THE CONSTRUCTION OF A LOW-PRESSURE FLASH TUBE
AND THE MEASUREMENT OF SOME OF
ITS PROPERTIES

by

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ABSTRACT

A low pressure coaxial flash tube of simple design has been constructed which does not suffer from deposition on the exit window. Some of the electrical and spectroscopic characteristics of the tube have been measured.

A method of measuring the brightness temperature over the visible range was used by comparing photoelectrically the intensity of the tube with that of a black body. The temperature was found to be lower than expected.
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1. Introduction

Sources of energy for use by man have always played an important part in the development of civilization. With each new and improved source of energy that has been evolved, significant advances in technology have been made. Take, for example, the technological growth which followed the "universal" use of coal and oil as fuels and marked the beginning of the industrial revolution.

However, ever increasing energy requirements threaten to deplete the fuel for the world's present-day energy sources. Fortunately the development of a new source of energy appears possible, and that is the process of nuclear fusion. The fuel required for this process can be extracted from sea water at negligible cost and affords a virtually unlimited supply of fuel. Bishop\textsuperscript{1}, for example, estimates that at the present rate of energy consumption (5 x 10\textsuperscript{9} kw) there is enough sea-water fuel in the world to last for 2 x 10\textsuperscript{10} years.

Controlled nuclear fusion is not without formidable difficulties, however. For a profitable reaction to take place extremely high temperatures (10\textsuperscript{8}°K) are needed and hence the fuel is in gaseous form and highly ionized. Such ionized gases are called plasmas.
Because of the problems involved in containing a gas at such high temperatures, a thorough knowledge of the properties of plasmas under many conditions is expedient. Consequently in the last decade or so, a great deal of time, effort and money has been spent in the diagnosis of plasmas merely to learn more about them, not only with the hope of ultimately achieving controlled fusion, but also to gather useful information in such related fields as astrophysics, magnetohydrodynamics, gaseous discharges, and so on.

Of the several main diagnostic techniques in popular use today, spectroscopic analysis gives quite precise results and does not suffer from the disadvantage of introducing perturbations into the plasmas.

Much can be learned from the study of the spectra of plasmas. However it is usually necessary in subsequent analysis to know the relative population densities and the transition probabilities between two energy levels of the gas molecules. Unfortunately in many cases these two quantities are not known and so preliminary experimentation must be undertaken to determine them.

Ladenburg\(^2\) has pointed out that by measuring the anomalous dispersion and the absorption spectra of the gas, one may determine the relative population densities and the transition probabilities.

However, to perform an absorption analysis upon the
plasma, a continuum background source is required whose temperature need be greater than that of the plasma which itself can be as high as \(10^8\) K. Also because one would like to examine the short-lived plasma reactions, such as a shock front or pinch effect, an extremely short-pulsed background light is required to get any time-resolved absorption spectra.

Both the high temperature and short duration requirements are aptly met in the high-voltage flash-discharge tube which is becoming increasingly popular in spectroscopic work. These flash tubes are also finding use in other fields such as photography of fast events, and flash photolysis.

The high intensity continuous spectra of the flash tube is achieved by the impulsive discharge of high energy through a gas at low pressure; the gas is confined within an insulating tube of small diameter. In early designs this tube suffered from fairly rapid erosion of wall material because of the high temperatures involved, and subsequent deposition onto the windows present in the system. Also qualitative intensity work has been impossible because the intensity has not been reproducible to a sufficiently accurate degree.

These flash-discharge sources may be roughly divided into three main types and although they appear to be quite similar in operation, all employing the discharge through a gas of capacitively stored electrical energy, there is a fundamental difference in the mechanism of emission and the
details of operation.

The first type of discharge tube is called the Lyman flash tube and has been used extensively in the production of the Lyman continuum which extends from about 600 Å to the visible range on the electromagnetic wavelength scale. The tube has a narrow bore (∼0.1 cm) and moderate length (∼5 cm). This source, however, suffers from the rapid erosion of electrode and wall material with a consequent reduction of current density.

The second type of tube is a thick-walled capillary (∼0.2 cm diameter by 3 cm length) between heavy electrodes in series with a heavy-current hydrogen thyratron and condensor bank. The inert gas in the tube is at a relatively high pressure.

The third general type increases the size of the capillary tube to about 1 cm and uses rapid discharge condensors. The circuitry is designed to reduce the inductance as much as possible and hence a coaxial symmetry is employed. Thus these tubes are called coaxial flash tubes. They show a marked improvement in electrical and spectroscopic properties over the Lyman flash tube, the main advantage being their reliable intensity reproducibility which allows them to be used for qualitative work.

Budd describes the construction of a coaxial flash tube inspired by the work of Garton and which he used in some preliminary experiments in absorption in neon gas.
Deposition of material on the exit window with consequent decrease of intensity was a great problem and since the tube's usefulness depends on an intensity which does not vary with the number of firings of the tube, the need of a more reliably operating flash tube was apparent.

This thesis describes the construction of a contamination-free continuum coaxial flash tube having good intensity reproducibility. Its construction and maintenance is extremely simple and inexpensive and the complete apparatus is very mobile which allows speed and convenience in its use. The brightness temperature of the flash tube is measured in the visible wavelength range by comparison with a tungsten filament lamp of known temperature.
2. Theory of Low-Pressure Discharges

2.1 Introduction

The main object of this experiment has been to design and construct a deposition-free flash tube with faithfully reproducible properties and simple constructional details; and also to measure its temperature. Although some of the early difficulties were overcome by a semi-empirical "cut-and-try" method it is useful and interesting to delve into the physics of a low-pressure gaseous discharge. The results of doing so have explained some of the shortcomings of the flash tube in its present configuration and will doubtless be equally rewarding in the future.

The theory of low-pressure discharge and all its ramifications covers an enormous field and much work has been done both theoretically and experimentally over the last few decades. Much theory is still incomplete, however, and consequently interpretation of data is sometimes somewhat unsatisfactory. It is obvious that the discussion to follow must be abbreviated perhaps to the point of being incomplete; the main aspects of discharges which are of interest to this work have been briefly touched upon and it is hoped the above mentioned fault is not apparent.
2.2 Particle Theory of Gases

2.2.1 Distribution Functions

To describe exactly the actions of two interacting particles is usually possible but when the number is three or more the mathematics becomes formidable and analytic approximations must be made. In dealing with plasmas, where the particle density may vary between \(10^{10} \text{ cm}^{-3}\) to \(10^{25} \text{ cm}^{-3}\), a mathematical description of the individual particle motions is obviously impossible.

Many properties of gases and plasmas may be predicted by considering the gas as composed of a large number of particles and treating them statistically. This is done by the introduction of the distribution function \(f\) which is defined such that

\[
f(x,y,z,u,v,w,t) \, \text{d}x \, \text{d}y \, \text{d}z \, \text{d}u \, \text{d}v \, \text{d}w
\]

represents the average number of particles between \(x\) and \(x + \text{d}x\), \(y\) and \(y + \text{d}y\), \(z\) and \(z + \text{d}z\) with velocities between \(u\) and \(u + \text{d}u\), \(v\) and \(v + \text{d}v\), \(w\) and \(w + \text{d}w\) at time \(t\), where \(x, y,\) and \(z\) are the rectangular cartesian coordinate positions and \(u, v,\) and \(w\) are the corresponding velocities. \(f\) is the particle density in position-velocity 6-space.

Many useful relations may be deduced from a knowledge of the distribution function. For example, the particle density in space is given by

\[
n(x,y,z,t) = \iiint f(x,y,z,u,v,w,t) \, \text{d}u \, \text{d}v \, \text{d}w
\]
and the average velocity by

\[ \vec{v}_{av} = \frac{1}{n} \int f \, d\vec{v} \]

where \( \vec{v}_{av} \) is the average velocity and \( d\vec{v} \) represents the volume \( du \, dv \, dw \) in velocity space. Many other macroscopic properties of a gas may be calculated from this position-velocity distribution.

For precise results in the kinetics of plasmas, Boltzmann's equation must be applied. This is an integro-differential equation involving \( f \) and describes its behaviour as a result of external forces on the particles and also encounters among the particles. It is derived by considering the conservation of particles in a small volume element in 6-space. In the absence of collisions, this equation reduces to Liouville's equation.

2.2.2. Collisions

Collisions between particles is an event which, at first sight, seems simple enough, but when a detailed investigation is made, any apparent simplicity disappears. Even a consistent definition of a collision is not an easy thing. A dictionary will define it as an act of hitting or coming into violent contact, which, from an atomic point of view, is wholly unsatisfactory. For it is a well accepted fact
that an atom is not solid and the word "contact" has no real meaning on this scale.

A collision could be defined, however, as an event between two or more particles that approach each other relatively closely and whose states of motion and/or energy are changed significantly by virtue of their proximity.

Collisions between particles may be roughly divided into two main categories - those in which the nature of one or more of the colliding particles is altered, and those in which the nature of the particles remain unaltered. Those in the first-mentioned category are called inelastic collisions and those in the second elastic collisions.

In both elastic and inelastic collisions, a useful concept is the collision cross-section which is represented by $\sigma$ and defined for binary collisions by the equation

$$\frac{dn}{dt} = \sigma n_1 n_2 \bar{u}$$

where $n_1$ and $n_2$ are the particle densities of the two colliding species, $\bar{u}$ is the average relative velocity between the particles, and $\frac{dn}{dt}$ is the rate of collision. A large value of $\sigma$ implies a high probability for collision, and conversely. The cross-section is dependent upon the nature of the interparticle forces and the relative velocity of the particles.
In elastic collisions the total kinetic energy of the particles is conserved; this type of collision is not of much interest in the study of the discharge of the gases and will not be further mentioned.

On the other hand, inelastic collisions play a cardinal part in ionization and excitation of gases. Inelastic collision processes may be subdivided into two classes, which are called collisions of the first kind and collisions of the second kind. In the first, the total kinetic energy of the colliding system is reduced by the collision; and in the second, the potential energy of at least one member is reduced. The product in both these collisions is such things as ionization, excitation, dissociation and so forth.

Some of the more frequent participants for binary inelastic collisions are electrons and neutral atoms either excited or in the ground state, electrons and ionized atoms, neutrals and ions, ions and ions.

2.3. Discharge Mechanics

2.3.1. Introduction

When a gas is located in a region of an electric field a current will flow in the direction of the field; however in small electric fields gases show little conductivity and the current is of low value. Cosmic rays, $\gamma$-radiation and radioactive traces in container walls produce this small amount of
conductivity. Application of any agency which causes liberation of electrons and ions from surfaces or liberation of electrons from atoms in the gas will augment these currents and breakdown of the gas with its corresponding increase in conductivity may occur.

2.3.2. Primary Ionization

The processes controlling conduction in the gas may be divided into two main categories, primary and secondary.

In the primary process each electron liberated creates an avalanche of new electrons and ions by collision with the gas molecules by transferring part of the kinetic energy of the impacting electron to the gas molecule which subsequently ionizes. The observed current growth is given by the relation

\[ I = I_0 \alpha^x \]

or more exactly

\[ I = I_0 \exp \int_0^x \alpha \, dx \] \hspace{1cm} \text{... (1)}

where \( I_0 \) is the initial current at \( x = 0 \) and \( I \) is the avalanche current at \( x \). \( \alpha \) is called the first Townsend coefficient and represents the number of new ion pairs created per unit distance in the field direction per electron.
This can be seen from the following considerations. Let \( n_0 \) electrons be present at \( x = 0 \); at the point \( x \) the number has been increased to \( n \) by ionizing collisions. These \( n \) electrons in moving through a lamina of thickness \( dx \) in the direction \( x \) of the electric field will generate by collision \( \alpha dx \) new electrons so that \( \Delta n = \alpha dx \). Since \( I \propto n \), equation (1) follows. It may also be written in the form

\[
I = I_0 (M + 1)
\]

where

\[
M = \exp(\int_0^x \alpha \, dx) - 1
\]

and is called the amplification factor.

### 2.3.3. Secondary Ionization

In the process of creating \( I_0 M \) avalanche electrons and ions, there may be secondary agencies which can regeneratively create \( \gamma I_0 M \) new electrons to start new avalanches. The current can then be given under many circumstances by

\[
I = \frac{I_0 \exp(\int_0^x \alpha \, dx)}{1 - \gamma M} \quad \text{... (2)}
\]

A derivation of this equation is given by von Engel. \( \gamma \) is called the second Townsend coefficient and for \( \gamma M \) less
than unity, \( I \) represents the current of increased magnitude over that caused by the primary \( I_0(M+1) \) process alone. \( \gamma \) is in general relatively small.

Some of the possible secondary processes are:

1) Secondary emission of electrons due to positive ions incident on the cathode.

2) Cathode emission of electrons due to incidence of photons from excited gas molecules.

3) Ionization by positive ions and metastable atoms on impact with molecules of the gas.

4) The action of photo-ionization in the gas.

The first two processes are influenced by the pressure of the gas, for the number of electrons released to actively take part in the subsequent conduction and ionization processes is reduced by back-diffusion to the cathode.

It should be pointed out that these mechanisms play a truly secondary role because they are relatively small with respect to the primary factor \( M \), and their most important function is to sustain primary action.

Returning now to equation (2), it is seen that as long as \( \gamma M < 1 \), the current flowing in the gas has a definite value, and is larger than it would be if the primary effect represented by \( \alpha \) were acting alone.

Ignoring equation (2) for the moment, note that when \( \gamma M = 1 \) the condition is such that for each avalanche of \( M \)
electrons there is produced a new electron capable of yielding a new avalanche. This is what is called the threshold condition of a self-sustaining discharge. An avalanche started by a single electron becomes self-perpetuating and the discharge is capable of maintaining itself regardless of the value of $I_0$. The gain in electron density resulting from the ionization of the gas becomes equal to the loss of electrons by diffusion, recombination or attachment.

For

$$\gamma M > 1 \quad \cdots \quad (3)$$

the succession of avalanches creates more current carriers than is necessary for self-maintenance and the current will become excessively large, the conductivity nominally going to infinity. The gas has undergone an electrical breakdown to a conducting state.

This breakdown condition may be brought about in several ways. One is to increase the voltage across the electrodes in the gap. This voltage required to accomplish breakdown is called the breakdown voltage and effectively increases the factor $M$ so that condition (3) is met.

A second method is to use a mechanism which increases the effect of the above-mentioned secondary processes such as an ultraviolet light pulse to increase secondary emission and ionization or a spark introduced in the gas across a
spark gap (the production of the spark is accomplished, of course, by the breakdown voltage method just mentioned). Now condition (3) is met by an effective increase in $\gamma$.

2.4. Radiation

2.4.1. Radiation Theory

Two processes must be considered when radiation from gaseous discharges is discussed; the release of radiant energy from the gas molecules, and the delivery of energy to the gas molecules.

In releasing radiant energy, the energy state of the molecule proceeds from a higher to a lower level; the frequency of the released radiation is given by the Planck relation

$$\hbar \nu_{nm} = E_n - E_m$$

where $\hbar$ is Planck's constant, $\nu_{nm}$ the frequency, and $E_n$ and $E_m$ are the higher and lower states of the molecule. The probability per unit time that a transition from the $n^{th}$ to the $m^{th}$ energy state will occur is given by

$$A_{nm} = \frac{64 \pi^2 \hbar^2 \nu_{nm}^3}{3 \hbar c^2} \left| \chi_{nm} \right|^2$$

where

$$\chi_{nm} = \int \psi^*_n \psi_m dV.$$
\( \psi_n \) and \( \psi_m \) are the wave functions pertaining to the energy states \( n \) and \( m \), and \( dV \) is an element of volume.

If the states are bound, that is, negative energies, then the \( \psi \)-functions are normalized to unity, and if either state is unbound, that is, the molecule is ionized, then the corresponding wave function has the asymptotic form of a plane-wave.

When both states are unbound, classically the free electron passes close to a nucleus and is accelerated by the nuclear charge; radiation takes place by virtue of the electron's acceleration. This process is called bremsstrahlung.

If the final energy state of the molecule lies higher than the initial, the reverse process to emission takes place, absorption. This process is governed by the probability \( B_{mn} \) that absorption will occur per unit time per unit density of monochromatic energy in the region of the absorber, where

\[
B_{mn} = \frac{8\pi^3 \hbar^2}{3g_n \hbar^2} |\chi_m|^2
\]

\( g_n \) stands for the statistical weight of state \( n \).

In addition to spontaneous emission, governed by \( A_{nm} \), there is the process of induced emission which can occur in the presence of radiation. For this process the coefficient \( B_{nm} \) is the probability for forced emission to occur per unit
time, per unit density of monochromatic radiant energy in the vicinity of the emitter. Theory shows that

\[ B_{nm} = \frac{8\pi^3 \omega^2}{3h^2} |\chi_{nm}|^2 \]

An energy balance equation can be written if a state of thermal equilibrium exists between radiation and radiators,

\[ (A_{nm} + B_{nm}\rho)N_n = B_{mn}\rho N_m \]

where \( \rho(n_m) \) is the monochromatic radiant energy density, and \( N_n \) and \( N_m \) are the number of molecules in states \( n \) and \( m \) respectively.

However in most practical instances, the radiators in a low-pressure gas discharge are not in a state of thermal equilibrium with the radiation. Spontaneous emission greatly exceeds absorption, which in turn occurs much more frequently than forced emission.

Before the radiative process can occur, the molecule must be in an elevated energy level. This brings up the second process that must be considered, the delivery of energy to the gas molecules. This is achieved by inelastic collisions.

The prime source for energy elevation is elatation which is the name for excitation and ionization by inelastic collisions of the first kind. Radiators in any state may
absorb the kinetic energy of impinging particles and transform to a higher energy level. The conditions to be fulfilled for this to happen are that energy and angular momentum must be conserved. The angular momentum requirement prohibits certain bound transitions.

Free electrons are the most efficient impacting particles because they possess the most favourable mass ratio for energy transfer. Von Engel\(^9\) shows that the maximum energy, \(\triangle\), that can be transferred from the impinging particle to the atom is given by

\[
\frac{\triangle}{E_0} = \frac{m_i}{m + m_i}
\]

where \(m = \text{mass of atom}\), \(m_i = \text{mass of impinging particle}\), and \(E_0 = \text{initial kinetic energy of the impinging particle}\). For an impinging electron, \(m_i \ll m\) and therefore \(\triangle \ll E_0\); for any heavier particle, \(\triangle \ll E_0\). Positrons are presumably just as effective.

Another process, mentioned previously, which excites or ionizes radiators is photon absorption. Rigorous selection rules govern the excitation process and for ionization there are probably three processes which occur.

First, the direct absorption of photons with energy exceeding the ionization energy and subsequent ejection of an electron. Second, the absorption of discrete line radiations
followed by ionization by collision with other particles while the excited state persists. Third, non-monatomic molecules can be excited to high molecular states and then spontaneously dissociate into molecular ions.

However, for gases at low pressure absorption of photons does not play as important a part in exciting or ionizing as do collisions.

2.4.2. Recombination

Once the gas molecules have been ionized and energy is no longer being injected into the system, the process of de-ionization takes place. The electrons and the ions are recombined and the gas returns to a neutral state. The two types of recombination are volume and surface recombination; volume recombination takes place in the volume of the gas and surface recombination takes place on the surface of the container walls.

Volume recombination depends on random collisions occurring in the volume of the gas. For binary collisions, the number of recombinations per unit time is given by

$$\frac{dn}{dt} = \sigma_r u n_+ n_-$$

where $\sigma_r$ is the recombination cross-section, $u$ is the relative speed, and $n_+$ and $n_-$ the density of the
recombining particles. The product $\sigma_r u$ is averaged. For three-particle collisions, the recombination rate is given by

$$\frac{dn}{dt} = \eta \sigma_r u n_+ n_- n_o$$

where $\eta$ is the effective volume of the third particle and $n_o$ its density. In either case these factors are combined into a single coefficient $\alpha$, called the recombination coefficient, so the rate is expressed as

$$\frac{dn}{dt} = \alpha n_+ n_-$$ \hspace{1cm} \text{(4)}$$

The probability of recombination depends on the relative speed of the particles and decreases the faster the particles move with respect to one another. This is because the time interval during which they are in close proximity and which is available for recombination varies inversely with the speed. It should also vary with the effective diameter of the ions, being larger for excited ions.

Volume recombination takes place by five principal methods.

1) Radiative electron recombination. A free electron combines with a positive ion into an excited atom and a photon possessing the surplus energy required to satisfy the
conservation of energy. The probability for electron capture into the lower states is greater the lower the state. In addition to satisfying conservation of energy, the liberated photon must satisfy conservation of angular momentum.

2) Dielectronic recombination. In this instance a free electron combines with a positive ion and the excess energy of the electron is given to a second electron in the atom so that a doubly excited ion is formed. This situation is unstable and may lead to auto-ionization or be stabilized by collision or by radiating.

3) Three-body electron recombination. If a third particle is in the vicinity of an electron-ion recombination, the surplus energy from the act is taken up by the third body in the form of kinetic energy.

4) Dissociative recombination. When a positive molecular ion combines with an electron, the excess energy may be utilized in dissociating the molecule into its constituent atoms of which one or all may be excited.

5) Mutual neutralization. This process is simply the recombination of a positive and a negative ion. Preliminary processes must involve the preparation of negative ions which limits this process to electronegative gases.

In a high density mixture of approximately equal concentrations of ions and electrons, the electrons tend to diffuse rapidly away towards regions of lower density such as
the walls of the containers thus creating a positive space change. An electric field is set up which retards the electrons and accelerates the ions so that both diffuse at the same rate. This process is known as ambipolar diffusion and is governed by the ambipolar diffusion constant \( D_a \). The equation for particle concentration under ambipolar diffusion effects only is

\[
\frac{dn}{dt} = D_a \nabla^2 n
\]  

Under ambipolar diffusion, the particles diffuse until they strike the walls of the enclosure and surface recombination takes place. It may result in luminescence but little is known about this process. Probably most of the surface recombination results merely in heating the surface. Surface recombination is an extreme case of three-body electron recombination.

If both ambipolar diffusion and volume recombination effects are present, then the equation for electron concentration becomes, from (4) and (5)

\[
\frac{dn_e}{dt} = D_a \nabla^2 n_e - \alpha n_e^2
\]  

It is assumed that the electrical discharge maintains a high degree of local neutrality so that \( n_e = n_i \) for singly
ionized gases.

Explicit solutions of this equation are possible but have not been utilized. Limiting solutions are obtainable, however, both for when recombination is negligible, and when diffusion is negligible. In the former case, the solution is in the form of an exponential decay, with the time constant dependent on the diffusion constant and the geometry of the discharge.

When diffusion is negligible, the solution of (6) is

\[ \frac{1}{n_e} - \frac{1}{(n_e)_0} = \alpha t \]...

where \((n_e)_0\) is the electron density at \(t = 0\).

2.4.3. Continua

The continuous spectrum observed in a gas discharge can originate in several ways.

For the case of electron-ion recombination, the electron can approach and be caught by the ion, while the energy of recombination may be emitted as a quantum of radiation. In general the electron has a kinetic energy \(E\) and so emits radiation of frequency

\[ \nu = \frac{eV}{\hbar} + E \]
where $V_i$ is the ionization potential of the ion. If the electrons have an energy distribution, then the emitted spectrum is a continuum beginning at the series limit and extending to infinity. However, since the probability for recombination is larger for a small relative velocity between the electron and the ion, the continuum will be most intense at the series limit and will fall rapidly beyond it.

Certainly the most important contribution to the continuum comes from the so-called free-free transition of the electron, or bremsstrahlung. This is, from a quantum point of view, the displacement of the electron from one free energy level to another with release of energy $\Delta E$ of frequency $\frac{\Delta E}{\hbar}$. Thus in a plasma where electrons move at random, energy is radiated continuously over a wide band of frequencies. This radiation is also called retardation radiation.

Some other types of continua of lesser importance are molecular dissociation continua, pressure continua from collision interference with line radiation, and attachment continua.
3. The Flash Tube

3.1. The Flash Tube Discharge Model

Briefly, the flash tube operates in the following manner. A gas at low pressure is confined in an insulating tube between two electrodes. This tube is placed across the terminals of a low inductance condenser which is charged to a high voltage. The condenser is discharged through the gas which emits copious amounts of high-intensity light.

An equivalent circuit for the flash tube and discharge condenser is desirable for analysis. The circuit is shown below.

\[
\begin{array}{c}
\text{C} \\
\hline
\text{L} \\
\hline
\text{R}_L \\
\hline
\text{R}_T
\end{array}
\]

where \( C \) = capacitance of the discharge condenser, \( L \) = condenser and tube inductance, \( R_L \) = tube lead resistance, and \( R_T \) = flash tube impedance. To make analysis simpler, it has been assumed that the discharge impedance is purely resistive.
The differential equation governing this circuit when the switch is closed at time \( t = 0 \), corresponding to the firing of the flash tube, is

\[
L \frac{d^2i}{dt^2} + R \frac{di}{dt} + \frac{i}{C} = 0
\]

where \( R = R_L + R_T \)

Three different solutions are possible.

1) \[
\left( \frac{R}{2L} \right)^2 > \frac{1}{LC}
\]

The solution is then given by

\[
i(t) = \frac{V_0}{2LN} \left( e^{at} - e^{-bt} \right)
\]

where \( \eta = \left[ \left( \frac{R}{2L} \right)^2 - \frac{1}{LC} \right]^{\frac{1}{2}} \)

\[
a = -\frac{R}{2L} + \eta
\]

\[
b = -\frac{R}{2L} - \eta
\]

\( V_0 \) = initial voltage on the condensor.

This is an exponential current form which for \( 0 < t \ll -\frac{1}{a} \) rises with time constant approximately equal to \( -\frac{1}{b} \) since
a > b , and for \( t \gg -\frac{1}{b} \), decays with time constant \(-\frac{1}{a}\).

2) \[
\left(\frac{R}{2L}\right)^2 = \frac{1}{LC}
\]

The solution is

\[
\dot{c}(t) = \frac{V_0 t}{L} e^{at}
\]

where

\[
a = \frac{R}{2L}
\]

This is a critically-damped wave.

3) \[
\left(\frac{R}{2L}\right)^2 < \frac{1}{LC}
\]

This case yields a solution which is given by

\[
\dot{c}(t) = \frac{V_0}{\omega L} e^{-\frac{R}{2L}t} \sin \omega t
\]

where

\[
\omega = \left[\frac{1}{LC} - \left(\frac{R}{2L}\right)^2\right]^{\frac{1}{2}}
\]

This is a damped sine wave.

If the logarithmic decrement is defined by

\[
\delta_D = \ln \left[ \frac{\dot{c}(t)}{\dot{c}(t + \frac{2\pi}{\omega})} \right] = \frac{\pi R}{\omega}
\]
then $L$ and $R$ may be calculated from

$$L = \frac{\tau^2}{C} \frac{1}{4\pi^2 + L_D^2} \quad \ldots \quad (8)$$

$$R = \frac{L \cdot L_D}{\tau} \quad \ldots \quad (9)$$

where $\tau$ is the period of oscillation.

3.2. Desirable Characteristics

Before a discussion of the construction of the flash tube and measurement of some of its properties is given, some of the desirable properties of a flash tube will now be mentioned. They are given in the approximate order of their importance.

The first requirement is that the emitted radiation be of a continuous nature. The need for continuum radiation for absorption spectroscopy is obvious and any emission or absorption lines introduced by the background source can only result in a further complication in the analysis. A few isolated lines may perhaps be tolerated provided they do not lie close to the wavelengths involved in any experiment, but any effort to remove them should be encouraged.

As was pointed out in Anderson's\textsuperscript{10} investigation of
the spectrum of flash tubes, current densities in the discharge must be of the order of 20,000 amp/cm$^2$ for the production of a strong continuum. It can be seen from the equations derived in the preceding section that high current may be achieved by using a high charging voltage and having a low circuit inductance. The first requisite is easy to accomplish. A low circuit inductance demands the use of a low inductance capacitor and a coaxial design of electrode leads. A low inductance will also reduce the discharge time which may or may not be an advantage depending on the desired use of the tube.

For absorption to take place in a gas, the background source must have a greater intensity than the absorber. This requires a high brightness temperature from the flash tube and as pointed out by Budd$^5$, both a continuous spectrum and high temperatures are products of the same condition; both may be achieved with high currents.

If the intensity of the tube is high enough, a single flash through the absorber may be sufficient to get a useful photographic record, otherwise a superposition of more than one flash may be necessary. In any case, the method that is hoped to be used for future work in absorption analysis will require the exposure of at least two different photographic plates. A prime necessity for the success of this procedure is that the intensity not vary from one shot to the next. Without this characteristic, quantitative analysis is not
possible.

It is hoped in the future to use the flash tube for analysis of short-lived phenomena such as shock fronts and pinched plasmas. This will require fastidious timing in the triggering of the flash tube and whether this is possible depends on the jitter time of the triggering process. By jitter time is meant the variation in time from the application of the triggering mechanism to the initiation of the discharge through the tube. Since shock fronts move at a speed of the order of 1 cm/μsec a jitter time of no greater than 1 μsec is required for any time-resolution studies.

And finally there are two mechanical properties to be desired. The first is easy alignment with other units, notably the absorber and the spectroscope, and the second is simple construction details for easy replacement or repairs.

3.3. Early Designs

A description of some of the earlier flash tube designs will now be given before the final design is discussed.

3.3.1. The Elbow Tube

In an effort to eliminate the deposition of materials on the exit windows, it was decided to try to use the scouring effect of the discharge current. This could most simply be done by using a right-angled tube, as shown schematically in figure 1(a). The current flowing around the corner would
(a) elbow tube
scale: full size

(b) low-inductance tube
scale: half size
scour the top section of the tube at the curve and prevent any ebullition from being deposited there.

The scouring process worked quite well; initially a transparent yellow substance was deposited all over the inside of the tube, but after the first 10 shots or so, did not get appreciably worse. The main drawback was that the spectrum contained too many emission lines overlying the continuum; because of the bend, the portion of the discharge which was scouring was cooled by the walls of the tube and the light from this cooler gas was entering the spectroscope, as well as the light from the hotter, continuum-forming gas in the center of the tube. A minor mechanical disadvantage was the difficulty encountered in aligning the tube accurately.

The tube was attached to the aluminum electrodes with black wax and the discharge triggered by a spark across a pair of tungsten wires waxed through a hole in the grounded electrode. The electrodes were clamped in copper collars by radial screws which were in turn attached to the condenser electrodes by copper plates.

Initially a glass tube was used, but the heat from the discharge crazed the glass, eventually causing it to break after about 50 shots. With a quartz tube, the crazing did not occur so the tube did not break.

The waveform of the current was an excellent reproduction of a damped sine wave, case 3) of section 3.1. The
resistance and inductance computed from equations (8) and (9) were .034 ohms and 84.4 μH henries respectively.

3.3.2. Low Inductance Tube

In an effort to achieve a better continuum, while still employing the scouring effect, a low inductance circuit was designed, as shown in figure 1(b).

The low inductance was achieved by use of a more coaxial circuit about the flash tube, and by having the connecting leads to the condenser close together. The grounded electrode of the tube was connected to the ground plate by a metal gauze collar.

The discharge was viewed side-on instead of end-on as before, by looking through a hole in the wire gauze. The spectrum did not seem to be much improved, if at all. Some of the emission lines were more diffuse but others were sharper than before. Also the intensity was much less so this configuration was abandoned.

The current was a damped sine wave with R and L found to be .036 Ω and 31.3 μH.

3.3.3. Tungsten-electrode Tube

In an attempt to keep the introduction of foreign materials into the discharge to a minimum, a radical type of flash tube was tried next. The electrodes at both ends of
2(a) tungsten-electrode tube

2(b) covar tube

2(c) covar tube with dump chamber
the tube consisted of 4 radial tungsten wires set through the glass tube, as shown in figure 2(a). These wires were then joined together externally by a copper strip and thence attached to the condenser. At one end of the tube, beyond the electrodes, was attached the vacuum pump while at the other end, a glass window was cemented on with de Kotinsky wax.

Triggering was effected by a spark between one of the grounded tungsten electrodes and a fifth tungsten wire inserted through the glass close to the grounded electrode.

The window stayed clean for the first ten shots but then a deposition rapidly formed. Also the spectrum, while possessing a good background continuum, had many overlying emission lines. For this reason, and also because of the awkward geometry, work on this tube was halted.

3.3.4. Covar-electrode Tube

Still keeping in mind the necessity for elimination of foreign materials from the discharge, the next attempt used covar electrodes with a covar-to-glass seal to the tube. This was to circumvent the use of wax as a seal which could cause contamination if any of it was immersed in the discharge. The arrangement of the capacitor leads was the same as was used in the final design and hence will be described below.

The tube was triggered by a covar wire sealed through the glass near the grounded electrode and bent back so it was
close to the electrode. Initially the window was cemented onto the covar (see figure 2(b)) but this introduced wax into the discharge so then a brass chamber was soldered onto the covar and the window waxed onto the brass (figure 2(c)). It was hoped that little of the discharge would reach the wax around the window. Deposit still formed on the window however, and also the covar trigger pin was affected by the discharge so that a spark between it and the electrode would not occur after only 5 discharges. Finally, after cleaning the trigger pin, a circular glass baffle was placed in the brass chamber close to the covar electrode. The hole in the center of the baffle was of such a size that the covar electrode could not "see" the window. This led to the final design of the tube and is now to be described.

3.4. Final Design

3.4.1. Description

The flash tube design finally arrived and is shown in figure 3. The operation of the tube is as follows. The aluminum electrode \( E_1 \) cemented to the quartz discharge tube is connected to the 4.8 cm long, 2.7 cm inner diameter copper collar \( C_1 \) by means of 8 radial screws \( S \). This copper collar is connected to the ground terminals of the condenser through the copper lead \( L_1 \). The other aluminum electrode \( E_2 \) is attached to the copper collar \( C_2 \) by a wire gauze which is
fig 3 final design
scale: full size
soldered to the collar and secured to the electrode by a metal strap. Collar $C_2$ is connected to the other terminal of the condenser by the copper lead $L_2$. When the tube is fired by application of the trigger pulse on the trigger pin, the current flows from the condenser up through $L_2$, along $C_2$ to $E_2$ by way of the wire gauze, through the inside of the quartz tube to $E_1$ and thence to the other condenser terminal via $S$, $C_1$, and $L_1$. $L_1$ and $L_2$ are insulated from each other by a perspex sleeve $P_s$, 7.5 cm long and 2.0 cm inner diameter, set in a perspex plate $P_1$, 1.5 mm thick.

The aluminum electrodes $E_1$ and $E_2$ are joined to the quartz tube with de Kotinsky wax, but because of the snug fit of the tube into the inner shoulder of the electrode, the wax remains in the outer shoulder and is not immersed in the discharge in any way. Aluminum was chosen as electrode material because of its low sputtering rate.

The tube itself was made of quartz 10 cm long and .9 cm inner diameter, 1.2 cm outer diameter. Quartz was chosen for its better ability to withstand the heat generated by the discharge. Quartz also does not show strong absorption lines caused by absorption in the vapour scoured from the walls of the tube. Glass shows the sodium D lines strongly in absorption.

The triggering device is a small covar tube in glass set into the electrode $E_1$ and a tungsten wire placed far
enough through it so the end of the wire is close to the opposite inner side of the electrode. The covar pin is permanently sealed to $E_1$ with epoxy resin, and the wire with de Kotinsky wax for easy replacement if necessary.

When a high voltage pulse is applied to the trigger wire, a spark jumps from the end of the wire to the electrode and discharge of the condenser begins.

A 1/16 inch circular glass baffle is set into the electrode $E_2$ as shown, and stops the discharge debris from reaching the window $W_2$. The hole in the baffle is small enough so that any particles travelling in a straight line from the discharge side of $E_2$ will hit the baffle rather than the window. The baffle is held in place by a thin-walled aluminum tube which fits closely into the chamber of $E_2$ and is braced against the window $W_2$. Both $W_1$ and $W_2$ are glued to their respective electrodes with de Kotinsky wax of which a minimum amount is used to allow as little as possible to enter and contaminate the discharge.

The coaxial symmetry of the leads were chosen for the low inductance and also for the low radiating efficiency.

Because of the high current flowing in opposite directions in the copper leads, a repulsive force is set up and the leads tend to be forced apart. The purpose of the wire gauze connecting the electrode to the copper collar is to absorb this shock. A perspex clamp is also used to help
hold the plates together. Originally both electrodes were clamped by radial screws, but the wax or even the tube would crack after not too many discharges.

3.4.2. Operation

The voltage impressed across the electrodes was from 15 to 20 kV. Below 15 kV the spectrum showed many emission lines overlying the background continuum and at 15 kV these lines were few and diffuse. An increase in charging voltage tended to broaden the lines and make the continuum better. Twenty kV was chosen as an upper limit for the charging voltage because this is close to the maximum voltage rated by the condenser manufacturer and also above 20 kV the danger of the tube shattering upon firing was increased.

The pressure in the tube was about .1 μ or lower. The actual value of the pressure was not measured accurately since the pressure required was just that which would "hold" the applied voltage without spontaneous breakdown. This would eliminate the need for any series trigger spark-gaps which would only complicate the circuitry and make a less efficient discharge. It has been found by other workers in this field ¹¹ that the intensity of the radiation is independent of initial pressure in the tube over a wide pressure range. Thus the low pressure was required only because of the high voltage.
3.4.3. Experimental

The experimental procedure in designing the flash tube was fairly straightforward. The two important requisites that had to be met were a high intensity continuum and a constant peak intensity. The light output of the different tube configurations was examined with a Hilger medium quartz spectroscope and a Hilger automatic quartz spectroscope to observe the quality of the continuum. A photomultiplier-emitter-follower unit, described below, was used to observe the intensity of the radiation from the flash tube. This was done by setting the photomultiplier about 10 feet from the tube and observing the intensity trace on a Tektronix oscilloscope type 533. The decrease in peak intensity with number of shots was recorded with a Polaroid oscilloscope camera.

To observe the discharge current a small pick-up coil was placed close to the discharge. The change of magnetic flux in the coil induced an e.m.f. given by

\[ V = M \frac{di}{dt} \]

where \( M \) is the mutual inductance between the coil and the discharge circuit and \( \frac{di}{dt} \) is the derivative of the current. This signal was fed through an analog integrator to the oscilloscope, giving a signal proportion to the current.
3.5. Apparatus

3.5.1. Charging Condenser and Charging Unit

As mentioned in Section 3.2. a low inductance circuit is desirable to achieve high current densities. For this reason the condenser used was a 1.6 μf low inductance, 25 μh, 25 kV condenser manufactured by Cornell-Dubilier, model NRC 323.

The charging unit is capable of delivering 27 kV at 50 ma and is a standard full-wave voltage-doubler circuit filtered by an L-C network. A current-sensitive relay in series with the current meter closes a set of contacts which opens primary power to the high voltage transformer and drops a shorting switch. Thus the voltage may be applied to the charging condenser up until the instant of firing; when the flash tube is discharged the charging unit is prevented from recharging the condenser by the current trip and shorting switch.

3.5.2. Trigger Unit

The trigger unit was designed after the work of Theophanis and delivers a 40 μsec, 32 kV pulse to the trigger pin to initiate the flash tube discharge. See figure 4. A three-meter long, type RG58u coaxial cable is charged to 16 kV. The far end of the cable is terminated with a 500 pf, 20 kV condenser paralleled with a 100 KΩ resistor; this gives essentially an infinite termination. The sheath of the coaxial cable is grounded while the inner conductor at 16 kV
Fig. 4. Trigger Unit

is connected to the anode of a 5C22 hydrogen-filled thyatron which is in its non-conducting state. When a positive pulse is applied to the grid of the thyatron causing it to conduct heavily, it essentially shorts the end of the attached coaxial cable, sending a negative 16 kV pulse down the cable. This pulse is reflected at the far end with a reflection factor of +1 and in order that the voltage across the condenser remains "instantaneously" constant, the far side of the condenser must fall to minus 32 kV. This pulse is taken off across the resistor.
The positive pulse required to trigger the thyatron is provided by a 2D21 tetrode which is normally in a state of cut-off until its grid is shorted by a manual micro-switch or by application of a positive pulse.

3.5.3. Photomultiplier Unit

The photomultiplier unit was used to determine the variation of the wavelength-integrated light output of the flash tube with the number of shots. This unit consisted of a 931A photomultiplier and a 2N1177 transistor in a common collector or emitter-follower configuration. See figure 5.

![Photomultiplier Unit Diagram]

**Fig. 5.** Photomultiplier Unit
The unit was completely enclosed with its power supplies in a brass box to avoid electrical pickup from the discharge. Even then it was found that the unit had to be placed about 10 feet from the discharge before pickup was negligible.

It was found that shot noise in the photomultiplier greatly masked the output signal at low output voltages; this shot noise originates essentially in the cathode-dianode-number-one region and can be reduced by increasing the current between these stages. Non-linear and saturation effects were found to occur in the later stages of the photomultiplier when all dianodes were connected, however, and so dianode No. 7 was used as the anode, and the anode and dianodes No. 8 and 9 were strapped to dianode No. 6. This almost completely eliminated the noise in the output voltage range that was encountered.

The common collector transistor circuit was used to match the high output impedance of the photomultiplier to the 52 ohm characteristic impedance of the coaxial cable connecting the unit to the oscilloscope. With a 52 ohm impedance match at the 'scope end of the cable, ringing in the circuit was eliminated. The unit was tested for linearity using a .5 μsec light pulse and was found to be linear for an output signal up to .4 volts. The rise-time was less than .1 μsec.
4. Brightness Temperature Measurement

4.1. Introduction

4.1.1. Black Bodies

Light radiation is the transfer of energy travelling in the form of electromagnetic waves, and the standard for all radiators is the black body.

A black body may be simply defined as a body that absorbs all the radiation which falls upon it. It can be shown theoretically and has been verified experimentally that such a body will radiate energy of an amount which depends only on the temperature of the body.

This leads to one of the fundamental laws which determines the manner in which a black body radiates its energy, the celebrated Planck radiation law which tells how the radiant energy varies with the wavelength of the radiation and with the temperature of the radiating body. This is given by

\[ J_\lambda d\lambda = \frac{C_1 d\lambda}{\lambda^5 \left[ \exp \left( \frac{C_2}{\lambda T} \right) - 1 \right]} \]

(10)

where \( J_\lambda \) = the spectral radiant intensity per unit wavelength at a temperature \( T \) in the wavelength interval \( (\lambda, \lambda + d\lambda) \), \( C_1 \) and \( C_2 \) are constants connected to the fundamental constants
h, c and k and \( C_2 = 1.438 \text{ cm-deg.} \)

Planck's law has two simplifying forms for the opposite end of the spectrum. If \( \lambda T \) is large with respect to \( C_2 \), then the Rayleigh-Jeans formula is obtained

\[
J_\lambda \, d\lambda = \frac{C_1}{C_2 \lambda^4} \frac{T}{d\lambda}
\]

(11)

On the other hand if \( \lambda T \) is small, Wien's formula is arrived at

\[
J_\lambda \, d\lambda = \frac{C_1}{\lambda^5} \exp \left( \frac{-C_2}{\lambda T} \right) \, d\lambda
\]

(12)

4.1.2. Temperature

In the measurement of radiation from bodies, one usually needs to know, or is interested in, its temperature. In pyrometry and colorimetry the important quantities are brightness temperature and colour temperature. Also of interest here is the electron temperature. They are defined as follows:

1) Brightness temperature. The brightness temperature of a body is that temperature of a black body which has the same radiant intensity of the surface of the body in question at a fixed wavelength. The relation between brightness
temperature \( S \) and true temperature \( T \) is given by

\[
J_\lambda(S) = \zeta \varepsilon(\lambda, T) J_\lambda(T)
\]

(13)

where \( J_\lambda(S) \) represents the radiant intensity of a black body with a temperature \( S \), \( J_\lambda(T) \) represents the radiant intensity of the body under consideration with a temperature \( T \), and \( \varepsilon(\lambda, T) \) is the emissivity of the body. \( \zeta \) is the transmission factor of any absorbers in the system between the source and the observer; for example the window of a tungsten filament lamp whose brightness temperature is to be measured.

2) Colour temperature. The colour temperature of a light source may be defined as the temperature of a black body which has the same colour. Thus colour temperature has meaning only in the visible range.

3) Electron temperature. If a collection of electrons are in thermal equilibrium with themselves a constant mean energy of the collection may be defined. With the equipartition theorem for energies in mind, it is possible to define the electron temperature as

\[
\overline{E} = \frac{3}{2} k T_e = \frac{1}{2} m \overline{v_r^2}
\]

where \( \overline{E} \) is the mean energy of the electron gas, \( m \) the electron mass, \( k \) is Boltzmann's constant, \( v_r \) the random
velocity and \( T_e \) the electron temperature. A local electron temperature may be defined if the electrons are in local equilibrium even though not necessarily in overall equilibrium. A temperature for other types of particles can similarly be defined. If a gas consists of two types of particles, their temperatures need not be the same.

4.2. Theory

To calculate the brightness temperature of the flash tube the radiant intensity per unit wavelength of the tube is compared to the radiant intensity of a tungsten-filament lamp by measuring the intensities at various wavelengths with a photomultiplier.

If the intensity of the radiation emitted by the flash tube and the tungsten lamp is denoted by \( I_\lambda (S)_{FT} \) \( d\lambda_{FT} \) and \( I_\lambda (S)_{TL} \) \( d\lambda_{TL} \) respectively, where \( d\lambda \) is the wavelength interval measured and is a function of wavelength, the intensities observed on the oscilloscope will be determined by

1) The variation in sensitivity \( G(\lambda) \) of the photomultiplier with wavelength. \( G(\lambda) \) will be a single-valued function whose value lies between 0 and 1, if 1 is its value at peak sensitivity.

2) Any filters which need to be placed in the path between the lamps and the photomultiplier in order to keep
the amplitude of the intensity below the non-linear level of the photomultiplier. For simplicity, neutral density filters should be used.

3) Any geometric differences in the experimental setup for measuring the radiation from the flash tube and the tungsten lamp. This will be such things as the subtending of different solid angles, different size sources, and so on.

Therefore the signals seen on the 'scope can be written

\[
V_{TL}(\lambda) = K S(\lambda) \tau_{TL} G_{TL} J_{TL}^T d\lambda_{TL}
\]

\[
V_{FT}(\lambda) = K S(\lambda) \tau_{FT} G_{FT} J_{FT}^T d\lambda_{FT}
\]

where \(K\) = amplification factor of emitter-follower and 'scope amplifier, \(S(\lambda)\) = photomultiplier sensitivity, \(\tau_{TL}, \tau_{FT}\) = transmission factors of the filters for the tungsten lamp and the flash tube respectively; not a function of wavelength for neutral density filters.

\(G_{TL}, G_{FT}\) = geometric factors for the tungsten lamp and the flash tube; also not a function of wavelength provided such effects as chromatic aberration of any lenses in the system may be neglected.

\(J_{TL}^T, J_{FT}^T\) = spectral radiant intensity per unit wavelength of the tungsten lamp and the flash tube.

\(d\lambda_{TL}, d\lambda_{FT}\) = the wavelength range over which the
intensity was measured for the tungsten lamp and the flash tube.

For the tungsten lamp Wien's law can be used in the visible region so that

\[ J_{\lambda}^{TL} = \frac{C_1}{\lambda^5} \exp\left( -\frac{C_2}{\lambda S_{TL}} \right) \]

whereas for the flash tube Planck's law gives

\[ J_{\lambda}^{FT} = \frac{C_1}{\lambda^5} \left[ \exp\left( \frac{C_2}{\lambda S_{FT}} \right) - 1 \right]^{-1} \]

so that if the maximum intensities of the lamp and the flash tube are measured at one wavelength and the ratio of the intensities taken, one gets

\[ R(\lambda) = \frac{V_{TL}(\lambda)}{V_{FT}(\lambda)} = \frac{\gamma_{TL} G_{TL} J_{\lambda}^{TL} d\lambda_{TL}}{\gamma_{FT} G_{FT} J_{\lambda}^{FT} d\lambda_{FT}} \]

If the wavelength interval for the two sources are the same then

\[ R(\lambda) = \frac{\gamma_{TL} G_{TL} J_{\lambda}^{TL}}{\gamma_{FT} G_{FT} J_{\lambda}^{FT}} \]

If the geometry is different for the two lamps, \( G_{TL}/G_{FT} \) will be difficult to calculate; if the geometry is made identical, then

\[ R(\lambda) = \frac{\gamma_{TL} J_{\lambda}^{TL}}{\gamma_{FT} J_{\lambda}^{FT}} = \frac{\gamma_{TL}}{\gamma_{FT}} \left[ \exp\left( \frac{C_2}{\lambda S_{FT}} \right) - 1 \right] \left[ \exp\left( \frac{C_2}{\lambda S_{TL}} \right) - 1 \right] \]

(14)
may be measured on a microphotometer or densitometer, 

\[ \frac{\gamma_{TL}}{\gamma_{FT}} \]

\( R(\lambda) \), \( \lambda \) and \( S_{TL} \) are known, and hence \( S_{FT} \) may be calculated from equation (14).

This is the method used by Parkinson and Reeves\(^{13}\), in their experiment of measuring the brightness temperature of various types of flash tubes.

If, however, the intensities are measured at two different wavelengths \( \lambda \) and \( \lambda' \), say, and the ratio of the intensity ratios is taken, then the filter factors and the geometric factors cancel and

\[
\frac{R(\lambda)}{R(\lambda')} = \frac{J_{\lambda}(S_{TL}) J_{\lambda}'(S'_{FT})}{J_{\lambda}(S_{FT}) J_{\lambda}'(S_{TL})}
\]

where \( S_{FT} \) and \( S'_{FT} \) are the brightness temperatures at wavelengths \( \lambda \) and \( \lambda' \) respectively.

Anderson\(^{10}\) found that the relative intensity distribution of the flash tube behaves in a fashion similar to that of a black body and if this is the case then one should be able to equate \( S_{FT} \) with \( S'_{FT} \). In any case, looking at the results of Parkinson and Reeves\(^{13}\), it can be seen that the temperature there calculated is a slowly varying function of wavelength so if the interval \( |\lambda - \lambda'| \) is not too large,
one can put $S_{FT} = S'_{FT}$ without too much error. Then

$$\frac{R(\lambda)}{R(\lambda')} = \exp\left[\frac{C^2}{S_{TL}}\left(\frac{1}{\lambda'} - \frac{1}{\lambda}\right)\right] \frac{\exp\left(\frac{C^2}{\lambda S_{FT}}\right)}{\exp\left(\frac{C^2}{\lambda' S_{FT}}\right)} - 1$$

If $B = \frac{C^2}{\lambda}$

$B' = \frac{C^2}{\lambda'}$

$$A = \frac{R(\lambda)}{R(\lambda')} \exp\left[\frac{C^2}{S_{TL}}\left(\frac{1}{\lambda'} - \frac{1}{\lambda}\right)\right]$$

then

$$\exp\left(\frac{B}{S_{FT}}\right) = A \exp\left(\frac{B'}{S_{FT}}\right) + 1 - A$$

This equation can be solved for $S_{FT}$ by iteration or as is done here by successive substitution.

4.3. Experimental Procedure

A general schematic view of the temperature-measuring apparatus is shown in figure 6.

Because of the emitter-follower circuit following the
fig. 6 temperature-measuring apparatus
photomultiplier unit a d.c. measurement of the tungsten-filament lamp intensity was not possible and so a pulsed tungsten source was necessary. Also to achieve more identical conditions with respect to transients in the photomultiplier-emitter-follower circuits, a tungsten light pulse of duration of the same order as that of the flash tube was desired. This meant a pulse of the order of 10 μsec and necessitated the use of a shutter of some sort. An optical shutter using a rotating mirror seemed ideal for this purpose.

Unfortunately, the only appropriate rotating mirror shutter was being used in another experiment and hence could not be readily removed for use in this one. See reference 5 wherein is described preliminary work in the study of absorption spectra of plasmas, which employs the use of a flash tube. This work is being continued and the experimental setup is almost exactly the same as described except for the substitution of the optical shutter for the mechanical one.

In order to save the time and expense necessary to build a similar shutter, it was decided to mount the flash tube in place of the one being used in the above-mentioned experiment and deflect the light from the tube into the constant-deviation spectroscope being used for intensity measurements. The plasma absorption tube shown in the diagram is used in the other experiment and does not affect the results of this one.
For measuring the intensity of the tungsten lamp, the lamp was placed directly behind the adjustable slit and as close to it as possible to ensure maximum illumination. The slit was focused by lens A onto the slit of the constant deviation spectroscope when the rotating mirror was lined up.

The length of the pulse could be adjusted either by varying the speed of the motor driving the mirror or by changing the width of the adjustable slit. This second method was employed to procure a pulse of about 10 μsec duration. The intensities were measured with the photomultiplier and oscilloscope and 'scope camera. Measurements were made every 100 angstroms on the drum scale of the spectroscope (which was approximately every 120 angstroms upon calibration of the drum) from 4440 Å to 6555 Å.

For the flash tube measurements, lens B and C focussed the light from the discharge onto the adjustable slit. The rotating mirror was stopped and positioned so the slit was focused on the spectroscope and similar intensity measurements were made.

It was found necessary to use a filter with the flash tube and three sheets of mylar were used. The mylar was a good neutral-density filter and had a transmission factor of about 45%.
4.4. Apparatus

The black body which was used as the standard light source was a 120 volt G.E. projection lamp which was operated on 125 volts d.c. The colour temperature of the lamp was measured with a Hartmann and Braun filament optical pyrometer in the 1500 to 3500°C range. The pyrometer calibration was checked using a G.E. T-24, 86-P-50 standard lamp.

The brightness temperature of the lamp was then found by using a nomogram calculated by Rutgers and de Vos\textsuperscript{14} which gives the relation between the brightness temperature, true temperature and colour temperature of a tungsten filament. The pyrometer was averaged over 10 readings and gave a colour temperature of 2940°K which corresponds to a brightness temperature of 2560°K.

The spectroscope used was a Hilger quartz-prism constant deviation spectroscope with an adjustable slit mounted in place of the plate-holder. The photomultiplier was placed behind the slit and was enclosed in a brass container attached to the slit to reduce pickup. The spectroscope was calibrated using the λ 5791, 5770, 5461, and 4358 angstrom lines of mercury and the λ 6563 and 4861 lines of hydrogen.

The photomultiplier circuit was as was described before except a 900 volt supply was used instead of 600 v. This was necessary to achieve sufficient sensitivity when measuring the light intensity of the tungsten lamp and the flash tube at both ends of the visible spectrum.
5. Results

5.1. Flash Tube Spectrum

Using the Hilger medium quartz spectroscope, the spectrum was observed from 6500 Å down to about 2300 Å. At low condenser voltages (11 kV) quite a few lines and bands were observed on a background continuum throughout the range and as the voltage was increased most of these lines spread out into the background. Several absorption lines were present at all voltages; a group of six around 2500 Å but none in the visible range which is the region of interest for the work the tube is hoped to be applied. Some lines seen in emission at low voltages were seen in absorption at higher voltages indicating a faster increase in temperature in the centre of the gas than in the extremities. An improvement in the continuum was noted when the capacitance was increased from 1.6 µf to 3.2 µf.

A time-resolution of the flash was attempted using the rotating mirror shutter and a delay unit to see at what stage of the discharge the emission lines occurred. Anderson found that the emission lines did not appear until the later part of the discharge when the current density was low. This same effect was found here but because the timing of the
shutter was not known very accurately, the instant of initial occurrence of the emission lines was unknown. In approximately the first 20 μsec of the discharge, however, hardly any emission lines were seen. At the present time work is being done to correct the uncertainty in timing of the shutter.

5.2. Current Waveform

The observed current waveshape is shown in Figure 7.

![Current Waveform](image)

Fig. 7. Current Waveform

It is seen to be a damped sine wave as discussed in 3.1, showing that the model chosen was quite correct, and is given by

\[ i = 81,400 e^{-6.1 \times 10^5 t} \sin 3.19 \times 10^6 t \text{ amps} \]

Calculation of R and L using (8) and (9) gives

\[ R = 0.07 \Omega \]

\[ L = 58 \text{ mH} \]
The maximum of the current occurs when \( \tan t = \frac{2\omega L}{R} \)
and gives a value of \( t = 0.43 \mu s \). The first zero of \( \frac{di}{dt} \) was observed at \( t = 0.44 \mu s \) which agrees well and gives \( i_{\text{max}} = 97,000 \ \text{amp/cm}^2 \) which is well above the 20,000 \( \text{amp/cm}^2 \) found necessary by Anderson for the production of a continuum.

To get a simple estimate of the time at which the current density ceases to be above the "continuum density" (20,000 \( \text{amps/cm}^2 \)), the sinusoidal current variation is put equal to 1 and one can say

\[
\frac{81,400 e^{-6.1x10^{5t_c}}}{\pi(0.45)^2} < 20,000
\]

where \( \pi(0.45)^2 \) is the cross-sectional area of the tube. Thus \( t_c > 2.2 \mu s \), whereas \( t_c \) was found to be greater than about 20 \( \mu s \) as mentioned above. Although the inequality is correct, a possible explanation of the order of magnitude difference is that even though the current density flowing between the electrodes is zero in about 3 \( \mu s \), the energy in the gas is still high enough to ensure that much ionization is present, so that the radiation emitted is of a continuous nature.

Of interest is the time lag between the application of the spark pulse and the initiation of the current discharge. This is shown in figure 7 where the trigger pulse and subsequent noise occurs at the beginning of the trace, and the current begins about 1 \( \mu s \) later, at which time it begins
abruptly. This raises the question of the mechanism for initial breakdown of the discharge and the reason for the delay.

The mean free path between air molecules at .1 μ is about 10 meters, and if kinetic gas theory applies, the mean free path between an electron and the air molecules will be about four times as great. When the triggering voltage is applied and breakdown occurs between the trigger pin and the grounded electrode, the positive ions will be attracted towards this electrode while the electrons which escape recombination with the ions will be attracted and move towards the positive electrode at the far end of the tube. Because of the long mean free path, it is unlikely that the electrons will collide with any of the air molecules and thus most of the electrons will strike the far electrode. Here some sort of surface process must take place such as the ejection of electrons and atoms and positive ions. The positive ions will move towards the far (grounded) electrode, strike it, and also eject electrons and ions, so the process is repeated. Once the particle density is increased enough by this electrode sputtering and also sputtering from the quartz tube, ionization through collision can take place and a "normal" breakdown can occur. One would expect from this explanation, however, that the initial current would rise gradually and not abruptly as observed. A reasonable explanation is
lacking and a more thorough investigation will be necessary.

The delay of the initiation of the current after the application of the trigger pulse was found to be almost of the same duration in every case. The jitter-time was about .2 μsec and allows the tube to be synchronized accurately with short-lived events.

5.3. Light Intensity

The time variation of the light output of the flash tube is shown in figure 8 which gives the intensity emitted at a wavelength of 5100 Å. The shape of the wave is very similar at other wavelengths. Initially the light rises rapidly to a maximum in about .5 μsec, then begins to drop off. At about 1 μsec after the peak, a break in the rate of fall sometimes occurs, indicating the presence of a smaller second peak in the intensity. In some of the tube configurations, such as the elbow tube, the second peak was very
prominent, being almost as large as the first, as shown in figure 9. The degree of prominence of the second peak not only varied with the tube used but also with the wavelength of the radiation, tending to be slightly more prominent at higher wavelengths.

The current and the intensity were examined simultaneously using a Tektronix type 551 dual beam oscilloscope. The trace is shown in figure 10. Notice that the light

Fig. 9. Light Intensity of Elbow Tube

Fig. 10. Current and Intensity of Flash Tube
intensity does not appear until about the first maxima of the current and the peak intensity occurs at the first zero of the current. The second intensity peak occurs slightly before the second zero of the current.

5.4. Deionization

Once the current between the electrodes ceased to flow, the process of deionization takes place. If volume recombination is considered, and the emission of light is assumed to be caused by recombination only, then it seems reasonable that the intensity of light in a small wavelength range will be proportional to the number of electrons present and thus also to the number of ions. If local neutrality holds, then

\[ n_e = n_i = n \quad \text{and} \quad J_\lambda = \left( \frac{n}{K_\lambda} \right)^2 \]  \hspace{1cm} (16)

where \( K_\lambda^{-2} \) is the constant of proportionality. Thus equation (7) becomes

\[ J_\lambda(t)^{-\frac{1}{2}} - J_\lambda(0)^{-\frac{1}{2}} = K_\lambda \alpha t \]  \hspace{1cm} (17)

and a plot of \( J_\lambda^{-\frac{1}{2}} \) versus \( t \) should yield a straight line of slope \( K_\lambda \alpha \). This was done for three different wavelengths and is shown in figure 11. Care was taken to ensure the intensity was measured after the current had stopped flowing.
fig. 11 $J_{\lambda}^{-\frac{1}{2}}$ versus time
To get an estimate of the value of $\alpha$, the following procedure was used. The rise in pressure in the flash tube after firing and after the temperature was back to room temperature was about 35 $\mu$. This gives a molecular density of $1.1 \times 10^{16}$ cm$^{-3}$ using the perfect gas relation $p = nRT$. If none of the material sputtered from the electrodes and the quartz tube is redeposited (highly questionable) and each atom of material is singly ionized, then an approximation for the electron density is $10^{16}$ cm$^{-3}$. If it is assumed that this is the electron density at peak intensity of the flash, a value for $K_\lambda$ can be calculated from (16) and hence $\alpha$ can be measured from the slope of the graph. In the three cases shown in figure 16 $\alpha$ was found to be $\sim 2 \times 10^{-11}$ cm$^3$/sec. It is difficult to compare this result with others that have been measured because $\alpha$ doubtless varies with the gas, its temperature, pressure, etc. Values of $\alpha$ found under various conditions given by Loeb$^{15}$ show that the value found here could be possible. Massey$^{16}$ found $\alpha \sim 10^{-13}$ cm$^3$/sec for a temperature of 8,000$^\circ$K in oxygen.

It should be pointed out that the value for $n$ is highly doubtful for two reasons. One is the assumption that no sputtered material is redeposited after the discharge, and the second is that this particle density occurs during the discharge and not at a later stage. Some results explained below indicate this second assumption may be false. A lower
value of $n$ would give a higher value of $\alpha$.

The straight-line plot of $\int_\lambda^{1/2}$ versus time would indicate that the primary process of deionization is volume recombination. However caution should be used because recombination is a process which is far from being completely understood and the apparent results may be misleading. A look at the diffusion-surface recombination process is necessary.

Loeb\textsuperscript{15} states that if the Debye length of the plasma is much less than the dimensions of the containing vessel, the diffusion will be ambipolar, while if the Debye length is much greater, the electrons will diffuse independently of the ions, and the diffusion will be called free. The electron Debye length $\lambda_D$ is given by

$$\frac{1}{\lambda_D^2} = \frac{\kappa^2 \epsilon_r}{\varepsilon_0 k T_e}$$

To get an order of magnitude of $\lambda_D$, assume a value of $T_e = 10,000^\circ K$ which is of the same order as that calculated by Budd\textsuperscript{5} for a similar flash tube. $\epsilon_r$ is as calculated before

$$\frac{1}{\lambda_D^2} \sim \frac{(10^{-19})^2 10^{16}}{10^{-11} 10^{-23} 10^4} = 10^8 \text{ m}^{-2}$$

so that $\lambda_D \sim 10^{-2}$ cm which is much smaller than the dimensions of the tube, and thus it appears that ambipolar
diffusion will occur rather than free diffusion. Francis\textsuperscript{17} states that if $\tau$ is the mean lifetime of an electron before it hits the wall then

$$\tau D_\alpha = L^2$$

(18)

where $D_\alpha$ is the ambipolar diffusion constant and $L$ is a characteristic length of the discharge known as the diffusion length. For a cylinder of length $d$ and radius $r$,

$$\frac{1}{L^2} = \left(\frac{\Pi}{d}\right)^2 + \left(\frac{2.4}{r}\right)^2$$

which gives $L = .18 \text{ cm}$ for the flash tube.

Von Engel\textsuperscript{18} gives the ambipolar diffusion constant by

$$D_\alpha = \frac{D^+k^- + D^-k^+}{k^+ + k^-}$$

where $D^+$ and $D^-$ are the free diffusion constants for the positive and negative ions, and $k^+$ and $k^-$ are their respective mobilities. For the usual case where $k^- \gg k^+$ and $T_e \gg T_i$, the ion temperature, it can be shown that

$$\frac{D^-}{k^-} \gg \frac{D^+}{k^+}$$

and then

$$D_\alpha \cdot \frac{D^-k^+}{k^-} = \frac{kT_e k^+}{L}$$
If \( k^+ \sim 10^3 \text{ cm}^2/\text{volt sec} \), which should be about the right order, then

\[
D_a \sim \frac{10^{-23} \times 10^4 \times 10^3}{10^{-19}} = 10^3 \text{ cm}^2/\text{sec}
\]

and from (18)

\[
\gamma \sim \frac{1}{D_a} \sim \frac{10^{-11}}{10^3} = 10 \mu\text{sec}
\]

which is the correct order of magnitude for the time of the discharge. Thus from these rough calculations it seems that this is a borderline case - ambipolar diffusion may be just possible. According to Mohler\(^{19}\) if surface recombination takes place because of diffusion, the curves of \( \int \bigwedge \frac{2}{3} - t \) will in general be steeper and concave upwards.

This upward concavity is apparent in the graphs shown. If the prominent radiation process is accepted as being a product of volume recombination, then a qualitative explanation of the shape of the intensity with time curve can be given. The energy put into the tube during the discharge as a function of time is given by

\[
E(t) = \int_0^t R_T i^2 dt = R_T \int_0^t i^2 dt
\]

if the resistance of the tube is assumed constant. \( i, i^2, \) and \( i^2 dt \) are shown in figure 12. If the energy decay due to radiative recombination is taken into account
the dotted line shows the energy of the discharge as a function of time. If the output of intensity is proportional to the energy content of the discharge, then the observed output should be similar to this curve. The relative
prominence of the second peak would then depend on the value of $\alpha$, a high value of $\alpha$ allowing a small or no second peak, while a small value of $\alpha$ gives a large second peak. $\alpha$ decreases with increasing temperature, so the hotter the gas, the more prominent the second peak.

5.5. Behaviour of Intensity with Number of Shots

The peak intensity of the final design of the flash tube was found to decrease by less than about 1% with each shot. The rate of decrease of intensity tended to vary slightly with each trial if some part of the tube had been replaced such as a new window glued on, so the above figure represents an approximate average. For an experiment requiring no decrease in the peak intensity and not requiring too many shots, this is probably a tolerable decrease. Figure 13 illustrates this decrease graphically for the first hundred shots. For comparison a curve for a "baffle-less" flash tube is also drawn.

For this tube the intensity dropped drastically in the first 10 shots, and then fell off more slowly in an approximately linear manner. To be noted is the dip and then the slight rise beginning at shot No. 7. This would seem to indicate that initially material is only being deposited on the window so the intensity falls off rapidly. Eventually (in this case, shot No. 7) some of the material already
fig. 13 intensity decrease

relative intensity

number of shots

final

"baffle-less"
deposited is removed, either by the heat generated by the discharge, or by mechanical impact from other ebullition just produced by the discharge, and the intensity rises somewhat. The two opposing processes of deposition and removal then occur concurrently, with the deposition process necessarily dominating. In some cases the dip occurred at the second shot and the rise at the third. Hence the ebullition is apparently deposited after the light has been emitted and thus the calculation above the electron density during the discharge is even more precarious.

The intensity of the final design tube, on the other hand, shows none of these characteristics but merely a slow decrease.

5.6. Temperature Measurements

The solution of equation (15) gives the brightness temperature of the flash tube; the results were not very satisfactory however. When $|\lambda - \lambda'|$ was small (\(\approx 120\ \text{Å}\)), the calculated temperatures, as the visible range was "scanned", varied between 1,000 and 60,000°K with no obvious regularity or pattern with respect to the wavelength. In some instances the equation had no real solution.

Some of the possible causes of these unstable results were not hard to find.

One of these is an inherent instability in equation (15).
If the derivative of (15) is taken

\[- \exp \left( B \left( \frac{B'}{S} \right) \right) \frac{dS}{S} = dA \left[ \exp \left( \frac{B'}{S} \right) - 1 \right] - \exp \left( \frac{B'}{S} \right) \frac{A dS}{S}\]

or

\[\frac{dS}{S} = \frac{S \left[ \exp \left( \frac{B'}{S} \right) - 1 \right]}{B' \exp \left( \frac{B'}{S} \right) - B \exp \left( \frac{B}{S} \right)}\]

now if \(|\lambda - \lambda'|\) is small, \(B' \approx B\) and \(\exp \left( \frac{B'}{S} \right) \approx \exp \left( \frac{B}{S} \right)\)

\[\therefore \frac{dS}{S} \approx \frac{S}{B} \frac{1 - \exp \left( - \frac{B}{S} \right)}{1 - \frac{1}{A}} \frac{dA}{A}\]

Since \(\exp \left( - \frac{B}{S} \right)\) cannot equal 1 for finite \(S\), the percentage change in \(S\) can be large if \(A\) is close to 1, which it will be if \(\lambda \rightarrow \lambda'\). A typical example can be given. If \(\frac{S}{B} \sim 1\) and \(A = .95\), then \(\frac{dS}{S} = 20 \frac{dA}{A}\), so any error in \(A\) is magnified 20 times in \(S\). Almost all error associated with \(A\) would come from measuring the intensities which has a possible error of about 5%. If \(|\lambda - \lambda'|\) is made larger, then \(A\) tends to move away from 1 and the solution may become more stable.

This was tried using \(\lambda = 4440\ \text{Å}\) which was the lowest wavelength in the range, and \(\lambda'\) ranged from 4700 Å to 6555 Å in increments of about 250 Å. The results from one trial are tabulated below.
TABLE I

Brightness Temperature for Variable Wavelength Interval

<table>
<thead>
<tr>
<th>λ</th>
<th>λ'</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>4440 Å</td>
<td>4680 Å</td>
<td>3943°K</td>
</tr>
<tr>
<td>4923</td>
<td>5666</td>
<td></td>
</tr>
<tr>
<td>5177</td>
<td>6891</td>
<td></td>
</tr>
<tr>
<td>5448</td>
<td>6268</td>
<td></td>
</tr>
<tr>
<td>5720</td>
<td>5624</td>
<td></td>
</tr>
<tr>
<td>5997</td>
<td>5850</td>
<td></td>
</tr>
<tr>
<td>6276</td>
<td>5277</td>
<td></td>
</tr>
<tr>
<td>7555</td>
<td>4490</td>
<td></td>
</tr>
</tbody>
</table>

This method does not allow a temperature to be associated with a certain wavelength, or small wavelength range as it does if \( |λ - λ'| \) is small. \( S \) has an average value of 5500°K and a standard deviation of 880°K.

The results for the same trial for \( |λ - λ'| \leq 250 \text{ Å} \) is shown below.

TABLE II

Brightness Temperature for Constant Wavelength Interval

<table>
<thead>
<tr>
<th>λ</th>
<th>λ'</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>4440 Å</td>
<td>4680 Å</td>
<td>3943°K</td>
</tr>
<tr>
<td>4680</td>
<td>4923</td>
<td>11549</td>
</tr>
<tr>
<td>4923</td>
<td>5177</td>
<td>14669</td>
</tr>
<tr>
<td>5177</td>
<td>5448</td>
<td>4826</td>
</tr>
<tr>
<td>5448</td>
<td>5720</td>
<td>3787</td>
</tr>
<tr>
<td>5720</td>
<td>5997</td>
<td>5850</td>
</tr>
<tr>
<td>5997</td>
<td>6276</td>
<td>2994</td>
</tr>
<tr>
<td>6276</td>
<td>6555</td>
<td>1848</td>
</tr>
</tbody>
</table>
The variation in the values of the temperature was not as great as when \(|\lambda - \lambda'\| \div \sim 120 \text{ Å}.

When \(|\lambda - \lambda'\|\) is not small, the question is raised as to how much error is introduced by putting \(S = S'\) in eqn (15). That is, does the flash tube behave as a black body? To calculate the relative intensity of the flash tube the relation 
\[
J^\text{FT}\lambda \propto \frac{1}{R(\lambda)} J^\text{TL}\lambda
\]
was used, where \(J^\text{TL}\lambda\) was calculated from Wien's law. This was done using the values of 
\(R(\lambda)\) observed from the trial of tables I and II and the result is shown in figure 14. It appears that the intensity distribution is far from that of a black body. Closer spaced points and a wider total wavelength range would tell more of the intensity behaviour. Because of the non-black body behaviour, it is perhaps surprising the temperatures given in Table I are as close as they are.

If 5500°K is a reasonable measure of the brightness temperature of the flash tube, it is obvious that this is not hot enough for absorption analysis of hot plasmas. In fact at present work is being done similar to that done by Budd using the flash tube discussed here, and it has been found that very slight absorption takes place but not enough for any accurate calculation. Budd was able to achieve better absorption indicating his flash tube had a hotter temperature. Significantly, the intensity waveform had a prominent second peak.
Int. Intensity Variation with Wavelength

Fig. 14 Intensity variation with wavelength
5.7. Conclusions

A low pressure flash tube of simple design has been constructed which does not suffer from deposition on the exit window. The spectrum in the visible range is a good continuum probably originating from electron retardation. A few emission and absorption lines are present but are believed to appear after the first 20 μsec of the discharge.

The deionization process in the discharge appears to be volume electron-ion recombination and the recombination coefficient $\alpha$ was estimated to be $2 \times 10^{-11} \text{ cm}^3/\text{sec}$.

A method of measuring the brightness temperature of the flash tube over the visible range was used by comparing photoelectrically the intensity of the tube with that of a black body. The temperatures calculated indicate that the intensities need to be measured extremely accurately and the temperature of the present tube ($\sim 5500^\circ\text{K}$) is lower than expected. The relative intensity distribution of the tube shows that it does not radiate as a black body.

It is not certain why the temperature of the flash tube is so low. The total energy put into the tube is 130 J and greater; other workers have constructed tubes which have achieved much higher temperatures at about the same energy, so other energy-dissipating processes must be looked for to explain this low temperature. Perhaps diffusion and surface recombination plays a more important role than it is thought
to, or the low pressure requires too much energy to be expended in sputtering to achieve breakdown.

At any rate it seems that one problem has been solved at the expense of creating another. The final design of the tube no longer suffers from deposition of material on the exit window as it did before. But on the other hand, earlier tube designs were hot enough for use in certain absorption experiments. What had seemed at first glance to be a reasonably simple mechanical problem of preventing deposition has turned out to be an extremely complex situation of which little is known.

Obviously to solve this problem, a more thorough investigation of the mechanisms occurring in the flash tube will be necessary and will doubtless be undertaken in the near future.
APPENDIX

Computer Program for Solving Temperature Equation

Equation (15) was solved on an IBM 1620 computer using Fortran 1A. The method of solution was that of direct substitution. If equation (15) is written

$$E_q = \exp\left(\frac{B}{S}\right) - \left(A \exp\left(\frac{B'}{S}\right) + 1 - A\right)$$

then the solution is that value of $S$ for which $E_q = 0$.

$S$ was first put equal to 1000, then increased in steps of 1000 until $E_q$ changed sign. $S$ was then increased in steps of 100 starting at the previous 1000 step. This procedure was repeated down to units. The solution was sought only in the range $1000 \leq S \leq 101,000$.

The program is shown below.

```
DIMENSION WL1(100), WL2(100), VTL(100), VTL2(100), VFT1(100)
DIMENSION VFT2(100)
1 FORMAT(6F8.2)
17 FORMAT(13,F8.0)
18 FORMAT(13)
READ 18, N
DO 19 I=1, N
19 READ 1, WL1(I), WL2(I), VTL1(I), VTL2(I), VFT1(I), VFT2(I)
DO 101 I=1, N
B1=(1.438E8/WL1(I))
B2=(1.438E8/WL2(I))
C=EXP ((1.438E8/2560.)*(1./WL1(I)-1./WL2(I)))
```
A = ((VTL1(I) * VFT2(I)) / (VTL2(I) * VFT1(I))) * C
T = 1000.
EQ = EXP(B1/T) - (A * EXP(B2/T) + 1. - A)
IF (EQ) 2, 3, 4
2 T = T + 1000.
IF (T < 1.E5) 20, 20, 3
20 EQ = EXP(B1/T) - (A * EXP(B2/T) + 1. - A)
IF (EQ) 2, 3, 5
5 T = T - 1000.
8 T = T + 100.
EQ = EXP(B1/T) - (A * EXP(B2/T) + 1. - A)
IF (EQ) 8, 3, 6
6 T = T - 100.
9 T = T + 10.
EQ = EXP(B1/T) - (A * EXP(B2/T) + 1. - A)
IF (EQ) 9, 3, 7
7 T = T - 10.
10 T = T + 1.
EQ = EXP(B1/T) - (A * EXP(B2/T) + 1. - A)
IF (EQ) 10, 3, 3
4 T = T + 1000.
IF (T < 1.E5) 22, 22, 3
22 EQ = EXP(B1/T) - (A * EXP(B2/T) + 1. - A)
IF (EQ) 11, 3, 4
11 T = T - 1000.
12 T = T + 100.
EQ = EXP(B1/T) - (A * EXP(B2/T) + 1. - A)
IF (EQ) 13, 3, 12
13 T = T - 100.
14 T = T + 10.
EQ = EXP(B1/T) - (A * EXP(B2/T) + 1. - A)
IF (EQ) 15, 3, 14
15 T = T - 10.
16 T = T + 1.
EQ = EXP(B1/T) - (A * EXP(B2/T) + 1. - A)
IF (EQ) 3, 3, 16
3 PRINT 17, I, T
101 CONTINUE
STOP
END

RELOCATABLE SUBROUTINES CALLED
EXP

OBJECT PROGRAM DATA TABLE
06550 STORAGE POSITIONS.
REFERENCES

2. Ladenburg, R., Rev. Mod. Phys., 5, 234 (1933).
3. Lyman, T., Science, 64, 89 (1926).


