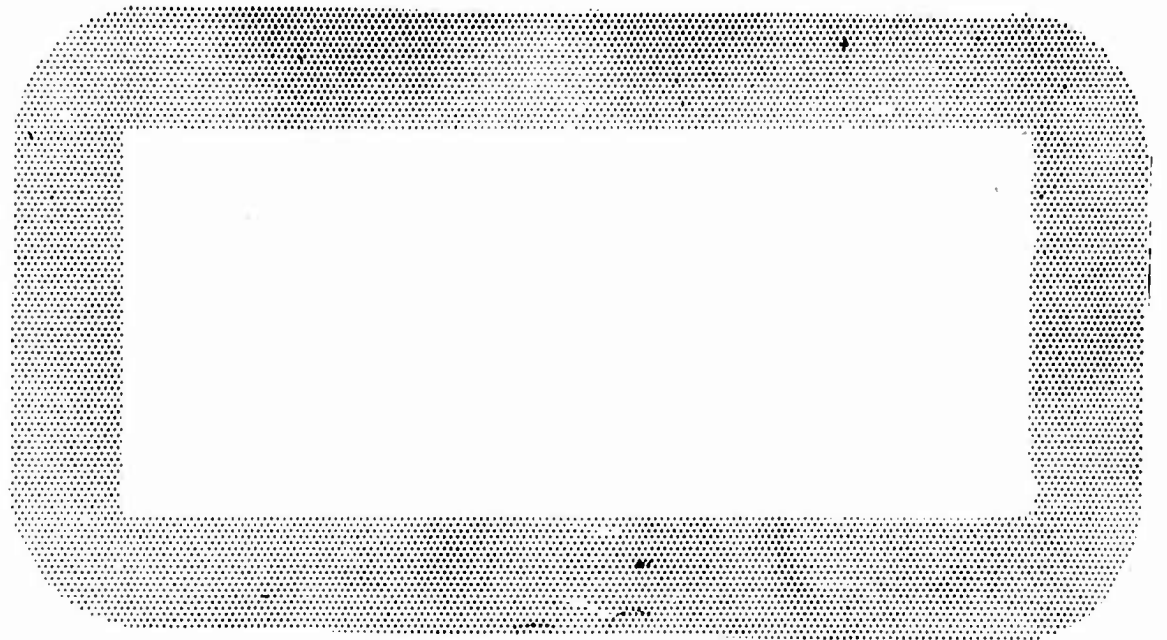


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A METHOD FOR PROTECTING ELECTROEXPLOSIVE
DEVICES FROM SPURIOUS ELECTRICAL INITIATION

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NWL Technical Memorandum No. W-3/60

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INTRODUCTION

This memorandum was prepared under BUORD Task Assignment 992-918/80004/01064, EM Radiation Hazards (HERO). The purpose of this memorandum is to provide a permanent record of a proposed method for protecting squibs or other electroexplosive devices from spurious electrical initiation. Acknowledgement is made of the helpful comments on the mathematical treatment given by Dr. G. E. H. Vibrans of the Computation and Analysis Laboratory.

BACKGROUND

Electroexplosive devices are hazardous if there is a possibility that spurious electrical signals may be introduced that can cause initiation of the explosion. Protection can be provided by preventing the introduction of spurious signals or by reducing the sensitivity of the EED to the point that the spurious signals cannot cause initiation. One general approach is to use frequency discrimination or some form of coding to give high sensitivity to the true signal and low sensitivity to spurious signals. Another approach is to use some simple device to lower the sensitivity to all signals until firing is to take place. Then an arming operation raises the sensitivity in preparation for the true firing signal. The method to be described is in this latter category.

DESCRIPTION OF METHOD

It is proposed to protect the EED from initiation from spurious signals by completely enclosing it in a metallic shield. To arm the device, a large dc current melts away the part of the shield that surrounds the firing leads to the EED. The novel feature is the use of a small silicon diode in series with the firing lead inside the shield to block the dc arming current from initiating the EED. An alternating current or a direct current of opposite polarity can then be used to fire the EED in the usual way at a later time. The advantage of separating the arming and firing functions is that the arming current may be made much larger than any available spurious signal. The firing sensitivity of the EED may be any value required by other design considerations such as limited available firing current. If the diode is not used, the fusible shunt merely lowers the EED sensitivity, and firing occurs at arming.

DESIGN FORMULAS

It is convenient to use a small circular section of metal foil centered on the "hot" firing lead as the part of the shield to be burned away. The following formula, which is derived in Appendix A, gives an approximate value for the maximum safe current, which will not cause the disk to reach melting temperature at any point:

$$I_s = \frac{12.6h \cos^{-1}(T_o/T_m)}{\log_e(r_2/r_1)} \left(\frac{k}{\rho_o/T_o} \right)^{1/2}$$

where

- I_s = maximum safe current (amp)
- h = thickness of foil (cm)
- r_1 = inside radius of disk (cm)
- r_2 = outside radius of disk (cm)
- k = heat conductivity (watts/°K-cm)
- T_o = ambient temperature (°K)
- T_m = melting temperature (°K)
- ρ_o = resistivity at T_o (ohm-cm)

In this formula it is assumed that the inside and outside radii are held constant at temperature T_o .

An estimate of the constant current which will melt the disk in a given time t_a is obtained from the formula of Appendix A,

$$I_a = [I_s^2 + (39h^2 T_o c d r_1 r_2 / \rho_o t_a) (\log_e T_m/T_o + Q/cT_m)]^{1/2}$$

where

- I_a = arming current (amp)
- t_a = arming time (sec)
- C = specific heat (joules/g°K)
- d = density (g/cm³)
- Q = latent heat of fusion (joules/g)

An estimate of the arming capacitor required to melt the burnout disk by discharge current in a time $t_a = RC$ is given by the formula of Appendix A,

$$C = (39h^2 T_o cd r_1 r_2 / \rho_o) (\log_e T_m / T_o + Q/cTm) (0.432 V_o^2 / R - I_s^2 R)^{-1}$$

where

- C = arming capacitance (farads)
- V_o = initial capacitor voltage (volts)
- R = discharge circuit resistance (ohms)

In this formula fixed discharge-circuit resistance is assumed large compared to variations in disk resistance so that R is a constant. The shunt resistance of the disk is given by

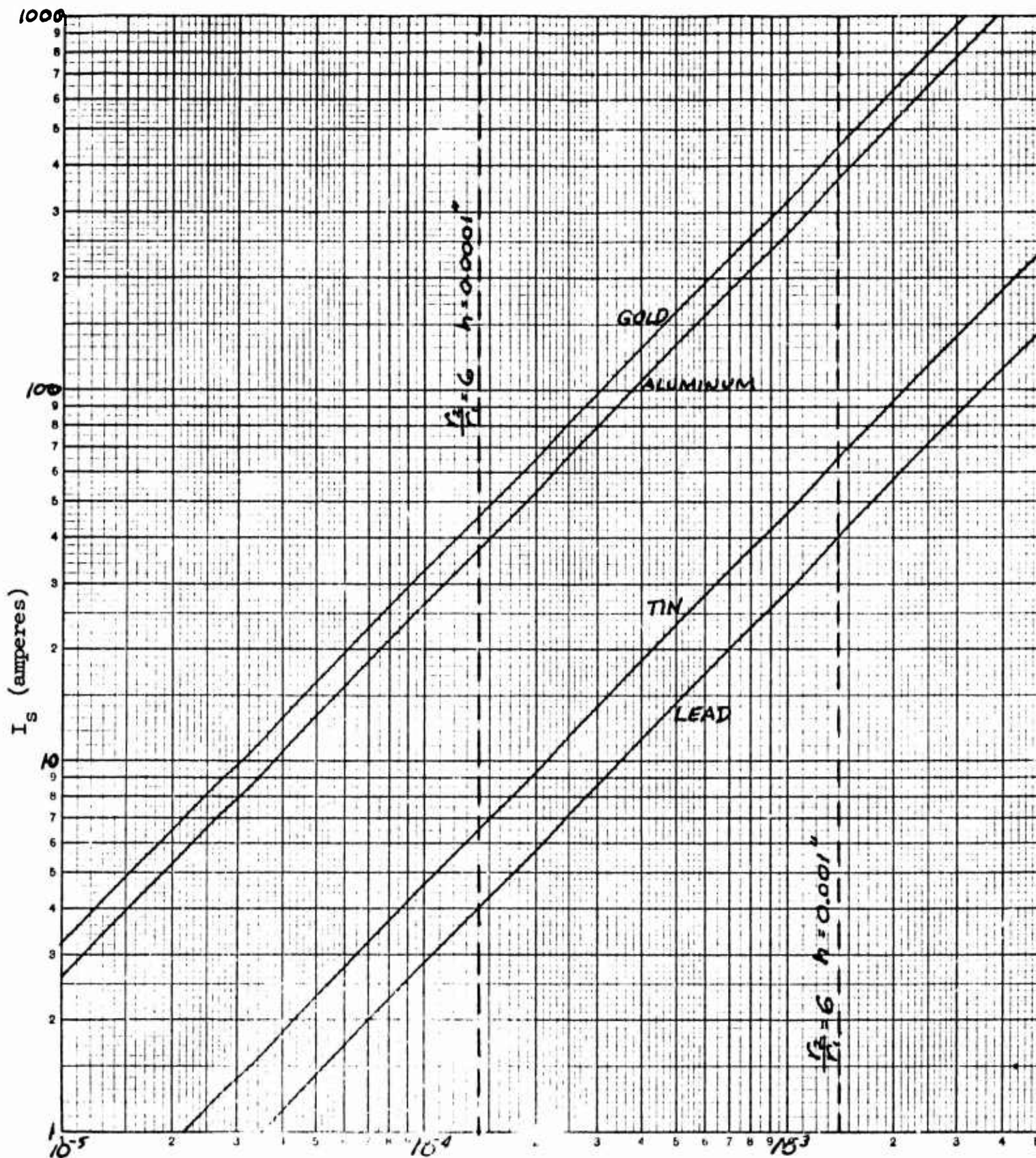
$$R_d = (\rho_o T \log_e r_2 / r_1) (6.3h T_o)^{-1} \text{ (ohms)}$$

TYPICAL DESIGNS

Figure 1 is a plot of the computed maximum safe current I_s as a function of geometry for several suitable metals. Also shown are the abscissas corresponding to a ratio of outside to inside radius of 6 and foil thicknesses of one mil and one-tenth mil. Figure 2 gives the ratio of computed minimum arming current to computed maximum safe current as a function of arming time and inside and outside radii. The condition corresponding to an inside radius of 0.5 mm, an outside radius of 3 mm, and an arming time of 10 milliseconds is marked.

EXAMPLE 1

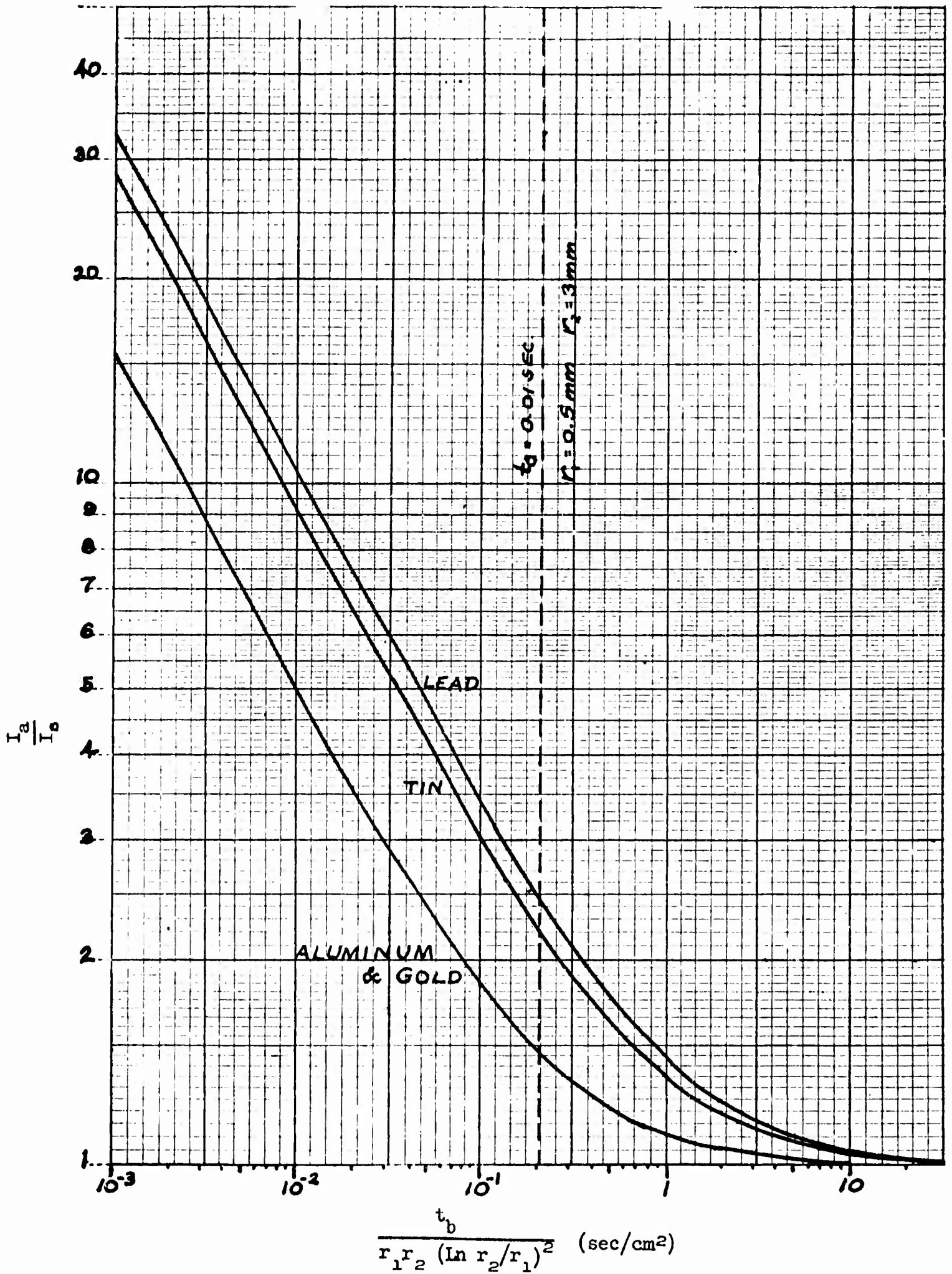
A typical design for the burnout disk might be one-mil tin foil with an inside radius of 0.5 mm and an outside radius of 3 mm. From Figure 1 the maximum safe current would be 65 amperes. From Figure 2 the ratio of arming to safe current is 2.22 for an arming time of 10 milliseconds. Then the characteristics for this example would be:



$$\frac{h}{\ln r_2/r_1} \quad (\text{cm})$$

Maximum safe current as a function of foil thickness and ratio of outside to inside radius

Figure 1



Ratio of arming current to safe current as a function of arming time and inside and outside radii

Figure 2

Example 1

Material - Tin

$$h = 0.001 \text{ in.} = 0.0025 \text{ cm}$$

$$r_1 = 0.5 \text{ mm} \quad r_2 = 3 \text{ mm}$$

$$R_d = 0.0013 \text{ ohms at } 300^\circ\text{K}$$

$$I_s = 65 \text{ a.}$$

$$I_a = 144 \text{ a. for } t_a = 10 \text{ msec}$$

EXAMPLE 2

If the disk of Example 1 were made of one-tenth-mil tin but was otherwise the same, the current values would be decreased by a factor of ten from Example 1. Conditions would now be favorable for arming by capacitor discharge. Let the arming capacitor be charged to an initial voltage of 25 volts and the arming circuit resistance be one-tenth ohm. Then by the design formulas the characteristics are computed to be

Example 2 *

Material - Tin

$$h = 0.0001 \text{ in.} = 0.00025 \text{ cm}$$

$$r_1 = 0.5 \text{ mm} \quad r_2 = 3 \text{ mm}$$

$$R_d = 0.013 \text{ ohms at } 300^\circ\text{K}$$

$$I_s = 6.5 \text{ a.}$$

Constant-current arming:

$$I_a = 14.4 \text{ a. for } t_a = 10 \text{ msec}$$

Capacitor-discharge arming:

$$V_o = 25 \text{ v} \quad R = 0.1 \text{ ohm}$$

$$C = 6200 \text{ uf}$$

$$t_a = 0.62 \text{ msec}$$

EXPERIMENTAL RESULTS

A burnout disk of one-mil tin foil was constructed with an inside radius of 0.5 mm and an outside radius of 3 mm. This corresponds

to the foregoing Example 1. Very rough measurements indicated no burnout with about 50 amperes and burnout with about 100 amperes. Neither of these were limiting values. However they do substantiate the computed value of 65 for maximum safe current.

APPLICATIONS

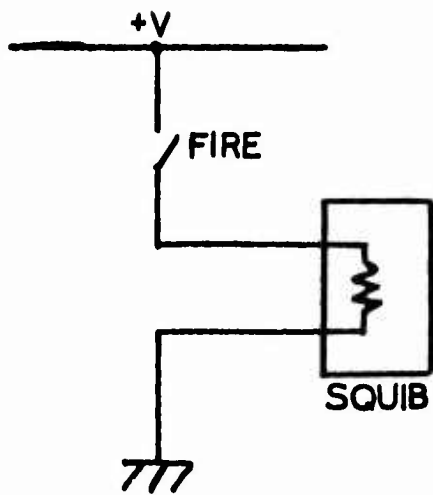
Figures 3 and 4 show two simple arrangements for utilizing the described method for protecting EED's from spurious electrical signals. Figure 3a shows a typical existing firing circuit with the improved method applied in Figure 3b. Here burnout of the protection disk (arming) is provided by discharge of a capacitor. Figure 4b shows the improved method applied to the capacitor-discharge firing circuit of Figure 4a.

Example 2 of the typical designs had a resistance of 0.013 ohms, a maximum safe current of 6.5 amperes, and a 6200 uf arming capacitor charged to 25 volts. Figure 5 shows such a disk used in the circuit of Figure 3 to protect a Mk 1 squib. Based on a no-fire current of 0.2 amperes for the Mk 1 squib, 30 db of protection is provided (current is considered more significant than power at these low impedance levels). More protection may be obtained by increasing h.

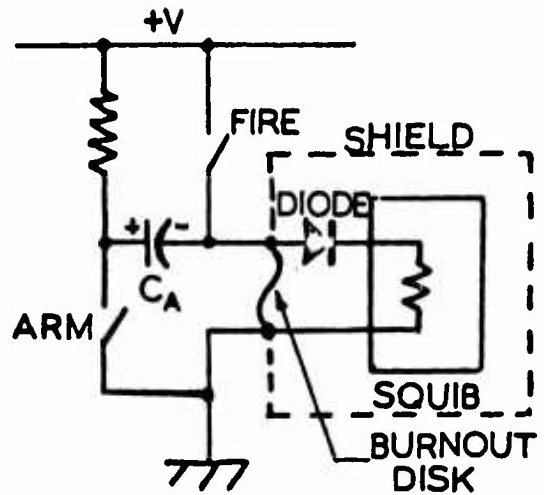
For large values of h, such as in Example 1, the high burnout current may be obtained more easily in the circuit of Figure 4. Figure 6 shows such an arrangement for protecting a Mk 1 squib. Here the 65-ampere safe current provides 50 db of protection.

The silicon diode shown in Figures 5 and 6 as well as the burnout disk will meet the environmental requirements for squibs. The 1N649 silicon diode used in the two examples has a reverse voltage limit of about 700 volts. In the detailed design of such circuits additional components might be required to suppress arming-circuit transients exceeding this voltage in the reverse direction or exceeding zero in the forward direction. However, such components would be in the firing circuit and would not cause any additional complexity in the squib assembly.

It should be understood that the design formulas and examples given in this memorandum are only approximate. The final design for a given application would have to be determined experimentally.

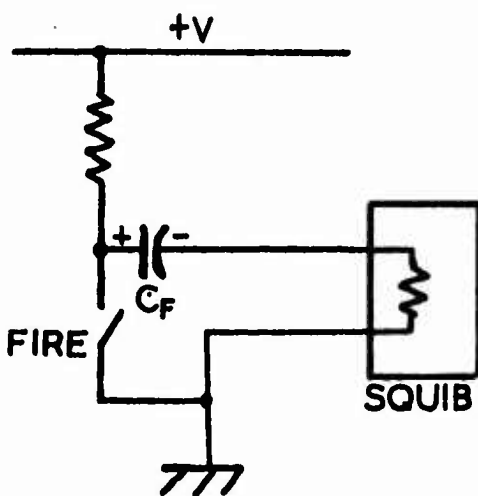


(a) Firing circuit only.

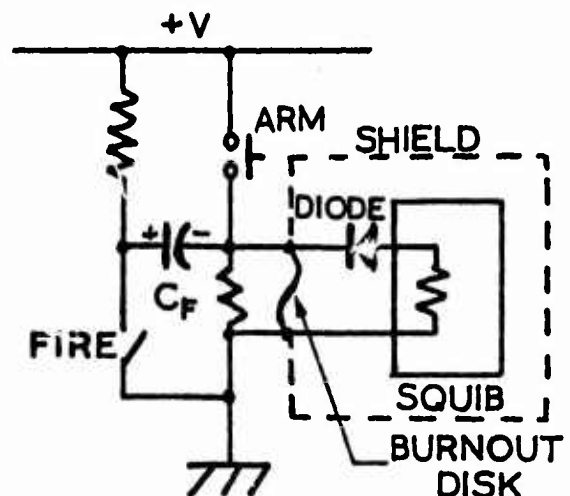


(b) Arming function added.

Fig. 3 - Capacitor-discharge arming.



(a) Firing circuit only.



(b) Arming function added.

Fig. 4 - Capacitor-discharge firing.

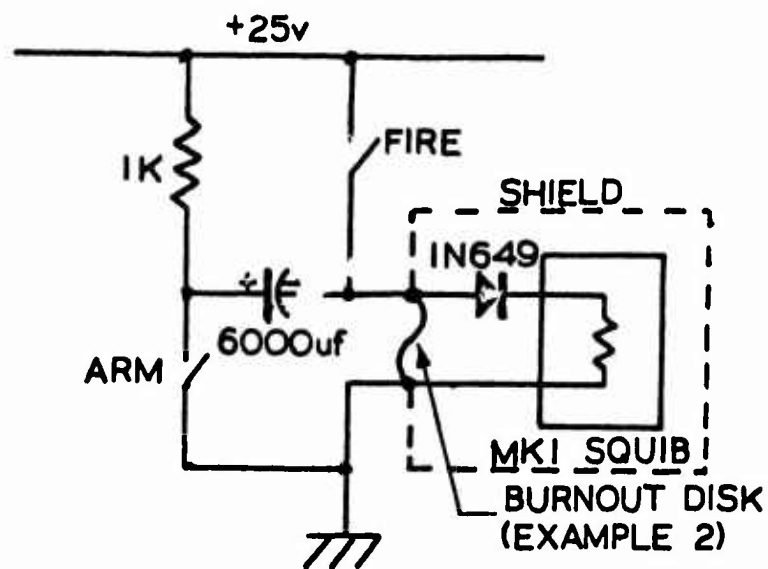


Fig. 5 - 30db protection for the Mk I squib.

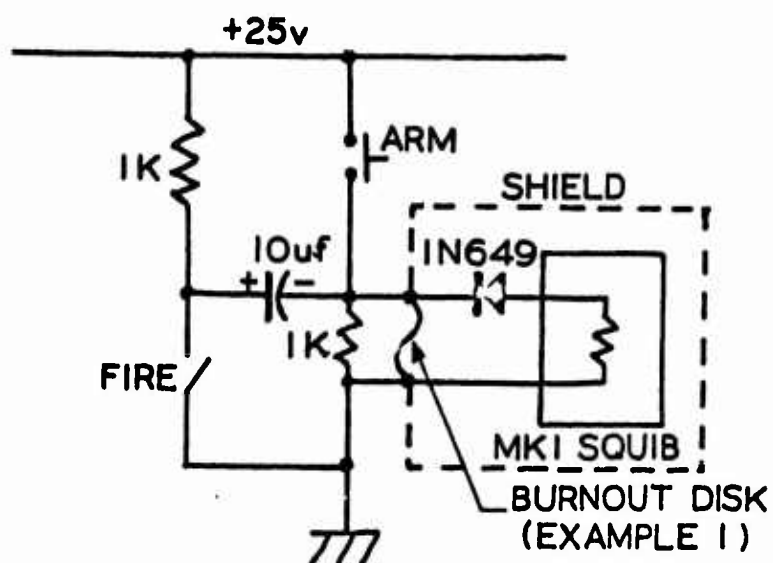


Fig. 6 - 50db protection for the Mk I squib.

APPENDIX A

DERIVATION OF DESIGN FORMULAS

1. Maximum Safe Current

Let the shield surrounding the EED be a relatively thick sheet of high-conductivity material. Let the part to be burned away in the arming operation be a disk of foil centered on the "hot" firing lead. Let the inside radius of the foil disk be r_1 (cm), the outer radius be r_2 (cm), and the thickness of the foil be h (cm). Let there be a constant current of I (amperes) from the center to the rim with uniform distribution around the disk. Then the current density at a radius r (cm) is

$$J = \frac{I}{2\pi r h} \text{ (amp/cm}^2\text{)}$$

Let the resistivity of the disk at absolute temperature T ($^{\circ}\text{K}$) be approximated by

$$\rho = \frac{\rho_0 T}{T_0} \text{ (ohm-cm)}$$

where ρ_0 is the resistivity at room temperature T_0 . Then the rate of heat gain by electrical dissipation is

$$P_g = J^2 \rho \text{ (watts/cm}^3\text{) or}$$

$$P_g = A \frac{T}{r^2}$$

$$\text{where } A = \frac{I^2 \rho_0}{4\pi^2 h^2 T_0} \text{ (watts/}^{\circ}\text{K-cm)}$$

The rate of heat gain by divergence of the heat flow is given by

$$P_f = k \nabla^2 T \text{ (watts/cm}^3\text{)}$$

where k is the heat conductivity (watts/ $^{\circ}\text{K-cm}$). Since flow is only radial and is uniform around the disk,

$$P_f = k \left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} \right)$$

If cooling by radiation and convection are neglected, the rate of temperature rise is given by

$$\frac{\partial T}{\partial t} = \frac{P_g + P_f}{cd} \text{ (}^\circ\text{K/sec)}$$

where c is the heat capacity (joules/g $^\circ$ K) and d is the density (g/cm 3). Then

$$T_t = \frac{k}{cd} (T_{rr} + \frac{1}{r} T_r) + \frac{A}{cd} \frac{T}{r^2}$$

is the general differential equation for the system.

The steady-state differential equation is

$$T_{rr} + \frac{1}{r} T_r + \frac{A}{k} \frac{T}{r^2} = 0$$

A steady-state solution is

$$T = T_m \cos [(A/k)^{1/2} \log (r/r_0)]$$

where T_m and r_0 are arbitrary constants. Let the inside and outside radii of the disk, r_1 and r_2 , be held at ambient temperature T_0 . Then

$$T_0 = T_m \cos [(A/k)^{1/2} \log (r_1/r_0)] = T_m \cos [(A/k)^{1/2} \log (r_2/r_0)]$$

$$r_0 = \sqrt{r_1 r_2}$$

$$T_0 = T_m \cos [(A/k)^{1/2} \log (r_2/\sqrt{r_1 r_2})]$$

$$T = T_0 \frac{\cos [(A/k)^{1/2} \log (r/\sqrt{r_1 r_2})]}{\cos [(A/k)^{1/2} \log (r_2/\sqrt{r_1 r_2})]}$$

The maximum temperature is T_m and is reached where $r = (r_1 r_2)^{1/2}$. If T_m is set equal to the melting temperature of the foil, the maximum safe value for A is

$$A_s = k \left(\frac{2 \cos^{-1} (T_0/T_m)}{\log (r_2/r_1)} \right)^2$$

This may be expressed as a design equation for maximum safe current

$$I_s = 12.6h (k T_o / \rho_o)^{1/2} \frac{\cos^{-1} (T_o / T_m)}{\log (r_2 / r_1)}$$

2. Arming Current

The general differential equation

$$T_t = \frac{k}{cd} (T_{rr} + \frac{1}{r} T_r) + \frac{A}{cd} \frac{T}{r^2} \quad (1)$$

has a transient solution involving Bessel functions of imaginary order which have not been tabulated. Therefore an approximate analysis will be presented.

The general equation shows that the temperature is changed by heat conduction $\frac{k}{cd} (T_{rr} + \frac{1}{r} T_r)$ and electrical power dissipation $\frac{A}{cd} \frac{T}{r^2}$. Initially there is no conduction, and

$$T_t = \frac{A}{cd} \frac{T}{r^2} \quad \text{or} \quad T = T_o e^{\frac{At}{cdr^2}} \quad (2)$$

As the temperature rises convex temperature contours develop near the boundaries which result in conduction losses and retardation of temperature rise. A concave temperature contour develops between the boundaries which results in a conduction gain and enhancement of temperature rise. The trend is therefore toward the generally convex steady-state contour when conduction loss equals heat input at all points. It is now assumed that this approach is monotonic and that losses are always less than or equal to the heat input term. Then (expressed as a gain)

$$\frac{k}{cd} (T_{rr} + \frac{1}{r} T_r) \geq - \frac{AT}{cdr^2} \quad (3)$$

By inspection of the general equation (1), it can be seen that larger values of A would cause the temperature function to behave more like equation (2) to higher values of T. However, equation (2) implies a conduction gain. On the basis of this observation it is assumed that for $A > A_s$, $r^2 = r_1 r_2$, and $T \leq T_m$,

$$\frac{k}{cd} (T_{rr} + \frac{1}{r} T_r) > - \frac{A_s T}{cd r_1 r_2} \quad (4)$$

Substitution of (4) into (1) gives

$$T_t > - \frac{A_s T}{cd r_1 r_2} + \frac{AT}{cd r_1 r_2}$$

$$\frac{T_t}{T} > \frac{A - A_s}{cd r_1 r_2} \quad (5)$$

Integration of (5) gives

$$\log T > \frac{A - A_s}{cd r_1 r_2} t + B$$

If $T = T_0$ when $t = 0$ and $T = T_m$ when $t = t_1$,

$$\log \frac{T_m}{T_0} > \frac{A - A_s}{cd r_1 r_2} t_1 \quad (6)$$

If the latent heat of fusion is Q (joules/g), a similar derivation will lead to the expression

$$\frac{Q}{cTm} > \frac{A - A_s}{cd r_1 r_2} t_2 \quad (7)$$

where t_2 is the time required to supply the latent heat of fusion after temperature T_m is reached. By combining (6) and (7) and letting the arming time be $t_a = t_1 + t_2$,

$$\log \frac{T_m}{T_0} + \frac{Q}{cTm} > \frac{A_a - A_s}{cd r_1 r_2} t_a$$

Expression of A_s and A_a in terms of the safe current I_s and arming current I_a gives

$$I_a < [I_s^2 + \frac{39h^2 T_o cd r_1 r_2}{\rho_o t_a} (\log T_m/T_o + Q/cTm)]^{1/2} \quad (8)$$

3. Capacitor Discharge

In the previous section the constant-current burnout condition was derived. The conditions for arming by a capacitor discharge would also be useful.

It is assumed that the fixed circuit impedance is large compared to the disk resistance and is resistive with a value R. Let an arming capacitor C be initially charged to voltage V_o and discharged through the burnout disk and arming-circuit resistance R beginning at time $t = 0$. The current is given by

$$I = \frac{V_o}{R} e^{-t/RC} \quad (9)$$

By equations (5) and (9)

$$\frac{T_t}{T} > \frac{A - A_s}{cd r_1 r_2} = \frac{\rho_o}{39h^2 T_o cd r_1 r_2} \frac{V_o^2}{R^2} e^{-2t/RC} - I_s^2$$

Integration gives

$$\log T_m/T_o > \frac{\rho_o}{39h^2 T_o cd r_1 r_2} \left[\frac{V_o^2 RC}{2R^2} (1 - e^{-2t_1/RC}) - I_s^2 t_1 \right]$$

A similar modification of equation (7) gives

$$\frac{Q}{cTm} > \frac{\rho_o}{39h^2 T_o cd r_1 r_2} \left[\frac{V_o^2 RC}{2R^2} (e^{-2t_1/RC} - e^{-2t_a/RC}) - I_s^2 t_2 \right]$$

Where t_a is the time from zero to burnout and $t_2 = t_a - t_1$. Then

$$\frac{39h^2 T_0 c d r_1 r_2}{\rho_0} (\log T_m/T_0 + Q/cTm) > \frac{V_0^2 RC}{2R^2} (1 - e^{-2t_a/RC}) - I_s^2 t_a \quad (10)$$

For convenience let $t_a = RC$. Then a design formula for the arming capacity for given values of V_0 and R is:

$$C = \frac{(39h^2 T_0 c d r_1 r_2 / \rho_0) (\log T_m/T_0 + Q/cTm)}{0.432 V_0^2 / R - I_s^2 R} \quad (11)$$