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FINAL REPORT

Survey of Kugelblitz Theories For Electromagnetic Incendiaries (U)

W. B. Lyttle
C. E. Wilson

December 1965

U. S. ARMY EDGEWOOD ARSENAL
CHEMICAL RESEARCH AND DEVELOPMENT LABORATORIES
Edgewood Arsenal, Maryland 21010

Contract No. DA 18-035-AMC-386(A)

MELPAR, INC.
7700 Arlington Boulevard
Falls Church, Virginia 22046

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FOREWORD

This report was prepared by Melpar, Incorporated, Falls Church, Virginia, on U.S. Army Contract number DA 18-035-AMC-386(A), Project number 1C014501-B71A02, Basic Research in Life Sciences (U). The study was performed for the New Concepts Division, under the direction of Mr. S. Harmats, Director of Special Projects of the Edgewood Arsenal Chemical Research and Development Laboratories. Work on the contract was initiated 28 June 1965 and concluded 28 September 1965.

Acknowledgment

The authors wish to acknowledge the contributions of Dr. R. Jones, of the University of Arizona, to the development of the ion-ion theory, various energy approximations, and many theoretical aspects of the Appendices.

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DIGEST

The purpose of this study was to review the theory and experimental data on ball lightning, to compare the existing theory and experimental data to determine whether ball lightning is a high or low energy phenomenon, and if it is a high energy phenomenon define an effective theoretical and experimental program required to develop a potential incendiary weapon.

The results of an extensive literature survey on the subject of Kugelblitz (Ball Lightning) are reviewed in detail, including the designation of information sources, the content of bibliographies, and a summary of those reports specifically related to the subject.

Three major categories were established for the purpose of grouping the numerous theories on the subject. These categories are the classical plasma theories, the quantum plasma theories, and the non-plasma theories. Each theory in the three major divisions is analyzed relative to energy content. The Kugelblitz is presented as both a low energy and a high energy phenomenon, and approximate calculations are performed to determine the magnitude of the energy involved. The results of the energy analysis are summarized and relative ratings are given to the more promising theories, and overall conclusions are presented.

A theoretical and experimental Kugelblitz program is recommended by which the most promising high energy theories could be developed so that a weapons application could be realized.

Appendices are presented which include: a coverage of basic plasma physics concepts; the details of the development of the Melpar low density Kugelblitz theory; guidance and feeding of Kugelblitz by laser beams; and a complete bibliography of reports directly relating to Kugelblitz.

TABLE OF CONTENTS

1. INTRODUCTION

This Final Comprehensive Report summarizes the work performed on Contract DA18-035-AMC-386(A) entitled "Survey of Kugelblitz Theories for Electromagnetic Incendiaries." The study conducted on this contract is divided into three tasks, as follows: A review of the theory and experimental data that have been published on ball lightning; comparison of the existing theory and experimental data to determine whether ball lightning is a high or low energy phenomenon. If it is a high energy phenomenon, define an effective theoretical and experimental program required to develop a potential incendiary weapon application.

The literature survey revealed that there are numerous reports extending back more than half a century (with unverified reports going back centuries), of observations of ball lightning (commonly referred to by its German name of Kugelblitz). The Germans, until recently, have collected most of the data and have proposed a number of explanations, culminating in the rather advanced theory of Neugebauer in 1937. However, the English were also active in this field, the most notable example of their interest being the Ozone theory proposed by W. M. Thornton in 1911. The Russians, Italians and Americans became really active in this field during the 1950's, most of the work being a variation of the standing wave theory usually credited to the Russian Kapitza. The most recent work known is that of Dr. Finklestein of Yeshiva University and Dr. R. Jones formerly of Melpar. These two theories are really low energy theories, with the Melpar theory being, in addition, a low electron energy theory (the electron energy range of the Finklestein theory is a rather fantastic 10^5 to 10^7 ev).

The descriptions of ball lightning contained in the literature suggest the possibility that both low and high energy modes occur in the natural electromagnetic disturbances of nature. Diameters have been observed in the range of 5 to 75 cm with lifetime durations varying from tenths to ten seconds. In addition, reports vary on destructive versus non destructive characteristics of the ball lightning. Some ball lightning has been observed to move slowly without any visible relationship to its immediate environment, and to decay or dissipate quietly. In contrast, some ball lightning has been observed to discharge explosively with a large exchange of energy involved, probably in the order of magnitude of 10^6 joules. If the discharge mechanism was of the millisecond to microsecond type, then the power level would be in the range of 10^9 to 10^{12} watts.

In the section of this report which is concerned with energy considerations, an attempt is made to approximate, within the scope of the study, the energy associated with both the low and high energy Kugelblitz relative to the various mechanisms. Several theories exist which have been developed to explain either the high or low energy phenomenon; however most of these theories can be placed in one of three major categories. These categories are: The Classical Plasma Theories; The Quantum Plasma Theories; The Non-Plasma Theories.

2. LITERATURE SURVEY

2.1 Bibliographies and Information Sources

Upon receiving the contract for the Kugelblitz Study, a literature survey was initiated to meet the requirement of A-1 of the Statement of Work. Three bibliographies on this subject were requested, from the Defense Documentation Center for Scientific and Technical Information, Cameron Station, Alexandria, Virginia; The Library of Congress, Washington, D.C., and the Melpar Research Library, Falls Church, Virginia.

The Defense Documentation Center supplied a computer run bibliography, dated 22 July 1965, and titled Ball Lightning and Fireballs ARB · No. A37133. The bibliography consisted of 33 listings of reports complete with descriptions, identifiers, and abstracts. The majority of the reports concerned aircraft protections from thunder storm effects; however, only three reports were selected as being related to the study topic and those three reports were ordered. The Defense Documentation Center was visited, to review certain reports referred to in the bibliography, and to explore the possibility of finding related information in other categories as identifiers.

The most worthwhile bibliography received was the one supplied by the Library of Congress. This bibliography contained 38 listings, of which 37 were selected as directly related to the subject of the study. The text of a majority of the reports in this bibliography were in a foreign language; the breakdown is as follows: 22 German, 7 Russian, 2 Dutch, 1 Czeck, 1 Rumanian, and 2 French. Approximately 75% of the listings in the bibliography were ordered for study. Most of the German reports were translated at Melpar; however, all reports were not formally reproduced in English since persons working on the Kugelblitz study were able to read German. A summary translation was available on the Russian reports.

The remainder of the reports and bibliographies were supplied by the Melpar Technical Information Center. The reproduction facilities of the TIC were made available to provide copies of reports which were made available on short-time loan basis. This Center also submitted the requests for all reports ordered on the study program.

Altogether, some 150 reports, letters, and other articles were reviewed. Of this number, 97 were selected as being directly related to the Kugelblitz Study and were compiled to form the bibliography presented in Appendix A. Each related report was read for theoretical approach, energy magnitude, and any unique concepts. A summary of the more worthwhile reports is given in the following section.

2.2 Summary of Literature Reviewed

2.2.1 Literature Summary

Several theories have been proposed to explain the nature of ball lightning. The theories of Kapitza, Finkelstein, Johnson and Pedersen have been based on the assumption that the contents of the ball is made up of a plasma, a theory assumed separately by Hill and Neugebauer, the nuclear theory by Dauvillier and the combustion theory by Nauer.

The plasma theory of Kapitza is based on the hypothesis that the energy required for ionization is continuously supplied by an outside source. Kapitza postulates the creation of electromagnetic waves by bolts of lightning. These waves are then reflected by conducting surfaces creating standing waves. Energy from the waves ionize a region of air at an antinode, the point of greatest field strength. The luminous ball created at the antinode moves to a node where radiation pressure holds it and energy is continuously supplied. The ultimate size of a ball based on the Kapitza theory would be directly related to the frequency of the radiation of the source furnishing the energy. Ball sizes which have been reported place the radiation frequency in the neighborhood of 10^9 cycles per second.

The major difficulties to the Kapitza theory are:

a. The large amount of ultrahigh-frequency radiation required has never been detected during a thunderstorm.

b. The presence of any resonance effects for specific dimensions of balls implies that radio waves must be concentrated at discrete frequencies, and Kapitza gives no indication of how this can occur.

A resurgence of interest in ball lightning has been stimulated by the proposed theory of Kapitza. Several persons have supported the theory of Kapitza and some have proposed models for ball lightning based on this theory.

None of the work performed to date has been able to relate Classical Plasma Theories to the high energy phenomenon. It is concluded that the low energy Kugelblitz decays quietly and has no relative destructive capability.

Most of the effort in this study has been devoted to the energy consideration of Kugelblitz and the literature survey. However, some previous thought was directed toward the feeding and guiding of Kugelblitz by use of laser beams as stated in Appendix D.

A program is developed by which it is believed that Kugelblitz can be properly investigated and removed from a semispeculative basis. This program contains sufficient experimental and theoretical effort to adequately advance the high energy non-plasma theories to the extent that a weapon applications can be realized.

Watson has presented a qualitative explanation of Kapitza's theory in terms of resonance absorption of standing waves due to conducting ionized plasma spheres occurring when the wavelength of radiation is approximately 4 times the ball diameter. Watson proposes that the atmosphere is weakly ionized because of a storm and the regions around the nodes of a polarized electromagnetic wave are ionized by electron collisions building up in an avalanche fashion due to focusing of the electromagnetic field till the plasma frequency is greater than the frequency of the applied field. At this point, further field penetration is impossible so surface absorption of energy becomes responsible for maintaining the ball in a manner similar to Kapitza's.

The ball lightning theory of Kapitza has been summarized by Silberg, and a model based on this theory has been proposed by Silberg. The model requires an external source of r-f energy with mechanisms for forming a spherical plasmoid which grows in size to a final diameter of $\frac{\pi d^3}{6}$. The plasmoid, while being supplied with energy of wavelength, $\lambda = 3.65d$, grows until it becomes stabilized. Only low-density, spherical plasmoids, at low pressures, have been produced and sustained with r-f energy.

Andersen has attempted to overcome one of the shortcomings of Kapitza's theory - that of not being able to account for the large amount of ultra-high-frequency radiation required to sustain the ball. Anderson attempts to show that these frequencies are emitted during the collision of charged water drops. An estimate was made of the volume of charged water drops necessary to produce the energy of a lightning ball if all the electrostatic energy of the charged drops are converted to usable electromagnetic energy. It is calculated that $2.5 \times 10^{12} m^3$ of rain cloud is required to supply 5×10^6 joules, the estimated energy of a typical lightning ball.

Tonks points out that a serious problem regarding Kapitza's theory lies in the magnitude of the power required to sustain the ball. A calculation was made which showed that 18 kw of radiated power at a 40 cm wavelength is necessary to maintain a fireball having a diameter of 10 cm.

The work of Pierce, as does that of Kapitza, points out that the energy stored in a lightning ball at its creation is insufficient to maintain the ball in existence for periods of the order of a second. Conclusion is made that an external source must supply this energy in the form of electromagnetic radiation. A study shows that possible external sources are the points in negative corona. This places the source in close proximity to the phenomenon. The results of an experimental study do not indicate any continued discreteness at a frequency of the order of 300 mc/s, but the possibility remains that the spectrum may have line character transiently even as high as 300 mc/s.

The requirement of Kapitza's theory for an ultrahigh-frequency radiation source has prompted Finkelstein and Rubinstein to propose a new ball lightning theory. Although the Kapitza and Finkelstein theories are similar in that both are based on the assumption of a plasma mass being supplied energy by an external source, the two differ in the type of external source supplying energy for sustaining the fire ball. The Finkelstein theory describes ball lightning as a dc nonlinear phenomenon. The electric field lines of force tend to concentrate within a possible existing dielectric inhomogeniety located in the region between a thundercloud and ground. If the field strength and focusing effect are great enough, breakdown may occur producing a localized discharge of plasma. A further focusing of the lines of force occurs tending to increase the volume of the plasma. This continues until a stable size is reached. The various ways in which balls have been reported to disappear have been considered and accounted for by the theory.

Dewan concludes that the Finkelstein and Rubinstein theory is the only promising one of all that have been proposed, but that even this theory needs modification. Objections to the theory are:

a. The lightning balls which have been reported to have existed in houses cannot be accounted for by a dc theory.

b. The theory does not explain the suppression of corona point discharges in the neighborhood of the plasma.

c. Such a corona discharge, as the ball lightning described in this theory, should propagate along the electric field lines of force and quickly turn into a lightning stroke.

Modification to the theory is suggested by Dewan which should remove these objections. Replacing the dc field with an ac field would permit the existence of balls in houses or other nonconducting enclosures. Also, an ac field would tend to cancel the avalanching effects since the particles in the plasma would not be continuously accelerated in one direction.

A theory has been proposed by Johnson for a plasma ball lightning model in which most of its energy is accounted for by a toroidal magnetic field within the ball. It is assumed that ball lightning is a discharge contained by a magnetic field with a total magnetic energy given by

$$E = \frac{1}{\pi} \int^{V} \mu H^{2} dV$$

Where μ is the permeability of free space, H is the magnetic field intensity and V is the volume of the ball. It is concluded that a shortcoming of this theory is that the magnitudes of the currents and electromagnetic intensity in the ball do not fall in the range encountered in plasma physics. In fact, the current is larger than that recorded in lightning by one or two orders of magnitude, but it is pointed out that this may be a result of repeated surges of current in a lightning bolt or the absorption of energy from an electromagnetic field outside the ball.

Work performed by Pedersen and Davis has led to a ball lightning model which differs from Kapitza's model in that it does not behave as a resonant cavity, but is similar in that its contents are a plasma and it requires energy from an outside source. If electromagnetic energy is incident on the sphere, some of it is absorbed and serves to offset any thermal energy losses. Calculations are performed which show that 10 MW/cm^2 must be incident on the sphere in a frequency range above 10^{10} rad/sec. If it is assumed that the ambient atmosphere around the ball is composed of pure gases (oxygen, nitrogen, etc.), it is concluded that it is unlikely that any electromagnetic resonance absorption phenomenon could sustain the lightning ball.

A theory differing from those mentioned above is one proposed by Hill, which is based on the assumption that the contents of ball lightning is a molecular plasma generated by direct lightning strokes. A condition of the atmosphere in which there exists a substantial concentration of negative ions and ionic clusters is referred to as a molecular plasma. The gas in the interior of an active lightning channel is in a state of strong ionization and high temperature (20,000°C). As soon as the main return stroke is over the process of negative ion formation sets in and within about 10^{-4} seconds, the air in the channel is in a state of a very energy-rich molecular-plasma. It has been well established that the occurrence of successive lightning strokes along a discharge channel is connected with the fact that in such a molecular plasma, electrons can be detached relatively easily from the negative ions by electric fields, and so can be made available for the production of fresh ionization. This means the original discharge along the channel preconditions the air in the channel by converting it to a molecular plasma state. Successive strokes find it much easier to develop along this preconditioned channel than to establish a new path in the un-ionized air. The preconditioning is one of the most immediate and significant effects of the molecular plasma.

The major part of the energy content of ball lightning is in the form of stored energy of ionization, the ionization existing largely in the form of molecular ions, ionic clusters, etc.

2.2.2 Kugelblitz Theories With Originators and Supporters

After reviewing the numerous reports and papers related to Kugelblitz, it was ascertained that only a small number of different theories exist, and that much of the writing on the subject has been done by persons other than the originator in attempts to either prove or disprove the theories by theoretical or experimental efforts. Following is a listing of the more acceptable theories together with definitions, originators, and supporters:

a. Theories that Contents of Ball is a Plasma.

(1) Plasma created by a lightning stroke and maintained by electromagnetic standing waves.

Originator - Kapitsa

Supporters - Watson, Silberg, Pierce, Anderson,
Kogan-Beletskii, Tonks

(2) Plasma created by lightning strokes and maintained by the high dc electric fields associated with lightning storms.

Originator - Finkelstein and Rubinstein

Supporter - Dewan

(3) A plasma model for ball lightning with most of its energy accounted for by a toroidal magnetic field. The magnetic field is maintained by the poloidal motion of its electrons.

Originator - Johnson

(4) Plasma created by a lightning stroke and maintained by electromagnetic waves.

Originator - Pedersen

b. Combustion Theory.

The lightning ball is a region of burning gas moving along a gradient of a combustible gas-air mixture. A lightning stroke serves to ignite this mixture.

Originator - Nauer

c. Theories Based on Assumption That Contents of Ball is a Non-plasma Phenomenon.

(1) The molecular-plasma theory based on the idea that the region of the ball contains a strongly - inhomogeneous distribution of space charge in the form of a highly ionized gas, the ionization being primarily in the molecular form, with few electrons.

Originator - Hill

(2) A theory based on the assumption that ball lightning consists of a collection of electrons together with positive charges spread throughout

its volume, and that the energy of the system is to be determined in accordance with quantum mechanical theory of a cloud described as an electron gas.

Originator - Neugebauer

Supporter - Flint

d. Nuclear Theory.

Theory based on the assumption that the contents of the ball is radioactive carbon-14 created from atmospheric nitrogen by the action of thermal neutrons liberated by a lightning stroke.

Originator - Dauvillier

2.2.3 Energy Estimations and Calculations from the Literature

One of the primary purposes for conducting the literature survey was to determine the magnitude of energy releases on content of Kugelblitz. As reports were received rates on energy measurements, estimates on calculations were made and later compiled as an alphabetic listing based on the name of the author.

Andersen - mentions energy calculation by Hill (1960) based on water butt observation.

Bruce, C.E.R. - assumes a particle energy of 2 to 12 ev giving a 10 cm diameter ball energy of at least 10^{10} to 10^{11} ergs (10^3 to 10^4 joules).

Dauvillier - makes no calculation of energy.

Dewan - in summarizing characteristics based on observations, energy is placed at 10^6 joules based on water-butt observation.

Finkelstein - also mentions 10^6 joules needed to account for water-butt observation.

Uses a virial theorem to show that the total energy density of an air-confined plasmoid cannot exceed a small multiple of the internal energy density of the ambient air. This allows maximum energy of approximately 10^3 joules. Shows this figure may be exceeded for time given by $\tau < \sqrt{\frac{2I_o}{E_o}}$ where I_o is maximum value of I and E_o is maximum value of $E-3p\,V$.

Concludes large reported energies stores in kinetic, thermal or electromagnetic form, and externally supplied by dc field.

Goodlet (1937) - mentions water-butt observation.

Hill - mentions his awareness of only one serious attempt at estimating energy - this is based on water-butt observation (10^6 to 10^7 joules), discounts plasma concept for explaining phenomenon due to magnitude, reported durations of luminosity of balls.

States that Neugebauer made theoretical estimate of 50 joules/cm^3, Thornton estimated 160 joules/cm^3. These figures give energies of 10^5 joules and 3.2×10^5 joules.

States that complete dissociation of all molecules in air requires about 30 joules/cm^3 and complete dissociation and single ionization requires about 150 joules/cm^3.

Johnson, P.O. - for a 5 cm diameter plasma ball, calculates a magnetic energy, electrostatic energy and total ionization energy of 10^7 joules, 2.8×10^2 joules and 2.2×10^1 joules, respectively.

Kapitza - makes no calculation of energy. Main contribution is suggesting external agency supplies energy for sustaining ball.

Lewis - states that an upper limit to the stored energy is set if assumed that air at atmospheric pressure is at most singly ionized (fully ionized plasma). This upper limit gives an energy density of 100 joules/cm^3. This gives an energy of 10^6 joules for a singly ionised 25 cm diameter fireball at atmospheric pressure. Mentions 10^6 joules as energy of ball based on water-butt observation.

Nauer - No energy calculations or statements are made as such; however, mention is made of the modified Hertz experimental apparatus and indicates temperature increases in a thermometer of the order of 10° to 15°C. The only other statement referring to energy concerns the large amounts of energy available in nature to produce natural Kugelblitz.

Neugebauer - He compares the Kugelblitz energy with the linien-blitz energy. Assuming an ionization energy of 14 ev, an electron density of 27×10^{18}, and a 10 cm diameter, the Kugelblitz energy is found to be 3×10^{11} ergs. The energy of a lightning discharge is about 2×10^{15} to 2×10^{16} ergs. The Kugelblitz energy is only a small fraction of that of the initial discharge. Converting the Kugelblitz energy from ergs to joules we have 2×10^{15} (10^7) or (joule = 10^7 ergs) 2×10^8 joules as a total energy which is 382×10^3 joules/cm^3.

Pedersen - no energy calculation.

Petrzilka - restates work of Neugebauer. Makes no energy calculation.

Prochnow - makes no energy calculation.

Silberg (1962) - calculates initial energy of plasmoids given off reverse current relay contacts as being between 0.04 and 0.4 M joules for a conversion efficiency of 10% and between 0.002 and 0.2 M joules for conversion efficiency of 5%.

Calculates an energy of 3.4×10^4 joules for a completely ionized 10 cm diameter nitrogen ball at standard atmospheric conditions. Note that this lies between $0.02 \leq 0.034 \leq 0.04$ M joules.

Singer - makes no calculation of energy content.

Tonks - calculates power of 18 kw is required of a 40 cm wavelength Kapitza wave to maintain a fireball 10 cm in diameter.

Watson - makes no energy calculation.

Wooding - states that plasma possesses thermal and ionization energies amounting to several megajoules. Energy is mainly lost by radiation at a rate in the order of 10^7 watts. This gives a lifetime of a few seconds or less.

3. EVALUATION OF KUGELBLITZ THEORIES

3.1 Introduction

Due to the rather rare nature of the Kugelblitz phenomenon, as well as the inability (up to the present) to produce true Kugelblitz in the laboratory, the data collected, even though quite voluminous, is not the result of dispassionate scientific measurement. As a result, there exists a large amount of skepticism, ranging from a denial of the existence of Kugelblitz to a disbelief in reported details (such as color, size, apparent mass, lifetime, etc.). However, it is unreasonable to discount all of the recorded observations as mere optical illusions or fabrications, and the reports of actual damage (to airplanes, etc.) leads quite reasonably to a belief in the reality of Kugelblitz.

It is the purpose of this section of the report to discuss the most promising theories, the "Kugelblitz-like" experiments and studies which have been performed and to present our viewpoints concerning the most likely approach.

The analyses of Kugelblitz theories concern the major works of importance. The Kugelblitz theories can be categorized in several ways, but it may be convenient to consider three divisions:

a. Classical Plasma Theories

b. Quantum Plasma Theories

c. Non-plasma Theories

There are several classical plasma theories, but each of the other categories has only one outstanding representative theory.

3.2 Low Energy Considerations - Classical Plasma Analysis

No classical plasma theory, nor any classical plasma theory presently conceivable, can account for appreciable energy storage without a continuous power flow of very large magnitude into the Kugelblitz. This is not so with the quantum plasma theory or with the ozone theory (the major non-plasma theory). Why, then, do so many investigators continue to attack the problem from the standpoint of classical plasma theory? Melpar, which has proposed one classical plasma theory, believes that the reasons may be stated as follows:

a. Most electrical engineers and physicists acquainted with lightning phenomena are loath to believe that a closely allied occurence such as Kugelblitz could possibly be non-electrical in nature. Granting this, it is a short step to assume that it is a collection of positive and negative charges of no special significance - that is, a classical plasma.

b. Due to a complete absence of experimental contact with quantum gas plasmas, it is difficult to accept the fact that a quantum plasma may be created in such a classical situation as Linienblitz even though the energies involved are tremendous.

c. There is no reliable evidence to indicate that combustibles of any sort are necessarily involved in Kugelblitz which detract from the probability that a "dirty, non-plasma, ionized ball" hypothesis is valid. For this reason, the non-plasma theories of category C will not be given detailed treatment relative to energy storage, in this report. Even though classical plasma theories are not very satisfactory (particularly for high energy implication), it is worthwhile to discuss the principles due to their frequency of usage in past studies. It is of interest to examine the following five cases:

(1) The unfed Kugelblitz

(2) The standing wave model

(3) The non-linear glow discharge model

(4) The low density streamer model (Melpar)

(5) The ion-ion theory

3.2.1 The Unfed Kugelblitz

The unfed Kugelblitz would be extremely attractive from a weapon standpoint, but it is easy to show, using classical plasma relations, that the life time would be exceedingly small. Suppose that the fireball consists solely of N_2 with the Oxygen and other gases being expelled from this region. This unlikely situation would eliminate attachment losses, leaving diffusion and especially recombination to consider. One should now be able to determine an upper limit for the lifetime of the unfed Kugelblitz.

In this case the expression for density is

$$\frac{dn}{dt} = D_a \nabla^2 n - \alpha n^2 \quad \text{or} \quad \frac{dn}{dt} = \frac{D_a}{r} \frac{\partial}{\partial r}\left(r \frac{\partial n}{\partial r}\right) - \alpha n^2$$

for a spherically symmetrical Kugelblitz with ambipolar diffusion. First neglecting diffusion

$$\frac{dn}{dt} = -\alpha n^2 \quad \text{or} \quad n = \frac{n_o}{1 + \alpha n_o t}$$

Assuming radiative recombination (which implies a rather high electron temperature) with an α of 10^{-12}

$$n \cong \frac{n_o}{1 + 10^{-12}{}_{o}t}$$

Now the usual assumption is that a fully ionized gas at nearly atmospheric pressure exists on $n_o \cong 10^{19}$ cm^{-3}. In such a situation, n would decrease about one order of magnitude in one microsecond. In the other extreme (although the stored energy now becomes very small) $n_o \cong 10^{14}$ cm^{-3}, this n would decrease one order of magnitude in approximately one-tenth of a second. However, in this low density extreme it is to noted that even a lapse of several seconds would leave a visible fireball. Of course, we have assumed a completely unreasonable case, as there is no known way of preventing the O_2 from existing within the Kugelblitz; hence, there is no way of preventing huge attachment losses.

However, before going to a more realistic situation, let us calculate the lifetime due to ambipolar diffusion. In this case

$$\frac{\partial n}{\partial t} = D_a \left\{ \frac{\partial^2 n}{\partial r^2} + \frac{1}{r}\frac{\partial n}{\partial r} \right\},$$

or (letting n = TR)

$$\frac{R}{D_a}\frac{\partial T}{\partial t} = T\frac{\partial^2 R}{\partial r^2} + \frac{I}{r}\frac{\partial R}{\partial r}.$$

Clearly, then,

$$T = T_o e^{-K^2 D_a t} \quad \text{and} \quad R = R_o V_o(kr)$$

when $\rho_o \cong 2.405$ is the first root of the zero order Bessel function. Thus $T = T_o e^{\frac{-\rho_o{}^2 D_a t}{a^2}}$, yielding a time constant of $\tau = \frac{a^2}{\rho_o{}^2 D_a}$. With usual ambipolar diffusion coefficients and Kugelblitz diameters, it is seen that τ is of the order of a second. Hence, in this unrealistic case, recombination is by far the dominant loss.

Unfortunately, if we go to the realistic case wherein O_2 exists in the fireball, attachment losses produce an exceedingly short lifetime. When attachment dominates, $n = n_o e^{-h\nu_c t}$ where h is the attachment coefficient

($\sim 10^{-4}$ for O_2) and ν_c is the elastic collision frequency (10^9/torr[sec^{-1}]). Consider an atmospheric pressure Kugelblitz, with the usual O_2 percentage. Then, $h\nu_c \approx 10^7$, so $n \approx n_o e^{-10}$ in one microsecond. For a low pressure fireball (if one can be created), $h\nu_c = 10^5$ for one torr pressure. Here, $n = n_o e^{-10}$ in about one-tenth of a millisecond. It should be clear by now that the unfed Kugelblitz is an impossible model.

3.2.2 The Standing Wave Model

Kapitza (and others) realized, of course, that the unfed Kugelblitz could not exist, so he postulated a method of feeding power into the length. However, it is easy to show that tremendous field strengths are required for "the standing wave model." Consider only replacing the decrease of ionization; this will require a power density

$$\frac{dE_i}{dt} = ne\nu_i V = neh\nu_c V_i \text{ (see attachment dominance).}$$

Thus, $\frac{dE_i}{dt} \approx 10^{19} \times 10^{-19} \times 10^7 \times 10^1 \approx 10^8$ watts/cm^3 for a fully ionized, atmospheric pressure fireball. For a volume of 10^3 cm^3, which is reasonable, the total power flow into this Kugelblitz would have to be 10^{11} watts. For a projected area of roughly 100 cm^2, the electromagnetic flux would have to be of the order of $10^9 \frac{\text{watts}}{\text{cm}^2}$, yielding a fantastic field strength of over six million volts/cm. Obviously, nothing like this exists in the aftermath of a thunderstorm (nor during a thunderstorm).

Now, even decreasing the density five orders of magnitude and the pressure more than two orders of magnitude will require a power density

$$\frac{dE_i}{dt} = 10^{14} \times 10^{-19} \times 10^5 \times 10^1 \approx 10 \text{ watts/cm}^3$$

or about 100 watts/cm^2 electromagnetic flux for the same projected area as previously assumed. Then the field strength would have to be nearly 200 volts/cm; this is still very large (one is almost certain that no such high frequency field strengths ever exist in the earth's atmosphere, unless generated by man) but it is admittedly possible. We have neglected many losses, however, such as radiation, recombination, convection, etc. At any rate, the stored energy would now be very small, and the Kugelblitz could not exhibit some of its reported destructive effects.

Although the above were only crude estimates, a precise electromagnetic boundary value solution will yield the same order of magnitude results. The standing wave model is therefore not feasible, an answer which Melpar is prepared to substantiate by more thorough calculations in an actual program. The fact that Kapitza was wrong on the stable point for a Kugelblitz (it is actually at a node, not an antinode) is rather immaterial; the power flow considerations eliminate the standing wave model as a reasonable hypothesis.

A number of other investigators (Cerrillo, Silberg, etc.) have considered the standing wave model with more refinements. However, it is concluded in this report that the standing wave model (or any other electromagnetic wave feed method) is unrealistic.

3.2.3 The Non-Linear Glow Discharge Model

David Finkelstein and Julius Rubenstein (referred to hereafter as F-R) have recently proposed a classical plasma theory which is at least worthy of discussion. It should be mentioned that F-R are implicitly considering a fully (or strongly) ionized medium, whereas the Melpar model to be discussed later makes the opposite assumption (a moderately ionized medium). Making a log-log plot of density vs. temperature (figure 1) it is shown that the plasma must "lie under" the line $\log_{10} \cong 12 + 3/2 \log_{10}T$ (for a Kugelblitz lifetime of one second). Further, to avoid a radiation time of less than one second, the plasma must lie "to the left" of the vertical line $\log_{10}T = 24 + \log_{10}0.24 + \log_{10}R$, yielding a value for T of about 10^7. Finally, the plasma must "lie between" two curves $\log_{10}n = \log_{10}P - \log_{10}eT$ with $P_1 = P_o \pm \Delta P$, P_o being 1 atmosphere pressure and ΔP being a small pressure differential. This reasoning yields plasma electron energies of 10^5 to 10^7 ev, which, in our opinion, is entirely unreasonable for any finite plasma.

Next, F-R show, by straightforward methods, that any efforts to explain isolation of the Kugelblitz from the surrounding cool air by means of fields yields a thin, intolerably lossy skin. So far, then, the attack on the problem by F-R was not very profitable.

F-R then discuss a so-called virial theorem (given in a number of other places in somewhat different form) to relate internal energy and external pressure (although this can be done very satisfactorily by less sophisticated methods). Nevertheless, they show that the energy is related to the pressure and the volume by $E_T < 3\ pV \lesssim 10^3$ joules.

Finally, F-R discuss their "nonlinear conductivity model", which, like Melpar's model, is an externally powered dc model. Although this is the only result of real value (outside of energy storage answers from the virial theorem), it is a very crude analysis, to say the least. Not only is it crude (and trivial), but power flow considerations, which are really fundamental to the question, are not given. Further, their model (as we see it)

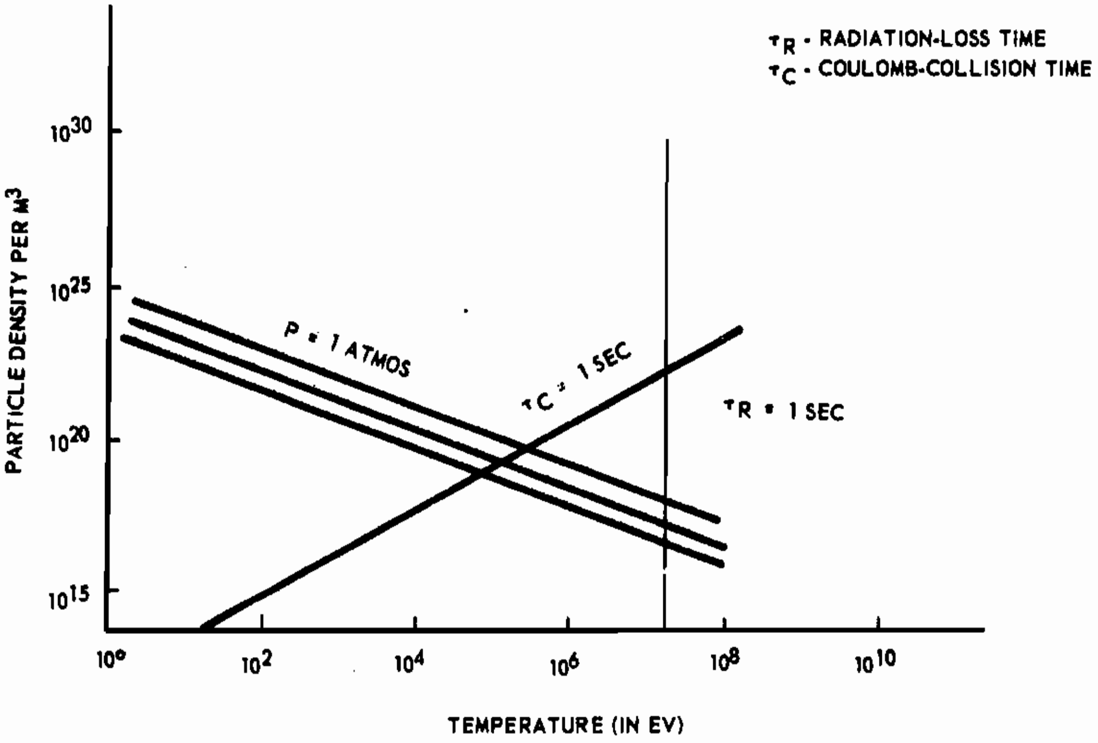


Figure 1. Bounds of Temperature and Density for Model

implies currents of a magnitude everywhere between earth and cloud which are known not to exist. For this reason, Melpar is forced to reject the F-R theory and present its own (derived long before the F-R theory was published).

3.2.4 The Low Density Streamer Model (Melpar)

So far we have presented sufficient reasons to reject the unfed Kugelblitz theory, the standing wave theory and the F-R theory. We now present our own theory which can be shown to be true for low energy Kugelblitz; we have no classical plasma theory to offer for extremely high energy storage at the present time (and we do not feel that any such classical plasma theory can be derived). There are hopes for composite theories, however, which we shall mention later in this report.

The Melpar low density streamer theory which is developed in appendix C employs the following:

a. A partially ionized low gas density plasma

b. The Kugelblitz is fed by a dc streamer (which can fluctuate).

c. A quiet decay.

First, in general, what total power input, volume power density, field strengths (dc), and current densities (hence streamer particle density) are required. A more general approach is taken than with the unfed Kugelblitz theory and several losses are included although diffusion is negligible. The particle density loss is

$$\frac{dn}{dt} \quad D_a\nabla^2 n - \alpha n^2 - h\nu_c n,$$

and each particle represents an ionization energy of eV_i. In addition to the input volume power density

$$P_i = -eV_i \left\{ D_a\nabla^2 n - \alpha n^2 - h\nu_c n \right\},$$

there are radiation and convection heat losses to consider, as well as line radiation and more trivial things (for the present case) such as Bremsstrahlung. As we shall assume a moderately ionized plasma, a rather severe non-equilibrium condition will prevail, with the electrons much hotter than the molecules and ions. Hence, as an approximate calculation we neglect heat losses. This argument does not permit us to neglect line radiation, but it can be shown to be small.

The approximate (since recombination is not an exponential decay) required power density input can be written as

$$P_i = neV_i \left[\frac{1}{\tau_0} + \frac{1}{\tau_R} + \frac{1}{\tau_A} \right]$$

with

$$\tau_0 = \frac{a^2}{P_o{}^2 Da}, \quad \tau_A = \frac{1}{n\nu_c} \text{ and } \tau_R \doteq \frac{1}{\alpha n_o}$$

letting $n \to n_o$ (as we wish no decay)

This gives

$$P_i \doteq 10^{14} \times 10^{-19} \times 10^{1} \; [1 \times 10^{2} + 10^{5}] \cong 10 \text{ watts/cm}^3$$

The density is not uniform (it usually varies as

$$n = n_o J_o \left(\frac{\rho_o T}{a} \right)$$

for a spherically symmetrical plasma with uniform excitation), but we shall neglect this in this order of magnitude treatment. A one liter Kugelblitz is apparently of normal size, so a continuous power flow of 10^4 watts will be required. With a streamer of 100 cm^2 cross-section (as a rough estimate) the energy flux will be $10^2 \frac{\text{watts}}{\text{cm}^2}$. In order to make the streamer fairly invisible (in daylight) we assume an upper density of $10^{10}/\text{cm}^3$, yielding (for a normal streamer velocity at $\sim 10^8 \frac{\text{cm}}{\text{sec}}$) a current density of $10^{-1} \frac{\text{amps}}{\text{cm}^2}$. For a power density of 10 watts/cm^2, then a field strength in the Kugelblitz of about $10^2 \frac{\text{volts}}{\text{cm}}$ is required; this is a very reasonable figure. Outside the Kugelblitz the field strength will rise, but it must remain way below $3 \times 10^4 \frac{\text{volts}}{\text{cm}}$ (depending upon conditions). Occasionally it might rise up to this value, perhaps giving the "rays" emanating from the Kugelblitz which have been reported (a drawing by V. Haidinger in 1868). Actually, of course, the current density can increase in the Kugelblitz, allowing a smaller field strength than has been estimated.

The energy stored in the Kugelblitz will be

$$E_s = 3/2 nkT_- + neV_i = ne(3/2 \frac{KT}{e} + V_i) \cong 10^{14} \times 10^{-19} (3/2 + 10) \doteq 10^{-4}$$

joules/cm^3 or 10^{-1} Joules for a one liter ball. This energy can be stretched about two orders of magnitude, but even this accounts for only a stored energy of 10 joules; thus, this classical plasma theory only explains the existence of low energy Kugelblitz. Upon cessation of the streamer, this model only shows a rapid quiet decay. It seems quite likely that Kugelblitz such as has been discussed could (and may) exist, but it would be harmless and useless for a weapon application. It is necessary to look at other theories to explain the violent form of Kugelblitz.

3.2.5 The Ion-Ion Theory

If the Kugelblitz is ordinary plasma, its lifetime must be exceedingly short. However, when the initial plasma density (electrons and positive ions) lies below some critical value the attachment losses predominate. In this case the lifetime of the electron-ion plasma is still very short; however, the electrons are not "lost" but have merely become attached - largely to oxygen. Thus, the ordinary electron-ion plasma is quickly converted into an ion-ion plasma. So, if we can explain adequate life-time with an ion-ion plasma, we will possess an apparently realistic theory of at least one type of Kugelblitz.

If conditions were really as optimistic as stated by Neugebauer (Zeitschrift fur Physik, p.p. 474-484, 106, 1937) we would (for a reasonably high temperature plasma) have little ion-ion recombination to worry about (in addition, we would have no need for Neugebauer's quantum plasma theory). Unfortunately, one thing is sure - ion-ion recombination is finite and of considerable magnitude.

If we accept the temperature dependence given by Gardner (Physical Review, p. 75, 53, 1938), we can determine the minimum Kugelblitz kinetic temperature to give a sufficiently low ion-ion recombination coefficient. Gardner deduced a $\frac{1}{T^{7/2}}$ dependence, and it is well known (Sayers, Proc. Roy. Soc., A169, 83, 1938) that $\alpha \cong 2\text{x}10^{-6}$ cm^3/ion-sec at 760 Torr and 300°K. Since α drops about 3160 times for every order of magnitude increase in temperature, a fairly moderate interior temperature of 3000°K would yield $\alpha \cong 6\text{x}10^{-10}$.

Even if a zero order Bessel function (or something similar) type of temperature distribution is ascribed, the group body heat radiation ($P_r = A \alpha \sigma T^4$) would become prohibitively high for extremely high temperatures. Hence, it would appear that recombination coefficients of at least 10^{-10} cm^3/ion-sec. for pure recombination fall-off are required; this means that $n = \frac{n_o}{1+\alpha n_o t}$, and only low density plasmas could have lifetimes of the order of seconds.

We do not have to give up yet; however, things are not so simple as they appear at first glance. In fact, it is not difficult to write down an involved set of non-linear equation -- the solution of which would be more enlightening than our previous semi-quantitative discussion. Such a set are the following:

1. For electrons : $\frac{dn_e}{dt} = - h\nu_c n_e - \alpha_{e,i} n_e n_+ + \sigma_{i,e} \langle V_e \rangle . n_e n_A$

$$+ BCO_{i,p} n_p n_A + \delta V_{-,K} n_-$$

2. For + ions, several species : $\frac{dn+}{dt} = -\alpha_{e,i}n_e n_+ - \alpha_{i,i}n_- n_+$
$+ \sigma_{i,e} < V_e > n_e n_A + BCO_{i,p} n_p n_A$

3. For - ions, several species : $\frac{dn}{dt} = hV_{co} n_e - \alpha_{i,i} n_- n_+ - \delta V_{-,A} n_-$

4. For excited states, several species : $\frac{d\hat{n}x}{dt} = M(E-E_i^{\prime})\sigma_x < V_e > n_e n_A$
$- \frac{\hat{n}x}{\tau}$

5. For photons : $\frac{dne}{dt} = \frac{\hat{n}x}{\tau} - BCO_{i,p} n_p n_A$

6. Phase-space distributions for the N species : $\overset{\xi}{1} \,\|\, \frac{\partial f_i}{\partial t} + \vec{V} \cdot \frac{\partial f_i}{\partial \vec{r}} + \vec{a} \cdot \frac{\partial f_i}{\partial \vec{v}} = \frac{\partial f_i}{\partial t}$

7. For energy : $\frac{dEtotal}{dt} = eV \left\{ V_x \frac{dntotal}{dt} + V_i \frac{dn+}{dt} + V_a \frac{dn-}{dt} + \right.$

$\left. \frac{3}{2} \frac{KTe}{.e} \frac{dne}{dt} \right\} - A\alpha\sigma T^4$ + terms of less importance.

Subsidiary Conditions

8. The plasma condition : $n_e + n_- = n_+$

9. Neutral condition : $n_A = n_o \, (1-n)$

$$n = \frac{\text{ionized species}}{\text{neutrel + ionized species}}$$

10. $\left. \begin{matrix} n = n & \gamma \leq a \\ n = o & \gamma \gtrless a \end{matrix} \right\} t = t_o$

11. $\left\{ n_e = n_{e_o}, \; n_+ = n_{+_o} = n_{e_o}, \; n_- = o \right\}$ att $= t_o$

$n_e = n_{e_Q}$ (small equilibrium density), $n_+ \cong n_{e_o}$, $n_- \cong n_{e_o} - n_{e_Q}$

for $t = to + \Delta t$

Δt being the destruction time of the electron-ion plasma.

Suggested Approximations (for a crude, but tractable, solution)

12. Phase-space Distributions: Maxwell-Boltzmann in velocity space Homogeneous in coordinate space

13. $\frac{dn_3}{dt} \cong 0$ for $t \geq to + \Delta t$, $n_e = n_{e_Q}$

14. $\frac{dn_x}{dt} \cong 0$ for $t \geq to + \Delta t$

15. $\frac{dn_e}{dt} \cong 0$ for $t \geq to + \Delta t$

A rather involved set of non-linear differential equations now exists together with a suggested "Oth order" approach to the solution of the set. Even the highly degenerated set will not be solved in a trivial manner. However, when considering the approximate nature of the expressions, a crude solution should be almost as good as a precise solution (were this possible) in determining the value of ion-ion plasma Kugelblitz theory.

Assuming that the solution indicates some appreciable lessening of the recombination problem (due to photon flux, etc.), it may represent a reasonable solution of the low energy Kugelblitz problem. That is, it may be possible for plasmas of density of the order of 10^{12}/c.c. (as a rough guess) to exist for some seconds without external power. There are so many interactions, however, that pure qualitative reasoning can not be depended upon much further - the answer lies in the indicated solution.

Since the result remains inconsistent with observations (^{t}lifetime <1 second), reasonable feed mechanisms should be considered. It is fairly obvious that unreasonable suggestions (such as the standing wave theory of Kapitsa and others) cannot be considered. There are other possibilities, however, which appear possible - or suggest, at least, an aid in delaying the plasma decay. Considerations are listed as follows:

a. Direct streamer feed (with $n \leq \frac{10^9}{cm^3}$ - to maintain invisible feed).

b. Fluctuation (displacement) feed - due to rapidly changing fields in the aftermath.

c. Charged particle accumulation (diffusion).

Then we are at the virtual limit of the "straightforward" approach. There can be little doubt but that this approach must be considered as a "last ditch" stand on normal plasma calculations. Additional calculations based on the necessary assumptions relating to the above three considerations will only provide the opportunity for mathematical gynmastics, unless a few experimentally determined values are available to curb the selection process.

3.3 High Energy Considerations

3.3.1 Quantum Plasma Approach

We believe that Melpar's classical plasma theory is a possible explanation of low energy, quiet decaying Kugelblitz. It may be unlikely that a feeding streamer such as we have postulated actually exists, but it does not disobey known streamer phenomena; nevertheless, it is a weak point, although it is a much more rational explanation than offered by the Kapitza or F-R theories. However, all classical plasma theories are weak, and it is worthwhile to examine the quantum plasma theory of Neugebauer.

It is somewhat surprising that Neugebauer's theory, which was published in 1937, is actually more advanced than any presented thereafter (although it is not necessarily more correct). The field of plasma physics was not even known as such in those days (although most of the foundation work had been done), and exchange forces were a new phenomenon. Furthermore, only a decade had elapsed since the modern form of elementary quantum mechanics was given a satisfactory treatment by Schrodinger, Heisenberg and others. Clearly, Neugebauer was capable of working at the limit of contemporary knowledge, and his work cannot be dismissed lightly.

For a fully ionized atmospheric density (or greater) Kugelblitz, there can be no doubt that the exclusion of spin (and, hence, exchange forces), as is done in classical models, is an error. The use of exchange forces enables two things to become slightly more reasonable:

a. A constant diameter fireball which does not expand as rapidly under diffusion forces.

b. An explanation of some stored energy in a form different from that considered elsewhere and, thus, a new source of help (very little) to keep the fireball alive.

It is easy to show that the total ambipolar diffusion energy is

$$E_o = M_{eff}/2 \; (\nabla n \; . \; \nabla n) \; D_3^2/n^2$$

where M_{eff} is the number of particles times the effective mass (approximately an ion mass). The total (per unit volume) exchange energy is

$$E_x = \frac{\pi}{2} \, h^2 h^2 e^2/mKT$$

so that

$$\frac{\pi}{2} h^2 n^2 e^2/mKT \gtrsim \frac{M_{icm} (\nabla h \;.\; \nabla h) \; D_a^2}{2\,h}$$

or

$$T \lesssim \frac{\pi h^2 n^3 e^2}{mKD_a^2 \; M_{ion} \; (\nabla h \;.\; \nabla n)} \quad \text{for stability.}$$

(Note: these are Melpar's expressions, <u>not</u> Neugebauer's which are very different.) Neugebauer's stability expression is derived from

$$1/2m < V^2 > = \frac{3}{2} KT$$

and

$$dE = 1/2m < V^2 > = \frac{\frac{\pi}{2} + n^2 e^2 h}{mKT}$$

However, this neglects the phenomenon of ambipolar diffusion, which is, in fact, one way to define a plasma. This is merely a consequence of the era (1937) when Neugebauer published his article. But the fact remains that Melpar's expression is more valid than that of Neugebauer and must be used.

For an approximation let $|\nabla n| = n/a$ where a is the radius and $M_{\overline{Icn}} \cong (28)\ (1837)\ (9 \times 10^{-28})$ grams. Then let $n = 10^{17}/cm^3$ which gives

$T \lesssim 10^5$ °K

as the maximum permissible "temperature" for the electrons of a Kugelblitz having a 20 cm radius. Obviously, this is much higher than the value obtained by Neugebauer (and we obtain about 10^7 °K if $10^{19}/cm^3$ is used). Unlike Neugebauer's arguments, we can now point very hot fireballs, so that destructive level becomes very reasonable (except for losses -- to be discussed). It is important to remember, however, that we will undoubtedly have non-equilibrium, and we are not demanding that ion and electron temperatures be equal.

Through use of modern reasoning we have been able to improve Neugebauer's theory substantially. Unfortunately, we now come to the point wherein we must treat it very unkindly. Again, modern theory and experiment are used. The lowest value of recombination coefficient ever measured is about $5 \times 10 \frac{^{-14} cm^3}{\text{ion-sec.}}$ Consequently, the energy lose rate for recombination at

$10^{19}/cm^3$ is equal to or greater than

$$\frac{dE_R}{dt} = an^2eV_i \cong 5x10^{-14}x10^{38}x1.6x10^{-13}x10^1 \cong 8x10^6 \text{ watts/cm}^3,$$

lost each second through recombination.

A still reasonable value for an atmospheric density model might be 10^{17} electrons/cm^3, in which case $\sim 8x10^2$ joules/cm^3 would be lost each second. Also for an atmospheric density plasma, the attachment loss is $\frac{dE_A}{dt} = h\nu_c neV_i$, yielding $\sim 10^8$ watt/cm^3 for $n = 10^{19}/cm^3$ and $\sim 10^6$ $\frac{\text{watts}}{cm^3}$ for $n = 10^{17}/cm^3$. For a very hot gas, the attachment coefficient might decrease considerably (as it does for Cl_2 and F_2), so perhaps $h = 10^{-6}$ might be reasonable (or even lower). In any case, we shall show that some power flow into Neugebauer's model is required, as the exchange energy is far too small to sustain the Kugelblitz throughout the observed time durations.

The total exchange energy per cubic centimeter is

$$E_x = 2\hbar n^2c^2/mKT \cong 3 \times 10^5 \frac{\text{ergs}}{cm^3} \cong 0.03 \frac{\text{Joules}}{cm^3}$$

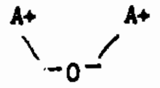
To equal a rate of even 800 $\frac{\text{watts}}{cm^3}$, this exchange energy must be converted in less than 0.04 milliseconds; obviously, the exchange energy cannot long stave off extinction. Thus, we come to the inevitable result (even neglecting the all important attachment) that the Neugebauer model also fails on an unfed Kugelblitz.

3.3.2 Molecular Cluster Energy Storage

Presently, no high energy satisfactory model is in view. Although the quantum plasma model is to be doubted (but not dismissed), the work of Neugebauer (op. cit.) does furnish a clue. This clue is that storage atomic (molecular) clusters should receive some attention.

Thus, one thing that can be proposed for further investigation is the possibility of long-lived (seconds) metastable materials -- probably with a combination of ionic and covalent bonding. We start out (before the return strobe (Linien blitz)) with largely N_2, O_2, CO_2 and A -- plus small amounts of other gases. For the four major gaseous components there are sufficient molecules present so that we could conceivably have a plasma composed of any of them or their combination, or any combination of the multitudinous derivatives (N_2+, N^+, O_2^-, O_3, A^+, etc).

Although it is not intended as a real suggestion, consider, for example,



The idea is this; if we are able to "hold in reserve" a large density of charged components (due to the formation of ionic bonds) -- then the plasma will be forced to exist for a rather long time. Furthermore, we can then tolerate a lower Kugelblitz temperature, which will reduce graybody radiation. The increase in α will not be so serious, because the charged components are unavailable for recombination (except upon slow release).

This means that, under this theory, the ion-ion plasma would also decay fairly fast, but recombination radiation (hence, visible Kugelblitz) would always exist due largely to breakup of the ionic bands and the finite probability of the species recombining (perhaps with other released species).

Although somewhat reluctantly, as the theory appears rather farfetched, some modification of the quantum plasma concept should be considered; quite frankly, no other satisfactory postulate of the high energy model has appeared. In considering a quantum plasma, we should give some thought as to how it may be generated in the first place.

We know that Kugelblitz appears to be slightly heavier than air, as it drops to the ground, according to various observers. It may be possible that Kugelblitz of this type is formed in the anti-node of a severe shock wave. Analysis using the Rankine-Hugoniot relations could be attempted. So, perhaps a very dense plasma can be formed -- initially of quite small diameter (say, 2 or 3 cm in diameter), with electron-ion densities even exceeding that dictated by the normal un-ionized molecular density.

Thus, a small diameter plasma with the full application of Fermi-Dirac statistics can be generated. Gradually, of course, some expansion would take place as electrons near the boundary (which do not see a totally correct spin force) diffuse away and "form a classical shell." This is quite similar to the metastable molecular approach, in that "slow release to the classical state" takes place.

When degeneration of the quantum plasma reaches a certain point, sudden transition away from Fermi-Dirac statistics will take place. Then, sudden "bang" would occur as electron-ion recombination proceeded at an enormous rate.

Involved though it may be, the above appears to be the only "reasonable" explanation of the high energy Kugelblitz. Clearly, extensive calculations are in order. The problem is an extremely difficult one and the time allotted to this study does not permit the undertaking of such a solution. We shall now consider non-plasma models and particularly the ozone theory.

3.3.3 Non-Plasma Theories

The plasma theories, classical or quantum, require a continuous input power. Although it is not impossible (nor even unlikely) that this could be in the form of invisible streamers or the like, it is still advisable to attempt to construct a self-surviving Kugelblitz model. The only way to do this is to go to non-plasma, or at least partially non-plasma concepts.

The two major non-plasma concepts are the ozone model of Thornton (1911) and the dirty charged mass model of Hill (1960). Thornton claims that the Kugelblitz is usually a luminous blue ball, whereas Hill reports that the Kugelblitz is usually seen as a red, brown or yellow ball. Needless to say, each interpretation aids them in their particular theory. At any rate, the ozone model will be examined first.

Thornton reports that various observers unanimously agree that a Kugelblitz is heavier than air. As ozone is 70% heavier than air, this is one argument for the ozone theory. Although ozone is claimed to have been given off by exploding Kugelblitzen, it is clear that this is no proof that a Kugelblitz contains ozone -- especially if the exploding Kugelblitz produces large electric fields. Now, the volume of 2 O_3 is less than 3 O_2, for example, and the energy is such that

$$E(2O_3) > E(3O_2).$$

As a result, O_2 and O_3 have an attractive force,

$$\sigma = \nabla \{ \nabla_E \} .$$

There is of course, the usual molecular outward pressure, but the forces will balance at some radius. We have not yet done the research to determine the volume of this radius. It may be, however, that the radius will agree with observed Kugelblitzen.

Ozone is known to be an unstable gas and an exothermic reaction can proceed. The energy released in changing one gram of O_3 to one gram of O_2 is listed by Thornton as 8×10^6 ft-lb. It is clear that this would, indeed, satisfy all the requirements of the most violent form of Kugelblitz, as this is equivalent to better than 10^7 joules. It thus is in excellent agreement (for a sufficiently large and dense fireball) with a reported case of a Kugelblitz entering a rain barrel; and resultant heating demanded more than 10^6 joules for a rational explanation.

It is clear that the ozone theory requires a great deal more to place it on a rigorous basis. It appears to Melpar, however, that it is the most likely candidate for the violent form of Kuglsblitz, and further work is certainly justified.

Hill's model is essentially a dirty molecular ensemble with charges residing in both molecules and foreign particles. He regards the luminosity as due to molecular recombination, internal corona, burning of internal gases, etc; his is a low temperature model with very few free electrons per unit volume. Since it is probable that corona discharge, burning and molecular combining might take the order of seconds, or even minutes, the lifetime problem is not too serious with this model.

Hill's paper is very qualitative, and it is difficult to argue against non-quantitative reasoning. Considerable calculation must be done before much can be said about this model. Even then, Hill has left it so general in nature that several different sub-models must be analyzed to dispose of the subject properly. Hill's work deserves further consideration (particularly experimental) before much can really be said about stored energy, decay, lifetime, luminoisity, color, size and the like.

3.4 Summary

It is worthwhile to summarize at this time the discussion on energy considerations, after which a recommended schedule of work leading toward a Kugelblitz weapon program will be outlined. After careful consideration, the major achievements and deficiencies of the previously discussed Kugelblitz theories may be stated as follows:

A. Classical Plasma Theories

1. The Unfed Kugelblitz
    - a. Very short lifetime
    - b. Satisfactory size stability (although the ball tends to increase in size)
    - c. Satisfactory energy storage at high densities, but with a vanishingly small lifetime
2. The Kapitza (Standing Wave) Model
    - a. Impossible electromagnetic power flow requirements
    - b. No satisfactory containment proof
    - c. No detailed plasma physics proofs
3. The Finklestein-Rubenstein (Non-Linear Conductivity) Model
    - a. Unreasonable electron energy demands
    - b. An unreasonable feed method
    - c. A primitive and unsatisfactory discharge model
    - d. A reasonable low density postulation
4. The Melpar (Streamer) Model
    - a. No proof that such streamers exist
    - b. A satisfactory low density and low electron energy model
    - c. Only a low energy model
    - d. Does not explain explosive decay

5. Ion-ion Theory (Melpar)
    - a. Accounts for low ion-ion recombination rates
    - b. High ion densities may exist for seconds without external power
    - c. Requires a difficult analytical solution to verify major assumption

B. <u>Quantum Plasma Theories</u>

1. The Neugebauer (exchange force) model
    - a. A novel and clever introduction of exchange forces
    - b. A wrong relation for maximum temperature
    - c. Exchange forces cannot greatly enhance lifetime
    - d. A radical underestimation of recombination losses, to say nothing of attachment losses
2. Melpar's modifications of Neugebauer's model
    - a. A more reasonable temperature limit (very high).
    - b. All the deficiencies and good points of the exchange force model

C. <u>Non-Plasma Theories</u>

1. Thornton's (Ozone) model
    - a. Almost the proper energy storage
    - b. Satisfactory stability
    - c. Quiet and explosive decay
    - d. Satisfactory high energy model
2. Hill's (Dirty, Molecular Charged Mass) Model
    - a. No quantitative treatment
    - b. Satisfactory lifetime
    - c. Possibly correct radius
    - d. Possibly a wide energy storage model

In general, it is possible to classify the theories relative to energy criterion as follows:

High Energy	Low Energy	Both Low and High
(1) Thornton's (Ozone) Model	(1) Modification of Melpar's Model	(1) Modification of Hill's Model
(2) Modification of Neugebauer's Model (by feed streamers)		

The rest of the theories are unworthy of any rating whatsoever, and they are not of sufficient value to merit further work. It is likely that at least two or three entirely different kinds of Kugelblitzen exist. Preference is given to either Melpar's or Hill's model for low energy (both may occur) and Thornton's model for high energy. Clever though Neugebauer's model is, it must be regarded largely as an academic exercise, and the other models were somewhat unsatisfactory pieces of work from any standpoint (except the later containment work, which is both academic and of use to other fields).

It is clear that the experiments which have been performed(as known to Melpar) have not been directed toward a logical, exhaustive all-out attack upon the Kugelblitz problem. It is likely that theoretical methods will remain somewhat speculative unless a cooperating experimental program is conducted simultaneously. The stage has been reached wherein exhaustive experimental work is called for in order to substantiate or negate the numerous theories.

3.5 Symbolism

D_a = ambipolar diffusion coefficient

∇ = linear vector operator

r = radius of a volume

t = time (independent variable)

T = temperature

J_o = zero order Bessel function

h = attachment efficiency

E = energy

p_o = atmospheric pressure

p_i = input power density

n_e = electron density

n_+ = positive ion density

n_- = negative ion density

$\hat{n}_x$ = excited state density of levels

E_i = ionization energy of one or more species

n_p = photondensity (from excited states $\hat{n}_x$) $\frac{1}{cm^3}$

h = attachment coefficient $[0]$ designates no units or dimensions

ν_{c_o} = elastic collision frequency of electrons with attaching atoms $\frac{1}{sec}$

$\nu_{-,A}$ = collision frequency of negative ions with other species

$\langle V_e \rangle$ = average electron velocity $\left[\frac{cm}{sec}\right]$,

$\alpha_{e,i}$ = recombination coefficient for electrons and positive ions $\left[\frac{cm^3}{ion\text{-}sec}\right]$

$\alpha_{i,i}$ = recombination coefficient for negative and positive ions $\left[\frac{cm^3}{ion\text{-}sec}\right]$

$\sigma_{i,e}$ = ionization cross-section for electron impact $\left[\mathrm{cm}^2\right]$

$\sigma_{i,p}$ = ionization cross-section for photon impact $\left[\mathrm{cm}^2\right]$

δ = detachment coefficient $\left[0\right]$

τ = lifetime of pertinent excited states $\left[\mathrm{sec}\right]$

β = geometrical coefficient for relativistic gas (photons) distribution $\left[0\right]$

c = velocity of light $\left[\frac{\mathrm{cm}}{\mathrm{sec}}\right]$

m_A = neutral atom density $\left[\frac{1}{\mathrm{cm}^3}\right]$

$M(\varepsilon-\varepsilon i)$ step function becoming unity at $E=E_o$ $\left[0\right]$

f_i = phase-space distribution function for the i^{th} species $\left[\frac{\mathrm{sec}^3}{\mathrm{cm}^6}\right]$

$\vec{V}$ = velocity variable $\left[\frac{\mathrm{cm}}{\mathrm{sec}}\right]$ - 3 dimensional

$\vec{a}$ = acceleration variable $\left[\frac{\mathrm{cm}}{\mathrm{sec}^2}\right]$ - 3 dimensional

$\vec{\gamma}$ = coordinate variable $\left[\frac{1}{\mathrm{cm}}\right]$ - 3 dimensional

t = time variable $\left[\mathrm{sec.}\right]$

e = electronic charge $\left[\mathrm{coulomb}\right]$

V = volume $\left[\mathrm{cm}^3\right]$

V_x = excitation potential

V_i = ionization potential

V_a = attachment potential $\left[\text{all in volts}\right]$

K = Boltzmann's constant $\left[\frac{\mathrm{ergs}}{{}^\circ\mathrm{K}}\right]$

T_e = electron temperature $\left[{}^\circ\mathrm{K}\right]$

A = area, α = emission coefficient $\left[0\right]$

σ = radiation constant $\left[\frac{\mathrm{erg}}{\mathrm{cm}^2\,\mathrm{sec}\;{}^\circ\mathrm{K}^4}\right]$

4. RECOMMENDED KUGELBLITZ PROGRAM

We have discussed, in rather brief fashion, the history of Kugelblitz; the classical plasma theories, the quantum plasma theories and the non-plasma theories and, finally, have mentioned some experiments that have been performed. Melpar, after having performed some work of its own, and having studied the literature intensively, has a clear picture of the most promising areas of research for Kugelblitz. As a result, we present our concepts of a thorough experimental and theoretical research program which is most likely to yield significant results.

Since the high energy Kugelblitz is clearly the only type weapon of importance, we believe that the major effort should be expended along these lines. Thornton's ozone theory is very promising, and we regard a program here as being of utmost importance. Although not specifically noted in the outlined program, work would also be performed in conjunction with the molecular cluster energy mechanism described in section 3.3.

A combination of Hill's model, somewhat modified, is also of importance for high energy Kugelblitz. Melpar has a large, high speed vacuum system and chamber in which some preliminary work for both Thornton's and Hill's ideas could be conducted.

Then, a modification of Melpar's low energy Kugelblitz theory should be subjected to experimental verification. The value of this program would be to substantiate Melpar's approach to the general subject, as well as to dispose finally, if possible, of one type of Kugelblitz.

In a more formal arrangement, the line of work should proceed in the following manner:

Phase I The Ozone Investigation

A. Theoretical Work

1. Obtain information on binding force between O_3 and O_2.
2. Calculate stability criteria.
3. Calculate energy storage.
4. Determine triggering mechanisms for explosive decay.

B. Experimental Work

1. Production of ozone through appropriate air discharges.
2. Injection of ozone into various atmospheres.

3. Determination of ozone cloud geometry, luminosity and lifetime.
4. Efforts to trigger explosive decay.

This work will require at least the following:

1.	Senior Physicist (theoretical) :	6 man months
2.	Senior Physicist (experimental):	12 man months
3.	Electrical Engineer :	9 man months
4.	Consulting Chemist :	4 man months

Appropriate material, machine work and technician time will also be required.

Phase II The Hill Model

A. Theoretical Work

1. Obtain appropriate precise sub-model.
2. Calculate stability.
3. Calculate external field.
4. Calculate energy storage.
5. Calculate decay modes.

B. Experimental Work

1. Inject mixture under appropriate discharge conditions and measure cloud stability, luminosity and lifetime.
2. Measure external field.
3. Induce, if possible, explosive decay.

This work will require the following staff:

1.	Senior Physicist (theoretical) :	9 man months
2.	Senior Physicist (experimental):	9 man months
3.	Electrical Engineer :	6 man months
4.	Chemist :	6 man months

Appropriate support time and practical material will also be required:

Phase III The Low Energy Kugelblitz

A. Theoretical Work

1. Refine all calculations.
2. Calculate required streamer process.
3. Design appropriate equipment.

B. Experimental Work

1. Produce low pressure fireball.
2. Inject fireball into atmosphere chamber.
3. Continue to feed fireball with streamer.
4. Measure luminosity, lifetime, stability, etc.

This work will demand the following effort:

1. Senior Plasma Physicist: 12 man months
2. Physicist : 6 man months
3. Electrical Engineer : 6 man months

In addition, purchased parts and material and appropriate technician and machine time will be required.

The Kugelblitz and Perlschnurtzblitz phenomena have been considered long enough on a semi-speculative basis. Only a program similar to that we have prepared will yield positive results within a reasonable time period. The ultimate potential is such that an intensive Kugelblitz program should be conducted.

5. CONCLUSIONS

After a rather thorough evaluation of the Kugelblitz problem, Melpar believes that it has a firm grasp of what is and is not possible. We have been forced to conclude that a pure plasma theory is hopeless for high energy Kugelblitz. On the other hand, it appears that the low energy Kugelblitz has a reasonable chance of explanation by means of the ion-ion plasma and/or the metastable molecule approach. The high energy Kugelblitz, on the other hand, seems to demand a quantum explanation. Although gaseous quantum plasmas are not a common experience, neither is the Kugelblitz phenomenon a common occurrence.

We can dispose of the Kapitza and Finkelstein theories, as well as the Neugebauer theory for its intended purpose. The Melpar theory shows distinct promise for low energy Kugelblitz, although this is not of much interest for a weapon application.

Both the Thornton (ozone) and Hill (dirty charged mass) show promise as high energy Kugelblitz as well as the molecular cluster approach. It appears that these are the most likely methods for the violent form of Kugelblitz and that further work is justified.

The experiments which have been done are meager and are not intimately connected with the direct or proper approach to Kugelblitz investigation. Further, much more detailed experiments are called for, together with a real quantitative theoretical effort.

The problem is a difficult ons, but some light is beginning to appear on the subject. A concentrated analytical and experimental effort should be made soon as the implications of successful work could be far reaching. Only an adequately planned program, utilizing a full time, competent staff with adequate equipment, can hope to succeed within a reasonable time period.

APPENDIX A

BALL LIGHTNING BIBLIOGRAPHY

APPENDIX A

BALL LIGHTNING BIBLIOGRAPHY

The bibliography included in this appendix is a result of information secured from four sources. These sources consist of bibliographies on Ball Lightning and Kugelblitz obtained from the Library of Congress, a Report Bibliography prepared by the Defense Documentation Center and referenced as ARB No. A37133 entitled "Ball Lightning plus Fireballs," a subject search performed by the Melpar Research Library on Ball Lightning and Kugelblitz, and finally references from various reports and books concerning the related subject of this appendix.

The bibliography supplied by the Defense Documentation Center contained thirty-three listings of which only three were selected as related to the subject. The majority of the DDC listed reports are related to aircraft protection from thunderstorm electromagnetic effects and have not been included in this Kugelblitz bibliography.

The bibliography compiled by the Library of Congress for this study contained thirty-eight listings; the greater majority of which were in foreign languages. The reports had the following language distribution: 14 in German, 8 in Russian, 4 in Dutch, 2 in French, 1 in Czech, 1 in Rumanian, and 8 in English. Out of the 38 listings, 37 were selected as related to the Kugelblitz study and included in this appendix.

The remainder of the reports contained in appendix A were located as a result of the Melpar Library Search and conversations with personal acquaintances.

The bibliography contained in appendix A is believed to be very complete with regard to the purpose of the contract under which the Kugelblitz study was performed and is probably the most extensive survey performed to date.

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APPENDIX B

REVIEW OF APPLICABLE PLASMA PHYSICS

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REVIEW OF APPLICABLE PLASMA PHYSICS

1. Introduction

This appendix is concerned with the presentation of fundamental plasma physics concepts in order that the significance of the results and conclusions of the study covered in this report might be better understood. The derivation of these elementary relations (largely of a simple kinetic theory nature) and definitions in the appendix makes possible a desirable reading continuity in the body of the report. Definitions and expressions to be considered are:

a. Mean free path

b. Average collision frequency

c. Electron energy loss upon collision

d. Distribution of free path lengths

e. Velocity distribution functions (particularly the Maxwellian)

f. The Boltzmann Transport equation

g. Attachment loss

h. Recombination loss

i. Diffusion loss

j Mobility

k. Diffusion length

A review of the electrical breakdown of gases using dc fields and r-f discharges is included in this appendix.

2. Relations, Definitions, and Concepts

Neglecting modern quantum theory (which plays a much less dominant role here than in solid state physics) and its implications, it is interesting (and important) to obtain a simple mechanical picture of a gas by merely considering the particles involved as hard, round balls of the proper dimensions and applying straightforward methods of mechanics and probability. Thus, if an atom has a cross-sectional area of σ(cm^2) and the density is mg per cm^3, shooting an electron at one cm^2 area will yield a "hitting chance" of mgσ. Clearly then, the average distance an electron will travel without striking an atom is

$$\langle \lambda \rangle = \frac{1}{mg\sigma}$$

which is known as the mean free path. If the average velocity is $\langle v \rangle$, the average time between collisions will be

$$\langle \tau \rangle = \frac{\langle \lambda \rangle}{\langle V \rangle} = \frac{1}{mg\sigma \langle V \rangle}$$

so that the average collision frequency becomes

$$v = \frac{1}{\langle \tau \rangle} = mg\sigma \langle V \rangle$$

also, by equating momentum before and after a head-on collision, and kinetic energy likewise, it can be shown that

$$\frac{\Delta E}{E} \cong \frac{4m}{M}$$

where E is the original electron energy, ΔE is the change in electron energy, m is the mass of the electron, and M is the mass of the atom (ΔE is, of course, a loss in electron energy). In an average collision it can be shown that the correct relation is

$$\frac{\Delta E}{E} \cong 2.66 \, \frac{m}{M}$$

(However, for "hard, round balls" and zero energy molecules, the expression would be rigorously,

$$\frac{\Delta E}{E} = \frac{2m}{M}$$

The spacing of molecules in a gas is, of course, random so that while $\langle \lambda \rangle = \frac{1}{mg\sigma}$ roughly represents the average path length, the path lengths will actually be distributed in some fashion. The average number of collisions made per unit distance of travel will be $V_1 = \frac{v}{\langle V \rangle}$, for a single particle. The number of particles (we are primarily interested in electrons) suffering collisions in the length z to z + dz is

$$dn = -n V_1 \, dz \quad , \text{ and}$$

$$n = N e^{-V_1 z}$$

where N is the total number entering at z = 0.

Now

$$\langle\lambda\rangle = \int_0^N \frac{z\,dN}{N}$$

where dN is the number of electrons with free paths lying between z and $z + dz$; since

$$dN = V_1 N e^{-V_1 z} dz$$

one obtains

$$\langle\lambda\rangle = \frac{1}{V_1}, \text{ or } n = N e^{-\frac{z}{\langle\lambda\rangle}}$$

Thus, the number of electrons having free paths greater than $\lambda_1 = z$ will be,

$$n = N e^{-\frac{\lambda_1}{\langle\lambda\rangle}}$$

which is in the form of the Boltzmann relation. (The Boltzmann relation is usually stated as

$$n_1 = n_2 e^{-\frac{\varepsilon_{12}}{KT}}$$

where n_1, and n_2 are densities at the potential energy points E_1 and E_2, and KT is the thermal energy.)

The Maxwellian distribution function (for detailed derivation refer to any textbook on Kinetic Theory of Gases) is very important; this distribution function is

$$\frac{dN}{N} = \sqrt{\frac{16}{\pi}} \left(\frac{m}{2KT}\right)^{\frac{3}{2}} V^2 e^{-\frac{mV^2}{2KT}} dV$$

This distribution function describes the manner in which the particles are distributed in velocity -- that is, how many particles, relative to the total number, exist in any velocity increment. Clearly, the function extends from zero to infinity, but only a small relative number exists at a few times the most probable velocity. The most probable velocity (that value which makes the function a maximum is

$$V_o = \sqrt{\frac{2KT}{m}}$$

the r.m.s. velocity is

$$\overline{V} = \sqrt{\frac{3KT}{m}}$$

and the average velocity is

$$\langle V \rangle = \sqrt{\frac{2KT}{\pi m}}$$

The distribution may also be written in terms of the most probable velocity, in which case it becomes

$$\frac{dN(V_o)}{N} = \frac{4}{\sqrt{\pi}} \frac{V^2}{V_o^{\,2}} e^{-\left(\frac{V}{V_o}\right)^2} dV$$

$\frac{dN(V)}{N}$ drops to about 0.02, for example, for the two limits $\frac{V}{V_1} \approx 0.1$ and 2.5. The Maxwellian distribution is the distribution of thermodynamic equilibrium, and it is by far the most dominant, recognized distribution function in gaseous physics, and even in gaseous discharges. In gaseous discharges, many other distribution functions are important, since thermodynamic equilibrium does not exist, frequently, although the peculiar distribution functions obtained usually appear somewhat Maxwellian.

For a number of conditions, usually obeyed in tenuous plasmas having appreciable electron energy, the distribution function, expressed in terms of energy is

$$f(E) = C_o E^{\frac{1}{2}} e^{-0.55\left(\frac{E}{\langle E \rangle}\right)^2}$$

termed the Druyvesteyn distribution. (The Maxwellian distribution expressed in this manner would be

$$f(E) = C_m E^{\frac{1}{2}} e^{-\frac{E}{KT}}$$

The most probable energy (or velocity) of the Druyvesteyn distribution function is greater than that of the Maxwellian, and the "tail" cuts off much more rapidly.

There are two other distribution functions that are commonly referred to in gaseous discharge literature; these are the Davydoff-Margenau and the Allis (sometimes known as the hyperbolic). Without going into the details, let us consider the general manner in which all four of the distribution functions are rigorously derived:

The almost all powerful tool in plasma physics is the so-called Boltzmann transport equation. This is an integro-differential equation of the form

$$\frac{df}{dt} = \left.\frac{\partial f}{\partial t}\right|_{\text{COLLISIONS}} \qquad \text{and}$$

$f(t, \vec{r}, \vec{V})$ is the "number-density" in phase space; this is a 6-dimensional space with three physical and three velocity coordinates. Hence, $f\,d\vec{r}\,d\vec{V}$ is the number of particles in an infinitesimal volume of phase space at the point $\vec{r}\,\vec{V}$. If there were no collisions, all the particles at $\vec{r}\,\vec{V}$ would arrive at $(\vec{r} + \vec{V}dt,\ \vec{V} + \vec{a}dt)$ at a time $t + dt$. Hence,

$$f(t+dt,\ \vec{r}+\vec{V}dt,\ \vec{V}+\vec{a}dt)\,d\vec{r}\,d\vec{V} = f(t, \vec{r}, \vec{V})\,d\vec{r}\,d\vec{V}$$

and expanding the left side in a Taylor series and letting $dt \to 0$, one obtains

$$\frac{df}{dt} = \frac{\partial f}{\partial t} + v\frac{\partial f}{\partial \vec{r}} + \vec{a}\frac{\partial f}{\partial \vec{V}} = 0$$

This result is known as Liouville's Theorem.

Two of the most common methods of solving the B.T.E. (the Boltzmann Transport Equation) are:

(a) A series expansion for f such as

$$f(t, \vec{r}, \vec{V}) = f_0(t, \vec{r}, \vec{V}) + \frac{V_x}{V} f_1(t, \vec{r}, \vec{V})$$

so that one obtains two equations for f_0 and f_1

(b) Assume a form for f with undetermined coefficients as

$$f = n(t, r)\,e^{-\frac{m}{KT}(\vec{V}-\vec{\omega})\cdot(\vec{V}-\vec{\omega})}$$

with n, $\vec{\omega}$ and KT to be determined. One may write the B.T.E. in the form

$$\frac{df}{dt} = \frac{\partial f}{\partial t} + v\cdot\vec{\nabla}_x f + \vec{a}\cdot\vec{\nabla}_V f + \left.\frac{df}{dt}\right|_{\substack{\text{ELASTIC}\\ \text{COLL.}}} + \left.\frac{df}{dt}\right|_{\substack{\text{INELASTIC}\\ \text{COLL.}}} ;$$

so that something equivalent to the f_o term of the expansion may be written as

$$\underset{(A)}{\left.\frac{de}{dt}\right|_{\text{FIELD}}} - \underset{(B)}{\left.\frac{de}{dt}\right|_{\substack{\text{ELASTIC-TO-}\\ \text{ATOMS}}}} + \underset{(C)}{\left.\frac{de}{dt}\right|_{\substack{\text{ELASTIC-}\\ \text{FROM-ATOMS}}}} - \underset{(D)}{\left.\frac{de}{dt}\right|_{\substack{\text{INELASTIC}\\ \text{LOSSES}}}} = 0 .$$

If one includes (B) and (C) only and solves, the Maxwellian distribution is obtained; (A) and (B) give the Druyvesteyn, (A) + (B) + (C) give the Davyoff-Margenau, and (A) + (D) give the Allis. It is clear then that when the electric field starts to become dominant the distribution function will deviate from the Maxwellian. For the details of the derivations, one must consult the literature.

Considering, for the moment, that a plasma has been created, it is clear that some form of loss must be operable; if this were not so, every plasma region would become completely ionized and/or the electron energy would rise indefinitely. The various forms of losses are:

(1) Attachment of electrons to atoms possessing such affinity.

(2) Recombination of electrons and ions.

(3) Diffusion of electrons and ions to the walls of a container.

(4) Collisions of the second kind (excited atoms transfer their energy to another atom in the form of kinetic energy.

(5) That portion of emitted light quanta which escape from the gas, or, partially, heat up the gas.

The losses appear, of course, in the form of heat, as well as visible and ultra violet radiation.

For attachment only, the appropriate equation of density is

$$\frac{dn}{dt} = -h\nu_c n$$

where h is the attachment efficiency and ν_c is the elastic collision frequency. To get some rough idea of the magnitudes, $\nu_c \approx 10^9$ collisions/sec/mm Hg (although this varies quite radically with gas type and electron energy) and h $\approx 10^{-4}$ (Probability of attachment per collision; this also varies radically with gas type and electron affinity, as do many complex gases such as Freon).

<u>For recombination only</u>, the appropriate equation is

$$\frac{dn}{dt} = -\alpha n^2$$

where the recombination coefficient, α, varies from about 2×10^{-6} to 10^{-12} $\frac{\text{cm}^3}{\text{ion-sec}}$ as the electron energy varies from thermal (i.e. room temperature) to a few volts. It is dependent upon pressure (although not lineraly, or simply), gas type, etc.

The solution of the differential equation for attachment <u>only</u> is

$$n = n_o e^{-h\nu_c t}$$

for recombination <u>only</u> it is

$$n = \frac{n_o}{1 + \alpha n_o t}$$

and for <u>both together</u> it is

$$n = \frac{n_o}{e^{h\nu_o t}\left\{1 + \frac{\alpha n_o}{h\nu_c}\right\} - \frac{\alpha n_c}{h_o}}$$

These apply, of course, only in a non-excited (i.e. decaying) plasma, as otherwise the excitation (production) terms must be taken into account.

The other type of loss which is dominant under certain conditions is that of diffusion. As electrons retreat from regions of high density, their velocity is

$$\langle v \rangle = -\frac{D}{n}\frac{dn}{dx}$$

where we are considering the one dimensional case and D is termed the diffusion coefficient. In the crude theory

$$D = \frac{1}{3}\langle\lambda\rangle\langle v\rangle = \frac{1}{3}\frac{\langle\lambda\rangle^2}{\tau} = \frac{1}{3}\tau\langle v\rangle^2 = \frac{1}{3\nu}\langle v\rangle^2$$

actually, this only gives an approximate value for D, which varies radically from gas to gas and with operating conditions. In a plasma of moderate density and above, $n \gtrsim 10^8$ electrons/cm^2, a condition known as ambipolar diffusion applies, that is, the electrons are held back by the field of the positive ions; the value of the ambipolar diffusion coefficient is roughly

$$D_a = \frac{\mu_+}{\mu_-} D_-$$

where μ_+ and μ_- are the mobilities of the positive ions and electrons, respectively. The mobility is defined by the relation

$$\mu = \frac{V_d}{E}$$

where E is the electric field and V_d is the resultant drift velocity. In the crude theory an electron gains a velocity

$$V_d = \frac{e E \tau}{m}$$

in a time τ, so that the mobility becomes

$$\mu = \frac{e \tau}{m}$$

a rather simple relationship.

The motion of electron and ions under a combined concentration gradient and electric field are, respectively.

$$\Gamma_- = -D_- \vec{\nabla} n_- - \mu_- E n_-$$

and

$$\Gamma_+ = -D_+ \vec{\nabla} n_+ - \mu_+ E n_+$$

If $E = 0$ and n is large, then $n_+ - n_- \ll n_-$ or $\Gamma_+ = \Gamma_-$, so that the current may be written

$$\Gamma = -D_a \vec{\nabla} n$$

where

$$D_a = \frac{D_+ \mu_- + D_- \mu_+}{\mu_+ + \mu_-} \cong \frac{\mu_+}{\mu_-} D_-$$

(It is to be noted that $\Gamma_+ \approx \Gamma_-$ even though $D_+ \ll D_-$; otherwise E could not go to zero because of the charge separation field. Clearly, this implies $\nabla n_+ \gg \nabla n_-$. If a simple parallel plate problem is considered (and only a decaying plasma is introduced), then

$$\frac{\partial n}{\partial t} = D_a \frac{\partial^2 n}{\partial x^2}$$

In the time part of the solution an expression

$$n(x, t) = n(x)\, e^{-\frac{t}{\tau}}$$

is assumed, so that the spatial equation becomes

$$\frac{\partial^2 n}{\partial x^2} + \frac{n}{D_a \tau} = 0$$

The Density must go to zero at $X = 0$ and $X = \ell$, so that the solution

$$n = A \sin \theta, \quad \theta \approx \sqrt{\frac{1}{D_a \tau}}$$

has a determining condition

$$\ell = \frac{1}{\sqrt{D_a \tau}} = \pi, \text{ or } \frac{\pi}{\ell} = \frac{1}{\Lambda}$$

where Λ is the so-called "diffusion length." Without going into further details, it will merely be stated here that the diffusion length relations of interest are:

(a.) $\frac{1}{\Lambda^2} = \frac{\pi^2}{\ell^2}$ for a parallel plate (ℓ = length
(R = radius

(b.) $\frac{1}{\Lambda^2} = \frac{\pi^2}{\ell^2} + \left(\frac{2.4}{R}\right)^2$ for a cylinder

(c.) $\frac{1}{\Lambda^2} = \frac{\pi^2}{R^2}$ for a spherical problem

Many problems involve a knowledge of the diffusion length, so that it is well to remember the above relations.

To terminate the diffusion discussion, for the present, it should be noted that $D_a \times P$ (where P is the pressure) is a constant, and at room temperature $D_a = 540\ \mathrm{cm}^2/\mathrm{sec/mm\text{-}Hg}$ for a Helium plasma.

3. Breakdown of Gases

3.1 D-C Breakdown

Only in recent years have some of the fine points concerning the electrical breakdown of gases been adequately treated. The subject of breakdown involving dc fields is particularly complex, but it will be treated here first for two reasons:

a. Historically, the subject was treated before that of r-f breakdown.

b. Physical insight is obtained by considering avalanches, streamers, etc.

It is found that a finite volume of space almost always contains free electrons. In the earth's atmosphere, for example, the ion-pair density is roughly 10^2 ions/cm^3, although, of course, this density n_o is a marked function of altitude and position around the earth. Similarly, if a discharge tube is filled with any type of gas an "initial" density of electrons will inevitably exist. This initial ionization is caused, in general, by three things:

a. Cosmic radiation

b. Proximity (i.e. earth) radiation

c. The high velocity particles in the tail (usually Maxwellian) of the distribution function (of the gas molecules or atoms).

One has to consider, therefore, how this initial density, n_o, can grow to a magnitude wherein macroscopic effects (radiation, conductivity, etc.) are noted; when well defined macroscopic effects (usually steady state) are observed, the gas is said to be "broken down." Breakdown is also said to have occurred when the current continues to flow with the source of initial ionization removed. That is usually an academic point, because only natural, inevitable sources are usually "employed." Sometimes, however, one uses an alpha source or some other ionizing source to enhance n_o; in this case the macroscopic effects must continue when such a source is removed, if true breakdown is to exist.

The thorough, logical investigation of breakdown in dc fields was first carried out by Townsend and his associates, commencing at about the start of the 20th century. They found that the initial ionization would grow spatially and in density, in the direction of the applied electric field. The growth was much like a physical avalanche, and this initial stage of breakdown came to be known as the Townsend avalanche. Townsend defined a coefficient, α, which indicated the number of electrons produced by a single electron in unit distance (viz. one centimeter). That is,

$$dn = \alpha n \, dx \; ; \quad \frac{dn}{n} = \alpha \, dx \quad \text{and} \quad n_o = n_o e^{\alpha x}$$

as the density growth rate of the avalanche. It is found that the "first Townsend coefficient" (i.e. α) is extremely small for $\frac{E}{p}$ 20 volts/cm/mm Hg. but above this value it increases very rapidly. Hence, if $\frac{E}{p} \gg 20$ volts/cm/mm Hg. an avalanche will grow to high density in a matter of just a few centimeters of travel. In almost all cases, and particularly for tubes containing electrodes (the Townsend process is, of course, applicable to natural atmospheric discharges where at most one "electrode" exists), it is found that α does not adequately describe the avalanche process. For this reason, Townsend introduced his "second coefficient," γ, which has the following significance:

In addition to the drifting electrons, various inelastic collisions along the avalanche path produce photons, positive ions and metastable atoms, both directly in the gas and at the electrodes; these particles can cause secondary electron emission. Let us assume (in order to get the same answer as Townsend, although his reasoning on this point was erroneous) that the effect of photons, positive ions and metastablee produce a density n^* at the start of the avalanche. Then,

$$n = (n_o + n^*) e^{\alpha x}$$

is the avalanche tip density, where the tip is at a coordinate X. Also,

$$n^* = \gamma \left[n - (n_o + n^*) \right]$$

where γ is the number of electrons emitted per incident photon, ion and metastable at the start of the avalanche and $n - (n_o + n^*)$ is taken as the number of such incident particles.

It should be noted that the terms "density" and "number" have been used rather indiscriminately. If one assumes that the initial cross section of the avalanche did not change, then this would be all right. Diffusion, however, causes lateral spreading, so that one should not inter-change number and density. This will be mentioned later.

From

$$n = (n_o + n^*) e^{\alpha x}$$

and

$$n^* = \gamma \left[n - (n_o + n^*) \right]$$

the expression

$$n = \frac{n_o e^{\alpha x}}{1 - \gamma(e^{\alpha x} - 1)}$$

is obtained. (A further note is necessary here: the total number of incident particles, $n - (n_o + n^*)$ is actually only the number of positive ions, since $n - n_t$ (the difference of electrons arriving at the tip and leaving the start of the avalanche, with $n_t = n_o + n^*$) represents positive charge transfer. Thus, although positive ions are believed to be a minor factor compared to either photons or metastables (in certain cases), Townsend believed otherwise. To obtain his form, the "positive ion assumption" had to be employed. One may regard γ, however, as merely a constant necessary to predict the correct avalanche characteristics). In some books a further constant, called β by Townsend, is described as "the second Townsend coefficient." This constant represents the number of ion pairs produced by a positive ion traveling 1 cm in the field, the resultant equation,

$$n = \frac{n_o (\alpha - \beta) e^{(\alpha-\beta)x}}{\alpha - \beta e^{(\alpha-\beta)x}}$$

is not too important, because the production process mentioned is extremely improbable. An equation which does have some importance, however, is

$$n = n_o \frac{\alpha e^{\alpha x}}{\alpha - \theta n g e^{(\alpha-\mu)x}}$$

which represents the avalanche process when one includes photoelectric emission: θ is the number of photons produced per cm, n is the photoelectric emission factor, g is the fraction of photons that reach the cathode (the start of the avalanche), and μ is the absorption coefficient for photons.

From a practical standpoint, the equation

$$n = n_o \frac{e^{\alpha x}}{1 - \gamma (e^{\alpha x} - 1)}$$

is sufficient for most purposes. One has to have tables of values for something equivalent to α and γ anyway, so that the detailed processes become largely of academic interest. The form of the equation is usually remarkably correct.

To get to the practical problems of dc breakdown, one notes, first, that the various avalanche equations show that the phenomenon will disappear if n_o 's caused to vanish. Hence, by the second previously mentioned criterion of breakdown, a pure avalanche cannot in itself represent breakdown — even if the tip density becomes very high. It turns out, however, that when the tip density becomes very high the general phenomena known as "streamers" occur; as will be shown, these represent true breakdown.

A streamer is a propagating bundle of ionization with a detailed balance of ion production and loss being maintained. The streamer may "choke" itself off periodically, or it may propagate "with no resting periods." If the head of the main avalanche is considered to be spherical, the resultant electric field due to charge separation (the electrons move ahead of the ions in the direction of avalanche buildup) is

$$E = e\,\frac{(Q_+ - Q_-)\,\vec{r}}{4\pi\,\theta_o\,r^3} = \vec{r}e\left(\frac{N_o\,e\,(\frac{4}{3}r\,\alpha - 1)\,e^{\alpha z}}{4\pi\,\theta_o\,r^3}\right)$$

since

$$N_- = N_o\,e^{\alpha z} \qquad \text{and} \qquad N_+ = \frac{4}{3}\,N_o\,r\,\alpha\,e^{\alpha z}$$

where N_- and N_+ are the total number of electrons and ions, respectively. The average radius of the avalanche tip is

$$\langle r \rangle = \sqrt{KDt}$$

where K is a constant (2, 3, or 4 depending upon conditions, mainly geometry), D is the appropriate diffusion coefficient, and t is the time of avalanche buildup. It appears that the determination of avalanche tip radius by means of pure diffusion is by no means always accurate. Now, the streamer forms when the electric field at the tip is sufficient to cause the production of secondary avalanches (mainly by photoionization) and to permit the buildup of these avalanches. An equivalent statement is that the denominator of the expression

$$n = \frac{n_o\,e^{\alpha x}}{1 - \gamma\,(e^{\alpha x} - 1)}$$

vanish, for at this point the density (or number) of electrons can be some constant, even if n_0 is reduced to zero. Because, usually, $e^{\alpha x} \gg 1$ the breakdown condition is written as $\gamma e^{\alpha x} \gg 1$; by merely using the breakdown condition, $\gamma e^{\alpha x} \gg 1$ and accurate (empirically determined) values for α and γ, it is found that dc gaseous breakdown can usually be predicted quite accurately.

Streamers may be either positive or negative and either diffuse or pinched. For negative streamers the growth mechanism is that of avalanches moving away from the tip, thereby causing extension of the tip. For positive streamers the avalanche forms ahead of the streamer and moves in towards the tip. A cloud is usually negative with respect to the ground, and yet the streamer is of the positive type. Therefore, the usual main lightning stroke goes from the ground to the cloud. Conditions are more favorable for a positive streamer than for a negative streamer; in fact, a positive streamer usually propagates about twice as fast as a negative streamer. The velocity of a streamer is roughly

$$V_s = n^{\frac{1}{3}} \langle V_d \rangle d_c$$

where n is the density in front of the tip, $\langle V_d \rangle$ is average drift velocity of the electrons, and d_c is the critical distance over which the field is greater than the critical value (usually taken to be 20 volts/cm/mm Hg. or slightly greater). Streamers remain diffuse until their current density reaches such a value that the self-magnetic field causes constriction. Low pressure streamers (or streamers proceeding through "virgin" gas, that is through gas that has not been recently ionized) are usually diffuse, while the preponderance of moderate and high pressure streamers are pinched.

There are numerous phenomena associated with dc breakdown that cannot be discussed here: For example, Trichel pulses, corona, time lags, etc. The literature is voluminous on these subjects.

The preceding information on dc breakdown is useful because it allows an understanding of the physical processes involved. When actually working with practical dc breakdown problems, however, one depends upon empirical curves, largely. These curves are plotted in the form of breakdown voltage versus pd, where breakdown voltage is specified in volts or kilovolts and pd is expressed in terms of millimeters or centimeters times millimeters of mercury gas pressure. Two good sources for such curves are:

(1) Physical Review, 55, 1939 by F. Ehrenkranz.

(2) Gasenthladungastabellen, J. Springer, Berlin, 1935 by Knoll et al.

More modern sources of information are:

(1) Electrical Breakdown of Gases, Oxford, 1953 by Meek and Craggs.

(2) Basic Processes of Gaseous Electronics, U. of California Press, Berkeley, 1955 by L. Loeb.

(3) Gaseous Conductors, Dover Press, 1958 (first published in 1941) by J. Cobine.

(4) Volumes XXI and XXII of Handbuch der Physik, Springer-Verlag, Berlin, 1956.

With the fundamentals of dc breakdown having been presented, it is possible to discuss the subject of r-f breakdown. This subject is somewhat more "clean cut," and the theoretical predictions are often extremely accurate. Even in an r-f discharge, however, stable charge separation sometimes occurs with resultant dc fields; then, occasionally, avalanches and streamers are encountered even in this case. In general, though, the subject will appear to be quite different.

3.2 R-F Breakdown

R-F discharges may be classified either as

a. Electrode or Electrodeless, or

b. "E" or "H"

By electrode discharge we mean a discharge with electrodes contracting the gas. If the electrodes are external, the discharge is classified as electrodeless. A more general way of classifying radio frequency discharge is by the nature of the directed currents in the gas. If the currents are not closed conduction currents, but, rather, are extended to the driving source by means of displacement currents or contacting electrodes, the discharge is of the "E" type. The dominant example here is that of a container with either internal or external disc or plate electrodes directly excited by a generator. If the gaseous directed currents occur in the form of closed conduction currents, then the discharge is of the "H" type. The prime example here is that of a container with a single turn coil, wrapped around it - said coil being directly connected to the generator. Obviously, a combination of the two types of currents may exist (and this inevitably occurs in cavities, etc.), in which case the discharge is said to be of the "E" + "H" type. In a geometry capable of "E" and "H" discharges it is always found that, as pressure, frequency and amplitude of excitation are varied, an "E" or "H" mode will be dominant under certain conditions. The "E" type is usually rather cold and uniform appearing (except at high powers), whereas the "H" type is more brilliant and with distinct spatial characteristics. With helical coil excitation the mode switching (by varying pressure, frequency, etc.) is particularly noticeable.

Speaking of alternating current discharges in general, it is clear that at very low frequencies the behavior will be similar to a dc discharge. That is, the cathode and anode will be interchanged periodically, but the frequency is so low that there is sufficient time during a half cycle for the complete cumulative avalanche and streamer phenomena to occur. As the frequency becomes higher and higher, however, the appearance of the plasma changes, and the breakdown voltage reduces. For "E" type discharges, the distinct regions are:

a. $\frac{T}{2} < \tau_{ion}$; this means that the transit time across the gap for a positive ion is greater than the one-half cycle time of the imposed alternating field. Hence, positive space charge accumulates, and the breakdown voltage reduces (because of field distortion) to a significantly lower value than that of the dc case. The field distortion is greater for point electrodes than for discs or plates. The lowering of the breakdown voltage is also more pronounced at large gap lengths. For example, with discs the breakdown voltage is lowered about 25 percent for a 10 cm gap (at atmospheric pressure), while it is lowered by more than 50 percent for a pair of point electrodes.

b. $\hat{A} = 0(\ell)$; this means that the amplitude of oscillation of the free electrons becomes of the order of the gap length. When this occurs, cumulative ionization with an effective path length of a number of times the gap length is obtained. Secondary emission off of the walls or electrodes can also occur. When the wavelength is so large that the amplitude of electron oscillations does not touch the walls, it is found that a sharp rise in the breakdown voltage (for sufficiently low pressure) occurs. At very low pressures this change may be several hundred percent.

c. $\left\{\begin{array}{c} \ell \ll \lambda \\ \lambda \ll \ell \\ \hat{A} \ll \ell \end{array}\right\}$; this means that the gap length is very much less than the wavelength, the electron mean free path is very much less than the gap length, and the peak amplitude of oscillation is very much less than the gap length. When these conditions occur at moderately low pressure, the assumption of ion production by collisions and electron and ion loss by diffusion only is employed. That is

$$\frac{\partial n}{\delta t} = V_i n - \vec{\nabla}\cdot\Gamma$$

where V_i is the ionization frequency, n is the electron density, and Γ is the diffusion current of electrons. This equation may be written as

$$V_i n - D_a \nabla^2 n = 0$$

for breakdown, since $\frac{\partial n}{\partial t}$ just starts to go positive at this point. Brown (M.I.T.) solved this problem by letting

$$D_a n = \Psi \quad \text{and} \quad \rho = \frac{\nu_i}{D_a E^2}$$

and solving the equation

$$\nabla^2 \Psi + \rho E^2 \Psi = 0$$

At first Brown and his associates determined ρ from accurate cavity breakdown measurements, but later they computed ρ without recourse to experimental data (other than cross-section and ionization potential). This theoretical calculation involved a rather complicated solution of the Boltzmann Transport Equation, and it seems out of place to reproduce it here. In any event, the semi-empirical approach is the most accurate. In this procedure, Brown plotted $E_{Breakdown}$ $(\frac{\text{Volts}}{\text{cm}})$ against pressure in mm Hg. Using the data from this plot, he was able to plot

$$\rho = \frac{\nu_i}{D_a E^2} = \frac{\pi^2}{\ell^2 E^2} \quad \text{versus} \quad \frac{E}{P}$$

The importance of doing this is that it shows the satisfactory nature of the diffusion assumption. For a gap length of 0.3 cm, ρ varies from about 10^{-4} $\frac{\text{ionizations}}{\text{volt}^2}$ at $\frac{E}{P} = 20$ $\frac{\text{volts/cm}}{\text{mm Hg.}}$ to 10^{-3} at $\frac{E}{P} = 100$ and back down to 10^{-4} at $\frac{E}{P} = 2000$. These values become greater as the gap length increases, although for $\frac{E}{P} \cong 50$ the gap length is more or less immaterial; an average value of $\rho = 5 \times 10^{-4}$ is a good figure to remember for this low $\frac{E}{P}$ region.

A good source for curves displaying the breakdown field strength against an appropriate parameter (for the cases (b) and (c) discussed here) are found in M.I.T. Technical Report 283. Here Brown plots $E_e \Lambda$ versus Λ, where Λ is the diffusion length, p is the pressure, and

$$E_e^2 = \frac{\hat{E}^2}{2} \frac{\nu_o^2}{\nu_c^2 + \omega^2}$$

is the effective electric field strength. For case (a), as well as (b), one is referred to "Electrical Breakdown of Gases" by Meek and Craggs.

Other criteria of breakdown are often used. One prominent criterion is the assumption that the field magnitude and frequency cause the electron to acquire the ionization energy level at the end of a single mean free path. Despite the variation of mean free path with energy, experiments at low pressures give quite good confirmation of this theory.

Before further consideration of the general r-f breakdown problem, it is well to give some special consideration to "H" type discharges. It has been found experimentally that the breakdown field strength is lower for a geometry capable of sustaining an "E" + "H" discharge than it is for an "E" type geometry only. By maintaining essentially the same E_z field in both cases, it is seen that the lowered breakdown field strength is caused by the E_{+} component. In a typical experiment, for example, an "E" + "H" system required 245 volts to break down 1 mm Hg. of Neon at 3 mc., whereas the "E" system required 260 volts; in addition, the E_{-} component of the "E" + "H" system was only one-tenth the E_z component.

One contributing factor to lowered breakdown field in the "H" case is deduced by considering the electron current under combined density gradients and electric fields. The electron current is

$$\Gamma_{-} = -D_{-}\vec{\nabla} n - \mu_{-}\vec{E} n_{-}$$

it is to be noted that D_{-} rather than D_a is used, because the density is so low in the prebreakdown condition that ambipolar diffusion does not apply (although immediately prior to breakdown D_a is frequently applicable). It is immediately apparent then, that the "H" breakdown will be lower, because $\Gamma_{-\text{"E"}}$ will exceed $\Gamma_{-\text{"H"}}$ by the E_n term, since E_n is not directed toward the walls in the "H" case. Another factor is that the diffusion rate is somewhat lowered, because the buildup of ionization occurs in a ring and some of the diffusion (roughly half, in fact) occurs towards the center of the tube (where it will not be counted as a total loss. The above modifications should yield an adequate theory of "H" breakdown via the Brown method.

Neglecting the fine points of r-f breakdown theory (and much work remains to be done), there is no great problem in adequately predicting r-f breakdown phenomena under the usual conditions encountered. Of course, some of the peculiar geometry and complex fields associated with various Sherwood projects (the attempt to obtain thermonuclear power) for example, lead to difficulties in predicting the breakdown condition accurately. The practical problems of alternating current breakdown are usually approached as follows:

(1) The case where the frequency lies below that value wherein ion inertia effects are appreciable. Here, any frequency below 100 kc (usually higher, in fact) is safe for any gas:

In this case one merely employs dc breakdown theory. For low frequency "H" type discharges (which require huge power), the situation will appear to be radically different from dc conditions. Even here, however, it is only necessary to determine $\frac{E_\theta}{p}$, pick appropriate values of α and γ out of tables, and utilize the appropriate breakdown condition; to improve the accuracy of the predicted breakdown value, the reduced diffusion current should then be taken into account.

(2) The case where gap length and applied frequency cause ion inertia effects to appear, and further, the mean free path is much less than the gap length (the pressure is high--several hundred mm Hg.). This is one of the most unfortunate cases, and the complex phenomena involved force one to simply use breakdown curves without too much thought to the theory. For various electrode configurations, some compromise estimate between point electrodes and plane electrodes (which are plotted in the literature) is possible. For rather smooth electrodes, the use of dc breakdown theory, plus the following rough rules, allows an approximate breakdown value to be established:

1. For large smooth electrodes.

(a) R-F breakdown value will be about 25 percent less than the dc value for $pd < 10^4$ mm Hg.-cm.; for $pd > 2 \times 10^4$ the value of r-f breakdown will be about 50 percent less than for dc.

2. For small smooth electrodes (looking something like points or rods)

(a) R-F breakdown value will be about 50 percent less than the dc value for $pd < 10^4$ mm Hg.cm.; for $pd > 2 \times 10^4$ the value of r-f breakdown will be about 150 percent less than for dc.

For accurate values there is no choice except to plot breakdown voltage versus pd for the type of gas and electrodes under consideration.

(3) For the case wherein the frequency is relatively high (> 5 mc), the pressure is relatively low (< 0.1 mm Hg.), and the tube dimensions are very much less than a wavelength. Here the Hale theory of breakdown (occuring when E and ω are such that ionizing energy is attained at the end of one mean free electron path) is employed. For close agreement between theory and experiment, the variation of mean free path with electron energy should be taken into account.

(4) For the case wherein conditions are the same as for case (3) except that the wavelength is comparable with the tube dimensions. Here, the curves of Gill and von Engel are employed. The unknown secondary emission from the walls of the tube forces the use of curves, as the wavelength decreases below a certain critical value.

(5) The case where mean free path and electron oscillation amplitude are small relative to the gap length, diffusion is the dominant loss, and the wavelength is not small relative to the gap length. For a large number of microwave cases, these conditions are obeyed. Here, the Brown theory (previously mentioned) is employed.

(6) For a case similar to case (5), except that the rather severe restrictions of $\omega > V$ (inelastic) but $\omega < V$ (elastic) is employed. The Holstein formula

$$(pd)^2 = \frac{\pi^2 \frac{KT_-}{e}}{\left(\frac{E}{p}\right)\left(\frac{\alpha}{p}\right)}$$

is used.

(7) For pulsed microwave discharges. Here the theory of abrum is employed. The electrons grow at the rate

$$n = n_o \ell^{\left\{\frac{\partial n}{\partial t}\right\}_p - \left\{\frac{\partial n}{\partial t}\right\}}$$

where $\left\{\frac{\partial n}{\partial t}\right\}_p$ represents the production rate of ions and $\frac{\partial n}{\partial t}$ is the loss rate of electrons (usually assumed zero for pulses < 5 μ sec.) Breakdown occurs when

$$\left\{\frac{\partial n}{\partial t}\right\}_p > \frac{1}{T} \ln \frac{n_c}{n_o}$$

where n_c (critical density) is about $10^{12}\ \frac{\text{electrons}}{\text{cm}^3}$.

The complete formula for breakdown (using average energy gain by an electron and letting said energy drop to zero after ionizing energy is attained) is

$$E_B{}^2 = \frac{4 V_i (\omega^2 + \frac{1}{3} v_c{}^2)}{\frac{\ell}{m} v_c} \left(\frac{1}{T}\right) \ln\left(\frac{10^{12}}{n_o}\right)$$

where T = pulse length, V_c = elastic collision frequency, V_i = ionization energy level, ω = angular applied frequency, and n_o is the initial density (usually about 10^2). One may then write the expression as

$$E_B{}^2 = \frac{92\ V_i\ (\omega^2 + \frac{1}{3} v_c{}^2)}{\frac{\ell}{m} v_c\ T},$$

for a single pulse. If the prf is high enough so that appreciable ionization remains in the gap between pulses, then n_o must be radically increased. A good value in this case would be $n_o = 10^8$, in which case

$$E_o^2 = \frac{36\, V_i\, (\omega^2 + \frac{1}{3}\, V_c^2)}{\frac{e}{m}\, V_c}$$

To derive a more accurate expression, one should take into account the diffusion loss of electrons, as well as (under certain conditions) attachment and recombination losses.

The object of this discussion on breakdown theory has been to initiate an understanding of the phenomena and to give some idea of the various theories employed under various conditions. Every individual breakdown case must be considered a complex situation in which combinations of pertinent theories must frequently be used. The experimental work presented in the literature must be used for accurate breakdown predictions, but this work cannot be satisfactorily employed if a fundamental knowledge of the subject is not possessed. Reference to Loeb, Meek and Craggs, and Handbuch der Physik (all previously mentioned) will allow ready access to the pertinent empirical data.

SYMBOLISM FOR APPENDIX B

A = Constant notation

α = Recombination coefficient

C = Constant notation

D = Diffusion coefficient

D_a = Ambipolar diffusion coefficient

E = Electric field intensity

e = Electronic charge

e = (As Exponential Base) 2.71628

E = Kinetic energy

Δ_E = Change in kinetic energy

g = Acceleration of gravity

Γ = Electron or ion motion (or current)

h = Attachment efficiency or probability

K = Boltzmann's constant

ℓ = Length

Λ = Diffusion length

λ = Electron mean free path (Ramsauer)

M = Atomic mass

m = Electronic mass

μ_+ = Mobility constant for positive ions

μ_- = Mobility constant for negative ions

N = Total number of particles in a medium

n = Number of particles experiencing collisions

SYMBOLISM FOR APPENDIX B (Continued)

ν_c = Collision frequency

V_i = Average number of collisions per unit distance travelled

P = Pressure

R = Radius

σ = Atomic cross sectional area in cm

T = Temperature

τ = Average time between collisions

t = Time

V = Particle velocity in cm/sec

V_a = Drift velocity

V_o = Initial velocity

APPENDIX C

DETAILS OF A KUGELBLITZ THEORY

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DETAILS OF A KUGELBLITZ THEORY

As an introduction to the details of Melpar's Kugelblitz theory, let us review the mechanisms of ionization and loss. For ionization in a normal plasma, only electron-atom inelastic collisions are of importance. The rate of production of new electrons and ions (rate of increase of plasma density) is given by $\frac{dn}{dt} = v_i n$, where n is the electron density and v_i is the ionization frequency. In terms of the phase-space distribution function

$$v_i(r) = \int_{v_i}^{\infty} \sigma_i \, v \, f(\vec{r},\vec{v}) \, d\vec{v},$$

and v_i obviously varies from point to point unless the plasma is homogeneous. In intense discharges (such as lightning) photon-atom inelastic collisions contribute markedly to plasma production. It may be that photoionization will enter, but after the initial stage of production it is unlikely, and we are forced, as a result, to work with v_i as defined above.

The loss terms involve diffusion $\left(\underline{D \nabla n},\right)$ attachment ($hv_c n$) and recombination (αn^2) all with dimension $\left[\frac{1}{L^3 T}\right]$ the same as the production term ($v_i n$). For sufficiently high density, even radiative recombination (in which α attains its smallest value) is sufficient to cause dominance of recombination over any other losses. The value of α (for air) ranges from a little over $10^{-6} \left[\frac{cm^3}{\text{ion-sec}}\right]$ to much smaller values (for radiative recombination) at very high temperatures.

In the case of attachment, h (the attachment efficiency) is about 10^{-4} for oxygen, while v_c (the transport elastic collision frequency) is of the order of 10^9/torr $\left[\frac{1}{T}\right]$. At high pressures, then, attachment causes severe losses.

Diffusion is dependent upon whether free electron diffusion (D_-) is effective or ambipolar diffusion (D_a). For any appreciable plasma density D_a (which is $\ll D_-$) is valid, so that diffusion is one of the least serious losses for a dense plasma such as Kugelblitz.

There is a wide variety of other things which characterize plasma production and decay such as field excitation geometry effects, radiation losses, sheaths, stability and hydromagnetic effects. These topics will be noted as pertinent during the course of the following discussion.

If there were no continued excitation (but there always must be as long as the supply of free electrons last; that is, as long as there exists a finite phase-space distribution function for the electrons), then, neglecting diffusion, it is easy to show that the density falls off as

$$n = n_o / \left\{ e^{t}/\gamma \left[1 - \alpha n_o \gamma \right] - \alpha n_o \gamma \right\} ,$$

where $= \frac{1}{hv_c}$ and n_o is the initial electron density. For reasonable values of n_o, α and γ, a simple calculation will show that even a moderately low pressure Kugelblitz could not survive for seconds (and we must explain times at least as high as ten seconds or more).

It is apparent that a continued generation mechanism is needed to explain the observed lifetimes of natural fireballs (certainly in excess of 10 seconds) in the presence of normal attachment, recombination, and diffusion losses. It is easy to calculate the required order of magnitude of power flow into the Kugelblitz, although we first simplify by neglecting diffusion and radiation losses, which will not affect the order of magnitude of the result. Severe though the power input requirement will be, it should be pointed out that the sole factor bringing this possibility within the bounds of practicality is the postulation of a low pressure fireball.

Let the density be $n \left[cm^{-3} \right]$, the elsctron temperature be $T \left[{}^{o}K \right]$, the pressure be p_o $\left[torr \right]$ and $v_c \cong 10^9/torr$ $\left[sec^{-1} \right]$. Then, the total particle loss rate is

$$\alpha n^2 + hv_c\, n = \frac{dn}{dt}_{loss} \cong 3.5x10^{25} \quad \beta p_o^{\,2} \,(h+3.5x10^{7}\,\alpha\,\beta).$$

Thus we have the condition

$$v_i(r) = \int_{v_i}^{\infty} \sigma_i \, v f(\vec{r},\vec{v}) d\vec{v} > 10^9 p_o \quad (h+3.5x10^{7}\,\alpha\,\beta)$$

to be obeyed. The energy gain rate per unit volume is

$$\frac{d\varepsilon}{dt}_{\text{gain/unit vol.}} = nev_i \; V_i + \frac{3}{2} \; n(KT-) \; v_c \; \frac{2m}{M} \; ,$$

so that

$$eV_i \int_0^{\infty} f(\vec{r},\vec{v})d\vec{v} \int_{v_i}^{\infty} \sigma i \; vf(\vec{r},\vec{v})d\vec{v} + 3 \; (kT-) \left(\frac{m}{M}\right)$$

$$\int_0^{\infty} \sigma_c \; vf(\vec{r},\vec{v})d\vec{v} \int_0^{\infty} f(\vec{r},\vec{v})d\vec{v} \geq 3.5x10^{25} \; \beta p_o(h+3.5x10^7\sigma\beta)$$

$$(e \; V_i + \frac{3}{2} \; KT-).$$

And, by the use of the Boltzmann equation,

$$\frac{\partial f}{\partial t} + \vec{v} \cdot \frac{\partial f}{\partial \vec{r}} + \vec{a} \cdot \frac{\partial f}{\partial \vec{v}} = \frac{\delta f}{\delta t}_{\text{collisions}} \; ,$$

it is possible to calculate the approximate distribution function $(f(\vec{r},\vec{v}))$ for a variety of actual cases. Actually, both diffusion and radiation were neglected, so the inequality must hold.

If we assume that the underpressure phase of the intense shock wave created near the actual linear stroke channel can be of a torr or less in magnitude, a lengthy treatment involving the Rankine-Hugoniot relations, radiative transfer theory, etc. would be required to verify this assumption.

It is probable, however, from observational reports, that the fireball is created in a low pressure vortex (the seething, rotary internal motion), so that the large peripheral currents probably exist. These currents will be damped out unless fed by an external power source continuously. In other words, the assumption is that the fireball is created by shock ionization and sustained by a set of currents similar to those utilized in the laboratory. Furthermore, since the standing wave theory is inherently weak, (for the calculated power flow $(\frac{\text{watts}}{\text{cm}^2})$ required is unrealistic), Melpar considers the feed mechanism to be current fed (dc) through an irregular "line of least resistance" from a cloud-to-ground path. Reasonable density fireballs can be sustained by discharge currents which are invisible ($n \leq 10^9/\text{cm}^3$). In summation, the prime point of Melpar's theory is: a low pressure fireball fed by dc (the currents can be widely flunctuating) from a cloud-to-ground path.

To proceed with an actual power flow calculation, let us assume the following reasonable Kugelblitz parameters:

1. $p_o = 1 \; [\text{torr}]$
2. $\beta = 0.1 \; [0]$
3. $\alpha = 10^{-12} \left[\frac{\text{cm}^3}{\text{ion-sec}}\right]$ (radiative recombination)
4. $h = 10^{-4} \; [0]$
5. $e = 1.6\text{x}10^{-19} \; [\text{coulombs}]$
6. $V_i = 10 \; [\text{volts}]$
7. $k = 1.38\text{x}10^{-23} \; [\text{joules}/{}^{o}\text{K}]$
8. $T- = 10^5 \; [{}^{o}\text{K}]$
9. Kugelblitz Diameter = 20 [centimeters]
10. $v_c = 10^9/\text{torr} \; [\text{sec}^{-1}]$

For this particular set of values, the power flow per unit volume into the Kugelblitz must be greater than $\cong$ 1285 watts/cm^3. As experiments in the laboratory have required approximately 1 watt/cm^3 for plasmas of density three orders of magnitude less than the above Kugelblitz, it is clear that 1285 watts/cm^3 is a reasonable figure. To maintain the above Kugelblitz indefinitely long would require about 5.4 megawatts of input power.

If the input current is spread uniformly over a hemisphere of the indicated Kugelblitz, and if the field strength is some 100 volts/cm, the required current density is about 4.3 amperes/cm^2. To achieve this requires an electron density of

$$n = \frac{i}{ev} = \frac{4.3\text{x}10^4 \text{ amp./meter}^2}{(1.6\text{x}10^{-19})(1.87\text{x}10^7 \frac{\text{meters}}{\text{sec}}} \cong 1.43\text{x}10^6 \; \frac{\text{electrons}}{(\text{meter})^3}$$

or $\quad n \geq 1.43\text{x}10^{10}$ electrons/cm^3.

In daylight such a density would probably be invisible, so the above calculation appears reasonable. Kugelblitz observed at night (if the observing eye is not suffering from a lightning induced scotoma) should have a visible trailing streamer. On the other hand, the stored energy in a Kugelblitz would only be of the order of 10^1 joules/cm$_3$ so we may have to account for larger and denser fireballs. However, the huge stored energy estimates of natural Kugelblitz have never been verified, and the average Kugelblitz energy may only be of the order of that calculated above.

Perhaps further theoretical refinements would allow accounting for very high energy Kugelblitz, although this is a subject for extended research.

APPENDIX D

LASER GUIDANCE OF KUGELBLITZ

If Kugelblitz is to be developed as a distinctive weapon, a means of guiding the energy concentration toward a potential target must be achieved. Some preliminary considerations on this subject have resulted in the idea of applying laser beams to such a task. A brief discussion of this approach follows.

The Kugelblitz will weigh about 7×10^{-6} grams, and the viscosity of air is about 181 $\frac{\text{dyne-sec}}{\text{cm}^2}$. From this, one can compute the necessary laser guidance and acceleration array characteristics.

The upward force, from Archimede's principle, is $F \ (5.4 \times 10^{-3}) \cdot (980)$ 5.3 dynes; this can be spread over the projected area of the fireball, giving a required downward pressure (for the 20 cm diameter Kugelblitz) of about $1.68 \times 10^{-2} \frac{\text{dynes}}{\text{cm}^2} = 1.68 \times 10^{-2} \frac{\text{ergs}}{\text{cm}^3}$; thus as energy density is equal to power flux $(\frac{\text{ergs}}{\text{cm}^2\text{-sec}})$ divided by the speed of quanta transport (c), the required laser power density is $p_d = 5 \times 10^8 \frac{\text{ergs}}{\text{cm}^2\text{-sec}} = 50 \frac{\text{watts}}{\text{cm}^2}$, which is high (on a continuous basis) but possible. Modulation of the vertical component of laser incident power thereby permits altitude control of the Kugelblitz. Other forces necessary for guidance only will depend upon local charges, as well as the net Kugelblitz charge and wind forces.

The equation of motion of the fireball in one dimension is, $M\ddot{X} = 6\pi\eta a\dot{X} = F_x$ with F_x being the constant driving force of the laser acceleration beam. Thus $\dot{X} + \frac{6\pi\eta a}{M} \ X = \frac{F_x}{M}$, or $V + \frac{6\pi\eta a}{M} V = \frac{F_x}{M}$,

giving a solution for the velocity as

$$V = \frac{F_x}{6\pi\eta a} \ (1 - e - \frac{6\pi\eta a}{M} t) + V_o e - \frac{6\pi\eta a}{M} t.$$

For moderate t (The time constant is shown, later, to be of the order of 10^{-10} sec) the initial velocity is damped out, and the velocity is dependent only upon the forces due to the laser input, viscosity, and fireball radius (the effect is mass independent). The force F_x is equal to the energy density multiplied by the impinging area, or in terms of the laser beam power density and area $F_x = \frac{Pd \cdot A_B}{c}$. Hence, for a given velocity of the Kugelblitz (at long distances), the required laser power is

$$Pd = \frac{6\pi\eta a V_{KB} c}{A_B}.$$

For velocities of the order of a rifle bullet (300 meters/sec), the required laser power for a 1 cm^2 beam is

$$Pd = \frac{(6\pi)(1.81\text{x}10^{2})(1\text{x}10^{1})(3\text{x}10^{4})(3\text{x}10^{10})}{1}$$

$3,07 \text{ x } 10^{19} \frac{\text{ergs}}{\text{cm}^2\text{-sec}} \cong 3.07 \text{ x } 10^{12} \frac{\text{watts}}{\text{cm}^2}$. This apparently is outside the realm of feasibility. As drastic reductions in postulated velocity would still require considerable power, the damping time constant becomes important. The time constant is $\frac{M}{6\ Na} = \frac{7 \text{ x } 10^{-6}}{(6)(1.81\text{x}10^{2})(1\text{x}10^{1})} \cong 2 \text{ x } 10^{-10}$ seconds, which seems too short to be of any use. For propelling purposes, then, we would have to accept small drift velocities while still using large laser systems. It is not surprising that no one has claimed to have seen an extremely fast moving Kugelblitz, but it is practical to consider directing the Kugelblitz by means of small corrections or guiding forces with inputs of moderate power densities produced by a laser array.

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( ) The purpose of this study was to review the theory and experimental data on [redacted]all lightning, to compare the existing theory and experimental data to determine whether ball lightning has possibility potential as an incendiary weapon. The results of the literature study are reviewed in detail. Three major categories were established to classify theories on the subject. (1) Classical plasma theory, (2) Quantum plasma theory, and (3) Non-plasma theory. Basically each theory was examined with regard to energy content. Results of the energy analysis are summarized and relative ratings are given to the more promising theories. A theoretical and experimental Kugelblitz program is recommended as a means of developing the theory into a weapons application.

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1. Kugelblitz
2. Energy, Classical plasma
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