CHAPTER V

DATA AND EXPERIMENTS

Impulse Voltage Testing Plant

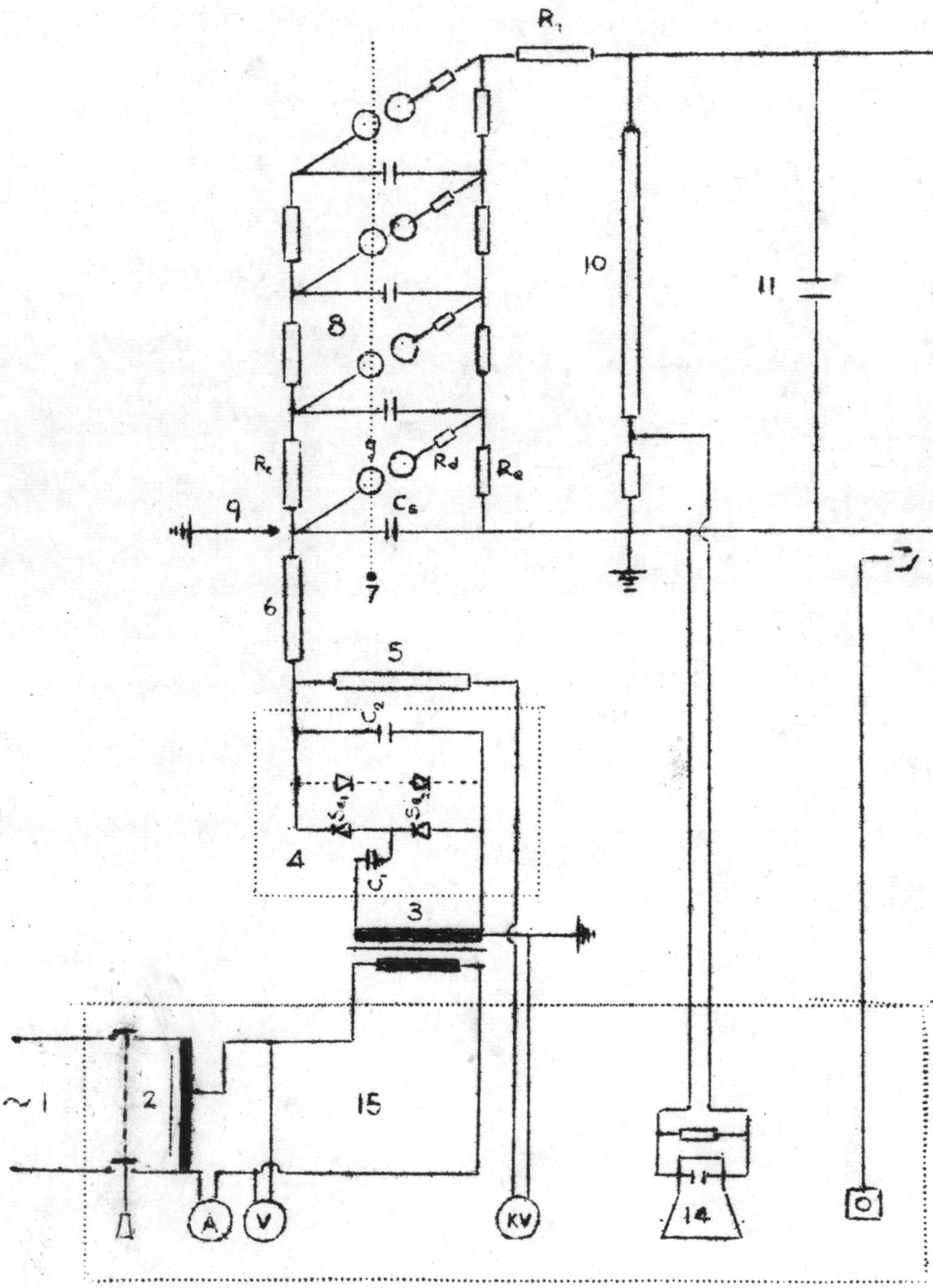


Fig. 5-1 Completed circuit diagram for testing purpose.

Explanation of the Diagram

1. AC supply mains
2. Potentiometer
3. High voltage transformer
4. Charging equipments
5. Measuring resistance
6. Limiting resistance
7. Movable insulating rod
8. Impulse generator
9. Earthing device
10. Resistance potential divider
11. Capacitance load
12. Measuring sphere gaps
13. Gaps controlled motor
14. Oscillograph
15. Control desk

Electrical Data

A. Impulse generator

C_s = impulse capacitors. Type CP 231 E00104 M, NTK, JAPAN

0.1 μF / 10 KV $\pm$ 10 %

R_c = charging resistors. Type Wire-wound 5-W.

10 KΩ/ 10 KV $\pm$ 10 %

R_e = discharging resistors. Type wire-wound 25-W.

887.5 Ω/ 10 KV $\pm$ 5 %

R_d = internal damping resistors. Type wire-wound 50-W.

54 Ω/ 10 KV $\pm$ 5 %

30 Ω/ 10 KV $\pm$ 5 %

g = spark gaps. Type steel balls.

2.5 cm. diameter $\pm$ 1 %

R_1 = series resistor. Type wire wound 25-W

2800 Ω/ 30 KV $\pm$ 5 %

B. Charging equipments

Se_1, Se_2 = Selenium rectifiers. Type CR 212, RCA

max.peak inversed voltage 10 KV

max. current at 20°C 1 A

C_1, C_2 = condensers. Type CP 231 E00104 M, NTK, JAPAN

0.1 μF / 10 KV $\pm$ 10 %

Measuring resistor. Type, Carbon 1-W

277 MΩ / 10 KV $\pm$ 20 %

Limiting resistor. Type, Liquid (Water)

Several megohms

Earthing device. Type, hot stick with lead connecting to ground rod, low impedance.

H.V. Transformer. Type CSP/A 1 ø 50 Hz., Oil-immearsed. U.S.A.

Rated voltage. L.V coils 240 - 480 V

H.V coil 12 KV

Power out put 5 KVA

C. Controlled desk

Main power supply : provided by push bottons with automatic circuit breakers 220 V AC 50 Hz.

Potentiometer : Type Yamabishi Electric Co., Ltd. JAPAN

AC voltage variation 0 - 240 V 50 Hz.

AC voltmeter : for main supplied voltage 0 - 240 V 50 Hz.

DC kilovoltmeter : by means of a microammeter with a high series resistance to indicate the DC charging voltage 0 - 8 KV

Scale 0 - 50μA

Impulse voltmeter : measures both positive and negative polarities of the samples of impulse voltage taken from a resistor divider.

Accuracy : impulse wave to be recorded > 0.5 μS, error = 2%.

impulse wave to be recorded 0.2-0.5 μS, error= 3%.

Multiplying factors 1, 2, 4, 6

Precision moving coil microammeter used in conjunction with the impulse voltmeter to measure the impulse voltage

Series number 331700/1

Calibrating value 0 - 200 V

Oscilloscope (C.R.O.) Type 565 Dual-Beam Textronix Inc. U.S.A.

Response time = 0.035 μS.

Scales : X = 0.1 - 10 μS/Div.

Y = 10 V/Div.

Photographic camera. Type Kodax, Retina IV, 35 mm.

Lens 2.8 f 50 mm

Single len reflex

provided with two closed up lens

Film. Type 400 ASA 20 Exposures, 35 mm.

Gaps controlled motor. For adjusting the measuring sphere gaps.

AC supply 220 V 50 Hz.

D. Accessories

Resistance potential divider. Type wo/oA 55.3189 EML

HAEFELY & CIE AG 4000 BASEL 28, Switzerland

resistance values. $R_1 = 7376\ \Omega$

$R_2 = 76\ \Omega$

Dividing ratios

Theoretical $\frac{7376 + 76}{76} = 98.2$

Positive wave $\frac{580 \times 169.6 \times 1}{171.5 \times 6} = 95.5$

Negative wave $\frac{580 \times 171.2 \times 1}{173.3 \times 6} = 95.5$

Dividing ratio to be used = 95.5 both for positive and negative polarities.

Load capacitors 200 pF / 350 KV $\pm$ 10 %

2000 pF / 700 KV $\pm$ 10 %

3000 pF / 700 KV $\pm$ 10 %

4000 pF / 700 KV $\pm$ 10 %

Resistors- Type-wire-wound 25 W

181 Ω / 32 KV $\pm$ 10 %

2800 Ω / 32 KV $\pm$ 10 %

3075 Ω / 32 KV $\pm$ 10 %

7200 Ω / 32 KV $\pm$ 10 %

Inductors. Type air core, copper coils

5.12 μH / 32 KV $\pm$ 10 %

7.42 μH / 32 KV $\pm$ 10 %

12.0 μH / 32 KV $\pm$ 1 %

15.58 μH / 32 KV $\pm$ 1 %

Measuring Sphere gaps. Type copper alloy, with one gap earthed

25 cm in diameter

Calculated and Experimental Data of 1/50 Wave

Calculated Impulse Circuit

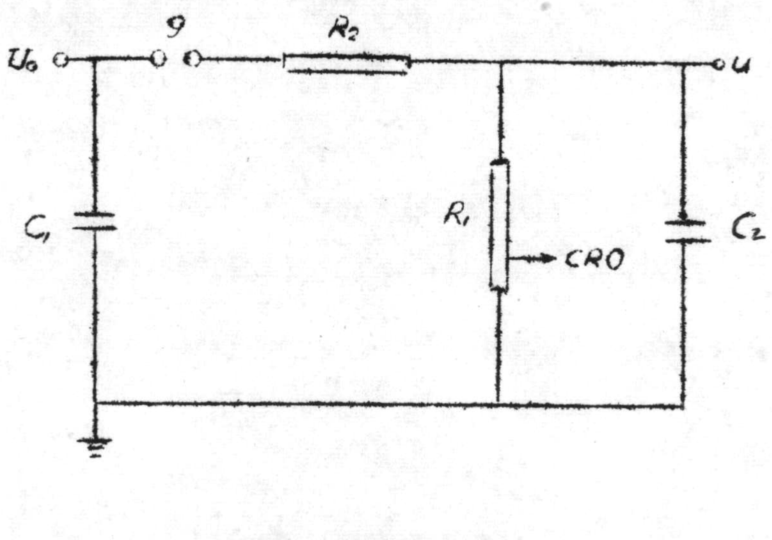


Fig. 5-2 Impulse circuit for 1/50 wave.

In figure 5-2,

C_1 = impulse generator capacitance

R_1 = discharging resistance

R_2 = series resistance

C_2 = load capacitance

g = spark - gaps

U_o = DC charging voltage

u = Impulse voltage

Calculated Data of 1/50 wave

Referring to graphical method in Chapter II

$$t_1 = 1 \mu S.$$

$$t_2 = 50 \mu S$$

$$\frac{t_1}{t_2} = 0.02$$

$$\alpha\theta_1 = 2.96$$

$$\theta_2 = 0.73$$

$$p_1 = \frac{\theta_2}{t_2} = 0.0146 \mu S^{-1}$$

$$p_2 = \frac{\alpha\theta_1}{t_1} = 2.96 \mu S^{-1}$$

$$\eta = 97.5 \%$$

$$\frac{C_1}{C_2} = 12.5$$

$$C_1 = 0.025 \mu F$$

$$C_2 = 2000 \text{ pF}$$

$$R_2 = \frac{1}{C_2\sqrt{p_1 p_2}} \approx 192 \Omega$$

$$R_2 = \frac{C_1}{C_2} R_2$$

$$\approx 2400 \ \Omega$$

$$u = \frac{U_o}{C_2 R_2} \frac{1}{p_2 - p_1} \left(\epsilon^{-p_1 t} - \epsilon^{-p_2 t} \right)$$

$$= 0.882 \ U_o \left(\epsilon^{-0.0146 \ t} - \epsilon^{-2.96 \ t} \right)$$

The wave shape of impulse voltage $u = 0.882 \ U_o \left(\epsilon^{-0.0146t} - \epsilon^{-2.96t} \right)$ is plotted to scale in the graph-paper by the using of the calculated values in table 5.

Table 5 . Calculated values for plotting equation

$$u = 0.882\ (\epsilon^{-0.0146t} - \epsilon^{-2.96t})$$

(1)	(2)	(3)	(4)	(5)	(6)=(4)-(5)	u=0.882 (6)
t μs	0.0146t	2.96t	$\epsilon^{-0.0146t}$	$\epsilon^{-2.96t}$	$\epsilon^{-0.0146t} - \epsilon^{-2.96t}$	u=0.882 ($\epsilon^{-0.0146t} - \epsilon^{-2.96t}$)
0.0	0.0000	0.000	1.000	1.000	0.000	0.000
0.1	0.0015	0.296	0.999	0.745	0.254	0.223
0.2	0.0029	0.592	0.998	0.552	0.446	0.394
0.3	0.0044	0.888	0.996	0.411	0.585	0.516
0.4	0.0058	1.184	0.995	0.307	0.688	0.607
0.5	0.0073	1.480	0.993	0.228	0.765	0.675
0.6	0.0088	1.776	0.992	0.170	0.882	0.726
0.7	0.0102	2.072	0.990	0.127	0.864	0.763
0.8	0.0117	2.368	0.989	0.094	0.895	0.790
0.9	0.0131	2.664	0.988	0.071	0.917	0.808
1.0	0.0146	2.960	0.986	0.052	0.934	0.825
1.2	0.0175	3.550	0.984	0.029	0.955	0.832
1.4	0.0204	4.150	0.979	0.016	0.963	0.850
1.6	0.0234	4.740	0.977	0.009	0.968	0.853
1.8	0.0263	5.330	0.975	0.005	0.970	0.856
2.0	0.292	5.920	0.970	0.003	0.963	0.850
3.0	0.0438	8.880	0.957	0.0003	0.957	0.843
4.0	0.0584	11.840	0.942	Negligible	0.942	0.832
5.0	0.0730	14.800	0.930	—	0.930	0.823
6.0	0.0876	17.760	0.917	—	0.917	0.808
7.0	0.1022	20.720	0.903	—	0.903	0.797
8.0	0.1168	23.680	0.888	—	0.888	0.783
9.0	0.1314	26.640	0.877	—	0.877	0.773
10.0	0.1460	29.600	0.865	—	0.865	0.763
15.0	0.2190	44.400	0.802	—	0.802	0.718
20.0	0.2920	59.200	0.749	—	0.749	0.660
25.0	0.3750	74.000	0.688	—	0.688	0.607
30.0	0.4380	88.800	0.645	—	0.645	0.569
35.0	0.5100	103.600	0.600	—	0.600	0.530
40.0	0.5840	118.400	0.558	—	0.558	0.459
45.0	0.6570	133.200	0.520	—	0.520	0.423
50.0	0.7300	148.000	0.479	—	0.479	0.394
55.0	0.8030	162.800	0.446	—	0.446	0.368

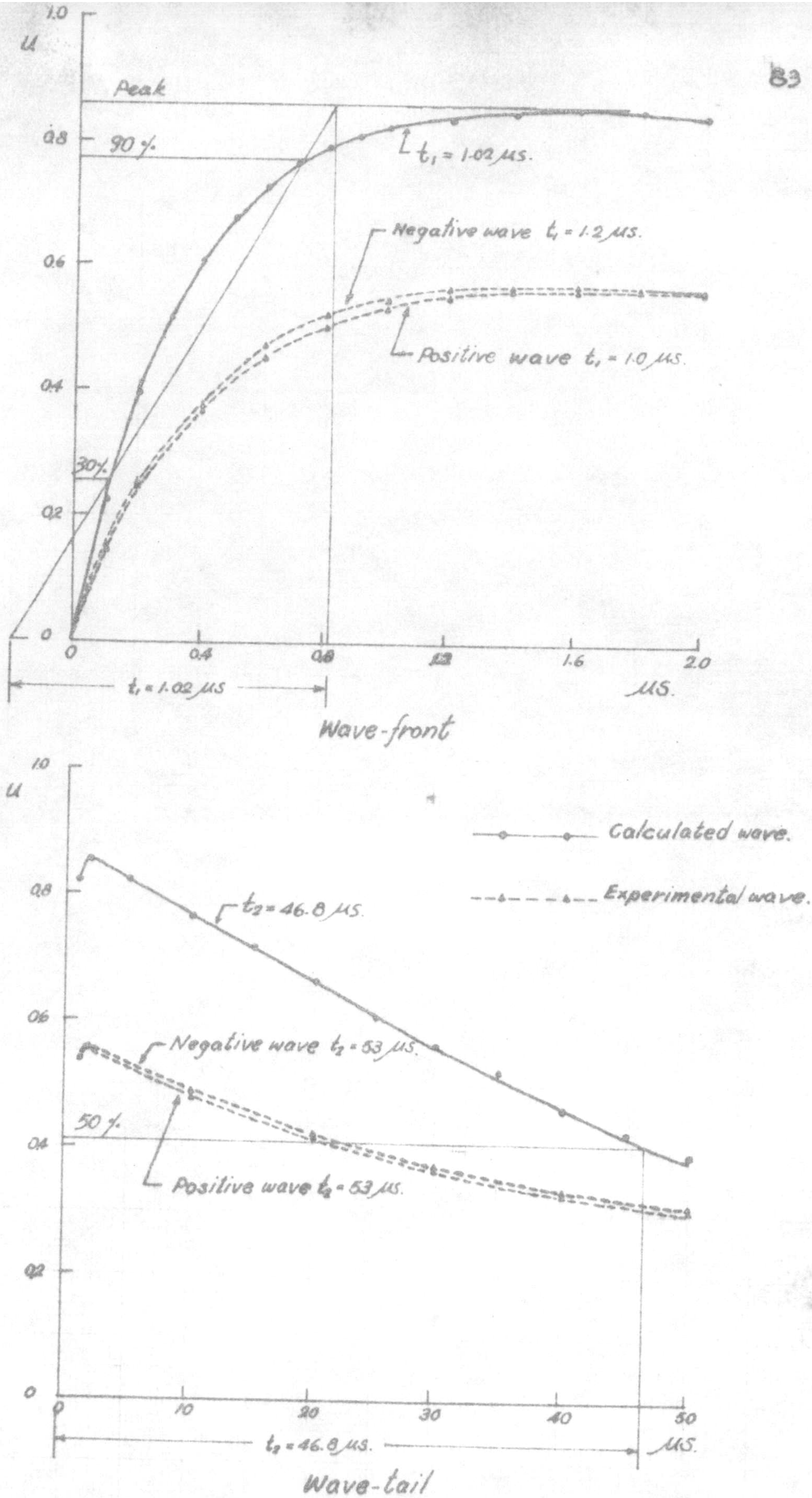


Fig. 5-3 Plotted front and tail of wave equation $u = 0.882(\epsilon^{-0.0146t} - \epsilon^{-2.96t})$ representing a standard unity-amplitude 1/50 wave; $U_0 = 1.0$.

Experimental Data of 1/50 Wave

Measurements

D-C Charging voltage

Microammeter 4 x 5 KV (4 multi-stages)

Impulse voltage

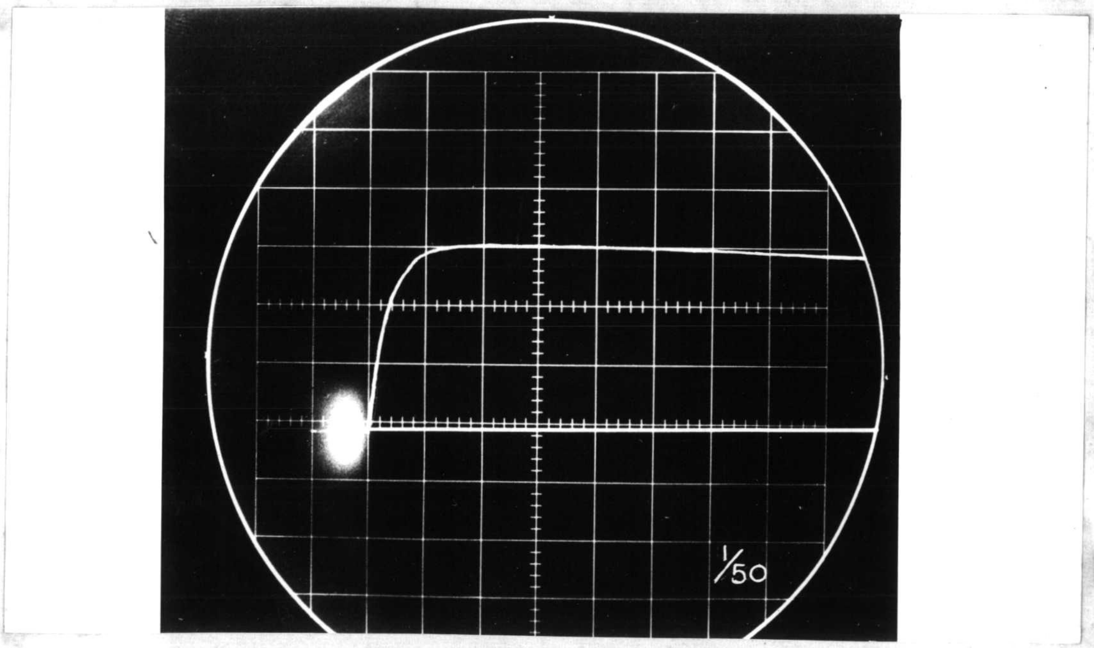
Resistance potential divider : dividing ratio 95.5 (positive-negative waves)

Impulse voltmeter : multiplying factor 4

C.R.O. scales X = 1, 10 μS/Div.

Y = 10 V / Div.

Experimental Wave Shapes

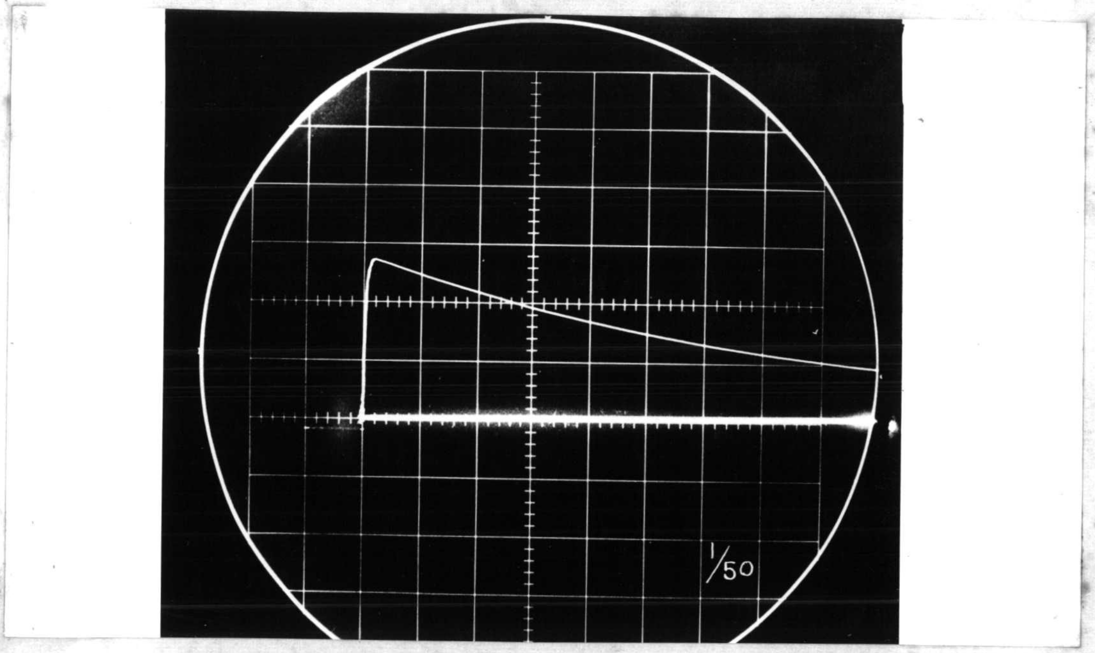


Polarity - positive wave

A. Scales X = 1 μS/Div.

Y = 10 V / Div.

Duration of wave front t_1 = 1.0 μS



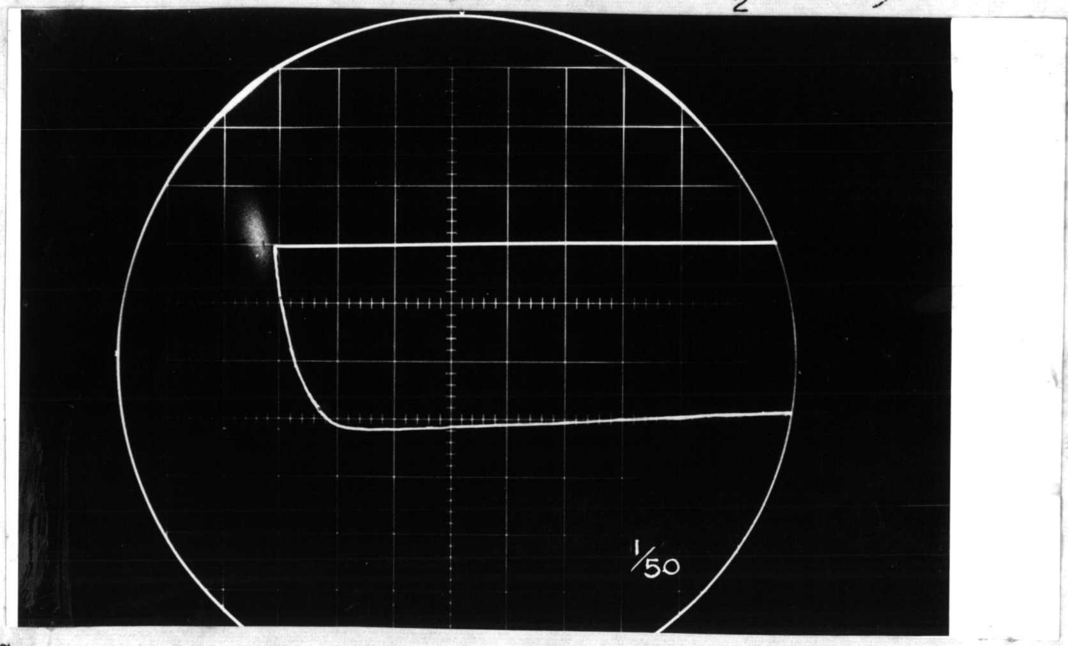
B.

Polarity - positive wave

scales X = 10 μS / Div.

Y = 10 V / Div.

Time to half value of wave-tail t_2 = 53 μS.

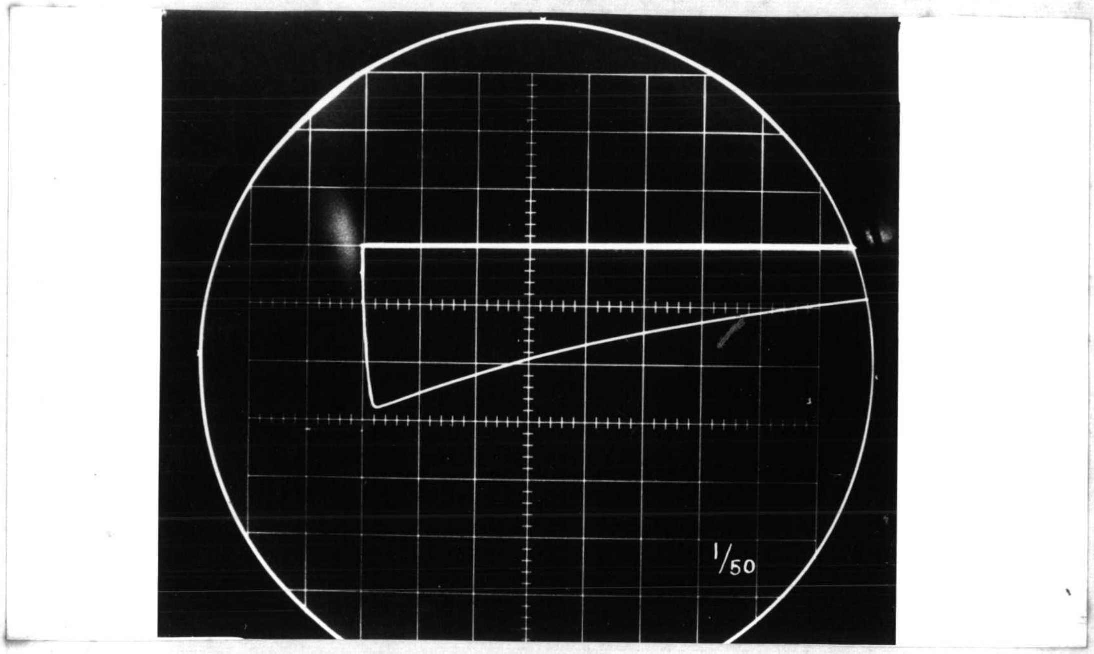


C. Polarity - negative wave

C. Scales X = 1 μS / Div.

Y = 10 V / Div.

Duration of wave-front $t_1 = 1.2 \mu S$.



Polarity - negative wave

D. Scales X = 10 μS / Div.

Y = 10 V / Div.

Time to half-value of wave tail $t_2 = 53 \mu S$.

Fig. 5-4 Experimental wave shapes of the calaulated impulse circuit of 1/50 wave $\left[u = 0.882\, U_o\left(\epsilon^{-0.0146t} - \epsilon^{-2.96t}\right)\right]$, showing the front and tail of waves for both positive and negative polarities.

Efficiency

Total DC charging voltage = 4 x 5 KV.

impulse voltage = 4 x 95.5 x 30 V = 11.25 KV.

$$\eta = \frac{11.25}{20} = 56.25\ \%$$

Calculated and Experimental Data of 1.5/40 wave

Calculated Impulse Circuit

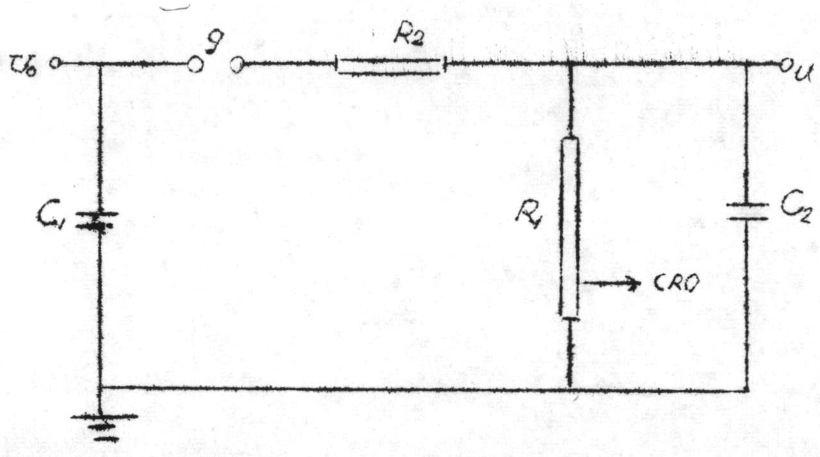


Fig. 5-5 Impulse circuit for 1.5/40 wave

In figure 5-5,

C_1 = impulse generator capacitance

R_1 = discharging resistance

R_2 = series resistance

C_2 = load capacitance

g = spark-gaps

U_o = DC charging voltage

u = impulse voltage

Calculated Data of 1.5/40 wave

Referring to graphical method in Chapter II

$$t_1 = 1.5\ \mu S$$

$$t_2 = 40\ \mu S$$

$$\frac{t_1}{t_2} = 0.0375$$

$$\alpha\theta_1 = 2.8$$

$$\theta_2 = 0.74$$

$$p_1 = \frac{\theta_2}{t_2} = 0.0185 \ \mu s^{-1}$$

$$p_2 = \frac{\alpha\theta_1}{t_1} = 1.87 \ \mu s^{-1}$$

$$\eta = 75 \%$$

$$\frac{C_1}{C_2} = 8$$

$$C_1 = 0.025 \ \mu F$$

$$C_2 = 3000 \ pF$$

$$R_2 = \frac{1}{C_2 \sqrt{p_1 p_2}} = 216 \ \Omega$$

$$R_1 = \frac{C_1}{C_2} R_2 = 1800 \ \Omega$$

$$u = \frac{U_o}{C_2 R_2} \frac{1}{p_2 - p_1} \left(\epsilon^{-p_1 t} - \epsilon^{-p_2 t} \right)$$

$$= 0.835 \ U_o \left(\epsilon^{-0.0185t} - \epsilon^{-1.87t} \right)$$

The wave shape of the impulse voltage $u = 0.835 \ U_o \ (\epsilon^{-0.0185t} - \epsilon^{-1.87t})$ is plotted to scale in the graph-paper by using the calculated values in table.**5.**

Table 6 . Calculated values for plotting equation

$$u = 0.835 \left(\epsilon^{-0.0185t} - \epsilon^{-1.87t} \right)$$

(1)	(2)	(3)	(4)	(5)	(6)=(4)-(5)	u=0.835(6)
t μS	0.0185 t	1.87t	$\epsilon^{-0.0185t}$	$\epsilon^{-1.87t}$	$\epsilon^{-0.0185t} - \epsilon^{-1.87t}$	$u = 0.835 (\epsilon^{-0.0185t} - \epsilon^{-1.87t})$
0.0	0.0000	0.000	1.000	1.000	0.000	0.000
0.1	0.0019	0.187	0.999	0.830	0.169	0.141
0.2	0.0037	0.374	0.997	0.688	0.309	0.258
0.3	0.0055	0.561	0.995	0.570	0.425	0.355
0.4	0.0074	0.748	0.993	0.474	0.519	0.433
0.5	0.0093	0.935	0.992	0.392	0.600	0.500
0.6	0.0111	1.122	0.990	0.326	0.664	0.555
0.7	0.0130	1.309	0.989	0.270	0.719	0.599
0.8	0.0148	1.496	0.987	0.224	0.763	0.638
0.9	0.0167	1.783	0.985	0.168	0.817	0.681
1.0	0.0185	1.870	0.983	0.154	0.829	0.692
1.2	0.0222	2.244	0.987	0.107	0.871	0.728
1.4	0.0259	2.620	0.976	0.074	0.902	0.754
1.6	0.0296	2.990	0.970	0.050	0.920	0.768
1.8	0.0333	3.370	0.967	0.031	0.936	0.780
2.0	0.0370	3.740	0.964	0.024	0.940	0.785
3.0	0.0550	5.610	0.950	0.004	0.946	0.789
4.0	0.0740	7.480	0.932	0.001	0.931	0.778
5.0	0.0925	9.350	0.911	0.0001	0.911	0.761
6.0	0.1110	11.220	0.897	—	0.897	0.748
7.0	0.1295	13.090	0.880	—	0.880	0.734
8.0	0.1480	14.960	0.863	—	0.863	0.721
9.0	0.1665	17.830	0.847	—	0.847	0.705
10.0	0.1850	18.700	0.812	—	0.812	0.678
15.0	0.2775	28.050	0.758	—	0.758	0.632
20.0	0.3700	37.400	0.690	—	0.690	0.577
25.0	0.4625	46.750	0.629	—	0.629	0.528
30.0	0.5550	56.100	0.575	—	0.575	0.480
35.0	0.6475	65.450	0.523	—	0.523	0.437
40.0	0.7400	74.800	0.476	—	0.476	0.397
45.0	0.8325	84.150	0.434	—	0.434	0.362
50.0	0.9250	93.500	0.397	—	0.397	0.332

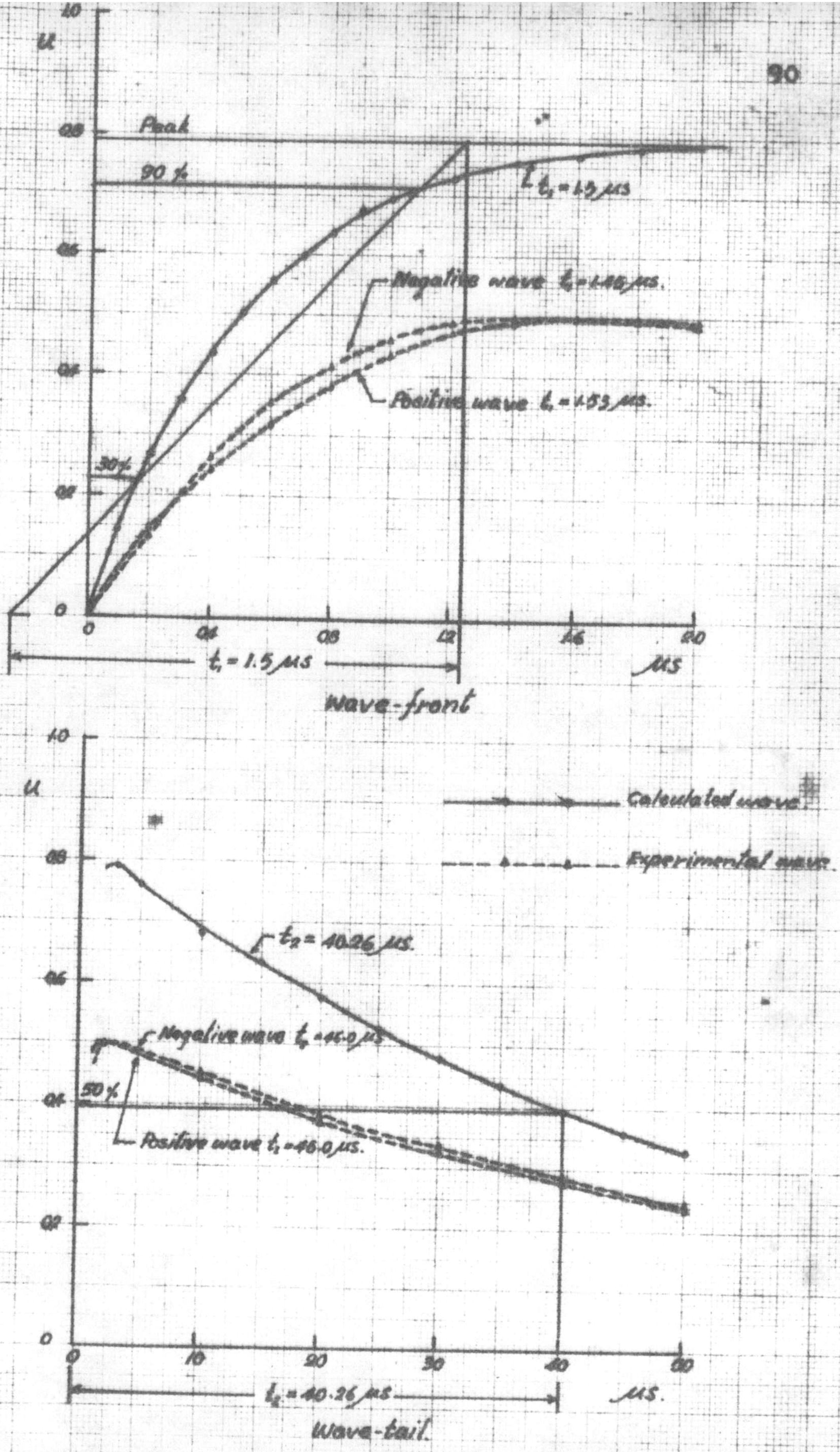


Fig. 5-6 Plotted front and tail of wave equation $u = 0.835(\epsilon^{-0.0185t} - \epsilon^{-1.87t})$ representing a standard unity-amplitude 1.5/40 wave; $U_0 = 1.0$.

Experimental Data of 1.5/40 wave

Measurements

DC charging voltage

microammeter 4 x 8 KV (4-multi-stages)

Impulse voltage

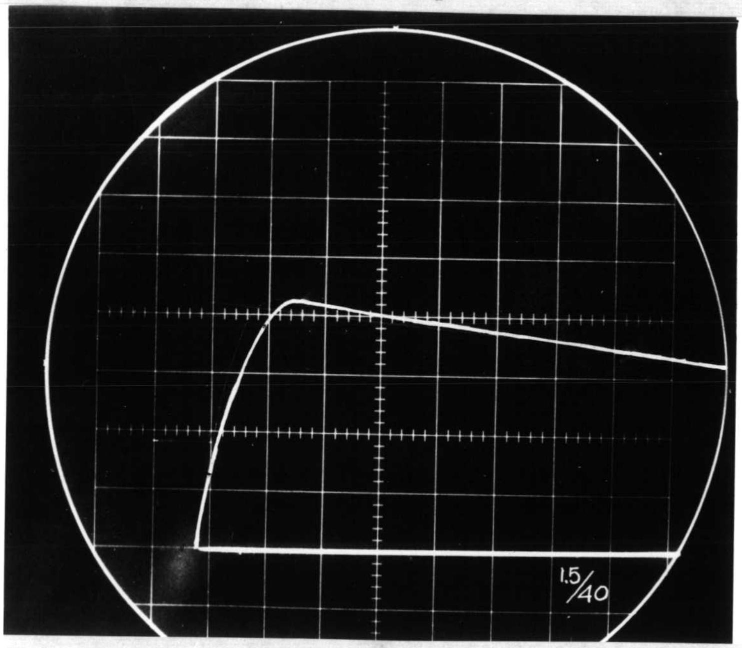
resistance potential divider: dividing ratio 95.5 (positive-negative waves)

impulse voltmeter : multiplying factor 4

C.R.O. scales : X = 1, 10 μS / Div.

Y = 10 V/Div.

Experimental wave shapes

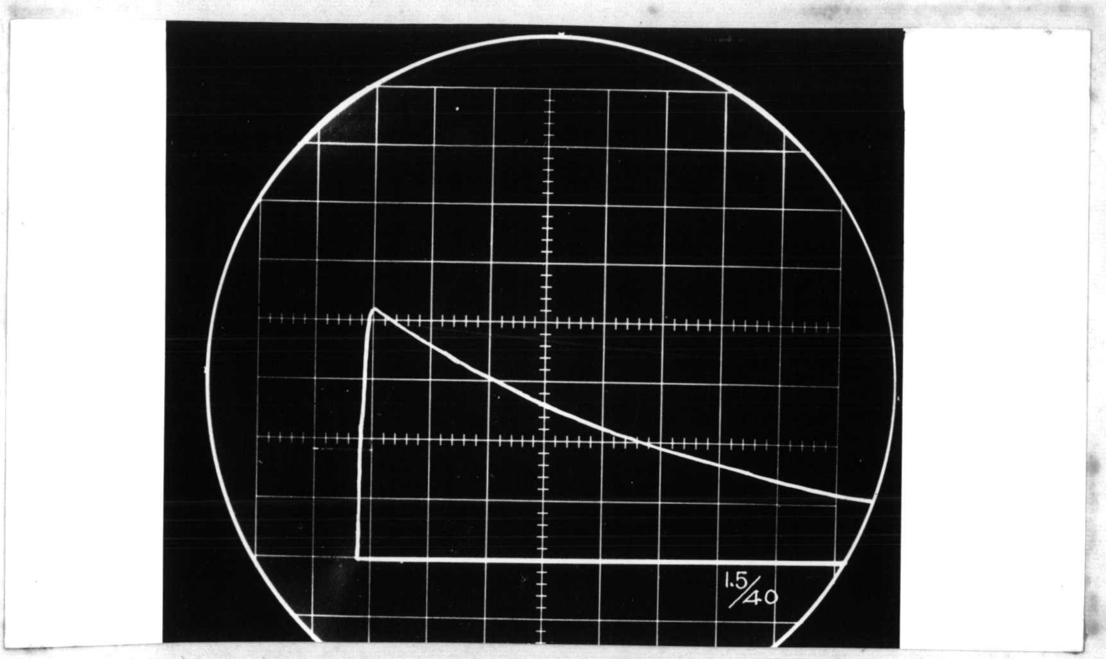


Polarity - positive wave

A. scales X = 1 μS/Div.

Y = 10 V/Div.

Duration of wave front t_1 =1.53 μS.



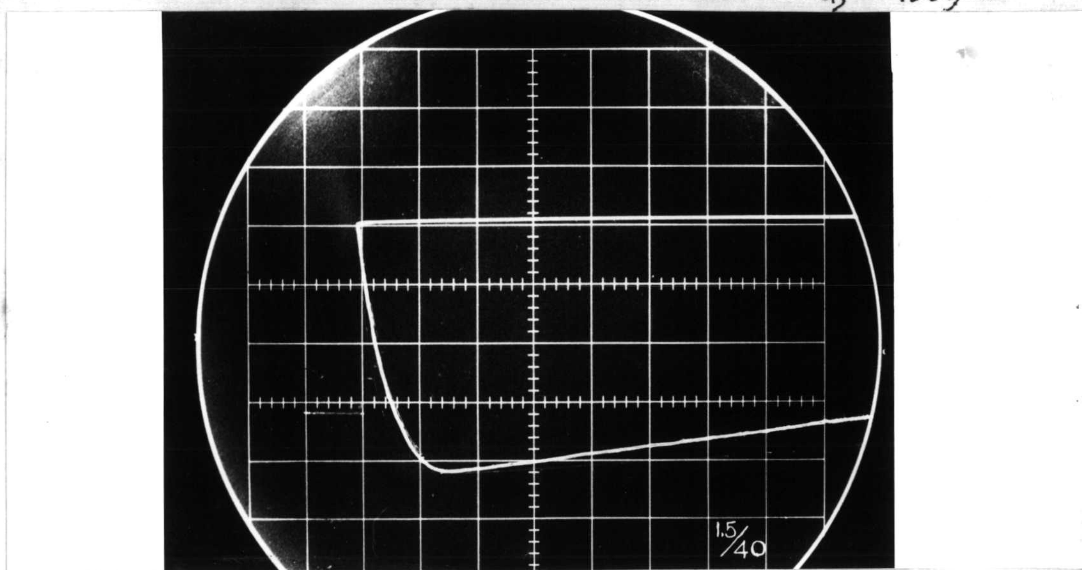
B.

Polarity - positive wave

Scales X = 10 μS / Div.

Y = 10 V / Div.

Time to half value of wave tail t_2 = 45.0μS



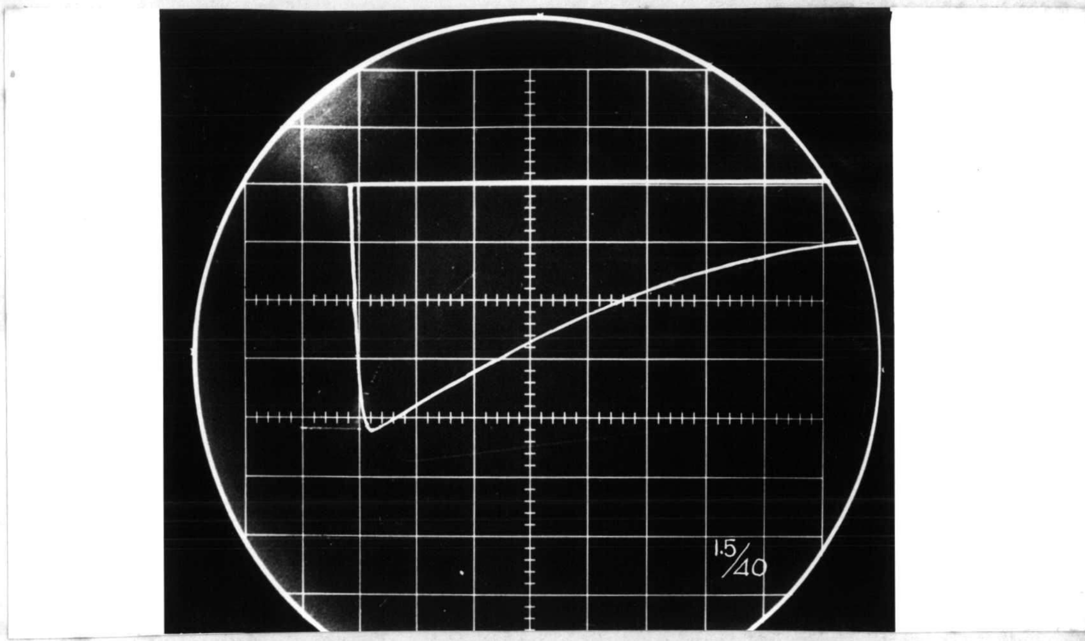
C.

Polarity - negative wave

scales X = 1 μS / Div.

Y = 10 V / Div.

Duration of wave front t_1 = 1.45μS



Polarity - negative wave

D.

Scales $X = 10\ \mu S$ / Div.

$Y = 10\ V$ / Div.

Time to half value of wave tail $t_2 = 46.0\ \mu S$.

Fig. 5-7 Experimental wave shapes of the calculated impulse circuit of 1.5/40 wave $u = 0.835\ U_o\ (\ ^{-0.0185t} - \ ^{-1.87t}\ )$, showing the front and tail of waves for both positive and negative polarities.

Efficiency

Total DC charging voltage = 4 x 8 KV.

Average experimental impulse voltage for

Positive wave = 4 x 95.5 x 42 V = 16 KV

Negative wave = 4 x 95.5 x 42 V = 16 KV

Therefore $\eta_{\text{positive wave}} = 50.0\ \%$

$\eta_{\text{negative wave}} = 50.0\ \%$

Calculated and Experimental Data of 1/5 wave

Calculated Impulse Circuit

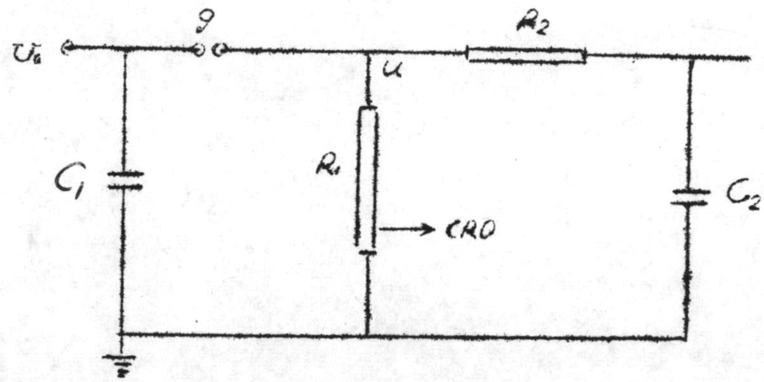


Fig. 5-8 Impulse circuit for 1/5 wave.

In figure 5-8,

C_1 = impulse generator capacitance

R_1 = discharging resistance

R_2 = series resistance

C_2 = load capacitance

g = spark-gaps

U_o = DC charging voltage

u = impulse voltage

Calculated Data of 1/5 wave

Referring to graphical method in Chapter II

$t_1 = 1 \ \mu S$

$t_2 = 5 \ \mu S$

$$\frac{t_1}{t_2} = 0.2$$

$$\alpha\theta_1 = 1.78$$

$$\theta_2 = 1.2$$

$$p_1 = \frac{\theta_2}{t_2} = 0.24 \ \mu s^{-1}$$

$$p_2 = \frac{\alpha\theta_1}{t_1} = 1.78 \ \mu s^{-1}$$

$$= 72 \%$$

$$\frac{C_1}{C_2} > 10^2$$

$$C_1 = 0.025 \ \mu F$$

$$C_2 = 200 \ pF$$

$$R_1 = \frac{1}{C_1 p_1} = 167 \ \Omega$$

$$R_2 = \frac{1}{C_2 p_2} = 2800 \ \Omega$$

$$u = \frac{U_o}{C_2 R_2} \frac{1}{p_2 - p_1} (\epsilon^{-p_1 t} - \epsilon^{-p_2 t})$$

$$= 0.865 \ U_o (\epsilon^{-0.24t} - \epsilon^{-1.78t})$$

The wave shape of the impulse voltage $u = 0.865 \ U_o \ (\epsilon^{-0.24t} - \epsilon^{-1.78t})$ is plotted to scale in the graph-paper by using the calculated values in table 7 .

Table 7 . Calculated values for plotting equation

$$u = 0.865 \left(^{-0.24t} - ^{-1.78t} \right)$$

(1) t μs	(2) 0.24t	(3) 1.78t	(4) $\epsilon^{-0.24t}$	(5) $\epsilon^{-1.78t}$	(6)=(4)-(5) $\epsilon^{-0.24t} - \epsilon^{-1.78t}$	u=0.865 (6) $u = 0.865 (\epsilon^{-0.24t} - \epsilon^{-1.78t})$
0.0	0.000	0.000	1.000	1.000	0.000	0.000
0.1	0.024	0.178	0.976	0.838	0.138	0.120
0.2	0.048	0.356	0.953	0.700	0.253	0.218
0.3	0.072	0.534	0.931	0.587	0.344	0.297
0.4	0.096	0.712	0.909	0.489	0.420	0.364
0.5	0.120	0.890	0.887	0.418	0.469	0.406
0.6	0.144	1.068	0.875	0.344	0.531	0.460
0.7	0.168	1.246	0.844	0.288	0.556	0.480
0.8	0.192	1.424	0.828	0.241	0.587	0.508
0.9	0.216	1.602	0.806	0.200	0.606	0.524
1.0	0.240	1.780	0.788	0.170	0.618	0.533
1.2	0.288	2.136	0.750	0.119	0.631	0.547
1.4	0.336	2.492	0.714	0.083	0.631	0.547
1.6	0.384	2.850	0.680	0.058	0.622	0.539
1.8	0.432	3.200	0.650	0.040	0.610	0.528
2.0	0.480	3.560	0.619	0.029	0.590	0.510
3.0	0.720	5.340	0.476	0.005	0.471	0.407
4.0	0.960	7.120	0.383	0.001	0.382	0.330
5.0	1.200	8.900	0.300	0.0013	0.300	0.259
6.0	1.440	10.680	0.238	0.0002	0.237	0.205
7.0	1.680	12.460	0.187	Negligible	0.187	0.162
8.0	1.920	14.240	0.147	—	0.147	0.127
9.0	2.160	16.020	0.115	—	0.115	0.099
10.0	2.400	17.800	0.091	—	0.091	0.079

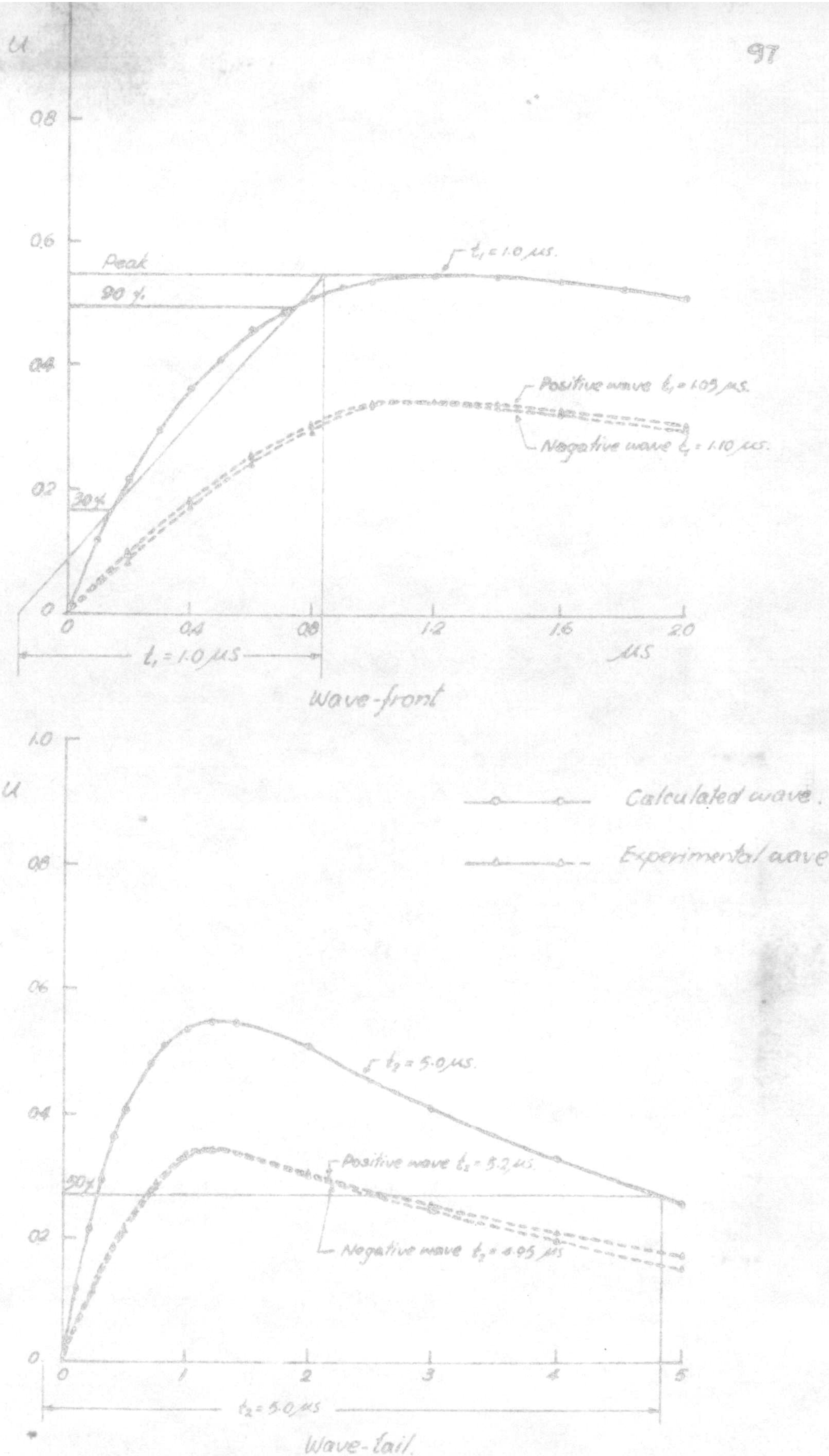


Fig. 5-9 Plotting front and tail of wave equation $u = 0.865(\epsilon^{-0.24t} - \epsilon^{-1.78t})$ representing a standard unity-amplitude 1/5 wave; U_0 = 1.0.

Experimental Data of 1/5 wave

Measurements

DC charging voltage

microammeter : 4 x 6 KV (4 -multi-stages)

Impulse voltage

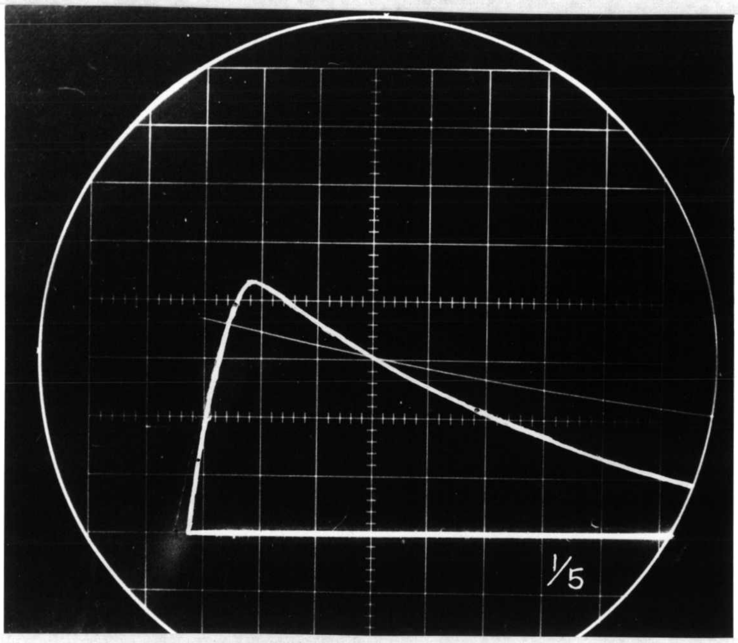
resistance potential divider : dividing ratio 95.5 (positive-negative waves

Impulse voltmeter : multiflying factor 2.

C.R.O. scales X = 1 μS / Div.

Y = 10 V / Div.

Experimental wave-shapes



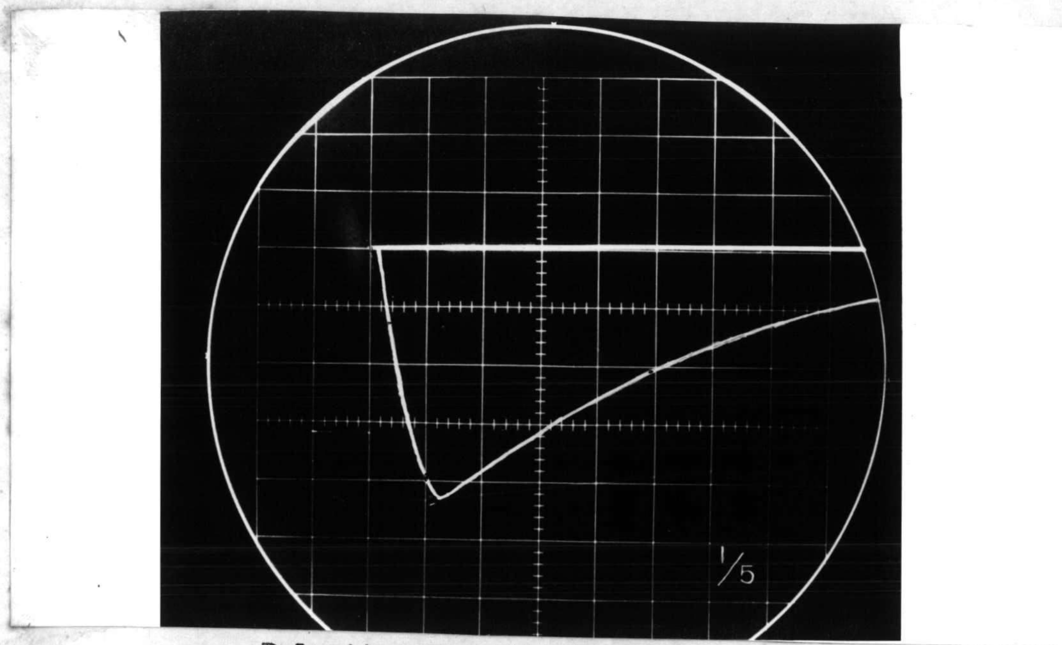
Polarity - positive wave

A. scales X = 1 μS / Div.

Y = 10 V / Div.

Duration of wave front t_1 =1.05 μS.

Time to half value of wave tail t_2 = 5.2 μS.



B.

Polarity - negative wave

Scales $X = 1 \mu S/Div.$

$Y = 10$ V/Div.

Duration of wave front $t_1 = 1.1 \mu S.$

Time to half value of wave tail $t_2 = 4.95 \mu S.$

Fig. 5-10 Experimental Wave-shapes of the calculated impulse circuit of 1/5 wave $u = 0.865\ U_o(\epsilon^{-0.24t} - \epsilon^{-1.78t})$, both positive and negative waves.

Efficiency

Total DC charging voltage 4 x 6 KV = 24 KV

Experimental impulse voltage for

Positive wave = 2 x 95.5 x 43 V = 8.2 KV

Negative wave = 2 x 95.5 x 43 V = 8.2 KV

Therefore

η positive wave = 34.1 %

η negative wave = 34.1 %

Chopped Impulse Voltage

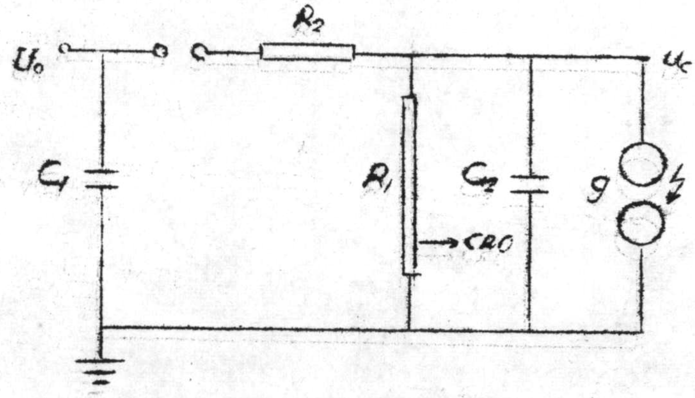


Fig. 5-11 Chopped impulse voltage testing circuit

C_1 = impulse generator capacitance

R_1 = discharging resistance

R_2 = series resistance

C_2 = load capacitance

g = sphere gaps

U_o = charging voltage

u_c = chopped impulse voltage

t_c = Time to chopping

Measurement

Resistance potential divider :

dividing ratio = 95.5

Impulse voltmeter : Multiplying factor = 4

C.R.O. Scales $X = 1\ \mu S/Div.$

$Y = 10\ V / Div.$

Experimental Data

$C_1 = 0.025\ \mu F$

$C_2 = 2000\ pF$

$R_1 = 2400\ \Omega$

$R_2 = 192\ \Omega$

$U_o = 28\ KV$

$u_c = 4 \times 95.5 \times 38\ V$

$= 14.5\ KV$

$t_c = 2.7\ \mu S$

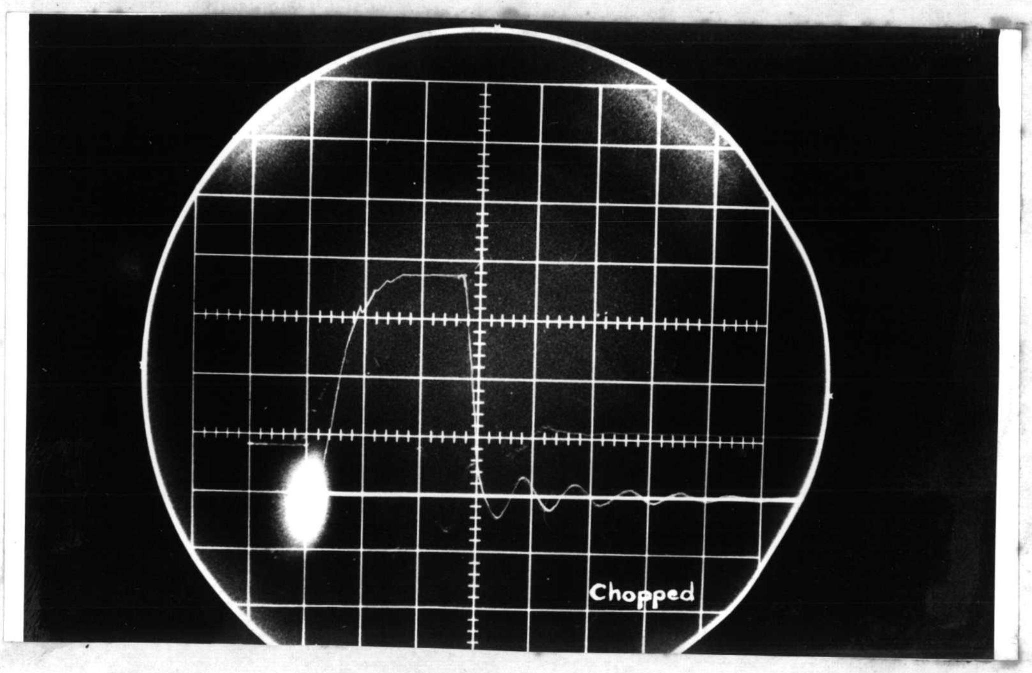


Fig. 5-12 Chopped Impulse Voltage

Voltage Efficiency of the Impulse Generator

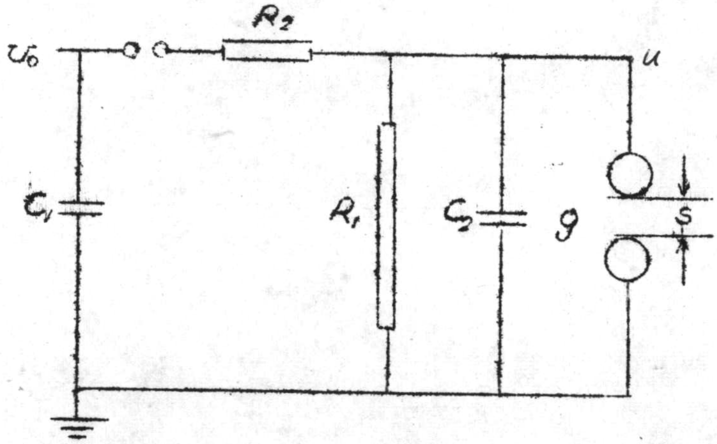


Fig. 5-13 Testing circuit used to find the voltage efficiency

C_1 = Impulse generator capacitance

R_1 = discharging resistance

R_2 = series resistance

C_2 = load capacitance

g = measuring sphere gaps. 25 cm. diameter

U_0 = charging voltage

u_{n} = impulse voltage at standard condition

u = impulse voltage

Kd = air density correction factor

η = voltage efficiency

Experimental Data

C_1 = 0.025 μF

C_2 = 2000 pF

$R_1 = 2400\ \Omega$

$R_2 = 192\ \Omega$

$U_0 = 56$ KV

sparking distance S = 1 cm. 50% Flashover.

polarity = positive

$u_n \approx 31.7$ KV

Air density condition

$p = 767.2$ mm.Hg.

$t = 33.8°C$

$H = 68\%$

$$Kd = \frac{0.386\ p}{273 + t}$$

$$= 0.965$$

$$u_n = \frac{u_n}{Kd} = 32.8\ \text{KV}$$

$$\eta = \frac{U_0}{U_n} = 58.6\ \%$$

Effect of C_1/C_2 Ratio on Wave-front

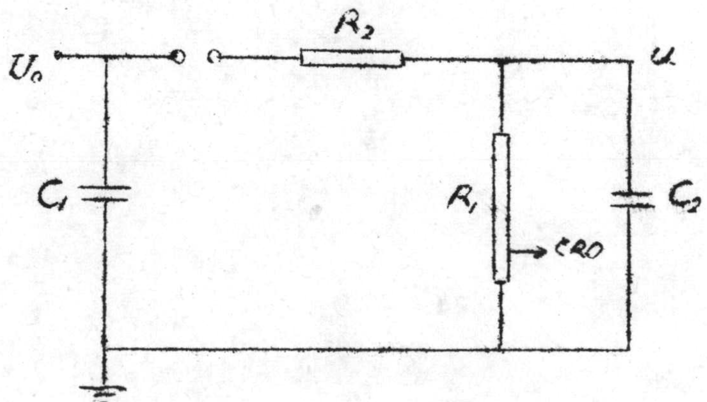


Fig. 5-14 Impulse testing circuit for various load capacitances

C_1 = impulse generator capacitance

R_1 = discharging resistance

R_2 = series resistance

C_2 = load capacitance

$\frac{C_1}{C_2}$ = ratio of generator to load capacitance

U_o = charging voltage

u = impulse voltage

Measurement

Resistance potential divider : dividing ratio = 95.5

Impulse voltmeter: Multiplying factor = 4

C.R.O. Scales X = 1 μS / Div.

Y = 10 V / Div.

Experiment Data

C_1 = 0.025 μF

C_2 = 2000 pF and 4000 pF

R_1 = 2400 Ω

R_2 = 216 Ω

U_o = 27.32 KV

u_1 = 4 x 95.5 x 35 V = 13.4 KV

u_2 = 4 x 95.5 x 32 V = 12.2 KV

$\frac{C_1}{C_2}$ = 12.5, t_1 = 1.2 μS.

$\frac{C_1}{C_2}$ = 6.25 ; t_2 = 2.0 μS.

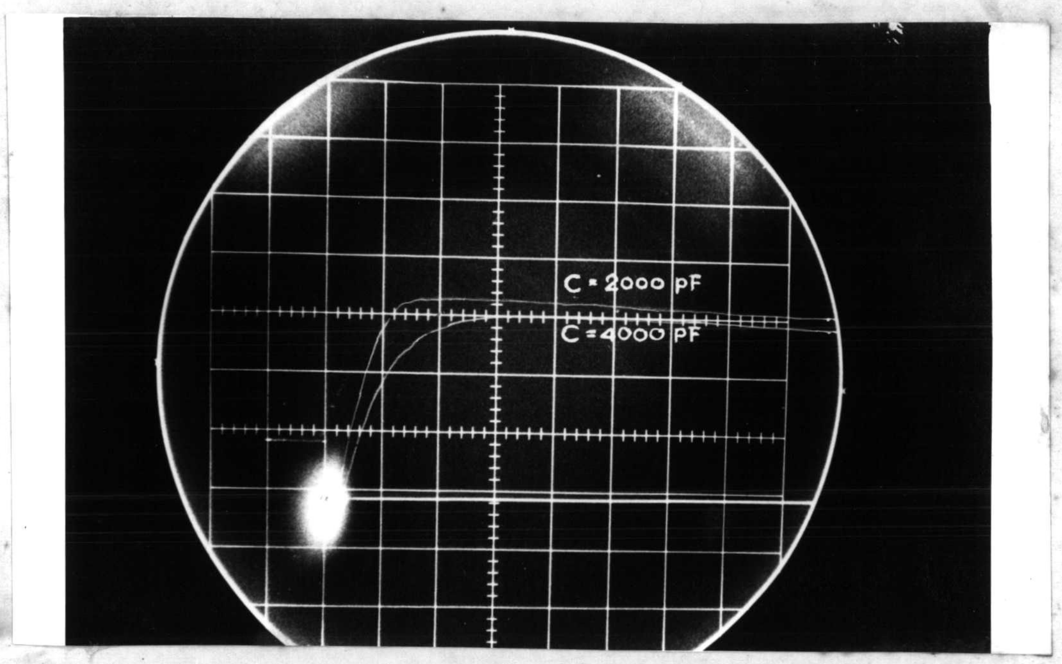


Fig. 5-15 Wave-shapes showing the effect of C_1/C_2 ratio on wave-front

Effect of Included Inductance on Wave-front

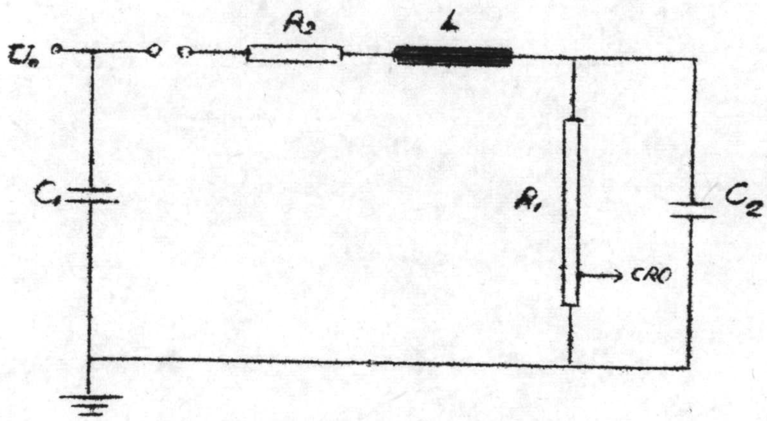


Fig. 5- 16 Impulse testing circuit with included inductance

C_1 = impulse generator capacitance

R_1 = discharging resistance

R_2 = series resistance

C_2 = load capacitance

L = included inductance

U_o = charging voltage

u = impulse voltage

t_1 = duration of wave-front

Measurement

Resistance potential divider : dividing ratio 95.5

Impulse voltmeter: multiply factor = 4

C.R.O. Scales X = 1 μS/Div.

Y = 10 V / Div.

Experimental Data

C_1 = 0.025 μF

C_2 = 2000 pF

R_1 = 2400 Ω

R_2 = 216 Ω

U_o = 27.32 KV

u = 4 x 95.5 x 30 V

= 11.5 KV (average)

L = 5.12 μH ; t_1 = 1.3 μS

L = 7.42 μH ; t_1 = 1.5 μS

L = 12.0 μH ; t_1 = 1.85 μS

L = 15.58 μH ; t_1 = 2.0 μS

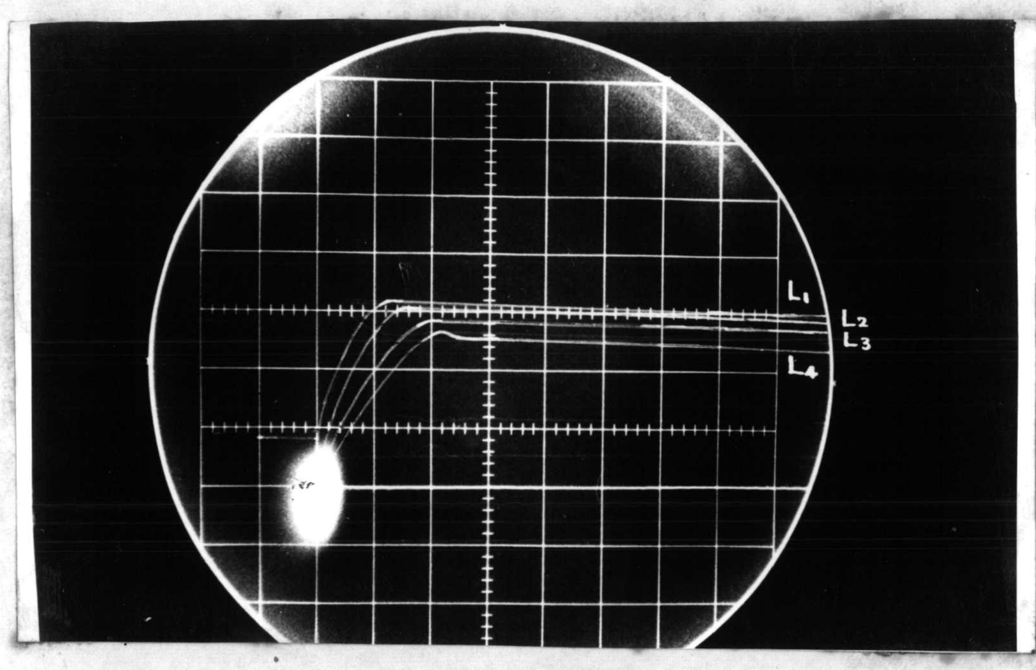


Fig. 5- 17 Wave-shapes showing the effect of included inductance on wave-front

Discussions and Conclusions

The discussions and conclusions can be stated as follow :-

1. The parameters R and C of the impulse circuits are obtained by the graphical method. The calculated wave shapes, which are compared to the standard wave shapes, are given below.

Figures	Standard waves		Calculated waves		Errors	
	t_1 (μS)	t_2 (μS)	t_1 (μS)	t_2 (μS)	t_1 (%)	t_2 (%)
5-3	1.0	50.0	1.02	46.8	2.0	6.4
5-6	1.5	40.0	1.50	40.26	0	0.65
5-9	1.0	5.0	1.0	5.0	0	0

But a tolerance of not more than ± 30 % on t_1 and ± 20% on t_2 is allowed, so that, the graphical method is satisfied in thisthesis.

2. In figures 5-4, 5-7 and 5-10, the experimental wave shapes are obtained without any oscillation. The errors, compared to the standard wave shapes, are given as:

Figures	Standard waves		Experimental waves				Errors			
			Positive		Negative		Positive		Negative	
	t_1 (μS)	t_2 (μS)	t_1 (μS)	t_2 (μS)	t_1 (μS)	t_2 (μS)	t_1 (%)	t_2 (%)	t_1 (%)	t_2 (%)
5-4	1.0	50.0	1.0	53.0	1.2	53.0	0	6.0	20.0	6.0
5-7	1.5	40.0	1.53	45.0	1.45	46.0	2.0	12.5	3.3	15.0
5-10	1.0	5.0	1.05	5.2	1.1	4.95	5.0	4.0	10.0	1.0

The errors are within the allowed tolerance.

3. The comparisons of the experimental wave shapes (dotted lines) to the calculated wave shapes (full lines) are also shown in figures 5-3, 5-6 and 5-9. The differences of the times t_1, t_2 and of the voltage efficiencies between them

are well shown in table below:-

Figures	Calculated waves			Experimental waves					
				Positive			Negative		
	t_1 (μS)	t_2 (μS)	η (%)	t_1 (μS)	t_2 (μS)	η (%)	t_2 (μS)	t_2 (μS)	η (%)
5-3, 4	1.02	46.8	85.6	1.0	53.0	56.25	1.2	53.0	56.25
5-6, 7	1.50	40.26	78.9	1.53	45.0	50.0	1.45	46.0	50.0
5-9, 10	1.0	5.0	54.7	1.05	5.2	34.1	1.1	4.95	34.1

The values of t_1 and t_2 for both positive and negative waves of the experimental data are slightly different from that of the calculated data; because the self inductance and the stray capacitance of the whole impulse circuit effect the wave shapes of the impulse voltages. In addition, the performance of the experiments may result some errors.

4. As in 3; the voltage efficiencies obtained by the experimental data are lower than that obtained by the calculated data. Because the voltage efficiencies are limited by the self inductance and the stray capacitance which tend to lower the peak value of the impulse voltages; and they are limited by voltage drops in the high resistors and connecting leads between the various components of the circuits. The high resistors are the series or damping resistor and the resistor divider. Sometimes, the voltage efficiencies may be limited by the attenuation of the delay cable.

5. The measuring sphere gaps with 25 cm. in diameter is used in recording the output impulse voltage should be avoided in this thesis; since the sparking distance of these gaps is at least 1 cm., and the value of impulse voltage, from Appendix III; is 31.7 KV. higher than that (23 KV.) of the generator. Therefore the charging voltage of the stage capacitors will be increased to 14 KV. in

order to give 50% flashover voltage at the gaps. This 14-KV. charging voltage may damage these stage capacitors. However, the voltage efficiency is obtained to be 58.6%.

6. In figure 5-12, the chopped impulse voltage is obtained, by means of the spark gaps. The impulse voltage is chopped on the wave-tail; and the time to chopping is $t_3 = 2.7\mu S$.

7. In figure 5-15, with varying the load capacitance C_2, 2000 pF and 4000 pF, compares to the generator capacitance C_1, $0.025\mu F$. Both the duration of wave-front (t_1) and the magnetude of the peak value of the impulse voltage ($\bar{u}$) are slightly varied corresponding to the decreasing ratio of C_1/C_2. That is, for a constant $U_o = 27.32$ KV; when the ratio C_1/C_2 is 12.5, $t_1 = 1.2\mu S$. and $\bar{u} = 13.4$ KV; but when the ratio C_1/C_2 is reduced to 6.25, $t_1 = 2.0\mu S$. and $\bar{u} = 12.2$ KV.

8. In figure 5-17, with varying the series inductance L, the durations of the wave-front (t_1) of the impulse voltage have nominal values for slightly different values of L; but the magnetude of the peak value of the impulse voltage ($\bar{u}$) varies little for the chosen range of L, for $U_o = 27.32$ KV. constant, $\bar{u}$ is 11.5 KV average. With L varies from 5.12, 7.42, 12.0 and 15.58 μH., t_1 varies from 1.3, 1.5, 1.85, and 2.0μS. respectively. All the waves are obtained without oscillation. The critical oscillating condition is given by $R_2 \geqslant \sqrt{\frac{4L}{C}}$, for $R_2 = 215\,\Omega$, $C = \frac{C_1 C_2}{C_1 + C_2} = 0.00185\,\mu F$, $L \leqslant 21.6\,\mu H$.

9. In taking oscillagrams, the author uses the 400 ASA film in recording the experimental wave-shapes from the C.R.O., the wave-front is not clear enough in the negative film, and it gets lost in the positive oscillogram. In this case, it is, for the author, better to rely on a hand-drawn reproduction in

order to obtain the clear oscillogram. In other case, the polaroid film of 3000 ASA is used, but this 3000 ASA poloroid is now absent from the market.

10. As a straight forward, the author likes to suggest ones who might study this generator to set the series inductance to a high value, so that the wave will oscillate, and then to vary the series resistance until the oscillation is damped out. Also ones would vary the discharging resistance and study its effect on the wave-tail of the impulse voltage. In applications, ones should test any insulation by the impulse voltages of this generator in order to study the characteristics of the insulations.

APPENDIX I

A List of Impulse Wave Constants for waves of The General Form

$$u = \frac{U_o}{K} \frac{1}{p_2 - p_1} \left(\epsilon^{-p_1 t} - \epsilon^{-p_2 t} \right)$$

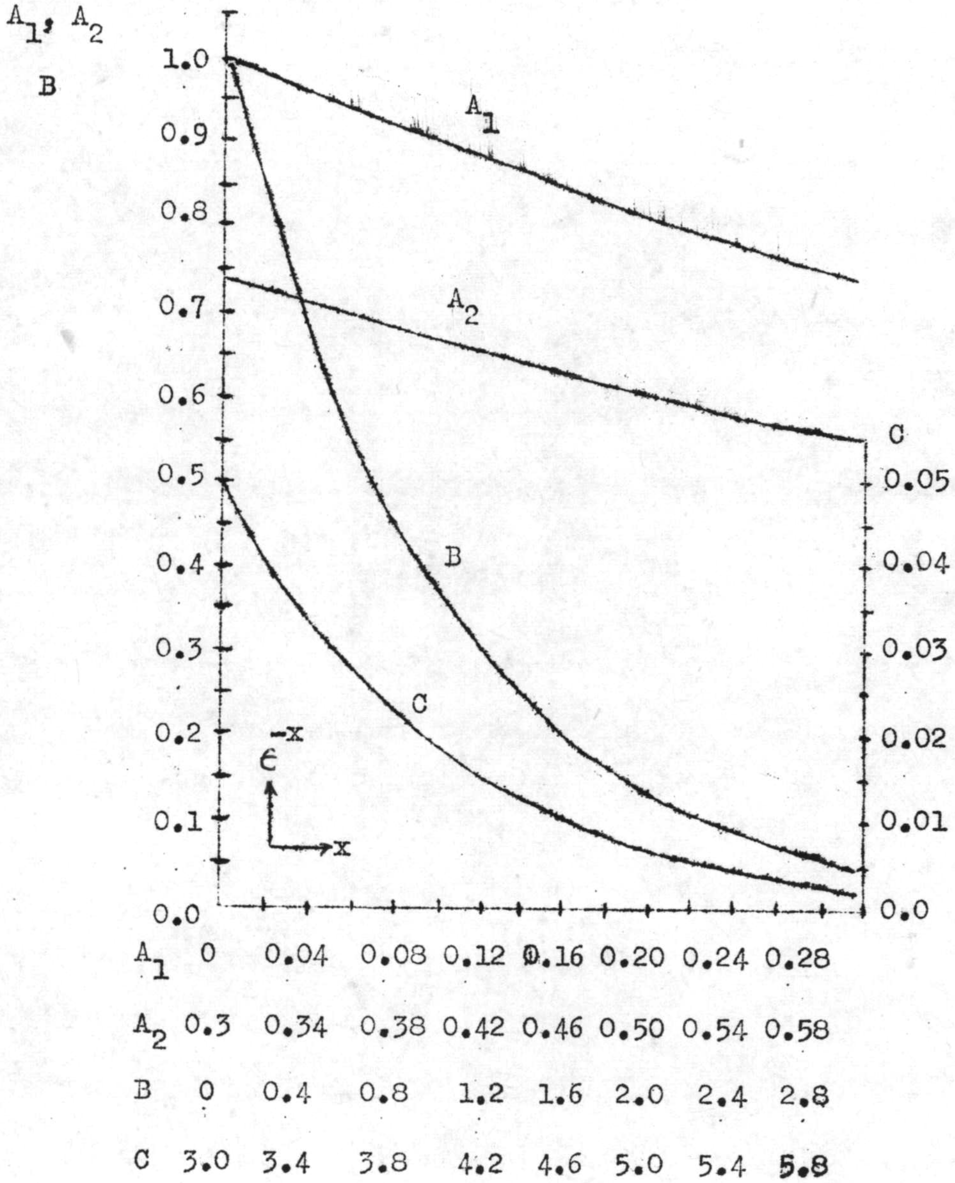
$\frac{t_1}{t_2}$ wave	$\alpha\theta_1$	θ_2	p_1	p_2
$\frac{0.5}{5}$	2.41	0.87	0.174	4.82
$\frac{1}{5}$	1.78	1.20	0.240	1.78
$\frac{1}{10}$	2.41	0.87	0.087	2.41
$\frac{1.5}{40}$	2.80	0.74	0.185	1.87
$\frac{1}{50}$	2.96	0.73	0.0146	2.96

The values of K depend on the circuit parameters R, L, and C of the various impulse testing circuits.

The waves conform to IEC regulations, i.e. the fronts of the waves are 1.67 times the time taken for the voltage to rise from 30 per cent to 90 per cent of the peak values.

APPENDIX II

Values of ϵ^{-x} for the plotting of Impulse Waves



APPENDIX III[24]

Breakdown Voltages in KV (peak) of Sphere-gap in air at 20°C and 760 mm of Hg barometric pressure, for <u>Negative</u> impulse voltages; one sphere earthed

Sphere gap spacing cm.	Sphere diameter (cm.)											
	2	5	6.25	10	12.5	15	25	50	75	100	150	200
0.05	2.8											
0.10	4.7											
0.15	6.4											
0.20	8.0	8.0										
0.25	9.6	9.6										
0.30	11.2	11.2										
0.40	14.4	14.3	14.2									
0.50	17.4	17.4	17.2	16.8	16.8	16.8						
0.60	20.4	20.4	20.2	19.9	19.9	19.9						
0.70	23.2	23.4	23.2	23.0	23.0	23.0						
0.80	25.8	26.3	26.2	26.0	26.0	26.0						
0.90	28.3	29.2	29.1	28.9	28.9	28.9						
1.00	30.7	32.0	31.9	31.7	31.7	31.7	31.7					
1.20	(35.1)	37.6	37.5	37.4	37.4	37.4	37.4					
1.40	(38.5)	42.9	42.9	42.9	42.9	42.9	42.9					
1.50	(40.0)	45.5	45.5	45.5	45.5	45.5	45.5					
1.60		48.1	48.1	48.1	48.1	48.1	48.1					
1.80		53.0	53.5	53.5	53.5	53.5	53.5					
2.00		57.5	58.5	59.0	59.0	59.0	59.0	59.0	59.0			
2.20		61.5	63.0	64.5	64.5	64.5	64.5	64.5	64.5			
2.40		65.5	67.5	69.5	70.0	70.0	70.0	70.0	70.0			
2.60		(69.0)	72.0	74.5	75.0	75.5	75.5	75.5	75.5			
2.80		(72.5)	76.0	79.5	80.0	80.5	81.0	81.0	81.0			
3.00		(75.5)	79.5	84.0	85.0	85.5	86.0	86.0	86.0	86.0		
3.50		(82.5)	(87.5)	95.0	97.0	98.0	99.0	99.0	99.0	99.0		
4.00		(88.5)	(95.0)	105	108	110	112	112	112	112		
4.50			(101)	115	119	122	125	125	125	125		
5.00			(107)	123	129	133	137	138	138	138	138	
5.50				(131)	138	143	149	151	151	151	151	
6.00				(138)	146	152	161	164	164	164	164	

Note : The figures in brackets, which are for spacings of more than 0.5 D, are of doubtful accuracy.

APPENDIX III

Breakdown Voltages in KV (peak) of Sphere-gap in air at 20°C and 760 mm of Hg barometric pressure, for <u>Positive</u> impulse voltages; one sphere earthed

Sphere gap spacing (cm.)	Sphere diameter (cm.)											
	2	5	6.25	10	12.5	15	25	50	75	100	150	200
0.05												
0.10												
0.15												
0.20												
0.25												
0.30	11.2	11.2										
0.40	14.4	14.3	14.2									
0.50	17.4	17.4	17.2	16.8	16.8	16.8						
0.60	20.4	20.4	20.2	19.9	19.9	19.9						
0.70	23.2	23.4	23.2	23.0	23.0	23.0						
0.80	25.8	26.3	26.2	26.0	26.0	26.0						
0.90	28.3	29.2	29.1	28.9	28.9	28.9						
1.00	30.7	32.0	31.9	31.7	31.7	31.7	31.7					
1.20	(35.1)	37.8	37.6	37.4	37.4	37.4	37.4					
1.40	(38.5)	43.3	43.2	42.9	42.9	42.9	42.9					
1.50	(40.0)	46.2	45.9	45.5	45.5	45.5	45.5					
1.60		49.0	48.6	48.1	48.1	48.1	48.1					
1.80		54.5	54.0	53.5	53.5	53.5	53.5					
2.00		59.5	59.0	59.0	59.0	59.0	59.0	59.0	59.0			
2.20		64.0	64.0	64.5	64.5	64.5	64.5	64.5	64.5			
2.40		69.0	69.0	70.0	70.0	70.0	70.0	70.0	70.0			
2.60		(73.0)	73.5	75.5	75.5	75.5	75.5	75.5	75.5			
2.80		(77.0)	78.0	80.5	80.5	80.5	81.0	81.0	81.0			
3.00		(81.0)	82.0	85.5	85.5	85.5	86.0	86.0	86.0	86.0		
3.50		(90.0)	(91.5)	97.5	98.0	98.5	99.0	99.0	99.0	99.0		
4.00		(97.5)	(101)	109	110	111	112	112	112	112		
4.50			(108)	120	122	124	125	125	125	125		
5.00			(115)	130	134	136	138	138	138	138	138	
5.50				(139)	145	147	151	151	151	151	151	
6.00				(148)	155	158	163	164	164	164	164	
6.50				(156)	(164)	168	175	177	177	177	177	
7.00				(163)	(173)	178	187	189	190	190	190	
7.50				(170)	(181)	187	199	202	203	203	203	
8.00					(189)	(196)	211	211	214	215	215	
9.00					(203)	(212)	233	239	240	241	241	

Note : The figures in brackets, which are for spacings of more than 0.5 D, are of doubtful accuracy.

APPENDIX IV

Matching of the Delay Cable

It is essential to terminated a delay cable with the right value of resistance in order to suppress successive reflection. The matching resistance must be equal to the surge impedance of the cable.

The surge impedance Z may be regarded as being equal to $\sqrt{L/C}$. Where the inductance and capacitance per cm. length for concentric cylinders are

$$C = K\left\{\left\{2\ \ln (R_2/R_1)\right\} 9 \times 10^{11}\right\} \text{ farads/cm.}$$

$$\text{and} \quad l = \left\{2\ \ln (R_2/R_1) + \frac{1}{2}\right\} \times 10^{-9} \quad \text{henrys/cm.}$$

where K is the permitivity of the medium between the cylinders,

R_2 is the internal diameter of the outer cylinder

and R_1 is the external diameter of the inner cylinder.

Then the surge impedance which is independent of length can be writter

$$Z = \sqrt{l/c}$$

$$= \sqrt{2\ \ln (R_2/R_1)^{\,2} \times 9 \times 10^{-2}/K}$$

$$= \frac{60\ \ln (R_2/R_1)}{K}$$

Note that, the 1/2 term in the inductance formula is omitted, and the frequency of impulse waves is high so that they travel along the surfaces of the conductors.

The natural oscillation frequency of the delay cable will be

$$f = 1/2\pi LC \quad \text{Hz.}$$

where L and C are the total inductance and total capacitance of the delay cable respectively.