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Exploding Foils and their Application to Magnetically Driven Flier Plates

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discussion within AWRE
and does not necessarily represent
the final views of AWRE or of SSWA Division

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1 INTRODUCTION

Conventional dynamic structural loading methods use pulsed magnetic fields to impulse structures directly, or by means of an intermediate flier foil. The capability of the methods can be extended by using exploding foils to shape the current that forms the magnetic field. Two circuit applications, the crowbar switch and dynamic damping resistance, are detailed and their use in pulse shaping is illustrated.

2 IMPULSE METHODS FOR STRUCTURAL EXPERIMENTS

The use of high speed condenser banks (Ref. 1, 2) is established as a routine technique fof investigating the dynamic response of structures. (Ref. 3, 4, 5). Two methods of applying the impulse to the structure have been utilised:

1 Impact - by a thin flying foil accelerated by magnetic pressure.

2 Push - when the structure is impulsed directly by a time-varying magnetic field without the intermediate flying foil.

In most dynamic structural investigations the magnitude of the applied impulse is the most important parameter. However, in certain applications the shape and duration of the pressure pulse which forms the impulse is also of importance.

To use the full potential of the two impulse methods it is desirable that the variance of magnetic pressure that either drives the flier foil or directly impulses the structure be fully controllable as a function of time. Normally the condenser bank, feed area, and load coil form a lightly damped LCR circuit (Fig. 1). The current flowing through the load is oscillatory and falls to an insignificant level in a few cycles. The magnetic pressure which does work in the load area is proportional to the square of the current and is thus a series of decaying pulses, each of approximately $\sin^2 \omega t$ shape. The impulse builds up progressively to its terminal value over several cycles.

To alter this shape a dynamic circuit element must be introduced into the LCR circuit which either diverts current into alternative routes at a required time or whose impedance varies as a function of time to change circuit damping and so gives the required waveform. A dynamic circuit element which is able to achieve some of these objectives is an exploding foil. Over a period of several years their properties have been applied in this laboratory to realise desired applications in pulse shaping. Also by using them for clamping the load area at peak current, the energy imparted to a flying foil may be considerably increased. This technique also has the advantage that the bank condensers do not experience any significant voltage reversal and may be used at higher streeses, again increasing the energy delivered to the structure.

This document presents the necessary background phenomena related to exploding foils and discusses applications which have been found useful in dynamic structural experiments.

TABLE I
THERMODYNAMIC AND ELECTRICAL PROPERTIES OF METALS

Material	Resistivity ($\mu\Omega$/cm)		Energy (kJ/cc)				Slope	
	ρ_o	ρ_1	ε_o	ε_1	ε_L	$\varepsilon_1 + \frac{\varepsilon_L}{3}$	$\frac{\varepsilon_o}{\rho_o}$	$\frac{\varepsilon_1}{\rho_1}$
Aluminium	2.7	37	.47	7	28	16	.17	.19
Copper	1.7	34	.71	12	48	28	.42	.35
Gold	2.35	55	.58	9	36	21	.25	.16
Iron	9.7	270	.62	18	53	36	.064	.067
Tungsten	5.65	190	.51	24	95	56	.09	.125
Tantalum	15.5		.86	(23)	114	61	.055	
Molybdenum	5.7		.43	20	56	39	.075	
Lead	22		.37	3	10	6.6	.017	
Silver	1.6		.56	7.8	25	16	.35	

where ρ_o = resistivity at room temperature
ρ_1 resistivity just below boiling
ε_o internal energy at room temperature
ε_1 internal energy just below boiling
ε_L latent energy of vaporisation

Both Fig. 2 and Table I show the approximate validity of the assumed relationship. For a given material the ratios of resistivity and internal energy are in most cases similar at room temperature and just below the boiling point, but for the purpose of calculation of action integral, where minor discrepancies exist in these mean values then, when it is available, the shape at the elevated temperature has been used. This estimates the higher dominant resistivities better and is not badly in error for low values.

It will be seen that the exact form of relationship one uses when evaluating action integral is not over-critical. The precision of the answer is only weakly dependent on the form of the law.

3.3 CALCULATION OF ACTION INTEGRAL

The incremental increase in energy $d\mathcal{E}$ per unit volume when a current i passes through a foil of cross sectional area A for time dt is given by

$$d\varepsilon = \frac{i^2\rho}{A^2} \cdot dt.$$

Integrating to a final energy condition $\mathcal{E}$ at time t

$$\int_{\varepsilon_o}^{\varepsilon} d\varepsilon = \int_{o}^{t} \frac{i^2\rho}{A^2} \cdot dt.$$

Using the electrical equation of state and rearranging:

$$\int_{\varepsilon_o}^{\varepsilon} \frac{d\varepsilon}{\varepsilon} = \left(\frac{\rho_1}{\varepsilon_1} \right) \int_{o}^{t} \frac{i^2}{A^2} \cdot dt .$$

Therefore

Action Integral

$$g_t = \int_{o}^{t} \frac{i^2}{A^2} \cdot dt$$

$$= \left\{ \frac{\varepsilon_1}{\rho_1} \right\} \text{Ln} \frac{\varepsilon}{\varepsilon_o} .$$

This relationship allows calculation of the action integral at any required energy level. In Table II it is evaluated for the time when the energy content is sufficient to vaporise one third of the foil and is compared with experimental values.

The reasonable agreement between measured and calculated values indicates that the approximate 'electrical equation of state' is adequate. The presumed 'one third vaporised' end condition at blow up is a little more nebulous, the action integral being rather insensitive to the degree of vaporisation.

The measured action integrals could be sensitive to the rate at which the foil is blown. It is possible that the results would not hold for slower bank systems and it is conceivable they could be in error for faster systems also. However, they form a good guide to values to be expected from condenser bank foil throwing systems now in use.

TABLE II

COMPARISON OF THEORETICAL AND EXPERIMENTAL ACTION INTEGRALS

Material	$g = \frac{\varepsilon_1}{\rho_1} \text{ Ln } \frac{\varepsilon + \frac{\varepsilon_L}{3}}{\varepsilon_0}$ (amp^2 sec cm^{-4})	
	Theoretical	Measured
Aluminium	6.7×10^8	6×10^8
Copper	13	14
Gold	5.8	
Iron	2.7	3
Tungsten	5.9	
Tantalum	2.4	4
Molybdenum	3.4	2.8
Lead	0.5	0.76
Silver	12	

3.4 MEASUREMENT OF ACTION INTEGRAL

Measurements of action integral were made using a BICC, Model ES108, 28µF capacitor charged to 22 kV and discharged through a series foil.

The system comprised the capacitor, a brass strip line current monitor, a solid dielectric start switch, and the foil with an attached voltage monitor. The complete discharge path was in strip line geometry to give low inductance and a short time period. Care was taken with the voltage monitor which comprised a resistive attenuator with leads arranged to measure the resistive voltage 'IR' and eliminate the inductive term '$L\,{}^{di}/_{dt}$'. The signals were recorded on low sensitivity mains isolated oscilloscopes.

Fig. 3 shows current and voltage waveforms obtained from some of the experiments. Table III gives materials and sizes of the foils exploded, as well as the measured values for the action integral at blow up, this being evaluated from the current waveform by squaring and integrating.

TABLE III

FOIL SIZES FOR ACTION INTEGRAL MEASUREMENT

Material	Length (cm)	Width (cm)	Thickness (cm)	Action Integral (amp^2 sec cm^{-4})
Aluminium	6	2.0	.0053	6.0×10^8
Copper	6	2.0	.0030	13.7
Brass	6	2.0	.0058	6.2
Steel	6	2.0	.0058	3.0
Tantalum	6	1.6	.0060	4.0
Molybdenum	6	0.9	.0081	2.8
Nichrome	3	0.6	.0135	4.5
Lead	3	0.45	.0228	0.76

The waveforms indicate how the current is interrupted when the foil explodes and how the voltage spike appears across the foil as its resistance initially increases, until restrike occurs, causing it to collapse again.

4 THE EXPLODING FOIL AS A CIRCUIT ELEMENT

Two applications of the exploding foil are described, the switch, and the dynamic damping resistance. It is then shown how they can be used together or in isolation to produce useful current waveforms.

4.1 THE CROWBAR SWITCH

The high energy densities associated with the blow up phenomena can be used to achieve a switching action by mechanically rupturing insulation.

The switch possesses

1 High reliability

2 Multi-channel or continuous line operation, to avoid excessive resistance and damage

3 Precise delay time until operation

4 Manufacturing simplicity.

Figs. 4 and 5 show the manner in which the crowbar switch is constructed and how it functions. Initially, the complete load current flows through the crowbar foil, which in the application described is 0.2" thou. thick, 0.2 cm long and 15 cm wide. This makes a volume of 1.55×10^{-3} cm^3 which will require 25 joules to explode and following this, more energy will be fed into the vapour. however, usually the stored electrical energy in the bank is many kilojoules, so maximum load energies or currents are not significantly affected by the inclusion of the crowbarring foil. As the complete load current must flow through the foil, it has no alternative but to explode at the position on the waveform determined by its cross-section. This assumes that care has been taken to achieve a good contact between the exploding foil and feed conductors, or local contact areas of the foil may explode early, to give premature switching.

Once the foil has exploded, the high energy density produced must be efficiently used to rupture the insulation between the high tension and earth conductor. This is achieved by careful attention to planarity when assembling the switch and by filling any minor residual air voids with silicone oil. The foil is then contained so as the only way the high pressure zone can relieve is by fracture of the main insulation. To guarantee fracture occurs rapidly, the insulation chopping mechanism is designed so that the degree of system expansion when the insulation breaks is minimised. The small 2 mm diameter holes give rupture after 0.3 µs, whereas an earlier system using 25 mm holes took 2.5 µs. Thus small chopping holes or slots seem to be an essential design feature, although the manner in which they operate is not fully understood.

In one experiment the velocity of the mylar ejected from the crowbar switch was checked by impacting it upon a 1 mm thick brass plate. A short duration pressure pulse was set up in the brass plate, which upon reflection from the free surface created a spall line along the far side of the plate. The spall damage was estimated to have been consistent with impact from mylar travelling at about 0.6 mm/µs. This represents a kinetic energy of ~ 10 joules/cm^2 in the ejected mylar. At this velocity the mylar has moved through a distance equivalent to its thickness in 300 ns, which accounts for the mechanical delay time. The figure of 10 joules/cm^2 represents good coupling of energy from the exploding foil.

When switching fast systems, an allowance must be made for rupture time and the foil must be exploded correspondingly earlier in the waveform. The time at which the foil will explode can be calculated in advance. As maximum currents are not affected by the inclusion of the foil, then the shape of the first half cycle of bank current is approximately given by:

$$i = i_{max} \sin \omega t$$

where $i_{max} = 1.08 \frac{V}{R+Z}$

V = charging voltage
R = circuit resistance
$Z = \sqrt{\frac{L}{C}}$, circuit impedance

Integrating this current waveform will give the action integral at any time.

$$\int_0^t i^2 dt = \frac{i_{max}^2}{2} \left\{ t - \frac{\sin 2\,\omega t}{2\omega} \right\}$$

As $\int_0^t i^2 dt = g_t A^2$ and $\omega = \frac{2\pi}{T}$

Then $$f\left(\frac{t}{T}\right) = \frac{2\, g_t A^2}{i_m^2 T} = \left\{ \left(\frac{t}{T}\right) - \frac{\sin 4\pi \left(\frac{t}{T}\right)}{4\pi} \right\}$$

This non-dimensional function is plotted in Fig. 6 as well as the form of the first half cycle of current.

The position in the current cycle at which one wishes to switch specifies the value of $f\left(\frac{t}{T}\right)$; from this parameter and values for g_t , i_m and T, the cross-section A can be calculated which will give switching at the required time When the current peaks, $f\left(\frac{t}{T}\right)$ is changing rapidly , considerable errors in estimating cross sectional area do not radically affect switching time. Thus switching at maximum current is easy. By contrast, $f\left(\frac{t}{T}\right)$ changes slowly at current zeros, making precise switching at zero current difficult. It is more suitable to use dynamic damping, discussed in the next section, to achieve this waveform.

As an example of the use of Figure 6, consider the problem: What aluminium foil cross section will explode 0.3 μs before peak current, given

Current max I_M = 2.6 M.amps

Period T = 6.0 μs

Action integral $g = 6 \times 10^8$. $amp^2\ sec\ cm^{-4}$.

Required switching time t = 1.2 μs

Therefore $\frac{t}{T} = 0.20$

and, using Fig. 6, $f\left(\frac{t}{T}\right) = 0.15$

Therefore $\frac{2gA^2}{i_M^2 T} = 0.15$

Substituting values $A = 7.25 \times 10^{-2}\ cm^2$.

In practical terms this would be a 0.4 thou. aluminium foil, 28" wide.

Once the switch has operated, it is important that its resistance be low. This is achieved by creating many current paths along the switch width and by allowing the gaseous switch products to expand. The switch electrodes, however, must be weighted to avoid disassembly. Measurements of the L/R decay time after crowbar indicate that the switch resistance is a fraction of a milli-ohm.

Other methods of crowbar switching were tried in the evaluation of the present system and these are detailed for completeness. Initially, the foils were exploded by separate crowbar banks, but this was a complex and less reliable system. A satisfactory development was to divert a fraction of the load current through the crowbar foils, using a suitable inductor attached downstream of the main start switch. This system was shown to function reliably. In the present method the total current, rather than just a fraction of it, flows through the crowbar foils. This dispenses with the added inductors and makes assembly of the switch easier. Also as $\int i^2 dt$ is larger, a bigger cross-section of foil can be exploded, giving the option of higher energy densities behind the driven insulant.

4.2 DYNAMIC DAMPING

An easy method of modifying the standard oscillatory LCR waveform to give increased damping, or a unidirectional current pulse, is to include a series foil. The advantage of using a series foil to increase damping rather than add passive resistance is that the foil resistance increases as a function of time. This gives a desirable condition by preferentially damping the late oscillations while not radically affecting the current amplitude on the first half cycle.

The foil cross section and length determine when the foil increases in resistance and how much energy it removes from the circuit. The foils used must be longer than the crowbar ones to avoid restrike and, in contrast to them, use significant amounts of bank energy. As this reduces achievable current and impulse levels, their application is limited to areas where bank energy is not restricted.

Prediction of the precise shape of foil required for a particular application is difficult, as the time varying foil resistance dominates the circuit. Approximate solutions can be achieved by numerical integrations of the LCR equation, using the electric equation of state to predict the time varying foil resistance. For an experimentally orientated group, the best approach is to achieve the desired waveform by experiment, using systems with scaled electrical parameters and foil sizes. The experiments, being simple, require little time and two or three taking half an hour are generally adequate to converge on a required solution.

4.3 SHAPING HIGH CURRENT WAVEFORMS

Current waveforms that can be obtained using the crowbar switch, the dynamic damping resistance, and a combination of the two, are shown in Fig. 7, with the circuits that achieved them. The first record shows the normal oscillatory situation. By crowbarring at peak current this can be modified to achieve the second record, a fast rising pulse with a long exponential tail. The next two records show how this tail can be shortened by including a further foil to give added damping (crowchop). The final record illustrates how a short duration current pulse is achieved by dynamic damping alone.

For structural experiments these pulses provide a range of durations and shapes which, when used in the magnetic push mode, supplement the short duration flier impact pulses. Pulse durations are typically 1 - 10 µs with pressure levels in the region of 1 k-bar. The pulses are unidirectional and avoid the disadvantage of the succession of decaying pressure pulses produced by the normal oscillatory current waveform.

In the impact mode the shaping techniques can also be used to avoid current flow in the flier foil after collision with the target.

When bank energy is at a premium, crowbarring increases efficiency by short circuiting the load at peak current. Removing the bank and feed resistance from the circuit increases the energy transfer to the load. It also protects the bank by avoiding a large voltage reversal and the very fact that the bank voltage does not reverse allows it to be charged to a higher value initially, giving more available energy.

5 IMPULSE LIMITS FOR FLYING FOILS

The electrical limits in flying foil thickness are clarified by exploding foil theory (Ref. 7).

When a target is given an impulse by foil impact, the pressure/time profile required in the target to some extent specifies the flier thickness and material. However, there are electrical limitations which put constraints on thickness also, for with thin fliers there is a possibility that the drive current levels could be such that the flier would melt. This undesirable event occurs when the action integral achieves a value corresponding to the melting energy level.

It can be shown that the magnetic impulse given to the flying foil is also specified by the same action integral, so a limiting value of impulse can be defined above which the foil melts.

$$\text{Impulse } I = \int p.dt \quad \text{(Bars x µs)}$$

$$= .02\pi\, d^2 \int_0^t \frac{i^2 dt}{A^2} \quad \text{(taps)}$$

$$= .02\pi\, d^2 g_t$$

where d = foil thickness
g_t = action integral.

The action integrals for copper and aluminium at the onset of melting are calculated in the table below.

TABLE IV

ACTION INTEGRALS AT MELTING

	Electrical Equation of State $\left(\frac{\varepsilon_1}{\rho_1}\right)$	Energy Ratio at Onset of Melting $\left(\frac{\varepsilon_t}{\varepsilon_o}\right)$	Action Integral $g_t = \left(\frac{\varepsilon_1}{\rho_1}\right) \mathrm{Ln} \left(\frac{\varepsilon_t}{\varepsilon_o}\right)$ (amps^2 sec cm^4)
Aluminium	$.19 \times 10^9$	3.9	2.6×10^8
Copper	$.35 \times 10^9$	6.1	6.3×10^8

Using these values, the impulse limits are plotted in Fig. 8 as a function of flier thickness. For combinations above the material line the foils will melt; below the line they will remain solid.

6 CONCLUSION

The elegance of using exploding foils to shape high current waveforms has been demonstrated. The fast acting, low inductance crowbar switch described provides

i a range of unidirectional pressure pulses for dynamic testing of structures in the push mode;

ii greater efficiency in either the impact or the push mode.

Also, by use of a subsidiary dynamic damping foil, further current waveform control is possible.

7 ACKNOWLEDGMENTS

J C Martin has constantly guided and encouraged our efforts with exploding foils. Many of the applications presented are derived from his concepts and any progress we have made has been entirely due to our many unsuccessful attempts to prove him wrong.

8 REFERENCES

1 D W Forster, J C Martin. 'Megagauss from a Capacitor Discharge'. Proc. of the High Magnetic Field Conference, pp. 361-370, September 1966.

2 J C Martin, A MacAulay: 'A Fast Cheap Megajoule Bank'. 5th Symposium on Fusion, Technology, Paper 33. St. Catherine's College, Oxford, July, 1968.

3 R Bealing. 'Impulsive Loading of Circular Rings. Proc. of 11th Symposium of Experimental Mechanics, pp 15-26, University of New Mexico, February 1971.

4 D G House. 'The Plastic Deformation of Simple Rings by Impulsive Loading'. SWAN 9/70.

5 H C Walling, M J Forrestal, W K Tucker. 'An Experimental Method for Impulsively Loading Ring Structures'. Sandia Laboratories. SC-DC-713931.

6 A R Bryant. 'Skin Effectsat High Field Intensities - I.' CON 1/62.

7 E C Cnare. 'Magnetic Flux Compression by Magnetically Imploded Metallic Foils'. JAP, Vol 37, No. 10, pp.3812-3816, September, 1966.

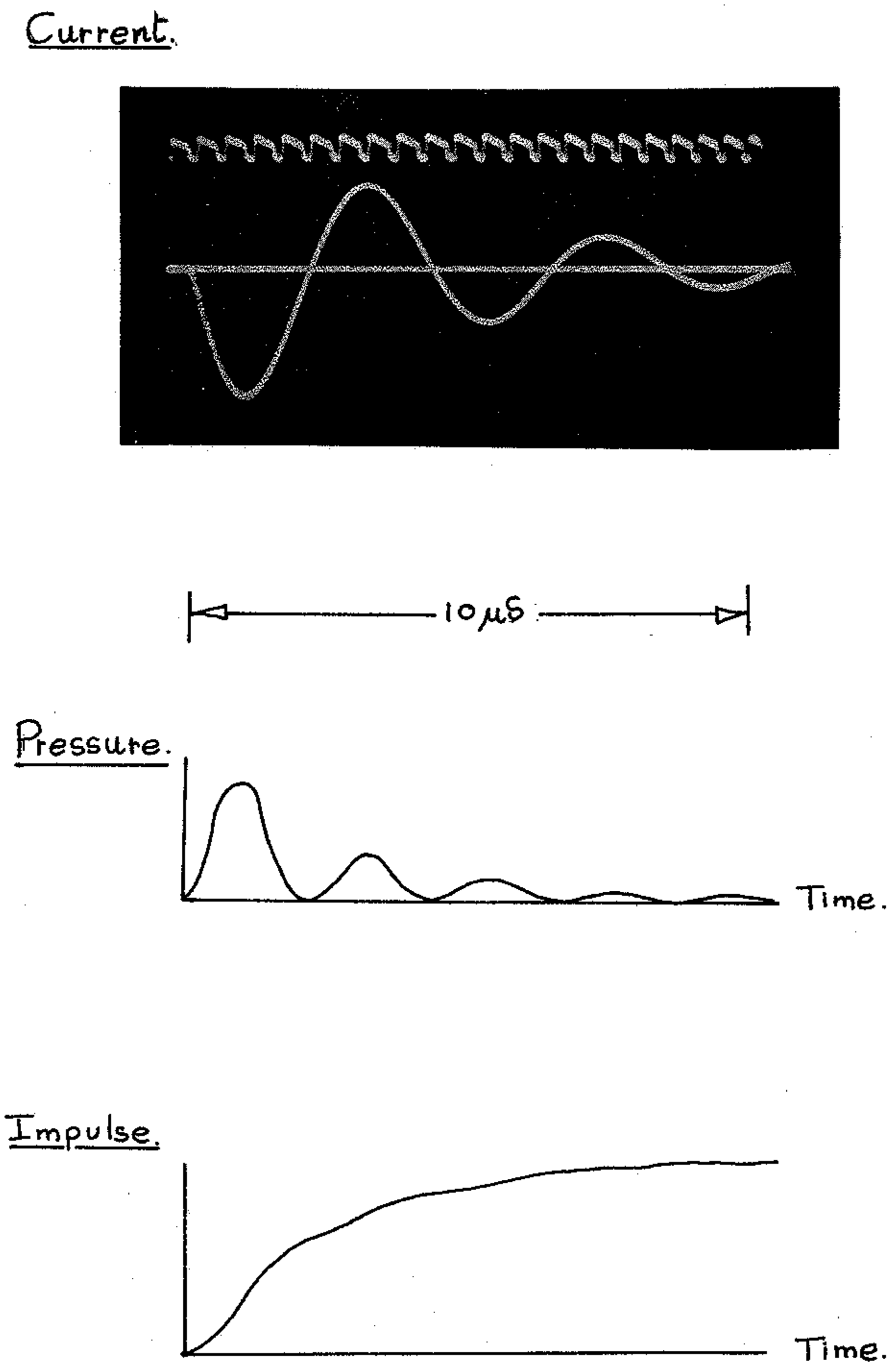


Fig (1) Normal Oscillatory Current.

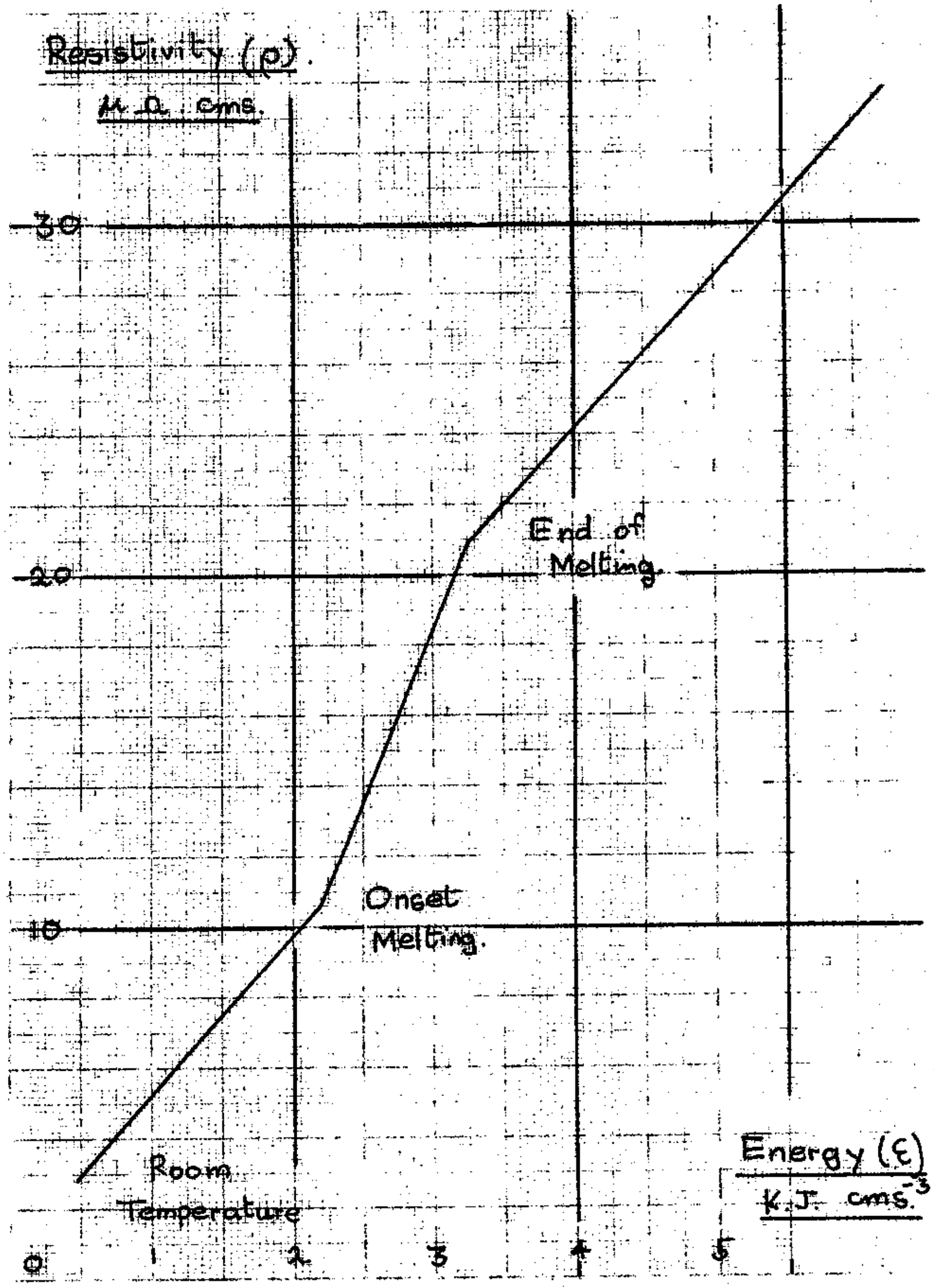


Fig (2). Electrical Equation of State. (Al).

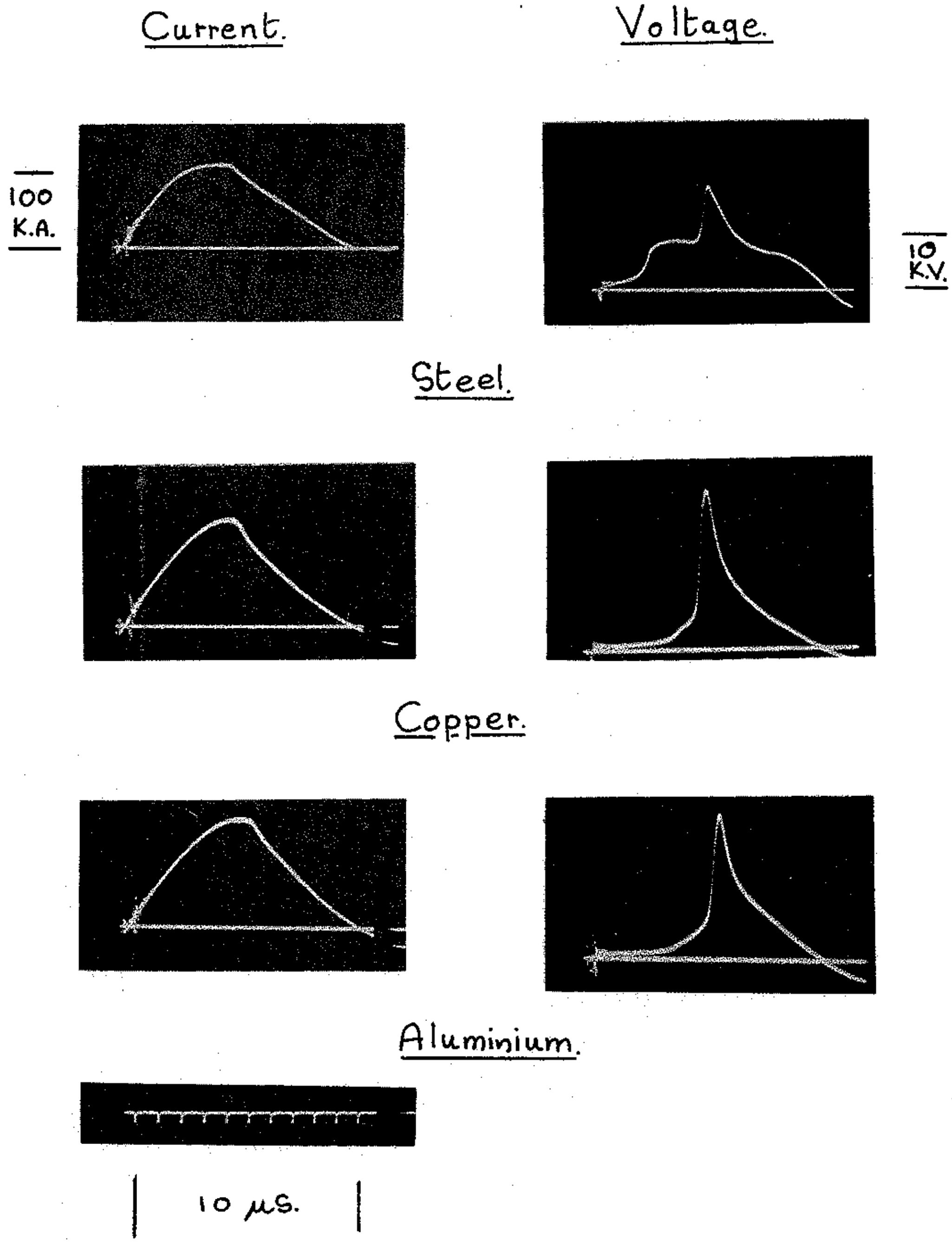


Fig (3) Exploding Foil Waveforms.

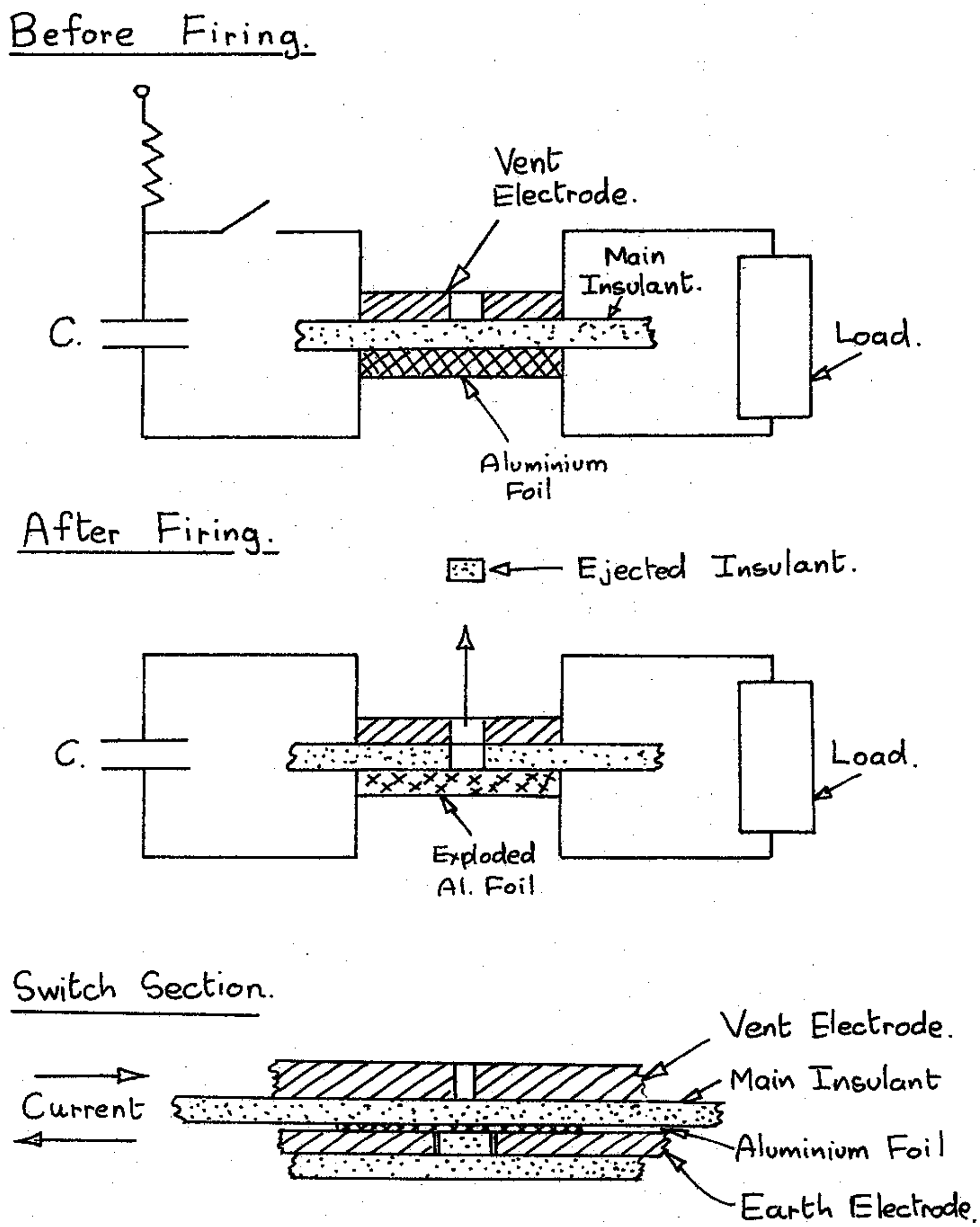
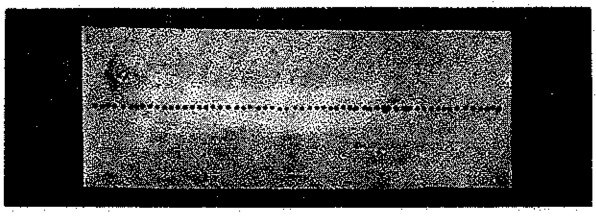
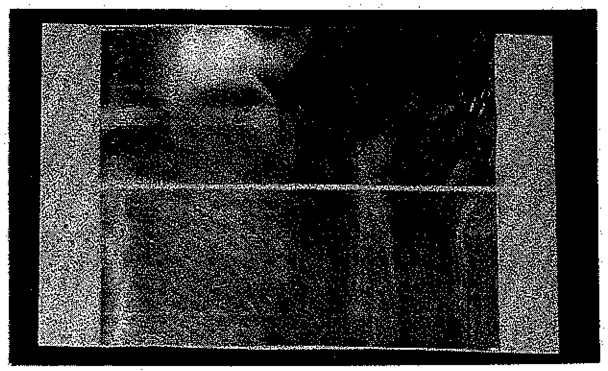


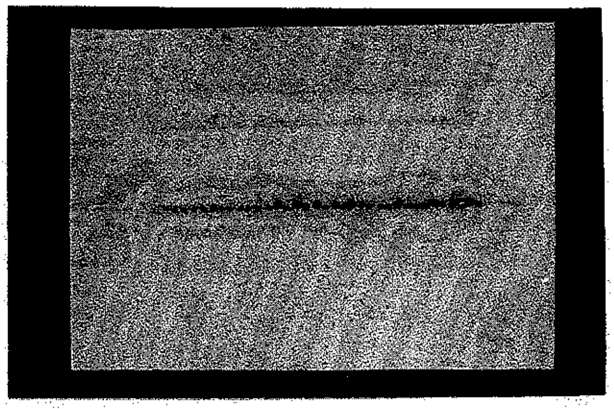
Fig (4) Crowbar Switch Construction.



Vent
Electrode.



Earth
Electrode.
(Before Al
Foil and main
Insulant added.)



Main
Insulant
(After
firing.)

Fig (5) Crowbar Switch Photographs.

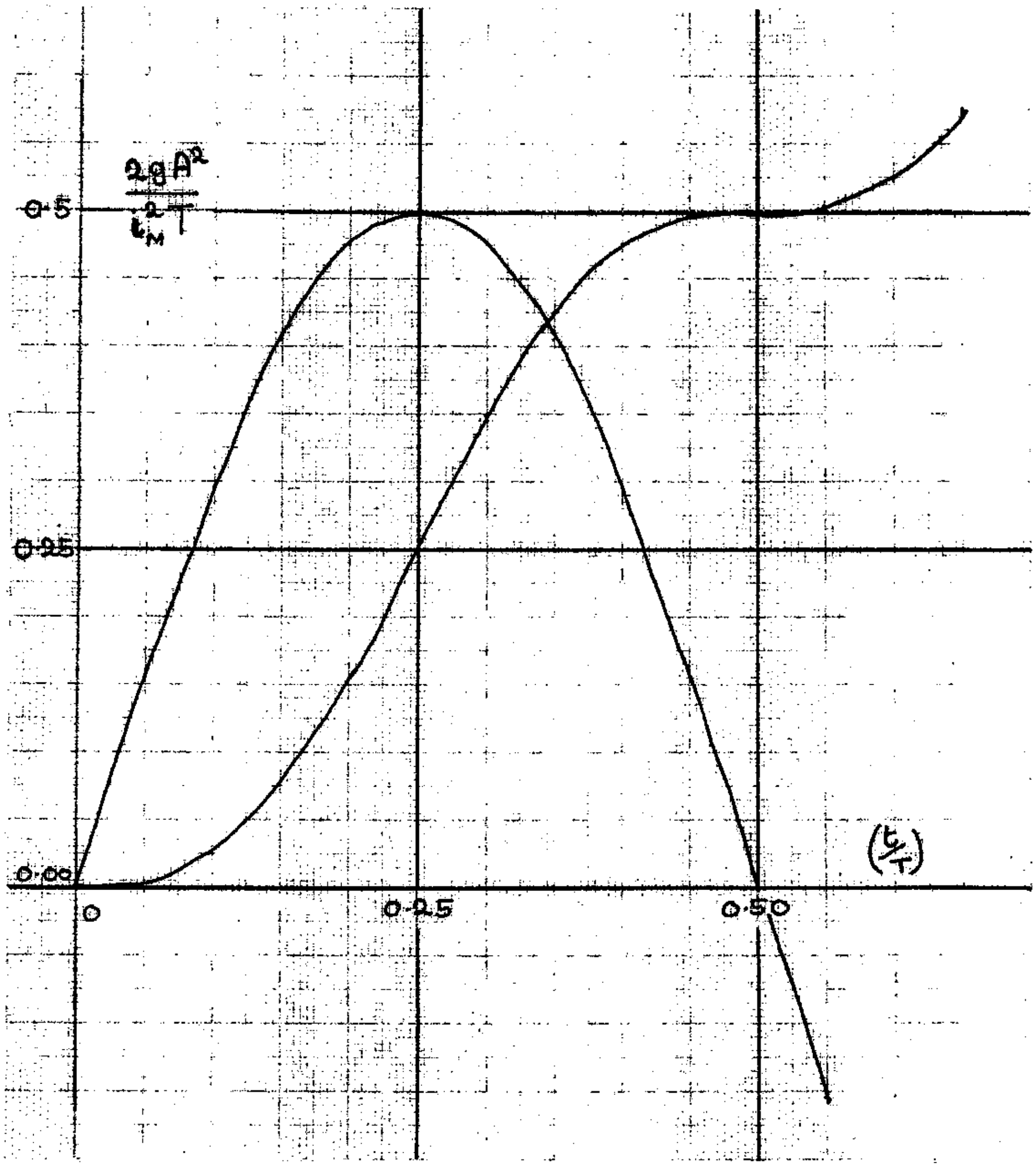


Fig (6) Normalised Action Integral.

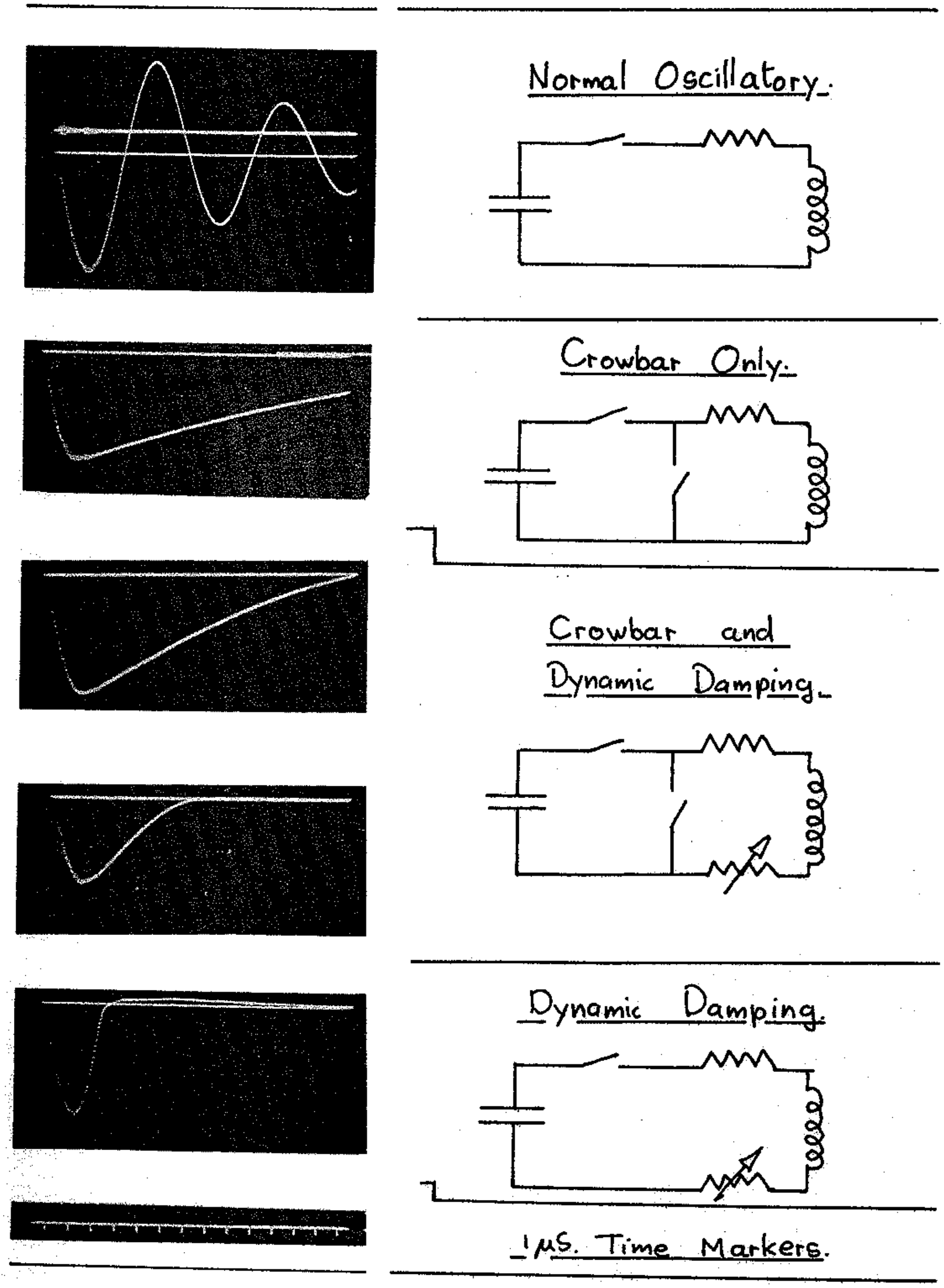


Fig (7) Shaped Current Waveforms.

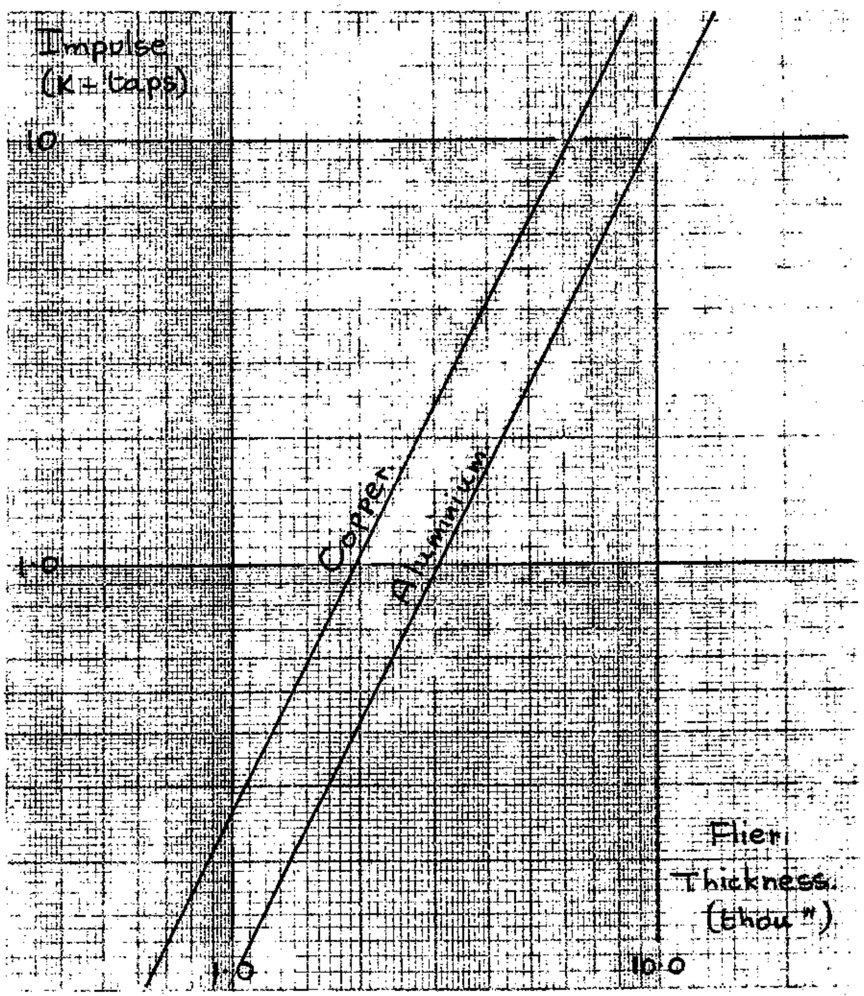


Fig (8) Impulse Limits for Flying Foils.