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where T is the interval of time over which the integral is taken. This does not vanish, in general. At distances x_1 from $x_1 = 0$ great compared with the wave-lengths, a progressive wave can be represented with good approximation in a domain containing many waves by

$$\beta = X_0 + a \sin \omega(x_4 - x_1),$$

where a is a constant (which, to be sure, is a substitute for a function depending weakly on x_1). In this case $X_1 = a \cos \omega x_1$, $X_2 = -a \sin \omega x_1$, so that the integral can be (approximately) represented by $-\frac{1}{2}a\omega^2 T$, and thus cannot vanish and always has the same sign. Progressive waves therefore produce a secular change in the metric.

This is related to the fact that the waves transport energy, which is bound up with a systematic change in time of a gravitating mass localized in the axis $x = 0$.

Note.—The second part of this paper was considerably altered by me after the departure of Mr. Rosen for Russia since we had originally interpreted our formula results erroneously. I wish to thank my colleague Professor Robertson for his friendly assistance in the clarification of the original error. I thank also Mr. Hoffmann for kind assistance in translation.

A. EINSTEIN.

IMPULSE CIRCUITS FOR OBTAINING A TIME SEPARATION BETWEEN THE APPEARANCE OF POTENTIAL AT DIFFERENT POINTS IN A SYSTEM.

BY

L. B. SNODDY, H. TROTTER, JR., W. T. HAM, JR., AND J. W. BEAMS,
University of Virginia.

The acceleration of ions to high speeds by impulsive methods requires an electrical circuit capable of transferring potential from electrode to electrode of the accelerating tube at the proper rate. To be of any practical value the circuit must be capable of operation with time delays between two successive points of the system as low as 2–3 × 10^{-8} sec. and at voltages above 100 kv. This paper gives the results of an investigation of various methods which are suitable for this purpose. A number of these circuits may be used to advantage in other types of problems involving longer time intervals and lower voltages. While the theory underlying some of these experiments is well known, a part of it as well as most of the experimental results are new. It is hoped that a discussion of the possibilities and limitations of the various devices will be of general interest.

The methods have been divided into the following groups.

1. Transmission lines with continuously distributed constants, i.e., real transmission lines.
2. Transmission lines with constant lumped constants, i.e., artificial transmission lines.
3. Spark gap lines.
4. Discharge tube lines.

For ion acceleration these methods are used in two ways which differ considerably in their impulse characteristics. In the first the electrical circuit together with the tube electrode is initially at zero potential and is charged impulsively by connecting the input end to a supply condenser. This starts a charging wave which travels from electrode to electrode along the system. The time delay in the building up of voltage at successive points is adjusted to correspond to the transit time of the ion between the two electrodes. This method has been used successfully for accelerating both ions and electrons.[1] In the second the electrical circuit and the electrodes are charged initially to a uniform constant potential. The voltage wave is then started by short circuiting the input end of the system. The potential in this case must be opposite in sign to that in the first. Electrons with speeds corresponding to 2.4×10^6 volts have been obtained [2] in this manner using a seven electrode tube with an applied potential of 700 kv.

For the charging method it is essential that the supply condenser have a low impedance since the steepness of the traveling voltage wave will be materially affected by any current limitation in the supply circuit. At high voltages this condition is difficult to obtain.

The discharging method avoids this difficulty since the steepness of the wave front is determined only by the constants of the transmission circuit and the rapidity of short circuiting at the input end. It has the disadvantage that the entire system must be capable of withstanding a high static potential. This requires much better insulation and shielding than is necessary in the first case where the tube is only required to withstand impulsive voltages of relatively short duration.

In all this work spark gaps are used for switching and short circuiting between points of the circuit. To prevent appreciable distortion of the wave front the switching operation must be completed as rapidly as possible. The total time involved should be smaller, certainly not greater than that of the time delay ($2\text{–}3 \times 10^{-8}$ sec.)

For a 1 cm. spark gap in air (2.54 cm. brass spheres) the potential falls to 1/3 value [3] in approximately 2×10^{-8} sec. It was found by means of a high speed cathode ray oscillograph that this time is increased with the wide spacings and large spheres necessary for high voltages. To reduce this time a

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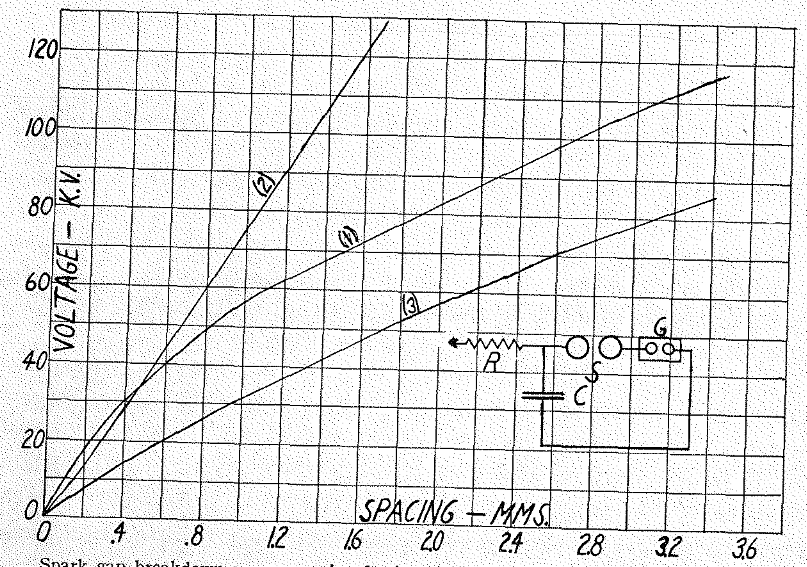
[1] Beams and Snoddy, *Phys. Rev.*, **44**, 784 (1933). Beams and Ham, *Phys. Rev.*, **45**, 746 (1934). Beams and Trotter, *Phys. Rev.*, **45**, 849 (1934).

[2] Beams and Trotter (unpublished).

[3] Street and Beams, *Phys. Rev.*, **38**, 416 (1931).

second gap *G* is placed in series with the first as shown in Fig. 1. This gap can be either a vacuum gap, a gap under oil or a gap in dry, filtered air. Curves of breakdown versus spacing for impulsive voltages are shown in Fig. 1 for these three types. (1) A vacuum gap with pure copper electrodes (2.54 cm. diameter) under excellent vacuum conditions. Since the breakdown voltage in a vacuum gap depends upon the condition of the electrode surface, the length of the impulse and the maximum current was kept approximately constant at all voltages.

FIG. 1.



Spark gap breakdown versus spacing for impulsive voltages applied to 2.54 cm. diameter spheres. Curve 1, vacuum gap with pure copper electrodes. Curve 2, steel spheres in transformer oil No. 10 C. Curve 3, steel spheres in dry filtered air.

(2) A gap with steel spheres (2.54 cm.) in Transil Oil No. 10C.
(3) A steel sphere gap (2.54 cm.) enclosed in a glass cylinder containing air at atmospheric pressure which had been carefully dried and filtered.

From these curves it is seen that it is possible to use gaps of this kind at small spacings for high impulsive potentials. The rate of potential fall observed with the oscillograph is considerably greater than in an ordinary gap at wide spacings. The approximate times to 1/3 value for the three gaps are

1–1.5 × 10^{-8} sec. for a vacuum gap at 100 kv., 2 × 10^{-8} sec. for the overvolted air gap at 120 kv., and 2–2.5 × 10^{-8} sec. for the oil gap at 200 kv. For the purpose of estimating the influence of this breakdown upon the shape of the wave front, the rate of potential fall is assumed to be exponential and in some cases linear.

1. REAL TRANSMISSION LINES.

The lines used were either of the simple two wire type or the single wire with return through a large grounded metal sheet on the floor. Since the speed of propagation of the impulse is approximately equal to that of light, this group is useful only with relatively short time intervals. A schematic diagram of typical systems is shown in Fig. 2 (*a*, *b*, *c*).

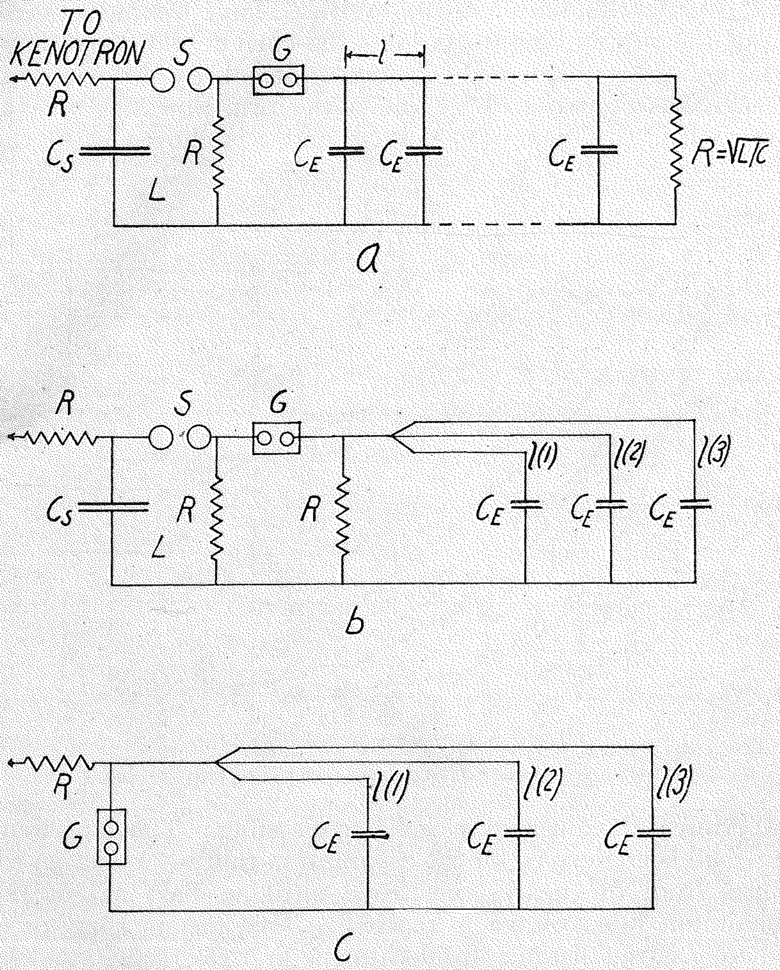
In this diagram C_s is the supply condenser, S the spark gap in air, G the overvolted type of gap, R relatively high charging resistances and C_e represents the capacity of the tube electrode. Since the lines are short, the resistance and leakage per unit length may be neglected without appreciable error and the transmission circuit itself taken as non-dissipative. C_s is assumed large enough to maintain a practically constant voltage during the initial charging of the line.

Figure 2 (*a*) the electrodes of the accelerating tube are connected in succession to the same simple line. The length of wire between electrodes is adjusted until l/v is equal to the desired time delay where v is the speed of light. To reduce reflections to a minimum, the output end is closed through a resistance $R = \sqrt{L/C}$ where L and C are the inductance and capacity per unit of length of the line. The correct value is easily determined by measuring the voltage at the output end with a spark gap or an oscillograph as a function of R. When the maximum voltage across R is equal to the input voltage V, the resistance is sufficiently near to the correct value for all practical purposes.

In Fig. 2 (*b*) a separate line goes to each electrode. The lines are joined together as near as possible to the gap G. The time delays are determined by the differences in wire lengths.

Figure 2 (*c*) is identical with (*b*) except that the lines and electrodes are charged initially and the wave produced by the breakdown of G. Provided the total capacity of this system is not too great, it can be charged impulsively through R from an auxiliary condenser circuit until the breakdown voltage of G is reached. In this way higher potentials can be used with the same insulation than could be done if the charging process is slow. It also enables an overvolted gap to be used at G which could not be done with a slow charging rate.

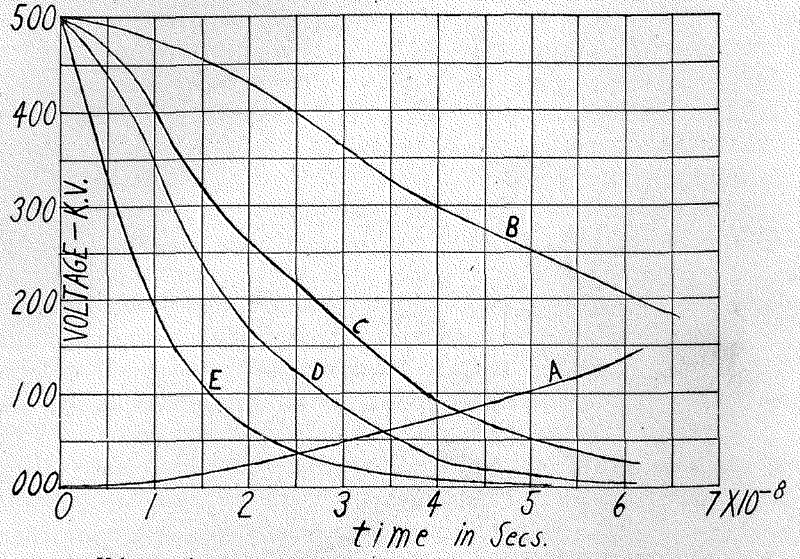
FIG. 2.



Three types of real transmission lines used for the acceleration of particles.

The wave front obtained in these three cases is dependent on the rate of fall of potential in G, the impedance of the supply circuit and the impedance of the transmission system observed from the input end. Since only the wave front is of importance, the impedance of a single line can be taken as $R = \sqrt{L/C}$ and of n parallel lines as R/n. With C_s large the inductance, L, of the supply circuit becomes the current limiting factor. The voltage applied to the system by the breakdown of G is assumed as a function of the time in the form $V = E(1 - e^{-\delta t})$, where E is the maximum voltage and δ is chosen to fit the experimental values as closely as possible. The equations have all been derived on the assumption that no reflection returns from the nearest electrode until at least 2/3 of the maximum line voltage is reached. This means that $2\,d/v$, where d is the distance from G to the first electrode, must be greater than the time length of 2/3 the wave front.

FIG. 3.



Voltage at input end of the real transmission lines with respect to time.

The line voltage as a function of time at the input end for Fig. 2, a and b, is given by

$$V(t) = E\delta\left[\frac{1}{\delta}(1 - e^{-\delta t}) + \left(\frac{e^{-\delta t} - e^{-Z/L^t}}{\delta - Z/L}\right)\right], \qquad (1)$$

where Z, i.e. R/n is the surge impedance of the transmission system and L is the inductance of the charging system. n equals the number of separate lines attached to G. For Fig. 2 (a) $n = 1$, and for Figs. 2 (b and c) $n = 3$. Equation (1) also serves for Fig. 2 (c) when the inductance L is replaced by that of the connecting wires of gap G.

Curves of typical wave fronts are shown in Fig. 3 and the values of the constants in Table I. The curves clearly illustrate the effect of the inductance L in slowing up the wave front and thus emphasize the great advantage obtained by the discharging type of line where the inductance can be reduced to a minimum value. The steepness of the wave front is also effected by the rate of breakdown of the spark gap used in the line. Thus, the difference in the rate of potential fall in curves B and C is due solely to the faster breakdown of the vacuum gap as contrasted with the non-overvolted air gap. Curves C and D illustrate the effect of reducing the inductance L. Curve A shows how the large inductance of the charging system effects the wave front in charging up the multiple line. It should be remembered that the surge impedance Z of a multiple wire circuit becomes very low (Z/n) and hence makes

TABLE I.

Curve.	Type of Gap.	Inductance L in henries.	Surge Impedance Z in ohms.
A Charging 7 lines	Air Gap $\delta = 2.2 \times 10^7$	4.5×10^{-6}	60
B Discharging 7 lines	Air Gap $\delta = 2.2 \times 10^7$	1×10^{-6}	60
C Discharging 7 lines	Vacuum Gap $\delta = 1.1 \times 10^8$	1×10^{-6}	60
D Discharging 7 lines	Vacuum Gap $\delta = 1.1 \times 10^8$	0.5×10^{-6}	60
E Discharging 1 line	Vacuum Gap $\delta = 1.1 \times 10^8$	0.5×10^{-6}	450

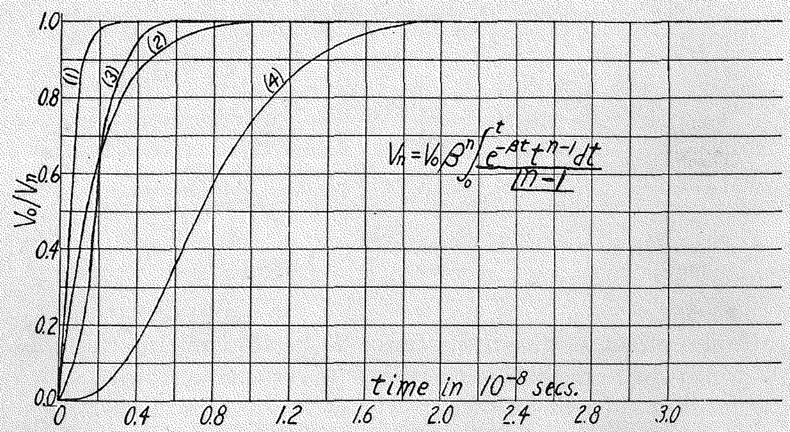
it unsuitable for a charging system. Curve E shows the wave front for a single line (as in Fig. 2 a) for the discharge case. Due to the higher surge impedance the potential falls more rapidly than in the multiple wire circuit.

The wave distortion produced by the loading of the line with the electrode capacities in Fig. 2 (a) is easily determined neglecting as before the effect of reflections between electrodes. With a perpendicular voltage, V_0, applied at the input end, the variation of voltage at the nth electrode as a function of time is given by[4]

$$V_n = V_0\beta^n \int_0^t \frac{\epsilon^{-\beta t}t^{n-1}}{\underline{|n - 1}}\,dt \qquad (2)$$

where $\beta = 2/ZC_e$. Curves for the wave front at the 1st and 4th electrodes are shown in Fig. 4 with $C_e = 1 \times 10^{-11}$ farads (curves 1 and 2) and $C_e = 4 \times 10^{-11}$ farads (curves 3 and 4). Z is taken as 100 ohms. Time is measured from the moment of arrival of the incident wave.

FIG. 4.



Wave fronts at the 1st and 4th electrodes of a loaded real transmission line. Curve 1 is the 1st electrode with C 1×10^{-11} farads. Curve 2 is for the 4th electrode with the same capacity. Curve 3 is the 1st electrode with C 4×10^{-11} farads and Curve 4 is for the 4th electrode with the same capacity.

With the potential at the input end of the lines in Fig. 2, b, c given by $V = V_0(1 - \epsilon^{-\delta t})$ the terminal voltage across any one of the capacities C_e is given by:

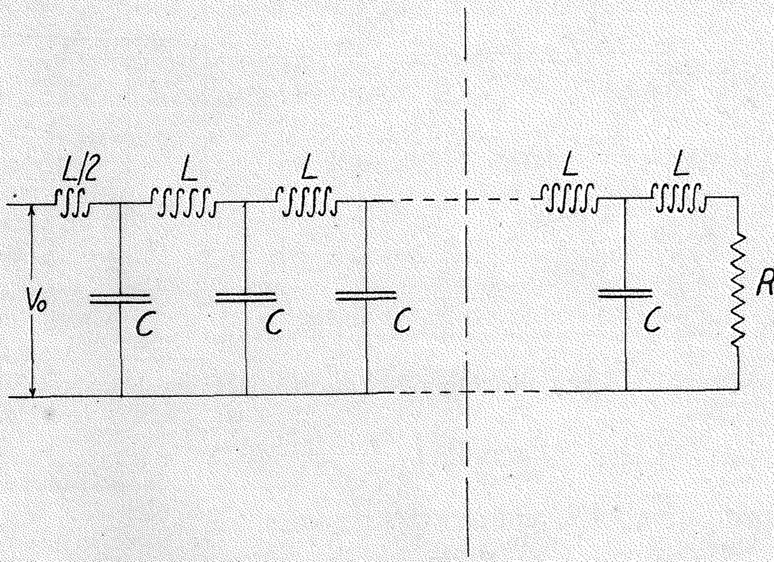
$$V = V_0\left[2 + \left(\frac{\delta ZC_e + 1}{\delta ZC_e - 1} - 1\right)e^{-\delta t} - \frac{2\delta ZC_e}{\delta ZC_e - 1}e^{-t/ZC_e}\right]. \qquad (3)$$

For small values of capacity (1–2×10^{-11} farads) the distortion is not noticeable and equation (3) reduces to $2V_0(1 - e^{-\delta t})$. The line is practically open circuited and it is seen that the voltage will be doubled by reflection. This fact must be taken into account in the computation of electrode sizes and separations.

2. ARTIFICIAL TRANSMISSION LINES.

A low pass filter line with series inductance and shunt capacity was used in this work. A schematic diagram is given in Fig. 5. For ion acceleration the tube electrodes are connected to the capacities C. With a constant voltage V_0 impressed at mid-series position of the 0th section ($n = 0$),

FIG. 5.



An artificial transmission line with series inductance and shunt capacity.

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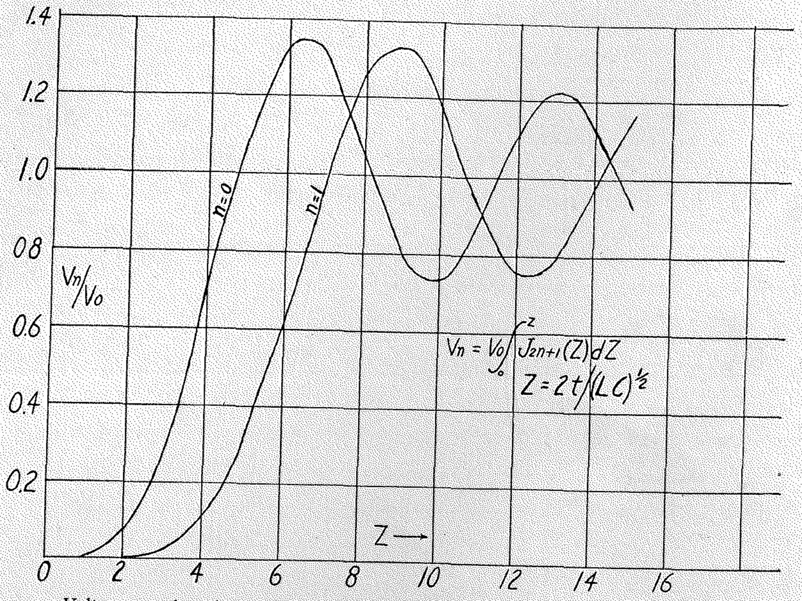
[4] For general methods of derivation, see J. R. Carson, "Electric Circuit Theory and Operational Calculus," McGraw-Hill, p. 132.

the current in the nth section is given by[5]

$$i_n = V_0\sqrt{\frac{C}{L}}\int_0^{\lambda t} J_{2n}(z)dz, \qquad (4)$$

where $\lambda = 2/\sqrt{LC}$ and $z = 2t/\sqrt{LC}$ and J_{2n} is the Bessel function of order $2n$ and argument z. This assumes the line to contain an infinite number of sections or to be terminated by an impedance which prevents reflection and to be non-dissipative. The voltage across the nth capacity is

FIG. 6.



Voltages on the 0th and 1st sections of the artificial line for unit applied voltage.

$$V_n = V_0\int_0^{t}\frac{i_n - i_{n+1}}{C}dt.$$

Substituting for i_n and i_{n+1} this becomes

$$V_n = V_0\int_0^{\lambda t} J_{2n+1}(z)dz. \qquad (5)$$

Curves of applied voltage with $V_0 = 1$ are shown in Fig. 6 for $n = 0, 1$. At a time approximately equal to $2n/\lambda$, measured from the moment the input voltage is applied, the condenser voltage, Vn, starts to increase rapidly. This line consequently serves as a system for transmitting voltage at a finite speed of $1/\sqrt{LC}$ sections per second. It is evident from equation (5) that this velocity is only apparent since Vn has a finite though small value for any time $t > 0$. The derivation of these equations assumes an idealized system in which there is no space factor. The actual construction of an experimental line in which the $\sqrt{LC}$ i.e., the time delay per section is small (2×10^{-8} sec.) must be carried out with some care. The necessary condition is evidently that $\frac{d}{v} \ll \sqrt{CL}$ where d is the electrical path between sections and v the speed of light. The capacitive and inductive coupling between adjacent sections is found to be of slight practical importance.

The voltage difference between successive sections, which is important for ion acceleration, is given by

$$V_n - V_{n+1} = L\frac{di_{n+1}}{dt}$$

or

$$V_n - V_{n+1} = 2J_{2n+2}(\lambda t). \qquad (6)$$

Curves of this difference are shown in Fig. 7 for $n = 0, 1, 2, 3$ and in Fig. 8 for $n = 10$ and 20. The applied voltage is unity. In the design of a tube to be used with this transmission system the electrode lengths and separations must be fitted to these curves.

The actual computation of i_n and V_n is easily carried out for any particular case. Since

$$i_n = C\frac{dV_n}{dt} + C\frac{dV_{n+1}}{dt} + \cdots + C\frac{dV_{n+q}}{dt} + i_{(n+q+1)},$$

i_n by (5) can be written in the form

$$i_n = \sqrt{\frac{C}{L}}\,2\sum_{q=0}^{q} J_{2n+2q+1}(\lambda t) + i_{(n+q+1)}. \qquad (7)$$

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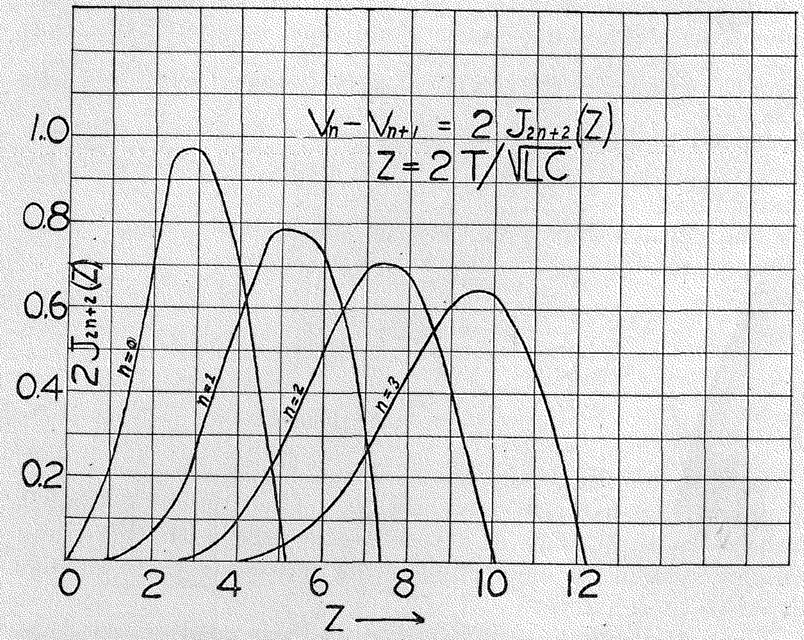
[5] See J. R. Carson, "Electrical Circuit Theory," p. 117.

By repeated use of (6) it is found that

$$V_n = 2 \sum_{q=1}^{q} J_{2n+2q}(\lambda t) + V_{(n+q)}.$$

If q is made sufficiently large, $i_{(n+q+1)}$ and $V_{(n+q)}$ will then be insignificant during the time for which the curves are wanted, and the values of i_n and V_n can be obtained directly from Bessel function tables.[6]

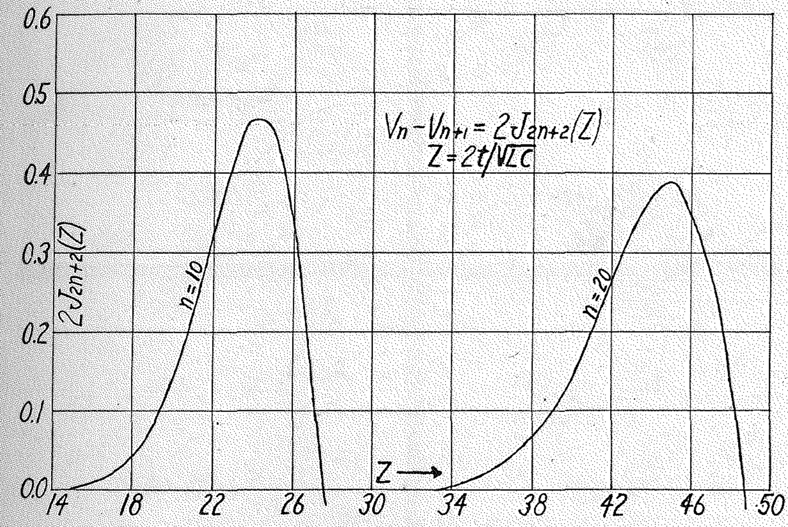
FIG. 7.



Voltage difference between the first four sections for the artificial line with unit applied voltage.

If the inductances in a line of this type are replaced by a straight connecting wire, the system becomes a real transmission line loaded at closely spaced intervals. Since d/v, where d is again the wire length between sections, can be made quite small there are a great many reflections between parts of the circuit before the voltage wave reaches its maximum value. The behavior of this line is approximated by an ideal artificial line with lumped inductances equivalent to the inductance of the loop formed by two of the condensers with their connecting wires. In the actual construction of an artificial line for use with time delays of 2–3 × 10^{-8} sec. the lumped inductance L is relatively small (1–3 × 10^{-6}). Allowance must consequently be made for the influence of the loop inductance when the coils, L, are made. Oscillograms of wave forms on an artificial line with 15 sections are shown in Fig. 9. The time per section is 4.31 × 10^{-8} sec. with $C = 830 \times 10^{-12}$ farads and $L = 2.4 \times 10^{-6}$ henries. The line was charged initially and discharged by a special gap at the point V_0 in Fig. 5. The resistance R was omitted. Fig. 9 (*a*) is the voltage wave at the 2d section; (*b*) and (*c*) are the voltage differences between the 2d and 3d and between the 10th and 11th sections respectively.

FIG. 8.



Voltage difference between 10th and 11th sections and between 20th and 21st sections for the artificial line with unit applied voltage.

For Fig. 9 (*d*) the lumped inductances were replaced by a straight connecting wire making a real line loaded at intervals of approximately 40 cms. with the same capacities as above

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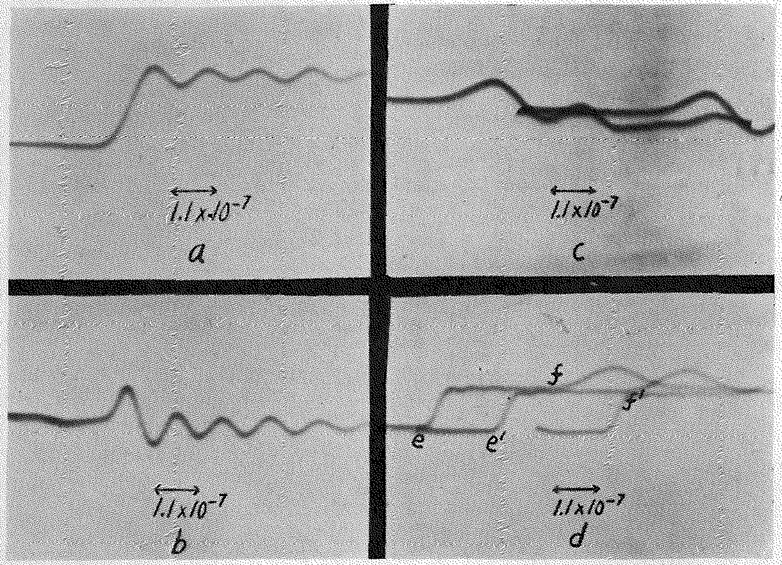
[6] Tables of Functions by Jahnke and Emde; B. G. Teubner, Leipzig.

(830×10^{-12} farads). The initial wave at the 2d section is shown at e and the reflected wave from the open circuited end at f. The time from e to f as measured on the oscillogram is 40×10^{-8} sec. while that computed on the assumption that the time per section is $\sqrt{LC}$ where L is the loop inductance and C the lumped capacity is 42×10^{-8} sec.

The maximum current is approximately $1.47 V_0 \sqrt{C/L}$. A lower limit to C is set by the condition that its value should not be appreciably affected by any change in the position of connecting wires or surrounding objects. For a definite time between sections this determines L. The $\sqrt{C/L}$ can consequently not be decreased indefinitely. For high voltages the input current will be quite large. This means that the supply circuit, if the line is to be charged, or the short circuiting gap system if the line is to be discharged, must be of low impedance if an undistorted wave is to be obtained.

FIG. 9.



Oscillograms of wave forms on an artificial line with 15 sections. (a) Voltage wave at the 20th section. (b) and (c) Voltage differences between the 2d and 3d and between the 10th and 11th sections respectively. (d) A real line loaded at 40 cm. intervals where the initial voltage on the 2d section is shown at e and the reflected wave from the open end at f.

To illustrate the effect of adding inductance in series with the input end of the line shown in Fig. 5, computations were made for current and voltage when a potential V_0 is applied with $L/2$ replaced by L. The current, voltage and voltage difference for the nth section are given by the following equations,

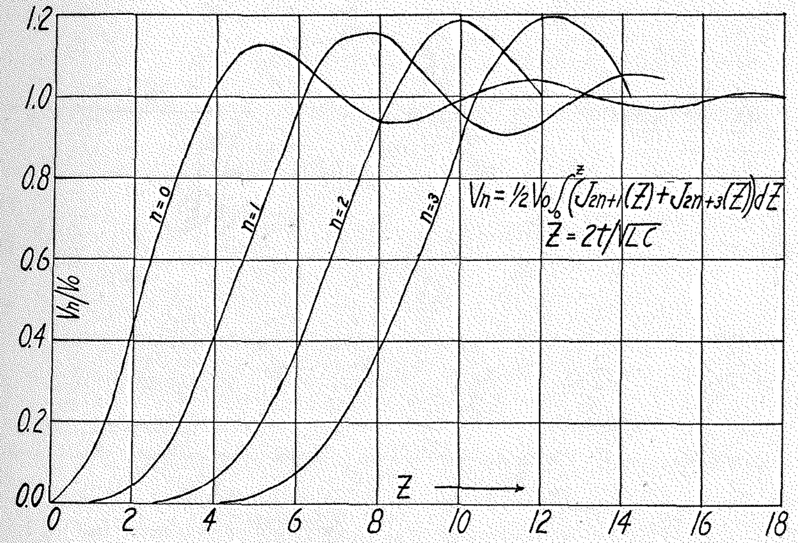
$$i_n = V_0 \sqrt{C/L}(2n + 1) \int_0^{\lambda t} \frac{J_{2n+1}(z)}{z} dz, \tag{8}$$

$$V_n = \frac{V_0}{2} \int_0^{\lambda t} (J_{2n+1}(z) + J_{2n+3}(z)) dz, \tag{9}$$

$$V_n - V_{n+1} = J_{2n+2}(\lambda t) + J_{2n+4}(\lambda t). \tag{10}$$

Curves of voltage as a function of z are illustrated in Fig. 10 for n : 0, 1, 2, 3 and voltage differences in Fig. 11 for n = 0, 1, 2. While the voltage differences do not decrease quite as rapidly as in the first case (Fig. 7), the maximum value is less.

FIG. 10.



Voltages on an artificial line, with full inductance in the 0th section, for the first four sections with unit applied voltage.

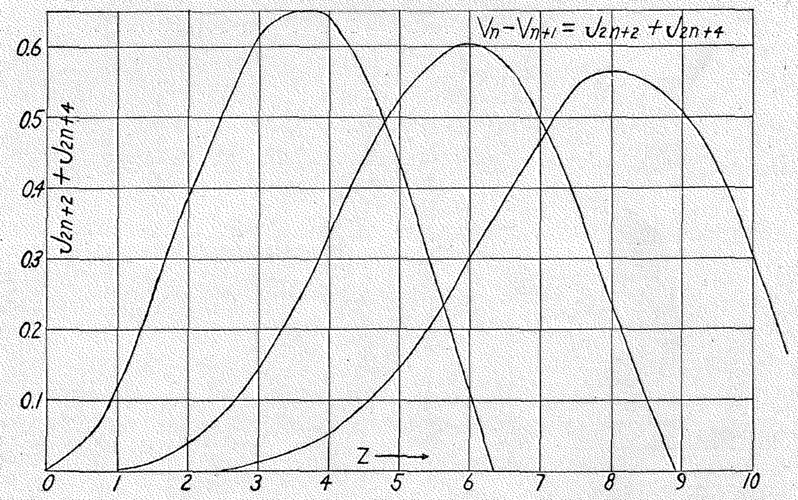
The change produced in the voltage difference between sections by the finite rate of breakdown of the short circuiting gap in the circuit of Fig. 5 (R-omitted) can be simply determined if the applied potential is assumed to be linear, i.e., $V_0 = at$. Denoting the difference for unit potential applied at $t = 0$ by $V_d = 2J_{2n+2}(\lambda t)$ the result is determined by the equation

$$V_n - V_{n+1} = \int_0^t V_d'(x)V_0(t - x)dx.$$

Introducing the values of V_d' and $V_0(t - x)$ this becomes

$$V_n - V_{n+1} = a\sqrt{LC}\int_0^{\lambda t} J_{2n+2}(z)dz. \qquad (11)$$

FIG. 11.

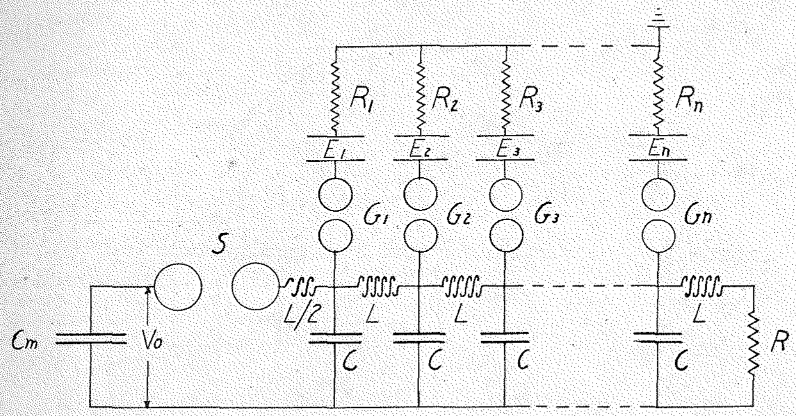


Voltage differences for the first three sections where unit voltage is applied to the artificial line with full inductance in the oth section.

The actual voltage difference between sections can be computed for any particular case from this if it is assumed that the applied voltage can be represented by the addition of $V_0 = at$ and $V_0 = -at'$ with the origin of t' displaced by an amount corresponding to the total time of breakdown of the switching gap.

There are a number of modifications in the artificial line system which are of interest and which improve the voltage efficiency. Before describing them a word of caution should be included. The artificial line is at best a complicated structure and considerable care is necessary in its construction if its transient performance is to follow the theoretical predictions. Any modifications or alterations introduced into its regular structure are apt to have a profound influence upon its operating characteristics. For this reason it is always necessary to determine the voltages and voltage differences in these modified systems by quantitative measurement with a cathode ray oscillograph before any attempt is made to use them for any purpose.

FIG. 12.



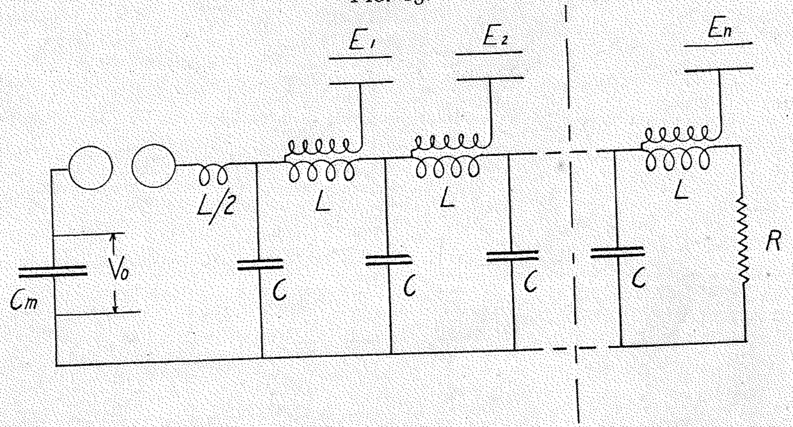
An artificial line where the voltage is applied to the electrodes by means of spark gaps.

The most useful addition to an artificial line is made by adding spark gaps between the line capacities C of Fig. 5 and the electrodes which are connected to them as shown in Fig. 12. High resistance leaks to ground $R_1, R_2 \cdots R_n$ are connected to each electrode. These spark gaps are set at such a value that breakdown occurs near the peak of the voltage wave for each section. In this way the voltage difference is increased. The only potential which appears at the electrode before breakdown of this series gap is that due to capacity coupling and this can usually be made a fairly small percentage of the line capacity voltage. The action of this system can readily be determined by an analysis of the curves for V_n (Fig. 6). For consistent performance the series gaps should be made of photo-sensitive material and intensely irradiated by ultra-violet light.

If it is desired to obtain an output voltage higher than that applied, the inductances L may be constructed with a secondary winding and operated as air core transformers as shown in Fig. 13. The capacity between windings prevents any great increase in voltage when such steep wave fronts are used, but a multiplication of 2 is certainly possible.

In the actual acceleration of ions the speed of the ion is increasing as it traverses the tube. This is usually allowed for by an increase in electrode length keeping the time interval constant. It is also possible to taper the constants in the artificial line so that electrode lengths are kept constant and the time interval changed.

FIG. 13.



An artificial line with transformer step up at each electrode.

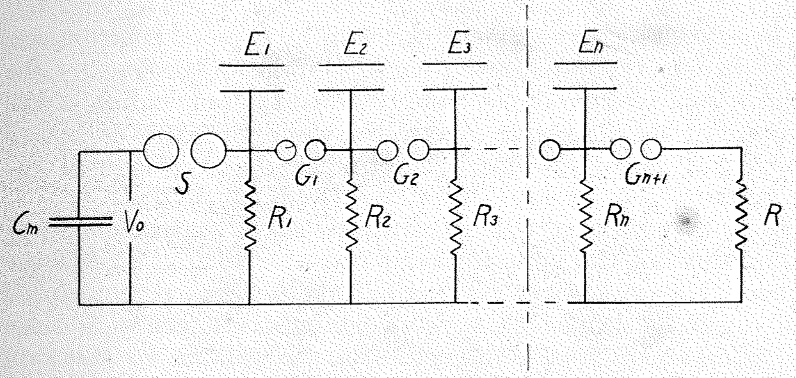
A mechanical model of such a line was constructed with tapered inductances and constant capacity. It was found that the time interval between sections decreased as the inductance was decreased and that the steepness of the wave front was maintained more nearly constant.

The artificial transmission line may also be used in a variety of ways to "Master" a series of discharges. For example the series of successive electrodes of the ion acceleration tube may be charged to a high voltage with respect to ground through high resistances by any type of charging system such as a kenetron and transformer or Marx impulse generator. Each of the successive electrodes may then be discharged through a three electrode spark gap in which the center electrodes are attached by appropriate resistances to the various successive sections of an artificial transmission line. In this way the time interval between the successive discharges of the tube electrodes is determined by the constants of the artificial transmission line.

3. THE SPARK GAP LINE.

In order to reduce the time between the application of the potential to the successive electrodes to as small a value as possible and still keep the applied wave front steep, a so-called spark gap line was devised. It is well known that a spark gap can be overvolted for a short time before it breaks down. This time may be made of the order of 10^{-8} sec. in special cases. Also it has been shown that with highly over-volted spark gaps the rate of fall of potential is very great.[3, 7] Fig. 14 shows a schematic diagram of the line. The spark gaps G_1 and G_n are connected directly to the electrodes E_1 to E_n respectively of the tube in which the ions are accelerated. To prevent them from floating, the electrodes are grounded

FIG. 14.



A spark gap transmission line.

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[7] Flowers, *Phys. Rev.*, **48**, 954, 1935.

through the 100,000 Ω resistances R_1 to R_n. The resistance R across the end of the line prevents reflection.

The impulse is applied to the line by the discharge of S. Since the capacities of the electrodes and spark gaps to ground are of the same order of magnitude as their intercapacities, the potential across G_1 is much higher (several times in our case) than across G_2 or G_3, etc. As a result G_1 breaks down, first followed by $G_2, G_3 \cdots G_{n+1}$ in succession. Since these capacities to ground C_1 and the intercapacities C_2 are known, the potential applied to the successive electrodes can be quite accurately determined. For example, if V is the applied potential, the potential V_k across G_k is given by

$$V_k = V\left(\frac{C_1}{C_1 + \frac{C_2}{2} + \left(\frac{C_2{}^2}{2} + C_1C_2\right)^{1/2}}\right)^k.$$

Therefore this arrangement serves as a type of transmission line in which the natural time lag in the breakdown of the spark gap determines the time between the application of the potential to successive electrodes while the rate of fall of potential across the spark determines the steepness of the wave front.

At first unprotected air gaps were used, but the changing conditions of the laboratory air caused the time lags of the gap to become erratic. To avoid this the gaps were enclosed in carefully cleaned glass tubes whose diameters were large in comparison to the diameters of the spheres of the gap. The air was carefully filtered, dried, and the ions removed by auxiliary fields so that the gaps could be highly overvolted in a manner previously described [3, 7] and advantage taken of the resulting steep wave fronts produced. With this arrangement it was possible to impress a voltage 10 times the static breakdown voltage across the gap for approximately 10^{-8} sec. before the potential started falling. Also the oscillograms showed that the potential across the gap fell to one-third its original value in a little over 10^{-8} sec. However, the spark gaps started to become somewhat erratic when the distance between the spheres of the gap exceeded 2 or 3 mm., which limited the usefulness of the line for our purpose to applied potentials not greater than 60,000 volts.

In the above arrangement considerable care must be taken to carefully filter and dry the air as well as keep it as free as possible of ions if the spark gaps are to function satisfactorily. However, it was found that all this trouble could be avoided if a few drops of carbon tetrachloride were put inside the spark gap chamber. With steel electrodes the gaps could easily be overvolted 10 times giving very steep wave fronts. Unfortunately, these gaps also became too erratic for our purpose for voltages over 60 or 70 K.V. The spark gaps were next surrounded by Transil oil No. 10. It was found that the oil gaps could be made to function satisfactorily up to applied potentials of 100 K.V. However, at 250 K.V. applied potential, the time lags became too variable for our purpose and 2.5×10^{-8} sec. were required for the potential to fall to 1/3 of its value. While the above types of spark gap lines can be made to operate successfully for voltages under 60 K.V., giving dependable time intervals of, roughly, the order of 2 to 2.5×10^{-8} sec. as well as very steep wave fronts, we abandoned them for our immediate purpose because of the voltage limitation.

4. THE DISCHARGE TUBE LINE.

It has long been known [8] that when an impulsive potential is applied to the ends of a long discharge tube that the luminosity starts at one end and progresses toward the other. When care is taken to maintain one end at ground while an impulsive voltage is applied to the other end, the luminosity progresses from the high voltage electrode to the grounded electrode regardless of the sign of the impressed voltage.[9] By means of the high speed cathode ray oscillograph we have found that the voltage wave also traverses the discharge tube from the high voltage electrode to the grounded electrode with a definite velocity. The velocity of the voltage wave can be varied over wide ranges as it depends upon the pressure of the gas and to some extent upon the applied voltage. When the applied voltage exceeds 100 K.V. and the pressure is properly adjusted there is no measurable attenuation or flattening of the wave front in a 10 meter tube.

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[8] J. J. Thomson, "Recent Researches," 115, 1893.

[9] Beams, *Phys. Rev.*, **36**, 997, 1930.

With a 5 mm. tube filled with air at .08 mm. Hg pressure a positive 127 K.V. wave traversed the tube with a speed of 9×10^8 cm./sec., while with the same applied voltage wave but with a pressure of 5.4 mm. Hg the wave traveled with a speed of 4.3×10^9 cm./sec. The current carried by the wave itself reached several hundred amperes while the maximum current in the tube during the discharge reached several thousand amperes. A detailed description of the action of this discharge tube line will be given later as it is still under investigation. However, we believe that there is little doubt that it will be of use for many problems, especially in the acceleration of ions to very high velocities.

We wish gratefully to acknowledge a grant from the Penrose Fund of the American Philosophical Society which made this work possible.

THE VISIBILITY OF VARIOUS TYPE FACES.

BY

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Although the vast majority of human beings begins life with unimpaired vision, a very large percentage has measurably defective vision at the age of fifty. Certainly it is possible that many of these changes result from the use and abuse of the visual mechanism in performing unnaturally severe and exacting near-vision tasks for prolonged periods. In fact, much evidence points toward such a conclusion. Severe and critical visual tasks are imposed by civilization, but they may be made easier through (1) the correction of ocular deficiencies, (2) the provision of adequate light and proper lighting and (3) by increasing the visibility of objects to be seen when this is possible. The present discussion pertains largely to the third of these controllable phases of ocular hygiene. Since reading is a universal visual task in the home, schoolroom, and office, the visibility of the reading matter is of major importance.

Obviously, the task of reading may be made easier by increasing type size within certain limits.[1, 4] However, the improvement in visibility which is possible through the use of larger type is usually limited by economic factors as well as practical considerations involving the convenience of certain page-sizes or number of pages in a given volume. In addition, the advantage derivable from larger type sizes is probably limited due to the increase in ocular muscular effort required in reading as the size of the type is increased. Furthermore, perceptual anomalies may be introduced by decreasing the number of letters included in a single perceptual span.[2] In general, an acceptable standard of type size has been more or less definitely indicated by the characteristics of good typography since these have been evolved through mass experience for generations.[3] Hence the fact that text-matter in a book or magazine is seldom, if ever, printed in larger than 12-point

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SOME PROBLEMS OF THE NATIONAL BUREAU OF STANDARDS.*

BY

LYMAN J. BRIGGS, Director.

The advantages of a uniform system of weights and measures for the whole nation are so obvious in our present-day development of commerce and industry that we seldom stop to consider how uniformity was brought about or the difficulties involved in maintaining it. I wish to invite your attention to certain features of this evolutionary process, in the course of which our standards have become more precisely defined and established.

Presumably the difficulties under which commerce had been carried out among the thirteen Colonies, owing to the lack of uniform standards, were responsible in part for that wise and far-sighted provision of the Constitution which delegated to Congress the authority "to fix the standards of weights and measures." It is remarkable that under such circumstances Congress did not take prompt steps to correct the situation. In the early days of the new Republic, Washington in his presidential messages to Congress repeatedly urged the importance of carrying out this constitutional provision; but for eighty years no formal action was taken by Congress to "fix" the standards, save for the adoption in 1828 of a standard Troy pound for coinage purposes.

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* Presented at a meeting held Thursday, March 26, 1936.