Memo to XTE Project: Response of a FM08 Style Fuse to a Pulse of Current

Dr. Henning Leidecker

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Webster: Melanie Ott

National Aeronautics and
Space Administration

Goddard Space Flight Center
Greenbelt, Maryland
20771

NASA

Reply to Attn of: 313

March 11, 1994

TO: Code 303.0/XTE Project/Mr. M. Delmont

FROM: 313.0/Materials Branch

SUBJECT: Response of a FM08 style fuse to a pulse of current

REFERENCE: (a) Report presented at the ISTFA symposia of 1981, "Incremental Failure Mechanism in Subminiature Hermetically Sealed Fuses", Esther Williams and Steven Battel.

(b) Report presented at the ISTFA symposia of 1982, "Study To Establish Limits For Reliable Fuse Application In Transient Environment", Esther Williams and Steven Battel.

Introduction:

Mr. M. Bay sent me a FAX of a scope trace of a current pulse, and asked me to compute the temperature rise this pulse would produce in an FM08 style fuse rated at 7 A. He also asked me for an estimate of the number of times such a fuse could safely endure such a pulse.

Finally, he asked me to develop a "first order" safe operating range for fuses under pulses.

Conclusions/Recommendations:

The temperature rise produced by this pulse, 1.1° C ±15%, has negligible consequences for this fuse: it will certainly endure many tens of thousands of such pulses.

Repetitions of this exercise would be simplified if the pulse were supplied in digital form.

The safe operating range reported in Refs (a) and (b) are based on results obtained for FM08 style fuses rated between 1.5 A and 4 A: these use filaments made of copper/silver alloy. Additional work is required to extend these results to FM08 style fuses rated at 5 A to 15 A, which use filaments made of pure copper with a thin silver coating. Thus, the requested development of a reliable operating range for fuses under pulses is deferred to a later time.

Discussion:

Rated current, and Interruption current:

The only pre-approved high reliability fuses are FM08 style, defined by MIL-F-23419. The rating of an FM08 fuse is a single number permanently printed on the case of the fuse. The interrupt current, however, is a variable which depends upon the rating, upon details

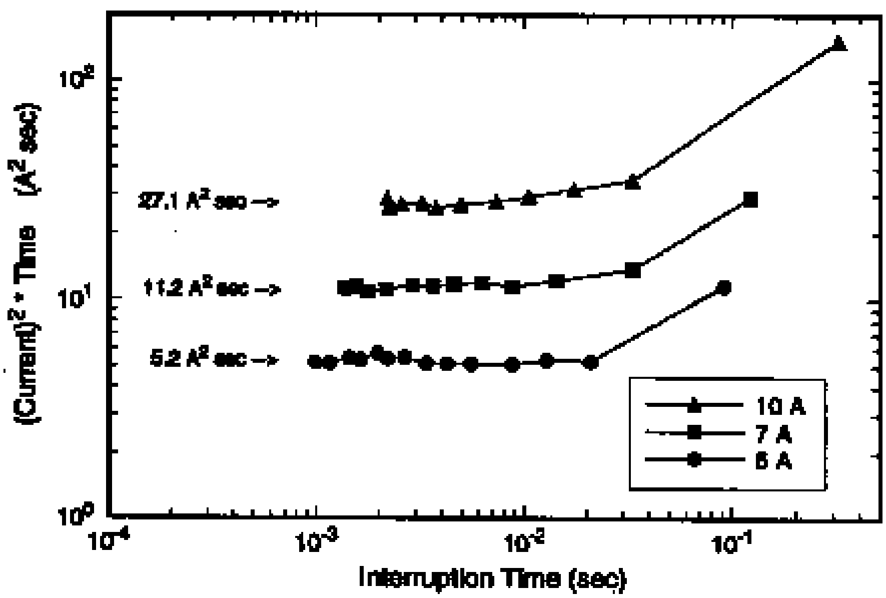

Figure 1: Plot of some of the data obtained by Mr. Peter O'Shea, then of Paramax at GSFC. This data is consistent with the manufacture's curves.

of the current pulse applied to the fuse, upon the thermal sinking of the filament of the fuse, and any degradation (such as oxidation or mechanical fatigue).

An undegraded FM08 fuse may be expected to carry its full rated current for at least four hours, but will interrupt within a few days; thus, the interruption current is close to the rated current for such times. However, for pulses shorter than about 20 msec, the interrupt current i_{int} grows much larger than the rated current; indeed, $i_{int}^2 \cdot t_{int} = \text{constant}$,[1] where t_{int} is the time duration of the interrupting current: this constant plays the role of the characteristic value that indicates whether a given pulse is likely to be damaging.

Figure 1 is a plot of $i_{int}^2 \cdot t_{int}$ vs. t for FM08 fuses rated at 5 A, 7 A, and 10 A, illustrating that the quantity $i_{int}^2 \cdot t_{int}$ becomes constant for interruption times t_{int} shorter than about 20 msec, and that the value of this constant increases with the rating of the fuse.

However, I know of no tests of this rule for FM08 fuses for times less than roughly 500 μsec. There is evidence that a new mechanism begins to operate for the huge currents that are implied by the "$i_{int}^2 \cdot t_{int}$ is constant" rule for shorter times. Hence, I recommend against extrapolation of this rule to times shorter than 500 μsec. We could consider carrying out some testing of this rule over the range 1 msec to 1 μsec. Until appropriate data becomes available, I recommend that the current through the fuse be limited to the value implied by use of the rule for a time of 500 μsec, in order to avoid interruption within a single pulse.

[1] For pulses of non-rectangular shape, use $\int_0^{t_{int}} i^2\, dt$ in place of $i_{int}^2 \cdot t_{int}$.

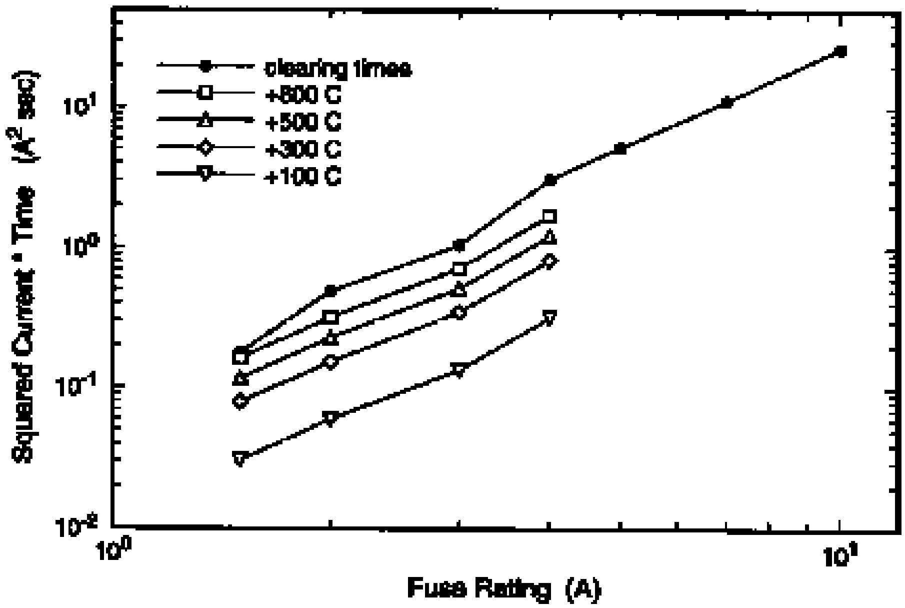

Figure 2: Plot of the $i^2 \cdot t$ values producing various temperature rises in FM08 filaments, as per Ref. (b). Also shown are the $i_{int} \cdot t_{int}$ values from Mr. O'Shea's data.

For example, for an FM08 fuse rated at 7 A, Figure 1 illustrates that interruption occurs for $i^2_{int} \cdot t_{int} = 11.2$ A$^2\cdot$sec over the interval from 1 msec to 20 msec. Use of this rule to extrapolate to shorter times gives currents of 150 A for 500 μsec, 335 A for 100 μsec, 1 058 A for 10 μsec, and 3 350 A for 1 μsec. I recommend that the maximum current through an FM08 fuse rated at 7 A be limited to 150 A even for times shorter than 500 μsec, to avoid interruption within a single pulse.

Pulse-degradation current:

References (a) and (b) report that repeated pulses can degrade an FM08 fuse to the point that it will eventually interrupt even when each pulse is within the $i^2_{int} \cdot t_{int}$ limit. The measure of the degradation stress produced by a single pulse is the $i^2 \cdot t$ product ($\int i^2\,dt$ for non-rectangular pulses), and the measure of the fuse's response is the increase in temperature of the filament caused by this pulse. Figure 2 displays the $i^2 \cdot t$ values that produce various temperature rises for FM08 fuses rated between 1.5 A and 4 A, according to Reference (b). Reference (b) also states a relation between these rises and the "safe" number of such cycles: see Table 1.

Inspection shows that these independently obtained data sets are in

which use filaments made of copper-silver alloy. This alloy begins to melt at $(780 \pm 1)^\circ$ C, and melting is complete at about 880° C; hence, an 800° C temperature rise (from about 20° C) is expected to produce partial melting of the filament.

the number of pulses $\mathcal{N}$ that the filament can safely withstand without interruption. Reference (b) offers a table relating $\mathcal{N}$ to $i^2 \cdot t$ for MF08 fuses rated from 1.5 A to 4 A: the

Temperature Rise of fuse filament	Number of Cycles
100° C	maximum life condition
300° C	> 20 000
500° C	> 1 000
800° C	potential damage in one cycle

Table 1: Relation between the temperature rise produced by a pulse, and the number of such pulses the fuse's filament can withstand without mechanical failure. These numbers were established for copper-silver alloy filaments: see Ref. (b).

filaments of these fuses is made of a copper/silver alloy.

I digitized the scope trace that you FAXed me, and re-plotted it: see Figure 3. The accuracy of the digitization is better than ± 1 μsec per point on the time axis and better than ± 0.1 A on the current axis, so digitization errors are less than 1% of the maximum values of this pulse, and thus are negligible compared with typical "pulse to pulse" variations. My experience is that these inrush pulse shapes vary by several percent during repetitions, when all the equipment kept in place, and that much greater changes happen when power supplies are swapped, or cabling is changed. I recommend that the limits of variability of this pulse be established.

The scope probably stored a digital record of this pulse; my digitization of a printed graph (such as the FAX) would be unnecessary if the actual digital data were available directly from the scope. I recommend using the scope's digital data directly if this exercise is repeated.

For times shorter than roughly 20 msec, the joule heat generated within the fuse's filament remains within the filament: there is insufficient time for it to diffuse into the fuse caps, or into air (if any) contained within the fuse barrel. Hence the temperature of the filament is given by

$$c\left(\frac{dT}{dt}\right) = \rho \cdot \left[\frac{i}{A}\right]^2 \tag{1}$$

where

c is the specific heat per volume of the fuse filament;

T is the temperature of the filament;

t is the time;

ρ is the electrical resistivity of the filament;

i is the electrical current through the filament; and

A is the cross-sectional area of the filament.

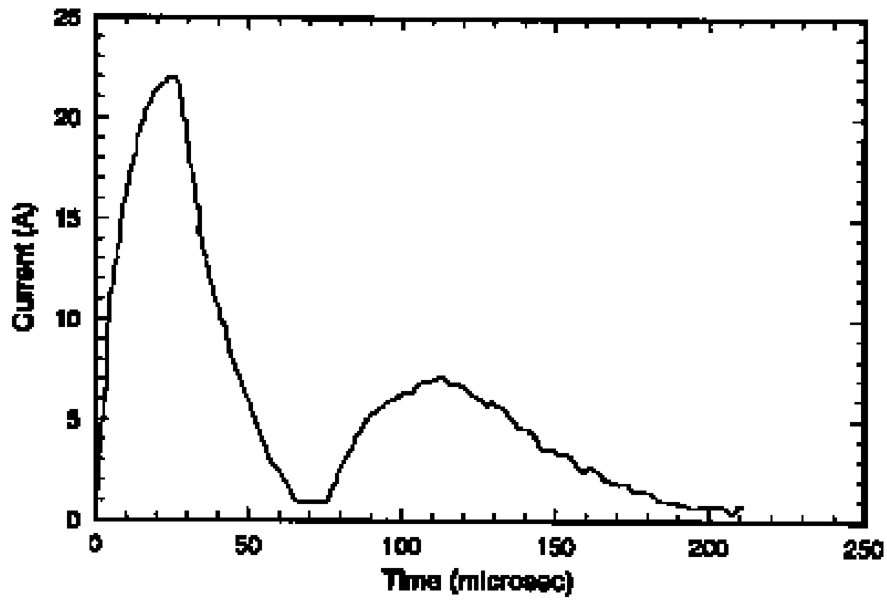

Figure 3: Plot of the current pulse displayed on the FAX.

FM08 fuses rated between 5 A and 15 A have filaments made of pure copper. It is a good approximation for them that c is independent of T and that the resistivity is proportional to the absolute temperature: $\rho = \rho_0 \cdot (T/T_0)$, where T is measured on the Kelvin scale, and T_0 is a reference temperature. I will fix $T_0 = 300\,\mathrm{K} = 27^\circ\,\mathrm{C}$.

Thus the equation for the temperature dynamics is

$$\frac{dT}{dt} = \left[\frac{i^2\rho_0}{cA^2T_0}\right] \cdot T = r \cdot T \tag{2}$$

where $r = r(i) = (i^2\rho_0)/(cA^2T_0)$ is the heating rate parameter for the fuse under the current i. The quantity A is not easily available, but we can obtain it from ρ and the observed resistance $R = \rho\ell/A$, where ℓ is the length of the filament. Hence we express the rate parameter as

$$r = \frac{i^2R_0^2}{T_0c\rho_0\ell^2} = \kappa \cdot i^2 \tag{3}$$

where

$R_0 = 9.95\ \mathrm{m}\Omega \pm 10\%$ is the resistance at 300 K of an FM08 fuse rated at 7 A;

$T_0 = 300\,\mathrm{K}$ is the reference temperature;

$c = 3.45$ joules/(cc$\cdot$ K) is the specific heat of copper;

$\rho_0 = 1.7 \times 10^{-6}\ \Omega$-cm is the electrical resistivity of copper at 300 K; and

$\ell = 0.480$ cm is the length of the filament; and

$\kappa = (R_0^2)/(T_0c\rho_0\ell^2) = (0.244)/(\mathrm{sec}\cdot\mathrm{A}^2) \pm 15\%$.

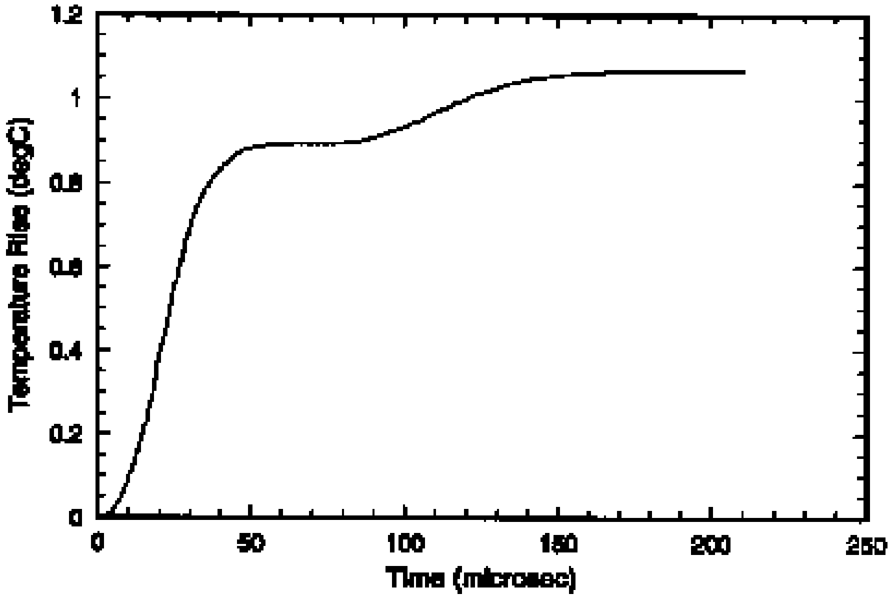

Figure 4: The temperature rise of an FM08 fuse rated at 7 A, under the current pulse given above, when the ambient temperature is in the range 20° C to 25° C.

Hence, the temperature at any time, when we start the fuse at the ambient temperature T_{amb}, is:

$$T(t) = T_{amb} \cdot \exp[\int_0^t r(i)\, dt] = T_{amb} \cdot \exp[\kappa \int_0^t i^2\, dt], \tag{4}$$

unless the temperature exceeds the melting temperature of the filament material; then, melting phenomenona have to be attended to.

And the temperature rise is

$$\Delta T(t) = T(t) - T_{amb} = T_{amb} \cdot \left\{ \exp[\int_0^t r(i)\, dt] - 1 \right\} = T_{amb} \cdot \left\{ \exp[\kappa \int_0^t i^2\, dt] - 1 \right\}; \tag{5}$$

this is plotted in Figure 4, assuming that T_{amb} is in the range 293 K to 298 K (= 20° C to 25° C). We observe that the first part of the pulse produces a temperature rise of about 0.9° C, and the second part of the pulse produces a further rise of about 0.2° C, for a total of about 1.1° C. The uncertainty is about ±15%.

This temperature rise would be 1.3° C ±15% if the ambient temperature were in the range T_{amb} = 340 K to 350 K (= 67° C to 77° C).

Note that the current pulse affects the result through the integral of the square of the current over the duration of the pulse, $\int i^2\, dt$, times a factor κ that depends on the cold resistance R_0 of the fuse (this changes as the fuse rating changes) and some other parameters that are nearly same for all FM08 fuses rated between 3/4 A and 15 A (namely T_0, c, ρ, and ℓ). Hence $\int i^2\, dt$ can be computed once and for all when the current pulse is known,

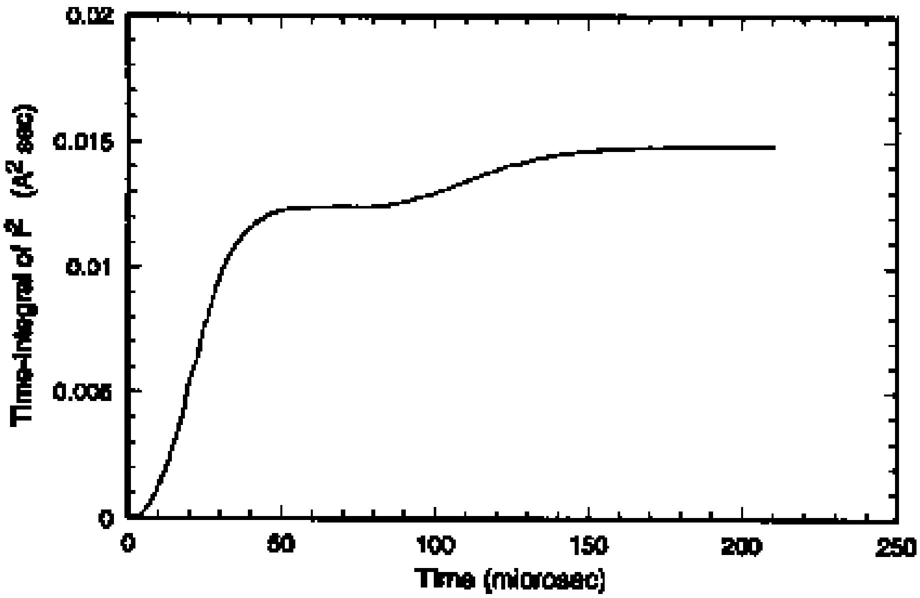

Figure 5: The value of $\int_0^t i^2\,dt$ for the subject pulse.

and then the temperature rise it will produce in a fuse of a given rating can be computed by looking up R_0 for that rating (from MIL–F–23419).

As an example, Figure 5 gives the numerical value of $\int_0^t i^2\,dt$ for the subject pulse. We see that the first (larger) pulse accumulates an $\int i^2\,dt$ of 0.0124 A^2-sec, and the second (smaller) pulse accumulates an additional 0.0024 A^2-sec, for a total of 0.0148 A^2-sec.

We can get about the same values by approximating the subject pulse(s) with a rectangular waveform. For the first pulse, one could use $i_{peak} = 20$ A and duration = 30 μsec, which gives $\int i^2\,dt = 0.012$ A^2-sec. For the second, one could use $i_{peak} = 6$ A and duration = 60 μsec, which gives 0.0022 A^2-sec. The total for this approximation is 0.014 A^2-sec. These approximate values are within a few percent of the more dependable numerical integration.

If we totally enclose the first and second pulses with rectangular pulses, rather than balancing the errors, then we would use 22.5 A and 50 μsec for the first rectangle, and 8 A and 90 μsec for the second. These give $\int i^2\,dt$ values of 0.025 A^2-sec and 0.006 A^2-sec respectively, which are double the accurate values.

Ref. (b) describes failures observed in FM08 fuses rated between 1.5 A and 4 A: these use filaments made of a copper/silver alloy. The failures happened after some number of current pulses were passed through a fuse: SEM-images show the filament broken near it's middle, with no sign of melting. The References relate the safe number of pulses to the temperature rise experienced by the filament: the relation is given in Table 2.

Although the relation of the temperature rise to the number of pulses that the fuse's filament can safely endure has only been established by Ref. (b) for copper-silver filaments,

Temperature Rise of fuse filament	Number of Cycles
100° C	maximum life condition
300° C	> 20 000
500° C	> 1 000
800° C	potential damage in one cycle

Table 2: Relation between the temperature rise produced by a pulse, and the number of such pulses the fuse's filament can withstand without mechanical failure. These numbers were established for copper-silver alloy filaments: see Ref. (b).

I believe that about the same relation will apply to the pure copper filaments used by FM08 fuses rated at 5 A to 15 A.[3]

From Figure 1, we see that interruption of a 7 A fuse happens for an $i^2 \cdot t$ value of 11.2 A^2·sec, which is about 760 times larger than the $\int i^2\, dt$ value generated by the subject pulse. This indicates, from a different perspective, that this pulse is non-damaging.

Henning Leidecker

cc: 313.0/Mr. R. Marriott
313.A/Dr. R. Predmore
313.1/Ms. J. Jellison
313.2/Dr. J. Scialdone
313.3/Mr. T. Heslin
313.4/Dr. H. Chu
313 files

[3]This should be tested.