \sigma' \in F \tag{12}
\]
gives the density of positive ions at some point. Integrating over the total distance, \( d \), between the electrodes, the total number of positive ions produced is found to be:

\[
\int_0^d \sigma_0 \, \varepsilon ^x \, dx = \sigma_0 \left( \frac{\varepsilon ^d}{x} - 1 \right)
\]

(13)

As mentioned, the total number of electrons produced by the \( \gamma \) process is proportional to the positive ions found in the sensitive volume per second. Also it is proportional to the probability \( \gamma \), that these positive ions will produce electron emission at the cathode. And finally it is proportional to the probability \( \chi \), that these electrons emitted will not diffuse back to the cathode. The effective number of electrons then emitted at the cathode per unit area is:

\[
\gamma \chi \sigma_0 \varepsilon ^d = \sigma_0 \left( \frac{\varepsilon ^d}{x} - 1 \right) = \sigma_0 \varepsilon ^d - \sigma_0
\]

and density of electrons emitted at the cathode is:

\[
\sigma_0 \varepsilon ^d = \frac{\sigma_0 \varepsilon ^d - \sigma_0}{1 - \gamma \chi \varepsilon ^d}
\]

(15)

The current density at a distance \( x \) from the cathode is then:

\[
J(x) = e \sigma_0 \varepsilon ^x = \frac{e \sigma_0 \varepsilon ^x}{1 - \gamma \chi \varepsilon ^d}
\]

(16)

Or it may be written as:

\[
J(x) = \frac{J_0 \varepsilon ^x}{1 - \gamma \chi \varepsilon ^d}
\]

(17)
where \( J_0 = e \alpha \).

Setting \( x = d \) in equation (17) gives the current density at the anode:

\[
J = J_\alpha = \frac{J_0 e^x}{1 - \gamma x (e^{\alpha d} - 1)}
\]  

(18)

Usually the fraction of electrons that diffuse back to the cathode is quite small, and in such cases \( x \) is assumed to be unity.\(^{11}\)

There is also some electron emission taking place at the anode, but these electrons are recaptured by the anode before they can ionize the gas atoms.\(^{11}\) The effect of photoionization throughout was not taken into account in the derivation of equation (17). The development of an equation for current density will not be done here. An equation that takes into account the photoionization of the gas atoms throughout the sensitive volume is usually not required. This is a result of the fact that photons of much higher frequency are required to ionize gas atoms than to arouse emission of electrons from the cathode surface.\(^{13}\)

In some gases, such as electronegative gases, there is a loss of electrons due to attachment. Let the coefficient \( Z \) be the number of attachments per electron per cm drift. \( Z \) is determined by the same factors which determine \( \alpha \) which are the average energy gained by an electron between collisions and the number of collisions in a cm of travel. Then by analogy:

\[
\frac{Z}{P} = W \left( \frac{E}{P} \right)
\]

(19)

where \( W \) is some function. Let \( \sigma \) be the number of negative ions that
reach the anode. If the \( \gamma \) process is ignored, then from equation (2)
\[ \sigma^-(x) = \sigma_o \epsilon^{(\alpha-Z)x} \quad (20) \]

The number of electrons at the anode would be:
\[ \sigma_a = \sigma_o \epsilon^{(\alpha-Z)d} \quad (21) \]

where the effective ionization coefficient is \((\alpha-Z)\).

Then:
\[ \sigma^- = \int_0^d Z \sigma^-(x) \, dx = \frac{Z \sigma_o}{\alpha-Z} \left( \epsilon^{(\alpha-Z)d} - 1 \right) \quad (22) \]

The current density at the anode is then:
\[ J = J_a = e \left( \sigma_a + \sigma^- \right) \]
\[ J = \epsilon \sigma_o \left[ \epsilon^{(\alpha-Z)d} \left( \frac{Z}{\alpha-Z} \epsilon^{(\alpha-Z)d} - \frac{Z}{\alpha-Z} \right) \right] \]
\[ J = \frac{J_o}{\alpha-Z} \left[ \alpha \epsilon^{(\alpha-Z)d} - Z \right] \quad (23) \]

If the production of electrons due to the \( \gamma \) process is included the current density equation becomes\(^{11,13}\)
\[ J = J_o \left[ \frac{\alpha \epsilon^{(\alpha-Z)d} - Z}{\alpha-Z - \alpha \gamma \chi \left( \epsilon^{(\alpha-Z)d} - 1 \right)} \right] \quad (24) \]

If the voltage as shown in Figure 2 is increased even further the collision between many of the electrons and gas molecules results in highly excited molecules. These excited molecules, upon returning to
the ground state release energy as photons. These photons may then cause photo-electrons to be emitted at the cathode. This is termed the \( \Theta \) process. These photons, on the other hand, may cause other excited atoms in the gas to be raised to the first ionization level. This process is called the \( \Phi \) process. These processes are believed to cause the final rise in current between point D and E as shown in Figure 2.

B. Spark Breakdown

If one neglects the effect of attachment as well as some of the miscellaneous secondary electron producing processes, then equation (17) can be used to predict conditions for breakdown in the gas. In Figure 2 it is seen that breakdown occurs with a very sharp rise in current. A sharp rise in current (or current density) will occur if the denominator of equation (17) approaches zero. The condition for breakdown is:

\[
\gamma \lambda \left( e^{\lambda_b d} - 1 \right) = 1
\]

(25)

where \( \lambda_b \) is the value of \( \lambda \) for the condition of breakdown. Since \( \lambda \) is usually close to unity, let \( \lambda = 1 \) and note also that \( e^{\lambda_b d} \gg 1 \).

The condition for spark breakdown then becomes

\[
\gamma = \frac{1}{e^{\lambda_b d}}
\]

(26)

Recalling equation (11) and noting that in a uniform field the breakdown potential for \( \lambda_b \) if \( V_b \), then:

\[
\lambda_b = Pf \left( \frac{V_b}{Pd} \right)
\]

(27)

From equation (27) it can be seen that \( V_b \) is a function of \( P_d \), and this
fact is called Paschen's law after the man who discovered it in 1889.\textsuperscript{11} Note that this function may not be a linear function even though it is linear over some regions.\textsuperscript{14} From equation (27) it can be seen that the conditions for breakdown vary indirectly with the product of $P_d$ and directly with the voltage $V_b$.

If the effect of attachment is included in the development, the condition for breakdown becomes:

$$\gamma = \frac{1}{\alpha_{b} - \frac{d}{Z}} (\varepsilon - 1)$$ \hspace{1cm} (28)

Note that if $Z = 0$, and keeping in mind that $\varepsilon > 1$, then equation (28) is the same as equation (26).\textsuperscript{11,13}

When a free electron is propelled through the gas due to the electric field it will collide with gas molecules and cause new ion pairs to form. This process of multiplication of the number of free electrons is called electron avalanche. If the conditions of breakdown are fulfilled one primary electron produces at least one secondary electron on the average, and there will result an avalanche. Not every avalanche will necessarily cause breakdown.\textsuperscript{13}

The time between the application of a voltage large enough to cause breakdown and the actual breakdown can be divided in two parts. The first time lag is called the statistical time lag while the second part is called the formative time lag. The statistical time lag is the time that passes between applications of the voltage and the actual production of a primary electron which can initiate the breakdown.
process. The production of a primary electron is dependent on the size of the gap and upon the irradiation that produces the primary electrons. The formative time lag is the time required for the breakdown to actually develop once a primary electron has appeared that is capable of initiating the breakdown process. This time is basically dependent on the time it takes for a positive ion to travel from the anode to the cathode. Positive ions are necessary in the production of necessary secondary electrons.\(^{13}\)

At pressures near atmospheric pressure the formative time lag is found to be much less than that of the positive ion transit time. Loeb has also shown that spark breakdown may occur in less time than the time required for the electrons to drift across the gap. It was seen, therefore, that some other process is forming electron-ion pairs in advance of the avalanche. This can be attributed to the formerly mentioned \(^{9}\) and \(^{15}\) processes. Observations have shown that streamers propagate from the anode. The Townsend criterion for breakdown is therefore weakened at high pressures.\(^{11,13}\)

An idealized streamer mechanism is shown in four steps in Figure 3.\(^{15}\) Step 1 shows an avalanche which was initiated by a free electron's collision with gas molecules when it traveled to the positive point. The electron ionized the gas molecules and also produced excited atoms. These excited atoms give off photons which in turn ionize molecules and produce more electrons. Two photons are shown liberating two electrons in step 1. Step 2 shows the results of the acceleration of the two electrons toward the positive tip of the first avalanche. The electrons in the first avalanche were formally absorbed into the
Fig. 3. The Streamer Mechanism Shown Idealized in Four Steps. (1) Start of an electron avalanche. (2) Emission of two photoelectrons. (3) Production of two weak avalanches. (4) Drifting of positive ions toward the plane cathode (which is not shown).
positive anode leaving the positive tip on the streamer. Likewise, the electrons from the newest avalanches flow to the anode through the channel of the first avalanche. Once again photons are emitted which in turn produce photoelectrons. Step 3 shows new avalanches again formed by the latest photoelectrons. However, the magnitudes of the newest avalanches are so small that formation of any new avalanches after this is not possible. Step 4 shows the streamers with all the electrons absorbed into the anode. These positive ions then drift toward the plane cathode (which is not shown). When the wedge-shaped streamers approach the cathode, an ionizing wave or backstroke develops due to the high field between the streamer and cathode. Breakdown then follows.\textsuperscript{13,15} The four steps described above may somewhat actually overlap in time in development. One step may start before the one preceding it has finished.

On longer gaps the streamer may not reach the cathode. In such a case, the streamer may cause such a high development of carrier concentration near the anode that a new ionization wave develops. This new wave, which involves secondary streamers, grows from the anode to the cathode. The secondary streamers are very different from the primary streamers. It has been found that in pure nitrogen secondary channels or streamers develop readily. But in any electronegative gas admixture they are suppressed entirely.\textsuperscript{15}

J. M. Meek has proposed that a streamer will develop when the radial field due to space charge in an electron avalanche has a value of the same order as that of the external impressed field.\textsuperscript{15,16}

Some think that the Townsend process can take place under all
conditions, but that it may be masked by the streamer process at the higher pressures.\textsuperscript{13}

C. Breakdown Under Alternating Fields

Under alternating field conditions, the breakdown characteristics of a d-c field are applicable if the frequency is below about 1 KHz.\textsuperscript{13}

The rate of production of electrons, considering the simplest case, is related to their rate of emission at the cathode. The rate of loss is simply the rate at which they flow to the anode in a steady field. Under an alternating field the charged particles are reversed in their direction of travel before they reach the electrodes. This means that the loss of electrons to the electrodes is decreased. At the same time, the rate of production of electrons is increased. The electrons make more ionizing collisions during their increased distance of travel under the alternating field. However, fewer positive ions reach the electrodes under the alternating field and therefore fewer secondary electrons will be released. If the latter effect has the greater impact, the breakdown voltage may increase as the frequency is increased. However, the first effect of each electron making more ionizing collisions, will cause the breakdown voltage to decrease as the frequency is further increased.\textsuperscript{13}
EQUIPMENT

A. Test Cells

1. General Description

Two M. J. Seavy and Sons Test Cells were used in finding the voltage strength of C\textsubscript{3}F\textsubscript{8} vs. the temperature of the gas. Each of the two cells used had a two inch inside diameter. One of the test cells is shown in Figure 4. Note that a high temperature value is not connected to the test cell in this figure. The test cells are similar to the one described in the ASTM Standards-Part 29.\textsuperscript{17}

In 1961 a series of round-robin tests using three different test cells were made to determine the dielectric strength of gases. These tests were conducted by Section III of the Electrical Tests Subcommittee N of ASTM Committee D-27 on Electrical Insulating Liquids and Gases.\textsuperscript{18,19} Eleven laboratories participated in these tests, one of which was the high voltage laboratory at South Dakota State University, under the direction of M. L. Manning. The objective of the tests was to develop a test cell and to propose a test method for the testing of the dielectric strength of gases.\textsuperscript{19} After the results of these tests were analyzed statistically and after some discussion by various men involved, the Seavy test cell was selected as the proposed ASTM cell.\textsuperscript{18,19}

2. Features of the Test Cells

The inside features of the test cells are shown in Figures 5 and 6. The inside volumes of the test cell with the sphere to grounded plane electrode system and the point to grounded plane electrode system are respectively 20.8 cubic inches and 20.9 cubic inches. On each test
Fig. 4. Test Cell with Sphere to Grounded Plane Electrode System.
Fig. 5. Inside Features of Test Cell #56667.
Fig. 6. Inside Features of Test Cell #53508.
cell Teflon gaskets were used at each end of the glass cylinder between the glass and the metal end plates. Since the metal end plates had a higher thermal coefficient of expansion than did the glass cylinder, the gaskets also served as a cushion between these two materials in the test cell.

Two high temperature, Fluoroelastic "O" rings were used as a seal between the top end plate and the upper electrode shaft which passed through the top end plate. Each test cell was equipped with a built-in micrometer to allow the adjustment of the gap between the electrodes after the cell had been completely assembled.

The electrode systems of the test cells were of two types; the sphere to grounded plane and the point to grounded plane. The sphere to grounded plane electrode system consisted of a 3/4" diameter brass sphere and a 1-3/4" diameter brass grounded plane electrode. At the small test gap spacing of 0.1" the field between the sphere and grounded plane was essentially uniform. The point to grounded plane electrode system consisted of a 3/32" diameter tungsten rod, sharpened to a point, and a 1-3/4" diameter brass grounded plane. The type of brass is unknown.

B. The Oven

The electric oven used for heating the test cells was a Blue M Electric Company automatically temperature controlled oven which had a heating range from approximately room temperature to 650 degrees centigrade. The oven was equipped with a blower which continuously circulated the heated air around the inside of the oven whenever it was operating. The inside dimensions of the oven were 20" high, 20" deep
and 24" wide. The oven had two portholes, one of which was used to bring the high voltage lead into the oven while the other was used to bring the ground lead as well as the wires for the thermocouples into the oven. The high voltage lead was insulated by a cylindrical ceramic insulator which was made by the Art Department at South Dakota State University.

Originally, a gap spacing of 0.2" was used between the electrodes inside the test cell. After some testing, the oven insulator began to breakdown between the high voltage lead running through it and the grounded oven wall. It was then necessary to reduce the gap spacing to permit lower test voltages. A gap spacing of 0.1" was chosen.

The oven door was also equipped with a safety lock such that, whenever the door was open, high voltage could not be applied to the inside of the oven. The oven frame and body was grounded.

Whenever the control kicked in, the oven experienced a slight mechanical jarring. It was noticed during the testing of the gas, that sometimes voltage breakdown of the gas occurred at the same instant that the kicking-in of the heating element control occurred.

C. Ionization Source

A weak source of ionization was used on some of the tests.\textsuperscript{20} This source was a millicurie of radium in a lead can 1.3" thick on the sides and placed approximately 18-3/4" from the electrode center line of the test cell. The source of irradiation was placed outside of the oven in such a manner that the irradiation passed through one of the side walls of the oven. The walls of the oven were constructed mainly of a sheet of stainless steel on the inside, heavy gauge cold rolled
steel reinforced through bracing on the outside, and with a minimum of four inches of non-hygroscopic, fireproof, Fiberglas wool insulation.\textsuperscript{21}

An attempt was made to have an equivalent source of irradiation as that used by Keith E. Crouch in his thesis titled, \textit{The Effect of Wave Shape on the Electrical Breakdown of Nitrogen Gas}.\textsuperscript{22}

In order to set up an equivalent source, the same system used by Keith Crouch was repeated outside of the oven and by using a Nuclear-Chicago count-rate instrument the number of counts per minute were measured. Then the irradiation source was moved to a location outside the oven adjacent to one of the side walls of the oven. The probe from the count-rate instrument was then moved inside the oven until a position was found where the counts per minute from the source were equal to the count found when the experiment was run outside of the oven. This location was marked and whenever the source was used, the test cell was placed in a position so that the center line of the electrodes was over this mark.

It was found that the oven walls have little or no effect on the count-rate. The distance from the can to the center line of the electrodes of the cell inside the oven was approximately equal to the same distance between the can and the electrode center-line when the experiment was conducted outside of the oven. In fact, the distance was slightly larger (1/2" to 3/4") when the irradiation was passed through the oven wall. This apparent increase in the irradiation strength of the case where it passed through the wall may be explained as no increase at all, but only due to slight errors in measuring the distances and count-rates.
The ionization in the cell from the source was attributed mainly to the low energy gamma rays.\(^{22}\)

D. The AC 60 Hz Voltage Test Equipment

A General Electric, AC 60 Hz, 0-75 KV, corona free, high voltage transformer was used in testing the gas. A circuit diagram for the test equipment is shown in Figure 7.\(^{23}\) Figure 8 shows the controls for the test equipment, without the motor drive unit. This motor drive unit was used to raise the voltage at a constant rate in the rapidly applied voltage tests.

A Westinghouse rectifier type AC RMS voltmeter was used to read the RMS voltage across the test cell. It was connected to the AC transformer control panel through a 1000 to 1 voltage reduction circuit. This allowed the voltage measured to be in volts instead of kilovolts. The 0-15 volts and 0-75 volts scales were used in all the tests.

The AC voltage transformer was equipped with circuit interrupting equipment which was the main circuit breaker on the low voltage side of the transformer. Figure 7 shows the position of this main circuit breaker. When breakdown occurred the circuit breaker would trip open and turn off the ac test equipment. This prevented contamination of the gas and damage to the electrodes due to a prolonged flow of current at breakdown. The complete electrical shutdown of the test equipment by the breaker was also a safety feature for the operator's protection.

The output voltage of the test equipment was lowered slightly whenever the heating element of the oven was operating. The heating element on the oven was rated at 8.5 KW. When the element was turned on automatically the voltage at the output of the test equipment was
Fig. 7. Circuit Diagram for the 60 Hz High Voltage Test Equipment and Test Circuit.
lowered by approximately 110 volts, which was approximately one percent or less of the breakdown voltage of the gas. The oven heating element remained on for only 3 seconds and was turned on every 20 seconds on the 200°C tests. The lower the temperature level of the oven the greater was the length of time between the on-times of the element.
TEST PROCEDURES

A. Test Cell - Cleaning and Maintenance

Before a test was made, the test cell was disassembled and all of the inside parts of the test cell were washed with tap water, thoroughly rinsed with distilled water, and finally rinsed with a commercial grade of acetone. The test cell was then set aside until the temperature of the parts of the cell was approximately equal to room temperature, at which time the cell was assembled. The distilled water was obtained from a machine in another laboratory and the quality of the distilled water was unknown. The acetone acted as a drying agent.

It was found that it was necessary to keep a light layer of grease on the "O" rings to prevent them from sticking permanently to the upper electrode shaft when the test cell was used at elevated temperatures. However, it was also found that any grease left on the part of the upper electrode shaft that extended into the inner part of the cell which contained the gas under test, would vaporize at the higher test temperatures (170°C and 200°C) and mix with the gas. Since this grease vapor may have caused erratic breakdown of the gas, it was necessary to disassemble the test cell, such that the "O" rings could be regreased and then to reassemble this part of the cell before washing it. This allowed all the parts that would be exposed to the gas to be free of grease, while the "O" rings themselves were exposed to a light layer of grease.

The micrometer on the test cell was periodically taken apart, cleaned and then lubricated with a very light grade of oil. This was
done to prevent the micrometer mechanism from sticking after the test cell had been heated to higher test temperatures a number of times.

Most of the electrodes were prepared (sanded) before they were washed. The only electrode which was not prepared was the 3/32" diameter tungsten rod which had been sharpened to a point. Preparation of the plane (lower) electrodes of the cells consisted of first sanding the electrodes with fine grades of no-load, silicon carbide paper. The papers used in sanding the plane electrodes were fastened to a flat board to insure a flat surface after sanding. Three grades of paper were used. Grade 240A, which was the coarsest of the three grades, was used first, followed by grade 320A and finally 500A. It was found that it was most practical to sand the upper sphere electrode with only the 500A grade of paper due to the difficulty of sanding the sphere evenly. All of the electrodes, with the exception of the tungsten rod, were then finally polished on an electric rouge wheel.

Preparation of the electrodes described above removed any residue deposits or small pits which may have developed on the electrodes during testing. It is important to prepare the electrodes as the roughness of the surface of the electrodes may affect the breakdown point of the gas. A surface that is rough may cause a lower breakdown point of the gas than would a smooth surface on the electrodes.  

B. Gap Spacing Adjustment

The gap spacing between the electrodes on the cell was adjusted to the desired setting by use of the micrometer. The gap spacing used for all tests was 0.1". It was important that the gap spacing was the same for all tests so as to not introduce another variable. In
general, the larger the gap spacing the higher the breakdown voltage of the gas.5,8

Adjustment of the gap spacing was accomplished by first connecting the leads of a continuity meter across the test cell; one of the leads was connected to the high voltage terminal while the other lead was connected to the ground terminal. The micrometer was then turned down until the upper electrode made contact with the lower electrode. Upon contact of the two electrodes the circuit was complete, causing the meter to register. Since the continuity meter was actually an ohmmeter, it would also measure any undesirable resistance in the conducting paths within the cell. This resistance may have been due to some residue or corrosion between parts which may have been built up as a result of operating the cell alternately at the higher test temperatures and then cooling to room temperature. If an undesirable resistance was found to exist, corrective measures were taken to insure a resistance-free electrical path within the test cell.

After having turned the micrometer to zero gap spacing the reading on the micrometer was recorded. By adding 0.1" to this reading and backing off the micrometer until the second reading was obtained the gap spacing was set at 0.1".

If the test was conducted at any temperature other than room temperature another step was necessary in the adjustment of the gap spacing due to the expansion of various parts of the test cell with an increase of temperature. The parts of the test cells expanded in such a manner to decrease the gap spacing with an increase in temperature. Table XI in Appendix IV shows the amount the gap spacing decreases
with an increase of the temperature by one degree centigrade. Since
the temperature of the room, as well as the test temperature, was
known at the time the gap was adjusted, the total increase of tempera­
ture of the cell and hence the amount of decrease of the gap spacing
was known. The micrometer was adjusted to give a gap spacing equal to
the desired gap spacing plus the distance that the gap spacing would
decrease due to linear expansion of the test cell. After heating the
cell and expansion had occurred, the gap spacing was adjusted
accordingly.

C. Filling the Test Cell with Gas - Gas Pressure and Temperature

Adjustments to Standard Conditions

After the electrode gap spacing was set, the test cell was connec­
ted to the test cell gas-filling apparatus, as shown in Figure 9. The
set-up of apparatus is basically the same as that used by Thomas J.
Lanoue in his thesis entitled The Effect of Test Cell Glass Cylinder
Diameter on Gaseous Insulation Dielectric Strength.18 The author
feels that the system shown in Figure 9 is superior in that it is more
versatile.

Referring to Figure 9, the test cell was filled with gas by first
closing the valve SC₁. Then the main valve, SC₀, on the gas cylinder
was opened and the gas regulator was adjusted to allow the gas to exist
at a low pressure (5 to 10 pounds). The valve SC₂ was open and the
leveler tube L₁ was raised until the silicone oil in L₂ was up to SC₂
which was then closed. Valves SC₃, SC₄, SC₅, SC₇, and SC₈ were then
opened. SC₆ was closed. The air or existing gas in the system was
then removed with the use of a vacuum pump. It was evacuated to a
Fig. 9. Apparatus Used to Fill the Test Cell with Gas and to Adjust the Gas Pressure within the Test Cell.
pressure of 2 to 3 mm of Hg. Valve SC\textsubscript{7} was then closed. The valve SC\textsubscript{1} was opened and adjusted to allow gas to pass through the bubbler tube at a medium rate and out into the atmosphere. Valve SC\textsubscript{6} was slowly opened, allowing gas to pass into the system such that gas continued to bubble through the bubbler tube at a slower rate than before. The gas was passed through tubes containing KOH and CaCl\textsubscript{2} which removed acids and moisture in the gas. After the system had been filled the valves SC\textsubscript{6} and SC\textsubscript{1} were closed. The system was then evacuated a second time and refilled with gas as before.

With valves SC\textsubscript{1}, SC\textsubscript{6} and SC\textsubscript{7} closed and the system filled with gas, valve SC\textsubscript{2} was slowly opened. Care was taken not to allow any of the silicone oil to go beyond valve SC\textsubscript{2} as it may have caused erratic breakdown of the gas. If any silicone oil escaped beyond valve SC\textsubscript{2}, the overflow tube adjacent to SC\textsubscript{2} was easily removed and cleaned. By raising or lowering \( L_1 \) the pressure in the system and test cell could be adjusted to the desired level. Valves SC\textsubscript{4} and SC\textsubscript{5} allowed the large spherical gas reservoir to be connected to or disconnected from the system which aided in the adjustment of the pressure in the system and test cell by changing the effective volume of the system. Valves SC\textsubscript{2} and SC\textsubscript{8} were then closed. Closing valves SC\textsubscript{3} and SC\textsubscript{4} at this point sealed the system so that the gas would not be allowed to escape, during cell fillings, from the system and thus keeping the gas content in the system high and the air content to a minimum.

Valve SC\textsubscript{8} was permanently connected to the test cell and sealed the gas in the test cell. It was capable of withstanding the temperatures used in the tests as it was also placed in the oven along with
the test cell.

With the use of the leveler tubes, as mentioned above, the pressure in the test cell was adjusted to average conditions in the laboratory which were $30^\circ F$ and 28.35 inches of Hg. The method of finding the amount that the pressure should be changed to, to correct the gas in the cell to standard conditions for any given laboratory conditions of pressure and temperature, is shown in Appendix V.

The change in the volumes of the test cells with temperature was approximately one tenth of one percent at the highest test temperature used. Hence, the change in the volume of the test cell with temperature was negligible. Therefore the density of the gas, that is the number of moles per cubic inch, remained constant at all temperatures and no pressure adjustments were needed to account for a volume change.

D. Method of Heating the Test Cell

After filling the cell with the proper amount of gas, the test cell was placed in an electric oven for heating to the desired test temperature. To permit a close monitoring of the temperature near the cell, three thermocouples were placed near the glass wall of the test cell, each one spaced 120 degrees apart around the cell. Figure 10 shows the test cell in position in the oven. The thermocouple heads were approximately $3/8''$ away from the glass wall and $4-1/2''$ up from the bottom of the test cell. The temperature of the air immediately adjacent to the test cell could be read within an accuracy of one degree centigrade with the thermocouples. Although ten thermocouples were available on the oven only 3 were used during the test.
Fig. 10. Test Cell in Place Inside the Oven.
With the heating element control on the high setting, the test cell was heated for one hour before the test was made if the final test temperature was less than 100°C. If the final test temperature was above 100°C, the test cell was heated for one and one-half hours. These time durations for heating were used to allow time for the gas inside the cell to heat up to the ambient temperature of the oven, as well as to allow time for the parts of the test cell to expand to their final values due to the heat. These time durations were chosen as a result of pilot tests run with a thermocouple placed inside the test cell. Appendix III discusses these tests. Also, the time for expansion of the metals was considered as a result of the tests run which are discussed in Appendix IV.

E. Conducting the Voltage Tests

After the test cell had been heated for the proper length of time, a 60 Hz rapidly applied test was run followed by a 60 Hz one-minute withstand test. Test data were found to be the same for a consecutive or for a separate order of the two above mentioned tests. It was not necessary to reclean and refill the test cell with fresh gas before running the one-minute withstand test, after the rapidly applied test was run.

The rapidly applied test was run by applying a zero voltage across the test cell and increasing the voltage at a constant rate of 500 volts per second until breakdown occurred as determined by the operation of the circuit-interrupting equipment. This breakdown voltage was recorded. After a one minute wait this test was repeated. Five such trials were made. An amount of 0.4 KV was added to the breakdown reading of the
voltmeter to account for the needle lag on the meter due to the rapid rise of the voltage.

After a five minute wait from the last trial of the rapidly applied test, the one-minute withstand test was run. These five minutes were allowed to insure ample time for the gas in the test cell to settle down after running the rapidly applied test. The voltage was quickly (2 to 5 seconds) raised to 75 percent of the average breakdown voltage obtained from the rapidly applied tests. Then at one minute intervals the voltage was then raised by 500 volts until breakdown occurred as determined by the circuit interrupting equipment. Five trials were run and each time the breakdown voltage was recorded. Again one minute was allowed between trials.

Each of the tests was conducted in general according to the methods described in the ASTM Standards - Electrical Insulating Materials (Part 29, February, 1969), American Standard for Measurement of Voltage in Dielectric Tests, and also according to the recommendations of M. L. Manning in his article entitled, Experience with the AIEE Subcommittee Test Cell for Gaseous Insulation.

The results of these tests are shown in Tables I-X in Appendix I.

F. Method of Cooling the Cell and Detecting the Grease Vapor

Upon completion of the testing, the oven was turned off and the door opened. At this time, a portable fan was used to blow cool air across the test cell. This caused one side of the cell to cool quickly. If any grease vapor from the "O" rings had vaporized into the gas at the high temperature, it would condense on the inside of the cool glass wall. This method was used to indicate if any grease
had vaporized into the gas. As mentioned before, such a mixture may have caused erratic breakdown voltages.

After the cooling was completed, the cell was removed from the oven and disassembled. The complete cycle of cleaning and filling the cell was then started over again.
between the maximum and minimum RMS values. The average value is the arithmetical mean of the values of the five trials run for each test. The standard deviation value given is the standard deviation of the values of the five trials run for each test. The determination method is described in more detail in Appendix VI. The coefficient of variation is found from the standard deviation for each test and is described in detail in Appendix VI.

The voltage breakdown strength plotted on Figures 11 through 24 is the average value shown in Tables I through X.

Note that on some tables, a temperature value may have a subscripted "G". If a "G" is found subscripted to a temperature value on a table, this means that a small amount of grease vapor was noticed on the inside wall of a cooled test cell, after the test.

B. Specific Observations

Several observations can be made about the results of the tests made on \( \text{C}_2\text{F}_6 \). It should be recalled that the sphere to grounded plane electrode system produces a uniform electric field, while the point to grounded plane electric system produces a non-uniform electric field. In the list below, the expression "both voltage tests" refers to the rapidly applied and the one-minute withstand voltage tests. The expression "two irradiation conditions" refers to test conditions, without and with, a source of irradiation. Finally, the expression "both electric field conditions" refers to the uniform and non-uniform electric field conditions.

(1) The uniform electric field breakdown strength of the gas is higher than that for the non-uniform electric field for the whole temperature
range tested. This occurs for both voltage tests and under the two irradiation conditions. (Figures 11, 12, 13, and 14)

(2) The coefficient of variation for both voltage tests is higher under uniform electric field conditions than it is for non-uniform electric field conditions. This occurs for the two irradiation conditions. (Figures 25, 26, 27 and 28)

(3) The voltage breakdown strength of the gas under uniform electric field conditions decreases or remains constant as the temperature of the gas is increased. This occurs for both voltage tests and under the two irradiation conditions. (Figures 17 and 19)

(4) The voltage breakdown strength of the gas under non-uniform electric field conditions increases as the temperature of the gas is increased. This occurs for both voltage tests and under the two irradiation conditions. (Figures 18 and 20)

(5) The coefficient of variation for both voltage tests under uniform electric field conditions and without a source of irradiation decreases with an increase in gas temperature. (Figure 31)

(6) The coefficient of variation for both voltage tests under uniform electric field conditions and with the use of a source of irradiation is essentially independent of the gas temperature. (Figure 33)

(7) The coefficient of variation for both voltage tests under non-uniform electric field conditions is essentially independent of the gas temperature. This occurs for the two irradiation conditions. (Figures 32 and 34)

(8) The voltage breakdown strength of the gas for the rapidly applied voltage tests is, in general, higher than the breakdown strength of
the one-minute withstand voltage tests. This occurs for both electric field conditions and for the two irradiation conditions. (Figures 17, 18, 19, and 20)

(9) The coefficient of variation for the rapidly applied voltage tests under uniform electric field conditions is higher than that of the one-minute withstand voltage tests. This occurs for the two irradiation conditions. (Figures 31 and 33)

(10) The coefficient of variation for the rapidly applied voltage tests under non-uniform electric field conditions is essentially the same as that of the one-minute withstand voltage tests. This occurs for the two irradiation conditions. (Figures 32 and 34)

(11) The voltage breakdown strength of the gas under uniform electric field conditions and for the rapidly applied voltage test is, for the most part, independent of the use of a source of irradiation during the tests. (Figure 21)

(12) The voltage breakdown strength of the gas under uniform electric field conditions and a one-minute withstand voltage test is higher without the use of a source of irradiation at the lower gas temperatures than it is with the use of irradiation. At the higher temperatures the reverse is true. (Figure 22).

(13) The voltage breakdown strength of the gas under non-uniform electric field conditions is higher (except at the highest temperatures tested, where it is independent of the use of irradiation) with the use of irradiation than it is without the use of irradiation. This occurs for both voltage tests. (Figures 23 and 24)

(14) The coefficient of variation of the test under uniform electric
field conditions is higher at the lower temperatures without the use of irradiation than it is with the use of irradiation. At the higher temperatures it is essentially independent of the use of irradiation. This occurs for both voltage tests. (Figures 35 and 36)

(15) The coefficient of variation of the test under non-uniform electric field conditions is essentially independent of the use of irradiation. This occurs for both voltage tests. (Figures 37 and 38)

C. Comparison - Original and Repeated Tests Results

Two separate series of tests were made for the rapidly applied and one-minute withstand voltage tests using the sphere to grounded plane electrode system. Figures 15, 16, 29, and 30 show the voltage breakdown strength and coefficient of variation vs. gas temperature for these two series of tests. These figures indicate that the two separate series of tests gave essentially the same results. Each series of tests were run in a different temperature order. For example in one series of tests, one test may have been run at 80°C, and the next at 110°C, etc. The next series of tests had a different order over-all. The fact that very similar results were obtained from two separate tests indicates that the test method used is reproducible.

D. Observations Linked with Theory

Apparently three basic mechanisms, with a high potential across the gap, are effective in the production of primary electrons in the sensitive volume of the gas. These electron producing mechanisms are: (1) thermal ionization, (2) a source of irradiation, and (3) a non-uniform field (which creates a very strong electric field). Probably, the majority of these electrons are given off at the cathode. The
volt-ampere characteristics of a gas at constant temperature with constant external irradiation under uniform electric field conditions are shown in Figure 2 in the Basic Theory section. The characteristics are shown for a pressure of several microns. Figure 3 in the Basic Theory section illustrates the streamer theory which describes activities at higher pressures. 12,15

As described under the section on basic theory, the time lag between the application of the necessary voltage and actual breakdown can be divided into two parts. These are the statistical and the formative time lags. The statistical time lag is directly dependent on the number of primary electrons produced. Thermal ionization, a strong non-uniform electric field, or a source of irradiation, therefore, can reduce the statistical time lag. The formative lag is essentially independent of the rate of production of electrons. The noticeable variations in the value of the coefficient of variation and the breakdown strength of the tests are dependent on the statistical time lag.

The greater the variation in the breakdown strength between the five trials run for each test, the larger the coefficient of variation. If the statistical time lag of each trial varies greatly from that of the other trials a large variation in the breakdown strengths may result and produce a large coefficient of variation. However, if some means is provided to increase the production of primary electrons, the statistical time lag will be made smaller. Any variation in the smaller time lag will not appreciably vary the breakdown strength. Hence, the coefficient of variation will be smaller.
The statistical time lag can be made very small by any one of the three electron producing mechanisms mentioned. And, the effect of the other two will not produce any noticeable change in the time lag, as far as the coefficient of variation is concerned.

The uniform electric field produces fewer primary electrons than does the non-uniform field. The statistical time lag will be larger for the tests under uniform field conditions. This means the coefficient of variation likewise may be larger for uniform field conditions, as compared with non-uniform field conditions.

In a uniform field, a low number of primary electrons will be produced by the field. The statistical time lag, therefore, can vary greatly. In a rapidly applied voltage test, the voltage is constantly changing. Any variations in the time lag will cause a variation in the breakdown strengths. A large coefficient of variation results for rapidly applied voltages. These variations, in time lag, will be masked by the one-minute holding time in a one-minute withstand test. Therefore, the coefficient of variation will be larger for the rapidly applied tests under uniform field conditions.

The high non-uniform electric field effectively has reduced the size of the time lag, so that even the rapidly applied test is slow enough to mask out any variation in the time lag. The one-minute withstand test, of course, will do the same. Hence, the coefficient of variation will be about the same for both voltage tests, under non-uniform field conditions.

In a uniform or non-uniform electric field, thermal ionization or a source of irradiation could play an important part in the production
of the necessary primary electrons needed for breakdown. However, other processes are involved in the breakdown strength under strong electric fields, especially under non-uniform electric fields. Two processes of interest are the negative ion space charge effect and the formation of positive ions in the gap.

Non-uniform fields are effected by negative space charge effects. C₃F₈ is an electronegative gas, and it tends to capture free electrons and form large negative ions. These large negative ions are quite immobile as compared with electrons. In a non-uniform field, when the point electrode is negative with respect to the plane electrode, a large number of electrons will be given off by the point (the cathode). Some electrons will attach themselves to the neutral gas molecules forming large negative ions on their way to the plane (the anode). If the gap is very small the electrons may cross the gap without attachment taking place. Since the negative ions drift slowly toward the anode, the field can reverse itself (alternating voltage was applied) before these ions reach the anode. If the gap is too small, for a given potential strength across the gap, the negative ions may be neutralized by making contact with the plane before the field can reverse itself. Now with the point being positive, these negative ions surround the point and produce a negative ion space charge. This will inhibit the formation of streamers. Until the space charge is cleared from the gap, breakdown cannot take place. Clearing of the space charge requires that the applied voltage level be increased.¹² Therefore, the breakdown strength is increased. Thermal ionization or a source of irradiation provide more electrons for attachment and increase the number of
negative ions. The space charge and breakdown strength, thereby, is increased.

This process is not as pronounced in a \textit{uniform} electric field because the negative ion space charge effectively does not inhibit breakdown near the larger electrode (the sphere). However, the negative space charge seems to have more influence on the one-minute withstand tests for both the \textit{uniform} and \textit{non-uniform} fields.

Another process that may be occurring in the strong electric field involves the formation of heavy, low mobile, positive ions. These ions are formed in the gap due to the ionization of the gas. The positive ions are formed, as a result of the $\text{C}_2\text{F}_8$ gas losing fluoride ions instead of electrons. The positive ions form an ion sheath which prevents the formation of a conducting path, by depriving that path of its source of electrons. Increasing the temperature may increase the ionization of the gas and increase the number of positive ions present.

The production of primary electrons in a \textit{uniform} electric field is lower than that in a \textit{non-uniform} electric field. Therefore, the breakdown strength under \textit{uniform} electric field conditions will be higher than that under \textit{non-uniform} field conditions, as the primary electrons are necessary in initiation of the breakdown mechanism. The effect of the negative ion space charge, and/or the formation of positive ions in the \textit{non-uniform} electric field, is not large enough to raise the breakdown strength of the \textit{non-uniform} electric field above that of the \textit{uniform} electric field in the temperature range tested.

Thermal ionization appreciably can affect the number of electrons produced in a \textit{uniform} field. A temperature increase of the gas and
test cell will decrease the breakdown strength of the gas in a uniform field. One exception to the above is the breakdown strength for the one-minute test, under uniform field conditions. The breakdown strength remains constant when a source of irradiation is used. Apparently, enough primary electrons are produced by the source of irradiation, in a one-minute interval, to mask the effect of those produced by thermal ionizations. Breakdown, therefore, is independent of temperature for this case. Negative ion space charge and/or positive ion formation may have played some part in this test.

The voltage level during a rapidly applied test is constantly changing, while a one-minute withstand test is held constant for one minute intervals. Therefore, any increase in the time lag will have a larger probability of increasing the breakdown strength for the rapidly applied test, as compared with the one-minute withstand test.

The breakdown strength for the rapidly applied test in a uniform field shows a slight indication of being lower when a source of irradiation is used. This occurred only at the lowest temperature tested. The source of irradiation could be expected to cause the breakdown strength to be lower, as it aids in the production of primary electrons. Possibly, the effect of the source of irradiation on the breakdown strength of this test should have been more pronounced. At the higher temperatures, this effect is not expected to be as great since primary electrons also are produced by thermal ionization.

Since the source of irradiation is effective in increasing the production of electrons, more free electrons will be available for attachment. This increases the number of negative ions and the space
charge effect. High energy electrons may also ionize the gas and form positive ions. Hence, the breakdown strength in a non-uniform field will be increased when a source of irradiation is used. At the higher temperatures, thermal ionization produces enough electrons so that the effect of the irradiation is hidden. Also, the higher temperatures may directly increase the number of positive ions by releasing fluoride ions from the gas.
CONCLUSIONS

The following conclusions apply to $C_3F_8$ gas tested for a temperature range of $25^\circ C$ to $200^\circ C$.

(1) The voltage breakdown strength of the gas under uniform electric field conditions decreases or remains constant as the temperature of the gas and test cell is increased. This is independent of the type of voltage test and irradiation conditions.

(2) The voltage breakdown strength of the gas under non-uniform electric field conditions increases as the temperature of the gas and test cell is increased. This is independent of the type of voltage test and irradiation conditions.

(3) The voltage breakdown strength of the gas under uniform electric field conditions and for the rapidly applied voltage test is essentially independent of the use of a source of irradiation.

(4) The voltage breakdown strength of the gas under uniform electric field conditions and a one-minute withstand voltage test is higher without the use of a source of irradiation at the lower gas temperatures than it is with the use of irradiation. At the higher temperatures the reverse is true. (The breakdown values are nearly the same, however, at the higher temperatures.)

(5) The voltage breakdown strength of the gas under non-uniform electric field conditions is higher (except at the highest temperatures tested, where it is independent of the use of irradiation) with the use of irradiation than it is without the use of irradiation. This is independent of the type of voltage test made.
(6) The uniform electric field breakdown strength of the gas is higher than that for the non-uniform electric field. This is independent of the type of voltage test and irradiation conditions.

(7) The voltage breakdown strength of the gas for the rapidly applied voltage tests is higher, for the most part, than the breakdown strength of the one-minute withstand voltage tests. This is independent of the type of electric field and irradiation conditions.

(8) The reason for the difference of the breakdown strength of the gas vs. temperature between the uniform and non-uniform electric field conditions is contributed to the negative ion space charge effect and/or the formation of positive ions in the gap.

(9) The difference in the breakdown strength between the rapidly applied and the one-minute withstand voltage tests is contributed to the effect of the statistical time lag.

(10) The variation of the breakdown strength with temperature is contributed to the effect of thermal ionization.

(11) The variation of the breakdown strength with irradiation conditions is contributed to the effect of increased ionization due to a source of irradiation.
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4. Product Data Sheet #PD-TA-218-4-59, Product Development Department, General Chemical Division, Allied Chemical Corporation.


23. Instructions, GEI - 79208, High Voltage A-C Testing Set (Stationary), Distribution Transformer Department, General Electric Co.

24. "Introductory Data - 3M Brand Octafluoropropene, Fc-30 (C₃F₈)," Chemical Division, 3-M Company.


APPENDIX I
TABLE I
Rapidly Applied Voltage Breakdown Strength of C\textsubscript{2}F\textsubscript{8} for the Sphere to Grounded Plane Electrode System at Various Gas Temperatures, without a Source of Irradiation.
(Refer to Figures 11, 17, 21, 25, 31, 35)

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<th>Various Values from the Five Trials at Each Temperature</th>
<th>Gas Temperature (°C)</th>
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<tr>
<td>Maximum (KV-RMS)</td>
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</table>
TABLE II

One-Minute Withstand Voltage Breakdown Strength of C3F8 for the Sphere to Grounded Plane Electrode System at Various Gas Temperatures, without a Source of Irradiation.

(Refer to Figures 12, 17, 22, 26, 31, 36)

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<th>50</th>
<th>80</th>
<th>110</th>
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<th>170</th>
<th>200°G</th>
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<td>15.5</td>
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<tr>
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<td>Range (KV-RMS)</td>
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<td>0.5</td>
</tr>
<tr>
<td>Average (KV-RMS)</td>
<td>16.4</td>
<td>16.4</td>
<td>15.5</td>
<td>15.4</td>
<td>14.5</td>
<td>14.7</td>
<td>15.1</td>
</tr>
<tr>
<td>Standard Deviation (KV-RMS)</td>
<td>1.39</td>
<td>0.65</td>
<td>1.06</td>
<td>0.78</td>
<td>0.58</td>
<td>0.52</td>
<td>0.22</td>
</tr>
<tr>
<td>Coefficient of Variation (Percent)</td>
<td>8.46</td>
<td>3.98</td>
<td>6.88</td>
<td>5.07</td>
<td>4.01</td>
<td>3.55</td>
<td>1.48</td>
</tr>
</tbody>
</table>
TABLE III

Rapidly Applied Voltage Breakdown Strength of $C_3F_8$ for the Point to Grounded Plane Electrode System at Various Gas Temperatures, without a Source of Irradiation.

(Refer to Figures 11, 18, 23, 25, 32, 37)

<table>
<thead>
<tr>
<th>RAPIDLY APPLIED VOLTAGE TEST</th>
</tr>
</thead>
<tbody>
<tr>
<td>Various Values from the Five Trials at Each Temperature</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Maximum (KV-RMS)</td>
</tr>
<tr>
<td>Minimum (KV-RMS)</td>
</tr>
<tr>
<td>Range (KV-RMS)</td>
</tr>
<tr>
<td>Average (KV-RMS)</td>
</tr>
<tr>
<td>Standard Deviation (KV-RMS)</td>
</tr>
<tr>
<td>Coefficient of Variation (Percent)</td>
</tr>
</tbody>
</table>
TABLE IV

One-Minute Withstand Voltage Breakdown Strength of C$_2$F$_8$ for the Point to Grounded Plane Electrode System at Various Gas Temperatures, without a Source of Irradiation.

(Refer to Figures 12, 13, 24, 26, 32, 38)

<table>
<thead>
<tr>
<th>Gas Temperature (°C)</th>
<th>30</th>
<th>50</th>
<th>80</th>
<th>110</th>
<th>142</th>
<th>170</th>
<th>200G</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum (KV-RMS)</td>
<td>10.6</td>
<td>10.8</td>
<td>11.3</td>
<td>12.0</td>
<td>12.0</td>
<td>12.5</td>
<td>13.0</td>
</tr>
<tr>
<td>Minimum (KV-RMS)</td>
<td>10.5</td>
<td>10.0</td>
<td>11.0</td>
<td>11.3</td>
<td>11.5</td>
<td>12.0</td>
<td>12.6</td>
</tr>
<tr>
<td>Range (KV-RMS)</td>
<td>0.1</td>
<td>0.8</td>
<td>0.3</td>
<td>0.7</td>
<td>0.5</td>
<td>0.5</td>
<td>0.4</td>
</tr>
<tr>
<td>Average (KV-RMS)</td>
<td>10.5</td>
<td>10.5</td>
<td>11.1</td>
<td>11.6</td>
<td>11.8</td>
<td>12.3</td>
<td>12.9</td>
</tr>
<tr>
<td>Standard Deviation (KV-RMS)</td>
<td>0.06</td>
<td>0.36</td>
<td>0.13</td>
<td>0.30</td>
<td>0.20</td>
<td>0.25</td>
<td>0.20</td>
</tr>
<tr>
<td>Coefficient of Variation (Percent)</td>
<td>0.52</td>
<td>3.42</td>
<td>1.21</td>
<td>2.55</td>
<td>1.70</td>
<td>2.05</td>
<td>1.52</td>
</tr>
</tbody>
</table>
TABLE V

Rapidly Applied Voltage Breakdown Strength of C\textsubscript{3}F\textsubscript{8} for the Sphere to Grounded Plane Electrode System at Various Gas Temperatures, with a Source of Irradiation.

(Refer to Figures 13, 15, 19, 21, 27, 29, 33, 35)

<table>
<thead>
<tr>
<th>Various Values from the Five Trials at Each Temperature</th>
<th>Gas Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>24</td>
</tr>
<tr>
<td>Maximum (KV-RMS)</td>
<td>17.8</td>
</tr>
<tr>
<td>Minimum (KV-RMS)</td>
<td>14.8</td>
</tr>
<tr>
<td>Range (KV-RMS)</td>
<td>3.0</td>
</tr>
<tr>
<td>Average (KV-RMS)</td>
<td>16.2</td>
</tr>
<tr>
<td>Standard Deviation (KV-RMS)</td>
<td>1.12</td>
</tr>
<tr>
<td>Coefficient of Variation (Percent)</td>
<td>6.89</td>
</tr>
</tbody>
</table>
TABLE VI

One-Minute Withstand Voltage Breakdown Strength of C3F8 for the Sphere to Grounded Plane Electrode System at Various Gas Temperatures, with a Source of Irradiation.

(Refer to Figures 14, 16, 19, 22, 28, 30, 33, 36)

<table>
<thead>
<tr>
<th>Various Values from the Five Trials at Each Temperature</th>
<th>Gas Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>24</td>
</tr>
<tr>
<td>Maximum (KV-RMS)</td>
<td>15.5</td>
</tr>
<tr>
<td>Minimum (KV-RMS)</td>
<td>14.0</td>
</tr>
<tr>
<td>Range (KV-RMS)</td>
<td>1.5</td>
</tr>
<tr>
<td>Average (KV-RMS)</td>
<td>15.0</td>
</tr>
<tr>
<td>Standard Deviation (KV-RMS)</td>
<td>0.61</td>
</tr>
<tr>
<td>Coefficient of Variation (Percent)</td>
<td>4.08</td>
</tr>
</tbody>
</table>
TABLE VII

Rapidly Applied Voltage Breakdown Strength of $\text{C}_2\text{F}_8$ for the Point to Grounded Plane Electrode System at Various Gas Temperatures, with a Source of Irradiation.

(Refer to Figures 13, 20, 23, 27, 34, 37)

<table>
<thead>
<tr>
<th>Various Values from the Five Trials at Each Temperature</th>
<th>Gas Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>24</td>
</tr>
<tr>
<td>Maximum (KV-RMS)</td>
<td>11.9</td>
</tr>
<tr>
<td>Minimum (KV-RMS)</td>
<td>11.4</td>
</tr>
<tr>
<td>Range (KV-RMS)</td>
<td>0.5</td>
</tr>
<tr>
<td>Average (KV-RMS)</td>
<td>11.7</td>
</tr>
<tr>
<td>Standard Deviation (KV-RMS)</td>
<td>0.21</td>
</tr>
<tr>
<td>Coefficient of Variation (Percent)</td>
<td>1.81</td>
</tr>
</tbody>
</table>
One-Minute Withstand Voltage Breakdown Strength of C$_2$F$_8$ for the Point to Grounded Plane Electrode System at Various Gas Temperatures, with a Source of Irradiation.

(Refer to Figures 14, 20, 24, 28, 34, 38)

<table>
<thead>
<tr>
<th>Variations from the Five Trials at Each Temperature</th>
<th>Gas Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>24</td>
</tr>
<tr>
<td>Maximum (KV-RMS)</td>
<td>11.5</td>
</tr>
<tr>
<td>Minimum (KV-RMS)</td>
<td>11.0</td>
</tr>
<tr>
<td>Range (KV-RMS)</td>
<td>0.5</td>
</tr>
<tr>
<td>Average (KV-RMS)</td>
<td>11.1</td>
</tr>
<tr>
<td>Standard Deviation (KV-RMS)</td>
<td>0.22</td>
</tr>
<tr>
<td>Coefficient of Variation (Percent)</td>
<td>2.01</td>
</tr>
</tbody>
</table>
TABLE IX
Rapidly Applied Voltage Breakdown Strength of \( \text{C}_2\text{F}_3 \) for the Sphere to Grounded Plane Electrode System at Various Gas Temperatures, with a Source of Irradiation. (The values shown in this table are the results obtained by repeating the test whose results are shown in Table V.)

(Refer to Figures 15, 29)

<table>
<thead>
<tr>
<th>RAPIDLY APPLIED VOLTAGE TEST</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Various Values from the Five Trials at Each Temperature</strong></td>
</tr>
<tr>
<td>Maximum (KV-RMS)</td>
</tr>
<tr>
<td>Minimum (KV-RMS)</td>
</tr>
<tr>
<td>Range (KV-RMS)</td>
</tr>
<tr>
<td>Average (KV-RMS)</td>
</tr>
<tr>
<td>Standard Deviation (KV-RMS)</td>
</tr>
<tr>
<td>Coefficient of Variation (Percent)</td>
</tr>
</tbody>
</table>
TABLE X

One-Minute Withstand Voltage Breakdown Strength of C₃F₈ for the Sphere to Grounded Plane Electrode System at Various Gas Temperatures, with a Source of Irradiation. (The values shown in this table are the results obtained by repeating the test whose results are shown in Table VI.)

(Refer to Figures 16, 30)

<table>
<thead>
<tr>
<th>Gas Temperature (°C)</th>
<th>23</th>
<th>50</th>
<th>80</th>
<th>111</th>
<th>140</th>
<th>170</th>
<th>200G</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum (KV-RMS)</td>
<td>15.5</td>
<td>15.5</td>
<td>15.7</td>
<td>16.0</td>
<td>15.5</td>
<td>15.0</td>
<td>15.0</td>
</tr>
<tr>
<td>Minimum (KV-RMS)</td>
<td>15.0</td>
<td>14.3</td>
<td>14.0</td>
<td>15.5</td>
<td>15.0</td>
<td>14.8</td>
<td>14.2</td>
</tr>
<tr>
<td>Range (KV-RMS)</td>
<td>0.5</td>
<td>1.2</td>
<td>1.7</td>
<td>0.5</td>
<td>0.5</td>
<td>0.2</td>
<td>0.8</td>
</tr>
<tr>
<td>Average (KV-RMS)</td>
<td>15.3</td>
<td>15.1</td>
<td>15.2</td>
<td>15.7</td>
<td>15.2</td>
<td>15.0</td>
<td>14.7</td>
</tr>
<tr>
<td>Standard Deviation (KV-RMS)</td>
<td>0.27</td>
<td>0.49</td>
<td>0.70</td>
<td>0.27</td>
<td>0.25</td>
<td>0.09</td>
<td>0.31</td>
</tr>
<tr>
<td>Coefficient of Variation (Percent)</td>
<td>1.79</td>
<td>3.27</td>
<td>4.58</td>
<td>1.74</td>
<td>1.65</td>
<td>0.60</td>
<td>2.12</td>
</tr>
</tbody>
</table>
APPENDIX II
Fig. 11. Rapidly Applied Voltage Breakdown Strength vs. Gas Temperature for the Sphere and Point to Grounded Plane Electrode Systems.
3/4" Dia. Sphere to Grd. Plane Electrode

3/32" Dia. Tungsten Rod (sharpened to a point) to Grd. Plane Electrode

Gas----------C₃F₈

Cell Filling Conditions:
Pressure----28.35 in. of Hg
Temperature--80°F (26.7°C)

Gap Spacing----0.1 in.
Without Irradiation
Refer to Tables II and IV

Fig. 12. One-Minute Withstand Voltage Breakdown Strength vs. Gas Temperature for the Sphere and Point to Grounded Plane Electrode Systems.
Fig. 13. Rapidly Applied Voltage Breakdown Strength vs. Gas Temperature for the Sphere and Point to Grounded Plane Electrode Systems.
Fig. 14. One-Minute Withstand Voltage Breakdown Strength vs. Gas Temperature for the Sphere and Point to Grounded Plane Electrode Systems.
Fig. 15. Two Separate Series of Tests - Rapidly Applied Voltage Breakdown Strength vs. Gas Temperature - Sphere to Grounded Plane Electrode System.
Fig. 16. Two Separate Series of Tests - One-Minute Withstand Voltage Breakdown Strength vs. Gas Temperature - Sphere to Grounded Plane Electrode System.
Fig. 17. Rapidly Applied and One-Minute Withstand Voltage Breakdown Strength Tests vs. Gas Temperature - Sphere to Grounded Plane Electrode System.

<table>
<thead>
<tr>
<th>Gas</th>
<th>( \text{C}_2\text{F}_8 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell Filling Conditions:</td>
<td></td>
</tr>
<tr>
<td>Pressure</td>
<td>28.35 in. of Hg</td>
</tr>
<tr>
<td>Temperature</td>
<td>(80^\circ\text{F} (26.7^\circ\text{C}))</td>
</tr>
<tr>
<td>Gap Spacing</td>
<td>0.1 in.</td>
</tr>
<tr>
<td>Without Irradiation</td>
<td></td>
</tr>
<tr>
<td>Refer to Tables I and II</td>
<td></td>
</tr>
</tbody>
</table>
Fig. 18. Rapidly Applied and One-Minute Withstand Voltage Breakdown Strength Tests vs. Gas Temperature - Point to Grounded Plane Electrode System.
3/4" Dia. Sphere to Grd. Plane Electrode

---0--- Rapidly Applied Test
---Q--- One-Minute Withstand Test

Gas--------C$_3$F$_8$

Cell Filling Conditions:
Pressure----28.35 in. of Hg
Temperature--80°F (26.7°C)
Gap Spacing-----0.1 in.

With Irradiation

Refer to Tables V and VI

Fig. 19. Rapidly Applied and One-Minute Withstand Voltage Breakdown Strength Tests vs. Gas Temperature - Sphere to Grounded Plane Electrode System.
3/32" Dia. Tungsten Rod (sharpened to a point) to Grd. Plane Electrode

Rapidly Applied Test

One-Minute Withstand Test

Gas Temperature (Degrees Centigrade)

Fig. 20. Rapidly Applied and One-Minute Withstand Voltage Breakdown Strength Tests vs. Gas Temperature - Point to Grounded Plane Electrode System.
Fig. 21. Rapidly Applied (with Irradiation) and Rapidly Applied (without Irradiation) Voltage Breakdown Strength Tests vs. Gas Temperature - Sphere to Grounded Plane Electrode System.

Gas: \( \text{C}_3\text{F}_8 \)

Cell Filling Conditions:
- Pressure: 28.35 in. of Hg
- Temperature: 80°F (26.7°C)

Gap Spacing: 0.1 in.

With and Without Irradiation

Refer to Tables I and V
3/4" Dia. Sphere to Grd. Plane Electrode

Gas-----$\text{CF}_3\text{F}_8$

Cell Filling Conditions:
- Pressure-----28.35 in. of Hg
- Temperature--80°F (26.7°C)

Gap Spacing-----0.1 in.

With and Without Irradiation
Refer to Tables II and VI

Fig. 22. One-Minute Withstand (with Irradiation) and One-Minute Withstand (without Irradiation) Voltage Breakdown Strength Tests vs. Gas Temperature - Sphere to Grounded Plane Electrode System.
3/32" Dia. Tungsten Rod (sharpened to a point) to Grd. Plane Electrode

--- ▼ --- Test with Irradiation
--- ▼ --- Test without Irradiation

Gas---------C₃F₈

Cell Filling Conditions:
Pressure------28.35 in. of Hg
Temperature--80°F (26.7°C)
Gap Spacing------0.1 in.
With and Without Irradiation
Refer to Tables III and VII

Fig. 23. Rapidly Applied (with Irradiation) and Rapidly Applied (without Irradiation) Voltage Breakdown Strength Tests vs. Gas Temperature - Point to Grounded Plane Electrode System.
3/32" Dia. Tungsten Rod (sharpened to a point) to Grd. Plane Electrode

--- Test with Irradiation

--- Test without Irradiation

Gas------C2F8

Cell Filling Conditions:
Pressure------28.35 in. of Hg
Temperature------80°F (26.7°C)

Gap Spacing------0.1 in.

With and Without Irradiation

Refer to Tables IV and VIII

Fig. 24. One-Minute Withstand (with Irradiation) and One-Minute Withstand (without Irradiation) Voltage Breakdown Strength Tests vs. Gas Temperature - Point to Grounded Plane Electrode System.
Fig. 25. Coefficient of Variation vs. Gas Temperature of the Rapidly Applied Voltage Tests for the Sphere and Point to Grounded Plane Electrode Systems.
Fig. 26. Coefficient of Variation vs. Gas Temperature of the One-Minute Withstand Voltage Tests for the Sphere and Point to Grounded Plane Electrode Systems.
Fig. 27. Coefficient of Variation vs. Gas Temperature of the Rapidly Applied Voltage Tests for the Sphere and Point to Grounded Plane Electrode Systems.
Fig. 28. Coefficient of Variation vs. Gas Temperature of the One-Minute Withstand Voltage Tests for the Sphere and Point to Grounded Plane Electrode Systems.
Fig. 29. Coefficient of Variation vs. Gas Temperature of the Two Separate Series of Tests for the Rapidly Applied Voltage Breakdown Strength - Sphere to Grounded Plane Electrode System.
Fig. 30. Coefficient of Variation vs. Gas Temperature of the Two Separate Series of Tests for the One-Minute Withstand Voltage Breakdown Strength - Sphere to Grounded Plane Electrode System.
Fig. 3.1. Coefficient of Variation vs. Gas Temperature of the Rapidly Applied and One-Minute Withstand Voltage Tests - Sphere to Grounded Plane Electrode System.

Gas----$C_2F_8$
Without Irradiation

This Figure corresponds to Figure 17.
Refer to Tables I and II
3/32" Dia. Tungsten Rod (sharpened to a point) to Grd. Plane Electrode

<table>
<thead>
<tr>
<th>Gas</th>
<th>$\text{C}_3\text{F}_8$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without Irradiation</td>
<td></td>
</tr>
</tbody>
</table>

This Figure corresponds to Figure 18.

Refer to Tables III and IV

---

**Fig. 32.** Coefficient of Variation vs. Gas Temperature of the Rapidly Applied and One-Minute Withstand Voltage Tests - Point to Grounded Plane Electrode System.
Fig. 33. Coefficient of Variation vs. Gas Temperature of the Rapidly Applied and One-Minute Withstand Voltage Tests - Sphere to Grounded Plane Electrode System.
Fig. 34. Coefficient of Variation vs. Gas Temperature of the Rapidly Applied and One-Minute Withstand Voltage Tests - Point to Grounded Plane Electrode System.
Fig. 35. Coefficient of Variation vs. Gas Temperature of the Rapidly Applied (with Irradiation) and Rapidly Applied (without Irradiation) Voltage Tests - Sphere to Grounded Plane Electrode System.
Fig. 36. Coefficient of Variation vs. Gas Temperature of the One-Minute Withstand (with Irradiation) and One-Minute Withstand (without Irradiation) Voltage Tests - Sphere to Grounded Plane Electrode System.

Gas——--C₃F₈
With and Without Irradiation
This Figure corresponds to Figure 22.
Refer to Tables II and VI
Fig. 37. Coefficient of Variation vs. Gas Temperature of the Rapidly Applied (with Irradiation) and Rapidly Applied (without Irradiation) Voltage Tests - Point to Grounded Plane Electrode System.
3/32" Dia. Tungsten Rod (sharpened to a point) to Grd. Plane Electrode

--- Test with Irradiation

--- Test without Irradiation

Gas----C_F_8

With and Without Irradiation

This Figure corresponds to Figure 24.

Refer to Tables IV and VIII

Fig. 38. Coefficient of Variation vs. Gas Temperature of the One-Minute Withstand (with Irradiation) and One-Minute Withstand (without Irradiation) Voltage Tests - Point to Grounded Plane Electrode System.
APPENDIX III
THERMOCOUPLE CONSTRUCTION AND DETERMINATION
OF TEST CELL HEATING TIME

A. The Thermocouples

Ten thermocouples were constructed out of iron-constantan, glass on asbestos wire which was obtained from Leeds and Northrup Company of Philadelphia, Pennsylvania.

A cold junction board was constructed and a standard mercury thermometer with a range of \(-20^\circ C\) to \(110^\circ C\) was hung directly above this terminal board.

Figure 39 shows the thermocouple circuit used for measuring temperatures inside the oven. The leads from the thermocouples were

![Thermocouple Circuit Diagram](chart.png)

Fig. 39. The Thermocouple Circuit Diagram Used to Measure Temperatures Inside the Oven.
connected to one side of the cold junction terminal board. Connecting leads also ran from the other side of the terminal board to a Leeds and Northrup 10 position rotary selector switch. This switch also had an off position to disconnect all of the thermocouples at one time during the calibration of the millivolt potentiometer. The Leeds and Northrup millivolt potentiometer was equipped with a reference (cold junction) compensator which permitted the reading of the true thermocouple (hot junction) voltage on the millivolt potentiometer. Let \( V_{\text{pot}} \) = voltage read on the potentiometer and \( V_2 \) = voltage developed at the thermocouples inside the oven, and \( V_1 \) = voltage developed at the cold junction outside of the oven. Then the voltage read on the potentiometer, without the use of the compensator circuit, would be:

\[ V_{\text{pot}} = V_2 - V_1 \]

If the compensator circuit was used and properly adjusted it would add a voltage equal and opposite to that of the cold junction voltage. The voltage reading on the potentiometer would then be:

\[ V_{\text{pot}} = V_2 \]

which was the desired reading.

The temperature of the cold junction was found by reading the Hg thermometer that hung directly above the cold junction terminal board. Entering standard conversion tables for thermocouples with the cold junction temperature one could find the voltage \( V_1 \) developed at the cold junction. This voltage was then set on the compensator circuit which applied an equal but opposite voltage to the cold junction.

It was necessary to convert the millivolt readings from the 10 thermocouples into degrees centigrade. The standard tables are set up to be entered with a temperature value and from them a millivolt value is obtained. Entering the tables with a millivolt reading was
inconvenient and in the majority of cases called for an interpolation of values in order to come out with a temperature reading. To overcome this problem the author wrote a computer program which in effect inverted the standard table as well as performed linear interpolation between the millivolt values. This permitted the conversion of millivolts to degrees centigrade with ease. The final table listed temperature values in degrees centigrade for every 0.01 millivolt value from 0 millivolts through 43.49 millivolts. This is equivalent to a temperature range from 0.0°C to 768.167°C which is beyond the range of the oven used.

B. Tests to Find Heating Time of Test Cell

The ten thermocouples were placed in various locations inside the oven to yield an idea of the temperatures throughout the oven. Some of the thermocouples were placed near the cell while #10 thermocouple was placed inside the cell. Figure 40 shows the location of the thermocouples inside the oven. The thermocouples #1 through #5 were placed near the upper part of the oven. Thermocouples #7 through #9 were placed around the outside of the test cell about 4 1/2" above the floor and about 1" from the test cell wall. Thermocouple #9 was placed on top of the test cell, about 0.5" above the top end plate.

Using the test cell #56667, a series of heat-run tests were conducted to determine the temperature vs. time curves for various locations inside the oven, as well as inside the test cell. The test cell was filled with air.
Figures 41 and 42 show the results from two of the tests run. Note that thermocouple #10, inside the test cell heated more slowly than the air inside the oven, represented by thermocouple #8. Also note that thermocouple #9 which is outside of the cell but near the top metal plate had a heating rate somewhat slower than thermocouple #8. This may have been due to the fact that the metal parts of the cell were absorbing heat and conducting the heat to other parts of the cell and to the gas inside the cell.

Since the temperature of the air throughout the oven was quite
Test cells #7, #6 were same as #8.
Test cell #9 was near top plate of cell.
Test cell #10 was inside the cell.

Time chosen to heat the test cell for the tests below 100°C.

Fig. 41. Temperature of Thermocouples Inside Oven vs. the On-Time of the Oven.
Test cells #7, #6 were same as #3.
Test cell #9 was near top plate of cell.
Test cell #10 was inside the cell.

Time chosen to heat the test cell for the tests above 100°C.

Fig. 42. Temperature of Thermocouples Inside Oven vs. the On-Time of the Oven.
uniform, thermocouples #1 through #7 are not shown in Figures 41 and 42. The temperatures of these seven thermocouples were about the same as the temperature of thermocouple #8.

The thermocouples were read starting with #10 first and then #9, #8, etc., for a given recorded time. This had the effect, especially during the first few minutes of heating, of causing the thermocouples that were read last to have a higher temperature reading than did those read first. This would have the effect of slightly increasing the separation between the curves on Figures 41 and 42.

Note also that the cell's temperature did not quite reach the final temperature of the air around the cell. It was however assumed in all the testing of the breakdown strength of C\textsubscript{3}F\textsubscript{8} that the temperature read with thermocouples #6, #7, and #8 was the actual temperature of the gas inside the cell. During the actual voltage breakdown tests of C\textsubscript{3}F\textsubscript{8} the thermocouples were placed 3/8" from the test cell's glass wall as compared to 1" for the tests discussed in this section. Thus the temperature measured by thermocouples #6 through #8 was probably closer to the actual temperature of the cell than is indicated by the curves in Figures 41 and 42.

The thermal conductivity of C\textsubscript{3}F\textsubscript{8} near room temperature is $3.6 \times 10^{-5}$ cal/sec-cm-\textdegree C,\textsuperscript{4,24} while that of air near room temperature is $5.7 \times 10^{-5}$ cal/sec-cm-\textdegree C.\textsuperscript{26} The thermal conductivity of C\textsubscript{3}F\textsubscript{8} is therefore 0.632 times that of air. This means that a test cell filled with C\textsubscript{3}F\textsubscript{8} gas would take up to approximately 1.5 times as long to heat. Also the molecular weight of C\textsubscript{3}F\textsubscript{8} is approximately 6.5 times as great as that of air. This means more mass is contained in the cell when it
is filled under the same conditions of temperature and pressure with $\text{C}_3\text{F}_8$ than when it is filled with air. This would also seem to contribute to added time for the heating of a cell filled with $\text{C}_3\text{F}_8$ over the time of one filled with air.

On the other hand, the specific heat of $\text{C}_3\text{F}_8$ at 90°C is 39.6 cal/gram-mole-°C, while that of air at 100°C is approximately 6.95 cal/gram-mole-°C. This means that the ability of $\text{C}_3\text{F}_8$ to transfer heat from one surface to another is 5.7 times as great as that of air. And if one assumes that the gas circulates inside the cell during heating, then it would seem that this would act to decrease the time of heating of the $\text{C}_3\text{F}_8$ gas and test cell.

Considering all three processes mentioned, it would seem that they would tend to cancel out most of the differences between the heating rates of cells filled with air or $\text{C}_3\text{F}_8$. Hence it was assumed that the time to heat the $\text{C}_3\text{F}_8$ gas and test cell was the same as that when the cell was filled with air. Basing the decision for the heating times of the test cell on the curves in Figures 41 and 42 would then seem legitimate.

Using the curves of Figures 41 and 42 it was decided to heat the cell for one hour, and for one and one half hours if the test temperature was respectively less than 100°C, or more than 100°C.

From Figures 41 and 42 one can also get an idea of the time required for the parts of the cell to heat and expand to this final length at the test temperature. The author feels that when the temperature of thermocouples #9 and #10 are equal then the gas and the test cell are at approximately the same temperature and the test cell
has expanded to nearly its final length due to the temperature change during heating. Heating the test cell for the time shown on the curves as specified above would then seem to allow enough time for the cell to expand. This time was approximately equal to or less than the time chosen for the heating of the gas.

A test was also made to check the accuracy of one of the thermocouples by running a heat test on the thermocouple placed next to a mercury thermometer. It was found that the two agreed within 0.5 degrees centigrade.
APPENDIX IV
DETERMINATION OF THE THERMAL LINEAR EXPANSION OF THE TEST CELLS

The test cells were heated through relatively large temperature changes before some of the tests were made. Since materials are subject to expansion due to a change of temperature, the author felt it was necessary to check the linear expansion of the test cells.

It is known that the change in the length, $\Delta L$, of a material due to a temperature change is equal to the original length, $L_0$, times the average coefficient of linear expansion for the temperature range used, $\alpha$, times the change in temperature, $\Delta T$, of the material. Hence: $\Delta L = L_0 \alpha \Delta T$. Using this equation and knowing the values of $L_0$ and $\alpha$ for the various parts of the test cells and the temperature change $\Delta T$, one is able to find the total change in the length of the gap spacing of the cell. And from this the final gap spacing distance at the new temperature can be found.

Values for the coefficient of expansion were found$^{25,26}$ and the original lengths of the parts of the test cells were measured. From this, a value of $\Delta L/\Delta T = L_0 \alpha$ was found for each test cell.

There was some doubt to the exact type of material used in the test cells. There were also some complications such as having bolts of one material securing parts which were made of another material. For these reasons the author felt that the $\Delta L/\Delta T$ values found for the test cells by analytical means were questionable.

It was decided to find the $\Delta L/\Delta T$ values for the test cells by experimental means. This was accomplished by first reading the
micrometer when the gap spacing was zero for each of the test cells. This reading was called the initial zero reading. The temperature of each of the test cells at the time of reading the micrometer was also recorded and called the initial temperature. Then the gap spacing was adjusted to 0.1" for each of the test cells. Both cells were placed in the oven and heated for two hours through a temperature change of approximately 123°C. From previous tests, two hours of heating seemed to be more than sufficient time to allow the parts of the cell to expand to their final lengths. After two hours of heating a final temperature of the test cells was read by reading the temperatures of a number of thermocouples placed near the test cells. The oven door was then quickly opened and the gap spacing adjusted to zero with the use of the micrometer. The reading of the micrometer was again recorded for each test cell. This was called the final zero reading.

From these readings the change in length of the gap spacing for a change in temperature could be found for each test cell. \( \Delta T = (\text{final temperature} - \text{initial temperature}) \). \( \Delta L = (\text{final zero reading} - \text{initial zero reading}) \). \( \Delta L/\Delta T \) was then easily found. This was the value of \( \Delta L/\Delta T \) for a zero gap spacing of each test cell. To adjust this value to a 0.1" gap spacing value, it was necessary to use analytical means. At 0.1" gap spacing, 0.1" less of steel in the micrometer screw was contributing to the decrease of the gap spacing as compared to the 0.0" gap spacing. The value of \( \Delta L/\Delta T \) for 0.1" of steel was found and subtracted from the value of \( \Delta L/\Delta T \) at zero gap spacing for each of the test cells. This gave a value of \( \Delta L/\Delta T \) at 0.1" gap spacing for the test cells. These values are shown in Table XI.
experimental values agreed very closely with the analytical values found before. The experimental values were used in adjusting the gap spacing for the tests.

TABLE XI

The Correction Factor for the Linear-Thermo-Expansion of the Test Cells at Various Gap Spacings.

(The value listed is the distance the gap spacing decreases due to the increase of the temperature of the test cell by one degree centigrade.)

<table>
<thead>
<tr>
<th>Gap Spacing Size (mils)</th>
<th>$\Delta L/\Delta T$ for the Sphere to Plane Electrode System, Test Cell: #56667 (mils/°C)</th>
<th>$\Delta L/\Delta T$ for the Point to Plane Electrode System, Test Cell: #53508 (mils/°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.0868</td>
<td>0.0747</td>
</tr>
<tr>
<td>100</td>
<td>0.0848</td>
<td>0.0735</td>
</tr>
</tbody>
</table>

When a new set of Teflon gaskets were used on a test cell they would tend to flatten out due to the great pressure and temperature exerted upon them. A gasket which had been used for some time tended to remain at the same thickness. For this reason a used set of gaskets were used during the testing for the linear expansion of the test cell. This would prevent any error from being introduced due to a change in the thickness of the gaskets. The same set of gaskets were then used with the same test cell for all tests thereafter.
APPENDIX V
ADJUSTMENT OF THE GAS TO STANDARD CONDITIONS

The equation of state of an ideal gas is:

\[ PV = nRT \tag{1} \]

where \( P \) = absolute pressure, \( V \) = volume, \( n \) = number of moles, \( R \) = universal gas constant, and \( T \) = absolute temperature. Changing the form of equation (1) slightly gives:

\[ n = \frac{PV}{RT} \tag{2} \]

The pressure in the test cell was never greater than 2 atmospheres and the temperature of the gas was always 55°C or more above the boiling point of the gas. Thus it will be assumed that \( \text{C}_3\text{F}_8 \) gas is an ideal gas under the conditions used. It then follows that the universal gas constant applies to the gas.

The volume of the test was found to change by approximately one tenth of one percent of the total volume when heated to the highest test temperature. This was a negligible change in volume and therefore the volume was assumed to remain constant.

With \( R \) and \( V \) constant for the test cell, the equation reduces to:

\[ n = K \frac{P}{T} \tag{3} \]

where \( K = \frac{V}{R} \).

If the temperature and pressure in the room could have been adjusted, it would have been possible to fill the cell with gas at the same temperature and pressure every time. This would mean at each filling, the number of moles in the test cell would be the same every time. Unfortunately, the temperature and pressure in the room was not controllable. However, the pressure of the gas inside the test cell could directly be
adjusted. The temperature of the gas was not directly adjustable.

An equation can be developed to provide a means of accounting for a needed temperature change in the gas by changing the pressure of the gas. This is done as follows.

It is desired to fill the test cell with the same number of moles, \( N_0 \), each time the cell is filled with gas. If \( P_S \) and \( T_S \) are the standard or chosen conditions of temperature and pressure respectively, then:

\[
N_0 = K \left( \frac{P_S}{T_S} \right). \tag{4}
\]

Now if some different conditions of pressure and temperature existed, say \( P_1 \) and \( T_1 \), such as to give the correct number of moles, \( N_0 \), the equation would be:

\[
N_0 = K \left( \frac{P_1}{T_1} \right). \tag{5}
\]

Comparing equations (4) and (5) it is seen that the ratio of \( P_S/T_S \) must be equal to the ratio \( P_1/T_1 \) or:

\[
P_S/T_S = P_1/T_1. \tag{6}
\]

Rearranging the terms in equation (6) yields:

\[
T_1/T_S = P_1/P_S. \tag{7}
\]

A small change in \( T_1 \) of equation (7) would cause a small change in \( P_1 \). Hence:

\[
\Delta T_1/T_S = \Delta P_1/P_S, \tag{8}
\]

or in general

\[
\Delta T/T_S = \Delta P/P_S. \tag{9}
\]

Rearranging the terms in equation (9) gives:

\[
\Delta P = (\Delta T/T_S) P_S = (\Delta T / T_S) P_S, \tag{10}
\]

where \( T_A \) = temperature of room at filling of the cell. By use of
equation (10), a needed temperature change, $\Delta T$, can be accounted for by a pressure change $\Delta P$. The gas in the test cell can be adjusted to standard conditions by a pressure change, $\Delta P_p$, to adjust the pressure to standard pressure, plus a pressure change, $\Delta P_T$, to account for a difference between the gas temperature and the standard temperature. This can be written in equation form as follows:

$$PCN = \Delta P_p + \Delta P_T,$$

where $PCN = \text{pressure change needed}$. Expanding this equation:

$$PCN = (P_S - P_A) + \left(\frac{(T_A - T_S)}{T_S}\right) P_S$$

(12)

where $P_A = \text{pressure of room at filling of cell}$, and $T_A = \text{temperature of room at filling of cell}$. The temperature and pressure chosen for $P_S$ and $T_S$ were respectively 28.35 in. of Hg, and 80°F. Substituting these values into equation (12) gives:

$$PCN = (28.35 \text{ in. of Hg} - P_A) + \left(\frac{(T_A - 80\degree F)}{(460\degree R + 32\degree F)}\right) 28.35 \text{ in. of Hg}.$$  

(13)

Since $1\degree R$ has the same value as $1\degree F$, equation (12) becomes

$$PCN = (28.35 - P_A) + ((T_A - 80\degree F) 28.35),$$

(14)

where $PCN$ and $P_A$ are in inches of Hg, and $T_A$ is in degrees Fahrenheit.

The leveler tubes used to change the pressure inside the test cell were filled with silicone oil which had a density of 0.870 gm/ml. Let $P_o = 1.0''$ of Hg, $D_s = \text{density of silicone oil}$ and $H_S = \text{height of silicone oil in a column}$. It is known that pressure = density times height, or:

$$P = DH$$

(15)
With the use of equation (15) one can find the height of the silicone oil to produce a pressure equal to the pressure produced by one inch of mercury.

\[ P_0 = D_s H_s \]

\[ H_s = P_0 / D_s \]

Since \( P_0 = 1' \) of \( H_g = 0.492 \text{ lb/in}^2 \),

\[ H_s = (0.492 \text{ lb/in}^2) / (0.870 \text{ gm/ml}) \]

\[ H_s = 15.66 \text{ inches of silicone oil}. \]

Therefore, 15.66 inches of silicone oil was equivalent to one inch of mercury.

15.66" of silicone oil = 1" of Hg

Combining equations (14) and (13) yields:

\[ PCN = ((23.35 - P_A) + ((T_A - 80)/540)(23.35)) \times 15.66, \]  

(19)

where \( PCN \) is in inches of silicone oil, \( P_A \) is in inches of mercury, and \( T_A \) is in degrees centigrade.

Equation (19) gave the difference between the level of silicone oil in the leveler tubes. A minus sign on \( PCN \) meant a decrease in pressure inside the cell was required. A positive sign on \( PCN \) meant an increase in pressure inside the cell was required. Referring to Figure 9, a minus sign on \( PCN \) meant leveler tube, \( L_1 \), should have been lowered, while a positive sign on \( PCN \) meant this tube, \( L_1 \), should have been raised relative to leveler tube, \( L_2 \).

The use of equation (19) was time consuming and inconvenient. The author chose to write a computer program which produced a table of proper levels for the leveler tubes for a range of temperatures and pressures. With the use of this table to determine the proper level
at which to adjust the leveler tubes, it was only necessary to enter the table with the room temperature and pressure.
APPENDIX VI
DETERMINATION OF THE STANDARD DEVIATION
AND THE COEFFICIENT OF VARIATION

For every test made on the C₃F₈ gas, five trials were run to insure a more representative value for the breakdown voltage of the gas. To obtain an idea of the variation among the values of the five trials made, the standard deviation as well as the range between the maximum and minimum values were found. The standard deviation measures the actual amount of variation present in a set of trials and is dependent on the scale of measurement. The equation used for the standard deviations was:

\[ S = \sqrt{\frac{1}{(n-1)} \sum_{i=1}^{n} (X_i - X_{\text{AVG}})^2} \] (1)

where \( n \) = number of trials, \( X_i \) = value of each trial, \( X_{\text{AVG}} \) = arithmetic mean of the trials.

Since five trials were run in each test the equation for the standard deviation, \( S \), becomes:

\[ S = \sqrt{\frac{1}{4} \sum_{i=1}^{5} (X_i - X_{\text{AVG}})^2} \] (2)

To permit the comparison of the variation in several sets of trials, the coefficient of variation, \( CV \), was found as follows:

\[ CV = \frac{S}{X_{\text{AVG}}} \times 100 \text{ percent} \] (3)

Note that the coefficient of variation gives the standard deviation as a percentage of the arithmetic mean of the five trials and therefore is independent of the scale of measurement.
A total of 70 sets of breakdown values (five trials per set) were obtained from tests made on the C$_3$F$_8$ gas. The author felt this situation warranted the use of the computer to help evaluate the data. A computer program was written to find the maximum value, the minimum value, and the range between the maximum and minimum values of the five trials of each test. This program also calculated the arithmetical mean, the standard deviation and the coefficient of variation from the values of the five trials for each test. The results are shown in Tables I through X in Appendix I.