A Study of High-Frequency Gas-Conduction Electronics in Digital Computers

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ABSTRACT

A new type of phenomenon, among those which have been proposed for application to digital computers, is the high-frequency glow discharge. Such discharges exhibit bistability, may be localized within a large gas-filled vessel, and may be transferred from point to point within that vessel under the control of external electrodes. An exceedingly simple, serial shifting register may be constructed from a piece of glass tubing, which contains only low-pressure gas, upon which are fixed an iterative array of external electrodes. Appropriate sequential excitation of the electrodes by thirty-megacycle driver units will shift a pattern of discharges and no-discharges, in either direction, at speeds up to thirty thousand bits per second.

This dissertation presents this new phenomenon, and especially the shifting-register application, by a detailed analysis of the physical and functional aspects of high-frequency discharges and glow-transfer techniques. Some very promising techniques for decreasing decay time and power consumption are appended, as are a number of stimulating possibilities for new structural and application innovations.

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I. INTRODUCTION

High-frequency glow discharges can be made to exhibit a bistable characteristic, i.e. either a discharge or a no-discharge state may exist over a given range of excitation voltage. These discharges may be localized within a large tube by the concentrated fields of external electrodes, and one such localized discharge may serve to "prime" another, adjacent discharge region. These three characteristics allow the realization of an n-bit, serial shifting register in a long glass tube fitted with simple external electrodes. This research has firmly established that such registers represent a practical and promising new device for the digital computer field, and the dissertation presents a basic physical and functional analysis of their design.

Previous glow-transfer applications have been limited to counting tubes, which differ markedly from this new application in two very important ways. First, the counting tubes use internal electrodes, whose geometrical uniformity and surface condition are quite critical. These registers, on the other hand, employ external electrodes, whose composition and uniformity are not critical. Secondly, at a given time, only one stage of an n-stage counting tube may contain a discharge, so that it has essentially n stable states. An "n-stage" register, however, may have simultaneous discharges in any of its "stages", and therefore has 2^n stable states. Much simpler construction, and a greatly increased functional utility have resulted from these differences.

A serial shifting register is essentially a linearly-ordered array of n bistable elements. Three essential characteristics necessary for such an array, in order that it may function as a serial shifting register, are that: (1) a suitable, externally-applied signal can cause each of the elements "2" through "n" to change its state to that which was occupied by the preceeding element immediately before the signal...the action upon element "1" need not be specified, (2) the first element may be set to either of its states by external control, and (3) the state of element "n" can be sensed by an external unit.

The first characteristic provides the "shifting" feature, and by a succession of n input bits (i.e. settings of the first element) alternated with n-1 shifts, the register can be "filled" with information. This means that any artibrary linear pattern of the element-states may so be established. A succeeding n-1 shifts will allow the sensing unit to be made aware of the pattern, and the information is thus "read out".

The diagram below presents the essential features of the new shifting register. The discharge regions 1, 2, 3, ...represent the array of bistable elements. Each of these "elements" is capable of remaining stably in either the discharge or the no-discharge state when line A is appropriately

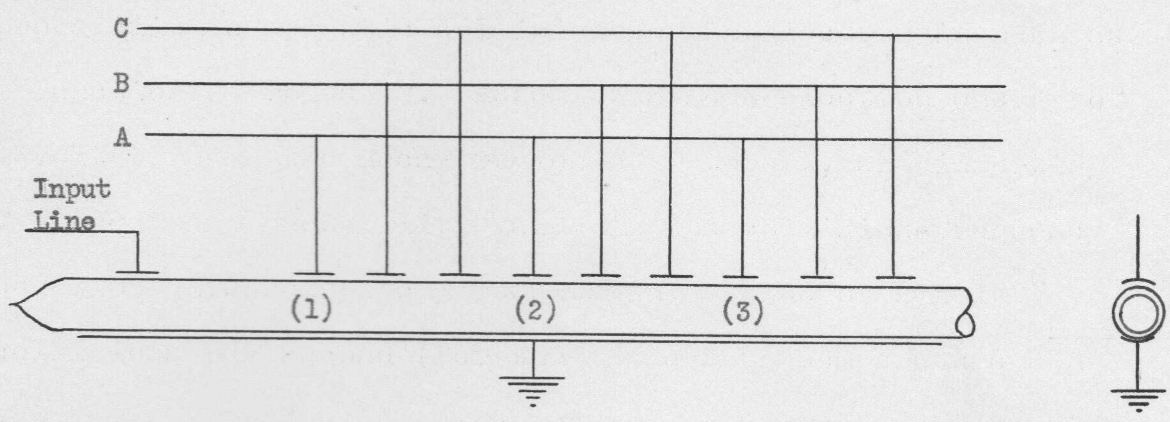

Figure 1-1. Representation of the input end of a high-frequency glow-transfer serial shifting register, which is constructed from a gas-filled glass tube to which are attached external electrodes as shown.

energized with a high-frequency voltage. Switching the high-frequency voltage in turn to lines B, C, and again to A, will cause one "shift" to the right. The priming characteristic will have caused each discharge-state to have been transferred to the succeeding "element" in a stepwise fashion, from electrode to electrode, and the bistable characteristic insures that a no-discharge-state will similarly be transferred. It is noteworthy that switching the high-frequency voltage from line A to lines C, B, and again to A, will effect one shift to the left.

Provision for the input facility is made by use of a separate high-frequency oscillator, which can be keyed between a low- and a high-output state, so that its continuously-present discharge can be contracted or extended to effect optional priming of the first "element". Read-out provision may be had by photo-electric sensing of the nth "element". Alternative methods for realizing each of these facilities are given later.

1.1 Outline of research.

Three working registers were constructed to demonstrate various structural and operational variations. The limitations of shifting speed and excitation-voltage variation were established, and estimates of power consumption were made from oscillator-loading characteristics. Considerable work was involved in establishing an appropriate set of functional parameters with which to specify some of the operational characteristics of these registers, and to ascertain the relationships required among these parameters in order to optimize the primary functional needs of maximum reliability and speed.

Once the basic feasibility of the high-frequency glow-transfer shifting register had been demonstrated experimentally, there remained the task of establishing the limits to which speed and power consumption could be taken by means of design improvements. The fact that some six different primary design variables affect the power consumption and all of the functional parameters, in a manner which in itself is complex, makes the establishment of an optimum relationship among these affected items an imposing task. These primary design variables include: gas composition, gas pressure, excitation frequency, electric-field geometry, discharge-container geometry, and dimensional scale.

Much has been done with high-frequency discharge in the study of basic phenomena of gases and discharges. The processes governing breakdown are quite extensively written upon, but those involving such equilibrium-conduction and discharge-decay phenomena as are here experienced are given only scattered mention. Actual quantitative analysis of any of these three phenomenon is only accomplished with great effort even for ideal conditions, and no hope was seen for such an analysis under the conditions found in the application being studied, at least within the scope of a single dissertation.

A qualitative understanding of the discharge phenomena has evolved, however, with which order-of-magnitude estimations may be made, and with which very helpful predictions are possible. These predictions agree quite well with what is presently known from experimental observations, but considerable work in both the theoretical and experimental aspects of the total problem needs yet to be done before the limitations of speed and power consumption are known.

A technique for accelerating the discharge decay process has evolved during the later stages of the research. This process, termed "quenching", utilizes externally-applied voltages, which contribute frequency components and internal-field strengths just low enough so that the charged particles which make up the discharge residue are swept to the vessel walls without causing new ionization in the process. These quenching techniques promise greatly increased shifting speeds, but they also introduce more design variables. Their introduction required a complete reorientation of much of the design criteria, since many design changes which will decrease power consumption, and now receive consideration, would previously not have been acceptable because of their adverse effect upon speed.

1.2 Summary of conclusions.

It seems quite well established that a high-frequency glow-transfer shifting register can be a practical device for every-day digital computer usage. The speed limitation which ruled out previous gas-discharge devices (e.g. decimal counting tubes) for general computer usage promises to be overcome in the near future. Working-model, experimental registers have operated successfully at a rate of thirty thousand bits per second...and experimental evidence was at hand, even before the introduction of quenching techniques, which predicted speeds of one-hundred-thousand bits per second. With quenching techniques now being available, this goal seems likely to be surpassed several fold. This brings the devices into a speed range such that it is entirely practical to consider their use in many computer and data-processing systems.

The incremental cost, per bit, of extending the storage capacity of such a register is exceedingly small. The driving circuitry is expected to cost somewhat more than that for other types of registers, but the abovementioned incremental cost should give these glow-transfer registers a competitive edge in price before the capacity reaches fifty bits. Register sizes of a thousand bits, or larger, seem entirely feasible, and their cost should be low enough to make them quite practical.

The size of the register units, exclusive of external circuitry, should be quite small. Present techniques could guarantee, for instance, a one-hundred-bit register unit in a cylindrical package three inches in diameter and six inches long. Expected future construction techniques should cut this size at least in half.

Power consumption seems quite nominal, apparently being of the order of one tenth of a watt per bit. This would allow the above hundred-bit register to be supplied by miniature-tube driving units. Promise of reduction of this power by future improvements has an estimated lower bound of five milliwatts per bit.

Reliability promises to be very high, as does the life of the tube. Having no internal electrodes means having no cathode sputtering, and also promises a greatly reduced rate of gas cleanup. Voltage tolerances seem quite large (as much as plus or minus 30%) in the test models, and timing of the excitation sequence can be given as much tolerance as is needed.

1.3 Organization of the dissertation.

Since high-frequency gas-conduction phenomena are new to the digital computer field, it was considered necessary to precede any actual application discussion with an introductory explanation of some of the more important of these phenomena. Consequently, Chapter II is devoted entirely to a discussion of electrodeless discharges. First, some of the basic mechanisms which occur within a gas are treated, and then the knowledge of these is utilized in a description of: breakdown, equilibrium, and decay, as they are probably occurring for the applications discussed later. Some qualitative curves are drawn, representing the bistable characteristics of these discharges in terms of the fundamental gas mechanisms which have previously been discussed.

Chapter III is devoted to actual descriptions of the two basic kinds of shifting registers which have been constructed to date. Construction is outlined, and typical excitation timing sequences are given, as well as the actual operational characteristics of corresponding test models. Included also in this chapter are discussions of possible methods of entering and removing information from the registers.

The background of Chapters II and III is then utilized to full extent in Chapter IV, where a detailed analysis of these shifting registers is given in several aspects. The functional parameters, such as critical transfer voltages and extinction times, are listed in detail, and their dependence upon the fundamental physical variables is noted both by experimental curves and qualitative prediction. The relationships among some of these parameters necessary for maximum-speed realization is given in a section on the timing considerations for each of the two kinds of registers. Analysis of the power losses is given, with some theoretical estimations which seem to bear close relationship with observation. The various possibilities which exist toward a reduction in power consumption by means of design manipulation of the physical variables are discussed in a qualitative manner. A final section in this chapter then lists the fundamental physical variables which may independently be varied, and with each in turn discusses the expected direction of change which will tend to favor the coordinated design criteria of a register, with mention made of the probable limiting factors in each case.

There exist various structural possibilities with regard to these shifting registers which seem quite worthy of inclusion in this dissertation. They offer definite advantages in construction, operation and reliability. Chapter V includes a discussion of several of these, and also includes mention of a number of other promising applications of high-frequency gas-conduction electronics in digital computers, besides the straightforward shifting register.

The concluding chapter serves to reiterate the salient characteristics of the devices included herein. Relative advantages with respect to competing devices are tabulated, and the nature of the application possibilities is discussed. A mention is made of the possible effect which large, cheap shifting registers may have on the trend of data-processing techniques. The list of more-or-less independent research problems arising from the needs, suggestions, and possibilities brought out within the dissertation serve to terminate the chapter.

II. ELECTRODELESS DISCHARGES

The term "electrodeless discharge" refers to a type of gaseous discharge wherein the primary sources of energy are the high frequency electric and magnetic fields which are produced by means of external electrodes. Only the electric-field type of discharge will be treated here, since it is the type applied to the devices under discussion.

A high-frequency discharge differs from a static-field discharge in three basic ways: (1) internal electrodes are absolutely necessary for the static-field discharge, whereas the high-frequency discharge may be caused by either internal or external electrodes. (2) The steady uni-directional field of the static-field discharge causes loss of electrons and ions by drift motions which are not as important, generally, in the high-frequency discharge. (3) The static-field discharge places almost equal dependence upon two modes of charge production....ionization of gas atoms (or molecules) by electron impact, and release of electrons from the cathode surface by positive-ion bombardment, photoelectric effect, or metastable-atom de-energization....while the high-frequency discharge need depend only upon ionization by electron impact, which is the predominant charge-production mechanism.

All three of these differences promise advantages to the use of electrodeless discharges for such purposes as are discussed herein. Elimination of internal electrodes can give a simpler and cheaper type of envelope construction, and can extend tube life by reducing the rate of gas cleanup and by eliminating cathode-sputtering effects. Reduction of the loss rate should enable development of devices which consume less power, and independence of surface phenomena which are very sensitive to contamination effects should result in a further decrease in construction cost and increase in tube life and reliability. That these advantages are obtained at the expense of introducing r-f circuitry into the picture should be no real deterrent to the development of electrodeless-discharge devices, since the overall advantage promises to be positive.

A brief discussion will be made of each of the more important mechanisms which are involved in typical high-frequency discharges, after which a qualitative description will be made of each of the three phases of such a discharge, i.e. breakdown, steady-state conduction, and decay.

2.1 Basic mechanisms.

Those mechanisms which are included below by no means exhaust the list of the fundamental actions and interactions which play a part in a typical gas discharge. Only those are included which are deemed important to the discussion of the present application of electrodeless discharges. The first three of these prove to be the most influential factors in the characteristic behaviour of high-frequency discharges in small vessels, and their understanding will be assumed in the following sections of this chapter.

2.11 Energy Transfer.

Charged particles, acted upon by an electric field $E = E_o \exp(j\omega t)$ in free space, have an equilibrium velocity which is in quadrature time phase with the applied field, and there is no net energy transfer. If the particles suffer elastic collisions such that a continual perturbation of this equilibrium condition is caused, there will result an in-phase component of displacement current by means of which energy will be supplied to the particles from the field. Brown (3) develops an expression for the result in the following manner, considering electrons of mass m and charge e.

Let f_c be the collision frequency, and include the effect of these collisions as a viscous damping term in the equation of motion

$$m(dv/dt) + (mf_c)v = -eE_o\exp(j\omega t). \qquad (2\text{-}1)$$

The steady-state solution for the resulting velocity is given as

$$v = eE_o \exp(j\omega t)/(j\omega m + mf_c). \qquad (2\text{-}2)$$

Setting the electron density at n electrons per unit volume gives us a resulting current density

$$J = -nev = \frac{ne^2E}{m\omega}\,\frac{f_c/\omega}{(f_c/\omega)^2+1} - j\,\frac{ne^2E}{m\omega}\,\frac{1}{(f_c/\omega)^2+1}$$
$$= J_r + J_i \qquad (2\text{-}3)$$

The power per unit volume absorbed by the electrons from the field is then given as

$$P = J_r E = \left(ne^2E^2/mf_c\right)\left[f_c^2/(f_c^2+\omega^2)\right] \qquad (2\text{-}4)$$

This gives rise to an expression for an effective voltage E_e, where

$$E_e^2 = E^2\left[f_c^2/(f_c^2+\omega^2)\right], \qquad (2\text{-}5)$$

which leaves us with an expression for power transfer as

$$P = ne^2E_e^2/mf_c \qquad (2\text{-}6)$$

Thus, the rate of energy transfer is proportional to the square of the applied field, and it can be shown that the rms value of E_e effects the same power transfer as would a static field of the same magnitude. Conditions involved in the present applications result in many collisions per cycle, so that E_e very nearly equals E.

The collisions suffered by the electrons are predominantly with neutral gas atoms whose mass M is very much larger than the mass m of the electrons. The result of such elastic impacts is an average net energy loss by the electron of approximately 2m/M of its energy per impact. If the collisions remain elastic, an equilibrium electron energy will be reached at which the average energy gained from the field between collisions just equals the average energy lost per collision. In this manner the electrons may attain energy levels many thousands of times higher than that possessed by an electron in the same field in a vacuum. (3, p.1)

The equilibrium energy for ions is very much lower than that for the electrons present in the same gas. This is due to the fact that the very much larger mass of the ions causes a proportionately lower rate of energy gain from the field, and a very much larger average energy loss per impact with neutral atoms.

2.12 Ionization.

There is effectively no ionization produced by ion-atom collisions, both because of the very low equilibrium energy attained by the ions, and because of the exceptionally high energy which they would require. (10, p. 758). The predominant ionization mechanism in the type of high-frequency discharge considered herein is that of ionization by electron-atom collisions. Some mixtures of gases find an appreciable ionization contribution due to collision of metastable atoms of one gas with atoms of another kind of gas, where the ionization potential of the second gas is lower than the metastable level of the first. Metastable atoms may also migrate to the walls, where they can release an electron if their energy is higher than the work function. Langmuir (9) cites a case where metastable neon atoms were found to be releasing electrons with five to ten electron-volts energy from glass walls. However, even if the latter mechanisms were to contribute appreciably to the overall ionization rate, the requisite energy must still come from inelastic collisions with electrons, and it is the energy and density distributions of the latter which control the ionization process.

2.13 Diffusion.

The random motions of the particles in a gas tend to produce an even distribution of the population of each type of particle found in that gas. Any density gradient existing for a particular type of particle then causes an average drift velocity to exist in the local population of that type of particle in such a sense as to tend to eliminate the gradient. This process is known as diffusion, and for each type of particle there will be a diffusion coefficient D such that the diffusion current density (the number of that type of particle per second per unit cross section) will be given by the expression

$$\Gamma = -D \nabla N \qquad (2\text{-}7)$$

where N is the population density of that type of particle as a function of the space coordinates. The coefficient D for a given population is given by the expression

$$D = \frac{L\bar{c}}{3} \qquad (2\text{-}8)$$

where L and $\bar{c}$ are, respectively, the mean free path and the average velocity experienced by the particles of the given population. In so far as the local values of D remain unaffected, the above diffusion phenomenon is being experienced by each separate population in a manner independent of other "superposed" populations and independent of other field-induced drift currents within itself.

When either an electron or an ion diffuses to one of the walls of the discharge container it is effectively eliminated from membership in its respective space population, since either sort of charge will remain trapped on the wall until neutralized by the arrival of an oppositely-charged particle. The introduction of this unilateral constraint upon the boundary of a region causes each of the separate populations (ion and electron) to see effectively a zero-density boundary slightly beyond the actual container wall (for practical purposes, this boundary is usually considered to coincide with the container wall).

From the condition expressed in equation 2-7 we can see that the rate of change of particle density at any point within the container due to diffusion loss is given by the equation

$$\partial N/\partial t = -\nabla\cdot\Gamma = -D\nabla^2 N, \qquad (2\text{-}9)$$

in which D is assumed to be constant with position. The containers which are utilized for the devices considered in this study are circular cylinders of radius R and length Z, where Z is very much larger than R. The elementary solutions for this equation, in the cylindrical coordinates r, Θ, and z are of the form

$$N = e^{-\frac{t}{\tau_\nu}}\left[A\sin\left(\frac{k\pi}{Z}z\right)+B\cos\left(\frac{k\pi}{Z}z\right)\right]\left[C\sin(n\Theta)+D\cos(n\Theta)\right]\times$$

$$\left[E J_\nu\left(r\sqrt{\frac{1}{D\tau_\nu}-\left(\frac{k\pi}{Z}\right)^2}\right)+F N_\nu\left(r\sqrt{\frac{1}{D\tau_\nu}-\left(\frac{k\pi}{Z}\right)^2}\right)\right] \quad (2\text{-}10)$$

where τ_ν is the time constant of the diffusion process; A,B,C,D,E,F are constants; and k and ν are integers. (2) Any arbitrary spatial distribution of N will then be composed of a unique linear combination of such solutions, each of which will have its characteristic time constant as given by the zeroes of the Bessel functions

$$J_\nu\left(R\sqrt{\frac{1}{D\tau_\nu}-\left(\frac{k\pi}{Z}\right)^2}\right) = 0 \quad (2\text{-}11)$$

If S_ν is the first zero of J_ν , then the time constant can be expressed explicitly as

$$\tau_\nu = \left[\left(\frac{S_\nu}{R}\right)^2+\left(\frac{k\pi}{Z}\right)^2\right]^{-1}D^{-1} = \frac{\Lambda_\nu^2}{D}, \quad (2\text{-}12)$$

where

$$\Lambda_\nu = \left(\sqrt{\left(\frac{S_\nu}{R}\right)^2+\left(\frac{k\pi}{Z}\right)^2}\right)^{-1} \quad (2\text{-}13)$$

is known as the characteristic diffusion length of mode m. With the above-stated condition that Z is very much larger than R, we can say that

$$\Lambda_v = \frac{R}{S_v} \tag{2-14}$$

and that

$$\tau_v = \frac{R^2}{S_v^2 D} \tag{2-15}$$

Thus we see that the higher modes have shorter characteristic diffusion lengths and shorter time constants than do the lower modes.

The above solutions hold for each population having the constraint that its particles are trapped when they strike the container wall, and therefore holds for electrons, each type of ion present, and probably for each type of metastable atom if τ is small enough compared to its lifetime. The independence of this process among the different populations was mentioned above, but it proves expedient in cases of sufficient electron-ion density to introduce a new "effective" diffusion coefficient, applicable to both populations separately, which includes both the effects of their independent diffusion processes and the effects of space-charge induced drift currents. Because the diffusion coefficient for the electron population is very much larger than that for the ions, regions which began with equal densities of both would soon develop a positive space charge. The steady-state condition will be such that the combined effects of space-charge induced drift currents (opposite directions for the two populations) and "free" diffusion currents (independent and unequal, but in the same direction for the two populations) will produce exactly the same net current for each population... and this loss can be attributed to a fictitious diffusion process, termed ambipolar diffusion.

Analysis of the above process combines the diffusion coefficients of the ions and electrons (D_+ and D_- respectively) as well as their mobilities (k_+ and k_- respectively) to give the following expression for D_a, the ambipolar diffusion coefficient.

$$D_a = \frac{D_+ k_- + D_- k_+}{k_+ + k_-} \qquad (2\text{-}16)$$

The mobility k of a charged particle may be defined as the ratio of its average, field-induced, drift velocity to the magnitude of the field causing the drift. Loeb (10, p. 208) shows that, when the electron temperature (T_-) is considerably higher than the ion temperature (T_+), the above expression reduces to

$$D_a = \frac{D_+ T_-}{T_+} \qquad (2\text{-}17)$$

and goes on to state that typical discharges may find this temperature ratio to be from five to twenty.

If we make some assumptions for neon gas at the pressure currently being used, 7.5 mm. of Hg., we can arrive at an estimate for the ratio of the diffusion coefficients of electrons and ions in a typical discharge. We find representative values for the mean free paths of electrons and ions, assuming that the electron energy is 4 electron volts and the gas temperature is 300°K, to be 0.0183 cm. (4,p.5) and 0.00185 cm. (7,p.143) respectively.

$$\frac{D_-}{D_+} = \frac{\frac{L_-\bar{v}_-}{3}}{\frac{L_+\bar{v}_+}{3}} = \frac{L_-\sqrt{\frac{T_-}{m}}}{L_+\sqrt{\frac{T_+}{M}}} = \frac{L_-}{L_+}\sqrt{\frac{T_-}{T_+}}\sqrt{\frac{M}{m}}$$

$$= \frac{0.0183}{0.00185}\sqrt{(20)(1838)}\sqrt{\frac{T_-}{T_+}} = 1{,}920\sqrt{\frac{T_-}{T_+}} \tag{2-18}$$

From equations 2-17 and 2-18 we can thus infer that a typical value for the ambipolar diffusion coefficient during a discharge can be perhaps five to twenty times that for free-ion diffusion, and 1/430 to 1/850 that for free-electron diffusion. Loeb further states (10, p.208) that, when T_- equals T_+, the ambipolar diffusion coefficient is "sensibly equal" to the ion diffusion coefficient.

At a given temperature, the coefficient of diffusion will be inversely proportional to pressure. A representative value for the ambipolar diffusion coefficient of neon at 300°K is given by the following expression. (13, Jan. 15,1949, p.11)

$$D_a p = 130 \ \frac{cm^2}{sec.} \ mm. \ Hg. \tag{2-19}$$

During a discharge, this value should be multiplied by the ratio of electron to gas temperature to obtain a representative figure, since both the electrons and the ions will diffuse faster under these conditions.

There is another mechanism, besides that of diffusion, by which electrons and ions may be lost to the vessel walls. The oscillating drift motions of the electrons, under the influence of the excitation fields, can tend to sweep a portion of the electron population into contact with the walls during each half cycle. At lower frequencies, where these oscillations will be relatively large, this loss can exceed greatly that due to normal diffusion processes. When plasma densities are high enough to impose ambipolar diffusion conditions, the greatly increased electron loss due to these drift currents will cause an increase in the potential difference between the space charge and the walls. This will then bring about a new "ambipolar-duffusion" condition, which has a higher transition density and a higher diffusion coefficient than the normal type, and correspondingly greater losses.

2.14 Volume Recombination.

For each random encounter of an electron and a positive ion within the plasma, there is a certain probability that these two particles will re-combine to form a neutral atom, thereby diminishing the plasma population. The effect of recombination is usually expressed by the equation

$$dN/dt = - a_r N^2 , \qquad (2\text{-}20)$$

where N represents the density of each the positive and negative particles, and a_r is the recombination coefficient.

This assumes both particles to be present in approximately equal densities, which is usually the case in a discharge plasma.

Recombination coefficients seem to be independent of pressure (at least below a few millimeters Hg.), but little is said in the literature about any expected relationship between a_r and temperature. It can be inferred, from discussions concerning the probability of capture upon encounter (10, p. 522), that an increase in electron temperature will cause a decrease in a_r, and this seems to be verified by the experimental evidence of Goldstein <u>et al</u> (6). The latter group subjected a decaying plasma to short bursts of microwave energy (e.g. a 10 usec. pulse, 100 usec. after excitation of discharge was removed, of 83.5 milliwatts at 8600 mc.) and observed a very marked coincident decrease in afterglow intensity. It was estimated that T_- was being raised to several times ambient temperature, and it appeared that the light intensity was decreased by a factor of about 45% during the pulse.

For neon, a_r is of the order of 10^{-7} $cm^3/sec.$ (8, p. 242) when the electrons are in thermal equilibrium with the gas at room temperature. Under these conditions, the predominant recombination is presumed to be a dissociative process, i.e. $Ne_2^+ + e \quad Ne + Ne$. No recombination data are found for the conditions existing during a discharge, but estimations of the order of 10^{-12} are found for the value of a_r during the discharge. (10, p. 566). Small traces of impurities can cause considerable variation in the effective value of the recombination coefficient, and this effect is very often pressure sensitive, depending upon the nature of the impurities. (10, p. 565).

2.15 Attachment.

There are certain molecules (e.g. O_2, SO_2, H_2O and NO_2) which, when encountering an electron, will exhibit a certain tendency to capture the electron and form a negative ion. This process is known as attachment, and it can be characterized by the attachment probability h, which is given as the inverse of the average number of collisions with the gas atoms per attaching collision. Apparently h is usually quite small, of the order of 10^{-3} attachments per collision or less. (2) If h is assumed independent of electron energy, and if the velocity distribution of the electrons is assumed Maxwellian (only justifiable when few inelastic collisions are experienced), Brown (2) shows that attachment loss can be expressed by the equation

$$n = n_o e^{-\frac{t}{\tau}}, \qquad (2\text{-}21)$$

where

$$\tau = \frac{L}{2h}\sqrt{\frac{\pi}{2}\,\frac{m}{kT}} \qquad (2\text{-}22)$$

n is the electron density, L is the electron mean free path, m is the electronic mass, k is Boltzmann's constant, and T is the electron temperature. This expression is for electron loss in a gas composed entirely of one kind of molecule with an attachment probability h. If a certain ratio s of this type of molecule to non-attaching atoms (or molecules) existed in a gas, then it could be assumed that the value of τ for the attachment loss in this case would be 1/s times that given above. This would be the case for these molecules appearing as an impurity.

2.2 Breakdown.

In section 2.12 we saw that the primary source of ionization in a high-frequency discharge is that due to electron-atom collisions, and it follows from this that the electron population is the controlling factor in the breakdown phenomenon. Assuming an initial small number of electrons present, we say that breakdown will occur when the production of new electrons by ionization exceeds the loss of electrons by the processes of diffusion, recombination and attachment (assuming diffusion loss to include that due to drift oscillation). For the pressure and container dimensions being utilized in the devices under discussion, the diffusion coefficients are relatively high and the characteristic diffusion lengths are relatively short. Prior to breakdown, the plasma density is too low to incur the conditions for ambipolar diffusion, and the very high value of D_- ensures domination of the diffusion loss over recombination losses. Losses by attachment are an undesireable occurrence, and suitable gas-purity precautions will render them negligible.

The rate of production of electrons may be expressed by the equation

$$dn/dt = r_i\, n \,, \qquad (2\text{-}23)$$

where r_i is the average frequency of ionization, expressed as electrons per second per electron. This value is a function of the electron energy-distribution function, which in itself is exceedingly difficult to calculate when non-ionizing inelastic impacts (excitation impacts) are liable to occur at electron energy-levels below that required for ionization. Since this condition prevails for the gases under consideration, r_i is simply assumed to depend, in a monotonically increasing fashion, upon the average energy gained per electron between collisions. It can be derived from equation 2-6 that this quantity is proportional to $(E/p)^2$ for the elastic-collision case (where f_c is assumed proportional to p), and it will be assumed that there will be some other monotonic relationship between this energy and E/p when inelastic collisions occur. It is usually the case then, for empirical work, that the value of r_i be assumed to increase monotonically with an increase in E/p, and breakdown data are often plotted as a function of this quantity.

Assuming the lower diffusion mode to be dominant (with its characteristic diffusion length Λ_o), we see that the net rate of change in the electron population is expressed by

$$dn/dt = r_i n - (D_-/\Lambda_o^2)n = (r_i - D_-/\Lambda_o^2)\, n. \qquad (2\text{-}24)$$

If the ionization rate exceeds the diffusion rate, the electron population will grow at a rate corresponding to their difference. When the electron density n reaches a certain value, termed the ambipolar transition density, the electron diffusion begins to be affected by the positive-ion space charge and the effective diffusion coefficient begins to decrease toward that expressed in equation 2-16 as the ambipolar diffusion coefficient. Assuming the value of r_i to remain constant in this region, the decrease in diffusion losses will cause an acceleration in the electron-density growth. Through this region, there is actually a positive third derivative of the electron density with respect to time, and the increase in density to its steady-state value is so rapid that breakdown can effectively be considered to have occurred when the density has reached the ambipolar transition point.

The actual transition from free to ambipolar diffusion is gradual and takes place over several orders of magnitude of electron density. Allis and Rose (1) have made an intensive theoretical analysis of this transition process. Elsewhere (13, Oct. 15, 1951, p. 9) it was illustrated that the ratio of the diffusion coefficient of electrons in the presence of space charge to that in the absence of space charge, D_s/D_- could be expressed as a function of $n_{-o}\Lambda^2$, where n_{-o} is the electron density at the center of the discharge region, and Λ is the characteristic diffusion length. This latter analysis was applied to hydrogen but seemed to be general in nature, and included a curve of the above relationship which, for the values of $n_{-o}\Lambda^2$ of 10^5, 10^6, and 10^7, gave the following respective values for D_s/D_- : 0.6, 0.15, and 0.04... with the curve apparently levelling off as it went beyond 10^7 on the abscissa.

Allis and Rose (1) state that the electron Debye length (λ_n) is the principle factor which controls the transition to ambipolar diffusion, and when $\lambda_n = \Lambda$ the ion density is about twice the electron density and $D_s \approx 2D_a$. They also state that this point is about midway in the transition. λ_n is the distance at which the electrons will shield any stationary charge, and is given by the relationship

$$\lambda_n^2 = \frac{\varepsilon_o D_-}{n e k_-} \qquad (2\text{-}25)$$

where ε_o is the permittivity of free space, and e is the electronic charge. The ratio k_-/D_- (mobility/diffusion) for electrons in any gas is a constant divided by f, the ratio of electron to gas temperatures. (10, p. 214) This constant has the value of 42.7 volts^{-1} (10, p. 194), and so the above transition point for a gas can be expressed as

$$n\Lambda^2 = \left(\frac{\varepsilon_o}{e}\right)\left(\frac{\text{VOLTS}}{42.7}\right)f = 1.3\times10^4 f \text{ cm}^{-1} \qquad (2\text{-}26)$$

The MIT group, in which both the above references were written, assumes a value of 100 for f in hydrogen quite consistently, which would give the above transition point at about $n\Lambda^2 = 10^6$, which seems to agree fairly well with the abovementioned curve.

Since the diffusion loss rate decreases quite rapidly in the ambipolar transition region, it is quite evident that, if the high-frequency excitation were applied to the container when there already existed space charges corresponding to these transition conditions, the "breakdown voltage" required across the external electrodes would be reduced from that for the case with no such "priming".

The above analysis of the breakdown phenomenon involved some implicit assumptions which will be brought out at this time. Brown (3) points out some limits of the physical parameters associated with the discharge breakdown beyond which diffusion is no longer the controlling phenomenon. Those limits pertinent to our discussion are the following:

1) Mean Free Path Limit, wherein the mean free path of an electron becomes large enough to be comparable in size with the container dimensions. This limit may be expressed by stating that we must have

$$L_- \leq \Lambda \qquad (2\text{-}27)$$

2) Oscillation Amplitude Limit, wherein the field-induced displacement of the electrons approaches in amplitude the dimensions of the container. From equation 2-2, assuming f_c to be considerably larger than ω, we can deduce that the electron displacement x will vary as

$$x = \frac{eE_o}{jm\omega f_c} e^{j\omega t} \qquad (2\text{-}28)$$

The limiting case here would be that in which all of the electrons would hit the walls, i.e. when $x_{max.}$ above is equal to half the length along the electric field from wall to wall.

When either of the above limits are approached, the breakdown mechanism is complicated by such secondary effects as increased wall loss, or secondary emission from the walls. It is estimated that the oscillation amplitude limit is reached or exceeded in some of the applications to be discussed herein, with the probable result that breakdown fields need be higher than if diffusion were the only loss. This, in itself, is actually a desireable effect. For analytical purposes, exceeding the oscillation amplitude limit causes increased wall losses which may be accounted for as an effective decrease in Λ.

2.3 Equilibrium Conduction.

By the time that the ambipolar transition density has been exceeded, the space charges within the container can no longer be neglected when calculating the forces on the electrons. The entire electron population will be displaced as a result of the applied field (the ions suffer a much smaller displacement, and their motion will be neglected in this discussion), and the resulting relative displacement of electron and ion populations will produce space-charge fields which counter the applied field. At the equilibrium condition, this countering field must reduce the effective field to the point where the electrons gain only enough energy to reproduce themselves, i.e. until $r_i = D_s/\Lambda^2$ (assuming diffusion to be the dominant loss factor). D_s may be other than D_a at this point if the electron-cloud oscillation amplitude is large enough to increase the static potential difference between the plasma and the walls. However, assuming this to remain essentially constant, it is evident that one would expect the electron temperature within the discharge to remain effectively constant even if the applied field were to be increased. This follows from the assumption that r_i is dependent primarily upon electron temperature.

Verification of this equilibrium, counter-field hypothesis is found in the literature (13, Jan. 15, '53, p.6). A special microwave cavity was constructed in which the steady-state discharge phenomena could be studied. It was found that the average electron energy at the center of a hydrogen discharge was 2.2 electron volts, and remained constant as nearly as could be determined while E/p was varied from 20 to 50 volts/cm-mm Hg.. The gas pressure was in the range 0.5 to 3 mm. Hg., and, although container size was not reported, work by the same group with cavities resonant at this same frequency has previously placed dependence upon the dominance of diffusion losses in hydrogen within this pressure range.

The above situation must be altered somewhat if recombination losses do not remain negligible. Recombination would seldom be an important factor in the breakdown mechanism because the free-diffusion loss of electrons is quite large and the electron density quite low. During equilibrium conduction conditions, however, the diffusion loss has decreased and the density has increased to the point where, in the total loss expression (neglecting attachment),

$$\frac{dn}{dt} = -\frac{D_s n}{\Lambda^2} - a_r n^2 \tag{2-29}$$

the second term on the right can attain relative importance. Which term dominates will be found to be primarily a matter of pressure, for a given gas and characteristic diffusion length. At higher pressures, the diffusion coefficient drops and the recombination loss becomes dominant. The transition pressure is, of course, dependent upon gas composition and container size.

A rough check will be made of the relative importance of the two loss mechanisms for typical parameters used in the devices to be discussed. Neon gas at 7.5 mm. Hg. is used in a container for which Λ is 0.0757 cm. . Values of $a_r = 2.1 \times 10^{-7}$ (13, Oct. 15, 1948, p. 7), of $D_a p = 130$ cm^2/sec--mm. Hg. at 300°K. (13, Jan. 15, 1949, p. 10), and of $f = 10^2$ seem valid. Actual losses over the volume will vary as n^2 for recombination, and as n for diffusion, and so total-loss comparison can only be made by a volume integration for a given density distribution. However, it is informative to consider the relative losses at the center, where n is undoubtedly greatest, bearing in mind that this makes the recombination losses seem greater than they really are. The value of n at this point, for which the two losses there become equal, is given as

$$n = \frac{D_a}{\Lambda^2 a_r} = 1.45 \times 10^{12} \text{ electrons/cm}^3. \qquad (2\text{-}30)$$

This can be compared with a reasonable estimate for the density at the center which can be obtained by use of equation 2-26, and assuming that the density is ten times the value at the ambipolar transition point (where D_s is down to $2D_a$). These seem to be quite reasonable assumptions for the types of discharge employed, and lead to a value for the density at the center of the container of

$$n = \frac{(1.3\times10^4)(10^2)(10)}{(5.73\times10^{-3})} = 2.27\times10^9 \text{ electrons/cm}^3 . \qquad (2\text{-}31)$$

At this estimated electron density, the diffusion loss rate is $D_a n/\Lambda^2 = 7 \times 10^{14}$ electrons/cm.^{3} sec., while the recombination loss rate is $a_r n^2 = 1 \times 10^{12}$ electrons/ cm.^{3} sec., and we see that the diffusion loss rate is some seven hundred times that for recombination loss. The observed decrease in a_r for neon at electron temperatures above that of the gas (cf. section 2.14), gives further weight to the consideration that recombination for the above discharge conditions is negligible. However, the very possible presence of impurities in some of the tests which have been made could well have caused attachment losses, as well as increased recombination losses, which could have altered the above relationship.

Higher wall losses, which may be caused by approaching the oscillation amplitude limit, would complicate the above discussion by imposing a higher electron density at equilibrium. This would increase the recombination losses, but it is certain that the losses to the walls under these conditions would still make the recombination loss appear relatively insignificant.

Having established that the primary loss mechanism is very probably that of diffusion allows us to illustrate the equilibrium condition with some rough, qualitative curves. Consider Figure 2-1, where a typical curve of D_s/Λ^2 vs. n is sketched, which illustrates the relative loss rate in electrons

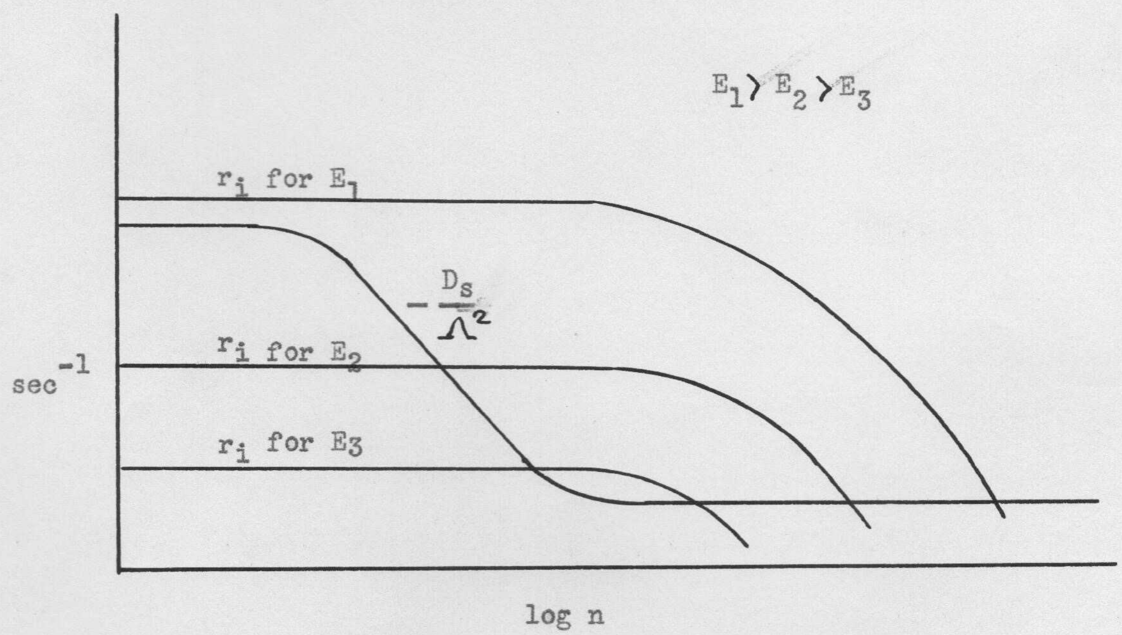

Figure 2-1. A qualitative sketch of the possible behaviour of the coefficients of gain and loss vs. electron density (with reference to the equation $dn/dt = (r_i - D_s/\Lambda^2)\, n$.)

per electron per second. Superposed on the same coordinates are three curves showing the possible form which r_i vs. n may take for each of three different values of applied field... this also being in the units of electrons per electron per second.

From Figure 2-1 can be developed a composite value of 1/n dn/dt vs. n by taking the differences between the production and loss curves for the different applied fields. The result is plotted on Figure 2-2.

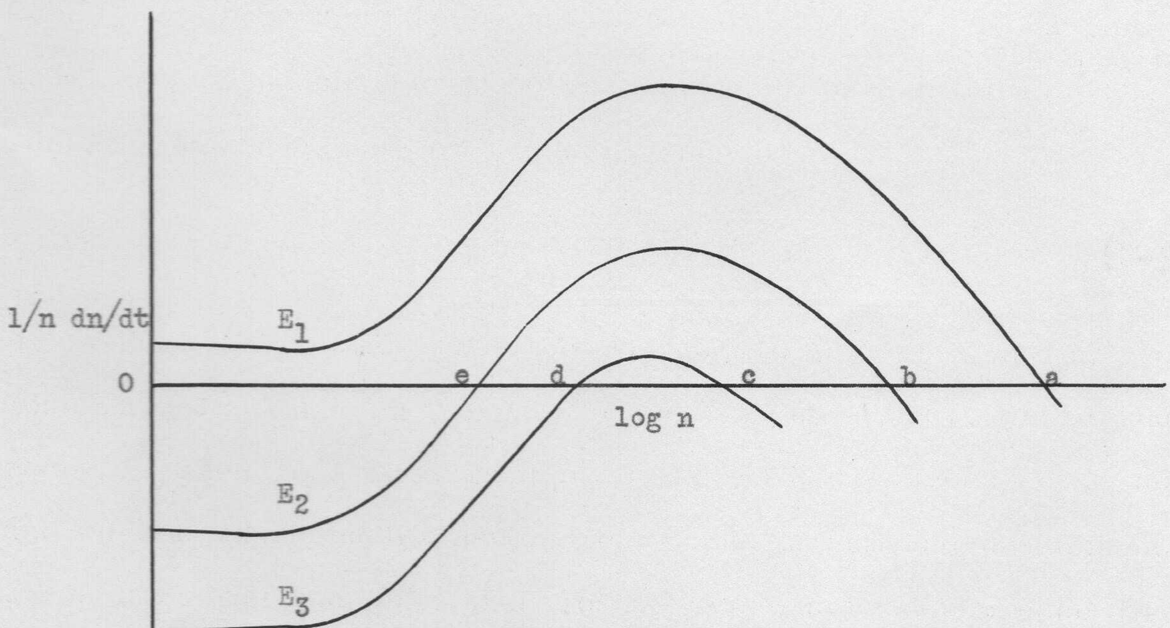

Figure 2-2. A qualitative sketch of the possible behaviour of the net rate of gain, in electrons per electron per second, as a function of the electron density. (Compiled from the hypothesized curves of Figure 2-1.)

It is quite apparent that E_1 is the only one of the three values of applied field which would effect an unprimed breakdown, and that the resulting equilibrium density will be that at a. E_2 and E_3 will neither be able to effect an unprimed breakdown, but both will be able to attain discharge equilibrium once the density has reached values above the points e and d respectively...and their respective equilibrium densities will be at the points b and c.

The effect upon the equilibrium discharge conditions of approaching the oscillation amplitude limit is an increased wall loss. The relatively large displacement of the "free" electron population causes a very high initial electron loss to the walls, but the resulting increase in positive space charge soon limits this loss per cycle to that which can be matched by the increase in positive-ion loss caused by this same space charge. In this respect, it has somewhat the same effect upon plasma loss as would a rise in the electron temperature, i.e. both the "ambipolar" transition density and the "ambipolar" diffusion coefficient will be increased. Alternatively, but with less of a natural connection, the effect of approaching the oscillation amplitude limit may be likened to a decrease in the characteristic diffusion length.

2.4 Extinction and Decay.

Inspection of Figure 2-2 reveals that if E_3 were reduced very much farther, no stable state such that $1/n \, dn/dt = 0$ and $d/dn \, (1/n \, dn/dt)$ is negative will exist, with the result

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Inspection of Figure 2-2 reveals that if E_3 were reduced very much farther, no stable state such that $1/n\ dn/dt = 0$ and $d/dn\ (1/n\ dn/dt)$ is negative will exist, with the result that the density must drop to zero with ever increasing rapidity. This limiting value is termed the extinction or minimum-maintenance field, and is the lowest value of applied field which permits bistable discharge conditions.

The electron-density decay under the above circumstances is at a rate corresponding to a curve (electrons per electron per second) very nearly like that of the E_3 curve to the left of point d in Figure 2-2. The decay conditions encountered with the devices to be considered herein will be slightly different from this in that excitation such as E_3 or E_2 will suddenly be terminated. For this situation the decay is at a rate corresponding to the $-D_s/\Lambda^2$ curve of Figure 2-1. Also, the effective decay time in these situations is that time which is required for the density to decrease to points d or e respectively of Figure 2-2, since the decay criterion here is that reapplication of the given value of applied field will not reinstate the discharge.

On the strength of the above analysis it would seem reasonable to assume that, since the rate of decay increases quite rapidly at densities below that of point d, the effective difference in decay times between the E_2 and E_3 values of applied field would be essentially the difference in ambipolar-diffusion decay from b and c to d. It must be introduced here, as a complicating factor, that the electron temperature will be decreasing rapidly during the decay time between densities b and d, and that it has been shown in Equation 2-26 that the ambipolar transition density is directly proportional to the ratio of electron to gas temperatures. It is thus quite probable that, within a few microseconds, the ambipolar transition density has dropped by a factor of perhaps 10^{-2}, and that the decay time for such at E_2 will probably be that required for ambipolar diffusion decay all the way down to point e. Re-establishment of excitation will raise the electron temperature so rapidly that it will still be the gain-density relations of Figure 2-2 which must be satisfied in order to reinstate the discharge.

It must also be pointed out, with reference to Equation 2-17, that a decrease in electron temperature, which causes the drop in the ambipolar transition density, will have the simultaneous effect of decreasing the value of the ambipolar diffusion coefficient by the same factor. And, if conditions were such as to have approached the oscillation amplitude limit, cessation of the excitation fields will cause an early increase in the effective diffusion length to cause an even further reduction in the "diffusion" losses.

To complete the above discussion, an estimation will be made of the temperature decay characteristics of the electron population after the termination of the excitation. Since the electron will lose approximately $2m/M$ of its energy per elastic collision (m and M are the respective masses of the electrons and gas atoms), the rate of temperature decay can be calculated if an estimate can be obtained for the collision frequency. Brown (4, p. 5) gives data for the probability of elastic collision for an electron in neon as a function of volts$^{1/2}$. Assuming a mean electron energy of 1 volt through the decay region of interest, and inserting the resulting probability value in the collision-frequency equation given on page 3 results in a value of 2×10^{10} collisions per second (for the gas a room temperature and 7.5 mm. Hg. pressure). The resulting time constant for the exponential temperature decrease is one microsecond...and so we could expect electron temperature to have decreased nearly to that of the gas after five or ten microseconds.

It has been discovered that application of low-frequency fields to the discharge region during the period following the removal of the excitation fields can effect a drastic reduction in the decay time. This is called quenching, and it is apparent that the quench fields override the space-charge fields to cause drift currents to the walls. The drift velocities of the charged particles due to field forces are considerably higher than the velocities involved in diffusion, where the "force" is due to a density gradient in the particle population. The application of quenching fields has become an important aspect in the design of high-frequency discharge devices.

III. DESCRIPTION OF BASIC SHIFT-REGISTER STRUCTURE

The bistable discharge characteristics which were illustrated in Figure 2-2 for typical high-frequency discharge conditions immediately introduce the possibility of the application of such to digital computer devices. The additional properties of having the discharge boundaries fixed within a given chamber by the configuration of the applied electric field, and of having the breakdown voltage effectively lowered by the initial presence of a suitable plasma density, are naturally suggestive of the functional requirements of a serial shifting register...a device in common usage in the digital computer field. This chapter will be devoted to a description of the fundamental structures by means of which these requirements may be met.

3.1 Three-line Register.

Figures 3-1 and 3-2 illustrate two fundamental structural realizations of what is called a three-line shifting register. The use of three separately-excited sets of electrodes, which are connected in iterative sequence to three driving lines, is the origin of the designation "three-line". The region within the tube which is under the influence of a given electrode is termed a "cell", and because three cells are required for every stored bit, the linear distance occupied by three adjacent cells is called one "bit length". The term, "transfer channel," is given to any continuous passageway along which a discharge may be transferred. Here, the entire inside of the tube represents the transfer channel, but later in the dissertation it will be shown that a number of separate transfer channels may exist within the same envelope.

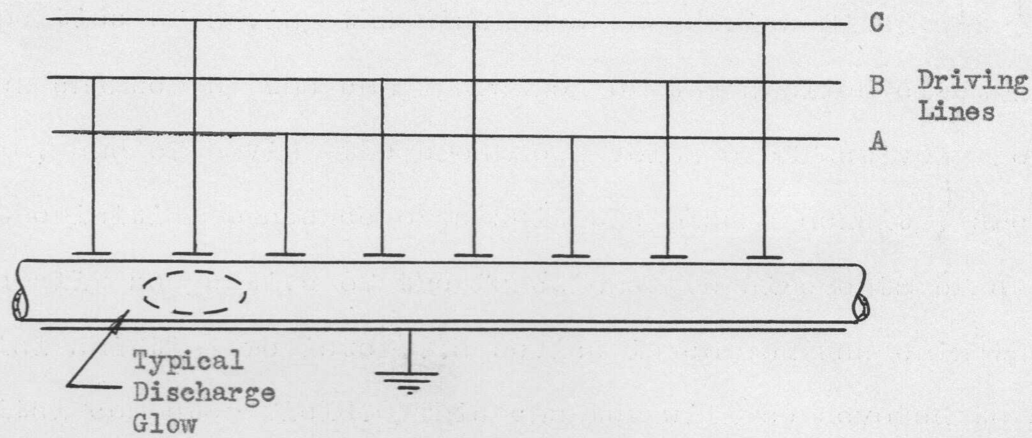

Figure 3-1. Representation of a three-line glow-transfer shifting register which utilizes transverse electric fields.

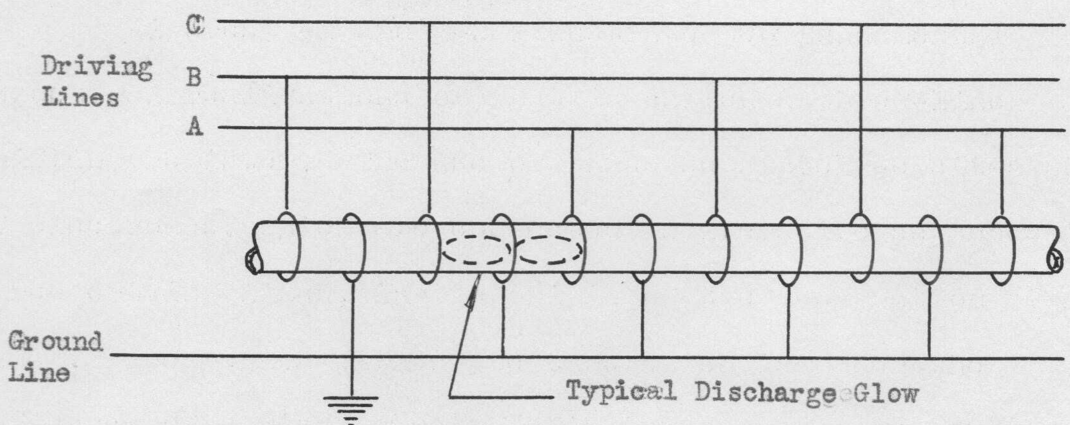

Figure 3-2. Representation of a three-line glow-transfer shifting register which utilizes axial electric fields.

The following functional description is applicable to either of the three-line registers illustrated here. Assume that the high-frequency voltage applied to line A is such that it will sustain a discharge which already exists in any one of its cells, but it will not initiate a discharge in any of these cells unless a discharge exists concurrently in a nearest-neighbor cell (or existed in the very near past). The latter condition assumes the following occurrence, that the equilibrium discharge in a given cell will, by reason of an overlap in their respective electric-field distributions, protrude a sufficient distance into each of its nearest-neighbor cells so that normal excitation of either cell will cause the discharge to spread into that cell. It is evident that the plasma density within the overlap volume is at least within the ambipolar transition range, and that the newly-applied excitation fields cause this localized region to

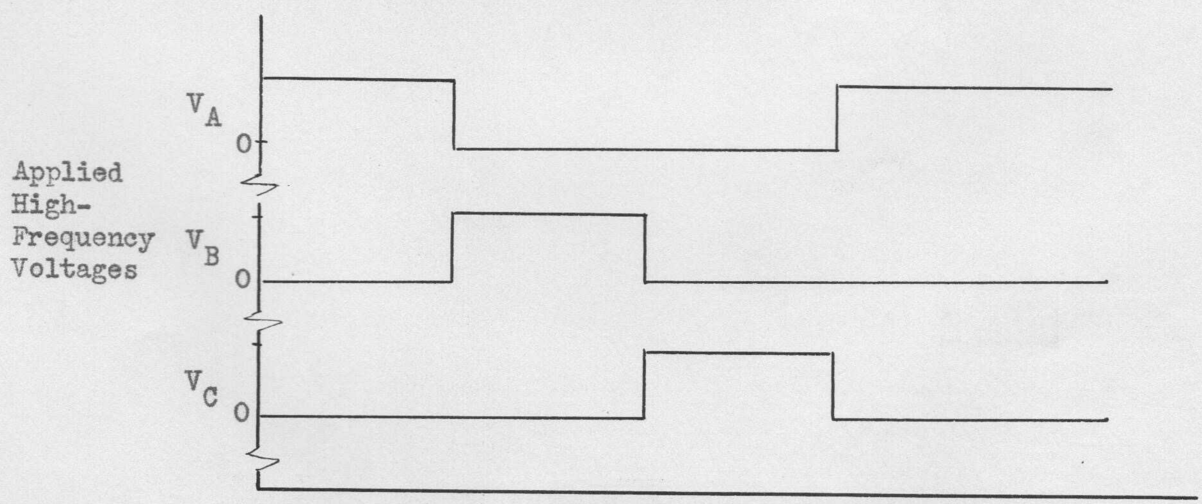

Figure 3-3. Typical sequence of excitation voltages to effect a one-bit shift in a three-line register.

establish an equilibrium density and then to spread and occupy the entire cell.

Assume the initial condition that line A is excited at the voltage level mentioned above, and that an arbitrary pattern of glow and no-glow states exists in the A-cells along the channel. If the excitation sequence illustrated in Figure 3-3 is then experienced, where the voltage on each line is switched between zero and the above-prescribed operating level as shown, the consequences of the specified discharge characteristics will be that our initial glow pattern will have moved one bit-length to the right. This assumes, of course, that the switching times which are involved are longer than the plasma decay times.

A working model of the transverse-field design was made using 3/8 O.D. Pyrex tubing filled with a 93%/7% neon-xenon mixture at 4.5 mm Hg., and using "3/16-wide foil electrodes spaced with about "7/8 between centers. Excitation voltages of 100 to 150 volts, 28 to 35 mc. were used, with fastest allowable operation of about 8,000 bits per second at the lower-voltage limits. Register capacity was 20 bits.

A working model of the axial-field design was later made using "1/8 O.D. Pyrex tubing, with a neon filling at 7.5 mm. Hg., and with electrodes made of A.W.G. size 20 bare copper wire (dia. of 0.032 inches). This register had a capacity of 27 bits, and could be shifted at up to 30,000 bits per second. Excitation voltages of 175 to 215 volts, at 35 to 40 megacycles, were used to drive this register.

3.2 <u>Two-line register</u>.

During the latter phases of the research the principle of quenching was discovered as was mentioned in Section 2.4, and this led to the conception of a means to realize a shifting register requiring only two separate sources of high-frequency excitation voltage. The basic form of such a register is shown in Figure 3-4.

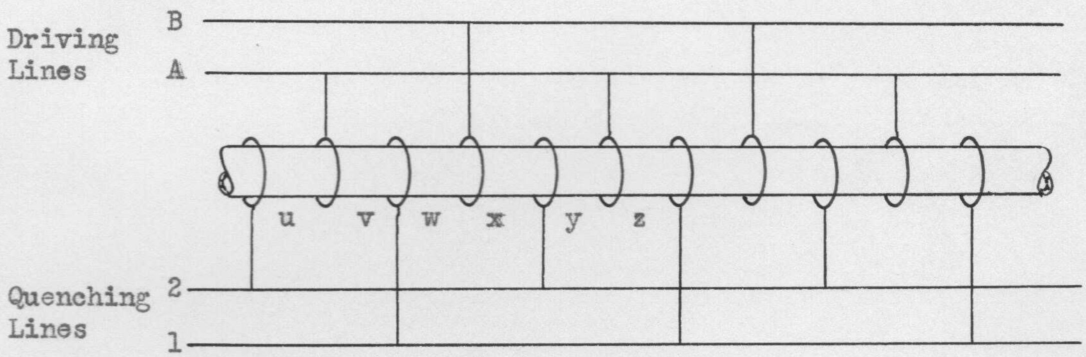

Figure 3-4. Representation of a two-line glow-transfer shifting register which utilizes axial electric fields.

Consider the respective cells here to have the same discharge characteristics which were attributed to the cells of the three-line register in section 3.1, with the exception that the period after the termination of the excitation of a given cell within which its priming of an adjacent cell is still effective now has two very different values, depending upon quench conditions. If the overlap region is subjected

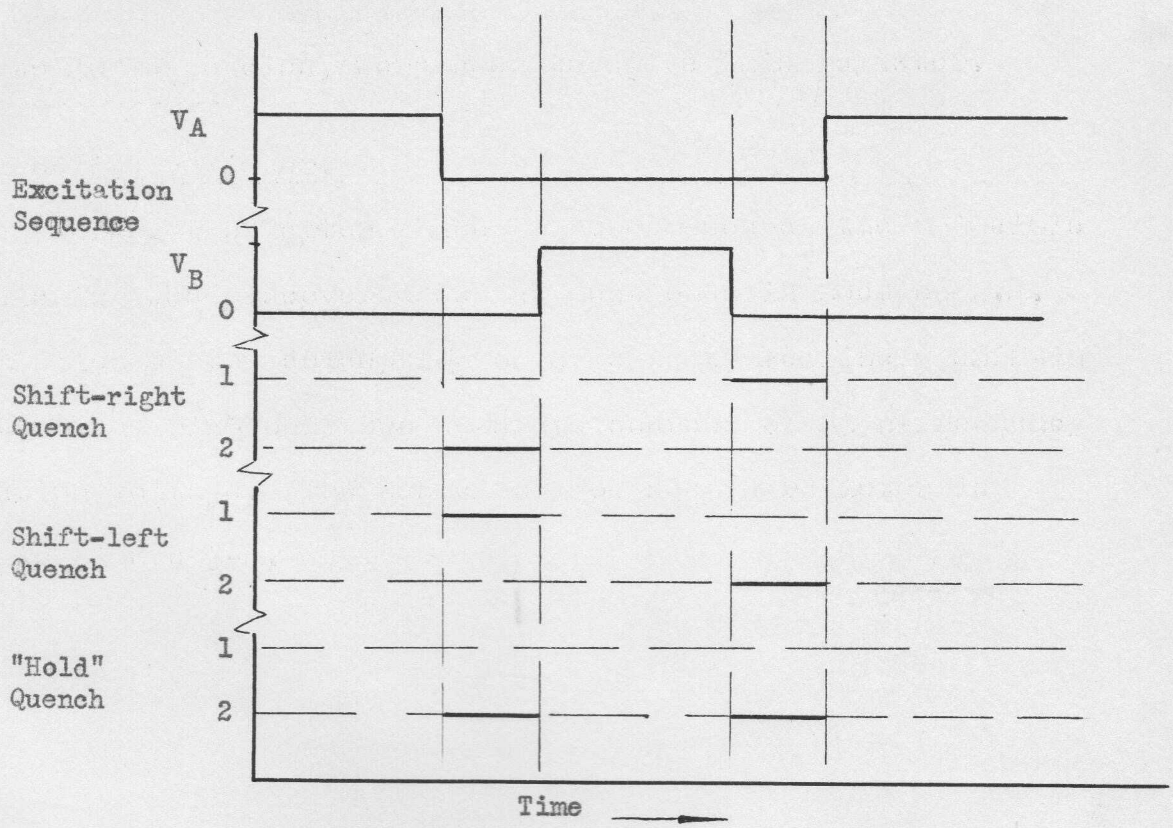

Figure 3-5. A typical "shift" sequence of excitation for a two-line register, with quench-voltage timing indicated for a one-bit shift to the right, a one-bit shift to the left, or a one-cell-right, one-cell-left sequence which is an equivalent "hold".

to a quench voltage, priming decay is very rapid, and the excitation gap illustrated in Figure 3-5 is too long to effect a glow transfer. If no quench voltage is present, however, the priming decay is slow enough so that this same excitation gap will not inhibit a glow transfer.

Suppose the first B-cell contains a discharge during a B-phase of excitation. If no quench voltages are impressed during the following excitation gap, the beginning of phase A will find discharges transferring into both of the first two A-cells. If, however, quench line 2 is energized during this gap, the plasma density in the x and y cell-halves will be decreased too far by the time the A-phase begins to prime the y cell-half, and the transfer will only occur into the v cell-half to the left. Conversely, quench voltage on line 1 instead of line 2 during this gap would have effected a transfer to the right.

A transverse-field version of the above type of two-line register could be realized by segmenting the ground-strip electrode so that each segment symmetrically overlapped a pair of adjacent exciting electrodes. Electrical connections and mode of operation would be the same as outlined above.

A working model of the axial-field design was made and tested using single-pulse quench voltages. This model utilized "1/4 Pyrex tubing with A.W.G. size 18 bare copper wire (dia. of 0.040 inches) for electrodes. A.c. quenching voltages have been found to be much more effective than the pulsed "d.c." voltages, but suitable switching and low-frequency-generator circuitry was not available, and time did not permit their construction for this model. For pulse quenching, the excitation-voltage and timing tolerances were quite close, as were the tolerances on quench-pulse amplitude, length, and relative location, but successful shifting control was demonstrated for each of the three shift modes illustrated in Figure 3-5.

3.3 Input Possibilities.

Successful operation of a serial shifting register requires a means of introducing information at the input end of the register. For the above-described glow-transfer shifting registers, this is satisfied by any technique which will allow optional instigation of the discharge condition in the first cell. Several possibilities for such are outlined below.

A general requirement for the input systems of these registers seems necessarily to be that a continuous discharge be held at some point which is isolated from the rest of the register, and that instigation of the discharge in the first cell be accomplished by transfer from this "keep-alive" discharge. This requirement stems from the statistical irregularity which is characteristic of the unprimed-breakdown formative times. It is felt that, in later working models, a pair of electrodes introduced into the envelope for the purpose of providing a d.c. keep-alive discharge would be the most practical solution to this problem. In the experimenting done to date, a separate high-frequency, low-power oscillator was used to hold a keep-alive discharge, but since no switching is involved, it is quite apparent that the cost of the electrode insertions would be justified by the resulting circuitry simplification.

Transfer of a discharge into the first regular register cell may be accomplished by several means. Figures 3-6 and 3-7 illustrate two of these. The requirements of the

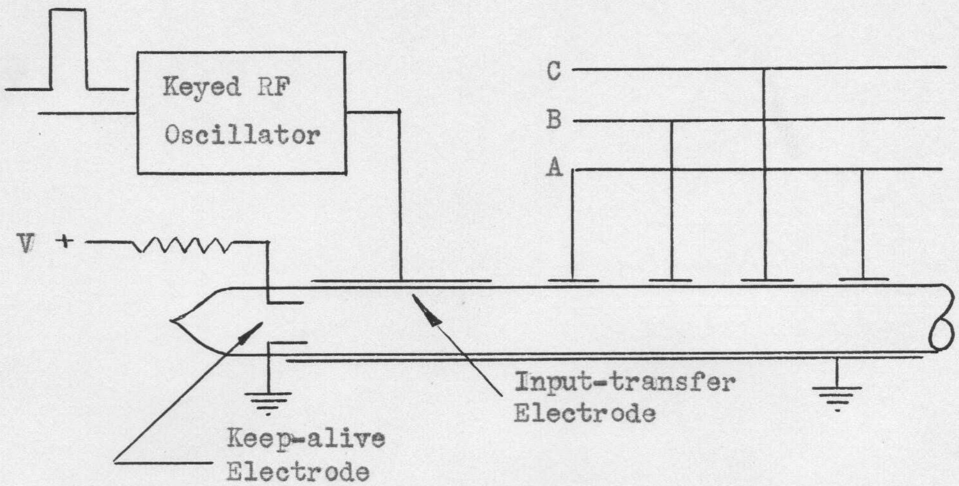

Figure 3-6. Means of optionally transferring discharge into first register cell by means of an auxiliary high-frequency keyed oscillator and external electrode.

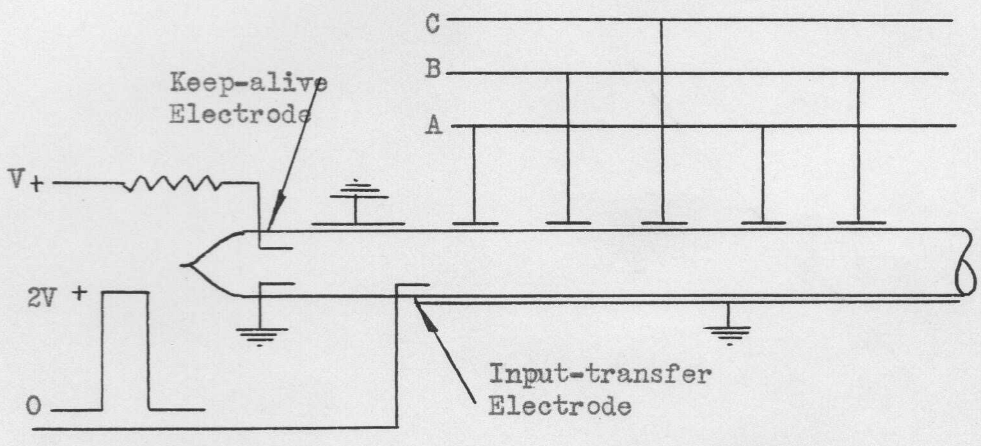

Figure 3-7. Means of optionally transferring discharge into first register cell by means of an auxiliary internal electrode.

input-transfer mechanism regarding decay times are considerably less stringent than those for the regular register units. The only requirement for the former is that the priming effectiveness of the transfer discharge must decay during one complete bit-shift cycle. The design of the r.f. transfer mechanism would be very straightforward...since plenty of power would be available, an extra long electrode could be utilized to ensure adequate isolation of the first register cell from the keep-alive discharge. In the design of the d.c. transfer mechanism, care must be taken that the electrode does not distort the high-frequency fields to the extent of altering appreciably any of the discharge characteristics of the first register cell. However, some portion of the plasma, which is caused by the d.c. transfer discharge between the grounded cathode and the auxiliary electrode, must extend into this same high-frequency field with sufficient density to ensure a reliable discharge transfer.

3.4 Output Possibilities.

The most obvious method of extracting the information which the glow-transfer shift register may contain, is by photoelectric conversion of the radiation which accompanies a discharge. All the information within the register is available on a time-sampling basis at the last cell, and so only one such readout terminal needs to be provided.

By means of a 931A photomultiplier tube, the radiation from some typical discharges was observed, and it was discovered that both the buildup and decay of this radiation involved what appeared to be exponential processes with a time constant of approximately three microseconds. The reason for the delay in the rise and fall times of the radiation is not understood, and further study is suggested if photo-readout is to be utilized at shifting speeds above 100,000 bits per second.

Alternative to the optical readout system would be a system utilizing internal electrodes to sense the presence of a discharge. Either of two general schemes could be employed for this purpose. Two electrodes, which are bounded by the plasma when discharge occurs, will experience a very large change in their two-terminal input conductance between the discharge and no-discharge states. Also, two electrodes, which are exposed to plasma regions of different electron temperatures, will experience a d.c. voltage across them. This voltage is equivalent to that from a high-impedance, 20- to 100-volt source. Either of these two phenomenon could be utilized by simple external circuitry to provide usable output signals.

These above phenomenon have been checked experimentally by the use of the small, commercially available Ne-2 neon diodes, which are rated at 1/25 watt. Effective d.c. resistances of the order of ten thousand ohms may be measured between the input leads of such a diode when it contains a high-frequency discharge. This discharge may be induced by means of either the internal electrodes, separate external electrodes, or an internal-external combination. Geisler, of the International Business Machines Corporation, Poughkeepsie Laboratories, reports the use of special gas diodes in this manner as high-speed switches, whose "opening" and "closing" are controlled by high-frequency voltages across external electrodes. (4)

If, with the above Ne-2 diodes, one electrode is grounded and the other isolated by high impedance from ground, so that the r.f. field strength near each is quite different when an external electrode is energized, as much as thirty volts d.c. may be measured across the internal electodes during an r.f.-induced discharge. The Decker Aviation Corporation, Philadelphia, Pennsylvania has recently put on the market a line of transducers which utilize gas-filled diodes excited by single external electrodes. The d.c. voltage appearing across the internal electrodes of one of these diodes, may be used as a sensitive indication of the degree of unbalance between the two electrode-to-ground capacitances.

IV. SHIFTING-REGISTER FUNCTION AND DESIGN CONSIDERATIONS

The proper design of the type of glow-transfer shifting registers which are under discussion will require a coordinated consideration of many items. First, there exists a large number of functional parameters among which the specification of reliability, speed, power consumption, fabrication means, etc. of these registers dictate certain limiting relationships. Then, among these parameters, there are mutual dependencies upon the fundamental physical variables of gas composition, gas pressure, excitation frequency, electrode geometry, cell geometry, and dimensional scale. To adjust these physical variables towards an optimum satisfaction of the reliability, speed and power-consumption requirements will necessitate a coordinated analysis of the effects upon all of the latter of changing each of the former.

The first requirement is assumed to be one of maximum reliability. The aim of establishing such registers as usable devices in the digital computer field has caused the matter of maximum speed to be the dominant secondary objective in this research. Minimization of power consumption is very important, but nevertheless was ranked third. Decreasing the overall size, and providing for cheap and simple structural techniques, are undoubtedly important for a final analysis of the worth of these devices, but it was felt from general observation that in these respects the glow-transfer devices seemed quite acceptable at the outset.

The first section of this chapter will be devoted to the definition of those functional parameters which have been found useful in analyzing the operation and design requirements of the registers. The dependence of each of these parameters upon the abovementioned physical variables will be outlined as it is presently understood. The actual coordinated discussion for overall register design is set up by a section each on the functional-parameter relationships which are dictated by a maximum-speed requirement, and on the phenomena and control of power consumption.

4.1 Functional parameters and their variation with physical changes.

An analysis of the operation of these shifting registers is facilitated by the definition of certain characteristic, functional parameters. These parameters are, for the most part, limiting values of excitation time-gaps and excitation voltages, with respect to the breakdown, extinction, and transfer characteristics of the discharges. Knowledge of the variation of these parameters, with changes in gas composition, gas pressure, excitation frequency, electrode geometry, cell geometry, and dimensional scale, is necessary for the proper design of a shifting register. Enough is known about this variation to enable the construction of working registers, and this knowledge is given in the form of facts and experimental data, with reference to the appropriate parameters. Predictions, based upon the present theoretical understanding of these discharge phenomena, are included wherever possible.

4.11 Breakdown voltage, V_b.

This is the voltage (measured in rms volts) required to be applied across a given set of electrodes to produce a discharge breakdown with no priming. This seems somewhat affected by the past history...at least since the preceding discharge. Reproducible values of V_b may be obtained during a given set of tests after the first breakdown, but if a few days have elapsed since the last discharge, the first breakdown may be very difficult to achieve even with the aid of a high-frequency spark coil which puts out about 15 kv. Since abnormally high values in themselves are no threat for our purpose, this phenomenon has not been studied further.

Included in the pertinent past history must be the change in d.c. voltage across the electrodes since the last discharge. This fact was not recognized during much of the early part of this research, and has invalidated a number of V_b test values which were obtained with the r.f. voltage which was fed directly from the plate tank of an r.f. power oscillator, whose outpul level was controlled by the d.c. plate voltage. This caused as much as one- to two-hundred volts of change in the d.c. voltage across the external electrodes, and so set up a static field within the discharge cell which served to sweep out the sporadically-generated initiating electrons before they could multiply enough to effect a breakdown. Only when the electrode-to-inside-surface capacitance becomes charged to neutralize this type of field can a normal high-frequency breakdown occur.

It may be feasible to utilize the above phenomenon to increase the safety factor of a working shift register by suitable superposition of d.c. and high-frequency voltages, but of more direct concern are the variations of V_b with such parameters as pressure and frequency. Figures 4-1 and 4-2 illustrate each of these for representative conditions. It is evident from the discussion of Chapter II that higher

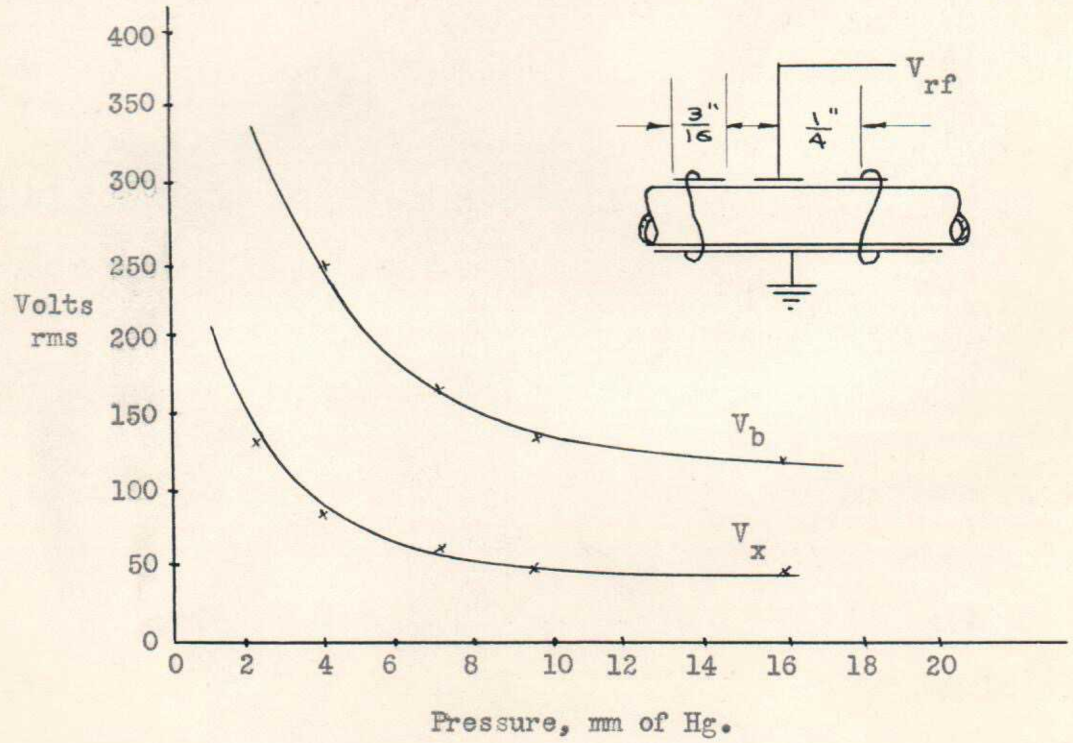

Figure 4-1. Breakdown and extinction voltages as a function of pressure for neon in a "1/4 O.D. Pyrex tube. Transverse-field electrodes arranged as indicated. Excitation frequency is 28 mc..

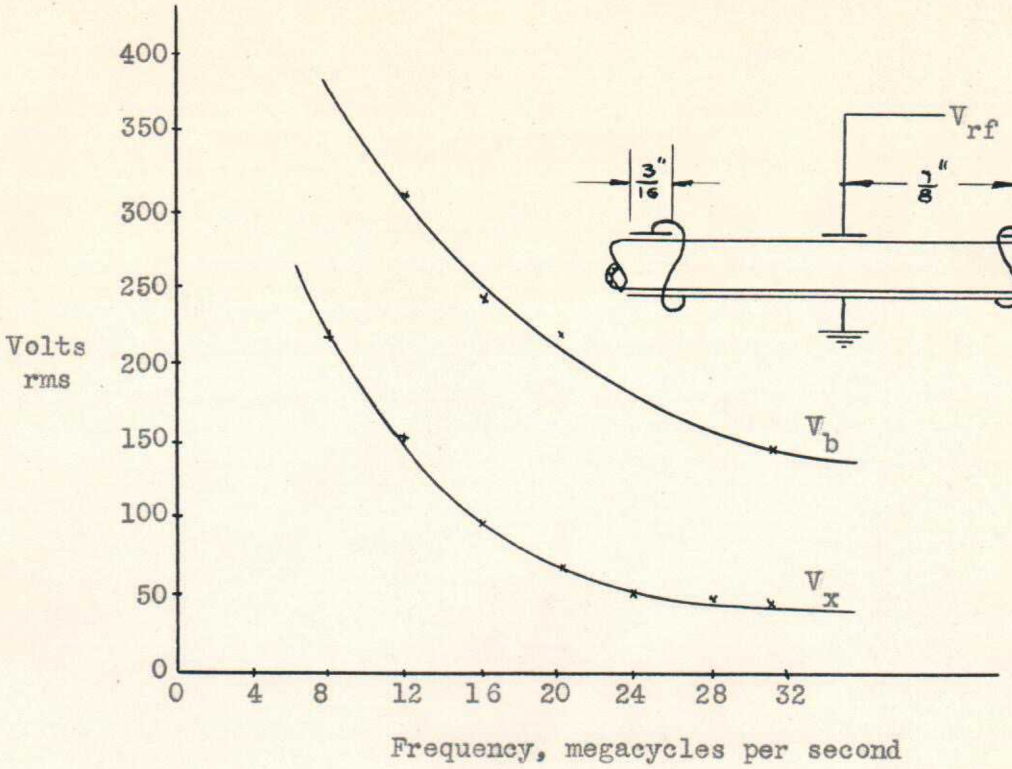

Figure 4-2. Breakdown and extinction voltage as a function of excitation frequency for xenon at 4.3 mm. Hg in a "3/8 O.D. Pyrex tube, with transverse-field electrodes as indicated.

pressures will decrease the diffusion loss and thus decrease the value of the field required to initiate breakdown. Above a certain pressure, however, the associated increase in electron collision frequency will reduce the rate of energy transfer to the electrons more rapidly than the losses will decrease, and the breakdown voltage will necessarily rise again. (See Equation 2-6) The explanation for the change in V_b due to changes in excitation frequency is that the wall losses which are due to the "oscillation amplitude" will decrease with increasing frequency.

4.12 Extinction voltage, V_x.

This is the voltage which is mentioned in section 2.4

as the lowest which permits bistable discharge conditions. It may also be described as the lowest voltage which will maintain an already-established discharge. Typical variations of V_x with pressure and excitation frequency are shown in Figures 4-1 and 4-2 respectively.

4.13 Self-transfer voltage, V_{ts}.

At low pressures and low frequencies, the discharges even in the transverse-field type of tube exhibit a reduction in discharge intensity directly under the excitation electrode. The result is that a discharge being established on one side of the electrode does not guarantee establishment of a discharge on the other side...which deprives us of a consequence which we know to be necessary for proper operation of a shifting register. The voltage to which the excitation electrode must be raised in order to effect a transfer from one side of the electrode to the other is called the self-transfer voltage.

The value of V_{ts} relative to V_x seems more affected by excitation frequency than any other factor, at least for the cylindrical transfer channels which have been used to date. The effect is quite probably due to the oscillation amplitude limit being passed in the discharge region where the electric field actually is predominantly transverse. At the two sides of the electrode there exists more of the axial component, which permits larger electron-cloud oscillation for a given wall loss. This same analysis seems applicable to the axial-field models, with the added feature that the actual field strength in the region directly under the electrode is quite small. A typical relative variation of V_{ts} to V_x with excitation frequency is illustrated in Figure 4-3.

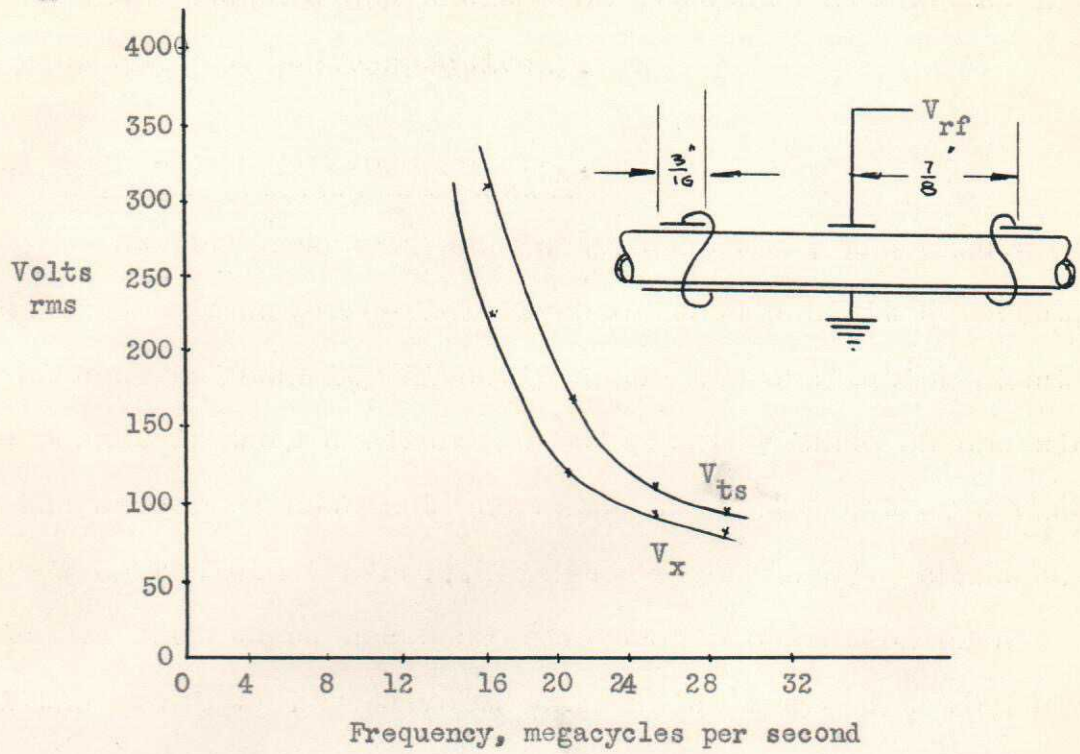

Figure 4-3. Self-transfer and extinction voltage as a function of frequency for a 93%/7% neon-xenon mixture at 4.5 mm. Hg. in a "1/8 O.D. Pyrex tube, with transverse-field electrodes as indicated.

4.14 Transfer voltage, first-nearest-neighbor, V_{t1}.

Consider the same excitation voltage being applied to two adjacent electrodes, with the value so little above V_x that we can assume a discharge to exist in one cell but not in the other. The value to which the common voltage must be raised before the discharge transfers over into the adjacent cell is V_{t1}. In the registers built to date, this voltage has always been lower than V_{ts} and no data have been taken on actual variation with physical changes. It is quite apparent that increasing the electrode separation, decreasing the frequency or pressure, or decreasing tube diameter should serve to increase V_{t1}.

4.15 Transfer voltage, nth-nearest-neighbor, V_{tn} (where n = 2, 3, ...).

Assume the electrodes between a given electrode and its nth nearest neighbor to be grounded, and a common excitation voltage applied to these two. If a discharge exists in the given cell, the level to which the common voltage must be raised in order to effect a transfer across to (but not an unprimed breakdown in) the nth nearest neighbor is V_{tn}. This voltage, since it is actually but a generalization of V_{t1}, is affected by the same type of physical changes. It is, of course, always larger than V_{t1}.

4.16 Operating voltage, V_o.

This is the value of the excitation voltage which is actually switched on and off the driving lines under the operating conditions for the register. It is obvious that V_o must be greater than the larger of V_{ts} and V_{t1}, and must be less than the smaller of V_b and V_{t3} (or, in some cases, V_{t2}).

4.17 Self-extinction time, T_{xs}.

The definition for this which is implicit in its usage for timing-limit discussions is, "the minimum time for which the excitation may be removed from a discharge-containing cell without causing re-establishment of the discharge upon the reapplication of the excitation." The easiest method of approaching this limit experimentally is to begin with a small gap in the excitation such that the discharge will be re-established, and to increase the gap until the discharge does not reappear.

Reference to Section 2.4 and to Figure 2-2 allows us to predict that higher pressures (lower diffusion coefficient), greater tube size, and increased V_o should each cause T_{xs} to increase. Remembering that the ambipolar transition density, as well as the ambipolar diffusion coefficient, will be decreasing towards about 0.01 times their equilibrium-discharge values as the electron temperature decays, we can see that T_{xs} can increase very rapidly as the above physical changes take effect and the electron population has time to cool off. Typical changes in T_{xs} with pressure and V_o are illustrated in Figure 4-4.

The value of T_{xs} when quenching fields are applied to the discharge region is identified as T_{xsq}, and these values can be significantly less than the normal T_{xs}. Experiments on the effect of quench voltage were carried out with a fairly large-sized tube and fairly high E_o, so that

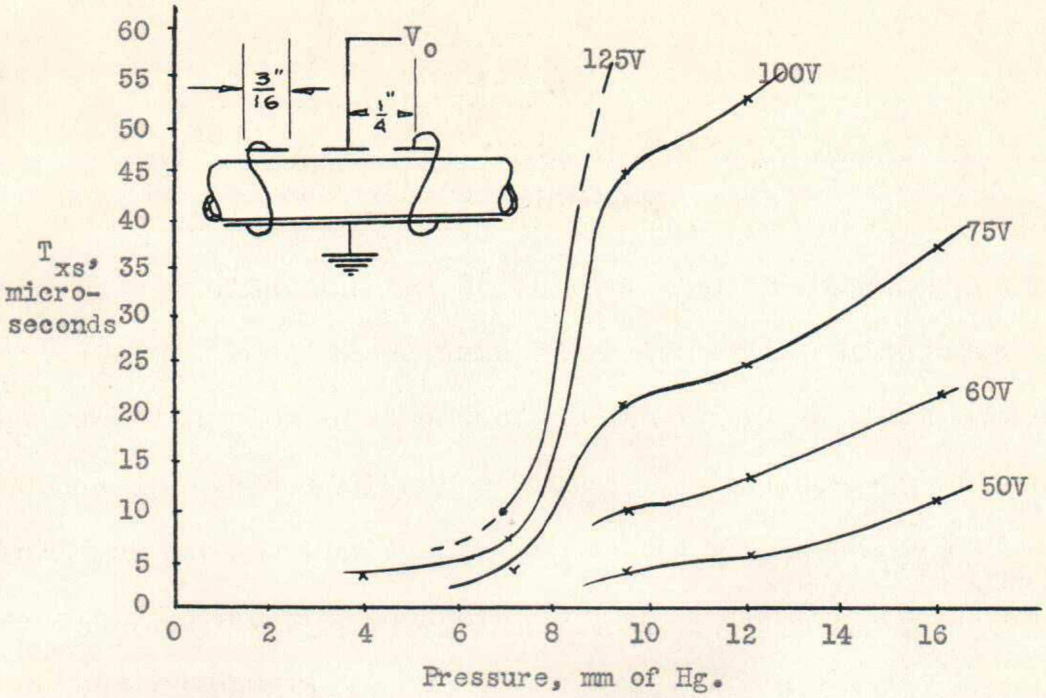

Figure 4-4. Variation in self-extinction time T_{xs} with pressure and operating voltage for neon in a "1/4 Pyrex tube. Excitation frequency is 28 mc., and transverse-field electrodes are arranged as shown.

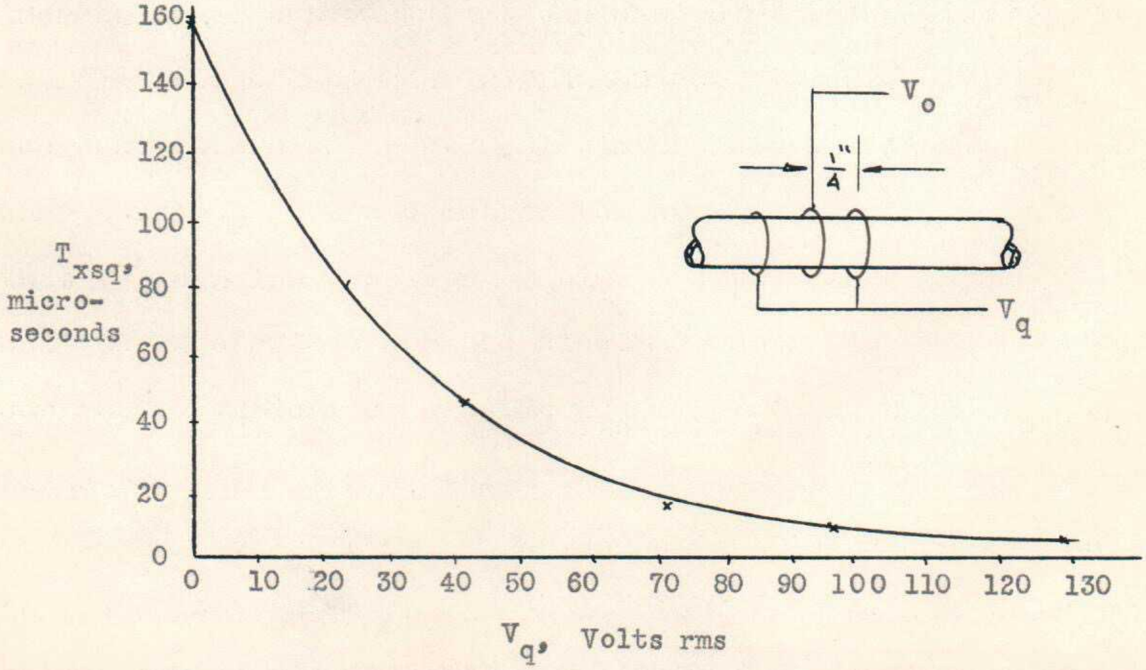

Figure 4-5. Variation in the quenched self-extinction time, T_{xsq}, with quenching voltage. V_o is 180 volts rms. at 35 mc., and V_q is at 2.5 mc.. Tube is "1/4 O.D., filled with neon at 7.5 mm. Hg., with axial-field electrodes (#18 A.W.G. wire) arranged as shown.

T_{xs} was abnormally high. This was done in order to be able to measure the resulting values of T_{xsq}, since the ratio of decrease would have precluded such measurement if T_{xs} had been small to begin with. Variation of T_{xsq} with a typical quench-frequency voltage is illustrated in Figure 4-5.

4.18 Extinction time, first-nearest-neighbor's priming, T_{x1}.

Assume the sudden termination of the excitation on a cell containing a discharge, and assume that the nearest neighbor cell was excited by the same value of voltage after a certain time interval. The minimum length of this interval which will not effect a transfer of the discharge into the neighboring cell is T_{x1}. It seems to be affected most by relative spacing and by V_o, when no quenching fields are present. The corresponding time limit under quenched conditions is referred to as T_{x1q}. Figure 4-6 shows a typical variation in T_{x1q} with quench-voltage magnitude.

4.19 Extinction time, nth-nearest-neighbor's priming, T_{xn} (n = 2, 3, ...).

Assume the electrodes between a given electrode and its nth nearest neighbor to be grounded. T_{xn} will be that minimum time interval between termination of the excitation voltage V_o on a discharge in the given cell and the application of the same voltage to the nth nearest neighbor cell which will not cause a primed discharge transfer into that cell. This is a meaningful value only when V_o is equal to

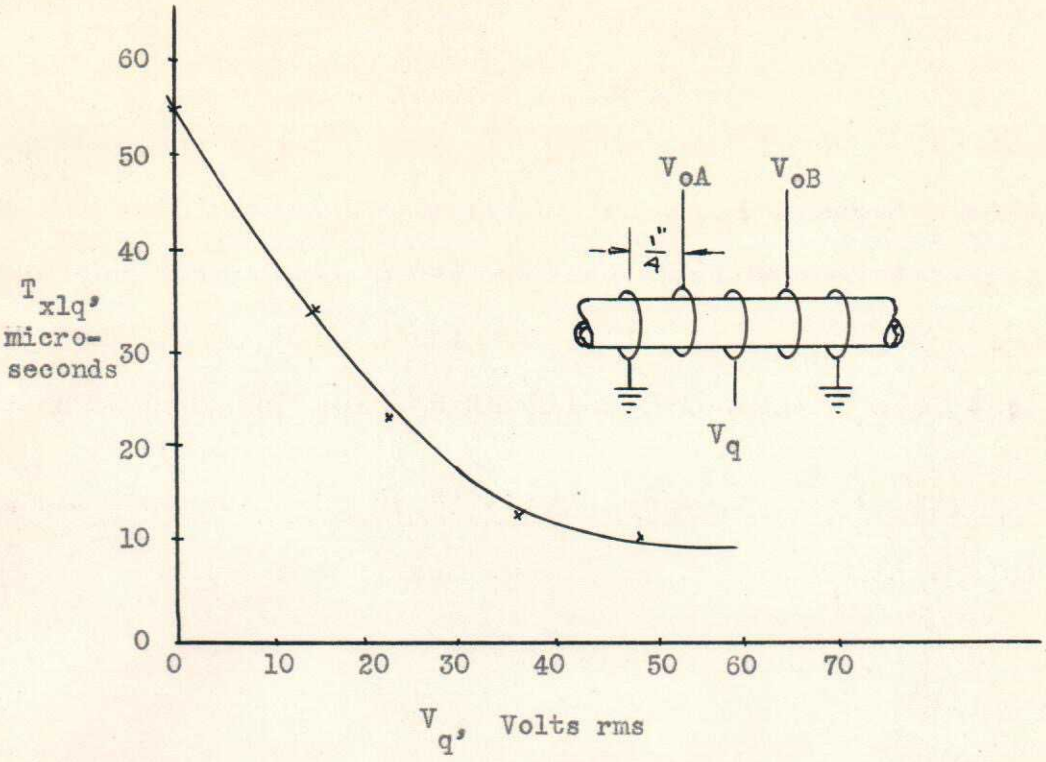

Figure 4-6. Variation in T_{xlq} with magnitude of a 2.5 mc. quench voltage for a "1/4 O.D. Pyrex tube filled with neon at 7.5 mm. Hg., and equipped with axial-field electrodes (#18 A.W.G. wire) spaced as shown. E_o is 110 volts rms. at 35 mc..

or greater than V_{tn}, and will be affected primarily by relative spacing and by V_o when no quenching fields are present. The values of this characteristic time which are affected by the presence of quenching fields are referred to as T_{xnq}.

4.2 Timing considerations.

The relative timing of the excitation on the various sets of electrodes of a register determines directly the shifting rate of the register. To achieve a maximum shifting rate, this timing must be coordinated with the extinction-time limits which were defined in the preceeding section.

4.21 Three-line registers.

It must be mentioned that the quenching technique was not developed until quite late in the research program, and that the very short extinction times promised by this means have shifted the design limitation now to the switching and r.f. generating circuitry. The analyses given below are still valid, however.

Consider Figure 4-7, which illustrates a general timing arrangement for a three-line register. The values for T_g will become negative if there exists an overlap in the excitation instead of an actual gap. A one-bit shift will require the time T_b, and a goal of higher speeds will require a reduction in T_b. Below is written a list of the limits on the excitation times with respect to the various extinction times.

$$\begin{aligned} 3\,T_g + 2\,T_o &> T_{xs} \\ 2\,T_g + T_o &> T_{x1} \\ T_g &> T_{x2} \\ T_g &< T_{x1} \end{aligned} \qquad (4\text{-}1)$$

The first inequality states that each cell has to experience an excitation time-gap greater than T_{xs} during each bit-shift cycle, and the second states that the discharge shifted out from the succeeding cell during the last bit-shift cycle must have been gone for a longer time than

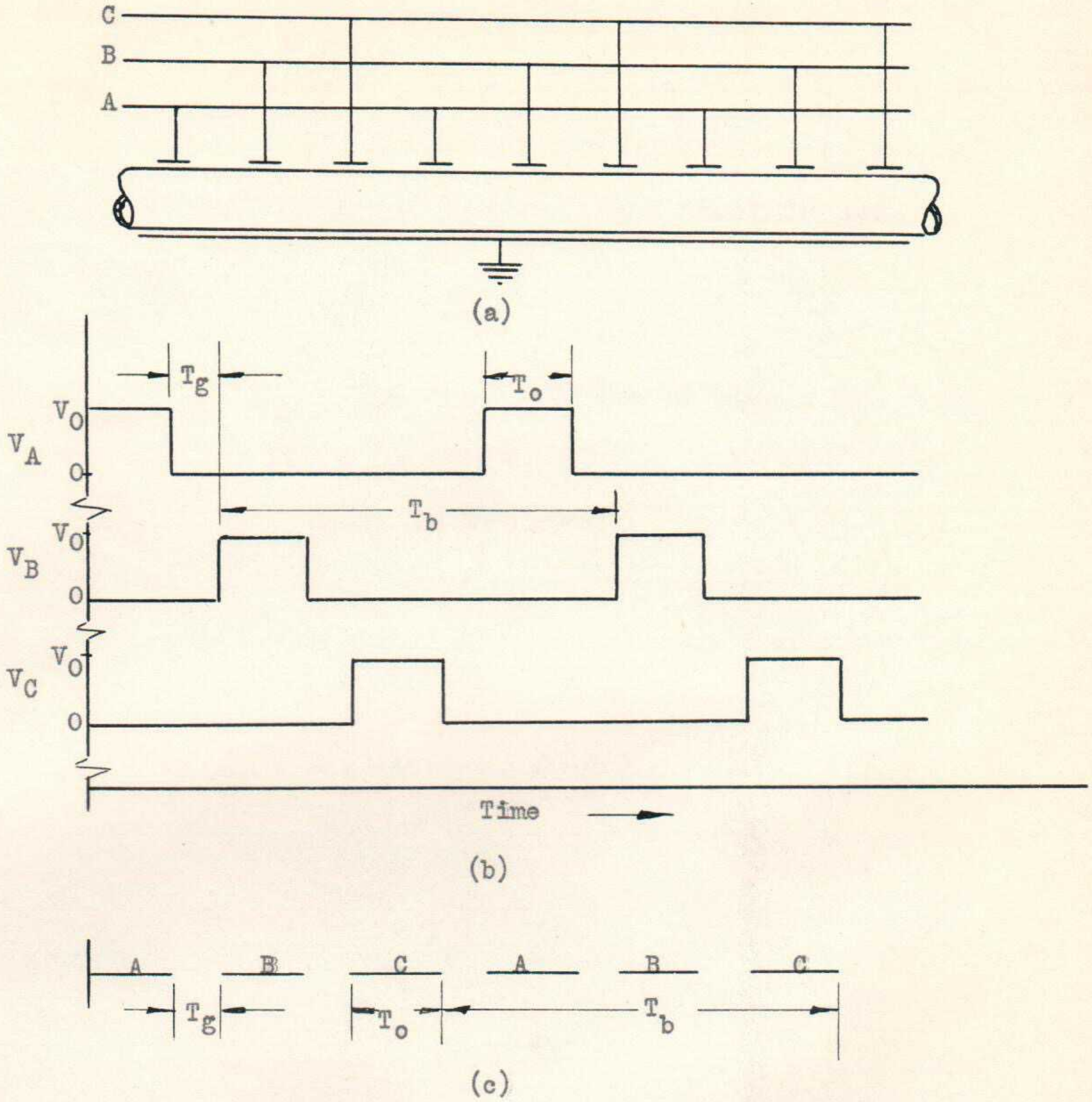

Figure 4-7. A typical three-line register diagram (a), with its excitation timing diagram (b), and with the preferred schematic representation of the timing diagram (c).

T_{x1} in order not to prime the given cell and cause a "flashback". The third inequality guarantees the same situation for the second cell ahead of the given one, and the last inequality guarantees that the given cell will be primed by its nearest neighbor during the present bit-shift cycle. The third inequality is assumed to be easily met for any practical case, since V_{t2} can usually be made greater than V_o. We shall assume, for the following discussion, that relative cell geometry can control T_{xl}, and that T_{xs} is to be the limiting parameter.

Consideration of the straightforward timing sequence given in Figure 3-3 for a three-line register reveals that T_b here will equal $3kT_{xs}/2$, where k represents the ratio by which the first inequality above is exceeded, and may be termed the safety factor on T_{xs}. A similar inspection of Figure 4-7 results in equating T_b to $kT_{xs} + T_o$, and it can be seen that, if it is possible to make T_o less than $kT_{xs}/2$, there will be a decrease in T_b and an increase in the shifting speed. The limit upon this, of course, is when T_o approaches zero, which will realize a fifty per cent increase in shifting speed for a given value of kT_{xs}. This mode of operation is based upon the fact that the discharge reaches its equilibrium state very rapidly, and it is accordingly assumed that this lower limit upon the length of T_o is not reached.

Since T_{xl} is bounded by two limits, it appears that a coordinated safety factor for this parameter would require T_{xl} to equal $T_g\sqrt{2 + T_o/T_g}$. As T_o is made ever smaller, the safety factor under which T_{xl} operates will approach a lower limit of 1.4. There would seem to be no advantage in making k greater than this, and it would seem risky to make it much less, so it appears that the lower limit for T_b which one could approach with reasonable safety would be about $1.5T_{xs}$.

The present switching and r.f. generating equipment is not capable of measuring the lower limit for T_{xsq}, much less be able to develop a switching sequence making T_o less than $kT_{xsq}/2$. It is not known, therefore, what sort of lower limit is realizeable for T_{xsq}. Present plans for attaining maximum shifting speed call for a constantly-applied quench voltage (since the low-frequency quench voltage would take too long to switch on and off) and a time overlap of successive excitation voltages (i.e. both above V_{t1} at the crossover point).

4.22 Two-line registers.

The two-line register described in Section 3.2 requires for its operation that the quench voltages be so switched that within one half of a bit-shift cycle there is a change from maximum quench to minimum quench. Unless techniques are found for improving the effectiveness of the single-pulse quench voltage, the only reliable quench voltage will be one which is oscillating at a frequency considerably lower than that of the excitation voltage. The speed of such a register therefore seems limited by the switching time of the quench voltages and is not expected to be able to compete in speed with the three-line registers.

4.3 Power considerations.

The power which is consumed per bit, while fairly small, is still an important factor to consider if register systems of large size are to be built. There are certain steps which can be taken to effect a reduction in this power, but it is not yet known to what extent these will be limited by speed and reliability requirements. The various mechanisms of power loss will be reviewed, and some possible measures toward power reduction will be discussed.

The fractional energy given up by an electron, per elastic collision with the gas atoms, is of the order of 2m/M. For neon, then, approximately 5.5×10^{-5} of the total electron energy is lost per elastic collision. If the collision frequency is evaluated for neon at an assumed average electron energy of 4 electron-volts, by the same process as was outlined in Section 2.4, a value of the collision frequency f_c of 6.5×10^{10} sec^{-1} is obtained. The power loss per unit volume may be expressed as $f_c nu2m/M$, where u is the average electron energy, and n is the number of electrons per unit volume. For the above figures, we see that the collision loss per unit volume will equal approximately 3.6×10^6 nu electron volts per second.

The energy lost as an electron reaches the wall will be the sum of its kinetic energy and the ionization energy, $u + V_i$. For neon, V_i is 21.6 volts, which is approximately five times the potential equivalent of the average kinetic energy, u. This means that the loss of an electron accounts for the loss of about 6u electron volts. If it is assumed that a characteristic diffusion length of 0.0757 cm. is typical, that u = 4 electron volts so that f is 10^2 (where f is the ratio of electron temperature to gas temperature), that the pressure is 7.5 mm. Hg., and that the room-temperature ambipolar diffusion coefficient for neon is 130 cm^2/sec, we can arrive at an estimate for the power lost per unit volume due to ambipolar diffusion of 1.8×10^6 nu electron volts per second. We thus see that the collision loss is approximately twice the normal diffusion loss for a typical discharge.

If a typical cell is assumed to have a diameter of 0.363 cm. and a length of 1.27 cm., and if, to be generous, it is assumed that the entire volume has a density of 10^{10} electrons per cm^3, each with an energy of four electron volts, an estimate for the order of magnitude of the expected power lost by the combined collision and normal diffusion processes will yield a value of about five milliwatts.

It is almost certain that the increased wall losses incurred by the electron-population oscillation, at the frequencies and vessel dimensions being used, exceeds the above listed losses. The peak to peak drift swing of an electron in neon, at 7.5 mm. of Hg., is of the order of a third of a centimeter at normally-expected values of the applied field. This swing should be reduced considerably at equilibrium-conduction densities, but it is quite evident that there will exist a considerably deeper potential well within the vessel than normal ambipolar-diffusion conditions would produce, and that the resulting losses will be accordingly greater.

The upper limit for the power lost by this mechanism can be established crudely by assuming that the electron-oscillation swing is so great that all of the electrons are removed at every half cycle. For a typical frequency of 30 mc., and assuming for neon that an electron which is lost to the walls dissipates about 6u electron volts, we can estimate that the upper limit for the power per unit volume lost due to the oscillation process would be $(2)\ (3 \times 10^7)\ (n)\ (6u) = 3.6 \times 10^8$ nu electron volts per second. This is one hundred times the estimated collision loss, and for the typical cell used above would result in a total power loss of some 333 milliwatts, or a third of a watt.

It has been observed in the laboratory that some ten discharges being loaded into a register would drop the output voltage of the power oscillators (832A twin tetrodes in push-pull, tuned-plate tuned-grid circuits) by as much as fifteen percent. A pure-resistance load connected in place of the register, with appropriate retuning, gave about the same fifteen percent output drop when it was absorbing slightly less than a watt. This implies that about 100 milliwatts per bit is being absorbed by the register, which seems entirely reasonable in the light of the above discussion.

Since the oscillation losses can be interpreted as an increase in the free electron diffusion rate, equilibrium conditions when these losses are effective would probably involve very nearly an equivalent ion-electron loss-equilibrium relationship to that analyzed for ambipolar diffusion. The effective "ambipolar" diffusion coefficient will be quite high, of course, but there would seem to be enough similarity so that an equivalent transition density would exist for this process just as for the normal diffusion case. This would imply that the minimal equilibrium density would vary inversely as the square of the characteristic diffusion length. Thus, increasing the diameter of the discharge vessel by a factor d should reduce the requisite electron density by d^{-2}, as well as decrease the loss per electron per second by d^{-2}. The volume is increased by d^3, and the net result is a net decrease in the total electron-per-second loss by a factor of d^{-1}. This first-order qualitative estimate is further strengthened by the second-order effects...the reduction in the necessary reproduction rate allows a decrease in electron temperature and a decrease in applied field, which cause yet a further reduction in loss.

Increase of the dimensions past a certain point where wall losses have decreased quite far, will result in the collision loss, which increases roughly as d^3, becoming dominant and causing the total loss to begin increasing with d. The relative dimensional increases required to reach a minimum such as this, or the relative decrease in total power consumption which might so be realized, are not known and will need experimental determination. This increase might well be limited by total-size or extinction-time considerations before such a minimum-loss point would be reached, but it seems that the use of quenching voltages to control the extinction times should allow some measure of power reduction by means of increasing the dimensions.

An increase in the excitation frequency is expected to reduce the oscillation losses, but at the same time will probably reduce the value of V_b at a greater rate than V_x. This latter trend is observed in experimental results up to 40 mc., but seems to be levelling off there. It is not yet known whether or not a safe range between V_b and V_x will remain as the frequency is raised much above the presently-used values.

It could be expected that, for a given discharge vessel, a change of gas filling should produce a decrease in the oscillation-induced losses if the new gas either has a lower positive-ion diffusion coefficient or a lower ionization potential. The former should reduce the losses for a given value of electron oscillation, and the latter should reduce the oscillation for a given reproduction rate by reducing the field strength required for discharge maintenance. Actually, decreasing the diffusion loss by the former means will produce a decrease in the applied field by reason of the decreased reproduction rate required, and the correspondingly decreased electron temperature requirement.

An increase in pressure, for a given filling, will serve to decrease the positive-ion diffusion coefficient, and therefore may be expected to reduce the power loss. The value of E/p, which determines the energy which the electrons will receive between collisions, will be able to decrease somewhat due to the secondary effect of a reduction in electron-temperature needs, but quite probably the pressure will increase faster, so that it is not expected to realize a decrease in applied voltage by this means. The increase in pressure will have the added effect, however, of increasing f_c in direct proportion, which we can see from Equation 2-28 to have the effect of decreasing the oscillation amplitude. It is therefore evident that increasing the pressure will serve both to decrease the effective "electron temperature" and to decrease the diffusion losses for a given value of that "temperature".

It is thus seen that there are four possibilities of decreasing the power requirements by altering the physical design factors. Increasing the dimensions of the cell, the frequency of the excitation voltage, the pressure of the gas, or making suitable changes in the gas filling, can each be expected to reduce the losses within the cell. This seems to be quite promising for the future, since the power consumption already seems to be of a quite acceptable value.

4.4 Design coordination.

This section will contain an analysis of the relationship which each of the basic physical variables has upon the combined set of fundamental operational characteristics of reliability, speed, and power consumption. These physical variables include gas composition, gas pressure, excitation frequency, dimensional scale, electric-field and cell geometries, and the quenching voltage and frequency. A brief review of the intermediate requirements which the so-called functional parameters must meet to satisfy the above fundamental desires is given first, and then the physical variables are considered in a sequence which seems best to allot priorities to the more important of possible interacting effects. The analysis is based upon three-line operation and the use of quenching voltages to control the extinction times.

The primary requirement of reliability will dictate, in a parametric sense, only that V_{t2} exceeds the larger of V_{ts} or V_{tl} by a margin within which V_o may easily be kept, and in an operational sense, that V_o be well controlled and that the inequalities

$$3T_g + 2T_o > T_{xs}$$

$$2T_g + T_o > T_{xl}$$

$$T_g > T_{x2}$$

$$T_g < T_{xl}$$

are generously exceeded. Meeting a given speed specification will require the various extinction times to be controlled so that these timing safety factors can be met with appropriately low values of T_o and T_g. Power minimization can be effected by judicious increase in pressure, frequency, dimensional scale, and by a proper choice of gas composition, but in the usual case these factors must be limited by their concurrent effect upon the extinction times.

4.41 Gas composition.

The easiest gas to quench will be one with a high ionization potential and high values of electron and ion mobility. Conversely, the easiest gas in which to maintain a discharge (i.e. power consumption lowest) will be one with a low ionization potential and a low value of ionic diffusion coefficient. In general, the most efficient gas which will provide the necessary extinction times will be chosen.

Reliability of the device is affected somewhat by the choice of gas composition. If successful operation is dependent upon a proper proportion of a mixture of gases, long-time cleanup effects can jeopardize the reliability because of the fact that the different component gases usually have different cleanup rates. Pure-gas fillings are best in this respect, although a noncritical mixture of noble gases would probably be acceptable. Use of a gas which suffers an excessive amount of cleanup must be avoided, although it can be predicted that one of the advantages in the usage of high-frequency discharges is that gas cleanup will be much less than it is with static-field discharges.

4.42 Gas pressure.

As the pressure goes up, the power consumption should decrease and the extinction times should increase. A balance of these two reactions with respect to the specified speed will have to be met. There is the additional reaction to an increased pressure in that the excitation voltages will rise. The problems which this will raise in respect to impedance matching and power distribution could well determine the upper tolerance for such a rise.

4.43 Excitation frequency.

This seems to be the only physical variable which has no effect upon the extinction times, at least in the first-order analysis. As the frequency is raised, the values of V_b and V_x are reduced, and the power consumption should decrease. An upper limit is placed upon the frequency by the practical fact that, beyond a certain point, the cost per watt of generating capacity begins to increase and will soon outweigh the gain in discharge efficiency which higher frequencies promise. It is possible that the upper limit caused by a too-narrow margin between V_b and V_x may be a controlling factor. At any rate, it would seem that the frequency should be as high as is practical to use, below the above limits.

4.44 Dimensional scale.

It could be pointed out that neither of the above limits may yet be reached at the point where the power consumption ceases to decrease with increasing frequency. In this case, it would be profitable to decrease the size of the vessel to the point where the oscillation amplitude limit gegins to be approached, and to operate at the lower of the frequency limits set by power cost or discharge voltages.

If it is not possible to utilize frequencies high enough to allow a reduction in size, as above, the optimum-power choice as to dimensions would be to increase them until a power-consumption minimum was reached. This, of course, will be limited by the specifications upon the extinction times.

4.45 Geometry.

If the values of the foregoing variables have been determined, the roles which the cell and electric-field geometries can play toward meeting the original goals are such as to control the relative values of V_{t2}, V_{t1}, and V_{ts}, as well as the relative values of T_{xl} and T_{xs}. Transfer channels which are rectangular in cross section, with the longer dimension in the field direction, could help to control V_{ts} as well as the power loss. Also, the relative size of the regions of high field strength will be a factor in controlling the power consumption.

4.46 Quenching fields.

The strength and frequency of the quenching fields for which a minimum self-extinction time may be realized will most certainly be dependent upon all of the other physical variables, with the exception of excitation frequency. The field strength must be low enough not to cause appreciable ionization, and the frequency must be low enough to induce displacement oscillations of sufficient magnitude.

If the quenching voltages were applied between electrodes which had relatively large areas, so that the capacitance from the electrodes to the inside surfaces of the tube were fairly large, it is predicted that lower-frequency components of quench voltage would be considerably more effective than they were with the wire-ring type of axial-field electrode. Effective single-pulse quenching voltages would be very advantageous for higher speed registers, because the switching time of the alternating quench voltages is so long that they will of necessity have to be applied constantly, which will cause an extra power loss that is undesireable. Single-pulse quenching, on the other hand, could easily be arranged to be applied to the cells only when the excitation voltages were removed, which would eliminate this added power loss. Also, the two-line mode of operation discussed in Section 3.2 would be much less limited in speed if single-pulse quenching were effective.

4.46 Quenching fields.

The strength and frequency of the quenching fields for which a minimum self-extinction time may be realized will most certainly be dependent upon all of the other physical variables, with the exception of excitation frequency. The field strength must be low enough not to cause appreciable ionization, and the frequency must be low enough to induce displacement oscillations of sufficient magnitude.

If the quenching voltages were applied between electrodes which had relatively large areas, so that the capacitance from the electrodes to the inside surfaces of the tube were fairly large, it is predicted that lower-frequency components of quench voltage would be considerably more effective than they were with the wire-ring type of axial-field electrode. Effective single-pulse quenching voltages would be very advantageous for higher speed registers, because the switching time of the alternating quench voltages is so long that they will of necessity have to be applied constantly, which will cause an extra power loss that is undesireable. Single-pulse quenching, on the other hand, could easily be arranged to be applied to the cells only when the excitation voltages were removed, which would eliminate this added power loss. Also, the two-line mode of operation discussed in Section 3.2 would be much less limited in speed if single-pulse quenching were effective.

V. MISCELLANEOUS POSSIBILITIES

A number of quite promising possibilities, regarding both structural and application innovations, have become apparent during the foregoing study. Some of the most promising of these are included in this chapter.

5.1 Structure. Of the three structural innovations discussed below, the first two are certain to be utilized in the next series of experimental and working models of the shifting registers to be built. The third possibility is more basic, and its realization can be adapted within the first two of the structural possibilities listed with fairly evident advantage. It also makes more practical most of the items in the second part of this chapter.

5.11 Parallel channels.

A single-channel shift register, under normal working conditions, will present a load to its r.f. generators which will fluctuate from zero to its maximum value in an unpredictable fashion, as the information content of the register is altered. The obvious result will be a corresponding fluctuation in the value of V_o, which means that either very wide voltage tolerances must be provided at a sacrifice of speed, or that the difficult problem of regulating the peak levels of the excitation-envelope pulses must be faced.

A solution to this situation which has some very desirable additional consequences, is to build each register with parallel transfer channels, with corresponding cells of the two channels being adjacent to the extent of appearing to be at the same point as far as the power distribution system is concerned. Under this arrangement, the bit of information held at a particular point along the register will be represented by which one of the two parallel cells at that point contains a discharge, and at every successive bit length along the register there will be a discharge in one or the other channel but not in both. In this manner, the total number of discharges sustained within the register at any instant is constant, as is the effective distribution of the r.f. load.

The type of random malfunctioning which is the usual forewarning of incipient breakdown of a system would have a very high probability of causing either both, or neither of the channels to contain a discharge at some point. A fairly simple check at the output of the two channels could make sure that one and only one channel contained a discharge in its output cell, or otherwise could indicate that an error had been detected. This would offer considerable improvement in the effective reliability of most systems. From a reliability point of view, it is apparent that the two channels should be part of the same continuous gas system. Any change of pressure or of impurity content in one, then, would naturally appear in both, so that any resulting possible change in operating characteristics could be compensated for by adjustment of their mutual control circuitry.

5.12 Helical channels.

Construction of the transfer channels in a helical form so that adjacent turns are in close contact seems to offer about the optimum arrangement for the two considerations of compactness and r.f.-distribution simplicity. The electrode separation and the helix diameter should be coordinated so that cells of like phase are adjacent axially, and therefore the driving lines can be straight and will have their cells spaced with maximum density along them.

If the parallel-channel feature is to be incorporated, the helix can be wound bifilarly as easily as not, or, if the ratio of helix to channel diameter is large, there can be an inner and an outer helix for which one common set of driving lines can be used. Furthermore, the use of the transverse-field mode of excitation can permit the external surface of the helix to be a grounded conductor, which should help to eliminate any objectional r.f. radiation or coupling. Use of a "1/4 O.D. Pyrex tube as the channel form, with transverse-field electrodes, would allow the bifilar, parallel-channel construction of a 100-bit register as a cylinder three inches in diameter and six inches long.

5.13 Sandwiched dielectric.

Adjacent channels in the above helical register forms can be placed much closer to each other if their separating walls do not have to withstand atmospheric pressure, as they do when glass tubing is utilized for the channel form. Assume that a suitable dielectric material is formed into a hollow cylinder, with bifilar threads cut into the outer surface so that their groove cross-sections are appropriate for transfer-channel operation. An outer cylinder, with smooth inner and outer surfaces, can then be slipped over the threaded dielectric cylinder, with relative diameters adjusted so that there is a reasonably snug fit. If the inner dielectric is suitable, the upper and lower rims of these cylinders can be sealed and the volume between can be given the desired gas filling. If not suitable for such, the inner dielectric can be fitted between two glass cylinders, or simply inside one envelope. We now have a much less fragile structure than the glass-tubing coil was, with probably more than twice the storage density possible.

Electrodes for this type structure can be of the "printed circuit" variety, since they are on continuous surfaces. The sandwiched dielectric may be machined or molded plastic, or molded ceramic or glass. It is not yet known what effect plastic surfaces will have upon discharge characteristics, but this would offer the simplest realization of this type of structure. There is a certain freedom associated with such a design in that the channel cross section need no longer be circular, nor need it be uniform along the length of a cell. This could well offer the opportunity to tailor such parameters as V_{ts} and V_{tl} more effectively.

5.2 Application.

There have arisen some other possibilities for the application of high-frequency gas-conduction electronics in digital computers besides that of a serial shifting register. The first is but an alteration of the input technique, which allows parallel input of information and so allows some added valuable applications, of which one important one is discussed as an example. The other three possibilities are much more basic and important than the first. Their very existence should give considerable impetus to the further research in this field.

5.21 Parallel input.

As is implied by the name, parallel input to a shifting register allows the insertion of more than one bit of information at a time. It appears that the use of quenching techniques in the following manner will allow a form of this to be realized, in what is otherwise very much like the ordinary shifting registers discussed above.

Assume that the quenching line associated with each "A" cell of a given channel is separately brought outside the given structure. Assume further that this channel is loaded with a discharge in each of the "A" cells. Then, if quenching voltages existed in some arbitrary pattern on the separate quenching lines, a suitable gap in the excitation would allow discharge extinction in the quenched cells but not in the unquenched cells. The resulting discharge pattern would now contain the information which previously had been contained in the configuration of quench and no-quench voltages. To provide this feature for a parallel-channel register would require that complementary sets of quenching voltages be provided, and that the parallel channels have separate sets of quenching lines brought out.

A very useful application of this feature is immediately apparent. Transferring information from punched cards into electronic data-processing equipment is made cumbersome by the fact that the information is taken from the cards in parallel, and is further complicated by the time separation in the arrival of this information (actually, the information is contained in the time of arrival). Four, eighty-one bit shifting registers, equipped with appropriate parallel-input facilities, can receive all the numerical information which an IBM card can normally contain, with simultaneous conversion from decimal to binary-coded decimal form. Between card-reading cycles there exists ample time for these registers to shift serially all of this information into the associated data-processing equipment.

5.22 Display.

The easy visibility of the individual discharges associated with the glow-transfer shifting registers suggests an alternative use of these shifting techniques, besides that of information storage. If only one channel of a register were made visible, and the register were laced back and forth in a plane so that every third cell was a member of a uniform spot-grid, the illumination of appropriate combinations of these cells can depict alphabetic or numeric characters in a manner which is common in the digital computer field. Sequences of such grids can be a serial extension of a single register, so that suitable shift series can move the entire display pattern to the right or left. A grid of five spots wide by seven spots high is common, and should be realizeable by a thirty-five bit register, which can be loaded in either serial or parallel fashion.

Alternative to such a construction could be the use of seven registers, each running horizontally, and spaced so that each five-bit linear interval would produce an appropriate five-by-seven spot grid. Each character could be loaded in parallel or series parallel. If the sandwiched-dielectric mode of construction is developed, so that these registers can all be contained within a common flat envelope, there exists an added input possibility. A short serial register, one column-height in length (in the above example, then, seven bits long), can be loaded in serial fashion with a given column pattern, and can find itself so located with respect to the first column that its serially-loaded discharges can be transferred in parallel into the first cells of the display registers.

Several added possibilities exist in this direction. For instance, the cells whose illumination will provide the actual display can be made larger than the auxiliary transfer cells, to effect an increase in apparent display-cell density. Or, these display cells can be divorced from the shifting function by having the actual shifting registers, with small cells and fast shifting speeds, be behind them, with intermediate transfer electrodes such that display and loading can be done independently.

5.23 Logic.

The three logical connectives of conjunction, disjunction, and negation are very important in the manipulation of information which is done within digital-computer types of equipment. To be able to realize these connectives with respect to the physical representation of the information within the glow-transfer devices, without the necessity of reading this information out into conventional logical circuitry and then, perhaps, re-inserting it into a shifting register, would effect a tremendous increase in the potential worth of the glow-transfer devices. Several possibilities for realizing these logical connectives have arisen within the course of the research, but the phenomena upon which they are based are not verified experimentally to the extent that those of the previously-mentioned application possibilities were. For this reason, their presentation will be omitted, although the importance of their existence warrants mention.

5.24 Stored-charge Memory.

The action of the diffusion processes discussed in Chapter II is such as to tend to bring all of the bounding surfaces of the discharge into relative equilibrium potentials. If a surface is not at such a potential, space currents flow to it that tend to bring it to the equilibrium value. If we assume that one of these surfaces is a conductor which is held at a given potential, then we must assume that the equilibrium potentials of the other, dielectric surfaces are fixed.

If some of the above mentioned dielectric surface is actually a thin film of dielectric material coated over a conducting surface, a very large capacitance per unit area may exist between the gas-exposed surface and the metal conductor. The charge stored by this capacitance is held fixed when a discharge is not present within the vessel, but will change to bring the dielectric surface to its equilibrium value whenever a discharge is initiated. The resulting charge displacement will, in effect, contain the information as to what relative potential change had taken place between the two conductors in question since the termination of the last discharge.

It is not intended here to go into the details as to how this phenomenon could be utilized in the memory system of a digital computer. A few salient points will, however, be mentioned. The surface-to-conductor capacitance could be of the order of a microfarad per square centimeter for voltage ratings quite usable in a memory system. The surface density of storage cells will be limited mainly, then, by the speed with which the cell capacitance must charge, and the current densities which the discharge can furnish, and these two factors can then set the appropriate value for the capacitance per unit area.

All the "memory cells" of a given block of memory may be excited by a common high-frequency generator. The isolated cell or groups of cells, to which access is desired at any given time, may then be "selected" by being primed by a single discharge that has been shifted into the appropriate location in response to the selection specifications. The use of the sandwiched-dielectric mode of construction will be necessary to realize fully the potential capabilities of this type of storage.

Good-quality, plastic dielectrics can hold a charge practically indefinitely, and it would seem that such a memory system could be constructed so that for practical purposes, it would not be classed as a "volatile" type, i.e. it would not require frequent inspection for the purpose of reinstating any charges which might be decaying towards ambiguous values.

VI. CONCLUSION

The title of this dissertation is, "A study of high-frequency gas-conduction electronics in digital computers," and it must here be stated that the conclusion of this study leaves this author in a very optimistic state of mind concerning the acceptance which this new art will find in the digital computer field. The only recognizeable disadvantage which is suffered by these gas-discharge devices is that their speed of operation is limited, although adequate for a large number of uses. (Speeds of thirty-thousand bits per second have been realized, and promise exists for speeds some ten times as great.) Speaking only of the devices of this art which have yet been built, the high-frequency glow-transfer shifting registers are endowed with the following list of advantages:

1). Their life should be very long, comparable with that predicted for transistors. Gas cleanup, leakage, or contamination should be the only limiting factor, and of these, cleanup should be very slow with no internal electrodes present, and contamination elements in the gas will diffuse evenly throughout all of the cells so that the register characteristics should change uniformly. This latter means that simple adjustments of the operating voltages or timing can take care of many of the consequences of contamination.

2). The reliability of these registers should be limited mainly by that of the associated circuitry. It is not expected that, within the life of the r.f. power tubes, changes in the characteristics of the register tubes will occur which are severe enough to require readjustment of voltage levels. When these latter tubes are replaced, the operating voltage level may be changed if necessary.

3). The one-tenth watt per bit power consumption of these devices seems already to be low enough to be acceptable, in many cases, in comparison with transistors, and seems definitely favorable in comparison with vacuum tubes. Future research should be able to reduce this consumption still further.

4). The simplicity and promised low cost of the register structure seems to be unparalleled in the present-day computer art.

5). The symmetrical structure of these registers allows either forward or backward shifting, the direction depending entirely upon the excitation sequencing. This effectively halves the access time for some applications, which serves to compensate for the relatively slow speed.

6). The contents of these registers are directly visible, which is a great operational advantage when a system is being searched for troubles.

7). With very little added cost, an error detecting system can serve to give a very high guarantee of error-free service within each shifting register.

8). The size of these registers is quite small. The estimate has been made that a hundred-bit register can be built into a cylindrical form which is three inches in diameter and six inches long. This is with presently-available techniques.

These register units have an area of application which is restricted by their speed limitation, but which promises to be expanded by the consequences of their low cost. In the approaching era of large-scale data-processing systems, there is a great deal of relatively slow-speed manipulation of data which must be done. Unless a very cheap, high-capacity, non-volatile type of memory is developed which is much faster than any which is yet publicly proposed, the above data processing will be forced into being done to a large extent at speeds attainable by the glow-transfer shift registers. The very fact that large-capacity, cheap registers are available may well stimulate the development of data-handling techniques which utilize more of them. The task of sorting seems quite ripe for this sort of effect.

Development of self-contained logical operations within a single envelope would seem to guarantee wide-scale usage of glow-transfer devices. Indications are promising that such a development can be realized. However, there is a great deal of research yet to be done in this new field before predictions can be of any great value. As a fitting termination to this dissertation, a number of the more important research and development tasks which are now faced will be listed in brief detail.

Techniques for the forming of glow-transfer channels in a suitable dielectric, so that freedom to utilize three-dimensional topology in channel flow and confluence may be had, would be very valuable. This type of project would need to include a development of appropriate excitation- and quench-voltage distribution systems for such structures.

The problem of realizing self-contained logic is an extremely vital one, but many of the possible techniques would rest upon the availability of the above type of structure...at least to be practical for production. However, a large amount of theoretical analysis and laboratory experiment could be done, and working logical-devices demonstrated, before these structural techniques were fully available.

The stored-charge type of memory system, which was briefly sketched in Section 5.24, could possibly furnish a very large semi-permanent memory system which could have some very novel and advantageous features. For instance, selection of the memory cells to which access is desired could be effected by the movement of a single discharge along some specified path through a large number of successively selected branches to the point where it would provide the necessary conductivity to the storage surface. Almost an absolute minimum of auxiliary selection equipment would be needed for such a system. Also possible is such as a serial readout or write sequence, in which successive memory cells are located at successive shifting-register cells and one discharge is shifted down the channel.

The display devices which were mentioned in Section 5.22 could prove to be very useful to the computer field. Cathode-ray-tube types of display seem to be the only real competitor...their resolution would be impossible to equal, but where character size may be desired to be large it would seem that the glow-transfer device would be very promising.

The high-frequency power sources for these glow-transfer devices, as well as the associated impedance-matching networks and distribution systems, will need attention. The present speeds are limited by the envelope rise and fall times of the high-frequency equipment which is being used. Higher frequencies will do much to alleviate this limitation, but it seems possible that the actual speed limitations which may be reached, for practical registers, may be similarly imposed. The change in impedance which is experienced during the buildup of the excitation envelope could well require special attention to the transmission and distribution system.

A careful study needs to be made of the actual relationship between the numerous physical variables (as listed in Section 4.4) and the amount of power consumed per cell. This would furnish a nicely combined theoretical and experimental problem, and the findings could do much for the development of the glow transfer devices.

A similar study is needed of the quenching techniques. How best to hasten the decay by practical means will be very important knowledge.

An applications study is needed, from a logical designer's point of view, as to the advantages which may be obtained, in the design of various functional systems common to the computing and data-processing field, by the free usage of shifting registers...of any desired capacity. Since the cost of large register systems promises to be low, even an inefficient usage of them could still furnish a cheaper over-all system. Special note in this respect can be taken of the fact that the two-line registers described in Section 3.2 are capable of being included in large systems in which all of the excitation power is furnished by two large generators, which are switching on and off at a clocked rate in a continuous timing sequence similar to that of Figure 3-5. The control of individual registers is then effected by separate low-power quench sources which, if single-pulse quenching can be improved in effectiveness, will be of very simple circuits. There is great promise here for very cheap and very large register systems...and there should be found good uses for such.

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